INTEGRATED DISINFECTION FOR MITIGATING MICROBIAL REGROWTH IN DRINKING WATER DISTRIBUTION SYSTEMS

By

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ABSTRACT

In the treatment and distribution of drinking water, disinfection is a key step for inactivating microbial pathogens and controlling biofouling in pipe lines. Biofilm, which forms on pipe walls, leads to microbial regrowth, biocorrosoin and headloss in distribution systems. Utilities depend on disinfection as a key step for the control of biofilm. Chlorine is traditionally the most widely used chemical disinfectant, however alternatives such as chlorine dioxide and chloramines are emerging, each showing benefits and drawbacks. Research has shown that by-products (DBPs) that are formed with these disinfectants can pose serious health threats. The result is new drinking water standards becoming stricter in the past few years. Ultraviolet light, which forms few DBPs and is more effective against chlorine-resistant pathogens, is a relatively new concept in drinking water treatment. It is being introduced as a viable disinfection option however does not provide residual protection for pipe systems. Utilities will often utilize primary and secondary disinfectants in combination in the treatment process for different reasons, and although this is a widely used practice little emphasis has been placed on the potential for synergistic benefits between disinfectants.

There have been few studies published designed specifically to investigate synergy, especially using UV light for the treatment of drinking water. The motivation for this study was to investigate interactions between UV light and chlorine-based disinfectants and determine if synergy enhances removal of microbial pathogens in drinking water distribution systems. The main hypothesis of this work is that UV in combination with chlorine-based disinfectants forms an integrated disinfection process that enables an improved reduction strategy than when working as independent disinfection agents. Field studies and laboratory studies were designed to compare effectiveness of chlorine, chlorine dioxide and monochloramine with and without UV treatment. Long-term field studies incorporated distribution system simulation and looked at the possibility of lowering required chemical dosages when UV light was introduced into the treatment process, thereby lowering formation of DBPs. Work included utilizing UV light as a primary disinfectant prior to any chemical application and also as a secondary disinfectant following chemical disinfection. In addition, various water sources and climates were tested including groundwater, surface water and blended water in California, Florida, and Nova Scotia. Laboratory studies investigated potential for synergy in a controlled setting and also the effect of UV treatment on chemical residuals in a water stream. The conclusions drawn from these studies are able to give insight into integrated disinfection strategies and the associated benefits and drawbacks.

LIST OF SYMBOLS AND ABBREVIATIONS

ANOVA	Analysis of Variance
AOB	Ammonia Oxidizing Bacteria
AOC	Assimable Organic Carbon
AODC	Acridine Orange Direct Counts
AR	Annular Reactor
ATCC	American Type Culture Collection
BOM	Biodegradable Organic Matter
BRP	Bacterial Regrowth Potential
CFU	Colony Forming Units
Cl_2	Chlorine
ClO_2	Chlorine Dioxide
ClO_2^-	Chlorite
ClO_3^-	Chlorate
CMA	Chemical Manufacturer's Association
CSTR	Completely Stirred Tank Reactor
CT	Concentration x Time
DBP	Disinfection Byproduct
DCA	Dichloroacetic Acid
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
GUDI	Groundwater Under the Direct Influence
GV	Guideline Value
HAA	Haloacetic Acid
HPC	Heterotrophic Plate Count
HRT	Hydraulic Retention Time
LOAEL	Lowest Observable Adverse Effect Level
LP	Low Pressure
MAC	Maximum Admissible Concentrations
MAP	Microbially Available Phosphorous

MCL (NS)	Maximum Concentration Level
MCL (US)	Maximum Contaminant Level
MP	Medium Pressure
MPN	Most Probable Number
MRDL	Maximum Residual Disinfectant Level
NCI	National Cancer Institute
NDMA	Nitrosamines
NH_2Cl	Monochloramine
NOAEL	No Observable Adverse Effect Level
NOB	Nitrite Oxidizing Bacteria
NOM	Natural Organic Matter
NSDEL	Nova Scotia Department of Environment and Labour
NTP	National Toxicology Program
O_3	Ozone
PBS	Phosphate Buffered Saline
PPM	Pats Per Million
PWS	Public Water System
TCA	Trichloroacetic Acid
TOC	Total Organic Carbon
TTHM	Total Trihalomethane
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
UVt	Ultraviolet Transmission
WHO	World Health Organization

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1.0 INTRODUCTION

The formation of biofilm on pipe walls leads to several issues in drinking water distribution systems including bacterial regrowth, biocorrosoin and headloss. Servais et al. (2004) determined that a 100-mm length of pipe contained 25 times more bacteria cells per unit length compared to the adjacent bulk water. It has also been found that although biofilm and bulk water bacteria have the same genetic makeup, biofilm cells are more resistant to treatment (Berry et al., In Press). Suppliers attempt different strategies, such as removal of organic matter through treatment processes and occasional flushing of pipe systems, to minimize biofilm formation. However, most depend on disinfection as the key step in controlling biofilm and providing residual protection in the distribution system. There are various alternatives for disinfection strategies used in the industry with varying success in the control of microbial regrowth. Each disinfectant has benefits and drawbacks, and formation of disinfection by-products (DBPs) is one of the major issues utilities have to contend with. Chlorine (Cl_2) is the most traditional and widely used disinfection method due to its simplicity and economic benefits, as well as its established disinfection capacity. However, when chlorine is applied to drinking water containing organic matter (surface water), total trihalomethanes (TTHMs) and haloacetic acids (HAAs) are formed, which have been linked to various health concerns. Dodds et al. (1999) reported an increased relative risk for stillbirths in women exposed to trihalomethane levels in drinking water and Hwang et al. (2002) determined there was an elevated relative risk of birth, cardiac, respiratory system and urinary tract defects with higher exposures to chlorinated by-products. TTHMs and HAAs are also suspected carcinogens, although limited studies have secured a link. Due to these associated health risks with chlorinated DBPs, standards in the drinking water industry are becoming stricter which is initiating research into alternative disinfectants.

Chlorine dioxide (ClO_2) is a strong disinfectant and oxidant that has demonstrated promise as a secondary disinfectant in full-scale distribution systems (Volk et al., 2002). The formation of organohalogens (e.g., TTHMs and HAAs) with ClO_2 is typically much lower when compared to the use of free chlorine (Hofmann et al., 1999; Werdehoff and Singer, 1987). Concerns related to the use of ClO_2 in drinking water treatment have

arisen as the result of toxicological studies, however, other studies conducted in both controlled laboratory experiments and full-scale systems have failed to link the ingestion of water treated with ClO_2 to any adverse health effects in humans (Lubbers et al., 1981, 1982, 1984; Bianchine et al., 1981; Michael et al., 1981). In addition, when chlorine dioxide is introduced to a water stream, the DBP chlorite (ClO_2^-) is immediately formed and there have been concerns related to this ion.

Chloramines, which result from the reaction between chlorine and ammonia, are also being researched and implemented in several utilities across North America for disinfection purposes. There are three types of chloramines including mono- (NH_2Cl), di- ($NHCl_2$), and tri-chloramine (NHCl), and these are formed depending on the ammonia to chlorine ratio and pH (Montgomery, 1985). Although not as effective as chlorine against certain pathogens (*Cryptosporidium parvum, Giardia lamblia*), it has been found that monochloramine potentially has better control of biofilm growth (Norton and LeChevallier, 1997). However chloramination of a system may lead to nitrification, the biological process by which free ammonia is converted into nitrite, and further into nitrate. Nitrification causes a decrease in disinfectant residual, and as well the product nitrite can cause blue-baby syndrome.

Ultraviolet light is an increasingly common form of disinfectant, however it has no residual protection for distribution, therefore must be paired with a disinfectant capable of having residual. One reason its popularity has increased is due to its potential to inactivate *Cryptosporidium parvum* and *Giardia lamblia* (Craik et al., 2000; Craik et al., 2001), and low possibility of forming harmful disinfection by-products (Cotton et al., 2001). UV light offers a potential solution to the control of biofilm in a distribution or transmission system while minimizing DBP formation. Using UV as a primary disinfectant could potentially lower the required chemical doses and also provide further disinfecting capabilities.

Utilities will often use primary and secondary disinfection for different purposes, and it is possible that pairing two different disinfectants will enhance inactivation. The theory of synergy between disinfectants could potentially transform compliance with regulations in the drinking water industry through enhanced removal. Currently the concentration of chemical disinfectants and their by-products are strictly regulated in

Canada and the US, and utilities struggle to meet inactivation requirements while continuing to meet DBP standards. Koivunen et al. (2005) described synergy as when the "efficiency of combined disinfection method is greater than the efficiency achieved when summing the effects of individual disinfectants". Their research showed synergistic benefits when using UV in combination with peracetic acid for treatment of wastewater. This report attributed synergy to the theory of "multiple damage mechanisms", where disinfection from two sources overloads repair mechanisms of cells rendering them unable to repair. Other studies have presented different hypotheses for observed synergistic effects. It is plausible that UV coupled with chlorine-based disinfectants would result in synergistic disinfection in drinking water. Preliminary evidence by Gagnon et al. (2004) suggests that free chlorine and chlorine dioxide act synergistically with UV treatment.

1.1 RESEARCH HYPOTHESES AND OBJECTIVES

The goal of this research was to give further insight into the abilities of disinfectants, alone and in combination, to control biofouling in distribution systems. Further to this objective, the potential for synergy between UV light and chlorine-based disinfectants was investigated.

The main hypothesis of this work was: UV light in combination with chlorine-based disinfectants form an integrated disinfection process that enables an improved reduction strategy than when working as independent disinfection agents. The hypothesis was tested through the completion of three main objectives:

Objective 1 evaluated the effectiveness of chlorine, chlorine dioxide and monochloramine through field-scale assessments of groundwater, surface water and blended water in various climates for the minimization of biofilm formation and suspended bacteria in transmission lines and distribution systems. The use of various chemical disinfectants to control microbial pathogens, such as *Escherichia coli,* in drinking water distribution systems was also considered, as well as the effect water matrix had on disinfection capabilities.

Objective 2 investigated the effect of implementing UV light in a treatment process through field-scale assessments of groundwater, surface water and blended water in various climates. This objective considered the ability of UV alone and in combination for mitigation of biofilm formation and inactivation of microbial pathogens in distribution systems. Finally, the effect of point of application in water treatment processes and varying water matrices on UV light efficacy was also considered.

Objective 3 studied interactions between UV light and chlorine-based disinfectants including the decay of chlorine-based disinfectants in the presence of UV light and the UV demand exerted by chlorine-based disinfectants.

A series of studies was conducted to accomplish these objectives:

Phase One involved investigating synergy between UV light as a primary disinfectant and chlorine-based secondary disinfectants in a controlled laboratory setting. The study looked at the common pathogen *E. coli* spiked in de-ionized source water being treated with UV light and chlorine, chlorine dioxide or monochloramine in series or in parallel.

Phase Two was to determine if synergy would be present in the field. Four separate studies were set up in various field locations including a surface water study in a warm climate, a surface water study in a cool climate, a groundwater study in a cool climate, and finally a blended water source in a warm climate. The experiments were based on long-term effects of various disinfection strategies. At each location, annular reactors (ARs) were used as model distribution system simulators. ARs contain coupons that promote biofilm growth and that can be removed for sampling, and therefore samples were obtained for suspended and attached heterotrophic bacteria.

Phase Three was designed to consider interactions between UV light as a secondary disinfectant and chlorine-based primary disinfectants in a controlled laboratory setting.

The experiment looked at the potential for degradation of chemicals in the presence of UV light and their absorbance of UV irradiation.

1.2 ORGANIZATION OF THESIS

The chapters of this thesis are designed as refereed journal articles and therefore each contains an abstract, introduction, experimental design, methods and materials, results and discussion, and conclusions section. It is anticipated that this format will provide ease of reading to reviewers with each phase of research clearly presented as well as corresponding results and conclusions.

Chapter 2 provides background information on the various disinfectants considered in this thesis including chlorine, chlorine dioxide, monochloramine and UV treatment. This section also provides a literature review of biological fouling in drinking water distribution systems and presents studies that have found synergistic benefits in disinfection strategies. Finally, and overview of current regulations and standards are presented for Canada, United States and the world.

Chapter 3 provides common methods and materials that were utilized for the various studies of this thesis. An overview of experimental equipment, chemical generation processes and analytical methods is presented.

Chapter 4 presents findings from the first phase of the thesis that investigated synergy between UV light and chlorine-based disinfectants in a controlled laboratory setting. The study considered UV light as a primary disinfectant with chlorine, monochloramine of chlorine dioxide as secondary disinfectants for the inactivation of *E. coli* in bulk water samples.

Chapter 5 reports results from two field studies designed to consider the second phase of the project, where the effectiveness of UV, Cl_2 and ClO_2 alone and in combination are compared for the reduction of heterotrophic bacteria in surface water

sources. The first study was carried out at the Pardee Reservoir in California where a 90-mile aqueduct transports surface water from the source to various treatment facilities. The second experiment took place in Halifax, Nova Scotia and simulated the distribution system for the city.

Chapter 6 presents findings from a groundwater study as part of the second phase of research comparing UV light, Cl_2 and NH_2Cl alone and in combination for the control of heterotrophic bacteria. This study was carried out in Port Williams, Nova Scotia were a small community has a chlorinated groundwater source.

Chapter 7 presents findings from experiments designed for the purposes of phases 2 and 3 of this thesis. This first was a blended water study in Pinellas County, Florida and compared the effectiveness of Cl_2 or NH_2Cl alone or in series with UV light as a secondary disinfectant. For the third phase of the project an experiment was designed to consider interactions between UV light and chlorine-based disinfectants in a controlled laboratory setting. The experiment looked at the potential for degradation of chemicals in the presence of UV light and their absorbance of UV irradiation.

Chapter 8 provides a comparative analysis of experimental data from each study presented in the thesis. Analysis of the effectiveness of disinfection strategies in different water matrices is presented and the impact of point of application is considered. In addition, the importance of disinfection synergy in drinking water distribution systems is discussed.

Chapter 9 provides a summary for all the studies conducted for this research and presents conclusions drawn from experimental results.

Chapter 10 offers recommendations for disinfection strategies that utilities could benefit from and that could potentially change regulatory compliance. This section also provides future research needs derived from research findings.

2.0 BACKGROUND

Four disinfectants were studies for the purpose of this thesis and a detailed review of the properties of each is included in this section. In order to provide a brief comparison of the disinfectants a table is provided below outlining the advantages and disadvantages of chlorine, chlorine dioxide, monochloramine and UV light.

Table 2.1: Comparison of Disinfectants

Disinfectant	Maintain Residual?	Disinfection Capacity	Byproduct Formation
Chlorine	Yes	Medium	TTHMs, HAAs
Chlorine Dioxide	Yes	Medium to High	Chlorite
Monochloramine	Yes	Medium	Nitrite, Nitrate
UV Light	No	High	Minimal

2.1 CHLORINE

Chlorine (Cl_2) is the most traditional and widely used disinfectant in the drinking water industry due to its simplicity and economic benefits, as well as its established disinfection capacity. The first use of chlorine as a disinfectant in drinking water was in the 1880's in England, believed to be in the form of hypochlorite or chloride of lime. The first recorded use was in 1897 in Maidstone, England (White, 1986). Many of the first uses were focused on one-time solutions for treatment, and the benefit of continuous use or residual was not realized. The use of residual protection from chlorine began between 1902 and 1905 in Europe (White, 1992). First application of chlorine in North America was in 1896 in Louisville Kentucky, and then continuous use was introduced in Boonton, New Jersey in 1908 (White, 1986). These utilities generated chlorine onsite by using electrolytic process, then chlorine gas (or liquid chlorine) became commercially available in 1909. Advancement in equipment to handle, feed, and measure chlorine gas

allowed it to become widely used by the 1920's, and has since become the most widely used disinfectant (USEPA, 1994).

Chlorine is a strong oxidant whose salts are harmless. It is generally added in the disinfection process in the form of Cl_2 gas, but can also be added as sodium hypochlorite and calcium hypochlorite, which are more expensive but safer. Chlorine gas rapidly hydrolyzes in water to form hypochlorous acid (HOCl), which in turn forms hypochlorite (OCl^-) (Droste, 1997). This dissociation is temperature and pH dependent, where below a pH of approximately 7.6, HOCl is dominant, and above, chlorine is in the form of OCl^-. Hypochlorous acid is by far the better disinfectant, and therefore the effectiveness of chlorine depends on pH (White, 1992). Chlorine can react with reducing agents, such as iron (Fe^{2+}), manganese (Mn^{2+}), and hydrogen sulfide (H_2S), and acts as an oxidant to these constituents (Droste, 1997). It also reacts with ammonia to form three forms of chloramines, including monochloramine (most common), dichloramine, and trichloramine, which are also pH dependent (Droste, 1997). Chlorine reacts with organic material, which is common in surface water, coincidentally with ammonia and other reactions (Droste, 1997).

Due to the presence of these impurities in water, there is a demand on chlorine that must be taken into consideration. Once reactions with inorganic constituents and ammonia are carried out, additional chlorine added can be considered "free" chlorine, or residual. Usually, the desired amount of free chlorine is in the 0.5-1.0 mg/L range. The maximum concentration level (MCL) set by the United States Environmental Protection Agency (USEPA, 1994) for chlorine is 4.0 mg/L.

Chlorine, however, does have its disadvantages, and this has promoted the research into new disinfection options. Although effective as a disinfectant, when chlorine reacts with organic matter in water it forms disinfection byproducts (DBPs) (Gang et al., 2003; Droste, 1997). The two DBPs of most concern with chlorination are trihalomethanes, (THMs, i.e. chloroform) and haloacetic acids, (HAAs, i.e. chloroacetic acid), both suspected carcinogens. There have been various studies conducted in order to find a link between surface water treated with chlorine and cancer rates or other health threats such as birth defects and spontaneous abortion. Dodds et al. (1999) reported an increased relative risk for stillbirths in women exposed to trihalomethane levels in

drinking water of 100 μg/L or more, compared to those exposed to 0-49 μg/L. Hwang et al. (2002) determined there was an elevated relative risk of any birth defect, and of cardiac, respiratory system and urinary tract defects with higher exposures to chlorination byproducts.

There have been many studies regarding the potential for chlorinated by-products to be carcinogenic, and most have shown either a weak relationship or none at all. In 1976, an NCI (National Cancer Institute) report suggested that chloroform, a form of trihalomethane, was carcinogenic in rats, with renal tumors being high in male rats, thyroid tumors in female rats, and liver tumors in both sexes. However, the chloroform was dosed with corn oil in a stomach tube, and a later study conducted by Jorgenson et al (1985) administered mice with chloroform in drinking water and no tumors resulted. This study also looked at the same rats used in the 1976 NCI study, and there was a link between kidney tumors in male rats, which confirmed the NCI report. Several studies (Herren-Freund et al., 1987; Bull et al., 1990) have also shown that the Dichloroacetic and Trichloroacetic acids (DCA and TCA, i.e. HAAs) have caused hepatic tumors in mice when administered through drinking water.

2.2 CHLORINE DIOXIDE

Sir Humphrey Davy discovered the chemical chlorine dioxide (ClO_2) in 1814 by a reaction between potassium chlorate and sulphuric acid (White, 1992). Other experiments followed, and soon it was discovered that chlorine dioxide exhibited strong oxidizing and bleaching properties. During the 1930's, the Mathison Alkali Works developed the first commercial process for producing ClO_2 from sodium chlorate, and in 1939 sodium chlorite was established as a commercial product in generating ClO_2 for small-scale oxidative and disinfecting applications (Chlorine Dioxide, 2003). During the 1940's its largest commercial use was in the pulp and paper manufacture business, where it acted as a bleaching agent that was not as susceptible to unproductive reactions as chlorine was (White, 1992).

In 1944, it went on record that ClO_2 was used for the first time in a water treatment plant for the purpose of taste and odour control in Niagara Falls, New York.

Chlorine dioxide is effective as a taste and odour control because it destroys phenolic compounds unlike chlorine, which reacts with them to produce chlorinated phenols that have an offensive chlorinous taste and odour (White, 1992). Soon other plants started recognizing the benefits to using chlorine dioxide and its use increased. In 1956, a survey reported that 56 utilities across the United States used chlorine dioxide, and by 1997 approximately 500 had implemented ClO_2 in their treatment process (Chlorine Dioxide, 2003). Although its use has been limited in North America until recently, ClO_2 has been utilized in Europe for decades, mainly as a secondary disinfectant to maintain a residual in their distribution systems (Droste, 1997).

Chlorine dioxide is generally utilized as an aqueous solution because the gas form is highly unstable. When ClO_2 is introduced into the water stream before going into the distribution system, it rapidly dissociates into chlorite (ClO_2^-) at approximately a 100% conversion rate (USEPA, 1994). Chlorite is then slowly converted to the chloride ion (Cl^-), chlorate ion (ClO_3^-), and also back to ClO_2 (Baribeau at al., 2002). Widely varying final concentrations of ClO_2^- formed from ClO_2 have been observed and reported in the literature, with proportions between 30 to 70% (Baribeau et al., 2002). Chlorite can be removed during treatment by iron salts, granular activated carbon, and softening (Iatrou and Knocke, 1992; Simpson, 2001). It is sometimes possible to form ClO_2^- and ClO_3^- directly from ClO_2 through disproportionation under highly basic conditions (USEPA, 1994). It has also been seen that conversion between these chemicals continues after ingestion into the body (USEPA, 2000). ClO_2 also undergoes photodecomposition when exposed to UV light to produce chlorate and chlorite ions (White, 1992).

There are potentially several benefits to using chlorine dioxide over chlorine. The formation of organohalogens (e.g., TTHMs and HAAs) with ClO_2 is typically much lower when compared to the use of free chlorine (Hofmann et al., 1999; Werdehoff and Singer, 1987). This is primarily due to the difference in oxidation reaction mechanisms between the two compounds, where ClO_2 is via free radical electrophilic abstraction and Cl_2 uses oxidative substitution and addition. Lafrance (1992) showed that when chlorine dioxide was implemented into two water treatment plants in Laval, Quebec, trihalomethanes virtually disappeared. The substitution with ClO_2 also led to 85% reduction in trihalomethanes and 60% in haloacetic acids after replacing chlorine in a

full-scale distribution system (Volk et al., 2002). There are several other benefits to ClO_2, such as it is effective over a much broader range of pH than chlorine, and it is effective against chlorine resistant parasitic pathogens such as *Cryptosporidium parvum*. It is considered to be an efficient and fast biocidal agent in a large pH range, and effectively kills pathogenic bacteria and viruses at ppm (parts per million) concentrations (White, 1992). It is effective in oxidizing iron, manganese and sulfides, converting iron (II) to iron (III), manganese (II) to manganese (III), and sulfides to sulfates very rapidly (Knocke, 1990). It can control compounds responsible for color and taste, and it doesn't react with bromide (Hoigne and Bader, 1994). It doesn't react with ammonia or primary and secondary amines either, resulting in controlling nitrification in systems (Thompson, 1993). Chlorine dioxide also requires less concentration and lower concentration x time (CT) than chlorine (Baribeau et al., 2002).

There are, however, some limitations and disadvantages to using chlorine dioxide as a disinfectant in the drinking water process. Primarily, it is more difficult to maintain ClO_2 residual due to its oxidative reactivity, volatility, and sensitivity to UV light. The tendency for ClO_2 to decay can lead to overuse of the chemical by plant operators in overcoming the demand, and having "free" residual. This can lead to unusual taste and odor concerns. Unlike chlorine, which is easily handled, chlorine dioxide has explosive properties, is highly volatile, and must be generated onsite, making it relatively more difficult to apply compared to chlorine and other disinfectants. There are also problems involving the analysis of chlorine dioxide, and to date, there really is no convenient test method available in a kit that can measure low-level chlorine dioxide.

Research into the health effects connected to chlorine dioxide is limited. Although there were some studies conducted by USEPA and other research laboratories in the 1970s and 1980s to determine potential health effects of ClO_2 and its by-products, none were specific enough to set regulatory guidelines. They did, however, raise several potential concerns for exposure to ClO_2 in drinking water. Many of these risks were also related to the chlorite ion, since it is the predominant by-product of ClO_2. The conversion continues after ingestion, however the ultimate metabolite of ClO_2 is the chloride ion. Chlorine dioxide is rapidly absorbed from the gastrointestinal tract, and is

primarily eliminated in urine (Abdel-Rahman et al, 1979), mostly in the form of chloride and smaller amounts of chlorite.

In the 1980s, Lubbers and associates conducted two human studies for the short-term toxicity of ClO_2. Neither of the two studies (Lubbers et al., 1981, Lubbers et al., 1984) resulted in any detrimental health effects. Other studies were conducted in communities receiving water treated with chlorine dioxide. Michael et al. (1981) conducted a study and other than slight differences in blood urea nitrogen levels, no hematologic or serum chemistry differences were found in pre- and post-blood analyses. Authors contributed this small difference to mild dehydration in the individuals receiving ClO_2 due to having more strenuous outdoor jobs. Several studies have also tried to link carcinogenity with ClO_2 in drinking water, however none has found any significant correlation. Due to these findings ClO_2 is classified as Group D under USEPA, which means it is not classifiable as to human carcinogenity because of inadequate data in humans and animals.

There are several indications that chlorite has damaging effects on the human body, but there has been little research focused on this subject, since thus far use of ClO_2 is limited as a primary disinfectant. Possible effects include the oxidization of hemoglobin, which causes methemoglobinemia, a disease infants are very susceptible to. It is also thought that at low concentrations, chlorite can decrease the blood concentration of hemoglobin and cause hemolytic anemia, a condition that dialysis patients would be vulnerable to.

A significant study in terms of the water drinking industry was that conducted by Mobley et al. in 1990, and is the basis for the guidelines set by the USEPA for the limit of chlorite in drinking water. This study exposed groups of 12 female rats to chlorite in drinking water at approximate concentrations of 0, 3 and 6 mg/kg-day. Results showed that there was a significant and consistent decrease in exploratory activity, or neurodevelopmental behavioral effects in the 6 mg/kg-day groups in some days. The neurodevelopmental effects found in the Mobley et al. (1990) study were confirmed by a Chemical Manufacturers Association (CMA) study conducted in 1996. It was found that, among other effects, a significant decrease in maximum response to auditory startle

stimulus was observed in groups exposed to high chlorite levels (5.9 mg/kg-day to 22.7 mg/kg-day).

Studies to identify links between carcinogenity and chlorite in drinking water have failed to be of any statistical significance. There have also been attempts without success to establish a relationship between chlorite and genotoxicity. An overall review of the limited available data indicates that the neurodevelopmental toxicity is the most critical effect of using chlorine dioxide in drinking water, which in turn directly correlates to the most sensitive effect of chlorite. As can be interpreted, these effects are caused through ingestion of chlorite.

The toxicity of chlorate has become more of an issue due to increased ClO_3^- levels in unstable hypochlorite salt solutions widely used for treating water. For this reason, it has been placed on the National Toxicology Program's (NTP) priority list for review by USEPA. Through some toxicity studies conducted with animals it has been shown that ClO_3^- is very similar to ClO_2^- in its effects. Most animal studies are conducted with sodium chlorate. One investigation in 1971 (Sheahan, Pugh and Winstanley) had dogs dosed with 0.5-2.0 g/kg $NaClO_3$ orally. In addition to an increase in methemoglobin and ClO_3^- in urine and blood, the high dose dogs exhibited depression, rapid heartbeat, cyanosis, and died 12 to 24 hours later. However, in human studies conducted by Lubbers and Bianchine (1984) and Lubbers et al. (1984), healthy adults were exposed to ClO_3^- in drinking water at concentrations as high as 24 mg/L and showed no adverse health effects.

2.3 CHLORAMINES

Chloramines are becoming much more popular as a disinfectant in the drinking water industry due to lack of by-product formation and other associated benefits. Chloramines are the result of the reaction between chlorine and ammonia. There are three types of chloramines including mono-, di-, and tri-chloramines, and these are formed depending on the ammonia to chlorine ratio and pH (Montgomery, 1985), where di- and tri-chloramine are not favoured at high pH. Monochloramine has favoured biocidal properties and creates fewer taste and odour issues and is therefore the preferred

type. It is generally formed when the ratio of chlorine to ammonia is less than 5:1. Monochloramine was first used as a disinfectant in Ottawa and Denver in 1917. It became a more popular alternative to chlorine through the 1930's as utilities found the disinfectant was able to maintain a more stable residual in the distribution systems and achieve better control of taste and odour issues. There was a decrease in its use through the mid-1900's as ammonia became less available during World War II.

Use of monochloramine as a disinfectant has, however, substantially increased recently and is expected to be used in up to 75% of utilities in the next few years. This is primarily because switching to chloramination is an economical alternative to chlorination and more stringent regulations including the Stage II Disinfection/Disinfection By-product rule introduced by the USEPA to control chlorinated by-products. Guay et al. (2005) ran pilot studies to investigate TTHM and HAA formation with ozone and chloramination compared to chlorine. This study found the highest reduction was obtained using ozone as a primary disinfectant followed by NH_2Cl. Another study (Carlson and Hardy, 1998) showed chloramination yielded lower levels of TTHMs and HAAs compared to chlorination. An additional benefit is that NH_2Cl residual persists longer in a distribution system compared to Cl_2 (Norman et al., 1980). Although generally considered a weaker disinfectant (Sobsey, 1989), it has been found that monochloramine does have better potential to control biofilm growth (Norton and LeChevallier, 1997). In addition, it has been established that use of monochloramine instead of chlorine would decrease risk of Legionnaire's Disease outbreaks from aspiration and inhalation of municipal drinking water (Kool et al., 1999).

The primary concern associated with the use of chloramines as a disinfectant is the potential for nitrification in the distribution system. Nitrification is the biological process by which free ammonia is converted into nitrite by ammonia oxidizing bacteria (AOB), and further into nitrate by nitrite oxidizing bacteria (NOB). Occurrence of nitrification depends on many system characteristics including water temperature, dissolved oxygen (DO), detention times, and reservoir circulation, however literature reports nitrification in a variety of situations (McGuire et al., 2006) and has been reported in up to 2/3 of utilities that use chloramines in the US (Odell et al., 1996). There are several problems associated with nitrification including deterioration of chloramine

residual by nitrifying bacteria by-products, which leads to increased biofilm formation and bacteria counts in the distribution system. Higher chloramine dosages can result in worst-case scenarios where high concentration residuals decay and can release high ammonia, and resulting residual can't control the nitrification. However, new findings by McGuire et al. (2006) have shown that control of nitrification can be obtained by continuous and even intermittent feed of chlorite into the system.

Nitrate and nitrite are also regulated due to potential health concerns associated with these ions in drinking water. One of the main concerns is methaemoglobinaemia, which involves reduced oxygen flow in the blood and results in cyanosis, asphyxia, and even death. This is especially a concern with infants (blue-baby syndrome) and people with low immunity, and is the result of nitrate forming nitrite upon ingestion, which oxidizes iron. Nitrite also can react with primary and secondary amines to produce nitrosamines (i.e. NDMA), which are suspected of carcinogenicity, mutagenicity and teratogenicty, and these compounds have been placed on USEPA's B2 list indicating probable carcinogenicity. Andrzejewski et al. (2005) reports that since a study in 1956 linking these compounds to cancer in rats, 90% of 300 nitrosamine compounds have been researched and are now considered carcinogens. This study also reported that NDMA can be formed in the presence of ammonia with chlorine or chlorine dioxide. Findings observed from the ingestion of nitrate and nitrite in drinking water have been contradictory in relating these ions directly to cancer, including studies throughout the world investigating occurrences of stomach cancer with the ingestion of various concentrations of nitrate (Gilli et al., 1984; Clough, 1983; Vincent et al., 1983). Nitrate in drinking water was linked to congenital malformation in a study carried out in Australia (Dorsch et al., 1984), but the findings from this study were questioned and have not been confirmed in following studies. No known studies have linked nitrite to teratogenicty.

2.4 ULTRAVIOLET LIGHT

In 1877 the germicidal properties of sunlight were reported by Downes and Blunt (Masschelein, 2002). The ability to use mercury to produce artificial UV light was

developed, as well as the discovery of quartz as a good transmitter. The first water treatment plant with a capacity of 200 m^3/day that used UV as a disinfection process was in Marseille, France from 1906 to 1909. In North America, Henderson, Kentucky implemented UV light in 1916 for a treatment plant supplying 12,000 people (Smith, 1917). Other towns in Ohio and Kansas followed suit but due to the convenience and low cost of chlorine, compared to aging lamps and maintenance costs, the use of UV light as a disinfection process was practically abandoned in the mid-1900s (Masschelein, 2002). In the 1930s, the fluorescent lamp was developed, which led to the germicidal tubular lamps (Ultraviolet Disinfection Guidance Manual, 2003). However, with the discovery of harmful DBPs associated with chlorine, and more research into UV treatment, UV systems started becoming more popular in the late 1950s and are now installed in up to 5,000 water treatment facilities throughout North America and Europe.

Current UV reactors are classified as closed-channel, which is the only type used in municipal drinking water to date, or open-channel, which is typically used in wastewater treatment systems. The closed-chamber reactors contain UV lamps, which are housed in sleeves that protect and insulate the lamps. Water flows through the chamber under pressure so that there is no free surface. The most commercially used lamps are mercury emission lamps, which operate under low pressure (LP), medium pressure (MP) and high pressure, although high pressure lamps are used less in drinking water because the continual emission of spectra at the high pressure is less appropriate for such applications (Masschelein, 2002).

Several studies have been conducted to determine the effect of UV treatment on various microorganisms, especially focusing on the chemical resistant pathogen *Cryptosporidium parvum*. Hijen et al. (2006) states that accumulative literature indicates UV light is effective against all pathogenic microorganisms that are relevant to present drinking water practices. The mechanism by which UV inactivates microorganisms is by penetrating the outer cell wall and disrupting the nucleic acids DNA and RNA, rendering the cell incapable of reproducing. Once the cell can no longer reproduce, it can not infect a host that has ingested it. Although the light is absorbed and the nucleic acids are damaged, the cell can still function in other ways such as metabolizing. Literature has

shown that the inactivation of cells by UV light can be described by first order kinetics (Hijen et al., 2006)

The DNA can absorb UV light in the range of 200 to 300 nm, which is within UV lamp ranges. However, microorganisms are more or less susceptible to UV light because of differing DNA structures. Viruses are considered the most resistant to UV inactivation. For instance rotovirus, a disease causing pathogen, requires over 7 mJ/cm^2 for only 1-log inactivation (Chang et al, 1985). Bacteria are more affected by UV light, especially *Escherichia coli.* Chang (1985) found that *E. Coli* was much more susceptible to UV treatment than *Bacillus subtillis* spores and required less than 4 mJ/cm^2 to achieve 1-log inactivation. These findings were later confirmed in a separate study, which also found that *E. coli* was inactivated at a greater rate in varying UV dose rates than *Bacillus subtillis* (Sommer et al, 1998). Parasites, such as *Cryptosporidium parvum* and *Giardia lamblia* can also be affected by UV treatment. Inactivation of *Cryptosporidium parvum* has been well documented, and a recent study conducted at the Mannheim Water Treatment Plant in Kitchener, Ontario, used a Calgon System to achieve 3.9 log removal at a UV dose as low as 19 mJ/cm^2 (Bolton et al, 2005).

In addition to the inactivation achieved with UV treatment, there is the possibility that damaged cells are more susceptible to secondary chemical disinfection. A recent AwwaRF study found that removal rates of suspended HPC bacteria were high in water treated with UV and either chlorine dioxide or chlorine, and low in water treated with UV light only (Dykstra, 2002).

There is come concern surrounding the potential for DNA in the affected cells having the ability to repair itself following UV treatment since there is no residual effect. The United USEPA reported in 1986 that some bacteria organisms and viruses do not have the ability to repair, whereas others such as *E. coli* are capable of photorepair (Masschelein, 2002). To eliminate photorepair, a higher dose would be required, and one study found that coliforms had little or no repair capabilities with higher doses (Lindenauer et al., 1994). Another study found that in addition to fast inactivation of *Cryptosporidium parvum* oocysts at varying doses in a LP UV lamp, no phenotypic evidence of light or dark repair of the microorganisms was produced from DNA damaged by UV light (Shin et al., 2001).

The presence and absence of organic matter in water treated with UV light is extremely important for several reasons, and one main concern is that organic material can shield mircoorganisms from exposure. One study suggested that organic particles protect bacteria and viruses from the UV light, thus reducing disinfection capacity (Qualls et al.,1983). Organic matter in the water can also cause deposition of material on the lamp sleeve surfaces, which decrease lamp intensity. Another concern is that organic material acts as the main absorber of UV light in water, and again disinfection capacity of the lamps is lost. Humic material, the product of decomposed organic material, has shown to be a limiting factor in disinfection because of it being the highest UV absorber (Lund and Hongve, 1994). Allard (1994) also showed that humic substances strongly absorb UV light. However, Linden (2002) and Passantino and Malley (2001) studies reported that UV dose-response of microorganisms are not affected by water turbidity. These studies both used injected microorganisms that were not naturally occurring in the water, so results can not be conclusive to that effect.

It has been determined in various studies that UV irradiation alters organic matter in water by reducing TOC content, colour and molecular size (Corin et al., 1996). A study by Lund and Hongve (1994) suggested that water containing humic material that is treated with UV produces new components that inhibit bacterial growth and formation of biofilm in a distribution system. This was followed up by a study in 1995 by Lund and Ormerod that found UV producing oxygen radicals with biocidal effects due to photochemical reactions with humic material. This study also found that UV irradiation did not increase easily degradable organic molecules. Lehtola et al. (2003) showed UV doses used in drinking water treatment were able to decrease assimable organic carbon (AOC), but higher doses of UV caused the release of microbially available phosphorous (MAP), which would be a stimulant for microbial growth. This study also concluded that the effects of UV light on microbiological and chemical properties vary between different water sources and therefore utilities need to test their own water.

Limited research has been conducted regarding UV effects on chemical disinfectants. A study that looked at interactions between chlorine and UV was conducted by Zheng (1999) and reported that UV at very high fluences can cause the photolysis of chlorine in water, which produces radicals that are very strong oxidants.

Ormeci et al. (2005) found that although UV absorbance of free chlorine and monochloramine was relatively small, they may affect the effectiveness of UV light toward targeted microorganisms. This study also found the chlorine and monochloramine in potable water decay steadily in presence of UV light, especially chlorine in poorer water quality with high UV dosages. Most studies have shown that UV disinfection does not affect DBP formation (USEPA, 2001).

2.5 BIOFILM

The goal of treating water is to have a biologically stable product in the distribution system that does not promote the growth of microorganisms. However, with the presence of dissolved organic carbon (DOC) in source water, which can't be completely removed through treatment, microorganisms have a nutrient source, and the possibility of biofilm formation exists. Bryers (1987) defined a biofilm as "a collection of microorganisms and their extracellular products bound to a solid surface". The solid surface in a distribution system can clearly be classified as the pipe walls, however it should be noted that biofilms could exist on any natural or synthetic surface. According to Bryers (1987), there are three main processes in the formation and development of biofilm, including deposition, metabolism, and removal. Several sub-processes also occur under these overall stages. Much of the procedure involved with the formation of biofilm is not clearly understood, making its control even more difficult.

It has been shown through various studies that biofilm accumulation not only promotes headloss in a pipe system but also promotes the regrowth of bacteria in a distribution system. This is of concern because bacteria formed could potentially be pathogenic, such as coliforms or *Legionella pneumophila*, and cause health problems in humans. For instance, the inhalation of *Legionella* bacteria causes the illness known as Legionnaire's Disease and is similar to pneumonia. The amount of regrowth depends on the availability of nutrients (i.e., carbon, nitrogen and phosphorous), the amount of disinfection residual in the system that would limit the growth (i.e., chlorine), and the accumulation of sediment and corrosion products. The bacteria can possibly come from

various sources, but it is most likely that they originate in the source water and pass through treatment.

The organic carbon in source water can be removed by various methods including coagulation and flocculation, adsorption, filtration and others, but as mentioned, none of these can be considered completely effective. Thus, utilities often depend on disinfection, and the presence of its residual in the distribution system, to limit the amount of regrowth. Often, disinfection is the last phase (if not the only one) in a treatment train before the water enters the distribution system. The purpose of disinfecting is to destroy many disease-causing organisms such as bacteria, viruses and protozoan cysts. At present, there are several types of disinfectants available, including chlorine, chloramines, ozone, UV light, and chlorine dioxide.

Biofilm is a diverse microbial community which is impacted by disinfection strategy, temperature, pipe surface, and nutrient source. Costerton (1999) states that biofilm bacteria differ from planktonic and adopt a profoundly different phenotype when attached to the surface. Biofilm bacteria have been observed to be more resistant to treatment compared to suspended bacteria. Various hypotheses on this include mass transfer resistance, formation of persister cells and protection owing to the production of extracellular polymeric substances (Berry et al., In Press). This is a problem because when biofilm attached to the surface of a 100-mm diameter pipe was examined, it contained 25 times more bacteria per unit length compared to the adjacent bulk water (Servais et al., 2004). There are varying reports on efficacy of disinfectants on biofilm formation. Although some reports indicate chloramines are effective in minimizing biofilm formation (Norton and LeChevallier, 1997), another has shown that biofilm promoted the decay of NH_2Cl and biofilm growth occurred in the presence of monochloramine (Chandy and Angles, 2001). This same study showed no biofilm was detected in chlorinated water, which is consistent with findings from Lehtola et al. (2005). Lehtola et al. (2005) also showed that UV alone has minimal effect on biofilm growth. Another study (Lund and Ormerod, 1995) found that sludge from biofilm growth decreased water flow up to 20% over time in UV irradiated water and 45% in water treated with ozone. Gagnon et al. (2005) showed chlorine dioxide was efficient in reducing biofilm formation in simulated drinking water systems.

Pipe material is important when considering the occurrence of biofilm growth in a distribution system. It has been shown that growth is promoted in the presence of iron, which would be an issue in cast iron pipes (Murphy et al., 2006; Butterfield et al., 2002). When humic material is adsorbed by iron oxide containing corrosion products it also stimulated biofilm growth (Butterfield et al., 2002). In the study mentioned previously by Lehtola et al. (2005), chlorine was more effective in polyethylene pipes than in copper pipes because the residual declined rapidly in the presence of copper.

2.6 DISINFECTANT SYNERGY

In water treatment processes, utilities will often include primary and secondary disinfection for various reasons. UV, which does not result in any residual in the water stream, is often used as a primary disinfectant to target organisms that are chemically-resistant. Chemical disinfectants, such as free chlorine, monochloramine and chlorine dioxide, are then used as secondary disinfectants in order to provide residual protection in the distribution system. It is possible that with these combination treatments, when used in certain sequences, utilities would see synergistic benefits in controlling microbial pathogens and biofilm formation in the distribution systems. Koivunen et al. (2005) described synergy as when the "efficiency of combined disinfection method is greater than the efficiency achieved when summing the effects of individual disinfectants". Their research showed synergistic benefits when using UV in combination with peracetic acid for treatment of wastewater, and specifically for inactivating *Escherichia coli*, *Enterococcus faecalis*, *Salmonella enteritidis*, and coliphage MS2 virus. This study introduced a calculation to determine if synergistic effects were present in a treatment combination. The equation is as follows:

Equation 2.1: Synergy (Koivunen et al., 2005)

Synergy (log units) = log reduction by combined **chemical/UV** disinfection – (log reduction **UV** disinfection + log reduction **chemical** disinfection)

When the calculated answer is positive it is an indication that synergy is present. This equation was applied to the results presented in this thesis.

UV coupled with chlorine-based disinfectants may result in synergistic benefits in the treatment of drinking water. Work carried out by Dykstra et al. (2002) suggests that that free chlorine and chlorine dioxide act synergistically with UV treatment at the bench-scale level. Although this is one of few studies investigating UV synergy, other work has considered synergy with other disinfectants. Kouame and Haas (2003) demonstrated synergistic benefits between chlorine and monochloramine for inactivating *E. coli* at bench-scale in a completely stirred tank reactor (CSTR). Work done by Straub et al. (2000) showed synergism existed in the inactivation of both *E. coli* and MS2 coliphage with significantly shorter required contact times using a combined chloramine- copper system. Rennecker et al. (2000) investigated the inactivation kinetics of *Cryptosporidium parvum* oocysts with ozone/free chlorine and ozone/monochloramine disinfection combinations. This study found that there was enhancement in the rate of inactivation with secondary disinfection when pre-treated with ozone (O_3) and a reduction in lag times for secondary disinfection. This was confirmed in a study by Vasques et al. (2002). Notably, a similar study was conducted by Vasques et al. (2002) using chlorine dioxide as a primary disinfectant with Cl_2 and NH_2Cl as secondary disinfectants. No synergy was observed in this instance, and this led to an amendment in the hypothesis of the mechanisms of synergy. Originally this group thought O_3 produced changes in the cell wall which enhanced secondary inactivation. With further investigations, it was found synergy between O_3 and Cl_2/NH_2Cl was due to the oxidants reacting with the same chemical groups within the cell wall while ClO_2 reacted with different groups. Li et al. (2004) tracked morphological changes in *Giardia lamblia* cysts following treatment with ozone, free chlorine, and a combination of both disinfectants. They found that preconditioning of the cell wall by the first oxidant allowed for easier penetration and more damage by the second oxidant, showing synergistic effects.

It is important to distinguish between disinfection synergy and selective disinfection. Synergy exists when the sum of effect of the disinfectants alone do not produce the same effect as the combination treatment of the disinfectants. Koivunen (2005) presents the theory of multiple damage mechanisms, where "two different

disinfection methods may cause different types of injuries for microorganisms", which was evident in the Li et al. (2004) study. When multiple damages lead to the repair mechanisms of the mircoorganisms to be overloaded, they are unable to repair and therefore die. Selective disinfection is when one disinfectant targets one type of microorganism while the second disinfectant targets another, resulting in a broader range of targeted cells, thus higher reduction. However, the combined reduction is limited to the summation efficacy of the two disinfectants, which could not be exceeded as it would be with disinfection synergy.

Disinfectant synergy is a relatively new concept in drinking water treatment and a full understanding of its implications in real-world situations has not yet been established. For instance, the synergy calculation presented above does not take into consideration factors that may influence bacteria present in drinking water distribution systems such as nutrient loading, flushing of pipes, pipe material and other important aspects. In addition, the significance of quantitative synergy analysis and associated synergy values is not fully identified. For instance, a positive synergy value of 3.75 may or may not be more significant than a positive synergy value of 0.375. For the purposes of this thesis, synergy is considered significant if analysis of the data for combination treatments is statistically different than treatment with chlorine-based disinfection alone and UV treatment alone.

2.7 WATER REGULATIONS AND GUIDELINES

2.7.1 Nova Scotia Regulations

The Nova Scotia Department of Environment and Labour introduced new Drinking Water Treatment Standards in 2003 and has allowed until 2008 for all utilities to come under compliance. The standards incorporate the Multi-Barrier Approach to drinking water treatment and focus on source water protection, effective treatment and disinfection, effective distribution system operation and quality control (sampling and monitoring). Two sets of standards include surface water (SW) and groundwater (GW) regulations. Any groundwater under the direct influence of surface water, or GUDI, are

considered surface water sources after going through the GUDI screening process. Surface water standards require filtration, which will be an economical and operational problem for many utilities considered GUDI. The SW and GW standards also require two disinfection units, 3-log removal of *Giardia lamblia* (SW), 4-log removal of viruses, and a minimum of 0.5-log reduction CT credit for disinfection. Free chlorine in the distribution system will be required to be at a minimum of 0.2 mg/L and maximum 4.0 mg/L.

2.7.2 United States of America

In 1974, the Safe Drinking Water Act was introduced in the US to establish federal water quality standards. The United States Environmental Protection Agency (USEPA) is a national organization that sets most guidelines for municipalities to adhere to in assessing drinking water quality, although some states do establish their own regulations. The main mission of the USEPA is to protect the health of the human population as well as the environment. There are various regulations in place at this time in relation to drinking water quality, and many are in the progress of being implemented. The most relevant to disinfection include the Surface Water Treatment Rule (SWTR), the Total Coliform Rule, the Total THM Rule, the Information Collection Rule, and the Disinfectant/Disinfection Byproducts Rule (D/DBP).

The SWTR was introduced by the USEPA in 1989 and became effective in 1990. It is applicable to all water supplies that have surface water for drinking water, where surface water is defined as "all water which is open to the atmosphere and subject to surface runoff" (USEPA, 2006). The goal of the rule is to protect humans from waterborne diseases caused by viruses such as *Legionella* and *Giardia lamblia*, which in turn means that utilities must use disinfection and filtration (unless given permission to eliminate filtration) to get 99.9% removal. The utilities affected by this rule must also ensure adequate disinfection in the distribution system, and therefore must provide continuous disinfection. Considering the significant amount of disinfection created from this rule, applied to surface water that would naturally have substantial organic matter, the opportunity for disinfection byproducts to form is considerable.

The Total Coliform rule was also put into effect in 1990 by the USEPA. In general, coliforms in drinking water represent any germs that may cause a health threat, but that are too numerous and expensive to monitor. Therefore, when coliforms are present it alerts regulators that these other organisms may be present. The rule sets both health goals and legal limits for total coliform levels, and also outlines testing and monitoring of the bacteria. As in the Surface Water Treatment Rule, utilities must provide disinfection under this rule.

There are several uncertainties as to the specific health threats that some disinfectants and their by-products may cause in consumers. For this reason, USEPA is implementing the Information Collection Rule, where large public water systems (PWSs) must report all data about DBPs in the water, as well as any pathogens present. With this information, USEPA hopes to recognize any changes that should be made to the current disinfectant and DBP rules.

The Total Trihalomethane Rule was established in 1979 to protect consumers from disinfectant byproducts including trihalomethanes. This rule states that the maximum contaminant level (MCL) is 0.10 mg/L as an annual average. This number applies to the sum concentrations of chloroform, bromodichloromethane, dibromochloromethane, and bromoform, all forms of trihalomethanes. The Disinfection/Disinfection Byproduct Rule was proposed to provide even more protection than the TTHM Rule. The D/DBP Rule has been broken into two phases, Stage 1 and Stage 2, to allow utilities the time to adapt to increasingly strict regulations over time, and also to allow more time for further investigation into the health effects of the disinfectants and their byproducts to be investigated. The first stage was set to reduce allowable levels of DBPs in drinking water, with all utilities complying by 2004. Stage 2 will then introduce even lower limits, and will take all new findings concerning the effects of DBPs into consideration.

The USEPA regulates by setting Maximum Residual Disinfectant Levels (MRDLs), Maximum Residual Disinfectant Level Goals (MRDLGs), Maximum Contaminant Levels (MCLs), and Maximum Contaminant Level Goals (MCLGs). MCLs and MRDLs are just as their title describes. A MCLG is defined as being set at levels at which no known or anticipated adverse health effects occur, allowing for an adequate

margin of safety, and is based on available evidence of carcinogenity or non-cancer adverse health effects. A MRDLG is defined as being the same as a MCLG, without reflecting the benefit of the addition of the disinfectant in controlling microbial growth. Presented below are the values derived from the D/DBP Rule, and it should be noted that chlorate is not included in the table due to lack of available information.

Table 2.2: USEPA MRDLG and MRDL Standards for Disinfectants

Disinfectant Residual	MRDLG (mg/L)	MRDL (mg/L)
Chlorine	4.0	4.0
Chloramines	4.0	4.0
Chlorine Dioxide	0.80	0.80

Table 2.3: USEPA MCLGs and MCLs for Disinfection By-Products

Disinfection By-Product	MCLG (mg/L)	MCL (mg/L)
Total Trihalomethanes	N/A	0.080
- Chloroform	0	---
- Bromodichloromethane	0	---
- Dibromochloromethane	0.060	---
- Bromoform	0	---
Haloacetic Acids	N/A	0.060
- Dichloroacetic Acid	0	---
- Trichloroacetic Acid	0.30	---
Chlorite	0.80	1.0
Bromate	0	0.010
NDMA	0.0070	
NDEA	0.0020	

Although there are no changes anticipated for the MRDLs of disinfectants under Stage 2 of the D/DBP rule, it is expected that the MCLs for disinfectant byproducts will become lower. Presented below is a comparison table for those changes between stage 1

and stage 2. There is also the possibility that new DBPs, such as chlorate, will be included in the next stage.

Table 2.4: Stage 1 and Stage 2 D/DBP Rule MCLs

Disinfectant Byproduct	Stage 1 MCL (mg/L)	Stage 2 MCL (mg/L)
Total Trihalomethanes	0.080	0.040
Haloacetic Acids	0.060	0.030
Bromate	0.010	0.0050
Chlorite	1.0	1.0

These values are mainly based on research studies that present lowest observable adverse effect levels (LOAELs) and no observable adverse effects levels (NOAELs). USEPA regularly bases its MCLs and MRDLs on the NOAEL of a study.

2.7.3 European Countries

Several European countries set their own standards and guidelines for various constituents in drinking water, however the World Health Organization (WHO), specifically the Water Sanitation and Health division, supplies Guide Values for countries to follow. WHO's Guidelines for Drinking Water Quality are "the international reference point for standard setting and drinking-water safety" (WHO, 2003). Under these guidelines, chlorine dioxide does not have a Guideline Value (GV) because WHO's position is that it breaks down very rapidly and the GV for chlorite would provide adequate protection from potential toxicity of ClO_2. The GV for both the chlorite ion and the chlorate ion is 0.7 mg/L according to WHO. However, these values are considered provisional, because using chlorine dioxide as a disinfectant may result in the GVs being exceeded. It is WHO's policy that any difficulties in reaching a GV should not compromise adequate disinfection.

WHO has set a GV of 5 mg/L for chlorine, with a residual concentration of free chlorine of 0.5 mg/L after 30 minutes of contact time. This GV is considered to be conservative since no adverse effect level was established with the critical study.

However, most people are able to taste chlorine at this Guideline Value. Chlorinated byproducts, THMs, also have set GVs from the WHO, including chloroform at 200 μg/L, Bromoform at 100 μg/L, Dibromochloromethane at 100 μg/L, and Dichlorobromomethane at 60 μg/L. It is noted that adequate disinfection should never be compromised in trying to reach GVs for trihalomethanes.

Since many European countries have been using chlorine dioxide in drinking water for decades, they legislate ClO_2 and its byproducts at a national level. Shown below is a table of a few countries and their government agencies' guidelines on chlorine dioxide, and also on sodium chlorite, the active ingredient for ClO_2, which must be registered prior to use in many cases.

Table 2.5: Examples of European Regulations on $NaClO_2$, ClO_2

COUNTRY	$NaClO_2$	ClO_2	Max. Allowable Quantity (mg/L)	Res. Conc. at end of treatment plant
Belgium	X		5	
France		X		
Germany		X	0.4	Min = 0.05 mg/L, Max = 0.2 mg/L
Great Britain				Max = 0.5 mg/L, Sum of ClO_2 + $NaClO_2$ + $NaClO_3$
Spain	X		30	
Sweden		X	0.7	

(Source: www.clo2.com, 2003)

Several countries around the world use chlorine and therefore have standards concerning TTHMs in drinking water. Presented on the next page is a table showing the variety of standards internationally for chlorinated by-products.

Table 2.6: Regulations Regarding Organic Content of Drinking Water

COUNTRY	TTHM µg/L		Chloroform µg/L		DCBM µg/L		DBCM µg/L		Bromoform µg/L	
	GV	MAC	GV	MAC	GV	MAC	GV	MAC	GV	MAC
Austria		30[a]								
Belgium		100								
Canada		100								
Denmark	1									
Finland				200		60				
France				30						
Germany		10								
Great Britain		100[b]								
Greece	1									
Ireland		100[c]								
Italy	1	30								
Luxemburg		50								
Netherlands	1[d]									
Norway		100								
Portugal	1									
Spain	1									
Sweden		50								
Switzerland		25[e]								
USA		100		100		100		100		100

(Source: www.clo2.com, 2003)

MAC: Maximum Admissible Concentrations

GV: Guide Values

DCBM: Dichlorobromomethane

DBCM: Dibromochloromethane

[a] Refers to total volatile aliphatic halogenated hydrocarbons to be met at the consumers' tap.

[b] To be met at consumers' tap.

[c] Organochlorine compounds of non-pesticide origin including THMs resulting from chlorination.

[d] Under discussion a MAC of 30 ug/L for THMs.

[e] Volatile halogenated hydrocarbons which quality objective is 1 ug/L. Under discussion MAC of 10 ug/L.

3.0 METHODS AND MATERIALS

The focus of this chapter is to present all sampling and analysis procedures, testing equipment used and experiment preparation. All sampling and testing protocols were carried out as described in the *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 1998). Studies were carried out in four field locations and two different laboratories. Most methods remained constant throughout each study and when they differed it is noted in this chapter.

3.1 EXPERIMENTAL EQUIPMENT

3.1.1 Annular Reactors

Annular Reactors (ARs, BioSurface Technologies Corporation, Bozeman, MT), which are widely used in drinking water research, were used to represent model distribution systems. The AR model used for these experiments was the 1120 LS (Laboratory Model Regrowth Monitor and Annular Reactor, BioSurface Technologies Corporation). Each AR consists of an outer glass cylinder that encompasses an inner rotating drum. A variable speed motor located above the reactor controls the rotation of the drum, which in turn controls the shear stress on the outer cylinder wall. The drum is able to rotate by resting on a ball bearing, which sits in a milled cup on top of the ball tower extending from the bottom plate. On the top plate of the AR there are multiple inlets allowing for various influents. The top plate is supported by four stand-offs in addition to the glass cylinder, which has rubber seals between both the top and bottom plates. Water flows through an annular gap within the reactor and is mixed by the rotating drum, which contains draft tubes to ensure sufficient vertical and horizontal mixing. Hydraulic retention time is controlled by the volumetric flow rate of the influents entering the AR. The total working volume in the annular gap is approximately 950 mL. The AR accommodates twenty removable coupons that are flush-mounted on the side of the inner rotating cylinder and which support biofilm growth. An opening in the top plate of the AR allows for the removal and replacement of the coupons and

remains closed using a hole plug except when sampling occurs. Effluent is controlled by an effluent pipe that is positioned above the outlet to build up head within the AR. In each study, all opaque surfaces were covered to discourage phototrophic growth since the ARs are simulating pipe systems that would be underground.

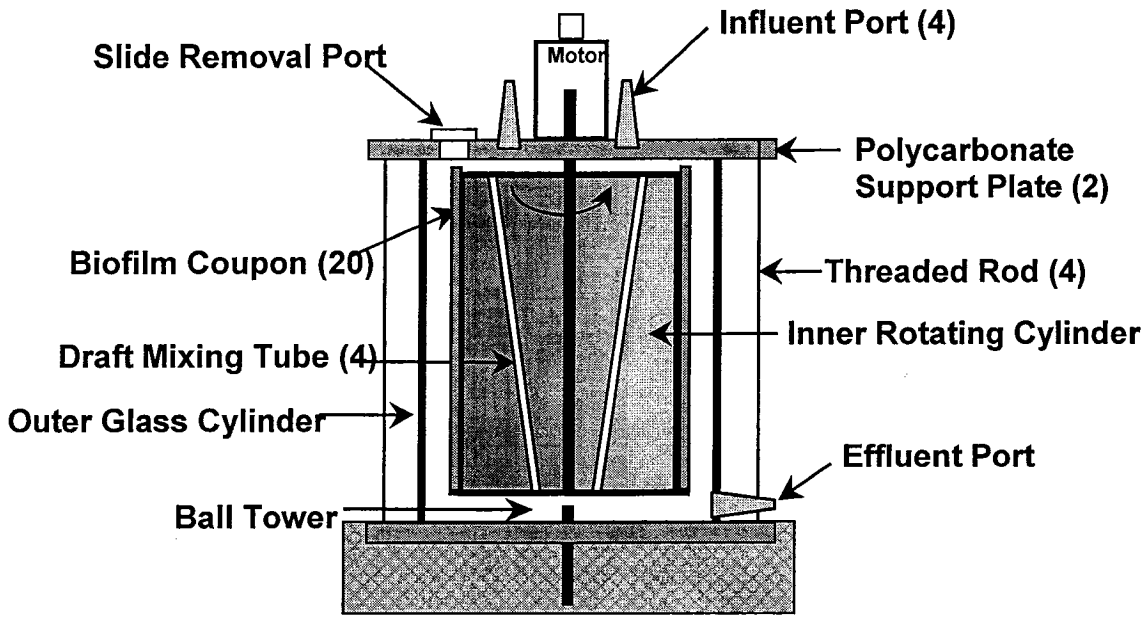

Figure 3.1: Schematic of an Annular Reactor

3.1.2 Ultraviolet Lamp

A low pressure UV lamp (TrojanUV Max Model C) provided by Trojan Technologies was used for each experiment. The lamp is capable of treating up to 64 L/min (17gpm) at a fluence of 16 mJ/cm^2 and a UV transmittance (UVt) of 95% (Trojan Technologies, 2006). At the Pardee Reservoir, the lamp was attached to a 1-in. PVC pipe and flow was controlled by a pressure gauge. In all other studies, it was required that water be pumped through the system using a variable speed modular peristaltic pump (Masterflex) at a flowrate of 500 - 700 mL/min which translated to a fluence of between 80 -100mJ/cm^2. Prior to the each experiment, the UV lamp was cleaned and soaked in 70% ethanol for 24 hours. The fluence was determined during a separate and previous

study in the Dalhousie laboratory by performing chemical actinometry using potassium ferrioxalate (Dykstra et al., 2002). UV fluence was calculated using equation 3.1 (Jagger 1967, Harris et al. 1987).

Equation 3.1: UV Fluence Calculation

$$Fluence(mJ/cm^3) = \frac{[Fe^{2+}]_a - [Fe^{2+}]_b}{\Phi} \times \frac{4.719 \times 10^8 mW - s}{einstein} \times \frac{r}{10^3 cm^3} \quad (3.1)$$

where	Φ= 1.26 moles Fe^{2+}/ Einstein adsorbed $[Fe^{2+}]_a$= sample concentration of Fe^{2+} after irradiation (mol/L) $[Fe^{2+}]_b$= sample concentration of Fe^{2+} before irradiation (mol/L) r= radius of the quartz tube
assumptions	• 100% of the radiation emitted by the lamp is at 253.7nm • Quantum yield at 253.7nm is 1.26 moles Fe^{2+}/ Einstein (Jagger, 1967; Harris *et al*, 1987)

3.2 DISINFECTANT PREPARATION AND MEASUREMENT

Throughout the experiments chlorine, chlorine dioxide and monochloramine were required as chemical disinfectants for field and laboratory studies. At the Pardee Reservoir, chlorine stocks were prepared using the 12.5% sodium hypochlorite solution used in full-scale treatment. Other studies involved chlorine preparation as outlined below.

3.2.1 Chlorine Dioxide

Chlorine dioxide was generated according to Method 4500-ClO_2 of *Standard Methods for the Examination of Water and Wastewater, 19th Ed.* The generator consists

of a bench-top apparatus, in which a 25% sodium chlorite solution is slowly added to an 18N sulphuric acid solution, producing chlorine dioxide. The chlorine dioxide is purged from the mixture in a gas-washing bottle, and trapped in water surrounded by an ice bath. Off-gas from this bottle is directed to a potassium iodide trap to prevent the release of chlorine dioxide into the air. The resulting chlorine dioxide solution is approximately 2-7 g/L. The ClO_2 was diluted with de-ionized water as necessary in 4-L demand-free amber bottles as stock solution for the various experiments.

At the Pardee Reservoir ClO_2 was measured using a spectrophotometric method employing lissamine green as previously described by Chiswell and O'Halloran (1991). Lissamine green is both selective and sensitive for the determination of low levels of chlorine dioxide. The DBP colorimetric method was also used as a check for the lissamine green method. A HACH DR/2000 (HACH Company, Loveland, CO) spectrophotometer was used at this site. It was determined in this field study that both methods resulted in very similar measurements. For all other experiments the DBP colorimetric method was used due to its simplicity with a HACH DR/4000 spectrophotometer.

3.2.2 Chlorine

Concentrated free chlorine was produced using a 12.5 – 16% solution of analytical grade sodium hypochlorite. Chlorine stock bottles were prepared in 4-L demand-free amber glass bottles containing de-ionized water.

Free and total chlorine were measured in each study using the DBP colorimetric method and a spectrophotometer. In the Pardee study, the model used was a HACH DR/2000 and in Florida a HACH DR/890 model was used. In all other experiments a HACH DR/4000 spectrophotometer was employed.

3.2.3 Monochloramine

Monochloramine was generated by diluting 100 mL of phosphate buffer solution (PBS) in 900 mL of de-ionized water. The pH of this solution was adjusted to 9.4 using

sodium hydroxide. Ammonium chloride (4 g) was dissolved in 500 mL of the diluted PBS. The remaining 500 mL PBS solution was mixed with 18.7 mL of 12.5 % analytical grade sodium hypochlorite The chlorine stock was then added to the ammonium chloride solution while being continuously stirred with a stir bar and magnetic stir plate. This procedure produced a 1-L monochloramine stock solution of between 2800 mg/L and 3500 mg/L. Required amounts of this stock solution were added to sterile 4-L amber bottles containing de-ionized water to obtain desired feed concentrations.

In the Florida study, monochloramine was measured using a HACH DR/890 spectrophotometer and the Indophenol Method 10200. In all other experiments, NH_2Cl was measured using the DPD ferrous titrimetric method (Standard Methods, 21st edition-4500 D).

3.3 SAMPLE COLLECTION AND ANALYSIS

Through four field studies and two laboratory experiments there were several different samples analyzed. This section outlines methods and materials used in obtaining and analyzing each type of sample.

3.3.1 Microbial Analysis

For all field studies effluent, biofilm and influent samples were collected one to two times weekly. For suspended heterotrophic bacteria analysis, influent and effluent samples were collected in sterile, 50mL disposable plastic tubes (Corning Inc., Acton, MA). During the disinfection phases, residual disinfectant was quenched by adding 10μL of sterile sodium thiosulfate (10% w/v) solution to each tube. These samples were used for the heterotrophic plate counts. Biofilm samples were collected when coupons were removed aseptically, in sequence, from the AR. Once taken out, they were transferred into sterile 50-mL test tubes containing 25 mL autoclaved phosphate buffered saline (PBS) and 0.1% w/v sodium thiosulfate. The attached cells were immediately removed by the scraping method as described by Gagnon and Slawson (1999), and plated on agar

to be analyzed for heterotrophic plate counts. Following sampling, the coupons were cleaned with soap and water, and treated with ethanol before being returned to the AR.

Microbial analysis for the Florida study differed slightly because samples were collected in Florida and shipped to Dalhousie University laboratory facilities overnight for analysis. Previous work has shown that HPC bacteria will not deteriorate within a week if kept refrigerated at 4 °C. Bulk samples were collected in 100mL IDEXX bottles containing 10% w/v sodium thiosulfate to quench disinfectant residual. The PVC coupons were removed aseptically and placed in sterile 50mL glass containing PBS and 0.1% w/v sodium thiosulfate. Once shipped, the coupons were scraped in the same method as other studies to remove attached cells. New coupons that were treated with ethanol were used to replace those that were removed and shipped from each AR.

3.3.2 Heterotrophic Plate Counts

Suspended and attached bacteria samples collected as described above were enumerated with heterotrophic plate counts. The process involved a standard spread plate technique as described in *Standard Methods for the Examination of Water and Wastewater* (21^{st} edition) on R2A agar (Difco Laboratories). Sterile glass tests tubes containing 9 mL phosphate buffer saline solution (PBS) were used in series to obtain dilutions from 10^{-1} to 10^{-5}, depending on concentration. Dilutions were used to target a microbial yield of 30 to 300 colonies per plate per 1 mL of sample. Duplicate plates were spread for each dilution and generally 2 to 3 dilutions were plated for each sample to ensure quality assurance. All equipment used was sterilized and work was completed on a clean surface near a flame to prevent contamination. Plates were incubated upside down in the dark for 7 days at room temperature, after which time colonies were counted.

3.3.3 Acridine Orange Direct Counts (AODC)

Acridine Orange Direct Counts (AODC) were used to enumerate all microbial cells. One mL of sample was mixed with 1 mL of a 0.1% (w/v) solution of acridine orange for five minutes. The mixture was filtered on black cellulose nitrate filters

(Millipore, Bedford, MA). The filters were observed by epifluorescence microscopy (Olympus model BX-60, Melville, NY), and enumerated using an image analysis system (Esprit™, Olympus).

3.3.4 Coliforms and *Escherichia coli*

In three of the field studies bulk influent and effluent water samples were collected to analyze for coliforms and *E. coli*. Coliforms were enumerated using the IDEXX Colilert® Quanti-tray® system. Sterilized glass vials were used to collect the 100-mL samples required for the analysis, which during disinfection were quenched with 100 μL sterile sodium thiosulfate (10% w/v) solution. One Colilert® reagent packet was added to each vial within 24 hours of collection and the sample was shaken to dissolve the package. The samples were then immediately transferred into the IDEXX Quanti-trays® and sealed used the Quanti-tray® Sealer. The trays were incubated at 37.5 °C for 24 hours during which a color change would occur to indicate presence/absence. Coliforms use the enzyme β-galactosidase to metabolize the substrate ONPG, which changes to yellow in the test kits. Coliforms are then counted using a Most Probable Number (MPN) table provided by IDEXX. To determine presence/absence of *E. coli*, the Quanti-trays® were placed under a blue light. If *E. coli* was present the wells would fluoresce and could be enumerated with the MPN table. It is acknowledged that there is a possibility of false positives for coliforms using Colilert® tests (Murphy, 2006). However, the purpose of coliform measurements in field studies was to compare disinfectants and not to quantify coliforms, and analysis of data was based on heterotrophic plate counts. Therefore, enumerating cells through more timely and expensive methods was not considered to be necessary.

For one laboratory study it was necessary to enumerate very low to very high concentrations of *E. coli*. Since the IDEXX Quanti-trays® are only capable of counting just over 2700 CFU/mL, the samples were diluted and cultured using a standard membrane-filtration technique for total coliforms as outlined in *Standard Methods for the Examination of Water and Wastewater* (21st edition). Sterile glass tests tubes containing 9 mL phosphate buffer saline solution (PBS) were used in series to obtain dilutions from

10^{-1} to 10^{-8}, depending on anticipated concentration. Samples were filtered aseptically through sterile 0.45μm filters using a vacuum aspirator. All filtration equipment and rinse water was autoclaved at 121°C for 15 minutes prior to use. The filters containing the 1-mL of sample were then transferred using sterile forceps to tight lid plates containing pre-dried m-Endo Agar LES (Difco Laboratories). These plates were then incubated upside down at 37.5 °C for 22- 24 hours during which time *E. coli* cultures turn a metallic color which can be counted. As a single species experiment, all coliforms cultured on the plate were considered to be *E. coli*. A photograph showing *E. coli* cultured on agar is shown in Figure 3.2.

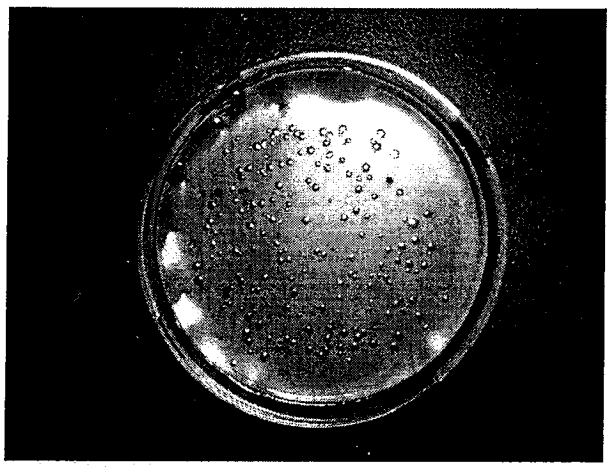

Figure 3.2: *E. coli* Cultured on m-Endo Agar

3.3.5 pH and Temperature

pH and temperature readings were measured using an Orion model 230A pH meter in all studies except in Pinellas County where the Oakton meter was used. Meters were calibrated as samples were taken on a weekly basis.

3.3.6 Turbidity

Turbidity was measured throughout the experiments using a HACH 2100P turbidimeter (HACH Company, Loveland, CO) following Standard Method 2130 B (APHA at al., 1998).

3.3.7 Total Organic Carbon (TOC) and Dissolved Organic Carbon (DOC)

Pure samples were poured headspace free into clean 40mL glass vials. Four drops of pure phosphoric acid was added and then the vials were covered with Teflon-lined and septum-free plastic caps. The TOC samples were refrigerated at 4 °C until analysis was performed using a TOC-V CHP analyzer (Shimadzu Corporation, Kyoto, Japan).

DOC samples were passed through a 0.45μm pore-size membrane filter and poured headspace free into clean 40mL glass vials and then analyzed in the same methods as TOC.

3.3.8 UV 254

Samples were passed through a 0.45μm pore-size membrane filter and then analyzed using a UV-Vis Spectrophotometer (Model DR 4000 HACH Co., Loveland, CO) at UVA 254 nm.

3.3.9 Nitrite and Nitrate

Nitrite and nitrate concentrations were measured in the Pinellas County Water Utilities laboratory using EPA Method 300 and Ion Chromatography with the Dionex Model IC25A. For the Port Williams study nitrate concentration was measured using a DBP colorimetric method and a HACH/DR2000 spectrophotometer (HACH Company, Loveland, CO).

3.3.10 Ammonia

Free and total ammonia were measured in the Pinellas County laboratory using an ion-selective probe and Standard Methods 4500NH_3F-Total and 4500NH_3F-Free (18^{th} Edition), Denver 250. Free ammonia was measured in the field using a DR/890 HACH Spectrophotometer and the Indophenol Method 10200.

3.3.11 Ultraviolet Transmission (UVt)

UVt_{254} measurements were performed at the University of Toronto on bulk water samples using an HF Scientific® UVT-15 photometer with a 1 cm path length.

3.3.12 Disinfection By-Products

Total trihalomethane (TTHM) and haloacetic acid (HAA) samples were collected in 23-mL vials and quenched with sodium thiosulfate. TTHM samples were additionally quenched with sodium sulphite and HAA samples with ammonium chloride. The samples were stored in the dark at 4 °C for less then 14 days before extraction. Concentrations were measured using a gas chromatograph (Hewlett Packard 5890 Series II) containing a 30 mm x 25 mm fused silica capillary column and an electron capture detector according to Standard Methods 6232 (TTHMs) and 6251 (HAAs) (APHA et al., 1998).

Chlorite samples were collected in 23-mL vials and quenched with ethylene diamine (EDA) for a concentration of 0.1 mmol/L. Concentrations were measured using a Dionex DX-500 ion chromatograph according to USEPA method 300.0 (USEPA, 1997).

3.4 STATISTICAL ANALYSES

Statistical tests were repeated for the various combinations of disinfectants type. In addition, statistical tests compared the significant differences between the average influent and effluent values for the water quality parameters measured. The level of significance that was used for all tests was $\alpha = 0.05$. Statistical procedures followed were an analysis of variance (ANOVA) test, as described by Box et al. (1978).

4.0 SYNERGISTIC BENEFITS BETWEEN UV LIGHT AND CHLORINE-BASED DISINFECTANTS IN REDUCING *ESCHERICHIA COLI*: A LABORATORY EVALUATION

4.1 ABSTRACT

Ultraviolet light is increasing in popularity as a primary disinfectant in drinking water treatment because of its effectiveness against chlorine-resistant pathogens (Bolton et al., 1998) and lack of disinfection by-product (DBP) formation. Previous bench-scale studies have shown there are possibly synergistic benefits in reducing heterotrophic bacteria when UV is coupled with chlorine (Cl_2) or monochloramine (NH_2Cl) (Dykstra et al., 2006). Additional experiments have demonstrated that synergy exists between various disinfectants in controlling numerous bacteria, viruses and protozoan (Koivunen et al., 2005; Kouame and Haas, 2003; Straub et al., 2000). No studies to date have specifically investigated synergy with UV in combination with chlorine-based drinking water disinfectants including chlorine dioxide (ClO_2), Cl_2 and NH_2Cl. This study looked at the effectiveness of seven disinfection strategies (UV, Cl_2, ClO_2, NH_2Cl, UV/ Cl_2, UV/ ClO_2 and UV/ NH_2Cl) against *Escherichia coli* in a single-species system at high and low CTs. Spiked solutions containing high concentrations of *E. coli* were treated by UV alone, chemical alone, or UV and chemical in combination using identical dosages. It was found that the combined disinfection strategies achieved the highest removal during both high and low CT experimental trial runs, and actually removed all *E. coli* in the high CT run (8.24-log removal). Data were additionally analyzed for synergistic benefits and each combination had a positive result. Although little research has been conducted to date regarding disinfection synergy, there is potential that drinking water utilities would see enhanced removal of bacteria and other pathogens due to synergistic benefits when UV was used in combination with any chlorine-based disinfectant.

4.2 INTRODUCTION

In water treatment processes, suppliers often will often include primary and secondary disinfection in the treatment process for various reasons. Ultraviolet light, which does not result in any residual in the water stream, is often used as a primary disinfectant to target organisms that are chemically-resistant. Chemical disinfectants, such as free chlorine (Cl_2), monochloramine (NH_2Cl) and chlorine dioxide (ClO_2), are then used as secondary disinfectants in order to provide residual protection in the distribution system. It is possible that when these combination treatments are used in certain sequences, utilities would see synergistic benefits in controlling microbial pathogens and biofilm formation in the distribution systems. Koivunen et al. (2005) described synergy as when the "efficiency of combined disinfection method is greater than the efficiency achieved when summing the effects of individual disinfectants". Their research showed synergistic benefits when using UV in combination with peracetic acid for treatment of wastewater, and specifically for inactivating *Escherichia coli*, *Enterococcus faecalis*, *Salmonella enteritidis*, and coliphage MS2 virus.

It is plausible that UV coupled with chlorine-based disinfectants would result in synergistic disinfection in drinking water. Dykstra et al. (2006) suggested that free chlorine and chlorine dioxide act synergistically with UV treatment at the bench-scale level. Although this is one of few studies investigating UV synergy, other work has considered synergy with chlorine-based disinfectants. Kouame and Haas (2003) demonstrated synergistic benefits between chlorine and monochloramine for inactivating *E. coli* at bench-scale in a continuously stirred tank reactor (CSTR). Straub et al. (2000) showed synergism existed in the inactivation of both *E. coli* and MS2 coliphage with significantly shorter required contact times using a combined chloramine copper system. Rennecker et al. (2000) investigated the inactivation kinetics of *Cryptosporidium parvum* oocysts with ozone/free chlorine and ozone/monochloramine disinfection combinations. That study found that there was enhancement in the rate of inactivation with secondary disinfection when pre-treated with ozone and a reduction in lag times for secondary disinfection. Li et al. (2004) tracked morphological changes in *Giardia lamblia* cysts following treatment with ozone, free chlorine, and a combination of both disinfectants.

They found that preconditioning of the cell wall by the first oxidant allowed for easier penetration and more damage by the second oxidant, showing synergistic effects.

The focus of this chapter was to perform a controlled bench-scale investigation focusing on the presence of synergy between UV and chlorine-based disinfectants. A common and strictly regulated pathogen, *Escherichia coli*, was the organism used in this single-species study. Disinfection strategies investigated included UV, Cl_2, ClO_2, NH_2Cl, UV/ Cl_2, UV/ ClO_2 and UV/ NH_2Cl.

4.3 EXPERIMENTAL DESIGN

E. coli K12 strains were acquired from the American Type Culture Collection (ATCC). The *E. coli* was cultured and transferred into 4-L amber bottles containing a salt solution which resulted in concentrations of 10^6 – 10^8 CFU/mL. The *E. coli* contained in the stock bottles were cultured and analyzed using an API test as previously described. This analysis provided a phenotypic response to twenty enzymes and was used as a background assay prior to treatment.

Treatment of samples took place in 120-mL amber bottles. These sample bottles were prepared by autoclaving for sterilization and by soaking with Cl_2 or ClO_2 in order to become oxidant demand free.

Seven disinfection treatments were compared for the inactivation of *E. coli* including free chlorine, chlorine dioxide, monochloramine, UV light, UV and free chlorine, UV and chlorine dioxide, and finally UV and monochloramine. Spiked solutions that were treated with chemical disinfectant only were simply transferred into the 120-mL bottle and dosed with Cl_2, ClO_2 or NH_2Cl. A 15-mL sample was then obtained after the desired exposure time and quenched with 0.1% (w/v) sodium thiosulfate. This sample was used for plating in order to determine *E. coli* concentration. Solution that was treated with UV light was pumped from the 4-L bottles through the UV lamp at a rate of 700 mL/min resulting in a dose of approximately 100 mJ/cm^2. Samples for treatment with UV only were directly transferred into 15-mL sterile vials. For the combination treatments, the UV-treated solution was directed into the 120-mL amber bottles for secondary disinfection with chlorine-based disinfectants. The samples were

identically dosed as the samples with chemical disinfection only. Similarly, once the desired exposure time was reached, samples were transferred into 15-mL sterile vials and quenched with sodium thiosulfate and then plated for concentration. A photograph of the experimental set-up is presented as Figure 4.1.

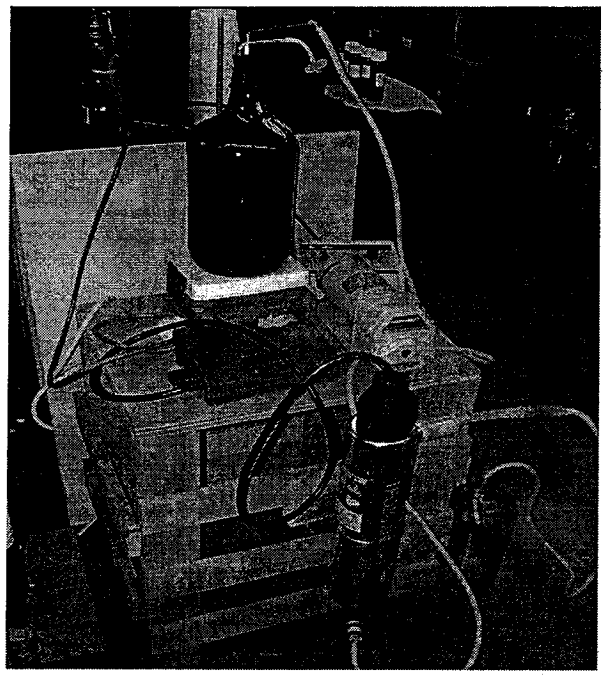

Figure 4.1: Experimental Set-up for Batch Synergy Experiments

Prior to the experiment, the UV lamp was sterilized with a 70% ethanol solution for a period of 24 hours then rinsed with Milli-Q water. In order to ensure *E. coli* was going through the system, one 4-L spiked stock bottle was pumped through the lamp to waste. The next stock bottle was used for the samples. A UV dose of 100mJ/cm^2 was applied because it was within the range of dosages for drinking water treatment and is similar to other bench and field-scale experiments.

Chemical dosages were calculated based on work previously carried out by Baribeau et al. (2005). In that study, log reduction of *E. coli* was determined for various dosages (CTs) of free chlorine and monochloramine, and results produced a decay equation for *E. coli* in relation to dose was developed. For the Baribeau et al. (2005) experiment, dose concentration of disinfectant was kept constant between 0.4 and 0.5 mg/L and contact time varied to achieve different CTs. The equation for inactivation by

free Cl_2 of *E. coli* O157:H7 ATCC 35150 is presented below (Equation 4.1), as well as the equation for inactivation by NH_2Cl (Equation 4.2).

Equation 4.1 (Baribeau et al., 2005) Inactivation of *E. coli* by Free Chlorine:

$$y = -14.994x - 0.2952$$

Equation 4.2 (Baribeau et al., 2005) Inactivation of *E. coli* by Monochloramine:

$$y = -0.1891x - 0.1809$$

Where: y = log reduction, and

x = CT (mg min/L)

For the present experiments, the desired log reduction from chemical disinfection was determined to be 2.0-log, which would allow for reduction to be observed for chemical disinfection only and also for the combined UV/chemical disinfection strategy. Based on the equations above, contact time for chlorine and monochloramine were established as 34.2 seconds and 19.5 minutes respectively. There was no available information for chlorine dioxide inactivation of *E. coli*. From previous bench-scale studies (Dykstra et al. 2006), it was shown that ClO_2 was a stronger disinfectant than Cl_2, and a lower CT was established with a 30 s contact time. In addition to CTs based on previous work, lower CTs for each disinfectant were also tested where contact times remained the same and disinfectant dose was lowered. Decay kinetics for the disinfectants were not observed due to time constraints. The equations were based on chemical residual at the time of sampling and therefore decay of chemical was estimated. At high CT, it was approximated that 0.2 mg/L residual concentration would be present at sampling time for Cl_2 and ClO_2 and 0.5 mg/L NH_2Cl and lower CTs were estimated at a lower value than high CT. Table 4.1 presents the experimental dosage CTs, disinfectant dose and exposure times.

Table 4.1: Experimental Chemical Disinfectants and Exposure Times

Disinfectant	$Dose_1$ (mg/L)	$Dose_2$ (mg/L)	Exposure Time (min)	CT_1 (mg min/L)	CT_2 (mg min/L)
Cl_2	0.60	0.45	0.57	0.34	0.24
NH_2Cl	1.30	0.90	19.5	25.4	17.6
ClO_2	0.40	0.30	0.50	0.20	0.15

Once quenched samples for each disinfection strategy were obtained, they were cultured on M-Endo LES agar according to the procedure described in Chapter 3, Methods and Materials, in order to determine concentration. Once cultured, the cells were tested for phenotypical changes using API tests.

4.4 METHODS AND MATERIALS

All sampling and testing protocols were carried out as described in the *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 1998) and as described in Chapter 3, Methods and Materials, of this document. Chlorine dioxide was generated onsite according to Method 4500-ClO_2 of *Standard Methods for the Examination of Water and Wastewater, 19th Ed* and as described in Chapter 3. Chlorine stocks were produced using a 16% analytical grade sodium hypochlorite solution. Monochloramine was produced by combining an ammonium chloride solution and 16% analytical grade sodium hypochlorite at a pH of 9.4 as described in Chapter 3. The low pressure UV lamp from Trojan Technologies Inc. described in Chapter 3 was used for primary UV disinfection of the *E. coli* spikes.

E. coli K12 strains were acquired from the American Type Culture Collection (ATCC), which was frozen in stock at the Dalhousie University laboratory. Following the procedure outlined in Chapter 3, *E. coli* cultures were washed to obtain a concentrated "pellet", which was suspended in solution and transferred into a sterile 0.85% sodium chloride solution in a 4-L amber bottle. The cultures were enumerated using a standard membrane filtration technique and cultured on m-Endo LES agar. The filtration set-up is pictures in Figure 4.2. Biochemical assays (API tests), were utilized to track phenotypic changes in *E. coli.*

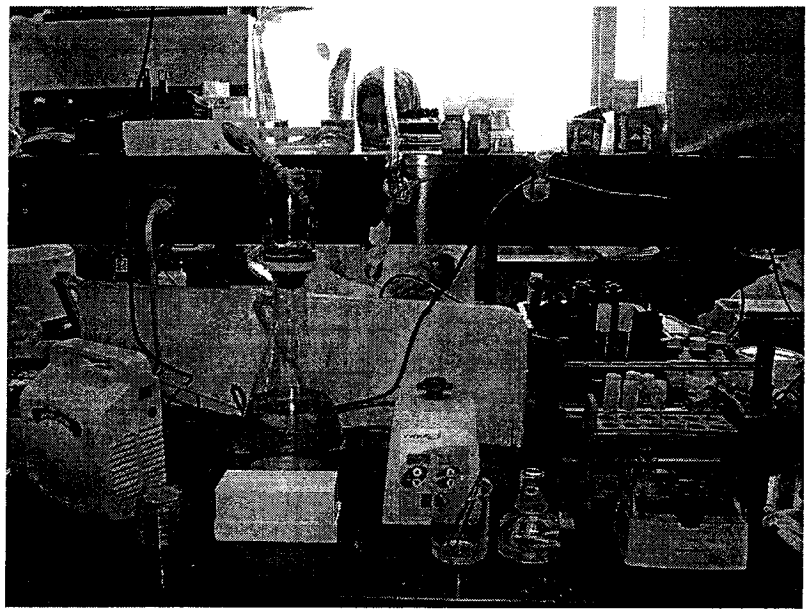

Figure 4.2: Membrane Filtration Set-up for *E. coli* Enumeration

4.5 RESULTS AND DISCUSSION

E. coli concentrations in spiked stock bottles were determined prior to the treatment processes. In total, five 4-L stock bottles were required for the completion of the experiment. The first acted as a solution rinse for the UV lamp and went to waste. The remaining four bottles ranged in concentration from 2.85×10^7 to 1.73×10^8 CFU/mL.

Following each disinfection strategy, samples were again cultured to determine *E. coli* concentration. All samples were duplicated and data presented are the resulting averages observed. At high CT, samples that received primary disinfection of UV light as well as secondary disinfection had no *E. coli* concentration following treatment. Each strategy (UV/Cl_2, UV/ClO_2, UV/NH_2Cl) received spiked water from the same bottle with an original concentration of 1.73×10^8 CFU/mL, which corresponded to a reduction in *E. coli* of 8.24-log, which was essentially limited by detection method. UV treatment was the second most effective disinfection strategy and achieved 4.31-log inactivation of *E. coli*. In comparing chemical disinfectants as primary disinfectants, chlorine dioxide was the most effective achieving 2.77-log reduction, followed by chlorine (1.32-log) and monochloramine (1.13-log). Figure 4.3 shows *E. coli* concentrations before and after treatment for each disinfection strategy.

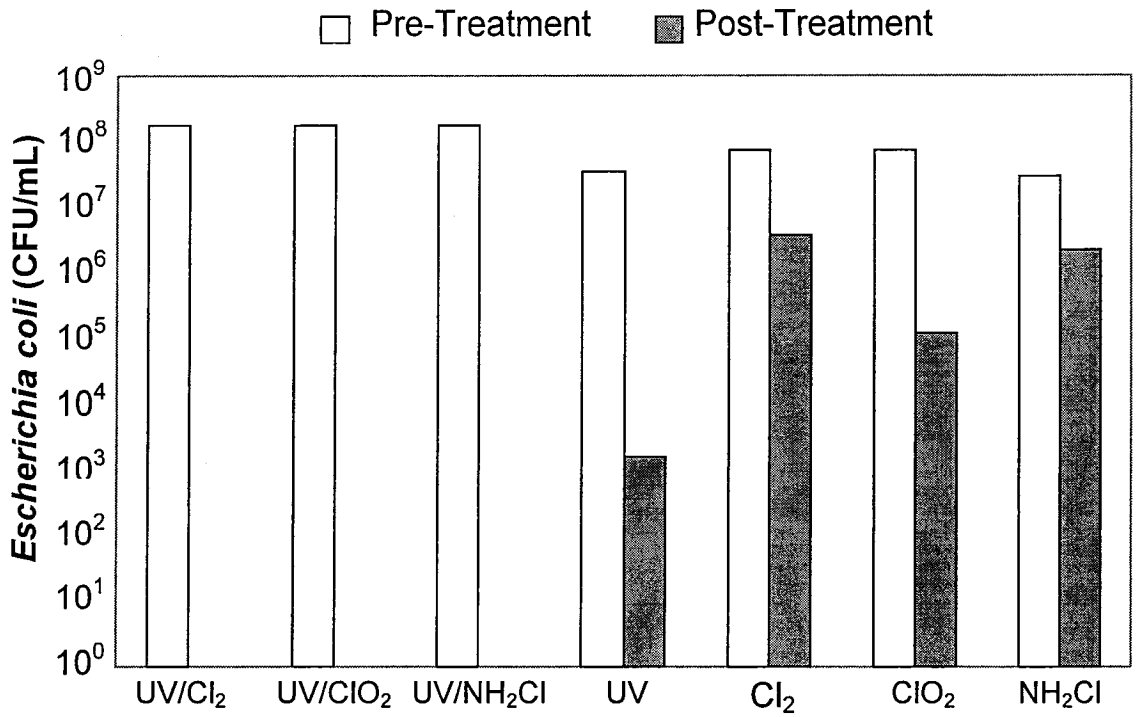

Figure 4.3: *Escherichia coli* Concentrations Before and After Treatments

At the low CT, combination strategies also achieved the highest log-removals compared to each disinfectant alone. The UV + NH_2Cl had the highest observed reduction at 4.75-log, which was similar to other combinations including UV + Cl_2 at 4.37-log and UV + ClO_2 at 4.11-log. Average reduction achieved by UV alone was similar to the first trial run at 3.65-log removal. Chemical disinfectants did not achieve significant removal with Cl_2 at 0.27-log, ClO_2 at 0.29-log and NH_2Cl at 0.93-log removal.

In comparing disinfection with chlorine-based disinfectants alone and in combination with UV light at both CTs, it was found that there was approximately 4-log difference at a low CT and up to 7-log difference observed at a high CT (Figures 4.4, 4.5 and 4.6). Each UV/chlorine-based disinfectant combination was compared statistically to treatment with chlorine-based disinfectant alone and all were significantly different, indicating synergistic effects have statistically meaningful values ($p = 0.000$). Considering UV reductions were similar in both trials, higher removals seen in combinations with a higher CT for chemical disinfection would logically be observed, just as higher reduction was seen with a higher CT when chemical disinfectants acted alone. It can be observed from the graphs that chlorine-based disinfection is more

effective when in combination with UV light, and lower dosages would be required when used in combination to achieve goal log reductions.

Due to the inability to measure disinfectant residual at the time that samples were quenched to enumerate the *E. coli*, it was difficult to compare results with the Baribeau et al. (2005) study. However, as previously mentioned, estimated residual concentrations were used to establish high CTs for the first trial run. Using equations derived from the Baribeau et al. (2005) results, CTs were calculated based on goal log reductions of 2.0. In the first high CT experiment, Cl_2 and NH_2Cl alone achieved 1.32-log and 1.13-log removals, which are close to the goal removal and indicate that data is comparable to results from this previous study. Actual concentrations at sample time were calculated using the achieved log reduction and the Baribeau et al. (2005) equations for Cl_2 and NH_2Cl inactivation. It was found that actual Cl_2 concentration was 0.19 mg/L and NH_2Cl was 0.36 mg/L, which are very close to estimated residual concentrations (0.20 mg/L and 0.50 mg/L respectively), confirming that results are comparable to previous studies.

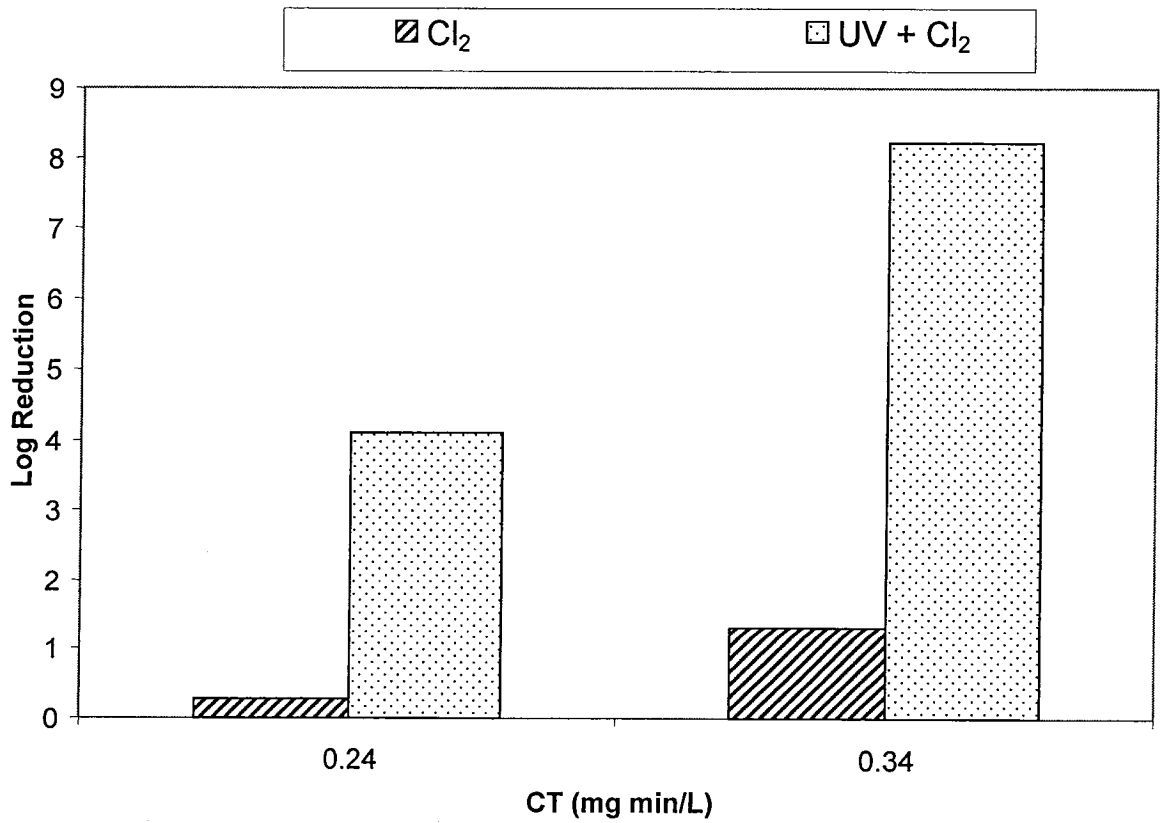

Figure 4.4: Log Reduction versus CT for Removal of *E. coli* by Cl_2 and UV + Cl_2

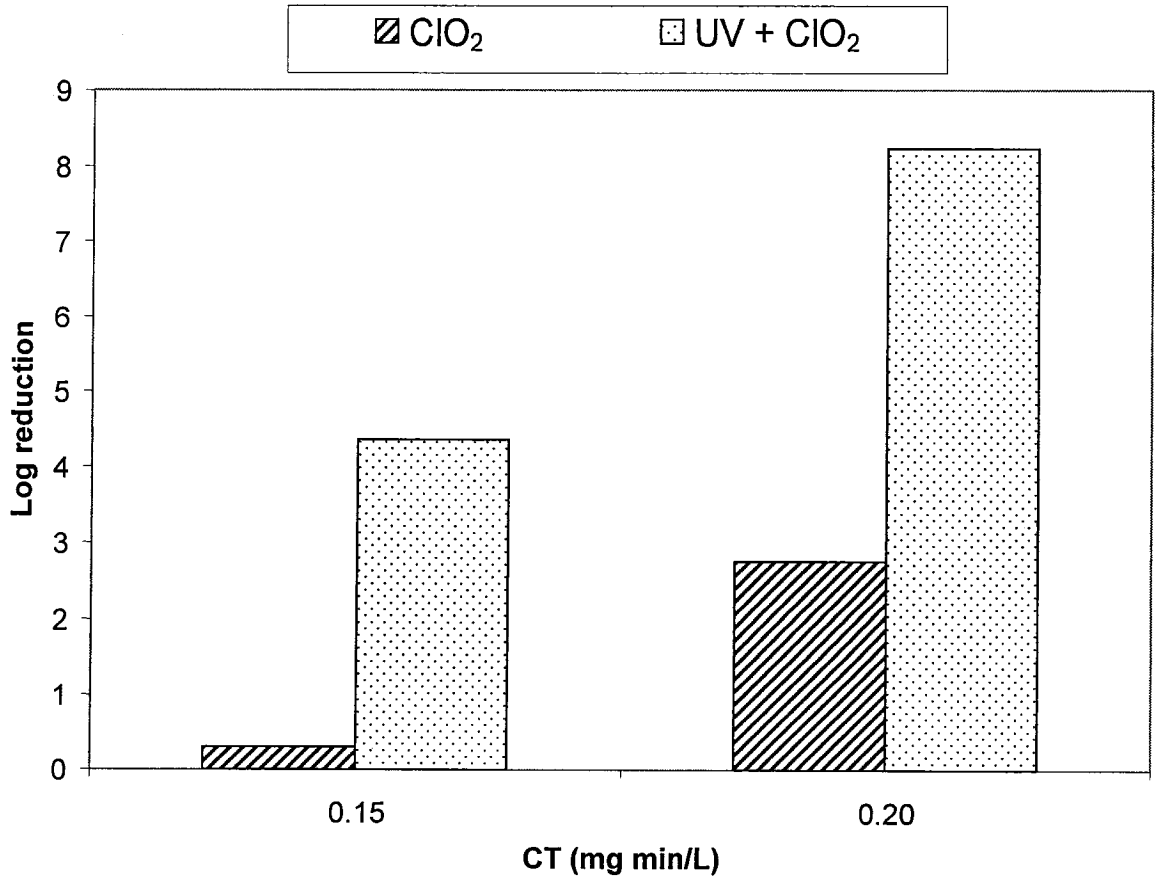

Figure 4.5: Log Reduction versus CT for Removal of *E. coli* by ClO_2 and UV + ClO_2

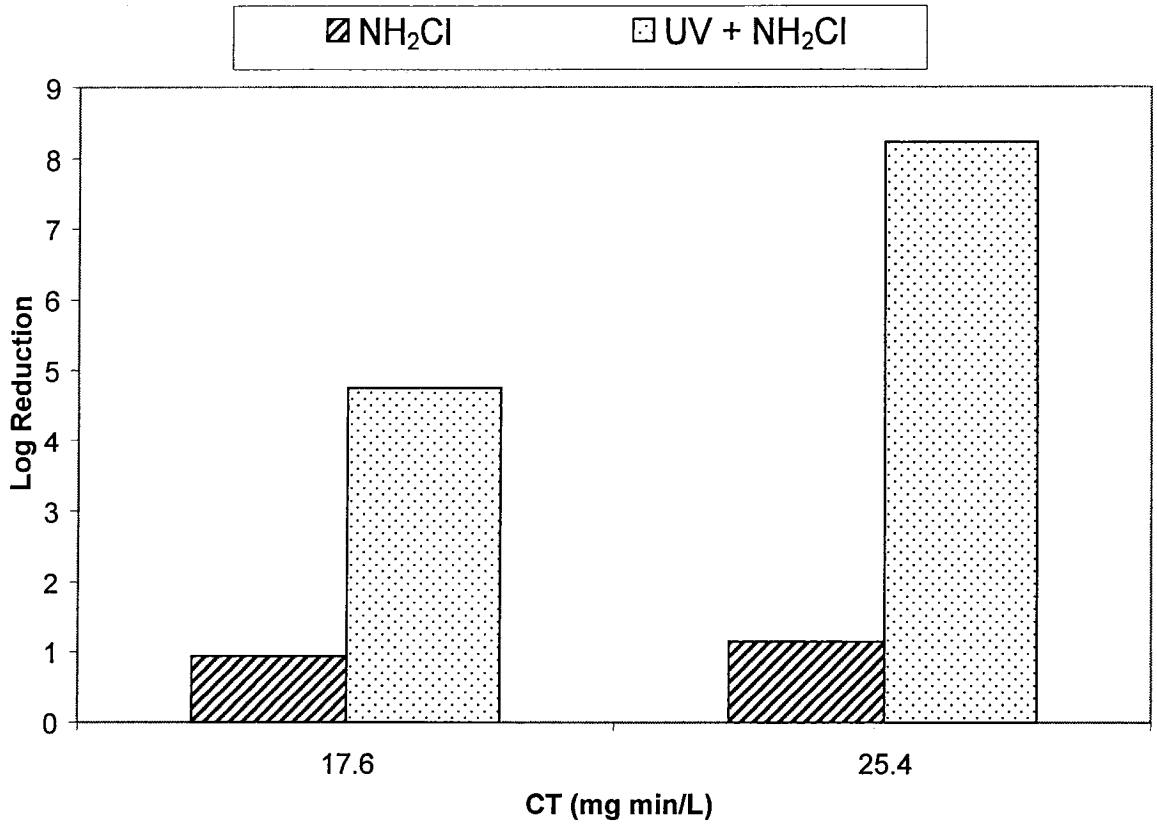

Figure 4.6: Log Reduction versus CT for Removal of *E. coli* by NH_2Cl and UV + NH_2Cl

As previously described, Koivunen et al. (2005) introduced a calculation for synergy in treatment combinations. The equation is as follows:

Equation 4.3: Synergy (Koivunen et al., 2005)

Synergy (log units) = log reduction by combined **chemical/UV** disinfection – (log reduction **UV** disinfection + log reduction **chemical** disinfection)

When the calculated answer is positive it is an indication that synergy is present. Synergistic effects were calculated for this experiment and compared the combination treatments (UV/Cl_2, UV/ClO_2, UV/NH_2Cl) to UV and chemical disinfectants alone. It was determined that each combination with the high CT values demonstrated synergy according to the Koivunen et al. (2005) equation. Table 4.2 presents *E. coli*

concentrations before and after treatment, corresponding log reductions, and finally synergy calculations.

Table 4.2: Log Removals and Synergy for *E. coli* at High CT

AR	*E. coli* Pre-Treatment (CFU/mL)	*E. coli* Post-Treatment (CFU/mL)	Log Reductions	Synergy
UV+Cl_2	$1.73x10^8$	$0.00x10^0$	8.24	+2.61
UV+ClO_2	$1.73x10^8$	$0.00x10^0$	8.24	+1.16
UV+NH_2Cl	$1.73x10^8$	$0.00x10^0$	8.24	+2.80
UV	$3.45x10^7$	$1.70x10^3$	4.31	
Cl_2	$7.20x10^7$	$3.49x10^6$	1.32	
ClO_2	$7.20x10^7$	$1.23x10^5$	2.77	
NH_2Cl	$2.85x10^7$	$2.11x10^6$	1.13	

At the lower CT, synergy calculations were also positive for all combination disinfection strategies, however synergy values were not as high compared to the high CT results. This would indicate that synergistic benefits may not be as stable at lower chlorine-based disinfection CTs.

Table 4.3: Log Removals and Synergy for *E. coli* at Low CT

AR	*E. coli* Pre-Treatment (CFU/mL)	*E. coli* Post-Treatment (CFU/mL)	Log Reductions	Synergy
UV+Cl_2	$1.69x10^7$	$1.31x10^3$	4.11	+0.19
UV+ClO_2	$1.69x10^7$	$7.15x10^2$	4.37	+0.43
UV+NH_2Cl	$1.69x10^7$	$2.98x10^2$	4.75	+0.17
UV	$1.69x10^7$	$1.04x10^4$	3.65	
Cl_2	$1.12x10^7$	$6.03x10^6$	0.27	
ClO_2	$1.12x10^7$	$5.68x10^6$	0.29	
NH_2Cl	$1.12x10^7$	$1.31x10^6$	0.93	

Positive synergistic benefits were observed for the combination treatments indicating that treatment plants implementing primary disinfection of UV light followed by any chlorine-based disinfectant may get added benefits in inactivating *E. coli* and potentially other bacteria and pathogens. Data confirm preliminary results found by Dykstra et al. (2006) that showed synergy between UV and Cl_2 or ClO_2. Results are also

consistent with findings by Koivunen et al. (2005) that showed synergy between UV and various chemicals for reducing *E. coli* and other pathogens.

Due to no existing cultures following combination disinfection with high CT treatments, biochemical assays were not able to be carried out to track any phenotypical changes. At low CT, API tests were completed but showed no changes between cultures before disinfection and after treatment. This method was limited to viable cells that would have survived batch-test disinfection only. Since no changes were observed, these cells that survived did not mutate to show effects of disinfection. However, it is possible that if cells had entered into a distribution systems, those that were damaged and would otherwise die may have been able to repair themselves as part of a biofilm community in a mutated form. Murphy (2006) found that *E. coli* isolates collected from biofilm samples in ARs containing polycarbonate or cast iron coupons differed in phenotypical profile from *E. coli* in stock solution. This study suggests reasons for the observed change include diversification of organisms within the biofilm communities, sub-lethal injury as a result of chemical disinfection, and the influence of UV treatment and pipe material causing phenotypical change in order to survive and cope in a different environment. These explanations for changes in biofilm *E. coli* would not apply to *E. coli* in bulk water, indicating changes in suspended *E. coli* can not be tracked phenotypically using API tests.

4.6 CONCLUSIONS

Previous studies have shown that synergistic benefits between two disinfectants may enhance inactivation of pathogens. However, no studies to date had been specifically designed to investigate synergy between UV light and chlorine-based disinfectants predominantly used in treatment of drinking water. This study looked at synergy between immediate disinfection with UV light as a primary disinfectant and Cl_2, ClO_2 or NH_2Cl as secondary disinfectants for the inactivation of *E. coli* in bulk water. It was observed that combination disinfection strategies achieved significantly higher removal of *E. coli* in comparison to the disinfectants being used alone. In fact, the combination disinfectants eliminated all *E. coli* in the treated samples with the high CT

disinfection and achieved removal of 8.24-log. As a primary disinfectant, UV treatment alone was effective against *E. coli* with an average of 3.98-log reduction. In comparing chemical disinfectants as a primary treatment alone, chlorine dioxide was tested at the lowest CTs (0.15 and 0.20 mg min/L) compared to Cl_2 (0.24 and 0.34 mg min/L) and NH_2Cl (17.6 and 25.4 mg min/L) but was the most effective during the high CT run indicating a strong ability to inactivate *E. coli*. Monochloramine was most effective for the low CT experiment, but did not change significantly in ability to inactivate *E. coli* at a higher CT, indicating NH_2Cl may have a limited ability for inactivation. Results for log removals with Cl_2 or NH_2Cl alone were comparable to log removals observed in previous studies.

When data obtained were analyzed using an equation presented in a study done by Koivunen et al. (2005) to calculate synergy, each disinfectant combination resulted in positive calculations for both CTs. In the case of UV and NH_2Cl in combination, a 7-log improvement in reduction over treatment with NH_2Cl alone was observed at high CT. This is possibly due to repair mechanisms being overloaded by two separate disinfectants, making it harder for cells to survive when compared to using one disinfectant alone, as pointed out by Koivunen et al. (2005). Since *E. coli* is representative of HPC bacteria and synergistic benefits enhance its removal from bulk water, this could eventually lead drinking water utilities to optimize treatment practices to achieve more removal of bacteria entering the distribution system.

5.0 FIELD EVALUATION OF MITIGATING BIOFOULING WITH CHLORINE DIOXIDE OR CHLORINE INTEGRATED WITH UV DISINFECTION FOR TREATING SURFACE WATER IN WARM AND COOL CLIMATES

5.1 ABSTRACT

The overall objective of this chapter was to compare various disinfection strategies for controlling biofouling in water distribution systems with a surface water source. The research compared the efficacy of chlorine (Cl_2) and chlorine dioxide (ClO_2) with and without pre-treatment with ultraviolet light (UV). An additional goal was to determine disinfection by-product (DBP) formation with each disinfection strategy. Previous studies have shown that replacing Cl_2 with ClO_2 has eliminated the formation of harmful DBPs. Annular reactors (ARs) containing polycarbonate coupons were used to simulate pipe systems that transport surface water from the source to treatment facilities and following treatment through a distribution system. Two studies were carried out for this chapter. The first study took place in the warm climate of California where a 90-mile aqueduct transports surface water from a reservoir to treatment facilities. The second study took place in the cooler climate of Halifax, Nova Scotia where the J. D. Kline Water treatment Plant uses a surface water source to supply its customers. ARs were dosed with chemical disinfection to achieve a residual of 0.20 mg/L, which was a value that is historically seen at the midpoint of the aqueduct and which is also the minimum required residual under Nova Scotia Drinking Water Regulations. The experiment matrix for each study included four strategies of disinfectants including UV/ ClO_2, ClO_2, UV/ Cl_2 and Cl_2. Two ARs acted as controls and received raw water (RW) or UV-treated water. In both studies it was found that the most effective strategy in controlling suspended and attached heterotrophic (HPC) bacteria included pre-treatment with UV. At the Pardee Reservoir, the data presented show that the UV/ ClO_2 combination was most effective against suspended and attached heterotrophic bacteria with 3.93 log and 2.05 log reductions respectively. Chlorine dioxide was more effective than Cl_2 at removing suspended HPC bacteria and similarly effective in biofilm bacterial removal. In Halifax the UV/ ClO_2 combinations was most effective against suspended bacteria (2.12 log reduction) and the UV/ Cl_2 AR had highest reduction for attached bacteria (1.71 log). Pre-treatment with UV was more effective overall for removal of HPC bacteria than treating with corresponding chemical disinfectants only, however it did not lower required chemical dosages. Treating with ClO_2 produced fewer total trihalomethanes (TTHMs) and haloacetic acids (HAAs) than treating with Cl_2, but did result in the formation of chlorite. These data indicate that pre-treating with UV light potentially causes synergistic effects that enhance removal of HPC bacteria and that ClO_2 is a viable alternative to Cl_2.

5.2 EVALUATION OF DISINFECTION STRATEGIES FOR THE PARDEE RESERVOIR AQUEDUCT

5.2.1 Introduction

The East Bay Municipal Utility District (EBMUD) operates six water treatment plants throughout the East Bay in California. The primary source water is snowmelt from the Sierra Nevada collected at the Pardee Reservoir. The water travels from the reservoir through 90 miles of aqueduct before reaching either immediate treatment or subsequent storage at one of several terminal reservoirs. EBMUD was interested in lowering total trihalomethane (TTHM) levels and haloacetic acid (HAA) levels in its treated water. An important mechanism leading to the formation of these disinfection by-products (DBPs) is the application of chlorine in aqueduct water to suppress biofilm. Biofilm control is critical to mitigate headloss and biocorrosion in the aqueduct. A potential method of controlling biofouling while minimizing TTHM and HAA formation would be to replace free chlorine with chlorine dioxide or UV light as primary disinfection. There is potential that UV treatment would reduce chemical dose, thereby decreasing THM and HAA formation. The potential for synergistic effects between UV light and chlorinated disinfectants might also enhance control of biological fouling. The focus of this project was to determine the effectiveness of UV, UV/Cl_2 and UV/ClO_2 in suppressing biofilm growth in aqueduct water, and to compare pre-treatment with UV to no UV treatment. The study also assessed DBP concentrations when using UV to allow a reduction in chemical disinfectants for aqueduct fouling control (and primary disinfection).

5.2.2 Experimental Design

To simulate the aqueduct, eight annular reactors (ARs) were set up in parallel at the Pardee Reservoir. Two trains of water, one treated with UV light and one un-treated, were pumped into separate clearwells and were dosed with a sodium hydroxide solution to adjust pH to a level similar to the full-scale aqueduct. The adjusted water was then pumped into each AR, which represented the first section of the aqueduct where residual disinfectant is still measurable (Figure 5.1). Due to fluctuating water pressure in the

source pipeline, equilibrium tanks were set up to control flow into each clearwell through gravity. The UV lamp was set up with a flow regulating valve in order to ensure constant dose, and was directed from the lamp into one of the equilibrium tanks.

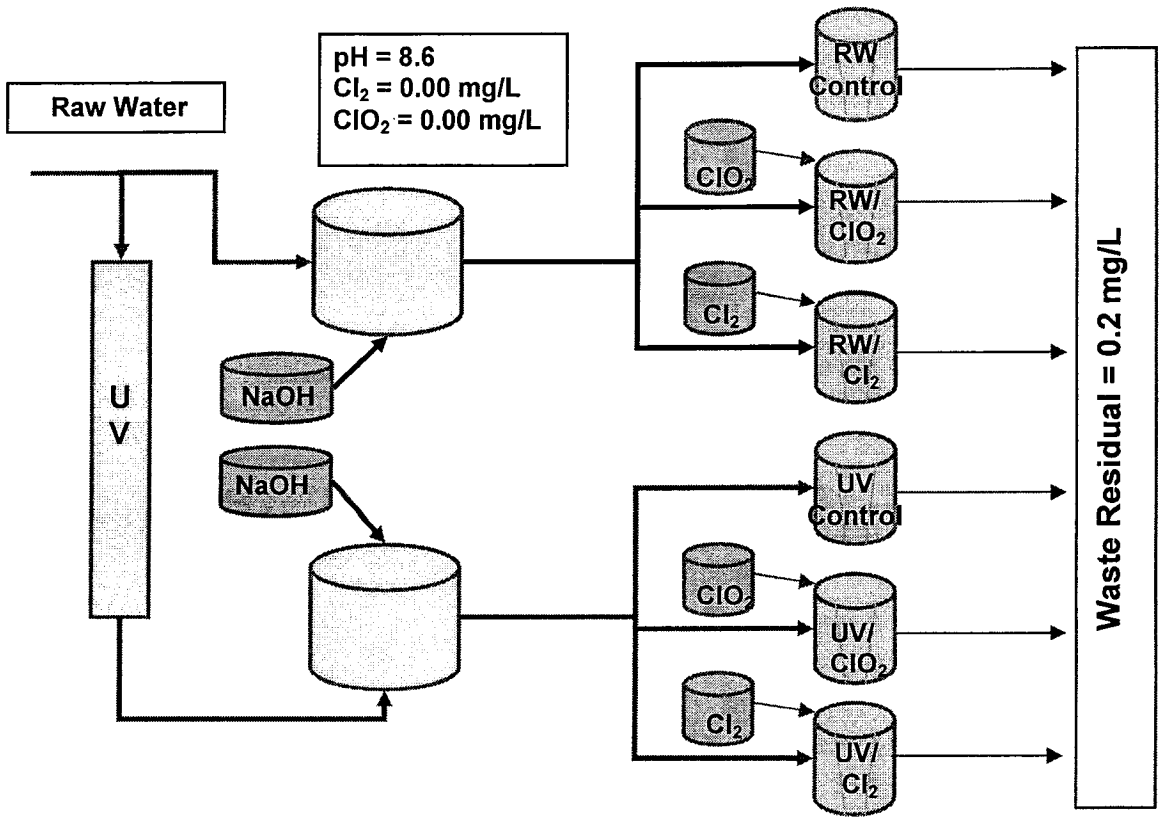

Figure 5.1: Bench-scale Set-up of Aqueduct Study

Each of the eight ARs contained coupons made of polycarbonate. One AR acted as a RW control and had no disinfection throughout the experiment, and one AR acted as a control for the UV stream. Two ARs were treated with chlorine dioxide, one that received water pre-treated with UV and one that received raw water. The final four ARs were treated with chlorine, and two of these were pre-treated with UV light (Table 5.1). The target disinfectant residual in the effluent of each chemically dosed AR was 0.20 mg/L. This disinfectant residual was selected on the basis of historical concentrations that have been measured at a mid-point in the aqueduct, namely San Joaquin. Based on data provided by EBMUD the full scale hydraulic retention time (HRT) in the aqueduct from Pardee to San Joaquin was just over 22 h. This corresponded to an HRT in the ARs

of 2.0 h, which was established based on a relationship between surface areas and volumes in ARs and pipes, as described by Gagnon and Huck (2001). In this study, the length of the simulated pipeline was approximately 59,860 m with a 65" diameter and 0.74 m/s flow. By calculating surface area and volume in this pipe section an Area (A)/Volume (V) ratio was established. Using the Gagnon and Huck (2001) AR A/V ratio, it was determined that the ratio of the surface area per unit volume in the AR compared to the aqueduct was 110, therefore an HRT of 22.3 h in the aqueduct corresponded to an AR HRT of 0.20 h. In order to compare with previous AR studies and to reduce water usage, the HRT was multiplied by a factor of 10 for a 2.0-h HRT. Camper (1995) and Gagnon (1997) have shown that the number of biofilm bacteria and the amount of chlorine decay is strongly correlated to available surface area. Therefore it is acknowledged that the biofilm measured in the ARs would not be quantitatively similar to that which would exist in the aqueduct, however it was expected that the experiment would still allow comparisons to be made between disinfectants in terms of their ability to control biofilm. The chemical disinfectant flowrate was established at 5% of the total flowrate, which corresponded to 0.4 mL/min for disinfectants and 7.7 mL/min for influent source water.

Table 5.1: Pardee Disinfection Scheme

Disinfection	Residual Concentration (mg/L)
UV	0.0
Control (no disinfectant)	0.0
UV + ClO_2	0.20
ClO_2	0.20
UV + Cl_2	0.20
Cl_2	0.20
UV + Cl_2	0.20
Cl_2	0.20

The ARs were set at a rotational speed that created the same shear stress at the surface promoting biofilm growth (i.e., coupon surface) as that which would be seen at the outer wall within the aqueduct. Using a friction factor for a large pipe diameter of

0.01 and the velocity seen in the aqueduct of 0.74 m/s, the shear stress in the pipe was determined to be 0.68 N/m^2. Using a spreadsheet provided by BioSurface Technologies (manufacturers of ARs), where several equations are solved simultaneously for convergence, data is obtained for shear stress and rotational speed using linearization constants. Results are plotted (Figure 5.2) and the resulting equation is rearranged to solve for desired rotational speed. For this study the required speed was approximately 160 rpm within each AR.

All non-opaque exposed surfaces of the ARs were covered to reduce the potential of phototrophic growth in the field systems. Before the experiment, all ARs were cleaned with antibacterial soap and disinfected using a 70% ethanol solution. In addition all tubing and clearwells used within the set-up were disinfected with ethanol for a period of 24 hours. This was followed by rinsing with Milli-Q water and the source water.

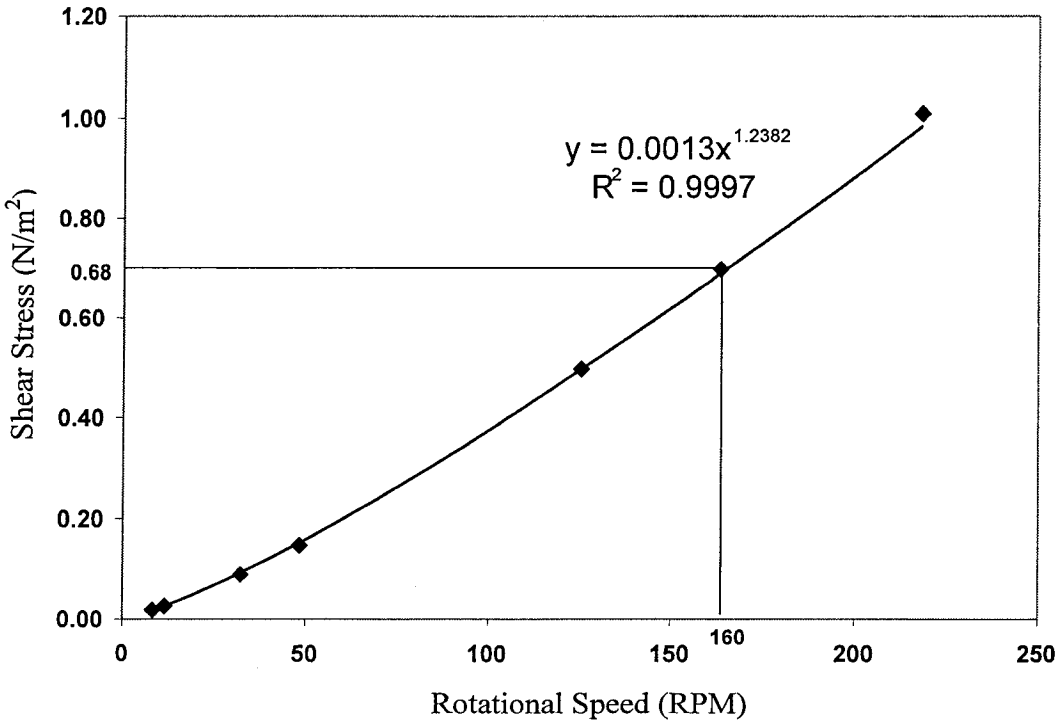

Figure 5.2: Shear Stress versus Rotational Speed in Annular Reactors

5.2.3 Methods and Materials

All sampling and testing protocols were carried out as described in the *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 1998) and as described in Chapter 3, Methods and Material, of this document. The ARs were operated for a four-week acclimation period in order to allow for biological steady-state conditions to be reached within the ARs. This period was followed by twelve weeks of disinfection, excluding control ARs that had no change throughout the experiment. During the study the ARs' effluent was collected 1-2 times per week to analyze for pH, temperature, turbidity, TOC and DOC. Once disinfection began the samples were also analyzed for disinfectant concentration, total trihalomethanes, haloacetic acids, chlorite and chlorate. In addition, effluent was collected for suspended heterotrophic bacteria counts and total cell counts (AODC) throughout the experiment 1-2 times per week. Coupons were also removed aseptically and scraped onsite to analyze for attached HPC bacteria and total cells.

Chlorine dioxide was generated onsite according to Method 4500-ClO_2 of *Standard Methods for the Examination of Water and Wastewater, 19th Ed* and as described in Chapter 3. Chlorine stock concentrations were produced using the 12.5% sodium hypochlorite solution that was used at the Pardee Reservoir in the full-scale aqueduct. Sodium hydroxide solutions for pH adjustment were obtained by dissolving NaOH pellets in de-ionized water to achieve a pH of ~9.5, and trial and error was then used in the commencement of the experiment to obtain the desired pH.

5.2.4 Results and Discussion

5.2.4.1 Acclimation/Pre-disinfection period

The ARs were operated for a period of four weeks prior to any application of disinfection to establish steady state biofilm. Steady state conditions over this biofilm acclimation period, or pre-disinfection, were determined for both heterotrophic and total cell counts. Pre-disinfection conditions were determined for ARs that would eventually receive no disinfectant, ClO_2 or Cl_2.

Before disinfection the overall average number of suspended heterotrophic bacteria in all ARs was $6.05x10^4 \pm 1.95x10^4$ CFU/mL and average attached (biofilm) heterotrophic bacteria for all ARs was $1.59x10^6 \pm 1.93x10^6$ CFU/cm^2. The number of heterotrophic bacteria was statistically similar during the acclimation period for all ARs for either suspended or attached cells. During the acclimation period the mean total suspended cell count was $1.64x10^6 \pm 1.96x10^6$ CFU/mL and the overall mean attached total cell count was $1.50x10^6 \pm 6.92x10^5$ CFU/cm^2.

The ratio of heterotrophic to total cells was determined in order to establish the proportion of culturable bacteria in the bulk water and the biofilm. The average ratio for bulk water, disregarding coupon composition, was 0.08 ± 0.06, and for biofilm the mean was 0.60 ± 0.42 indicating much higher culturability on the bacteria attached to the pipe wall. Previous work conducted in the laboratory found that biofilm bacteria were proportionally easier to culture than their suspended counterparts (Gagnon et al., 2005). It is plausible that the cells in suspension are largely dormant and are viable when they attach themselves to the biofilm community.

5.2.4.2 Post-disinfection HPC data

After a four-week acclimation period two ARs that were receiving UV-treated water started being disinfected with chlorine and one AR treated with UV was disinfected with chlorine dioxide. Two ARs that had no UV disinfection were disinfected with Cl_2, and another with ClO_2. The remaining two ARs were not altered and continued as experimental controls, one for UV water and one for raw water. For an additional 12 weeks the ARs were monitored for suspended and attached HPC bacteria while chemical disinfection was applied (Table 5.2). All ARs that were treated with Cl_2 or ClO_2 showed a decrease in suspended heterotrophic bacteria, especially those treated with ClO_2 (Figure 5.3). The average log reduction for suspended HPC bacteria for ARs treated with chemical disinfection was 2.74 ± 1.02 log. ARs treated with ClO_2 had the greatest log reductions including 3.93 log for the AR treated with both UV and chlorine dioxide, and 3.23 log for the AR treated with ClO_2 only. The ARs treated with UV and chlorine had an average log reduction of 2.07 log for suspended HPC bacteria and similarly the ARs treated with Cl_2 had an average log reduction of 1.72 log. Overall, ARs treated with UV

had slightly greater reductions in suspended bacteria than those treated with corresponding chemical disinfection only.

Table 5.2: Pardee Suspended and Attached HPC Bacteria Pre- and Post-Disinfection

AR	Suspended HPC (CFU/mL) Acclimation	Attached HPC (CFU/cm^2) Acclimation	Suspended HPC (CFU/mL) Post-Disinfection	Attached HPC (CFU/cm^2) Post-Disinfection
UV Control	$5.38x10^4$	$1.80x10^6$	$4.95x10^3$	$2.05x10^6$
RW Control	$4.81x10^4$	$1.87x10^5$	$4.63x10^3$	$7.08x10^6$
UV+ClO_2	$4.58x10^4$	$4.15x10^5$	$5.41x10^0$	$3.72x10^3$
ClO_2	$9.06x10^4$	$1.48x10^5$	$5.34x10^1$	$1.33x10^4$
UV+Cl_2	$7.95x10^4$	$1.78x10^6$	$6.70x10^2$	$7.80x10^4$
Cl_2	$4.54x10^4$	$5.20x10^6$	$8.65x10^2$	$2.83x10^5$

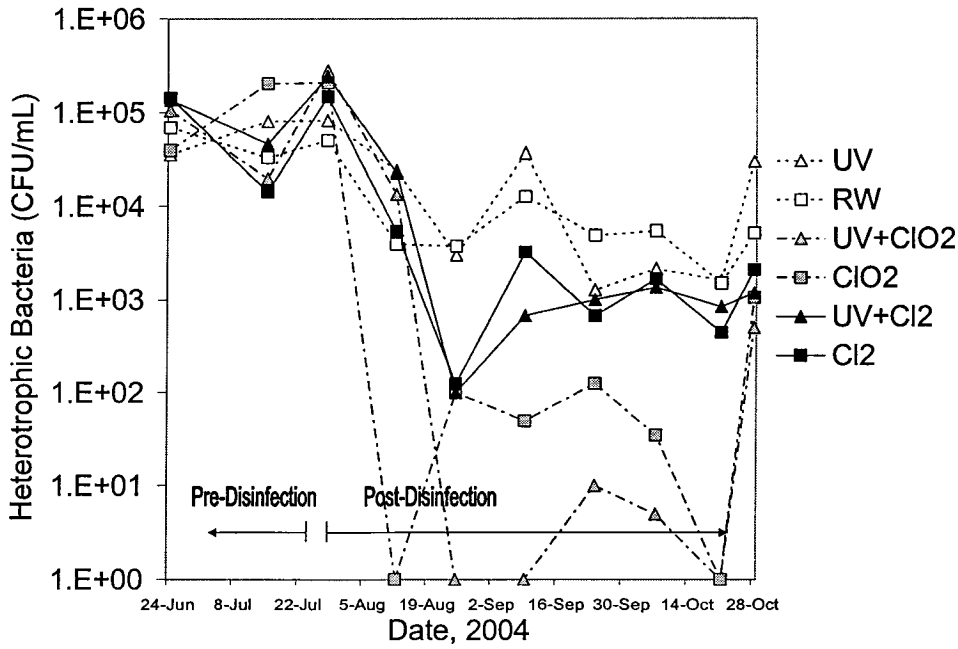

Figure 5.3: Number of Suspended Heterotrophic Bacteria Collected in the ARs located at the Pardee Reservoir

Control ARs increased in average heterotrophic biofilm bacteria over the course of the project but there was a decrease in the average HPC bacteria in ARs treated with chemical (Figure 5.4). The average log reduction in ARs treated with chemical disinfection was 1.43 ± 0.43 log, and the AR treated with UV and ClO_2 had the highest for attached HPC bacteria with a reduction of 2.05 log. Similarly to suspended bacteria, ARs treated with UV prior to chemical disinfection had slightly higher log reductions of attached HPC bacteria. ARs that acted as controls for the experiments increased in attached HPC bacteria during the disinfection phase with the UV AR having -0.057 log reduction and the RW AR with a -1.58 log reduction.

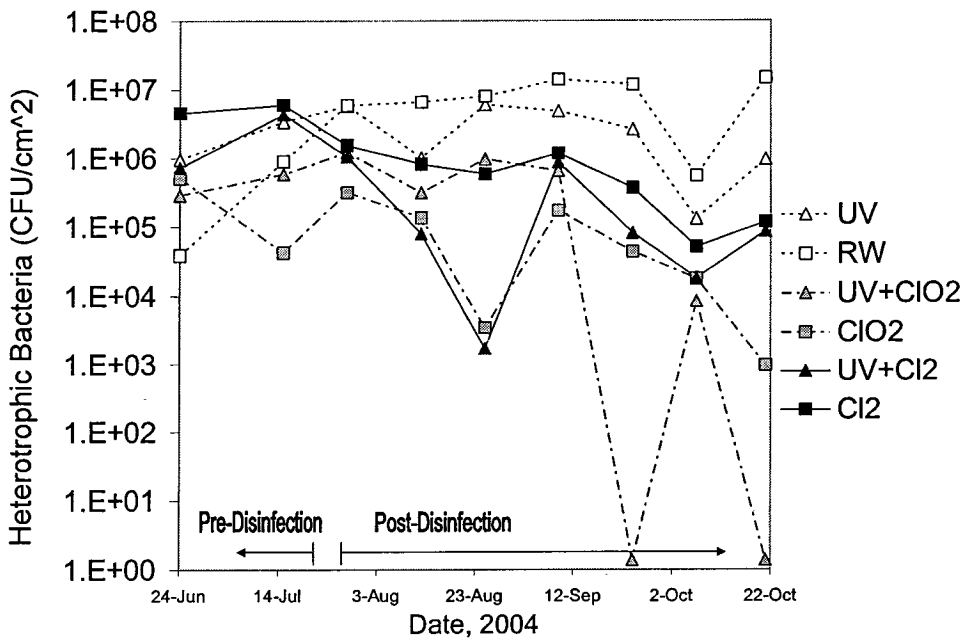

Figure 5.4: Number of Attached Heterotrophic Bacteria Collected in the ARs located at the Pardee Reservoir

It can be observed from Figures 5.3 and 5.4 that there is substantial scatter in data for field studies. This scatter is not evident in controlled laboratory studies where steady-state biofilm is achieved during acclimation, followed by a removal period during initial disinfection stages and finally resulting in a second steady-state condition at a reduced concentration (i.e., Gagnon et al., 2005). Scatter in field studies can be attributed to changing water quality over the course of the project, making true steady-state difficult to

achieve. Therefore, analysis of field data must rely on average counts during acclimation and disinfection stages rather than steady-state concentrations.

5.2.4.3 Post-disinfection Total Cell Counts Data

Total cell counts were also monitored by the AODC method before and after disinfection began, however there were no statistically significant differences for either suspended or attached cells in any AR between stages (Figures 5.5 and 5.6). The average log reduction for ARs treated with chemical disinfection in bulk water samples was greater than biofilm samples with values of 0.79 log and 0.08 log respectively. ARs treated with Cl_2 only had the highest reduction in bulk AODC with a value of 1.56 log

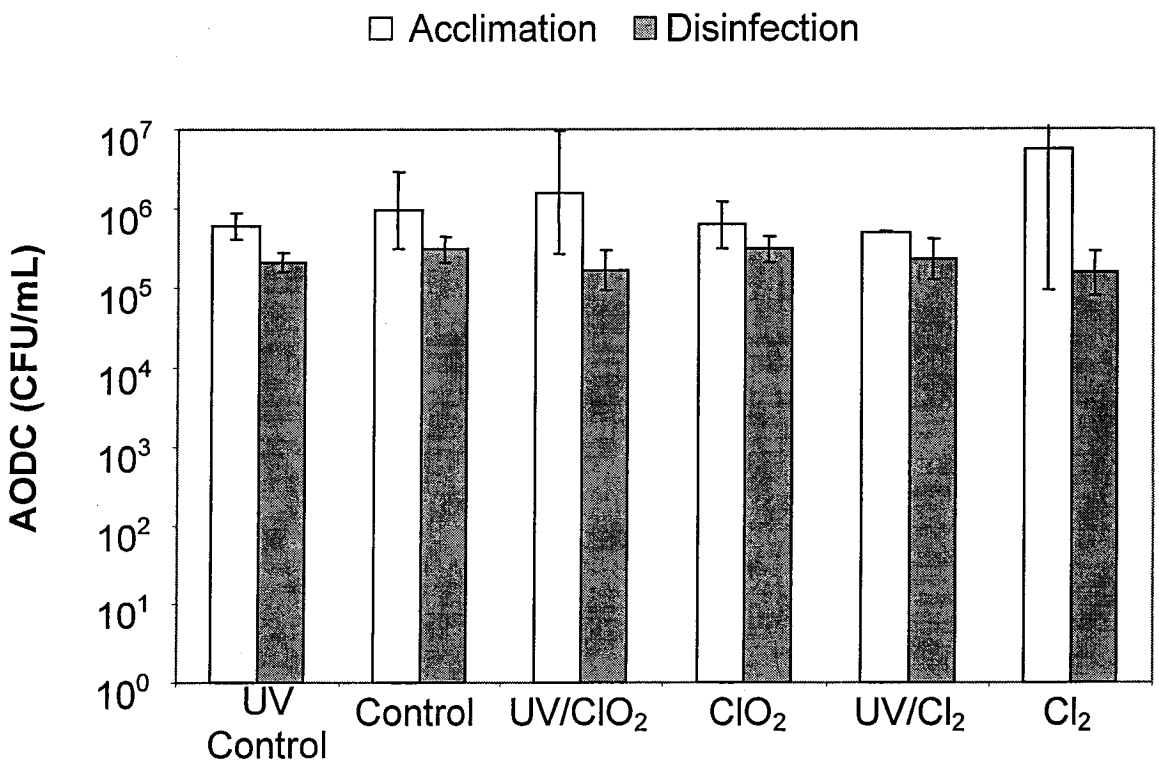

Figure 5.5: Log Reductions of Suspended AODC Bacteria in ARs at the Pardee Reservoir

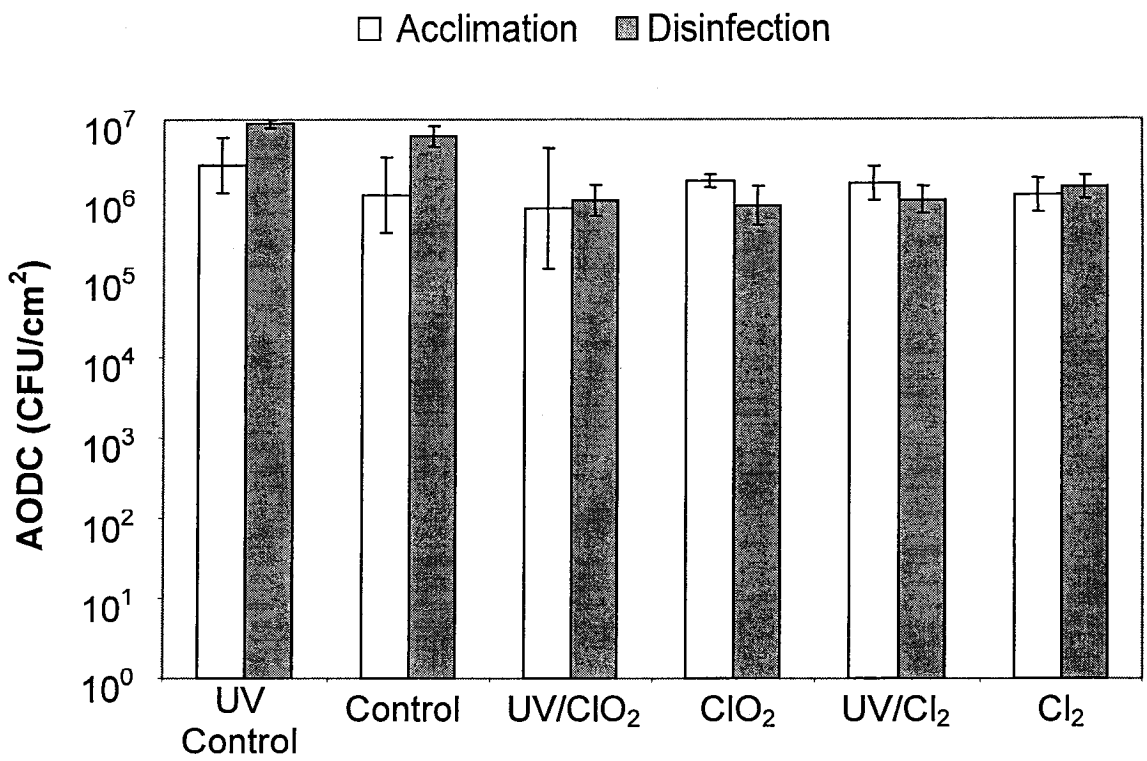

Figure 5.6: Log Reductions of Attached AODC Bacteria in ARs at the Pardee Reservoir

5.2.4.4 Post-disinfection Ratio of Heterotrophic to Total Cells

The ratio of HPC/AODC bacteria was determined for pre- and post-disinfection. For suspended cells the average ratio decreased slightly in control ARs from 0.07 ± 0.03 to 0.02 ± 0.006 however the average reduction was statistically significant in ARs treated with Cl_2 or ClO_2 down from 0.09 ± 0.08 to 0.002 ± 0.003 after disinfection in bulk water, indicating that chemical disinfection eliminated culturable cells while total cell counts remained constant. There was no statistically significant difference between pre- and post-disinfection ratios for either suspended or attached cells. The ARs treated with chlorine dioxide showed the greatest reduction in the suspended HPC/AODC ratios after chemical disinfection began going from 0.03 to 0.00003 in the AR treated with UV and ClO_2 and from 0.15 to 0.00017 in the AR treated with ClO_2 only. Similarly, Gagnon et al. (2004) and Volk et al. (2002) found that HPC/AODC ratios decreased after treatment with chlorine dioxide. ARs treated with UV and chemical disinfection showed higher ratio reductions for suspended cells than those that were treated with the corresponding

chemical disinfection only. This indicates that previously culturable cells are inactivated following disinfection with ClO_2 or combined UV/chemical disinfection.

The ratio also decreased for attached cells in ARs treated with chemical disinfection. The average biofilm ratio in the acclimation phase for ARs treated with Cl_2 or ClO_2 was 1.61 ± 2.09 and this decreased to 0.076 ± 0.09 post-disinfection. The greatest ratio reduction was seen in the AR treated with UV and ClO_2, going from 0.55 to 0.0039, again indicating that disinfection, especially with ClO_2, caused elimination of culturable cells. Overall pre-treatment with UV did not seem to affect the change in ratio from acclimation to the disinfection stage for attached cells as it did for suspended cells.

5.2.4.5 Comparison of Disinfectants

The most effective disinfection option overall was UV and ClO_2 for both suspended and attached heterotrophic bacteria. Using ANOVA it was determined that average bulk bacteria counts statistically differed at a 95% confidence level during the disinfection stage in ARs with ClO_2 only compared to ARs treated with Cl_2 only ($p = 0.024$), with chlorine dioxide having a higher log removal (Figure 5.7). There was also a statistically significant difference between the Cl_2 and ClO_2 ARs when pre-treated with UV ($p = 0.001$), and the UV + ClO_2 AR had higher log removal than any other AR. However, there was no statistically significant difference when ARs were pre-treated with UV and then chemical disinfection compared to the ARs with corresponding chemical disinfection only ($p = 0.123 - 0.689$), but combination ARs consistently achieved higher removal. All treated ARs showed statistically significant differences when compared to the control ARs for suspended bacteria.

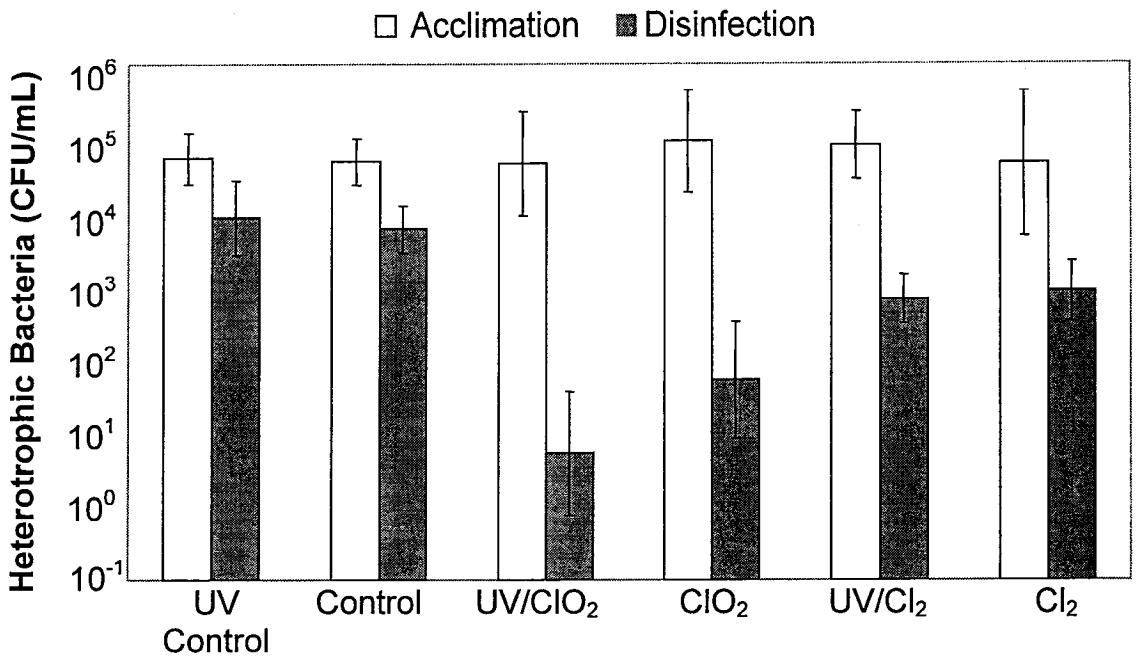

Figure 5.7: Average Suspended Heterotrophic Bacteria Collected in the ARs located at the Pardee Reservoir

The biofilm data was similar to bulk samples and the AR treated with UV and ClO_2 had the highest removal of attached bacteria with 2.05 log, however this was not statistically different ($p = 0.299$) than the AR treated with UV and Cl_2 with a 1.36 log removal (Figure 5.8). The AR treated with ClO_2 only had the lowest removal of attached HPC bacteria at 1.05, which was statistically different than the ARs treated with Cl_2 only which had an average log removal of 1.26 ($p = 0.006$).

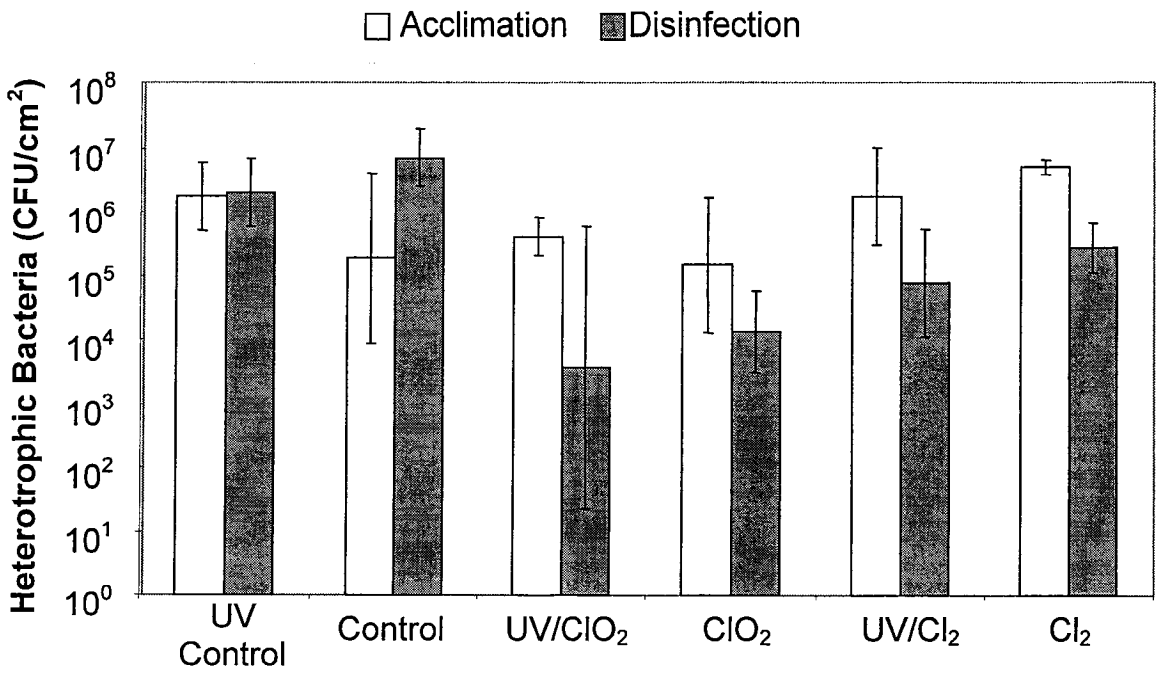

Figure 5.8: Average Attached Heterotrophic Bacteria Collected in the ARs located at the Pardee Reservoir

5.2.4.6 Water Quality Analysis

During the 12-week period following acclimation, ARs were dosed with chemical disinfection excluding the control ARs. The presence of UV treatment did not generally seem to affect the required chemical dose for ARs. The average ClO_2 dose for the AR pre-treated with UV was 1.40 ± 0.42 mg/L, which was higher than the average dose for the AR treated with ClO_2 only which was 1.33 ± 0.44 mg/L. ARs treated with Cl_2 required less chemical dosages overall than the ClO_2 ARs. The average dose for ARs treated with UV and Cl_2 was 0.62 ± 0.15 mg/L Cl_2 and 0.68 ± 0.15 mg/L for ARs treated with Cl_2 only. The resulting average chemical residual was slightly lower in ARs treated with ClO_2 than Cl_2. During the course of disinfection, the AR treated with UV and ClO_2 had an average residual of 0.18 ± 0.14 mg/L ClO_2, the ClO_2 AR averaged 0.20 ± 0.12 mg/L ClO_2, the UV and Cl_2 ARs averaged 0.22 ± 0.13 mg/L Cl_2, and finally the ARs treated with Cl_2 only had an average residual of 0.23 ± 0.08 mg/L Cl_2.

The average pH for all ARs during the acclimation phase and post-disinfection was 8.41 ± 0.019. The ARs operated at an average temperature of 24.1 ± 0.11 °C during the experiment, and the average influent temperature was slightly lower at 23.7 ± 0.47 °C.

The average turbidity for the raw water influent was 0.81 NTU throughout the experiment which was higher then the average UV water influent at 0.30 NTU. This was consistent with average turbidities of the control ARs with the UV control at 0.21 NTU and the RW control AR at 1.28 NTU. Overall the turbidity decreased in AR post-disinfection except for the ARs treated with Cl_2 only, which increased from 0.40 NTU to 0.69 NTU. The average turbidity for all ARs during the acclimation phase was 0.44 ± 0.37 NTU and 0.34 ± 0.16 NTU after disinfection for all ARs excluding the controls.

5.2.4.7 Organic Content

Total organic carbon (TOC) was higher in ARs prior to disinfection, however this time period corresponded with early summer months which may have had some influence (Figure 5.9). TOC levels in all ARs, including control ARs, decreased after disinfection which ran into October. The average TOC concentration in all ARs in the acclimation phase was 2.49 ± 0.20 mg/L and 1.76 ± 0.12 mg/L during disinfection. The ratio of dissolved organic carbon (DOC) to TOC was high. The average DOC concentration in all ARs prior to disinfection was 2.38 ± 0.20 mg/L and 1.77 ± 0.14 mg/L in the disinfection stage (Figure 5.10).

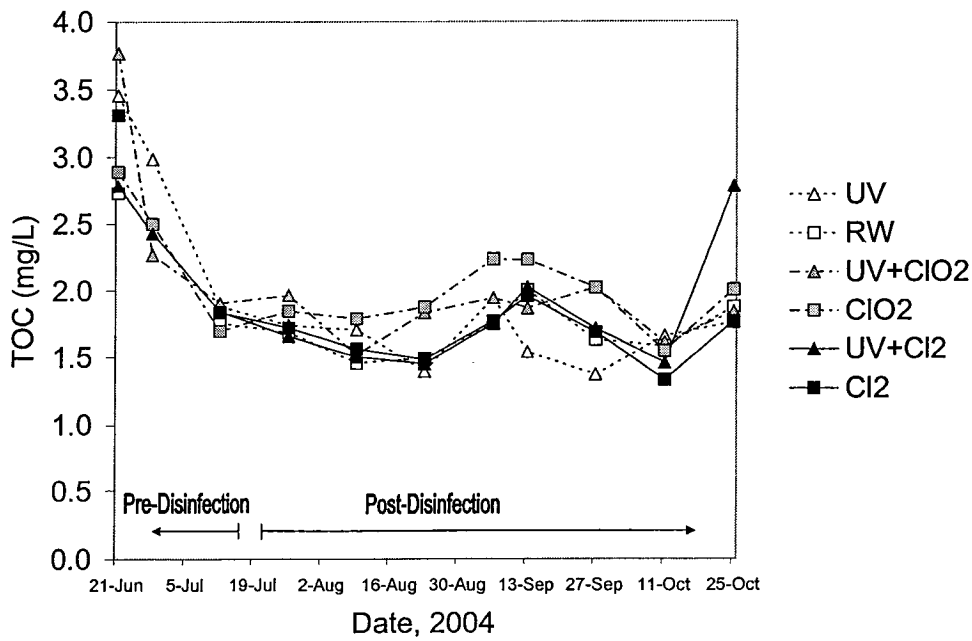

Figure 5.9: Total Organic Carbon Levels in ARs at the Pardee Reservoir

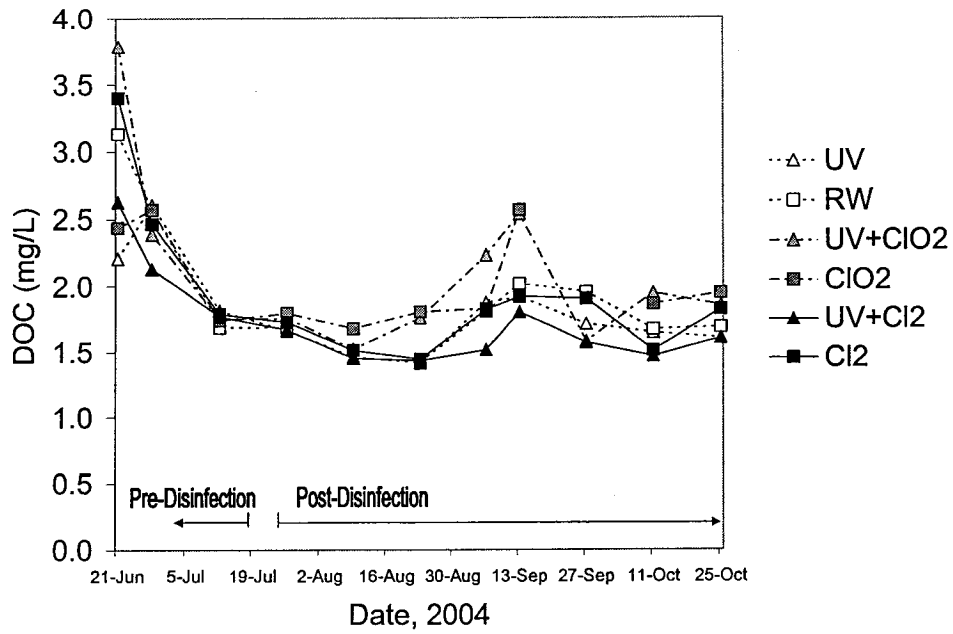

Figure 5.10: Dissolved Organic Carbon Levels in ARs at the Pardee Reservoir

5.2.4.8 Disinfection By-products

Total trihalomethanes (TTHMs) and haloacetic acids (HAAs) were measured following the application of disinfectants. TTHM levels were highest in ARs treated with chlorine, which is consistent with several studies that have been previously conducted (Hofmann et al., 1999; Werdehoff and Singer, 1987). However, the average TTHM concentration in the ARs treated with Cl_2 only was 6.33 ± 2.0 μg/L and 8.23 ± 2.3 μg/L and in the ARs treated with UV and Cl_2, which are minimal compared to the United States Environmental Protection Agency (USEPA) maximum contaminant level (MCL) for TTHMs of 0.08 mg/L. ARs treated with UV and/or ClO_2 had the same average TTHM concentration at 0.45 ± 0.64 μg/L. No TTHMs were observed in the control ARs.

ARs treated with Cl_2 also had the highest HAA concentrations. The average HAA concentration in the ARs treated with UV and Cl_2 was 4.90 ± 2.6 μg/L and 5.43 ± 2.9 μg/L in the ARs treated with Cl_2. ARs treated with ClO_2 showed higher HAA concentrations than TTHMs, but remained lower than Cl_2 ARs. The average HAA concentration in the AR treated with UV and ClO_2 was 2.41 ± 2.3 μg/L and 3.08 ± 2.1 μg/L in the AR treated with ClO_2 only, both very low values compared to the USEPA

MCL for HAAs of 0.06 mg/L.. The control ARs held a 0 μg/L average for this experiment.

In addition to TTHMs and HAAs, samples were collected to monitor the presence of chlorite and chlorate in the ARs. No chlorite was present in any ARs except those treated with ClO_2. The UV + ClO_2 AR had an average chlorite concentration of 0.57 ± 0.18 mg/L which was lower than the AR treated with ClO_2 only with an average ClO_2^- concentration of 0.68 ± 0.25 mg/L. The USEPA MCL for chlorite is 1.0 mg/L. The conversion to chlorite from the ClO_2 dose ranged from 40.8% in the UV + ClO_2 AR to 51.0% in the ClO_2 AR, which is within the 30-70% range generally demonstrated in other studies (Gordon, 1992; Gordon et al., 1990; Noack and Doerr, 1981). The ClO_2 AR effluent carried an average concentration of 0.050 ± 0.012 mg/L and the UV + ClO_2 AR averaged 0.043 ± 0.028 mg/L chlorate. ARs treated with Cl_2 also had chlorate present in bulk samples but at a lower concentration than those treated with ClO_2. The UV and Cl_2 AR averaged 0.034 ± 0.005 mg/L chlorate and the Cl_2 AR had an average of 0.031 ± 0.005 mg/L for chlorate concentration over the duration of the experiment. The control ARs and the UV and RW influents had no presence of chlorate or chlorite throughout the study.

5.2.4.9 Synergistic Effects

As previously mentioned, Koivunen et al. (2005) introduced a calculation to determine if synergistic effects were present in a treatment combination. The equation is as follows:

Equation 5.1: Synergy (Koivunen et al., 2005)

Synergy (log units) = log reduction by combined **chemical/UV** disinfection – (log reduction **UV** disinfection + log reduction **chemical** disinfection)

When the calculated answer is positive it is an indication that synergy is present. This equation was applied to the results found from the Pardee study for the UV and Cl_2 AR and the UV and ClO_2 AR (Table 5.3). For the attached heterotrophic bacteria

samples it was shown with this calculation that synergistic benefits contributed to higher log reductions in those ARs pre-treated with UV light. The answer for the UV and Cl_2 AR was +0.15 and +1.06 for the UV and ClO_2 AR. Although log reductions were higher in the ARs pre-treated with UV light in bulk HPC samples, no synergy was evident using the above equation. For UV and Cl_2 the answer was -0.68 and -0.34 for the UV and ClO_2 combination. It is believed that this is not necessarily due to lack of synergy in reducing bulk samples but because raw water quality improved over the course of the project. High log reduction was observed in the ARs that were treated with UV alone even though there was no change in treatment between the acclimation and disinfection stages, as can be seen in Figure 5.3. Therefore, the reductions shouldn't be attributed to the treatment with UV but to less HPC bacteria in untreated water, making synergy calculations less appropriately applicable.

Table 5.3: Pardee Log Removals and Synergy for Suspended and Attached HPC Bacteria

AR	Log Removal Suspended HPC	Log Removal Attached HPC	Synergy for Suspended HPC	Synergy for Attached HPC
UV Control	1.04	-0.06		
RW Control	1.02	-1.58		
UV+ClO_2	3.93	2.04	-0.34	+1.06
ClO_2	3.23	1.04		
UV+Cl_2	2.07	1.36	-0.68	+0.15
Cl_2	1.72	1.26		

5.3 EVALUATION OF DISINFECTION STRATEGIES FOR THE HALIFAX SURFACE WATER SOURCE

5.3.1 Introduction

The Halifax Regional Water Commission (HRWC) services over 310,000 people in the greater Halifax area in Nova Scotia. The J.D Kline Water Supply Plant is one of two major plants operated by HRWC that has a capacity of 220 ML/day and treats raw surface water from Pockwock Lake in Halifax, Nova Scotia. The treatment process consists of direct filtration with chlorination for final disinfection. The source water is low in alkalinity (<10 mg/L as $CaCO_3$) and typically has no occurrences of *Cryptosporidium parvum* or *Giardia lamblia* since HRWC owns the land surrounding their watershed. Although no significant problems plague the operation of the plant in its current state, new Nova Scotia regulations will be implemented by 2008 and the HRWC wants to ensure that practices result in absolute compliance at that time. With chlorination of surface water, the potential for TTHM and HAA formation is a concern. It is possible that changing to UV and/or ClO_2 disinfection may reduce these DBP concentrations to a minimal level. In addition, HRWC was interested in the effectiveness of different disinfection strategies against heterotrophic bacteria including *Escherichia coli* in the distribution system. The focus of this chapter was to determine the effectiveness of UV, UV/ Cl_2, and UV/ ClO_2 in suppressing biofilm growth and controlling microbial pathogens in drinking water distribution systems through a field-scale study, and to compare pre-treatment with UV to no UV treatment. Heterotrophic plate counts and coliforms were used to compare disinfection treatments for bacteria within the systems. In addition, water quality parameters were monitored throughout the experiments.

5.3.2 Experimental Design

Annular reactors were used to simulate the drinking water distribution systems for this field experiment. The set-up in Halifax consisted of six ARs in parallel receiving either raw surface water (RW) or raw water pre-treated with Ultraviolet light (UV).

Chemical disinfection schemes included chlorine and chlorine dioxide alone and also following UV pre-treatment. A three-week acclimation period that allowed biological steady-state conditions to be reached within the ARs was followed by a disinfection period lasting a total of twelve weeks.

Table 5.4: Halifax Disinfection Scheme

Disinfection	Residual Concentration (mg/L)
UV	0.0
Control (no disinfectant)	0.0
UV + ClO_2	0.20
ClO_2	0.20
UV + Cl_2	0.20
Cl_2	0.20

Each of the six ARs contained coupons made of polycarbonate. The hydraulic retention time (2.0h) was controlled by the volumetric flow rate of the influents entering the AR and was established based on a relationship between surface areas and volumes in ARs and pipes, as described by Gagnon and Huck (2001). Similarly to previous studies, the chemical flowrate was established at 5% of the total flowrate, which corresponded to 0.4 mL/min for disinfectants and 7.7 mL/min for influent source water. The ARs operated at a rotational speed of 50 rpm which translates into a shear stress of 0.25 N/m^2 (Camper 1995). A shear stress of 0.25 N/m^2 corresponds to a flow of approximately 0.30 m/s (1fps) in a 100mm (4in) diameter smooth pipe which is similar to shear conditions of other pilot and bench scale investigations. One AR acted as a control for each water source (raw and UV-treated) and received no chemical disinfection. One RW AR and one UV AR were disinfected with chlorine, and one of each was disinfected with chlorine dioxide. The target disinfection residual concentration was 0.2 mg/L for each chemical, which is the minimum allowed in distribution systems under Nova Scotia drinking water regulations.

A photograph showing the Halifax distribution system setup is presented in Figure 5.11. Surface water from Pockwock Lake was the primary source water for the model distribution systems. The water collected from a raw water tap was directed into a

RW clearwell. The flow pumped from this clearwell was split to feed both the UV unit and three ARs. Once water passed through the UV system it was directed towards another clearwell which fed three additional ARs.

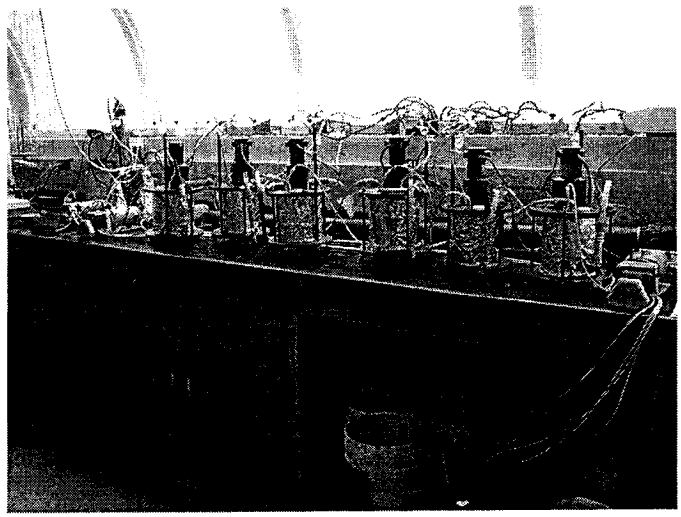

Figure 5.11 Halifax Annular Reactor Set-up

All non-opaque exposed surfaces of the ARs were covered to reduce the potential of phototrophic growth in the field systems. Before each experimental trial, all ARs were cleaned with antibacterial soap and disinfected using a 70% ethanol solution. In addition all tubing and clearwells used within the set-up were disinfected with ethanol for a period of 24 hours. This was followed by rinsing with Milli-Q water and the source water.

5.3.3 Methods and Materials

All sampling and testing protocols were carried out as described in the *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 1998) and as described in Chapter 3, Methods and Materials, of this document. During the study, the ARs were monitored 1-2 times per week for heterotrophic bacteria counts (suspended and biofilm), pH, temperature, UV254, turbidity, TOC, and coliforms. Once disinfection began, disinfectant residual was measured 2 times per week and samples were collected to be analysed for TTHMs once per week. In addition, weekly checks of flowrates throughout the system and the rotational speeds of the ARs were performed to ensure

consistent operating conditions. Chlorine dioxide was generated onsite according to Method 4500-ClO_2 of *Standard Methods for the Examination of Water and Wastewater, 19th Ed* and as described in Chapter 3. Chlorine stocks were produced using a 16% analytical grade sodium hypochlorite solution.

5.3.4 Results and Discussion

5.3.4.1 Acclimation/Pre-disinfection period

During acclimation samples were collected to determine HPC bacteria concentrations in bulk water and on coupon surface. Following the first trial run, the experiment was repeated under identical conditions, allowing for a re-acclimation period between runs. Data presented represent the combined acclimation and disinfection stages of both trial runs. Before disinfection the overall average number of suspended heterotrophic bacteria in all ARs was $3.48x10^4 \pm 3.19x10^4$ CFU/mL and overall average attached (biofilm) heterotrophic bacteria for all ARs was $6.20x10^4 \pm 4.70x10^4$ CFU/cm^2. There was no statistically significant difference between any AR for heterotrophic bacteria in the acclimation period for either suspended or attached cells.

5.3.4.2 Post-disinfection HPC data

After a three-week acclimation period to allow for steady-state to be reached one AR that was receiving UV-treated water started being disinfected with chlorine and one AR pre-treated with UV was disinfected with chlorine dioxide. Two ARs that had no UV disinfection were also disinfected with either Cl_2, or ClO_2. The remaining two ARs were not altered and continued as experimental controls, one for UV water and one for raw water, and all ARs were monitored for suspended and attached HPC bacteria (Table 5.5). All ARs that were treated with Cl_2 or ClO_2 showed a decrease in suspended heterotrophic bacteria, especially those treated with ClO_2 (Figure 5.12). The average log reduction for suspended HPC bacteria for ARs treated with chemical disinfection was 1.33 ± 0.73 log. ARs treated with ClO_2 had the greatest log reductions including 2.12 log for the AR treated with both UV and chlorine dioxide, and 1.64 log for the AR treated with ClO_2 only. The AR treated with UV and chlorine had a reduction of 1.15 log for suspended

HPC bacteria and similarly the AR treated with Cl_2 had a reduction of 0.40 log. Overall the ARs treated with UV had slightly greater reductions in suspended bacteria than those ARs treated with corresponding chemical disinfection only.

Table 5.5: Halifax Suspended and Attached HPC Bacteria Pre- and Post-Disinfection

AR	Suspended HPC (CFU/mL) Acclimation	Attached HPC (CFU/cm^2) Acclimation	Suspended HPC (CFU/mL) Post-Disinfection	Attached HPC (CFU/cm^2) Post-Disinfection
UV Control	$9.44x10^4$	$9.86x10^4$	$5.24x10^4$	$1.89x10^5$
RW Control	$2.42x10^4$	$3.20x10^4$	$5.57x10^3$	$5.84x10^4$
UV+ClO_2	$3.46x10^4$	$8.86x10^4$	$2.63x10^2$	$3.26x10^3$
ClO_2	$7.32x10^3$	$8.87x10^3$	$1.66x10^2$	$1.87x10^3$
UV+Cl_2	$3.90x10^4$	$1.22x10^5$	$2.79x10^3$	$2.43x10^3$
Cl_2	$9.38x10^3$	$2.15x10^4$	$3.71x10^3$	$3.90x10^3$

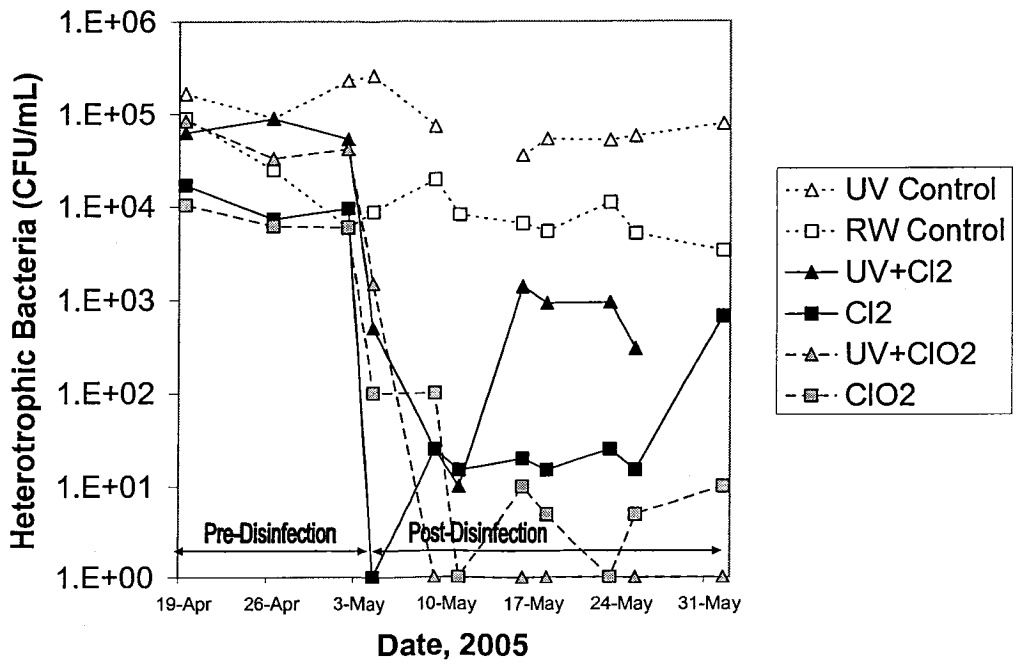

Figure 5.12: Number of Suspended Heterotrophic Bacteria Collected in the ARs located at the Pockwock WTP

Despite an increase in average biofilm HPC bacteria counts in ARs receiving no chemical disinfection from $6.53x10^4 \pm 4.71x10^4$ CFU/cm^2 during acclimation to $1.23x10^5 \pm 9.20x10^4$ CFU/cm^2, there was a decrease in the average HPC bacteria in ARs treated with chemical disinfection to $2.86x10^3 \pm 9.00x10^2$ CFU/cm^2 post-disinfection from $6.03x10^4 \pm 5.42x10^4$ CFU/cm^2 during the acclimation phase (Figure 5.13). The average log reduction in ARs treated with chemical disinfection was 1.14 ± 0.51, and the AR treated with UV and Cl_2 had the highest for attached HPC bacteria with a reduction of 1.71 log. Similarly to suspended HPC bacteria, ARs treated with UV prior to chemical disinfection had slightly higher log reductions of attached HPC bacteria. ARs that acted as controls for the experiments had no decrease in HPC bacteria in the disinfection phase with the UV AR having -0.28 log reduction and the RW AR with a -0.26 log reduction.

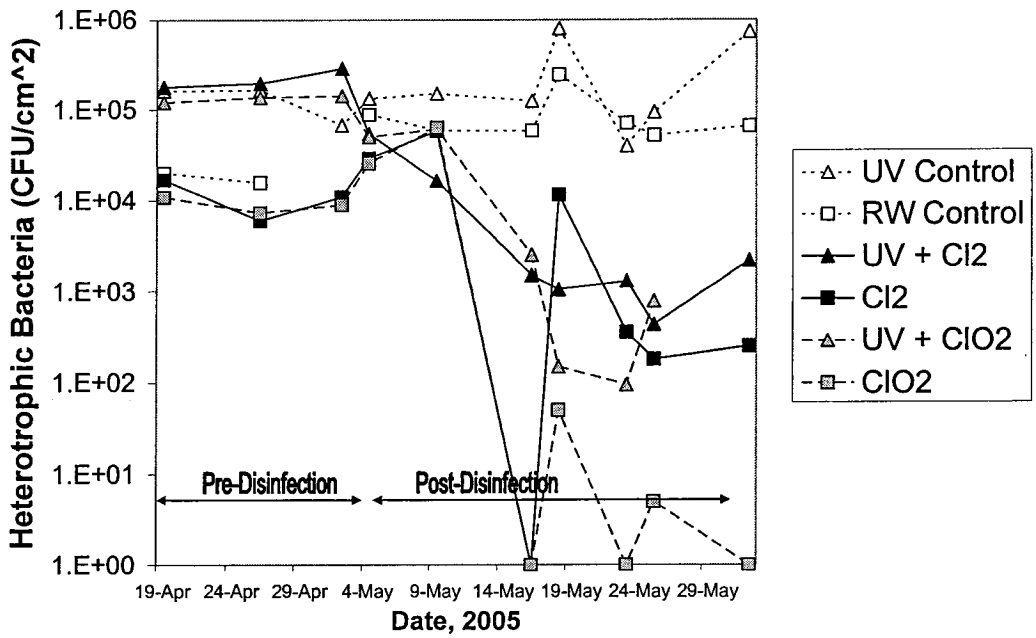

Figure 5.13: Number of Attached Heterotrophic Bacteria Collected in the ARs located at the Pockwock WTP

5.3.4.3 Comparison of Disinfectants

There was a statistically significant difference for bulk bacteria counts between the AR treated with ClO_2 only and AR treated with Cl_2 only ($p = 0.002$), with chlorine dioxide having a higher log removal. The UV and ClO_2 treatment was slightly more

effective for suspended bacteria was (Figure 5.14). However, when ARs were pre-treated with UV and then chemical disinfection there was no statistically significant difference observed when comparing to the ARs with corresponding chemical disinfection only ($p = 0.367 - 0.711$) , although similarly to Pardee data combination treatments consistently achieved higher removals. All treated ARs showed significant differences when compared to the control ARs for suspended bacteria ($p = 0.000$). In addition, there was a statistically significant difference between counts for the UV-treated AR and the RW AR ($p = 0.004$), where the UV control had significantly higher average counts than the RW control. This could be attributed to fouling within the UV system or increase in bacterial regrowth potential of natural organic matter (NOM), which was found by Parkinson et al. (2003) with UV treatment of water.

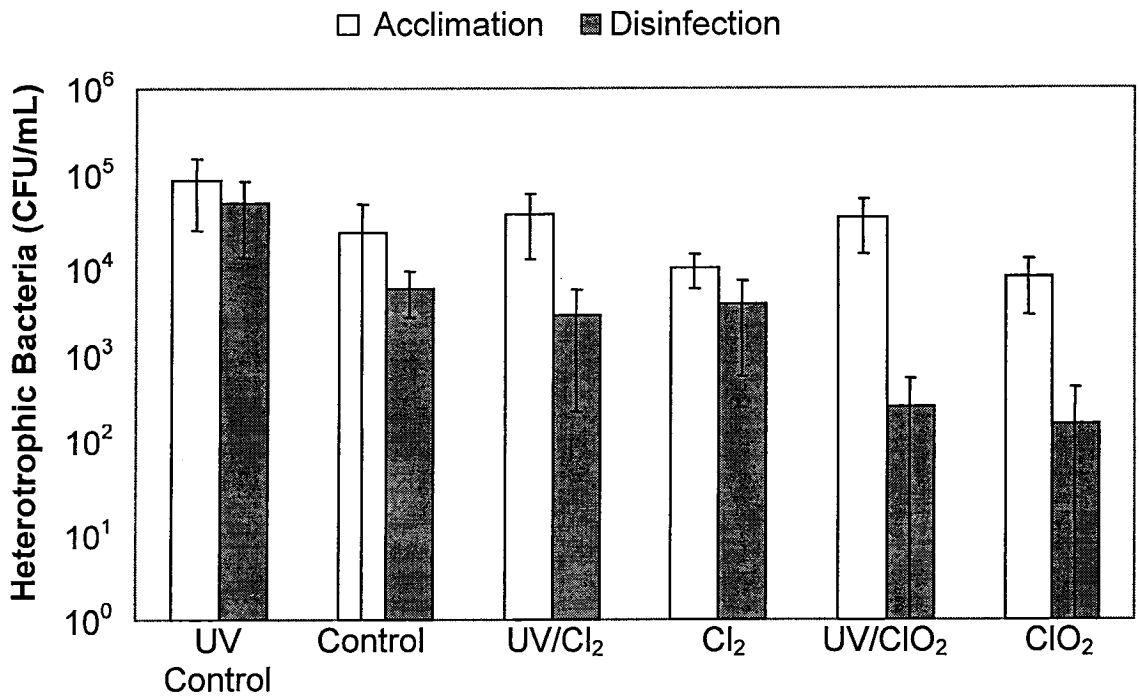

Figure 5.14: Average Suspended Heterotrophic Bacteria Collected in the ARs located at the Pockwock WTP

In biofilm data the AR treated with UV and Cl_2 had the highest removal of attached bacteria with 1.71-log, however this was not statistically different than the AR treated with UV and ClO_2 ($p = 0.722$) with a 1.43 log removal (Figure 5.15). The AR treated with ClO_2 only had the lowest removal of attached HPC bacteria at 0.68-log,

which was statistically different than the ARs treated with Cl_2 only ($p = 0.026$) which had an average log removal of 0.74. Each of the disinfected ARs was significantly different from the corresponding control ARs ($p = 0.000$). The UV and Cl_2 combination AR was not significantly different from the Cl_2 alone AR ($p = 0.446$), however the UV and ClO_2 combined AR was statistically different than the ClO_2 AR ($p = 0.011$) with the UV pre-treated AR having a higher log removal. In the biofilm samples, there was no significant difference between the control UV and RW ARs ($p = 0.131$).

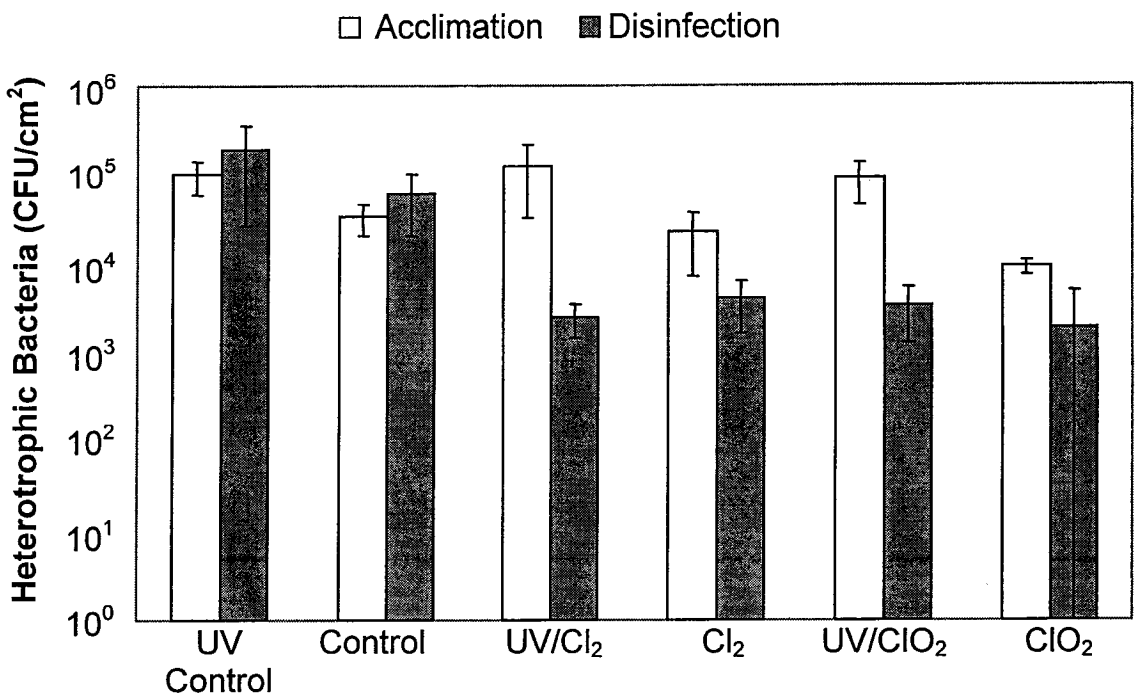

Figure 5.15: Average Attached Heterotrophic Bacteria Collected in the ARs located at the Pockwock WTP

5.3.4.4 Water Quality Analysis

During the 6-week period following acclimation, ARs were dosed with chemical disinfection excluding the control ARs. The presence of UV treatment did not generally seem to affect the required chemical dose for ARs. The average ClO_2 dose for the AR pre-treated with UV was 1.61 ± 0.13 mg/L, which was higher than the average dose for the AR treated with ClO_2 only which was 1.52 ± 0.10 mg/L. ARs treated with Cl_2 required similar dosages to the ClO_2 ARs. The average dose for ARs treated with UV

and Cl_2 was 1.65 ± 0.22 mg/L Cl_2 and 1.37 ± 0.10 mg/L for ARs treated with Cl_2 only. The resulting average chemical residual was slightly lower in ARs treated with ClO_2 than Cl_2. During the course of disinfection, the AR treated with UV and ClO_2 had an average residual of 0.17 ± 0.08 mg/L ClO_2, the ClO_2 AR averaged 0.19 ± 0.07 mg/L ClO_2, the UV and Cl_2 ARs averaged 0.21 ± 0.14 mg/L Cl_2, and finally the ARs treated with Cl_2 only had an average residual of 0.22 ± 0.06 mg/L Cl_2.

The average pH for all ARs during the acclimation phase and post-disinfection was 5.02 ± 0.20. The ARs operated at an average temperature of 21.6 ± 0.27 °C during the experiment, and the average influent temperature was slightly lower at 19.6 ± 0.37 °C.

The average turbidity for the raw water influent was 1.94 ± 1.14 NTU throughout the experiment which was higher then the average UV water influent at 1.81 ± 0.99 NTU. This was consistent with average turbidities of the control ARs with the UV control at 0.67 ± 0.41 NTU and the RW control AR at 1.10 ± 0.35 NTU. There were no significant difference between turbidity pre- and post-disinfection, and the average turbidity for all ARs was 1.00 ± 0.66 NTU during acclimation and disinfection stages.

5.3.4.5 Organic Content

Total organic carbon (TOC) in all ARs, including control ARs, was similar without significant changes over the course of the studies. The average TOC concentration in all ARs during acclimation and disinfection was 3.88 ± 0.41 mg/L. The ratio of dissolved organic carbon (DOC) to TOC was high at an average of 92.5 ± 5.7%. The average DOC concentration in all ARs during acclimation and disinfection was 3.63 ± 0.23 mg/L. UV 254 was also monitored and the average in all ARs was 0.095 ± 0.007.

5.3.4.6 Disinfection By-products

Total trihalomethanes (TTHMs) were measured following the application of disinfectants. TTHM levels were highest in ARs treated with chlorine, which is consistent with several studies that have been previously conducted (Hofmann et al., 1999; Werdehoff and Singer, 1987). The average TTHM concentration in the ARs treated with Cl_2 only was 18.6 ± 4.6 µg/L and 25.4 ± 8.5 µg/L and in the ARs treated

with UV and Cl_2. The United States Environmental Protection Agency (USEPA) maximum contaminant level (MCL) for TTHMs is 0.080 mg/L. No TTHMs were observed in ARs treated with chlorine dioxide or the control ARs.

5.3.4.7 Total Coliforms and *Escherichia coli*

Samples were taken to analyze for total coliforms and *Escherichia coli* five times over the course of the project for raw water influent, UV-treated influent and AR effluents. No positive occurrences were observed in any sample for coliforms or *E. coli*.

5.3.4.8 Synergistic Effects

When the equation presented by Koivunen (2005) was applied to the Halifax data for the UV + Cl_2 AR and the UV + ClO_2 AR, answers were positive for suspended and attached cells. Log removal data and the corresponding synergy calculations are presented in Table 5.6.

Table 5.6: Halifax Log Removals and Synergy Calculations for Suspended and Attached HPC Bacteria

AR	Log Removal Suspended HPC	Log Removal Attached HPC	Synergy for Suspended HPC	Synergy for Attached HPC
UV Control	0.26	-0.28		
RW Control	0.64	-0.26		
UV+ClO_2	2.12	1.43	+0.22	+1.04
ClO_2	1.64	0.68		
UV+Cl_2	1.15	1.70	+0.49	+1.25
Cl_2	0.40	0.74		

The UV and Cl_2 AR showed +0.49 for suspended bacteria and +1.25 for attached bacteria indicating that UV and chlorine are working together to produce a synergistic effect in reducing HPC bacteria. This is also true for the UV and ClO_2 AR that resulted in +0.22 for suspended and +1.04 for attached bacteria. In this study results showed that

combination ARs achieved the highest log removal of bacteria and also indicated that synergy was enhancing removal of bacteria.

5.4 CONCLUSIONS

It was found in this study that in general chlorine dioxide in combination with UV light as a primary treatment was most effective in reducing heterotrophic bacteria when compared to UV, ClO_2, Cl_2, and UV/Cl_2 treatments. In the California aqueduct study, UV + ClO_2 achieved the highest log reduction in suspended (3.93 log) and attached (2.05 log) heterotrophic bacteria. In addition, TTHM and HAA concentrations were lower in ARs treated with ClO_2 than those treated with Cl_2, therefore TTHM and HAA concerns would be virtually eliminated with the implementation of ClO_2 treatment. However, the DBP chlorite was not formed in Cl_2 ARs but was measured in ClO_2 ARs at a conversion rate consistent with previous studies. All disinfection by-products were kept well below USEPA guidelines. UV light did not lower required chemical dosages in order to reach goal residuals in the simulated drinking water distribution systems.

In Halifax results, UV + ClO_2 achieved highest log reduction for suspended (2.12 log) bacteria and similar removal for attached (1.43 log) HPC cells. Similarly to the Pardee study, chlorinated ARs showed elevated levels of TTHMs compared to controls and ARs treated with ClO_2 that had no presence of this disinfection by-product.

ClO_2 alone was shown to be more effective at removing suspended HPC bacteria and similarly as effective at controlling biofilm bacteria, while minimizing TTHM and HAA formation, suggesting replacement of Cl_2 with ClO_2 is a viable option for water utilities. In addition, pre-treatment with UV light allowed higher log reductions when compared to ARs with no UV treatment for both chlorinated ARs and ARs treated with ClO_2. This indicates that synergistic effects between UV and chlorine-based disinfectants enhance disinfectant capabilities to remove bacteria. As is known, UV attacks the DNA and RNA of cells while chlorine-based disinfectants attack the cell wall. Therefore, it is possible that repair mechanisms are being overloaded by multiple disinfectants to fix the cells, as Koivunen (2005) suggested, and more bacteria are eliminated.

6.0 FIELD EVALUATION OF DISINFECTANT STRATEGIES WITH AND WITHOUT UV PRE-TREATMENT FOR TREATING GROUNDWATER IN A COOL CLIMATE

6.1 ABSTRACT

The goal of this chapter was to compare disinfection strategies with a groundwater source. This research compared the efficacy of chlorine (Cl_2) to monochloramine (NH_2Cl) with and without pre-treatment with ultraviolet (UV) light for heterotrophic bacteria control. An additional objective was to monitor nitrate levels to determine the possibility of nitrification in the systems. Annular reactors (ARs) containing polycarbonate coupons were used to simulate a distribution system with a groundwater source and chlorination as the only treatment. ARs were dosed with chemical disinfection to achieve a residual of 0.20 mg/L, the minimum residual allowed by Nova Scotia Drinking Water Regulations. The experiment matrix included four strategies of disinfectants including UV/Cl_2, Cl_2, UV/NH_2Cl and NH_2Cl. Two ARs acted as controls and received raw water (RW) or UV-treated water. The data presented show that the UV/Cl_2 combination was most effective against suspended heterotrophic (HPC) bacteria with 3.45 log reduction. No disinfection strategy was significantly effective against attached bacteria, although chlorine alone achieved 1.58-log removal. Due to slow flow through the UV reactor, it is believed that biofouling led to increased biofilm growth in UV ARs resulting in higher counts than those ARs not pre-treated with UV. Chlorine was more effective than monochloramine at removing suspended and attached HPC bacteria. Synergistic effects observed enhanced removal of suspended bacteria in the AR effluents. Implementing UV as a primary disinfectant would be a viable option for Port Williams to achieve a secondary disinfection unit and to further reduce bacteria in bulk water.

6.2 INTRODUCTION

Supply of potable groundwater often relies on disinfection as the only treatment step between source and distribution system. Unlike surface water that requires economically and operationally demanding treatment processes like filtration and sedimentation, groundwater treatment is highly simplified. However, treatment is equally as important and several illnesses and deaths around the world have resulted from breeches in the treatment and supply of groundwater. In May, 2000 tragedy struck Walkerton, ON where over 2300 people became ill and 7 died as a result of a contaminated water supply. In particular, a heavy rainfall caused cow manure to wash into a shallow wellfield, which resulted in *Escherichia coli* contamination. In addition, failure to maintain the appropriate chlorine residual of 0.5 mg/L and lack of residual monitoring by operators led to exposure to citizens with no warning (Hrudey et al., 2002). There are several other cases where supply of contaminated groundwater resulted in illnesses or deaths, including Orangeville, Ontario in 1985 where 241 cases of Campylobacter jejuni were caused by 6 "deep" wells that were not required to be disinfected, and in Gideon, MO in 1993 where there were 600 reports of salmonellosis and 7 resulting deaths due to an undisinfected groundwater supply (Hrudey et al., 2002).

Several contamination cases are a result of groundwater under the direct influence of surface water, or "GUDI". In these instances, treatment is set up for groundwater and surface water treatment is not available so contamination may reach consumers. For this reason, the Nova Scotia Department of Environment and Labour (NSDEL) have recently produced standards requiring groundwater utilities to undergo GUDI screening in a three-step process where each step must be passed in order to be established as a strictly groundwater source. If a utility fails a step it is classified as a surface water source and must comply with surface water drinking water regulations, which includes adding filtration to the treatment process.

In a review of outbreaks caused by drinking water carried out by Hrudey et al. in 2002, it was established that a wide variety of groundwater supplies have been contaminated and caused illnesses or deaths. For instance, 3000 people reported gastroenteritis due to an unchlorinated public groundwater supply in Bramham, England

in 1980, and 110 people were afflicted with the same illness due to an unchlorinated private well in Oakcreek Canyon, AZ, 1989. This establishes the importance of treatment for any groundwater source regardless the size of the community or supply demand.

Considering the importance of disinfection for groundwater supplies, the focus of this chapter was to compare the effectiveness of disinfection with UV light, UV/Cl_2 and UV/NH_2Cl in microbiological quality in the distribution system from an untreated groundwater supplier. Thus a secondary objective of this chapter was to compare pre-treatment with UV to no UV treatment.

6.3 EXPERIMENTAL DESIGN

6.3.1 Description of Field Location

Port Williams is a rural community of almost 1000 residents located in the Annapolis Valley of Nova Scotia. The water system consists of five groundwater wells that produce anywhere between 3 and 96 gpm each on a daily basis. The water is pumped as needed into a concrete-lined storage tank where it is chlorinated through a recirculation process. From the storage tank water is directed into the distribution system that includes approximately 45,750 feet of 150-300 mm diameter pipeline. Water quality monitoring through 1998-2003 showed each well in compliance with Canadian Drinking Water Guidelines with the exception of a few occurrences of high turbidity and colour, and also an increase in nitrate concentration, especially in Well No. 1. This has led to the elimination of Well No. 1 from the water supply since levels were consistently exceeding the MAC of 10 mg/L. The water commission is currently in the process of GUDI screening in compliance with new Nova Scotia drinking water guidelines that will be in effect by 2008. Regardless of the outcome of GUDI/Non-GUDI screening, under the new regulations all water treatment plants will be required to implement two disinfection units. The community was interested in investigating options for disinfection strategies including the potential for UV light as primary disinfection.

6.3.2 Experimental Set-up

Annular reactors (ARs) were set up at the Port Williams treatment facility to simulate the distribution system. The six ARs were set up in parallel and received either UV-treated water (UV) or raw water (RW). A pipeline leading to the storage tank that included a mixture of water from wells 2, 3, 4 and 5 was tapped into and fed to a RW clearwell. From this clearwell water was either pumped directly into three of the ARs or through the UV lamp. After treatment with UV, the water was directed into a second UV clearwell, from which water was pumped into the remaining three ARs.

All ARs went through a three-week acclimation period to allow steady-state biofilm to be reached. Two ARs acted as controls for the experiment, one for UV-treated water and the second for raw water. These ARs did not change treatment throughout the study. Following acclimation, the remaining four ARs were chemically disinfected for an additional eight weeks. Two ARs were chlorinated, one that was receiving RW and the other water pre-treated with UV light. The remaining two ARs received monochloramine, one UV-treated and one RW. The disinfection schemes are presented in Table 6.1. The target disinfection residual for each AR was 0.2 mg/L free Cl_2 and 1.0 mg/L NH_2Cl, which are the minimum residuals allowed by Nova Scotia Drinking Water Regulations.

Table 6.1: Port Williams Disinfection Scheme

Disinfection	Residual Concentration (mg/L)
Control (no disinfectant)	0.0
UV	0.0
Cl_2	0.20
UV + Cl_2	0.20
NH_2Cl	1.0
UV + NH_2Cl	1.0

The hydraulic retention time (2.0h) was controlled by the volumetric flow rate of the influents entering the AR and was established based on a relationship between surface areas and volumes in ARs and pipes, as described by Gagnon and Huck (2001).

Similarly to previous studies, the chemical flowrate was established at 5% of the total flowrate, which corresponded to 0.4 mL/min for disinfectants and 7.7 mL/min for influent source water. The ARs operated at a rotational speed of 50 rpm which translates into a shear stress of 0.25 N/m^2 (Camper 1995). A shear stress of 0.25 N/m^2 corresponds to a flow of approximately 0.30 m/s (1fps) in a 100mm (4in) diameter smooth pipe which is similar to shear conditions of other pilot and bench scale investigations.

All non-opaque exposed surfaces of the ARs were covered to reduce the potential of phototrophic growth in the field systems. Before each experimental trial, all ARs were cleaned with antibacterial soap and disinfected using a 70% ethanol solution. In addition all tubing and clearwells used within the set-up were disinfected with ethanol for a period of 24 hours. This was followed by rinsing with Milli-Q water and the source water. A photograph showing the set-up in Port Williams is presented in Figure 6.1.

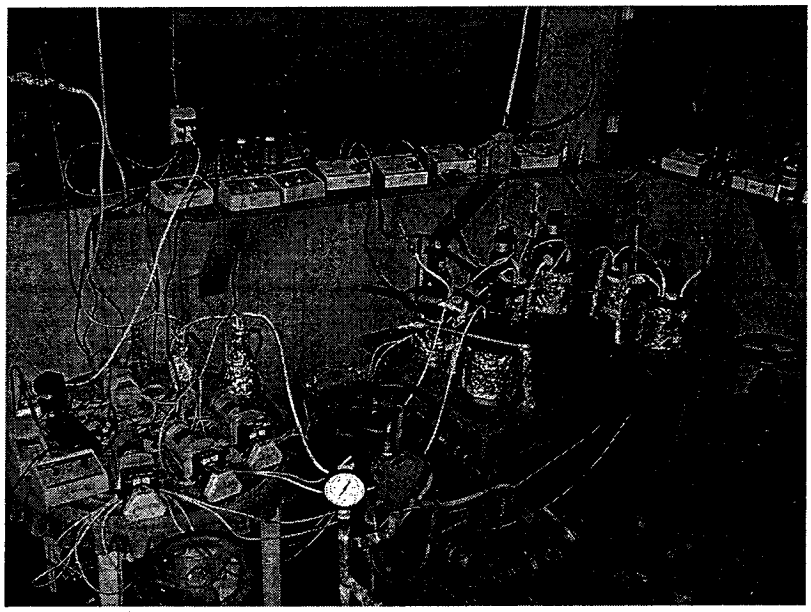

Figure 6.1: Port Williams Annular Reactor Set-up

6.4 METHODS AND MATERIALS

All sampling and testing protocols were carried out as described in the *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 1998) and as described in Chapter 3, Methods and Materials, of this document. During the study, the

ARs were monitored 1-2 times per week for heterotrophic bacteria counts (suspended and biofilm), pH, temperature, UV254, turbidity, TOC, and coliforms. Once disinfection began, disinfectant residual was measured 2-3 times per week and nitrate levels were measured once weekly. In addition, weekly checks of flowrates throughout the system and the rotational speeds of the ARs were performed to ensure consistent operating conditions. Chlorine stock bottles were produced using a 16% analytical grade sodium hypochlorite solution. Monochloramine was produced by combining an ammonium chloride solution and 16% analytical grade sodium hypochlorite at a pH of 9.4 as described in Chapter 3.

6.5 RESULTS AND DISCUSSION

6.5.1 Acclimation/Pre-disinfection Period

The ARs were operated for a period of three weeks prior to any application of disinfection to establish steady state biofilm. Steady state conditions over this biofilm acclimation period, or pre-disinfection, were determined for heterotrophic bacteria counts. Pre-disinfection conditions were determined for ARs that would eventually receive no disinfectant, NH_2Cl or Cl_2.

Before disinfection the overall mean number of suspended heterotrophic bacteria was $9.37x10^4 \pm 1.20x10^5$ CFU/mL and mean attached (biofilm) heterotrophic bacteria for all ARs was $5.44x10^4 \pm 2.56x10^4$ CFU/cm^2. No ARs were statistically different for heterotrophic bacteria in the acclimation period for attached cells. With bulk samples the Cl_2 AR had a significantly higher count than the RW AR, with a difference of 1.19 log.

6.5.2 Post-disinfection HPC Data

After a four-week acclimation period one AR that was receiving UV-treated water started being disinfected with chlorine and one AR treated with UV was disinfected with monochloramine. One AR that had no UV disinfection was disinfected with Cl_2, and another with NH_2Cl. The remaining two ARs were not altered and continued as

experimental controls, one for UV water and one for raw water. For an additional 8 weeks the ARs were monitored for suspended and attached HPC bacteria while chemical disinfection was applied (Table 2). All ARs that were treated with Cl_2 or NH_2Cl showed a decrease in suspended heterotrophic bacteria. The average log reduction for suspended HPC bacteria for ARs treated with chemical disinfection was 1.53 ± 1.42. ARs treated with Cl_2 had greater log reductions including 3.18 for the AR treated with both UV and chlorine, and 0.54 for the AR treated with Cl_2 only. The AR treated with UV and monochloramine had a log reduction of 2.22 for suspended HPC bacteria and similarly the AR treated with NH_2Cl had a log reduction of 0.18. Each chemically disinfected AR showed a statistically significant decrease except for the AR treated with Cl_2 only. Overall the ARs treated with UV had consistently greater reductions in suspended bacteria than those ARs treated with corresponding chemical disinfection only.

Table 6.2: Port Williams Suspended and Attached HPC Bacteria Pre- and Post-Disinfection

AR	Suspended HPC (CFU/mL) Acclimation	Attached HPC (CFU/cm^2) Acclimation	Suspended HPC (CFU/mL) Post-Disinfection	Attached HPC (CFU/cm^2) Post-Disinfection
RW Control	$1.79x10^3$	$2.15x10^4$	$1.63x10^4$	$1.07x10^4$
UV Control	$9.20x10^4$	$7.10x10^4$	$1.46x10^5$	$1.42x10^6$
Cl_2	$2.78x10^4$	$6.98x10^4$	$8.02x10^3$	$1.83x10^3$
UV + Cl_2	$3.16x10^5$	$6.46x10^4$	$2.08x10^2$	$3.29x10^4$
NH_2Cl	$2.23x10^3$	$2.20x10^4$	$1.48x10^3$	$1.10x10^3$
UV + NH_2Cl	$1.22x10^5$	$7.75x10^4$	$7.33x10^2$	$4.05x10^3$

For biofilm HPC bacteria, the Cl_2 and NH_2Cl ARs receiving raw water did not differ statistically from the RW control AR. The disinfected ARs receiving UV treated water did differ statistically from the UV control AR and the average count in disinfected UV ARs decreased slightly from $7.10x10^4 \pm 9.11x10^3$ CFU/cm^2 to $1.85x10^4 \pm 2.04x10^4$ CFU/cm^2. The average log reduction in ARs treated with chemical disinfection was 1.14 ± 0.57, and the AR treated with Cl_2 only had the highest for attached HPC bacteria with a

reduction of 1.58 log. The control UV AR had a significant increase in average attached HPC bacteria by 1.30 log, while the RW AR had a 0.30-log reduction in biofilm HPC bacteria.

6.5.3 Comparison of Disinfectants

The most effective disinfection option for suspended bacteria was UV and Cl_2 with 3.18 log removal (Figure 6.2), which statistically differed from the AR treated with Cl_2 only ($p = 0.000$). There was a statistically significant difference for bulk bacteria counts between the AR treated with Cl_2 only and the AR treated with NH_2Cl only ($p = 0.003$), with chlorine having a higher log removal, which is similar to findings from Dykstra et al. (2002) which showed Cl_2 being more effective than NH_2Cl at removing suspended HPC bacteria. There was no statistically significant difference between the Cl_2 and NH_2Cl ARs when pre-treated with UV ($p = 0.054$). There was a significant difference between the AR treated with UV and Cl_2 compared to the control UV AR ($p = 0.000$). There was no significant difference between the Cl_2 and RW ARs following disinfection ($p = 0.135$) although the log removal in the Cl_2 AR was higher at 0.54-log compared to -0.96 in the RW control AR. There was a significant difference between the NH_2Cl ARs and the corresponding controls ($p = 0.000 - 0.004$), however not between the NH_2Cl and the UV + NH_2Cl AR ($p = 0.287$) even though the combination AR had a higher removal at 2.22-log. It should be noted that the RW and UV control ARs differed significantly for suspended HPC bacteria counts following the acclimation phase ($p = 0.000$).

The AR treated with Cl_2 only was slightly more effective against attached heterotrophic bacteria once disinfection began achieving 1.58-log removal (Figure 6.3), which is consistent with findings from Dykstra et al. (2002) which found Cl_2 more effective against attached HPC bacteria than NH_2Cl at both low and high disinfection dosages. The Cl_2 AR was statistically similar to the NH_2Cl AR ($p = 0.548$) that achieved 1.30-log removal and average counts in both ARs were statistically similar to RW counts ($p = 0.107 - 0.118$), indicating neither disinfectant was significantly effective. This conflicts with the Norton and LeChevallier (1997) study where NH_2Cl displayed good

potential for control of biofilm bacteria compared to Cl_2 and controls. Log removal was lower in the UV + Cl_2 AR (0.29-log) compared to all other ARs, which was inconsistent with previous studies in this thesis and results from Dykstra et al. (2002), where pre-treatment with UV resulted in enhanced removal following chlorination. However, the UV control AR increased by 1.30-log in biofilm HPC bacteria counts during the disinfection stage, indicating potential contamination in the UV experimental system and making it difficult for disinfected ARs receiving UV-treated water to achieve high removals. Similarly to suspended bacteria data, the RW and UV ARs differed significantly following acclimation ($p = 0.000$) with the UV counts averaging much higher than the RW counts. This further indicates that pipeline entering UV ARs was contaminated, which would also explain higher average counts in UV treated ARs.

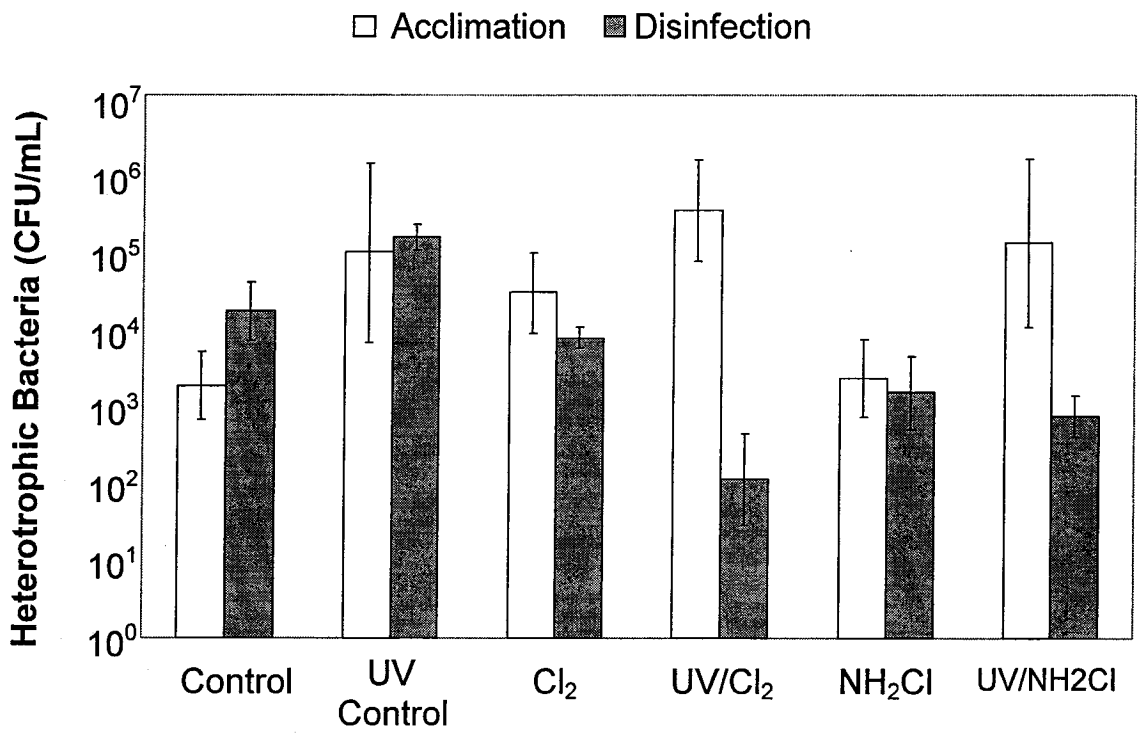

Figure 6.2: Suspended Heterotrophic Bacteria Log Reductions for PW ARs

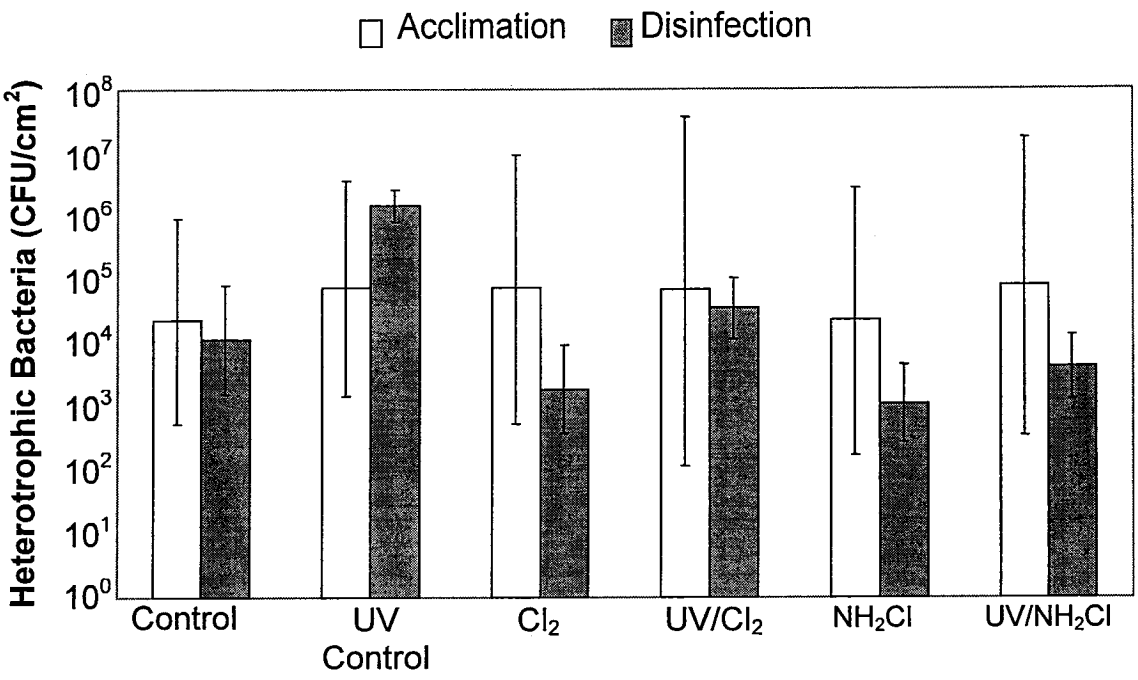

Figure 6.3: Attached Heterotrophic Bacteria Log Reductions for PW ARs

6.5.4 Water Quality Analysis

During the 6-week period following acclimation, ARs were dosed with chemical disinfection excluding the control ARs. The presence of UV treatment did not generally seem to affect the required chemical dose for ARs, however dosages required to achieve the desired residual were higher in the UV ARs most likely due to fouling within the UV system creating higher demand. The demand for chlorine was low and the average Cl_2 dose for the AR pre-treated with UV was 0.51 ± 0.08 mg/L, which was higher than the average dose for the AR treated with Cl_2 only which was 0.32 ± 0.09 mg/L. These dosages resulted in an average residual of 0.23 ± 0.05 mg/L free Cl_2 and 0.30 ± 0.07 mg/L total Cl_2 in the UV + Cl_2 AR, and 0.25 ± 0.06 mg/L free Cl_2 and 0.37 ± 0.05 mg/L total Cl_2 in the chlorine AR.

The desired residual for monochloramine was 1.0 mg/L. Due to problems with production and accurate measuring of NH_2Cl in the field, this residual was not achieved until 3 weeks following initial disinfection. Once achieved, the average dose for the AR treated with UV and NH_2Cl was 2.39 ± 0.40 mg/L and 1.92 ± 0.70 mg/L for the AR

treated with NH_2Cl only. Similarly to chlorine, the AR pre-treated with UV required higher NH_2Cl dosages to achieve the goal residual. Resulting average NH_2Cl residual was 1.08 ± 0.34 mg/L in the UV and NH_2Cl AR and 1.28 ± 0.47 mg/L in the NH_2Cl AR.

The average pH for all ARs during the acclimation phase and post-disinfection was 6.78 ± 0.04, and the influent average pH was slightly lower at 6.67 ± 0.02. The ARs operated at an average temperature of 13.5 ± 0.16 °C during the experiment, and the average influent temperature was also slightly lower at 12.7 ± 0.12 °C.

The average turbidity for the raw water influent was very low at 0.27 ± 0.05 NTU throughout the experiment, but was slightly higher then the average UV water influent at 0.24 ± 0.08 NTU. Average turbidities in the effluent of control ARs were higher than influent streams with the UV control at 0.41 ± 0.22 NTU and the RW control AR at 0.58 ± 0.45 NTU. There were no significant difference between turbidity pre- and post-disinfection, and the average turbidity was low for all ARs at 0.39 ± 0.11 NTU during acclimation and disinfection stages.

6.5.5 Nitrate

Nitrate concentrations were measured for all AR effluents, as well as the RW and UV influents once disinfection with chlorine and monochloramine began. The average concentration of nitrate in all ARs and influents was 7.36 ± 0.14 mg/L, and no samples were significantly different from the others. The maximum concentration allowed by Nova Scotia Drinking Water Regulations is 10 mg/L. The different disinfection schemes did not have an effect on nitrification, and no differences were observed between ARs pre-treated with UV light or not pre-treated, or ARs treated with chlorine compared to monochloramine. This differs from previous studies that have shown nitrate as a strong absorber of UV light which results in reduction of nitrate to nitrite (Sharpless and Linden, 2001; Mack and Bolton, 1999). Nitrite concentrations were not monitored in this study, however a decrease in nitrate concentrations was not observed in UV-treated ARs. In addition, Shaples and Linden (2001) indicated that higher NOM concentration increased potential for nitrite formation with UV light.

6.5.6 Total Coliforms and *Escherichia coli*

Samples were taken to analyze for total coliforms and *Escherichia coli* five times over the course of the experiment for raw water influent, UV-treated influent and AR effluents. No positive occurrences were observed in any sample for coliforms or *E. coli*.

6.5.7 Synergistic Effects

As previously described, a study done by Koivunen (2005) presented a calculation for synergy between disinfectants as seen in Equation 6.1.

Equation 6.1: Synergy (Koivunen et al., 2005)

Synergy (log units) = log reduction by combined **chemical/UV** disinfection – (log reduction **UV** disinfection + log reduction **chemical** disinfection)

Data obtained from the Port Williams study was analyzed using this equation presented and log removal data and the corresponding synergy calculations are presented in Table 6.3.

Table 6.3: Port Williams Log Removals and Synergy Calculations for Suspended and Attached HPC Bacteria

AR	Log Removal Suspended HPC	Log Removal Attached HPC	Synergy for Suspended HPC	Synergy for Attached HPC
RW Control	-0.96	0.30		
UV Control	-0.20	-1.30		
Cl_2	0.57	1.58		
UV+Cl_2	3.45	0.29	+2.84	+0.01
NH_2Cl	0.18	1.30		
UV+NH_2Cl	2.22	1.28	+2.25	+1.28

The benefits of combined UV/Cl_2 and UV/ NH_2Cl disinfection was observed for suspended bacteria. The calculated synergy effect was +2.84 for UV and Cl_2 AR and +2.25 for the UV and NH_2Cl AR. Both combination disinfection schemes resulted in the highest log reductions for suspended bacteria indicating that UV with chlorine or monochloramine produces a synergistic effect that enhances removal.

Although calculations resulted in positive synergy for attached bacteria, it was previously shown the combination of disinfectants actually resulted in lower log removals. A problem encountered in these calculations is the significantly negative removal of the attached cells in the UV AR. Biofilm counts increased in the UV AR over the course of the study by 1.30-log and chemical disinfection in UV-treated ARs had to therefore combat this increase. This trend may have led to the minor removals achieved in the combination ARs. Therefore, although the synergy results are positive, it is due to the negative removal in the UV control AR, making the Koivunen (2005) equation less applicable.

6.6 CONCLUSIONS

It was found in this study that chlorine in combination with UV light as a primary treatment was most effective in reducing suspended heterotrophic bacteria when compared to UV, NH_2Cl, Cl_2, and UV/NH_2Cl treatments. Maintaining a residual of approximately 0.23 mg/L Cl_2, the UV/Cl_2 combination achieved the highest reduction for suspended (3.45 log) HPC bacteria. In general, the ARs pre-treated with UV light followed by chemical disinfection achieved higher removals in bulk samples when compared with ARs with no UV pre-treatment, indicating that synergistic benefits enhanced removal of suspended HPC bacteria. This also suggests that UV and Cl_2 would be a viable option for treatment in Port Williams when a secondary disinfection unit is required. The combination treatments were not as effective when considering biofilm removal, however no ARs achieved significant decreases in attached cell counts and the Cl_2 and NH_2Cl ARs did not differ significantly from the RW control. Increased counts in the UV control AR suggests that fouling within the UV treatment systems may have led to increased counts in UV ARs. Chlorine was more effective in general than monochloramine in removing heterotrophic bacteria. Demand for chlorine was very low,

especially in the AR treated only with Cl_2. Nitrate levels were not affected by treatment type and were just below the maximum level of 10.0 mg/L throughout the course of the study. Based on the data collected through this study the most effect treatment solution would be to include UV as a primary disinfectant allowing for synergistic effects with chlorine to maximize microbial control across the distribution system.

7.0 FIELD EVALUATION OF SECONDARY TREATMENT OF BLENDED WATER WITH UV LIGHT IN A WARM CLIMATE

7.1 ABSTRACT

The goal of this chapter was to compare disinfection strategies with a blended water source in a warm climate. This research compared the efficacy of chlorine (Cl_2) to monochloramine (NH_2Cl) with and without treatment with ultraviolet (UV) light for heterotrophic bacteria control. Two influent streams were pre-treated with either chlorine or monochloramine, and consisted of a blend of groundwater, surface water and desalinated water. Annular reactors (ARs) containing coupons made of PVC material were used to simulate a distribution system. The experiment matrix included four strategies of disinfection including UV/Cl_2, Cl_2, UV/NH_2Cl and NH_2Cl. Two ARs acted as controls and received the chlorinated water or water treated with monochloramine. The remaining two ARs received water that was additionally treated with UV light. The data presented show that the Cl_2 treatment was most effective against suspended heterotrophic (HPC) bacteria in influent and effluent samples, and also against attached HPC bacteria. Chlorine in general was more effective than monochloramine at removing suspended and attached HPC bacteria. UV treatment hindered control of HPC bacteria and resulted in higher counts in most samples and also appeared to enable nitrification in the AR treated with NH_2Cl and UV. It was believed that free chlorine and monochloramine were decaying in the presence of UV light, or that they were absorbing UV irradiation, which would result in the increased bacteria counts. It was confirmed through a bench-scale study that chemical disinfectants decay when samples are exposed to UV light, especially in poorer quality water. No absorption of UV irradiation by chemical disinfectants was observed.

7.2 INTRODUCTION

Treatment of drinking water in warm climates can be difficult considering degradation of disinfection residual in finished water storage facilities and distribution systems that are sometimes subject to high temperatures. Chloramines are often considered as an alternative to chlorine since they have been shown to persist longer in a distribution system (Norman et al., 1980). Martel et al. (2002) found that chloramines improved water quality in storage facilities in a warm climate where chlorination resulted in residual loss and increased bacteria counts. However, when considering a switch to chloramines, utilities must consider other possible issues that may arise in warm climates, primarily the potential for nitrification. It has been reported in literature that conditions that favour nitrification include warm climates or high temperatures in summer months (McGuire et al., 2006; Pintar and Slawson, 2003). Pryor et al. (2004) found that a switchover to monochloramine at a utility in Florida resulted in lower Legionella but increased total coliforms and HPC bacteria and also caused nitrification. Nitrification leads to decreased residual and increased bacteria levels in distribution systems. In addition, nitrate and nitrite concentrations increase during nitrification and these DBPs may lead to serious illnesses such as blue-baby syndrome and cancer.

There have been few studies focused on disinfection of drinking water in distribution systems conducted in warm climates. Most annular reactor experiments have been carried out in cooler climates (Gagnon et al., 2005; Batte et al., 2003; Sharp et al., 2001; Camper, 1996). With changing standards that are becoming stricter on DBP formation, it is estimated that several more utilities will consider changing to chloramines from chlorine to lower THM and HAA formation. It is important for these utilities to consider benefits and implications for the distribution system when switching disinfectants.

There is also the possibility for enhanced disinfection through combination strategies, since previous studies have shown synergistic benefits with sequential disinfection (Dykstra et al., 2006; Koivunen et al., 2005; etc.). Investigation of implementing UV light in combination with chlorine-based disinfection is needed to determine the possibility of enhanced removal of bacteria in warm climate distribution

systems. A potential concern related to the implementation of UV treatment is the interaction between UV light and chemical disinfection. Some studies have shown that free chlorine or monochloramine in water exerts demand on the UV light through absorbance of UV irradiation, and conversely that the UV light destroys the chemical disinfectants reducing the available residual for inactivation of microbial cells. Ormeci et al. (2005) found that although UV absorbance of free chlorine and monochloramine was relatively small, they may affect the effectiveness of UV light toward targeted microorganisms. This study also found the chlorine and monochloramine in potable water decay steadily in presence of UV light, especially chlorine in poorer water quality.

The focus of this chapter was to determine the effectiveness of Cl_2, NH_2Cl, UV/Cl_2, and UV/NH_2Cl in suppressing biofilm growth and controlling microbial pathogens in drinking water distribution systems through a field-scale study, and to compare treatment with UV to no UV treatment. Heterotrophic plate counts and coliforms were used to compare disinfection treatments for bacteria within the systems. In addition, water quality parameters were monitored throughout the experiments. A second objective was to determine the extent of free chlorine and monochloramine decay in the presence of UV light, and the potential for these chemicals to absorb UV light. Observations from the field study were analyzed to meet this objective in addition to a separate bench-scale study.

7.3 EXPERIMENTAL DESIGN

7.3.1 Description of Field Location

The Keller Water Treatment Plant is located in Pinellas County, Florida and collects water from sources that are regionally managed by the Tampa Bay Water supplier. The source for Keller is a blended mixture of groundwater, treated surface water and desalinated seawater. The primary source of groundwater is the Floridan Aquifer. Surface water is collected from the Alafia River, Hillsborough River and the Tampa Bypass Canal and is then treated with chlorine or chloramines. Finally, water from Hillsborough Bay goes through a desalination process to become the third source of

potable water for the region. Separate streams treated with chlorine or monochloramine are directed into the Keller treatment facility, which has various processes for hydrogen sulphide removal, corrosion control, pH adjustment, addition of fluoride, and finally disinfection for residual protection in the distribution system. In 2002, the utility switched from chlorination as the final disinfection step to adding monochloramine.

Pinellas County Utility was interested in implementing treatment with UV light into the treatment process at the Keller WTP and needed to determine the effect on bacteria counts in both water streams. In addition, the 2001 Consumer Confidence Report, Pinellas County reported 0.3% of their samples positive for total coliforms and 0% positive for fecal coliforms and the effect UV light would have on coliforms was therefore also investigated.

7.3.1 Field Experiment Set-up

Annular reactors containing coupons made of PVC material were used to simulate the distribution system in Pinellas County. The hydraulic retention time (2.0h) was controlled by the volumetric flow rate of the influent entering the AR and was established based on a relationship between surface areas and volumes in ARs and pipes, as described by Gagnon and Huck (2001). The influent water stream was maintained at approximately 8.1 mL/min for each AR. The ARs operated at a rotational speed of 50 rpm which translates into a shear stress of 0.25 N/m^2 (Camper, 1995). A shear stress of 0.25 N/m^2 corresponds to a flow of approximately 0.30 m/s (1fps) in a 100 mm (4in) diameter smooth pipe which is similar to shear conditions of other pilot and bench scale investigations. Two ARs acted as controls and received raw source water containing free chlorine or chloramine residual. Two more ARs received water with either Cl_2 or NH_2Cl and were additionally treated with UV light. The set-up in Pinellas County differed from other experiments because the water sources for this plant were pre-treated with either chlorine or monochloramine. Therefore, there was no acclimation period and also UV treatment followed chemical disinfection. Disinfectant residual was the result of the concentration within the source waters as no additional chemical disinfectant was fed to

the experiment system. The study ran over a seven-month period from April to November, 2005.

All non-opaque exposed surfaces of the ARs were covered to reduce the potential of phototrophic growth in the field systems. Before each experimental trial, all ARs were cleaned with antibacterial soap and disinfected using a 70% ethanol solution. In addition all tubing and clearwells used within the set-up were disinfected with ethanol for a period of 24 hours. This was followed by rinsing with Milli-Q water and the source water.

A general schematic of the Florida set-up is presented in Figure 7.1. Two streams, one containing monochloramine and one with free chlorine, were the primary source waters for the model distribution systems. The water collected from each stream was directed into separate RW clearwells. The flow pumped from each of these clearwells was split to feed both a UV unit and one AR. Each water stream had a separate UV system. Once water streams passed through the UV treatment they were directed towards two additional separate clearwells which fed the remaining two ARs.

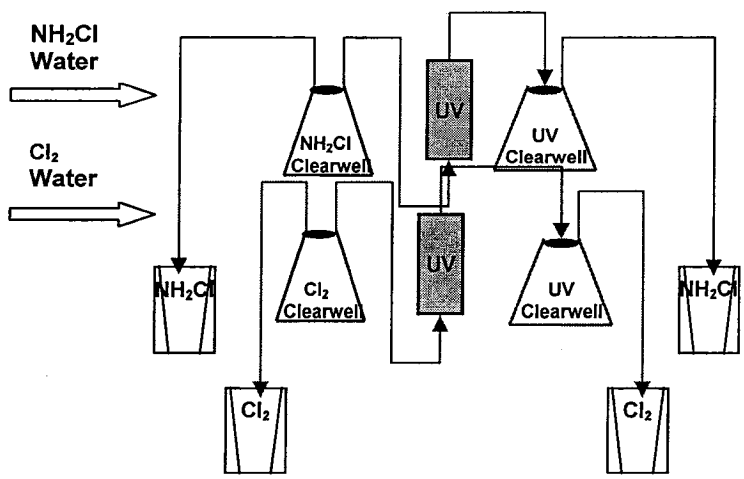

Figure 7.1: Schematic of Pinellas County Field Scale Set-up

The ARs were monitored once weekly for heterotrophic bacteria counts (suspended and biofilm), pH, temperature, turbidity, disinfectant residual, TOC, coliforms, nitrite, nitrate, free ammonia, and total ammonia. In addition, weekly checks of flowrates throughout the system and the rotational speeds of the ARs were performed

to ensure consistent operating conditions. Finally, three times over the course of the experiment samples were analyzed for total trihalomethanes. A photograph of the ARs at the Keller Plant is presented in Figure 7.2.

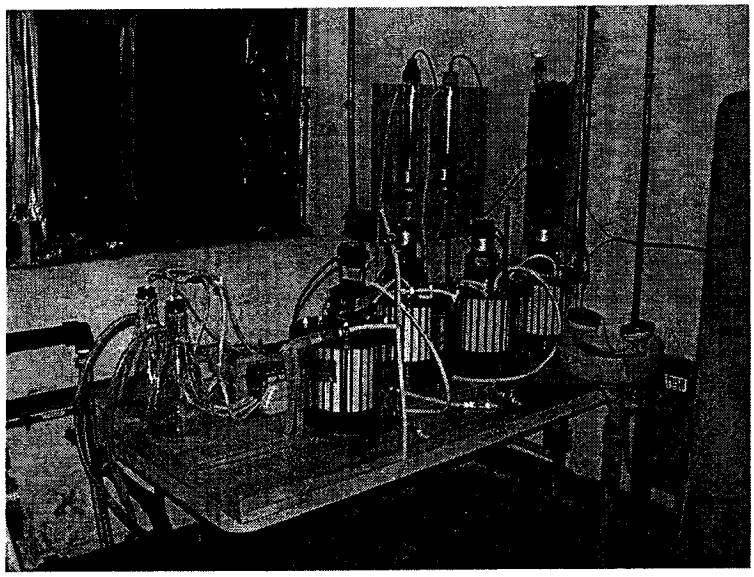

Figure 7.2: Pinellas County Field Scale Set-up

7.3.2 Interactions between UV and Chlorine-based Disinfectants Bench-scale Study

A bench-scale experiment was designed to further investigate interactions between UV light and chlorine-based disinfectants. This included the decay of these chlorine-based disinfectants in the presence of UV light and their absorbance of UV irradiation. Water was collected from three sources including groundwater from Pinellas County, surface water from Halifax, Nova Scotia, and Milli-Q water. Each water sample was dosed with a disinfectant to achieve a desired concentration. The Milli-Q water was dosed with chlorine, monochloramine and chlorine dioxide and had resulting concentrations of approximately 0.2, 0.5, 1.0, 2.0, 3.0 and 5.0 mg/L. Samples from Pinellas County had existing free chlorine or monochloramine. The chlorinated water was analyzed with no additional dosage as well as at residuals of approximately 0.2, 0.5, 1.0, 2.0, 3.0 and 5.0 mg/L free chlorine. The sample pre-treated with monochloramine was also analyzed with no additional chemical added as well as approximate concentrations of 0.4, 1.0, and 5.0 mg/L monochloramine. Finally, the surface water

sample from Halifax was dosed with chlorine, monochloramine or chlorine dioxide with resulting concentrations of approximately 0.5, 1.0 and 5.0 mg/L.

Each sample was analyzed for turbidity, UV transmittance (UVt) and disinfectant residual. The samples were then placed on a stirrer and exposed to UV light to achieve a dose of 100 mJ/cm^2. A control sample was also stirred for the same time to account for volatization of the samples. Following exposure, the samples were re-measured for disinfectant residual and UVt to compare values pre- and post-UV treatment. Exposure to UV light was achieved by using a collimated beam apparatus. Dosages were achieved by following a method written by Bolton and Linden (2003) that attempts to standardize the determination of UV fluence.

7.4 METHODS AND MATERIALS

7.4.1 Pinellas County Field Study

All sampling and testing protocols were carried out as described in the *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 1998) and as described in Chapter 3, Methods and Materials, of this document. During the study, the ARs were monitored once weekly for heterotrophic bacteria counts (suspended and biofilm), pH, temperature, TOC, turbidity, nitrate, nitrite, ammonia, disinfectant residual and coliforms. Samples were collected to be analysed for TTHMs three times throughout the experiment. In addition, weekly checks of flowrates throughout the system and the rotational speeds of the ARs were performed to ensure consistent operating conditions. As previously mentioned, no additional chemicals were added for disinfection of the ARs. Original chlorination was accomplished using a sodium hypochlorite solution, and monochloramine through addition of ammonia to a chlorinated stream at a pH of approximately 9.4.

7.4.2 Bench-scale Study

All sampling and testing protocols were carried out as described in the *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 1998) and as described in Chapter 3, Methods and Materials, of this document. The study was carried out in the University of Toronto Water Laboratory. Chlorine dioxide was generated onsite according to Method 4500-ClO_2 of *Standard Methods for the Examination of Water and Wastewater, 19th Ed* and as described in Chapter 3. Chlorine stocks were produced using a 16% analytical grade sodium hypochlorite solution. Monochloramine was produced by combining an ammonium chloride solution and 16% analytical grade sodium hypochlorite at a pH of 9.4 as described in Chapter 3. Turbidity, UVt, pH, and disinfectant concentration were measured for each sample before exposure to UV light, and disinfectant residual and UVt were also measured post-UV treatment. UVt was measured using an HF Scientific UVT-15 photometer with a 1-cm pathlength. Turbidity was analysed for using a HACH 2100P turbidimeter (HACH Company, Loveland, CO) and pH was measured using an ORION model 230A. Finally, chlorine and chlorine dioxide were measured using the DBP colorimetric method and a HACH DR/2100 Spectrophotometer (HACH Company, Loveland, CO). Monochloramine was measured using a DPD ferrous titrimetric method (Standard Methods, 21st edition-4500 D).

The collimated beam apparatus (Figure 7.3) consisted of a low pressure light which was encased. At the center of the lamp, a UV-transparent window directed the light down a tunnel-like path, which was also encased, toward a stirrer. A Petri dish containing the sample is placed on the stirrer for the UV exposure. The UV dose was set at 100 mJ/cm^2 using a method presented by Bolton and Linden (2003). A spreadsheet programmed by Bolton in 2004 (Appendix C) was used to determine exposure times in order to reach the goal dose. A reading from a radiometer at the center of the stirrer is input into the spreadsheet, as well as the absorption coefficient of the sample, vertical distance from the surface of the lamp to the Petri dish, sample volume, and desired fluence. Taking into consideration a reflection factor, a divergence factor, and a Petri factor (irradiation at outer edge of Petri dish compared to center), exposure times for various dosages are calculated and output with the spreadsheet.

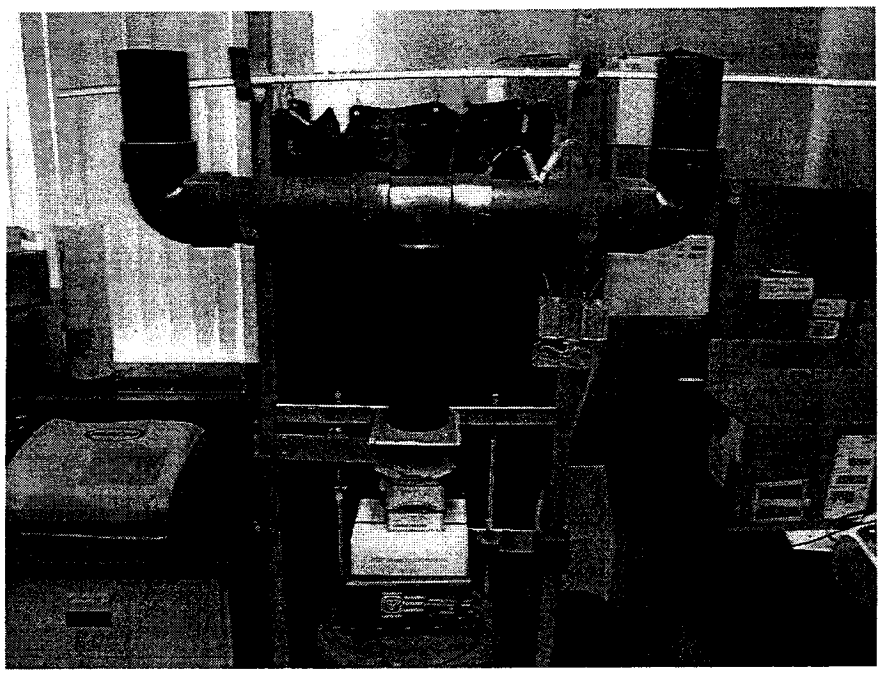

Figure 7.3 Collimated Beam Apparatus

Sample volumes were constant at 45 mL, and the radiometer reading and distance between the Petri dish and the lamp was also consistent throughout the experiment. Absorption coefficients did not change significantly between different disinfectant concentrations and were therefore kept constant for each water source for the purposes of the spreadsheet. However, the coefficients varied between water sources and were adjusted accordingly for Milli-Q water, Halifax water and Florida water. Exposure times for each water source to obtain a 100 mJ/cm^2 dose are presented in Table 7.1.

Table 7.1: Bench-scale Study UV Exposure Times

Water Source	Exposure Time (min)
Milli-Q	8.42
Pockwock	9.37
Florida (Cl_2)	9.10
Florida (NH_2Cl)	8.67

7.5 RESULTS AND DISCUSSION

7.5.1 Florida AR Study

Unlike other field experiments previously presented, the annular reactors for this study went through no acclimation period and therefore average counts include every sample throughout the 30-week study. Samples for HPC bacteria included the influent to each AR, the effluent of each AR as well as biofilm samples from the coupons of each AR. The overall mean number of suspended heterotrophic bacteria in the influents was $6.10x10^5 \pm 4.81x10^5$ CFU/mL and $4.04x10^5 \pm 5.11x10^5$ CFU/mL in the effluent of all ARs for the duration of the project. The mean attached (biofilm) heterotrophic bacteria for all ARs was higher at $1.79x10^6 \pm 8.01x10^5$ CFU/cm^2. The average counts for both bulk samples were statistically different than biofilm average counts but were not significantly different from each other.

7.5.1.1 Comparison of Disinfectants

The most effective disinfection option for influent suspended bacteria (Figure 7.4) was Cl_2 alone with an average count over the course of the experiment of $4.20x10^2 \pm 1.37x10^3$ CFU/mL which was a statistically significant difference compared to all other ARs ($p = 0.000 - 0.002$). The highest average count was observed in the AR treated with NH_2Cl alone at $1.09x10^6 \pm 1.17x10^6$ CFU/mL but this did not differ significantly from the UV + NH_2Cl AR with an average count of $8.33x10^5 \pm 7.17x10^5$ CFU/mL ($p = 0.674$).

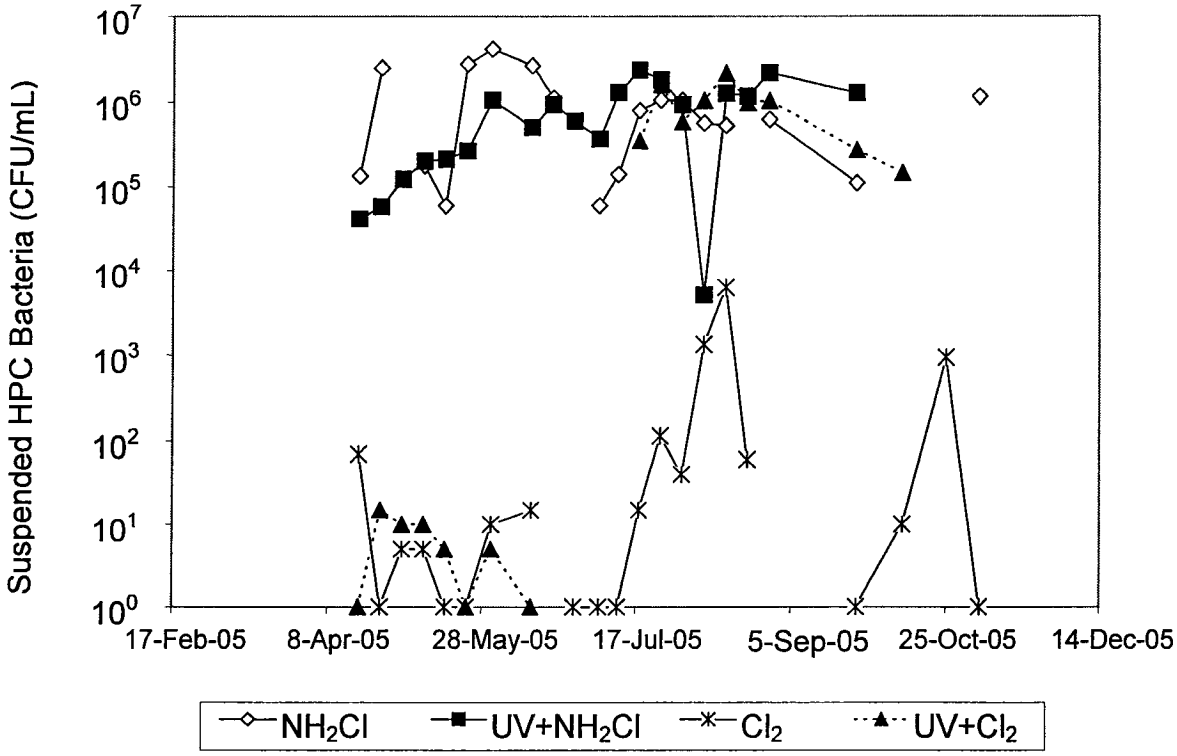

Figure 7.4: Average Suspended Heterotrophic Bacteria in the Influent Streams Collected in Pinellas County

The suspended heterotrophic bacteria counts increased over the course of the experiment in the influent of the AR treated with UV + Cl_2 jumping from an average count of $6.00x10^0 \pm 5.21x10^0$ CFU/mL in the first eight weeks of the project to $8.90x10^5 \pm 6.59x10^5$ CFU/mL for the final 20 weeks resulting in an overall average of $5.15x10^5 \pm 6.67x10^5$ CFU/mL. The increase in heterotrophic bacteria for the UV and Cl_2 AR corresponded to decrease in free chlorine in the influent to below detection limits (Figure 7.5). A potential explanation would be that demand in the UV influent line was exceeded due to increased biofilm formation and degradation of chlorine in the UV lamp. This decrease in residual did not occur in the AR receiving water treated with Cl_2 only, where although data is scattered as is common in field studies, overall residual and heterotrophic bacteria concentrations remain fairly constant (Figure 7.6). Nevertheless, this data set indicated that maintaining chlorine residual was essential for the control of heterotrophic bacteria and is consistent with other reports (LeChevallier et al., 1996; Gagnon and Huck, 2004; Baribeau et al., 2005). As can be seen in Figure 7.7, no chlorine residual results in

high average HPC bacteria in the influent of both Cl_2-treated ARs, and when free Cl_2 is present, bacterial growth is controlled.

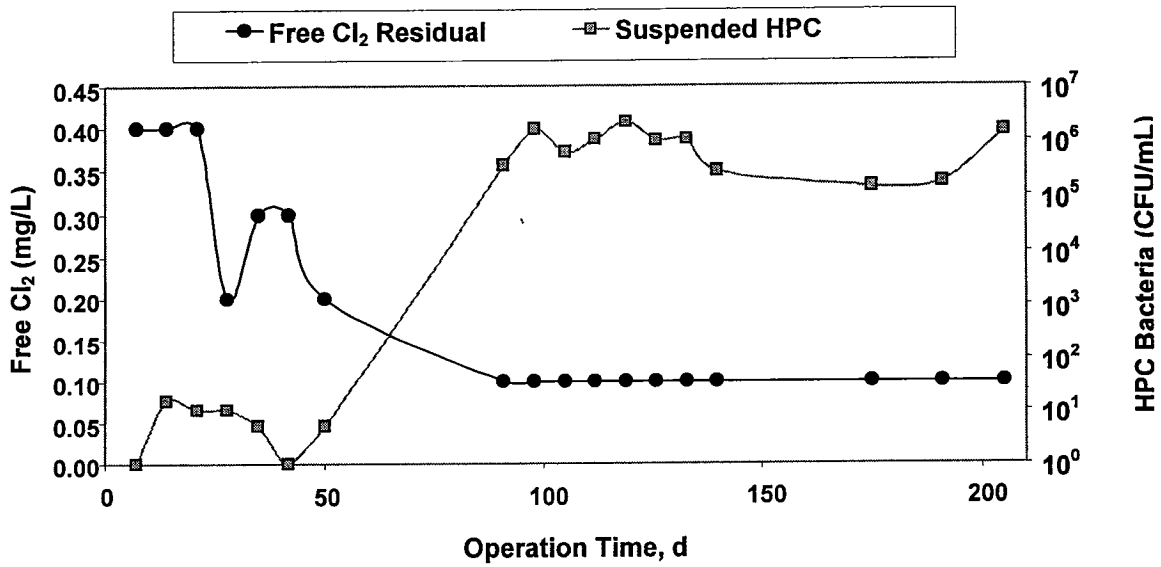

Figure 7.5: Free Chlorine Residual with Corresponding HPC Bacteria in the Influent of the AR Receiving Water Treated with UV and Cl_2 in Pinellas Co.

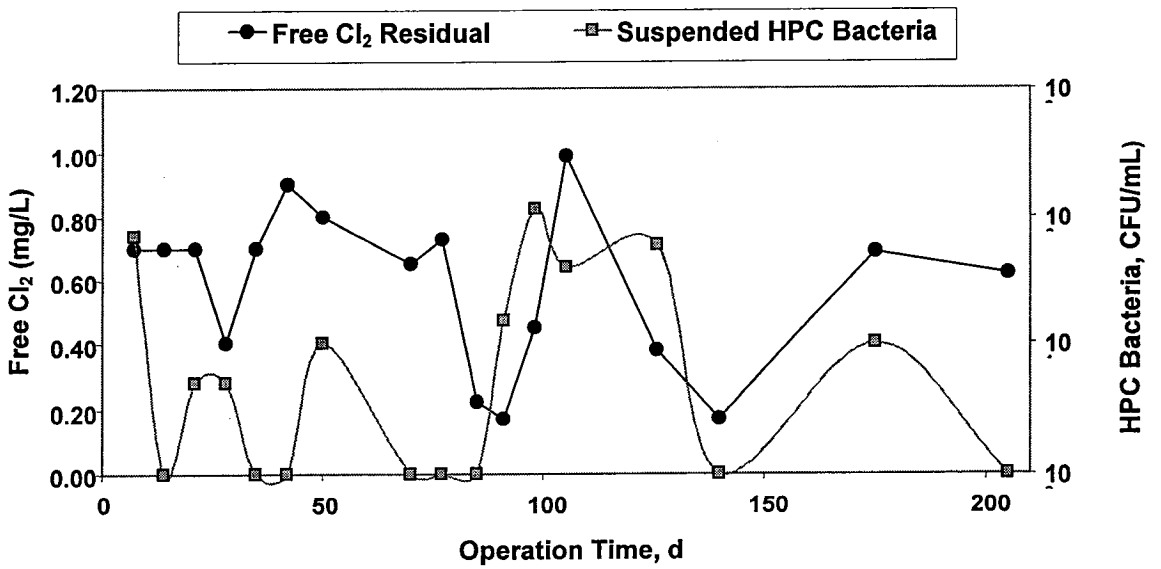

Figure 7.6: Free Chlorine Residual with Corresponding HPC Bacteria in the Influent of the AR Receiving Water Treated with Cl_2 Only in Pinellas Co.

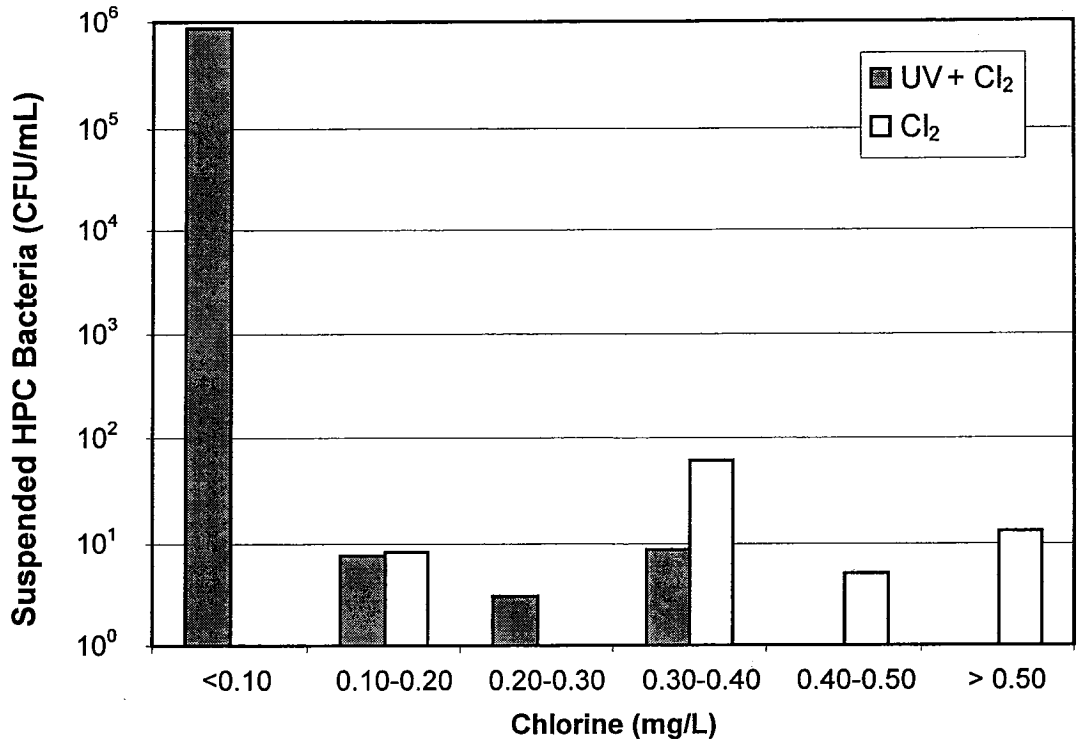

Figure 7.7: Average Suspended HPC Bacteria in AR Influents versus Free Chlorine Residual for Pinellas County Data (Note: Where no bars appear, data resulted in values of zero.)

Similarly to influent data, the AR treated with Cl_2 alone had the lowest average count for effluent samples at $8.19x10^2 \pm 9.38x10^2$ CFU/mL and differed significantly from all other ARs ($p = 0.000$), (Figure 7.8). The UV + Cl_2 AR had increasing counts in effluent samples as was observed in its influent however not as significant going from $3.60x10^4 \pm 4.83x10^4$ CFU/mL to $6.31x10^5 \pm 4.76x10^5$ CFU/mL. This resulted in an overall average of $3.53x10^5 \pm 4.40x10^5$ CFU/mL which did not differ significantly from the AR treated with UV + NH_2Cl or NH_2Cl alone ($p = 0.251 - 0.310$). The highest average count was observed in the UV + NH_2Cl AR at $1.00x10^6 \pm 1.19x10^6$ CFU/mL which was significantly different than the NH_2Cl AR ($p = 0.005$) which had an average count of $2.61x10^5 \pm 2.51x10^5$ CFU/mL. Overall for bulk samples of the effluent, ARs treated with UV in addition to the chemical disinfectants had higher average counts compared to ARs with no UV treatment.

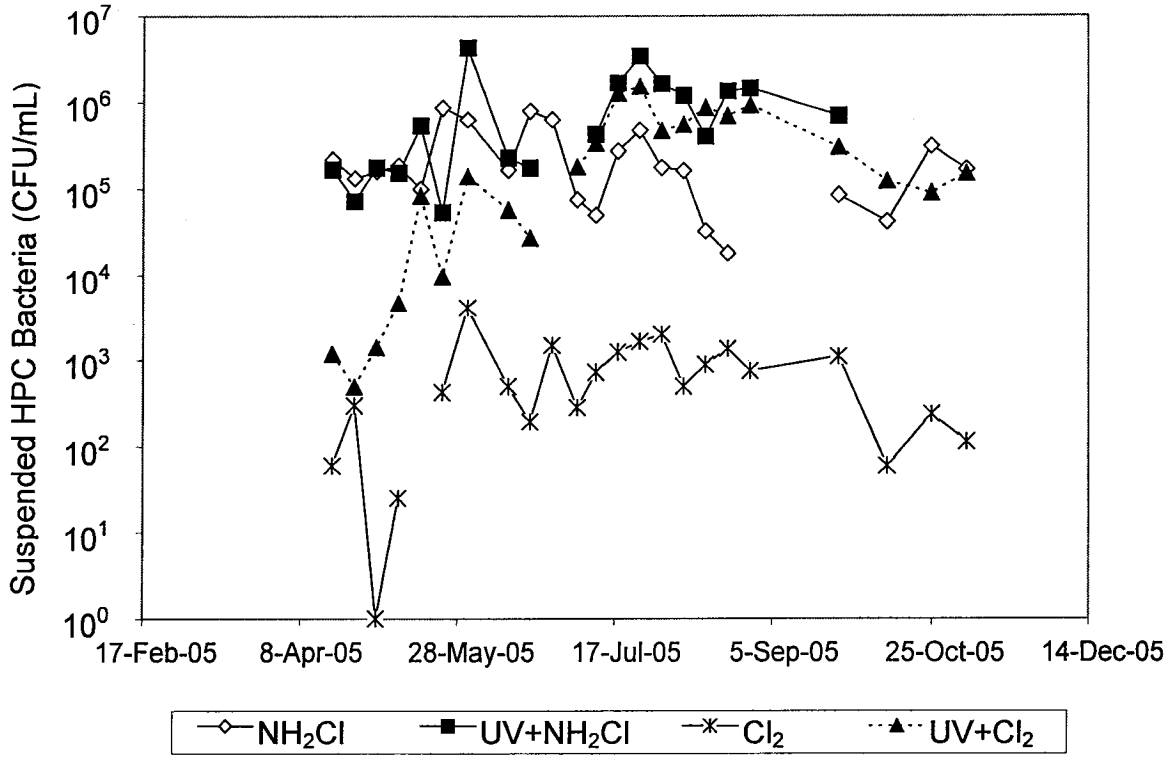

Figure 7.8: Average Suspended Heterotrophic Bacteria in the Effluent of Each AR collect in Pinellas County

In biofilm data the AR treated with Cl_2 had the lowest level of attached bacteria with an average count of $4.11x10^5 \pm 7.38x10^5$ CFU/cm^2 (Figure 7.9). This was a significantly lower count compared to all other ARs ($p = 0.000 - 0.005$), but there was no statistically significant difference between average counts for the remaining three ARs. The AR treated with UV and Cl_2 had the highest average count overall at $2.49x10^6 \pm 2.43x10^6$ CFU/cm^2. The AR that received NH_2Cl treated water had an average count of $1.86x10^6 \pm 2.40x10^6$ CFU/cm^2 and the UV + NH_2Cl AR averaged $2.41x10^6 \pm 2.11x10^6$ CFU/cm^2 for attached heterotrophic bacteria. Similarly to effluent samples, ARs with the additional treatment of UV had higher overall average counts than the ARs that had no UV treatment.

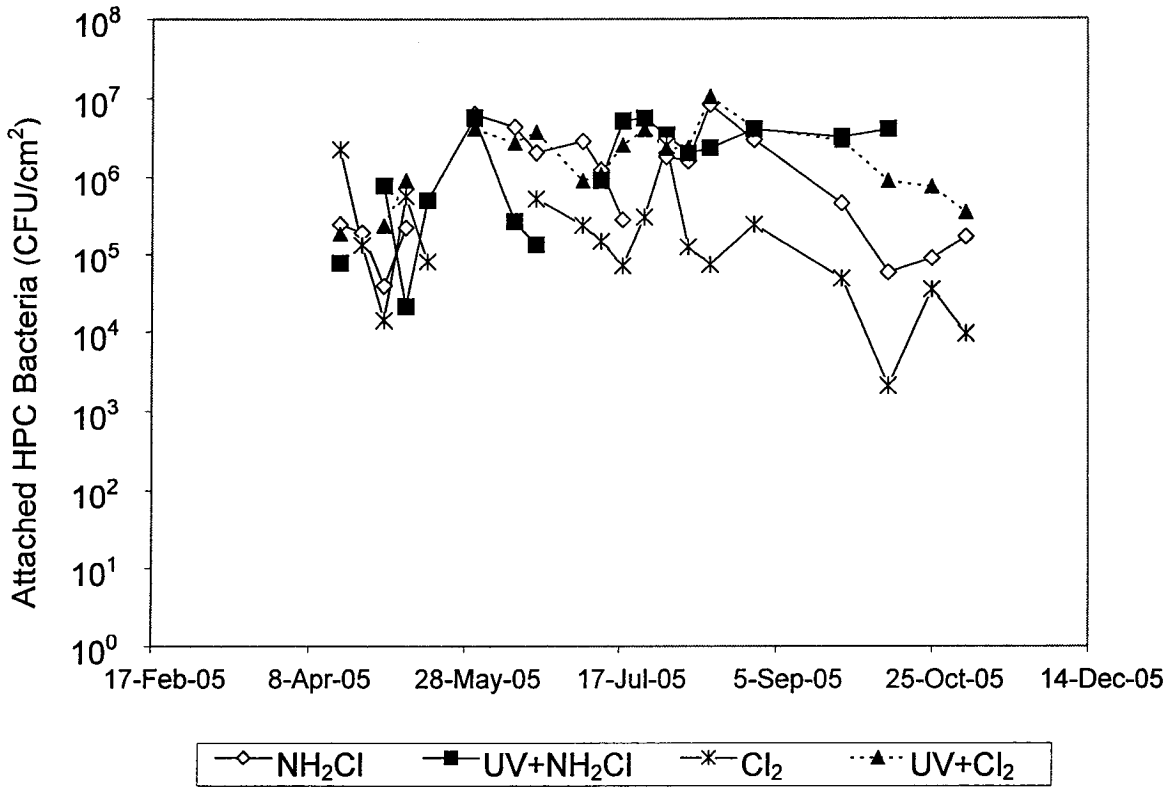

Figure 7.9: Average Attached Heterotrophic Bacteria from PVC Coupons Collected in Pinellas County

7.5.1.2 Water Quality Analysis

Over the 30-week study period water samples were taken of influent and effluent water streams to analyze for several parameters including pH, temperature, turbidity, TOC, disinfectant residual, total coliforms, and *Escherichia coli.* In addition, samples were monitored both onsite and in a laboratory for ammonia and nitrate. Finally samples were taken to analyze from the disinfection by-products of TTHMs three times over the course of the experiment.

7.5.1.2.1 Disinfectant Residual

For both chlorine and monochloramine, the presence of UV treatment appeared to decrease disinfectant residuals in both influent and effluent water streams. The average residual NH_2Cl in the influent of that AR was 1.67 ± 0.74 mg/L compared to 0.90 ± 0.66 mg/L for the UV + NH_2Cl AR influent. Similarly, the NH_2Cl residual was lower in the

UV + NH_2Cl effluent with an average of 0.62 ± 0.65 mg/L compared to 0.87 ± 0.60 mg/L in the effluent of the AR receiving water treated only with NH_2Cl.

This trend held true free and total chlorine residuals in influent and effluent samples. The average influent free Cl_2 residual for the AR also treated with UV was 0.17 ± 0.11 mg/L compared to 0.53 ± 0.26 mg/L in the Cl_2 alone AR. Also, the average effluent residual concentration was 0.11 ± 0.03 mg/L in the UV + Cl_2 AR and 0.32 ± 0.17 mg/L in the Cl_2 AR. As previously mentioned, free chlorine residual concentration in the UV + Cl_2 AR influent and effluent streams was below the detection limit of 0.10 mg/L for the majority of the experiment. Total chlorine levels in the influent streams were also lover in ARs treated with UV (UV + Cl_2 = 0.27 ± 0.10 mg/L, Cl_2 = 0.68 ± 0.32 mg/L, UV + NH_2Cl = 1.30 ± 1.16 mg/L, NH_2Cl = 2.13 ± 0.80 mg/L), which was also observed in effluent streams (UV + Cl_2 = 0.20 ± 0.02 mg/L, Cl_2 = 0.43 ± 0.18 mg/L, UV + NH_2Cl = 0.86 ± 0.86 mg/L, NH_2Cl = 1.33 ± 0.83 mg/L).

7.5.1.2.2 pH, Temperature and Turbidity

The average pH for all ARs in the influent water streams was 7.76 ± 0.04 and 7.84 ± 0.02 in effluent streams. The ARs operated at an average temperature of 25.2 ± 0.16 °C during the experiment, and the average influent temperature was slightly higher at 26.3 ± 0.23 °C. In comparison, during the field tests in Halifax, PW and EBMUD the mean influent temp was 19.4 ± 2.79 °C, 12.7 ± 2.77 °C and 24.0 ± 2.75 °C respectively.

The average turbidity for the NH_2Cl influent water streams was higher than the Cl_2 influent water streams. In addition, water treated with UV had lower turbidity on average than water that was not treated with UV. The average turbidity for the UV + NH_2Cl influent was 1.58 ± 1.75 NTU and 2.12 ± 3.45 NTU for the NH_2Cl influent. For effluent samples, the average turbidity in the UV + NH_2Cl AR was 0.73 ± 0.35 NTU and 0.89 ± 0.81 NTU in the NH_2Cl AR. Average influent turbidities for the UV + Cl_2 and Cl_2 ARs were 0.45 ± 0.29 NTU and 0.50 ± 0.26 NTU respectively, and for effluent the average turbidity for the UV + Cl_2 and was 0.31 ± 0.12 NTU and 0.38 ± 0.21 NTU for the Cl_2 AR.

7.5.1.2.3 Organic Content

Total organic carbon (TOC) was similar without significant changes over the course of the study and the presence of UV light did not appear to affect TOC levels. The average influent TOC concentration in all ARs was 3.81 ± 0.08 mg/L and 3.92 ± 0.20 mg/L in the effluent of all ARs.

7.5.1.2.4 Disinfection By-products

Total trihalomethanes (TTHMs) were measured three times near the end of the experiment in September and October 2005. The AR receiving NH_2Cl and UV-treated water was shut down in October due to operational problems therefore only one TTHM measurement was obtained for that AR. The average TTHM concentration in the AR treated with Cl_2 alone was 53.7 ± 5.3 μg/L and 43.3 ± 3.2 μg/L in the AR treated with UV and Cl_2. The measurement obtained for the UV + NH_2Cl AR showed a TTHM concentration of 41.6 μg/L and the AR treated with NH_2Cl alone had an average TTHM concentration of 48.5 ± 2.0 μg/L. The USEPA maximum contaminant level (MCL) for TTHMs is 0.080 mg/L.

7.5.1.2.5 Total Coliforms and Escherichia coli

Data was obtained for total coliforms and *E. coli* six times over the course of the project. For influent samples, the water treated with UV and NH_2Cl was positive for total coliforms once resulting in an average concentration of 1.03 MPN/100mL, and the NH_2Cl treated water was positive twice resulting in an average concentration of 0.87 MPN/100mL. These occurrences were negative for *E. coli*. The chlorinated influent water streams had no positive occurrences for total coliforms. There were positive occurrences in all AR effluents. The effluent for the NH_2Cl and UV + NH_2Cl ARs each tested positive five out of six times resulting in average concentrations of 11.8 MPN/100mL and 5.98 MPN/100mL respectively. The Cl_2 AR tested positive three out of six times resulting in an average concentration for total coliforms of 6.77 MPN/100mL. The UV + Cl_2 had positive occurrences 4 times which resulted in an average concentration of 6.75 MPN/100mL. No occurrences in any samples tested positive for *E. coli* throughout the experiment.

7.5.1.2.6 Nitrate and Nitrite

Nitrate and nitrite were measured in the Pinellas County laboratory for the entire study period. Nitrification was suspected to occur in water streams treated with NH_2Cl only. Samples collected from the Cl_2 streams and corresponding chlorinated ARs had nitrite and nitrate concentrations that were below the detection limit for all sample dates. The average nitrate concentration for the NH_2Cl influent stream measured in the lab was 0.07 ± 0.05 mg/L as N and 0.09 ± 0.05 mg/L as N for the UV + NH_2Cl influent. The effluent of the NH_2Cl AR had an average nitrate concentration of 0.12 ± 0.07 mg/L as N and the average concentration was 0.30 ± 0.34 mg/L as N for the effluent of the UV + NH_2Cl AR in lab analysis.

Nitrite concentrations were also measured for AR influent and effluent streams. The influent of the NH_2Cl AR had an average nitrite concentration of 0.12 ± 0.10 mg/L as N in lab analysis and the UV + NH_2Cl stream averaged 0.19 ± 0.15 mg/L as N. The effluent of the NH_2Cl AR averaged 0.18 ± 0.15 mg/L as N and the UV + NH_2Cl AR had an average nitrite concentration of 0.13 ± 0.19 mg/L as N in lab analysis of the effluent stream. Observing the data, the AR receiving UV-treated water had higher concentration levels of nitrate and nitrite compared to the AR with NH_2Cl disinfection only, indicating photolysis of NH_2Cl may have occurred as well as nitrification.

7.5.1.2.7 Free and Total Ammonia

Free ammonia for water streams treated with NH_2Cl was measured at the Pinellas County laboratory and in addition in the field from June 2005 to the end of the experiment as a check for lab analysis. Field and lab results were fairly consistent therefore only lab analysis results are reported. The average free ammonia concentration in the influent treated with NH_2Cl alone was 0.44 ± 0.14 mg/L as N, and for the UV + NH_2Cl influent the average was 0.46 ± 0.15 mg/L as N in the lab analysis.

Total ammonia was measured in the lab alone for all water streams including the chlorinated ARs. Average influent concentrations were slightly higher than effluent concentrations and ARs that were not treated with UV had slightly lower total ammonia levels. The average influent concentrations for the NH_2Cl and the UV + NH_2Cl were 0.89 ± 0.26 mg/L as N and 0.69 ± 0.30 mg/L as N respectively. The effluent of the

NH_2Cl AR had an average concentration of 0.73 ± 0.32 mg/L as N and the average was 0.50 ± 0.41 mg/L as N for the UV + NH_2Cl AR. The Cl_2 ARs all measured close to the detection limit for free and total ammonia.

Free ammonia, nitrite and nitrate concentrations were all measured as nitrogen for analysis, and in order to determine if nitrification occurred in the ARs treated with monochloramine, the variation in concentration of each in the effluent over the course of the experiment was analyzed. Figure 7.10 shows that free ammonia, nitrate and nitrite concentration in the NH_2Cl AR varied but did not change overall during the study, indicating nitrification didn't occur in this AR.

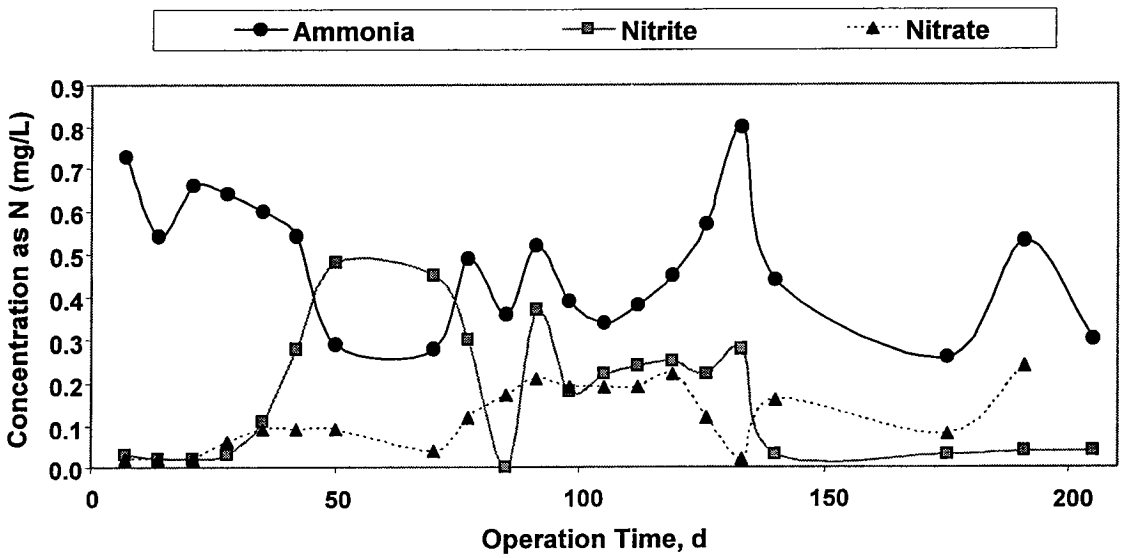

Figure 7.10: Ammonia, Nitrite and Nitrate Concentrations in the Effluent of the AR Treated with NH_2Cl Only in Pinellas County

Nitrification did appear to occur in the AR receiving NH_2Cl and UV-treated water (Figure 7.11). Nitrification is a process that can take up to several weeks in a distribution system and occurs when free ammonia is oxidized into nitrite which is additionally oxidized to form nitrate (McQuire et al., 2006). From Figure 7.11 it can be observed that a reduction in free ammonia concentration occurred in the 12th week of the study, which corresponded to an increase in nitrite concentration. This was followed by a decrease in nitrite levels and a corresponding increase of nitrate concentration in the 16th week. Accelerated nitrification in systems with UV light disinfection following

monochloramine has not yet been reported in literature. Ammonia (NH_3) concentrations in the first 11 weeks of the experiment were similar in both ARs (NH_2Cl = 0.50 ± 0.15 mg/L as N and UV+NH_2Cl = 0.55 ± 0.16 mg/L as N), therefore nitrification didn't initially occur in the UV + NH_2Cl AR due to a higher level of excess NH_3 compared to the NH_2Cl AR. A possible explanation could be similar to that for increased HPC counts in Cl_2 and NH_2Cl ARs with UV treatment, where UV light increases bacterial regrowth potential of NOM (Parkinson et al., 2003), thereby causing elevated levels of ammonia oxidizing bacteria (AOB) which leads to oxidation of ammonia into nitrite. In addition, Mack and Bolton (1999) established –OH radicals are the result of photolysis of nitrate and nitrite, which could be achieved with the UV lamp. Gagnon et al. (2004) suggest -OH radicals react with humic material in water to form biodegradable organic matter, which act as a nutrient source for bacteria in distribution systems. This would create a stronger biofilm community where AOB were able to thrive and in the UV-treated AR, which eventually led to occurrence of nitrification. Also, photolysis caused by UV light would have increased degradation of NH_2Cl and released more ammonia, which would also allow AOB to proliferate (McGuire et al., 2006). Without the elevated levels of AOB in the AR receiving water treated with NH_2Cl nitrification was not accomplished.

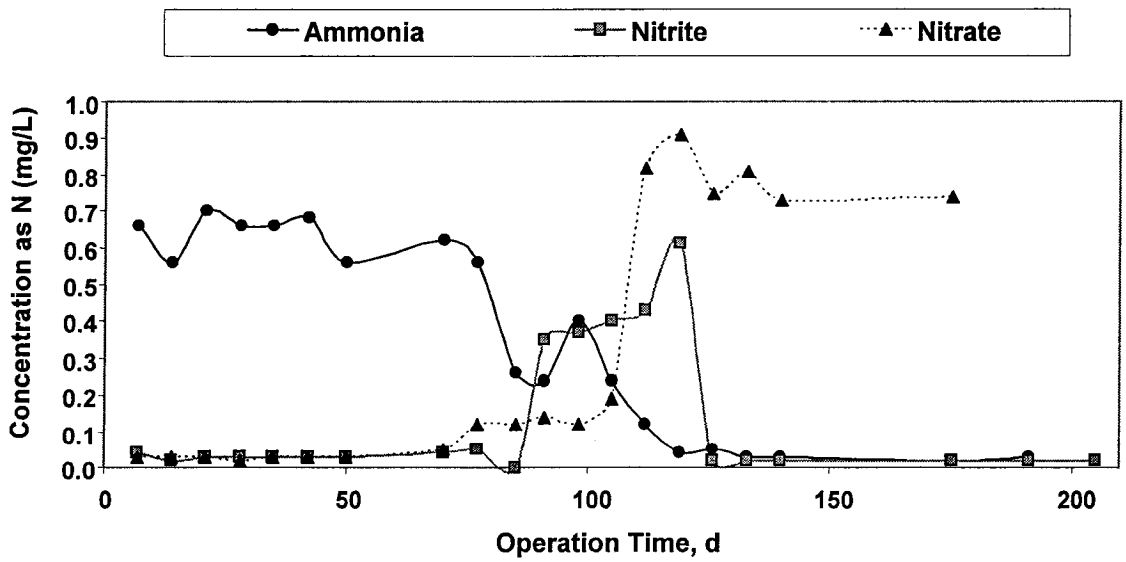

Figure 7.11: Ammonia, Nitrite and Nitrate Concentrations in the Effluent of the AR Treated with UV and NH_2Cl in Pinellas County

7.5.1.3 Bacteria Occurrences in Water Streams Treated with Monochloramine

Over the course of the experiment, white flakes were often seen in the influent to the ARs treated with monochloramine, especially in the AR with no UV treatment. Samplers would observe the flakes that appeared to grow and/or accumulate in the tubing leading to each AR, and on occasion the growths would be large enough to slow and even stop flow of water. Replacement of tubing proved to be only a temporary solution as the flakes would re-grow, especially in hotter summer months. Flakes formed in the tubing were collected (Figure 7.12) and examined under a microscope at the Pinellas County laboratory (Figure 7.13) and cultured. The growths were determined to be clusters of different types of bacteria.

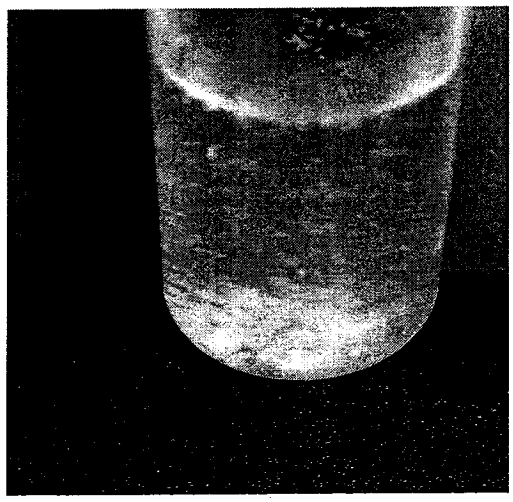

Figure 7.12: White Flakes Collected in Monochloramine Influent in Pinellas County

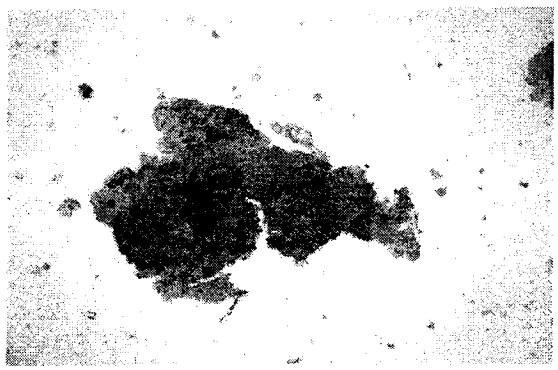

Figure 7.13: White Flake under Microscope: 10x Magnification

7.5.2 Bench-scale Study

In 2005, Ormeci et al. found that chlorine and monochloramine in potable water decay steadily in presence of UV light, especially chlorine in poorer water quality. Considering the observed decrease of residual concentration in the ARs treated with UV light in the Florida study, it was hypothesized that UV light degraded the chemical in the water stream and therefore increased potential for bacterial re-growth in the AR systems. To further investigate, the laboratory study was conducted using the two Pinellas County water sources, a surface water source and Milli-Q water. Water quality parameters measured for each water source are presented in Table 7.2.

Table 7.2: Bench-scale Study Source Water Quality

Water Source	pH	Absorption Coefficient (cm^{-1})	Average Turbidity (NTU)
Milli-Q	8.05	0.001	0.117
Pockwock	7.42	0.125	0.817
Florida (Cl_2)	7.87	0.091	0.809
Florida (NH_2Cl)	7.83	0.036	0.292

7.5.2.1 Disinfectant Residuals

In calculating reductions, control samples were taken into consideration. Chlorine was reduced in every type of water source and at every residual concentration. In general, higher percentage reductions were observed in samples with lower initial concentrations. On average, chlorine was reduced by 11.4% in Milli-Q water, 33.5% in surface water, and 27.3% in chlorinated Florida water. The Florida water had an existing free chlorine concentration of 0.45 mg/L. No change occurred in the control stirred sample, and the sample exposed to UV light while stirred had a decrease in free chlorine to 0.17 mg/L, which corresponded to a 62.2 % decrease.

Monochloramine did not show high reductions as chlorine did, however concentrations were reduced in every water source. On average, NH_2Cl was reduced by 9.8% in Milli-Q water, 6.3% in surface water, and 7.9% in Florida water pre-treated with

NH_2Cl. The Florida water had an existing NH_2Cl concentration of 3.10 mg/L. The control sample decreased to 3.0 mg/L after being stirred, and the UV-exposed sample showed an even larger reduction to 2.80 mg/L, which corresponded to a 6.5% reduction.

Only Milli-Q and the surface water source were treated with chlorine dioxide to observe any reductions in the presence of UV light. Although there was an average 19.6% reduction in surface water, there was no reduction observed in the Milli-Q water. This was mainly due to control samples having large losses of residual since it is widely known that ClO_2 is a highly volatile substance.

In general, higher quality water sources (i.e., low turbidity, low absorption coefficient) showed less decay of disinfectant residual compared to sources lower in quality. This is consistent with Ormeci et al. (2005) findings where chlorine decayed at a higher rate in poorer quality water.

7.5.2.2 Ultraviolet Light Transmission

Less significant changes in UVt were observed compared to the reduction of disinfectant residual, however there was an increase of UVt in each sample for each disinfectant. Chlorinated samples on average showed an increase of 0.4% in Milli-Q water, 1.4% in surface water and 1.5% in Florida water. Samples containing monochloramine showed increase in UVt for surface water (1.0%) and Florida water (0.5%), but none in Milli-Q water. Chlorine dioxide samples showed an increase in UVt for both surface water (1.3%) and Milli-Q (0.7%). As with disinfectant residual, less change was observed in higher quality sources. Milli-Q on average had less increase in UVt for each type of disinfectant compared to Florida and surface water sources.

7.6 CONCLUSIONS

It was found in this study that chlorine alone was significantly more effective against suspended heterotrophic bacteria in influent and effluent samples and against attached HPC bacteria compared to other treatments. Chlorinated influent maintained a low bacteria count and this trend was repeated in the AR effluent and samples taken from the PVC coupons. Monochloramine was not effective against the HPC bacteria and had

the highest counts in the influent water. In the NH_2Cl influent streams, bacteria growth was significant enough to hinder flow through the tubing.

In general, streams that were additionally treated with UV light had higher HPC bacteria counts than those ARs with no UV treatment. A Parkinson et al. study (2003) showed UV treatment resulted in increased bacterial re-growth potential (BRP) for NOM, which could explain spiked HPC counts in UV-treated water streams. Also, Gagnon et al. (2004) suggests UV light is able to photocatalyze HOCl to form hydroxyl radicals, which react quickly with humic substances to form biodegradable organic matter (BOM). BOM serves as a nutrient source for heterotrophic bacteria, which may lead to increased counts. It is believed that the substantial bacteria growth in the tubing of the NH_2Cl streams was reduced slightly through the UV lamp causing a lower count in the UV + NH_2Cl influent than the NH_2Cl influent.

It was also observed that a lower chlorine and monochloramine residual was observed in the ARs that were treated with UV light compared to those with no UV treatment. An increase in HPC bacteria in the influent of the chlorinated AR with UV treatment directly corresponded to a drop in chlorine residual. It is believed that the UV light degraded chemical residual allowing for increased growth of heterotrophic bacteria. In addition, TTHM concentration was highest in the AR treated with chlorine only compared to the UV and Cl_2 AR. This could be due to UV light breaking down chlorine making it less available for a reaction with NOM to produce the disinfection by-products. Hugul et al. (2000) showed that organo-bound chlorine is converted to inorganic chloride in the presence of UV and hydrogen peroxide.

Several studies have shown that NH_2Cl is removed by sunlight or UV light, and that photolysis of NH_2Cl by UV light produces nitrate. It was observed in this study that nitrate levels were significantly higher in the influent treated with UV and NH_2Cl compared to treatment with NH_2Cl only. Nitrification occurred in the 12^{th} week of the experiment in the UV + NH_2Cl AR, which could have contributed to lower residual concentrations, increased bacterial counts and higher levels of nitrite and nitrate. No nitrification was observed in the AR treated with NH_2Cl alone.

A bench-scale study confirmed degradation of chlorine-based disinfectants with UV treatment, where varying concentrations of chlorine, monochloramine and chlorine

dioxide decayed with exposure to UV light. This could It was observed that at low concentrations, chlorine could be reduced up to 66% with UV exposure. In addition, chemical residual decreased at a higher rate in poorer quality water, as was previously found by Ormeci et al. (2005). This could lead to increased bacteria counts in water when UV treatment follows chemical disinfection. UV transmittance also increased slightly, which would indicate that UV irradiation was not being absorbed by chemical concentration and was able to break down absorbers, such as natural organic matter and perhaps chemicals.

8.0 SYNTHESIS AND ANALYSIS OF EXPERIMENTAL DATA

Four separate field studies were carried out to investigate the effectiveness of various disinfection strategies on biofouling in drinking water distribution systems. Treatment included chlorine, chlorine dioxide and monochloramine alone or in combination with UV light. As has been demonstrated in the previous chapters of this thesis, enhanced removal of HPC bacteria was observed in the field studies with UV light pre-treatment in combination with chlorine-based disinfectants, however not when UV light was applied following chemical disinfection. This chapter is designed to compare results from the various studies to determine the effect of water matrix and point of application on disinfection strategy, and will assess synergistic benefits between UV light and chlorine-based disinfectants.

8.1 IMPACT OF WATER MATRICES ON TREATMENT

In this project four independent water sources were utilized in field studies including a warm climate surface water source at the Pardee Reservoir, CA, (average influent temperature 24.0 ± 2.75 °C), a cold climate surface water in Halifax, NS, (average influent temperature 19.4 ± 2.94 °C), a warm climate blended water in Pinellas County, FL, (average influent temperature 26.3 ± 0.23 °C) and a cold climate groundwater source in Port Williams, NS (average influent temperature 12.7 ± 2.77 °C). Each study utilized annular reactors (ARs) to simulate distribution systems. Of these four sites, three studies looked at UV pre-treatment followed by chlorine-based disinfection, including Pardee, Halifax and Port Williams (PW). Field results are often variable, as was demonstrated in each chapter, and unlike controlled laboratory studies, source water quality can vary throughout the course of a study. An "ideal" AR run would show steady-state biofilm during the acclimation period followed by a reduction of HPC bacteria during disinfection, which results in a reduced second steady-state condition. An example of a controlled lab run with ARs is shown in Figure 8.1, where chlorine dioxide was used to treat one AR containing polycarbonate coupons and one containing cast iron coupons, then compared to two corresponding control ARs (Gagnon et al., 2005) .

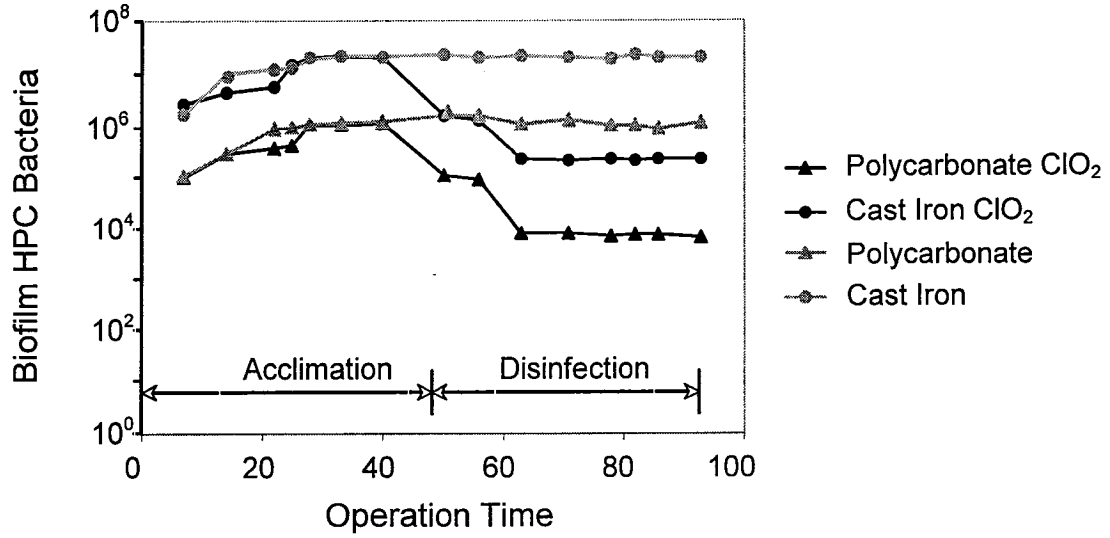

Figure 8.1: Typical Lab AR Run with ClO2 for Removal of Attached HPC Bacteria (Source: Gagnon et al. 2005)

This differs from typical field studies where data is often scattered, due to variations in source water quality over several weeks, as can be seen in Figure 8.2.

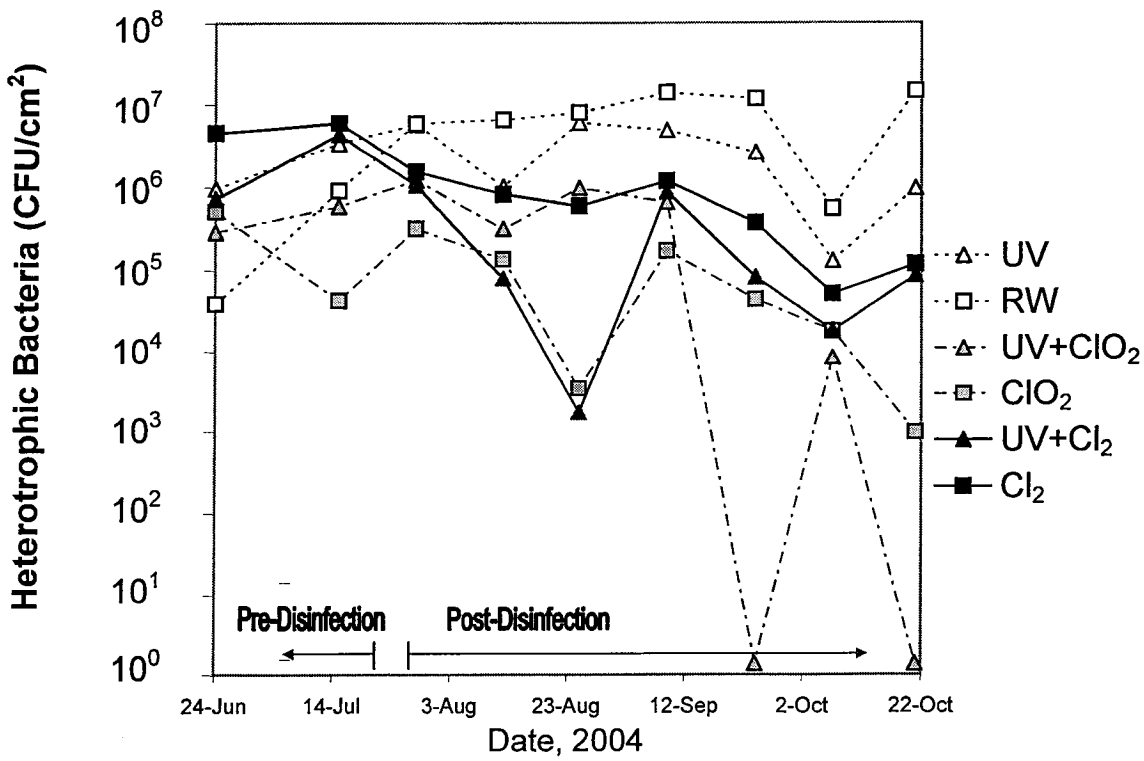

Figure 8.2: Scattered Data from Pardee Reservoir Field Study Comparing Cl_2 and ClO_2 with and without UV Pre-treatment for Removal of Attached HPC Bacteria

In order to fully determine effectiveness of the different disinfection strategies, it is important to compare different water matrices including purified water which would be used in laboratory studies. Dykstra (2002) completed a lab AR study comparing Cl_2, ClO_2 and NH_2Cl with and without pre-treatment with UV light. The experimental design of that project was similar to field studies completed for this thesis, including comparable disinfectant dosages, hydraulic retention times, coupon material, and sampling methods. Results from the Dykstra (2002) study were compared to results from the Pardee, Halifax and PW field studies. It was observed when comparing treatment with Cl_2 alone to treatment with a UV/ Cl_2 combination, each water type had an increased log reduction of suspended HPC bacteria with the combination disinfection (Figure 8.3).

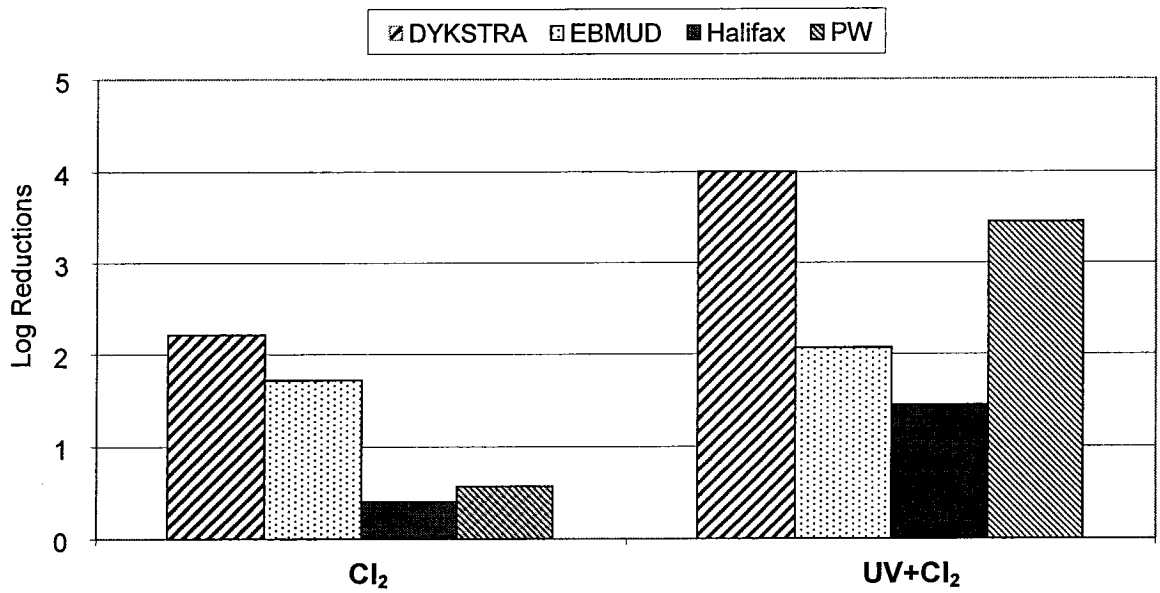

Figure 8.3: Reductions of Suspended HPC Bacteria with Cl_2 or UV/Cl_2 Treatment

Overall, the lab ARs showed greater removal of suspended HPC bacteria. Interestingly the source water for the Dykstra (i.e., Halifax raw water), had the highest reduction overall, which suggests that particles and other material still present in the raw water may have decreased the overall disinfection performance. Particle shielding has been shown to be an important factor for impacting the performance of UV disinfection (Templeton et al., 2005). However, it should also be noted that the lab study carried a slightly higher Cl_2 residual of 0.5 mg/L compared to the field studies at approximately 0.2 mg/L, which would cause slightly higher removals. The cold climate (CC)

groundwater (GW) had the largest increase in removal from treatment with Cl_2 alone to UV/Cl_2 with 2.88-log increase. The average increase of log reduction between Cl_2 and UV/ Cl_2 for all water sources was 1.52-log, which was similar to that lab increase of 1.80-log. Thus the combination treatment enhanced the removal of suspended HPC bacteria regardless of the water source.

A similar trend was observed for attached HPC bacteria, with the exception of CC GW, where removal was lower with UV/ Cl_2 treatment compared to Cl_2 treatment (Figure 8.4). Considering this is the only circumstance where combination treatment achieves significantly lower reduction, (including data yet to be presented), it is assumed that there may have been contamination of the AR or its components during operation. Average increase of removal between Cl_2 treatment and UV/ Cl_2 treatment (excluding PW) was lower with attached HPC bacteria at 0.50-log, which again was comparable to the lab increase of 0.42-log. As with suspended HPC bacteria, the warm climate (WC) SW showed the least amount of change between disinfection strategy including 0.10-log for attached and 0.35-log for suspended. The lab study showed highest removal of biofilm HPC bacteria regardless of treatment, which indicates removal in purified water is more easily achieved compared to lower quality water such as unfiltered surface water.

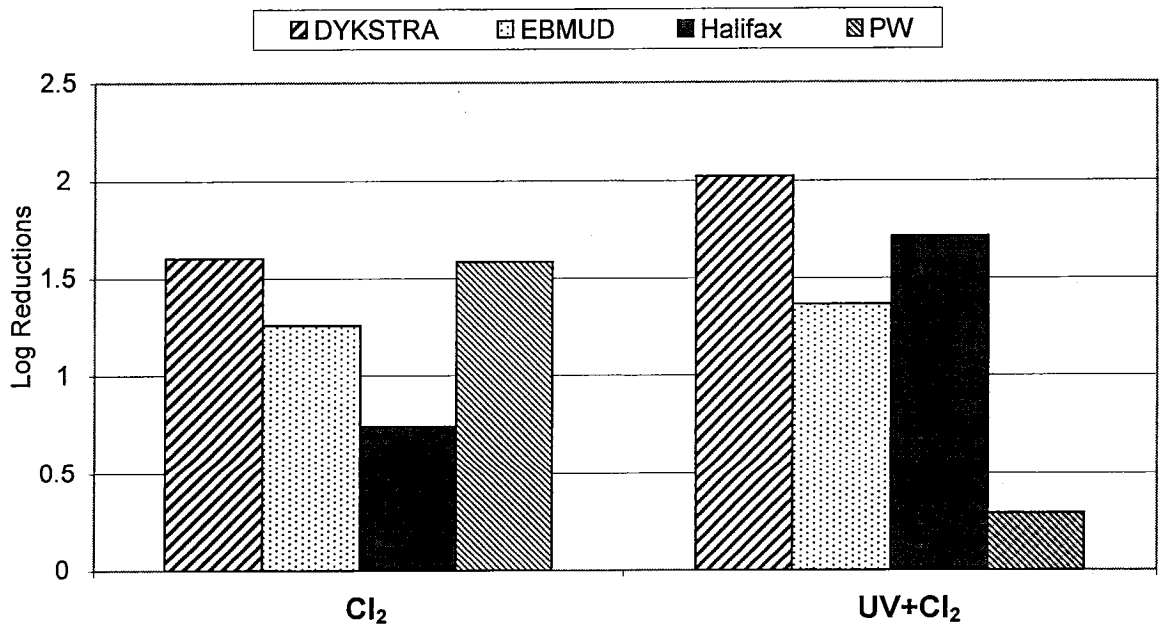

Figure 8.4: Reductions of Attached HPC Bacteria with Cl_2 or UV/Cl_2 Treatment

Data for removal with ClO_2 and ClO_2 with UV light pre-treatment was also compared between the lab study, the Pardee study and the Halifax study. It was found that similarly to chlorine treatment, removal increased when ClO_2 was combined with UV pre-treatment (Figure 8.5). Each water source showed improved reduction of suspended HPC bacteria with combination treatment, and lab water had the greatest improvement between ClO_2 and UV + ClO_2 treatments at 2.34-log difference. Interestingly, the WC SW showed equal or greater removal of suspended HPC bacteria than the lab water, indicating ClO_2 is a strong oxidant even in water with poorer quality, such as increased TOC and turbidity.

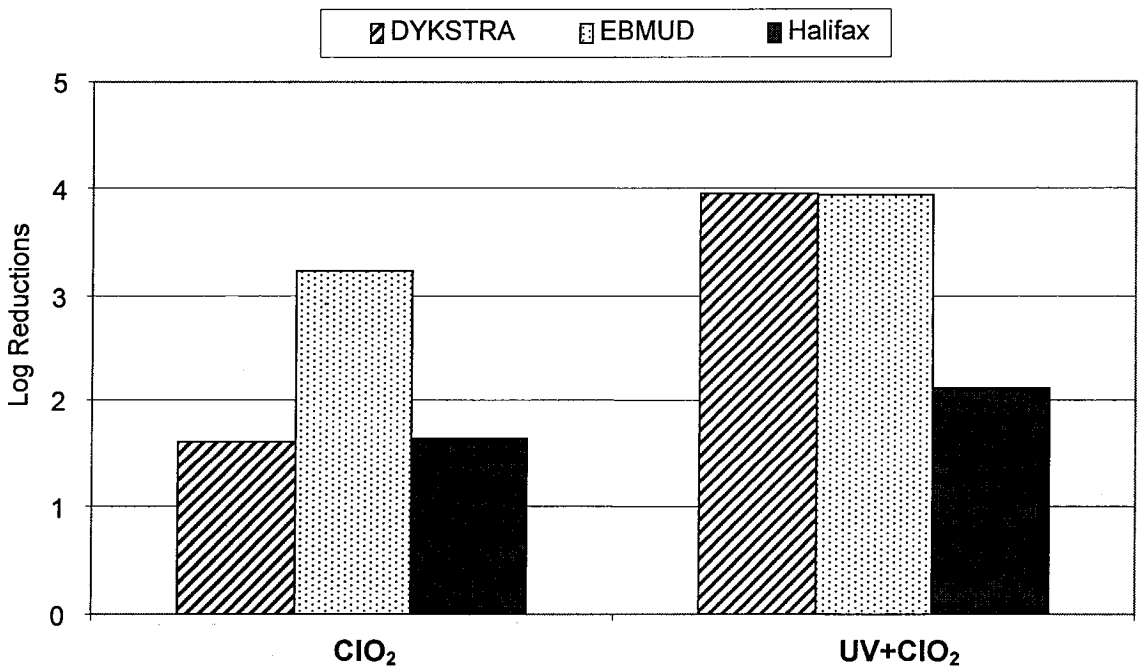

Figure 8.5: Reductions of Suspended HPC Bacteria with ClO_2 or UV/ClO_2 Treatment

Although overall removal was slightly lower than suspended HPC bacteria, the trend of enhanced removal with combination UV/ ClO_2 disinfection held true for attached HPC bacteria (Figure 8.6). It was found that each water source showed approximately 1-log improvement in removal with combination disinfection compared to treatment with ClO_2 alone. In addition, higher removal was achieved in the WC SW than control water, and the CC SW had similar or higher removal compared to lab water for ClO_2 with and

without UV pre-treatment. This is an important finding confirming ClO_2 as a strong disinfectant and that removal of biofilm HPC bacteria is enhanced by 1-log when ClO_2 follows UV treatment regardless of water quality.

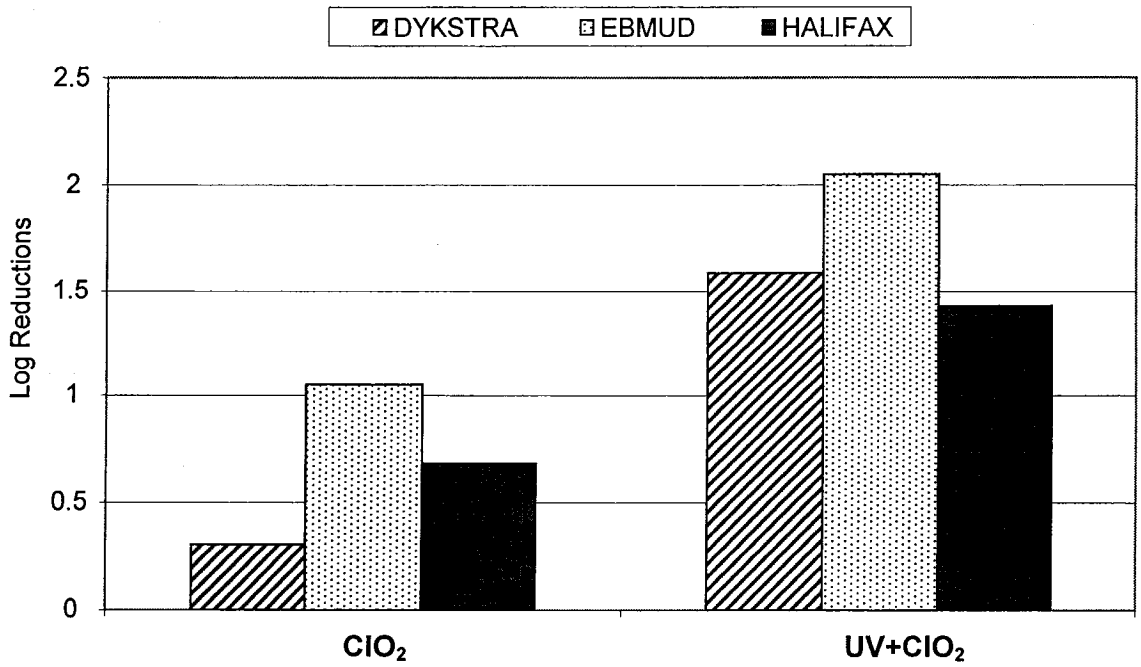

Figure 8.6: Reductions of Attached HPC Bacteria with ClO_2 or UV/ClO_2 Treatment

Only one field study in this thesis, Port Williams, considered monochloramine with UV light pre-treatment. Although there is some indication of enhanced removal of suspended HPC bacteria with the combination UV/NH_2Cl treatment compared to NH_2Cl alone, the trend was not as evident as with Cl_2 and ClO_2 treatments in other studies. In the CC GW, NH2Cl alone achieved very little reduction compared to the UV/ NH_2Cl combination treatment. However, in the lab study removals were similar with both treatments. The opposite occurred with attached HPC bacteria (Figure 8.8), where removal in the PW field study was similar between NH_2Cl and UV/ NH_2Cl treatments, but there was an enhanced removal when lab water was pre-treated with UV light by approximately 1-log. These findings indicate that the combination of UV and NH_2Cl achieves similar or greater removal than NH_2Cl alone regardless of water quality.

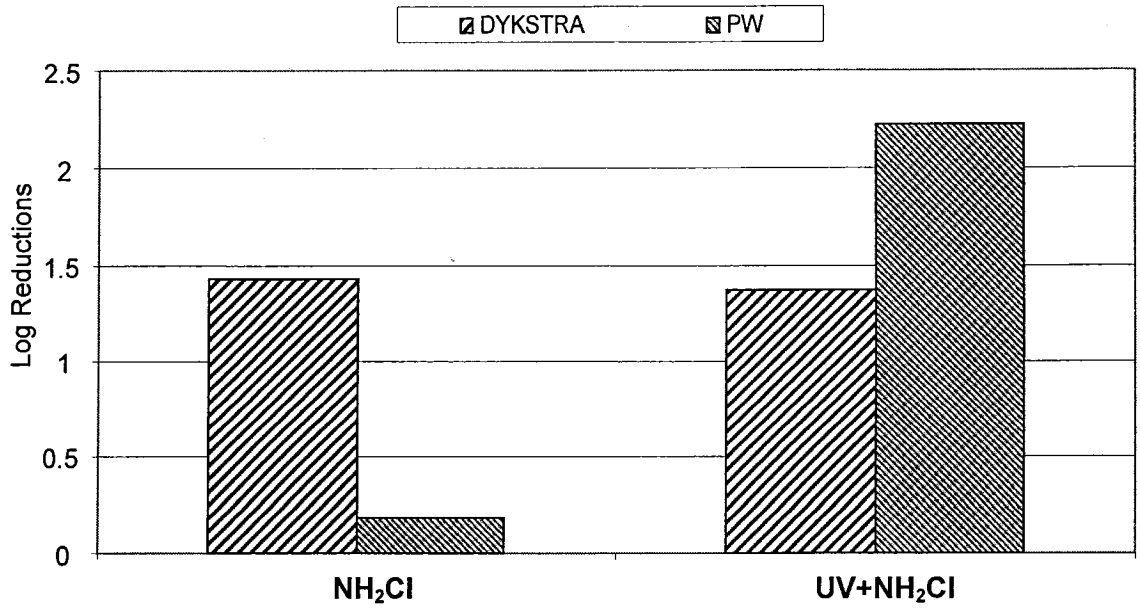

Figure 8.7: Reductions of Suspended HPC Bacteria with NH_2Cl or UV/NH_2Cl Treatment

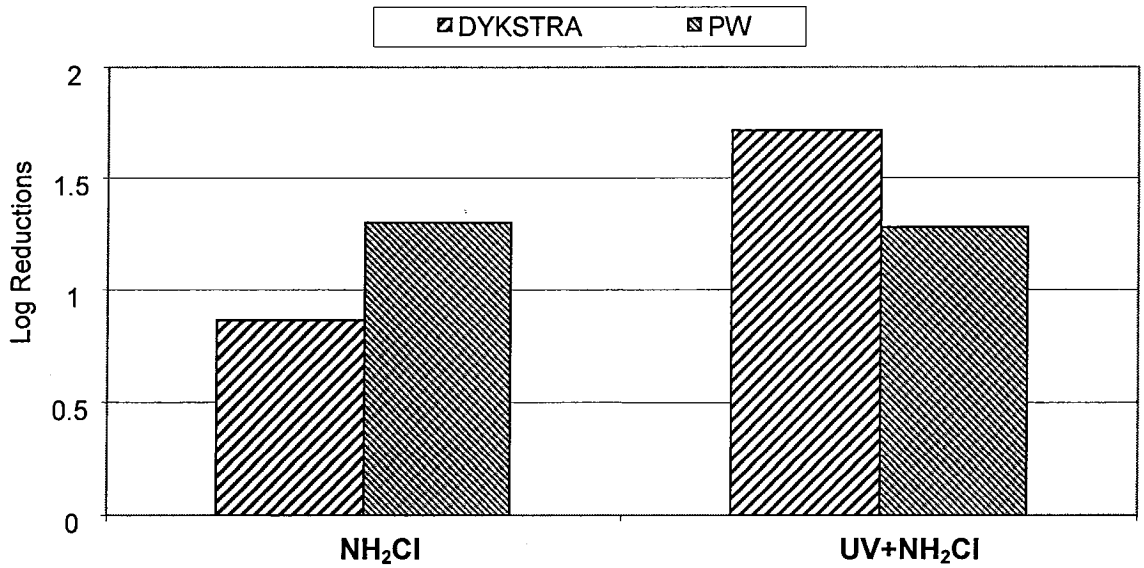

Figure 8.8: Reductions of Attached HPC Bacteria with NH_2Cl or UV/NH_2Cl Treatment

8.2 IMPACT OF POINT OF APPLICATION

The Pinellas County field study investigated treatment of a warm climate blended water source with Cl_2 or NH_2Cl alone or in combination with secondary UV disinfection. Chapter 7 of this thesis showed that unlike other field studies where there was enhanced removal observed with combination disinfection, UV light following chlorine-based disinfection generally resulted in higher HPC bacteria concentrations. Results from this study were compared to results from the Port Williams study which compared Cl_2 and NH_2Cl with and without UV light pre-treatment. The Pinellas County study had no acclimation and therefore only data from the disinfection stage of the Port Williams study was analyzed for the comparison.

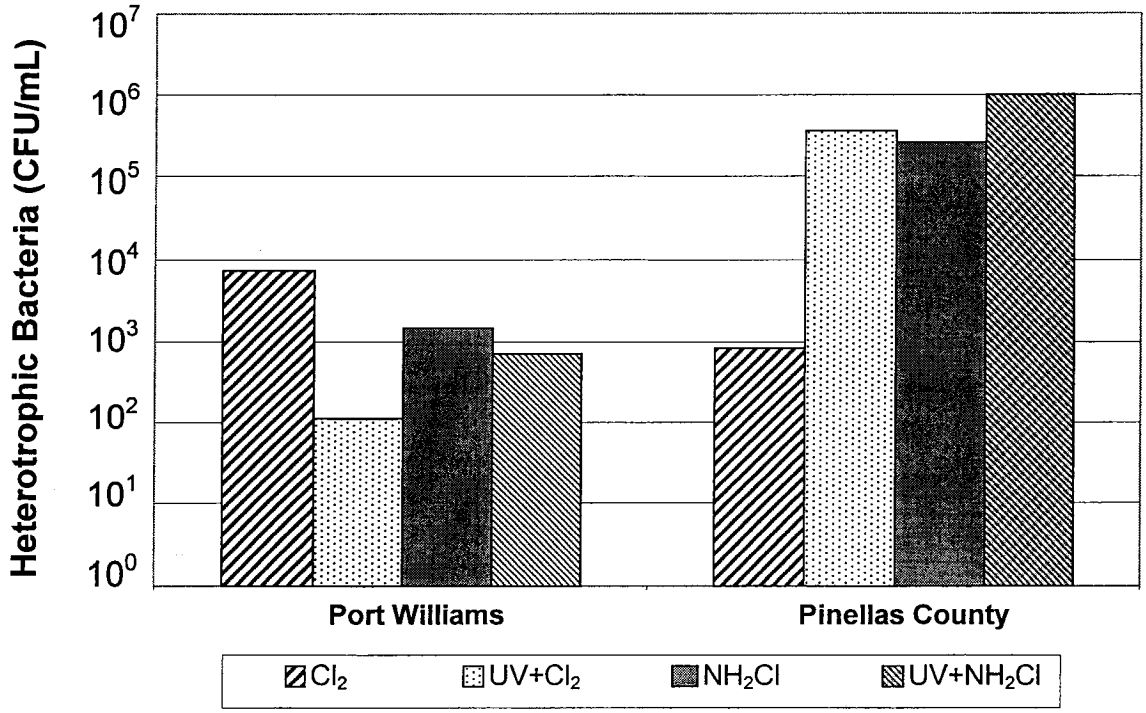

Figure 8.9: Average Suspended HPC Bacteria for Port Williams and Pinellas County Studies during Disinfection Stages

It can be observed from Figure 8.9 that average suspended HPC counts are lower in ARs receiving UV-treated water for the Port Williams study, but that the opposite occurs in the Pinellas County study. In addition, chlorine is more effective against the suspended HPC bacteria in the Pinellas County Study but NH_2Cl shows lower counts in the Port Williams study. However, it must be noted that no acclimation period has been

considered for the PW data, and a more conclusive analysis would show log reductions rather than average counts since counts during acclimation differed between ARs.

The Pinellas County study also had higher attached HPC bacteria in ARs treated with UV light compared to ARs with no secondary UV disinfection. This was similar to PW results with primary UV disinfection, however as previously mentioned, data does not reflect acclimation counts and it has been demonstrated that NH_2Cl and UV + NH_2Cl treatments achieved similar log reductions in Port Williams. In addition, the UV + Cl_2 AR was the only circumstance where UV pre-treatment resulted in significantly higher counts and therefore data may not be reliable.

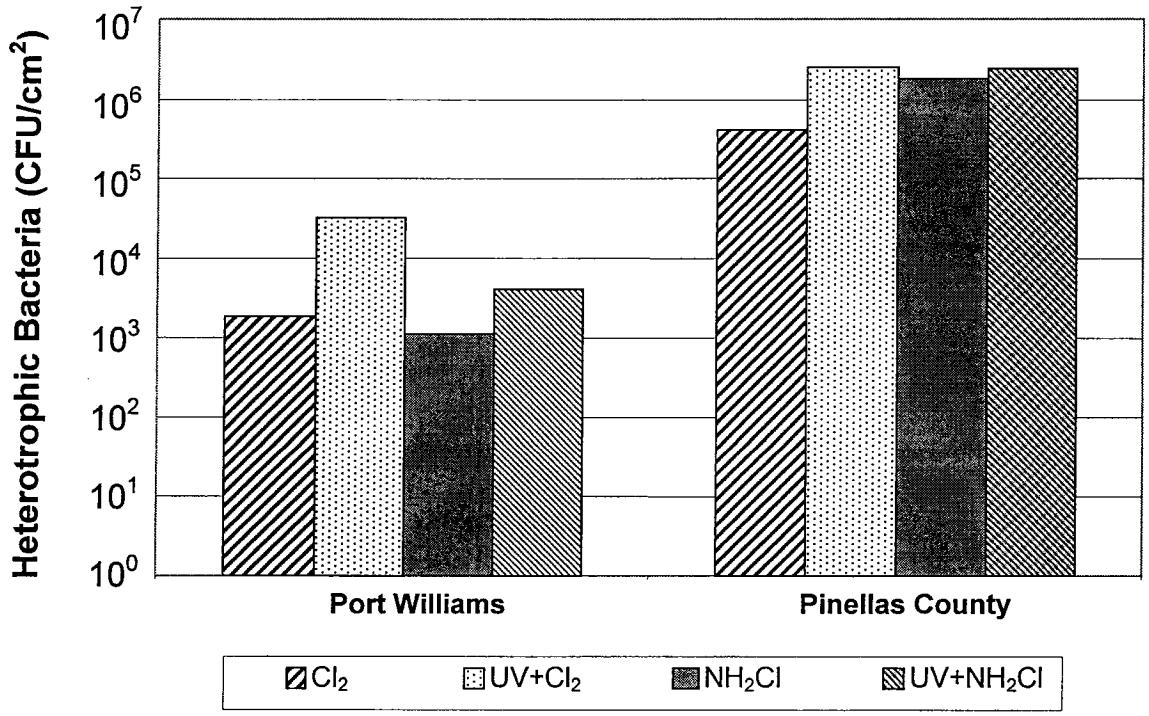

Figure 8.10: Average Attached HPC Bacteria for Port Williams and Pinellas County Studies during Disinfection Stages

Considering the consistent increase in HPC bacteria concentration in ARs treated with UV light following chemical disinfection compared to enhanced removal with UV treatment prior to chlorine-based disinfection, it was determined that point of application for UV light is important in the treatment process. To further investigate this, a laboratory study was conducted to determine the effect of UV treatment on disinfectant residual in varying water matrices including the Pinellas County blended water, surface

water and purified laboratory water. As previously described in Chapter 7, chlorine and chlorine dioxide were significantly reduced in the presence of UV light, and higher reductions were seen in surface water and blended water compared to Milli-Q water. Monochloramine residual was not as affected by UV treatment as Cl_2 and ClO_2, and water source had no impact on the reduction of NH_2Cl. This indicates that NH_2Cl is more stable compared to Cl_2 or ClO_2 in the presence of UV light, which is consistent with Ormeci et al. (2005) findings. This also corresponds with the Pinellas County data. The log difference in average suspended HPC bacteria between UV + NH_2Cl and NH_2Cl was 0.59-log, but the difference between UV + Cl_2 and Cl_2 was much higher at 2.64-log. This trend held true for biofilm bacteria where difference between NH_2Cl treatments was only 0.11-log but 0.78-log difference between Cl_2 ARs. It can be concluded that chlorine residual was more significantly affected by UV light than NH_2Cl which resulted in higher counts in the Cl_2 AR treated with UV light compared to the AR treated with Cl_2 alone. Therefore, in relation to water treatment, secondary disinfection with UV light would degrade Cl_2 and ClO_2 residual and possibly lead to increased counts in the distribution system, especially in poorer quality water, and NH_2Cl would remain more stable but there would also be some degradation of residual regardless of water quality. If instead UV light was used as a primary disinfectant, enhanced removal with Cl_2, ClO_2 or NH_2Cl secondary treatment would potentially be observed.

8.3 ASSESSING SYNERGY FOR WATER DISTRIBUTION SYSTEMS

It has been established in various field and lab studies described in this thesis that combining UV light primary disinfection and secondary chlorine-based disinfection provides an enhanced strategy for the removal of suspended and attached HPC bacteria. However, the field studies described differed from the laboratory *E. coli* removal study in that the lab study consisted of a single-species system in a batch-test set-up, therefore biofilm and varying water matrices were not considered. For this instantaneous type of disinfection, a simple synergy calculation such as the one presented by Koivunen et al. (2005) is applicable. For the *E. coli* removal study, combination disinfection strategies achieved higher log inactivation by anywhere from 4-log up 7-log than either UV or

chemical disinfection alone. Applying the Koivunen et al. (2005) equation showed that synergistic effects were most likely responsible for this observed enhanced removal, and statistical analysis indicated that combination treatments differed significantly from treatment with UV or chlorine-based disinfection alone. Cells that may have otherwise repaired themselves after UV treatment and flourished in a distribution system were instead eliminated by immediate secondary chlorine-based disinfection. As Koivunen et al. (2005) suggests, repair mechanisms following two disinfection steps are most likely overloaded and cells are unable to repair. This phenomenon would be consistent with the Pardee field study where total cells did not decease but viable cells did, especially in water pre-treated with UV light.

Insightful as the Koivunen et al. (2005) approach is, it is difficult to apply such a simple equation to a long-term field study investigating a multi-species system in a simulated distribution system that supports biofilm growth. A substantial percentage of bacteria in bulk water can be attributed to sloughing of biofilm bacteria. In this case, treatment of suspended bacteria is dependent upon residual disinfection only, and primary treatment with UV light at the head of the distribution system would be expected to have an initial impact but perhaps a reduced role in systems with long water age. In full-scale systems, biofilm growth is not only dependent on amount of bacteria present but also on system operation (i.e., flushing, pipe material, dead zones), and biofilm growth potential of the treated water (i.e., TOC, BDOC). In these early stages of synergy research it is difficult to determine which of the limiting factors are most critical. However, it can be concluded that any synergistic effects between primary and secondary disinfection would reduce the amount of viable bacteria entering the distribution system, leading to limitation of biofilm formation and bacterial regrowth in the larger mains or areas with constant flow.

In comparing field and laboratory studies it was evident that variable water quality at the source plays a significant role in integrated disinfection systems. In comparison, data collected from the Pardee reservoir (Chapter 5) to laboratory data reported by either Dykstra et al. (2006) or Gagnon et al. (2005) (Figure 8.1), shows that the impact of disinfection is much clearer under laboratory conditions. Furthermore,

"steady-state" is rarely reached under field conditions. Nevertheless the overall benefits of combining UV-with ClO_2 or Cl_2 was consistently observed at all sites.

There are two possible mechanisms that potentially provide a basis for understanding why the combination of UV with ClO_2 or Cl_2 is enhanced: 1) selective disinfection and 2) disinfection synergy. There are several ways in which two disinfectants could act synergistically in removing HPC bacteria in addition to the multiple damage theory presented by Koivunen et al. (2005). For instance, UV has been shown to reduce TOC content in water (Corin et al., 1996), which would result in less demand exerted on the secondary disinfectant allowing for increased HPC bacteria removal. Selective disinfection can generally be described as one disinfectant targeting a susceptible organism while a second disinfectant would target a different susceptible organism. A combination of the two disinfectants would then allow for a broader range of organisms targeted and inactivated, resulting in a greater overall reduction. However, selective disinfection with combined treatments could only result in the additive removal of each disinfectant. In contrast, the combined inactivation observed through synergistic disinfection would result in an overall removal that is greater than the summation of the two individual disinfectants (i.e., greater inactivation than selective disinfection). On the basis inactivation level, the data from the lab study and three field studies generally demonstrated that a synergistic disinfection pathway was the predominant mechanism between UV and chlorine-based disinfectants.

8.4 SUMMARY OF CHAPTER

Through analysis of disinfectants in combination, it was found that although water matrix changes the effectiveness of disinfectants, the enhanced removal with disinfectants in combination was consistent. In fact, the UV/ClO_2 combination achieved higher removal of attached HPC bacteria by 1-log compared to ClO_2 alone for three different water sources. It was also shown that point of application plays a key role for enhanced removal, and UV as a primary disinfectant can improve reduction when followed by chlorine-based disinfectants, however may degrade residual when used as a secondary disinfectant which would lead to higher HPC bacteria counts. Finally, results

from each of the studies presented in this thesis lead to the conclusion that sequential inactivation of heterotrophic bacteria with UV light and secondary chlorine-based disinfectants shows synergistic effects, which could lead utilities to reach higher removal, even with lower CTs.

9.0 SUMMARY AND CONCLUSIONS

9.1 SUMMARY

The overall goal of this project was to investigate integrated disinfection strategies to compare effectiveness against microbial regrowth in drinking water distribution systems. The studies looked at ultraviolet light, chlorine, chlorine dioxide and monochloramine as primary and/or secondary disinfectants, and considered the potential for synergistic benefits when UV light is coupled with chlorine-based disinfectants. The bench-scale and field experiments were designed to consider the following research questions:

- Are there synergistic effects between UV light and chlorine-based disinfectants that enhance control of microbial regrowth in drinking water distribution systems?

- How do various disinfectant strategies compare in controlling biofilm formation in distribution systems and inactivating *Escherichia coli* in bulk water?

- What effect does water matrix (i.e. climate, water quality) have on disinfection capacity?

- How does point of application impact efficacy of UV light in treatment of drinking water?

Previous studies have indicated that synergy may exist between disinfectants in treating water and wastewater, and the first phase of this project involved investigating synergy between UV light and chlorine based disinfectants in a controlled laboratory experiment. The study looked at the common pathogen *Escherichia coli* spiked in de-ionized source water being treated with UV light and chlorine, chlorine dioxide or monochloramine in series or in parallel. In this study UV light was utilized as a primary

disinfectant and only batch-test experiments were performed. Results showed that synergistic effects did appear to enhance removal of *E. coli* in bulk water samples.

The next phase of the overall project was to determine if synergy observed in laboratory studies would be present in the field. Four separate studies were set up in various field locations including a surface water study in a warm climate, a surface water study in a cool climate, a groundwater study in a cool climate, and finally a blended water source in a warm climate. The experiments were based on long-term effects of various disinfection strategies. At each location, annular reactors (ARs) were used as model distribution system simulators. The ARs contained coupons that promote biofilm growth and can be removed for sampling, and therefore samples were obtained for suspended and attached heterotrophic bacteria.

The first experiment was a 16-week study carried out at the Pardee Reservoir in California where a 90-mile aqueduct transports surface water from the source to various treatment facilities. The second experiment included duplicate and identical studies in Halifax, Nova Scotia and simulated the distribution system for the city. Both surface water studies compared chlorine and chlorine dioxide with and without pre-treatment with UV light. The third study was carried out in Port Williams, Nova Scotia where a small community has a chlorinated groundwater source. This experiment compared chlorine and monochloramine with and without UV light as a primary disinfectant.

The final study was a 4-month run of ARs in Pinellas County, Florida. The Keller Water Treatment Plant receives water from three sources including groundwater, surface water and desalinated water. Two water streams of the blended water enter the plant pre-treated with either chlorine or monochloramine. The experiment compared the effectiveness of these two disinfectants alone or in series with UV light as a secondary disinfectant.

The third phase of the project was designed based on results observed in the Florida study to consider interactions between UV light and chlorine-based disinfectants in a controlled laboratory setting. The experiment looked at the potential for degradation of chemicals in the presence of UV light and their absorbance of UV irradiation.

Combining results from these experiments gave insight into the effects of various disinfection strategies on heterotrophic bacteria in biofilm and in bulk water samples.

The project considered UV light as a primary or secondary disinfectant and the effect it may have on microbial regrowth and chemical residual in distribution systems. In addition, synergistic benefits were assessed for drinking water distribution systems

9.2 CONCLUSIONS

Obtaining results from each study allowed for various conclusions to be reached regarding integrated disinfection strategies in drinking water treatment. The first phase of the project considered synergy between UV light and chlorine-based disinfectants in a single-species controlled laboratory setting. It was found that synergistic effects between disinfectants in combination enhanced the removal of *E. coli* when compared to the disinfectants acting alone. UV in combination with chlorine, monochloramine and chlorine dioxide at high CT values eliminated all *E. coli* in the spiked water which corresponded to a reduction of 8.25-log and showed highest inactivation compared to disinfectant acting alone at both low and high CTs. Results were consistent with other studies that have shown synergistic benefits in disinfection. Koivunen et al. (2005) showed synergy in reducing enteric bacteria with a peracetic acid/UV light combination, and suggested synergy was a multiple damage mechanism. Li et al. (2001) also observed multiple damage mechanisms and found that pre-conditioning of the cyst wall with one oxidant allowed for easier penetration and increased damage by a second oxidant. Synergy observed in the *E. coli* study presented could be explained by this occurrence, where UV light attacks the DNA of the cells and the chlorine-based disinfectants affect the cell walls. These damages in series overloaded the repair mechanisms of the cells which therefore lead to their death. With the disinfectant acting alone, the damage caused would have been less significant from one source, and therefore more susceptible to repair. Phenotyping of *E. coli* cells in the lab study showed no variation in cells surviving treatment compared to spiked cells, and therefore mechanisms of synergistic inactivation at the molecular level were not conclusively determined.

Results from this lab study are also consistent with findings of Dykstra (2002), who observed synergy between UV and chlorine as well as chlorine dioxide in reducing heterotrophic bacteria using ARs in a controlled laboratory setting. The second objective

of the project was to test the theory of synergy outside of a controlled setting over a longer term. Four studies employed ARs in the field to compare disinfection strategies for surface water, groundwater and blended water. It was found in the surface water studies that combination disinfection strategies achieved the highest log removals of attached and suspended heterotrophic bacteria. When calculations for synergy were applied they were positive for attached and suspended bacteria in one study but only attached for a second surface water study. It was found in this study that raw water quality improved over the course of the project, allowing for high log reduction in the UV control AR, which led to a negative calculated synergy result. However, the combination strategies achieved higher log reduction for the suspended bacteria, indicating UV light damages cells to make them more susceptible to secondary disinfection. When comparing data from each field study to the lab study by Dykstra, (2002), it was observed that results were typically more scattered in the field. The changing water quality in field studies made simple synergy analysis less applicable when compared to a controlled laboratory setting. However, it was also observed that although water matrix caused variation in the effectiveness of disinfectants, combination strategies consistently achieved higher inactivation of HPC bacteria in bulk and biofilm samples.

It was determined in the surface water studies that chlorine dioxide was in general more effective then chlorine when acting alone or in combination with UV treatment, indicating it was a stronger oxidant than chlorine. An added benefit with ClO_2 was the observed elimination of TTHMs and HAAs when compared to chlorine. The by-product chlorite was formed in ARs treated with ClO_2, however all DBPs were kept below USEPA MCLs. Pre-treatment with UV light did not lower required chemical dosages however, and therefore similar levels of DBPs were observed in ARs with or without UV pre-treatment.

Considering data from surface water field studies, it can be concluded that the implementation of UV light as a primary disinfectant enhanced removal of attached and suspended heterotrophic bacteria and results indicated that synergy exists between UV light and chlorine and chlorine dioxide. UV was not effective when used as the only disinfectant, and increased counts were observed in the UV ARs of the Halifax study. This occurrence could be accredited to several possibilities, including higher re-growth

potential of NOM as was observed by Parkinson et al., (2003) or fouling in the UV experimental system. These issues would result in higher counts when no residual protection is supplied, which would lead to increased biofilm formation, as was seen in most UV ARs in the studies. However, when chemical disinfection was applied following the acclimation period, the synergistic benefits between UV and the secondary disinfectants decreased viable cells entering the systems and also applied residual which overall was able to reduce suspended and biofilm bacteria.

Biofilm counts were very high and increased over the course of the Port Williams groundwater project in the UV-treated ARs as well, which could also be attributed to fouling of the UV experimental system. The increased biofilm bacteria concentrations during acclimation led to a greater difficulty for disinfectant to achieve reduction during the disinfection stage. The demand for chemical disinfection was extremely low in Port Williams, especially in the AR with no UV pre-treatment, and therefore doses were also low. Synergy calculations were less applicable because of the high negative log reduction observed in the UV control AR. All calculated synergy results were positive however the combination ARs had lower removals for attached bacteria. Therefore, synergy was only true for suspended bacteria where the combination ARs had the highest removal compared to ARs treated with only one disinfectant. The UV + Cl_2 AR had the highest removal of suspended bacteria and in general chlorine was more effective against HPC bacteria than monochloramine. Port Williams water had very low turbidity but had consistent nitrate concentrations. Nitrate levels were always below regulated limits and were not affected by disinfection strategy, indicating that nitrification did not occur with monochloramine treatment. As a general conclusion, implementing UV light as a primary disinfectant offers potential to enhance suspended bacterial removal. There were indications that synergistic effects occur between UV light and chlorine and monochloramine, but UV alone was not effective and did not lower the required dosages of the chemical disinfectants when used in combination.

Although synergy was indicated in three field studies where UV was used as a primary disinfectant, increased heterotrophic bacteria counts were observed in a fourth field study when UV light was implemented as a secondary disinfectant. In the Florida study, when UV light followed disinfection with chlorine or monochloramine, suspended

and attached HPC bacteria generally increased compared to treatment with chemical disinfection alone. This contradicted findings from Dykstra (2002) that concluded pre-chlorination followed by UV disinfection improved microbial control and inhibited organic material deposits on the quartz tube of the lamp itself. However, this study also recommended the use of secondary disinfection with Cl_2 and did not consider by-product formation.

It was observed in the Florida field study that residual concentrations were reduced in ARs treated with UV light post-chemical disinfection and it was hypothesized that UV light degraded chlorine and monochloramine. An increase in suspended bacteria in the influent of the UV and Cl_2 AR directly corresponded to a drop in Cl_2 residual below detection limits, most likely due to increased demand and degradation of Cl_2 by UV light. An Ormeci et al. (2005) study found chlorine and monochloramine decayed at several different dosages of UV irradiation. It is believed that in the Florida study UV irradiation caused the photolysis of chlorine and monochloramine. Nowell and Hoigne (1992) found that the photolysis of Cl_2 in sunlight occurred with a half life of 12 minutes and suggested UV photo-oxidizes chlorine into the chloride ion. It has been previously established that the photolysis of NH_2Cl by UV produces nitrate, and higher nitrate levels were observed in the AR treated with UV and NH_2Cl compared to the NH_2Cl AR. Degradation of chemical concentration was confirmed in a controlled laboratory where it was found that chlorine, monochloramine and chlorine dioxide decreased up to 66% with exposure to UV light compared to controls, especially in poorer quality water.

In addition to degradation of disinfectant residual, it is possible that treatment with UV light increased bacterial regrowth potential for NOM, which was observed by Parkinson et al. (2003) and also reduced HOCl to produce –OH radicals that reacted with NOM in water resulting in biodegradable organic matter. BOM would act as a nutrient source for bacteria in the distribution system. This could indirectly explain the occurrence of nitrification in the AR treated with NH_2Cl and UV light while no nitrification occurred in the NH_2Cl AR.

Considering all observations from the various studies, it is concluded that the sequential inactivation of heterotrophic bacteria with UV light and secondary chlorine-based disinfectants shows synergistic benefits. Although calculated synergy was not

consistently seen in field studies, changing water quality and potential fouling in UV experimental systems made simple synergy analysis less applicable. In addition, the synergy equation utilized by this thesis does not take into consideration factors influencing biofilm formation other than disinfection, such as temperature, DOC, NOM, and others. In the controlled laboratory setting, synergistic effects were clearly observed for the inactivation of *E. coli*. In comparing disinfection strategies in field studies, combination treatments with UV as a primary disinfectant generally achieved highest log removals, and chlorine dioxide was the most effective disinfectant followed by chlorine and finally monochloramine. UV alone was not effective against heterotrophic bacteria and possibly increased bacterial regrowth potential in the ARs which let to increased HPC bacteria without secondary residual disinfection. Enhanced reduction with UV light in combination with secondary chlorine-based disinfection was observed in all water types regardless of quality or climate. Finally, it was observed that UV treatment as a secondary disinfectant promoted microbial regrowth and nitrification in chloraminated systems most likely because it degraded residual concentration and indirectly provided increased nutrient sources for heterotrophic and ammonia-oxidizing bacteria.

10.0 RECOMMENDATIONS

10.1 PRIMARY DISINFECTION WITH UV LIGHT

It is recommended that implementing UV light as a primary disinfectant with chlorine-based secondary disinfection could enhance removal of HPC bacteria entering a distribution system due to synergistic effects and the previously established added benefit of a wider range of bacteria inactivated (i.e. chlorine-resistant pathogens such as *Cryptosporidium parvum*). Utilities would be able to benefit from high reductions in HPC bacteria and resulting lower formation of biofilm in the distribution systems. However, this study does not intend to overlook the need for additional research in the area of synergy to fully establish long-term impacts of synergy on bacterial regrowth in distribution systems enabling utilities to depend on its benefits. There would also be potential for lower CTs required for chlorine-based disinfectants with UV light pre-treatment to achieve higher reductions than chemical disinfectant alone at high CT. However, utilities would not be able to depend on UV pre-treatment to lower required dosages of chlorine-based disinfectant to maintain minimum residual concentrations. It is also recommended that UV light not be used as the primary and only disinfection because bacteria counts actually increased with UV-treated water when no residual protection was supplied.

10.2 SECONDARY DISINFECTION WITH UV LIGHT

It is not recommended to implement UV treatment as a secondary disinfectant following chemical disinfection due to the degradation of chemical residual in the presence of UV light. Although studies have shown that pre-chlorination aids in controlling biological growth on the lamp itself, it is believed that this study shows this benefit is overshadowed by the negative impacts of pre-chemical disinfection. The reduction of residual due to UV treatment leads to increased bacteria counts because there is less available to control microbial regrowth in the distribution system. In addition, UV light has been shown to increase bacterial regrowth potential of NOM, and

with corresponding decreased residual concentration, this potential would be further increased. To combat this problem, utilities would need to additionally treat with chemical disinfection following UV irradiation in order to increase residual protection, which would potentially lead to higher disinfection by-product formation. It is especially not recommended to implement secondary UV disinfection with monochloramine as a primary disinfectant, since it has been observed that nitrification occurred with this disinfection strategy leading to higher nitrate and nitrite concentrations.

10.3 CHLORINE-BASED DISINFECTANTS

It is recommended that in general, pairing secondary disinfection with a chlorine-based disinfectant with UV light as a primary disinfectant produces synergistic effects that enhance mitigation of microbial regrowth in a drinking water distribution system.

It is also recommended that chlorine dioxide is a viable option as an alternative to chlorine. It was able to achieve similar or higher log reductions alone or in combination with UV compared to chlorine without producing the DBPs total trihalomethanes or haloacetic acids. It would be recommended, however, to consider the production of the ClO_2 by-product chlorite, which was observed in field studies under the regulated level.

Results from field studies show that monochloramine was not as effective against heterotrophic bacteria as chlorine. In addition, lab studies showed that NH_2Cl was in general the least effective biocide compared to Cl_2 or ClO_2 and was not able to achieve high log reductions. Although it is an economical alternative to chlorine when TTHMs and HAAs are an issue with utilities, treatment with NH_2Cl may also lead to nitrification and it is recommended that this potential be considered prior to switching over.

10.4 FUTURE RESEARCH NEEDS

Findings presented in this document could potentially generate several future studies that would enhance knowledge of integrated disinfection strategies. Recommendations for future work are featured below.

10.4.1 Synergistic Potential with a UV-Resistant Pathogen

The laboratory study presented in this thesis showed synergistic effects in reducing *Escherichia coli*, which is a pathogen easily reduced by UV light and chemical disinfection. It would be recommended to investigate if synergistic benefits still occur with a pathogen that would not be easily affected by UV light, and to determine if multiple damage mechanisms still enhance removal.

10.4.2 Mechanisms of Synergy at a Molecular Level

Although this thesis and other studies have shown that synergy is present with integrated disinfection strategies, none has been able to identify specific reasons for this occurrence. There have been hypotheses as to possible mechanisms of synergy, but it is recommended that an experiment be designed to track changes in cells through various disinfection stages to determine what lead to death. There has been an attempt to track phenotypical changes in this document, however only with live cells in bulk water, which led to no conclusive findings.

10.4.3 Bacterial Regrowth Potential of NOM in the Presence of UV Light

Results from this thesis showed that HPC bacteria levels were sometimes higher in ARs treated with either primary or secondary UV light. It was suspected that without secondary disinfection, bacterial regrowth potential of NOM was increased causing higher counts, as previous studies had found (Parkinson et al., 2003), however this was not investigated during these studies. Results also showed that nitrification occurred with NH_2Cl followed by UV disinfection but not with NH_2Cl treatment alone. It was suspected that UV light indirectly provided a larger nutrient source for bacteria through forming hydroxyl radicals that react with NOM to create BOM. It would be beneficial to investigate these potential explanations for increased HPC bacteria and nitrification in ARs with UV disinfection.

10.4.4 Impact of Pipe Material

Findings in this study showed synergistic effects using ARs to simulate PVC or polycarbonate distribution systems, which would also be similar to concrete-lined pipes. It is recommended that field studies be carried out to determine the impact of cast iron material on synergistic benefits. This material had proven to have much higher demand on chemical disinfectants and introduces varying reactions due to background metals.

10.4.5 Optimum Strategy for Pre-Chlorination

Results from this thesis indicate the pre-treatment with chemical disinfection leads to increased HPC bacteria due to reduction in residual protection and increased BRP. Previous studies have shown pre-chlorination aids in keeping lamps clean and lowers fouling. If utilities did not depend on pre-chlorination to reduce bacteria and used it as a microbial control for the UV system only, there is potential this could enhance overall removal without increasing secondary chemical disinfection and the corresponding DBPs significantly. It is recommended that a study is designed to determine optimal chemical dosages for pre-treatment with chemical disinfection considering the potential benefits and drawbacks.

10.4.6 Alternative Disinfection Dosages

This document presented findings from four field studies with UV and chlorine-based disinfectants. At each site, chemical residuals that were controlled were kept constant and at a minimum allowed concentration. In addition, the synergy study presented data from only two CTs value for each disinfectant. It is recommended that similar synergy studies be carried out at varying CTs for each disinfectant to establish CT inactivation curves and the optimum treatment strategy to achieve synergy between disinfectants.

10.4.7 Long-Term Laboratory Synergy Study

Studies from this thesis took place in the field over months where water quality varied. The controlled laboratory synergy study was a short-term batch test and did not take into consideration biofilm bacteria. It is recommended that a controlled synergy study be carried out in a laboratory over a long period of time taking into consideration the effect of biofilm formation, nitrification, varying controlled organic content, by-product formation, and other possible issues with integrated disinfection.

10.4.8 Alternative Methods to Quantify Synergy

Although the equation presented by Koivunen et al. (2005) provides a straight-forward method in quantifying synergy, application to drinking water treatment for distribution systems may require additional considerations. Bacterial regrowth is dependent not only on disinfection efficacy but also on DOC, pipe material, temperature, and other water quality and operational parameters. It is recommended that a more sophisticated tool for assessing synergy in drinking water treatment should be developed in order to fully understand the impact of synergistic benefits. For instance, a mathematical model could be created where utilities could input critical factors for biological growth in individual systems to determine possibility synergy and the significance of calculated values.

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APPENDIX A:

Surface Water Field Sites Experimental Data

Pardee Suspended HPC Data

	AR HPC Bacteria (CFU/mL)					
Date	**UV**	**RW**	**UV+ClO2**	**ClO2**	**UV+Cl2**	**Cl2**
Acclimation:						
6/24/2004	3.60E+04	6.90E+04	1.05E+05	4.00E+04	1.36E+05	1.43E+05
7/15/2004	8.05E+04	3.35E+04	2.00E+04	2.05E+05	4.64E+04	1.45E+04
Disinfection:						
7/28/2004	8.25E+04	5.05E+04	2.80E+05	2.09E+05	2.43E+05	1.49E+05
8/12/2004	2.43E+04	3.95E+03	1.35E+04	1.00E+00	2.29E+04	5.38E+03
8/25/2004	3.00E+03	3.75E+03	1.00E+00	1.00E+02	1.00E+02	1.25E+02
9/9/2004	3.75E+04	1.28E+04	1.00E+00	5.00E+01	6.75E+02	3.23E+03
9/24/2004	1.27E+03	4.90E+03	1.00E+01	1.25E+02	1.00E+03	6.75E+02
10/7/2004	2.14E+03	5.45E+03	5.00E+00	3.50E+01	1.36E+03	1.67E+03
10/21/2004	1.60E+03	1.50E+03	1.00E+00	1.00E+00	8.40E+02	4.45E+02
10/28/2004	3.02E+04	5.15E+03	5.00E+02	1.06E+03	1.18E+03	2.08E+03

Pardee Attached HPC Data

	AR HPC Bacteria (CFU/cm^2)					
Date	**UV**	**RW**	**UV+ClO2**	**ClO2**	**UV+Cl2**	**Cl2**
Acclimation:						
6/24/2004	9.58E+05	3.89E+04	2.92E+05	5.14E+05	7.31E+05	4.53E+06
7/15/2004	3.39E+06	9.03E+05	5.90E+05	4.24E+04	4.33E+06	5.97E+06
Disinfection:						
7/28/2004	5.76E+06	5.90E+06	1.22E+06	3.19E+05	1.06E+06	1.53E+06
8/12/2004	1.01E+06	6.60E+06	3.19E+05	1.37E+05	7.99E+04	8.25E+05
8/25/2004	6.02E+06	7.99E+06	9.72E+05	3.47E+03	1.74E+03	5.95E+05
9/9/2004	4.86E+06	1.40E+07	6.60E+05	1.74E+05	8.78E+05	1.18E+06
9/24/2004	2.62E+06	1.18E+07	1.39E+00	4.38E+04	8.19E+04	3.72E+05
10/7/2004	1.32E+05	5.56E+05	8.40E+03	1.79E+04	1.82E+04	5.14E+04
10/21/2004	9.65E+05	1.47E+07	1.39E+00	9.72E+02	8.64E+04	1.18E+05
10/28/2004	7.71E+06	1.17E+07	2.57E+05	1.18E+04	1.14E+06	3.26E+05

Pardee:	**SUSPENDED**			**ATTACHED**		
AR	**Acclimation HPC, CFU/mL**	**Post-Dis. HPC, CFU/mL**	**Log Reduction**	**Acclimation HPC, CFU/mL**	**Post-Dis. HPC, CFU/cm^2**	**Log Reduction**
UV Control	5.38E+04	4.95E+03	1.036	1.80E+06	2.05E+06	-0.057
RW Control	4.81E+04	4.63E+03	1.016	1.87E+05	7.08E+06	-1.578
UV + ClO2	4.58E+04	5.41E+00	3.928	4.15E+05	3.72E+03	2.047
ClO2	9.06E+04	5.34E+01	3.230	1.48E+05	1.33E+04	1.047
UV + Cl2	7.95E+04	6.70E+02	2.074	1.78E+06	7.80E+04	1.359
Cl2	4.54E+04	8.65E+02	1.720	5.20E+06	2.83E+05	1.264
Averages:	**6.05E+04**	**1.86E+03**		**1.59E+06**	**1.59E+06**	
STd. Dev.:	1.95E+04	2.30E+03		1.93E+06	2.81E+06	
Std. Error:	7.97E+03	9.37E+02		7.87E+05	1.15E+06	

Pardee Suspended AODC Data

	AR HPC Bacteria (CFU/mL)					
Date	**UV**	**RW**	**UV+ClO2**	**ClO2**	**UV+Cl2**	**Cl2**
Acclimation:						
6/24/2004	7.25E+05	1.71E+06	3.95E+06	8.56E+05	5.06E+05	4.42E+07
7/15/2004	4.89E+05	5.45E+05	6.36E+05	4.37E+05	4.98E+05	7.01E+05
Disinfection:						
7/28/2004	1.82E+05	5.06E+05	4.98E+05	7.18E+05	5.88E+05	3.50E+05
8/12/2004	3.72E+05	9.30E+05	3.98E+05	9.30E+05	1.51E+05	2.12E+05
8/25/2004	2.21E+05	6.23E+05	5.11E+05	6.23E+05	8.22E+05	4.89E+05
9/9/2004	2.12E+05	3.50E+05	7.36E+04	3.50E+05	2.62E+05	1.77E+05
9/24/2004	1.12E+05	1.64E+05	1.08E+05	1.64E+05	1.51E+05	7.79E+04
10/7/2004	2.12E+05	3.76E+05	2.42E+05	3.76E+05	1.19E+05	5.19E+04
10/21/2004	3.03E+05	2.34E+05	2.08E+05	2.34E+05	2.75E+05	1.73E+05
10/28/2004	2.64E+05	2.81E+05	1.08E+05	2.81E+05	1.34E+05	2.21E+05

Pardee Attached AODC Data

	AR HPC Bacteria (CFU/cm^2)					
Date	**UV**	**RW**	**UV+ClO2**	**ClO2**	**UV+Cl2**	**Cl2**
Acclimation:						
6/24/2004	1.80E+06	6.31E+05	3.00E+05	1.89E+06	1.23E+06	8.56E+05
7/15/2004	4.09E+06	1.95E+06	1.86E+06	1.56E+06	2.03E+06	1.44E+06
Disinfection:						
7/28/2004	5.17E+06	3.79E+06	1.86E+06	7.21E+05	1.89E+06	2.24E+06
8/12/2004	7.69E+06	4.39E+06	1.23E+06	1.68E+06	1.46E+06	2.76E+06
8/25/2004	8.41E+06	8.53E+06	2.40E+06	2.82E+06	1.92E+06	2.84E+06
9/9/2004	9.01E+06	4.87E+06	1.38E+06	9.61E+05	1.67E+06	1.58E+06
9/24/2004	6.97E+06	3.76E+06	7.51E+05	8.41E+05	6.61E+05	1.40E+06
10/7/2004	1.02E+07	5.80E+06	7.21E+05	8.11E+05	8.56E+05	1.52E+06
10/21/2004	9.61E+06	1.05E+07	9.31E+05	5.71E+05	5.26E+05	9.46E+05
10/28/2004	9.49E+06	6.10E+06	4.51E+05	3.00E+05	8.41E+05	8.41E+05

Pardee:	**SUSPENDED**			**ATTACHED**		
AR	**Acclimation AODC, CFU/mL**	**Post-Dis. AODC, CFU/mL**	**Log Reduction**	**Acclimation AODC, CFU/mL**	**Post-Dis. AODC, CFU/cm^2**	**Log Reduction**
UV Control	5.38E+04	4.95E+03	1.036	1.80E+06	2.05E+06	-0.057
RW Control	4.81E+04	4.63E+03	1.016	1.87E+05	7.08E+06	-1.578
UV + ClO2	4.58E+04	5.41E+00	3.928	4.15E+05	3.72E+03	2.047
ClO2	9.06E+04	5.34E+01	3.230	1.48E+05	1.33E+04	1.047
UV + Cl2	7.95E+04	6.70E+02	2.074	1.78E+06	7.80E+04	1.359
Cl2	4.54E+04	8.65E+02	1.720	5.20E+06	2.83E+05	1.264
Averages:	**6.05E+04**	**1.86E+03**		**1.59E+06**	**1.59E+06**	
Std. Dev.:	1.95E+04	2.30E+03		1.93E+06	2.81E+06	
Std. Error:	7.97E+03	9.37E+02		7.87E+05	1.15E+06	

Pardee Disinfection Residuals

	Residual, mg/L			
Date	UV + ClO2	ClO2	UV + Cl2	Cl2
22-Jul-04	0.06	0.05	0.04	0.01
23-Jul-04	0.04	0.12	0.04	0.02
26-Jul-04	0.05	0.05	0.09	0.03
27-Jul-04	0.00	0.10	0.09	0.04
28-Jul-04	0.02	0.15	0.15	0.14
2-Aug-04	0.08	0.33	0.26	0.25
4-Aug-04	0.13	0.30	0.30	0.33
5-Aug-04	0.18	0.27	0.18	0.21
6-Aug-04	0.28	0.23	0.23	0.21
9-Aug-04	0.02	0.12	0.20	0.20
10-Aug-04	0.05	0.06	0.13	0.18
11-Aug-04	0.03	0.05	0.11	0.17
12-Aug-04	0.05	0.17	0.12	0.19
13-Aug-04	0.09	0.13	0.12	0.21
16-Aug-04	0.06	0.10	0.14	0.27
17-Aug-04	0.07	0.11	0.13	0.21
18-Aug-04	0.19	0.19	0.19	
19-Aug-04	0.12	0.18	0.20	0.23
20-Aug-04	0.14	0.14	0.24	0.26
23-Aug-04	0.30	0.36	0.23	0.22
27-Aug-04	0.27	0.28	0.23	0.21
2-Sep-04	0.15	0.37	0.14	0.18
3-Sep-04	0.27	0.38		
6-Sep-04	0.24	0.23	0.11	0.10
7-Sep-04	0.37	0.18	0.22	0.24
8-Sep-04	0.44	0.31		
9-Sep-04	0.13	0.27	0.34	0.32
13-Sep-04	0.13	0.23	0.24	0.20
16-Sep-04	0.10	0.07	0.16	0.18
24-Sep-04	0.11	0.06	0.20	0.13
27-Sep-04	0.18	0.07	0.21	0.25
30-Sep-04	0.05	0.05	0.88	0.56
4-Oct-04	0.08	0.08	0.22	0.19
7-Oct-04	0.13	0.10	0.19	0.25
11-Oct-04	0.30	0.31	0.22	0.37
14-Oct-04	0.10	0.05	0.23	0.21
18-Oct-04	0.64	0.39	0.26	0.24
21-Oct-04	0.52	0.40	0.23	0.22
25-Oct-04	0.08	0.35	0.21	0.25
28-Oct-04	0.09	0.32	0.24	0.22

Pardee Disinfection Doses

	Dose, mg/L			
Date	UV + ClO2	ClO2	UV + Cl2	Cl2
22-Jul-04			0.66	0.66
23-Jul-04			0.76	0.76
26-Jul-04			0.70	0.80
27-Jul-04			0.83	0.95
28-Jul-04			0.88	1.00
2-Aug-04			0.83	0.87
4-Aug-04			0.78	0.84
5-Aug-04			0.81	0.84
6-Aug-04			0.81	0.84
9-Aug-04			0.39	0.84
10-Aug-04			0.39	0.84
11-Aug-04			0.39	0.84
12-Aug-04			0.39	0.84
13-Aug-04			0.39	0.88
16-Aug-04			0.76	0.82
17-Aug-04			0.76	0.82
18-Aug-04	1.10	1.30	0.76	0.82
19-Aug-04	0.90	1.20	0.77	0.80
20-Aug-04	0.90	1.20	0.77	0.80
23-Aug-04	1.60	2.10	0.77	0.80
27-Aug-04	1.34	1.27	0.76	0.78
2-Sep-04	0.97			0.53
3-Sep-04				
6-Sep-04		1.53		
7-Sep-04				
8-Sep-04	0.98	1.23	0.54	0.54
9-Sep-04	1.25	1.56	0.72	0.72
13-Sep-04	1.43	1.53	0.59	0.54
16-Sep-04	1.39	1.06	0.53	0.47
24-Sep-04		1.20	0.58	0.47
27-Sep-04	1.44	0.49	0.64	0.58
30-Sep-04			0.70	0.57
4-Oct-04			0.58	0.60
7-Oct-04	1.31	1.25	0.54	0.67
11-Oct-04	1.53	1.62	0.57	0.61
14-Oct-04	1.03	0.12	0.55	0.50
18-Oct-04	2.27	1.73	0.52	0.48
21-Oct-04	2.05	1.74	0.52	0.48
25-Oct-04	1.46	1.59	0.51	0.48
28-Oct-04	2.19	1.59	0.51	0.48

Pardee pH

Date	UV	RW	UV+ClO2	ClO2	UV+Cl2 1	Cl2 1	UV+Cl2 2	Cl2 2	RW Infl	UV Infl
24-Jun-04	8.55	8.55	8.54	8.38	8.48	8.44	8.50	8.27		
15-Jul-04	8.15	8.14	8.14	8.16	8.10	8.11	8.14	8.13	8.2	
28-Jul-04	8.18	8.18	8.12	8.13	8.21	8.21	8.18	8.19	8.24	
12-Aug-04	7.99	7.92	8.03	7.92	8.01	7.93	8.02	7.95	8.16	8.38
6-Sep-04	7.92	8.04	7.84	8.25	7.96	8.16	8.03	8.17	8.18	8.05
13-Sep-04	8.72	8.71	8.7	8.7	8.71	8.73	8.72	8.73	8.76	8.74
27-Sep-04	8.74	8.72	8.75	8.71	8.78	8.74	8.80	8.76	8.76	8.76
11-Oct-04	8.84	8.55	8.83	8.53	8.84	8.60	8.83	8.57	8.87	8.63
25-Oct-04	8.74	8.72	8.72	8.7	8.73	8.76	8.73	8.74	8.77	8.77

Pardee Temperature, degrees Celcius

Date	UV	RW	UV+ClO2	ClO2	UV+Cl2 1	Cl2 1	UV+Cl2 2	Cl2 2	RW Infl	UV Infl
24-Jun-04	23.7	24.0	23.9	24.0	23.5	23.7	23.9	24.3		
15-Jul-04	26.5	26.4	26.5	26.2	26.5	26.4	26.2	26.3	25.9	
28-Jul-04	25.5	25.5	25.4	25.3	25.3	25.2	25.6	25.6	25.7	
12-Aug-04	27.9	28.3	27.7	27.8	28.5	29.6	28.2	28.7	26.1	26.1
6-Sep-04	25.6	26.2	25.8	25.5	25.7	25.8	25.7	26.1	26.2	26.1
13-Sep-04	23.4	23.4	23.3	23.3	23.2	23.5	23.6	23.4	22.9	22.9
27-Sep-04	23.7	23.6	23.5	23.4	23.6	23.7	23.4	23.7	24.2	23.9
11-Oct-04	22.8	22.6	22.4	22.4	22.5	22.5	22.6	22.7	22.9	23.0
25-Oct-04	17.8	17.8	17.9	17.8	17.9	17.9	18	18	18.1	18

Pardee Turbidity, NTU

Date	UV	RW	UV+ClO2	ClO2	UV+Cl2 1	Cl2 1	UV+Cl2 2	Cl2 2	RW Infl	UV Infl
24-Jun-04	0.33	0.40	0.43	0.56	0.36	0.59	0.44	0.43		
15-Jul-04	0.29	0.52	0.35	0.30	0.29	0.27	0.27	0.31	0.39	
28-Jul-04	0.23	3.50	0.28	0.39	0.33	1.53	0.63	0.40	0.42	
12-Aug-04	0.19	0.72	0.33	0.38	0.26	0.65	0.26	0.24	0.42	0.31
6-Sep-04	0.17	1.57	0.23	0.30	0.21	0.34	0.23	0.41	3.16	0.26
13-Sep-04	0.15	0.52	0.28	0.29	0.21	0.34	0.19	1.43	0.85	0.24
27-Sep-04	0.18	1.40	0.33	0.32	0.19	0.89	0.17	0.84	0.39	0.22
11-Oct-04	0.12	1.55	0.25	0.30	0.16	0.36	0.17	0.93	0.24	0.41
25-Oct-04	0.23	1.37	0.30	1.09	0.25	0.51	0.22	0.79	0.62	0.37

Pardee Total Organic Carbon

	TOC, mg/L							
Date	**RW Infl**	**UV Infl**	**UV**	**RW**	**UV+ClO2**	**ClO2**	**UV+Cl2**	**Cl2**
21-Jun			3.46	2.73	3.77	2.89	2.78	3.31
28-Jun			2.99		2.27	2.50	2.43	
12-Jul			1.88	1.76	1.91	1.69	1.84	1.84
26-Jul	1.61	1.57	1.74	1.69	1.97	1.85	1.66	1.72
9-Aug	1.44	1.49	1.70	1.46	1.52	1.79	1.50	1.56
23-Aug		1.52	1.39	1.49	1.83	1.88	1.45	1.48
6-Sep	1.77	1.52	1.94	1.75	1.94	2.23	1.75	1.77
13-Sep	2.02	2.34	1.54	2.00	1.87	2.23	2.03	1.96
27-Sep			1.37	1.63	2.02	2.02	1.71	1.68
11-Oct	1.34	1.30	1.66	1.58	1.61	1.54	1.46	1.33
25-Oct	1.56	1.39	1.76	1.88	1.84	2.01	2.78	1.77

Pardee Dissolved Organic Carbon

	DOC, mg/L							
Date	**RW Infl**	**UV Infl**	**UV**	**RW**	**UV+ClO2**	**ClO2**	**UV+Cl2**	**Cl2**
21-Jun			2.21	3.13	3.79	2.44	2.63	3.40
28-Jun			2.60	2.57	2.39	2.57	2.13	2.46
12-Jul			1.82	1.69	1.75	1.74	1.77	1.79
26-Jul	1.54	1.61	1.67	1.69	1.76	1.80	1.67	1.73
9-Aug	1.48	1.51	1.47		1.52	1.68	1.45	1.51
23-Aug	1.50	1.37	1.42	1.43	1.76	1.81	1.43	1.45
6-Sep	1.90	1.84	1.88	1.81	2.23	1.83	1.52	1.82
13-Sep	1.61	1.98	1.92	2.02	2.54	2.56	1.80	1.92
27-Sep			1.71	1.95	1.58		1.57	1.90
11-Oct	1.37	1.31	1.65	1.67	1.95	1.86	1.47	1.51
25-Oct	1.37	1.35	1.61	1.69	1.86	1.95	1.61	1.82

Pardee Chlorite Data

	Chlorite, mg/L							
	RW Infl	UV Infl	UV	RW	UV+ClO2	ClO2	UV+Cl2	Cl2
28-Jul	0	0	0	0	0.57	0.81	0	0
12-Aug	0	0	0	0	0.62	0.81	0	0
25-Aug	0	0	0	0	0.62	1.04	0	0
9-Sep	0	0	0	0	0.905	0.968	0	0
24-Sep	0	0	0	0	0.65	0.54	0	0
7-Oct	0	0	0	0	0.52	0.44	0	0
21-Oct	0	0	0	0	0.29	0.47	0	0
28-Oct	0	0	0	0	0.412	0.401	0	0

Pardee Chlorate Data

	Chlorate, mg/L							
	RW Infl	UV Infl	UV	RW	UV+ClO2	ClO2	UV+Cl2	Cl2
28-Jul	0	0	0	0		0.053	0.0325	0.0355
12-Aug	0	0	0	0	0.024	0.052	0.016	0.0125
25-Aug	0	0	0	0		0.055		
9-Sep	0	0	0	0	0.023	0.069	0.036	0.0315
24-Sep	0	0	0	0	0.041	0.041	0.0365	0.0335
7-Oct	0	0	0	0	0.035	0.028	0.028	0.033
21-Oct	0	0	0	0	0.098	0.054	0.0385	0.0275
28-Oct	0	0	0	0	0.037	0.049	0.0335	0.026

Pardee Total Trihalomethanes

	TTHMs, µg/L					
Date	UV	RW	UV+ClO2	ClO2	UV+Cl2	Cl2
28-Jul	16.6	16.4	16.2	15.6	19.4	35.45
24-Sep	0	0	0.9	0.9	9.85	4.9
7-Oct	0	0	0	0	6.6	7.75
28-Oct	43.5	19	20.1	10.3	32.05	31.45

Pardee Haloacetic Acids

	HAA, µg/L					
Date	UV	RW	UV+ClO2	ClO2	UV+Cl2	Cl2
28-Jul	0	0	0	2.95	8.125	8.35
12-Aug	0	0	2.15	3.3	4.25	7.3
9-Sep	4.1	3	9.2	10.9	10.85	10.6
24-Sep	0	0	5.5	5.3	6.8	5.725
7-Oct	0	0	4.7	5.4	5.75	6.95
21-Oct	0	0	0	0	0.85	0.55
28-Oct	0	0	2.1	1.5	3.65	3.7

Halifax Suspended HPC Data Run 1

	HPC Bacteria (CFU/mL)							
Date	**UV**	**RW**	**UV + Cl2**	**Cl2**	**UV + ClO2**	**ClO2**	**UV In**	**RW In**
Acclimation:								
19-Apr-05	1.66E+05	8.90E+04	6.20E+04	1.69E+04	8.40E+04	1.04E+04	3.00E+02	2.60E+03
26-Apr-05	8.95E+04	2.45E+04	8.80E+04	7.30E+03	3.25E+04	6.15E+03	9.35E+03	1.29E+03
2-May-05	2.30E+05	5.90E+03	5.30E+04	9.50E+03	4.15E+04	6.00E+03	5.40E+03	5.50E+03
Disinfection:								
4-May-05	2.59E+05	8.75E+03	5.00E+02	1.00E+00	1.50E+03	1.00E+02		
9-May-05	7.30E+04	1.95E+04	2.50E+01	2.50E+01	1.00E+00	1.00E+02	3.95E+03	7.40E+02
11-May-05		8.20E+03	1.00E+01	1.50E+01	1.00E+00	1.00E+00		
16-May-05	3.50E+04	6.55E+03	1.39E+03	2.00E+01	1.00E+00	1.00E+01	2.13E+04	4.55E+03
18-May-05	5.30E+04	5.40E+03	9.25E+02	1.50E+01	1.00E+00	5.00E+00		
23-May-05	5.15E+04	1.10E+04	9.40E+02	2.50E+01	1.00E+00	1.00E+00	1.89E+04	7.40E+03
25-May-05	5.70E+04	5.15E+03	3.00E+02	1.50E+01	1.00E+00	5.00E+00		
1-Jun-05	7.75E+04	3.35E+03		6.65E+02	1.00E+00	1.00E+01	7.00E+04	

Halifax Suspended HPC Data Run 2

	HPC Bacteria (CFU/mL)							
Date	**UV**	**RW**	**UV + Cl2**	**Cl2**	**UV + ClO2**	**ClO2**	**UV In**	**RW In**
Acclimation:								
21-Jun-05	3.65E+04	3.40E+03	1.46E+04	1.28E+04	2.30E+04	1.70E+04	1.92E+04	1.29E+04
28-Jun-05	6.15E+03	1.73E+04	5.40E+03	3.05E+03	1.37E+04	2.60E+03	8.50E+03	6.20E+03
29-Jun-05	3.90E+04	4.80E+03	1.09E+04	6.75E+03	1.31E+04	1.75E+03		
Disinfection:								
4-Jul-05			9.50E+03	2.41E+04	1.85E+03	2.25E+03		
5-Jul-05	8.55E+03	2.05E+03	1.87E+04	8.55E+03	4.85E+02	1.25E+02	1.49E+04	1.01E+04
13-Jul-05			1.65E+03	9.55E+03	2.75E+02	1.00E+01		
14-Jul-05	8.10E+03	1.24E+03	1.51E+03	8.35E+03	5.00E+00	1.00E+01	1.83E+04	4.60E+03
19-Jul-05	2.14E+03	4.25E+02	6.60E+02	1.64E+03	3.00E+01	1.00E+01		
20-Jul-05	3.20E+03	3.50E+02	3.95E+02	1.64E+03	1.00E+00	1.00E+00	2.00E+03	2.15E+03
26-Jul-05	1.33E+03	5.35E+02	3.90E+02	2.60E+03	5.50E+01	1.00E+01	2.65E+03	
27-Jul-05			4.95E+03	2.15E+03	1.00E+00	1.00E+01		

Halifax Attached HPC Data Run 1

	AR HPC Bacteria (CFU/cm^2)					
Date	**UV**	**RW**	**UV + Cl2**	**Cl2**	**UV + ClO2**	**ClO2**
Acclimation:						
19-Apr-05	1.62E+05	2.03E+04	1.78E+05	1.70E+04	1.21E+05	1.09E+04
26-Apr-05	1.65E+05	1.57E+04	1.95E+05	5.92E+03	1.36E+05	7.28E+03
2-May-05	6.74E+04		2.86E+05	1.09E+04	1.42E+05	8.91E+03
Disinfection:						
4-May-05	1.33E+05	8.85E+04				
9-May-05	1.51E+05	5.90E+04				
16-May-05	1.25E+05	5.85E+04	1.50E+03	1.00E+00	2.50E+03	1.00E+00
18-May-05	8.00E+05	2.45E+05	1.05E+03	1.16E+04	1.50E+02	5.00E+01
23-May-05	4.00E+04	7.10E+04	1.30E+03	3.55E+02	9.50E+01	1.00E+00
25-May-05	9.35E+04	5.20E+04	4.35E+02	1.80E+02	7.80E+02	5.00E+00
1-Jun-05	7.35E+05	6.55E+04	2.17E+03	2.50E+02		1.00E+00

Halifax Attached HPC Data Run 2

	AR HPC Bacteria (CFU/cm^2)					
Date	**UV**	**RW**	**UV + Cl2**	**Cl2**	**UV + ClO2**	**ClO2**
Acclimation:						
21-Jun-05	7.45E+04	3.20E+04	1.69E+04	2.08E+04	2.29E+04	1.18E+04
28-Jun-05	5.25E+04	4.10E+04	1.62E+04	1.73E+04	2.16E+04	7.60E+03
29-Jun-05	7.00E+04	5.10E+04	4.20E+04	5.70E+04	8.75E+04	6.75E+03
Disinfection:						
4-Jul-05			2.95E+03	8.55E+03		
5-Jul-05	1.64E+04	9.60E+03	5.45E+03	8.00E+03		
13-Jul-05			4.50E+03	2.73E+03	6.40E+03	1.62E+03
14-Jul-05	1.29E+05	1.31E+04	6.75E+03	1.19E+04	3.45E+03	7.55E+02
19-Jul-05			1.11E+03	3.05E+03	2.70E+03	4.30E+02
20-Jul-05	2.10E+04	1.94E+04	1.50E+03	2.40E+03	1.05E+03	2.00E+02
26-Jul-05	1.87E+04	1.89E+04	1.24E+03	1.33E+03	1.17E+04	1.74E+04
27-Jul-05	1.00E+00	1.00E+00	1.48E+03	4.05E+02	3.80E+03	5.50E+01

Average:	SUSPENDED			ATTACHED		
AR	Acclimation HPC, CFU/mL	Post-Dis. HPC, CFU/mL	Log Reduction	Acclimation HPC, CFU/mL	Post-Dis. HPC, CFU/cm^2	Log Reduction
UV Control	1.51E+05	6.97E+04	0.335	1.22E+05	1.77E+05	-0.164
RW Control	2.34E+04	7.44E+03	0.498	1.79E+04	7.83E+04	-0.642
UV + Cl2	6.61E+04	2.40E+02	2.441	2.15E+05	2.90E+03	1.870
Cl2	1.05E+04	2.02E+01	2.717	1.03E+04	8.47E+02	1.085
UV + ClO2	4.84E+04	2.49E+00	4.288	1.33E+05	2.10E+03	1.802
ClO2	7.27E+03	8.41E+00	2.937	8.90E+03	4.56E+01	2.290
Averages:	**5.10E+04**	**1.29E+04**		**8.45E+04**	**4.36E+04**	
STd. Dev.:	5.38E+04	2.80E+04		8.54E+04	7.24E+04	
Std. Error:	2.19E+04	1.14E+04		3.49E+04	2.96E+04	

Halifax Chlorine Measurements:

UV + Cl2: **Cl2:**

	Cl2, mg/L			Cl2, mg/L		
Date	Dose	Residual	Total	Dose	Residual	Total
5-May-05	1.41	0.14		1.48	0.22	
9-May-05	1.76	0.25	0.35	1.48	0.30	0.39
11-May-05	1.70	0.25		1.38	0.21	
16-May-05	1.66	0.19	0.28	1.38	0.26	0.35
18-May-05	1.82	0.22		1.31	0.21	
23-May-05		0.31	0.39		0.32	
25-May-05	1.59	0.26		1.30	0.23	
30-May-05		0.21	0.29		0.19	0.29
1-Jun-05	1.52	0.15		1.27	0.16	
4-Jul-05	1.14	0.02		1.14	0.10	
5-Jul-05	1.58	0.02	0.09	1.43	0.16	0.25
12-Jul-05	1.83	0.01	0.10	1.48	0.20	0.28
13-Jul-05	1.98	0.53		1.48	0.28	
19-Jul-05	1.81	0.38	0.50	1.31	0.20	0.29
20-Jul-05	1.61	0.29		1.31	0.23	

Halifax Chlorine Dioxide Measurements:

UV + ClO2: **ClO2:**

	ClO2, mg/L		ClO2, mg/L	
Date	Dose	Residual	Dose	Residual
5-May-05	1.52	0.19	1.48	0.15
9-May-05	1.84	0.33	1.67	0.27
11-May-05	1.75	0.27	1.41	0.21
16-May-05	1.56	0.18	1.41	0.17
18-May-05	1.62	0.23	1.65	0.24
23-May-05		0.24		0.28
25-May-05	1.63	0.23	1.41	
30-May-05		0.16		0.21
1-Jun-05	1.60	0.16	1.52	0.20
4-Jul-05	1.45	0.04	1.49	0.07
5-Jul-05	1.57	0.08	1.58	0.09
12-Jul-05	1.75	0.06	1.69	0.11
13-Jul-05	1.41	0.19	1.46	0.29
19-Jul-05		0.07		0.11
20-Jul-05	1.56	0.19	1.44	0.22

Halifax Temperature, degrees Celcius

Date	UV In	RW In	UV	RW	UV+Cl2	Cl2	UV+ClO2	ClO2
18-Apr-05			21.4	20.8	21.3	21.3	21.5	21.6
9-May-05	16.8	16.4	18.4	18.3	19.1	18.9	19.6	19.4
16-May-05	17.8	16.9	20.1	20.2	20.9	20.6	20.7	20.8
23-May-05	16.8	16	17.5	17.6	18.1	19.2	17.9	18.1
30-May-05	18	17.7	19.8	19.9	20.7	20.6	20.7	21
1-Jun-05	18.1	17.3	19.6	19.7	20.5	20.6	20.8	21.2
21-Jun-05	20.2	19.7	22.4	22.8	22.9	22.8	22.9	23.1
28-Jun-05	21.2	20.9	22.3	22.5	22.6	22.8	22.9	22.6
5-Jul-05	22.8	22.5	24.3	25.1	24.9	24.3	24.9	25.4
12-Jul-05	22.3	21.6	23.4	23.4	23.4	22.3	22.1	22.6
19-Jul-05	24.8	24.6	24.4	24.6	24.9	24.9	25.3	25.5

Halifax pH

Date	UV In	RW In	UV	RW	UV+Cl2	Cl2	UV+ClO2	ClO2
18-Apr-05			5.02	5.07	4.98	4.95	5.01	5.04
9-May-05	5.07	5.03	5.22	5.16	5.55	5.52	4.63	4.67
16-May-05	5.11	5.01	5.17	5.06	5.41	5.41	4.61	4.67
23-May-05	5.11	5.08	5.08	5.12	5.43		4.68	4.62
30-May-05	4.86	4.82	4.95	4.85	5.25	5.18	4.47	4.48
1-Jun-05	5.01	4.98	5.10	5.03	5.10	5.08	4.86	4.71
21-Jun-05	4.95	5.02	5.15	4.98	5.11	5.05	5.02	5.08
28-Jun-05	4.94	4.96	5.11	5.04	4.96	4.97	4.95	4.94
5-Jul-05	4.98	5.07	5.22	5.09	5.36	5.36	4.65	4.68
12-Jul-05	4.95	4.93	5.07	5.04	5.55	5.23	4.60	4.56
19-Jul-05	5.07	5.05	5.28	5.06	5.59	5.39	4.60	4.69

Halifax Turbidity, NTU

Date	UV In	RW In	UV	RW	UV+Cl2	Cl2	UV+ClO2	ClO2
18-Apr-05			1.82	1.27	0.44	0.48	0.46	0.46
9-May-05	1.12	1.08	0.69	0.97	1.21	0.82	0.83	1.19
16-May-05	1.70	1.16	0.59	1.16	3.30	1.13	1.00	0.79
23-May-05	2.40	2.47	0.54	2.02	1.26	0.97	1.53	1.60
30-May-05	3.47	3.40	0.45	1.17	1.42	0.70	0.59	1.00
1-Jun-05	3.17	0.96	0.42	1.15	2.63	0.41	1.06	0.74
21-Jun-05	1.21	4.29	0.46	1.06	0.60	0.35	0.42	0.45
28-Jun-05	2.27	2.17	0.84	0.86	0.33	0.33	0.36	0.42
5-Jul-05	1.50	1.30	0.40	0.82	0.51	0.51	0.38	0.43
12-Jul-05	0.65	1.59	0.46	0.93	6.27	0.64	0.42	0.43
19-Jul-05	0.62	0.99	0.75	0.70	3.87	0.51	0.43	0.46

Halifax Total Organic Carbon

	TOC, mg/L							
Date	RW Infl	UV Infl	UV	RW	UV+Cl2	Cl2	UV+ClO2	ClO2
18-Apr	3.28	3.13	3.24	3.36	3.39	3.50	3.38	3.35
26-Apr	5.07	5.14	5.08	4.94	7.85	3.71	5.90	8.67
2-May	3.84	3.33	3.25	3.52	4.71	5.12	3.81	4.15
9-May	3.27	3.24	3.36	3.32	3.35	3.29	3.12	3.73
25-May	3.10	3.12	3.18	3.00	3.05	2.96	3.22	3.82
7-Jun	3.37	3.09	3.07	3.13	3.26	3.44	3.17	3.41

Halifax Dissolved Organic Carbon

	DOC, mg/L							
Date	RW Infl	UV Infl	UV	RW	UV+Cl2	Cl2	UV+ClO2	ClO2
26-Apr	6.90	3.67	4.50	3.58	4.98	4.63	5.79	4.65
2-May	3.22	3.27		4.43	4.18	3.87	5.16	3.24
9-May	2.78	3.01	3.10		2.83	2.94	2.98	3.03
25-May	3.02	3.35	3.06	3.25	2.81	2.83	3.33	3.96
7-Jun	3.04	3.06	3.05	3.07	3.02	3.17	3.08	3.41

Halifax Total Trihalomethanes, µg/L

AR	16-May	25-May	30-May
UV Contrc	0.00	0.00	0.00
RW Contr	0.00	0.00	0.00
UV+Cl2	16.81	33.83	25.47
Cl2	13.44	22.28	19.94
UV+ClO2	0.00	0.00	0.00
ClO2	0.00	0.00	0.00

APPENDIX B:

Groundwater Field Sites Experimental Data

Florida Influent Suspended HPC Bacteria

	HPC Bacteria, CFU/mL			
Date	NH2Cl	UV+NH2Cl	Cl2	UV+Cl2
18-Apr-05	1.35E+05	4.15E+04	7.00E+01	1.00E+00
25-Apr-05	2.49E+06	5.85E+04	1.00E+00	1.50E+01
2-May-05		1.23E+05	5.00E+00	1.00E+01
9-May-05	1.77E+05	2.01E+05	5.00E+00	1.00E+01
16-May-05	5.95E+04	2.12E+05	1.00E+00	5.00E+00
23-May-05	2.77E+06	2.66E+05	1.00E+00	1.00E+00
31-May-05	4.15E+06	1.06E+06	1.00E+01	5.00E+00
13-Jun-05	2.67E+06	5.05E+05	1.50E+01	1.00E+00
20-Jun-05	1.12E+06	9.40E+05		
27-Jun-05		6.05E+05	1.00E+00	
5-Jul-05	6.00E+04	3.70E+05	1.00E+00	
11-Jul-05	1.40E+05	1.30E+06	1.00E+00	
18-Jul-05	7.95E+05	2.35E+06	1.50E+01	3.49E+05
25-Jul-05	1.06E+06	1.82E+06	1.15E+02	1.60E+06
1-Aug-05	1.05E+06	9.25E+05	4.00E+01	5.90E+05
8-Aug-05	5.65E+05	5.00E+03	1.33E+03	1.05E+06
15-Aug-05	5.30E+05	1.26E+06	6.20E+03	2.18E+06
22-Aug-05		1.18E+06	6.00E+01	9.75E+05
29-Aug-05	6.25E+05	2.19E+06		1.04E+06
26-Sep-05	1.10E+05	1.27E+06	1.00E+00	2.70E+05
11-Oct-05			1.00E+01	1.45E+05
25-Oct-05			9.35E+02	1.73E+05
5-Nov-05	1.15E+06		1.00E+00	1.43E+06

Florida Effluent Suspended HPC Bacteria

	HPC Bacteria, CFU/mL			
Date	NH2Cl	UV+NH2Cl	Cl2	UV+Cl2
18-Apr-05	2.19E+05	1.68E+05	6.00E+01	1.19E+03
25-Apr-05	1.32E+05	7.25E+04	3.00E+02	4.95E+02
2-May-05	1.60E+05	1.76E+05	1.00E+00	1.41E+03
9-May-05	1.85E+05	1.52E+05	2.50E+01	4.65E+03
16-May-05	9.90E+04	5.35E+05		8.35E+04
23-May-05	8.60E+05	5.35E+04	4.30E+02	9.65E+03
31-May-05	6.30E+05	4.27E+06	4.10E+03	1.39E+05
13-Jun-05	1.65E+05	2.25E+05	5.00E+02	5.75E+04
20-Jun-05	7.90E+05	1.75E+05	1.95E+02	2.72E+04
27-Jun-05	6.30E+05		1.49E+03	
5-Jul-05	7.50E+04		2.85E+02	1.79E+05
11-Jul-05	5.00E+04	4.26E+05	7.25E+02	3.36E+05
18-Jul-05	2.72E+05	1.66E+06	1.25E+03	1.27E+06
25-Jul-05	4.75E+05	3.45E+06	1.66E+03	1.52E+06
1-Aug-05	1.76E+05	1.63E+06	2.00E+03	4.70E+05
8-Aug-05	1.62E+05	1.20E+06	5.00E+02	5.50E+05
15-Aug-05	3.25E+04	4.00E+05	8.85E+02	8.60E+05
22-Aug-05	1.80E+04	1.34E+06	1.35E+03	6.90E+05
29-Aug-05		1.44E+06	7.50E+02	9.15E+05
26-Sep-05	8.40E+04	6.90E+05	1.10E+03	3.00E+05
11-Oct-05	4.20E+04		6.00E+01	1.22E+05
25-Oct-05	3.09E+05		2.40E+02	8.90E+04
5-Nov-05	1.67E+05		1.15E+02	1.50E+05

Florida Attached HPC Bacteria

HPC Bacteria, CFU/cm^2				
Date	NH2Cl	UV+NH2Cl	Cl2	UV+Cl2
18-Apr-05	2.46E+05	7.72E+04	2.25E+06	1.86E+05
25-Apr-05	1.93E+05		1.33E+05	
2-May-05	3.86E+04	7.72E+05	1.39E+04	2.37E+05
9-May-05	2.24E+05	2.09E+04	5.72E+05	9.08E+05
16-May-05		5.06E+05	8.03E+04	
31-May-05	6.37E+06	5.76E+06		4.13E+06
13-Jun-05	4.38E+06	2.69E+05		2.75E+06
20-Jun-05	2.07E+06	1.34E+05	5.31E+05	3.77E+06
5-Jul-05	2.87E+06		2.40E+05	8.97E+05
11-Jul-05	1.24E+06	9.18E+05	1.48E+05	1.09E+06
18-Jul-05	2.83E+05	5.24E+06	7.10E+04	2.57E+06
25-Jul-05		5.66E+06	3.06E+05	4.08E+06
1-Aug-05	1.81E+06	3.46E+06	2.51E+06	2.32E+06
8-Aug-05	1.61E+06	2.01E+06	1.25E+05	2.38E+06
15-Aug-05	8.45E+06	2.35E+06	7.30E+04	1.04E+07
29-Aug-05	2.96E+06	4.07E+06	2.44E+05	4.15E+06
26-Sep-05	4.59E+05	3.26E+06	4.80E+04	2.92E+06
11-Oct-05	5.74E+04	4.05E+06	2.09E+03	8.87E+05
25-Oct-05	8.87E+04		3.46E+04	7.51E+05
5-Nov-05	1.70E+05		9.39E+03	3.53E+05

	Average HPC Bacteria			
Sample	NH2Cl	UV+NH2Cl	Cl2	UV+Cl2
Influent	1.09E+06	8.33E+05	4.20E+02	5.15E+05
Effluent	2.61E+05	1.00E+06	8.19E+02	3.53E+05
Biofilm	1.86E+06	2.41E+06	4.11E+05	2.49E+06

Florida Free Cl2, mg/L

DATE	4/18/2005	4/25/2005	5/2/2005	5/9/2005	5/16/2005	5/23/2005	5/31/2005	6/6/2005	6/14/2005
Cl2	0.50	0.50	0.50	0.50	0.10	0.60	0.30	NA	0.17
UV+Cl2	0.20	0.20	0.10	0.10	0.10	0.10	0.10	NA	0.10
Cl2 In	0.70	0.70	0.70	0.40	0.70	0.90	0.80	NA	0.41
UV+Cl2 In	0.40	0.40	0.40	0.20	0.30	0.30	0.20	NA	0.19

DATE	6/20/2005	6/27/2005	7/5/2005	7/11/2005	7/18/2005	7/25/2005	8/1/2005	8/8/2005	8/15/2005
Cl2	0.33	0.31	0.17	0.10	0.27	0.43	0.25	0.26	0.13
UV+Cl2	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Cl2 In	0.65	0.73	0.22	0.17	0.45	0.99	0.37	0.47	0.38
UV+Cl2 In	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10

DATE	8/22/2005	8/29/2005	9/26/2005	10/11/2005	10/25/2005
Cl2	0.10	0.10	0.47	0.49	0.48
UV+Cl2	0.10	0.10	0.10	0.10	0.10
Cl2 In	0.31	0.17	0.69	0.01	0.62
UV+Cl2 In	0.10	0.10	0.10	0.10	0.10

Florida Total Trihalomethanes, μg/L

Date	NH2Cl	UV+NH2Cl	Cl2	UV+Cl2
26-Sep-05	47.92	41.57	55.87	41.36
11-Oct-05	46.90		47.66	41.66
25-Oct-05	50.79		57.47	46.99

Florida Total Cl2, mg/L

DATE	4/18/2005	4/25/2005	5/2/2005	5/9/2005	5/16/2005	5/23/2005	5/31/2005	6/6/2005	6/14/2005
NH2Cl	4.0	2.6	2.0	1.8	1.7	1.3	1.1	0.95	0.09
UV+NH2Cl	2.5	2.7	2.0	1.8	1.5	1.5	1.5	0.85	1.24
Cl2	0.60	0.60	0.60	0.60	0.20	0.70	0.40	0.73	0.27
UV+Cl2	0.30	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
NH2Cl In	3.10	2.60	2.50	2.00	2.20	2.00	1.90	3.50	1.54
UV+NH2Cl In	3.0	2.70	2.60	2.30	2.20	2.10	2.00	3.90	1.80
Cl2 In	0.70	0.70	0.70	0.50	0.90	1.00	1.00	1.70	0.49
UV+Cl2 In	0.50	0.40	0.50	0.20	0.40	0.40	0.30	0.30	0.31

DATE	6/20/2005	6/27/2005	7/5/2005	7/11/2005	7/18/2005	7/25/2005	8/1/2005	8/8/2005	8/15/2005
NH2Cl	0.69	0.85	0.80	1.14	0.58	0.82	1.32	0.90	1.85
UV+NH2Cl	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Cl2	0.46	0.46	0.48	0.44	0.33	0.29	0.16	0.41	0.23
UV+Cl2	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
NH2Cl In	1.58	0.84	2.10	2.14	1.87	1.58	0.64	1.61	3.14
UV+NH2Cl In	0.25	0.20	0.64	0.30	0.20	0.20	0.20	0.74	0.55
Cl2 In	0.97	0.81	0.31	0.78	0.62	0.55	0.47	0.57	0.45
UV+Cl2 In	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20

DATE	8/22/2005	8/29/2005	9/26/2005	10/11/2005	10/25/2005
NH2Cl	2.15	0.52	1.21	0.95	1.21
UV+NH2Cl	0.20	0.20	0.20		
Cl2	0.20	0.11	0.56	0.58	0.49
UV+Cl2	0.20	0.20	0.20	0.20	0.20
NH2Cl In	2.96	3.46	2.53	0.75	2.37
UV+NH2Cl In	0.29	0.39	0.75		
Cl2 In	0.49	0.34	0.88	0.06	0.63
UV+Cl2 In	0.20	0.20	0.20	0.20	0.20

Florida NH2Cl, mg/L

DATE	4/18/2005	4/25/2005	5/2/2005	5/9/2005	5/16/2005	5/23/2005	5/31/2005	6/6/2005	6/14/2005
NH2Cl	2.20	1.7	1.5	1.3	1.2	0.79	0.52	0.45	0.05
UV+NH2Cl	2.1	1.8	1.4	1.4	1.2	1.0	1.0	0.79	0.86
NH2Cl In	2.30	2.00	1.70	1.50	1.40	1.20	1.10	1.05	0.65
UV+NH2Cl In	2.2	2.00	1.80	1.60	1.50	1.40	1.30	1.17	1.10

DATE	6/20/2005	6/27/2005	7/5/2005	7/11/2005	7/18/2005	7/25/2005	8/1/2005	8/8/2005	8/15/2005
NH2Cl	0.25	0.32	0.47	0.44	0.47	0.57	0.78	0.58	1.47
UV+NH2Cl	0.05	0.21	0.05	0.10	0.18	0.17	0.05	0.05	0.05
NH2Cl In	0.95	0.53	1.34	1.48	1.33	1.67	1.31	1.30	2.55
UV+NH2Cl In	0.13	0.17	0.17	0.17	0.28	0.44	0.30	0.84	0.63

DATE	8/22/2005	8/29/2005	9/26/2005	10/11/2005	10/25/2005
NH2Cl	2.23	0.48	0.77	0.55	0.80
UV+NH2Cl	0.05	0.23	0.31		
NH2Cl In	2.59	3.23	2.55		2.95
UV+NH2Cl In	0.37	0.52	0.83		

Florida Temperature, degrees Celcius

DATE	4/18/2005	4/25/2005	5/2/2005	5/9/2005	5/16/2005	5/23/2005	5/31/2005	6/6/2005	6/14/2005
NH2Cl	19.9	19.6	23.6	23.5	24.9	25.8	25.2	26.5	27.6
UV+NH2Cl	19.4	19.3	23.5	23.7	24.9	25.8	26.0	26.0	27.8
Cl2	19.2	19.0	23.5	23.6	25.1	25.7	26.0	26.0	27.6
UV+Cl2	19.8	18.9	23.5	23.8	25.1	25.6	26.1	26.5	27.2
NH2Cl In	21.9	20.3	24.1	24.9	26.8	27.0	25.6	27.1	28.9
UV+NH2Cl In	22.7	21.2	24.6	25.3	27.0	27.1	25.6	27.1	29.2
Cl2 In	22.0	20.6	24.1	25.0	26.9	27.1	25.6	27.4	28.9
UV+Cl2 In	22.9	21.5	24.4	25.2	26.8	27.4	26.0	27.7	29.0

DATE	6/20/2005	6/27/2005	7/5/2005	7/11/2005	7/18/2005	7/25/2005	8/1/2005	8/8/2005	8/15/2005
NH2Cl	27.4	25.3	24.2	23.1	27.2	27.4	28.7	27.2	26.3
UV+NH2Cl	26.5	24.8	22.9	23.7	27.6	27.5	28.4	27.4	26.7
Cl2	26.1	24.1	22.1	23.7	27.7	27.6	28.6	26.9	26.8
UV+Cl2	25.6	24.0	21.9	23.5	27.9	27.8	28.3	27.8	26.9
NH2Cl In	26.2	24.7	25.3	23.4	29.1	27.9	29.2	28.1	28.2
UV+NH2Cl In	25.5	24.7	25.7	22.6	28.8	28.1	29.2	28.5	28.4
Cl2 In	25.5	25.0	27.4	23.2	28.9	28.2	29.4	28.3	28.3
UV+Cl2 In	25.5	25.2	27.5	23.8	29.1	28.3	29.6	29.1	28.7

DATE	8/22/2005	8/29/2005	9/26/2005	10/11/2005	10/25/2005
NH2Cl	27.7	27.6	26	25.5	19.8
UV+NH2Cl	27.8	27.8	26.2		
Cl2	27.9	27.7	26.4	25.7	19.5
UV+Cl2	28	27.7	26.5	25.9	19
NH2Cl In	28.9	28.5	27.1	25.8	20.4
UV+NH2Cl In	29.1	28.5	27.7		
Cl2 In	29.5	28.5	27.2	25.9	20.5
UV+Cl2 In	29.6	28.7	28.3	26.0	20.1

Florida pH

DATE	4/18/2005	4/25/2005	5/2/2005	5/9/2005	5/16/2005	5/23/2005	5/31/2005	6/6/2005	6/14/2005
NH2Cl	7.98	7.88	7.77	8.00	7.88	7.87	7.90	7.83	8.08
UV+NH2Cl	8.03	7.94	7.72	7.94	7.84	7.92	7.96	7.84	8.04
Cl2	7.94	7.87	7.74	7.88	7.77	7.90	8.01	7.85	7.98
UV+Cl2	7.96	7.91	7.81	7.95	7.83	7.85	7.98	7.87	7.98
NH2Cl In	7.90	7.85	7.83	7.83	7.58	7.77	7.73	7.84	7.87
UV+NH2Cl In	7.98	7.88	7.86	7.91	7.67	7.81	7.93	7.91	8.06
Cl2 In	7.92	7.72	7.71	7.79	7.65	7.76	7.92	7.8	7.97
UV+Cl2 In	7.79	7.82	7.79	7.89	7.58	7.83	7.83	7.78	8.01

DATE	6/20/2005	6/27/2005	7/5/2005	7/11/2005	7/18/2005	7/25/2005	8/1/2005	8/8/2005	8/15/2005
NH2Cl	7.85	8.05	7.82	7.81	7.83	7.86	7.75	7.8	7.9
UV+NH2Cl	7.85	8.00	7.69	7.71	7.73	7.75	7.73	7.78	7.79
Cl2	7.78	8.04	7.75	7.74	7.87	7.86	7.73	7.83	7.88
UV+Cl2	7.77	7.96	7.69	7.76	7.86	7.88	7.73	7.78	7.84
NH2Cl In	7.85	8.06	7.81	7.69	7.71	7.80	7.74	7.80	7.90
UV+NH2Cl In	7.71	8.09	7.71	7.65	7.62	7.67	7.69	7.78	7.78
Cl2 In	7.68	7.97	7.79	7.61	7.67	7.73	7.61	7.63	7.74
UV+Cl2 In	7.74	7.97	7.65	7.72	7.74	7.77	7.58	7.61	7.65

DATE	8/22/2005	8/29/2005	9/26/2005	10/11/2005	10/25/2005
NH2Cl	7.86	7.8	7.82	7.72	7.87
UV+NH2Cl	7.70	7.64	7.72		
Cl2	7.89	7.80	7.89	7.58	7.87
UV+Cl2	7.84	7.76	7.82	7.50	7.80
NH2Cl In	7.76	7.74	7.74	7.75	7.80
UV+NH2Cl In	7.52	7.66	7.54		
Cl2 In	7.67	7.73	7.57	7.48	7.75
UV+Cl2 In	7.58	7.61	7.50	7.44	7.75

Florida Turbidity, NTU

DATE	4/18/2005	4/25/2005	5/2/2005	5/9/2005	5/16/2005	5/23/2005	5/31/2005	6/6/2005	6/14/2005
NH2Cl	0.44	0.55	0.50	1.18	1.38	0.56	0.58	0.52	0.75
UV+NH2Cl	0.62	0.56	0.73	0.81	1.44	0.84	1.94	0.54	0.58
Cl2	0.51	0.71	0.48	0.90	0.42	0.44	0.27	0.16	0.22
UV+Cl2	0.47	0.47	0.44	0.34	0.50	0.50	0.26	0.19	0.34
NH2Cl In	0.68	0.93	1.57	2.35	1.95	0.94	16.50	0.51	3.38
UV+NH2Cl In	0.87	0.87	0.68	1.71	1.15	0.89	1.27	0.64	6.18
Cl2 In	0.56	1.17	0.52	0.33	0.67	0.48	0.44	0.19	0.33
UV+Cl2 In	0.53	1.49	0.48	0.24	0.99	0.44	0.34	0.17	0.33

DATE	6/20/2005	6/27/2005	7/5/2005	7/11/2005	7/18/2005	7/25/2005	8/1/2005	8/8/2005	8/15/2005
NH2Cl	0.63	0.50	0.48	0.44	0.36	0.53	0.28	0.50	0.53
UV+NH2Cl	0.70	0.60	0.42	0.65	0.49	0.64	0.65	0.61	0.44
Cl2	0.30	0.32	0.23	0.26	0.17	0.30	0.53	0.29	0.20
UV+Cl2	0.29	0.18	0.18	0.19	0.21	0.24	0.47	0.26	0.18
NH2Cl In	1.07		0.58	0.66	1.28	0.97	5.51	0.64	0.30
UV+NH2Cl In	0.99	1.61	0.47	1.98	0.99	1.07	1.50	0.31	0.22
Cl2 In	0.35	0.57	0.45	0.28	0.39	0.47	0.35	0.19	0.27
UV+Cl2 In	0.30	0.42	0.35	0.30	0.60	0.44	0.56	0.18	0.23

DATE	8/22/2005	8/29/2005	9/26/2005	10/11/2005	10/25/2005
NH2Cl	0.54	2.66	2.62	3.20	0.73
UV+NH2Cl	0.91	0.64	0.52		
Cl2	0.31	0.35	0.22	0.89	0.32
UV+Cl2	0.35	0.20	0.22	0.39	0.19
NH2Cl In	3.16	1.09	0.73	0.95	0.87
UV+NH2Cl In	6.91	0.40	2.42		
Cl2 In	0.61	0.44	0.58	1.21	0.60
UV+Cl2 In	0.41	0.26	0.50	0.56	0.24

Florida TOC, mg/L

DATE	4/18/2005	4/25/2005	5/2/2005	5/9/2005	5/16/2005	5/23/2005	5/31/2005
NH2Cl In	4.853	4.165	3.304	4.198	3.684	4.084	3.833
UV+NH2Cl In	5.22	6.762	3.268	3.888	3.761	4.161	3.851
Cl2 In	4.87	4.549	3.357	3.65	3.633	3.924	3.421
UV+Cl2 In	4.841	3.694	3.423	3.485	3.696	3.832	3.379
NH2Cl	4.581	4.187	3.584	3.801	3.968	4.073	3.887
UV+NH2Cl	4.4	4.802	3.853	3.911	4.006		4.144
Cl2	4.72	4.884	3.908	3.682	11.16	4.125	3.641
UV+Cl2	4.995	3.947	3.997	6.265	3.755	3.855	3.945

DATE	6/6/2005	6/14/2005	6/27/2005	7/5/2005	7/11/2005	7/18/2005	7/25/2005
NH2Cl In	4.095	3.889	3.672	3.09	3.513	3.792	3.992
UV+NH2Cl In	3.931	3.821	3.364	2.868	3.525	3.442	3.638
Cl2 In	3.831	3.61	3.373	3.129	3.546	3.317	3.734
UV+Cl2 In	3.627	3.668	3.062		3.107	2.92	3.556
NH2Cl	4.191	3.797	3.883	3.407	3.43	3.58	3.764
UV+NH2Cl	4.103	3.443	3.113	2.906	3.033	7.29	3.904
Cl2	3.981	3.584	3.287	3.086	3.409	3.223	3.798
UV+Cl2	3.526	3.363	3.272	2.988	3.319	3.012	3.413

DATE	8/8/2005	8/15/2005	8/22/2005	8/29/2005
NH2Cl In	3.619	3.959	3.288	3.709
UV+NH2Cl In	3.197	3.817	3.037	3.828
Cl2 In	3.637	3.646	3.077	3.955
UV+Cl2 In	7.878		3.279	3.736
NH2Cl	3.816	4.204	3.5	5.09
UV+NH2Cl	3.197	3.579	3.046	
Cl2	3.285	3.645	3.113	
UV+Cl2	2.959	2.987	2.949	3.483

Florida Nitrate Concentrations, mg/L

DATE	4/18/2005	5/2/2005	5/9/2005	5/16/2005	5/23/2005	5/31/2005	6/6/2005	6/14/2005	6/27/2005
NH2Cl	0.02	0.02	0.02	0.06	0.09	0.09	0.09	0.04	0.12
UV+NH2Cl	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.05	0.12
Cl2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
UV+Cl2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
NH2Cl In	0.02	0.03	0.02	0.06	0.09	0.10	0.08	0.09	0.10
UV+NH2Cl In	0.02	0.04	0.03	0.02	0.03	0.03	0.02	0.04	0.13
Cl2 In	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
UV+Cl2 In	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

DATE	7/5/2005	7/11/2005	7/18/2005	7/25/2005	8/1/2005	8/8/2005	8/15/2005	8/22/2005	8/29/2005
NH2Cl	0.17	0.21	0.19	0.19	0.19	0.22	0.12	0.02	0.16
UV+NH2Cl	0.12	0.14	0.12	0.19	0.82	0.91	0.75	0.81	0.73
Cl2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
UV+Cl2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
NH2Cl In	0.12	0.16	0.15	0.12	0.11	0.13	0.02	0.04	0.03
UV+NH2Cl In	0.12	0.15	0.12	0.12	0.12	0.13	0.11	0.14	0.12
Cl2 In	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
UV+Cl2 In	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

DATE	9/26/2005	10/11/2005	10/25/2005
NH2Cl	**0.08**	**0.24**	
UV+NH2Cl	0.74		
Cl2	0.02	0.02	0.02
UV+Cl2	0.02	0.02	0.02
NH2Cl In	0.03	0.02	0.03
UV+NH2Cl In	0.14		
Cl2 In	0.02	0.02	0.02
UV+Cl2 In	0.02	0.02	0.02

Florida Nitrite Concentrations, mg/L

DATE	4/18/2005	5/2/2005	5/9/2005	5/16/2005	5/23/2005	5/31/2005	6/6/2005	6/14/2005	6/27/2005
NH2Cl	0.03	0.02	0.02	0.03	0.11	0.28	0.48	0.45	0.30
UV+NH2Cl	0.04	0.02	0.03	0.03	0.03	0.03	0.03	0.04	0.05
Cl2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
UV+Cl2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
NH2Cl In	0.03	0.02	0.02	0.02	0.08	0.20	0.24	0.33	0.19
UV+NH2Cl In	0.04	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.05
Cl2 In	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
UV+Cl2 In	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

DATE	7/5/2005	7/11/2005	7/18/2005	7/25/2005	8/1/2005	8/8/2005	8/15/2005	8/22/2005	8/29/2005
NH2Cl	NA	0.37	0.18	0.22	0.24	0.25	0.22	0.28	0.03
UV+NH2Cl	NA	0.35	0.37	0.40	0.43	0.61	0.02	0.02	0.02
Cl2	NA	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
UV+Cl2	NA	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
NH2Cl In	NA	0.27	0.12	0.15	0.14	0.19	0.18	0.23	0.03
UV+NH2Cl In	NA	0.35	0.35	0.41	0.38	0.37	0.36	0.29	0.27
Cl2 In	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
UV+Cl2 In	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

DATE	9/26/2005	10/11/2005	10/25/2005
NH2Cl	0.03	0.04	0.04
UV+NH2Cl	0.02	0.02	0.02
Cl2	0.02	0.02	0.02
UV+Cl2	0.02	0.02	0.02
NH2Cl In	0.03	0.02	0.02
UV+NH2Cl In	0.26	0.25	0.21
Cl2 In	0.02	0.02	0.02
UV+Cl2 In	0.02	0.02	0.02

Florida Free Ammonia, mg/L as N

DATE	4/18/2005	4/25/2005	5/2/2005	5/9/2005	5/16/2005	5/23/2005	5/31/2005	6/6/2005	6/14/2005
NH2Cl	0.73	0.54	0.66	0.64	0.60	0.54	0.29	0.28	0.49
UV NH2Cl	0.66	0.56	0.70	0.66	0.66	0.68	0.56	0.62	0.56
NH2Cl In	0.59	0.50	0.60	0.56	0.53	0.50	0.30	0.34	0.40
UV NH2Cl In	0.65	0.47	0.58	0.53	0.56	0.59	0.48	0.59	0.48

DATE	6/27/2005	7/5/2005	7/11/2005	7/18/2005	7/25/2005	8/1/2005	8/8/2005	8/15/2005	8/22/2005
NH2Cl	0.36	0.52	0.39	0.34	0.38	0.45	0.57	0.80	0.44
UV NH2Cl	0.26	0.24	0.40	0.24	0.12	0.04	0.05	0.03	0.03
NH2Cl In	0.36	0.42	0.46	0.38	0.46	0.5	0.73	0.62	0.19
UV NH2Cl In	0.21	0.29	0.37	0.3	0.35	0.69	0.61	0.55	0.25

DATE	8/29/2005	9/26/2005	10/11/2005
NH2Cl	0.26	0.53	0.3
UV NH2Cl	0.02	0.03	
NH2Cl In	0.18	0.36	0.34
UV NH2Cl In	0.25	0.33	

Florida Total Ammonia, mg/L as N

DATE	4/18/2005	4/25/2005	5/2/2005	5/9/2005	5/16/2005	5/23/2005	5/31/2005	6/6/2005	6/14/2005
NH2Cl	1.32	1.06	1.04	0.91	0.84	0.68	0.42	0.40	0.53
UV+NH2Cl	1.24	0.99	1.07	0.90	0.93	0.69	0.84	0.83	0.78
Cl2	0.02	0.02	0.03	0.05	0.02	0.03	0.02	0.03	0.03
UV+Cl2	0.02	0.02	0.03	0.03	0.03	0.02	0.02	0.03	0.02
NH2Cl In	1.24	1.00	1.10	0.90	0.83	0.71	0.50	0.54	0.46
UV+NH2Cl In	1.28	0.95	1.13	0.88	0.92	0.90	0.79	0.83	0.84
Cl2 In	0.02	0.02	0.02	0.03	0.03	0.02	0.02	0.04	0.02
UV+Cl2 In	0.02	0.02	0.03	0.02	0.03	0.02	0.03	0.02	0.03

DATE	7/5/2005	7/11/2005	7/18/2005	7/25/2005	8/1/2005	8/8/2005	8/15/2005	8/22/2005	8/29/2005
NH2Cl	0.38	0.55	0.61	0.49	0.56	0.48	0.84	1.62	0.85
UV+NH2Cl	0.27	0.29	0.42	0.27	0.13	0.08	0.05	0.06	0.04
Cl2	0.03	0.02	0.04	0.05	0.04	0.02	0.05	0.03	0.02
UV+Cl2	0.02	0.04	0.02	0.05	0.05	0.04	0.02	0.02	0.02
NH2Cl In	0.57	0.80	0.87	0.64	0.81	1.37	1.20	1.36	0.96
UV+NH2Cl In	0.22	0.35	0.43	0.33	0.35	0.80	0.90	0.85	0.34
Cl2 In	0.02	0.04	0.04	0.02	0.05	0.11	0.07	0.02	0.02
UV+Cl2 In	0.02	0.02	0.04	0.04	0.02	0.08	0.11	0.03	0.02

DATE	9/26/2005	10/11/2005	10/25/2005
NH2Cl	0.30	0.70	0.69
UV+NH2Cl	0.04	0.03	
Cl2	0.02	0.02	0.02
UV+Cl2	0.02	0.02	0.02
NH2Cl In	0.78	0.90	1.09
UV+NH2Cl In	0.29	0.46	
Cl2 In	0.02	0.02	0.02
UV+Cl2 In	0.02	0.02	0.02

Port Williams Suspended HPC Data

	AR HPC Bacteria (CFU/mL)							
Date	RW	UV	Cl2	UV+Cl2	NH2Cl	UV+NH2Cl	RW In	UV In
Acclimation:								
26-Sep-05	4.50E+03	6.25E+03	3.39E+04	6.82E+04	4.90E+03	9.83E+03	2.00E+02	1.00E+00
3-Oct-05	7.43E+02	2.82E+05	9.00E+03	5.88E+05	7.00E+02	5.53E+05	1.00E+00	1.00E+01
11-Oct-05	1.73E+03	4.42E+05	7.01E+04	7.88E+05	3.24E+03	3.36E+05	1.00E+00	5.00E+00
Disinfection:								
18-Oct-05	2.38E+03	3.63E+05	1.22E+04	1.10E+04	5.70E+03	1.15E+05	5.00E+01	4.00E+01
19-Oct-05	9.15E+03	2.99E+05	1.38E+04	1.21E+04	1.07E+04	1.03E+05		
25-Oct-05	1.28E+04	2.11E+05	1.06E+04	8.50E+02	5.70E+03	9.23E+04	1.00E+01	
26-Oct-05	2.07E+04	1.21E+05	1.06E+04	1.06E+03	4.09E+03	2.05E+04		
5-Nov-05	1.05E+05	2.22E+05	3.09E+04	6.55E+02	3.07E+03	1.48E+04	2.00E+01	1.33E+03
6-Nov-05	2.24E+05	2.50E+05		6.20E+02	1.45E+03	1.43E+04	1.50E+02	
12-Nov-05	1.80E+05	1.70E+05	7.60E+03	6.00E+01	5.15E+03	2.88E+04	1.00E+02	
13-Nov-05	2.16E+05	1.51E+05	6.50E+03	8.00E+01	8.95E+02	1.88E+04		9.35E+02
17-Nov-05	6.00E+03	1.83E+05	1.04E+04	4.00E+02	5.10E+02	2.40E+02		1.00E+00
21-Nov-05	1.00E+04	1.28E+05	6.87E+03	2.85E+02	2.78E+04	6.00E+02	1.50E+01	1.50E+01
23-Nov-05	3.74E+04	1.90E+05	5.88E+03	2.13E+02	3.73E+02	2.95E+02	5.00E+00	1.00E+01
29-Nov-05	5.55E+03	3.15E+04	4.17E+03	6.00E+01	9.18E+02	8.38E+02	1.00E+00	4.00E+01
1-Dec-05	2.25E+03	5.55E+04	3.81E+03	1.00E+00	8.38E+02	8.38E+02	2.50E+01	8.00E+01
4-Dec-05	5.35E+03	3.45E+04	4.53E+03	1.00E+00	1.54E+03	1.54E+03	1.00E+00	1.50E+01
7-Dec-05	1.92E+03	2.80E+05	5.23E+03	1.75E+02	2.48E+03	2.48E+03	1.00E+00	5.00E+01

Port Williams Attached HPC Data

AR HPC Bacteria (CFU/cm^2)						
Date	RW	UV	Cl2	UV+Cl2	NH2Cl	UV+NH2Cl
Acclimation:						
26-Sep-05	6.52E+02	2.28E+03	5.43E+02	1.09E+02	2.17E+02	3.26E+02
3-Oct-05	3.52E+04	6.65E+04	3.14E+05	6.78E+05	4.71E+04	6.48E+05
11-Oct-05	4.32E+05	2.36E+06	1.99E+06	3.66E+06	1.03E+06	2.20E+06
Disinfection:						
18-Oct-05	8.64E+05	2.40E+06	6.70E+05	1.01E+06	7.99E+05	2.61E+06
19-Oct-05			5.33E+05	6.76E+05	5.98E+05	3.59E+06
25-Oct-05	6.03E+05	1.82E+06	6.41E+03	7.13E+04	6.52E+05	1.85E+05
26-Oct-05			2.02E+04	4.13E+04	9.78E+03	8.70E+04
5-Nov-05	6.25E+03	9.13E+05	2.45E+03	4.88E+04	1.85E+04	9.86E+03
6-Nov-05			2.12E+02	8.88E+04	4.08E+02	2.17E+03
12-Nov-05	6.66E+03	1.49E+06	3.59E+02	4.10E+04	8.15E+02	1.16E+04
13-Nov-05	2.88E+02	1.92E+06	1.16E+03	2.83E+03	1.41E+02	3.70E+04
17-Nov-05	1.85E+03	5.49E+06	5.00E+03	1.67E+05	1.52E+03	8.59E+02
1-Dec-05	7.77E+03	8.91E+05	6.58E+02	2.50E+03	1.01E+03	1.20E+03

PW:	SUSPENDED			ATTACHED		
AR	Acclimation HPC, CFU/mL	Post-Dis. HPC, CFU/mL	Log Reduction	Acclimation HPC, CFU/mL	Post-Dis. HPC, CFU/cm^2	Log Reduction
RW Control	1.79E+03	1.63E+04	-0.958	2.15E+04	1.07E+04	0.302
UV Control	9.20E+04	1.46E+05	-0.201	7.10E+04	1.42E+06	-1.302
Cl2	2.78E+04	7.40E+03	0.574	6.98E+04	1.83E+03	1.582
UV + Cl2	3.16E+05	1.12E+02	3.450	6.46E+04	3.29E+04	0.292
NH2Cl	2.23E+03	1.48E+03	0.179	2.20E+04	1.10E+03	1.300
UV + NH2Cl	1.22E+05	7.33E+02	2.222	7.75E+04	4.05E+03	1.282
Averages:	**9.37E+04**	**2.87E+04**		**5.44E+04**	**2.46E+05**	
STd. Dev.:	1.20E+05	5.79E+04		2.56E+04	5.77E+05	
Std. Error:	4.88E+04	2.36E+04		1.05E+04	2.36E+05	

Port Williams Chlorine Measurements:

UV + Cl2:				Cl2:		
	Cl2, mg/L			Cl2, mg/L		
Date	Dose	Residual	Total	Dose	Residual	Total
16-Oct-05	1.53	0.18		1.53	0.40	
16-Oct-05	0.81	0.27		0.76	0.49	
17-Oct-05				0.57	0.34	
17-Oct-05	0.74	0.28		0.43	0.33	
18-Oct-05	0.64	0.29		0.32	0.28	
19-Oct-05	0.56	0.23		0.3	0.14	
22-Oct-05	0.56	0.21		0.3	0.17	
25-Oct-05	0.56	0.30	0.37	0.3	0.26	0.37
26-Oct-05	0.55	0.22		0.31	0.21	
5-Nov-05		0.23	0.32		0.34	0.45
12-Nov-05		0.32	0.39		0.28	0.41
15-Nov-05	0.46	0.20		0.29	0.20	
18-Nov-05	0.46	0.24	0.30	0.28	0.30	0.40
21-Nov-05	0.45	0.21		0.29	0.31	
23-Nov-05		0.19	0.26		0.23	0.32
25-Nov-05		0.20			0.13	
29-Nov-05	0.45	0.25	0.26	0.26	0.26	0.33
1-Dec-05	0.35	0.20		0.23	0.21	
5-Dec-05	0.35	0.14	0.20	0.24	0.28	0.34
7-Dec-05		0.20			0.22	

Port Williams Monochloramine Measurements:

UV + NH2Cl:			NH2Cl:	
	NH2Cl, mg/L		NH2Cl, mg/L	
Date	Dose	Residual	Dose	Residual
18-Oct-05		0.03		0.22
25-Oct-05		0.01		0.15
26-Oct-05		0.42		0.50
5-Nov-05		0.40		0.82
12-Nov-05		0.30		0.40
15-Nov-05		0.65		1.20
16-Nov-05		1.90		1.60
17-Nov-05		2.60		2.55
18-Nov-05	3.21	1.90	3.21	2.25
20-Nov-05	2.22	1.10	2.22	1.40
21-Nov-05		1.00		1.20
23-Nov-05		0.80		1.00
25-Nov-05	2.22	1.00	1.73	1.60
29-Nov-05	2.22	0.95	1.47	1.10
5-Dec-05	2.22	0.95	1.47	0.90
7-Dec-05	2.22	0.90	1.43	0.78

Port Williams Temperature, degrees Celcius

Date	RW	UV	Cl2	UV+Cl2	NH2Cl	UV+NH2Cl	RW In	UV In
27-Sep-05	17.9	18.0	17.7	17.9	17.8	17.8	16.7	16.5
4-Oct-05	15.3	15.3	15.2	15.4	15.2	15.5	14.6	14.6
11-Oct-05	15.9	15.8	15.6	15.5	15.3	15.5	13.8	14.1
18-Oct-05	14.2	14.1	14.0	13.9	13.7	13.9	13.0	13.2
25-Oct-05	12.3				12.3	12.3		
25-Nov-05	12.0	12.0	11.9	12.0	11.8	12.0	11.1	11.6
29-Nov-05	11.9	12.0	11.7	12.0	11.6	12.0	11.2	11.6
5-Dec-05	9.0	8.9	8.5	8.6	8.4	8.7	8.2	8.2

Port Williams pH

Date	RW	UV	Cl2	UV+Cl2	NH2Cl	UV+NH2Cl	RW In	UV In
27-Sep-05	7.40	7.18	7.12	6.97	6.95	6.81	6.64	6.42
4-Oct-05	6.47	6.67	6.68	6.87	7.05	7.18	6.48	6.46
11-Oct-05	6.55	6.75	6.95	6.71	6.85	7.02	6.41	6.64
18-Oct-05	6.67	6.83	6.59	6.66	6.55	6.60	6.57	6.41
25-Oct-05	6.34	6.46	6.54	6.59	6.46	6.63	6.83	6.82
5-Nov-05	6.84	6.90	6.93	6.96	6.76	6.81	6.95	6.92
13-Nov-05	6.76	6.76	6.83	6.84	6.69	6.76	6.92	6.90

Port Williams Turbidity, NTU

Date	RW	UV	Cl2	UV+Cl2	NH2Cl	UV+NH2Cl	RW In	UV In
27-Sep-05	0.53	0.92	0.42	1.11	0.51	0.53	0.36	0.24
4-Oct-05	0.30	0.25	0.31	0.33	0.19	0.22	0.28	0.44
11-Oct-05	0.55	0.36	0.32	0.27	0.38	0.33	0.28	0.19
18-Oct-05	0.27	0.27	0.38	0.39	0.36	0.25	0.21	0.19
5-Nov-05	0.46	0.32	0.18	0.20	0.17	0.27	0.25	0.26
12-Nov-05	0.36	0.33	0.77	0.24	0.18	0.49	0.24	0.16
18-Nov-05	1.74	0.58	0.23	0.42	0.19	0.29	0.22	0.27
23-Nov-05	0.55	0.36	0.18	0.18	0.17	0.55	0.29	0.19
29-Nov-05	0.45	0.26	0.21	0.19	0.19	0.83	0.29	0.23

Port Williams Nitrate, mg/L

Date	RW	UV	Cl2	UV+Cl2	NH2Cl	UV+NH2Cl	RW In	UV In
12-Nov-05	6.8	8.0	6.5	8.1	6.4	7.4	7.9	9.1
15-Nov-05		7.6	6.8	7.9	7.8	9.0	7.9	9.5
18-Nov-05	9.0	8.0	8.4	7.8	7.3	7.9	6.2	6.3
21-Nov-05	6.9	6.5	7.3	6.4	6.7	5.5	4.8	5.8
25-Nov-05	7.1	8.3	6.9	8.1	8.5	7.3	9.6	8.3
29-Nov-05	7.5	6.1	6.5	5.5	7.4	6.2	8.3	7.1
5-Dec-05	7.1	8.7	8.4	6.9	8.0	6.9	7.0	5.8

APPENDIX C:

Collimated Beam Apparatus Exposure Times Spreadsheet

Date of this Version 06-May-04

Germicidal Fluence (UV Dose) Calculations for a Low Pressure UV Lamp

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Comments and/or questions are welcome

Note that this Spreadsheet includes the new "Divergence Factor", which has been found to be necessary due to the fact that the beam "diverges" as it passes through the solution.

Note: This Spreadsheet should only be used if the suspension depth in the "Petri" dish is less than 2 cm.
For suspensions with depths greater than 2 cm, use the Spreadsheet "Fluence = MP - deep.xls

DO NOT CHANGE ANY CELLS OTHER THAN THE CELLS WITH A YELLOW BACKGROUND

INSTRUCTIONS AND NOTES

1. Set up a "quasi" collimated beam apparatus. If possible, do not use a "collimating tube", but rather use circular "masks" to define the beam. Make sure that safety measures are taken to protect workers from exposure to the UV from the lamp. EYE PROTECTION IS AN **ABSOLUTE** REQUIREMENT.
2. Place the detector head of the UV radiometer on a horizontal surface, containing a 0.5 cm x 0.5 cm grid, such that the "calibration plane" (see the Calibration Sheet provided by the manufacturer of the Radiometer) is at the level of where the top of the solution will be during exposures to the UV.
3. Determine the "Petri Factor" using the procedure given in the "Petri Factor" Worksheet.
4. Measure the absorption coefficient (1 cm absorbance) at 254 nm for the water to be irradiated and insert into Cell **C43**.
   Make sure that the instrument is balanced with distilled water in the same cuvette.
5. Insert the solution volume into Cell **F34**.
6. Insert the distance from the center of the UV lamp to the surface of the water in the Petri Dish into cell **F36**.
7. Insert the center meter reading into cell **G46**.
8. Insert the desired Fluences (UV Doses) into cells **E55 to E61**.
9. Remove the radiometer detector head and place a Petri Dish (or other container), containing the cell suspension, on a stirring motor placed so that the top of the solution is at the same level as that of the "calibration plane" of the detector head. Add a very small stir bar and make sure that the stirring rate is such that there is no vortex.
10. Expose samples in the UV beam for the times calculated in rows **55 to 61**. Do at least three exposures for each time and in random order.
11. The "example" Worksheet shows how to analyze the data and obtain the Fluence (UV Dose) Response Curve.

solution volume = 45 mL
water path length = 0.77 cm
distance from UV lamp to top of water surface = 45 cm
Divergence Factor = 0.9831

absorption coefficient cm^{-1}	total absorbance (A)	Water Factor (WF)	WF X DF
0.0910	0.070	0.9231	0.9074

Uvt = 0.81 0.091 1
0.8109611

Radiometer reading at the center of Petri Dish = 0.210 mW/cm^2

Petri factor = 0.986

True irradiance across the Petri dish = 0.207 mW/cm^2

Reflection factor = 0.975
Water factor *
Divergence factor = 0.907

Average Germicidal Irradiance throughout the water volume = 0.183 mW/cm^2

Time for a Fluence (UV Dose) of	1	mJ/cm^2 =	5.461 s			
Time for a Fluence (UV Dose) of	5	mJ/cm^2 =	27.3 s	=	0 min	27 s
Time for a Fluence (UV Dose) of	10	mJ/cm^2 =	54.6 s	=	0 min	55 s
Time for a Fluence (UV Dose) of	20	mJ/cm^2 =	109.2 s	=	1 min	49 s
Time for a Fluence (UV Dose) of	40	mJ/cm^2 =	218.5 s	=	3 min	38 s
Time for a Fluence (UV Dose) of	80	mJ/cm^2 =	436.9 s	=	7 min	17 s
Time for a Fluence (UV Dose) of	100	mJ/cm^2 =	546.1 s	=	9 min	6 s
Time for a Fluence (UV Dose) of	120	mJ/cm^2 =	655.4 s	=	10 min	55 s
Time for a Fluence (UV Dose) of	200	mJ/cm^2 =	1092.3 s	=	18 min	12 s

Note: the exposure times should be at least 30 s. If they are calculated to be shorter, arrange the irradiation platform further away from the UV lamp so that the irradiance will be smaller.