Improvement and optimization of the A. H. Weeks plant water treatment processes, Windsor, Ontario.

Samar Mazloum

University of Windsor

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Improvement & Optimization of the A. H. Weeks Plant Water Treatment Processes, Windsor, Ontario

By

Samar Mazloum

A Thesis Submitted to the Faculty of Graduate Studies and Research Through the Department of Civil & Environmental Engineering In Partial Fulfillment of the Requirements for the Degree in Master of Applied Science at the University of Windsor

Windsor, Ontario, Canada

2002

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Abstract

The drinking water industry is constantly facing new increasing demands for the improvement of water quality. Disinfection criteria are concentrated on the inactivation of *Giardia Lamblia* and viruses. At the present time, the inactivation of *Cryptosporidium* is unregulated in Canada, however, the presence of *Cryptosporidium* oocysts in source water (Detroit River) made the Windsor Utilities Commission decide to use ozone as its primary disinfectant. The ozone system at the A.H. Weeks Water Treatment Plant (WTP) is designed for a 2-log *Cryptosporidium* inactivation in the summer and 1-log *Cryptosporidium* inactivation in the winter.

The ozone system was brought on-line in June 2001. The plant was monitored to see the effects that implementing ozone had on the plant operation and filtered water quality. An optimization process has been conducted to improve the operation of the ozone system at the A.H. Weeks WTP. Introduction of ozone into the treatment process showed an improvement in overall plant performance compared to the year ozone was not used. Filter performance showed improvement, longer filter run time and lower filtered water turbidity was achieved with the implementation of ozone. Particles of the size range 2-5 μm and 5-10 μm was also improved.

Optimization included automation of the addition of ozone dosage using CT Trim Control, using the IDDF method approximation to calculate Performance Ratio, and the automation of the addition of quenching agent. The benefits of ozone optimization resulted in more consistency in meeting performance objectives, and improved plant
operation. Ozone generator power requirement was decreased, while ozone generator efficiency was 18% higher by the end of the monitoring year. Overdosing of ozone quenching agent was less frequent after automation. The actual amount of quenching agent used was close to the theoretical amount.

Reduction in total operational cost was also observed for the year ozone was applied. Overall cost savings for the year ozone was implemented is $4.55/ML. As a result of optimization, ozone cost was decreased by approximately 18% by the end of the monitoring year. Therefore, optimization of a newly operated ozone system provided better plant operation while reducing operational cost.
ACKNOWLEDGEMENTS

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<th>Description</th>
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<tbody>
<tr>
<td>ALC</td>
<td>Air Liquide Canada</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CSTR</td>
<td>Continuous Stirred Tank Reactor</td>
</tr>
<tr>
<td>CT</td>
<td>Disinfectant Concentration (mg/L) x Disinfectant Contact Time (min)</td>
</tr>
<tr>
<td>D</td>
<td>Detention Time</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>HDT</td>
<td>Hydraulic Detention Time</td>
</tr>
<tr>
<td>IDDF</td>
<td>Integrated Disinfection Design Framework</td>
</tr>
<tr>
<td>LOX</td>
<td>Liquid Oxygen</td>
</tr>
<tr>
<td>MOE</td>
<td>Ontario Ministry of Environment</td>
</tr>
<tr>
<td>NOM</td>
<td>Natural Organic Matter</td>
</tr>
<tr>
<td>PACL</td>
<td>Poly Aluminum Chloride</td>
</tr>
<tr>
<td>PFD</td>
<td>Plug Flow With Dispersion</td>
</tr>
<tr>
<td>PR</td>
<td>Performance Ratio</td>
</tr>
<tr>
<td>PSU</td>
<td>Power Supply Unit</td>
</tr>
<tr>
<td>RTD</td>
<td>Residence Time Distribution</td>
</tr>
<tr>
<td>S.G.</td>
<td>Specific Gravity</td>
</tr>
<tr>
<td>SWTR</td>
<td>Surface Water Treatment Rule</td>
</tr>
<tr>
<td>T_{10}/T</td>
<td>Short Circuiting Ratio</td>
</tr>
<tr>
<td>TB</td>
<td>Turbidity</td>
</tr>
<tr>
<td>TOC</td>
<td>Total Organic Carbon</td>
</tr>
<tr>
<td>VOD</td>
<td>Vent Ozone Destruction Unit</td>
</tr>
<tr>
<td>WTP</td>
<td>Water Treatment Plant</td>
</tr>
<tr>
<td>WUC</td>
<td>Windsor Utilities Commission</td>
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</table>
Chapter 1

Background

1.1 Introduction

Disinfection is the chemical inactivation or kill of a specific pathogenic microorganism. Many chemicals and physical agents are used as disinfectants; however, ozone is gaining popularity due to the increasing concern of the removal and inactivation of more resistant pathogens and a reduction in disinfection by products. The first application of ozone as a potable water disinfectant was in 1893 at Oudshoorn, Netherlands (Haas, 1999; Langlais et al., 1991). Other early applications of ozone were to control taste and odour (Langlais et al., 1991). It has also been observed that preozonation enhances particulate agglomeration and thus coagulation & flocculation (Langlais et al., 1991; Jasim, 1998). Of the oxidants used in water treatment, ozone was the only one capable of destroying by oxidation the range of toxins produced by Cyanobacteria (Rositano et al., 1998).

In case of drinking water, the most pathogens include, Giardia lamblia, e. coli, viruses, and most recently Cryptosporidium parvum. The drinking water industry has been linked to an increasing risk of microbial disease. According to Armani et al. (2001), recent studies and numerous past outbreaks suggest that drinking water may be a substantial contributor to endemic (non-outbreak related) gastroenteritis. Cryptosporidium parvum are resistant oocyst, which cause an acute diarrheal illness in humans, called Cryptosporidiosis (Solo_Gabriele & Neumeister, 1996). For immune-compromised patients the infection can potentially become life threatening (Svaboda et al., 1999). The
number of identified Cryptosporidiosis cases began to increase in 1982 due to newly developed laboratory diagnostic techniques (Juranek et al., 1995). In 1993, Cryptosporidium was the cause of the largest US waterborne outbreak affecting more than 400,000 people in Milwaukee, Wisconsin (Juranek et al., 1995). Most recently, in April 2001, a cryptosporidiosis outbreak in North Battleford, Saskatchewan affected an estimated 5,800 - 7,100 individuals (Sterling et al., 2001). An infection was later confirmed in 275 people.

The use of chlorine does not eliminate all risk of waterborne disease transmission (Aramini et al., 2001). Cryptosporidium parvum in particular is not easily inactivated using conventional chemical disinfection technologies (Finch et al., 2001). Thus an alternative disinfectant, such as ozone, is considered because it is proven to be the most effective chemical disinfectant for the inactivation of Cryptosporidium parvum (Finch et al., 2001). Water treatment plants retrofitting with ozone is seen lately after the North American outbreaks of giardiasis and cryptosporidiosis (Rice, 1999).

According to the USEPA and Ontario Ministry of the Environment (MOE) drinking water regulations, a minimum of 3-log (99.9%) removal of G. lamblia and 4-log (99.99%) removal of viruses is required for surface water sources. A conventional filter plant is allowed removal credit of 2.5-logs for Giardia and 2-logs for viruses, thus leaving 0.5-log Giardia and 2-logs viruses to be inactivated by disinfection (USEPA, 1990). At this time Cryptosporidium parvum inactivation is unregulated by the EPA, but is implemented by policy decision at several utilities in North America (Rakness et al.,
2000). Most recently, ozone disinfection was implemented at the A. H. Weeks Water Treatment Plant in Windsor, Ontario, Canada, to meet 2-log inactivation of *Cryptosporidium parvum* in the summer and 1-log inactivation in the winter, which exceeds MOE regulation for *Giardia* and virus inactivation guidelines. The decision came after reviewing the analysis for raw water confirmed that it contained *Cryptosporidium parvum* oocysts at levels up to 602 oocysts/100 ml (Jasim, 2001). Due to its strong disinfection capacity, ozone’s CT (disinfectant concentration x contact time) values are lower than those for chlorine, chlorine dioxide and monochloramine, which have been specified as appropriate disinfectants by the EPA (Rice, 1999).

Drinking water regulations specify the use of the effluent method as the standard approved method for calculating ozone CT and microbial disinfection credit. The CT concept relates the product of disinfectant concentration (C in mg/L) and contact time (T in min) to microbial inactivation at a specific water temperature and pH (Rice, 1999). The calculation of CT using the effluent method has been shown to underestimate the inactivation of viruses and *Giardia* cysts (Ballantyne et al., 2000; Bellamy et al., 2000; LeChevallier et al., 1995). The Integrated Disinfection Design Framework (IDDF) method is considered more accurate than either the effluent or log integration methods (Ballantyne et al., 2000; Bellamy et al., 2000; Rakness et al., 2000). By implementing the use of the IDDF method, utilities can lower disinfectant dosages, operational cost, and disinfection by-products (Bellamy et al., 2000); thus, optimizing their overall performance. “The goal of ozone optimization is to achieve performance objectives at minimum operating cost.” (Rakness et al., 1999). Optimization of plant performance is
done by comparing three criteria, 1) Performance Ratio, 2) Ozone Consumption / Dose, 3) Energy and Liquid Oxygen Consumption to assess operational cost (Rakness et al., 1997). These criteria have to be observed with respect to pH, temperature, and turbidity.

In an attempt to optimize their operation, the A. H. Weeks Water Treatment Plant in Windsor, Ontario decided to use the IDDF method approximation. This project will use the IDDF method approximation to determine what parameters should be changed in order to optimize the plants performance.

1.2 Full Scale Application

The Water Treatment Centre, Windsor Utilities Commission (WUC), Windsor, Ontario obtains its water from the Detroit River which links Lake St. Clair and Lake Erie. The Water Treatment Centre serves three municipalities with a consumer population of 230,000. The raw water quality is considered of low turbidity (an elevated turbidity was noticed during previous months) with a total organic carbon (TOC) of 1.5 – 1.8 mg/L and a Hardness of 100-150 mg/L as CaCO₃. In 1994, the Treatment Center upgraded its facility with the construction of the A. H. Weeks Water Treatment Plant. The old water treatment plant is undergoing rehabilitation with a capacity of 81 ML/d.

The Ontario Water Resources Act (MOE, 2000) states that a water treatment system that obtains its water from a surface water source should maintain a minimum level of treatment, which includes chemically assisted filtration and disinfection. The A. H.
Weeks Plant incorporates a conventional water treatment process, including screening, coagulation, flocculation, sedimentation, filtration, and disinfection.

The ozone system at the A. H. Weeks plant included two contactors when it was constructed. Additional contact time for Cryptosporidium parvum oocyst inactivation was obtained by including two enclosed flocculation tanks as part of the ozone contact zone. The ozone generation system includes two 500 kg/day ozone generators plus ozone destruct units. The ozone generators are fed with liquid oxygen (LOX) from a 162,478 lbs capacity vertical storage tank. Chlorine is added at the end of the filtration to provide a residual disinfectant. Chlorine residue is maintained in the distribution system to protect the water from microbial pathogens and prevent biofilm buildup (Lewin, et al., 2001).

1.3 Objectives

Plant performance should be met without compromising filtered water quality, meeting the MOE regulations, or reducing the inactivation of 2-log Cryptosporidium oocysts in the summer and 1-log Cryptosporidium oocysts inactivation in the winter.

The objectives of this research are:

1. To investigate the effect of ozone on the A. H. Weeks Water Treatment Plant performance

2. To optimize the A. H. Weeks Water Treatment Plant Ozone System.
3. To evaluate the effect of ozone on chemical use especially coagulant and coagulant aid.

4. To compare the cost of running the treatment plant with and without ozone.

1.4 Scope

The study is conducted at the A. H. Weeks Water Treatment Plant in Windsor, Ontario.

The scope of this study includes:

- Collecting data for a full year of operation in presence or absence of ozone.

- Monitoring of plant performance for a full year of operation during which ozone was implemented, and to focus on optimization during operation.

- Implementing changes in the ozone system to improve performance. Such changes included,
  
  - Automation of the ozone dose addition using CT-Trim Control
  
  - Modifying the calculation of Cryptosporidium log inactivation with the use of the IDDF approximation
  
  - Automation of ozone quenching agent addition
Chapter 2

Literature Review

2.1 Fundamentals of Ozone Disinfection

Ozone is considered the most effective single disinfectant in the inactivation of Cryptosporidium parvum oocyst (Finch et al., 1997).

2.1.1.1 Disinfectant Chemistry

Organics and inorganics in water can cause an instantaneous ozone demand and so ozone starts to decay as soon as it is added to water (Langlais et al., 1991). The effectiveness of disinfection decreases as it decays. It continuously dissipates during contact time due to volatilization, autodecomposition and reaction with other constituents (Finch et al., 2001). The stability of ozone in aqueous solution is affected by pH, ultraviolet (UV) light, ozone dose, the presence of hydrogen peroxide, the presence of ammonia and the concentration of radical scavengers such as alkalinity (Ozekin, 1994). The ozone decomposition rate is expressed as pseudo first order kinetic equation in presence of excess radical scavengers, which prevent secondary reactions (Langlais, 1991).

Ozone decay in the Detroit River raw water can be described by pseudo-first order reaction kinetics indicated by the straight line forms in Figure 2-1 (Sladic, 2001). The decay rate (d) was determined using a minimum of three doses of ozone during the test.
Figure 2-1  First Order Decay Profile: Temperature = 21°C & pH=7.7 (Sladic, 2001)

The following first order kinetic equation was used to calculate the decay rate constant, k (Sladic, 2001):

\[
k = \ln \left( \frac{[O_3]_t}{[O_3]_{60 \text{ sec}}} \right) / (t - 1 \text{ min.})
\]

(1)

Where, \( k \) (minutes\(^{-1}\)) is the first order decay rate constant; \([O_3]_t \) (mg/L) is the concentration of the ozone residual at time \( t \); \([O_3]_{60 \text{ sec}} \) (mg/L) is the 60 second ozone residual and \( t \) (minutes) is time.

Table 2.1 shows the equations that were determined in that study (Sladic, 2001) to estimate 60 seconds ozone residual for Detroit River raw water at operating conditions:
Table 2.1: 60 second ozone residual equation for Detroit River raw water

<table>
<thead>
<tr>
<th>Temp.</th>
<th>pH</th>
<th>([O_3]_{60\text{sec}}) equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 °C</td>
<td>8.1</td>
<td>0.8942 \times [O_3]_{dose} - 0.6899</td>
</tr>
<tr>
<td>21 °C</td>
<td>7.7</td>
<td>0.7908 \times [O_3]_{dose} - 0.4064</td>
</tr>
<tr>
<td>5 °C</td>
<td>8.1</td>
<td>0.8332 \times [O_3]_{dose} - 0.0461</td>
</tr>
<tr>
<td>5 °C</td>
<td>7.7</td>
<td>0.9242 \times [O_3]_{dose} - 0.2734</td>
</tr>
</tbody>
</table>

Where, \([O_3]_{dose}\) (mg/L) is the ozone dose.

2.1.1.2 Inactivation Kinetics

Site specific conditions should be used to determine inactivation kinetics of a particular disinfection system and, the effect of disinfectant concentration on the rate of disinfection should be considered (Bellamy et al., 1998). The disinfectant concentration in natural water is not constant; therefore the use of a single concentration at the end of the contactor for determining disinfection requirements does not result in an optimum operation (Bellamy et al., 2000). However, if natural water ozone demand is satisfied prior to microorganism reduction then ozone inactivation kinetics of Cryptosporidium parvum oocyst will be adequately predicted by laboratory water (Lewin et al., 2001).

Determining inactivation kinetics can be done using one of three approaches, (see Table 2.1). The inactivation kinetics at the A. H. Weeks Water Treatment Plant were determined through previous literature (Rennecker et al., 1999; Oppenheimer et al., 1999; Finch et. al., 2000). Figure 2-2 shows the Cryptosporidium oocyst inactivation rate used
at the A. H. Weeks Water Treatment Plant. The line of best fit values were used in the inactivation equation (Rakness & Hunter, 2001). Figure 2-3 shows Giardia and virus inactivation rate at the A. H. Weeks WTP based on USEPA tables, where LogI represents Log Inactivation.

![Graph showing inactivation rate vs. water temperature](image1)

**Figure 2-2** The equation used to calculate Cryptosporidium oocyst inactivation rate.

![Graph showing inactivation rate vs. temperature](image2)

**Figure 2-3** The Giardia cyst and virus inactivation rate are based on USEPA tables.
The following equation represents the inactivation rate \( y \) for either virus, Giardia or Crypto:

\[
y = a \times e^{b \times Temp}
\]  

(2)

Where, 
- \( a = 2.1507\) for virus, 1.0237 for Giardia and 0.0406 for Crypto
- \( b = 0.0707\) for virus, 0.0722 for Giardia and 0.1186 for Crypto

\( Temp = \) Water Temperature in °C

### 2.1.1.3 Contactor Hydraulics

Hydraulic characteristics are used to determine the fraction of Cryptosporidium oocysts remaining in the contactor after a specific time (Bellamy et al., 2000). Models that represent contactor flow are based on parameters that describe the detention time characteristics, such as the residence time distribution (RTD), are most common (Bellamy et al., 1998). These models generate a site specific hydraulic detention time (HDT), which is used as a basis to calculate the time profile for the IDDF, and the RTD curve, which describes the mass flow characteristics for the contactor and the contactor mixing efficiency (Carlson et al., 2001).

Three levels of the hydraulic characterization module can be used to quantify the hydraulic efficiency of an existing contactor (Carlson, et al., 2001). These include; 1) single parameter models such as a plug flow with dispersion (PFD) model or a continuous stirred tank reactor (CSTR) model, 2) Computational fluid dynamics (CFD) or 3) Experimental tracer studies (Carlson et al., 2001). Chemical tracer tests are the most common method for determining the RTD, since they can be easily converted to
represent the RTD of cysts. A normalized RTD curve can be used to predict the $T_{10}/T$ value for any flow rate for contact basins with near ideal hydraulic characteristics (i.e. $T_{10}/T \geq 0.75$) (Bellamy et al., 2000).

Tracer Studies were conducted at the A. H. Weeks Water Treatment Plant to obtain the IDDF hydraulic information. The chemical tracer used was fluoride in the form of hydrofluosilicic acid and the procedure followed outlines by Teefy (1996) and Mulwyk (2000) (Sladic, 2001). The tracer was added upstream from the contactor inlet. After the addition of stainless steel baffles to the original contactor, the $T_{10}/T$ ratio was established to be 0.71 to 0.79, which corresponds to superior baffling conditions (Sladic, 2001).

2.2 Disinfection Credit Calculation Models

Disinfection credit calculations are calculated by one of many different methods, ranging from first order rate expressions to models that are site specific. Microbial Inactivation, represented as CT, is dependent on the disinfectant residual concentration (C) and the disinfectant contact time (T) when applied to a reactor of know hydraulic characteristics (Oppenheimer et. al., 1997). The basic concept of CT is to maintain a certain minimum concentration for a given period of time (Langlais et al., 1991). The following represent the three models used most often in the drinking water industry; 1) Effluent Method, 2) Log Integration Method, 3) Integrated Disinfection Design Framework.
2.2.1 Effluent Method

The effluent method is also referred to as the CT concept. It is the standard Surface Water Treatment Rule (SWTR) EPA Guidance Manuel approved method for calculating drinking water microbial disinfection credit, CT. The effluent method uses the measured outlet residual for cells that have a residual analyzer and the detention time for upstream cells (Figure 2-4; Rakness et al., 2000). The black dots indicate where residual analyzers are located in the A. H. Weeks WTP ozone contactor (Figure 2-5).

![Diagram showing Effluent Method of CT-value Calculation](image)

Figure 2-4 The Effluent Method of CT-value Calculation Includes the Area of the Rectangle Defined by the Outlet Residual and HDT in Upstream Cells (Rakness et al., 2000)
Figure 2-5 A. H. Weeks Water Treatment Plant Ozone Contactor

The CT concept is derived from the Chick Watson rule; which is expressed as follows (Finch et al., 1997; Langlais et al., 1991):

$$\log \left( \frac{N}{N_0} \right) = -LC^oT$$

(3)

Where, $N =$ number of viable *Cryptosporidium* oocysts, oocyst/L

$N_0 =$ influent *Cryptosporidium* oocyst count, oocyst/L

$C =$ ozone residual concentration, mg/L

$L =$ lethality coefficient or pseudo first-order rate constant, (mg/L)$^o$(min)$^{-1}$

$n =$ coefficient of dilution or empirical constant

The effluent method assumes that the residual concentration of ozone is equal to the contactor effluent concentration (Rakness et al., 2000). This model does not take into
account specific site water quality deviations, the disinfectant application or the hydraulics of the treatment plant (Ballantyne et al., 2000). The residual concentration used in this method is greater than actual (Rakness et al., 2000). The steps to calculation of CT using the effluent method are as follows (Rakness et al., 2000):

Step 1: 0.5 log direct *Giardia* credit if the initial residual is $\geq 0.3$ mg/L

1.0 log direct virus credit if the initial residual is $\geq 0.1$ mg/L

Step 2: CT-values are calculated using ozone residuals (C) measured at the end of each contactor where an ozone residual monitor is installed.

Step 3: Time (T) is assumed as the liquid Hydraulic Detention Time (HDT) between the outlets of the contactors for which CT is being calculated. This is done by dividing the volume of the contactors by the flow rate.

$$CT_{b-a} = \frac{T_{10}}{T} \times C_b \times T_{a-b}$$

(4)

Where, $CT_{b-a} =$ calculated CT between end of cell a and end of cell b.

$T_{10}/T =$ short circuiting ratio = 0.6-0.7

$C_b =$ ozone residual at end of cell b

$T_{a-b} =$ HDT from end of cell a to end of cell b.

$a-b =$ represents contactor 1-2, 2-8 and 8-A, Figure 2-1.

Step 4: All the CT values are then added and that gives the final $CT_{total}$. 
Step 5: The inactivation rate is then calculated for Giardia and viruses, using the following equations (USEPA, 1990),

\[ y_G = 1.0237 \times e^{0.0722 \times WT} \]

(5)

\[ y_V = 2.1507 \times e^{0.0707 \times WT} \]

(6)

Where, \( y_G = \) Giardia cyst inactivation rate, (Log inactivation/ CT)

\( y_V = \) Virus inactivation rate, (Log Inactivation/CT)

\( WT = \) water temperature, (°C)

Step 6: log inactivation Credit is calculated by the following equation

\[ \text{Log Inactivation} = y \times CT \]

(7)

\[ 2.2.2 \ \text{Log Integration Method} \]

The log integration method is considered to be more accurate in predicting CT than the effluent method (Rakness et al., 2000). The detention time (\( T_{10} \)) where 10% of the tracer passes through the disinfection basin, is based on tracer studies (Teefy, 1996). The integrated average value of the ozone residual for \( C_{\text{avg}} \) is used for the actual ozone residual concentration calculation in the log integration method (Rakness et al., 2000). The CT can be calculated using only two residual readings because the log integration method incorporates first order decay kinetics residual profile (Figure 2-6, Rakness et al.) (Sladic, 2001).
Figure 2-6 The Log Integration Method of CT-value Calculation Includes the Area Under the Residual Profile Curve (Rakness et al., 2000).

The steps to calculate CT by the log integration method are as follows (Rakness et al., 2000):

Step 1: $T_{10}/T$ is calculated from tracer studies

Step 2: the value for the decay rate is calculated using the first two analyzer locations excluding the outlet of the first cell. The equation used is:

$$k = \frac{\ln(C_2/C_3)}{T_{2-3}}$$

(8)

Where, $C_2 =$ the residual measured at the outlet of cell 2

$C_3 =$ the residual measured at the outlet of cell 3

$T_{2-3} =$ the detention time between the outlet of cell 2 and the outlet of cell 3
Step 3: Time (T) is the detention time between the outlets of the contactors for which CT is being calculated. This is done by dividing the volume of the contactors by the flow rate.

Step 4: The residual at the end of the first cell is calculated using the following equation

\[ C_{\text{initial}} = \frac{C_2}{e^{kT_2}} \]  

(9)

Where, \( C_2 \) = the measured residual at the end of cell 2
\( k \) = calculated decay rate
\( T_2 \) = cell 2 detention time

Step 5: CT is calculated using the following equation

\[ CT_{2-2} = \left( \frac{T_{10}}{T} \right) \times \left( \frac{C_{\text{initial}}}{k} \right) \times \left( e^{kT_2} - 1 \right) \]  

(10)

Where, \( CT_{2-2} \) = calculated CT between end of cell 2 and end of cell 8.
\( T_{10}/T \) = short circuiting ratio from tracer studies
\( C_{\text{initial}} \) = ozone residual at end of the first cell
\( T_{2-8} \) = detention time from end of cell 2 to end of cell 8.

Step 6: The Rapid Mix and flocculation basin CT are calculated using the effluent method. All the CT values are then added and that gives the final CT_{total}.

Step 7: The inactivation rate is then calculated for Cryptosporidium, using the following equation (Rakness & Hunter, 2001).
\[ y_c = 0.0406 \times e^{0.1186 \times WT} \]

(11)

Where, \( y_c \) = *Cryptosporidium* oocyst inactivation rate, (Log inactivation/ CT)

\( WT \) = water temperature, (°C)

Step 8: *Cryptosporidium* Log Inactivation credit is then calculated using the following equation.

\[ \text{Crypto Log Inactivation} = y_c \times CT_{\text{Total}} \]

(12)

2.2.3 Integrated Disinfection Design Framework (IDDF)

The IDDF concept allows utility personnel to determine site-specific disinfection requirements (Bellamy et al., 1998). The model can be specific to a selected organism, source water and treatment plant (Ballantyne et al., 2000). This makes the IDDF method more accurate than either the effluent or log integration methods (Ballantyne et al., 2000; Bellamy et al., 2000; Rakness et al., 2000). Utilities can use the IDDF method to optimize their overall plant performance by lowering disinfectant dosages, operational cost and disinfection by-products (Bellamy et al., 2000).

Three components are needed for the determination of the IDDF model; 1) disinfectant residual decay information obtained from a decay curve, 2) inactivation kinetics are available through site specific inactivation studies, or from water with similar disinfectant and inactivation characteristics or from generic curves developed from CT tables (USEPA), and 3) hydraulic characteristics obtained from tracer study results from which
$T_{10}/T$ ratio is determined (Ballantyne et al., 2000; Bellamy et al., 1998; Bellamy et al., 2000; Rakness et al., 2000).

The IDDF model allows the user to adapt one of three levels of accuracy and complexity, (Table 2.2). The Basic level, which is the simplest, allows the development of the model input parameters without experimentation such as values from the USEPA SWTR guidance manual. The Standard level requires site specific experimentation and is anticipated to be the most common application of the IDDF. The third level is the Advanced level, which is expected to be used by utilities that would result in a significant benefit from its implementation (Bellamy et al. 2000). These levels of accuracy can be used for any of the IDDF components.
Table 2.2: IDDF component levels of accuracy (Carlson et al., 2001)

<table>
<thead>
<tr>
<th>Component</th>
<th>Level</th>
<th>IDDF model inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disinfectant Chemistry</td>
<td>Basic</td>
<td>$k$, $C_0$ values from Literature models</td>
</tr>
<tr>
<td></td>
<td>Standard</td>
<td>$k$, $C_0$ values for one dose (assumes dose independent)</td>
</tr>
<tr>
<td></td>
<td>Advanced</td>
<td>$k$, $C_0$ values for three doses (develop dose dependent relationship)</td>
</tr>
<tr>
<td>Inactivation Kinetics</td>
<td>Basic</td>
<td>Literature $y$, $a$, $b$ values</td>
</tr>
<tr>
<td></td>
<td>Standard</td>
<td>Confirmation testing to verify applicability of literature $y$, $a$, $b$ values</td>
</tr>
<tr>
<td></td>
<td>Advanced</td>
<td>Site specific inactivation testing to determine $y$, $a$, $b$</td>
</tr>
<tr>
<td>Hydraulic Characteristics for existing contactor</td>
<td>Basic</td>
<td>Detention Time or $T_{10}/T$</td>
</tr>
<tr>
<td></td>
<td>Standard</td>
<td>Tracer Data</td>
</tr>
<tr>
<td></td>
<td>Advanced</td>
<td>Computational Fluid Dynamics derived RTD</td>
</tr>
</tbody>
</table>

2.3 Optimization of Ozone System

Ozone disinfection was applied at the A. H. Weeks Water Treatment Plant to improve overall water quality. These water quality objectives include taste & odour control, decrease in disinfection by products and improvement of disinfection. Further optimization of the ozone disinfection system to achieve higher Cryptosporidium oocyst log removal as well as lowering the cost of operation and improving overall plant performance are examined in this study. Comparing current performance with
benchmark criteria, such as, performance ratio (PR), applied ozone dose and energy and liquid oxygen consumption, will aid in optimization (Rakness & DeMers, 1998).

2.3.1 Optimization Criteria

Performance ratio (PR) is calculated as the actual log inactivation divided by the required log inactivation (Rakness et al., 1997). It is a means to assess current ozone system performance versus target performance (Rakness & DeMers, 1998). Several factors aid in controlling PR, these include presence and reliability of on-line ozone residual monitors, degree of variability in treated water quality, and level of disinfection (Rakness & DeMers, 1998). If the measured disinfection performance is equal to the required performance it will yield a PR equal to 1.0 (Rakness et al., 1997). However, a much higher PR indicates that more ozone than necessary is being used (Rakness et al., 1997). A dose adjustment is usually not required if PR is with in an acceptable range such as 0.9 to 1.2 (Rakness et al., 1997).

The amount of ozone required to meet performance objectives is referred to as ozone dose or ozone consumption. The ozone dose is site specific and varies with water quality and treatment objectives. Overdosing with ozone will increase the ozone residual without affecting water quality parameters; it will only increase the cost. Various techniques are used to minimize ozone dose, these include adjustments to the PR, varying points of ozone application, and ozone contactor time (Rakness et al., 1997; Rakness & DeMers, 1998).
The unit cost of ozone production is affected by the electrical energy and liquid oxygen (LOX) consumption. Energy cost is usually lower in oxygen fed facilities compared to air fed systems and so it justifies the purchasing of LOX. The use of LOX increases the ozone generation rate. Maintaining the unit cost of ozone as low as possible by selecting the proper equipment and maintaining optimum ozone concentration is the goal for achieving an optimum ozone generation system. Implementing an ozone data collection and monitoring system that identifies performance trends can attain optimization (Rakness et al., 1997; Rakness & DeMers, 1998).

2.3.2 Optimization Stages

Research done by Rakness & Hunter (1999), identifies ideas on how to improve the benefit/cost ratio of a water treatment plant. Optimization of ozone water treatment plants is done in three phases, 1) pre design, 2) during design, and 3) during operation (Rakness & Hunter, 1999).

During pre-design, decisions are made with regard to the level of ozone performance goal that is desired (Rakness & Hunter, 1999). Depending on the level of ozone performance ozone contactors/ generators are sized as well a decision on feed gas and application point is made (Rakness & Hunter, 1999). A 2-log Cryptosporidium oocyst inactivation was chosen for the operation at The A. H. Weeks Water Treatment Plant in summer. During winter months Pr was difficult to achieve and so 1-log Cryptosporidium oocyst inactivation in winter was set as the performance target, which is considered as enhanced disinfection (Jasim et al., 2002). However, the plant’s ozone contactors were only
designed to provide taste and odour control, which is unable to provide the required new-set targets for *Cryptosporidium* inactivation. The decision was thus made to increase the contact time for *Cryptosporidium* oocyst inactivation by including two enclosed flocculation tanks as part of the ozone contact zone. The generator feed gas was chosen to be Liquid Oxygen (LOX). Due to its high oxygen concentration, LOX provides more opportunity for reaction than air (Hunter, 2000). The generating capacity is increased by a factor ranging from 1.7 to 2.5 when using an oxygen-enriched process as compared to air (Langlais et al., 1991). Nitrogen is introduced to the LOX feed gas system at low concentrations in order to make the process more efficient (Hunter, 2000; Langlais et al., 1991).

During the design stage many processes can be optimized. To ensure ozone optimization is achieved, key instrumentation has to be accurate. Process controllability is achieved through enhanced gas flow control and reliable ozone system automation. Optimum performance is also achieved through process flexibility, which involves equipment seizing as well as provides decrease in operating cost during turndown flow and so power is reduced in proportion to gas flow rate (Rakness & Hunter, 1999).

During design, ozone system instruments; as well as, their location and field verification of accuracy is determined (Rakness & Hunter, 1999). Important process instrumentation include gas flow meters, ozone concentration monitors, power meters and ozone residual monitors (Rakness & DeMers, 1998). Ozone residual monitor readings are used to calculate PR. Detention time between the sample point and the residual monitor is
minimized to ensure accurate ozone residual readings. Gas flow meters are used to calculate ozone operating parameters, to monitor and control ozone process and to determine flow split between parallel units (Rakness & Hunter, 1999). Ozone concentration meters can be used to determine the development of ozone generator performance. Finally, generator power meters are needed to assess unit-volume cost of operation ($/MG) and generator loss of efficiency trend. Generator power is the biggest energy consuming component in LOX ozone systems and so by controlling generator power optimization is achieved (Rakness & Hunter, 1999).

This thesis will focus on optimization during the operation of an ozone water treatment plant.

The two most frequent occurring factors impacting optimization are operations related. In order to achieve optimization during performance, one should first implement an optimization parameters monitoring program, evaluate and interpret the data, and then implement operating strategies to achieve the required optimized performance (Rakness & Hunter, 1999; Rakness & DeMers, 1998).

Optimization should be measured in the form of PR and unit-volume operating cost ($/MG), and parameters that should be monitored include ozone residual, water flow rates, water temperature, gas flow rate, ozone concentration, generator and other power consumed (Rakness & Hunter, 1999). Chemical use should also be monitored to ensure that it is not being used excessively.
Accurate meter readings are extremely important for determining optimization status (Rakness & Hunter, 1999). Plants that had formalized data monitoring procedures were further ahead in their optimization than those that did not collect any data or that did not develop data collected for process control (Rakness & DeMers, 1998). Gas flow meters gave incorrect readings in a few plants however ozone concentration meters and power demand meters have performed well with only occasional incorrect readings (Rakness & Hunter, 1999). Thus when dealing with these meters, their accuracy has to be verified routinely. Once meter accuracy has been established, data can be collected and used in optimization.

2.4 Effect of Ozone on Coagulation and Filtration

Ozone can react with both organic and inorganic raw water to form a diverse group of reaction products (Langlais et al., 1991). The six most likely mechanisms for the coagulating effects of ozone are as follows: 1) Loss of organic coating, which involves ozone stripping organic matter from the surface of the particles and returning them to their destabilized state, thus they are free of high negative surface charges and thick adsorbed organic layers that serve as a barrier to particle agglomeration. 2) Increased aluminum complexation, involves the increase of oxygenated functional groups following ozonation, especially carboxylic acids. It is proposed that it is the carboxylic and phenolic functional groups in natural organic matter (NOM) that form complexes with aluminum oxide surfaces and thus responsible for organic matter-aluminum surface associations. 3) Increased calcium complexation, comprise of an increase in the number of carboxylic acid groups which leads to an increase in the degree of complexation,
resulting in direct precipitation of the organic matter. 4) Organic polymerization, includes ozone induced oxidative coupling, which may play a role in the coagulation effects of ozone. Oxidative coupling involves the joining of small soluble molecules via C-C and C-O bonds to give large fluvic type molecules and eventually the larger and insoluble humic acid type molecules. It is assumed that small ozone doses could initiate chain polymerization reactions and thus it is expected to see an increase in molecular size resulting in improved removal of organic material by coagulation. 5) Breakup of Fe and Mn complexes, under proper conditions ozone can be effective in breaking up certain types of organic complexes of iron and manganese. This can result in the production of metal coagulants. 6) Reactions with Algae, during the kill or lyses of algae by ozone, a release of biopolymers occurs which may be equivalent to the release of natural organic coagulants (Langlais et al., 1991; Reckhow et al., 1993; Becker & O’Melia, 1996).

Filter performance is assessed by determining the amount of suspended particulate material (or other contaminants) removal and the extent of headloss development that occurs as particulates deposit. It depends on suspended particle properties, the suspending water quality and the filter specifications. Prefiltration process such as ozonation and coagulation alter characteristics of suspended particles to increase the rate of transport to and attachment on filter media. The effects of preozonation on filtration performance are the result of direct or indirect effects of ozone on the concentration, mean size, size distribution and stability of suspended particles applied to the filter (Reckhow et al., 1993). According to Reckhow et al., 1993, “A lower rate of head loss accumulation could be caused by the application and removal of larger suspended particles... A Lower rate
of head loss may also be the result of a reduction in concentration of suspended particles being applied to a filter."

Improved filter performance occurs when; 1) the initial or clean bed removal is improved; 2) the time for filter ripening (period of improving effluent quality) is decreased; 3) a lower steady state filtered turbidity is achieved (Reckhow et al., 1993).
Chapter 3

A.H. Weeks Water Treatment Plant

The Water Treatment Centre consists of two treatment plants, three pumping stations and two reservoirs serving approximately 250,000 people in the City of Windsor, the Town of LaSalle and part of the Town of Tecumseh (former Sandwich South township). The Detroit River provides the only source of raw water for the Water Treatment Centre. The water supply is relatively consistent in quality with varying levels of turbidity as a result of the relatively shallow depth of Lake St. Clair immediately upstream from the river and treatment plant. Treatment is designed to remove the suspended particles and disease producing bacteria/viruses from the water providing water that is both potable and palatable.

The A. H. Weeks water treatment facility was brought on-line in the winter of 1994, replacing an old treatment facility that had been in operation supplying drinking water to the City of Windsor since the mid 1920's. Introduction of ozone as part of the treatment program for the Windsor Utilities Commission treatment plant was completed in June of 2001 with the startup of the newly constructed Ozone Generation and Feed System.

3.1 Treatment Plant System

The A. H. Weeks plant incorporates conventional treatment, which includes screening, coagulation, flocculation, sedimentation, filtration and disinfection, Figure 4-1.
Figure 4-1 A. H. Weeks WTP Process Schematic
The CO₂ System at the A. H. Weeks WTP was supplied by Air Liquide Canada (ALC). It was designed to drop Detroit River raw water pH form 8.1-8.3 to a post CO₂ treatment pH of 7.4. A CO₂ storage tank was supplied to the A. H. Weeks WTP and is continuously filled by ALC bulk distribution department. The CO₂ is injected through a bubble porous stainless steel diffuser positioned at the center of the raw water header. The A. H. Weeks Plant uses CO₂ to decrease its raw water pH before it’s ozonated. This is done because improved inactivation was achieved for reduced pH levels (Sladic, 2001). The presence of hydroxide anions (OH⁻) and H₂O₂ in water can initiate the decomposition of ozone (Hoigne, 1994). By reducing pH values, the OH⁻ and H₂O₂ concentrations decrease producing a stabilizing effect on molecular ozone and thus slow and selective reactions with constituents (Urfer et al., 1999).

The addition and rapid dispersion of liquid aluminum sulphate (Alum) in the incoming river water produces jelly-like pinpoint particles called “floc”. These floc particles attract and enmesh colour particles, bacteria and suspended solids as they form. To assist in the formation of stronger floc particles with increased size and settling characteristics, a cationic polymer Magnafloc LT-22 is added at the time of liquid alum addition. LT-22 is supplied as a granular material that is dissolved in water and the liquid solution of long microscopic chains along with the alum binds the floc particles together.

Flocculation is a process in which small alum floc particles along with polymer are mixed in a series of four mixing chambers. The gentle mixing promotes collisions and attraction to form larger, denser floc particles, which are easier to settle under quiescent...
conditions of the settling basins. The flocculated water is passed through two plate settling tanks at a very slow rate in order to permit most of the floc particles to settle out. This passage allows the suspended material to be removed by gravity. The cleaner effluent (overflow) is then collected in the overflow trough and transported to the filters through a settled water channel.

Fine suspended particles not removed by settling are removed by downward passage through a filter consisting of a bed of graduated gravel, sand and anthracite. The water passes first through a layer of relatively coarse anthracite coal particles where the majority of suspended particles are removed. The next layer of fine sand acts as a "polishing" filter and removes virtually all of the remaining suspended matter. The graded gravel layer acts as a support for the filtering layers of sand and anthracite. The filtrate is collected as a palatable product in a filtered water channel and conveyed to a clearwell reservoir.

As the filtered water enters the clearwell, a stream of Chlorine solution in water is added in a quantity sufficient to destroy any disease causing organisms present and maintain the required concentration residual in the finished water.

Fluoridation of all finished water to a level of 0.6 mg/L of fluoride ion (F) is accomplished by the controlled and precise addition of hydrolufluorisorilic acid. A reduction of the concentration of fluoride in Windsor’s drinking water from 1.0 mg/L to the present level of 0.6 mg/L was initiated in October 2000 as recommended by the
MOE. Monitoring of the final fluoride residual is conducted on a continuous basis at the purification plant. Fluoride is added to help prevent tooth decay in children.

The new Drinking Water Protection Regulation 459/00 utilizes the MOE policies for minimum mandatory treatment requirements. No water should be allowed to enter a distribution system unless it has been treated with chlorination or equivalent. The A. H. Weeks plant follows the regulations by using treatment consisting of chemically assisted filtration and disinfection. Chlorine concentration is maintained at a level of 1.1 ppm as it exits the treatment plant and maintained at a level of 1 ppm as it enters the distribution system. Under MOE Regulations the minimum chlorine residual at the user end should not be below 0.2 ppm.

3.2 Ozone Treatment System

The ozone system was designed to supply ozone for water treatment at the A. H. Weeks Water Treatment Plant. Ozone gas is continuously generated and injected into the raw water as it enters the treatment facility. The addition of ozone destroys bacteria and viruses and oxidizes certain taste and odour causing material.

Oxygen from the LOX (Liquid Oxygen) system passes through ambient vaporizers where it is changed to a gaseous form and finally through inlet filters to feed the ozone generators. A small amount of nitrogen gas is mixed to the inlet gas from nitrogen generator. In the ozone generator the oxygen is exposed to a silent electrical discharge.
Under the influence of this discharge ozone is formed continuously in the gas stream. Each ozone generator has a power supply unit for power and control. To remove heat generated by the ozone generator and power supply unit cooling water is supplied.

The ozone/oxygen mixture from the ozone generators is injected into the contactors through a common header. The flow control valves controls the rate of flow.

In the ozone system contactors, ceramic diffusers distributed in the contact basin diffuse the gas throughout the water in the basins. Treated water exits the basins continuously.

The off-gas from each contactor passes through a demister to a common header to the inlets of the two ozone destruct units. In the destruct units, an electric heater raises the off gas temperature before it enters the ozone destruct chamber where ozone is destroyed by a catalytic reaction. The vent blower vents the ozone free gas to atmosphere.

3.2.1 Liquid Oxygen System

The LOX system at the A. H. Weeks plant was provided by Air Liquide Canada (ALC). Liquid oxygen is drawn from a cryogenic vacuum jacketed storage tank and vaporized through a set of ambient vaporizers. The gaseous oxygen pressure is then reduced from the tank pressure to the required operating pressure with the use of a dual regulator pressure control station. Oxygen then passes through a 2μm dual filter.
Table 3-1 The liquid oxygen quality as supplied by ALC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Purity</td>
<td>≥ 99.5 %</td>
</tr>
<tr>
<td>Dew Point</td>
<td>-64 °C or better at 14.7 psia</td>
</tr>
<tr>
<td>Moisture</td>
<td>≤ 6 ppmv</td>
</tr>
<tr>
<td>Total Hydrocarbons (as Methane)</td>
<td>&lt; 15 ppmv on average</td>
</tr>
<tr>
<td></td>
<td>&lt; 25 ppmv for 80% of the time</td>
</tr>
<tr>
<td></td>
<td>&lt; 40 ppmv for 100% of the time</td>
</tr>
<tr>
<td>Odour</td>
<td>None</td>
</tr>
</tbody>
</table>

The liquid oxygen cryogenic storage tank is made of two vessels, an outer carbon steel shell and a stainless steel inner vessel where the liquid oxygen is stored. A perlite insulation (a fine powder with great insulating characteristics) and drawing of a vacuum in the inter-space minimize heat sink and potential vaporization losses. Figure 4-2 shows a diagram of a typical storage tank.

The ambient vaporizers are used to convert the cryogenic fluid to a gaseous state so that it can be used in the formation of ozone. Ambient air temperature is used to transfer heat to the liquid oxygen thereby converting it to gas. The system is designed to handle the maximum oxygen consumption regardless of the season. Ice racks are designed to handle most of the frost formation resulting from continuous vaporization of cryogenic liquids, making ambient vaporizers more efficient in the process. Ice racks and ambient vaporizers are made of aluminum and are designed for working pressure of up to 400 psig.
Although the specification calls for a minimum oxygen temperature of minus 40 °C, ALC installed a 12 kw electric heater right after the vaporization system. The reason for this addition is that the ozone generators cannot tolerate an oxygen temperature below –1 °C. Given the typical -7 °C difference between ambient temperature and the vaporized oxygen, the oxygen temperature could fall below the threshold on any given winter day. The installation of the trim heater will ensure a smooth operation of the ozone system by maintaining the temperature above the threshold.

The nitrogen generator introduces a small amount of nitrogen in the oxygen feed gas, the proper operation and optimization of the ozone production process requires the addition of a small amount of nitrogen to the feed gas stream. The nitrogen generator was supplied as a complete package including: oil-less compressor, desiccant dryer, filters, valves and controls.

The oxygen filter prevents dust and other contaminants from entering the ozone generators. The filter system is composed of two filter assemblies in parallel, each one complete with isolating valves, housing/cartridge, and pressure drop indicators. The cartridges were sized to stop any particulates larger than 2 μm. It is necessary to maintain the filters regularly to assure proper operation of the ozone generators and can extend the cleaning interval of the generators and reduce maintenance.
Figure 4-2 Typical LOX Storage Tank
3.2.2 Ozone Generation System

The ozone generators produce ozone from enriched oxygen feed at a constant concentration regardless of the flow rate of the gas. An ozone monitor, located in the discharge piping header of the ozone generators is used to control the concentration at a constant value.

Oxygen flows to the ozone generation system, which consists of two medium frequency generator vessels located adjacent to the power supply units. In the generators, oxygen passes through an electric discharge called a corona where a portion of the oxygen is converted to ozone. Each generator is equipped with devices to monitor and protect the generator vessel and power supply unit. Gas flow, temperature and pressure are monitored along with the cooling water flow, temperature to shutdown the generator unit in the event of an unacceptable process parameter. Heat produced from the formation of ozone is removed from the vessel with cooling water.

The ozone generators installed in the A. H. Weeks Water Treatment Plant are supplied by Ozonia North America, NJ (Figure 4-3). Each horizontal tube, water cooled generator is capable of producing ozone at the design conditions specified in Appendix B.
Figure 4-3 A. H. Weeks WTP Ozone Generator Layout
Ozone concentration is controlled by adjusting the applied power. Each generator has the capacity to vary ozone production from 10 to 100% at design gas flow. Although the output concentration, and correspondingly the production, can range from approximately 1 to 14% of ozone by weight, it will typically operate at maximum design production and concentration. The total amount of ozone generated is a function of the number of generators in operation, ozone concentration, the quantity of feed gas and the amount of power applied.

The ozone-generating vessel is a horizontal cylindrical vessel with flanged heads and viton gaskets, which are fully ozone resistant. The ozone vessel end covers are bolted to the vessel by means of the main vessel flanges. The generator end flanges must be separately supported when the flanges are loosened and the vessel is opened. Most generators have a shell mounted davit to hold the end cover. Some covers are removed with overhead cranes or hoists. All metal parts in contact with the feed gas and with ozone are constructed of 316 stainless steel. The ozone-generating vessel is designed to withstand an internal operating pressure of 20.3 psi.

Each ozone generator is powered by a Power Supply Unit (PSU). The PSU includes power electronics equipment, magnetic equipment, feeders and protecting devices. PSU is controlled and monitored by a programmable controller, the PLC communicates with the master ozone control panel PLC via a data highway, plus allowing for remote control and monitoring. In addition, the PLC is also used to control and monitor generator valves and safety interlocks.
Each ozone-generating vessel has a specific number of stainless steel tubes, which are welded in a honeycomb pattern between the end plates of the cylindrical body section. The stainless tubes are the ground electrodes and serve as receptacles for precisely made, non-glass, AT dielectric segments. The high voltage segments are centered so that a small uniform gas gap is created between the stainless steel tube and non-glass segments. This is the area where ozone is formed. These segments are joined and electrically connected. The high voltage applied to the non-glass segments are joined and electrically connected. The high voltage applied to the non-glass segments produces a silent electrical discharge across the circular gap. Under the influence of this discharge, ozone is formed continuously in the feed gas stream. The gas leaving the ozone generator will have a certain ozone concentration when the vessel is operated under design conditions.

Proper operation demands the correct gas flow rate, oxygen quality, oxygen concentration, nitrogen concentration, gas pressure, dew point, cooling water flow rate and cooling water temperature.

Each series of dielectric segments is provided with a fuse. The fusing of segments allows the ozone generator vessel to continue operating if there is a defective segment or a blown fuse. A blown or several blown fuses do not necessarily impact ozone production. The same power from the power supply unit is applied to fewer dielectrics so that a higher power density is felt on the remaining dielectrics. This compensates for the loss of dielectric segments and therefore ozone production remains constant. Dielectric loss can be tolerated to a certain point by the PSU. When the dielectric loss is too great, the PSU
will sound an alarm and go into "current reduction". Up to 10% of fuses can be lost until
the PSU switches to current reduction.

During the production of ozone, heat buildup occurs inside the circular gap between the
non-glass dielectric segment and the stainless steel ground tube of the ozone generator
vessel. The heat produced is removed by cooling water flowing around the outside of the
stainless steel tubes, similar to a shell and tube heat exchanger.

High voltage cables are run from the PSU to the ozone generator vessel and supply the
necessary power, frequency and current needed for ozone production. The vessel body is
grounded to an earth ground.

3.2.3 Ozone Diffusion System

The ozone diffusion system is the means by which ozone is mixed with the water. A
conventional ozone diffusion system is used for the ozone system contactors. The
diffusion grid sits near the bottom of a concrete contact basin, which water to be treated
flows through it mixing with the ozone. The concrete basin has baffled walls inside of it
so that the water flow is counter current with the gas flow. That is, the water is flowing
downwards into the chamber, and the gas is bubbling upwards. The flow of gas to each
chamber can be varied depending on the needs of the system.
3.2.4 Ozone Destruction System

The off gases, containing residual ozone, oxygen and the gaseous byproducts from the ozone reaction are collected in a gas tight system. An applied vacuum by the gas blower draws the gas stream towards the Vent Ozone Destruction Unit (VOD). The gas stream enters the VOD through a demister where entrained droplets of moisture are removed. The gas is then passed across a set of electric resistance heater elements to reduce relative humidity in the gas. After passing the heater a catalyst bed destroys the remaining ozone. The blower then discharges the vent gas to the atmosphere after checking for proper ozone concentration.

3.2.5 Ozone Quenching Agent

Due to the high disinfectant dosages that are needed for the inactivation of Cryptosporidium oocysts especially in cold water temperatures and during high turbidity, the issue of quenching high ozone residuals at the end of the contact zone was addressed.

High ozone residuals in the water could have an impact on downstream processes. Ozone is corrosive to a variety of metals and can cause corrosion of equipment. The high ozone residual may also present a potential health hazard at high ambient air levels. Ozone transferred into the ambient air, could be elevated above levels acceptable for workers safety, and may force a shutdown of the ozone system. Due to these reasons, ozone residuals are to be eliminated before it leaves the contact zone.
Different quenching agents are available to eliminate ozone residuals. At the startup of the ozone system at the A. H. Weeks Plant, sodium bisulfite was used as the ozone quenching agent due to its availability, and fast reaction to eliminate ozone residuals.

A bench scale investigation of ozone quenching agents was conducted to evaluate any possible improvement in the quenching process. Sodium bisulfite and calcium thiosulfate were used in these experiments as the quenching agents. The bench scale results indicated that calcium thiosulfate is a better quenching agent, due to the lower amounts needed to quench the ozone residual, and since it eliminates handling issues, also it does not emit compounds to sodium bisulfids (Table 3-2, Richey et al., 2000). The A. H. Weeks water treatment plant switched its quenching agent to calcium thiosulfate on Dec 27, 2001.

The stoichiometric oxidation reduction reaction that occur in water near a neutral pH and the corresponding weight ratio for both sodium bisulfite and calcium thiosulfate are as follows (Richey et al., 2000).

**Sodium Bisulfite**

\[ \text{NaHSO}_3 + \text{O}_3 \rightarrow \text{Na}^+ + \text{H}^+ + \text{SO}_4^{2-} + \text{O}_2 \]

Stoichiometric Weight Ratio: 104 gm/mole: 48 gm/mole = 2.2 : 1

**Calcium Thiosulfate**

\[ \text{CaS}_2\text{O}_3 + \text{H}_2\text{O} + 4 \text{O}_3 \rightarrow \text{Ca}^{2+} + 2 \text{H}^+ + 2 \text{SO}_4^{2-} + 4 \text{O}_2 \]

Stoichiometric Weight Ratio: 152 gm/mole: 192 gm/mole = 0.8 : 1
<table>
<thead>
<tr>
<th><strong>Ozone Quenching Chemicals</strong></th>
<th><strong>Sodium Bisulfite (NaHSO₃)</strong></th>
<th><strong>Calcium Thiosulfate (CaS₂O₃)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material Type</strong></td>
<td>Reducing Agent</td>
<td>Reducing Agent</td>
</tr>
<tr>
<td><strong>Ozone Reduction Reaction Rate</strong></td>
<td>Fast</td>
<td>Fast</td>
</tr>
<tr>
<td><strong>Handling Issues</strong></td>
<td>Reducing agent fumes and contact and pH</td>
<td>Container size</td>
</tr>
<tr>
<td><strong>Material Requirements</strong></td>
<td>RVC, Corrosive to brass and copper</td>
<td>PVC or CPVC, Corrosive to brass and copper</td>
</tr>
<tr>
<td><strong>pH</strong></td>
<td>+/- 5</td>
<td>6.5-7.5</td>
</tr>
<tr>
<td><strong>Metering pump can lose Prime due to off gas</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Low Temperature Crystalization</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Stoichiometric Weight Ratio</strong></td>
<td>2.2 to 1</td>
<td>0.8 to 1</td>
</tr>
<tr>
<td><strong>Cost per Dry Unit Weight</strong></td>
<td>$0.53/pound</td>
<td>$0.95/pound</td>
</tr>
</tbody>
</table>
Chapter 4

Data Collection & Analysis Methods

The Windsor Utilities Commission has been conducting studies to improve and optimize the performance at the A. H. Weeks Water Treatment Plant (Jasim et al., 2002). The goal is a disinfection related target of reaching a 2-log Cryptosporidium oocyst inactivation in the summer and 1-log Cryptosporidium oocyst inactivation in the winter (Jasim et al., 2002). The objective is to achieve this while minimizing overall plant operational cost. The first step in optimizing any water treatment plant is to gather and document plant data. This data has to be compared to plant treatment and cost goals. Once the areas that need optimization are identified an optimization plan can be drafted and implemented. After initial changes are made, more data is collected and compared to previous data to identify if optimization goals have been met or if more changes have to be done.

4.1 Data Collection:

Data at the A. H. Weeks Water treatment plant is collected via the RSView32 scada system provided by Rockwell Software. The RSView32 scada system software is used for monitoring and controlling automation equipment and processes. Each day, data is collected which include temperature, pH, turbidity, particle counting, CO₂ use, chlorine, fluoride, and amount of water filtered. At the same time data is being gathered on ozone use in the plant, which included; power use, oxygen consumption, ozone production, ozone dosage, ozone residuals, disinfection credit and performance ratio.
4.1.1 Ozone System Monitoring

The ozone system is continuously monitored. "Data collection should focus on water quality impacts, ozone system performance and established targets for meeting ozone system objectives." (DeMers et al., 1996). The most important ozone system parameters to be monitored are 1) Ozone dose, in order to maintain optimal dosage; 2) Disinfection credit, including virus, Giardia and Cryptosporidium oocyst log inactivation to determine how the system is meeting PR targets and 3) Ozone system efficiency, which is used to identify dirty or malfunctioning dielectrics (DeMers et al., 1996). Also the amount ozone quenching agent used is collected, to determine how the actual amount used compares to the theoretical amount used, thus minimizing over dosing of the chemical.

The following Table indicates the data that is collected by the ozone system as well as the frequency that it is collected.

<table>
<thead>
<tr>
<th>Description</th>
<th>PLC Units</th>
<th>Read Frequency</th>
<th>Calculation</th>
<th>Data Min</th>
<th>Data Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Plant Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plant Raw Water Flow</td>
<td>m³/min</td>
<td>1/10min.</td>
<td>Average 6 hourly readings into 1 archived hourly reading.</td>
<td>0</td>
<td>9999</td>
</tr>
<tr>
<td>Plant Raw Water Temperature</td>
<td>°C</td>
<td>1/10min.</td>
<td>Average 6 hourly readings into 1 archived hourly reading.</td>
<td>4.4</td>
<td>93.3</td>
</tr>
<tr>
<td>Total Plant Ozone Production</td>
<td>kg/hr</td>
<td>1/5min.</td>
<td>Average 12 hourly readings into 1 archived hourly reading.</td>
<td>0</td>
<td>??</td>
</tr>
<tr>
<td>Plant Inlet GOX Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GOX Inlet Temperature</td>
<td>°C</td>
<td>1/10min.</td>
<td>Average 6 hourly readings into 1 archived hourly reading.</td>
<td>-45.6</td>
<td>65.6</td>
</tr>
<tr>
<td>GOX Inlet Pressure</td>
<td>psig</td>
<td>1/10min.</td>
<td>Average 6 hourly readings into 1 archived hourly reading.</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>GOX Purity</td>
<td>%</td>
<td>1/10min.</td>
<td>Average 6 hourly readings into 1 archived hourly reading.</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>GOX Dewpoint</td>
<td>°C</td>
<td>1/10min.</td>
<td>Average 6 hourly readings into 1 archived hourly reading.</td>
<td>-110</td>
<td>80</td>
</tr>
</tbody>
</table>
### Ozone Generator No.1 and No. 2 Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Interval</th>
<th>Reading Method</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>OZG1 &amp; 2 Oxygen Inlet Gas Flow</td>
<td>Nm³/hr</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 610</td>
</tr>
<tr>
<td>OZG1 &amp; 2 Oxygen Inlet Gas Pressure</td>
<td>bar</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 3</td>
</tr>
<tr>
<td>OZG1 &amp; 2 Oxygen Inlet Gas Temperature</td>
<td>°C</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 70</td>
</tr>
<tr>
<td>OZG1 &amp; 2 Ozone Outlet Concentration</td>
<td>%/wt</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 15</td>
</tr>
<tr>
<td>OZG1 &amp; 2 Ozone Outlet Gas Temperature</td>
<td>°C</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 70</td>
</tr>
<tr>
<td>OZG1 &amp; 2 PSU Setpoint</td>
<td>%</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 100</td>
</tr>
<tr>
<td>OZG1 &amp; 2 Instantaneous Power</td>
<td>kW</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 400</td>
</tr>
<tr>
<td>OZG1 &amp; 2 Ozone Production</td>
<td>kg/hr</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 ??</td>
</tr>
</tbody>
</table>

### Ozone Contactor No.1 and 2 Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Interval</th>
<th>Reading Method</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contactor 1 &amp; 2 Inlet Gas Flow</td>
<td>Nm³/hr</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 300</td>
</tr>
<tr>
<td>Contactor 1 &amp; 2 Off-Gas Pressure</td>
<td>mmH₂O</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>-635 254</td>
</tr>
<tr>
<td>Contactor 1 &amp; 2 Off-Gas Ozone Concentration</td>
<td>%/wt</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 4</td>
</tr>
<tr>
<td>Contactor 1 &amp; 2 Analyzer No.1 Ozone-In-Water Residual</td>
<td>ppm</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 10</td>
</tr>
<tr>
<td>Contactor 1 &amp; 2 Analyzer No.2 Ozone-In-Water Residual</td>
<td>ppm</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 10</td>
</tr>
<tr>
<td>Contactor 1 &amp; 2 Analyzer No.3 Ozone-In-Water Residual</td>
<td>ppm</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 10</td>
</tr>
<tr>
<td>Contactor 1 &amp; 2 Performance Ratio</td>
<td></td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 100</td>
</tr>
<tr>
<td>Contactor 1 &amp; 2 Crypto Log Inactivation</td>
<td>log</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 100</td>
</tr>
<tr>
<td>Contactor 1 &amp; 2 Virus Log Inactivation</td>
<td>log</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 100</td>
</tr>
<tr>
<td>Contactor 1 &amp; 2 Virus Log Inactivation</td>
<td>log</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 100</td>
</tr>
</tbody>
</table>

### Vent Ozone Destruct No.1 & 2 Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Interval</th>
<th>Reading Method</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vent Gas Ozone Concentration</td>
<td>ppm</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 10</td>
</tr>
</tbody>
</table>

### Quenching Agent Data

<table>
<thead>
<tr>
<th>Quenching Agent Storage Tank Level</th>
<th>%</th>
<th>1/hour</th>
<th>Reading Method</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quenching Agent Storage Tank Level</td>
<td>%</td>
<td>1/hour</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 100</td>
</tr>
<tr>
<td>Metering Pump No.1 Stroke Rate</td>
<td>strokes/min</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 180</td>
</tr>
<tr>
<td>Metering Pump No.2 Stroke Rate</td>
<td>strokes/min</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 180</td>
</tr>
<tr>
<td>Metering Pump No.3 Stroke Rate</td>
<td>strokes/min</td>
<td>1/5min</td>
<td>Average 12 hourly readings into 1 archived hourly reading</td>
<td>0 180</td>
</tr>
</tbody>
</table>
4.1.2 Filtration Plant Daily Operation System Monitoring

The A. H. Weeks water treatment centre collects data related to daily plant operation. The data is continuously updated by the plant's Historian system. Every hour the data is compiled and then a 24 hr daily average is recorded. At the end of the month a spreadsheet is prepared which includes the daily averages of the data as well as the monthly average, High and low values for that month and the total. The plant operational data collected includes information on water flow, chemical dosages, turbidity, pH, temperature, aluminum, filter run, and carbon dioxide use.

4.1.2.1 Particle Count

Particle count is considered one of the methods for monitoring water quality. It provides more information and greater sensitivity since particles are individually sized & enumerated (Hargesheimer et al., 1992). Turbidity and particle counting cannot be related because turbidity is a one-dimensional measure of water clarity and particle counting is a two-dimensional measure (Hargesheimer et al., 1992). Three types of particle counting exists, discrete batch sample mode, online sample mode or a combination of both. On-line particle counting is preferred because it provides a real time picture of particulates in a process stream (Hargesheimer et al., 1992). At the A. H.
Weeks water treatment plant, particle counts are used to evaluate filter performance. Generally, particle counting installations in full-scale treatment plants monitor source water as well as filter effluent particulate concentrations (Hargesheimer & Lewis, 1995). The particle size ranges that is of most interest to the drinking water industry are 2-5 µm and 5-10 µm this is due to Cryptosporidium parvum oocysts being spheres of 3-5 µm, while Giardia cysts are elliptical with a size range of 8-14 µm long and 7-10 µm wide (Hargesheimer et al., 1991). During start up of the ozone implementation at the A. H. Weeks WTP, only filters 3 and 6 had particle counters connected to them, thus data was collected from these filters to be compared to the year before ozone implementation. Currently, nine Chemtrac Laser Trac on-line particle counters are used in the A. H. Weeks plant, one for raw water and one on each of the eight filters. Tracware, a custom software program for trending, storing and reporting data, collects the data produced from the filters and raw water particle counters.

4.2 Data Analysis & System Modification

Data that is collected from the ozone system and filtration plant daily operation is input into system monitoring spreadsheets to allow for daily, weekly, and monthly trending. This data is later used to assess the performance of the plant and how it relates to optimization. Graphs and tables are used to show the trends in the data and to identify the areas that need optimization. Data from prior years was collected and compared to recent data to show how ozone has optimized the plant operation and its filtrate quality. Optimization criteria; such as performance ratio, ozone consumption, energy consumption, and chemical consumption, were finally used to assess the operation of the
plant. Areas that needed optimization were identified and system modifications were implemented.

System modifications to enhance the A. H. Weeks WTP performance included: 1) Reduction of PR targets; 2) implementation of CT-Trim Control for Dosage automation; 3) Use of the IDDF method approximation for disinfection credit calculations; 4) Automation of the ozone quenching agent addition; and 5) Maintenance of the Ozone Generators.

4.2.1 PR Target Modification

Performance Ratio modifications are implemented when plant performance is strained to meet a set target. At the A. H. Weeks WTP the PR target was originally set to 2 log Cryptosporidium inactivation credit. During the winter months when temperatures were below 5 °C the plant needed to pump high ozone dosages to meet the PR target. At the same time quenching agent use had to be increased to meet the excess ozone residual. Due to this the plant Cryptosporidium log inactivation credit was lowered to 1 log during the winter months.

4.2.2 CT Trim Control

At the end of February the plant was switched from Dosage Control to CT Trim Control. During Dosage Control the plant staff increased the dosage manually to meet the target PR, however with the CT Trim Control, the Dosage is controlled automatically, dosage is
changed in small increments to meet the required amount needed and thus there is a small change in the process at a time.

4.2.3 IDDF Method Approximation

The IDDF Method was chosen by the A. H. Weeks WTP due to its accuracy in calculating Cryptosporidium log inactivation credit. However, the IDDF method was very calculation intensive and difficult to program to scada. Thus an IDDF Approximation was used, where the log inactivation calculation of the actual IDDF was done and compared to the log inactivation calculation using the Log Integration method and substituting the short circuiting ratio ($T_{10}/T$) values to meet a suitable ratio that provides close results to the actual IDDF.

4.2.4 Ozone Quenching Agent Addition

The calcium thiosulfate quenching agent solution used at the A. H. Weeks is at a 30 percent concentration by mass. At the beginning of the operation, the quenching agent was added manually. Later in the year the quenching agent was added automatically depending on the residual readings from the first flocculation tank. The amount added is calculated as follows.

S. G. of $\text{CaS}_2\text{O}_3 = 1.245$

$1 \text{ g of } O_3 = 0.8 \text{ g of } \text{CaS}_2\text{O}_3 \text{ and } 2.67 \text{ g of } \text{CaS}_2\text{O}_3 \text{ solution at } 30 \% \text{ concentration}$

Volume of $\text{CaS}_2\text{O}_3 = (Q \times O_3 \text{ Residual} \times 2.67)/ \text{S. G. CaS}_2\text{O}_3$

(12)

Where, $Q$ = plant flow rate and S. G. = Specific Gravity

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4.2.5 Ozone Generator Maintenance

The ozone generator power and efficiency measurements are most important to determine how well an ozone generator is performing and when maintenance is needed (DeMers et al., 1996). It is very important that the ozone generators internal parts including dielectrics are kept clean and that fuses are checked. Maintaining the ozone generator will ensure peak performance.
Chapter 5

Results and Discussion

Results are presented in three sections in this chapter. First, data showing the filter plant performance improvement achieved by comparing two separate years, one prior to ozone application and the other after ozone was applied. The second section shows how the plant has performed since ozone has been applied as a primary disinfectant. Finally the discussion concentrates on the cost benefits of the use of ozone.

5.1 Effect of Ozone on Filtration Plant Daily Operation

This section will focus on comparing the year before ozone was applied, June 2000 to May 2001, at the A. H. Weeks Water Treatment Plant versus the year after ozone was applied, June 2001 to May 2002, to see the effects of ozone addition on filtration plant daily operation.

Comparing the raw water quality between the two years shows significant changes in some raw water parameters. Raw water turbidity is shown to be much higher during the year when ozone was applied (Figure 5-1). The pre ozone year also shows on average higher temperatures during the winter and spring months (Figure 5-2). During some months raw water turbidity was 10 times higher than that during the year when ozone was not used. Raw water pH for both years are found to be comparable (Figure 5-3).
Figure 5-1 Raw Water Turbidity

Figure 5-2 Raw Water Temperature
Figure 5-3 Raw Water pH

Ozone addition has been shown to improve water treatment plant performance. Data collected during this study shows that filter performance has improved since the addition of ozone. Filter run time was on average longer during the year when ozone was applied (41.2 hrs) compared to that before the ozone implementation (34.8 hrs), Figure 5-4. The only time filter run time was shorter was during the beginning stages of implementing the ozone system, at which time more filtered water was pumped. The improvement of the filter run time can also be shown through comparing filter run time with settled turbidity. Though settled turbidity which is applied to the filter was on average higher during the year ozone was applied we were able to achieve longer filter run time, Figure 5-5. It is shown that even at times of much higher raw water turbidity, filter run times were longer during the pre ozone year, Appendix A Figure A-1. The percent filter reduction of settled
water turbidity has increased since ozone was implemented thus showing better filter turbidity removal, Figure 5-6. Raw water yearly average turbidity for the year ozone was used was 31.3 NTU and for the year before ozone use was 14.3 NTU. Settled & filtered water turbidity was 1.76 NTU & 0.07 NTU for pre Ozone and 2.48 NTU & 0.05 NTU for post ozone implementation, respectively. The ratio of backwash water to filtered water was also lower during most of the post ozone year indicating that less volume of backwash water was used per volume of filtered water used, Figure 5-7. The yearly average of backwash water to filtered water ratio was 2.1 during the year ozone was applied and 2.7 for the previous year. This is due to the longer filter run times, since the filters had to be backwashed less often the volume of backwash water was decreased.

Filtered Water Data

![Filtered Water Data Graph](image)

Figure 5-4 Filtered Water Data, Showing Filtered Water Used Versus Filter Run Time
Figure 5-5 Turbidity versus Filter Run Time for the year before ozone and after ozone application

Figure 5-6 Percent Reduction of Settled Water Turbidity in Filter.
Figure 5-7  Ratio of Backwash Water Used to Filtered Water Used

Chemicals used in coagulation and flocculation, are very important to the water treatment process. Pre-coagulation ozonation at the A. H. Weeks Plant made an improvement to the coagulation process. Raw water quality plays a major role in determining the efficiency of ozone as a coagulant aid. Thus it is difficult to predict how ozone will affect the process since raw water quality is always changing. However at the A. H. Weeks water treatment plant the following trends were observed. Figure 5-8 shows that even though raw water turbidity was much higher during the year ozone was applied, filtered water turbidity was lower than prior to the ozone application. The percent reduction between the raw water and filtered water turbidity is shown in Figure 5-9. During the start up process, ozone was added during the day and shut down during the night. Filtered water turbidity was reduced from 0.06 NTU to 0.03 NTU, Figure 5-10. This data
shows that the addition of ozone to Detroit River water improves its filtered water quality.

Alum or poly aluminum chloride (PACl) is used as the coagulant, and Magnafloc LT-22 is used as the coagulant aid. Magnafloc LT-22 average dosage was lower (0.063 kg/ML) during the ozone application year compared to the dosage before ozone application (0.079 kg/ML), except during January 2002 when Turbidity was 10 folds higher than the previous year (Figure 5-11). However, Coagulant use was higher throughout the year when ozone was implemented, Figure 5-12. The higher values of Alum can be a result of the very high raw water turbidities encountered during that year, also PACl was used during the year before ozone was implemented. In previous studies done at the A. H. Weeks WTP, the use of PACl on Detroit River raw water decreased the amount of coagulant use by almost half, however its cost is also almost double that of Alum.

**Figure 5-8** Raw Water Turbidity versus Treated Water Turbidity for Pre and Post O₃ years
Figure 5-9 Percent Reduction between Raw Water and Filtered Water Turbidity

Figure 5-10 Pre-Coagulation Ozonation effect on Turbidity During Start Up
Figure 5-11  Turbidity versus Magnafloc LT-22 use for the Year Before and After Ozone Application.

Figure 5-12  Turbidity versus Coagulant use for the year Before and After Ozone Application.
The use of pre-coagulation ozonation improved particle removal compared to the previous year when ozone was not in use, especially for size ranges of 2-5 μm and 5-10 μm, which are the size ranges for some pathogens. The filter run time has also increased since the use of ozone. Filter 3 and 6 were compared in this study to show how ozone application has improved the reduction of particle count for filtered water (Figures 5-13, 5-14, also Appendix A; Figure A-2, Figure A-3).
5.2 Ozone System Optimization

Many improvements in the ozone system operation were observed throughout a full year of ozone system monitoring. The most important parameters monitored were performance ratio, ozone production and energy consumption. By monitoring these parameters we were able to identify how well the ozone system at the A. H. Weeks Plant has been operating.

The A. H. Weeks Water Treatment Plant operates its ozone system to meet a 2-log Cryptosporidium oocyst inactivation credit goal in the summer, and a 1-log Cryptosporidium oocyst inactivation credit goal in the winter. The target Performance Ratio (PR) was set originally to be in the range of 0.9 to 1.2. During the beginning months of ozone system operation the PR reached values above the target range. The PR levels were closer to the target range by September 2001, however once temperatures dropped during the winter months, it was difficult to achieve a 2-log removal. The high amount of ozone required, during the winter months, and the difficulty in quenching high residual levels at the flocculation tanks, which could exceed 1.00 mg/L and would cause the system to shutdown due to an excess ozone concentration in ambient air. When raw water temperature was lower than 1°C, at the end of December 2001, a 1-log Cryptosporidium parvum inactivation credit goal was set, which is still considered superior disinfection by the water treatment industry.

At the end of February 2002 the plant was switched from Dosage Control to CT Trim Control. Initially, during Dosage Control the plant staff increased the dosage manually to
meet the target PR. However with the CT Trim Control, the Dosage is controlled automatically, dosage is changed in small increments to meet the required amount needed and thus there is a small change in the process at a time. Figures 5-15 and 5-16 show how the PR at the A. H. Weeks Water Treatment Plant has improved throughout the year. After the implementation of CT Trim Control it was observed that the PR ratio was met at a more consistent level. During the month of July the system was being tested to prepare for the generator performance tests and that is the reason for the high ozone dosages and the high PR.

**Performance Ratio vs Raw Water Quality**

![Graph showing PR range, Crypto Log change, and Temp C, pH, Turbidity (NTU) over months]

**Figure 5-15** Performance Ratio versus Raw Water Quality at the A. H. Weeks Water Treatment Plant.
Figure 5-16 A. H. Weeks Water Treatment Plant Performance Ratio Throughout the First Year of Operation
Ozone should be applied at the lowest possible dose while maintaining a target performance ratio, in-order to meet optimal plant performance and lower cost. Many factors affect the amount of ozone needed to meet the target PR. Water quality, such as temperature and turbidity effect ozone affectivity and thus as turbidity increases and water temperatures drop, ozone dose increases to be able to meet the extra demand due to the high turbidity and lower inactivation rate due to the lower temperature (Figures 5-17, and 5-18). When temperature rises, ozone is less soluble and less stable in water but the reaction rate with the substrate increases (Langlais et al., 1991). Sladic (2001) found that a higher operating temperature of 21 °C met the required log inactivation at a lower initial ozone dosage with the baffled contactor than at the lower operating temperature of 5 °C. Throughout a full year of monitoring of the A. H. Weeks Water Treatment Plant the ozone dose was modified without compromising the PR. The ozone dosages were sporadic however, after the plant dosage addition was automated, in the end of February, by switching to CT Trim Control the ozone dosage was controlled in a more refined manner (Figure 5-18).

![Ozone Dose vs Turbidity & Temperature](image)

**Figure 5-17** Monthly Average Ozone Dose versus Turbidity and Temperature
Figure 5-18 Daily Average Ozone Dose versus Turbidity

[Diagram showing daily average ozone dose versus turbidity with a trend line and turbidity values on the Y-axis and ozone dose on the X-axis.]
Figure 5-19 indicates that ozone residual increase with ozone dose increase. The ozone residual profile shows that ozone decay increases in the summer and thus we are able to yield lower residuals during that time, Figure 5-20. Turbidity also is a factor that reduces ozone residual by increasing ozone demand, Figure 5-21. As turbidity increases, ozone residual decreases.
Figure 5-19 Daily Average Ozone Dose versus Daily Average Ozone Residual
Figure 5-20 Daily Average Ozone Residual versus Temperature

[Graph showing a relationship between residual and temperature over a period of time, with data points and dates along the vertical axis and temperature on the horizontal axis]
Figure 5-21 Daily Average Ozone Residual versus Turbidity

- **Ozone Residual (mg/L)**
- **Turbidity (NTU)**

Legend:
- Black line: Turbidity
- Red line: Ozone Residual

Data points for dates from 11/26/2001 to 7/31/2002.
The Ontario Ministry of the Environment regulation 459/00 indicated the required log inactivation for Giardia and virus for a surface water source is 3-log and 4-log respectively. Through conventional treatment 2.5-log inactivation of Giardia is achieved and 2-log inactivation of virus (MOE, Regulation 459/00). Ozone application at the A. H. Weeks Plant provides a much higher log inactivation than is required by the regulations (Figure 5-22). Giardia inactivation range was 11 to 33-log inactivation, Figure 5-23, and virus inactivation range was 23 to 67-log inactivation, Figure 5-24.

![Log Inactivation Credit](image)

**Figure 5-22 Log Inactivation Credit for Virus, Giardia and Cryptosporidium**
Figure 5-23  Giardia Log Inactivation Credit

Figure 5-24  Virus Log Inactivation Credit
During plant Start up the log integration method was used to calculate *Cryptosporidium* oocyst inactivation credit. Later on, the IDDF method was adopted by the A. H. Weeks Water Treatment Plant to measure *Cryptosporidium* oocyst Log inactivation. The IDDF was chosen because it provided the plant with a more accurate log inactivation. It was able to yield a higher value of inactivation than the log integration method, Figure 5-25, thus allowing the plant to operate at optimal conditions. Since the IDDF method is much more calculation intensive and is difficult to program to SCADA, the log integration calculations were used to approximate the IDDF calculations by adjusting the short circuiting ratio ($T_{10}/T$) set point.

![IDDF vs Log Integration](image)

**Figure 5-25** IDDF versus Log Integration Method
To approximate the IDDF Method the log inactivation calculation of the actual IDDF was done and compared to the log inactivation calculation using the Log Integration method and substituting the short circuiting ratio \( (T_{10}/T) \) values to meet a suitable ratio that provides close results to the actual IDDF. The actual IDDF is calculated using a \( T_{10}/T \) value of 75% for the contactors and the flocculation basins we assumed to be complete-mix reactors. The results of the actual IDDF versus the approximated IDDF method using Log Integration, with a \( T_{10}/T \) of 99% for the contactor and 15% for the Flocculation basins, is shown in Figure 5-26. Notice that the calculated Crypto credit using the IDDF, represented by the point values, is almost always slightly higher than the Crypto credit calculated using Log Integration method, represented by the line.

![Graph](image)

**Figure 5-26** Crypto Credit Calculation using the IDDF Method versus the Log Integration Method using a Short Circuiting Ration = 99%
The A. H. Weeks uses calcium thiosulfate as their ozone quenching agent. The amount of calcium thiosulfate quenching agent used depends on the ozone residual exiting flocculation tank A. The chemical is then added at the exit of flocculation tank B, Figure 2-1. The relation between ozone residual and quenching agent is seen in Figure 5-27. During the summer months, the use of ozone quenching agent is lower due to the increased ozone decay rate at higher temperature, Figure 5-28. During the beginning of the ozone treatment the quenching agent was added manually, however at the end of February the system was automated allowing for better control of the amount of quenching agent used and thus less over dosing. During the time that quenching agent was monitored, it can be seen that the actual amount of agent used is close to theoretical values, Figure 5-29.
Figure 5-27 Effect of Ozone Residual on Amount of Ozone Quenching Agent Used
Figure 5-29 Ozone Quenching Agent Used to Theoretical Ozone Quenching Agent Used Ratio
About 75 percent of an ozone system's annual operating cost is for electricity (DeMers et al., 1996). The A. H. Weeks monthly average ozone generator power is shown in Figure 5-30 along with ozone production and generator efficiency. Ozone generator power and demand decreased during the year, and ozone generator efficiency increased. This is due to the maintenance that was done on the ozone generator during the month of May. The maintenance included cleaning of the generator and LOX lines. Soon after the generators were cleaned their efficiency increased to the highest level for the year monitored.

![Monthly Average Power Demand & Ozone Production vs Ozone Generator Efficiency](image)

Figure 5-30 Monthly Average Power Demand & Ozone Production versus Ozone Generator Efficiency
5.3 Cost Analysis

Industry is always looking for ways to decrease their operational cost. Part of plant optimization is decreasing operational cost while maintaining the quality of the water produced. The A. H. Weeks Water Treatment Plant collected data on operational cost. This data included chemical and hydro costs. The chemicals used in the plant operation include the coagulant Alum or poly aluminum chloride (when it was used briefly in 2001), the coagulant aid Magnafloc LT-22, Powder Activated Carbon for taste and odour control and chlorine for maintaining a residual in the distribution system. Table 5-1 shows the difference in chemical cost for pre and post ozone years.
Table 5-1 Chemical Cost for the year before ozone and after ozone implementation

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Alum</td>
<td>573,445.2</td>
<td>693,502.67</td>
</tr>
<tr>
<td>Poly Aluminium Chloride</td>
<td>126,805.70</td>
<td>0</td>
</tr>
<tr>
<td>Magnafloc LT-22</td>
<td>30,453.97</td>
<td>24,150.32</td>
</tr>
<tr>
<td>Chlorine</td>
<td>102,153.00</td>
<td>109,346.60</td>
</tr>
<tr>
<td>Powder Activated Carbon</td>
<td>493,500.00</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>1,326,357.86</td>
<td>826,999.63</td>
</tr>
</tbody>
</table>

There was a significant savings in chemical cost since the implementation of ozone at the A. H. Weeks Water Treatment Plant. The coagulant use savings since ozone was implemented was $6,748.23 per year. The savings of coagulant aid use totaled $6,303.65 per year. The cost of chlorine increased by $7,193.60 per year. The use of Powder Activated Carbon was eliminated since ozone was implemented, saving the utilities $493, 500.00 per year. Even though the plant pumped 1373.85 ML more during the year ozone was used it still managed to reduce chemical cost by $499, 358.23.

Figure 5-32 shows the weekly average ozone cost, which includes hydro, quenching agent and liquid oxygen cost. Figure 5-33 shows the monthly average ozone hydro cost versus monthly average plant flow rate. Ozone cost was decreased since the start up of the ozone system. By the end of the monitoring year of the ozone cost we can see that ozone cost was lower by approximately 18 percent. The total ozone cost for the year was $251, 393.75. Therefore the price associated with the use of ozone including chemical
cost is 1,078,393.35, which yields a total saving of $247,964.55, since ozone was implemented. Thus the price of chemical use per mega liter of filtered water for the year before was implemented was $22.17/ML and the cost of ozone production including chemical use per mega liter for the year ozone was implemented is $17.62/ML, which is a savings of $4.55/ML during the year ozone was used.

Ozone Cost per Day Based on a Weekly Average

![Ozone Cost Graph]

Figure 5-32 Weekly Average Ozone Cost Per Day
Figure 5-33  Monthly Average Ozone Cost versus Plant Flow Rate
Chapter 6

Conclusions

This study investigated the potential of ozone on the improvement of the A. H. Weeks Water Treatment Plant performance. The potential for optimization of the A. H. Weeks ozone system was studied. The effect of ozone on chemical use was also investigated. Finally a cost evaluation of the system conducted to show the cost savings from implementing ozone disinfection at the plant. The following conclusions are based on these findings.

In general, it is concluded that The A. H. Weeks Water Treatment Plant operation was improved since the addition of ozone, specifically:

- Filter performance was improved since the addition of ozone. Filter run time was on average longer during the year when ozone was applied (41.2 hrs) compared to the year before ozone was applied (34.8 hrs). Filtered water average yearly turbidity (0.05 NTU) was lower during the year ozone was used than the year before ozone was implemented (0.07 NTU). There was also an increase in percent reduction of filtered turbidity of the settled water.

- Less volume of back wash water was used per volume of filtered water during the year ozone was implemented compared to the year before ozone was implemented.

- The use of pre-coagulation ozonation improved particle removal especially for size ranges of 2-5 μm and 5-10 μm, which are pathogen sizes.
The Ozone system at the A. H. Weeks Water Treatment Plant was optimized through the implementation of CT Trim Control, a decrease in Cryptosporidium inactivation target during the winter, the use of the IDDF method approximation for the calculation of Cryptosporidium log inactivation, the automation of ozone quenching agent addition, and the cleaning of the ozone generator.

- Performance Ratio was improved throughout the year. The range of plant PR was refined after CT Trim Control was introduced as a dosage control process.
- Meeting PR target was also easier when the Cryptosporidium inactivation target was lowered.
- Ozone dosage was controlled in a more refined manner after the implementation of the CT Trim Control.
- After automation the ozone quenching agent addition was refined. Over dosing was infrequent, and thus the actual amount of quenching agent used was close to the theoretical values.
- Meeting the goal of 1-2 log inactivation credit of Cryptosporidium oocysts provided inactivation credit for Giardia and viruses in excess to the total regulatory requirement of 3 and 4 log inactivation/removal.
- The IDDF approximation was able to yield a higher value of inactivation than the Log Integration method.
- Power requirement for the ozone generator decreased during the year, and ozone generator efficiency increased by approximately 6.95%.
Chemicals used in the operation of the A. H. Weeks Water Treatment Plant include Alum or Poly Aluminum Chloride for Coagulation, Magnafloc Lt-22 as a coagulant aid, Chlorine for disinfectant residual, and Powder Activated Carbon for taste and odour control.

- The yearly average amount of Magnafloc Lt-22 dosage was lower (0.063 kg/ML) during the year ozone was implemented compared to the previous year (0.079 kg/ML).
- Although coagulant dosage increased, the use of PACl was eliminated, and this produced an overall saving in coagulant cost.
- The use of powder activated carbon was eliminated after ozone implementation.
- The use of chlorine was on average slightly higher during the year ozone was applied, 1.71 kg/ML compared to 1.64 kg/ML.

One of the main reasons for optimization is to decrease the cost of operation, while maintaining equivalent or improved performance.

- Over all, the chemical savings were a total of $ 499,358.23, which amount to a saving of $ 8.66/ML.
- By the end of the monitoring year, ozone cost decreased by approximately 18 percent, which is a direct result of the optimization of the plant.
- The price for chemical before ozone implementation was $ 22.17/ ML and the cost of ozone production including chemical use per mega liter for the year ozone was implemented is $ 17.62/ ML, which is a savings of $ 4.55/ ML during the year ozone was used.

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References


Appendix A

A. H. Weeks Plant Operation Graphs
Figure A-1 Raw Water Turbidity vs Filter Run Time
Figure A-2  Before Ozone Application Filter 6 Particle Count Data for May 15-16, 2001

Figure A-3  After Ozone Application Filter 6 Particle Count Data for May 14-17, 2002
Appendix B

Ozone System Specifications
OXYGEN SPECIFICATION FOR
OZONIA’S
OZONE GENERATORS

Minimum Requirements

<table>
<thead>
<tr>
<th>Component</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>&gt; 90 wt%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>500 ppm range up to 5 wt%</td>
</tr>
<tr>
<td>Dew Point (atmospheric pressure)</td>
<td>&lt; -60 C</td>
</tr>
<tr>
<td>Moisture content</td>
<td>&lt; 10 ppmv</td>
</tr>
<tr>
<td>Total hydrocarbons (expressed as</td>
<td>&lt; 15 ppmv on average</td>
</tr>
<tr>
<td>CH₄)</td>
<td>&lt; 25 ppmv 80% of the time</td>
</tr>
<tr>
<td></td>
<td>&lt; 50 ppmv 100% of the time</td>
</tr>
<tr>
<td>Freons or similar</td>
<td>To be vented totally before startup</td>
</tr>
<tr>
<td>Solvents</td>
<td>To be vented totally before startup</td>
</tr>
<tr>
<td>Particle size</td>
<td>&lt; 2 μm, particle buildup to be avoided</td>
</tr>
<tr>
<td>Remainder</td>
<td>Essentially Argon</td>
</tr>
</tbody>
</table>

Service parameters

Temperature

Temperature: > 5°C > 41°F
< 90°C < 194°F

Pressure at ozone generator inlet

For VPSA & VSA: 0.9 to 1.5 bar g 13.1 to 21.8 psig
For PSA & LOX: 1.0 to 2.5 bar g 14.5 to 36.3 psig
For OZAT units: 2.5 to 7.0 bar g 36.3 to 101.5 psig

Delivery pressure: ± 100 mbar ± 1.45 psi
## Recommended Water Quality Characteristics for Ozone Generators

<table>
<thead>
<tr>
<th>Water Quality Characteristics *1)</th>
<th>Cooling Water mg/l</th>
<th>Chilled Water mg/l</th>
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</thead>
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<tr>
<td>Chloride or any compound of chlorine</td>
<td>&lt; 50</td>
<td>&lt; 50</td>
</tr>
<tr>
<td>Iron *1)</td>
<td>*1)</td>
<td></td>
</tr>
<tr>
<td>Silica *1)</td>
<td>*1)</td>
<td></td>
</tr>
<tr>
<td>Manganese *1)</td>
<td>*1)</td>
<td></td>
</tr>
<tr>
<td>Calcium *1)</td>
<td>*1)</td>
<td></td>
</tr>
<tr>
<td>Total Hardness (as CaCO3) *1)</td>
<td>*1)</td>
<td></td>
</tr>
<tr>
<td>Total Alkalinity (as CaCO3) *1)</td>
<td>*1)</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>7 – 9</td>
<td>7 – 9</td>
</tr>
<tr>
<td>Turbidity measurement (TE/F)</td>
<td>&lt; 0.2</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>Total Dissolved Solids *1)</td>
<td>*1)</td>
<td></td>
</tr>
<tr>
<td>Total Suspended Solids *1)</td>
<td>*1)</td>
<td></td>
</tr>
<tr>
<td>Specific Conductivity *2), *3)</td>
<td>&lt; 20 μS/ cm</td>
<td>&lt; 20 μS/ cm</td>
</tr>
<tr>
<td>Others</td>
<td>As per sheet No. 2</td>
<td>As per sheet No. 2</td>
</tr>
</tbody>
</table>

### Note:

*1) As a general guideline, the cooling water quality shall comply with local potable water regulations. If potable water is not available please contact Ozonia North America for recommendations.

*2) In closed loop cooling water systems.

*3) Unit in Siemens (S) = SI unit of conductance. "mho" is used for this unit in the USA.
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<thead>
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<th>TECHNICAL DATA</th>
<th>ENGLISH UNITS</th>
<th>SI UNITS</th>
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</thead>
<tbody>
<tr>
<td>Ambient pressure</td>
<td>14.69 psig</td>
<td>1.013 bar</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>96 °F max.</td>
<td>30°C max.</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>100 % max.</td>
<td></td>
</tr>
</tbody>
</table>

| FEED GAS                                         |               |            |
| Feed gas                                         | Liquid Oxygen  |            |
| Inlet gas composition                            | (O2+N2+Ar/Inerts) | (97.7% O2 + 2.3% N2 + Ar/Inert) |
| Minimum feed gas quality                         | As per Data Sheet A14000-10-0101 "Oxygen Specification for Ozonia's OG" |
| Specific feed gas quality                        | As specified within this document |
| Pressure from the feed gas system max            | 20.31 psig    | 1.40 bar g |
| Design liquid oxygen mass flow rate              | 45,194.94 lb/d | 854.17 kg/h |
| Gas temperature to ozone generator               | 86 °F approx.  | 30 °C approx. |
| Free of contaminates                              | Oil and dust free |
### TECHNICAL DATA

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<th>ENGLISH UNITS</th>
<th>SI UNITS</th>
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<td>1.013 bar</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>86 °F max.</td>
<td>30 °C max.</td>
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<tr>
<td>Relative humidity</td>
<td>100 % max.</td>
<td></td>
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### FEED GAS

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<tr>
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<th>ENGLISH UNITS</th>
<th>SI UNITS</th>
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<tbody>
<tr>
<td>Feed gas</td>
<td>Liquid Oxygen</td>
<td></td>
</tr>
<tr>
<td>Inlet gas composition</td>
<td>(O2+N2+Ar/Inerts)</td>
<td>(97.7% O2 + 2.3% N2 + Ar/Inert)</td>
</tr>
<tr>
<td>Minimum feed gas quality</td>
<td>As per Data Sheet A14000-10-0101 &quot;Oxygen Specification for Ozonia's OG&quot;</td>
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<tr>
<td>Specific feed gas quality</td>
<td>As specified within this document</td>
<td></td>
</tr>
<tr>
<td>Pressure from the feed gas system max</td>
<td>20.31 psig</td>
<td>1.40 bar g</td>
</tr>
<tr>
<td>Design liquid oxygen mass flow rate</td>
<td>36,744.00 lb/d</td>
<td>694.45 kg/h</td>
</tr>
<tr>
<td>Gas temperature to ozone generator</td>
<td>86 °F approx.</td>
<td>30 °C approx.</td>
</tr>
<tr>
<td>Free of contaminates</td>
<td>Oil and dust free</td>
<td></td>
</tr>
</tbody>
</table>

### Ozone Generator (OG)

<table>
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<tr>
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<th>ENGLISH UNITS</th>
<th>SI UNITS</th>
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</thead>
<tbody>
<tr>
<td>Number of ozone generators installed</td>
<td>2 (One stand-by Unit)</td>
<td></td>
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<tr>
<td>Type of OG</td>
<td>As per Data Sheet A14034-02-0101 &quot;Generator Shell Data Sheet&quot;</td>
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<tr>
<td>Ozone production per OG</td>
<td>2,204.6 lb/d</td>
<td>41.67 kg/h</td>
</tr>
<tr>
<td>System design ozone production</td>
<td>4,409.2 lb/d</td>
<td>88.33 kg/h</td>
</tr>
<tr>
<td>Corresponding ozone concentration</td>
<td>6 % by weight at the OG</td>
<td></td>
</tr>
<tr>
<td>Corresponding oxygen mass flow rate per OG</td>
<td>36,744.00 lb/d</td>
<td>694.45 kg/h</td>
</tr>
<tr>
<td>Inlet gas pressure max</td>
<td>20.31 psig</td>
<td>1.40 bar g</td>
</tr>
<tr>
<td>Cooling water temperature at design</td>
<td>82.4 °F maximum</td>
<td>28 °C</td>
</tr>
<tr>
<td>Cooling water flow rate per OG</td>
<td>160 gpm (nominal)</td>
<td>36.339 m³/h</td>
</tr>
<tr>
<td>Cooling water temperature increase</td>
<td>10.29 °F Max</td>
<td>5.72 °C</td>
</tr>
<tr>
<td>Recommended water quality</td>
<td>As per Data Sheet A14000-02-0110 &quot;Recommended Water Quality for OG&quot;</td>
<td></td>
</tr>
<tr>
<td>Power Consumption</td>
<td>To be provided at a later date</td>
<td></td>
</tr>
</tbody>
</table>

1000 kg/d @ 6% O3 @ 28°C c.w.  

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<table>
<thead>
<tr>
<th>TECHNICAL DATA</th>
<th>ENGLISH UNITS</th>
<th>SI UNITS</th>
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<tr>
<td>Ambient pressure</td>
<td>14.69 psig</td>
<td>1.013 bar</td>
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<tr>
<td>Ambient temperature</td>
<td>86 °F max.</td>
<td>30 °C max.</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>100 % max.</td>
<td></td>
</tr>
</tbody>
</table>

| FEED GAS                           |                     |                   |
| Feed gas                            | Liquid Oxygen        |                   |
| Inlet gas composition               | (O2+N2+Ar/Inerts)    |                   |
| Minimum feed gas quality            | As per Data Sheet A14000-10-0101 "Oxygen Specification for Ozonia's OG" | |
| Specific feed gas quality           | As specified within this document | |
| Pressure from the feed gas system   | 20.31 psig           | 1.40 bar g        |
| Design liquid oxygen mass flow rate | 11,941.47 lb/d       | 225.69 kg/h       |
| Gas temperature to ozone generator  | 86 °F approx.        | 30 °C approx.     |
| Free of contaminate                 | Oil and dust free    |                   |

| Ozone Generator (OG)                |                     |                   |
| Number of ozone generators installed| 2 (One stand-by Unit)|                   |
| Type of OG                          | As per Data Sheet A14003-02-0101 "Generator Shell Data Sheet" | |
| Ozone production per OG             | 1,433 lb/d          | 27.06 kg/h        |
| System design ozone production      | 2,866 lb/d          | 54.167 kg/h       |
| Corresponding ozone concentration   | 12 % by weight at the OG |                   |
| Corresponding oxygen mass flow rate per OG | 11,941.47 lb/d     | 225.69 kg/h       |
| Inlet gas pressure max              | 20.31 psig max       | 1.40 bar g        |
| Cooling water temperature at design| 35.6 °F minimum     | 2 °C              |
| Cooling water flow rate per OG      | 160 gpm (nominal)   | 36.339 m³/h       |
| Cooling water temperature increase  | 7.9 °F Max          | 4.4 °C            |
| Recommended water quality           | As per Data Sheet A14000-02-0110 "Recommended Water Quality for OG" | |
| Power Consumption                   | To be provided at a later date | |

650 kg/d @ 12% O3 @ 2°C c.w.

115
<table>
<thead>
<tr>
<th>TECHNICAL DATA</th>
<th>ENGLISH UNITS</th>
<th>SI UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient pressure</td>
<td>14.69 psig</td>
<td>1.013 bar</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>86 °F max.</td>
<td>30°C max.</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>100 % max.</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>FEED GAS</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed gas</td>
<td>Liquid Oxygen</td>
<td></td>
</tr>
<tr>
<td>Inlet gas composition</td>
<td>(O2+N2+Ar/Inerts)</td>
<td>(97.7% O2 = 2.3% N2 + Ar/Inert)</td>
</tr>
<tr>
<td>Minimum feed gas quality</td>
<td>As per Data Sheet A14000-10-0101 &quot;Oxygen Specification for Ozonia's OG&quot;</td>
<td></td>
</tr>
<tr>
<td>Specific feed gas quality</td>
<td>As specified within this document</td>
<td></td>
</tr>
<tr>
<td>Pressure from the feed gas system</td>
<td>20.31 psig</td>
<td>1.40 bar g</td>
</tr>
<tr>
<td>Design liquid oxygen mass flow rate</td>
<td>9,185.86 lb/d</td>
<td>173.61 kg/h</td>
</tr>
<tr>
<td>Gas temperature to ozone generator</td>
<td>86 °F approx.</td>
<td>30 °C approx.</td>
</tr>
<tr>
<td>Free of contaminateles</td>
<td>Oil and dust free</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ozone Generator (OG)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of ozone generators installed</td>
<td>2 (One stand-by Unit)</td>
<td></td>
</tr>
<tr>
<td>Type of OG</td>
<td>As per Data Sheet A14034-02-0101 &quot;Generator Shell Data Sheet&quot;</td>
<td></td>
</tr>
<tr>
<td>Ozone production per OG</td>
<td>1,102.311 lb/d</td>
<td>20.833 kg/h</td>
</tr>
<tr>
<td>System design ozone production</td>
<td>2,204.6 lb/d</td>
<td>41.667 kg/h</td>
</tr>
<tr>
<td>Corresponding ozone concentration</td>
<td>12 % by weight at the OG</td>
<td></td>
</tr>
<tr>
<td>Corresponding oxygen mass flow rate per OG</td>
<td>9,185.86 lb/d</td>
<td>173.61 kg/h</td>
</tr>
<tr>
<td>Inlet gas pressure max</td>
<td>20.31 psig</td>
<td>1.40 bar g</td>
</tr>
<tr>
<td>Cooling water temperature at design</td>
<td>82.4 °F maximum</td>
<td>28 °C</td>
</tr>
<tr>
<td>Cooling water flow rate per OG</td>
<td>160 gpm (nominal)</td>
<td>36,339 m³/h</td>
</tr>
<tr>
<td>Cooling water temperature increase</td>
<td>7.51 °F Max</td>
<td>4.17 °C</td>
</tr>
<tr>
<td>Recommended water quality</td>
<td>As per Data Sheet A14000-02-0110 &quot;Recommended Water Quality for OG&quot;</td>
<td></td>
</tr>
<tr>
<td>Power Consumption</td>
<td>To be provided at a later date</td>
<td></td>
</tr>
</tbody>
</table>

500 kg/d @ 12% O3 @ 28°C c.w.
NAME: Samar Mazloum
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DATE OF BIRTH: March 31, 1977
EDUCATION:

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