Wyoming Clean Water Plant Tertiary Treatment Project Feasibility Study

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Calvin College ENGR 339 Senior Design Project

December 7, 2011
Executive Summary

The team performed a feasibility study regarding the tertiary treatment for the City of Wyoming Clean Water Plant (CWP). The study focused on replacing the CWP’s current chlorine based disinfection system with a more sustainable and safe wastewater disinfection system. Ultraviolet light and other disinfection methods were evaluated because they could achieve the same disinfection efficiency as the chlorine gas based system. The team also researched advanced oxidation processes (AOPs) to assess potential removal of five emerging contaminants of concern that were present in the treated effluent that is discharged from the CWP.

The Clean Water Plant treats an average of sixteen million gallons of wastewater per day. The CWP typically meets wastewater requirements specified by National Pollutant Discharge Elimination System (NPDES) regulations; however, during large rain events, the dissolved oxygen content of the wastewater drops below permitted levels. As a result, the team also considered reaeration for the CWP’s effluent to ensure compliance with NPDES regulations.

Based on research and client information, the team selected ultraviolet disinfection as the tertiary treatment alternative. The team found that ultraviolet (UV) disinfection provided a cost effective, chemical-free tertiary treatment option that reduces disinfection byproducts in the effluent wastewater. The team recommends low pressure, high intensity ultraviolet lamps in closed channels. A UV disinfection system is expected to cost $3-4 million for construction with an annual operation cost of approximately $80,000-$120,000.

The team selected five emerging contaminants from a list of pharmaceutical and personal care compounds that the CWP monitored for the past three years. The following contaminants were selected: erythromycin (antibiotic), atrazine (pesticide), iopromide (x-ray contrast medium), carbamazepine (anticonvulsant), and ethinyl estradiol 17-alpha (hormonal steroid). The contaminants of interest were selected based on presence in the effluent stream of the CWP and because significant information is available on the contaminant. These contaminants are currently not regulated; however, their increasing use and presence in the environment is raising awareness to potential health and environmental concerns.

AOPs remove the contaminants of interest. Therefore, the team performed extensive literature review and investigation on advanced oxidation processes for the CWP. The team determined that ozone coupled with UV is the optimal choice for the CWP. The UV/ozone system for the CWP is estimated to cost $4.5 million for construction and $4.1 million to operate annually, assuming a 5 mg/L ozone dose.

The team determined that fine bubble diffusers were the most appropriate reaeration technology to increase dissolved oxygen content in the wastewater. Fine bubble diffusers will cost between $300,000-400,000 for construction and $10,000 to $15,000 for annual operation.

Total capital cost for all three projects is estimated to be $8-10 million, with an annual operating cost estimated to be $4.2-4.5 million.

During January and early spring of 2012, the team will conduct a pilot test to determine the most effective UV/ozone system for the CWP by varying the ozone dose and contact time. The team will use the data gained from pilot testing to design a UV/ozone system that will achieve 99% disinfection by UV and 90% removal of the contaminants of interest by ozonation. In addition, fine bubble diffusers will be designed to raise the DO concentration in the final treated effluent by at least 2.5 mg/L. A written report and a presentation of the final results of the design will be presented.
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<th>Full Form</th>
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<tr>
<td>AOP</td>
<td>Advanced Oxidation Process</td>
</tr>
<tr>
<td>BOD</td>
<td>Biochemical Oxygen Demand</td>
</tr>
<tr>
<td>CCL</td>
<td>Chemical Contaminant List</td>
</tr>
<tr>
<td>CFU</td>
<td>Colony Forming Units</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical Oxygen Demand</td>
</tr>
<tr>
<td>CWP</td>
<td>Wyoming Clean Water Plant</td>
</tr>
<tr>
<td>DBP</td>
<td>Disinfection Byproduct</td>
</tr>
<tr>
<td>DNA</td>
<td>Deoxyribonucleic Acids</td>
</tr>
<tr>
<td>DO</td>
<td>Dissolved Oxygen</td>
</tr>
<tr>
<td>EC50</td>
<td>Half Maximum Effective Concentration</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>HAA</td>
<td>Haloacetic Acid</td>
</tr>
<tr>
<td>LBS</td>
<td>Pounds</td>
</tr>
<tr>
<td>LC50</td>
<td>Lethal Dose at a single time for half of a population</td>
</tr>
<tr>
<td>LPHI</td>
<td>Low Pressure, High Intensity</td>
</tr>
<tr>
<td>MF</td>
<td>Membrane Filtration</td>
</tr>
<tr>
<td>MSDS</td>
<td>Material Safety and Data Sheet</td>
</tr>
<tr>
<td>NOM</td>
<td>Natural Organic Matter</td>
</tr>
<tr>
<td>NPDES</td>
<td>National Pollutant Discharge Elimination System</td>
</tr>
<tr>
<td>PPB</td>
<td>Parts per Billion</td>
</tr>
<tr>
<td>PPCP</td>
<td>Pharmaceuticals and Personal Care Products</td>
</tr>
<tr>
<td>RNA</td>
<td>Ribonucleic Acid</td>
</tr>
<tr>
<td>THM</td>
<td>Trihalomethane</td>
</tr>
<tr>
<td>TOC</td>
<td>Total Organic Carbon</td>
</tr>
<tr>
<td>TSS</td>
<td>Total Suspended Solids</td>
</tr>
<tr>
<td>UF</td>
<td>Ultrafiltration</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>WBS</td>
<td>Work Breakdown Schedule</td>
</tr>
</tbody>
</table>
1 Introduction

1.1 Problem Statement

The purpose of the project is to create a preliminary design for ultra-violet light tertiary treatment at the Wyoming Clean Water Plant (CWP) in Wyoming, Michigan. The design will also include advanced oxidation and reaeration processes.

1.2 The Project

In 2011, Black & Veatch prepared a facility plan for the CWP. However, the facility plan did not consider replacing chlorine gas disinfection with ultraviolet light. David Koch, facility plan project manager and employee of Black & Veatch, recommended to Anna Boersma that a senior design team could complete a preliminary design of an ultraviolet disinfection system for the plant. At the same time, Mark Stehouwer was in contact Myron Erickson, the CWP’s laboratory services manager and future CWP superintendent. After collaboration with David Koch and Myron Erickson, the senior design team formed a project that would investigate an ultraviolet disinfection system coupled with an advanced oxidation process for removal of select micro-contaminants from the CWP.

1.3 Wastewater Treatment Introduction

There are currently 16,583 wastewater treatment facilities in the United States. Data from a 2008 study for Congress regarding different treatment plant sizes is shown below (Table 1). The CWP falls in the existing flow range of 10 to 100 MGD with an average flow of 16 MGD, placing it in the top 3.5% of facilities based on the magnitude of treated flows.

<table>
<thead>
<tr>
<th>Existing Flow Range (MGD)</th>
<th>Number of Facilities</th>
<th>Total Existing Flow (MGD)</th>
<th>Present Design Capacity (MGD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 0.1</td>
<td>5,703</td>
<td>257</td>
<td>490</td>
</tr>
<tr>
<td>0.1 to 1</td>
<td>5,863</td>
<td>2,150</td>
<td>3,685</td>
</tr>
<tr>
<td>1 to 10</td>
<td>2,690</td>
<td>8,538</td>
<td>13,082</td>
</tr>
<tr>
<td>10 to 100</td>
<td>480</td>
<td>12,847</td>
<td>17,267</td>
</tr>
<tr>
<td>100 and greater</td>
<td>38</td>
<td>8,553</td>
<td>10,344</td>
</tr>
<tr>
<td>Other</td>
<td>6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>14,780</td>
<td>32,345</td>
<td>44,868</td>
</tr>
</tbody>
</table>

Wastewater treatment typically involves four phases: preliminary, primary, secondary and tertiary, also known as disinfection (Figure 1). During preliminary treatment, wastewater flows through screens that remove large objects such as rags and plastics that can damage downstream equipment. Preliminary treatment usually consists of a series of screens, where each consecutive screen has a smaller mesh to remove smaller sized particles. The removed solids are then sent to a landfill or incinerator. After the wastewater is screened, it travels through a grit removal tank where solids such as sand and gravel settle out of the stream.
Primary treatment is the second phase in the wastewater treatment process. During primary treatment, the wastewater is held in clarifiers. Clarifiers are large, concrete basins that allow large sludge particles to settle and grease and oils to rise and be scraped off of the water. The sludge particles that settled to the bottom are collected in a hopper and pumped to the sludge treatment facility at the wastewater treatment plant. From there, the sludge is commonly applied to land as fertilizer, but can also be incinerated to produce electricity or anaerobically digested to produce biogas.

Secondary treatment, the third phase of wastewater treatment, is designed to remove the organic content in wastewater. Bacteria that digest the organic matter in the water are added to the wastewater stream flowing through aeration basins, which provide the oxygen for the bacteria to live.

The final treatment phase is tertiary treatment. In tertiary treatment, a disinfectant eradicates the remaining microorganisms and pathogens. The most common disinfectant is chlorine. However, plant operators have concerns about the use of chlorine due to safety concerns associated with the transportation, handling, and storage of chlorine. Because of this concern, many treatment plants are now switching to alternative forms of disinfection such as ultraviolet light.

2 Client

2.1 City of Wyoming

The city of Wyoming lies within the western half of Michigan. The city is directly southwest of Grand Rapids, as shown in Figure 2. Wyoming spans 24.5 square miles. According to the 2010 U.S. Census, the city has a population of 72,125 people divided over 26,970 households. The city also has 1850 commercial uses.
2.2 Wyoming Clean Water Plant

2.2.1 Overview

Wyoming operates its own drinking water and wastewater treatment plants. The city refers to its wastewater treatment plant as the Wyoming Clean Water Plant (CWP). In addition to treating wastewater, the plant manages a household hazardous waste program for the proper disposal of household hazardous wastes such as prescription drugs, cleaning products and used oil.
The CWP has received many awards and much recognition, including the National Biosolids Partnership’s certificate in 2010 for the plant’s biosolids management system. The plant also received the Michigan Department of Environmental Quality’s Clean Corporate Citizen Award in May of 2011 and two EPA awards in 2000 for excellence in biosolids and industrial pretreatment program management.\(^6\)

### 2.2.2 Plant System

![Process schematic of the CWP’s wastewater treatment system.](image)

Influent entering the CWP flows through the typical preliminary process of screening and grit removal (Figure 3). Next, the water is pumped to a higher elevation to provide enough head for gravity to carry the flow through the remaining treatment processes. The flow then enters a flocculation basin that removes small particles from the water. After flocculation, the flow goes through primary clarification and then to the aeration basins, where activated sludge is used to decompose the organic matter and phosphorous. Next, the flow sits in secondary clarifiers to allow the activated sludge to settle out of the water. Some activated sludge returns to the aeration basins, while other sludge is dewatered and then either applied to farmer’s fields as a fertilizer or pumped to Grand Rapids’ wastewater treatment facility and Grand Rapids to disposes of it. The last process is disinfection, where chlorine is injected into the flow. Finally, residual chlorine is removed using sodium bisulfite (NaHSO\(_4\)) and sulfur dioxide (SO\(_2\)). Enough chlorine is removed so as not to discharge excessive chlorine into the Grand River. Finally, the flow is discharged into the Grand River.\(^7,8\)

### 2.2.3 Plant Layout

The CWP has plenty of available space to construct a new disinfection system and an advanced oxidation process. The older chlorine contact tank (Chlorine Contact Basin No. 1) is also available for reuse. The plant layout and available space is seen in Appendix A.

### 2.2.4 Influent
The CWP treats the wastewater from Wyoming and the neighboring communities of Kentwood, Grandville, and Byron and Gaines Townships (Figure 2). The plant serves a total population of 170,000 people, with an average flow of 16 MGD and a maximum month flow of 16.2 MGD (Figure 4). Table 2 gives additional influent data such as influent biological oxygen demand (BOD) and influent temperature. The 2020 and 2030 year designs were approximated by Black & Veatch assuming a yearly, exponential 1.5% population growth. Grandville is in the process of expanding its own wastewater treatment facility, and will not be sending its 1.6 MGD to the CWP starting in the spring of 2013. Black & Veatch took into consideration this loss of flow when estimating the future flows.

![Influent Flow (mgd)](image)

**Figure 4. 30-day average influent flows from the four communities that send their wastewater to CWP.**

<table>
<thead>
<tr>
<th>Table 2. Flow data from the CWP.</th>
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<tr>
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<tr>
<td><strong>Flow, Annual Average (MGD)</strong></td>
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<td></td>
</tr>
<tr>
<td><strong>Flow, Max. Month (MGD)</strong></td>
</tr>
<tr>
<td><strong>BOD (mg/L)</strong></td>
</tr>
<tr>
<td><strong>TSS (lbs/day)</strong></td>
</tr>
<tr>
<td><strong>NH3-N (mg/L)</strong></td>
</tr>
<tr>
<td><strong>Fecal Coliform (cfu)</strong></td>
</tr>
<tr>
<td><strong>Total Phosphorous (lbs/day)</strong></td>
</tr>
<tr>
<td><strong>Temperature (°F)</strong></td>
</tr>
</tbody>
</table>
3 Background Information

3.1 Government Regulations and Requirements

A part of the Clean Water Act, the National Pollutant Discharge Elimination System (NPDES) regulates the quality of wastewater discharge into surface waters. The EPA bases it permits on the discharger’s receiving stream. The permit limits the concentrations of pollutants that can be discharged. Therefore, the team’s design must comply with the CWP’s permit. A copy of the CWP effluent permit, which is valid until October 1, 2015, can be found in Appendix B.

3.2 Chlorine to Ultraviolet Disinfection

The desire for disinfection systems that are safe for the environment and require minimal chemicals is the primary reason for the switch from a chlorine-based disinfection system to a UV disinfection system. Treatment plant operators have safety concerns associated with a chlorine-based disinfection system, including plant operation and chemical transportation, handling, and storage. In addition, there is a concern that certain microorganisms, such as cryptosporidium which can cause severe diarrhea in humans, may survive current chlorine disinfection processes. Chlorine disinfection also has the potential to produce chlorine byproducts that are hazardous and carcinogenic.

3.3 Addition of AOPs

The threat of emerging contaminants in the environment is an increasing concern leading government agencies to look at the feasibility of regulating emerging contaminants. The CWP hopes to have a leading role in the removal of emerging contaminants from wastewater streams.

The only way to remove emerging contaminants is through AOPs, because conventional treatment methods do not remove the emerging contaminants. In order for the CWP to play a leading role, the plant needs to operate an AOP that removes the emerging contaminants from the plant’s discharge.

3.4 Dissolved Oxygen Contents

The CWP’s current NPDES permit requires the dissolved oxygen (DO) of the effluent stream to be greater than 5 mg/L between June 1 and September 30 and greater than 3 mg/L for the remainder of the year (Appendix B). Minimum DO concentrations are regulated to maintain enough oxygen in surface waters for fish and other aquatic life. From January 2006 to August 2010, dissolved oxygen levels for the CWP ranged from 1.3 mg/L to 12.5 mg/L with an average of 7.0 mg/L from June to September and an average of 8.0 mg/L from October to May. The CWP increases its DO concentrations by making water flow over weirs after the chlorine contact basin. However, during wet weather events the river level rises and restricts the flow over weirs, causing the DO concentration to be lower than the permit allows.

4 Overall Design Goals and Objectives

Design goals, considerations, and constraints exist beyond the technical aspects of the project. The project should be economically viable and effective in its use of financial resources needed to complete a quality system. However, the project must not overuse the financial resources available through water bills and taxpayer dollars.

In addition, since AOP disinfection is an emerging technology, the system must be designed with a focus on integrity. The system should have well-designed individual parts that work together as an efficient, large system. Integrity of the system is also important due to the scope of the project; when dealing with a wastewater stream, there is little opportunity for remediation if some portion of the system were to fail.
Operators at the CWP are well-trained, so adding new processes will not hinder plant operations. However, the system should still have an intuitive operator interface to reduce confusion when introducing an unfamiliar disinfection system, as well as easier training of future operators.

The CWP must meet government regulations for effluent as previously described (Section 1), but the goal of outputting clean water into the environment should exist even without the imposed constraints. Raw sewage pollutes fresh water, stressing many organisms such as fish, birds, and amphibians that are dependent on rivers. The project proposes to upgrade the existing facilities to ensure that effluent water quality is at the highest level possible, helping the Grand River and ultimately, Lake Michigan, remain habitable to wildlife and organisms.

The team is also working to make the proposed technologies understandable not just to engineers, but also the public. Because the CWP is a publicly-funded utility, a high level of transparency is important so that all taxpayers and city officials understand where their money is going.

5  Process Design

The team separately examined each component of the overall system to determine the best option for the CWP. Interactions between the components were taken into account with the decisions.

5.1  Disinfection

Disinfection rids wastewater of pathogens and microorganisms by chemical or radiation processes. The disinfectant is added to the wastewater, mixed, and allowed time to react. A good disinfection system will kill pathogens and microorganisms while being nontoxic to humans, animals and other aquatic species. The system will also allow for safe transportation, handling, and storage of the disinfecting chemical or operating mechanism while being economically viable and easily understood or analyzed. Chlorination and ultraviolet irradiation are the two most commonly used methods in the United States; they have proved to be simple, safe, reliable, and cost-effective.

5.1.1  Disinfection Options

The team examined six disinfection alternatives including chlorine gas, hypochlorite, chlorine dioxide, ozone and ultraviolet irradiation.

5.1.1.1  Chlorine Gas

Chlorine gas is the most common wastewater disinfectant in the United States. Chlorine gas reacts with water to form hypochlorous acid, which acts as the disinfectant (Equation 1, Equation 2).

\[
\begin{align*}
\text{Cl}_2 + \text{H}_2\text{O} & \rightarrow \text{HOCI} + \text{HCl} \\
\text{HOCI} & \rightarrow \text{OCI}^{-1} + \text{H}^+
\end{align*}
\]

Equation 1  
Equation 2

However, because of chlorine’s toxicity to aquatic life, a dechlorination system is also needed, which increases disinfection costs by 30 to 50%. Additional chlorine gas costs include chemical shipping and safe storage of chlorine at the plant. Chlorine can also cause reactions with certain chemicals in the water forming disinfection by products that can be hazardous to humans or even carcinogenic, thus, replacing one toxin in the water with another. Chlorine gas requires an emergency response plan for possible chlorine gas leaks. This emergency response plan is usually expensive and time-consuming for operators.
5.1.1.2 Hypochlorite

A second free chlorine option is the use of either sodium hypochlorite (NaOCl) or calcium hypochlorite (Ca(OCl)₂), which dissociates to OCl⁻ and Na or Ca. Calcium hypochlorite forms hypochlorous acid (HOCl) and calcium hydroxide (Ca(OH)₂) in water (Equation 3), also forming OCl⁻, a form of free chlorine.¹⁶ This free chlorine proceeds to react with the wastewater as if it were added simply by itself. Because overdosing can be quite common with calcium hypochlorite tablets, a long discharge path is recommended.¹⁸

\[ \text{Ca(OCl)}_2 + 2\text{H}_2\text{O} \rightarrow 2\text{HOCl} + \text{Ca(OH)}_2 \]  
Equation 3

Today, sodium hypochlorite is much more common than calcium hypochlorite. Hypochlorite is not a stable chemical and therefore requires safety considerations regarding storage of the chemical. Its corrosive nature causes increased material costs, even for the pipes used to transport it. Hypochlorite can cause formation of chlorite and chlorate ions in the effluent, which, though not yet regulated federally, is regulated by some states.²⁰ A sodium or calcium hypochlorite (NaOCl, Ca(OCl)₂) system is more expensive than a chlorine gas system, but can slightly reduce the transportation of hazardous chemicals. Sodium hypochlorite costs are 150 to 200% greater than those of liquid chlorine. The chemical must be stored in a cool location in a corrosion-resistant tank.¹⁸ Sodium hypochlorite is more reliable than calcium hypochlorite, but requires more supervision by site operators.¹⁷

5.1.1.3 Chlorine Dioxide

Chlorine dioxide is the third free chlorine alternative. Chlorine dioxide must be manufactured on site due to its instability and rapid decomposition. It is produced in a simple mixing chamber from chlorine and chlorite, and then added to the water stream in a contact tank.²⁰ Few disinfection byproducts are caused by chlorine dioxide disinfection, though chlorite and chloride ions can be present. The use of chlorine dioxide is therefore generally limited to low total organic carbon (TOC) water. Chlorine dioxide is more effective at killing viruses than chlorine or hypochlorite but eliminates equal levels of bacteria as chlorine and hypochlorite. The primary DBP is chloroform, formed from chlorate and chlorite ions. Chlorine dioxide is less harmful to aquatic life less than chlorine.¹⁸

5.1.1.4 Ozone

Ozone can achieve a higher level of disinfection than chlorine or UV. In addition, ozone requires a shorter contact time than chlorine to reach the same removal level of viruses and bacteria. Ozone has recently been used for wastewater treatment because of its ability to reduce trace constituents. Ozone also increases dissolved oxygen content in the water, aiding reaeration processes. Another advantage of ozone is that no “de-ozonation” post-treatment is required, unlike chlorine. Ozone is typically used at medium to large sized plants for tertiary treatment or odor control.²¹ Ozone is not a common disinfectant due to economic constraints and complex engineering.¹⁷

In an ozone disinfection process, the water stream is injected with gaseous ozone. Since ozone decomposes relatively quickly, it must be created on-site. This is done by running an air stream with oxygen through a high voltage alternating current. Ozone creation causes ozone disinfection to be very energy intensive, increasing its costs.²¹ Because of on-site ozone creation, there are no shipping safety concerns.

An ozone system is also more complicated to run and install than either UV or chlorine; the equipment and contact systems are more complex (Figure 5). If not enough ozone is used, then no viruses or cysts are destroyed. Special materials must be used to avoid corrosion or reaction by ozone, as it is unstable at any concentration in the air greater than 23%.²⁰ Any excess gases from ozone formation must be destroyed to prevent exposure to possibly irritating substances.²¹ Ozone will not form the same DBPs as chlorine, but can form other DBPs such as aldehydes, ketones, peroxides, and bromate ions.¹⁸
5.1.1.5 Ultraviolet Irradiation

Ultraviolet (UV) irradiation disinfection is a process which uses UV radiation from lamps to rid the water of microorganisms. UV disinfection is still Typical design considerations for UV disinfection are shown below (Table 3).

Mercury-vapor lamps generate short range UV light (UVC) between 235 to 270 nm, which is especially effective at eradicating the bacteria and viruses found in wastewater. The electromagnetic energy from the light is readily absorbed by deoxyribonucleic acids (DNA), and the radiation renders the organism unable to replicate. Although this effect can be reversed in some cases, overall, UV disinfection is a proven method of wastewater treatment. The effectiveness of a UV disinfection system is dependent on the characteristics of the wastewater before treatment; high levels of TSS, BOD, ammonia, and nitrate can diminish the efficiency of UV treatment. Water, pH, and hardness affect the solubility of metals that readily absorb UV radiation thereby hindering disinfection. Finally, uniform flow through a system allows for maximum exposure to radiation.

Table 3. Typical ultraviolet system design parameters.

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Typical Design Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV dosage</td>
<td>20 to 140 mW/s/cm²</td>
</tr>
<tr>
<td>Contact time</td>
<td>6 to 40 seconds</td>
</tr>
<tr>
<td>UV intensity</td>
<td>3 to 12 mW/s/cm²</td>
</tr>
<tr>
<td>Wastewater UV transmittance</td>
<td>50 to 70%</td>
</tr>
<tr>
<td>Wastewater velocity</td>
<td>0.17 to 1.25 fps</td>
</tr>
</tbody>
</table>

UV disinfection systems are more expensive than chlorine disinfection itself, but if the costs of dechlorination are considered, UV disinfection becomes competitively priced with chlorination. UV disinfection requires fewer safety parameters to meet fire code regulations as well as eliminating process safety management and an emergency response plan, providing an additional cost benefit over chlorine.

5.1.2 Decision Matrix

The team created a decision matrix (Table 4) to aide in determining the best disinfection option. The decision matrix included many different design considerations such as cost, safety, size of system, pathogen removal, and monitoring needs. Calcium hypochlorite was not scored in the decision matrix, since a sodium hypochlorite system was found more reliable. The decision matrix shows UV as the best disinfection option for the CWP. This is due, in part, to the client’s preferences for a new disinfection system that requires minimal onsite storage of chemicals and contains low DBPs in the effluent stream. Chlorine gas was the second option because it is the currently used disinfection method of the plant, so it
would not have installation costs. Below are the questions that were used in the rating of disinfectant options for the decision matrix.

- Capital Cost: What is the initial cost of the system including installation and setup?
- Operational Cost: What is the annual cost to operate and maintain the system?
- Storage: Does the system require onsite storage of chemicals?
- Safety: If the system requires chemicals, how volatile are they?
- Familiarity: How familiar are the operators at the WCWP with the proposed method?
- Contact Time/Footprint: How much space does the system require? How long will the wastewater need to be stored in that space to be properly treated?
- DBPs: Does the system produce DBPs? If so, to what extent are they produced?
- Ease of Integration: How well does the proposed disinfection method fit into the existing facility?
- Ease of Use/Monitoring: To what extent will the operators need to monitor and calibrate the system?
- Bacteria Removal: What percent of the bacteria are eradicated with this method?
- Virus Removal: What percent of the viruses are eradicated with this method?
- Protozoa Removal: What percent of the protozoa are eradicated with this method?

Table 4. Decision matrix for disinfection. The assigned values range from 1 to 5, with 1 being poor and 5 being excellent.

<table>
<thead>
<tr>
<th></th>
<th>Weight</th>
<th>Chlorine Gas</th>
<th>Chlorine Dioxide</th>
<th>Sodium Hypochlorite</th>
<th>Ozone</th>
<th>UV</th>
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</thead>
<tbody>
<tr>
<td>Capital Cost</td>
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<td>1</td>
</tr>
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<td>Operational Cost</td>
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<td>Storage</td>
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<td>3</td>
<td>3</td>
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<td>Familiarity</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Contact Time/Footprint</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>DBPs</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Ease of Integration</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
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<tr>
<td>Ease of Use/Monitoring</td>
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<td>4</td>
<td>3</td>
<td>4</td>
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<td>5</td>
</tr>
<tr>
<td>Bacteria Removal</td>
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<td>5</td>
<td>5</td>
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<td>Virus Removal</td>
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<td>5</td>
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<td>5</td>
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<td>5</td>
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<tr>
<td>Protozoa Removal</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>175</td>
</tr>
</tbody>
</table>

5.2 Ultraviolet Disinfection

Ultraviolet disinfection, the chosen technology, is discussed in the following sections, as well as options for specific configurations of ultraviolet disinfection systems.

5.2.1 UV Options

Three main technologies exist for UV disinfection. For each system the combination of pressure and intensity is varied. The pressure of a UV system refers to the internal pressure of the mercury-vapor lamp used in the system and the intensity refers to the power emitted from a lamp per unit area. Intensity is used to measure the magnitude of UV light radiation. All lamps have a typical length ranging from 0.75 m to 1.5 m.
Low pressure, low intensity systems are the oldest of the three technologies; they were the form in which UV disinfection processes were pioneered. They can be configured with horizontal or vertical lamps (Figure 6) and run on power of 0.065 kW to 0.085 kW per bulb. However, low pressure, low intensity systems are no longer being developed and updated since newer technologies have emerged.

Medium pressure systems were developed next, allowing fewer bulbs to be used in an open channel or a closed pipe because of an ultraviolet intensity around 15 to 20 times the intensity of low-pressure lamps. These systems are typically used at larger facilities, as they work faster and are therefore more efficient with higher flows. The tradeoff, however, is that medium pressure systems have a much higher power consumption requiring between 2.8 kW to 10 kW per bulb. An automatic cleaning system was developed for medium pressure disinfection as the high lamp temperature caused a material to form a film on the lamp.

The most recent technology of the three is a low pressure, high intensity (LPHI) UV system. This technology has fewer lamps than a normal low pressure system, but more than the medium pressure system, yet it runs on the same amount of power as a low pressure system. The system is still self-cleaning like the medium pressure system and can be operated in an open or closed channel. A LPHI system uses 15 to 20 lamps per MGD and 3.8 kW to 4.8 kW per MGD at a lamp temperature near 60 °C, an average of 0.23 kW to 1.5 kW per bulb.

UV lamps that are made with exterior quartz sleeves operate between 250 nm and 270 nm to most effectively eradicate harmful organisms. Low pressure lamps emit light at 253.7 nm and have a typical diameter of 1.5 cm to 2.0 cm. The temperature of the lamp exterior is ideally between 95 °F and 122 °F. UV lamps generally need to be replaced every 10,000 to 12,000 hours.

UV systems are made as contact or noncontact systems. Contact systems have lamps enclosed in quartz sleeves to decrease the cooling of the lamps by the wastewater flow in which the lamps are submerged. Noncontact systems have UV lamps exterior to the wastewater which flows through a transparent pipe. Contact reactors are more common than noncontact reactors.

### 5.2.2 Recommended Option

Based on the decision matrix previously in Table 4, a UV disinfection system is recommended. The system should include the more advanced LPHI lamps due to the reduced footprint and higher energy efficiency. Although many different companies offer these systems, the configurations can differ greatly. Most systems utilize a horizontal light formation, so the lamps are parallel to the flow. Some manufacturers mount the lamps in a staggered configuration, ensuring the particles will come into contact with the emitted UV. From a maintenance standpoint, a system with all of the electrical controls and connections above water is much easier to maintain. Trojan, Ozonia, and Siemens UV systems are currently the main UV disinfection companies that are being considered which meet the desired criteria.
5.3 Advanced Oxidation

Advanced oxidation processes (AOPs) are emerging water treatment methods that can eliminate elusive compounds of concern. Current research has led to a variety of advanced oxidative treatments available for use in wastewater treatment systems based on desired removal efficiencies and contaminants of interest. AOPs use chemical oxidants and are frequently coupled with ultraviolet light to synergistically reduce biological oxygen demand, chemical oxygen demand, and organic and inorganic compounds. The high reactivity of hydroxyl radicals drives the oxidation process, resulting in elimination and demineralization of typically less reactive wastewater pollutants.\(^\text{13}\)

Molecules with an odd number of electrons in their Lewis structures are called free radicals. This means that the octet rule is not satisfied, since the outermost shell of an atom requires eight electrons to be the most stable. A molecule with an incomplete octet is unstable and highly reactive. The hydroxyl radical is a free radical and therefore has an incomplete octet. One electron is missing from the outermost shell of the oxygen atom, leaving a free, unpaired electron (Figure 7).

![Figure 7. Hydroxyl radical diagram.](image)

The hydroxyl radical can be abbreviated by using dot terminology and simply including a dot after the molecule’s name. This indicates that the atom has one unpaired electron. Thus, the hydroxyl radical can be written as HO·. In reactions, excited oxygen atoms react with water vapor to form the hydroxyl radical. Ultraviolet light often provides the energy for this reaction. Hydroxyl radical formation mechanisms include:

**System of Equations**

\[
\begin{align*}
\text{H}_3\text{O}^+ + e^- & \rightarrow \text{HO}^- + \text{H}_2 & (1a) \text{ Dissociative recombination} \\
\text{H}_3\text{O}^+ + e^- & \rightarrow \text{HO}^- + '\text{H} + '\text{H} & (1b) \text{ Dissociative recombination} \\
\text{HCO}_2^+ + e^- & \rightarrow \text{HO}^- + \text{CO} & (2a) \text{ Dissociative recombination} \\
'\text{O} + \text{HCO} & \rightarrow \text{HO}^- + \text{CO} & (3a) \text{ Neutral-neutral} \\
\text{H}^- + \text{H}_3\text{O}^+ & \rightarrow \text{HO}^- + \text{H}_2 + '\text{H} & (4a) \text{ Ion-molecular ion neutralization} \\
\text{HCO}_2^- + e^- & \rightarrow \text{HO}^- + \text{CO} & (5a) \text{ Dissociative recombination}
\end{align*}
\]

Complete abatement and destruction of contaminants is the primary advantage of AOP treatment methods because a final pollutant disposal step associated with phase or compound separation, such as settling, is not necessary. The only byproducts from an advanced oxidation process are carbon dioxide, water, inorganic compounds, or transformation of contaminants into innocuous products. Biological processes are often combined with AOPs to provide additional treatment and allow for biodegradation of remaining intermediate compounds.

Advanced oxidation processes can be classified into two categories: established technologies and emerging technologies. Established technologies have full-scale applications while emerging technologies
have few, if any, full-scale applications. Some established and emerging AOP technologies are shown below (Figure 8). It is important to remember that most AOPs are emerging technologies and even the more established AOP technologies have limited data.

**Figure 8. Alternatives for advanced oxidation.**

### 5.3.1 Advanced Oxidation Options

#### 5.3.1.1 Ozone with UV

Ozone, or “ozonation,” is an AOP that utilizes gaseous ozone (O₃) to produce the hydrogen peroxide, which then forms the hydroxyl radicals (Equation 4).²⁵,²⁶ Because ozone decomposes quickly, it is typically produced on-site with an ozone generator. Ozone from the generator is injected into a preliminary mixing vessel with clean water before injection into the actual wastewater stream. Off-gas of ozone from the mixture vessel is collected and treated to decompose any remaining ozone that could escape into the environment. After mixture, the ozone-water stream from the mixing vessel is fed to a contact reactor where it is introduced to the wastewater stream. The combined stream then flows through a section of the contact tank with ultraviolet light, which forms hydroxyl radicals and provides disinfection. The combination of ozone and ultraviolet light as an advanced oxidation process creates a synergistic contaminant degradation process.

\[
O_3 + H_2O + UV (\lambda < 320 \text{ nm}) \rightarrow O_2 + HO \cdot + HO \cdot \rightarrow O_2 + H_2O_2 \quad \text{Equation 4}
\]

Ozone has been shown to produce a higher concentration of hydroxyl radicals in wastewater streams than other AOP technologies, including the second most prevalent AOP, hydrogen peroxide. In addition, ozone has disinfection potential while being used as an AOP, making it also effective at immobilizing specific pathogens and disease-causing protozoan such as *cryptosporidium* and *giardia*. However, ozonation requires substantial energy to produce appropriate concentrations of ozone for contaminant removal. The process requires a generator to produce ozone, as well as off-gas treatment following
injection into the mixing tank. In addition, use of ozone as an AOP must take into account the conditions of the specific wastewater stream. If a wastewater has concentrations of bromide greater than 10 µg/L, then byproduct formation of bromoform, a potential human carcinogen, is a concern.26

5.3.1.2 Hydrogen Peroxide with UV

The addition of hydrogen peroxide (H₂O₂) to wastewater alongside ultraviolet radiation produces hydroxyl radicals (Equation 5).26 Typically, hydrogen peroxide is injected in liquid form into the wastewater stream where mixing occurs. UV radiation is employed in a contact chamber downstream before the wastewater is discharged into a receiving water body. Figure 9 demonstrates that the removal efficiencies for the hydrogen peroxide and UV combination are much higher than the efficiencies of only UV.

\[
H_2O_2 + UV (\lambda = 200 \text{ to } 280 \text{ nm}) \rightarrow HO \cdot +HO \cdot +3O_2 \rightarrow 2HO \cdot
\]

Equation 5

![Figure 9. Removal efficiencies of H₂O₂/UV for contaminants of interest.](image)

Hydrogen peroxide has been employed for full-scale drinking water applications. Despite differences between drinking water and wastewater, the reaction and interaction of hydrogen peroxide with contaminants in drinking water treat can provide an initial understanding of the effect of using hydrogen peroxide as an AOP for wastewater. When treating drinking water, the residual hydrogen peroxide concentration needs to be reduced before entering a distribution network to prevent human ingestion and biological growth inside pipes. When used as an AOP, however, the residual hydrogen peroxide concentration is not a concern and does not need to be removed because the wastewater discharge will not directly enter the drinking water stream or piping systems. Hydrogen peroxide and UV act synergistically as an AOP, similar to ozone and UV.

With hydrogen peroxide, there is no fear of producing disinfection byproducts from reactions with the certain constituents in the wastewater. As a result, the bromoform formation from reactions between ozone and bromate in wastewater is not a concern. The disadvantage of hydrogen peroxide is the necessity for large chemical storage and handling.27
5.3.1.3 Hydrogen Peroxide with Ozone

Hydrogen peroxide (H$_2$O$_2$) and ozone (O$_3$) can be combined to form an alternative AOP that does not require UV radiation to form hydroxyl radicals. The hydrogen peroxide molecule slowly reacts with ozone to produce hydroxyl radicals. At the same time, disassociating hydrogen peroxide molecules form hydroperoxide ions (HO$_2^-$) that react quickly with ozone to produce hydroxyl radicals at a faster rate. The double-reaction (Equation 6) gives hydrogen peroxide and ozone the advantage of a wide variety of hydroxyl compounds, which all can react with wastewater contaminants. This creates a more efficient and reactive AOP system.$^{26}$

$$H_2O_2 + H_2O \rightarrow HO_2^- + H_2O + O_3 + HO_2^- \rightarrow HO \cdot + O_2^- + O_2$$  \hspace{1cm} \text{Equation 6}

Using hydrogen peroxide and ozone in combination as an AOP reduces the individual amounts of both chemicals required or needed to be generated. By decreasing the amount of ozone in the wastewater, the risk of bromoform formation is nearly eliminated. In addition, because UV radiation is not included in the combined AOP, the overall reaction is not hindered by the turbidity of the wastewater. The removal efficiencies of hydrogen peroxide with ozone are very similar to the removal efficiencies of ozone alone (Figure 10). Using both hydrogen peroxide and ozone in combination as an AOP requires almost double the setup, equipment, and training as that required for only ozone, and provides little additional treatment, making this process generally undesirable.$^{27}$

![Figure 10. Ozone/hydrogen peroxide removal efficiencies for contaminants of interest.](image)

5.3.1.4 Hydrogen Peroxide with Ozone and UV

This tri-component oxidation system is the most effective of all established AOP technologies because it combines the individual benefits associated with using hydrogen peroxide, ozone, and UV individually. However, it also includes all the disadvantages related to using hydrogen peroxide, ozone, and UV as AOPs. This tri-component AOP process is very expensive since it incorporates three AOP technologies as well as requires the need for appropriate equipment, training, and operation of each AOP.$^{27}$
5.3.1.5 Electron-Beam Treatment

High Energy Electron Beam Irradiation or “E-Beam treatment” is an advanced oxidation process that utilizes radiation from an electron beam to change the molecular structure of compounds without radioactivity. A voltage differential causes electrons to accelerate; a magnetic field then deflects the electrons into a beam directed to the wastewater. The electrons enter the water and rapidly react with water molecules to form hydroxyl radicals. Equation 7 describes the hydroxyl radical formation, with \( ^{\text{\textasciitilde}} \) representing the electron beam irradiation.

\[
H_2O + ^{\text{\textasciitilde}} \rightarrow 2.7HO \cdot + 0.6H \cdot + 2.6e_{\text{aq}}^- + 0.45H_2 + 0.7H_2O_2 + 2.6H_3O^+ \quad \text{Equation 7}
\]

E-beam treatment has little potential for byproduct formation due to the large number of hydroxyl radicals produced. The radicals are so prevalent in the wastewater that they degrade all initial contaminants and their intermediate species. Turbidity of wastewater does not affect E-beam treatment, but E-beam treatment is a very energy intensive process and requires specially-trained operators to work near radioactive sources.\(^{27}\)

5.3.1.6 Cavitation

Cavitation is the rapid formation and collapse of vapor pockets in a region with flowing liquid and low pressure. Typically, cavitation should be avoided due to the structural damage of pumps and related mechanics it incurs. However, cavitation is a promising technology as an advanced oxidation process because the rapid formation and collapse of microbubbles trigger thermal decomposition of surrounding particles. The extreme conditions produced by cavitation also decompose water to oxidizing and reducing radicals that destroy compounds.

Cavitation requires minimal maintenance and has energy costs comparable to those of UV radiation lamps. Unfortunately, cavitation is a black box technology because the vendor will not share specific information about the product, making it difficult for other scientists and engineers to test the system.\(^{27}\)

5.3.1.7 Photocatalytic Oxidation

Photocatalytic oxidation occurs when photons bombard titanium dioxide (\(\text{TiO}_2\)) through radiation, causing an electron to move from a valence band to a conduction band. This electron movement creates an electron hole at its former location in the valence band of the titanium dioxide molecule. The electron hole acts as a catalyst for other chemical reactions that produce hydroxyl radicals, which will proceed to degrade and react with contaminants in wastewater.\(^{12}\)

Titanium dioxide with photocatalytic oxidation is a low cost AOP.\(^{12}\) However, photocatalytic oxidation requires very high dissolved oxygen content and a very specific pH. Anions such as chloride and phosphate in the water can also foul the titanium dioxide AOP system, decreasing the effectiveness of the system and increasing maintenance costs.\(^{27}\)

5.3.1.8 Fenton’s Reaction

Fenton’s reaction is an AOP that uses the reaction of hydrogen peroxide with iron. The hydrogen peroxide and iron keep reacting until all the hydrogen peroxide is consumed. The product formed from this reaction is Fenton’s reagent, the combination of the unstable. The reagent then reacts to form hydroxyl radicals that react with and degrade contaminants in wastewater (Equations 8,9,10).

\[
\begin{align*}
\text{Fe}^{2+} + H_2O_2 & \rightarrow \text{Fe}^{3+} + OH^- + HO \cdot \\
\text{Fe}^{3+} + H_2O_2 & \rightarrow \text{Fe}^{2+} + O_2 \cdot + 2H^+ \\
O_2 \cdot + \text{Fe}^{3+} & \rightarrow \text{Fe}^{2+} + O_2
\end{align*}
\]  

Equation 8  
Equation 9  
Equation 10
Fenton’s reaction is simple and a feasible alternative for commercial uses. However, the reaction produces an iron-sludge waste that needs to be disposed of properly.  

5.3.2 Decision Matrix

A decision matrix (Table 5) was made to determine the optimal AOP. Some of the criteria were based off AOP compilation by Gina Menes. The following criteria were used:

- Mechanical Reliability: Examples include number of moving parts, frequency of cleaning needs
- Process Reliability: The ability of the system to meet effluent requirements
- Adaptability: The ability of the system to adjust for varying water conditions and qualities
- Flexibility: The ability of a system to handle changes in flows
- Potential for Modifications: Ease of implementing future changes to the system
- Energy Efficiency: The amount of energy used to meet a certain level of treatment
- Public Acceptance: The ease of obtaining public support
- Influent Requirements: Specific needs for influent temperature, pH, and turbidity
- Byproduct Treatment: The amount of byproducts produced and the cost and need of removing those byproducts
- Capital Cost: The up-front costs related to the project, such as pipes, pumps, and reaction tanks
- Operation and Maintenance Cost: The daily operational and maintenance cost, such as replacement of equipment and labor
- Removal Efficiencies: The ability of the system to remove the specific contaminants of concern
- Full Scale Treatment: Number of successful full-scale implementations
- Easily Applicable: How well can the process can be applied to the CWP
Table 5. Decision Matrix for AOPs. The assigned values range from 1 to 5, with 1 being poor and 5 being excellent.

<table>
<thead>
<tr>
<th></th>
<th>Weighted Average</th>
<th>H₂O₂ &amp; O₃</th>
<th>H₂O₂ &amp; UV</th>
<th>O₃ &amp; UV</th>
<th>H₂O₂ &amp; O₃ &amp; UV</th>
<th>E-Beam</th>
<th>Hydrodynamic Cavitation</th>
<th>TiO₂ – Catalyzed UV Oxidation</th>
<th>Fenton’s Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical Reliability</strong></td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Process Reliability</strong></td>
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<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Adaptability</strong></td>
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<td>3</td>
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<td>3</td>
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<tr>
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<td><strong>Byproduct Treatment</strong></td>
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<tr>
<td><strong>Full Scale Treatment</strong></td>
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<tr>
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<td><strong>115</strong></td>
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</table>

5.3.3 Recommended Option

The top ranked technologies in the decision matrix were hydrogen peroxide with ozone, ozone with UV, hydrogen peroxide with ozone and UV, and hydrogen peroxide with UV. It was decided that ozone with UV would be the optimal choice through the process of elimination. The combination of hydrogen peroxide and ozone is an effective method for removing contaminants, but since UV will already be installed for disinfection, it makes sense to include it in the AOP for the synergistic affect UV produces. Also, the combination of ozone and hydrogen peroxide has minimal improvement for removal of contaminants compared to ozone alone. The team also decided that the combination of hydrogen peroxide and UV or hydrogen peroxide with ozone and UV are not practical systems for the plant because of chemical storage. According to hydrogen peroxide’s MSDS only 1000 lbs of hydrogen peroxide can be stored on site at one time without a permit and emergency plan. Assuming the plant would inject 6 mg/L of hydrogen peroxide into the wastewater, the plant would be able to store a maximum of three days of hydrogen peroxide on-site. Having a delivery of hydrogen peroxide every three days is very impractical for the plant operators. Also, a major reason of switching from chlorine to UV is the elimination of the
need for an emergency response plan for chlorine; imposing a new emergency response plan for hydrogen peroxide counteracts the removal of chlorine’s emergency response plan.

5.4 Reaeration

A reaeration process adds air – and therefore oxygen – back into the wastewater stream. The CWP requires this process to ensure that the effluent dissolved oxygen (DO) content is above the required limit (See Section 3.4). Reaeration systems are common in wastewater treatment plants across the United States where the effluents are discharged into natural environments.

Based on the CWP data gathered over the years, the DO concentrations for the CWP effluent wastewater stream do not normally drop below the NPDES permit limitation of 5.0 mg/L and 3.0 mg/L for the months of June to September and October to May respectively. In fact, the CWP often is able to exceed mandatory DO level required by the NPDES permit by approximately 2 mg/L and 5 mg/L for the months of June to September and October to May respectively. There are a few times in the past years that the CWP’s effluent wastewater stream DO concentrations have dropped below the NPDES permit levels. These anomalies can usually be attributed to large storm events where the CWP is required to operate under almost full capacity. The CWP recognizes the need to meet NPDES required DO levels and is looking for reparation strategies to increase DO levels when necessary. Based on plant DO concentration data, the desired reaeration system must be able to add an additional DO concentration of at least 1.7 mg/L to the wastewater effluent stream during spring storm events (March to May) to meet NPDES permit DO levels.

![Figure 11. Dissolved oxygen concentrations for the CWP treated effluent.](image-url)
5.4.1 Reaeration Options

The technology options for reaeration of the effluent wastewater stream are the same as those for the aeration that occurs previously in the system during the wastewater treatment process. A tank is required for many of the reaeration options. If one of these options were to be chosen, Chlorine Contact Basin No. 1 with a volume of 27,000 cubic feet could be converted to the aeration tank, since it is not currently used and will not be necessary with UV disinfection. Black & Veatch has also done extended research and analysis of the reaeration alternatives in its facilities plan, which will be summarized in the following sections. The construction costs include modifications needed to ready Chlorine Contact Basin No. 1 for use as an aeration tank.

5.4.1.1 Fine Bubble Diffusers

Fine bubble diffusers are the typical aeration system implemented today when a plant wants to improve aeration efficiency. A diffusion system is powered by air compressors known as blowers that pump a high volume of air at a low pressure. This air is then split into small bubbles by diffusers with small holes in them. With any type of diffuser that incorporates a blower, keeping blower size minimal is important to reduce costs. Fine bubble diffusers could use either new blowers located in a new building or use the existing blowers and blower building that is already used for aeration earlier in the plant process. Chlorine Contact Basin No. 1, which is not in use, would be divided into two sections to allow for baffling for increased DO concentrations. Depending on configuration of Chlorine Contact Basin No. 1, there is potential to design a reaeration system so that one section and aerator could be used under average flow conditions, and the other section and aerator could be added on when maximum flow conditions would occur.

![Figure 12. A schematic of a membrane disc diffuser, a type of fine bubble diffuser.](image)

Fine bubble diffusers, given the use of the existing building, would cost approximately $369,200 for construction, with a daily cost of $34.

5.4.1.2 Coarse Bubble Diffusers

Coarse bubble diffusers are similar to fine bubble diffusers, only the air bubbles they emit are larger in diameter than the fine bubble diffusers. This causes a lower surface area to volume ratio, decreasing effectiveness of the aeration. Greater airflow would be needed for the same aeration of the water, increasing cost. Coarse bubble diffusers have the same basic structure as the fine bubble diffuser shown in Figure 12.
Coarse bubble diffusers, given the use of the existing building, would cost approximately $386,400 for construction with a daily cost of $61.9

5.4.1.3 **Surface Aerators**

Surface aerators are mechanical blowers that essentially mix air into the water, causing oxygen to dissolve into the water.28 Under this scenario, surface aerators could be used in Chlorine Contact Basin No. 1. The basin would be divided into two sections. Fine or coarse bubble diffusers could be used for the reaeration. High-rate mechanical aerators could be used in each section so that the plant operator could easily raise or lower the aeration provided to meet seasonal DO limits.9

![Figure 13. A side view schematic of a mechanical surface aerator.](image13)

Mechanical surface aerators, given the use of Chlorine Contact Basin No. 1, would cost approximately $168,900 for construction with a daily cost of $63.9

5.4.1.4 **Gravity Cascade Aeration**

Cascade aeration would require pumping to raise the level of the wastewater for it to flow by gravity downwards over a series of steps while exposed to air.16 This pumping could use the settled sewage pump station that is available for use or a new pump station. If high water levels necessitate additional pumping, cascade aeration would become more feasible because the pumping station would already be built. To achieve the total required additional DO in the effluent, the minimum fall distance would be 5.3 ft.9
Cascade aeration, given the use of the existing settled sewage pumping system, would cost approximately $1,078,125 for construction with a daily cost of $122.⁹

5.4.2 Decision Matrix

A decision matrix (Table 6) was created to aide in choosing the best reaeration option. Design considerations included the following:
- Construction Cost: Based on construction costs from the above descriptions
- Operation Cost: Based on operational costs from the above descriptions
- Flexibility: Ability to raise or lower the aeration capacity
- Implementation: The number of new structures required
- Ease of Use: Attention required from operators
- Maintenance: Difficulty of keeping the technology in good working order

Table 6. Decision matrix for the four reaeration alternatives. The assigned values range from 1 to 5, with 1 being poor and 5 being excellent.

<table>
<thead>
<tr>
<th>Category</th>
<th>Weight</th>
<th>Fine Bubble</th>
<th>Coarse Bubble</th>
<th>Surface</th>
<th>Cascade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Cost</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Operation Cost</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Flexibility</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Implementation</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Ease of Use</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Maintenance</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>69</td>
<td>48</td>
<td>64</td>
<td>26</td>
<td></td>
</tr>
</tbody>
</table>

The decision matrix shows fine bubble diffusers as the ideal reaeration option for the CWP given the current plant facilities. The overall rating for cascade aeration in the decision matrix would change if a pumping system were to be built allowing for this pumping system to also be used for reaeration.
5.4.3 Recommended Option

Fine bubble diffuser aerators are recommended for the CWP for reaeration because of their flexibility in aeration capacity, ease of use, and flexibility. This reaeration option will also not use any additional footprint on the plant site because of the reuse of Chlorine Contact Basin No. 1.

5.5 Alternatives

The plant could choose from additional treatment alternatives besides advanced oxidation processes and an updated disinfection system, but none of these alternatives provided increased water treatment benefits at a reasonable cost, given the current good quality of the effluent.

5.5.1 Filtration

5.5.1.1 Overview

Granular filtration is one of the oldest water quality techniques. It was originally applied to drinking water; however, wastewater filtration has recently gained popularity in the United States. The two main types of granular filters are slow sand filters and rapid gravity filtration. Rapid gravity filters contain larger media diameters ranging from 0.5 to 1.2 mm and filtration rates as high as 15 m/h.\(^{20}\) Because rapid filters have a high filtration rate, they require a much smaller footprint than a slow sand filter. As rapid gravity filters accumulate particles, they must be backwashed to dislodge the suspended particles. Time between backwashing varies on filter, but it generally ranges between one and four days.\(^{16}\) Slow sand filters contain media with a diameter of 0.3 to 0.45 mm and have slower filtrations rates of 0.05 to 0.2 m/h.\(^{20}\) Filter beds for slow sand filters are generally over 100 square meters, due to the slow filtration rates associated with slow sand filters. Although slow sand filters have a larger footprint than rapid gravity filters, slow sand filters do not need to be cleaned as often as rapid filters. About every six months the top 2 cm of the bed are scraped off, and two weeks of time with no flow entering are generally required for the filter to regenerate.\(^{16}\)

5.5.1.2 Consideration

Although granular filtration is a proven method for wastewater treatment, it is not the most viable solution for the city of Wyoming. Slow sand filters are easily maintained and require relatively low energy input, but slow sand filters have extensive land requirements. The CWP does not have space allotted for a system of that magnitude, thus slow sand filters are not a feasible option. Rapid gravity filters do not have large space requirements; however, they are energy intensive. Furthermore, extensive cleaning and monitoring is required in rapid filtration applications. For these reasons, rapid filtration is not a practical solution for the city of Wyoming. Additionally, both rapid gravity and slow sand filters have limited removal of the emerging contaminants targeted in this study.\(^{20}\)

5.5.2 Biofiltration

5.5.2.1 Overview

Biological filtration is an emerging technique in North America for wastewater treatment. As the name suggests, biological filtration is the process of integrating microbes into filter media to enhance the filtration process. It is particularly effective at removing nitrates and natural organic matter (NOM), consequently increasing the biological stability of the wastewater. Both slow sand filters and rapid gravity filters provide a hosting ground for biological treatment. However, rapid filter applications are used much less often due to upstream oxygen levels greatly affecting the organisms. Pre-oxidation of the organic matter is required for biological filters to flourish, and ozone is by far the most implemented oxidation agent. In addition to ozone, virtually any AOP can be used as an oxidizing agent for the wastewater.\(^{16}\)
5.5.2.2 Consideration

There are a number of advantages and disadvantages to implementing a biological filtrations system. A large cost to biofiltration is oxidizing the water before it passes through the filter. However, this report already proposes installing an AOP system that could be used to oxidize the water, thereby alleviating the need to construct an AOP system for the biofilter. A biological filter would reduce the amount of nitrates and NOM in the effluent stream; however, neither of these two substances is of concern to Wyoming at this time. Biological slow sand filters have a fairly large footprint, making them a poor option for the CWP. Conversely, biological rapid gravity filters could be implemented at the existing site. The major drawbacks for rapid gravity filters are the high energy requirements and added maintenance requirements to keep the microbes at an optimum population. Because biological filters are not especially effective at removing any of the targeted contaminants and have footprint and energy usage drawbacks, implementation is not recommended at the CWP. \(^ {16} \)

6 Emerging Contaminants

Five contaminants of interest were selected to be targeted for removal by advanced oxidation processes during disinfection (Table 7). These contaminants were chosen from a list of eighty-seven pollutants that the CWP has been monitoring in the influent and effluent wastewater streams (Appendix C). The list of pollutants includes pharmaceuticals, antibiotics, steroids, pesticides and personal care products. The team selected contaminants based on four criteria:

1. Presence in Clean Water Plant wastewater
2. Class of contaminant
3. Environmental and health concern
4. Available information

All pollutants on the list were ranked according to their effluent concentrations in the CWP. The scope and class of each contaminant was then considered to ensure that each contaminant was representative of a different sub category of emerging contaminants found in wastewater. Environmental and health concerns associated with each contaminant were then researched to determine the impacts of the contaminant on humans and aquatic ecosystems. If there was not enough research and documentation on a contaminant and its treatment, the team began the contaminant selection process again, evaluating the next potential contaminant on the list following the same steps and criteria.

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Influent (ng/L)</th>
<th>Effluent (ng/L)</th>
<th>Class of Contaminant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erythromycin</td>
<td>0 - 360</td>
<td>0 - 150</td>
<td>Antibiotic</td>
</tr>
<tr>
<td>Atrazine</td>
<td>13 - 36</td>
<td>13 - 37</td>
<td>Pesticide/Herbicide</td>
</tr>
<tr>
<td>Iopromide</td>
<td>0 - 1200</td>
<td>0 - 1900</td>
<td>X-Ray Contrast Medium</td>
</tr>
<tr>
<td>Carbamazepine</td>
<td>80 - 350</td>
<td>230 - 380</td>
<td>Anticonvulsant/Analgesic</td>
</tr>
<tr>
<td>Ethinyl Estradiol 17-alpha</td>
<td>0</td>
<td>0 - 1600</td>
<td>Hormonal Steroid/Endocrine Disrupter</td>
</tr>
</tbody>
</table>
6.1 Erythromycin

6.1.1 Overview and Prevalence

Erythromycin is an antibiotic developed from the metabolic products of a strain of *Saccharopolyspora erythraea*. Filipino scientist Abelardo Aguilar discovered the compound in a set of soil samples in 1949. Aguilar then isolated erythromycin as a compound and subsequently patented the compound in 1953 for medical use inside the United States. Erythromycin was developed as a macrolide antibiotic that could be used to treat bacterial infections such as pertussis (whooping cough), pneumonia and bronchitis. Generally, it can treat ear, lung, intestine, urinary tract, and skin infections caused by bacteria. Medical erythromycin comes in the form of a capsule, tablet, or liquid that should be taken orally every six to eight hours for a period of 7 to 21 days, depending on the severity of the infection. Leftover prescription erythromycin is often disposed of by flushing the antibiotic down the toilet or washing it down the sink. When erythromycin is disposed of in this manner, it is directly introduced to wastewater and the environment if not treated. Erythromycin is also introduced into the wastewater stream inadvertently through human and animal waste because neither body is able to completely metabolize the antibiotic dosage.

Studies have reported that erythromycin has been found in surface and wastewater streams at concentrations of parts per billion and parts per trillion. Karthikeyan and Meyer, in a study on the occurrence of antibiotics in wastewater treatment facilities in the state of Wisconsin found that concentrations of erythromycin in raw urban wastewater influents were in the range of 0.07 to 1.2 µg/L. Gobel et al., in a study on the occurrence of macrolide antimicrobials in the environment, reports that erythromycin was found at concentrations of 70 to 190 ng/L in the raw influent of a wastewater treatment plant and subsequently at concentrations of 70 to 110 ng/L following tertiary treatment. Additional literature review confirms erythromycin in wastewater at concentrations of ng/L. The CWP has an effluent erythromycin concentration of approximately 0.15 µg/L, which is consistent with the literature concentrations.

There are no current regulations on erythromycin in wastewater or drinking water. However, the United States Environmental Protection Agency (EPA) has placed erythromycin on the Chemical Contaminant List (CCL). This is a list of contaminants that are not yet subject to drinking water regulations despite potential occurrence in public water systems. Contaminants in the EPA’s CCL list are anticipated to be regulated in the future by the Safe Drinking Water Act.

6.1.2 Structure and Kinetics

Erythromycin (Figure 15) is from the class of antibiotics known as the macrolides that have a large, lactone ring structure. It is a crystalline, colorless compound that is slightly soluble in water up to 1 mg/mL and easily dissolves in most common organic solvents. Erythromycin exhibits a base pH with a pKₐ of 8.6. The compound weakly absorbs ultraviolet light with a maximum absorbance wavelength of 278 µm. The half-life of erythromycin can vary depending on its environment. In biosolids, the half-life of erythromycin is approximately 7.0 to 17 days. In aquatic environments, the half-life of erythromycin is reported to be around 20 days.
6.1.3 Health and Environmental Concerns

The persistence of erythromycin in wastewaters is an ever-increasing concern because conventional wastewater treatment processes are ineffective at eliminating erythromycin. In addition, the impacts of erythromycin on humans and aquatic ecosystems at sub-therapeutic levels in the environment are largely unknown. Louvet et al., reports erythromycin was more frequently detected in 139 United States streams than twenty-one other human and veterinary antibiotics. Amin et al. and Louvet et al., found that chemical oxygen demand (COD) concentrations in wastewater increased when erythromycin concentrations were 10 mg/L or greater. High COD levels in wastewater deplete dissolved oxygen content, and therefore adversely affect biological treatment processes in water treatment plants and aquatic ecosystems downstream of discharge sites. Miao et al., after conducting a study on antibiotics in wastewaters, concludes that chronic exposure of bacteria and other microorganisms to antimicrobials such as erythromycin can contribute to the development of antibiotic resistance in the environment. Antibiotic resistance in the environment, biological processes inhibition, and inadvertent secondary human exposure to erythromycin make the removal of erythromycin advisable to preserve human and environmental health.

6.1.4 Treatment Options

Erythromycin in wastewater can be partially or fully eliminated by treatment technologies including biofiltration and advanced oxidation. Biofiltration involves biodegradation of the antibiotic erythromycin during a filtration process. Advanced oxidation technologies offer different treatment options. Kim and Tanaka report that ozone, ozone and UV, and O₃/H₂O₂ treatment systems have a 100% removal efficiency of erythromycin when tested in a wastewater treatment plant reactor. Luiz et al., confirms the use of AOPs including O₃/UV, O₃/H₂O₂, and UV/H₂O₂ for the mineralization of erythromycin, stating that degradation by AOP technologies is orders of magnitude faster than ozone treatment alone.

6.2 Atrazine

6.2.1 Overview and Prevalence

Atrazine is a widely used pesticide used to control broadleaf and grassy weeds (Figure 16). Approximately 76.5 million pounds of atrazine are applied every year. The majority of atrazine is applied on agricultural sites growing corn and sugarcane, but atrazine is also used on residential lawns and golf courses. In 1991, the EPA’s Safe Drinking Water Act limited the concentration of atrazine to 3.0 ppb in drinking water. The European Union limits the concentration of atrazine in drinking water to 0.1 ppb.
The CWP has influent and effluent atrazine concentrations of 36 ng/L indicating that atrazine is not being removed during the treatment processes.

6.2.2 Structure and Kinetics

Atrazine (Figure 17) is white, crystalline solid also known as 1,3,5 triazine herbicide. Under normal room conditions, atrazine is stable. It does not dissolve in water. Atrazine has a water solubility of 33 mg/L, an aerobic soil half-life of 146 days (Table 8), an anaerobic soil half-life of 33 days, and a half-life in water of 146 days.

Figure 16. Amount of land-applied atrazine in the United States.

Figure 17. Chemical structure of atrazine.
Table 8. Half-life decomposition time in minutes for atrazine using different oxidation processes.\textsuperscript{53}

<table>
<thead>
<tr>
<th>Process</th>
<th>pH</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.3 to 4.8</td>
<td>6.7 to 7.2</td>
<td>10.1 to 11.7</td>
</tr>
<tr>
<td>UV</td>
<td>9.7</td>
<td>8.2</td>
<td>7.1</td>
</tr>
<tr>
<td>Ozonation</td>
<td>81</td>
<td>38</td>
<td>3.6</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}_2$</td>
<td>--</td>
<td>--</td>
<td>32</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}_2$/UV</td>
<td>4.7</td>
<td>2.2</td>
<td>25.4</td>
</tr>
<tr>
<td>Ozone/UV</td>
<td>14</td>
<td>9</td>
<td>8.5</td>
</tr>
<tr>
<td>Ozone $\text{H}_2\text{O}_2$</td>
<td>52</td>
<td>10</td>
<td>16</td>
</tr>
<tr>
<td>Ozone/$\text{H}_2\text{O}_2$/UV</td>
<td>4.9</td>
<td>3.1</td>
<td>20</td>
</tr>
</tbody>
</table>

6.2.3 Health and Environmental Concerns

The World Health Organization classifies atrazine as a pesticide that is unlikely to be toxic during normal usage. Studies have shown that atrazine does not cause birth defects and does not decrease the ability to reproduce.\textsuperscript{54} According to the National Center for Biotechnology Information, atrazine does not cause certain cancers such as prostate cancer. However, there could be links between atrazine and the development of non-Hodgkin lymphoma, lung cancer and bladder cancer.\textsuperscript{55} Atrazine is also a known endocrine disruptor, causing tumors in rats during laboratory studies.\textsuperscript{56}

While not directly toxic to many living organisms, atrazine can greatly affect aquatic plant life by decreasing the dissolved oxygen levels in the water, which then reduces aquatic plant growth.\textsuperscript{54} Atrazine has been found in surface waters at concentrations ranging from 0.5 µg/L to 100 µg/L. Kotrikla et al., found that atrazine has an EC\textsubscript{50} ranging from 68 µg/L to 77 µg/L for \textit{Chlorella fusca var-fusca}, a type of alga. An atrazine concentration of 100 µg/L decreased the growth rate of the alga by 65%.\textsuperscript{57} For other freshwater plants the EC\textsubscript{50} for atrazine ranges from 22 µg/L over 14 days to 8,700 µg/L for 14 days, depending on the plant.

Atrazine can also affect fish and other aquatic animals. \textit{Salmo gairdneri}, the salmon trout has a LC\textsubscript{50} of 8,800 µg/L over four days. \textit{Brachydanio}, the zebrafish, has an LC\textsubscript{50} of only 1200 µg/L over 35 days.

6.2.4 Treatment Options

As shown in Table 8, atrazine degrades the quickest with a combination of hydrogen peroxide and UV at a pH around 7, making hydrogen peroxide and ultraviolet light the most efficient method for removing atrazine. However, a combination of UV, ozone and hydrogen peroxide is also an effective treatment option for removing atrazine. The EPA estimates that granular activated carbon can remove 99% of atrazine, according to data compiled from full scale drinking water treatment systems.\textsuperscript{58} However, since granular activated carbon does not absorb other emerging contaminants, activated carbon is not the optimal choice for the CWP.

6.3 Iopromide

6.3.1 Overview and Prevalence

Iopromide is a radiographic diagnostic aid that is commonly called Ultravist\textsuperscript{®}. When injected into the bloodstream, iopromide enhances the contrast of fluids and structures within the body to improve medical radiographic imaging. As a result, soft tissues, blood vessels, and internal organs within the body appear sharper under imaging techniques and rendering. Iopromide is typically used as a contrast medium during CT scans, X-rays, ultrasounds, peripheral venography, and excretory urography.\textsuperscript{59}

Hospital effluent streams are the primary source of iopromide occurring in wastewater because of their significant usage of iopromide during scans and x-rays, ranging up to 200 grams of iopromide per
application. Ternes et al. reports that iopromide has been detected in wastewater treatment plant effluents at maximum concentrations of 7.5 and 8.1 µg/L. Van Beelen found that iopromide was measured at concentrations up to 5.7 µg/L in the effluents of wastewater treatment plants. Schulz et al. detected iopromide at concentrations between 3.1 and 3.7 µg/L when sampling wastewater from two municipal wastewater treatment plants.

The CWP has an effluent iopromide concentration of approximately 1.9 µg/L.

### 6.3.2 Structure and Kinetics

Iopromide belongs to the family of iodated X-ray contrast media used in medical practices. It is a water soluble, nonionic compound. Schulz et al. reports that iopromide excrete is mainly non-metabolized (>95%). When iopromide is in the body, it is almost completely excreted within one day, resulting in frequent, high concentrations of iopromide found in some wastewater streams. In activated sludge batch studies performed by Perez, iopromide was found to achieve 90% biodegradation in a period of nine days. Iopromide has a log Kow of -2, meaning that it has low sorption and can easily pass through wastewater treatment plants into surface rivers, lakes, and raw drinking water sources.

### 6.3.3 Health and Environmental Concerns

Currently, there are no regulations on iopromide in wastewater. The impacts of iopromide on human environmental health are also unknown. However, the concentrations of iopromide that are being detected in the environment have been reported to be up to 1 µg/L in raw sewage. Iopromide also has a tendency to biotransform into three transformation products when persisting in wastewater and discharged into the environment. The eco-toxicity of these transformation products may have a mutagenic effect on microorganisms in aquatic ecosystems. As a result, iopromide should be considered as an emerging contaminant of interest because of its detected presence in the environment, high excretion rate, and potential toxic impacts of its transformation products.

### 6.3.4 Treatment Options

Kormos et al. reports that traditional wastewater treatment plants are only capable of eliminating 80% of influent iopromide. Jones performed similar research as Kormos, reporting that iopromide was detected in eight German sewage treatment plants at influent concentrations up to 1 µg/L. Jones concludes that iopromide was not significantly degraded during conventional wastewater treatment processes at all German sewage treatment plants studied. The CWP in Wyoming, Michigan reports in is 2010 PPCP data that it has an influent concentration of 1.9 µg/L for iopromide. This concentration is very close to the concentrations of iopromide detected by Jones in German wastewater treatment plants.
Advanced oxidation technologies hold some promise for degrading iopromide from wastewater streams. Van Beelen reports that \( \text{O}_3/\text{H}_2\text{O}_2 \) is not successful at removing iopromide.\(^6\) However, Tusnelda and Frimmel demonstrate that iopromide can be degraded using photocatalysis with \( \text{TiO}_2 \) at a reaction rate constant of \( 0.18 \text{ min}^{-1} \).\(^6\) Ning et al. found that ozone was more effective at degrading iopromide than a combination of ultrasound and ozone.\(^6\) It can only be concluded from these research reports that iopromide can potentially be degraded using AOPs.

### 6.4 Carbamazepine

#### 6.4.1 Overview and Prevalence

Carbamazepine is an anticonvulsant that is used to prevent and control seizures. In addition to controlling seizures, it is also used for psychiatric disorders such as bi-polar disorder and to relieve nerve pain by reducing excessive nerve signals in the brain.\(^6\) Common brand drug names for carbamazepine are Carbatrol, Equetro, Tegretol, Tegretol XR, and Epitol; typical dosage ranges from 400 to 80 mg/day.\(^6\)

Like other drugs such as erythromycin, the body cannot absorb all of the medicine. As a result, a fraction of the carbamezapine daily dosage is excreted in urine and feces which can then enter the influent stream of a wastewater treatment plant.

In a study on the presence of organic substances in the effluents of wastewater treatment plants, van Beelen found that the Rhine Water Works, a water regulating agency in the Netherlands, reported on average that carbamezapine was present at average influent concentrations around 400 ng/L. In addition, van Beelen was able to conclude from his study that water treatment processes at the Rhine Water Works do not have any effect in removing or degrading carbamazepine. Ternes reports that a wastewater treatment plant in Switzerland had a 3 month period where the effluent average was as high as 950 ng/L. Ternes also found that the mean concentration of carbamazepine in German wastewater effluent from treatment plants was around 2100 ng/L. The study by Terne showed that a sewage treatment plant located near Frankfort achieved a 7% removal rate of carbamazepine in the treatment process.\(^6\) The CWP in Wyoming Michigan, during 2010 PPCP testing, detected an influent carbamazepine concentration of 350 ng/L and an effluent concentration of 340 ng/L. From these influent and effluent concentrations, it can be concluded that at present, the CWP has a 3% removal rate of carbamazepine.

#### 6.4.2 Structure and Kinetics

Inside the human body, carbamazepine has a half-life ranging from 25 to 65 hours, depending on the amount of drug administered and subsequently the metabolic rate which governs how fast the liver is capable of utilizing the carbamazepine compound (Figure 19).\(^6\) If carbamazepine is present in the environment, its half-life is 82 days. Carbamazepine has a \( pK_a \) of 13.9, indicating that it is a basic compound.

[Figure 19. Chemical structure of carbamazepine.]\(^7\)
6.4.3 Health and Environmental Concerns

According to research by Oetken on the effects of pharmaceuticals on aquatic invertebrates, carbamazepine is characterized by low acute toxicity to aquatic organisms. Oetken also concludes that long-term exposure to low concentrations of carbamazepine can be dangerous to aquatic life. Specifically, Oetken through a study on the effects of carbamazepine on *Chironomus riparius*, a common fly, observed that carbamazepine at concentrations ranging from 70 to 210 µg/kg in sediment near water sources could impact reproduction of aquatic insects. Dussault et al. demonstrated that *Daphnia magna*, a freshwater flea, had lethal concentration 50 and effective concentration 50 when carbamazepine was present in water at concentrations of 9.9 mg/L to 47.3 respectively. Lethal concentration 50 corresponds to the concentration of a chemical in water which can kill 50% of a specific group of organisms. Effective concentration 50 refers to the concentration of a drug that induces a response in 50% of the group of organisms under observation. Often times biological processes are inhibited at effective concentration 50.

Zhi-Hua Li determined that long term exposure (2 mg/L for 42 days) of rainbow fish to carbamazepine caused alterations of enzymatic and RNA/DNA ratios in the fish. Dussault et al. recently published an article that consisted of research and a compilation of research findings by others on the effects of carbamazepine in the environment. It was determined that typical toxicity from exposure to carbamazepine ranged from 25.2 mg/L over 7 days for the macrophyte *Lemma minor* to 140 mg/L over 24 hours for a the fairy shrimp *Thamnocephalus platyurus*. Dussault et al. concludes that uncertainty exists regarding the potential impacts of chronic exposure of benthic organisms to carbamazepine, suggesting that long-term studies on impacts and treatment need to be performed.

6.4.4 Treatment Options

Lekkerkerker researched the effect of H₂O₂, UV, and ozonation for removing carbamazepine from wastewater. Lekkerkerker observed that H₂O₂, UV, and ozonation as well as other advanced oxidation processes were able to remove approximately 100% of carbamazepine from wastewater. Lekkerkerker experimented with combinations of AOPs while varying the concentrations of ozone and hydrogen peroxide if applicable and altering UV light intensity. Almost all of the combinations of AOPs tested by Lekkerkerker obtained 100% removal of carbamazepine, with the exception of a test where carbamazepine was removed only 70% when H₂O₂ was applied at a low dose with minimal UV light intensity. It can be concluded from these studies that advanced oxidation processes are very effective at removing carbamazepine from wastewater.

6.5 Ethinyl Estradiol 17-α

6.5.1 Overview and Prevalence

Ethinyl estradiol 17-α is a synthetic hormonal steroid that is prepared from estrone. In wastewater treatment and the environment it can be classified as an endocrine disrupting compound because of its ability to disrupt the hormonal system in animals and humans. The primary use of ethinyl estradiol 17-α is for providing the estrogen component of oral contraceptives. It can also be used as an estrogenic drug in the treatment of menopausal and post-menopausal symptoms, acne prevention, Turner’s symptom, and possibly mammary carcinogenesis.

Ethinyl estradiol 17-α is introduced into wastewater streams primarily through human excretion and perhaps the occasional non-ideal disposal of leftover prescription down the sink or drain. Ethinyl estradiol 17-α is transported mainly in human or animal urine and minimally through feces. The natural excretion rate of natural estrogens such as ethinyl estradiol 17-α is approximately 10 to 100 µg/day for women, 5 to 10 µg/day for women after menopause, and 2 to 25 µg/day for men. The average dose of a synthetic hormone such as ethinyl estradiol 17-α in a contraceptive pill is 35 µg over 21 days of a 28 day period. Up to 80% of this hormonal dose is not metabolized by the body and excreted, resulting in high concentrations in wastewater and potentially the environment.
Ethinyl estradiol 17-α has increasingly been detected in wastewater streams at nanogram per liter (ng/L) concentrations. Komori et al. reports that wastewater treatment plants in Japan have detected concentrations of ethinyl estradiol 17-α in the ranges of 0.10 to 0.32 ng/L in the influent wastewater streams and around 0.13 ng/L in the effluent wastewater streams.\(^{81}\) Ying et al. found that ethinyl estradiol 17-α was present at concentrations of 0.1 and 1.3 ng/L in four South Australian sewage treatment plants.\(^{82}\) de Mes et al. presents research where ethinyl estradiol 17-α concentrations are detected in sewage treatment plant influent and effluent streams from countries and locations all across the globe (Table 9).\(^{83}\)

<table>
<thead>
<tr>
<th>Country</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Italy</td>
<td>0.48 - 2.93 ng/L</td>
</tr>
<tr>
<td>Netherlands</td>
<td>0.2 - 9.7 ng/L</td>
</tr>
<tr>
<td>France</td>
<td>0.8 - 59.0 ng/L</td>
</tr>
<tr>
<td>Canada</td>
<td>0.0 - 64.0 ng/L</td>
</tr>
<tr>
<td>Japan</td>
<td>0.0 - 70.0 ng/L</td>
</tr>
<tr>
<td>Germany</td>
<td>0.05 - 59.0 ng/L</td>
</tr>
<tr>
<td>Spain</td>
<td>&lt; 5.0 ng/L</td>
</tr>
<tr>
<td>United States</td>
<td>320 – 1770 ng/L</td>
</tr>
</tbody>
</table>

From the information compiled by de Mes et al. it is surprising to observe such variations in the concentrations of ethinyl estradiol 17-α detected in wastewater treatment plants. It should be pointed out that ethinyl estradiol 17-α is detected at the highest concentrations up to 150 times greater in the United States according to the study performed by de Mes et al. in 2005. Currently, the CWP influent stream has ethinyl estradiol 17-α concentrations of 0 ng/L and 1600 ng/L for its influent and effluent wastewater streams respectively. The extreme disparity between influent and effluent concentrations of ethinyl estradiol 17-α is suspected to result from an unknown source in the plant, masking/transformation of ethinyl estradiol 17-α by another compound, or errors in detection methods.

### 6.5.2 Structure and Kinetics

![Figure 20. Chemical structure of ethinyl estradiol 17-α.\(^{46}\)](image-url)
Ethinyl estradiol 17-α is a synthetic estrogen and has a hemihydrate chemical structure which means that it contains one molecule of water for every two molecules of the compound. The solubility of ethinyl estradiol 17-α is up to 11.3 mg/L in water. Liu et al. reports that ethinyl estradiol 17-α follows a pseudo-first order kinetic model for degradation. Xu et al. reports from studies on batch tests that the biodegradation rates or half-lives of ethinyl estradiol 17-α can be from 7 hours to several days. This accounts for the bioaccumulation and high concentrations of ethinyl estradiol 17-α present in the environment.

6.5.3 Health and Environmental Concerns

Despite being present in wastewater at such low concentrations of nanograms per liter, ethinyl estradiol is still considered one of the most potent endocrine disrupters. As a result, the impacts of ethinyl estradiol 17-α on humans and aquatic organisms and ecosystems has been widely researched recently and continues to be targeted for removal in wastewater streams. Ying et al. states that ethinyl estradiol 17-α is of “great concern” to local fish populations downstream of wastewater treatment plant effluents when it is present at concentrations of 0.5 ng/L or greater in the effluent wastewater stream. Nakada et al. reports that captured male carp near a wastewater treatment plant in Tokyo, Japan showed changes in reproductive organs and increased levels of vitellogenin, a female egg yolk, in the blood. Nash et al. reports that the presence of ethinyl estradiol 17-α has been linked to the feminization of fish which could lead to potential disruptions affecting the breeding dynamics and reproductive success in group-spawning fish. Nash et al. found that lifetime exposure of zebra fish to a concentration of 5 ng/L ethinyl estradiol 17-α resulted in infertility and disturbed sexual differentiation where male fish had no functional testes and undifferentiated or intersex gonads. Another study performed by Dussault et al. reported that exposure of the midge Chironomus tentans and freshwater amphipod Hyallela azteca at concentrations of 0.36 to 1.5 mg/L ethinyl estradiol 17-α resulted in a 50% decrease in reproduction rates.

Researchers also speculate that estrogens such as ethinyl estradiol 17-α play various roles in the development of testicular and prostate cancer in humans. In addition, the feminization of fish and other lower forms of invertebrates has stirred up concern over the potential feminization of human males with prolonged and chronic exposure to low level concentrations of ethinyl estradiol 17-α in either the environment or drinking water sources. These concerns for humans and animals have placed ethinyl estradiol on the Environmental Protection Agency’s Third Contaminant Candidate List, identifying contaminants that are not currently under subject to regulation, but are anticipated to require regulation in the near future.

6.5.4 Treatment Options

Ethinyl estradiol 17-α is not fully metabolized in the body and as a result is excreted through human urine and feces into wastewater where it persists because of its low biodegradability. Khanal et al. suggests that biotic degradation of ethinyl estradiol 17-α can be potentially achieved under the right conditions. Caliman and Gavrilescu suggest that advanced oxidation processes be used to treat waters contaminated with endocrine disrupting compounds such as ethinyl estradiol 17-α. Specifically, Caliman and Gavrilescu mention the use of ozone, H₂O₂/UV, photocatalysis, and a photo-Fenton process making use of Fe²⁺/H₂O₂/TiO₂. Hashimoto et al. in a study on the effects of ozonation as a method to remove ethinyl estradiol reports that 1 mg/L ozone successfully removes 90% of ethinyl estradiol 17-α whereas 3 mg/L ozone fully removes ethinyl estradiol 17-α to concentrations below current technology’s detection limits. The normal dose of ozone for disinfection is 5 mg/L. Liu et al. also confirms that ozonation can be used to treat ethinyl estradiol 17-α suggesting ozone be applied at concentrations 1.9 times those of the contaminant that can be detected. Both of these studies suggest that ozone is a prime advanced oxidation treatment option to remove ethinyl estradiol 17-α from wastewater especially if an ozonation system is already in place.
7 Adjustments to Plant Layout

The new combined UV disinfection and AOP system will likely be placed near the chlorine contact tanks already constructed. Piping already exists from this area to discharge the effluent to the Grand River, so it would require less new construction. Land area is available in this region for construction as well. This area of the site plan can be seen in Figure 21, Appendix A.

Proposed Design

The following design is proposed for the CWP.

7.1 UV Disinfection

To ensure the hydraulic levels throughout the plant will not be disturbed, the team recommends a closed-vessel system. A closed system is also proposed because it can easily be integrated with AOP processes, which generally require closed systems. The system will utilize LPHI lamps which offer a reduced footprint and energy saving when compared to other lamp types. Many companies offer UV disinfections systems, but Trojan, Ozonia, and Siemens offer systems that work best for the CWP.

7.2 Advanced Oxidation Process

The team concluded that ozone/UV would be the most cost effective AOP to effectively remove the contaminants of interest and recommends implementing an ozone/UV AOP for the CWP. Ozone research has shown that 6 mg/L of ozone with UV has removal efficiencies of at least 90% for all five contaminants of interest. The team will further investigate appropriate ozone dosage and system configuration next semester as when designing the actual disinfection and AOP systems for the CWP.

The team recommends that ozone be added at the same location as the proposed UV system in order for the UV to act as both an advanced oxidation process and as a disinfectant. The equipment needed for ozone would be built up around the UV system.

7.3 Reaeration

The team proposes reaeration using a fine bubble diffuser system installed in the unused Chlorine Contact Basin No. 1. These aerators are flexible in use and therefore a logical choice since reaeration is likely only needed around six days a year. The aeration system does not need to be turned on when DO content is above requirements. In addition, depending on pilot testing done with advanced oxidation processes, reaeration may not be necessary. This is because the ozone used in the AOP leaves residual oxygen in the effluent stream, increasing the DO.

8 Cost Analysis

8.1 Ultraviolet Disinfection

An UV disinfection system is estimated to cost between $3 million to $4 million for construction, with an annual operation cost of between $80,000 to $120,000 (1.4 to 2 cents/1,000 gal). A cost of $700,000 is estimated for the UV lamps and installation based on construction estimates from 1993 scaled to the ENR CCI for today of 9116. However, this is only a small fraction of total costs incurred for this project. Trojan, Ozonia, and Siemens systems are possibilities. Once we have narrowed down our UV system selection, we will request pricing on the specific system options.
8.2 Advanced Oxidation

Currently, there is little information on the costs associated with implementing and operating an ozone/UV based AOP. The team has found preliminary costs through research and case studies to provide a preliminary cost estimate. The costs are based on an ozone/AOP system that operates throughout the entire year and with an ozone dosage of 5 mg/L.

Table 10. Cost estimate of ozone/UV AOP system for the CWP (ozone dose of 5 mg/L)

<table>
<thead>
<tr>
<th></th>
<th>Capital Costs</th>
<th>Annual Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>$4,000,000</td>
<td>Operation</td>
</tr>
<tr>
<td>Ozone Generator</td>
<td>$500,000</td>
<td>Maintenance</td>
</tr>
<tr>
<td>Total</td>
<td>$4,500,000</td>
<td>Total</td>
</tr>
</tbody>
</table>

8.3 Reaeration

Reaeration using fine bubble diffusers is estimated to cost $300,000 to $400,000 for construction and $10,000 to $15,000 (0.2 to 0.3 cents/1,000 gal) yearly for operation.

8.4 Pumping

An additional pumping station for the plant will be required with the addition of ozone due to the change in the plant’s hydraulic grade line. However, the pumping station cannot be designed efficiently until a better estimate of the future change in hydraulic grade is determined.

8.5 Total Costs

The total tertiary system with UV disinfection, advanced oxidation, and reaeration is estimated to cost between 8 and 10 million dollars. The annual operational cost of this system is expected to between $4.2 and $4.5 million or 72 to 77 cents/1,000 gal. The operational costs are calculated based upon the current rate that the WCWP pays for electricity (7.5 cents per kW-hr).

9 Project Management

9.1 Team Dynamics

To most effectively approach the city of Wyoming water treatment project, the team split into two sub-groups. Anna and Mark worked on the AOP portion of the project, while Bonnie and Mike were responsible for the UV section of the project. All of the other tasks were evenly divided among team members during regular meeting times. The team met with the faculty advisor, Dr. David Wunder, on Friday mornings to discuss the progress of the project and set goals for the following week. The group also met on Tuesday evenings for two hours to collaborate on the project and divide auxiliary tasks.
9.2 Schedule
A work breakdown schedule (WBS) and calendar were utilized to ensure deadlines were met. The
group created a calendar with all of the class deadlines for the semester. It was also filled with the team’s
goals for portions of the project. A WBS was then drafted based on the calendar the group had crafted; the
WBS is located in Appendix D. The WBS was regularly updated to allow for accurate planning
throughout the semester.

10 Feasibility
Based on the research and basic analysis of the project, the team has deemed this project feasible.

10.1 Long Term Feasibility
Implementing a low pressure, high intensity UV disinfection system as well as mechanical surface
aerators using the older chlorine contact basin on the CWP site is feasible for the plant. The team has yet
to determine if a specific AOP will be feasible for the plant, since literature and case studies are limited
on advanced oxidation processes at wastewater treatment plants.

10.1.1 CWP Future Operational Needs
The CWP will need to train operators to run the changed facilities, but it should not need to hire any
additional operators, as the system should not be overly complex to run. Also, depending on the possible
AOP system, certain chemicals may need to be regularly purchased and stored on site. Maintenance will
need to be regularly performed on the UV disinfection system to ensure lamp quality, and lamps must be
replaced yearly.

10.1.2 CWP Financial Impact
Based on the total costs above (Section 8), the CWP will be able to implement changes in the plant
when the City of Wyoming has funding. If regulations are changed, however, the CWP may have to seek
funding elsewhere to construct the new systems sooner.

10.2 Short Term Feasibility
The team will complete the preliminary design of a UV, ozone, and reaeration system during the
upcoming spring semester. During the months of January and February, the team will perform pilot
testing to determine the optimal ozone concentration and contact time. From the information gathered, the
team will be able to design the system during March. The team will spend April writing the final report
and designing the additional components of the system such as a pumping station and the ozone storage
building.

11 Conclusion
The team has concluded over the course of the fall semester that the proposed preliminary design for
the WCWP is feasible and possible to complete during spring semester. The design will consist of low
pressure, high intensity UV lamps integrated with an ozone/UV AOP in a closed vessel system, as well as
a building to house the design.

For the remainder of the senior design project, the team will continue to focus on creating a
preliminary design for a UV disinfection and ozone/UV combination AOP system. Dissolved oxygen
content requirements will be met by the final design, whether by the advanced oxidation process residual
oxygen or by the design of an additional reaeration system. The next phase of the project will consist of designing and performing a bench scale test for the ozone/UV AOP system.

12 Acknowledgements

The team would like to thank our advisor, Dr. David Wunder (Ph.D., P.E.), for his continued advice and dedication for this project. We would also like to thank Myron Erickson (P.E.) from the Wyoming Clean Water Plant for helping us better understand the CWP and obtaining requested plant data, as well as being enthusiastic about the project. David Koch (P.E.) from Black & Veatch was instrumental in helping us obtain this project and providing us with information that Black & Veatch had collected and analyzed in its Facilities Plan Update. Jack Rafter from the Grand Rapids office of Fishbeck, Thompson, Carr & Huber, Inc. was helpful in meeting with us to give us professional advice and suggestions for resources to continue on work with our project. In addition, we would like to acknowledge Tom Kent and Craig Smith from the City of Wyoming Utilities Department.
References


8 Erickson, Myron. Personal interview. 3 Oct. 2011.


10 "UV disinfection replaces chlorine as the disinfection of choice." Business Wire 11 May 1999.


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Appendix A: Plant Layout

Figure 21 indicates a possible location for a building to house a UV disinfection system combined with an AOP system. An overall layout of the plant can be accessed via the team website.¹

![Figure 21](http://www.calvin.edu/academic/engineering/2011-12-team12/Documents/WCWPSitePlan.pdf)

Figure 21. Plan view of the current site layout at the CWP. The dashed outline indicates a possible location for a UV disinfection and advanced oxidation process building.

Below is the NPDES permit for the CWP.

### Section A. Limitations and Monitoring Requirements

#### 1. Final Effluent Limitations, Monitoring Point 001A

During the period beginning on the effective date of this permit and lasting until the expiration date of this permit, the permittee is authorized to discharge treated municipal wastewater from Monitoring Point 001A through Outfall 001. Outfall 001 discharges to the Grand River. Such discharge shall be limited and monitored by the permittee as specified below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Maximum Limits for Quantity or Loading</th>
<th>Maximum Limits for Quality or Concentration</th>
<th>Monitoring Frequency</th>
<th>Sample Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Monthly</td>
<td>7-Day</td>
<td>Daily</td>
<td>Units</td>
</tr>
<tr>
<td>Flow (report)</td>
<td></td>
<td></td>
<td></td>
<td>MGD</td>
</tr>
<tr>
<td>Carbonaceous Biochemical Oxygen Demand (CBOD₅)</td>
<td></td>
<td></td>
<td></td>
<td>lbs/day</td>
</tr>
<tr>
<td></td>
<td>Oct. 1 – May 31</td>
<td>7300</td>
<td>---</td>
<td>lbs/day</td>
</tr>
<tr>
<td>Total Suspended Solids</td>
<td>5500</td>
<td>8300</td>
<td>---</td>
<td>lbs/day</td>
</tr>
<tr>
<td>Ammonia Nitrogen (as N)</td>
<td></td>
<td></td>
<td></td>
<td>lbs/day</td>
</tr>
<tr>
<td></td>
<td>June 1 – Sept. 30</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Total Phosphorus (as P)</td>
<td>180</td>
<td>---</td>
<td>---</td>
<td>lbs/day</td>
</tr>
<tr>
<td>Fecal Coliform Bacteria</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Total Residual Chlorine</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Total Mercury (report)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>lbs/day</td>
</tr>
<tr>
<td>12 Month Rolling Average</td>
<td>0.00073</td>
<td>---</td>
<td>---</td>
<td>lbs/day</td>
</tr>
<tr>
<td>13 Month Rolling Average</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>CBOD₅ Minimum % Removal</td>
<td>Oct. 1 – May 31</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Total Suspended Solids Minimum % Removal</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>pH</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>June 1 – Sept. 30</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>
## Appendix C: CWP PPCP Concentrations

Table 11. Data supplied by the Clean Water Plant on influent and effluent concentrations of certain contaminants.

<table>
<thead>
<tr>
<th>Compound</th>
<th>August 2008</th>
<th>May 2009</th>
<th>August 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Influent</td>
<td>Effluent</td>
<td>Influent</td>
</tr>
<tr>
<td>1,7-Dimethylxanthine</td>
<td>21800</td>
<td>16</td>
<td>8900</td>
</tr>
<tr>
<td>2,4-D</td>
<td>98</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>4-Methylphenol</td>
<td>43000</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td>4-Nonyl Phenol</td>
<td>ND</td>
<td>ND</td>
<td>7500</td>
</tr>
<tr>
<td>Acetaminophen</td>
<td>82000</td>
<td>ND</td>
<td>75800</td>
</tr>
<tr>
<td>Albuterol</td>
<td>17</td>
<td>ND</td>
<td>18</td>
</tr>
<tr>
<td>Amoxicillin (semi-quantitative)</td>
<td>290</td>
<td>ND</td>
<td>330</td>
</tr>
<tr>
<td>Andorostenedione</td>
<td>18</td>
<td>ND</td>
<td>29</td>
</tr>
<tr>
<td>Atenolol</td>
<td>4900</td>
<td>3700</td>
<td>1100</td>
</tr>
<tr>
<td>Atrazine</td>
<td>36</td>
<td>37</td>
<td>13</td>
</tr>
<tr>
<td>Bezafibrate</td>
<td>ND</td>
<td>ND</td>
<td>260</td>
</tr>
<tr>
<td>BHT-d21 (70-130)</td>
<td>0</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Bis Phenol A (BPA)</td>
<td>54000</td>
<td>ND</td>
<td>2700</td>
</tr>
<tr>
<td>Bromacil</td>
<td>17</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td>Butalbital</td>
<td>ND</td>
<td>29</td>
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</tr>
<tr>
<td>Butylparaben</td>
<td>160</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td>Caffeine</td>
<td>32000</td>
<td>ND</td>
<td>120000</td>
</tr>
<tr>
<td>Caffeine by GCMS LLE</td>
<td>14000</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td>Carbamazepine</td>
<td>80</td>
<td>230</td>
<td>190</td>
</tr>
<tr>
<td>Carisoprodol</td>
<td>ND</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>Cimetidine</td>
<td>1000</td>
<td>ND</td>
<td>1500</td>
</tr>
<tr>
<td>Cotinine</td>
<td>1200</td>
<td>26</td>
<td>2600</td>
</tr>
<tr>
<td>Cyanazine</td>
<td>ND</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td>r</td>
<td>60</td>
<td>ND</td>
<td>430</td>
</tr>
<tr>
<td>DEA</td>
<td>100</td>
<td>23</td>
<td>22</td>
</tr>
<tr>
<td>DEET</td>
<td>ND</td>
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</tr>
<tr>
<td>Dehydroxylatedipine</td>
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<td>30</td>
<td></td>
</tr>
<tr>
<td>DIA</td>
<td>36</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Diclofenac</td>
<td>37</td>
<td>44</td>
<td>850</td>
</tr>
<tr>
<td>Dilantin</td>
<td>270</td>
<td>280</td>
<td>170</td>
</tr>
<tr>
<td>Diuron</td>
<td>8.1</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Erythromycin</td>
<td></td>
<td></td>
<td>360</td>
</tr>
<tr>
<td>Ethnlyl Estradiol-17 alpha</td>
<td>ND</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td>Fluoxetine</td>
<td>ND</td>
<td>104</td>
<td>61</td>
</tr>
<tr>
<td>Furosimide</td>
<td></td>
<td></td>
<td>3700</td>
</tr>
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## Appendix D: Work Breakdown Schedule

Following is a work breakdown schedule of the team’s tasks (Table 12).

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