UBC Social Ecological Economic Development Studies (SEEDS) Student Report

An Investigation into Cistern for Rainwater Storage and Sterilization for the new UBC Student Union Building

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ABSTRACT

The design of new Student Union Building at UBC is implementing a rainwater harvesting system which includes several major components like collection, filtration, disinfection, storage and distribution. This report looks into the storage system of the rainwater harvesting system in addition to the disinfection approaches applicable to the tank. Moreover, the design of the system needs to cater to the LEED platinum+ Certificate requirements.

Underground cistern is made to store water in a tank which can utilize different materials for construction. Materials like galvanized steel, poured concrete and polyplastic have been studied to make a tank of around $22m^3$. Triple bottom analysis was carried out which reflected that concrete is the cheapest option at $\$250/m^3$ and with the least environmental impacts and social implications.

Furthermore, chlorination and UV disinfection were chosen to be investigated for possible application to the proposed cistern. Chlorination proved to have low operating cost of only $38/yr but with high initial cost of $1186. For UV disinfection, the capital cost is $600 whereas operating and maintenance costs are close to $70/year. Despite the higher operating cost, UV disinfection is recommended since it has no environmental impacts when used in a tank and no social affects.

TABLE OF CONTENTS

ABSTRACT..2
LIST OF FIGURES..4
GLOSSARY 5
LIST OF ABBREVIATIONS...6
1.0 INTRODUCTION...7
2.0 CISTERN MATERIAL..8
2.1 Galvanised Steel...9
2.1.1 Galvanised Steel Description...9
2.1.2 Triple Bottom Analysis for Galvanized Steel..9
2.2 Polyplastic...10
2.2.1 Polyplastic Description..10
2.2.2 Triple Bottom Analysis for Polyplastic...10
2.3 Poured Concrete..11
2.2.1 Concrete Description...11
2.2.2 Triple Bottom Analysis for Concrete...11
2.4 Recommended Material...12
3.0 DISINFECTION...13
3.1 Chlorine Disinfection..13
3.1.1 Chlorination Description..13
3.1.2 Proposed Chlorination..13
3.2 Ultraviolet Radiation...15
3.2.1 UV Disinfection Description...15
3.2.2 Proposed UV Disinfection System..15
3.3 Triple Bottom Analysis for Disinfection..16
3.3.1 Environmental Analysis..16
3.3.2 Social Analysis..16
3.3.3 Economic Analysis..16
3.4 Recommended Disinfection..17
4.0 CONCLUSION..18
REFERENCES...19

APPENDIX

Appendix A: Reaction for Free Chlorine Formation..22

Appendix B: Cost Calculation for Disinfection 23

Appendix C: Disinfection Mechanisms...24

LIST OF FIGURES

Figure 1: Chlorine Injection System....................14

Figure 2: Pellet Chlorination System....................14

Figure 3: Schematic of UV disinfection installation upstream of a clearwell....................15

LIST OF ABBREVIATIONS

Abbreviations	Expansions
CT	Contact Time
DBP	Disinfection By-Products
UV	Ultraviolet
UVC	Ultraviolet radiation subtype C
O&M	Operation & Maintenance
Mpa	Mega pascal
SUB	Student Union Building

1.0 INTRODUCTION

The new UBC SUB is projected to be completed by 2014 with an estimated budget of $110 million. Vancouver has an annual precipitation of 1277mm. As a result, the new SUB will be designed with a rain harvesting system that will utilize the approximate 50,000 square feet of available roof surface area in order to collect about 2055 gallons of water per day. The collected rainwater will be filtered and then stored in tank until distributed to the toilet sinks. This report will focus on the cistern that is used to store the filtered rainwater. Furthermore, the scope of the project includes sterilization of the water which is a crucial requirement for water storage. The report will present the several material options available for building a cistern and also the available methods for sterilization. Triple bottom analysis was conducted on each cistern material and sterilization methods. The final decision on the proposed material and sterilization will be based on this analysis taking into account the need to fulfill the requirement for LEED Platinum+ Certificate which is the greenest building rating in North America.

2.0 CISTERN MATERIAL

The cistern is a very important component of the entire rainwater harvesting system. The new SUB is expected to harvest and consume roughly 750,000 gallons per year. This large amount of water consumption requires a cistern volume of about $22m^3$. The choice of material for the cistern is an important matter to be considered when making design choices for the new SUB. Among the materials that we are considering for making the cistern are galvanised steel, poly plastic and poured reinforced concrete. These are the three main materials that we found to be the most appropriate ones to make a cistern. Among the factors that have been considered are the environmental impacts, cost, lifetime, density and inertness. Following are the descriptions of why each factor is essential.

One of the most important factors to be considered when comparing these materials is their impact on the environment. The new SUB is trying to achieve the LEED Platinum Plus certificate, which requires the design choices to have minimal negative impacts on the environment.. Another important factor is the price of the materials. As this project is to be done in the most sustainable way, having a moderate cost will be helpful in minimising the budget. Not only the material cost is important, but it is also important to consider the lifetime of the materials, since it indirectly reflects the overall cost. The cost is calculated per cubic meter basis. This is because, the volume of a particular material that will be used to build a cistern will be the same regardless of its type. thus by comparing in terms of volume, we can actually observe how expensive or cheap a material is as compared to the others. Certain materials can be cheap but can be used for a short period. This will result in higher long term cost. Next, when building a cistern, it is important to consider its weight. Lighter cisterns can be easily handled during the installation and dismemberment. Thus the material density needs to be considered as well. The reactivity of each material with water and the surrounding is also considered. Rain water, which is being stored in the cistern, can be acidic. Hence, choosing the right material which is inert and non-reactive with acidic water is important. In addition, the material has be to corrosive-free as the collected water will be used for plantation purpose. As a result, these factors have been considered in depth and discussed below for each material. Finally, the response of each material towards fire was also analysed.

2.1 Galvanised Steel

2.1.1 Galvanised Steel Description

Galvanised steel describes a type of steel which is coated with layers of zinc to prevent metal corrosion. As a result the stored water will not be contaminated due to corrosion. Apart from that, galvanised steel has a lifetime of five years and is considerably cheap. Its tensile strength is also high with the value of 550MPa (Calvert & Farrar, 2008). However, galvanised steel is a heavy material with a density of 7850kg/m^3(Calvert et al., 2008), which can cause difficulties during installation and dismemberment. Also, in case of fire galvanised steel has the tendency to unbuckle from uneven heating.

2.1.2 Triple Bottom Analysis for Galvanized Steel

Environmentally, the use of steel in construction can be viewed as a beneficial choice. One of the environmental advantages of using steel is that it is highly recyclable, with almost 69% of it recycled every year (Barekat et al., 2010). Another advantage is that steel is very efficient when it comes to maintenance; very little energy is required for maintaining steel structures. On the other hand, the use of steel may leave some negative impacts on the environment. The energy used during the process of manufacturing steel is almost twice as much as that of concrete (Barekat et al., 2010). In addition to that, steel cisterns are very heavy, which would require a lot of energy to operate the heavy machinery used to transport and install the cistern.

From an economic perspective, choosing steel may not be the cheapest option. As mentioned above, the initial cost of a steel cistern (including transportation and installation) is significantly higher than other alternatives. On average, it costs about $13,816 per cubic meter of steel , which is seven times more than plastic and 55 times more than concrete (MEPS). In addition to that, the corrosive nature of steel makes its lifetime shorter, which requires the cistern to be replaced more frequently.

As far as the social impacts go, steel can be beneficial in that it is locally produced. Local communities that make a living from the mining of iron ore that is used in the manufacturing of steel are greatly benefited when steel is consumed. On the other hand, the use of steel in storing water can become poisonous after some time due to the rusting nature of steel.

2.2 Polyplastic

2.2.1 Polyplastic Description

Polyplastics, such as polyvinyl chloride, are another potential type of material that can be used to make a cistern. Polyplastic is chemically inert and does not corrode. It is also ultraviolet stabilised, which means that it does not suffer from the long-term degradation effects due to ultraviolet light, namely sunlight. Polyplastic is also very resistant to cracking and water tight, thus the chances of water leaking out of the cistern are extremely low. In occasions of damage, it is very easy to be replaced and handled as it is light with a density of 1380kg/m3(Calvert et al., 2008). Moreover, polyplastic is relatively cheap and is very durable with a life time of 15 years (UK Cooperative Extension Service, 2005). However, polyplastic tend to have lower effluent level. Water cannot be stored for a long term in a poly plastic cistern tank as it can be toxic. Apart from that, polyplastics also have low tensile strengths. For instance, the rigid polypropylene (PP) has a tensile strength of 35MPa (Calvert et al., 2008). Most types of polyplastic are made from petrochemical compounds, which melt and release toxins in the case of fire.

2.2.2 Triple Bottom Analysis for Polyplastic

From an environmental point of view, polyplastic is highly non-recyclable. In addition to that, polyplastic is not biodegradable, which makes it a very environmentally-unfriendly choice.

Economically, plastic is relatively cheap. The initial cost for a plastic tank is low when compared to steel; it costs about $2001 per cubic meter of plastic(ICIS.com), which is seven times lower than that of steel. Moreover, plastic has a lifetime longer than that of concrete as well as a lower maintenance cost (UK Cooperative Extension Services). On the other hand, plastic has s cost that is about eight times higher than that of concrete.

One of the most important social dangers of using plastic is that it is highly toxic. If water remains in a plastic cistern for a lengthy period, there is a high chance of that water becoming poisonous.

2.3 Poured Concrete

2.3.1 Poured Concrete Description

Poured reinforced concrete is yet another type of material which can be used to make the cistern. Concrete cistern is long lasting with a life time of 20 years and cheap (UK Cooperative Extension Service, 2005). It is strong and rigid with a high density of 2400kg/m3 (Calvert et al., 2008). In addition, concrete helps lower water acidity level to an extent and has higher effluent levels than a plastics tank. Another added advantage of this material is that the cistern can be made at the exact size and on-site. However, if the concrete wall is not reinforced well, it can crack and can result in leakage. The concrete is susceptible to leak and corrosion, but these can be prevented by having a lining of PVC in the tank. The tensile strength of poured concrete is 40MPa, which is the lowest compared to the other materials being considered (Calvert et al., 2008). Also, if the water has high level of acidity, this can result in reaction between the concrete and the water. Since concrete is a porous material, water can penetrate into concrete through time and can cause corrosion in relation to steel framework. This, however, can be avoided with the usage of liner. In case of fire, the concrete tank has a tendency of exploding.

2.3.2 Triple Bottom Analysis for Poured Concrete

From an environmental perspective, concrete has the advantage of being a re-usable material; different applications and structures can afford the use of recycled concrete while maintaining the same standards (Barekat et al., 2010). Since concrete is produced locally, the environmental and financial cost of transportation is relatively low.

Economically, concrete may be one of the cheaper options to consider. The initial cost of concrete is lower than that of steel and plastic. It costs about $250 per cubic meter of concrete, which is 55 times lower than that of steel (Service Magic). However, because concrete is susceptible to leaking and corrosion, the maintenance cost for a concrete cistern may be higher than that of other materials.

When considering the social impacts of using a concrete cistern, the reactivity of the water with concrete needs to be taken into account. Acidic water is highly reactive with concrete, and could become poisonous if the acidity level is high enough. However, according to Environment Canada, the rain in Vancouver is very unlikely to be highly acidic, since most of the wind is coming from the west and acid rain impact is only critical in south eastern Canada (Environment Canada). As a result, the acidity of the water can be safely assumed to be low at most times. On the other hand, concrete structures provide good air circulation, which reduces the likelihood for bacteria to grow inside the cistern (Barekat et al., 2010).

2.4 Recommended Material

As was indicated above, each type of material has a set of advantages and disadvantages in each of the three different aspects that were studied. However, some of the costs may be tolerated, while some benefits may not be completely useful to the specific application being investigated under this report.

The highest priority when making a decision regarding which material to choose is the environmental impact. Because the SUB is being considered for a LEED Platinum certificate, the materials used in the building need to be extremely environmentally-friendly. In addition, the ideal choice of material needs to have a positive impact on society, as well as a reasonably low cost.

The process through which we came to choose the most ideal material is by eliminating the least suitable material first. From the information provided above, we can see that polyplastic can be extremely dangerous for its toxicity. This disadvantage is not something that can be tolerated or over-looked. In addition, plastic is not biodegradable or recyclable, which makes it a very harmful choice for the environment. As a result, we chose to eliminate polyplastic.

This leaves concrete and steel for consideration. Although steel is a lot more stronger than concrete, this feature is not necessarily useful for the overall quality of the cistern. Moreover, the energy consumed in manufacturing and transporting a steel cistern can be significantly higher than that of concrete one. A concrete cistern does not need to be manufactured in a plant; it can simply be built on-site. Moreover, the initial cost of a concrete cistern is about 55 times lower than that of a steel one.

With the above analysis, we propose that concrete is the most appropriate choice of material to use for the cistern. Concrete is cheap, strong, rigid and inert when used with non-acidic water, which is the case with much of the collected rainwater in Vancouver.

3.0 DISINFECTION

The filtered rainwater entering the cistern need to be sterilized as they contain harmful chemicals and microorganisms. There are several commercial methods available to sterilize the water like chlorination, ozonation, UV disinfection, chloro-amine, chlorine dioxide, hydrogen peroxide addition. Based on our research, the two best methods applicable to the new SUB are delved in detail.

3.1 Chlorine Disinfection

Chlorine is used for primary disinfection at water treatment plants to meet contact time (CT) requirements for inactivation of *Giardia* and viruses (Lehr, Keeley & Lehr, 2005). When using free chlorine for disinfection, it is typical to provide a period of free chlorine contact time with a clearwell following filtration. Free chlorine is also widely used for residual disinfection; however, its residual decays more rapidly than a monochloramine residual in the distribution system and free chlorine also typically forms disinfection by-products (DBPs) more quickly than monochloramine (Reynolds & Richard, 1996).

3.1.1 Chlorination Description

When chlorine is added to water it reacts with microorganisms, certain chemicals, plant material, and compounds that can cause taste, odor or color in the water (Letterman, 1999). These components "tie up" some of the chlorine and this is called the chlorine demand. The chlorine demand exerted by organic and inorganic compounds present in the water must be overcome; chlorine is then present as “free chlorine” (Reynolds et al., 1996). If ammonia is present, the chlorine reacts with ammonia to form chloramines (Reynolds et al., 1996). These reactions are substantially the same, regardless of which form of chlorine is used. The disinfecting ability of chlorine is due to its powerful oxidizing properties, which oxide those enzymes that are essential to the cells’ metabolic process (Excel Water Technologies, 2007).

3.1.2 Proposed Chlorination

For the chlorine application in the cistern chlorine cylinders (125-lb cylinders or l-ton containers), evaporators (in some cases), chlorinators, and injectors need to be installed (Lehr et al., 2005). Furthermore appurtenances, such as scales and injection systems are also required. In our system, chlorine can be applied in either dry form as a powder or pellets (calcium hypochlorite), illustrated in figure 1 or in liquid form (sodium hypochlorite) shown in figure 2. (Lehr et al., 2005). Both forms of chlorine must be stored in accordance with the manufacturers' recommendations for safety purposes and to maintain the chemical integrity of the product. In the liquid chlorination system using sodium hypochlorite, a fixed amount of chlorine solution is delivered with each pump discharge stroke whereas for pellet system, chlorine pellets are directly dropped into the well. Due to economic and operational considerations of the cistern, liquid chlorination system is recommended.

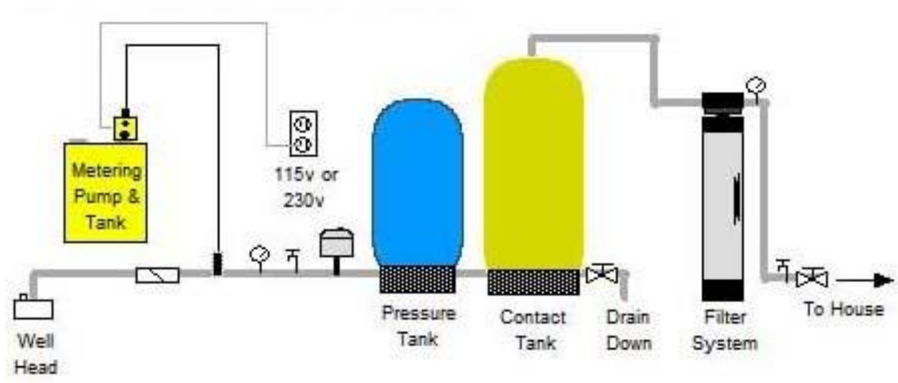

Figure 1 : Chlorine Injection System (Excel Water Technologies, 2007)

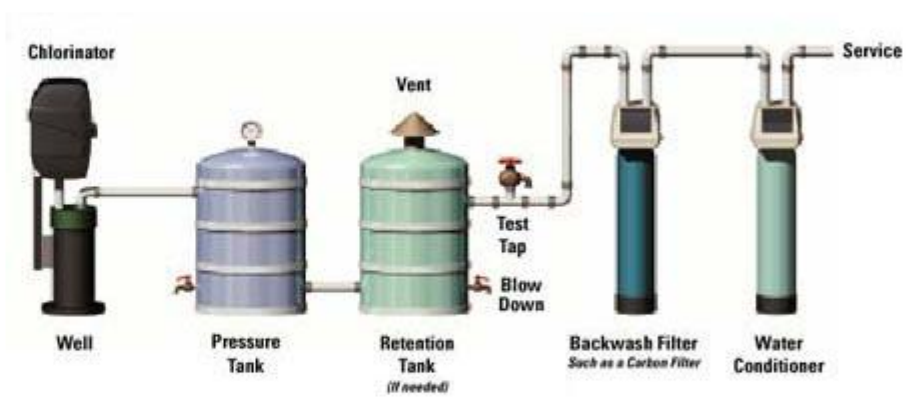

Figure 2 : Pellet Chlorination System(Excel Water Technologies, 2007)

3.2 Ultraviolet Radiation

UV is an effective primary disinfectant against *Giardia*, *Cryptosporidium*, bacteria, and many viruses (Hatt, Belinda Deletic & Fletcher, 2005). UV systems typically are located downstream of filtration, but UV disinfection can be applied to unfiltered water supplies, surface water, or groundwater with sufficiently high transmissivity.

3.2.1 UV Disinfection Description

UV disinfection is a physical disinfection method; other methods rely on chemical agents. UV light penetrates the cell wall and causes photochemical damage to the cell's DNA and RNA. UV light is part of the electromagnetic spectrum. Short-wave UV, or UV-C, spans 200 to 280 nm and is the most "germicidal" band of UV light (Lehr et al., 2005). Damage to DNA and RNA effectively inactivates the cell as they carry genetic information for reproduction (Lehr et al., 2005).

3.2.2 Proposed UV Disinfection System

An overview of the proposed UV disinfection system is shown in figure 3 where UV lamp with effective wavelength of 254nm is used for microbial inactivation (Reynolds et al., 1996). The system requires the continuous application of UV light as water passes through the UV disinfection system. Consequently, it also requires a stable and reliable power source.

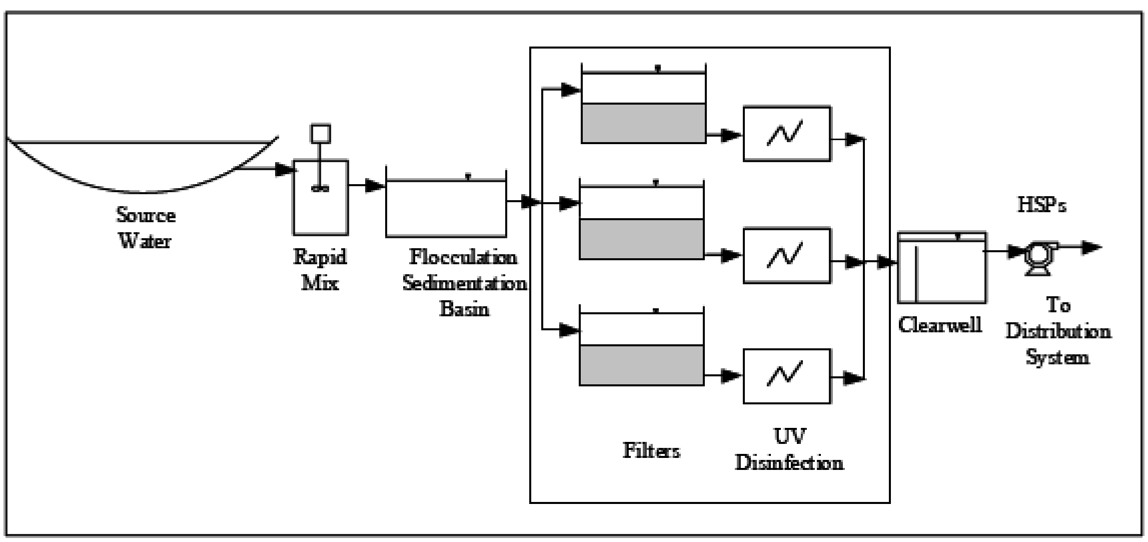

Figure 3 : Schematic of UV disinfection installation upstream of a clearwell (Lehr et al., 2005)

3.3 Triple Bottom Analysis for Disinfection

Chlorination and UV disinfectant are both effective disinfectant for the stored cistern water. A detailed triple bottom analysis was performed to choose the best option to implement.

3.3.1 Environmental Analysis.

In chlorination, chlorine dissolves when mixed with water which can further form disintegrated by products that can be harmful to the environment even at low levels. DBP like organochlorines and dioxins remain in the environment as they do not break down readily and therefore bio-accumulate. On the other hand UV does not generate any unwanted DBPs as UV light is not a chemical agent. Furthermore, it is environmentally friendly, no dangerous chemicals to handle or store and no problems of overdosing. However, there is a slight possibility of mercury contamination into the water due to UV lamp leakage. (Reynolds et al., 1996).

3.3.2 Social Analysis.

UV disinfection system handling may lead operators to exposure to radiation which can lead to skin cancer due to immediate mutation or change in immune system. Chlorination also has several social impacts. Water with chlorine concentrations above five parts per million (ppm) are irritating to the nose, throat, and eyes and even in concentrations around 1-3 ppm causes mild eye and respiratory-tract irritation after several hours. (Choi et al., 2010) Chlorine is also known to have long term residual effects on organisms especially living in water and in soil. However, using chlorination will benefit the local chemical industry as the high water consumption for UBC's new SUB will reflect into greater demands for sodium hypochlorite, ammonia and other associated chemicals.

3.3.3 Economic Analysis

The initial operating cost for chlorination is quite high at $1186 which includes meters, pump, pressure tanks, etc. The high initial cost for chlorination is due to additional pumping, validation testing and evaluation of complex test. This high cost is offset by the low chemical cost of hypochlorite which will be $38/year only. For UV disinfection, initial capital cost is only about $600 whereas the UV dose will cost around $56/year and the bulb replacement cost is $15 each year. Detailed calculations in Appendix B.

3.4 Recommended Disinfection

The use of chlorine gas is a well-established, proven approach that is attractive due to its simplicity and cost-effectiveness in the long run. However, obtaining a LEED Platinum+ Certificate will not favour the use of chemicals in the filtered rainwater. On the other hand UV is a chemical free method that is disfavoured only due to high operating cost. The main objective of the SUB is to go greener and the higher UV operating cost is so minute that we recommend UV disinfection for the Cistern Rainwater filtration system.

4.0 CONCLUSION

This report has looked into three different materials that can be used to build a cistern tank. Their properties and effects have been studied. Furthermore, triple bottom analysis was conducted on each type of material to determine the cost and benefits from environmental, economic and social perspectives. From our study, we were able to exclude polyplastic because of its potential to make stored water toxic as well as its non-recyclable, non-biodegradable nature. Steel was also eliminated because of its high initial cost and the high levels of CO_2 emissions during the manufacturing process. In the end, we came to the conclusion that concrete is the most suitable option for this application. Concrete is cheap, strong and has minimal negative environmental impacts.

A secondary topic investigated in this report was disinfection of water in the cistern. Two clear effective methods: chlorination and UV disinfection were delved in detail. Further analysis of each process and the target of chemical free environment resulted in choosing UV disinfection for the cistern. It has barely any environmental impacts when used inside a water tank. Furthermore, UV disinfection does not pose any social impacts as well. Initial operating cost is low enough to offset the operating cost over the years and the operation is simple.

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Appendix A

Reaction for free chlorine formation:

From Cl_2 (gas):

$$Cl_2(g) + H_2O \leftrightarrow HOCl + H^+ + Cl^-$$
$$HOCl \leftrightarrow H^+ + OCl^-$$

Hypoclorite of calcium (solid):

$$Ca(OCl)_2 \rightarrow Ca^{2+} + 2OCl^-$$

Hypochlorite of sodium (liquid):

$$NaOCl \rightarrow Na^+ + OCl^-$$

Appendix B

Chlorine Chemical Cost Calculation:

Chlorine = $2/pound

Scale down factor = 1mgd/0.002055mgd = 486.6

Chlorine required = 4661 pounds @ 1ppm/scale down factor

Chlorine required = 4661/486.6 = 9.57 pounds @ 1ppm

Chlorine required @ 2ppm = 9.57 * 2 = 19.14 pounds

Total Chlorine chemical cost for a year = 19.14 * $2 = $38/year

UV disinfection operating cost:

At UV dose of 40,000 µW-s/cm2 = $0.02/m^3 of water

Per year need to disinfect 750,000 gallons of water or 2839m^3

Total cost of disinfection dose = 2839 * $0.02 = $56/year

Bulb replacement cost every 7500 hours = $15

Appendix C

Disinfection Mechanism and Effectiveness*	Operational Considerations	Most Typical Uses	Safety Considerations
FREE CHLORINE (ALL FORMS OF CHLORINE)†			
Free chlorine is a strong disinfectant, formed following breakpoint chlorination when all of the demand (ammonia, organics, etc.) has been met. If ammonia is present, chloramines form. See section on chloramines for information. Chlorine demand of water or wastewater must be met to establish a free chlorine residual concentration. Chlorine demand depends on ammonia organics (e.g., DOC), water temperature, and other factors. Generally effective for disinfection of bacteria, viruses, and *Giardia*. Ineffective at inactivating *Cryptosporidium* at practical dosages. CT necessary to achieve disinfection objectives depends on water temperature, level of inactivation, pH, and disinfectant residual concentration. Refer to CT tables.	Free chlorine residual must be monitored. Forms halogenated DBPs. Decays in distribution system.	Commonly used for both primary and residual disinfectant for drinking water. Commonly used for wastewater disinfection. Commonly used for disinfection for water reuse and for residual disinfection for reuse applications. In most cases, free chlorine is likely to represent the lowest cost option for disinfection.	See specific sections below pertaining to the chlorine form used.
Free Chlorine: additional considerations for chlorine gas (White 1999, p. 703)			
Chlorine gas is diffused and dissolved in water to form hypochlorous acid, which serves as the source of primary and residual disinfection.	Operation/equipment ranges from relatively simple to complex for large systems using multiple cylinders and evaporators. Depending on buffering capacity of water, addition may cause pH to decrease.		Chlorine is a hazardous gas. Impacts of a potential leak on workers and the surrounding community must be addressed through adequate safety and security systems and programs. The level of the required programs is dependent on local conditions and risks.
Free chlorine: additional considerations for sodium hypochlorite—bulk delivered			
A reaction between sodium hypochlorite and water forms the disinfectant, hypochlorous acid.	Requires greater storage tank capacity to manage equivalent volume of free chlorine. Metering pumps feed liquid to the point of application. Metering pumps and piping must be properly vented.		Corrosive oxidant that requires proper personal protection equipment for workers. Mixing with acidic compounds and alkalis releases chlorine gas.

Table 1 : Disinfection mechanisms and effectiveness (Lehr et al., 2005).

Disinfection Mechanism and Effectiveness'	Operational Considerations	Most Typical Uses	Safety Considerations
	Solution strength decreases with time and temperature. Basic solution. Depending on buffering capacity of water, addition may cause pH to increase. Scaling has the potential to occur when hypochlorite is injected into a dilution stream.		
Free Chlorine: additional considerations for sodium hypochlorite—generated on-site			
A reaction between sodium hypochlorite and water forms the disinfectant, hypochlorous acid.	Metering pumps are required to feed liquid to the point of application. Requires adequate day tank capacity to manage rapid change in water demand. Comparatively high energy use and high energy costs.		Generation at lower concentrations than bulk delivered hypochlorite avoids safety issues associated with higher concentrations. Potentially explosive hydrogen gas must be vented to the outdoors.
CHLORAMINE			
Chloramine is formed by the reaction between chlorine and ammonia. Chloramine residual may also be referred to as "total chlorine" or "combined chlorine." For drinking water, the preferred form of chloramine is monochloramine. Either chlorine gas or sodium hypochlorite (either bulk delivery or generated on-site) is still necessary. Generally ineffective for primary disinfection of bacteria and viruses. Ineffective for disinfection of *Giardia* and *Cryptosporidium*. Refer to CT tables. Typically provides a long-lasting residual.	Ammonia is available in various forms. Aqueous ammonia (liquid), anhydrous ammonia (gas/compressed liquid), and ammonium sulfate (dry chemical) are most commonly used. Free chlorine residual, chlorine-to-ammonia ratio, and total chlorine residual must be monitored. Formation of halogenated DBPs occurs more slowly than when applying free chlorine. Metering pumps and piping must be properly vented. Addition of aqueous ammonia to water may cause pH to increase.	Commonly used as residual disinfectant for drinking water. The use of another disinfectant is necessary for surface water to meet CT requirements. Commonly used for wastewater disinfection, typically through chlorine addition to nonnitrified wastewater. Can be used for disinfection for water reuse and for residual disinfection for reuse applications.	Aqueous ammonia is classified as a toxic and an irritant, and corresponding safety provisions are required. Anhydrous ammonia has safety issues similar to gas chlorine.

Table 1 : Disinfection mechanisms and effectiveness (Lehr et al., 2005). *continued*

Disinfection Mechanism and Effectiveness'	Operational Considerations	Most Typical Uses	Safety Considerations
UV			
UV light damages the DNA or RNA of the microbe, preventing replication and infection. UV light is effective for disinfection of *Giardia*, *Cryptosporidium*, bacteria, and most viruses. UV doses vary depending on disinfection goals and target organisms. For drinking water applications, UV doses for *Cryptosporidium* and *Giardia* are small compared to those for adenovirus. Refer to USEPA's UV Disinfection Guidance Manual for calculations of UV dose. The amount of UV equipment and the energy use by UV disinfection are dependent on the water quality and, most important, the UV transmittance of the water. UV performance must be validated to develop the operating window within which performance is known for the given installation. Does not provide residual disinfection.	Water characteristics and UV reactor design determine process efficiency. No disinfectant residual is imparted to water. Validation results and programmed algorithms are used for assurance of disinfection. Lamps and other components must be monitored and replaced regularly. Does not form DBPs at disinfection doses. Comparatively high energy use and high energy costs.	Commonly used as primary disinfectant for drinking water. A separate residual disinfectant is required. Commonly used for wastewater disinfection. Commonly used for disinfection for water reuse.	UV lamps contain mercury, so provisions for lamp recycling and emergency response are necessary. Safety measures should be incorporated to ensure operators are not exposed to UV light from UV lamps.
CHLORINE DIOXIDE			
A more powerful disinfectant than free chlorine but less effective than ozone. Must be generated on-site. Limited efficacy in inactivating *Cryptosporidium*, but an effective disinfectant of *Giardia*, viruses, and bacteria. Refer to CT tables.	Chlorine dioxide residual must be monitored. Forms undesirable by-products including chlorate and chlorite, which is regulated by Stage 1 DBPR of SDWA.	Often used as a pre-oxidant for drinking water. Also used as a primary disinfectant for drinking water. A separate residual disinfectant is typically used. Internationally, chlorine dioxide has been used as a residual disinfectant for drinking water. Not frequently used for wastewater disinfection. Not frequently used for disinfection for water reuse.	Chlorine dioxide is an explosive, unstable gas that is very sensitive to increases in temperature. It is generated on-site from other chemicals, often including sodium chlorite. Sodium chlorite is a class 2 oxidizer and it is corrosive and toxic. Chlorine dioxide generation may also involve chlorine gas or other chlorine forms, hydrogen peroxide, or other chemicals. These chemicals have their own safety considerations.

Table 1 : Disinfection mechanisms and effectiveness (Lehr et al., 2005). *continued*

Disinfection Mechanism and Effectiveness*	Operational Considerations	Most Typical Uses	Safety Considerations
OZONE			
Ozone is effective for disinfection of bacteria, viruses, *Giardia*, and *Cryptosporidium*. For a desired level of inactivation, ozone usually requires lower CT values compared to chlorine disinfectants. Refer to CT tables. To achieve a measurable ozone residual for disinfection, the ozone demand must be overcome and the residual decay of ozone must be accounted for. Ozone demand and residual decay are dependent on pH, alkalinity, and organics (e.g., DOC). Ozone generator sizing depends on the water's specific ozone demand, ozone demand slope, and ozone decay rates. As water temperature increases, ozone solubility decreases and the inactivation efficiency of the soluble ozone increases. For drinking water, USEPA's CT requirements for *Cryptosporidium* inactivation increase significantly with decreasing water temperature. Does not provide residual disinfection.	Ozone must be generated on-site. Operations and equipment are complex and consist of four primary components: a gas feed system, an ozone generator, an ozone contactor, and an off-gas destruction system. Separate building required to address safety concerns. Skilled technicians are required for maintenance of generators. Although complex, equipment is highly automated and very reliable. Ozone reacts with bromide to form bromate, a regulated DBP. Bromate formation increases with increasing bromide content of the water and with increasing ozone dose. Comparatively high energy use and high energy costs.	Commonly used as primary disinfectant for drinking water. Ozone also provides other treatment benefits, as shown in Table 2-2. A separate residual disinfectant is required. Not frequently used for wastewater disinfection. Not frequently used for disinfection for water reuse, although there has been recent interest.	Ozone is typically generated from LOX. LOX is an oxidizer when in contact with combustible materials. Ambient air monitoring is required in work areas to ensure levels are below OSHA threshold values. Off-gases are hazardous and must be collected and destroyed.

Table 1 : Disinfection mechanisms and effectiveness (Lehr et al., 2005). *continued*