Evaluation of Disinfection Technologies for the Calumet and North Side Water Reclamation Plants

Technical Memorandum 1

Date: December 12, 2011

To: Disinfection Task Force Advisory Committee

From: Disinfection Task Force

Subject: Available Disinfection Technologies and Short List of Technologies for Further Evaluation

1.0. Purpose

This Technical Memorandum describes the available disinfection technologies that were considered for use in meeting proposed fecal coliform standards for the final effluent of the Calumet and North Side Water Reclamation Plants (WRPs). The available technologies were reviewed for applicability, and based on this review a "short list" was created for further evaluation.

2.0. Available Disinfection Technologies

Table 1 lists the available disinfection technologies that were considered for application at the Calumet and North Side WRPs. The list was created based on information found in literature and other studies done by and for the Metropolitan Water Reclamation District of Greater Chicago (District).

TABLE 1: AVAILABLE DISINFECTION TECHNOLOGIES

Mature Technologies
- Chlorination/Dechlorination
- Chloramination
- Ozonation
- Ultraviolet Irradiation

Practicable Technologies
- Chlorine Dioxide
- Peracetic Acid

Combination Technologies (Advanced Oxidation Processes)
- Ultraviolet Irradiation/Ozonation
- Ultraviolet Irradiation/Peracetic Acid
- Ozonation/Hydrogen Peroxide
- Ultraviolet Irrad./Hydrogen Peroxide
- Ultraviolet Irradiation/Chlorination

Emerging and Innovative Technologies
- Bromine Chemicals
- Ferrate
- Gamma/Electron Beam Irradiation
- Membrane
- Microwave Irradiation
- Pasteurization
- Pulsed Ultraviolet
- Quaternary Ammonium
- Tin Oxide Anodes
- TiO_2 and other Photocatalysis
- Ultrasonic Cavitation
- Zero Valent Iron

3.0. Description and Applicability of Technologies

Each disinfection technology listed in Table 1 was evaluated for applicability by reviewing academic research, industry practice literature, and results from previous District studies. Information obtained from these sources included such items as efficacy, use at other WRPs, safety, how the technology disinfects, maturity of technology, systems needed, and any other pertinent information required to evaluate whether or not the technology would be applicable for the District's WRPs. A brief description of each technology and its applicability are detailed in the following subsections.

3.1. Chlorination

Chlorine is a strong oxidant and rapidly reacts with cellular material, such as cell membranes and nucleic acids, resulting in the inactivation of microorganisms. Chlorine can inactivate bacteria and viruses, but does not inactivate *Cryptosporidia* or *Giardia* at practical doses. In addition to being an effective disinfectant, chlorine may remove some pharmaceuticals and personal care products (PPCPs) and endocrine disrupting compounds (EDCs). The level of inactivation of a specific microorganism or removal of a specific compound will vary and depend on the chlorine dose and the contact time. Various forms of chlorine are used, including chlorine gas, sodium hypochlorite, and calcium hypochlorite. Based on the United States Environmental Protection Agency's (USEPA) 2008 Clean Watersheds Needs Survey (CWNS), chlorination is the most commonly used method of disinfection at WRPs that treat greater than 100 million gallons per day (MGD). Chlorination was included in the short list of technologies because it is a mature technology and the most commonly used at large WRPs.

Of the various forms of chlorine available for chlorination, sodium hypochlorite was chosen for inclusion in the short list; chlorine gas and calcium hypochlorite were eliminated from consideration. Chlorine gas was eliminated due to the concern for the safety of the District's staff and neighbors as well as other health and environmental risks associated with the transport and use of the gas. Sodium hypochlorite does not have the same health and environmental risks that are associated with chlorine gas, so is a safer alternative. Calcium hypochlorite was eliminated from consideration as it is more expensive than sodium hypochlorite and chlorine gas. Calcium hypochlorite is marketed in solid form and must be dissolved into a slurry feed for use. This additional operational step can result in the formation of a precipitate, leading to clogged pipes and other fouling issues.

Using chlorination for disinfection will require a dechlorination step. There are various chemicals available for achieving dechlorination, including sulfur dioxide, sodium bisulfite, calcium thiosulfate, sodium thiosulfate, and ascorbic acid. Sulfur dioxide and sodium bisulfite are the most frequently used. Although cheaper than sodium bisulfite, sulfur dioxide has many of the same health and safety issues as chlorine gas, and was therefore eliminated from consideration. Sodium bisulfite was included on the short list for dechlorination.

3.2. Chloramination

Chloramination disinfection is achieved using combined chlorine (chlorine plus ammonia) in the form of chloramines: monochloramine, dichloramine and trichloromine. Chloramination is usually deployed at WRPs that do not remove ammonia, as it is not economical to add enough chlorine to achieve free chlorine residuals. Disinfection using chloramines is much slower than using free chlorine. Chloramination was eliminated from consideration as it requires long contact times and the addition of ammonia, since both the Calumet and North Side WRPs nitrify and achieve low effluent ammonia concentrations.

3.3. Ozonation

Ozone is a strong oxidizer and reacts with both organic and inorganic substances. As ozone decomposes in water, it forms free radicals, such as the hydroxyl radical, which are also strong oxidizers. The ozone, together with the free radicals, oxidizes the outer membranes, walls, etc. of microorganisms, allowing for damage to occur inside the cells. Ozone is very effective at inactivating bacteria and viruses. *Cryptosporidia* and *Giardia* are more resistant to ozone, but ozone is still more effective than chlorine at inactivating these microorganisms. In addition to being an effective disinfectant, ozone has been shown to reduce concentrations of many trace organic contaminants such as PPCPs and EDCs. The level of inactivation or removal will vary depending on the ozone dose, contact time, and target microorganisms or compound.

Ozone is unstable and would need to be generated onsite using either air or oxygen. Preliminary calculations for the design of an ozone system have shown that ozone generated from air is not feasible because of the large quantity of ozone needed to disinfect the flow volumes at the Calumet and North Side WRPs. Therefore, if ozone is to be used at these WRPs, it will need to be generated using oxygen.

According to a Water Environment Research Foundation 2008 report, only seven publicly owned WRPs were using ozone for effluent disinfection in the United States (U.S.)

during 2006. The USEPA's 2008 CWNS listed one WRP greater than 100 MGD which used ozone for disinfection. Even though few WRPs use ozone, there is more than 30 years of design experience with ozone, and it is an established technology for potable water disinfection. Therefore, ozone using oxygen was included in the short list of technologies for further evaluation.

3.4. Ultraviolet Irradiation

Ultraviolet irradiation (UV) alters cellular proteins and nucleic acids, which damages the microorganisms and prevents them from replicating. UV is effective at inactivating *Giardia*, *Cryptosporidia*, bacteria, and viruses. However, it is common for different strains of bacteria and viruses to react differently to UV, which is due to variations in DNA content and how that DNA absorbs UV light. In addition to being an effective disinfectant, UV may remove some micropollutants by photolysis at higher doses. The level of inactivation or removal depends on UV dose, and is specific to the target microorganism or micropollulant.

According to the USEPA's 2008 CWNS, UV is the second most commonly used disinfection technology at WRPs greater than 100 MGD. Currently, there are four different lamp types that can be used in a UV system: low pressure low output (LPLO), low pressure high output (LPHO), medium pressure (MP), and microwave powered LPHO lamp (MLPHO). The LPLO lamps were eliminated from consideration as they are an outdated technology and would require an impractical number of lamps for the volume of flows at the Calumet and North Side WRPs. The MLPHO lamps were eliminated from further consideration due to its infrequent use and its poor performance during pilot testing at the District's Hanover Park WRP. Applications using the LPHO and MP lamps are the most commonly used and are suitable for the Calumet and North Side WRPs. Therefore, these two types of lamp were included on the short list of technologies for further evaluation.

3.5. Chlorine Dioxide

Chlorine dioxide is a gas that has been used for disinfecting potable water. It is as good, if not better, at inactivating microorganisms than chlorine. However, very few pilot-scale studies have been conducted at WRPs, and no major publicly owned WRPs currently uses it in the U.S. The disinfection mechanism is not well understood, but chlorine dioxide is thought to react with biomolecules, damaging peripheral structures and disrupting internal cell functions (USEPA, 1999). Chlorine dioxide requires onsite generation due to its unstable and explosive nature. Due to the hazardous nature of the gas, higher costs associated with its use, and the complexity of controlling the system, chlorine dioxide was eliminated from further consideration.

3.6. Peracetic Acid

Peracetic acid (PAA) is thought to release active oxygen or hydroxyl radicals which attack and disrupt cell walls, membranes, enzymes, nucleic acids, and/or other surface structures. Similar to chlorine, PAA is effective at inactivating bacteria and viruses, but is not effective at inactivating *Cryptosporidia* and *Giardia*. The level of inactivation of a specific microorganism is dependent on the PAA dose and the contact time. PAA has been mostly used in the beverage, food, and pharmaceutical industries, but just recently has started to be used in wastewater treatment, particularly in Europe. PAA use in the U.S. has been limited to small WRPs, demonstrations, and treatment of combined sewer overflows. The largest WRP using PAA is currently a WRP in Milan, Italy, with an average and maximum flow of 114 and 342 MGD, respectively.

Application of PAA is similar to that of sodium hypochlorite. The treatment effectiveness is a function of dose of PAA and contact time. Current applications and studies indicate that a deactivation of residual oxidant step is not needed, no chlorinated disinfection by-products are formed, and the decomposition products consist of acetic acid, water, carbon dioxide and oxygen. However, PAA has been shown to increase the amount of biological oxygen demand in the treated water. Further, it is not clear that there will not be a need to remove residual oxidant following treatment with PAA. PAA was included in the short list due to its low capital cost, speculation that no deactivation of residual oxidant step will be required, report that no disinfection by-products are formed with its use, and its increasing use as a wastewater disinfectant.

3.7. Ultraviolet Irradiation with Ozonation (In Series)

UV in series with ozone is considered an advanced oxidation process (AOP). It has shown synergistic effects for disinfection, can reduce the production of disinfection byproducts, and can effectively reduce EDCs and PPCPs. Some studies have shown that the combined process may be more economical than UV alone at removing some contaminants, and that ozone applied upstream of UV may improve transmittance, allowing for a decrease in the number of UV lamps. The economic benefit of using a UV/ozone system depends on the specific wastewater and the treatment goal. The focus of much AOP research has been for water reuse and not strictly disinfection to meet an effluent standard for fecal coliform, so an appropriate dose of UV/ozone is not readily available. Based on preliminary collimated beam tests done for the North Side and Calumet WRPs, the UV dose required to meet the proposed standards is relatively low and available UV transmittance data has been at or above 65 percent, so it is unlikely that applying ozone upstream of UV at these WRPs will result in any significant benefit. Pilot testing of the UV/ozone technology would provide site-specific design parameters such as the doses for ozone and UV and a clearer indication of the benefit of such a system. UV/ozone was not considered for further evaluation because an appropriate dose of each oxidant is not available in the literature.

3.8. Ultraviolet Irradiation with Peracetic Acid (In Series)

UV with PAA addition has been shown to enhance disinfection. A study by Caretti and Lubello (2003) showed that UV with PAA addition upstream of the UV system performed the best, followed by UV with PAA addition downstream, compared to PAA or UV alone. The increased performance is due to hydroxyl radical formation from the photolysis of PAA by UV. Very little information on dosing is available in the literature for the UV/PAA combination and full scale application of the process is limited. Pilot testing would be needed to determine design parameters. PAA is also expected to increase the organic carbon in the effluent. Due to the limited full scale use at large WRPs and the lack of dosing information, the combined UV/PAA technology was not considered for further evaluation.

3.9. Ozonation with Hydrogen Peroxide (In Series)

Hydrogen peroxide used in series with ozone, also called peroxone, is another AOP. The hydrogen peroxide speeds up the decomposition of ozone, creating a higher concentration of hydroxyl radicals. There has been a lot of research conducted on the efficacy of peroxone to control organics and odor in potable water. There are some conflicting reports regarding the effectiveness of peroxone as a disinfectant for wastewater. The USEPA (1999) states that peroxone is as effective, if not more effective, as ozone alone at inactivating bacteria. Ferron et al. (2005) suggested ozone alone was more effective at disinfecting secondary wastewater effluent. This combined process may be difficult to control. Hydrogen peroxide will immediately react with the ozone, and no ozone residual will be present, and no follow-up quenching process will be required. Hydrogen peroxide may need to be quenched prior to discharge. Hydrogen peroxide/ozone systems are typically applied in potable water treatment or water reuse systems. The process is good at removing hard-to-remove organics such as halogenated compounds, PPCPs, EDCs, and taste and odor-causing compounds. It has also been shown to achieve reuse standards, but is typically not used at non-reuse WRPs. There are some safety and security issues involved with the use and storage of hydrogen peroxide. Use of peroxone would require pilot testing to determine design parameters such as dosing, contact time, and an ideal control scheme. Due to the lack of site-specific testing data, the safety risks involved with the use of hydrogen peroxide, and the conflicting reports of performance, peroxone was eliminated from further consideration.

3.10. Ultraviolet Irradiation with Hydrogen Peroxide (In Series)

UV in series with hydrogen peroxide is a commonly used AOP in potable water treatment for the destruction of emerging contaminants and many EDCs. However, if bacteria inactivation is the treatment goal, there appears to be no significant benefit in using hydrogen peroxide in series with UV (Koivunen, 2005). Application of a UV/peroxide system is site-dependent and dosage will vary depending on water quality. The chemistry of the process can be complicated and difficult to predict. Consideration must be given to quenching any hydrogen peroxide left after irradiation. There is also some concern regarding the safety and security of using and storing hydrogen peroxide. The combined UV/hydrogen peroxide system was eliminated from further consideration.

3.11. Ultraviolet Irradiation with Chlorine (In Series)

UV in series with chlorine addition has been shown to have a synergistic effect. In some cases, the addition of chlorine resulted in the need for a lower UV dose. This synergy is desired at WRPs that need to meet more stringent reuse standards or have treatment goals other than or in addition to disinfection, such as the removal of organics. For WRPs not practicing reuse, it is unclear what type of dosing would be required in the combined system, as individually the technologies require a relatively low dose for meeting the proposed fecal coliform standard. If UV/chlorine were to be used, pilot testing would be advised to determine optimal doses for design purposes. UV in series with chlorine was not considered for further evaluation.

3.12. Bromine Chemicals

Several compounds containing bromine have been used as biocides including bromine (Br_2), bromine chloride (BrCl), and 1-bromo, 3-chloro, 5,5-dimethylhydantoin (BCDMH).

These compounds have typically been used for disinfection in swimming pools, cooling towers, and spas. Br_2 is a liquid which requires safe handling and can be a safety hazard. BrCl is a fuming agent that can be generated onsite from sodium or potassium bromide and hypochlorous ions. BrCl is not widely available and is more expensive than chlorine. BCDMH is certified as a disinfectant for public water supplies by NSF International. However, only a few WRPs in Japan use it as a disinfectant. Brominated compounds are not currently used at a large WRP, and have not been applied to a full-scale application such that there is performance data available for evaluation. As a result, bromine chemicals were not considered for further evaluation.

3.13. Ferrate

Ferrate can refer to FeO_4^{-2} (Fe(VI)) or FeO_4^{-3} (Fe(V)). It is a strong oxidizer, with Fe(V) being three to five times more reactive than Fe(VI). Little is known about the mechanism leading to inactivation of microorganisms. Ferrate must be generated on-site due to low stability. Current generation methods result in low yields, increasing costs. In addition, ferrate increases the pH and total dissolved solids of the treated solution water. Pilot studies have been conducted, but there has not been full-scale application of this technology. The District conducted a bench-scale evaluation of ferrate in 2010. The results showed good disinfection using a higher dose than expected. The dose required to meet the proposed permit limits resulted in a pH greater than 9 for the treated effluent. An additional process to adjust the pH would be needed to meet current National Pollutant Discharge Elimination System permit pH limits, adding to the costs. Ferrate is not currently used at a large WRP for disinfection, and has not been applied to a full scale application in which there is full scale performance data available for evaluation. As a result, ferrate was not considered for further evaluation.

3.14. Gamma and Electron Beam Irradiation

During gamma and electron beam irradiation, high energy electrons react with the wastewater resulting in the creation of smaller and smaller energy electrons. Eventually a large number of small energy electrons are created, which ionize the wastewater so that electrons and positive ions are created and then react with the wastewater. This is also known as indirect radiolysis. A number of different species are created through indirect radiolysis, but most notable are the hydroxyl radical, hydrogen atoms, and hydrated electrons. These species inactivate microorganisms by damaging their proteins, nucleic acids, and other molecules. Gamma and electron beam irradiation is still experimental and a lot of information such as costs, efficacy, and byproducts is lacking. In addition, there is some concern regarding the safety of operators. Gamma and electron beam irradiation is not currently used at large WRPs, and has not been applied to a full scale application in which there is full scale performance data for evaluation. As a result, gamma and electron beam irradiation was not considered for further evaluation.

3.15. Membrane

Membranes are not effective for inactivating microorganisms but are used to remove the microorganisms from the water along with organics, phosphorus, suspended solids and colloidal solids. Membranes are more likely to be used to provide potable water, indirect reuse water, and high quality water and are not common for meeting total or fecal coliform standards for discharge to general use waters. One of the major problems with membranes is dealing with membrane fouling and handling the concentrate. For designing a membrane system, the site-specific product water flux is needed and can only be obtained from pilot testing. Due to the lack of use at large WRPs, fouling potential, and handling of concentrate, membranes were not considered for further evaluation.

3.16. Microwave Irradiation

Microwave irradiation results in the vibration of water molecules to align with the microwave frequency. The vibration results in friction which in turn leads to heating and boiling of water. Boiling water molecules inside microorganisms will try to escape, resulting in expansion and explosion of the cells (Alderman, 2004). Microwave irradiation has been used to treat medical wastes and has been tested as an alternative for treating wastewater sludges. However, there are very few performance data on the efficacy of microwave disinfection of WRP effluent. Microwave irradiation is not currently used at a large WRP, and has not been applied to a full scale application in which there is full scale performance data available for evaluation. As a result, microwave irradiation was not considered for further evaluation.

3.17. Pasteurization

Pasteurization uses heat to denature proteins and inactivate microorganisms. Pasteurization is most commonly used in the food and beverage industry such as during milk processing. There are no publicly owned WRPs in the U.S. using pasteurization for disinfection; however, there have been a few pilot studies. One such study validated the pasteurization process, which led to the California Department of Public Health approving pasteurization for the disinfection of reclaimed water. However, there is still a lack of data for full-scale application of pasteurization at WRPs. The process can be costly if no existing heat source is available, and the process will raise the temperature of the treated effluent. Pasteurization is not currently used at a large WRP, and has not been applied to a full scale application in which there is full scale performance data available for evaluation. As a result, pasteurization was not considered for further evaluation.

3.18. Pulsed UV

Pulsed UV light is approved by the U.S. Food and Drug Administration for use in the production and handling of food. Instead of continuous irradiation using the typical mercury low pressure and medium pressure UV lamps, pulsed UV disinfection provides a pulsed irradiation of a much higher intensity. Pulsed UV is not required to be "on" all the time. While this technology is used in the food industry, very little data exists for its use in wastewater disinfection. Pulsed UV is not currently used at a large WRP, and has not been applied to a full scale application in which there is full scale performance data available for evaluation. As a result, pulsed UV was not considered for further evaluation.

3.19. Quaternary Ammonium

Quaternary ammonium compounds, better known as "quats," are commonly used as disinfectants, surfactants, fabric softeners, antistatic agents, and wood preservatives. There is a large variety of quats, and even blends of quats depending on the end use. All quats are cationic compounds with a basic ammonium structure, which penetrate the cell wall causing lysis. Quats are used as a disinfectant in the food industry, but have not been used for wastewater disinfection. Quats are more expensive than chlorine and require pilot testing to determine dose and contact time. In 2008, the District tested a sand treated with quaternary ammonia chloride to assess the potential for secondary effluent disinfection. Non-disinfected plant effluent was run through a filter with the quat-treated sand and a filter with untreated sand. Results showed there was no improvement in the removal/inactivation of fecal coliform in the effluent of the quat-treated sand filter when compared to the effluent of the untreated sand filter. Excessive foaming was also observed in the quat-treated sand system during this study. Quaternary ammonium is not currently used at a large WRP, and has not been applied to a full-scale application such that there is performance data available for consideration. As a result, quaternary ammonium was not considered for further evaluation.

3.20. Tin Oxide Anodes

Tin oxide anodes, submerged in water, have the potential to create hydroxyl radicals through application of a direct current. The hydroxyl radials are then responsible for damaging the cell walls, membranes, etc. which leads to the inactivation of microorganisms. Disinfection with tin oxide anodes has been tested in a laboratory setting, but is not currently used at a large WRP. It has not been applied to a full-scale application such that there is performance data available for evaluation. As a result, tin oxide anodes were not considered for further evaluation.

3.21. Titanium Dioxide and Photocatalysis

Photocatalysts, commonly titanium dioxide for disinfection, are activated with UV or visible light. When activated, they create an electron hole in the photocatalyst valence band which reacts with sorbed compounds and forms radical species, particularly the hydroxyl radical. The hydroxyl radical then damages cell membranes, walls, internal structures, etc., leading to the inactivation of microorganisms. Photocatalysis has not been tested on a pilot- or full-scale level, and there is still some uncertainty regarding the inactivation performance of mixed cultures. Photocatalysis is not used at a large WRP and has not been applied to a full-scale application such that there is performance data available for consideration. As a result, photocatalysis was not considered for further evaluation.

3.22. Ultrasonic Cavitation

During transient cavitation, bubbles are rapidly formed followed by expansion and collapse. The implosion of the bubbles is quite violent and can cause micro-jets and formation of chemical species such as the hydroxyl radical and hydrogen peroxide. During stable cavitation, bubbles oscillate causing liquid immediately next to the bubbles to flow in a microstream. Disinfection is typically attributed to high temperatures, hydrodynamic forces (micro-jets and microstreams), and chemical reactions. The most commonly used source of cavitation for disinfection is ultrasound. Energy requirements for ultrasound disinfection at large WRPs may be prohibitively high. Ultrasonic cavitation is not used at a large WRP, and has not been applied to a full-scale application such that there is performance data available for consideration. As a result, ultrasonic caviation was not considered for further evaluation.

3.23. Zero Valent Iron

Zero valent iron, originally used for groundwater remediation of chlorinated solvents, has been shown to be able to remove a wide range of organic and inorganic contaminants. Zero valent iron works in two ways: through reduction and/or adsorption. Laboratory tests have shown zero valent iron is effective for inactivating viruses. Zero valent iron is not currently used at a large WRP, and has not been applied to a full-scale application such that there is full scale performance data available for consideration. As a result, zero valent iron was not considered for further evaluation.

4.0. Short List of Disinfection Technologies

The short list of technologies consists of those technologies that are used at large WRPs which have full-scale performance data available. This list is provided in Table 2. The "in series" combined technologies, or AOPs, were not included in the list as they are typically used for contaminants that are more difficult to remove, such as EDCs, PPCPs, and taste and odor-causing compounds, and for meeting more stringent wastewater reuse standards. The emerging and innovative technologies were not included in the short list as they have not been applied full-scale, and performance data other than bench or pilot scale are lacking. Each technology included in the short list will be evaluated for treating the maximum hourly flow at each WRP. In addition, combinations of the short list technologies will be evaluated for parallel treatment of wet weather and dry weather flows. Evaluation of the short list of technologies will be carried out using an engineering decision matrix.

TABLE 2: SHORT LIST OF DISINFECTION TECHNOLOGIES*

Chlorination/Dechlorination
- Sodium hypochlorite with sodium bisulfite

Ultraviolet Irradiation
- Low pressure high output lamps
- Medium pressure lamps

Ozonation
- Oxygen

Peracetic Acid

Ultraviolet Irradiation for DWF with Chlorination/Dechlorination for WWF
- Low pressure high output lamps
- Medium pressure lamps
- Sodium hypochlorite with sodium bisulfite

Ultraviolet Irradiation for DWF with Peracetic Acid for WWF
- Low pressure high output lamps
- Medium pressure lamps

Ozonation for DWF with Chlorination/Dechlorination for WWF
- Oxygen
- Sodium hypochlorite with sodium bisulfite

Ozonation for DWF with Peracetic Acid for WWF
- Oxygen

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* DWF – dry weather flow
WWF – wet weather flow

5.0. References

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