APPLICATION OF OZONATION AND ULTRAFILTRATION IN DRINKING WATER TREATMENT OPERATIONAL COMPARISON

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Abstract

The Spectacle Pond Water Treatment Facility in Littleton, Massachusetts has been successfully operating for over ten years relying on a combination of ozone oxidation followed by ultrafiltration membranes. This paper compares the operation of the plant in Littleton with more recent installations utilizing ozone and ultrafiltration membranes at the Mattapoisett River Valley Water Treatment Facility in Mattapoisett, Massachusetts and the Baldwin Pond Water Treatment Facility in Wayland, Massachusetts with regard to similarities as well as changes that have affected the industry.

Introduction

The first ultrafiltration membrane treatment facility in Massachusetts was built by a municipally owned water department in the Town of Littleton in 1997. The Safe Drinking Water Act (SDWA) had been amended the year before making drinking water regulations even more stringent. The Spectacle Pond Water Production Facility (WPF) in Littleton first conducted a pilot test program to find a solution to their treatment needs that would enable the Littleton Water Department to not only meet current regulations, but anticipated future regulations as well. The facility was designed and constructed to treat 1.5 million gallons per day (mgd) of well water that is high in iron and manganese and potentially under the influence of the adjacent Spectacle Pond. The Littleton Water Department selected a combination of ozone oxidation followed by ultrafiltration membranes which was considered the most innovative treatment process available at the time.

In 2007, the Mattapoisett River Valley (MRV) Water District was formed by the consortium of the Towns of Fairhaven, Mattapoisett, Marion and Rochester. The MRV Water District selected the process of ozone oxidation followed by ultrafiltration membranes for their new water treatment facility (WTF) which was constructed in 2008 in Mattapoisett, Massachusetts. In 2010, the Town of Wayland, Board of Water Commissioners selected this same process to treat high iron and manganese from the Baldwin Pond wells that had been determined to be under the influence of the adjacent Baldwin Pond.

Objective

This study highlights the advances in ozone pretreatment technology and ultrafiltration technology for use in drinking water. The objectives of this analysis are:

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- Present a general comparative overview of three WTFs that utilize a combination of ozonation and ultrafiltration,
- Identify changes that have occurred with ozonation and ultrafiltration technologies,
- Present a comparison of three featured drinking WTFs, and
- Discuss regulatory compliance achieved at these facilities.

The three facilities described in this paper consistently produce and deliver high quality drinking water to the customers they serve. The advancements in ozonation and ultrafiltration technologies since the start-up of the Littleton WPF have not only assisted in meeting changing regulatory requirements but have also reduced the overall cost of treatment.

General Overview

<u>Spectacle Pond Water Production Facility</u>

The first of the three featured WTFs using ozone oxidation followed by ultrafiltration membranes to be constructed was Littleton's Spectacle Pond WPF in 1997. Ozone systems were used in drinking water prior to construction of Spectacle Pond. However, ultrafiltration membranes were an emerging technology for the treatment of potable water. The Spectacle Pond WPF in Littleton was the first drinking water facility in the United States to employ ozone and ultrafiltration together. It was also the first large scale municipal ultrafiltration membrane system in Massachusetts. Prior to 1997, the AWWA Research Foundation evaluated membrane filtration technology and determined that significant work was needed prior to the widespread acceptance of the technology. For example, there was virtually no data available on the potential fouling, cleaning or life of ultrafiltration membranes treating potable water. The experience gathered from the successful operation of the Spectacle Pond WPF played a significant role in gaining that acceptance.

The ozone generator at the Spectacle Pond WPF is a 25 pound per day (ppd) horizontally mounted unit that produces ozone from compressed air that has passed through both refrigerant and desiccant dyers prior to being fed to fine bubble diffusers located at the bottom of two oxidation chambers. The ozone gas mixes with the raw water as it enters the chambers in a counter current fashion. The ozone oxidizes the soluble iron and manganese within a few seconds. Compressed air can be fed to the third chamber in series in order to drive off any excess ozone that could be harmful to the ultrafiltration membranes. The final chamber in series is the membrane feed tank where water is pumped to the prefilters on the upper level of the WPF. An ozone monitor measures any residual ozone in the water prior to the membranes. The pumping system is shut down if any residual ozone is detected in order to protect the membranes.

Stainless steel mesh prefilters protect the membranes from any particles larger than 50 microns (μm). The ultrafiltration membrane equipment supplied by Koch Membrane Systems (KMS) of Wilmington, Massachusetts consists of four skid mounted units with 50 individual, five-inch diameter membrane cartridges. A system to recover backwash water includes a series of three precast concrete settling tanks where solids are settled out of the backwash water. Supernatant is pumped from these settling tanks through a prefilter and into a separate ultrafiltration membrane skid. This backwash recovery skid consists of 20, five-inch diameter membrane filtration cartridges with the same 100,000 molecular weight (MW) pore size as the primary skids but with a slightly larger fiber diameter to accommodate the increased concentration of solids in the settled backwash water. The permeate from the backwash recovery skid is of the same quality as the permeate from the primary skids. However, it is recycled back to the head of the treatment process and combined with the incoming raw water. This system of recycling of backwash water increases the overall recovery, or efficiency in the use of water, of the WPF from 95 percent to 99.9 percent.

Mattapoisett River Valley Water Treatment Facility

The MRV Water District was formed to treat water sources from four Towns in order to reduce the cost of building separate facilities. The Massachusetts Towns of Fairhaven, Mattapoisett, Marion, and Rochester combined resources to realize a capital savings estimated at $5,000,000 when compared to building separate facilities. The MRV facility went online in 2008 and treats up to 6 mgd. The pilot program compared the costs and effectiveness of traditional greensand media against ozone oxidation followed by ultrafiltration. The combination of ozone and ultrafiltration demonstrated superior and more consistent water quality results after contacting the dissolved ozone.

The ozone generator supplied by Mitsubishi Electric is a 40 ppd horizontally mounted unit which produces ozone from liquid oxygen stored in a tank located outside the facility. Ozone is injected through a venturi-type, patented Mazzei injector into a sidestream water flow and then into the ozone contact tank. The super-ozonated water mixes with the raw water as it enters the ozone contact chamber. The soluble iron and manganese is oxidized within a few seconds.

The ultrafiltration equipment supplied by KMS consists of four skid mounted units. Each unit contains 45 individual, 10-inch diameter membrane cartridges for a total of 180 cartridges. The backwash recovery system is designed with a series of three settling tanks. Decanted water from these tanks is sent back to the head of the facility to achieve greater than 99 percent overall recovery.

The Baldwin Pond Water Treatment Facility

The Baldwin Pond WTF in Wayland, Massachusetts was completed two years after the MRV WTF and is almost identical in process scheme. The 1.5 mgd WTF began producing water in 2010. The close proximity of the wells to Baldwin Pond and concern over the possibility of influence of the nearby surface water on the wells led to the decision to employ ozone oxidation followed by ultrafiltration as the process of choice.

The ozone generator supplied by Mitsubishi Electric is a 50 ppd horizontally mounted unit which feeds ozone inline to the raw water prior to the membrane tank. The ozone system is supplied with oxygen from oxygen generators adjacent to the ozone generators. Air compressors provide an air supply to the oxygen generators to produce the high quality oxygen.

The ultrafiltration equipment supplied by KMS consists of two skid mounted units. Each unit contains 44 individual, 10-inch diameter membranes cartridges for a total of 88 cartridges. The backwash recovery system is designed with a series of three settling tanks and decanted water from these tanks is sent back to the head of the facility to achieve greater than 97 percent overall recovery.

Design Technology

Ozone

Ozone technology has been in continual commercial use for over 100 years. The main historical use has been for disinfection, but can also be used for many other applications including taste and odor control, color removal, hydrogen sulfide removal, nitrite and cyanide destruction, algae destruction, coagulant aid and for oxidation of iron, manganese and organic compounds. It is considered the strongest available disinfectant and strongest available oxidant for use in potable water. All of the featured WTFs use ozone for its strong oxidation properties and all three treat well water containing elevated levels of iron and manganese. The main goal of each plant is to remove iron and manganese below secondary maximum contaminant levels (SMCLs). Pilot studies at each featured WTF demonstrated the effectiveness of ozone oxidization followed by filtration to achieve this goal.

At ambient temperatures, ozone is an unstable gas. Due to its instability, ozone cannot be produced, bottled, shipped or stored prior to use. Ozone must be generated on-site. The four basic components of an ozone system include the feed gas, high voltage electrical power supply, an ozone contacting system and an ozone off-gas destruction and venting system. The feed gas supply flows through the ozone production vessel where high voltage electricity is introduced. The ozone must then be combined with the raw water through fine bubble diffusers, static mixers or venturi injectors.

The Spectacle Pond WPF injects ozone through fine bubble diffusers located on the bottom of the ozone contact tank. The MRV WTF uses side-stream injection along with a static mixer. The Baldwin Pond WTF uses high velocity injectors for mixing. Ozone injection has replaced fine bubble diffusers as the ozone application method of choice due to the higher efficiency in dissolving ozone in water.

Ozone gas is a health hazard when present in the environment. Small amounts of ozone can cause eye, throat, and nose irritation while larger amounts can be fatal. Safety concerns are handled through the proper use of ambient ozone monitoring, tank venting and ozone destruction. All of the featured WTFs rely on these safety features. Rooms containing ozone production equipment are well ventilated with complete changes of air every six minutes.

A design feature incorporated in each of these plants specifically for the safety of the ultrafiltration membranes is the use of residual ozone monitors placed strategically in the treatment process. All three plants have a residual ozone monitor after the contact tanks and prior to the membranes for emergency shutdown upon a measurable presence of ozone. Ultrafiltration membranes are permanently damaged and warrantees can be voided when they come into contact with ozone. Therefore, the initial ozone application dose must be carefully set to supply sufficient ozone to completely oxidize all of the iron and manganese while not allowing any residual ozone to reach and damage the membranes. In addition to residual ozone monitoring in the water, the Spectacle Pond WPF has the ability to use air stripping at the end of the contact chamber to remove any excess ozone. The MRV WTF and Baldwin Pond WTF rely on an emergency bisulfate injection system to eliminate any residual ozone prior to the ultrafiltration membranes. Additionally, the MRV WTF and Baldwin Pond WTF utilize mid-tank residual ozone monitors in order to gauge ozone consumption within the tank.

Ozone is a very effective oxidant and has to be closely monitored for the safety concerns and protection of downstream equipment. The systems installed at the three featured WTFs have demonstrated that ozone can achieve the goal of complete oxidation of iron and manganese without posing a threat to the integrity of the membrane filters.

Ultrafiltration

Ultrafiltration membranes are used in a variety of industries to filter oil and water, fruit juice, milk and whey, paints, pharmaceuticals, potable water, and tertiary wastewater. Ultrafiltration generally has a pore size between 0.001 micron and 0.1 micron. Any suspended solid larger than 0.1 micron will be removed with an ultrafiltration membrane. All oxidized metals can be removed using ultrafiltration. In addition, many studies have been performed to determine the effectiveness of removal of bacteria and viruses using ultrafiltration membranes. The removal is characterized as a log value where 99 percent removal is 2-log removal, 99.9 percent removal is 3-log removal, and so on. KMS ultrafiltration membranes have demonstrated 6-log removal of viruses through challenge testing. However, the Environmental Protection Agency (EPA) has issued guidelines to determine the maximum recommended log removal value to be allowed in designing a potable water treatment process. The allowable log removal is also influenced by each system's capability to monitor the integrity of the membrane system in real time. Most membrane manufacturers have a limited capability to monitor real-time log removal values up to 4-log. Even with the EPA recommendations and provided calculations, every State issues their own credits to each membrane manufacturer, generally on a case-by-case basis. The Commonwealth of Massachusetts currently does not have any standard guideline on log credits for virus removal by ultrafiltration. A similar procedure can be described for Giardia and Cryptosporidium removal. These contaminants have a standard size that can be removed by ultrafiltration membranes. However, continuous or regular monitoring is required to demonstrate that the online ultrafiltration membrane is providing the log removal that has been credited by the State.

Ultrafiltration membranes also provide limited removal of organic carbon. The removal is demonstrated on a case by case basis and depends on water quality. Removal can be enhanced with pretreatment by oxidation or by the addition of a coagulant. Dissolved organic carbon is not removed using ultrafiltration membranes.

Flux rate is the term used to measure flow through membranes and is measured as gallons per square foot of membrane area per day (gfd). Flux rates vary between membrane type, the source water quality and water temperature. Rates generally vary between 40 gfd and 100 gfd. As water is filtered, the pressure increases as particulates build up on the surface of the membrane. Flow of water is reversed on a regular basis to flush filtered water back through the membranes and lift solids off the surface and send them to waste or recycle tanks. This process is called backflushing and is set on a timed basis, generally between every 20 to 60 minutes. Chemically enhanced backflushing (CEBs) using citric acid can also be used on an as-needed basis to increase removal of solids during a backflush cycle. CEBs using citric acid cannot be recycled in a manganese removal treatment process because of the chemical reaction between the acid and manganese. The acid dissolves the suspended manganese, but does not allow for re-precipitation. Therefore, citric acid backflushes must be sent to waste and are only used when necessary to maintain higher recovery values.

Recycle Design

The volume of water that is sent to the distribution system compared to the volume pumped from the raw water source is measured as overall recovery. The ultrafiltration systems at the three featured WTFs operate in a recirculation mode, meaning that raw water is sent through the filters and separated into permeate (finished water) and retentate (concentrated feed water). Water that is not filtered but remains on the feed side of the membrane is recirculated and mixed with fresh incoming raw water. To prevent an over concentration of solids in the recirculated loop, a portion of the water is sent directly to recycle tanks. This is called the retentate. The retentate is set to 5 percent of the membrane feed water flow at all of the featured WTFs. The retentate and backflush water are sent to recycle tanks where solids are allowed to settle out before being sent back to the head of the treatment facility, allowing for high recovery at these facilities.

Treatment Design Comparison

The Spectacle Pond WPF treats the water from a single well. This well contains elevated levels of iron and manganese with little total organic carbon (TOC) present. The MRV WTF treats water from eight different wells in three towns. The combined water quality from these eight wells contains elevated iron and manganese with low TOC.

The Baldwin Pond WTF provides treatment of three different wells located onsite. The combined water quality from these three wells contains elevated iron and manganese and a high TOC for a well source. TOC levels measured greater than 6 mg/L during pilot testing. The wells have also been tested for groundwater under the influence of surface water. Microscopic Particulate Analysis testing results reveal that the site is at low to moderate risk of being under the influence.

The raw water iron and manganese levels for each facility are listed in Table No. 1.

Table No. 1
Raw Water Quality

	Spectacle Pond WPF	MRV WTF	Baldwin Pond WTF
Iron levels (mg/L)	0.3	0.0 - 5.4	0.0 - 5.2
Manganese levels (mg/L)	1.0	0.02 - 1.08	0.03 - 2.40

Each facility is designed based upon the performance of a pilot test. The pilot test performance is directly related to the water quality of the source(s). An overview of the design and operation of each facility is listed in Table No. 2.

Table No. 2
Design Highlights

	Spectacle Pond WPF	MRV WTF	Baldwin Pond WTF
Plant capacity	1.4 mgd	6.0 mgd	1.5 mgd
Membrane design flux rate	85 gfd	70 gfd	40 gfd
Design backflush interval	60 min.	45 min	35 min
Membrane cartridge diameter	5-inch	10-inch	10-inch
Total membrane cartridges	220	180	88
Ozone design capacity	25 ppd	40 ppd	50 ppd
Overall recovery	99.8%	99%	97%

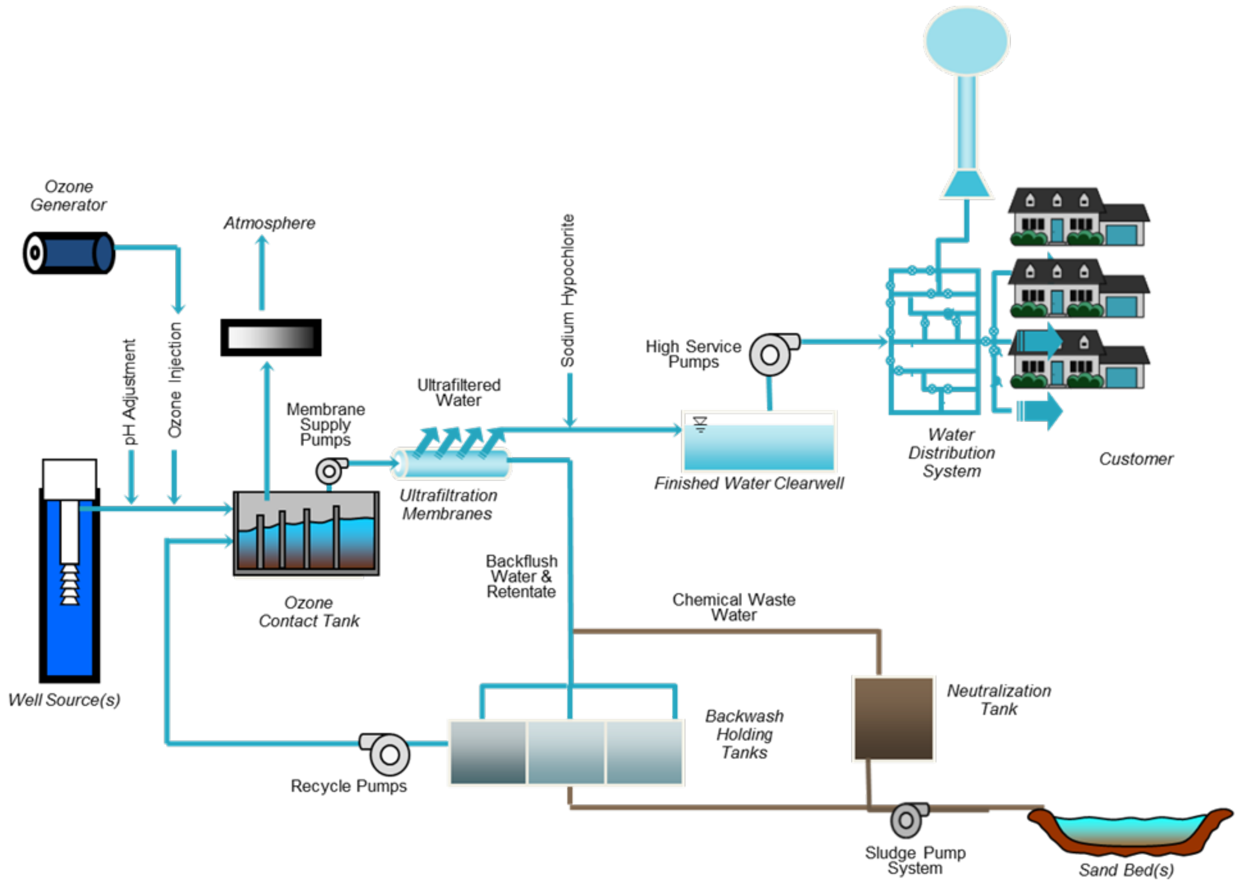
<u>Comparison Overview</u>
Each water treatment facility was designed to meet the demands associated with the current water quality and quantity. They were also designed to meet future regulatory standards by using the best filtration technology available.

The Baldwin Pond WTF has the largest ozone generator despite similar iron and manganese levels to MRV's well water supply. Additionally, the facility produces one quarter of the capacity of the MRV WTF. The major difference in water quality between the two facilities is the higher level of TOC at the Baldwin Pond WTF. Manganese binds with TOC creating a particle that is difficult to remove from the membrane surface. The Baldwin Pond WTF had TOC levels in excess of 6 mg/L during the piloting testing. This experience highlights the importance of pilot testing when organics are present with the iron and manganese in the source water.

The process flow diagram in Figure No. 1 illustrates the path that water follows from the well(s), through the treatment process and into the distribution system. It also illustrates the flow path for the recycled water and solid waste. The difference in recovery from 99.8 percent at the Spectacle Pond WPF to 97 percent at the Baldwin Pond WTF is because of the use of CEBs. CEBs are now standard to help stabilize and maintain flux rates.

The standard KMS cartridge in 1997 was a 5-inch diameter clear cartridge and is used at the Spectacle Pond WPF. As the technology improved, KMS released 8-inch, then 10-inch diameter cartridges. Unfortunately, in order to stay competitive in the market, the clear cartridges were replaced with solid plastic at the 10-inch size. The visual benefit of observing the discoloration associated with oxidized iron and manganese in the clear cartridge was not available. Therefore, a single clear 8-inch diameter cartridge was installed on the skid.

Figure No. 1
Process Flow Diagram



Larger membrane skids are used to support the larger cartridges. The skid used to house 50 small diameter membrane cartridges at the Spectacle Pond WPF takes up one half the floor space as the skid used for 52 larger diameter cartridges at the MRV and Baldwin Pond WTFs. The capacity of the larger skid is nearly seven times greater when using comparable flux rates.

A 5-year warranty was supplied with the membrane cartridges at all of the facilities. At the Spectacle Pond WPF, the longevity has proven much greater and has saved the facility money by deferring replacement costs. Replacement of the membrane cartridges began in 2011 and continued into 2012. While a thirteen to fourteen year membrane life may be optimistic based on the case of a single facility, a life of more than five years provides an improved life cycle cost.

Water Quality/Meeting Regulations
The theoretical dosages for iron and manganese oxidation using ozone are listed below.

- mg/L iron * 0.43 = mg/L ozone
- mg/L manganese * 0.88 = mg/L ozone

Complete oxidation is necessary in order for these metals to be removed by the ultrafiltration membranes. The goal is to achieve iron and manganese levels in the product water that meet the secondary maximum contaminant limits, 0.3 mg/L for iron and 0.05 mg/L for manganese. Oxidation followed by ultrafiltration is capable of achieving non-detect levels of iron and manganese.

With only one well source, Littleton's raw water quality is fairly constant and the ozone dose was easily determined. The complexity of the MRV system using eight wells in three Towns was more challenging to optimize. Significant work was required by the operators, SCADA integrator and engineer during plant startup to set up the correct dosages for each well, some located miles away, so that the ozone system could be varied according to the pumping rate and status of each individual well. The complexity added by the presence of organics in the three wells at the Baldwin Pond WTF also required substantial coordination during WTF startup. Today, all facilities continuously produce drinking water quality that meets the standard limits for iron and manganese.

Alternatives to ultrafiltration for iron and manganese removal are media filters such as Greensand, LayneOx™ , Pureflow™ filtration, and other adsorption technologies, none of which provide the equivalent log removal capabilities of ultrafiltration. Ultrafiltration membranes not only help to meet the standards developed for the 2006 Ground Water Rule, but also provide added protection against viruses.

Results and Conclusions

Similarities and advancements in technology were observed from the first ozone and ultrafiltration system constructed in 1997 to the most recent constructed in 2010. Ozone systems saw small changes in this time period, with modifications to the air supply, injection technology, and upgrades to the residual monitoring. Ultrafiltration systems have seen a more significant change over this same period. The ultrafiltration footprint has been reduced allowing for more water to be treated in less building space. Littleton built a system using four skids, which can be constructed today with half the size of a single larger skid.

The treatment capabilities of ozone oxidation followed by ultrafiltration membranes demonstrated in this study exceed industry standards for secondary limits of iron and manganese and also provide capabilities to help meet the Ground Water Rule and removal of viruses.

Ultrafiltration systems have shown an increase in use between 1997 and now. The Commonwealth of Massachusetts currently considers membrane treatment as the best available technology for iron and manganese removal in water treatment. With more and more membrane treatment plants being built worldwide, along with the improvements discussed herein, the cost of having the best available technology has become more affordable.

When the Spectacle Pond WPF was built, the life expectancy of the membranes was unknown. These membranes, which were supplied with a five-year warranty in 1997, began replacement in 2011, almost fourteen years after installation. While all membranes may not last 14 years, any year beyond the warranty period provides real savings to municipalities.

Public water systems have long been faced with not only meeting current drinking water regulations, but eminent future regulations as well. The process of combining ozone pretreatment with ultrafiltration membranes is approved as the best available technology and has also demonstrated the ability to achieve and exceed current standards. This combination has the ability to remove many constituents found in raw water supplies. It has also demonstrated longevity and has become more affordable in today's marketplace through the reduction in overall footprint.