

Advancing Material and Technologies for Drinking Water Purification

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ABSTRACT: The development and implementation of water treatment technologies have been mostly driven by three primary factors: the discovery of new rarer contaminants, the promulgation of new water quality standards, and cost. For the first 75 years of this century, chemical clarification, granular media filtration, and chlorination were virtually the only treatment processes used in municipal water treatment. However, the past 20 years have seen a dramatic change in the water industry's approach to water treatment in which water utilities have started to seriously consider alternative treatment technologies to the traditional filtration/chlorination treatment approach. A wide range of water treatment technologies have been developed or are currently in development. This paper focuses on technologies that can be applied in purification technologies. Such a technology should meet the following criteria:

- The technology can be scaled to large applications (i.e., > 5 MGD).
- The technology can be cost competitive with existing technologies at large scale.
- The technology can produce water that meets regulatory requirements.
- The technology has a high degree of reliability.

In this paper the following technologies are screened and evaluated: membrane filtration (low pressure and high pressure), ultraviolet irradiation, advanced oxidation, ion-exchange, and biological filtration. Many of these technologies are certainly not new to the water industry. However, either their application has been limited or they were introduced to the water industry so recently that many questions remain unanswered about their large-scale application.

KEYWORDS: drinking water, chlorination, uv radiation, advanced oxidation, reverse osmosis, homes

I.INTRODUCTION

There are two classes of membrane treatment systems that should be discussed: low-pressure membrane systems (such as microfiltration and ultrafiltration) and high-pressure membrane systems (such as nanofiltration and reverse osmosis). Low-pressure membranes, including microfiltration (MF) and ultrafiltration (UF), are operated at pressures ranging from 10 to 30 psi, whereas high-pressure membranes, including nanofiltration (NF) and reverse osmosis (RO), are operated at pressures ranging from 75 to 250 psi. Figure 11-1 shows a schematic of the pore size of each membrane system as compared to the size of common water contaminants.¹

Low-Pressure Membranes

If there is a "Cinderella" story of a water treatment technology it is that of the application of low-pressure membranes for surface water treatment. The idea of using low-pressure membrane filtration for surface water treatment began developing in the early 1980s. At the time, low-pressure membranes² had long been used in the food-processing industry as nonchemical disinfectants. During the latter half of the 1980s, several research projects were initiated by west coast water utilities (East Bay Municipal Utilities District and Contra Costa Water District), the American Water Works Association (AWWA) Research Foundation, and other organizations to evaluate MF and UF for municipal surface water treatment. The studies clearly showed that both MF membranes (with a nominal pore size of 0.2 mm and UF membranes (with a nominal pore size of 0.01 mm are highly capable of removing particulate matter (turbidity) and microorganisms.³ In fact, the research results showed that, when it came to these contaminants, membrane-treated water was of much better quality than that produced by the best conventional filtration plants. Figure 2 shows an example plot of turbidity removal by an MF membrane. The majority of treated-water samples had a turbidity level

near the limit of the on-line turbidimeter (less than 0.05 Nephelometric Turbidity Units (NTU)). In addition, membrane filtration (both MF and UF) was proven to be an "absolute barrier" to *Giardia* cysts and *Cryptosporidium* oocysts when the membrane fibers and fittings were intact. Finally, the particular UF membranes tested by Jacangelo et al. (1995) were also proven to act as absolute barriers to viruses because of their nominal pore size of 0.01 μm .⁴ As a surface water treatment technology, low-pressure membrane filtration has several advantages over conventional filtration and chlorination. These include smaller waste stream, lower chemical usage, smaller footprint, greater pathogen reduction, no disinfection byproduct formation, and more automation. For a while it was also believed that low-pressure membrane filtration is highly susceptible to excursions in raw water turbidity.⁵ However, pilot- and full-scale operational data have demonstrated that low-pressure membranes can treat turbidity excursions as high as several hundred NTUs with manageable impacts on process operation and efficiency (Yoo et al., 1995). All of the above advantages greatly favor membrane filtration over conventional filtration with chlorine. On the other hand, because of their porous structure, low-pressure membranes are ineffective for the removal of dissolved organic matter. Therefore, color-causing organic matter, taste-and-odor-causing compounds such as Geosmin and methylisoborneol, and anthropogenic chemicals can pass through the membranes into treated water.⁶ This limits the applicability of low-pressure membrane filtration to surface water sources where the removal of organic matter is not required.

SIZE, MICRONS	0.001	0.01	0.1	1.0	10	100	1,000
RELATIVE SIZE OF VARIOUS MATERIALS IN WATER	← AQUEOUS SALTS → ← HUMIC ACIDS → ← METAL IONS →	← VIRUSES →	← BACTERIA → ← ALGAE → ← CYSTS → ← CLAYS → ← SILT → ← ASBESTOS FIBERS →	← SAND →			
SEPARATION PROCESSES	REVERSE OSMOSIS NANO-FILTRATION ULTRAFILTRATION			MICROFILTRATION			CONVENTIONAL FILTRATION PROCESSES

Figure 1: Pore size ranges of various membranes.

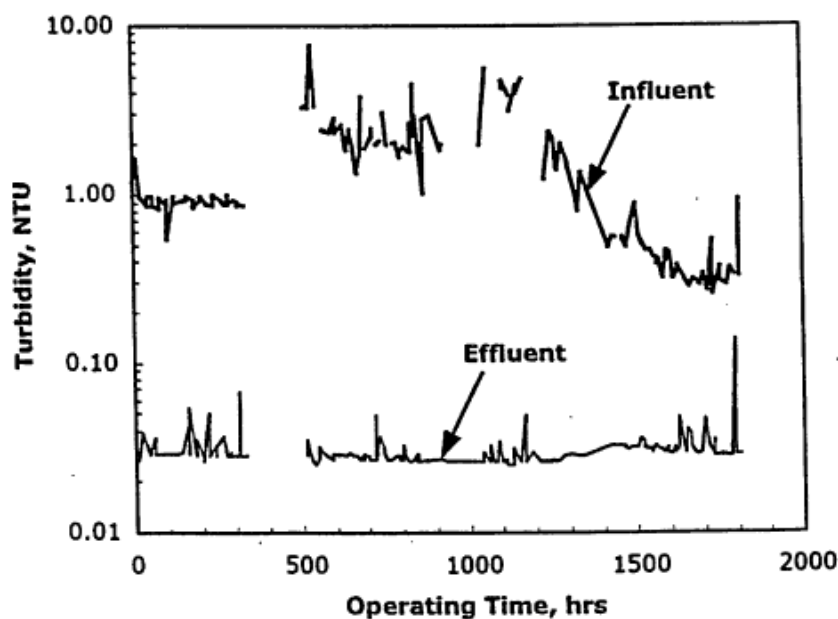


Figure 2: Example plot of turbidity reduction by MF membranes.

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High-Pressure Membranes

As noted earlier, included in this category are nanofiltration (NF) and reverse osmosis (RO) membranes. NF membranes are actually thin-film composite Re membranes that were developed specifically to cover the pore size between Re membranes (<1 nm) and UF membranes (>2 nm) (Matsuura, 1993)--hence the name nanofiltration.⁷ Thin-film composite (TFC) membranes are discussed later in this paper. The result was a type of membrane that operates at higher flux and lower pressure than traditional cellulose acetate (CA) RO membranes. In fact, NF membranes are sometimes referred to as "loose" RO membranes and are typically used when high sodium rejection, which is achieved by RO membranes, is not required, but divalent ions (such as calcium and magnesium) are to be removed (Scott, 1995).⁸ Nevertheless, NF membranes are viewed by the water industry as a separate class of membranes than RO membranes and are discussed in this paper as such. NF membranes are commonly operated at pressures ranging from 75 to 150 psi (Lozier et al., 1997). NF membranes have been used successfully for groundwater softening since they achieve greater than 90 percent rejection of divalent ions such as calcium and magnesium. Several NF membrane-softening plants are currently in operation in the United States, with the first plant installed in Florida in 1977⁹ (Conlon and McClellan, 1989). By 1996 the combined total capacity of NF plants in the United States was greater than 60 MGD, all in Florida (Bergman, 1996). It is estimated that approximately 150 NF membrane plants existed around the world by 1995, with a combined total capacity of approximately 160 MGD (Scott, 1995). Because most commercially available NF membranes have molecular weight cutoff values ranging from 200 to 500 daltons (Bergman, 1992; Scott, 1995), they are also capable of removing greater than 90 percent of natural organic matter present in the water.¹⁰ Therefore, they are also excellent candidates for the removal of color and, more importantly, disinfection byproduct (DBP) precursor material (Taylor et al., 1987; Tan and Amy, 1989; Bleu et al., 1992; Chellam et al., 1997).

Currently, NF membranes are being considered as a total organic carbon (TOC) removal technology in surface water treatment.¹¹ The idea is to install NF membranes downstream of media filtration in order to maintain a very low solids-loading rate on the membranes. Although NF membranes have been designated by the U. S. Environmental Protection Agency (EPA) as one of two best available technologies (BATs) for meeting stage 2 of the Disinfectants/Disinfection Byproducts Rule, they have not been applied for surface water treatment at full scale.¹² To date, pilot studies have been conducted to evaluate the applicability of NF membrane filtration downstream of media filtration during surface water treatment with mixed results (Reiss and Taylor, 1991; Tooker and Robinson, 1996; Chellam et al., 1997). The study reported by Chellam et al. (1997) clearly demonstrated that the fouling rate of NF membranes downstream of conventional filtration was two times higher than that of NF membranes downstream of MF or UF membranes.¹³ This was supported by the study of Reiss and Taylor (1991), which showed that conventional filtration pretreatment did not reduce the fouling rate of NF membranes to acceptable levels. Nevertheless, the Information Collection Rule includes data gathering on the applicability of NF membrane filtration for TOC removal from surface water sources.¹⁴ The majority of the data will be from bench-scale testing, which does not include information on long-term operational design and reliability, but some data will be obtained from pilot-testing programs. These data will provide additional input into the viability of NF membranes for surface water treatment. RO membranes have long been used for desalination of seawater around the world.¹⁵ These membranes can consistently remove about 99 percent of the total dissolved solids (TDSs) present in the water, including monovalent ions such as chloride, bromide, and sodium. However, for a long time these membranes were predominantly made from CA and required operating pressures at or greater than 250 psi. Recent innovations in Re membrane manufacturing have developed a new class of Re membranes, called TFC membranes that can achieve higher rejection of inorganic and organic contaminants than CA Re membranes while operating at substantially lower pressures (100 to 150 psi). In addition, CA Re membranes commonly require acid addition to lower the pH of the water to a range of 5.5 to 6.0 to avoid hydrolysis of the membrane material.¹⁶ TFC RO membranes do not hydrolyze at neutral or high pH and therefore do not require pH depression with acid addition. It should be noted that the need for pH depression for preventing the precipitation of salts on the membrane surface (such as CaCO_3) may still be necessary in some cases depending on the quality of the water being treated and the availability of suitable antiscalants.¹⁷ TFC RO membranes are currently being evaluated for water reclamation. Results from ongoing pilot studies have shown that TFC RO membranes can achieve greater than 90 to 95 percent rejection of nitrate and nitrite, compared to 50 to 70 percent removal with CA Re membranes.¹⁸

III.DISCUSSION

Ultraviolet Irradiation Technology

Ultraviolet (UV) irradiation technology is primarily used in the water and wastewater treatment industry as a disinfection process that capitalizes on the germicidal effect of UV light in the wavelength range of 250 to 270 nm (EPA, 1996). The process is commonly designed such that water flows in a narrow region around a series of UV lamps. The microorganisms in the water are inactivated through exposure to the UV light.¹⁹ The process is compact since the time of exposure (which translates into hydraulic retention time) is commonly measured in seconds. The process works on the principle that UV energy disrupts the DNA of the microorganisms and prevents it from reproducing. UV irradiation technology has been used since the 1950s at approximately 500 drinking water facilities in the United States²⁰, and more than 1,500 facilities in Europe (Kruithof et al., 1992; Parrotta and Bekdash, 1998). However, the vast majority of the U.S. facilities are either transient-noncommunity groundwater systems or nontransient-noncommunity groundwater systems serving less than 3,000 people each. These are facilities that provide water to restaurants, highway rest areas, airports, schools, camps, factories, rest homes, and hospitals.²¹ In fact, UV disinfection technology in drinking water treatment is currently only promoted for small-scale groundwater systems. However, the process can certainly be scaled up to large-scale applications since it is currently applied at large-scale wastewater treatment plants for final effluent disinfection.²² The largest wastewater treatment UV system in the world is located in Edmonton, Alberta, Canada, with a peak design capacity of 265 MGD (Reed, 1998). For water treatment systems, a minimum UV dose is commonly set for UV systems. The National Sanitation Foundation (NSF) standard for Class A UV systems (i.e., those that can be used as point-of-use (POU) and point-of-entry (POE) treatment devices) requires that they emit a minimum UV dose of 38 mW-sec/cm²,²³ which is the dose determined to inactivate *Bacillus subtilis* spores (ANSI/NSF, 1991). Several states, including New Jersey and Wisconsin, have specific criteria for UV systems in the form of a minimum dose (Parrotta and Bekdash, 1998). Several European countries have also adopted minimum UV doses for pretreated drinking water (Norway at 16 mW-sec/cm² and Austria at 30 mW-sec/cm²).²⁴ All of these doses are based on the requirement to inactivate bacteria and viruses but not protozoans. There is limited information on the ability of UV irradiation to inactivate *Giardia* cysts. Karanis et al. (1992) conducted a laboratory study to evaluate the UV inactivation of *Giardia lamblia* cysts obtained from infected humans and gerbils.²⁵ The testing results conducted in distilled water are shown in Figure 11-4. The results show that a UV dose of approximately 40 mW-sec/cm² achieved 0.5-log inactivation of *Giardia lamblia*, whereas a UV dose of 180 mW-sec/cm² was required to achieve 2-log inactivation of *Giardia* cysts.²⁶ Rice and Hoff (1981) also showed that a UV dose of 63 mW-sec/cm² achieved 0.5-log inactivation of *Giardia* cysts, also in distilled water. EPA has recently developed and published a guidance document for the application of UV technology for surface water treatment (EPA, 1997a). The California Department of Health Services has set a specific dose of 140 mW-sec/cm² as a requirement to meet the Title 22 criteria of 2.2 coliforms/100 ml in reclaimed water.²⁷

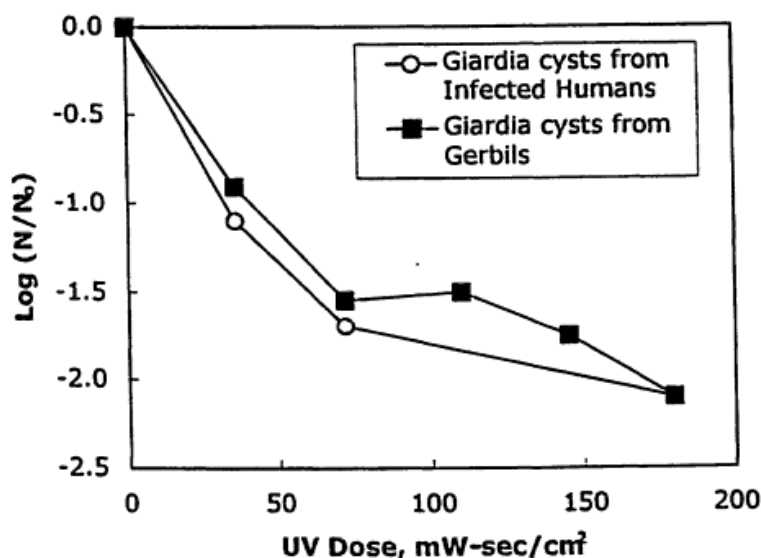


Figure 3: Inactivation of Giardia lamblia cysts with UV irradiation in distilled water

The new UV technology under development is pulsed UV technology. In this process the energy is stored in a capacitor and then released to the lamp in a short, high-intensity pulse. The duration between pulses is approximately 30 milliseconds, and each pulse lasts for less than 1 millisecond. The intensity of each pulse is believed to be about 107 mW/cm².²⁸ One manufacturer of this technology claims that the high energy emitted with each pulse is far more effective for the inactivation of microorganisms compared to the same level of energy emitted over an extended period of time.²⁹

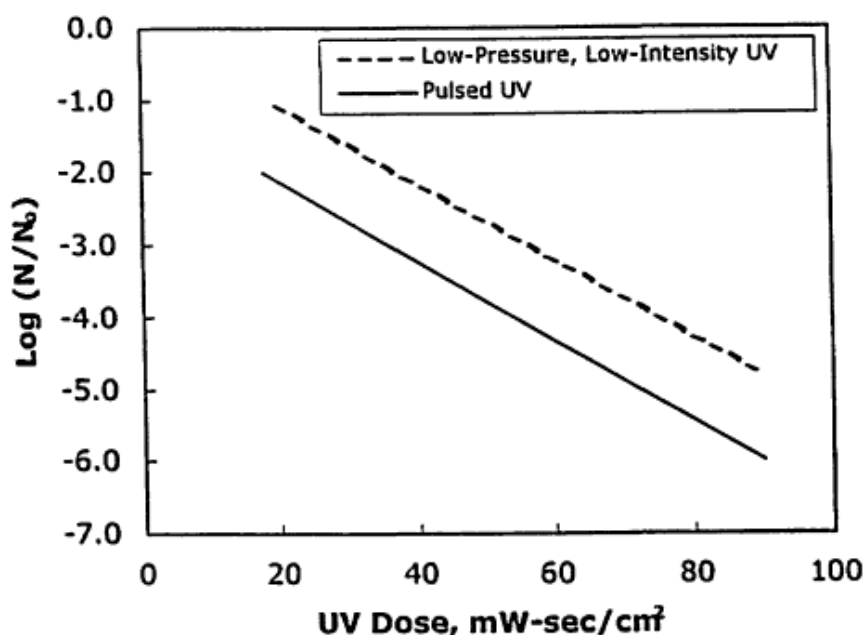


Fig.4: Inactivation rate of MS2 bacterial virus with pulsed UV and low-pressure UV systems.

III.RESULTS

Advanced Oxidation Technology

The term "advanced oxidation processes" (AOPs) was first used by Glaze et al. (1987) and Aieta et al. (1988) to describe a process that produces hydroxyl radicals (OH) for the oxidation of organic and inorganic water impurities. AOPs include a number of processes. However, three main AOPs are discussed herein: ³⁰ozone, ozone with hydrogen peroxide addition, and UV irradiation with hydrogen peroxide addition. AOPs can have multiple uses in water treatment. Examples include oxidation of synthetic organic chemicals, color, taste-and-odor-causing compounds, sulfide, iron, and manganese and destruction of DBP precursors prior to the addition of chlorine³¹. However, Trussell and Najm (in press) have demonstrated that AOPs may not be good candidates (i.e., cost effective) for DBP precursor destruction. In this paper the application of each of the above processes in municipal water treatment is briefly discussed, and some of the challenges facing each process are presented.³²

Ozone with Hydrogen Peroxide Addition

When hydrogen peroxide (H₂O₂) is added to ozonated water, it reacts with the molecular ozone, which accelerates the formation of hydroxyl radicals. Therefore, in an ozone-H₂O₂ process the goal is to increase the concentration of hydroxyl radicals,³³ which is a stronger oxidizer than molecular ozone, and consequently rapidly reduce the concentration of molecular ozone. Therefore, hydrogen peroxide is added to an ozone process if it is used as an oxidation process but not as a disinfection process, which relies on the prevalence of a high concentration of molecular ozone.³⁴ The ozone-H₂O₂ process is used for the destruction of taste-and-odor-causing compounds, color removal, and destruction of micropollutants, such as volatile organic compounds (Karimi et al., 1997), pesticides, and herbicides. Stoichiometric analysis suggests that the optimum H₂O₂-to-ozone ratio is approximately 0.3:1 (mg/mg). However,

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pilot-and full-scale studies have shown that the optimum ratio is more on the order of 0.5:1 to 0.6:1 mg/mg (Karimi et al., 1997; Najm et al., in press). Currently, the conventional design of an ozone-H₂O₂ treatment process is one in which hydrogen peroxide is fed as a liquid to the influent water and an ozone-rich gas is fed through fine-bubble diffusers at the bottom of a contactor.³⁵

Ion Exchange Technology

Ion exchange (IX) technology has been used in the chemical and environmental engineering fields for a long time. However, its use has been mostly limited to water softening (Ca²⁺ and Mg²⁺ removal), either at the water treatment plant or as a point-of-use treatment process and for industrial applications, such as the production of fully demineralized water. However, with new limits being set on several inorganic chemicals, IX technology is finding new applications in water treatment³⁶. Some of the primary candidates for removal with IX include nitrate, arsenic, selenium, barium, radium, lead, fluoride, and chromate. Surveys conducted in the early 1980s showed that 400 communities exceeded the nitrate MCL of 10 mg/L as nitrogen (AWWA, 1985) and 400 communities exceeded the fluoride MCL of 4 mg/L (EPA, 1985). A new contaminant recently discovered in groundwater is perchlorate (ClO₄-),³⁷ which is a component of solid-rocket fuel. The California Department of Health Services has adopted a perchlorate action level of 18 g/L. IX technology is ideal for the removal of perchlorate ion from contaminated groundwater.³⁸ Ions present in the water are exchanged with ions on the resin surface, thus removing the contaminant ions from the water and concentrating them on the resin. The resin is frequently regenerated to remove the contaminant from the resin surface and replenish it with the original exchange ion. There are four primary types of IX resins: strong acid cationic (SAC) resin, weak acid cationic (WAC) resin, strong base anionic (SBA) resin, and weak base anionic (WBA) resin.³⁹

Implications

Biological Filtration

All of the technologies discussed above are physical and/or chemical processes. In fact, the water treatment industry depends solely on physical and/or chemical processes to meet water quality goals. Utilization of biological processes in water treatment has been frowned on by the industry because of concern about the introduction of microorganisms to water.⁴⁰ However, this barrier has been broken by the introduction of biological filtration as the most effective process for the production of biologically stable water. This was specifically driven by concern about the increase in the concentration of biodegradable organic matter (BOM) as a result of ozonating natural waters. There is concern that higher BOM levels may result in increased potential for biological regrowth in the distribution system. Therefore, implementing biological filtration in the water treatment plant reduces BOM concentrations in the water before it is introduced into the distribution system.⁴¹ Several plants in the United States currently use biological filtration after ozonation. In fact, Stage 1 of the D/DBP Rule, which became final in December 1998, requires water utilities to implement biological filtration for BOM removal if ozone is used at the treatment plant (EPA, 1997b). There are several unanswered questions about the design and operation of biological filtration, such as what filter media type and size to use and what minimum empty bed contact time (EBCT) can be used while maintaining satisfactory BOM removal. Pilot studies conducted by various researchers have concluded that either granular-activated carbon (GAC) or anthracite,⁴² compared to sand, is required as the attachment medium for the biofilm. Clearly, anthracite is substantially less expensive than GAC. Anthracite has been shown to be equivalent to GAC as a biological filtration medium when used in warm climates (Montgomery Watson, 1992). However, it may not be satisfactory in cold climates, as studies have shown that a higher GAC surface area, compared to that of anthracite, is required to maintain an active biofilm when treating cold water.⁴³ Wang et al. (1995) showed that the concentration of biomass on the surface of biologically active GAC filters was approximately three to eight times greater than that on the surface of biologically active anthracite filters.

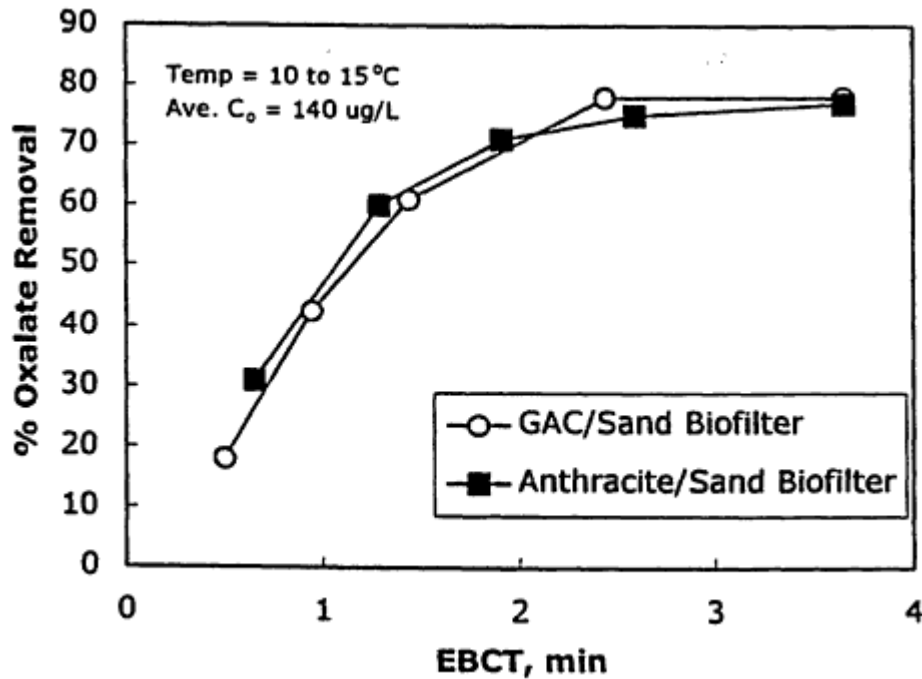


Fig.5: Impact of media type and EBCT on the removal of oxalate by biological filtration

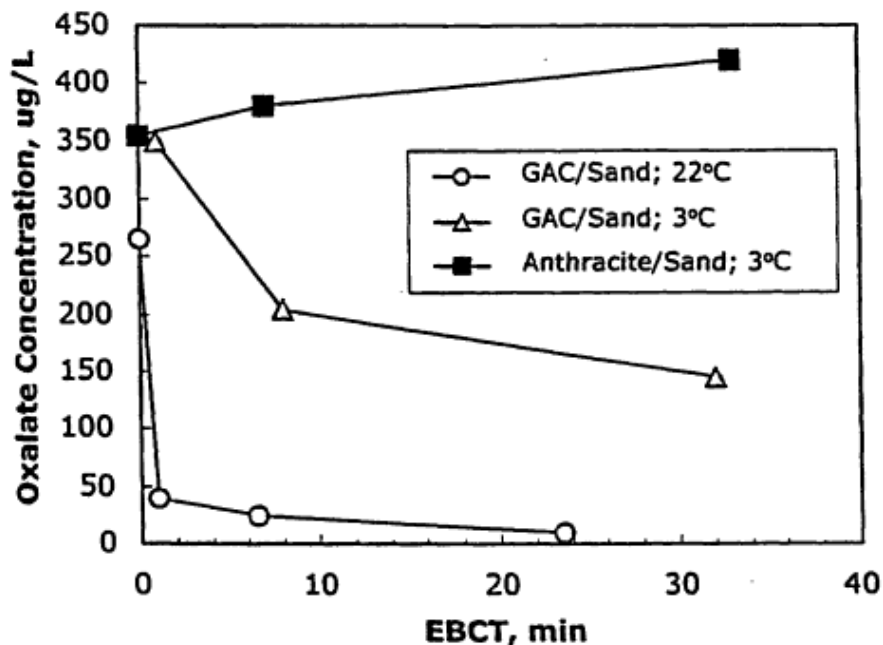


Fig. 6: Impact of water temperature and EBCT on the removal of oxalate by biological filtration

IV.CONCLUSIONS

Historically, the water industry has adapted to new technologies at a slow, incremental pace. In the past 20 years there has been a rapid entry of new technologies that continue to be developed, tested, demonstrated, and introduced into the municipal water treatment market. Some of these technologies are membrane filtration, UV irradiation, advanced oxidation, ion exchange, and biological filtration.⁴⁴ These are certainly not the only technologies being considered by

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the water treatment industry. However, they have come a long way toward demonstrating their reliability and applicability to large-scale municipal water treatment plants. As the cost of these technologies continues to decrease, their applicability will steadily increase. There is almost no contaminant that cannot be removed from water. The question becomes that of cost. As alternative water resources become increasingly less available, the need for innovative and cost-effective treatment technologies will rise steadily.⁴⁵

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