Membrane Filtration: Past, Present, and Future

Karla Kinser

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***Editor's note:** Having completed the inaugural Water Quality Matters column series focusing on the theme "Hot Topics in Water Quality," initiated in the April 2019 issue of* Journal AWWA, *the AWWA Water Quality and Technology Division's committees extend the conversation in this recurring column by expounding on a common question, "What keeps you up at night?"*

Filtration using microfiltration (MF) and ultrafiltration (UF) membranes, also known as low-pressure membrane filtration, gained acceptance in the United States for municipal water and wastewater treatment (primarily reuse) in the 1990s. Since then, hundreds of membrane filtration systems have been installed. Adapting this new technology to municipal treatment has had great successes and challenges—challenges that have kept water system operators and owners up at night. As municipalities operating MF and UF plants have overcome these challenges, the technology has matured, leading to innovations and improvements of many early design and operational paradigms.

Technology Advances

Membrane filtration was used in industrial applications before it was introduced to the municipal market. UF was used in areas such as the dairy industry from the 1980s to 1990s as the technology evolved (Figure 1). Since then, increasingly stringent regulations, water scarcity, and decreasing membrane costs have helped membrane processes gain acceptance as a cost-effective method for water and wastewater treatment and water reuse. In addition, a key advantage of membrane filtration, compared with media filtration, is superior filtered water quality. Because water quality matters, this advantage has led to the technology's use in routine applications such as low-level phosphorus removal at wastewater treatment plants and pretreatment for desalination.

Membrane filtration growth continues globally, with new installations and new applications. The global membrane market was estimated at US$1.8 billion in 2011, according to the 2020 Markets and Markets research report *Membranes Market by Material (Polymeric, Ceramic), Technology (RO, UF, MF, NF), Application (Water & Wastewater Treatment, Industrial Processing), Region (North America, APAC, Europe, MEA, South America)—Global Forecast to 2024.* This number increased to approximately $13.4 billion in 2019 and is projected to reach $25.1 billion by 2027, at a compound annual growth rate of 8.4% from 2020 to 2027.

Historically, a variety of materials have been used to fabricate MF and UF membranes, using nonsolvent- or thermally induced phase-separation techniques:

- Cellulose acetate (CA)
- Polyacrylonitrile (PAN)

- Polypropylene (PP)
- Polysulfone (PSF)
- Polyethersulfone (PES)
- Polyvinylidene fluoride (PVDF)

Besides polymers, other materials such as ceramics were slow to be adopted, and the first water treatment plant using ceramics wasn't constructed until 2015. Each membrane material has different properties with respect to surface charge, degree of hydrophobicity, pH and oxidant tolerance, chemical stability, strength, and flexibility. PVDF membranes are popular in the membrane filtration industry because of their increased permeability, durability, chemical and fouling resistance, and thermal and mechanical performance.

In terms of an operational driving force, there are two major types of membrane systems: pressurized and submerged (immersed). In a pressurized system, membranes are mounted in a housing on a skid and feed water is forced through the membrane by a pump under pressure. In a submerged system, membranes are placed on a rack in a basin or tank that is open to the atmosphere. Feedwater is introduced into the tank or basin, and the filtrate is drawn through the membrane by a vacuum on the filtrate side created by the pump's suction.

The first membrane plants built for municipal treatment were primarily pressurized systems. The pace of construction for submerged systems slowly grew until the mid-2000s, when the submerged industry experienced tremendous growth in drinking water and reuse treatment plants. Both pressurized and submerged systems still have a place in municipal treatment, but most new drinking water and reuse treatment plants are now pressure systems. A manufacturer is exploring gravity membrane filtration for drinking water media filtration retrofits; these operate at a lower flux, using only the driving head of the original installation. However, the primary growth area for submerged systems is membrane bioreactors in wastewater treatment.

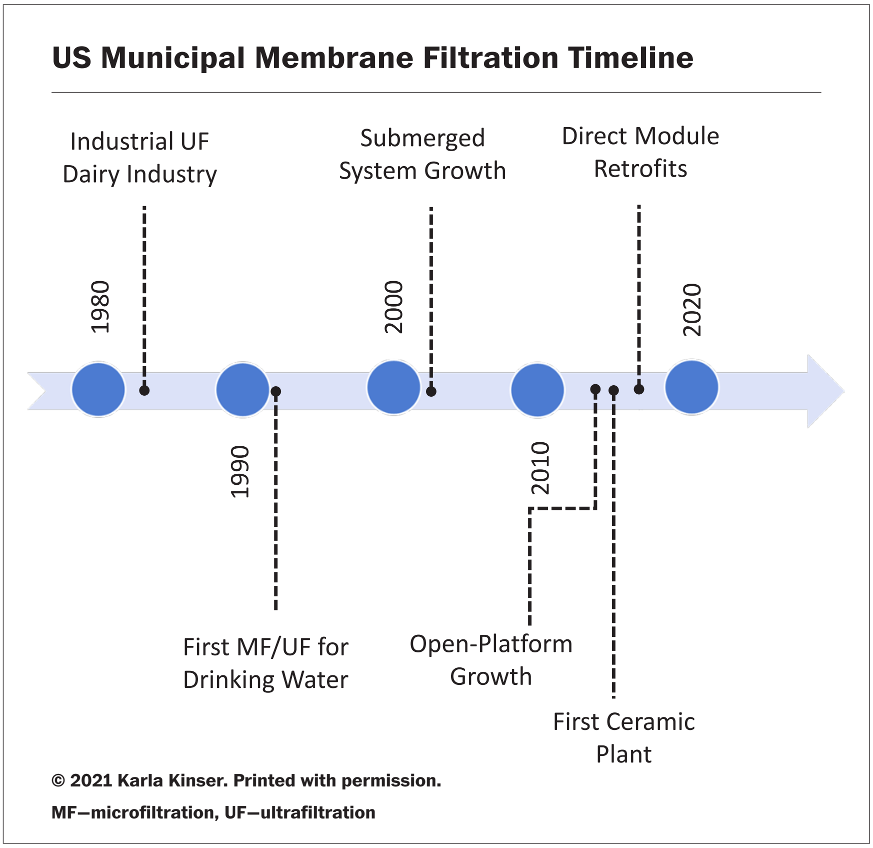

Figure 1

Industry Challenges

As membrane filtration has evolved in drinking water and reuse plants, there have been challenges for numerous installations that have limited their ability to attain their nameplate design capacity. Two issues contributing to these challenges were fouling and integrity (fiber breaks). The need to address these problems was a catalyst for research and a shift in some of the original design approaches by manufacturers and engineers in the 1990s and 2000s.

Membrane Fouling

Membrane fouling has serious consequences on overall membrane performance, including higher energy consumption and increased chemical use, and it ultimately reduces production as a result of decreased membrane permeability. Fouling is generally characterized as reversible or irreversible.

There are four fouling types:

- Inorganic scaling
- Particulate fouling

- Organic fouling
- Biological fouling

Reversible fouling is controlled by backwash and chemical cleaning, whereas irreversible fouling can't be removed. Causes of irreversible fouling vary and have been studied extensively by the private and public sectors. This research and the practical experience gained from full-scale operating plants have led to new strategies for designing membrane filtration plants, as described in the following sections.

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Lower Average and Instantaneous Fluxes

Design flux values for installations have generally decreased over the past 30 years as manufacturers and engineers have gained experience in long-term operations, demonstrating that lower operating fluxes reduce long-term membrane fouling and increase membrane life.

Pretreatment Before Membrane Filtration

Many plants were originally installed on the premise that membrane filtration doesn't need pretreatment because membranes can tolerate higher solids-loading than media filtration. However, for most surface water applications, it's critical to have a pretreatment process to reduce membrane foulants, such as metals and organics, to ensure sufficient operating permeabilities and thus longer membrane module life. Popular pretreatment methods include physicochemical methods using coagulation, adsorption, and softening. In addition, proper coagulant selection is critical in these applications; many membrane manufacturers prefer aluminum chlorohydrate (ACH) to coagulants such as ferric chloride. Dozens of plants in the United States have switched to ACH to reduce long-term irreversible fouling.

Changes in Cleaning Techniques

Knowledge about effective cleaning methodologies for MF and UF membranes has improved greatly with industry experience. Some of the changes include incorporating maintenance cleans, which are more common than 20 years ago, using combinations of acids to target metals at particular pH ranges (e.g., sulfuric with citric acid at a pH of 2) and adding cleaners to target different types of foulants during the clean-in-place process.

Membrane Integrity

Although membrane materials are physically strong and chemically resistant, membrane integrity may be compromised because of mechanical damage, chemical attacks, and in rare instances manufacturing defects. In the early years of the municipal market's development, many membrane filtration plants in the United States had severe integrity problems. During this period, a national standard was established to help measure membrane integrity for drinking water plants. The US Environmental Protection Agency's *Membrane Filtration Guidance Manual*, published in 2005, established a standard regulatory framework to measure the integrity of MF and UF fibers to protect public health and demonstrate removal of *Cryptosporidium* and other pathogens present in source waters. The test is known as the membrane integrity test.

Currently, most manufacturers have modified the construction of their fibers and membrane modules to address fiber breaks. In addition, changes such as reducing design flux and removing continuous air scouring at drinking water and reuse treatment plants have been nearly universally implemented to reduce fiber breaks.

Current Trends

New developments in membrane filtration are emerging as the technology continues to mature. The following areas are current trends that may shape the future as they evolve and the industry gains experience from treatment plants implementing these changes.

Standardized Skids and Modules

Open-platform pressure systems, also known as universal systems, have matured in the past 10 years, experiencing exponential growth. Open-platform systems allow multiple manufacturers' membrane modules to fit interchangeably into a system with little modification. The most comprehensive evaluation conducted on an open-platform system compared the performance of multiple, side-by-side modules at West Basin Municipal Water District in Carson, Calif., as part of Water Research Foundation Project #4906 (*West Basin Municipal Water District Custom Engineered Membrane Filtration Pilot: Evaluation of Fouling Characteristics and Cleaning Efficacy*).

Several manufacturers offer an open-platform design and have many installations at operating treatment plants. Part of the development of these systems is to address the shortfalls in the industry for treatment plants that have had fouling or integrity issues, providing a way to change membrane manufacturers more easily than completely replacing the system. In addition, an open-platform system provides flexibility and competition in pricing when bidding replacement modules. Finally, open-platform systems and the ability to easily retrofit competitors' installations are driving the standardization of membranes to cylindrical modules of similar size and membrane area.

Retrofit Solutions

Membrane module manufacturers now offer the ability to retrofit a different manufacturer's module from what was originally installed in both pressure and submerged systems. The objective of a direct module retrofit is to avoid system modifications. For example, multiple pilot- and full-scale single train or full plant retrofits in the past five years have demonstrated the ability to attain similar or improved operations in submerged plants in water and reuse treatment plants with little modification to existing operations. In addition, the number of treatment plants that have been retrofitted at the system level (modifications to rack and piping, ancillaries, and control) is increasing every year, providing detailed engineering information that can be used for future retrofits. However, a complete system retrofit is complex, and the risks and costs associated with retrofitting systems continue to be a barrier for many plants.

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Membrane Materials

As mentioned, PVDF is the dominant type of membrane in municipal treatment. A new development proposed by several engineers and manufacturers is a differentiation between nonsolvent-induced and thermally induced phase-separation PVDF membranes based on resistance to fiber breaks. In addition, the number of ceramic membrane installations has grown. Finally, several current manufacturing and academic developments in membrane technology—such as inorganic membranes, graphene, organic–inorganic hybrid membranes, and nanocomposite membranes—may result in robust membranes with longer usable lives and high permeability.

Operations Guidance, Optimization, and Training

Historically, operations support and training for membrane filtration plants have been provided by system manufacturers. A few regional workshops, manufacturer user groups, and operator training classes are offered, but guidance for membrane filtration plants on methodologies for monitoring and managing operations, as well as continuing education opportunities beyond basic theory and procedures, are largely missing. Such guidance is needed to support the large number of plants in water, wastewater, and industrial applications across the United States and is slowly gaining momentum. For example, members of AWWA's Membrane Processes Committee recently began working on the forthcoming Manual of Water Supply Practices M84, *Operations Guide for Membrane Filtration Plants*.

New Treatment Applications

Membrane filtration continues to expand into all areas of industrial applications and has become commonplace in boiler feed treatment, wine and beer production, and dairy facilities that produce products with reduced lactose concentrations. Membrane filtration is viewed as the best available technology for pretreatment to reverse osmosis and is now the most prevalent technology used in potable reuse. Conversely, membrane bioreactors are being evaluated to replace membrane filtration in some potable reuse applications. Integrity testing is being developed to evaluate fiber health in reuse treatment plants similar to what was developed for drinking water treatment.

Ongoing Development

As the membrane filtration industry continues to evolve, there will be additional paradigm shifts as the fate of open-platform systems is resolved. Full-scale global adoption of membrane filtration will be limited by reliability concerns related to fouling and fiber breaks. The membrane filtration industry will continue to strive for reliability, longevity, and predictability as well as a module with high permeability that will maintain long-term integrity.

Karla Kinser is a senior process engineer with Burns & McDonnell Engineering Co. Inc., Centennial, Colo.; kjkinser@burnsmcd.com. She is a member of several AWWA committees and chairs the M84, Operations Guide for Membrane Filtration Plants, Committee.

Brent Alspach is director of applied research at Arcadis in Carlsbad, Calif., and the Water Quality Matters column coordinator; brent.alspach@arcadis.com.

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