

Hollow Fiber and Tubular UF Pilot Testing Procedures & Case Studies

Several membrane technologies are available to use for industrial water preparation and wastewater recycling. Typical membrane processes for solids removal include microfiltration (MF) and ultrafiltration (UF). Hollow fiber membranes are one relatively cost effective MF / UF design. Other designs include spiral wound and tubular. Hollow fiber design for UF and MF is a popular configuration used today on surface water and water reuse applications due to the ability to handle tough waters at a reasonable cost and with a small footprint. Tubular designs can handle higher solids and higher emulsified oil concentrations.

Membrane pore sizes are commonly expressed as nominal which means that a membrane with a specified nominal pore size or Molecular Weight Cut-off (MWCO) would be expected to remove 90% of material of that size. The largest pores in these membranes are likely larger than the nominal pore size. Variations in pore size occur depending upon the membrane type and manufacturer.

Microfiltration ranges in size from approximately 0.05 μm to 1.0 μm .

Ultrafiltration is a tighter membrane and is in the micron range of approximately 0.005 - 0.1 μm . UF is typically expressed in terms of molecular weight cut-off and ranges from 1,000 Daltons for a very tight UF membrane to approximately 500,000 Daltons for a very open UF membrane. By convention for MWCO it is assumed that the molecules are a polysaccharide of that molecular weight, so actual filtration effectiveness varies according to the actual chemistry of the molecule. There is some overlap between the stated ranges for MF and UF, so a membrane with a pore size that might be considered to be a loose UF membrane might also be considered to be a tight MF membrane depending on the industry or manufacturer.

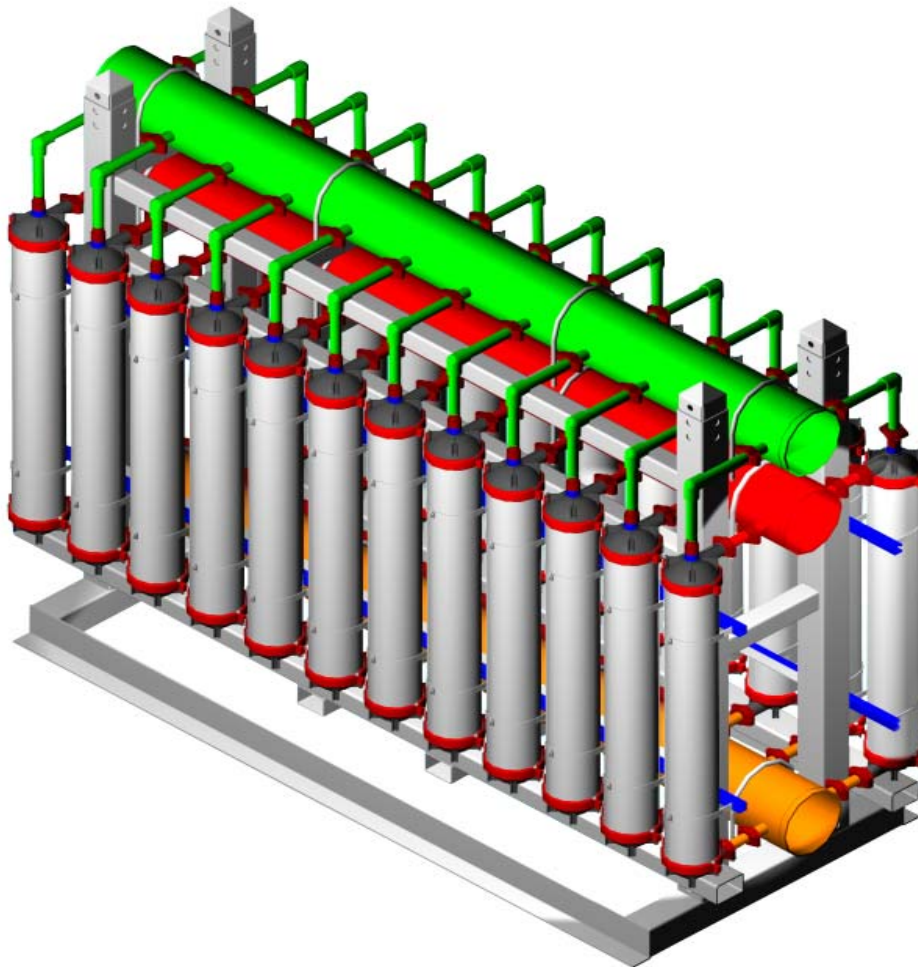
Hollow Fiber UF and MF

Hollow fiber membrane systems for filtration have gained wide acceptance in surface water treatment for potable water production. For potable water applications, hollow fiber membrane systems can guarantee removal of bacteria such as *giardia* cysts and *cryptosporidium* oocysts because the integrity of the membrane system can be verified with integrity tests of the membranes in the field. Extensive application of hollow fiber UF and MF for potable water production has led to the costs of this technology coming down to the point where it is cost competitive with conventional water treatment and spiral wound UF systems for RO pretreatment.

Industrial applications include wastewater recycle after primary or secondary treatment, metals removal, raw water clarification, and RO pretreatment, among others.

Hollow fiber membranes used for filtration in industrial water treatment may either be UF or MF membranes. The I.D. of fibers are typically 0.5 mm (0.02 inch) – 1.2 mm (0.047 inch) diameter.

Up to several thousand hollow fibers are bundled into a membrane element. At either one or both ends of the membrane element, the fibers are cast in epoxy. Based upon membrane design, feedwater can either be fed to the inside of the fibers, with filtrate leaving from the outside of the fibers (inside-out), or else feedwater can be directed to the outside of the fibers with filtrate leaving from the inside of the fibers (outside-in). Membranes are manufactured from several different materials, depending on the membrane supplier. Typical membrane materials are polymeric, are naturally hydrophobic and include polysulfone, polyethersulfone (PES), PVDF, polypropylene, polyacrylonitrile (PAN), and polyethylene.



A UF system can be set up with membrane modules arranged in parallel or blocks as shown above.

Modes of Operation: Dead-end or Cross-flow

Dead-end Flow:

Hollow fiber systems are commonly operated in a dead-end mode. All the feedwater is directed across the membrane, leaving the filtered particles behind on the membrane. Particulates are removed from the membrane surface by means of a physical backwash that forces the particulates out of the membrane pores and away from the surface of the membranes. The

backwash may occur every 20 minutes to every few hours, depending on the system and the feedwater source. With the system operating in a dead-end mode, operating pressures are generally low (commonly around 10-25 psi), and there is no recirculation stream which would require extra pumping power.

Over time, the physical backwash will not remove some of the membrane fouling. Most membrane systems allow the feed pressure to gradually increase to around 20 - 30 psi and then perform a clean-in-place (CIP). CIP frequency might vary from 7 days to several months. A good target is every one to two months. Another approach is to use a Chemically Enhanced Backwash (CEB), where, on a frequent basis, chemicals are injected with the backwash water to clean the membrane and maintain system performance at low pressure without going off-line for a CIP. CEB chemicals are usually sodium hypochlorite, caustic, or acid. Much of the success of the hollow fiber filtration process is establishing an effective backwash and CEB program.

The backwash and CEB strategy should minimize backwash water losses while effectively returning the trans membrane pressure back to where it was at the start of the previous cycle. A good target recovery rate calculated as $(\text{filtrate volume}/\text{total volume including flushes}) \times 100$, is 92 – 95% with dead-end flow operation.

Flushing and backwash commonly use filtrate water. Sometimes it may be necessary to use other or better water sources for this operation. The flushing and backwash cycles allow the following options:

- a. Drain downs: This is used to evacuate the water and can be assisted with air pressure.
- a. Air pressurization: This allows a slight expansion of the membranes and flaking of the deposit to induce better cleaning.
- b. Forward flush: Under this step, the filtrate valve is closed and water is pushed through the feed side of the module to clear accumulated solids.
- c. Bottom backwash: Backwash water enters at the top of the module through the filtrate line on the filtrate side, through the membrane and out of the module at the bottom and to drain. The backwash flux will be about three times the processing flux rate.
- d. Top backwash: This is the same as bottom backwash, however, the water exits out of the top feedwater port and then to drain.
- e. Chemically enhanced backwash: Provisions for feed of two or three chemicals are made to inject into the backwash water in front of the membranes. Typically citric acid, caustic, or sodium hypochlorite is used. They can be pumped in during the backwash step. Also soak times can be programmed in to allow longer contact time to help clean the membrane.
- f. A second drain down and air pressurization followed by a second top backwash may be included.
- g. A final rinse puts the unit back into operation mode, but wastes the filtrate for a short period of time.

An example of a hollow fiber single module pilot unit set-up may be as follows:

1. Processing time: 45 minutes.
2. Filtrate flow set point: 12 gpm.
3. First drain down: 8 seconds.
4. First air pressurization: 15 seconds.

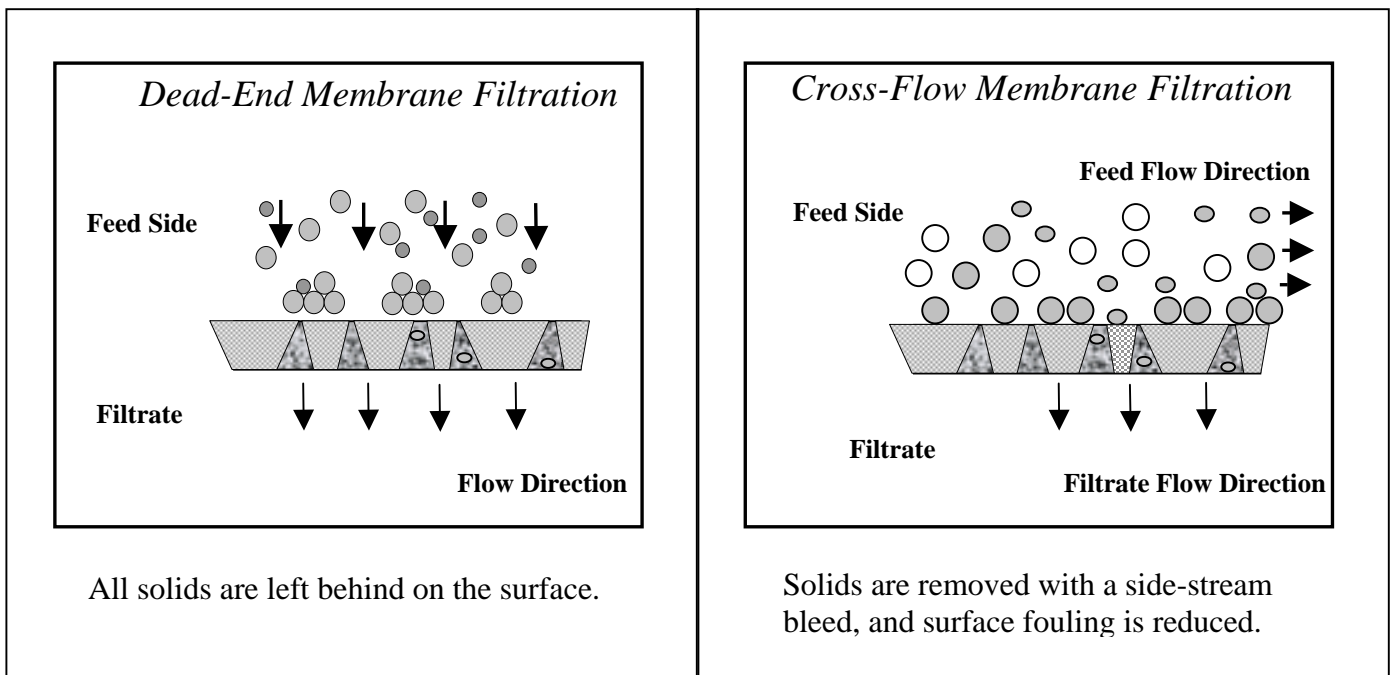
5. Forward flush: 0
6. Forward flush flow: 0
7. Bottom backwash: 12 seconds.
8. First top backwash: 14 seconds.
9. Chlorine soak: 200 seconds.
10. Chemical soak: 200 seconds.
11. Second drain down: 10 seconds.
12. Second air pressurization: 0
13. Second top backwash: 10 seconds.
14. Final rinse: 10 seconds.
15. Chlorine inject: 4 cycles.
16. Chemical inject: 16 cycles.

Cross-flow:

For higher solids waters, the membrane may be set up to operate in a cross-flow mode.

What could be a rapid buildup of solids at the membrane surface is overcome by continuously removing a small portion of the flow from the dirty feedwater side of the membrane. This wastewater along with the water lost in flushes and backwashes lowers the overall recovery rate down to the 80 – 90% range. In both the dead-end flow or the cross-flow, strategies can be incorporated to capture, treat, and reapply the backwash water to the front end of the membrane filtration process to improve actual overall system recovery rate.

Forward flush, backwash, and chemically enhanced backwash strategies are similarly applied whether the system is operated in the dead-end or cross-flow mode.



The performance and economics of filtration depend upon the rate at which water flows through the membrane. This is the flux rate and is expressed in gallons per square foot of membrane surface area per day (GFD). The system is set up to operate at a fixed flux rate or filtrate flow rate by the use of a VFD on the supply pump. Any accumulation of retained material at the surface will reduce the effective filtration rate and create the need for higher supply pressure to maintain the set flux rate. Concentration of solids at the surface occurs in a dynamic state but its effect is similar to the filter cake build-up at the separation surface in conventional filtration. The trans membrane pressure builds and the unit will go into the backwash cleaning cycle. This is established by service cycle time. Excessive trans membrane pressures must be avoided to prevent damage to the membranes.

Actual desirable flux rates depend upon the membrane manufacturer, flow path, membrane material, water characteristics, and water temperature. Some starting point guidelines are shown below. The high-end flux rates are for relatively clean feedwaters with turbidities of less than 1 NTU or total suspended solids of less than 1. The low-end flux rates are for dirtier waters with turbidities of 15 NTU or greater, and total suspended solids of 20 ppm or greater.

Water Source:	Hollow Fiber Flux Rate (GFD)
City water or pretreated surface water	70 – 85
Well water	65 – 85
Raw surface water	58 – 70
Sea water	45 – 70
Tertiary waste water	32 – 50
Treated industrial waste water	35 – 55

Filtrate Water Quality

Both UF and MF will remove suspended particles, algae, and bacteria. UF will also remove viruses. Table 2 shows the expected filtrate water quality from MF and UF systems on raw water clarification and compares with multi-media filtration. Microfiltration will generally provide a 15-minute silt density index (SDI₁₅) of less than 3 for surface or well waters. Ultrafiltration commonly achieves an SDI₁₅ below 2. The lower SDI indicates a diminished potential for downstream reverse osmosis fouling where an RO machine is part of the treatment process. The removal of suspended solids prevents fouling and blockage of the RO brine spacer. Biofouling of RO membranes will be less likely with the removal of bacteria by a MF or UF membrane process used in front of the RO. Waste waters containing oils and surfactants and high TOC's that are filtered by MF or UF will commonly result in higher turbidities and higher SDI's than surface or well waters. Generally, emulsified oils and certainly free oils are not desirable for most hollow fiber UF or MF membrane.

Table 2. Filtrate Water Quality on Surface or Well Waters

Water Quality	Multi-media	MF	UF
Turbidity	0.1 – 2 NTU	< 0.1 NTU	< 0.1 NTU
SDI ₁₅	3 – Filter Blinding	< 3	< 2

CROWN Solutions, Inc., Equipment Division designed and built a pilot UF system to allow dead-end and cross-flow testing of hollow fiber UF membrane technology for industrial applications. The purpose for pilot testing includes the following:

1. Evaluate the effectiveness and reliability of the technology.
2. Determine chemistry requirements, if any, of the UF feedwater.
3. Determine reliable flux rates.
4. Determine necessary backwash frequencies, flow rates, and durations.
5. Determine chemically enhanced backwash strategies (CEB).
6. Develop budgetary costs for full-scale operation.
7. Test CIP effectiveness.

There are many challenges faced with this technology including variations of influent water quality, temperature changes, high TOC water, microbiological effects, and others. Conducting a UF or MF pilot test requires monitoring of several parameters and making effective adjustments to determine if a full-scale system will be effective and to determine how to design it properly.

The pilot system has supervisory control and data acquisition (SCADA) capability where operating data is automatically acquired and stored. The data is stored in the RS View software, then periodically downloaded into an Excel spreadsheet. Manual data logging is also advisable to backup the electronically stored data and to check the sensor transmitters.

Hollow Fiber Data Logging and Key Performance Indicators:

The following data should be collected. Manual logging should occur at least once per day and once per shift if possible. A data set should include data two minutes before backwash and two minutes after the backwash sequence is complete. Automatic data entry should be every 2 – 10 minutes during pilot testing:

- Date.
- Time.
- Machine run time, hours.
- Feedwater temperature, °C or °F.
- Screen filter inlet pressure and out pressure, psi.
- Membrane module top feedwater pressure, psi.
- Membrane module bottom feedwater pressure, psi.
- Filtrate pressure, psi.
- Feed turbidity, NTU.
- Filtrate turbidity, NTU.
- Filtrate flow, gpm.
- Bleed flow (if in cross-flow mode), gpm.
- Recycle flow, gpm.
- Drain flow and totalizer.

Filtrate Flux

“Filtrate flux” is expressed in gallons per square foot of filter area per day (gfd). Therefore the average filtrate flux is the flow of product water divided by the surface area of the filter. Filtrate flux is expressed according to the following equation:

$$F = Q/S$$

Where F = filtrate flux (gfd).

Q= filtrate flow in gallons per day (gpd).

S = filter surface area (ft²).

Trans Membrane Pressure

This term describes the average pressure across the filter. It is the net driving pressure on the membrane and is calculated as follows:

$$TMP = ((P_T + P_B)/2) - P_F$$

Where TMP = Trans membrane pressure (psi).

P_T = Pressure of feedwater at the top of the filter (psi).

P_B = Pressure of feedwater at the bottom of the filter (psi).

P_F = Filtrate pressure (psi).

Temperature Compensation Factor for Trans Membrane Pressure (TCF)

The temperature compensation factor is used to normalize the TMP to some temperature such as 20 °C to account for the influence on membrane expansion or contraction and water viscosity. If the temperature is above 20 °C, the TMP would be lower than it would be at 20 °C since the pores in the membrane will be slightly larger and the water will be less viscous. To normalize to 20 °C the TCF will be a number greater than 1.

Likewise, for a temperature below 20 °C, the TCF will be less than 1 to normalize to 20 °C, since the membrane will become somewhat tighter and the water will become more viscous.

The TCF will vary by the manufacturer and the membrane material.

One example for calculating TCF is as follows:

$$TCF = e^{0.031(T-20)}$$

Where TCF = Temperature Correction Factor

T = Water Temperature in °C.

Temperature Compensated Trans Membrane Pressure $TMP_{20^{\circ}C}$

This term normalizes the TMP to account for variations in water temperature.

$$TMP_{20^{\circ}C} = TMP * TCF$$

Where $TMP_{20^{\circ}C}$ = Temperature compensated TMP.

TMP = Trans membrane pressure (psi).

TCF = Temperature correction factor.

Specific Flux

The term “specific flux” is used to refer to filtrate flux that has been normalized for the trans membrane pressure. The equation for specific flux is as follows:

$$F_{TM} = F / TMP_{20^{\circ}C}$$

Where F_{TM} = Specific flux (gfd/psi).

F = filtrate flux (gfd).

$TMP_{20^{\circ}C}$ = Temperature compensated trans membrane pressure (psi).

Differential Pressure or ΔP

The pressure difference between the top and the bottom of the UF module of the feedwater during processing is used to monitor feedwater side fouling. (Differential pressure of the prefilters should also be monitored).

$$\Delta P = P_{Feedbottom} - P_{Feedtop} \quad (\text{for bottom feed setup})$$

Where $P_{Feedbottom}$ = Bottom feed pressure.

$P_{Feedtop}$ = Top feed pressure.

Instantaneous Recovery

This is the recovery of water from the system for one processing/backwash cycle. This only looks at the efficiency based upon backwashes and does not include chemically enhanced backwashes, CIP's, or bleedoff if in a cross-flow mode.

$$R_I = \left[1 - V_{Backwash} / V_{TotalCycle} \right] * 100, (\%).$$

Where R_I = Instantaneous Recovery

$V_{Backwash}$ = Total volume of filtrate used during the single backwash sequence.

$V_{TotalCycle}$ = Total amount a filtrate produced from a single processing cycle.

Total UF System Recovery

This looks at the percent of filtrate made from the total feedwater flow and includes water loss to backwash, CEB's, CIP's, and bleedoff.

$$R_T = \left[1 - V_{\text{Filtrate to Process}} / V_{\text{Total Feedwater}} \right] * 100, (\%).$$

Where R_T = Total System Recovery

$V_{\text{Filtrate to Process}}$ = Total volume of filtrate available for use after accounting for filtrate used for backwashes, CEB's, CIP's, and bleed-off.

$V_{\text{Total Feedwater}}$ = Total amount a feedwater sent to the UF for a sufficient period of time that captures all water consumption's.

Tubular UF

A tubular membrane design is better than hollow fiber for high solids or high emulsified oil levels. A typical design is a one-inch diameter tube with the water flowing in a cross-flow on the inside of the tube. High cross-flow rates minimize fouling and the larger open tube design allows for effective cleaning. Sponge balls can be used during the CIP for mechanical cleaning. Koch tubular membranes and Koch pilot units have been used for tubular applications.

The membranes are tubular in shape and are bonded to the inner surface of the tube support backings. The process fluid is circulated through these membrane tubes under pressure. The pore structure of the membrane acts as the filter, passing water and small solutes such as salt ions, while retaining the larger emulsified and suspended matter. The particles cannot enter the smaller membrane pores, so the pores do not become plugged.

In the Koch FEG tube design, the membrane is cylindrical and bonded to the inner surface of a protective, porous backing called a support tube. Each membrane and backing is enclosed in a tubular housing. The housing is threaded at both ends for connecting them in series and to the process inlet and outlet manifolds.

Boot seals, installed at each end of the membrane and the support tube, isolate the permeate from the process stream. The boot seal wraps around the inside and the outside of the tube ends. A stainless steel ferrule holds the boot seal in place, and the outer portion of the boot has two formed O-rings to provide the boot-to-housing seal. When in operation, permeate travels through the membrane, collects in the annular space between the membrane tube housing and the boot seals, and then flows out of the permeate port.

Mode of Operation:

- A. **Batch:** In batch operation, process fluid is pumped from a large process tank through the UF membrane tubes and back to the process tank. As permeate is removed from the process fluid, the process fluid becomes more concentrated. When a predetermined concentration has been reached, the batch is completed and the remaining emulsion is disposed of in whatever manner is best. For example, it may be hauled away or run through a filter press. The process tank is then refilled and processing of the new batch will begin following a cleaning of the UF. This concentrated solution may get up to 30% TSS or emulsified oils.
- B. **Modified Batch:** The modified batch is similar to batch except that as the level in the process tank drops due to removal of permeate, fresh process feed material is added to the process tank. The advantage of the modified batch is that run times are extended and cleaning frequency may be reduced.

Pilot Test Unit:

A Koch pilot UF system may consist of 1 pass of 8 or 16 tube membranes in series. Each membrane is 10 feet long. The rest of the system includes a circulation pump rated at 60 gpm, a 250-gallon process tank, a 50-gallon cleaning tank, associated piping, switches and gauges, and a control panel.

Chemical cleaning is accomplished with the circulation pump. Also sponge balls can be used for mechanical cleaning. They are pushed through the membranes hydraulically.

The pilot testing may include several different membrane types to determine which material provides the best and most extended flux rates, and which clean up the best. Flow rates are measured by collecting samples in calibrated cylinders or beakers from each membrane filtrate sample port.

Tubular Membrane Data Logging and Key Performance Indicators:

The following data should be collected. Manual logging should occur once per shift, or more frequently on some processes.

- Date.
- Time.
- Machine run time, hours.
- Feedwater temperature, °C or °F.
- Flux rate per membrane or membrane series, mls per minute.

Flux

The flux for the tubular membrane is gallons of filtrate per square foot of membrane surface area per day (GFD).

$$F = (\text{Filtrate Rate in GPM}) / \text{Total membrane ft}^2.$$

Normalized Flux

The measured flux can be normalized to standard conditions using a temperature correction factor and incorporating operating pressures. The temperature correction factors are provided in table format by the manufacturer:

$$F_{\text{Corr}} = F * \text{Temp. Correction Factor} * 100 / (\text{Inlet Pressure} + \text{Outlet Pressure})$$

Normal flux for clean membranes at 50 psig and 25 °C is 100 – 150 GFD. Achievable flux rates for applications will be much lower, perhaps 20 – 80 GFD.

Case Studies:

1. Pharmaceutical plant SBR wastewater for recycle.

This was an extremely challenging water. The plant's wastewater is high in organics so it is treated biologically with four sequential batch reactors (SBR). The effluent from this secondary treatment is then sent through a clarifier followed by multi-media filters prior to RO and then recycled for plant cooling. Even after biological treatment and clarification, the water was still high in TOC and TSS. It was the plant's desire to eliminate the clarifiers and go directly from the SBR's to multi-media, and then UF. We included a multi-media filter as part of the pilot equipment.

The pilot required the addition of ferric chloride ahead of the filter to reduce TOC, since TOC can blind UF membranes rather quickly. The pilot extended several months to establish an effective strategy. Some key points were as follows:

- a. Ferric chloride dosage and mix time were important.
- b. Backwashing with UF filtrate water created problems when caustic was used with the CEB cycle. The water is relatively high in calcium and very high in alkalinity, so the caustic caused scaling. The backwash water was changed to RO permeate.
- c. Backwash cycle times, sodium hypochlorite and caustic dosages and feed frequencies were important to combat organic fouling.
- d. With variable influent levels of TSS, operation in cross-flow was necessary.

2. Copper removal of cooling tower blowdown.

A large industrial air separation plant required copper removal from their cooling tower blowdown water to be less than 17 ppb. Benchtop testing using an organic metal precipitator followed by ultrafiltration showed that single digit Cu ppb numbers could be achieved. The pilot included a mix tank and chemical precipitator feed along with the UF pilot unit. Very consistent and reliable results were shown in dead-end mode and 94% recovery.

3. Clarification process for HRSG makeup.

A treatment strategy to provide several thousand gallons per minute of high purity makeup water for new heat recovery steam generators (HRSG's) needed to be determined for a large oil refinery. The source water was from a river notorious for presenting bacteria problems and organic loading. The water was first clarified with conventional clarification, then a pilot UF

showed that it could operate at high recovery and high flux rate as a good pretreatment strategy for RO and demineralizers.

4. Lake water clarification.

The city of Chicago uses clarified Lake Michigan water to supply a large industrial complex. A UF pilot was conducted to determine if UF could be used for the site to produce their own water. Removal of bacteria and pathogens was important. Operation of the UF to changing TSS levels and water temperature were important from a design basis.

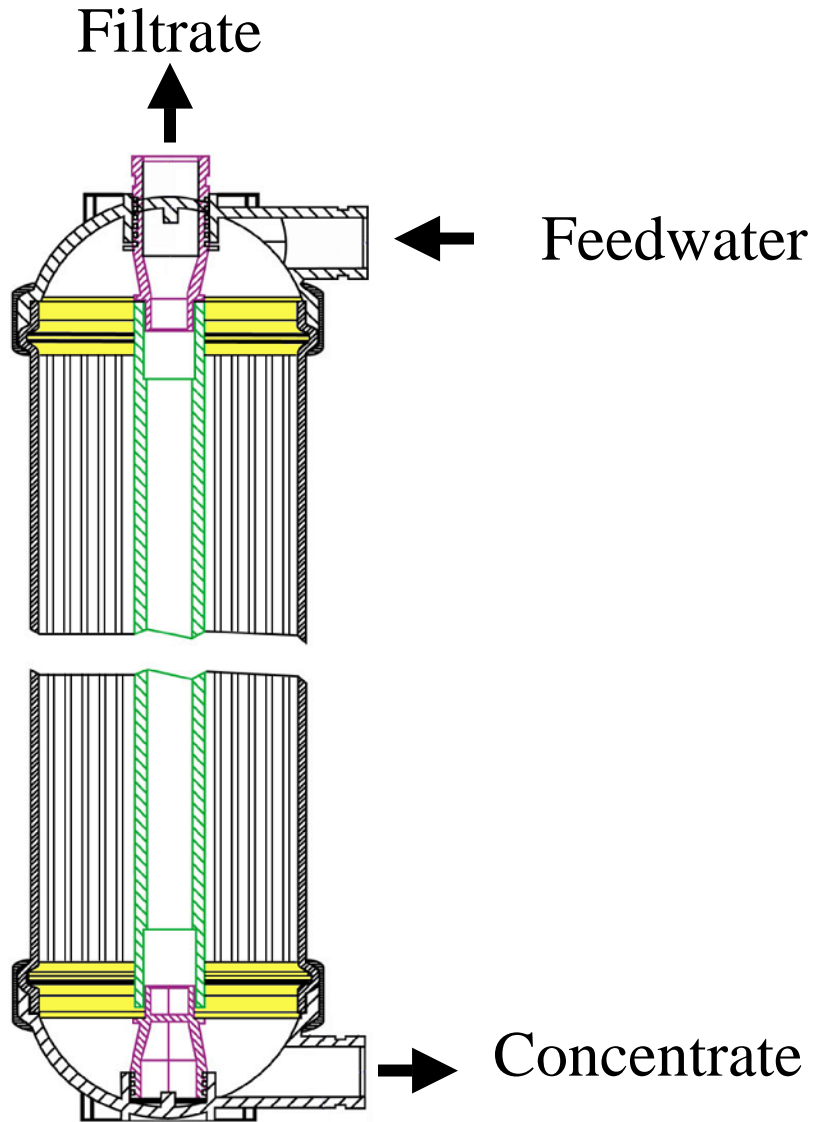
A multi-media filter was installed in front of the unit to act as a prefilter for lake upset conditions. Results showed very low turbidities of < 0.04 NTU were obtained in dead-end mode. The silt density index (SDI) was <1. High recovery, moderate flux rate of 40 GFD, and tolerable membrane fouling showed that this would be an effective strategy.

References:

1. Hydranautics technical literature.
2. Koch technical literature.
3. Omexell product literature.
4. Ionics Paper at 2003 Electric Utility Chemistry Workshop.

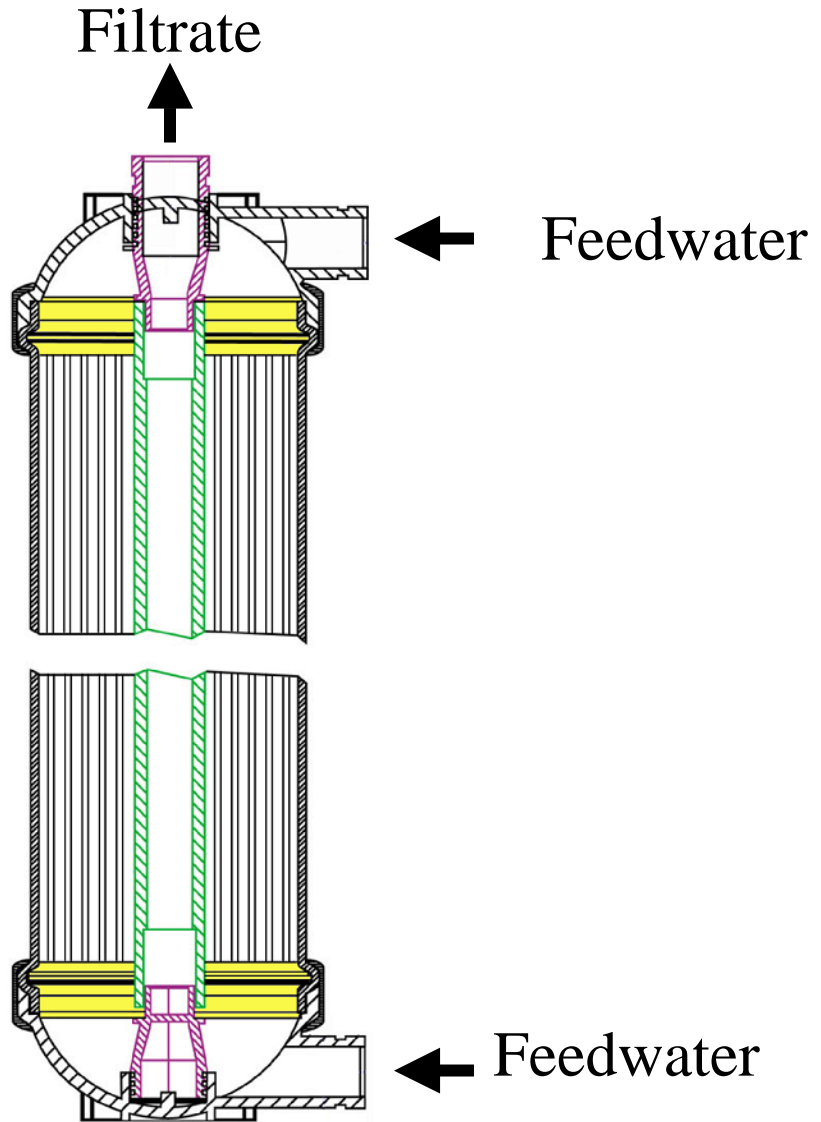
Hollow Fiber Design

Inside-Out
Cross-flow
Top Feed



Hollow Fiber Design

Inside-Out
Dead-end Flow



Hollow Fiber Design

Inside-Out
Backwash
Bottom

