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Wastewater Recovery & Reuse – Part I

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by

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INTRODUCTION

These lectures address the role that advanced treatment technologies play in the processing of wastewater to enable reuse in virtually any application. Emphasis is placed on the crossflow, pressure-driven membrane separation technologies:

Part I is devoted to those wastewaters that contain the classes of contaminants that include suspended inorganic solids, dissolved salts and relatively low concentrations of organic contaminants in both suspended and dissolved forms.

Depending upon the chemical characteristics of a particular wastewater source, the optimum treatment scenario may include additional technologies besides membranes, and the most appropriate treatments are also described.

Part II details a particular type of wastewater most commonly found in residential and municipal sewage flows, as well as certain industrial/commercial manufacturing operations. This wastewater is characterized by high concentrations of BOD (Biochemical Oxygen Demand) and possibly COD (Chemical Oxygen Demand). Virtually all municipal sewage treatment plants treat wastewaters high in BOD, and many manufacturing operations produce wastewater high in either BOD or COD, or both.

WASTEWATER SOURCES

Wastewater basically originates from these sources:

- **Rainwater/Stormwater**
- **Residential discharges**
- **Municipal sewage**
- **Industrial/commercial discharges**

1. **Rainwater/Stormwater** – While it can be argued that rainwater is not “wastewater” in the true sense of the word, it is included here because rainwater can be collected onsite and virtually always requires some treatment prior to use. Stormwater is rainwater (or flood water) that can be collected from a ground surface.

Collection and consumption of rainwater has been a common practice of humankind for centuries. To minimize contamination, the normal practice is to collect rainwater from a roof by means of gutters (troughs) directing the water through downspouts and into rain barrels or cisterns. Although very clean compared to stormwater (water collected from roads, ditches, lakes, rivers, etc.), rainwater is contaminated from particles and gases in the air as well as debris from the roof (bird and animal droppings, leaves, dirt, etc.). Stormwater runoff from roads, parking lots, etc. can be collected, treated and reused; however, treatment is much more involved because of the typical heavy loading from oils, greases and other ground surface contamination.

2. **Residential discharges (Graywater)** – Within the home, graywater is generated from laundry, showering, bathing and handwashing; blackwater is the wastewater from toilets and kitchen sinks. Whereas graywater treatment is directed towards suspended solids, dissolved organics and salts, blackwater contains much higher concentrations of bacteria, BOD and COD.
3. **Municipal sewage** – The discharge from a sewage treatment plant may contain a multiplicity of contaminants, running the entire gamut of contamination classes: suspended solids, dissolved organics, dissolved inorganics, microorganisms and gases. On the other hand, the particular kinds of contaminants are generally well known, and usually fall within predictable concentration ranges. Obviously, there are also many areas where sewage is deposited into surface water supplies without any treatment whatsoever, an ongoing sanitation issue.
4. **Industrial/commercial discharges** – Many processing and manufacturing facilities discharge wastewater of some sort, from streams as innocuous as cooling water to waters containing high concentrations of very hazardous chemicals. As to be expected, the kinds, concentrations and forms of contaminants in these discharges are as variable as the industries from which they come. Depending on the kinds of specific contaminants, certain specialized treatment technologies may be required.

RAINWATER HARVESTING

Introduction

Before the development of treatment processes, rainwater was the primary source of potable water for those people for which other clean water sources (rivers, lakes, etc.) were not available.

As cities developed, infrastructures became more centralized, and municipalities took over the responsibility of collecting rainwater (stormwater), and generally discharging it to the nearest lake or river. Although household rainwater catchment systems (generally homemade), utilizing gutters, downspouts and rain barrels (remember the song?), had been commonly employed to collect water for landscape and gardens, even those largely faded from the urban North American scene several decades ago. Still quite common in Europe for non-potable applications, and widely used in the developing world for all applications, rainwater harvesting is a major relatively untapped water source available for recovery and reuse.

Our air has become increasingly polluted with years of irresponsible behavior by all segments of society, and is much dirtier now than when rainwater was collected and consumed thousands of years ago. Likewise, drinking water quality standards are constantly becoming more stringent. In spite of this, treating rainwater requires generally less technology than for any other source of wastewater. The reason is because rainwater is the purest of virtually all sources of water, is naturally soft and is free from disinfection byproducts. When used for most non-potable applications (garden watering, landscape irrigation, etc.), it requires little or no treatment.

The attributes of harvested rainwater include:

- Water is free; only utility costs are for collection and use.
- The collected water is used close to the source; little cost for distribution.
- Rainwater harvesting reduces flows to stormwater drains and reduces non-point pollution.
- Rainwater harvesting reduces expansion pressure on municipal water treatment plants.
- Collection tank overflows can recharge aquifers.
- Augments or replaces limited quantities of groundwater.
- Provides good quality alternative if groundwater quality is unacceptable.
- Provides a source if tap charges are too high for water supply connection.
- Reduces erosion in urban environments.
- Source of water that is naturally soft (no need for water softeners).
- Provides water that is pH neutral/slightly acidic.
- Water that is sodium-free, important for those on low-sodium diets
- Good quality water for landscape irrigation
- Water for nonpotable indoor uses
- Safe water for human consumption, after appropriate treatment
- Helps utilities in reducing peak water demand in the summer
- Provides water for cooling and air-conditioning plants
- Provides water for fire protection
- Saves money for the consumer in utility bills

Rainwater harvesting also provides several additional benefits. As it is soft, it can reduce scale build-up in hot water heaters, plumbing, faucets, and showerheads. Rainwater requires less soap and detergent than most public water supplies because of its natural softness. In particular, this source of water can be valuable for the hotels, helping them reduce the use of municipal water supplies and the quantity of detergents used for daily laundry.

Rainwater collection is applicable not only for houses, but for all other buildings and structures – virtually anything with a roof. One inch of rainfall provides 620 gallons of water per 1,000 ft² of roof area. In the metric system, one centimeter of rainfall on one square meter of collection surface will deposit about 10 liters of water.

Depending on the location, legal restrictions may limit the use of such reclaimed water for potable purposes. Some laws require disinfection of all water brought into the building, even if only for toilet flushing.

Rainfall Patterns

The frequency of rain events and rainfall quantities vary considerably from one geographical area to another; however, historical patterns are usually available for use in rainwater harvesting system design.

Rainwater Quality

While rainwater is invariably cleaner than stormwater, it is not really free of all contamination.

All air contains particles, liquids and gases formed by natural processes such as erosion of land surfaces resulting in dust, salt-spray from ocean wave action, biological decay, forest fires, chemical reactions of atmospheric gases, and volcanic activity, as well as those from human origins – industry, agriculture, transportation (including aviation), and construction. The composition of these air-borne contaminants varies widely depending on their source; they may contain gases, salts (predominantly sulfates), minerals (such as silica), organic materials and, in most cases, water.

Bacterial action in the collected water may produce gases such as hydrogen sulfide that are both unpleasant and dangerous. This speaks to the value of rigorous microbial inactivation. Regarding potable uses, activated carbon adsorption is usually effective in removing these gases. More on treatment later.

Lest one should become discouraged by the apparent level and diversity of contaminants in collected rainwater, it is important to underscore the fact that both the kinds and concentrations of contaminants in collected rainwater are much, much less than those found in most ground and surface water supplies. This is a primary incentive to consider rainwater as a resource to augment (or replace) other water sources in residential, commercial, industrial and agricultural applications.

System Components

A rainwater harvesting system is comprised of the following components:

1. Collection surface (usually a roof).
2. Conveying system (gutters, downspouts and piping).
3. “First Flush” diverter and filters for roof trash removal.
4. Collection Tank/cistern.
5. Distribution system.

If required, the collected water is directly treated with technologies dictated by intended use and/or regulatory requirements, and sent to use.

An optional approach is to include a “day tank” for internal storage, distribution and municipal water makeup.

Collection surface: This is usually a sloping or flat roof. As the roof material can have a significant impact on the quality of the collected rainwater, a discussion of materials is in order.

a) Metals -

Aluminum is the best all-around metal roofing material, as it is very inert, releasing only trace amounts into the collected water.

Galvanized sheet metals are available in a number of alloy formulations, with or without painted surfaces.

Sheet steel, because of its poor weather resistance, is no longer in wide use today.

Lead and copper flashing are not recommended due to the potential for these metals to be leached into the water.

b) Ceramic materials –

Clay tiles are very inert; however, unless sealed, they are porous, and tend to absorb a percentage (as much as 10%) of the rainwater.

Concrete tiles have similar absorptive characteristics as clay, but tend to neutralize the somewhat acidic pH of most rainwater.

Slate tiles are inert, smooth and dense. As a result, they are probably the most ideal roofing material.

c) Composite materials –

Sheet roofing/shingles are generally asphalt based, often containing fillers and any number of potentially contaminating materials. This, plus the fact that they are rather porous, make them generally undesirable as collection surfaces.

System Design

The design of a rainwater harvesting system is influenced by the following considerations:

- Building type (residence, office building, etc.)
- Intended uses of water (toilet flushing, culinary, etc.)
- Applicable regulations
- Local climate
- Economic situation

The basic rainwater harvesting system components have been described earlier; however, the selection and assembly of these and possible additional components, the degree of automation and monitoring, etc., are all part of the total system design.

The two illustrations below are of a large residential installation and an office installation.



Residential Installation



www.stormsaver.com

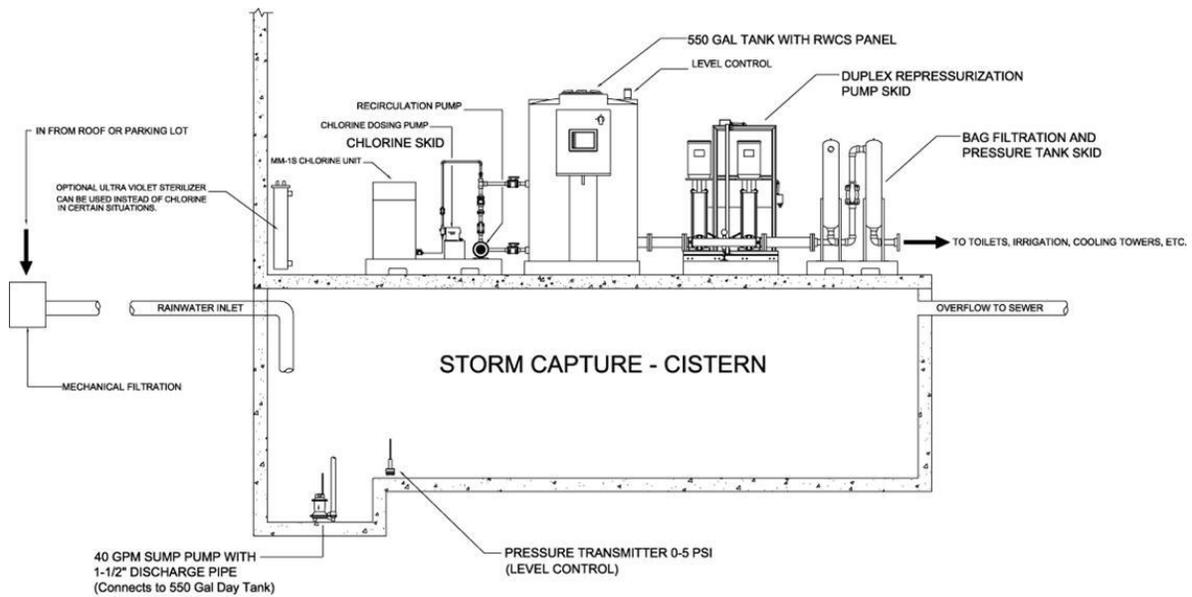
Industrial Installation

STORMWATER COLLECTION

The rainwater that falls onto such “ground-level” surfaces as parking lots, driveways, streets, sidewalks, etc., can be defined as stormwater. It can also include floodwaters from river or lake overflow, or other such events.

As with rainwater harvesting, a tank or cistern is used to collect the stormwater for treatment and subsequent use.

An example of this is illustrated below:



www.stormcapture.com

Stormwater Collection

Treatment technologies appropriate for these supplies are detailed later in this document.

GRAYWATER

Residential Discharges

Introduction

In the U.S. today, virtually all the municipal water entering a building must be treated to meet the USEPA Drinking Water Standards, which means it must be of potable quality, even if used to flush toilets. This water is used once and then discharged to the sewer and treated as if its only source is from toilets.

Graywater (also called “greywater,” “gray water” and “grey water”) is usually defined as untreated wastewater from domestic activities, specifically bathing, showering, laundry, and lavatory sink use. It excludes water from toilets, urinals, dishwashers, kitchen sinks and garbage disposers (all considered “blackwater”). The wastewater from diaper washing is considered “blackwater” and is also excluded from reuse consideration.

All blackwater supplies typically contain high concentrations of BOD and microorganisms.

While we tend to think of “domestic activities” as those resulting from a single-family household, they can be expanded to include the activities from apartments, condominiums, multifamily houses, vacation homes – any residential dwelling. “Domestic activities” can also result from non-residential locations: institutions such as schools and nursing homes; commercial establishments such as restaurants, hotels, etc., as well as industrial facilities.

Keeping in mind that the graywater is specifically from handwashing, bathing/showering and laundry activities, virtually all residential dwellings should produce similar per capita quantities and qualities of water. With regard to handwashing, the quantity and quality of wastewater generated in institutions, commercial establishments and industrial facilities should also be similar; however, the presence and size of bathing/showering, laundry and cooling/HVAC facilities will vary considerably from one location to another.

Water Usage

1998 Census data indicate that the average U.S. household size is 2.7 people, and an AWWA (American Water Works Association) study determined the median daily per capita flow rate to be 54 to 67 gallons/day (204 to 253 liters/day) for residential applications.

If we use a figure of 60 gpd/person, the profile of all indoor household wastewater generation per person per day is summarized in the table below.

Water Source	Gallons/person/day
Laundry	13.0
Bath	1.0
Shower	10.2
Handwashing	9.5
Toilet Flushing	16.2
Dishwasher	0.8
Leakage	8.3
Other	1.0

Typical Graywater Constituents

Although the specific chemical parameters in graywater result both from the particular incoming water source as well as from chemicals introduced during the activities, and can vary considerably from one location to another, the table below lists the typical ranges of significant contaminants.

Parameter	Unit	Range
BOD₅ (Biochemical Oxygen Demand)	mg/L	60-300
TSS (Total Suspended Solids)	mg/L	30-185
E.Coli (Bacteria)	cfu*/100 ml	80-30,000
Fecal Coliform (Bacteria)	cfu*/100 ml	50-100,000
P_{total} (Phosphorus)	mg/L	1-15
N_{total} (Nitrogen)	mg/L	4-30
pH (Acidity/Alkalinity)	units	5-10

**Colony Forming Units*

By comparison, the BOD and bacterial concentrations of blackwater are easily 100 to 1,000 times greater than those of graywater, whereas the other contaminant concentrations are usually similar.

When the range of chemicals put into water used in domestic activities is considered, the number of different chemicals is almost beyond measurement. In addition to soaps, detergents, fabric softeners and other products used during laundering, even more contaminants are introduced from hands, faces, bodies and fabrics.

The following table lists examples of graywater chemical contaminants and typical concentrations in the resulting graywater.

Ingredient	Concentration (mg/L)
Sunscreen	1500
Moisturizer	1000
Toothpaste	3250
Deodorant	1000
Na ₂ SO ₄ (Sodium sulfate)	3500
NaHCO ₃ (Sodium bicarbonate)	2500
Na ₃ PO ₄ (Trisodium phosphate)	3900
Clay	5000
Vegetable Oil	700
Shampoo or Hand Soap	7200
Laundry Detergent	15000
Boric Acid	140
Lactic Acid	2800

It is estimated that normal household graywater contains more than 2500 chemicals.

Non-Residential Discharges

Introduction

Given that graywater is generated as the result of human activity, there should be little difference between residential and non-residential (commercial) graywater quality; however, the relative quantities of graywater produced vary considerably as a function of the facility. Following is a table listing total typical water usage by building type.

	Hospitals	Schools	Hotels	Office Buildings	Restaurants
Landscape Irrigation	10%	38%	21%	10%	3%
Restrooms, Showers	30%	43%	23%	39%	30%
Laundry	5%	3%	10%	—	—
Cleaning, Sanitation	5%	1%	12%	—	2%
Cooling, HVAC	30%	4%	5%	37%	2%
Kitchen	5%	6%	15%	2%	50%
Miscellaneous	15%	5%	14%	12%	13%

Extracted from MCERF, "Water-Efficiency Technologies for Mechanical Contractors: New Business Opportunities", Figure 1.

From the above, it is apparent that graywater could be utilized in most of these water usage areas.

Standards

The leading U.S. standards development and testing organization in the area of water and wastewater treatment and distribution is NSF International.

They have developed two product standards addressing graywater: NSF 350 and NSF 350-1, which establish design and performance requirements for treatment systems for wastewater from both residential and commercial facilities.

NSF/ANSI Standard 350 can be applied to either graywater as defined earlier or to combined graywater and blackwater. NSF/ANSI Standard 350-1 applies to subsurface discharge only, whereas Standard 350 addresses surface irrigation, toilet/urinal flushing and similar nonpotable applications.

Both standards define residential applications as wastewater flows up to 1500 gpd (5.7 m³/day) and commercial as generating flows exceeding 1500 gpd (5.7 m³/day).

Commercial laundries are not categorized by flow rates.

The following tables summarize these standards.

NSF/ANSI Standard 350: On-site Residential and Commercial Water Reuse Treatment Systems	
Building Types	Residential, up to 1,500 gallons per day Commercial, more than 1,500 gallons per day and all capacities of commercial laundry water
Influent Types	Combined black and graywater Graywater Bathing water only Laundry water only
Effluent Uses	Nonpotable applications, such as surface and subsurface irrigation and toilet and urinal flushing
Ratings	Two classifications that vary slightly in effluent quality: <ul style="list-style-type: none"> • Class R: single-family residential • Class C: multifamily and commercial Systems are further described based on the type of influent (combined, graywater, bathing only, laundry only).

Source:
 Tom Bruursema
 Plumbing Systems & Design
 October 2011

NSF/ANSI Standard 350-1: On-site Residential and Commercial Graywater Treatment Systems for Subsurface Discharge	
Building Types	Residential, up to 1,500 gallons per day Commercial, more than 1,500 gallons per day and all capacities of commercial laundry water
Influent Types	Combined black and graywater Graywater Bathing water only Laundry water only
Effluent Uses	Subsurface irrigation only
Ratings	Single effluent quality with no classifications Systems are further described based on the type of influent (graywater, bathing only, laundry only).

Source:
 Tom Bruursema
 Plumbing Systems & Design
 October 2011

For graywater reuse applications, in addition to individual residences, the standards apply to such commercial applications as:

- Lodging facilities
- Business parks
- Schools
- Shopping establishments
- Public buildings without food processing or manufacturing operations

They also apply to laundry facilities for hospitals, hotels, rental uniforms, etc., where the wastewater may contain large amounts of soil and high strength cleaners.

The standards include requirements for:

- Water tightness
- Noise levels
- Access ports
- Monitoring
- Bypass
- Product literature
- Performance evaluation

Testing Requirements

Residential Systems

Both Standards 350 and 350-1 require 26 weeks of continuous testing with regularly scheduled sampling at a frequency of three days per week.

The following table lists the graywater challenge test water analysis:

Parameter	Range
TSS (Total Suspended Solids)	80-160 mg/L
BOD ₅ (Biochemical Oxygen Demand)	130-180 mg/L
Temperature	25-30°C
pH (Acidity/Alkalinity)	6.5-8 units
Turbidity	50-100 NTU
P _{total} (Phosphorus)	1-3 mg/L
N _{total} (Nitrogen)	3-5 mg/L
COD (Chemical Oxygen Demand)	250-400 mg/L
TOC (Total Organic Carbon)	50-100 mg/L
Total Coliform (Bacteria)	10 ³ -10 ⁴ cfu/100 mL
E.coli (Bacteria)	10 ³ -10 ⁴ cfu/100 mL

The challenge water is generated from normal household constituents mixed into tap water with hardness in the range of 110-220 mg/L (as CaCO₃) and alkalinity greater than 40 mg/L (as CaCO₃).

Depending upon the intended application against which the system is to be tested (bathing, laundry, combined graywater), the challenge water is to be prepared from the following components:

Bathing Source Water

Wastewater Component	Amount/100 L
Body wash with moisturizer	30 g
Toothpaste	3 g
Deodorant	2 g
Shampoo	19 g
Conditioner	21 g
Lactic Acid	3 g
Secondary effluent	2 L
Bath cleaner	10 g
Liquid hand soap	23 g
Test dust	10g

The 30 day average concentration of the bathing water delivered to the system shall be as follows:

Parameter	Required Range
TSS (Total Suspended Solids)	50-100 mg/L
BOD₅ (Biochemical Oxygen Demand)	100-180 mg/L
Temperature	25-35°C
pH (Acidity/Alkalinity)	6.0-7.5 units
Turbidity	30-70 NTU
P_{total} (Phosphorus)	1.0-4.0 mg/L
N_{total} (Nitrogen)	3.0-5.0mg/L
COD (Chemical Oxygen Demand)	200-400 mg/L
TOC (Total Organic Carbon)	30-60 mg/L
Total Coliform (Bacteria)	10 ³ -10 ⁴ cfu/100 mL
E.coli (Bacteria)	10 ² -10 ³ cfu/100 mL

Laundry Source Water

Wastewater Component	Amount/100 L
Liquid detergent (2X)	40 mL
Test dust	10 g
Secondary effluent	2 L
Liquid laundry fabric softener	21 mL
Na ₂ SO ₄	4 g
NaHCO ₃	2 g
Na ₃ PO ₄	4 g

The 30 day average concentration of the laundry water delivered to the system shall be as follows:

Parameter	Required Range
TSS (Total Suspended Solids)	50-100 mg/L
BOD ₅ (Biochemical Oxygen Demand)	220-300 mg/L
Temperature	25-35°C
pH (Acidity/Alkalinity)	7.0-8.5 units
Turbidity	50-90 NTU
P _{total} (Phosphorus)	<2 mg/L
N _{total} (Nitrogen)	4.0-6.0 mg/L
COD (Chemical Oxygen Demand)	300-500 mg/L
TOC (Total Organic Carbon)	50-100 mg/L
Total Coliform (Bacteria)	10 ³ -10 ⁴ cfu/100 mL
E.coli (Bacteria)	10 ² -10 ³ cfu/100 mL

Bathing and Laundry Source Waters Combined

Each 100 L quantity of challenge water shall be prepared using 53 L of bathing and 47 L laundry challenge waters. The 30 day average concentration of the graywater delivered to the system shall be as follows:

Parameter	Range
TSS (Total Suspended Solids)	80-160 mg/L
BOD ₅ (Biochemical Oxygen Demand)	130-180 mg/L
Temperature	25-30°C
pH (Acidity/Alkalinity)	6.5-8.0 units
Turbidity	50-100 NTU
P _{total} (Phosphorus)	1-3 mg/L
N _{total} (Nitrogen)	3-5 mg/L
COD (Chemical Oxygen Demand)	250-400 mg/L
TOC (Total Organic Carbon)	50-100 mg/L
Total Coliform (Bacteria)	10 ³ -10 ⁴ cfu/100 mL
E.coli (Bacteria)	10 ² -10 ³ cfu/100 mL

Commercial Systems

For systems designed to treat graywater from any source generating more than 1500 gpd (5.7 m³/day), and from commercial laundry establishments producing wastewater of any volume, testing is performed on the actual wastewater under field conditions.

The sampling and testing is performed under the same protocol as residential treatment systems.

Hydraulic Loading and Schedules

During the minimum 6 month (26 weeks) testing and evaluation period, the system shall be subjected to periods of design loading, followed by stress loading, and then additional weeks of design loading. Class R and Class C systems claiming service intervals of greater than 6 months shall be loaded beginning in week 27 at design loading, according to the time frame and percent rated daily hydraulic capacity as shown below, and shall continue dosing such that the test period equals the prescribed service interval.

Loading of the systems will be based on the following matrix:

System Design	Design loading					Stress test				
	First 16 weeks	First 20 weeks	Last 4 weeks	Last 3.5 weeks	Last 2.5 weeks	Wash-day surge	Power/equipment failure	Vacation	Water efficiency	Cleaning solution
R-Bathing only	X			X			X	X	X	
R-Laundry only	X				X	X	X	X	X	
R-Combined	X				X	X	X	X	X	
C-Bathing only		X	X				X	X		
C-Laundry only		X	X				X	X		
C-Combined		X	X				X	X		X

Addition of cleaning solution during final 4.5 weeks of test.

Stress events indicate typical events in a residence that affect treatment performance. These include clothes washing activities, increased hydraulic loadings to simulate working-parent events, power failure events and vacations.

Extreme stress conditions (overfeeding of corrosive cleaners, excessive hydraulic overloading, other conditions that deviate from the manufacturer's recommendations) are not included in the testing.

Effluent Quality Requirements

The treated effluent must meet the criteria as listed below for both residential and commercial systems.

Summary of effluent criteria for individual classifications

Measure	Class R		Class C	
	Test Average	Single Sample Maximum	Test Average	Single Sample Maximum
TSS (Total Suspended Solids) mg/L	10	30	10	30
BOD ₅ (Biochemical Oxygen Demand) mg/L	10	25	10	25
Turbidity NTU	5	10	2	5
E.coli ² (Bacteria) MPN/100 mL	14	240	2.2	200
pH (Acidity/Alkalinity) SU	6.0-9.0	NA ¹	6.0-9.0	NA
Storage Vessel Disinfection mg/L	≥ 0.5 - ≤ 2.5			
Color	MR ³	NA	MR	NA
Odor	Non-offensive	NA	Non-offensive	NA
Oily Film and Foam	Non-detectable	Non-detectable	Non-detectable	Non-detectable
Energy Consumption	MR	NA	MR	NA
SAR	MR	MR	MR	MR

¹ NA not calculated

² Calculated as geometric mean

³ MR measured and reported only

Regulations

As expected with such a new initiative, U.S. state regulations addressing graywater reuse are highly variable, and only 12 states have listed requirements to date. The USEPA has guidelines, as well as NOWRA (National Onsite Wastewater Recycling Association).

Graywater reuse is seen by many U.S. public health officials and water utilities as a threat to the health and safety of the users themselves and their neighbors, particularly with regard to microorganism contaminants.

No cases of any disease have been documented to be caused by exposure to graywater – although systematic research on this public health issue is virtually nonexistent. While this does not prove that there has never been such a case, the fact remains that graywater is wastewater with microbial concentrations far in excess of levels established in drinking, bathing, and irrigation water standards for recycled water.

Regarding the acceptance of NSF350 by code-setting bodies, it is currently referenced in the following:

- IAPMO Green Plumbing and Mechanical Code Supplement
- International Construction Code
- 2015 International Plumbing Code
- 2015 Uniform Plumbing Code
- 2015 International Green Construction Code (IgCC)

Treatment

The selection of treatment technologies in any graywater reuse application is dictated by the following factors:

- Ultimate use of the recovered graywater
- Specific contaminants in the graywater to be reduced
- Total volume requirements
- Regulations
- Economics

Specific treatment technologies are detailed later in this document.

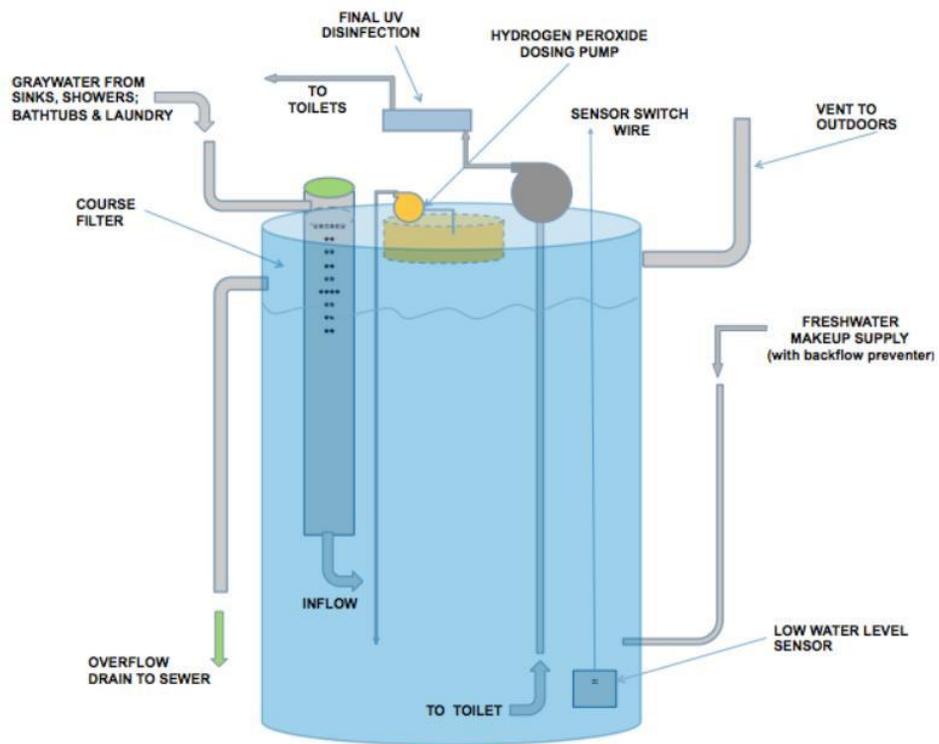
Example System

A Master's Thesis prepared by Brock Hodgson at Colorado State University, Fort Collins, CO, evaluated the design requirements for a system treating graywater collected from showers and lavatory sinks from a number of units at a residence hall at the University. The treated water was to be used for toilet flushing.

The treatment included media filtration and cartridge filtration followed by disinfection. Both the sand filtration (20-40 μ) and 100 μ cartridge filtration technologies effectively reduced TSS (total suspended solids) concentrations.

For disinfection, the researcher evaluated UV (ultraviolet) with H₂O₂ (hydrogen peroxide), chlorine (sodium hypochlorite), UV with chlorine residual and ozone with chlorine residual. In terms of cost and efficacy, chlorine (sodium hypochlorite) performed the best, with almost complete inactivation of E.coli and total coliform bacteria.

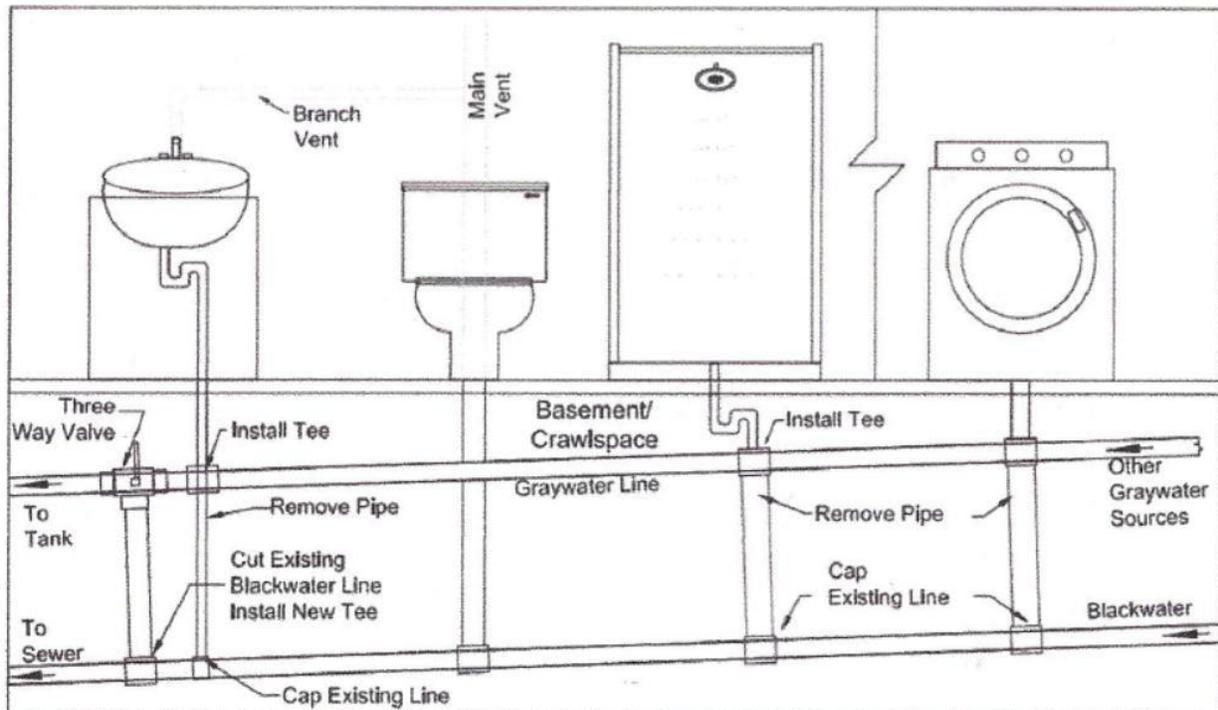
A photograph and illustration of this system are below:



Designs

The Urban Water Center at Colorado State University has significant expertise in graywater treatment system design and application of treated graywater. They recommend that its use be confined to toilet flushing and outdoor irrigation. Those uses alone can reduce potable water demand in a residence by as much as 50%.

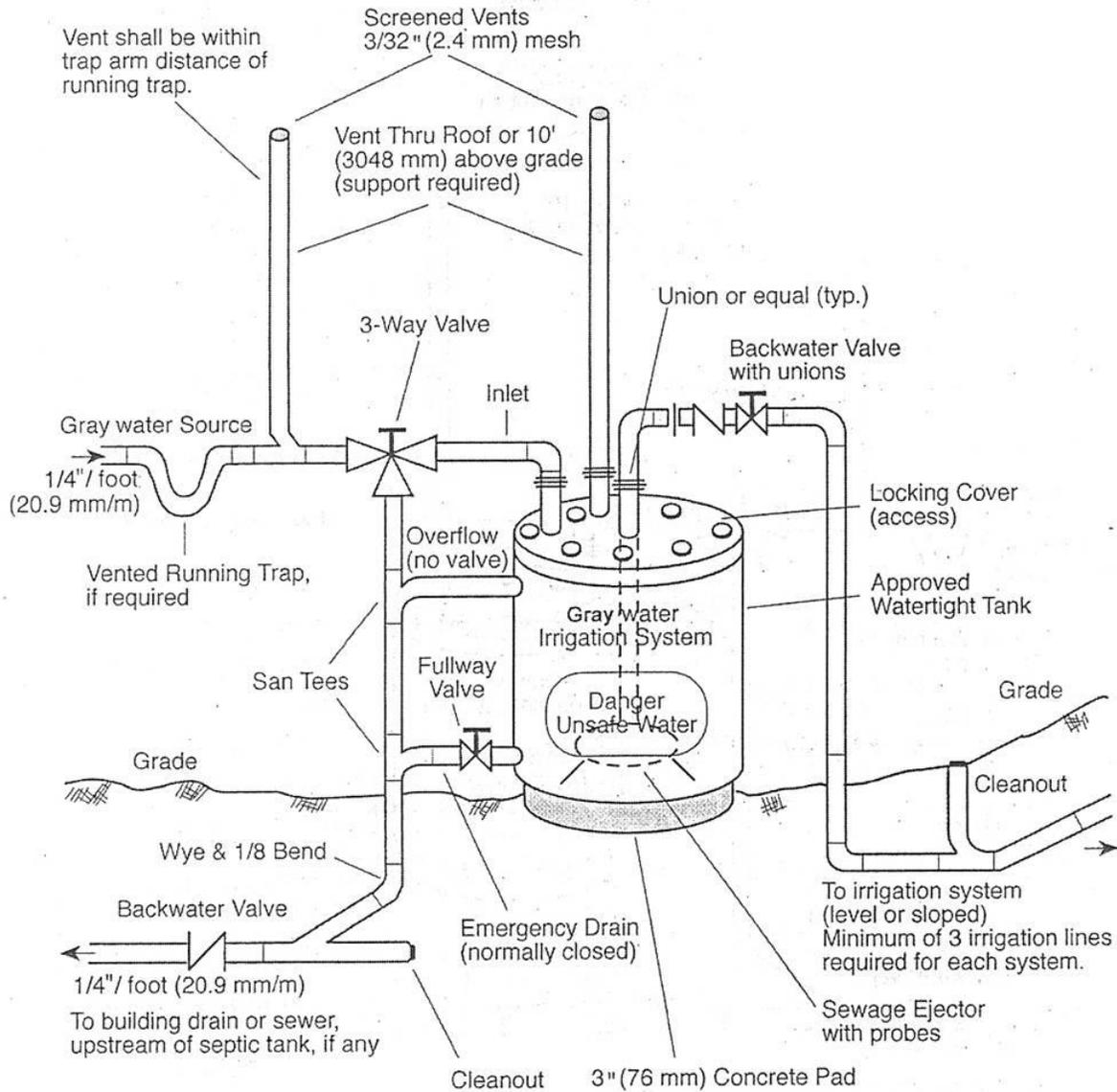
They offer the following retrofit design to separate and collect graywater from sinks, showers and washing machines:



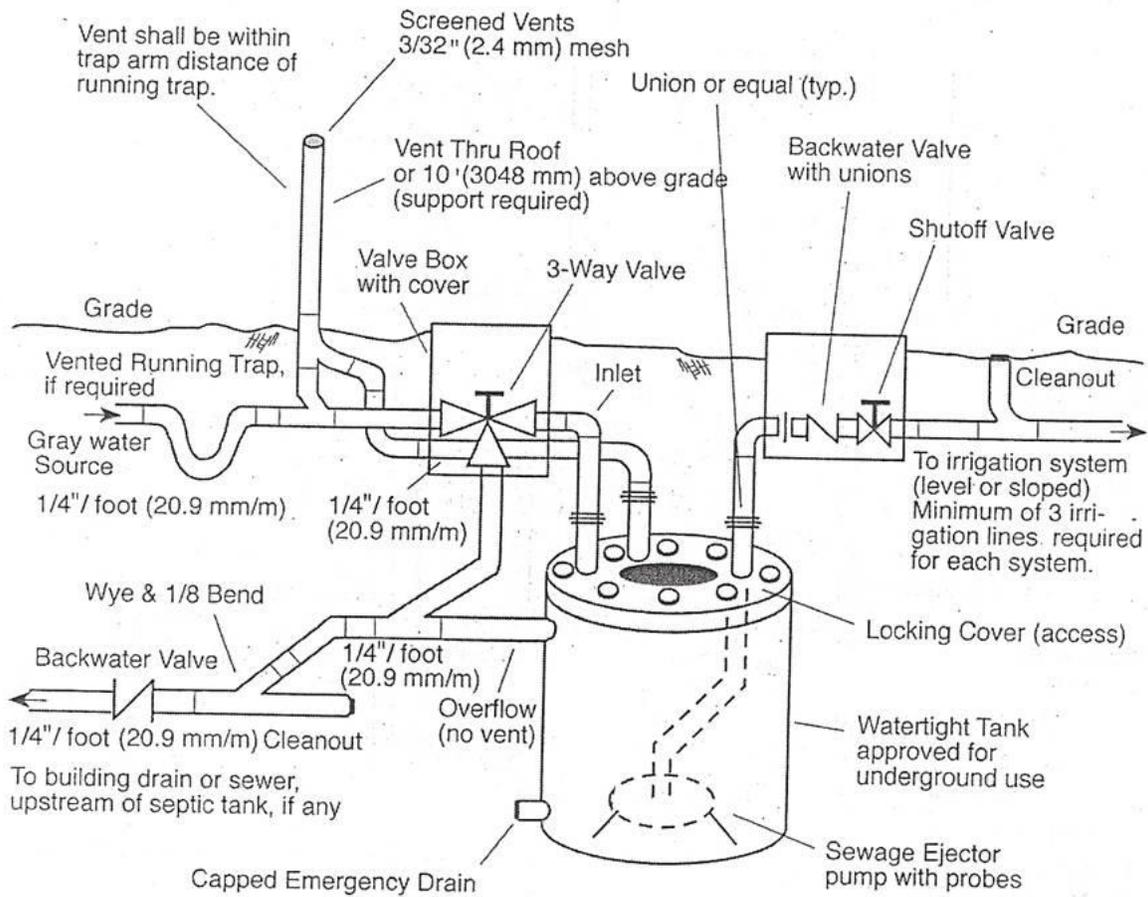
Regarding outdoor irrigation, they recommend that the graywater be applied through subsurface or drip irrigation (no surface exposure).

WERF (Water Environment Research Foundation) sponsored a study on the effect of graywater application on landscape plants over a five year period in the southwest U.S. Out of 22 plant species studied, only 3 (avocado, lemon and Scotch pine) showed any negative response from graywater irrigation. Those responses included reduced growth, leaf burning and a small reduction in fruit production.

The following illustrations are from “Graywater Guide” published by the California Department of Water Resources, and depict surface mounted and underground storage tanks, including pumps and piping:



Graywater System Surface Mounted Tank – Pumped (conceptual)



Graywater System Underground Tank – Pumped (conceptual)

It is important that we understand the technical details associated with graywater, and become proficient in the treatment technologies and system design requirements to take advantage of these opportunities.

INDUSTRIAL/COMMERCIAL DISCHARGES

Introduction

The discharges leaving commercial and industrial manufacturing facilities are extremely diverse and variable. In many cases, the kinds and concentrations of contaminants are unique to a particular site.

For this reason, a comprehensive site-specific test is required to generate such data as the most appropriate treatment technology and total system design.

Water shortages, regulatory pressures, and a desire to be “environmentally responsible,” are some of the driving forces behind the paradigm shift towards water reuse. It has been slow starting, but, in the U.S., one estimate puts the overall growth rate at 14% per year.

In treating wastewater for reuse, there is usually incentive to “dewater” the stream, or extract as much reusable water as possible. As a result, the contaminants are concentrated to a very high degree, which can often produce issues in the treatment system.

TREATMENT TECHNOLOGIES

Introduction

So far, this document has presented information on the sources of wastewater, how it may be collected and, to some degree, quality requirements for reuse. The following sections will address technologies, which basically cover the treatment of wastewater from virtually all sources.

The chart below illustrates the sizes of some contaminants, with appropriate treatment technologies.

Over the years, a plethora of treatment technologies have been developed for contaminant reduction and the following table identifies those that are appropriate for each contaminant class. Since removal of gaseous contaminants is not a major requirement in most wastewater treatment activities, it is omitted from this table.

Treatment Technologies

Treatment Technologies	Suspended Solids Removal	Dissolved Organic Removal	Dissolved Salts Removal	Microorganism Removal
BIOLOGICAL PROCESSES				
MBR (Membrane Bioreactor)	X	—	—	X
Activated sludge	X	X	—	X
Anaerobic digestion	X	X	—	—
Bio-filters	—	X	—	—
EXTENDED AERATION				
Bio-denitrification	—	L	—	—
Bio-nitrification	X	X	—	—
Pasveer oxidation ditch	X	X	—	X
CHEMICAL PROCESSES				
CHEMICAL OXIDATION				
Catalytic oxidation	X	X	—	X
Chlorination	X	X	—	X
Ozonation	—	L	—	X
Wet air oxidation	X	X	—	X
CHEMICAL PRECIPITATION				
CHEMICAL REDUCTION				
Ion exchange	—	—	X	—
Liquid-liquid (solvent)	—	—	X	—
COAGULATION				
Inorganic chemicals	X	X	—	X
Polyelectrolytes	X	X	—	X

L = under certain conditions there will be limited effectiveness

Treatment Technologies (cont.)

Treatment Technologies	Suspended Solids Removal	Dissolved Organic Removal	Dissolved Salts Removal	Microorganism Removal
ELECTROLYTIC PROCESSES				
Electrodialysis	—	—	X	L
Electrodeionization	—	—	X	—
Electrolysis	—	—	X	—
Ultraviolet irradiation	—	—	—	X
INCINERATION				
Fluidized-bed	X	X	—	X
PHYSICAL PROCESSES				
CARBON ADSORPTION				
Granular activated	X	X	—	—
Powdered	X	X	—	X
SPECIALTY RESINS	—	L	L	—
FILTRATION				
Diatomaceous-earth filtration	X	—	—	X
Multi-media filtration	X	—	—	X
Micro-screening	X	—	—	X
Sand filtration	X	—	—	X
Flocculation-sedimentation	X	—	—	X
DAF (Dissolved air flotation)	X	X	—	—
Foam separation	X	—	X	—

L = under certain conditions there will be limited effectiveness

Treatment Technologies (cont.)

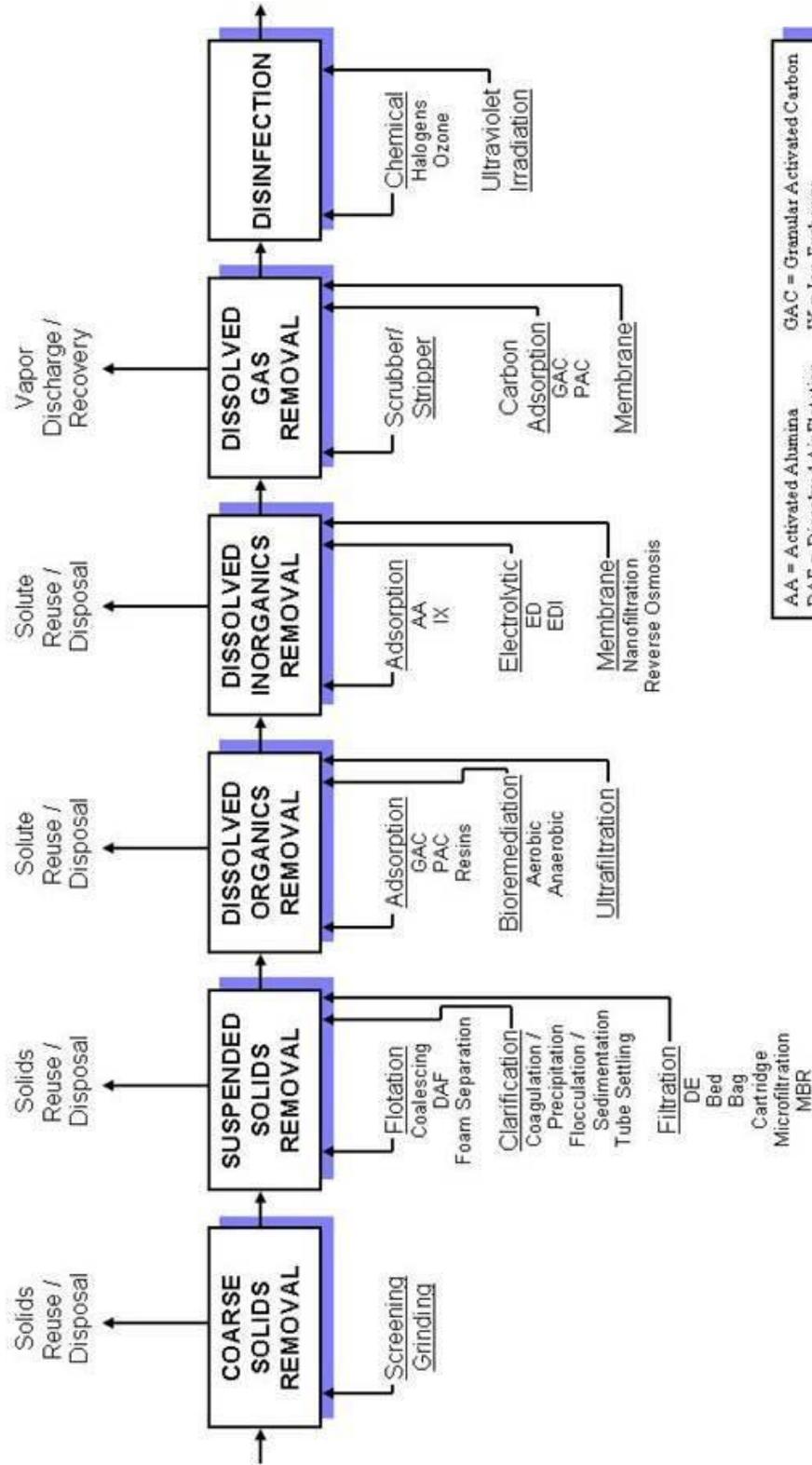
Treatment Technologies	Suspended Solids Removal	Dissolved Organic Removal	Dissolved Salts Removal	Microorganism Removal
MEMBRANE PROCESSES				
Microfiltration	X	—	—	X
Ultrafiltration	X	X	—	X
Nanofiltration	X	X	L	X
Reverse osmosis	X	X	X	X
Stripping (air or steam)	X	X	—	—
THERMAL PROCESSES				
Distillation	X	X	X	X
Freezing	—	X	X	—

L = under certain conditions there will be limited effectiveness

The following chart illustrates the treatment technologies most often utilized in industrial wastewater treatment.

Note that technologies for removal of dissolved gasses are included here.

INDUSTRIAL WASTEWATER TREATMENT



AA = Activated Alumina	GAC = Granular Activated Carbon
DAF = Dissolved Air Flotation	IX = Ion Exchange
DE = Diatomaceous Earth	MBR = Membrane Bioreactor
ED = Electrodialysis	PAC = Powdered Activated Carbon
EDI = Electrodeionization	

The key to wastewater reuse is to draw from the above arsenal of technologies to efficiently and economically remove hazardous or undesirable contaminants from the wastewater supply. There is no single technology that will accomplish this; however, there are treatment technologies that, collectively, are capable of effectively reducing the concentration of virtually any contaminant down to acceptable levels for any water use.

There is no contaminated water supply that cannot be reclaimed with the treatment technologies we have on hand.

The requirement for system designers is to be experienced and knowledgeable enough about the treatment choices to make an intelligent decision regarding which to select for additional investigation and possibly further testing for the particular wastewater stream and reuse application.

For this presentation covering those wastewater sources which contain relatively low concentrations of biodegradable contaminants, the treatment technologies of choice are usually filtration and membrane technologies.

Therefore, both are detailed below.

Filtration

As one of the original water treatment processes, filtration technologies have undergone many improvements over the centuries.

From simple gravity filtration through sand to the membrane technologies of microfiltration and ultrafiltration, filtration is the lynchpin of basic treatment for non-biological wastewater sources.

Filtration technology is primarily utilized to remove suspended solids from water supplies. These solids can be dirt, silt or other particulate material that may affect the downstream treatment process or final use of the water.

Following are descriptions of the most common filtration products in use today.

Media (Bed) Filters – These consist of a tank containing granular media such as sand, anthracite, garnet, etc. which capture suspended solids and retain them inside the bed until it is taken offline and backwashed. Media filters are typically capable of removing suspended solids down to 10-20 microns in size.

These are also known as bed filters, and range from large slow sand (gravity) filters utilized for municipal water and wastewater treatment to smaller pressure filters, as illustrated below.



Media Filter

Compared to cartridge filters, media filters are typically higher in capital cost, but have lower operating costs.

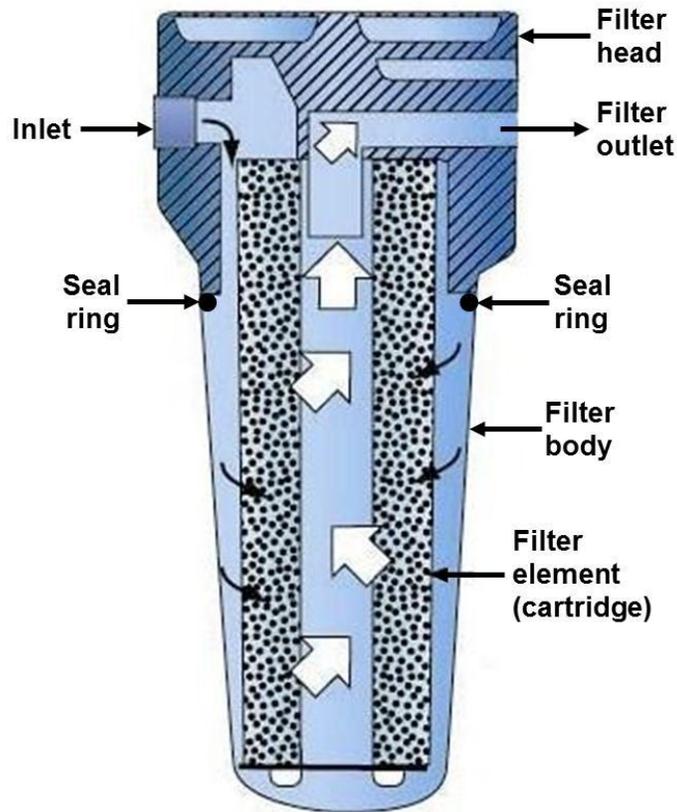
The two mechanisms involved in media filtration are known as transport and attachment:

Transport is the movement of particles (suspended solids) through and around the media material.

Attachment is the term for the numerous complicated mechanisms by which solids are captured within the media. These include diffusion, straining, interception, inertia, sedimentation and hydrodynamic action. The mechanism most commonly associated with filtration, sieving, is the buildup of solids too large to pass through the pores of the medium. As these contaminants accumulate on the surface, they form a “cake” layer that often compresses and reduces the pore openings, improving the filter performance until the water flow is so reduced as to require backwashing.

Cartridge filters – Cartridge filters are replaceable “inserts” comprised of fibrous materials, ceramics, or special adsorptive media. Usually cylindrical in configuration, they are placed into housings, and are typically replaced when they have captured so much suspended solids that the pressure drop across the housing becomes unacceptable [usually above 10 psig (0.68 bar)]. Offered in many different designs and micron removal ratings (down into the submicron range), they provide an excellent array of choices to the knowledgeable design engineer.

A typical cartridge filter in its housing is illustrated below.



Cartridge Filter

Compared to media filters, cartridge filters are utilized in low flow rate applications, and have relatively low capital costs, but relatively high operating costs (replacement cartridges).

Bag filters – these are similar to cartridge filters except that the medium is fabricated into a bag through which the water flows. Although not available with a micron rating as small as cartridge filters, bag filters are generally “tighter” than media filters. The bag filter medium selection is more limited than for cartridges.

A bag filter is illustrated below.



Bag filter

Both cartridge and bag filtration technologies can be modified with the addition of a fine “enhancing” medium, such as diatomaceous earth (DE), to provide finer filtration.

Materials - For filter cartridges used in water environments, the medium can be composed of one or more of the following materials:

- Cellulosic polymers
- Polypropylene
- Polyethylene
- Nylon
- PTFE
- PVDF
- Polysulfone
- Ceramics
- Activated carbon

Removal Mechanisms – Suspended solids removal by a filter cartridge is effected through one of two mechanisms: surface filtration and depth filtration

Surface filtration largely involves a sieving process in that particles which are too big to pass through the openings (pores) are simply retained on the surface of the filter. These filters are also known as “screen” or “membrane” filters and as the structure is more uniform, pore sizes can be more accurately controlled.

Depth filtration utilizes a more porous medium, which contains non-uniform openings that do not extend straight through the medium. This “tortuous” path, and the fact that these pores are of varying diameters throughout the depth of the medium, results in entrapment of the particles within the body of the cartridge. Another phenomenon known as “adsorption” contributes to the entrapment of particles by utilizing chemical attraction forces which result in particles adhering to the medium inside the pores. .

In reality, no filter is either a pure surface or depth filter, in that the membranes of surface filters have a finite thickness in which some depth filtration can occur, and depth filters also retain some particulate matter on their surfaces.

Carbon and Specialty Filters

Not all filter cartridges are designed to simply remove sediment or particulate material; carbon filters constitute a large family of cartridges primarily designed to remove chlorine, trace organic contaminants and certain gases from water supplies through adsorption.

Activated carbon is typically manufactured from a carbon source such as coconut husks, nutshells, or coal. It is typically processed by heating the carbon at high temperatures in the absence of air, significantly increasing the porosity of the carbon and thus its ability to adsorb many gases and organic compounds.

Granular Activated Carbon (GAC) consists of loose carbon granules contained in a plastic housing that allows water to flow through the carbon from one end of the housing to the other. GAC filters usually exhibit good adsorption of various contaminants, but are not particularly effective at particulate reduction, due to the relatively large spaces between the carbon granules.

Powdered Activated Carbon (PAC) cartridges consist of finely ground activated carbon deposited on a fibrous backing material (in sheet or fiber form) and fabricated into a cylinder with a hollow internal core and with molded plastic end caps to ensure proper flow through the cartridge. PAC cartridges exhibit filtration properties of the substrate material (typically spun-bonded or melt-blown fibers) combined with the adsorption properties of carbon.

Carbon block cartridges consist of powdered activated carbon to which a thermoplastic binder has been added and then compressed either by molding or in an extrusion operation to yield a product with very small pores to effect fine filtration, again with the adsorption properties of activated carbon. Carbon block cartridges are capable of the finest filtration of any carbon cartridges.

Activated alumina cartridges are similar in design to GAC products, but are designed to adsorb specific contaminants such as fluoride, arsenic and selenium.

Construction

Surface filters are generally manufactured by laminating or casting a thin membrane coating on a backing material. The coating is produced with pores tailored to meet the specifications of the filter cartridge manufacturer.

Depth filters are produced through a number of manufacturing techniques. Probably the oldest is “string-wound,” which involves winding a length of string or yarn around a porous core to produce cartridges with the desired properties. “Melt-blown” cartridges are produced by extruding polymeric fibers onto a core. “Felt-type” cartridges are produced by winding or otherwise adhering layers of felt to a core. Numerous ratings are available for all these filters.

There are many products also manufactured by utilizing more than one of these technologies to produce hybrid designs.

Pore Size Ratings

An important characteristic of filter cartridges is their contaminant removal rating, usually expressed in microns. The industry has generally settled on two removal categories: *nominal* and *absolute*. Unfortunately, there is no agreement among manufacturers and various industry users as to the definitions of these terms. For example, the U.S. National Fluid Power Association (NFPA) defines *nominal* as “an arbitrary micron value assigned by the filter manufacturer, based on the weight removal of a percentage of all particles of a given size or larger. It is rarely defined and not reproducible.” On the other hand, the Water Quality Association (WQA), in their “Glossary of Terms,” defines Nominal Filter Rating as “generally interpreted as meaning that 85% of the particles of the size equal to the nominal filter rating will be retained by the filter.” What this means is that when a manufacturer claims to have “five

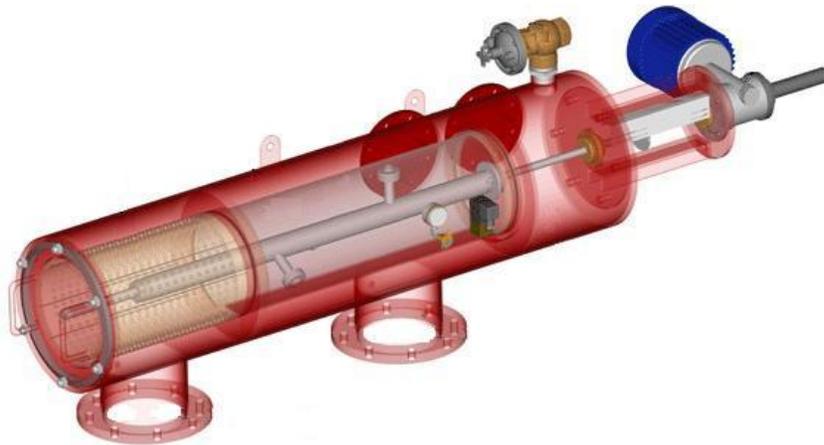
micron filter cartridges” (for example), unless what is meant by this value is defined, such as the percentage removal of particles five micron and larger, it is basically meaningless.

The NFPA defines an Absolute Filter Rating as “the diameter of the largest hard spherical particle that will pass through a filter under specified test conditions. It is an indication of the largest opening in the filter cartridge.” The WQA defines *absolute* as meaning that “99.9% of all particles larger than the rated size will not pass through the filter cartridge.” Unfortunately, there is also a lack of complete agreement among manufacturers, users, and industry trade groups on the definition of Absolute Filter Ratings, although most agree on percentages above 99%.

Continuous filters

To meet the demands of continuous processing, a number of filters have been developed which are capable of backwashing during continuous operation. These range from moving belt filters to sophisticated rotating cylinders with automatic backwashing capabilities. Most of these devices are screen or wedgewire construction, and cannot filter below about 2-3 microns.

Following is an illustration of a continuous filter.



Continuous filter (Courtesy Orival, Inc.)

Membrane Technologies

Technology Review

Some of the most versatile and least technically understood water treatment processes are the crossflow, pressure-driven membrane separation technologies of microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO).

Membrane technologies offer great potential with regard to effective removal of most water borne contaminants. As a result, they are now widely used in most water treatment applications, and offer great potential in wastewater recovery and reuse.

Membrane technologies possess specific advantages that make them unique when compared to other solid/liquid separation operations. These include:

- ▶ Continuous process, resulting in automatic and uninterrupted operation
- ▶ Low energy utilization involving neither phase nor temperature changes
- ▶ Modular design – no significant size limitations
- ▶ Minimal moving parts with low maintenance requirements
- ▶ No effect on form or chemistry of contaminants
- ▶ Discrete membrane barrier to ensure physical separation of contaminants
- ▶ No chemical addition requirements to effect separation

The membrane separations technologies include:

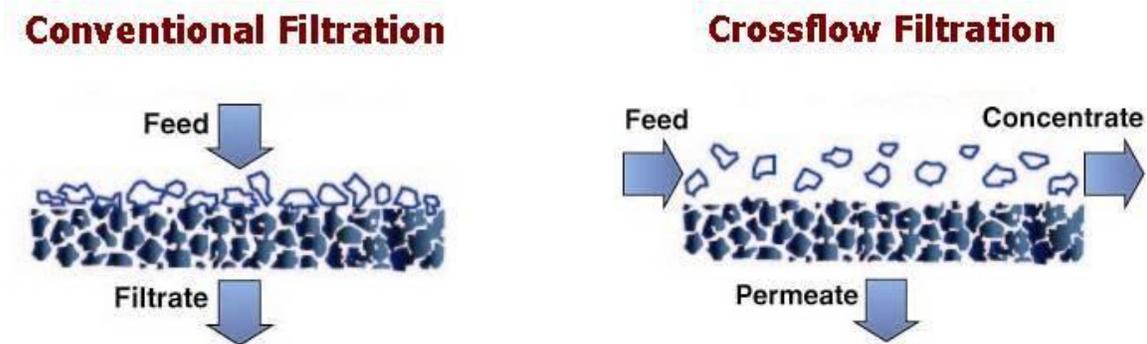
Microfiltration (MF)
Ultrafiltration (UF)
Nanofiltration (NF)
Reverse Osmosis (RO)

Simply put, these technologies are continuous filters. The class of contaminant and degree of removal are a function of membrane polymer selection and its particular performance characteristics.

Although they all provide separation of contaminants from the solvent (usually water), each technology performs a specific function and has advantages and disadvantages when compared to the others in a particular application.

The development in filtration technology, known as crossflow filtration, allows for continuous processing of liquid streams. In this process, the bulk solution flows over and parallel to the membrane surface, and because the system is pressurized, water is forced through the membrane and becomes "permeate." The relatively high flow rate of the bulk solution across the surface minimizes the accumulation of particulate matter on the surface and facilitates continuous operation of the system.

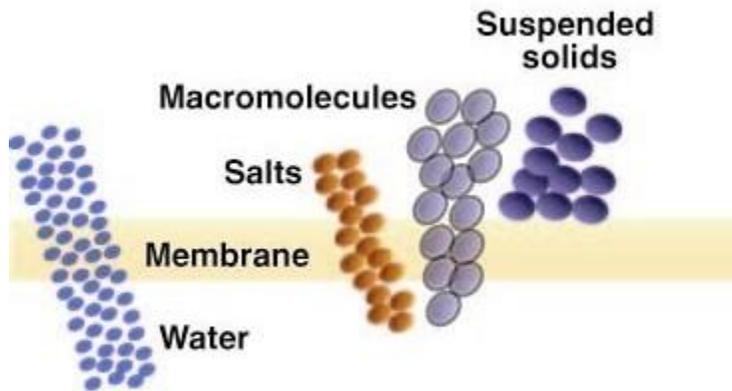
The following figure compares conventional filtration to crossflow filtration.



Conventional vs. Crossflow Filtration.

Microfiltration (MF)

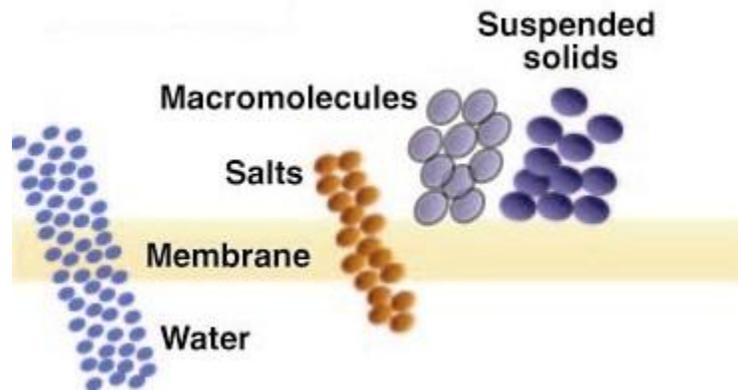
Below is an illustration of the mechanism of microfiltration. Generally, MF involves the removal of particles or suspended materials, ranging in size from approximately 0.01 to 1 microns (100 to 10,000 angstroms).



Microfiltration

Ultrafiltration (UF)

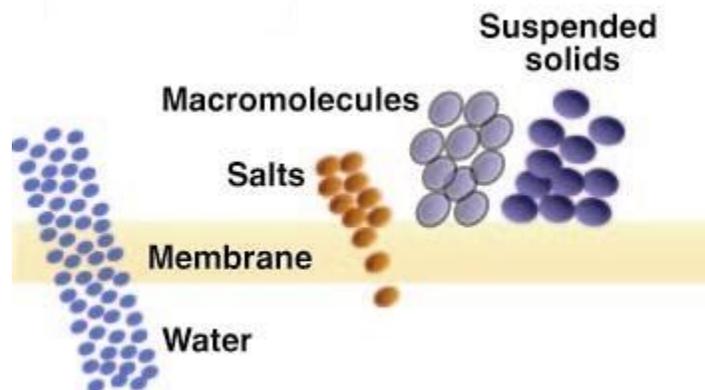
The figure below depicts ultrafiltration, which removes dissolved, non-ionic materials typically smaller than 0.01 micron (100 angstroms). The removal characteristics of UF membranes can be described in terms of "molecular weight cutoff" (MWCO), the maximum molecular weight of compounds that will pass through the membrane pores. MWCO terminology is expressed in Daltons. Basically, ultrafiltration is used to remove dissolved organic contaminants, while suspended solids are removed by microfiltration.



Ultrafiltration

Nanofiltration (NF)

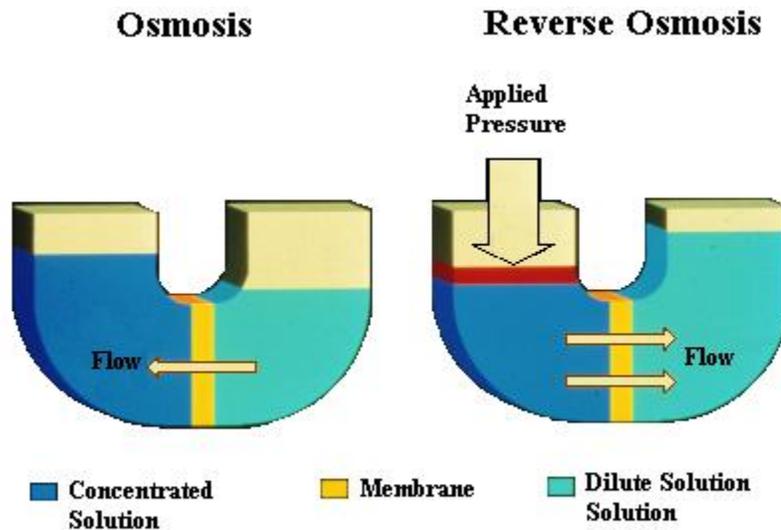
This is an intermediate process between ultrafiltration and reverse osmosis. The molecular weight cut-off (MWCO) properties of nanofiltration membranes are in the range of 400 to 800 Daltons (<10 angstroms). Ionic rejections vary based on the valence of the salts; multivalent salts such as magnesium sulfate ($MgSO_4$) are rejected as much as 99%, while monovalent salts such as sodium chloride ($NaCl$) may have rejections as low as 10%. Nanofiltration is illustrated below.



Nanofiltration

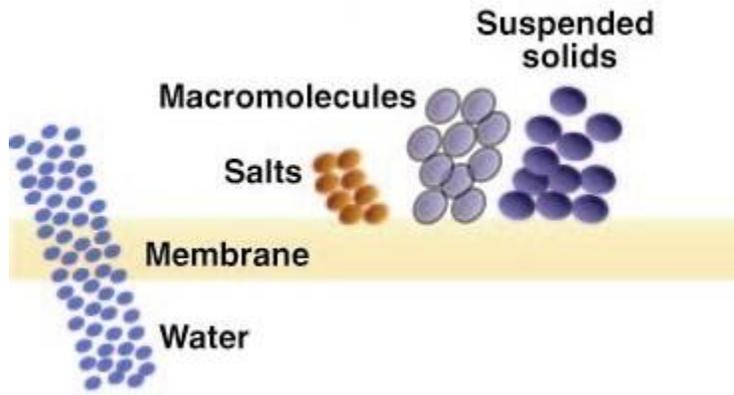
Reverse Osmosis (RO)

Reverse osmosis is best understood by first defining the phenomenon of osmosis, the natural passage of water through a semipermeable membrane from a water supply of low salts concentration (high energy) to a region of high salts concentration (low energy). By applying pressure to the high salts concentration side and overcoming the natural osmotic pressure (π), water is forced back through the membrane. This is reverse osmosis. Osmosis and reverse osmosis are depicted in the following illustrations.



Reverse Osmosis

This process will remove almost all dissolved organic (non-ionic) solids with molecular weights above approximately 100 Daltons, as well as a high percentage of ionic materials. Because reverse osmosis membranes are not perfect (they will typically remove 98-99+% of the ionic contaminants), for high purity water production, they are usually used as pretreatment to a final "polishing" resin deionization or electrodeionization step.



Reverse Osmosis

Mechanisms

The movement of water through a membrane is a function of net driving pressure, the applied (pump) pressure minus any back pressure on the permeate stream. This includes osmotic pressure as well as the pressure required to convey permeate through piping to storage tanks, etc. Also known as Transmembrane Pressure (TMP), it applies to all four crossflow, pressure-driven membrane separation technologies.

Although not universally accepted, it is believed that the salts rejection for NF and RO membranes is based on the diffusion of salts into and through the membrane polymer, whereas the water (permeate) flow is a function of TMP.

In general, pure water passes through the membrane at a much higher flow rate than salts passage; hence the rejection mechanism.

The following table summarizes the various properties of membrane technologies.

Membrane Technologies Comparison Chart

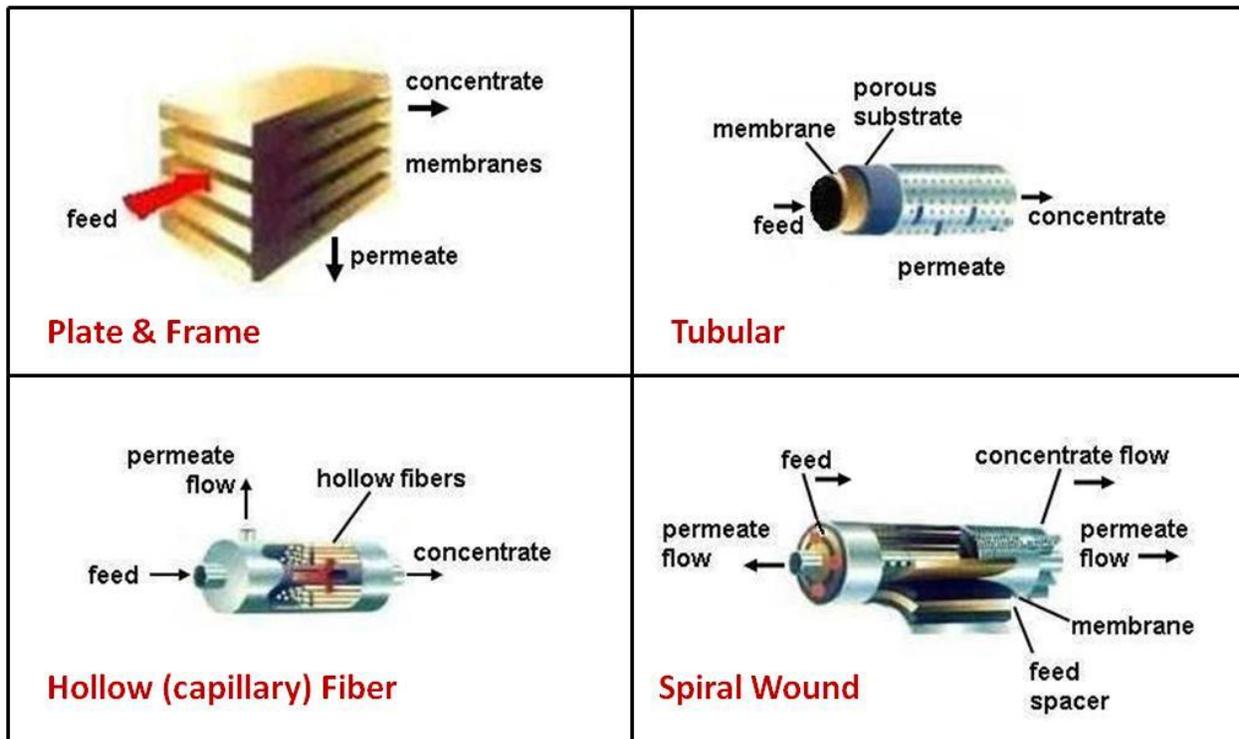
Feature	Microfiltration	Ultrafiltration	Nanofiltration	Reverse Osmosis
Materials of Construction	Ceramics, Sintered metals, Polypropylene, Polysulfone, Polyethersulfone, Polyvinylidene fluoride, Polytetrafluoroethylene	Ceramics, Sintered metals, Polypropylene, Polysulfone, Polyethersulfone, Polyvinylidene fluoride	Thin film composites, Cellulosics	Thin film composites, Cellulosics
Pore Size Range (micrometers)	0.1 - 1.0	0.001 - 0.1	0.0001 - 0.001	<0.0001
Molecular Weight Cutoff Range (Daltons)	>100,000	1,000 - 100,000	300 - 1,000	50 - 300
Operating Pressure Range	<30	20 - 100	50 - 300	225 - 1,000
Suspended Solids Removal	Yes	Yes	Yes	Yes
Dissolved Organics Removal	None	Yes	Yes	Yes
Dissolved Inorganics Removal	None	None	20-95%	95-99+%
Microorganism Removal	Protozoan cysts, algae, bacteria*	Protozoan cysts, algae, bacteria*, viruses	All*	All*
Osmotic Pressure Effects	None	Slight	Moderate	High
Concentration Capabilities	High	High	Moderate	Moderate
Permeate Purity (overall)	Low	Moderate	Moderate-high	High
Energy Usage	Low	Low	Low-moderate	Moderate
Membrane Stability	High	High	Moderate	Moderate

** Under certain conditions, bacteria may grow through the membrane.*

Membrane Element Configurations

In an effort to package the membrane as economically as possible and minimize fouling, a number of membrane device configurations have been developed over the years. The devices (elements or modules) in common use today are illustrated below:

- Plate & Frame
- Tubular
- Hollow (Capillary) Fiber
- Spiral Wound



Membrane Element Configurations

Following are descriptions of each configuration.

Plate & Frame This element incorporates sheet membrane stretched over a frame to separate the layers and facilitate collection of permeate, which is directed to a collection tube.



Plate & Frame Element

Tubular Manufactured from ceramic, carbon, stainless steel, or a number of thermoplastics, these tubes have inside diameters ranging from ¼ inch up to approximately 1 inch (6 to 25 mm). The membrane is typically coated on the inside of the tube and the feed solution flows under pressure through the interior (lumen) from one end to the other, with the permeate passing through the wall and collected outside of the tube.



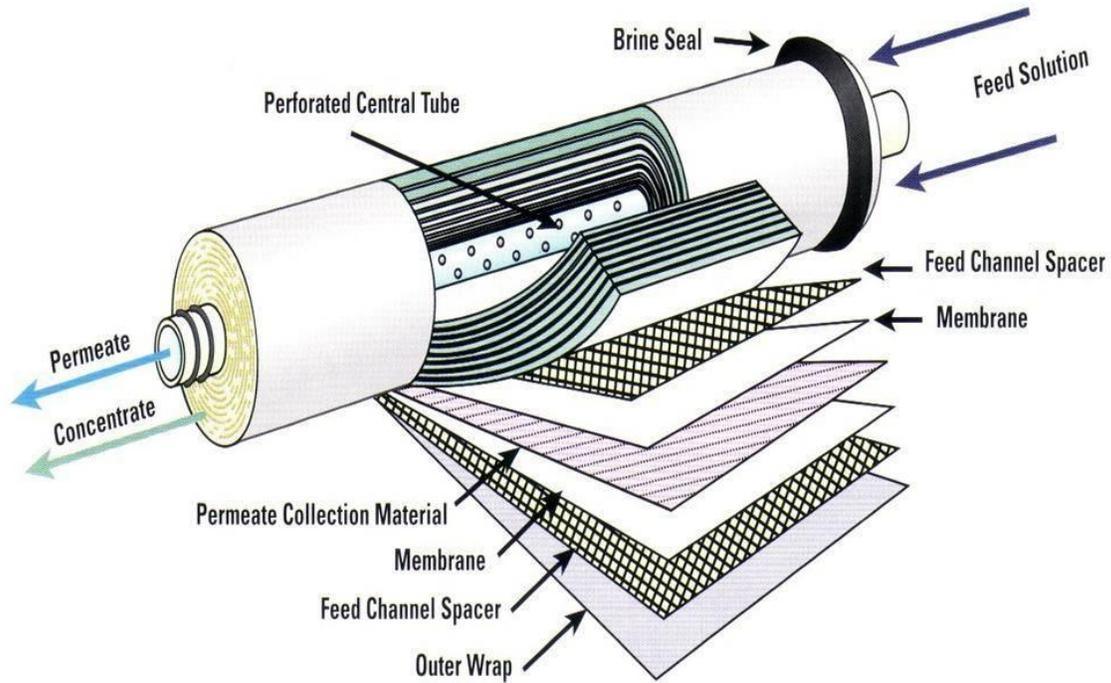
Tubular Membrane Element

Hollow (Capillary) Fiber These elements are similar to the tubular element in design, but are much smaller in diameter, are usually unsupported membrane polymers or ceramics and require rigid support on each end provided by an epoxy “potting” of a bundle of the fibers inside a cylinder. Feed flow is either down the interior of the fiber (“lumen feed”) or around the outside of the fiber (“outside-in”).



Hollow Fiber Element

Spiral Wound This element is constructed from an envelope of sheet membrane wound around a permeate tube that is perforated to allow collection of permeate. Water is purified by passing through one layer of the membrane and, following a spiral pattern, flows into the permeate tube. It is by far the most common configuration in RO water purification applications.



Courtesy of: John Peichel – GE Water & Processes Technologies

Spiral Wound Element

From the perspective of cost and convenience, it is beneficial to pack as much membrane area into as small a volume as possible. This is known as “packing density.” The greater the packing density, the greater the membrane area enclosed in a certain size element, and generally, the lower its cost. The downside of the high packing density membrane elements is their greater propensity for fouling. The table below compares the element configurations with regard to their packing densities and fouling propensities:

Membrane Element Configuration Comparison

Element Configuration	Packing Density *	Fouling Resistance **
Plate & Frame	Low	High
Hollow (Capillary) Fiber	High	High
Tubular	Low	Very High
Spiral Wound	Medium	Low

* Membrane area per unit volume

** Tolerance to suspended solids

Membrane Polymers

To clarify the membrane materials used for the various element configurations, the follow tables are provided.

Microfiltration (MF) & Ultrafiltration (UF)

Materials of Construction	Device Configuration			
	Hollow Fiber	Tubular	Plate & Frame	Spiral Wound
<u>Polymeric</u>				
PS	X	X	X	X
PES	X	X	X	X
PAN	X	X	X	X
PE	—	X	—	—
PP	X	X	X	—
PVC	—	X	—	—
PVDF	X	X	—	—
PTFE	X	—	X	—
PVP	X	X	—	—
CA	X	—	—	—
<u>Non-Polymeric</u>				
Coated 316LSS	—	X	—	None
α - Alumina	—	X	X	None
Titanium Dioxide	—	X	—	None
Silicon Dioxide	—	X	—	None

PS = Polysulfone

PES = Polyethersulfone

PE = Polyethylene

PP = Polypropylene

PAN = Polyacrylonitrile

PVDF = Polyvinylidene Fluoride

PTFE = Polytetrafluoroethylene

CA = Cellulose Acetate

PVP = Polyvinylpyrrolidone

TF = Thin Film Composite

Nanofiltration (NF) & Reverse Osmosis (RO)

Materials of Construction	Device Configuration			
	Hollow Fiber	Tubular	Plate & Frame	Spiral Wound
<u>Polymeric</u>				
PS*	—	X	X	X
PES*	—	X	X	X
CA	—	X	X	X
TF	—	X	X	X
<u>Non-Polymeric</u>				
None	—	—	—	—

* Base polymer below TF polymer

PS = Polysulfone

CA = Cellulose Acetate

PES = Polyethersulfone

TF = Thin Film Composite

The salt rejection requirements of NF and RO membranes significantly limit the polymer selection to either cellulose acetate, cellulose triacetate, or to “thin film membranes.” These latter polymers are a family of complex crosslinked polyamide polymers produced in a thin film composite construction, with the salt-rejection polymer deposited on a polysulfone substrate layer by an interfacial polycondensation reaction. Because of their vastly superior performance properties, thin film RO membranes dominate today’s market. Although these polymers are very chemically resistant, they are more susceptible to chemical attack than the MF and UF polymers, particularly by oxidizing agents.

Today, almost all RO membrane elements are spiral wound, and the polymer of choice is the thin film composite.

Basic Calculations

Listed below are a number of calculations useful in the design of all membrane systems:

Transmembrane pressure (TMP)
$$\text{TMP} = \frac{P_i + P_o}{2} - P_p$$

P_i = Inlet (feed) pressure

P_o = Outlet (concentrate) pressure

P_p = Permeate pressure

Pressure Drop (ΔP) = $P_i - P_o$

Crossflow velocity
$$V = \frac{\text{Flow rate}}{\text{Cross-sectional area}} = f(\Delta P)$$

Energy consumption = Flow rate x ΔP

Flux (J)
$$J = \frac{\text{Volume of permeate}}{\text{Membrane area} \times \text{Time}} = \frac{\text{Liters}}{\text{m}^2\text{hour}} = \text{LMH} = \frac{\text{Gallons}}{\text{ft}^2\text{day}} = \text{GFD}$$

1 GFD (gallons/sq.ft./day) = 1.7 LMH

Rejection = $1 - C_p/C_c$

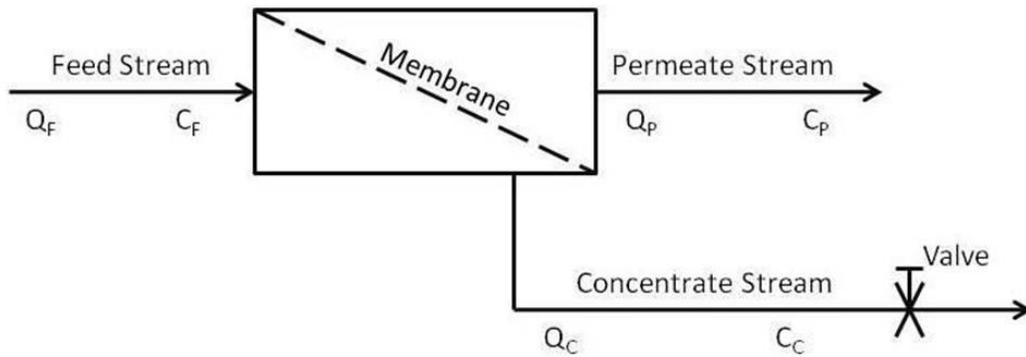
C_p = Permeate concentration

C_c = Concentrate concentration

Rejection = 100% when $C_p = 0$

System Design

A complete membrane processing system is illustrated below. In terms of function, it could also represent a single membrane element.



Q_F = Feed Flow Rate
 C_F = Solute Concentration in Feed
 Q_P = Permeate Flow Rate
 C_P = Solute Concentration in Permeate
 Q_C = Concentrate Flow Rate
 C_C = Solute Concentration in Concentrate

$$\text{Recovery} = \frac{Q_P}{Q_F}$$

(Expressed as Percent)

TDS = Total Dissolved Solids: Usually considered the total of the ionic contaminants (salts) in solution. mg/L (milligrams per liter) is the same as ppm (parts per million).

Membrane System Schematic

Note that the feed stream enters the system (or membrane element), and as the stream passes along and parallel to the surface of the membrane under pressure, a percentage of the water is forced through the membrane polymer producing the permeate stream. Contaminants are prevented from passing through the membrane based on the polymer characteristics. This contaminant-laden stream exits the membrane system (or element) as the “concentrate” stream, also known as the “brine” or “reject”.

Recovery

A very important design factor is “recovery,” that portion of the feedwater flow that is forced through the membrane and becomes permeate. Recovery is part of the system design and has a profound effect on membrane system performance.

The permeate rate of a given membrane element cannot be changed without varying the net driving pressure or water temperature. Recovery, however, can be easily changed by varying the feed flow rate to the element, and this is one of the variables that is controlled by the system designer.

As recovery is increased, the flow rate of the concentrate stream diminishes; thereby increasing the concentration of contaminants rejected by the membrane. It is important to realize that the **quantity** of contaminants is not increased, but since there is less solvent (water), the **concentration** is increased.

The advantage of operating systems at high recoveries is that the volume of concentrate is small and the flow rate of the feed pump is smaller. The potential disadvantages are numerous:

- Higher concentration of certain contaminants can result in precipitation and greater propensity for membrane fouling.
- In nanofiltration and reverse osmosis applications, the concentrated salts will result in higher osmotic pressure, requiring a higher pressure pump and a more pressure resistant system.
- In RO and NF applications, as recovery is increased, the salts concentration of the permeate goes up. This is because the membrane rejects a percentage of what it sees.
- As higher recoveries reduce the quantity of concentrate to be discharged, the higher concentration of this concentrate stream can present discharge problems.

Since the primary goal in most wastewater applications is to make the waste go away, the system recoveries are normally very high – up to 95% or higher.

The relationship between recovery and the concentration of contaminants left behind is illustrated in the table and figure below. Note that the mathematical increase in contaminant concentration is expressed as “Concentration Factor.”

An analogy is the evaporation of water on a stove: if $\frac{3}{4}$ of the original quantity is evaporated (75% recovery) and recovered as permeate, all the rejected contaminants are left in $\frac{1}{4}$ of the original volume, so the concentration has been increased by a factor of 4.

The “take away” from this exercise is that as the percent recovery increases numerically, the concentration factor goes up exponentially. In other words, a small increase in percent recovery results in a large increase of the concentration of contaminants left behind.

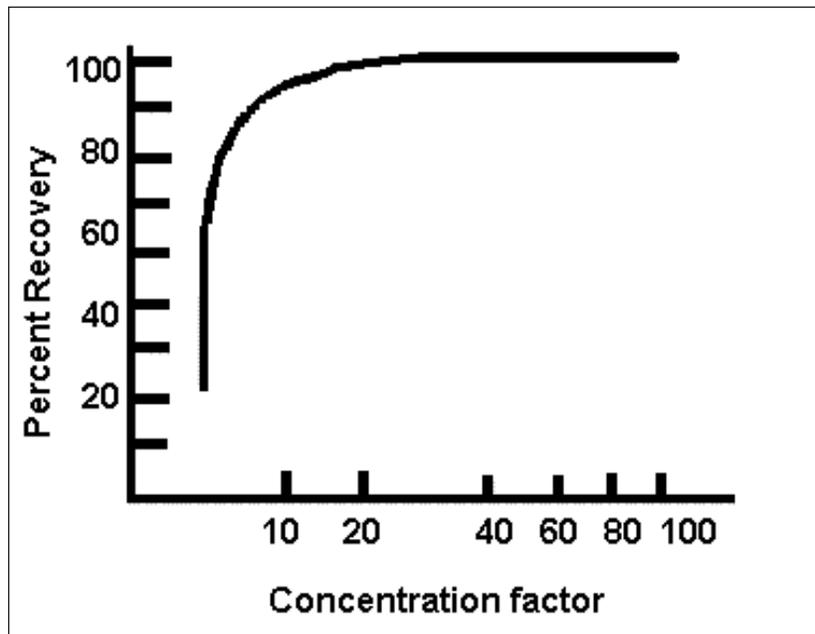
Effect of Recovery on Concentration

$$C_c \approx \frac{C_F}{1 - \text{Recovery}} = X C_F$$

$$X = \frac{1}{1 - \text{Recovery}} = \text{Concentration Factor}$$

Percent Recovery	Concentration Factor
33%	1.5
50%	2
67%	3
75%	4
80%	5
90%	10
95%	20
97.5%	40
98%	50
99%	100

Where: C_F = Feed Stream Concentration
 C_c = Concentrate Stream Concentration



Effect of Recovery on Concentration Factor

Osmotic Pressure

In RO and NF applications (and to a lesser extent, ultrafiltration), osmotic pressure can have a significant effect on the system design. Osmotic pressure (π) is loosely defined as the resistance of a particular solution to becoming concentrated by the membrane process. It is a function of both the solute itself and its concentration.

It is mathematically defined as follows:
$$\pi = 1.19(T + 273) \Sigma M_i$$

Where: π = Osmotic Pressure (psi)
T = Water Temperature ($^{\circ}$ C)
 M_i = Molar Concentration of individual ions (gmol/L)

Note that it is a function of both the particular solute and its concentration. It basically manifests itself as a “back pressure” component, and a specific test is usually required to accurately determine osmotic pressure of a specific solution.

As recovery is increased (typically through the use of a flow restrictor or concentrate valve), with the resulting decrease in concentrate flow, the concentration of solute in the concentrate stream increases, resulting in increased osmotic pressure.

The table below illustrates typical osmotic pressures.

Typical Osmotic Pressure at 25 $^{\circ}$ C

Compound	Conc. (mg/L)	Conc. (mol/L)	Osmotic Pressure	
			(psi)	(bar)
NaCl	35,000	0.6	398	27.1
NaCl	1,000	0.0171	11.4	0.78
NaHCO ₃	1,000	0.0119	12.8	0.87
Na ₂ SO ₄	1,000	0.00705	6	0.41
MgSO ₄	1,000	0.00831	3.6	0.24
MgCl ₂	1,000	0.0105	9.7	0.66
CaCl ₂	1,000	0.009	8.3	0.56
Sucrose	1,000	0.00292	1.05	0.07
Dextrose	1,000	0.00555	2.0	0.14

Because osmotic pressure is related to ionic concentration, such factors as pH and temperature may also have an effect on osmotic pressure with certain solutes. In most water purification applications, the total dissolved solids (TDS) concentration of the feed water is sufficiently low so that osmotic pressure is not significant. Exceptions to this are brackish (TDS >10,000 mg/L) and seawater (TDS >25,000 mg/L) supplies.

In wastewater treatment and many chemical processing applications, osmotic pressure considerations become increasingly important. These applications typically involve higher TDS, as well as high recoveries than for water purification.

For most design purposes, osmotic pressure can be estimated with the following formulae:

1. For monovalent salts (Na^+ , Cl^- , etc.), use 1 psi/100 mg/L solute (0.07 bar/100 mg/L solute).
2. For multivalent salts (Ca^{2+} , SO_4^{2-} , Al^{3+} , PO_4^{3-}) use ½ psi/100 mg/L solute (0.034 bar/100 mg/L solute).

Design Development

In general, for membrane technology wastewater treatment applications, every stream should be tested to develop the following design factors:

- Optimum membrane element configuration
- Total membrane area
- Specific membrane polymer
- Temperature effects
- Optimum pressure
- Maximum system recovery
- Flow conditions
- Membrane element array
- Pretreatment requirements

Specific parameters which influence these design factors include:

Feedwater Chemistry - The chemical composition of the feedwater can affect the membrane element in a number of ways. The polymer itself (or components of the membrane element) can be degraded by certain chemicals. For example, cellulosic membrane polymers are subject to hydrolysis at high pH, thin film composite polymers are degraded by virtually all oxidizing agents, and most of the polymers are affected by chlorinated hydrocarbon solvents in concentrations above 5%.

The most significant feedwater parameters are:

- Total solids content
- Suspended solids (TSS)
- Dissolved organic (TOC, MBAS, COD, BOD)
- Dissolved inorganic (TDS)

Chemicals of concern include:

- Oxidizing chemicals
- Organic solvents
- Saturated solutes
- Surfactants

Other factors include:

- pH
- Operating temperature
- Osmotic pressure as a function of system recovery
- Variation in feed stream chemistry as a function of time

Membrane Area - In general, the greater the membrane area, the higher the permeate rate, everything else being equal.

Membrane Element Configuration – This parameter has been discussed earlier.

Membrane Polymer - As indicated previously, many different membrane polymers are now on the market, with new ones frequently becoming available. Obviously, these are the key components with regard to effecting the separation, and each polymer has its particular strong and weak points; none is perfect. It is essential that the design engineer understand the particular characteristics of each polymer well enough to select the one(s) most appropriate for the testing.

Temperature - Because of its lower viscosity, warm water will flow more readily through membrane pores than cold water; therefore, as temperature is increased, permeate rate increases. Unfortunately, most membrane polymers are thermoplastic, and become more compressible when warmed. The combination of temperature and pressure can cause irreversible compaction in some polymers, resulting in premature failure. Many membrane polymers, as well as virtually all ceramic and metallic membranes exhibit excellent thermal stability and offer significant promise in those applications where it is considered desirable to process a stream at elevated temperatures. Each membrane element manufacturer provides data on temperature limits and the relationship of temperature to permeate rate for its products. The performance of non-polymeric membranes is generally not affected by temperature extremes.

Applied Pressure -The permeate rate of a membrane element is directly proportional to the net driving pressure. Net driving pressure is defined as the total pump pressure minus osmotic pressure minus any back pressure in the permeate line. Net driving pressures range from as low as 30psi (2 bar) for microfiltration systems to as high as 1000psi (68 bar) for reverse osmosis systems.

Recovery – This factor has been addressed earlier.

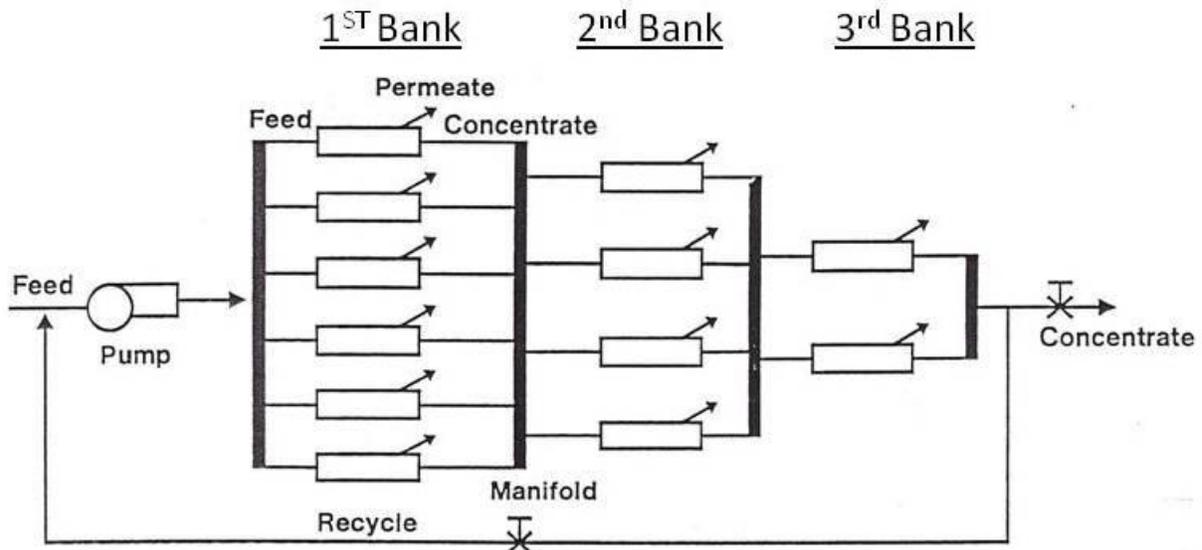
Flow Conditions - It has been shown that membrane elements are much less susceptible to fouling from suspended or precipitated solids if all of the flows through the element are turbulent. This is indicated by the term “Reynolds Number,” which is a dimensionless number defined as:

$$R_e = \frac{\text{diameter} \times \text{mass velocity}}{\text{viscosity}}$$

By definition, Reynolds Numbers above 4000 indicate turbulent (chaotic) flow, and those below 2000 indicate laminar (smooth) flow. Each membrane element manufacturer has determined the flow requirements for their elements which result in turbulent flow (if allowed), and all systems should be designed using these data. Certain membrane device configurations are susceptible to damage under turbulent flow conditions.

In general, spiral wound and tubular elements are operated under turbulent flow conditions. Polymeric hollow fiber elements cannot be operated under these conditions, but are usually run with high shear rates to minimize fouling.

Membrane Element Array - In order to maintain turbulent flow conditions, elements must be grouped according to specific criteria. Typically, permeate from each element (or pressure vessel in the case of spiral wound configurations) is collected separately in a manifold, where the concentrate from one becomes the feed for the next element (or pressure vessel). Obviously, as permeate is removed from a feed stream, the total volume of concentrate available as feed to the next bank of elements decreases, so the total number of elements in parallel in each successive bank must decrease. With this design, turbulent flow conditions are maintained throughout the entire system.



Pretreatment Requirements – These have been addressed previously, and are further discussed below.

Fouling

Because all membrane technologies are based on the passage of water through a semi-permeable membrane to effect separation, the membrane surface is subjected to the accumulation of suspended solids, precipitated solute, or other contaminants intended to be separated or concentrated from the feed stream, but are not carried out in the concentrate stream.

This phenomenon, known as “fouling,” can be linked to four causes:

1. *Plugging* - Particulate material (dirt, sand, etc.) accumulation on the membrane surface.
2. *Scaling* - As certain dissolved inorganic compounds become more concentrated during processing (usually limited to NF and RO), they may exceed their solubility limits and precipitate on the membrane surface (examples include CaCO₃, CaSO₄, BaSO₄).
3. *Organic Fouling* - Some organic molecules (oils, grease, humic/fulvic acids, surfactants), either naturally occurring or synthetic, may coat and plug the membrane pores.
4. *Microorganisms* - Bacteria, in particular, present a significant fouling problem. As they grow and multiply, many species produce biofilms (organic films of lypopolysaccharides), to encase and protect the bacteria. These biofilms can cover the membrane surface, resulting in fouling, and are capable of collecting and subsequently releasing contaminants, also.

Membrane fouling cannot be prevented, but can be minimized. The following table summarizes the fouling mechanisms, and the specific foulants are discussed below.

Fouling Summary

Foulant	Primary Mechanism	Examples
Suspended solids	Settling	Dirt, clay, silt, dust, hydrous metal oxides, <i>e.g.</i> $Fe(OH)_3$
Precipitated salts (scaling)	Precipitation from concentration effects, Adsorption	$CaCO_3$, $MgCO_3$, $BaSO_4$, $CaSO_4$, SiO_2 , and other insoluble salts
Microorganisms (biofouling)	Adhesion, Adsorption, Biofilm Formation	Bacteria, viruses, protozoan cysts, fungi, algae, molds, yeast cells
Organics	Adsorption, Film forming	Oils, grease, surfactants, coagulants, antiscalants, humic and fulvic acids

Suspended Solids

Most feedwater supplies contain insoluble materials ranging from dirt, clay, colloidal particulate material to film-forming organic material which coats the membrane surface, thus inhibiting normal water permeation through the membrane. These insoluble contaminants are usually grouped together under the heading of TSS (total suspended solids) and can be individually identified from a thorough chemical analysis of the water stream.

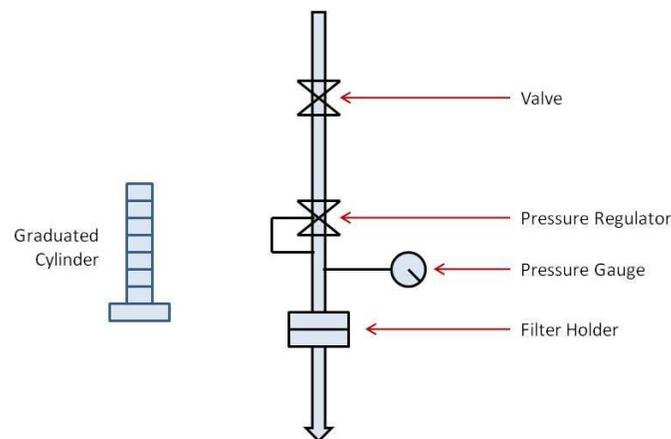
That said, a word of caution about the normal analytical procedure for determining suspended solids concentrations. TSS analytical measurements defined in Standard Methods 2540 D are based on suspended solids removed by glass fiber disc filters. Only solids retained on the disc constitute TSS. The method does not specify disc filter pore size; rather it specifies several disc filters by brand and product number. The ratings vary between 0.7 and 1.5 μ . Since virtually all membrane pore sizes are below 0.50 μ , the concentration of these smaller submicron contaminants cannot be accurately measured by this procedure.

Silt Density Index – This index (SDI), along with turbidity, is also used to measure the potential for membrane fouling from suspended solids.

The advantage of SDI over turbidity alone is that SDI can be used on relatively low turbidity (<1 NTU) water, and as such, is a more sensitive measure of suspended solids in water. The disadvantage of SDI is that it utilizes a “dead-end” test to predict fouling in what is usually a crossflow process.

The lower the SDI, the lower the potential for fouling a spiral membrane. As part of their warranty, most membrane manufacturers require that the feedwater SDI to their elements be <5. SDI is a dimensionless number.

The SDI test itself involves measuring the rate of plugging a 0.45 micron filter, so it is only slightly more sensitive than the Standards Methods test. This test must be conducted online using RO feedwater, and the test equipment is shown below.



Precipitated Salts (Scaling)

In the crossflow membrane processes, purified water is extracted as the permeate stream and contaminants to be removed remain behind. Because these contaminants are concentrated in the concentrate stream [through the process of removing a percentage of the solvent (water) stream as permeate], with the salt rejecting membranes of NF and RO, the solubility of certain compounds may be exceeded by this concentration process, resulting in the formation of a precipitate. This process is commonly called “scaling,” particularly when it involves mineral deposits such as calcium carbonate or calcium sulfate.

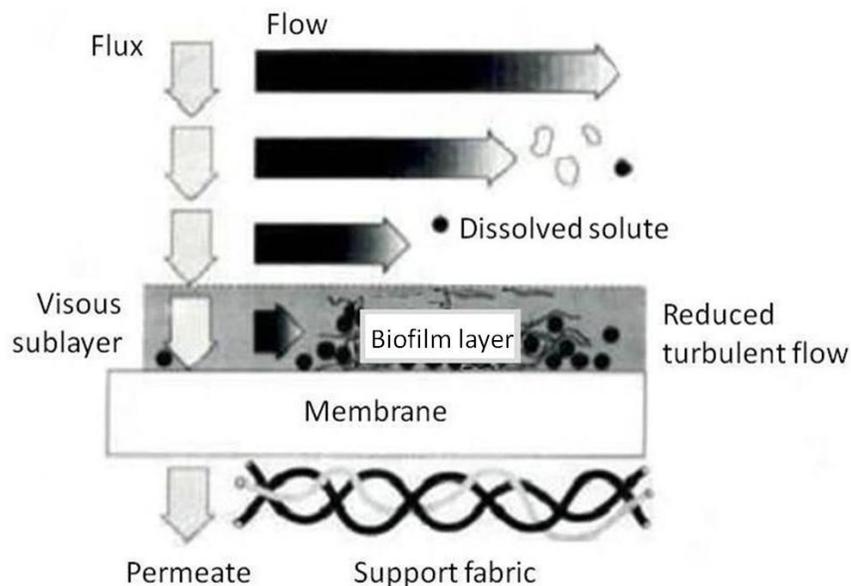
If the feedwater supply is municipally treated drinking water from a groundwater source, it will typically be low in suspended solids, organic contaminants and microorganisms; however, it will likely contain relatively high concentrations of slightly soluble hardness salts such as calcium carbonate. These supplies also often contain iron, discussed below.

Iron and Manganese - Iron and manganese deserve special mention. In groundwater, iron is usually in the soluble ferrous form (Fe^{+2}), but once exposed to air, becomes the insoluble ferric form (Fe^{+3}), potentially causing fouling, as well as staining and other aesthetic issues if the concentration exceeds 0.30 mg/L. For manganese, its solubility limit is 0.05 mg/L, and it can also cause membrane fouling. Interestingly, manganese is under scrutiny by the USEPA as a potential health related contaminant, and will likely end up on the Primary Drinking Water List.

Microorganisms

Certain microorganisms (particularly bacteria) are capable of attaching themselves to the membrane surface and growing prolifically. Because they are “viable” (capable of multiplying without a host), bacteria constitute the most common biofouling class of microorganisms. As they grow, some generate a matrix of organic material (glycocalyx/lypopolysaccharide) that forms a biofilm, which is capable of capturing particulate material, making the film more dense and impervious to water passage. As bacteria are capable of growing under almost any environmental condition, it is impossible to prevent biofilm formation; the best that can be expected is to minimize the rate of growth.

The illustration below indicates the effects of biofilm formation.



Biofilm Formation on a Membrane

Organics Deposition

Organic contaminants (generally non-ionic chemicals) include a huge array of materials such as food products, surfactants, antiscalants, coagulants and pharmaceuticals.

Oily Wastes - These organic contaminants deserve special mention because they can present particular problems with membranes. Most oils encountered in industrial applications are largely insoluble in water. As such, they are capable of coating and fouling all membrane surfaces.

Free Oil – forming a discrete layer on top of the water stream, free oil can be removed by skimming or decanting. Because of the immiscibility of oil and water, free oil is readily removed from the water supply. A number of technologies are available to accomplish this, including activated carbon adsorption, a special clay with oil absorbing properties (oilsorb), dissolved air flotation (DAF), coalescing filters, and others.

Emulsion – oil can be emulsified in water by either using special chemicals (chemical emulsion) or high-speed agitation (mechanical emulsion). If the emulsion is stable, it behaves like a suspended solid and can be removed with microfiltration. Otherwise, the emulsion can be broken by acidification and either the free oil is brought to the surface with dissolved air flotation, or a coagulant such as alum is added to absorb the oil and form an insoluble sludge. Oil-water coalescers, devices that mechanically break emulsions, are also widely used.

Dissolved – certain oily contaminants are soluble in water. These can be treated as other organics and are typically effectively removed with ultrafiltration.

Concentration Polarization

With the salts rejecting characteristics of NF and RO membranes, fouling usually creates a phenomenon known as “concentration polarization.” The fouling layers tend to “capture” salts and inhibit free movement away from the membrane surface and back into the feed stream. Therefore, as salts are rejected from the membrane, their concentration at the surface is higher than in the bulk solution (that portion above the fouling layer). Since ionic rejection is always a percentage of the salts concentration at the surface of the membrane, the permeate quality decreases as a result of concentration polarization, and this phenomenon may actually indicate the presence of foulants before a reduction in permeate rate is detected. The increased salts concentration at the membrane surface also promotes precipitation of those salts whose solubility limit is exceeded as a result of concentration polarization. Concentration polarization is defined by the following equation:

$$C_m/C = B = e^{K(F_p/F_b)}$$

Where: C_m = Concentration at the membrane surface

C = Average bulk concentration

B = Concentration polarization

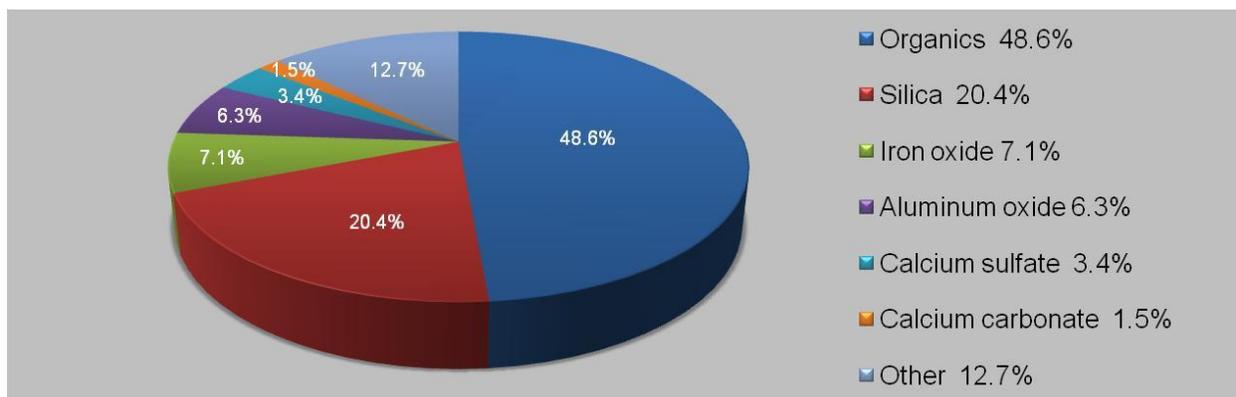
K = A proportionality constant

F_p = Product flow rate

F_b = Average brine flow rate

Other sources of wastewater or processing water within a manufacturing operation may present particular pretreatment challenges. In addition, the system design can play a major role in the likelihood of a membrane fouling.

The figure below illustrates the relative concentrations of specific contaminants identified in numerous autopsies on spiral RO membranes in general water treatment applications.



Fouling Mitigation

To minimize membrane fouling, the following approaches are possible:

- ❖ Pretreatment
- ❖ Membrane device selection
- ❖ System design considerations

Pretreatment

It is imperative that a complete wastewater analysis be run in order to identify which (and how much) of these classes of contaminants is present. This analysis will dictate the pretreatment technologies required. By accurately identifying those contaminants in a feedwater stream that could foul a membrane and by designing a pretreatment scheme to specifically remove them, the fouling potential of a given wastewater supply can be significantly reduced.

In addition to identifying all of the chemical components, such as ionic and organic constituents, the analysis must also address suspended solids, and, if necessary, even the particle size ranges of these suspended solids.

Filtration technologies, described previously, are generally the best candidates for removal of suspended solids. In addition to media, cartridge, bag and continuous technologies, there is a significant movement towards the use of microfiltration to minimize the accumulation of these contaminants on spiral wound reverse osmosis membranes.

In almost all raw water supplies, calcium carbonate concentration is close to the saturation level (~11 mg/L), so this must be addressed by such processes as:

- 1) Softening - Special cation exchange resins are employed as a pretreatment technology to exchange the calcium/magnesium ions in the water with sodium ions on the resin. The sodium is released from the resin into solution, while calcium and magnesium ions are adsorbed onto the resin surface. When the resin has adsorbed as much calcium as its capacity allows, it is automatically regenerated using sodium chloride brine.
- 2) pH adjustment - By lowering the pH of the feedwater to 6.0, 80% of the bicarbonate ion (HCO_3^-) is converted to carbon dioxide (CO_2) and water. The carbon dioxide gas must then be air scrubbed or removed with a special degasification membrane.

The potential for fouling (scaling) from other low solubility compounds can be minimized by the addition of antiscalants which “tie up” these salts. This involves the use of special chemistries for specific potential foulants.

As almost all potable water supplies in the U.S. and many other countries contain a chlorine compound for disinfection, and because the vast majority of RO membrane elements utilize the thin film composite polymer construction, this disinfectant must be removed to prevent oxidation of the polymer, which can result in permanent, irreversible damage. This removal can be accomplished with an activated carbon filter, or by adding a reducing agent such as a sodium bisulfite (NaHSO_3).

The following table lists the appropriate pretreatment technologies for the classes of contaminants.

Pretreatment Technologies

Foulant	Recommended Pretreatment
Suspended solids	Filtration Coagulation followed by filtration
Precipitated salts (scaling)	pH adjustment Softening Antiscalant addition
Microorganisms (biofouling)	Disinfection Chemical addition Ozonation Ultraviolet irradiation Filtration
Organics	Filtration Adsorption Activated carbon Organo clays Special resins Coagulation followed by filtration Oil/water separation Skimmers Dissolved air floatation

The downside to these pretreatment technologies is that most are batch operations, in that once the prefiltration technology has reached its capacity for contaminant removal, it must be taken offline, discarded or otherwise treated to restore (or replace) its capabilities.

Membrane Device Selection

In applications where salts removal are required, NF and RO technologies are leading choices. For these technologies, with almost no exception, the device configuration is spiral wound. The reason is primarily economics. All of the spiral elements on the market are sized by the manufacturers to compete with each other. This competitive pressure means that these elements are significantly less expensive in capital cost than the other configurations. On the other hand, the weakness of the spiral elements is their susceptibility to fouling. The inability to be backwashed exacerbates this problem.

The capability of a membrane element to be backwashed to remove accumulated fouling material from the membrane surface is very important. Spiral wound NF and RO elements cannot be backwashed, because the pressure differential can delaminate the thin film. The close spacing of the membrane layers also contributes to their higher pretreatment requirements, as compared to the other configurations. Although most of the plate & frame devices cannot be readily backwashed, the tubular and hollow fiber configurations usually incorporate backwashing as a component of system design. MF and UF spiral wound elements are also capable of being backwashed.

The following table indicates which element configuration and membrane technology can be backwashed/backpulsed.

Membrane Element Backwashing Capability

Element Configuration	Membrane Technology				Backwashable?
	MF	UF	NF	RO	
Plate & Frame	Yes	Yes	Yes	Yes	No (except for inorganic membrane)
Tubular	Yes	Yes	Yes	Yes	Yes
Hollow Fiber	Yes	Yes	Yes	No	Yes
Spiral Wound	Yes	Yes	Yes	Yes	No (NF, RO) Yes (MF, UF)

To minimize fouling events in spiral wound element systems, several approaches have been incorporated into system designs. One is the “fast flush” process, whereby the concentrate valve is temporarily bypassed to lower the recovery and increase the flow rate over the membrane surface. Most large systems are equipped with an automatic feature set to accomplish this at preset intervals.

Another is the “reverse flow” procedure where the feedwater is piped to allow an occasional change in direction. This helps to dislodge membrane deposits, but requires rather involved piping and valving.

Yet another approach is known as “Direct Osmosis High Salinity Cleaning.” This involves running a “plug” of very high TDS saline feedwater through the system, and the resulting osmotic pressure differential causes some permeate to flow backwards into the feed side of the membrane, thereby removing fouling materials. Obviously, this approach is quite involved.

For tubular elements, “sponge balling” has been used to effect cleaning. Small sponge balls are retained in the elements and occasionally directed through the element from one end to the other to scrub the interior surface.

System Design Considerations

The mitigation of membrane fouling is the dominant factor driving membrane system design.

The permeate rate of a given membrane element cannot be changed without varying the applied pressure or temperature. Recovery, however, can be easily changed by varying the feed flow rate to the element, and this is one of the variables controlled by the system designer.

The effect of recovery on system performance is important and has been addressed earlier.

Also as discussed earlier, if turbulent flow rates can be maintained in those elements that can accommodate them, they can help keep suspended solids from fouling membranes.

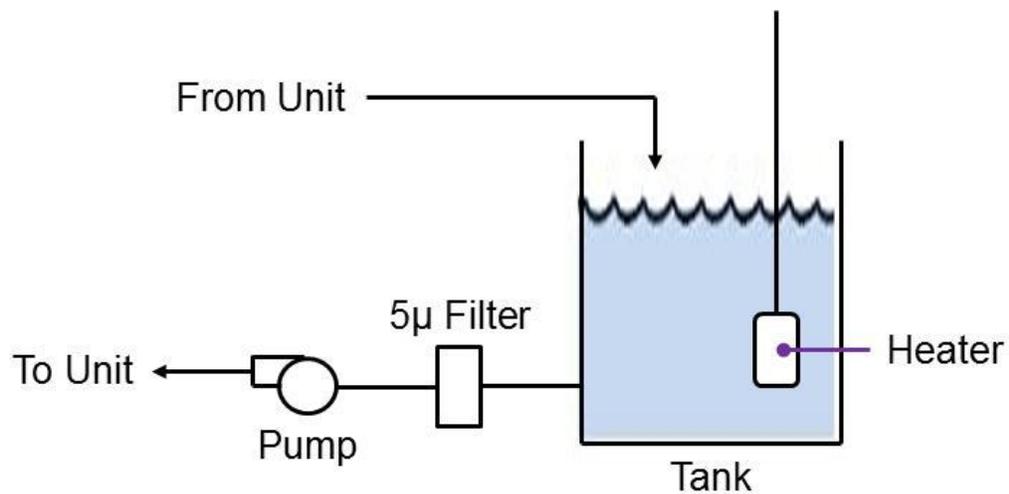
In straight pipe, the water velocity range for turbulent flow is 3-5 m/sec (10-16 ft./sec.).

Cleaning & Disinfection

Cleaning

Because no amount of pretreatment will completely eliminate fouling, cleaning ultimately will become necessary. As a rule of thumb, the time to clean is dictated by a 10% to 15% reduction either in product water flow or, for NF and RO, product water quality. As a result of concentration polarization with NF and RO membranes, a drop in product water quality may signal the onset of fouling before a drop in permeate flow.

A well-designed membrane processing system includes a clean-in-place (CIP) system. An appropriately sized tank containing the cleaning solution is equipped with a pump to direct the cleaning solution into the membrane system. The permeate and concentrate flows are returned to the cleaning system storage tank to accomplish recirculation of the solution. Depending on the nature of the foulant and type of cleaner used, the solution may be heated and the membrane exposed to high velocities, soaking, etc. In addition, the cleaning solution may be reused several times before discarding. A typical CIP system is illustrated below:



CIP System

Just as there is an almost endless array of fouling materials, there are numerous chemical cleaners that have been developed for specific classes of foulants: typically acids for removal of scalants such as ferric hydroxide and calcium carbonate, caustics for silicates and many organic contaminants, and enzymatic cleaners for biofilms and other organic contaminants.

Scale removal often is accomplished by cleaning with a weak acid such as citric or sulfamic. Chelating agents such as EDTA tend to complex the scale and aid in its removal. Mineral acids such as hydrochloric (HCl) and sulfuric (H₂SO₄) are effective, but are hazardous to handle and may attack certain membrane polymers. Weak acids are easier to handle, but generally require longer cleaning times.

Colloidal foulants may be removed with chelating agents or dispersants, often in combination with surfactants. Metal oxides are usually removed with acidic cleaners and chelating agents. Biofilms are most effectively removed with enzymes, often accompanied by surfactants and chelating agents. Oil/grease foulants can be dissolved with alkaline solutions containing surfactants and emulsifying agents such as sodium lauryl sulfate. Strong alkaline solutions may hydrolyze cellulosic membrane polymers and attack some ceramics.

Following cleaning, it is usually very important to disinfect the system.

Disinfection

In water supplies, microorganisms are particularly difficult contaminants to control. These include bacteria, viruses, protozoa, fungi, and algae. The ubiquitous nature of these contaminants, especially bacteria, and the fact that some bacteria multiply under virtually any condition, make it impossible to eliminate them completely from a water treatment system. Disinfection is the process used to kill or inactivate these organisms. Most chemical disinfectants are normally fed into the water treatment system following the cleaning step. They are allowed to circulate for a time and then rinsed out with clean water prior to returning the system to use.

With regard to disinfecting thin film composite RO and NF membranes, it is important to understand that virtually all oxidizing agents will attack the polymer and render it unusable. Some success has been realized with peroxyacetic acid (PAA); however, its efficacy is marginal, is difficult to rinse out of the membrane element, and does shorten membrane life.

A non-oxidizing biocide, DBNPA (2,2-dibromo-3-nitrilopropionamide), has found some success, but is not approved for potable or other human-contact applications. It may be useful in wastewater applications, however.

The MF and UF membrane polymers generally all have acceptable resistance to oxidizing disinfectants.

A more complete discussion of water disinfection is in Part II.

Testing for Membrane Applications

Introduction

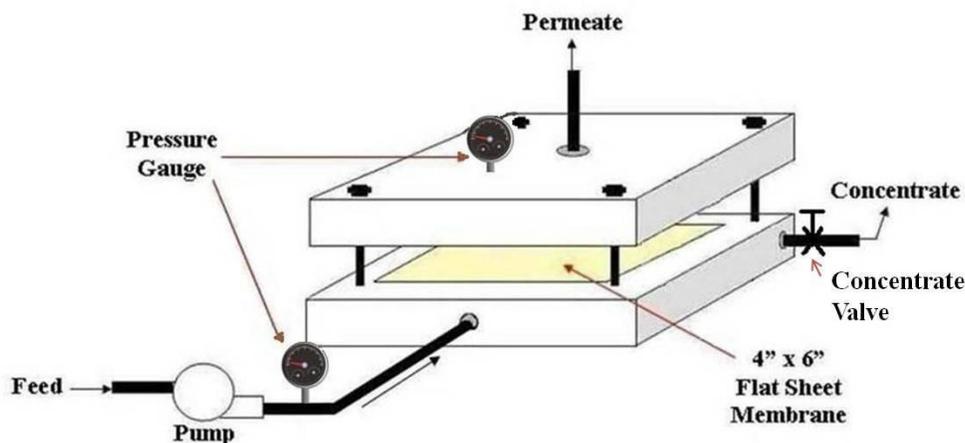
The importance of testing a given wastewater stream cannot be overstated. This is especially critical in wastewater reuse applications for the following reasons:

- The stream may be unique, one-of-a-kind; therefore lacking any prior test data.
- The high system recovery typically characteristic of these applications significantly amplifies the concentration effects of the stream constituents.
- To generate membrane-based design data, it is necessary to evaluate the effect of the concentrated constituents, not only on the various membrane choices, but on the system operation and even on each other.

To generate the necessary design data, several testing options are available, as described below.

Cell Testing

A typical cell testing device is illustrated below:



Cell Test Unit

Cell test devices are available for purchase (or use through a consulting engineering firm skilled in the art), which evaluate small sheets of membranes on the stream to be processed. Typically, the sheet is placed between two stainless steel plates, and the test stream pumped across the membrane surface at a selected pressure and flow rate. Permeate is collected and analyzed for degree of separation, possible effect of the stream on the test membrane, and other characteristics.

The cell test offers a number of *advantages*:

- ✓ Only small areas of membranes are needed; excellent for screening membrane polymer candidates.
- ✓ Can be run on small volumes of test stream.
- ✓ Takes very little time.
- ✓ Unit is simple to operate.

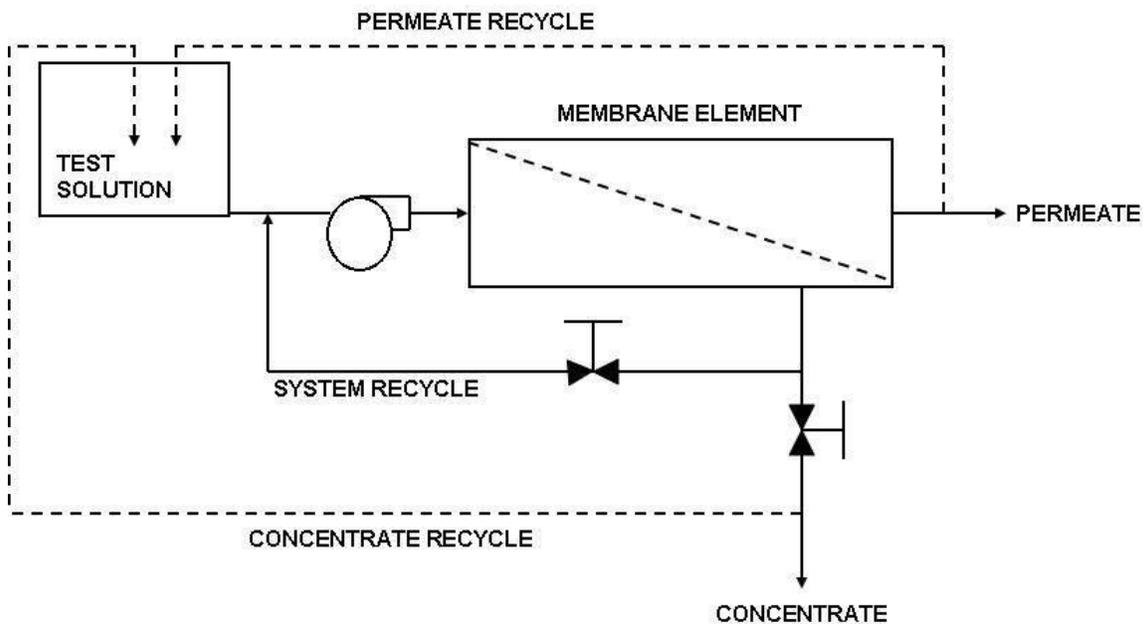
The *disadvantages* of this testing approach are:

- ✓ Cannot obtain engineering design data.
- ✓ Cannot be used for long-term fouling study.
- ✓ Is only useful with membranes available as flat sheet.

The cell test approach is useful as an initial step, primarily to select one or more membrane candidates for further evaluation.

Applications Testing

The figure below illustrates an applications test schematic.



Applications Test Schematic

Applications testing utilizes a membrane element in a test unit capable of operating similar to a production unit. Since the data from this testing will be used to scale up the design to full size, it is essential that the membrane element manufacturer supplies an element capable of this scale up.

The applications test equipment should be designed so that very high recoveries can be achieved without compromising the flow rates required to produce turbulent flow, for example. This requires that the pump be capable of not only producing the desired pressure, but also the flow rate to accomplish the minimum crossflow velocity across the membrane surface.

Because the system must be capable of testing at very high recoveries, the concentrate valving must be adjustable to accurately produce extremely low flow rates. This typically involves the assembly of a “valve nest” using micrometer valves. Additionally, the recycle line should be equipped with a diaphragm valve for adjustment of flow and pressure.

The most important feature for application testing equipment is versatility. Different membrane elements have very specific operating parameters, and the equipment must accommodate these.

To cover the entire gamut of membrane technologies, two different pieces of application testing equipment are normally required: one for MF and UF, and the other for NF and RO.

The latter must be capable of pressures up to 1,000 psi (68 bar), and it is virtually impossible to find a single pump capable of supplying the flows and pressures required for all four technologies. For MF and UF applications, a variable speed drive centrifugal pump works fine, although the variable speed feature makes it expensive.

Materials of construction are an important consideration in testing considerations: 316L stainless steel is essential for applications requiring pressures in excess of 60 psi (4 bar); below that, schedule 80 PVC is sufficient.

Applications testing is capable of generating complete design data for the full sized system. An applications test can be run on as little as 50 gallons (200L) of test stream, and after setup, can be completed in one hour or less, for each membrane element tested.

A typical applications test is run as follows:

1. To establish “control conditions,” high quality water (tap water or water treated with RO or DI) is run into the system at low recovery to minimize any possible contaminant concentration effects. Data are then recorded (see Membrane Application Test Data Sheet).

2. Wastewater is then run into the unit set at low recovery, and after stabilization (usually less than 5 minutes), the following data are taken:

Pressures

 Prefilter

 Primary (feed)

 Final (concentrate line)

Flow Rates

 Recycle

 Permeate

 Concentrate

Temperature (recycle)

Quality (conductivity)

 Feed

 Permeate

 Concentrate

The system recovery is then increased incrementally while adjusting the recycle valve to ensure that the correct crossflow velocity is maintained.

3. At the conclusion of the testing, high quality water is again run through the system to determine if the permeate rate or other operating characteristics have been affected.

At each recovery, in addition to the collection of flow and pressure data, analytical samples should be taken for performance evaluation. Of course, the choice of parameters to be measured depends upon the separation goals of the test. It is unusual for system recoveries to exceed 95%; however, that also depends upon the goals of the testing, and it is possible to run a well designed test unit up to 99% recovery.

Once the optimum conditions have been established, such as operating pressure and maximum system recovery, the normalized performance data will enable the test engineer to determine the total membrane area required for the full sized system.

Application testing provides the following advantages and disadvantages:

Advantages:

- ✓ Fast.
- ✓ Provides scale-up data (flow, osmotic pressure as a function of recovery, pressure requirements, etc.).
- ✓ Can provide an indication of membrane stability.

Disadvantages:

- ✓ Does not reveal long term chemical effects.
- ✓ Does not provide data on long term fouling effects.

Pilot Testing

Usually this involves placing a test machine (such as that used for applications testing) in the process, operating continuously on a “side-stream” for a minimum of 30 days.

Advantages:

- ✓ Accomplishes all of the functions of the applications test plus provides long term membrane fouling and stability data.

Disadvantages:

- ✓ Expensive in terms of monitoring and time requirements.

Following is a summary data chart for the testing options.

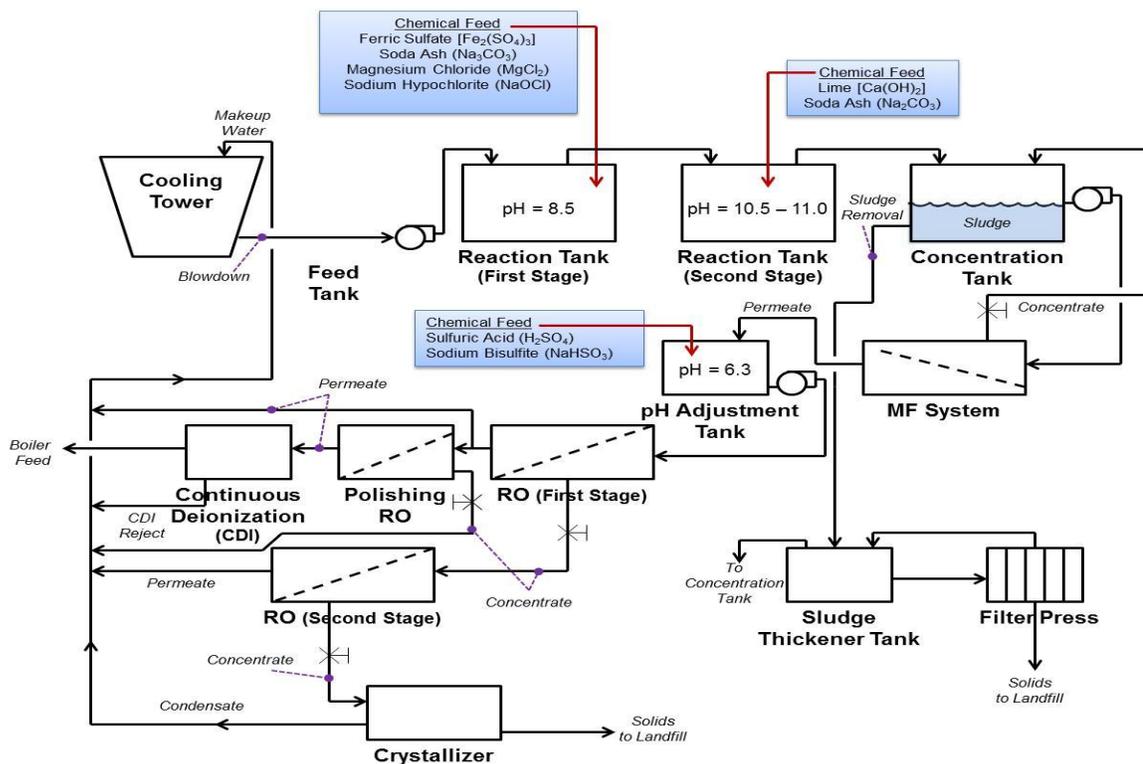
CASE HISTORIES

Zero Liquid Discharge of Cooling Tower Blowdown

The feedwater to a large municipal power plant contains unacceptably high concentrations of hardness salts and silica. The blowdown is chemically treated to precipitate these contaminants, and MF (microfiltration) is utilized to dewater the precipitated solids. The sludge is further dewatered in a filter press and the solids landfilled.

The MF permeate is treated in several stages of RO (reverse osmosis), with a portion highly purified with electrodeionization for boiler feed, and the rest returned to the cooling tower as makeup water.

The total feed rate to the treatment system is 350 gpm (1909 m³/day), and the illustration below depicts the total treatment system.



Cooling Tower Blowdown Treatment System

Introduction

The High Desert Power Project, LLC, is a large California power generator using microfiltration (MF) technology to treat and reuse cooling tower blowdown in a ZLD (Zero Liquid Discharge) process.

In operation since 2003, the process consists of chemical addition to the blowdown water to effect hardness and silica removal by precipitation. The precipitated solids are then continuously removed with microfiltration technology.

The MF treated water (permeate) is pH adjusted and directed to a first stage reverse osmosis (RO) unit, where a portion of its permeate is sent directly to the cooling tower as makeup water, and the remainder to a polishing RO with its permeate treated with Continuous Deionization (CDI) technology for boiler feed. The concentrate stream from the first stage RO unit is sent to a second stage RO with its permeate utilized as cooling tower makeup, and concentrate dewatered in a crystallizer. The polishing RO concentrate stream is utilized as cooling tower makeup water.

Process Description

The cooling tower is fed by clarified California Aquaduct Water. Cooling tower blowdown is pumped to a first stage reaction tank. Ferric sulfate, soda ash, magnesium chloride and sodium hypochlorite (bleach) are added; the pH in this tank is approximately 8.5, which initiates precipitation of calcium carbonate and silica.

Effluent from the first stage reaction tank overflows into a second stage reaction tank which receives lime and soda ash, raising the pH to 10.5-11.0, to further precipitate calcium carbonate and silica.

This tank overflows into a concentration tank which also receives the concentrate (“reject”) stream from a microfiltration (MF) system. The concentration tank collects precipitated and chemically saturated solids, and the resulting sludge is fed to a sludge thickener tank.

The suspended solids slurry in the concentration tank is directed to an MF system for virtually complete removal of these solids. The MF permeate (that portion of the feed stream that passes through the membrane), flows into the pH adjustment tank where it receives sodium bisulfite to neutralize chlorine (from the bleach addition) in the tank, and hydrochloric acid to lower the pH to 6.3.

As stated earlier, the MF concentrate transports suspended solids out of the MF system and back to the concentration tank. Over time, the total solids concentration in this tank increases to about 5%, at which time, the solids are pumped to the sludge thickener tank that feeds a filter press. The dewatered solids are hauled to a landfill and the liquid portion is directed back to the concentration tank.

From the pH adjustment tank, the treated MF permeate is processed with reverse osmosis (RO) technology, and the first stage permeate stream is either returned as makeup to the cooling tower or fed to a polishing RO. The permeate from the polishing RO is directed to a Continuous Deionization system to produce boiler feedwater, and the concentrate stream becomes part of the cooling tower makeup water.

The concentrate stream from the first stage RO is fed to a second stage RO, with the permeate from this system directed back to the cooling tower as makeup water, and the concentrate stream fed to a crystallizer. The solids from this unit are delivered to a landfill, and the crystallizer condensate returned to the cooling tower as makeup.

Treatment Technologies

To allow reuse of cooling tower blowdown water as boiler feed, it is necessary to employ a number of advanced technologies.

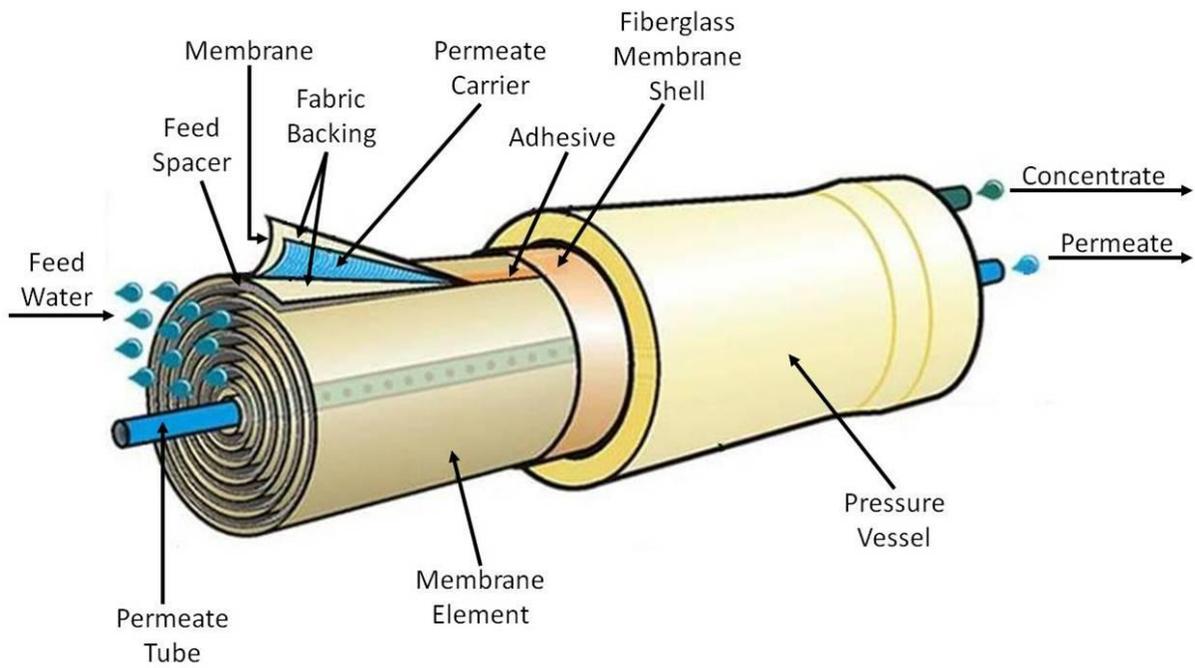
Usually, suspended solids have to be removed, followed by dissolved solids.

The technologies required to remove dissolved solids (reverse osmosis, Continuous Deionization, and others), are deleteriously affected by suspended solids and slightly soluble salts that precipitate upon concentration.

Conventional lime softening is the traditional hardness reduction process for high volume flows, and involves adding lime $[\text{Ca}(\text{OH})_2]$ and soda ash (Na_2CO_3). As the pH is increased from the lime addition, calcium carbonate, magnesium hydroxide and magnesium carbonate precipitate. Magnesium hydroxide also removes silica via adsorption as it precipitates.

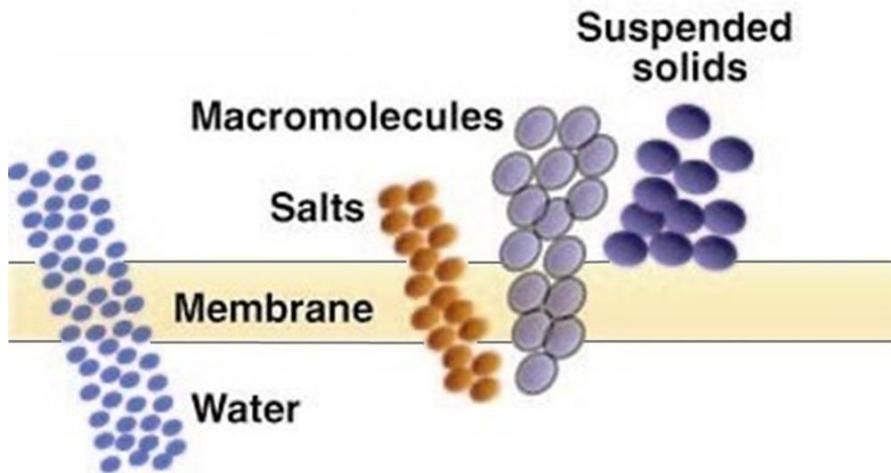
As stated earlier, spiral wound RO membrane elements are the least expensive, but most susceptible to fouling by suspended solids. In many cases, the normal multimedia filtration process, often utilized in lime softening, does not provide adequate suspended solids removal to minimize membrane fouling. This is where the superior filtration capabilities of MF technology can be exploited.

An RO element in its pressure vessel is illustrated below.



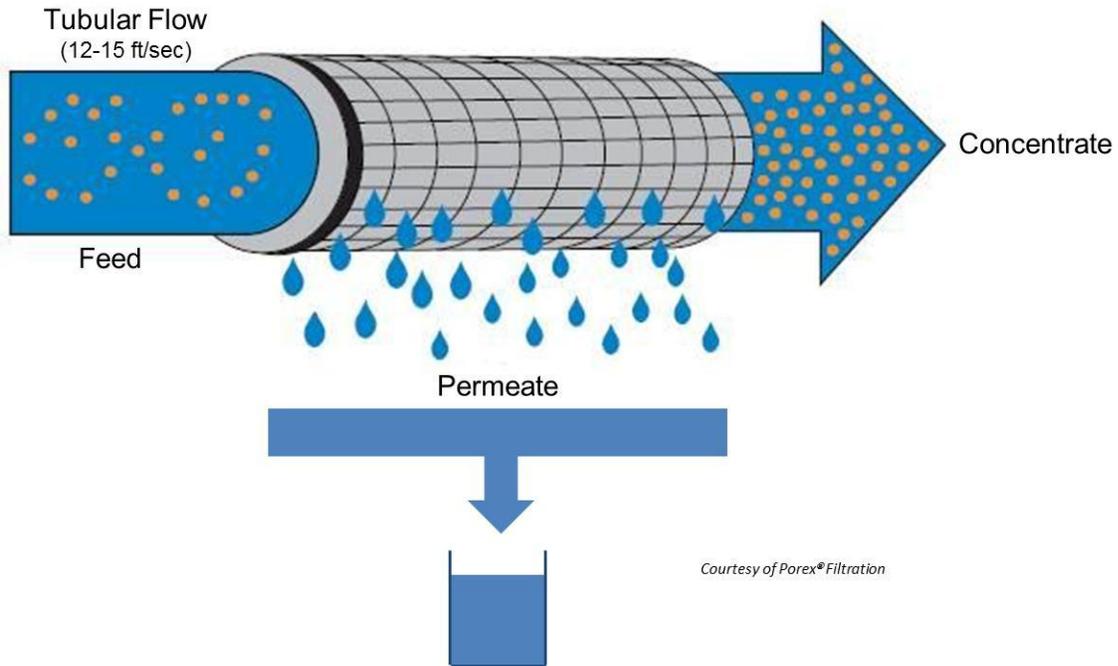
Spiral Wound Element Inside a Pressure Vessel

The mechanism of microfiltration is depicted below.

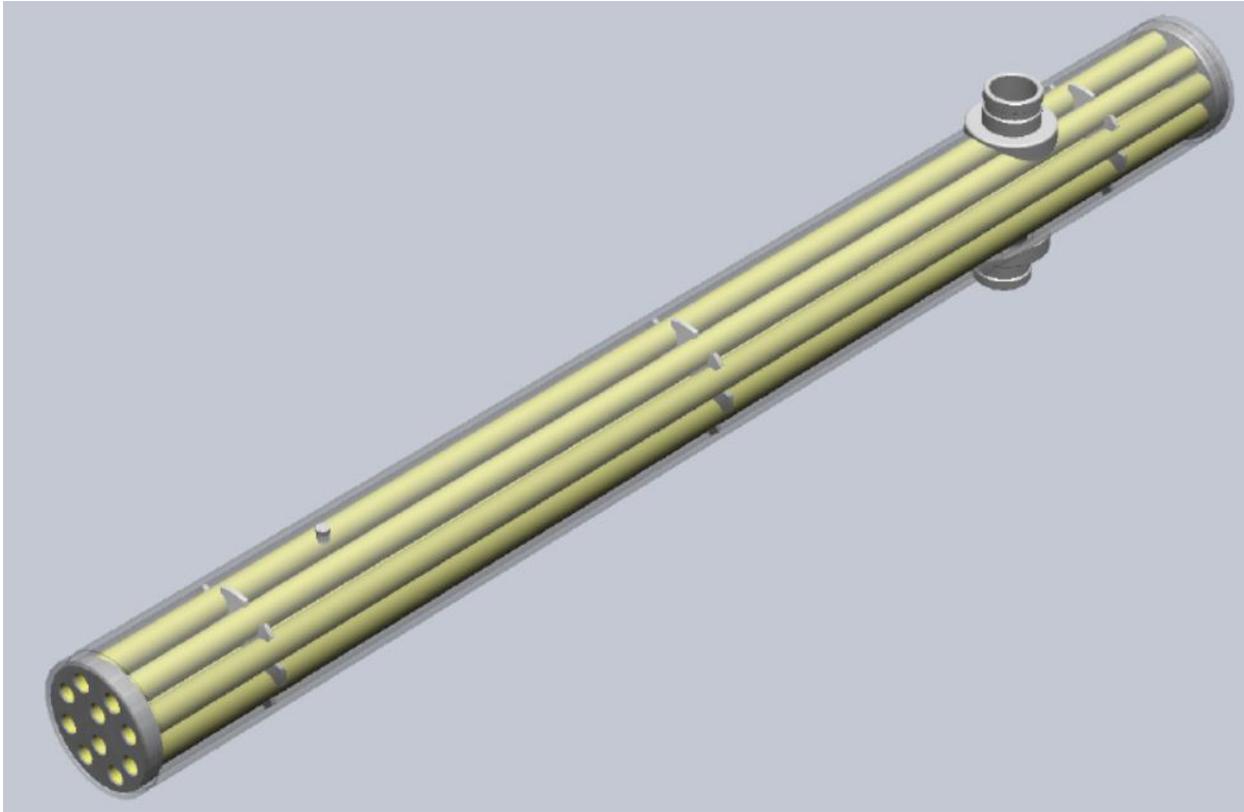


Microfiltration

The MF membranes used in this application are Porex® TMF tubular membranes, below.



Specifically, the tubes are 1" I.D., with a polyethylene substrate supporting a PVDF (polyvinylidene fluoride) layer with 0.10 μ pores. The membrane modules are illustrated below.



Each membrane module consists of ten 72” long tubes enclosed inside a PVC housing. Specifications on the modules and tubes are as follows:

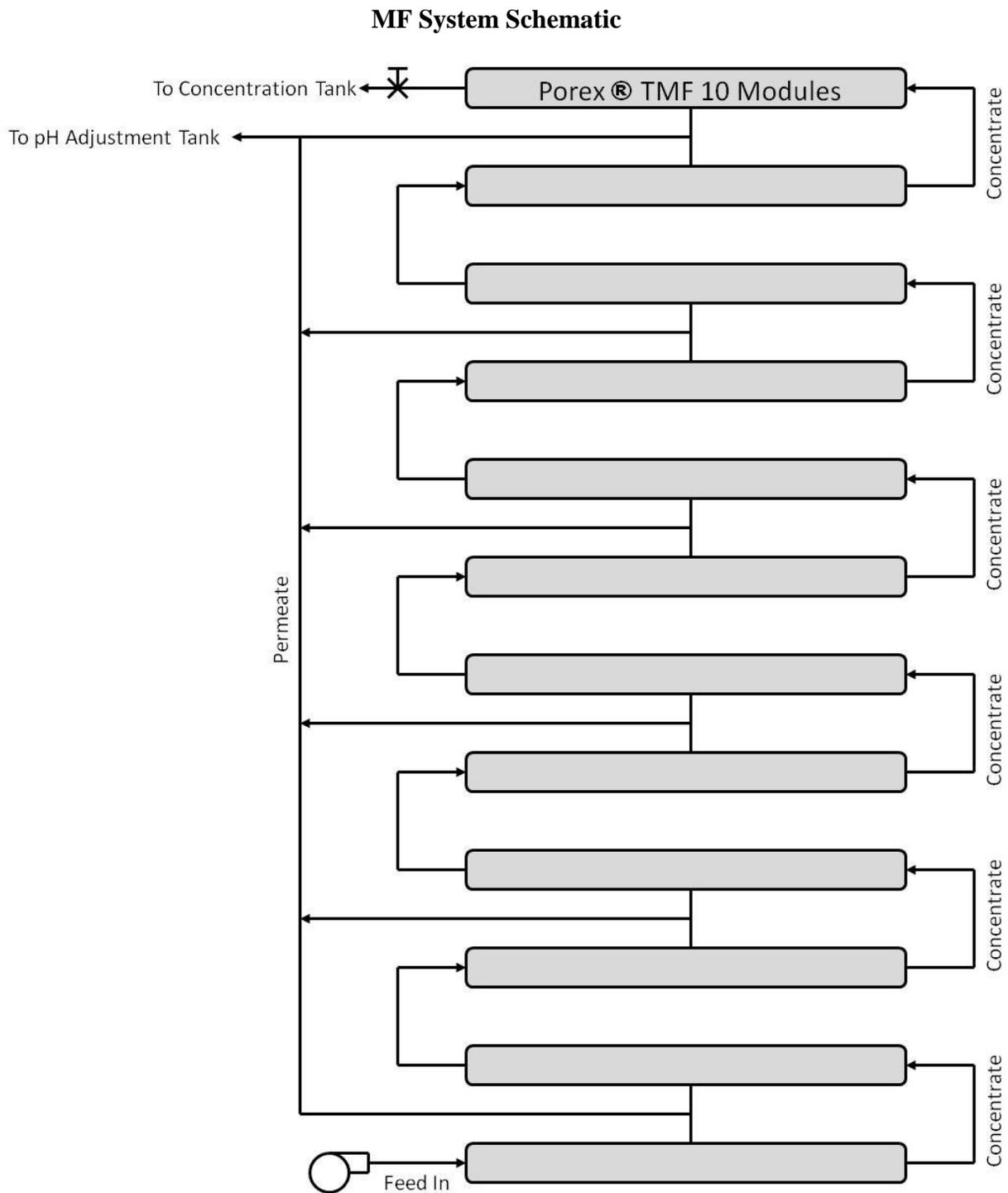
Modules	
Housing Diameter	6" Schedule 40
Permeate Port (Qty 2)	2.875"Ø x 1.89" L pipe stub
Concentrate Ports	6"Ø pipe Anvil Gruvlok groove
Mounting Required	Horizontal; 2 point
Module Length	72"
Tubes	
Number of Tubes	10
Nominal ID	1"
Nominal OD	1.34"
Total Active Surface Area	15.2 ft ²
Internal Liquid Volume	
Permeate Volume	4.33 gallons
Concentrate Volume	2.45 gallons
Total Volume	6.78 gallons
Materials of Construction	
Potting	Solvent Cement
Internal Supports	Polypropylene
Gasket Material	None
Preservative (Shipping)	Propylene Glycol
Membrane	PVDF

The feed flow is down the center of the tube (lumen feed) with the permeate passing through the tubular wall and collected from the area around the outside of the tubes inside the housing. A total of 216 Porex® modules are in this MF system.

System Design

The modules are divided into six skids, each containing three trains of 12 modules linked in series. The feed stream enters one end of the first module with the concentrate exiting the other end as feed for the next module. This flow continues through the 12 modules, and returns to the concentration tank. Meanwhile, the permeate from each module is collected in parallel and fed to a header where it is directed to the pH adjustment tank for further treatment by reverse osmosis.

A train of 12 modules is illustrated below.



The following table summarizes the performance of this MF system:

Parameter	MF Feedwater	MF Permeate
pH	8.0	10.7
Total Hardness	2122 mg/L	127 mg/L
Total Alkalinity	58 mg/L	197 mg/L
Turbidity	4.63	0.03 NTU
Silica	99 mg/L	6 mg/L

Reverse Osmosis

The first stage RO removes dissolved solids with a portion of its permeate supplying the cooling tower with makeup water, and the remaining permeate flow directed to a polishing RO for additional dissolved solids removal and then further purified in a Continuous Deionization unit to produce high quality boiler feedwater.

The concentrate streams from the first stage and polishing RO units are combined and fed to a second stage RO with its permeate utilized as cooling tower makeup water, and its concentrate treated in a crystallizer to produce solids for landfilling. The crystallizer condensate is used for cooling water makeup.

The following table lists the feed and permeate rates for the RO systems; along with the resulting recovery calculations (permeate rate ÷ feed rate) for each.

	Membrane Systems Flows and Recoveries		
	First Stage RO	Polishing RO	Second Stage RO
Feed Rate (gpm)	350	110	150
Permeate Rate (gpm)	255	82	100
System Recovery (%)	73%	75%	67%

Cleaning

Because the MF system continually dewateres the precipitated hardness and silica solids, removing the filtered water and returning the solids to the concentration tank, these solids steadily increase in this tank to 5% (weight). At this point, the solids are drained into the sludge thickener tank ahead of the filter press.

As the solids in the concentration tank increase, the fouling layer inside the tubular membrane elements also increases, which reduces the permeate flow through the membrane. To minimize this, the velocity of liquid is maintained at a high flow rate (12-15 ft/sec)(4-6 m/sec) to ensure turbulence inside the membrane elements.

The idyllic climate of southern California is not only attractive to two-legged creatures, but also to microorganisms. When the weather turns hot, bacteria proliferate, resulting in significant biofouling in the treatment system.

Although chlorine is added to reduce bacterial activity, the high pH environment reduces the efficacy of this disinfectant, and care must also be taken to ensure that is completely removed prior to the RO units.

When fouling increases to a certain point, a number of procedures can be employed to restore flux, including backpulsing with air or permeate, backwashing with permeate, or interrupting the flow through the modules to allow the membranes to “relax,” and fouling material to drop off the membrane surface.

Acid Cleaning

When the permeate rate from a skid drops to approximately 60 gpm (~14 m³/hr), chemical cleaning is required. Usually, the modules are initially cleaned with a 3-5% hydrochloric acid (HCl) solution to dissolve accumulated calcium carbonate and other acid-soluble deposits.

Utilizing a dedicated CIP (clean-in-place) system, the acid solution is pumped into the skid, and this cleaning solution is circulated through the MF modules for 15 minutes, followed by a 45 minute soak. The solution is then recirculated through the membrane system for another 45 minutes. This solution is then returned to the CIP storage tank and the modules flushed and rinsed with high quality water, which is also returned to the rinse tank for reuse.

Caustic Cleaning

When acid cleaning is no longer effective in restoring the flux rate (usually between one and four times per month – a function of the time of year), a high pH cleaning is performed. This CIP system utilizes sodium hydroxide (NaOH) and sodium hypochlorite (NaOCl) in a cleaning solution containing 12-15% NaOCl at a pH of 12-13. This cleaning step is effective in removing biofilm and other organic foulants.

The solution is circulated through the MF modules for 30 minutes, followed by a 150 minute soak and 30 minutes of recirculation.

The MF system was designed with an extra skid so that one is always available during these cleaning processes, without affecting the total plant processing rate.

Conclusions

Each component in this system contributes to the overall success of this unique design. The chemical additions to the reaction tanks result in hardness and silica precipitation. The MF system continuously removes clarified water from the solids. This treated water is further polished with RO technology to remove salts to either generate cooling tower makeup water or to feed Continuous Deionization technology to produce boiler feedwater.

The effectiveness of MF technology is underscored by the fact that the RO units can recover a very high percentage of the treated water for complete reuse. In addition, the RO membranes need cleaning no more frequently than every six months.

The sludge resulting from hardness and silica precipitation is dewatered in a filter press and landfilled. The liquid stream from the filter press is redirected to the MF system.

The concentrated salts from the reverse osmosis units are rendered insoluble in a crystallizer with these solids landfilled. The crystallizer condensate is also used as cooling tower makeup.

Orange County Ground Water Replenishment System

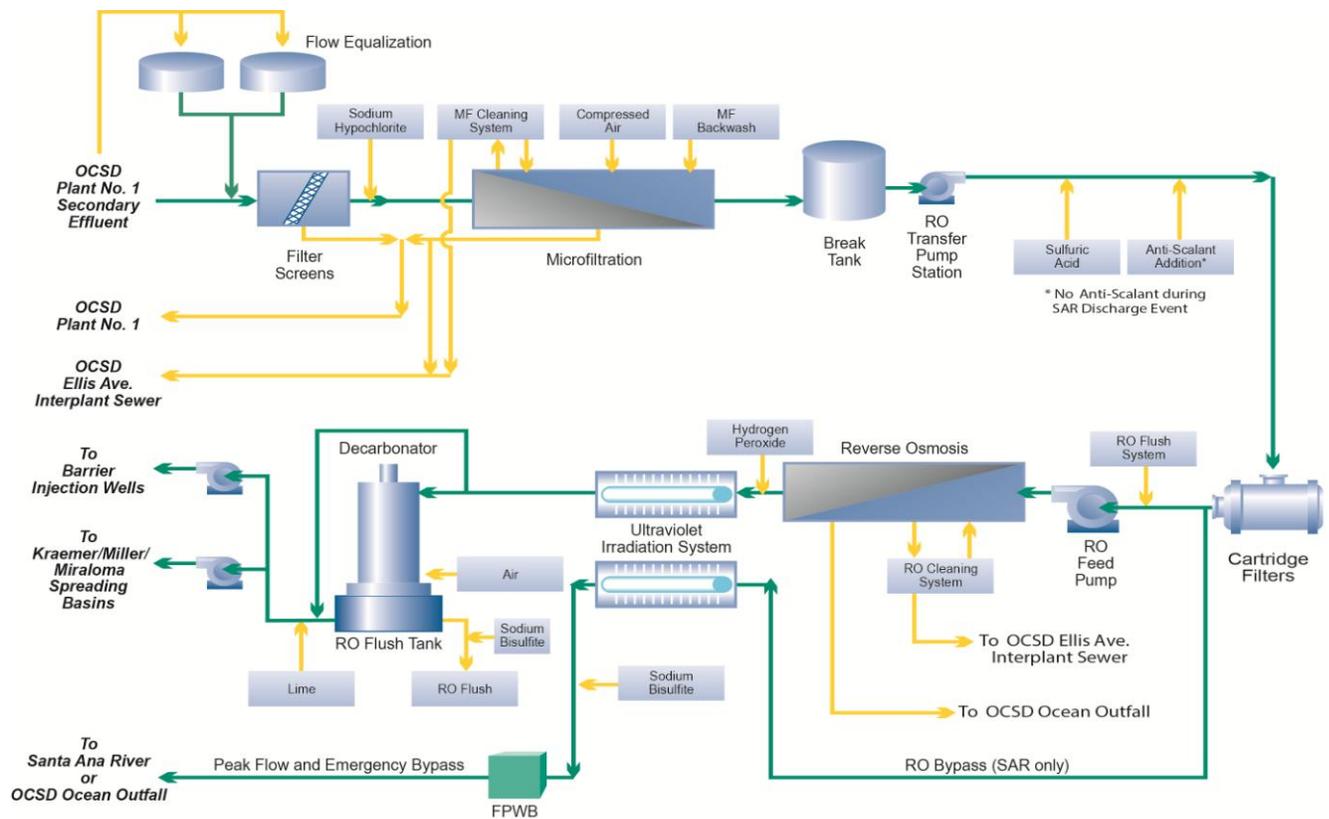
Introduction

The "poster child" in the U.S. for Indirect Potable Reuse is the Ground Water Replenishment System (GWRS) located in Orange County, CA, just south of Los Angeles.

Operational since 2008, the system now produces 100 million gallons per day (100MGD or 379,000 m³/day) of high quality potable water from secondary treated sewage.

This treated water is injected into the aquifer as the municipal water supply, and to minimize seawater intrusion. It is the only drinking water source for 850,000 people.

The illustration, below, depicts the complete system.



Orange County Ground Water Replenishment System

The wastewater comes from the Orange County Sanitation District following Secondary Treatment, which includes activated sludge and trickling filter treatment.

The influent TDS averages about 950 mg/L, with 22 mg/L of silica.

If the total treatment system is broken down into its three components, Pretreatment, Primary Treatment and Post Treatment, the technologies can be identified as follows:

Pretreatment

Hollow fiber MF unit (Evoqua) rated at 0.2 μ pore size. This unit produces 144MGD and is designed to backwash every 22 minutes with CIP (Clean in Place) every 21 days.

Primary Treatment

RO unit (100MGD) with three banks (stages), and an array of 78-48-24 pressure vessels. RO elements are from Hydranautics, Dow and CSM. The overall recovery for this unit is 85%, with an operating pressure in the range of 150 to 220 psi (10-15 bar).

Post Treatment

Advanced Oxidation unit consisting of low pressure UV (Trojan) with 3 mg/L of hydrogen peroxide added to enhance oxidation and disinfection. Also included decarbonation to remove absorbed carbon dioxide, and lime addition to raise the pH.

The concentrate and backwash streams from the MF and RO units are delivered to the Orange County Sanitation District for ocean outfall.

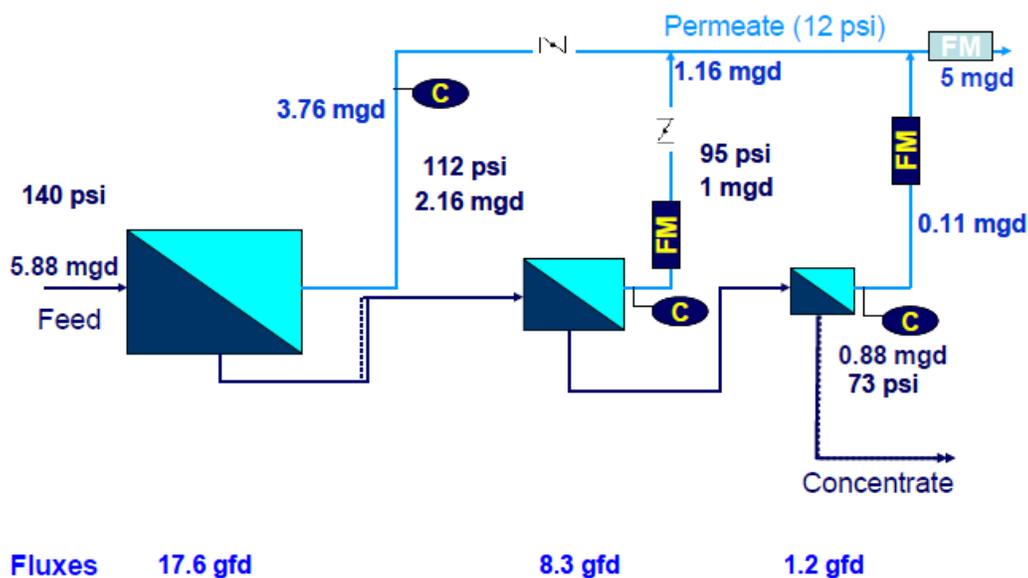
Economics

The total capital cost is slightly over \$480 million.

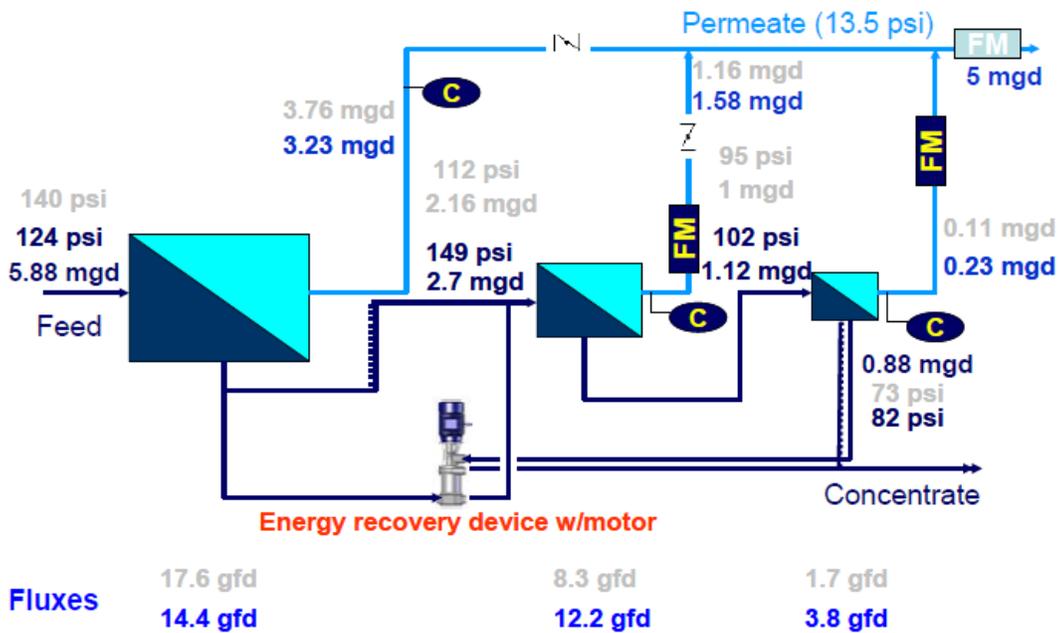
The operating cost, including debt service amounts to \$1.72/1000 gallons (\$0.454/m³). Without debt service, this figure is \$1.11/1000 gallons (\$0.293/m³). These data are based on actual operating costs incurred during the period from July to December, 2015.

Energy Recovery

ERDs (Energy Recovery Devices) have been installed on the concentrate streams of the third banks of the RO units. These ERDs boost the feed pressure to the second banks. Average energy consumption has been reduced by 21.5 kW, amounting to a savings of \$17,000/year (based on electricity cost of \$0.010/kWh and 90% operating time), providing a 5 to 9 year payback. The “before” and “after” illustrations are below.



Schematic of Existing RO Units without ERD



Schematic of New RO Units with ERD

Credit: Veerapaneni, S, "Expansion of the Orange County's Ground Water Recharge System – Energy and Performance Optimization" (IDAWC 15)

Conclusions

Without a doubt, the greatest accomplishment leading to the construction and installation of this system is the full support of the community embracing the concept of "Toilet to Tap." This public outreach activity included more than 1200 presentations to the public as well as 700 tours provided to interested parties.

Support came from such diverse groups as health experts, hospitals, environmental organizations, businesses, educational, religious, police and fire leaders, and other community entities.

A relatively small city in Texas has recently installed direct potable reuse, where the treated wastewater is being fed directly into the drinking water distribution system.

This is the wave of the future, and will continue to grow as the public recognizes the value of conservation and reclamation.

Food Processing Wastewater Treatment & Reuse

Introduction

Commercial Bakery

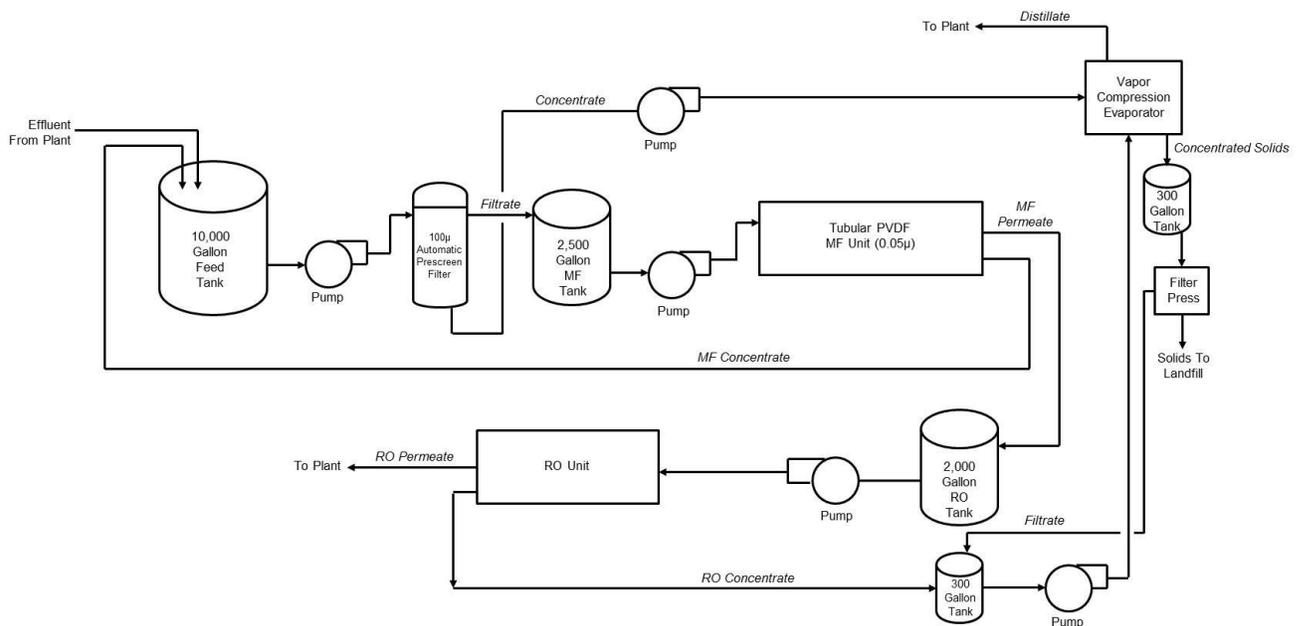
Source – Wastewater from grain steeping (soaking) process

Volume – 15,000 gpd (57 m³/day)

Contaminants – Up to 50,000 mg/L BOD (biochemical oxygen demand) and over 5000 mg/L TSS (total suspended solids). Discharge limit for each parameter is 250 mg/L.

Testing determined that the high organic loading of the feedwater required prescreening down to 100µ with a continuous filter, followed by MF, utilizing a 0.05µ tubular PVDF membrane. The concentrate from this unit is directed back to the feed tank and the permeate directed to an RO unit for polishing. This permeate is used for process water in the plant, and the RO concentrate processed in a vapor compression evaporator with the solids further dewatered in a filter process.

Following is an illustration of the final treatment system.



Total Treatment System

Background

A large, commercial and institutional baking company is located in Southern California. The company generates up to 15,000 gpd of wastewater, primarily from a steeping process, wherein grains are steeped for 24 to 48 hours. That water is run through a rotary screen and is then discharged. Wastewater is also generated from equipment cleaning and floor scrubbing operations.

The wastewater contains highly variable levels of BOD (up to 50,000 mg/L) and TSS concentrations often exceeding 5,000 mg/L. The discharge limits mandated by the city are 250 mg/L for both parameters. As a result, the company had been adding sodium hydroxide to the untreated wastewater to raise the pH, and then hauling virtually all of it to a facility some distance away for treatment and disposal, at a cost of ~\$50,000.00/month.

Cartwright Consulting Co. was retained to investigate treatment technologies to remove BOD and TSS contaminants from this wastewater, so that the treated effluent could be either discharged to the city treatment plant, or reused.

After reviewing the wastewater generation processes and numerous analyses, the recommendation was that the wastewater be treated as follows:

1. Prescreening to 50-100 μ to remove large sized contaminants.
2. Treatment with MF technology to remove suspended solids down into the submicron size range.
3. Further treat with RO technology to remove dissolved solids, any remaining BOD and color.

This treated effluent stream quality must be acceptable for discharge to the city's wastewater treatment plant or possible reuse back into the plant.

It was also important to concentrate the removed solids into as small a volume as possible to facilitate discharge to a sanitary landfill.

The mandate was to design a ZLD (Zero Liquid Discharge) treatment facility.

Testing

Prescreen Filtration

Approximately 100 gallons of wastewater were filtered through a 105 μ vibrating screen processor (filter A).

Concurrently, 150 gallons of wastewater were processed through an automatic backwashing filtration unit with a 100 μ screen (filter B).

The filtrate from both samples was then placed in a refrigerated storage area to minimize biodegradation. Stirred samples from each were placed in a graduated cylinder and allowed to sit for about 30 minutes. The sample from filter A showed a layer of settled solids occupying approximately 15% of the total volume of sample. The filter B sample had no layer of settled solids. This absence of settleable solids in the filtrate indicated more complete filtration and resulted in the selection of filter B for further evaluation.

Applications Testing

As the bulk of the contamination is in the form of suspended solids (both TSS and BOD), it was decided to utilize MF as the next treatment process.

Testing was performed utilizing two different MF membrane elements, each sized to generate “scalable” data, to a full-sized system. The Applications Test Unit, previously illustrated, was utilized to generate these data.

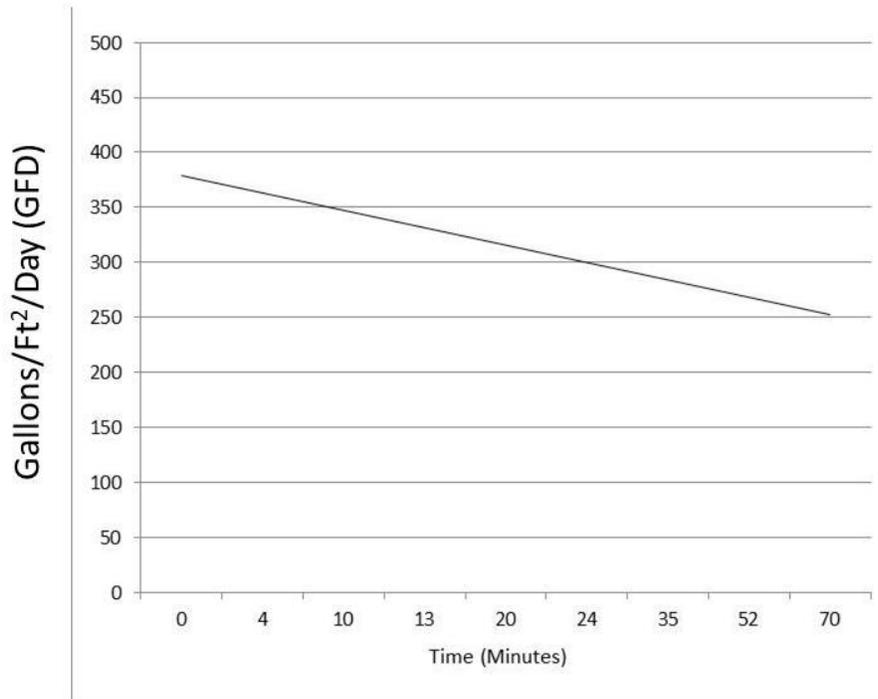
Microfiltration

1. The pretreated wastewater from filter B was fed into a tubular ceramic (silicon carbide) membrane with a pore size of $\sim 0.05\mu$ at a feed rate of approximately 17 gpm. System recovery was increased from 48% to 95% during the test period, and data collected.

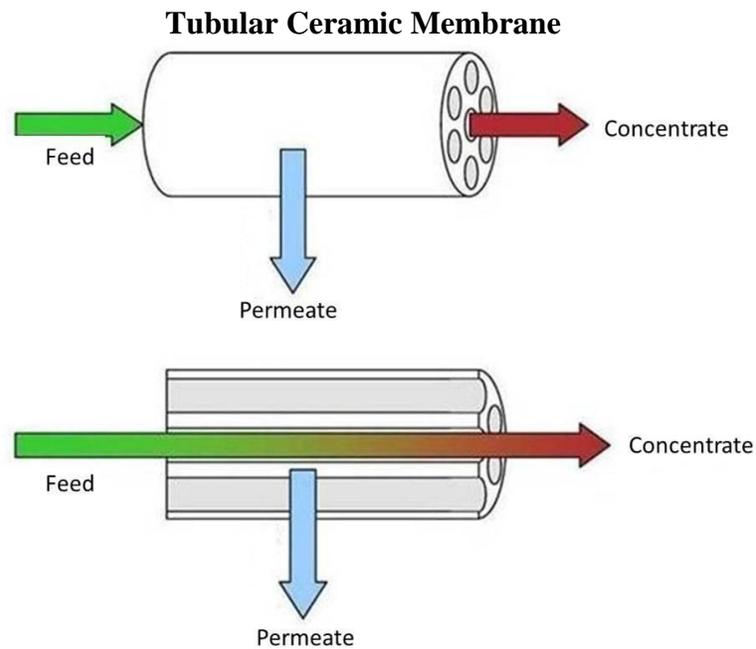
Although the permeate flux rate declined as a function of time, it should be noted that over this time period, the recovery was increased up to 95%, thereby significantly increasing the propensity of the suspended solids in the wastewater to foul the membrane.

A graph illustrating the permeate rate (flux) as a function of time during the test period is below.

0.05 μ Ceramic Membrane on Filtered Effluent



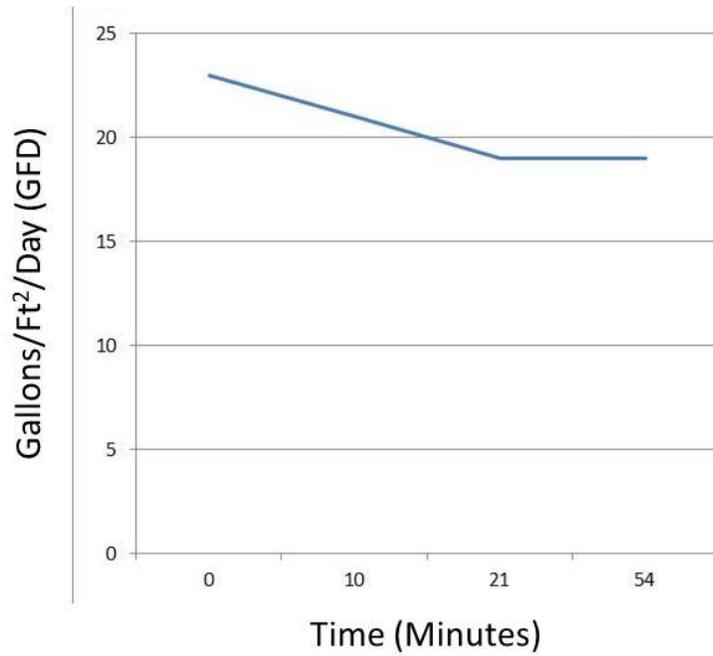
This ceramic MF membrane is illustrated below.



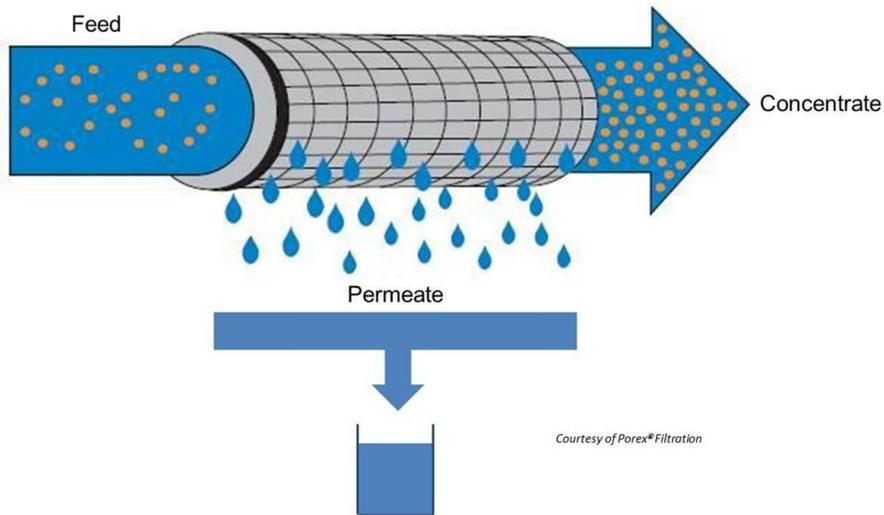
2. The pretreated wastewater from filter B was fed into a polymeric tubular membrane with a pore size of $\sim 0.05\mu$ at a feed rate of approximately 17 gpm. The system recovery was increased from 60% to 78% and data collected.

A graph of the flux rate as a function of time during the test period is below.

0.05 μ Polymeric Membrane on Filtered Effluent



The illustration below shows the basic operation of the polymeric MF membrane.

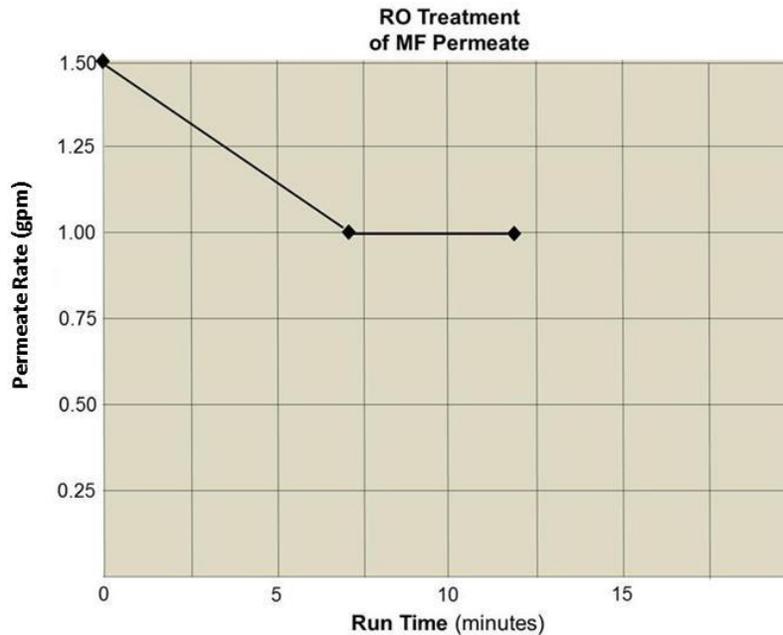


Reverse Osmosis

The permeate collected from both MF membranes was fed into a reverse osmosis test unit and recovery incrementally increased to 83%.

Salts in this feedwater were rejected in the range of 97-99%, and the permeate from this unit was free of measurable suspended solids, but with a slight organic odor.

The data from this test are plotted below.



Results

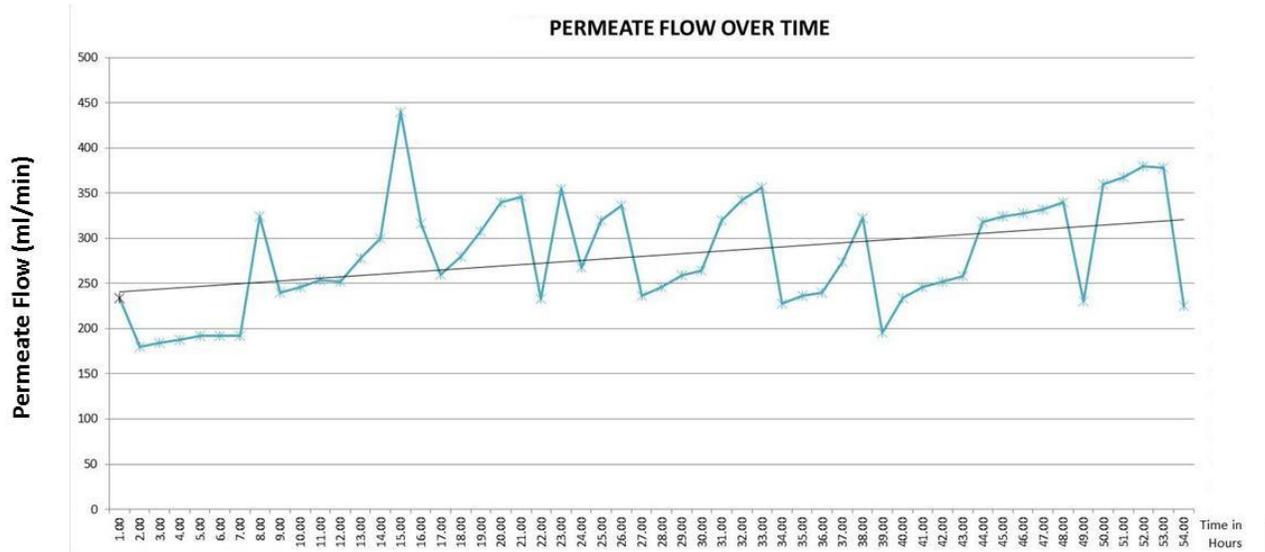
Although both MF elements (1) and (2) provided sufficient filtration for the spiral RO membrane, it was determined that the lower cost and more scalable design of the polymeric MF element made it more acceptable for this application.

The effective filtration provided by the MF membranes allow the utilization of any of the available thin film composite RO membrane elements to produce low TDS (total dissolved solids) effluent, allowing for reuse of the treated wastewater.

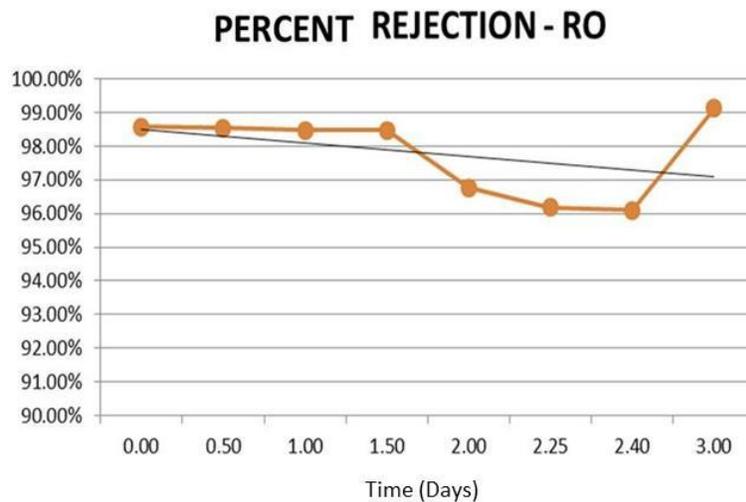
Pilot Testing

The initial testing was followed by a long term (30 day) continuous pilot test utilizing filter B and the selected MF element. During this testing, the recovery was incrementally increased and any drop in permeate rate noted.

The chart below illustrates the performance of polymeric MF element operating at 90% recovery.



The following graph illustrates the rejection of TDS in the RO unit operating at 90% recovery on the MF permeate.



System Design

To minimize the quantity of the waste streams from each treatment technology (prescreen filter, MF membrane and RO membrane), a vapor compression evaporator was designed. The concentrate solids from this unit are fed to a filter press and the resulting dry cake hauled to a sanitary landfill.

The quality data for the primary treatment technologies are summarized as follows:

	Plant Effluent	MF Permeate	RO Permeate	Distillate
TDS (mg/L)	2100	2100	240	40
TSS (mg/L)	450	110	ND	ND
BOD (mg/L)	3000	1500	100	ND

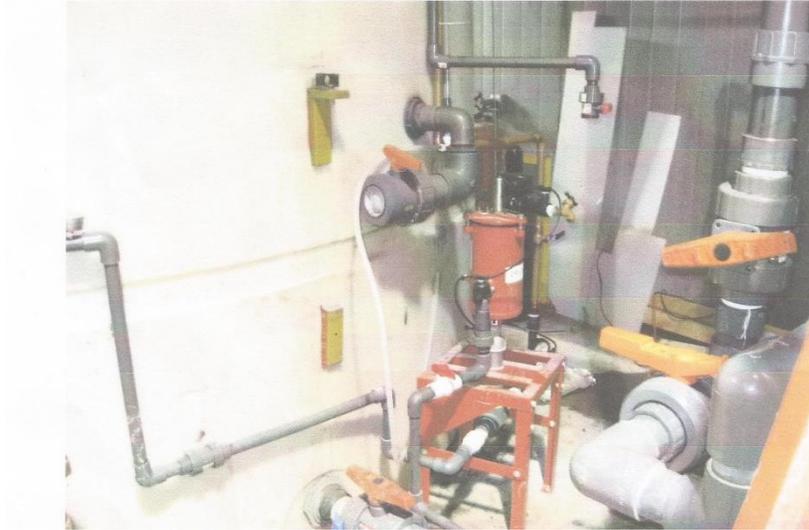
ND = Non Detectable

Conclusions

Following the successful completion of the pilot testing, a total treatment system was designed, and a membrane system manufacturer was contracted to retrofit an existing MF system that had never operated successfully, and to install the rest of the new equipment.

It should be noted that the treated effluent from the reverse osmosis unit and vapor compression evaporator is redirected back into the plant for reuse.

To accommodate expansion, the system was designed to process up to 25,000 gpd of effluent. Photographs of several components are below.



Prescreen Filter



MF System

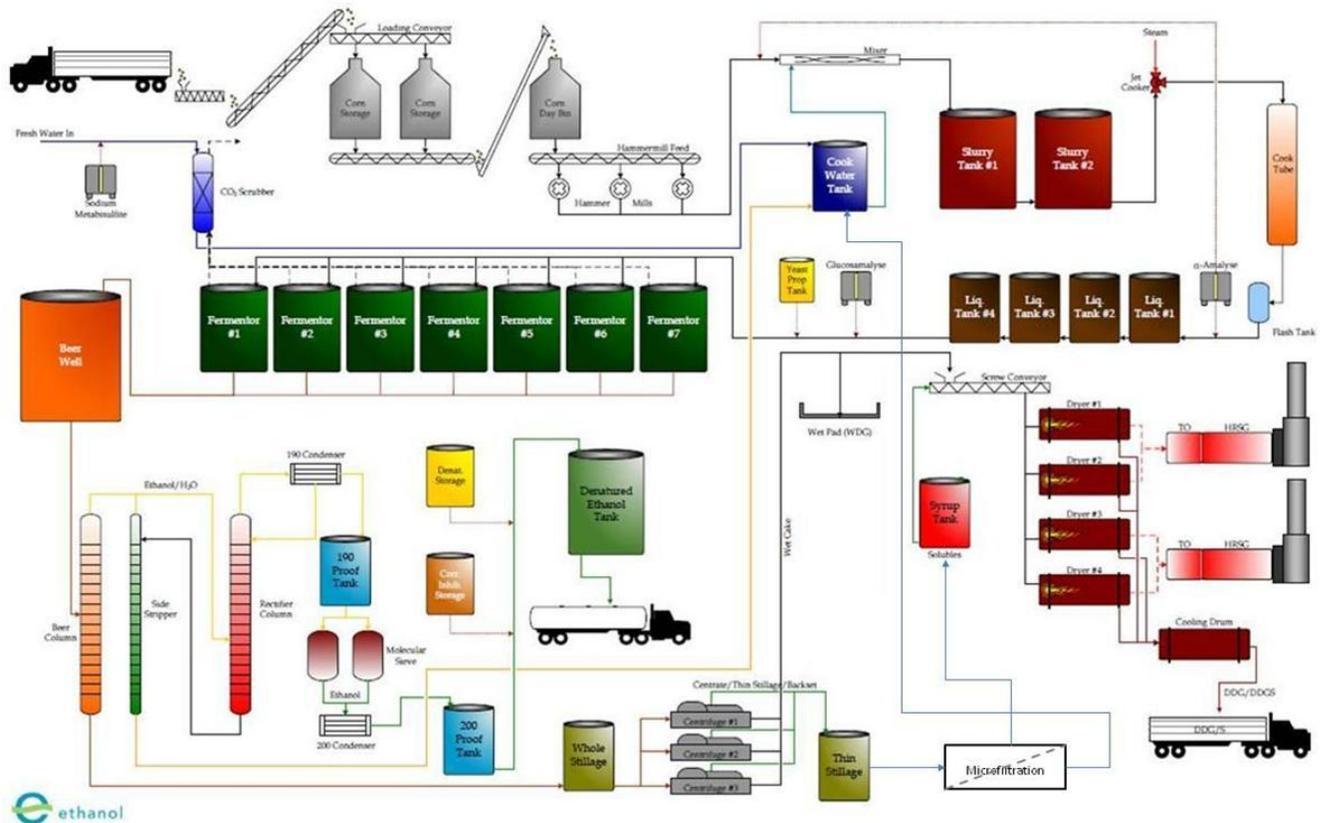


RO System

Ethanol Plant Thin Stillage Treatment

Introduction

Ethanol is produced by fermenting corn and distilling off the alcohol. The remaining solids (whole stillage) are centrifuged. The resulting wet cake is dried and used as cattle feed. The liquid from the centrifugation operation (centrate) is known as thin stillage, and requires treatment so a portion (backset water) can be used to initiate the next fermentation operation. The current technology to separate solids from this backset water is evaporation, and the entire treatment process is illustrated below.



Total Treatment System

The client wanted to investigate MF to replace the more expensive evaporation process. As the thin stillage had to be processed at a temperature of 180°F (82°C), a normal polymeric membrane could not be used.

Treatment Technologies

Below is a chart of ceramic membrane elements currently available and their configurations.

Membrane Materials

Materials of Construction	Device Configuration	
	Plate & Frame	Tubular
Coated 316LSS	—	X
<i>a</i> - Alumina	X	X
Titanium Dioxide	—	X
Silicon Carbide	—	X

The special characteristics of these ceramic membranes include:

- High temperature resistance: -10 to 250°C (50 to 482°F)
- High flux rates and long life
- pH operating range: 1-14
- Solvent and oxidation resistance; abrasion resistance
- Mechanical resistance: Burst pressure up to 60 bar (880 psi)
- Operating pressure up to 10 bar (150 psi)
- Backflushing and backpulsing
- Compatible with standard housings

Examples of these elements and pressure vessels are shown below:

Tubular Ceramic Membranes

Stainless Steel and FRP Pressure Vessels

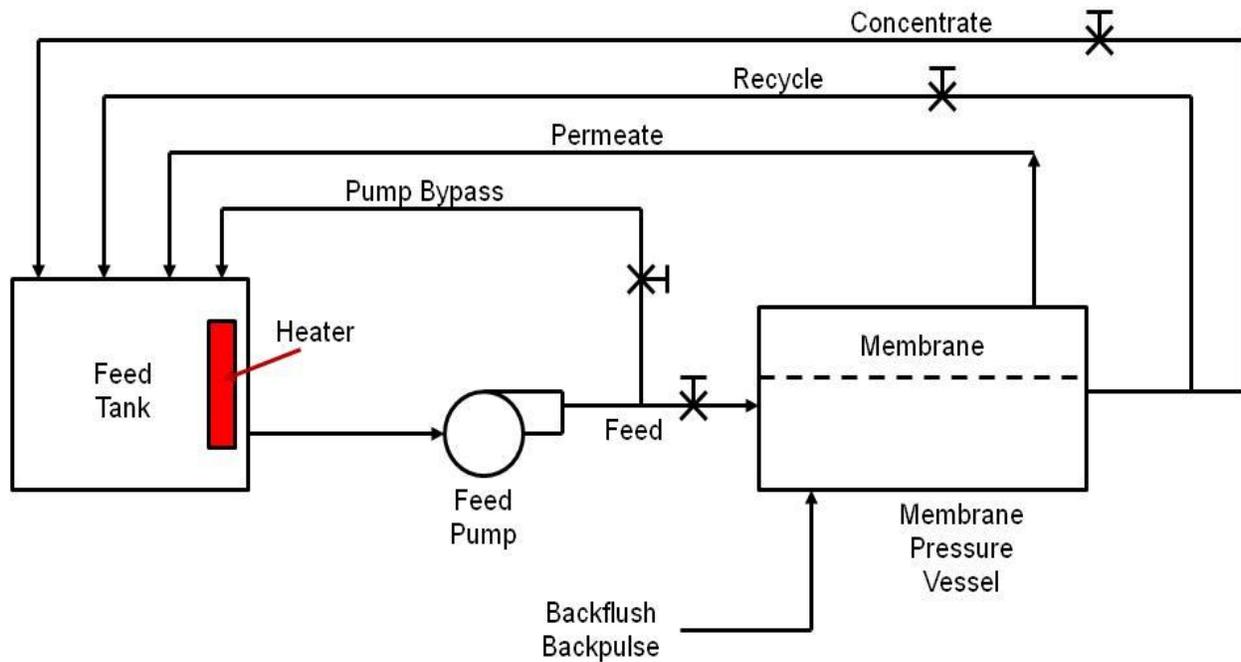


For this evaluation, tubular elements manufactured from α -alumina ceramic were used, housed in stainless steel vessels. The flow was inside-out (lumen feed).

Applications Testing

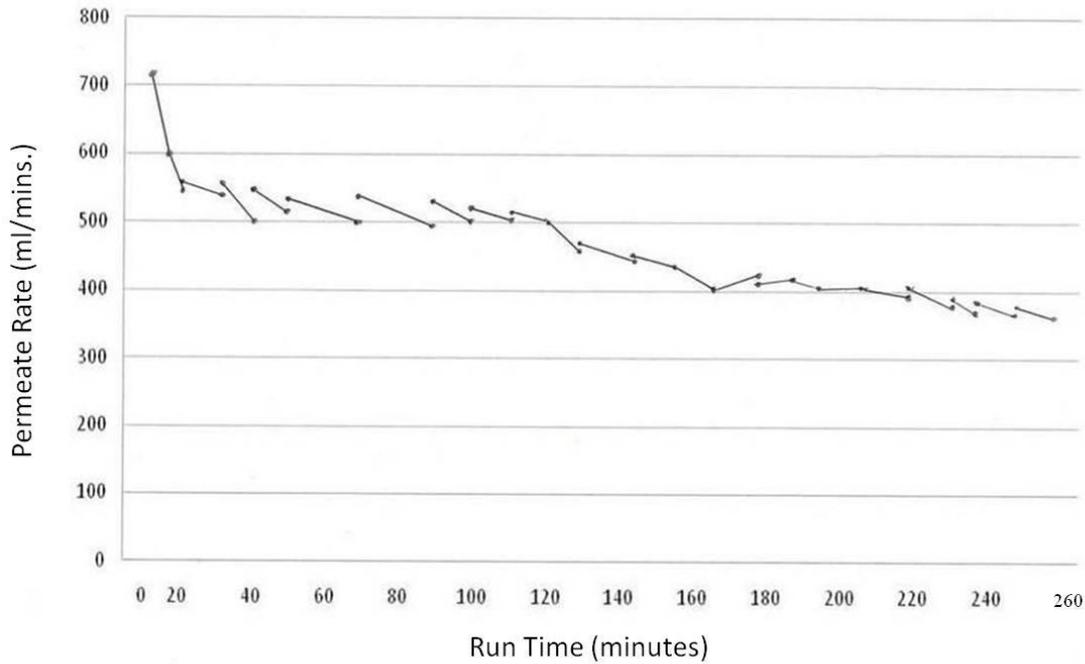
A representative thin stillage sample was collected in a tank heated to maintain the temperature. It was pumped into a stainless steel pressure vessel containing a 0.10μ α -alumina ceramic membrane element. The test system schematic is shown below.

Test System

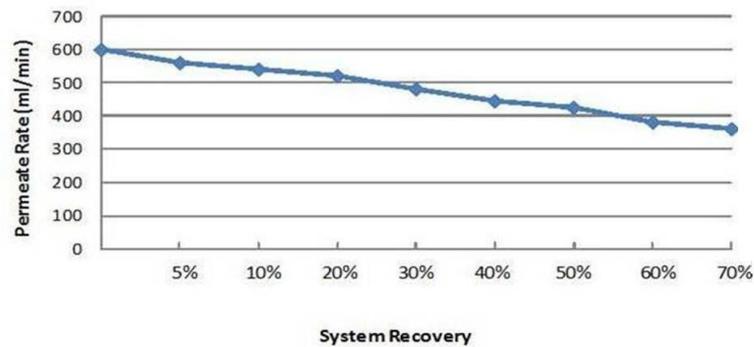


As the testing progressed, system recovery was manually increased, and the permeate rate plotted as a function of run time. These data are plotted below.

Permeate Rate vs. Run Time

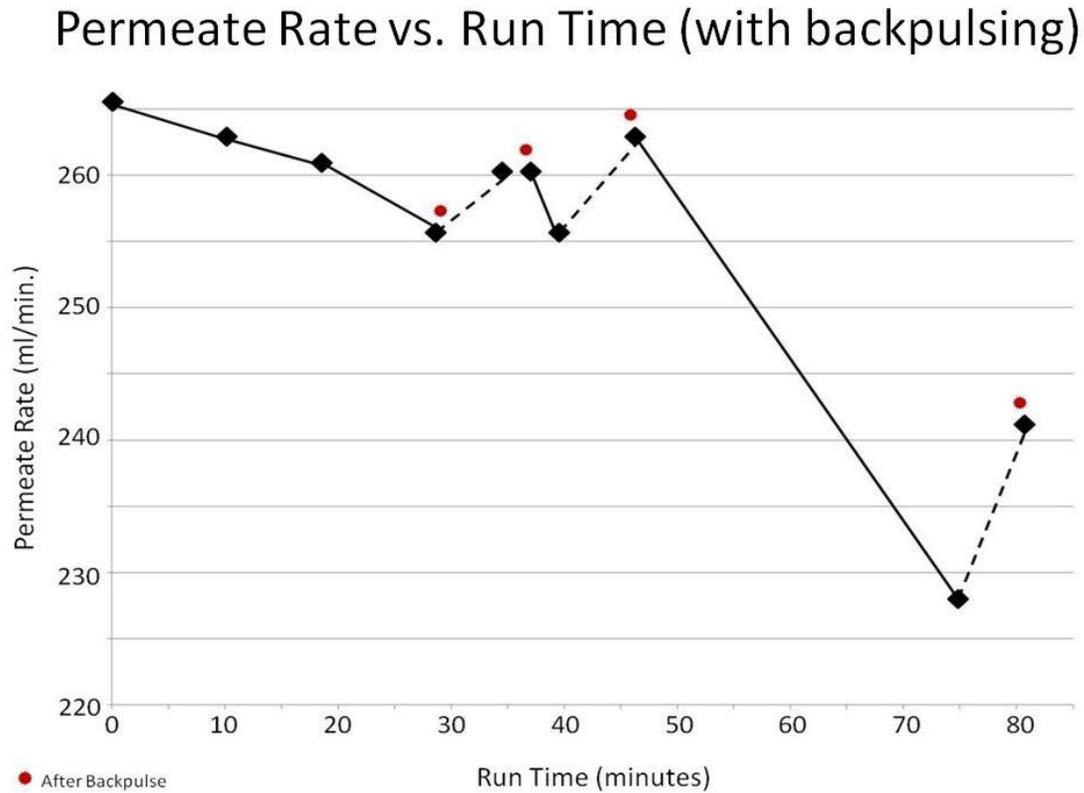


The following graph illustrates the permeate rate as a function of system recovery for the same test run as above.



To minimize fouling, a second test was performed on a similar feedwater, but the test system utilized backpulsing to force permeate backwards through the permeate piping to dislodge fouling materials from the membrane surface in an attempt to recover the permeate rate.

The efficacy of backpulsing can be affected by a number of factors, such as backpulsing pressure, backpulsing duration and run time between backpulsing events. The graph below illustrates one such test.



Conclusions

Although additional testing is required to identify the appropriate pretreatment technology and to optimize the system design, this testing confirms the value of ceramic microfiltration in this application.

GLOSSARIES

Rainwater Harvesting

Air Gap	The atmospheric space between the outlet of a pipe that fills a tank and the maximum water level in the tank. The vertical distance between the pipe outlet and the water must be large enough to prevent water from backing up.
ANSI	American National Standards Institute
Auxiliary Supply	Water supply that is arranged and protected from contamination that is available to provide an alternate means of filling a cistern.
Blackwater	Wastewater from household activities such as toilet flushing and all kitchen usage.
Calming Inlet	A device located at the bottom of a storage tank, that permits water to enter a storage tank with minimal disturbance to particles that may have settled to the bottom of the tank. See <i>Quiescent Flow</i> .
Cistern	The central storage component of the rainwater harvesting system. Protection and maintenance of the cistern is essential for the health of the system. It is also know as the Collection Tank.
Code	Refers to the local written authority, i.e. the Uniform Plumbing Code, International Plumbing Code, NSF International, etc.
Collection Area	Area from which rainwater is collected for use in a rainwater harvesting system (e.g. roof footprint area).
Contaminant	Any chemical, microbe, or other material that is not found in pure water and that can make water unsuitable for its intended use. Some contaminants only affect aesthetic qualities such as the appearance, taste, or odor of the water, while others can produce adverse health effects if present in high concentrations.
Debris	A contaminant that you can see. Debris can include leaves, twigs, dust, dirt, bird and animal droppings, and insects.
Debris Excluder	A screen or other device installed on the gutter or downspout system to prevent the accumulation of leaves, needles, or other debris in the system.
Disinfection	Reduction of viable microorganisms to a level that is deemed suitable for the intended application. Typical units of measure are Colony Forming Units (CFU) per 100 ml.
Drinking Water	See " <i>potable water</i> ", in this document, the terms "drinking water" and "potable water" are used interchangeably.

Dry Running Protection	System for protecting the process water pump against running dry.
Erosion Chlorinator	An in-line treatment unit that contains calcium hypochlorite tablets or pellets. As water flows through an erosion chlorinator, the calcium hypochlorite slowly dissolves and releases chlorine into the water.
Evaporation Field	Element in the ground that is filled with gravel, ballast or special non-permeable plastic elements and that stores rainwater that is fed into it on an intermediate basis before the water evaporates into the atmosphere or seeps into the surrounding soil.
Filtration	Physical removal of liquid-borne contaminants by means of separation from the output flow. Particulate filtration removes suspended particles [measured in units of Total Suspended Solids (TSS)] while other forms of filtration, such as carbon adsorption, removes dissolved organic compounds and gases.
Fire Sprinkler Reserve	Volume of water needed for the fire protection sprinkler operation that is delivered only by the fire pump.
Flat	Having a slope no greater than 1 in 50.
Graywater (greywater)	Wastewater resulting from household activities such as bathing, showering, laundry, etc., but does not include wastewater from toilets, kitchen sinks and dishwashers (blackwater).
Harvested Water System	Process system for utilizing rainwater for potable, nonpotable, industrial or irrigation applications.
Hybrid Container	Collection container for process water to which both utility water (with approved backflow prevention) and rainwater are collected and stored.
Hydraulic Filter Efficiency	Ratio between the water amount flowing to the filter and the water amount supplied for utilization.
Leach Field, Evaporation/Transpiration Field	Element in the ground that is filled with gravel, ballast or special permeable plastic elements and that stores rainwater that is fed into it before the water seeps into the surrounding soil.
mg/L (milligrams per liter)	A unit of measurement, the amount of a chemical found in each liter of water. Used interchangeable with ppm (parts per million).
Nonpathogenic Microbe	A bacteria, parasite, or virus that does not cause an infection or disease in humans.

Nonpotable Water	Water that may have received some treatment but not enough to make it safe for potable use. Nonpotable water can be used for watering lawns and gardens, washing clothes or flushing toilets, but should not be used for any purpose that might result in the ingestion of the water or its contact with the skin.
NSF	National Sanitation Foundation
Overflow Level	The highest level to which water from a drainage system can rise.
Overflow Line	Line for draining away rainwater when the rainwater reservoir is full, e.g. into the sewage system or a seepage system.
Pathogen	A bacteria, parasite, or virus that can cause infection or disease in humans.
Piping System	Pipes that convey the harvested rainwater and distribute it to various fixtures.
Point of Entry (POE)	The point where water enters a home's plumbing system. A point-of-entry treatment unit treats all of the water entering the home, rather than treating the water at the point where it is consumed. A whole-house water softener is an example of a common point-of-entry treatment unit.
Point of Use (POU)	The point in a home where water is actually used. A carbon filter installed under the sink is an example of a common point-of-use treatment unit.
Potable Water	Water that is used for preparing food or beverages for human consumption, for washing dishes and utensils that are used to prepare or consume food or beverages, for bathing, or for any other purpose that might result in the ingestion of water or its contact with the skin. It does not include water that is used for landscape irrigation, washing clothes, or flushing toilets.
Precipitation	Water that has precipitated from the atmosphere (e.g. rain, snow, mist, dew).
Precipitation Characteristics	Characteristics of a precipitation event (e.g. intensity, duration).
Process Water	Water for household and commercial areas of use that does not have to have the quality of drinking water.
Process Water Line	System of lines from the process water pump to the individual points at which water is used.

Process Water Pump	Pumps water from the rainwater reservoir to the points at which it is used.
Process Water Requirements	The process water quantity that is required in a specific period of time.
psi (Pounds per square inch)	A unit of measure; the amount of pressure applied to each square inch of surface.
Public Water System (PWS)	A public water system is any system that serves at least 25 people per day for at least 60 days each year or that serves at least 15 service connections such as homes, apartments, or businesses.
Pump or System Pressure System	Any water system that serves at least 25 people per day for at least 60 days each year or that supplies at least 15 service connections.
Quantity of Precipitation	Precipitation at a certain place, expressed as the water height over a horizontal area for a span of time under consideration.
Quiescent Inflow	Routing of rainwater into rainwater reservoirs so that the existing sediment is not disturbed in the rainwater reservoir.
Rainwater	Water from natural precipitation.
Rainwater Harvesting System	Water system for utilizing rainwater, consisting of a cisterns, pipe, fittings, pumps and/or other plumbing components required for and/or used to harvest and distribute rainwater.
Rainwater Line	Resupply, drainage, overflow and emptying lines of rainwater harvesting system.
Rainwater Yield	Useful water volume (water inflow) determined over a certain period of time for use as process water.
Return Elbow	A section of pipe with a 180-degree bend.
Roof Drainage System	A system, comprised of roof drains, overflow drains, scupper, gutters and down spouts, used to convey the rainwater from the roof to the cistern.

Roof Filtration	A device or procedure to mechanically remove sediment and debris.
Roof Surface	The surface for the collection of rainwater that has fallen on a building roof.
Roof Wash or Roof Washer	A device or method for removal of sediment and debris from the collection surface by diverting initial rainfall away from entry into the cisterns).
Screen	A filtration device, constructed of corrosion resistant wire or other approved mesh, having openings of determined sizes.
Sedimentation	Separation of solids from water via gravity.
Slope or Sloping	Having a slope greater than 1 in 50.
Sub-Surface Irrigation	Water that is applied below ground level, and is not directly exposed to the above ground surface and/or surrounding air.
Suction Line	Line through which a process water pump sucks in rainwater.
Sun Barriers	A cover, or erected structure, specifically to shelter a cistern from the direct rays of the sun.
Supplemental Supply	Equipment for providing a supplemental supply of water into process water systems.
Surface Irrigation	Water that is applied above ground level and is directly exposed to the above ground surface and/or air.
Surface Water	Any rain water that touches the ground and flows across the surface of the ground (roadway, parking surface, gully, creeks, streams, etc.).
System Control Unit	Control unit for the automatic operation of the rainwater harvesting system.

<i>Transfer Pump</i>	A mechanical device to transfer collected water from downspouts to cisterns.
<i>Treated Water</i>	Water that has been filtered and disinfected and is safe for potable use. In this document, the terms "treated water", "drinking water" and "potable water" are used interchangeably.
<i>Untreated Water</i>	Water that has not received enough treatment to make it safe for potable use.
<i>Useful Volume</i>	Volume that can be completely used during operation.
<i>Yield Coefficient</i>	Ratio of the rainwater annually flowing into the rainwater harvesting system to the total amount of rainwater in the accompanying precipitation area, allowing for leakage splashing, evaporation, etc. (typically .75 - .90).

Membrane Technology

boundary layer – A very thin liquid layer immediately adjacent to the rejecting surface of membranes in which the concentration of suspended or dissolved solids is higher than it is in the main body of the water being processed. Also known as “gel layer”.

brackish water – Water ranging from about 1,000 ppm total dissolved solids to an arbitrary seawater concentration. In many cases, this upper level is defined as 25,000 ppm.

brine – see *concentrate*

brine seal – A truncated cone of synthetic rubber attached to the upstream end of a spiral wound membrane element. Under water pressure, it forms a seal with the inner surface of the pressure vessel in which the element is placed to prevent water from bypassing around the outside of the element.

channel – The opening or spacing between membrane layers, such as inside diameters of tubular or hollow fibers, or that resulting from netting in spirals, etc. Also known as “bore”.

concentrate – The stream exiting the membrane element which has not passed through the membrane, and, ideally, contains all the contaminants removed by the membrane. Concentrate is also known as: “brine”, “rententate”, “reject”, “effluent”, and “waste”.

concentration factor (CF) – Also abbreviated as VCF and VCR, this is the term that quantifies the effect of system recovery on the concentration of the rejected contaminants in a membrane element or operating system. It is mathematically related to recovery by the formula:
$$CF = \frac{1}{1 - \text{recovery}}$$

This equation results from a mass balance based on the assumption that the membrane provides complete rejection of the contaminant in question.

concentration polarization – The formation of a more concentrated gradient of rejected material near the surface of the membrane (in the boundary layer) causing either increased resistance to solvent transport or an increase in local osmotic pressure, and possibly a change in rejection characteristics of the membrane.

crossflow – Flow of solution tangentially or parallel to the surface of the membrane. This contrasts with “dead-end” flow seen in conventional filters, in which the liquid flows perpendicular to the surface of the filter. In crossflow, only a fraction of the crossflow solution passes through the membrane.

crossflow membrane filtration – Separation of the components of a fluid by semipermeable membranes through the application of pressure and tangential flow to the membrane surface. This includes the processes of reverse osmosis, ultrafiltration, nanofiltration and microfiltration.

desalination – The general term applied to the removal of salts, particularly sodium chloride in seawater “desalting” applications. In actuality, it describes any act of removing ionic contaminants from water.

diafiltration – A crossflow filtration process allowing for the transfer of low molecular weight species, water and/or solvents through a membrane without changing the solution volume, accomplished by adding solvent (usually water) back into the feed. This process is used for purifying retained large molecular weight species, increasing the recovery of low molecular weight species, buffer exchange or simply changing the properties of a given solution.

effluent – see *concentrate*

feed – The feedwater stream entering the membrane element. It is also known as influent or feedwater.

filtrate – see *permeate*

flux – The quantity of solution that passes through a unit of membrane area in a given amount of time. For example, a membrane element might have a flux of 10 liters per minute per square meter.

fresh water – Water containing less than 500 parts per million (ppm) solids. Water above 1,000 ppm is not recommended to be used for human consumption.

influent – see *feed*

membrane element – The package containing the membrane and equipped with the necessary fittings to allow the feed stream to enter, and the permeate and concentrate streams to exit. The membrane element enables the membrane to effect separation. Synonyms are “membrane device” and “membrane module”. The general categories of membrane element configuration are: “spiral wound”, “capillary (hollow) fiber”, “tubular” and “plate and frame”

molecular weight cutoff (MWCO) – Referred to as the molecular weight above which a certain percentage (e.g., >90 percent) of the solute in the feed solution is rejected by the membrane. It is typically expressed in units of Daltons and used as an indication of the pore size of ultrafiltration and nanofiltration membranes.

net driving pressure – Applied (pump) pressure minus the sum of all back pressures [osmotic pressure, pipe pressure losses, head (elevation) losses, etc.]

normalization – The calculations that allow performance data to be compared on a uniform basis. For example, flux should be corrected to a temperature of 25°C (77°F) and a constant pressure.

permeate – The stream which has passed through the membrane (also known as “product” or “filtrate”).

recovery - That percentage of the feed flow rate that passes through the membrane and becomes the permeate stream.

reject – see *concentrate*

rejection rate – When pressure is applied to water in contact with a membrane, water passes through the membrane and the solids that were in the water are rejected. The degree to which they are repelled is the rejection rate. The overall rejection rate depends upon the average concentration of dissolved solids in the entire unit, and is calculated from the equation:

$$\% \text{ Rejection} = 100 \left(1 - \frac{\text{Permeate concentration}}{\text{Average feed concentration}} \right)$$

Although the average feed concentration is not actually the arithmetic average of the feed and the concentrate, but rather the integrated average composition, the arithmetic average provides a good approximation.

retentate – see concentrate

seawater – Concentrations of dissolved solids in oceans and seas vary around the world. Typically, a level of 35,000 ppm total dissolved solids is considered average.

specific flux – Flux rate divided by net driving pressure.

tangential flow filtration (TFF) – Filtration in which liquid flows tangential to (along) the surface of the membrane. Synonymous with the term “crossflow”. The sweeping action of fluid helps to minimize gel layer formation and surface fouling. Contrast with “dead-end” filtration.

total dissolved solids (TDS) – Although actually a measurement of both dissolved salts and organics, TDS is commonly equated with dissolved salts only, and is often expressed as conductivity (mmho/cm or ms/cm).

transmembrane pressure (TMP) – The force which drives liquid flow through a crossflow membrane. In crossflow devices, the TMP is calculated as an average related to the pressures of the inlet, outlet and permeate ports. The TMP can be expressed as:

$$\text{TMP} = \left(\frac{\text{P}_f + \text{P}_c}{2} \right) - \text{P}_p$$

where: P_f = Feed pressure

P_c = Concentrate pressure

P_p = Permeate pressure

waste – see concentrate