TANGENTIAL FLOW MEMBRANE FILTRATION (TFMF) APPLICATIONS IN WASTEWATER REUSE AND BRACKISH GROUNDWATER PLUS HIGH CHLORIDE SURFACE WATER TREATMENT

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Abstract

This paper will address the challenges the nation, especially Texas, is facing due to the ongoing drought, and discuss how proper optimized application of TFF Membrane Processes can offset the acute shortage in water supply by tapping strategic water supply resources available in abundance.

This strategy is promoted by the Texas Water Development Board, Texas Commission of Environmental Quality and various regulatory agencies nationwide while currently, actively promoted by AWWA, WEF and ASCE.

Understanding membrane operational processes and conditions that promote the longevity of the membrane and maximum operational efficiency to provide the best return on investment at the lowest life cycle cost is important to make membrane processes competitive with conventional water treatment. This paper hopes to bridge concept and reality with practical experiences in concept implementation, optimal design and strategic application to the national water crisis.

Tangential Flow Membrane Filtration is a viable solution to increase the nation's water supply especially in drought stricken areas by application of this technology to brackish groundwater and wastewater effluent reuse applications.

Introduction

Tangential Flow Filtration (TFF), also called Cross Flow Filtration (CFF), is a rapid and efficient method for filtration to treat brackish ground water and wastewater for reuse applications to augment the current national shortage of water supply and the acute shortage currently being faced in Texas. TFF is a process whereby raw water flow (feed) is directed tangentially along the surface of a membrane with most of the solution circulated back to the feed tank. The rapid flow of feed solution across the membrane acts to 'sweep' the surface, reducing concentration polarization (product concentration at the membrane surface). It also prevents build-up of foulants that can plug the pores at the membrane surface. The rapid cross flow creates a pressure drop, which forces some of the feed solution and dissolved molecules that are smaller than the pores in the membrane, through the membrane filter. The solution that passes through the membrane is referred to as filtrate or permeate. Molecules or particles larger than the membrane pores are retained in the feed solution and effectively concentrated.

The fluid dynamics of cross flow filtration reduces membrane fouling and maintains filtration rates (flux) for a longer period of use, thus increasing membrane throughput (greater capacity) compared to traditional cartridge (direct flow) filtration. Additional advantages of TFF include the ability to reuse the filter modules and relatively low capital costs.

TFF can be applied to a wide range of water and wastewater fields right through pilot and full-scale production. In order for TFF to be successful a thorough knowledge of design and operational criteria is important from project conception to implementation.

Outline of this Paper

This paper will progress using the following outline for effective organization and readability.

- What is filtration? Types of Filtration?
- Filtration Classification
- Introduction to TFF and Applications
- Configurations & Operational Concerns
- Quality Control and Filtrate Monitoring
- Increasing Filtration Rate and Filtration Theory
- Advantages of TFF
- TFF Design Principles and Example

What is Filtration?

- Filtration is the use of a medium to separate solids from liquid.
- The solids can be from the size of particles down to cells or cellular tissue down to individual molecules.
- Depending on the filtration medium chosen as the filter material, selective cut-off of particle sizes are achieved in the filtration process.

Selectivity in Filtration

- Filtration is usually utilized to concentrate the material for mineral extraction or purification.
- Filtration can provide selectivity based on size, but not on charge.

Types of Filtration

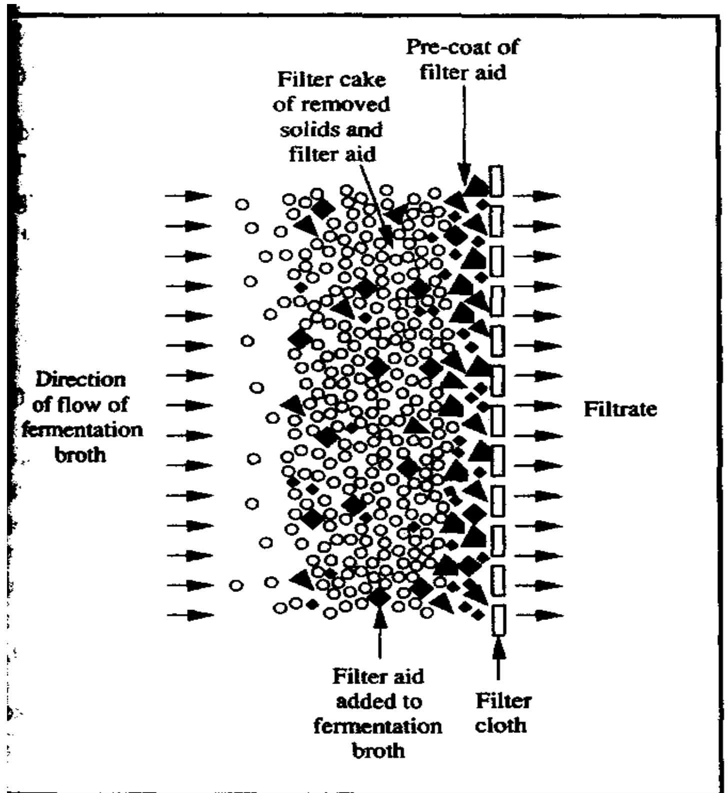
Filtration is usually broken down into two primary techniques:

- deadend
- cross-flow filtration

Theory of Filtration

Filtration theory is explained in the following illustration.

- In filtration, solid particles are separated from solid-liquid mixtures by forcing the fluid through a filter medium or filter cloth that retains the particles.
- The Filtration rate can be improved either by using a vacuum or pressure.
- Filter aides such as Diatomaceous Earth which are highly porous also improve the filtration rate.
- Filtration theory is used to estimate the rate of filtration.



The rate of filtration is usually measured as the rate at which liquid filtrate is collected. Filtration rate depends upon:

- Area of the filter cloth or membrane
- Viscosity of the fluid
- The pressure difference across the filter
- The resistance to filtration offered by the cloth or membrane and deposited filter cake.

There are several ways to increase the filtration rate in theory:

- increase the filtration area (A)
- reducing the filtration pressure drop (membrane cleaning) ΔP decreases α, which causes filtration rate to increase.
- reduce the cake mass
- reduce the liquid viscosity (by dilution)
- reduce specific cake resistance (α)
- Increase porosity
- Reduce particle size

Deadend Filtration

Deadend filtration is when the feed material is forced through the membrane. The flow is only in the direction perpendicular to the membrane. All the suspended solids in the feed end up on the membrane in a filter cake.

Crossflow Filtration (Tangential Flow Filtration or TFF)

In cross-flow filtration the feed material is allowed to flow parallel to the membrane, while the pressure gradient is across the membrane. The primary advantage of cross-flow filtration is that it allows the solids to be kept in suspension and minimizes the build up of a filter cake to plug or foul the membrane. This is achieved by keeping the flow direction of the retentate perpendicular to the flow direction of the permeate.

The differences between the two filtration types are shown on Figure 1.

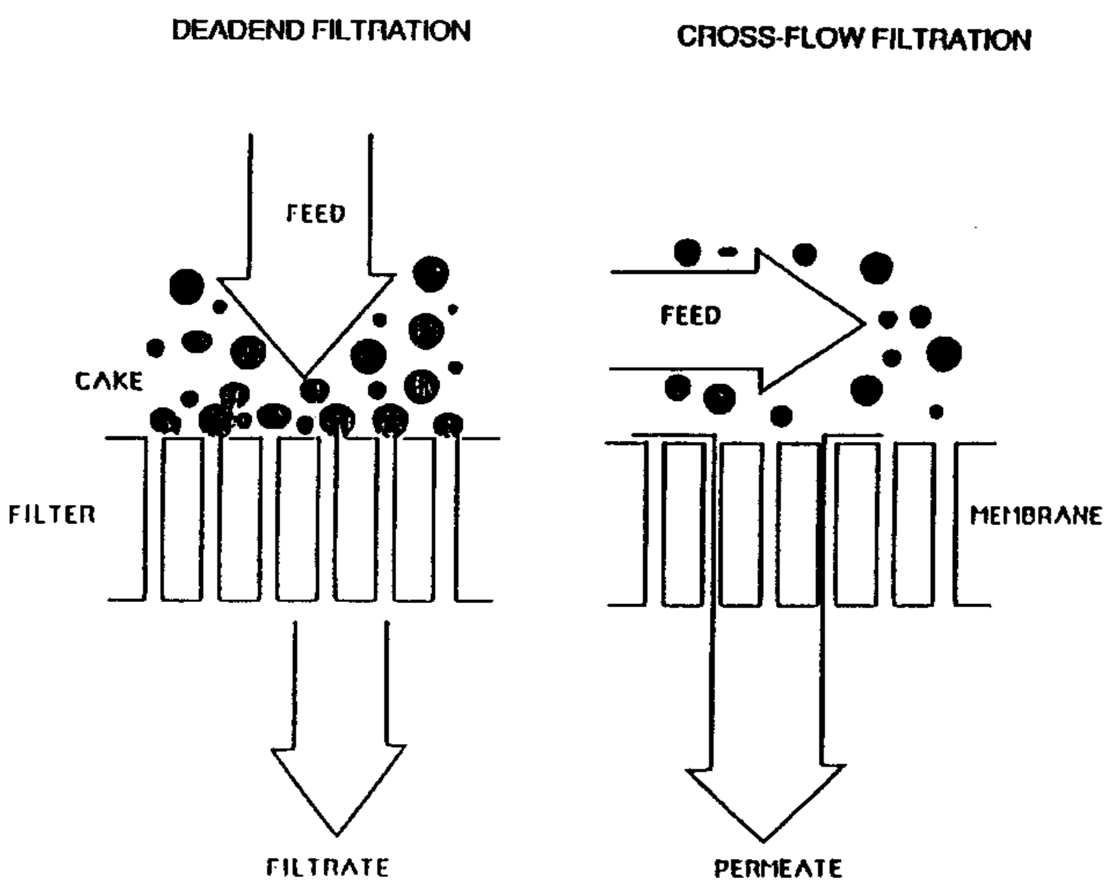


Figure 1 Two Types of Filtration

Filtration Classification

Filtration classification falls into several categorizes as illustrated in Tables 1, 2 and 3, depending on the size of the substance being excluded by the membrane.

Table 1 Filtration Classification

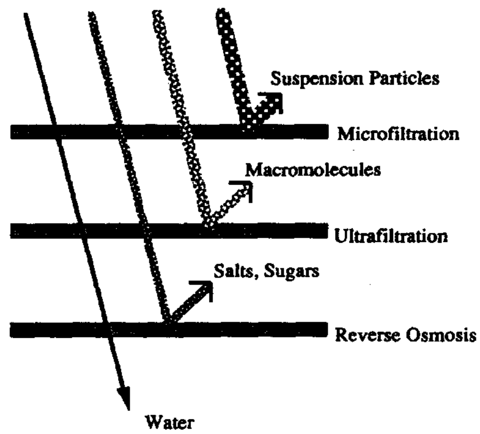
Classification	Schematic
Microfiltration generally refers to the filtration of suspension particle such as cells and cellular fragments **Ultrafiltration** is the filtration of macromolecules **Reverse Osmosis** is the filtration of molecules such as salts and sugars	

Table 2 Cutoff Ranges in Filtration Based on Membrane Classification

	Microfiltration	Virus Filtration	High-Performance Filtration	Ultrafiltration TFF	Nanofiltration/ Reverse Osmosis
Components retained by membrane	Intact cells Cell debris	Viruses	Proteins	Proteins	Antibiotics Sugars Salts
membrane membrane membrane membrane membrane membrane membrane membrane membrane membrane membrane membrane membrane membrane					
Components passed through membrane	Colloidal material Viruses Proteins Salts	Proteins Salts	Proteins Salts	Small Peptides Salts	(Salts) Water
Approximate membrane cutoff range	0.05 µm – 1 µm	100 kD – 0.05 µm	10 kD – 300 kD	1 kD – 1000 kD	<1 kD

Table 3 Relationship Between The Common Measurements Used in Filtration

- Equivalence between kiloDalton (KD), Microns (micrometers), Nanometers, and Angstroms

KD's	Microns	Nanometers	Angstroms
1,000 KD	0.1 micron	100	1000
500 KD	0.02 micron	20	200
200 KD	0.01 micron	10	100
50 KD	0.004 micron	4	40
10 KD	0.0025 micron	2.5	25
5 KD	0.0015 micron	1.5	15

The above tables illustrate that pressure driven membranes are divided into four main divisions based on pore size:

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

Decreasing Pore Size

Some highlights related to microfiltration and ultrafiltration are provided below.

- Microfiltration
    - 0.1 to 10 μm filter sizes
    - Used to separate cells
- Ultrafiltration
    - MW range 2000 to 500,000 (2 to 500 kilo Daltons (kD))
    - Used to concentrate or sieve proteins based on size

- A thin membrane with small pores supported by a thicker membrane with larger pores
- Low MW solutes pass through the filter and high MW solutes are retained
- Pressure driven process
- Can result in concentration polarization and gel formation at membrane surface

TFF Applications

Microfiltration and ultrafiltration processes incorporating tangential flow or cross flow filtration is utilized in a wide range of biopharmaceutical applications. Examples of a few typical applications are listed below:

- Water Desalination and Brackish Water Treatment + Concentration and desalting of protein, peptide, and oligonucleotide solutions
- Purification and recovery of antibodies or recombinant proteins
- Vaccine and conjugate concentration and diafiltration.
- Fractionation of protein mixtures
- Blood plasma fractionation and purification
- Cell broth clarification, concentration
- Cell culture perfusion such as in monoclonal antibody (Mab) production
- Clarification of Fermentation broths
- Concentration and washing of bacterial cells
- Water and buffer purification (endotoxin removal)

In cross-flow filtration (TFF) the membrane does the primary work compared to the combination of cake and membrane in deadend cake filtration. The cross-flow allows the membrane to be swept free of solids allowing for a lower resistance to fluid flow through the membrane. As illustrated in Figure 2 and 3, the permeate flows through the membrane, and the retentate flows parallel or tangential to the membrane along with solids and is swept away. The retentate can be further concentrated for product recovery.

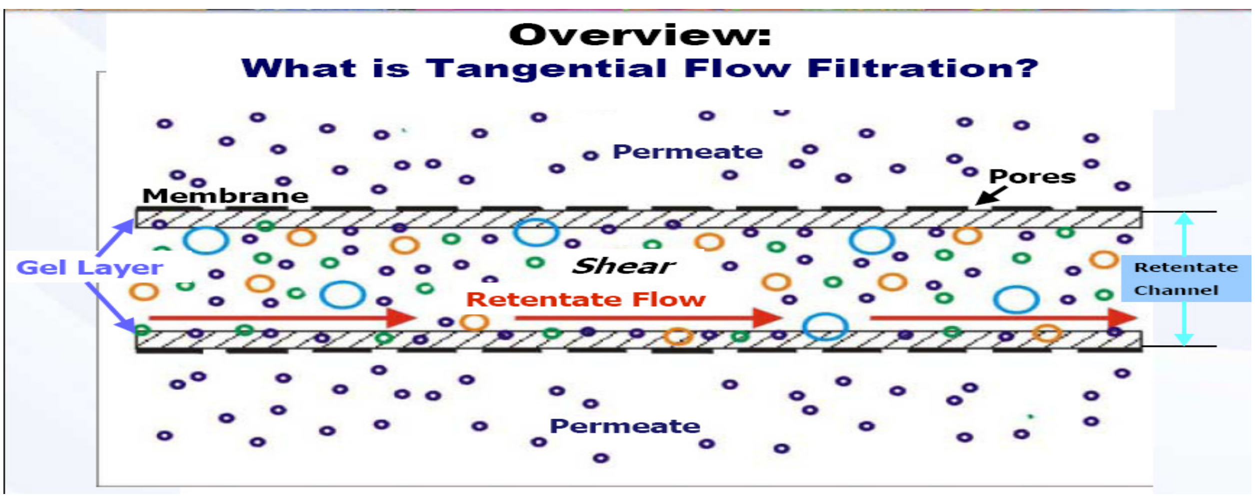


Figure 2 A Simplified Illustration of Tangential Flow Filtration (TFF)

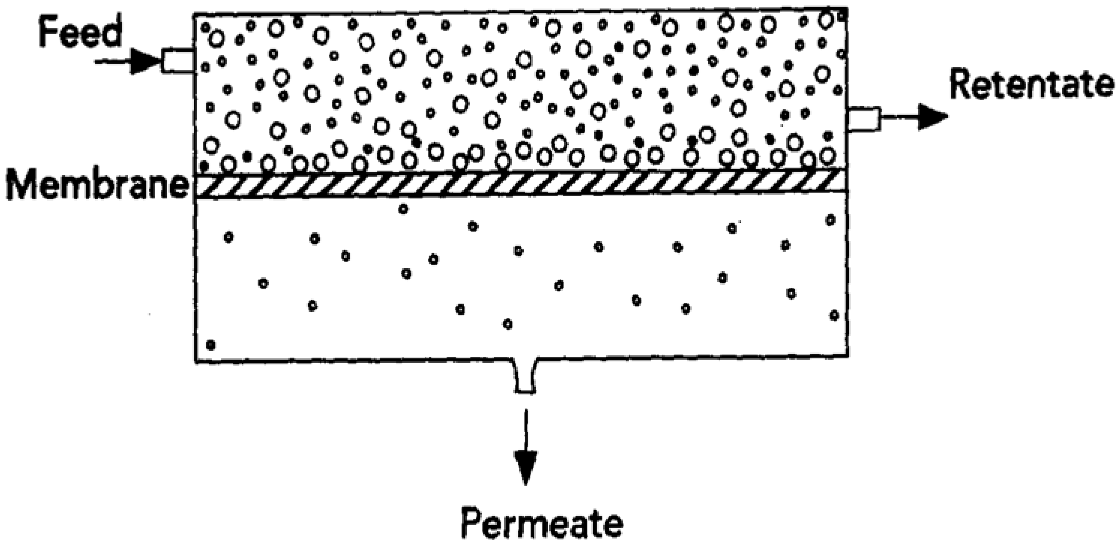


Figure 3 A Typical Tangential Flow Filtration (TFF) Ultrafiltration

Cross-flow also allows the concentration of the retentate without the contamination with filter aids. Therefore TFF can be used to collect either the permeate or the retentate as shown on Figure 4

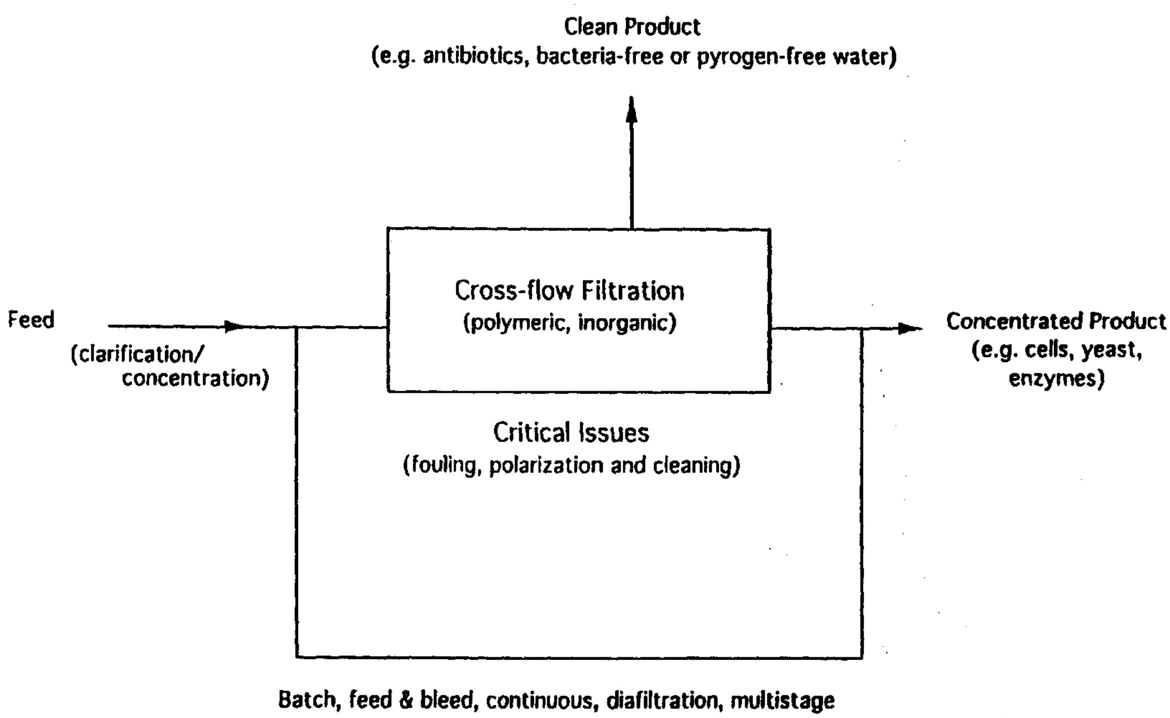


Figure 4 Schematic of Cross Flow of TFF

Operational Considerations

Membrane fouling control through backwashing and solvent cleaning is illustrated in Figure 5.

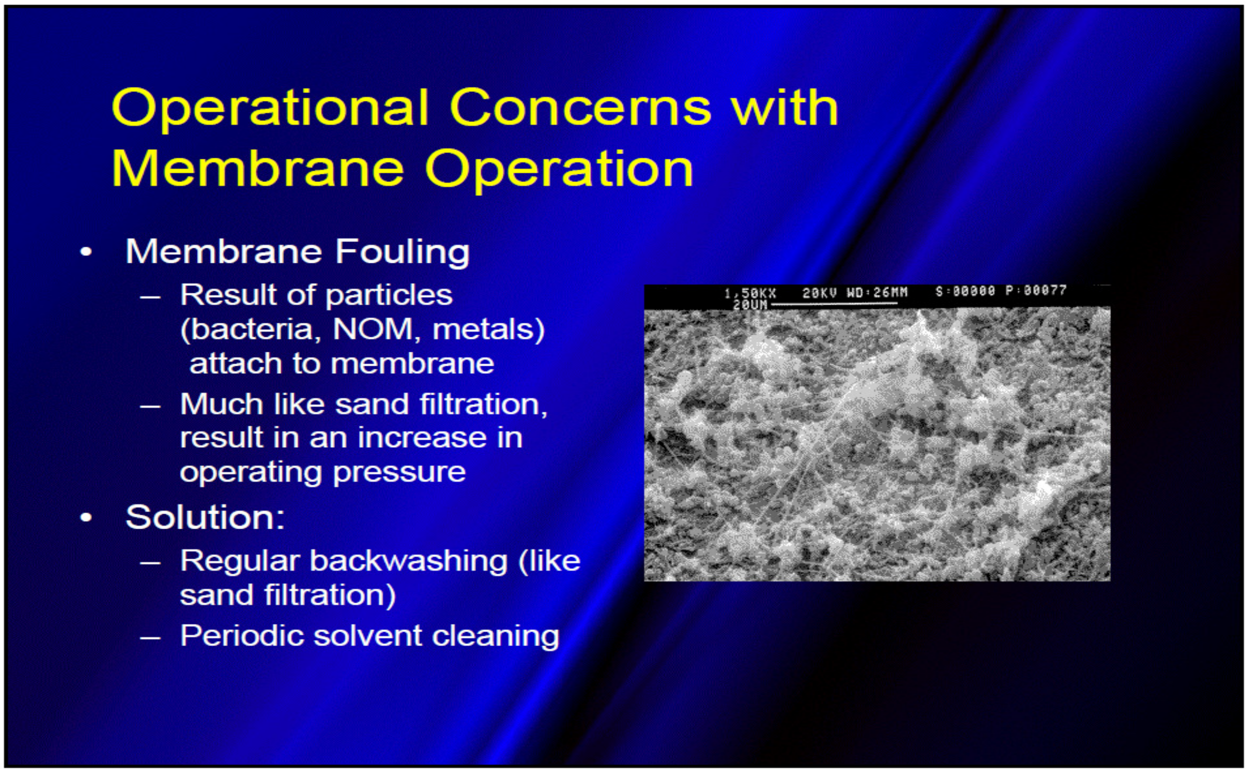


Figure 5 Operational Considerations Associated With Membrane Longevity and Effectiveness

Buildup of a cake layer at the membrane surface in cross-flow filtration with suspended solids in the feed is illustrated in Figure 6.

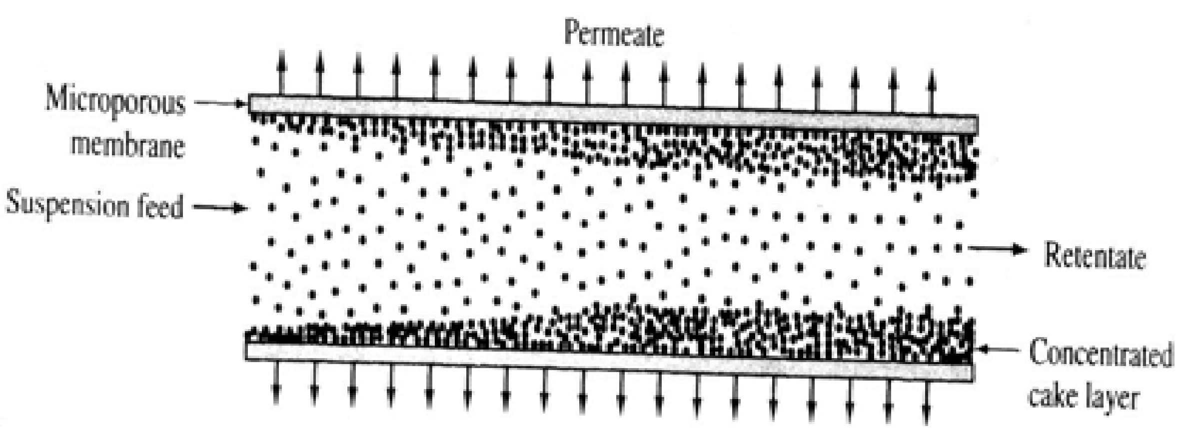


Figure 6 Cake Layer Buildup

Various feed driven configurations including spiral bound and hollow fibers can be used in TFF based on the application as further illustrated in Figure 7.

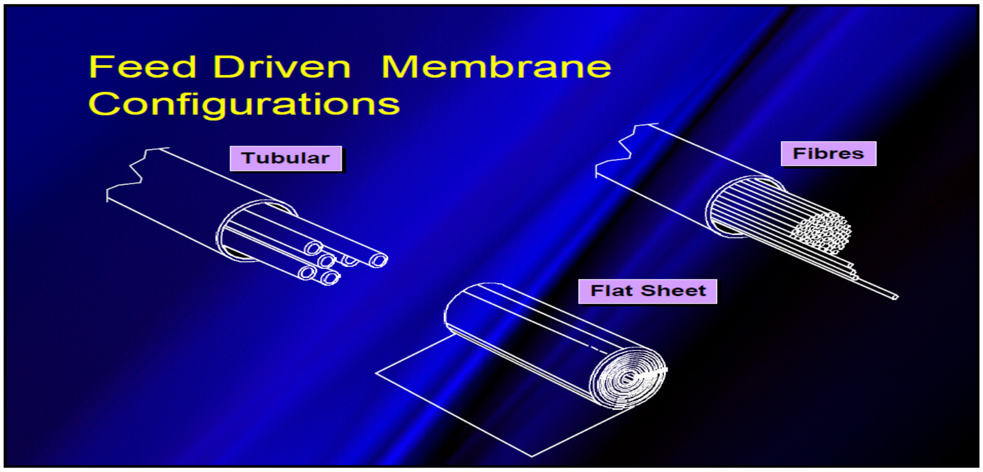


Figure 7 Feed Driven Membrane Configurations

A spiral wound membrane configuration is illustrated in Figure 8

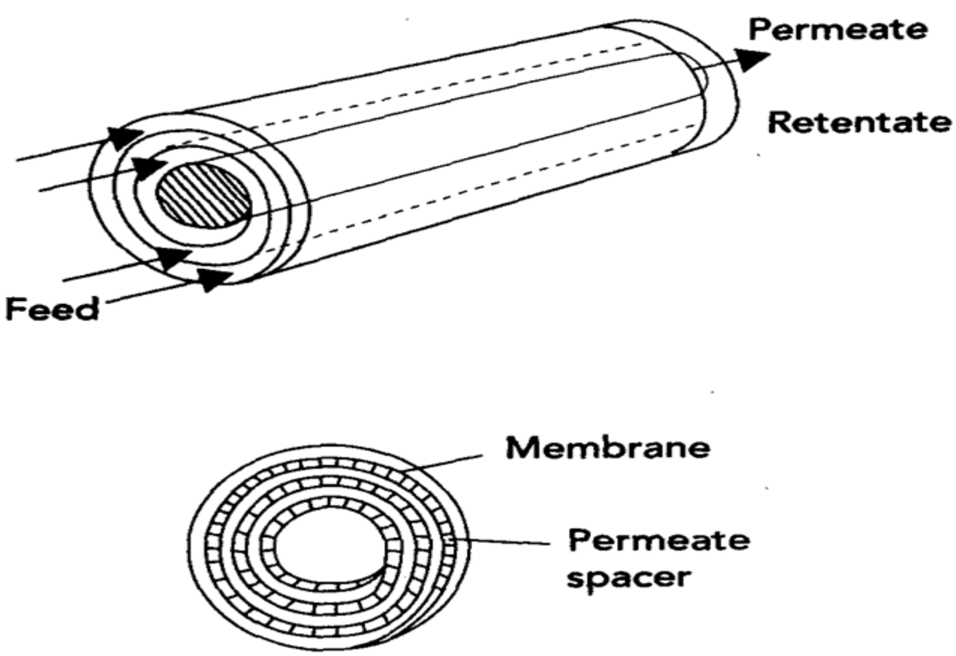


Figure 8 Spiral Wound Membrane Configuration

Water flow patterns are further illustrated in Figure 9.

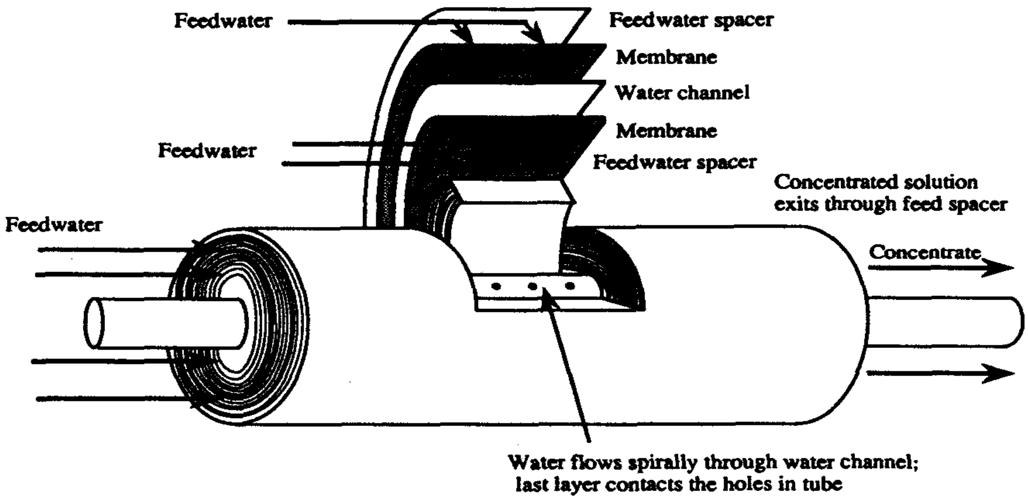


Figure 9 Water Flow Patterns in Spiral Wound Membranes

Hollow fiber membrane arrangements are illustrated in Figure 10

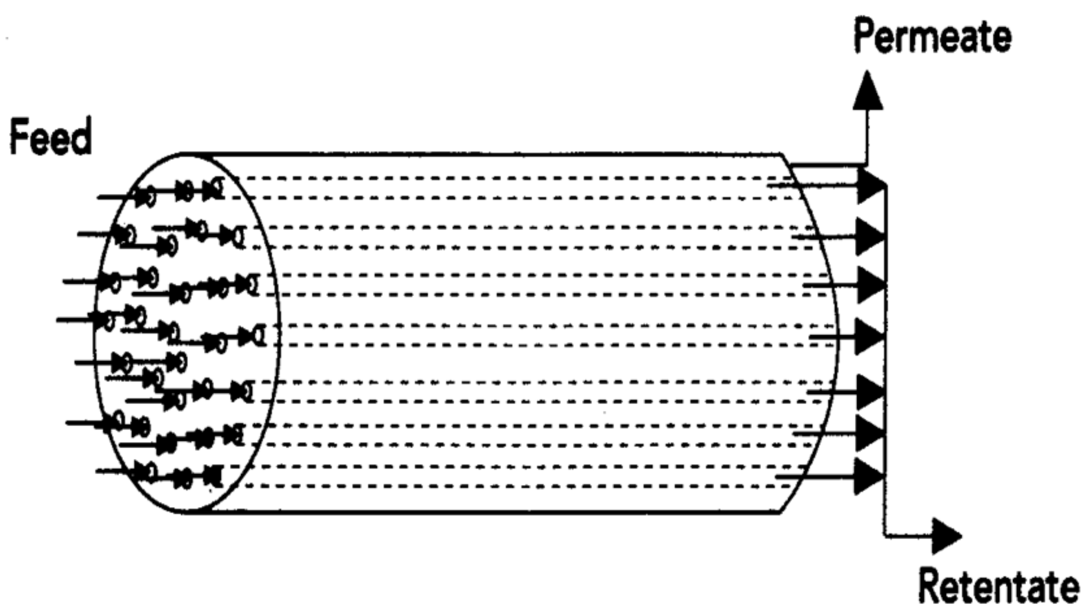


Figure 10 Hollow Fiber Membrane Arrangement

Achieving Quality Control in Tangential Flow Filtration

Inline real time photometers are an extremely effective way of monitoring filtration performance to achieve the most efficient and cost effective means of clarifying product as it passes from filtration step to filtration step. Sensors can determine the point at which acceptable purity is achieved or detect filter upset or breakthrough.

Inline photometric control guarantees the clarification of final product. Any deviation can be instantly detected, allowing process changes to be initiated immediately. The photometric system becomes an unsurpassed tool for quality assurance and quality control; thereby, reducing lab analysis, visual inspection and increasing filter system automation.

An illustration of how quality control can be achieved in TFF Applications is provided on Figure 11.

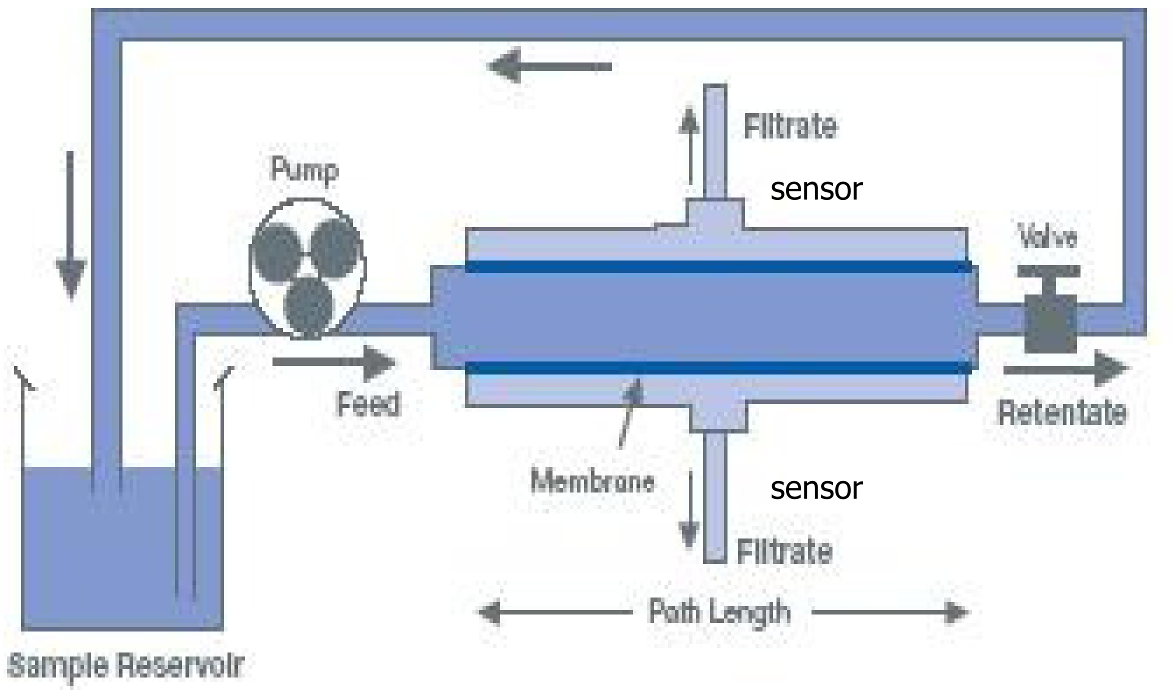


Figure 11 Achieving Quality Control in TFF Applications

Advantages of TFF

TFF Advantages is illustrated on Figure 12.

Process Goal	Cross Flow Filtration	Deadend Filtration
Ability to handle wide variation in particle size	Excellent	Generally poor
Ability to handle wide variations in solids concentration	Excellent	Poor or unacceptable
Continuous concentration with recycle	Excellent	Poor or unacceptable
Waste minimization	Superior	Can minimize waste if handling low solids feed where cartridge disposal is infrequent
High product purity or yield	Excellent	Performance is generally acceptable except in situations involving high solids or adsorptive fouling

Figure 12 TFF Advantages

TFF Systems

Typical TFF systems are batch and closed loop systems illustrated in Figures 13 and 14.

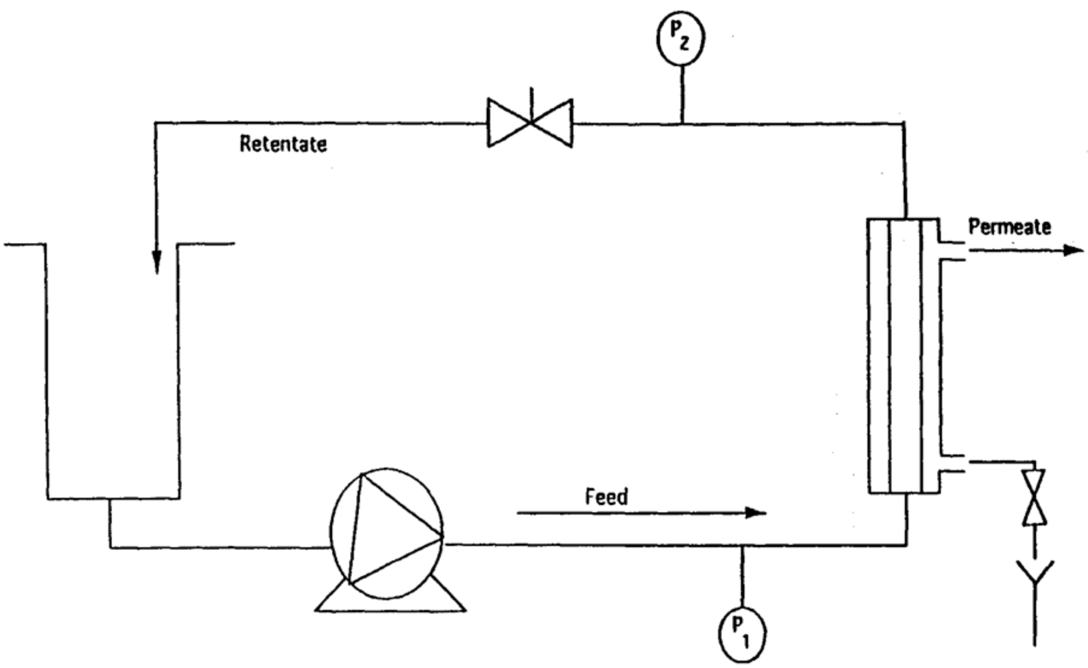


Figure 13 Batch (open loop) systems

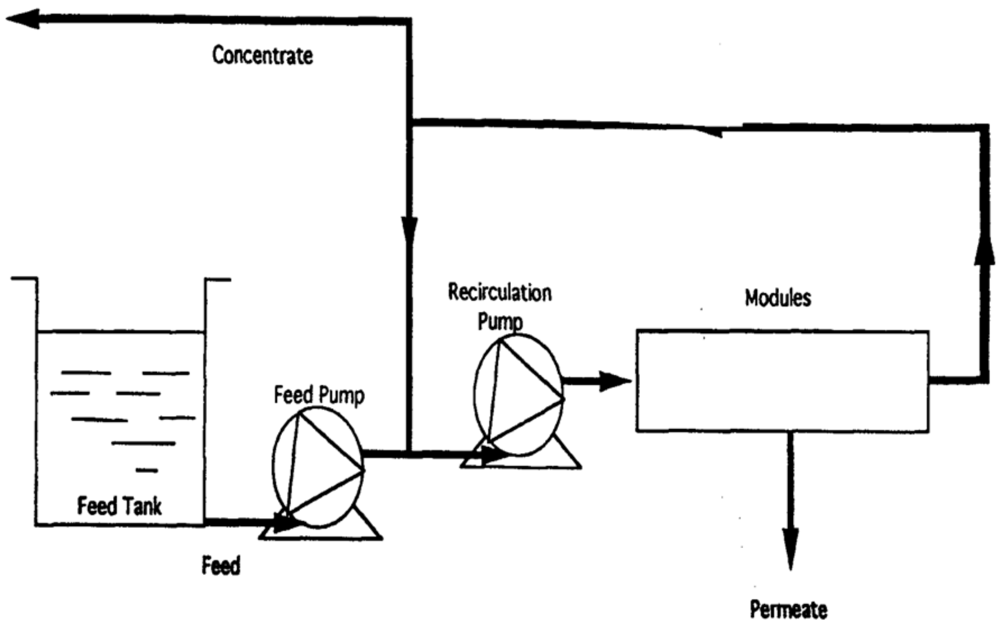


Figure 14 Closed Loop Feed and Bleed System

TFF Design Example Using a Biomolecule Concentration Application

Define the purpose of the TFF process:

- The biomolecule of interest in your sample is called a product. Separation can occur by choosing a membrane that retains the product while passing any low molecular weight contaminants.

- Alternatively, a membrane can be chosen that passes the product while retaining higher molecular weight components in the sample.

- It is important to know the concentration factor or the level of salt reduction required in order to choose the most appropriate membrane and system for the process.

Choose the membrane molecular weight cutoff:

- The molecular weight cutoff (MWCO) of a membrane is defined by its ability to retain a given percent of a molecule in solution (typically 90% retention). To retain a product, select a membrane with a MWCO that is 3 to 6 times lower than the molecular weight of the target protein. For fractionation, select a membrane MWCO that is lower than the molecular weight of the molecule to be retained but higher than the molecular weight of the molecule you are trying to pass.

Determine the required membrane area for the application:

- Choosing an appropriate TFF system depends on the total sample volume, required process time, and desired final sample volume.

- Use the following equation to calculate the membrane area required for processing a sample in a specified time:

$$A = \frac{V}{J \times T}$$

Where:

A = Membrane area (m^2)
V = Volume of filtrate generated (liters)
J = Filtrate flux rate [liters/ m^2/hour (LMH)]
T = Process time (hours)

Example 1: What TFF system should I use to concentrate 10 liters to 200 mL in 2.5 hours? Assume the average filtrate flux rate of 50 liters/m^2/hour (L/m2/h, LMH).

V = Volume of filtrate generated (L) = 10L – 0.2L (200 mL) = 9.8 L

$$A = \frac{9.8\ L}{50L/\ m^2/h \times 2.5h} = \frac{9.8}{125} = 0.08\ m^2$$

Transmembrane Pressure (TMP) or driving force for liquid transport through the ultrafiltration membrane, calculated as the average pressure applied to the membrane minus any filtrate pressure.

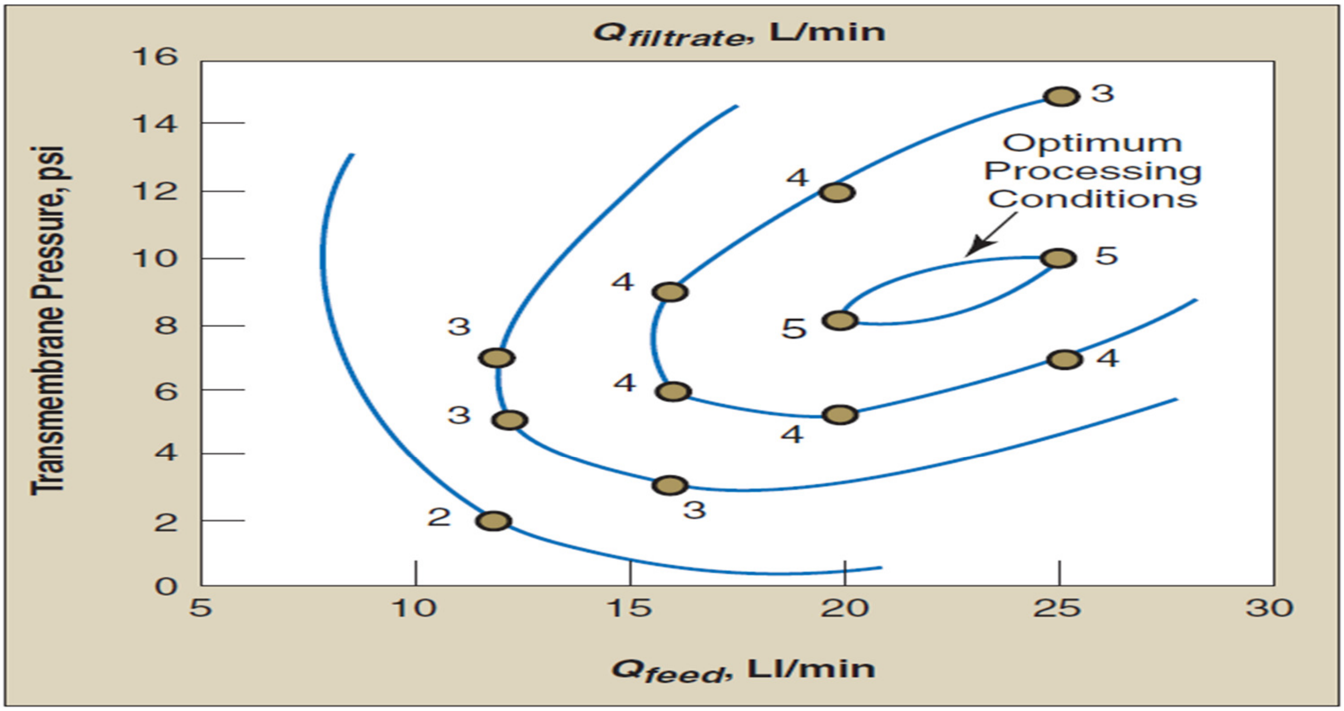
In most cases, pressure at filtrate port = $P_{filtrate} = 0$

$$TMP = \frac{(P_{feed} + P_{retentate})}{2} - P_{filtrate}$$

ΔP = (30 - 20) = 10 PSI, i.e. Inlet Pressure minus Retentate Pressure

Pin P_{feed} (1)	**Pout** $P_{retentate}$ (2)	**TMP** $\frac{(1) + (2)}{2}$	**ΔP** (1) – (2)
40	0	20	40
30	10	20	20
25	15	20	10

Using the above principle a process map shown in Figure 15 can be generated from Table 4 data.



A process map can be effectively used to determine optimal processing conditions. Here, feed flowrate, Q_{feed}, is shown on the *x*-axis and transmembrane pressure, *TMP*, is shown on the y-axis. Each *x*, *y* coordinate is labeled with the filtrate flowrate, $Q_{filtrate}$, generated with the corresponding Q_{feed} and *TMP* conditions. Lines are drawn between the *x*, *y* coordinates that have the same corresponding $Q_{filtrate}$ to form the map.

Figure 15 Process Map

Table 4 Data for Process Map

Table. Data for Figure 2.

$Q_{filtrate}$, L/min	Q_{feed}, L/min	*TMP*, psi
2	12	2
3	12	5
3	12	7
3	16	3
4	16	6
4	16	9
4	20	5
5	20	8
4	20	12
4	25	7
5	25	10
3	25	15

Nomenclature

P_{fi} = feed pressure on inlet side of membrane, psig

P_{fo} = feed pressure on outlet side of membrane, psig

P_{po} = permeate (or filtrate) pressure on outlet side of membrane, psig

Q_{feed} = feed volumetric flowrate, L/min

$Q_{filtrate}$ = filtrate volumetric flowrate, L/min

TMP = transmembrane pressure, psi (Eq.1)

$$TMP = (P_{fi} + P_{fo})/2 - P_{po}$$

Data shown on Table 4 is generated utilizing the following procedure:

1. Using a representative cell culture feed fluid, perform TFF clarification under a variety of combinations Q_{feed} and TMP. Record $Q_{filtrate}$ at each combination of Q_{feed} and TMP.
2. Plot the TMP vs. Q_{feed} values on an x, y scatter plot.
3. Enter the correlating $Q_{filtrate}$ beside each point on the graph.
4. Draw a line that connects equal $Q_{filtrate}$ values; the lines should form a circle surrounded by concentric lines. The circle should contain the highest $Q_{filtrate}$ values — the TMP and flowrate conditions within this circle represent the optimum processing conditions.
5. Perform further process mapping by:

- using the worst-case feed fluid.
- working within the optimum processing-conditions boundary to establish final process conditions.
- conducting the process at full-scale flow conditions; perform limited mapping and optimization as necessary.

Typical operating pressures in TFF Applications are provided on Figure 16.

Typical Operating Values

	MWCO/Pore Size	Flux	Pressure
MF	0.1 to 2 µm	115 L/m^2/h	15 to 60 psi
UF	0.005 to 0.1 µm	100 L/m^2/h	30 to 100 psi
NF	0.0005 to 0.005 µm	17 L/m^2/h	90 psi (typical)
RO	< 0.5 nm 50 to 200 daltons	n.a.	200 psi

Figure 16 TFF Operating Values

Filter Ratings

- Microfiltration
  - Rated by pore size
    - 0.1 - 0.65 Micron
- Ultrafiltration
  - Rated by size of molecule retained
    - 1,000 - 1,000,000 NMWL
- Reverse Osmosis
  - Rated by retention of marker ions
    - NaCl

Membrane Chemistry

- Microfiltration
    - PVDF (Durapore™)
    - Polyethersulfone
- Ultrafiltration
    - Polyethersulfone (Biomax™)
    - Regenerated Cellulose (Ultracell™)
- Reverse Osmosis
    - Thin Film Composite (TFC)
    - Polyamide on Polysulfone
- UF Membranes
    - Conventional with subsurface voids
    - New void-free
    - composite structure
    - (Ultracell™)

Feed Water Quality

Guidelines for acceptable feed water quality to the TFF Membrane are provided on Table 5.

Table 5 Guidelines for Acceptable Feed Water Quality

Parameter	Recommended maximum value for membrane desalination processes
Iron	0.1 mg/L*
Manganese	0.05 mg/L
Turbidity	0.5 Nepholometric Turbidity Units (NTU)
Hydrogen Sulphide	3-5 mg/L
Total Organic Carbon	2 mg/L
Volatile Organic Chemicals	In µg/L range
Silt Density Index-15	3
Oil and Grease	0.1 mg/L
Reactive (Soluble) Silica	40 mg/L**
Total Hardness	0 LSI (Langelier Saturation Index)

* - values as high as 1-2 mg/L acceptable if pH < 7 and absolutely no chance of air entry and oxidation

** - The limit is not on the feed water but in the brine. The feedwater threshold concentration has been back-calculated from a brine concentration threshold of 150 mg/L assuming no anti-scalants are used and achieving 75 per cent recovery rate. Colloidal silica is included in turbidity and LSI threshold values.

Source: Feasibility Study Report to Australian Ministry of Water, URS 2011

Texas Drought and TFF

The Texas drought is ongoing in many parts of the state:

- Communities face prospect of running out of water
- Brackish groundwater desalination identified as one viable option that can provide water in an emergency and long term

A simple process schematic of brackish highly saline groundwater desalination is provided on Figure 17.

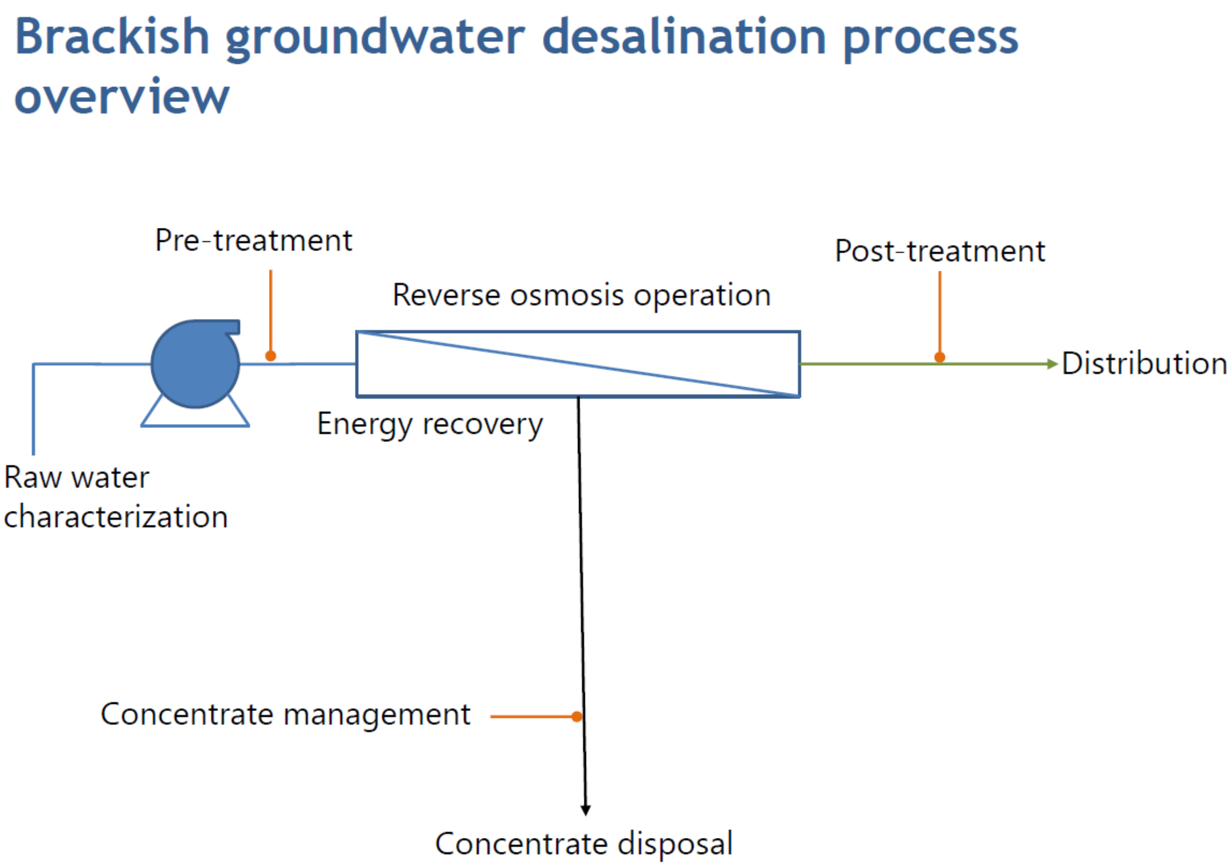


Figure 17 Simple Process Schematic on Brackish Groundwater Desalination

Pilot Study

Prior to full scale study, a thorough pilot study should be undertaken to evaluate the TFF Membrane treatability of the wastewater effluent, brackish groundwater and high saline surface water.

If desalination is the focus of the pilot study, performance of the membrane for the typical desalination parameters of interest that may be encountered in the source water should be studied. These parameters are outlined on Table 6.

Table 6 Desalination Parameters of Interest

Desalination parameters of interest

Physical Parameters	Chemical Parameters		
	Cations (mg/L)	Anions (mg/L)	Other Chemical Parameters
Conductivity (mS/cm)	As^{3+}	Cl^-	Alkalinity (mg/L as $CaCO_3$)
pH	As^{5+}	F^-	Boron (mg/L)
Silt density index	Ba^{2+}	HCO_3^-	Dissolved oxygen concentration (mg/L)
Temperature (°C)	Ca^{2+}	NO_2^- -N	H_2S (mg/L)
Turbidity (NTU)	Cu^{2+}	NO_3^- -N	Hardness (mg/L as $CaCO_3$)
	Fe_3^+	SO_4^{2-}	Pesticides(mg/L)
	K^+		Radionuclides (pCi/L) Uranium (µg/L)
	Mg^{2+}		Silica (mg/L)
	Mn^{2+}		TDS (mg/L)
	Na^+		
	NH_4^+ -N		
	Ni^{2+}		
	Zn^{2+}		

TFF Industrial Applications Process Flow Diagrams

In addition to TFF for brackish and saline source water treatment, common TFF Applications in the industry are represented in process flow diagrams provided on the following pages. All of these process diagrams illustrate that TFF Membrane Processes which include MF, UF and RO are integral to municipal and industrial wastewater reuse. It is evident in the processes displayed that strategic pretreatment is important to promote the longevity of the TFF membranes integral to the reuse treatment schematic.

These typical process diagrams represented for the petroleum and municipal sectors are illustrated as Figures 18 through 21.

Figure 18 Refinery Wastewater Reuse for the Process Industry

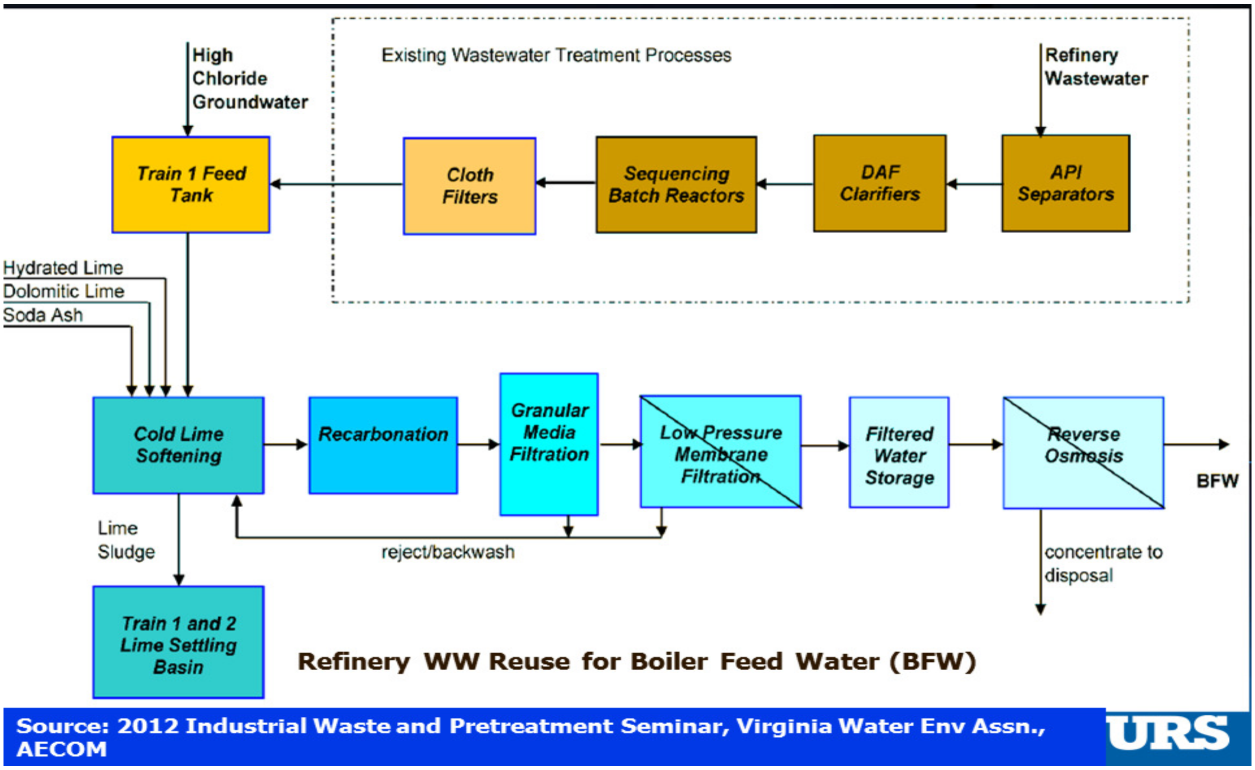


Figure 19 Marine Terminal TFF Water Reuse Application

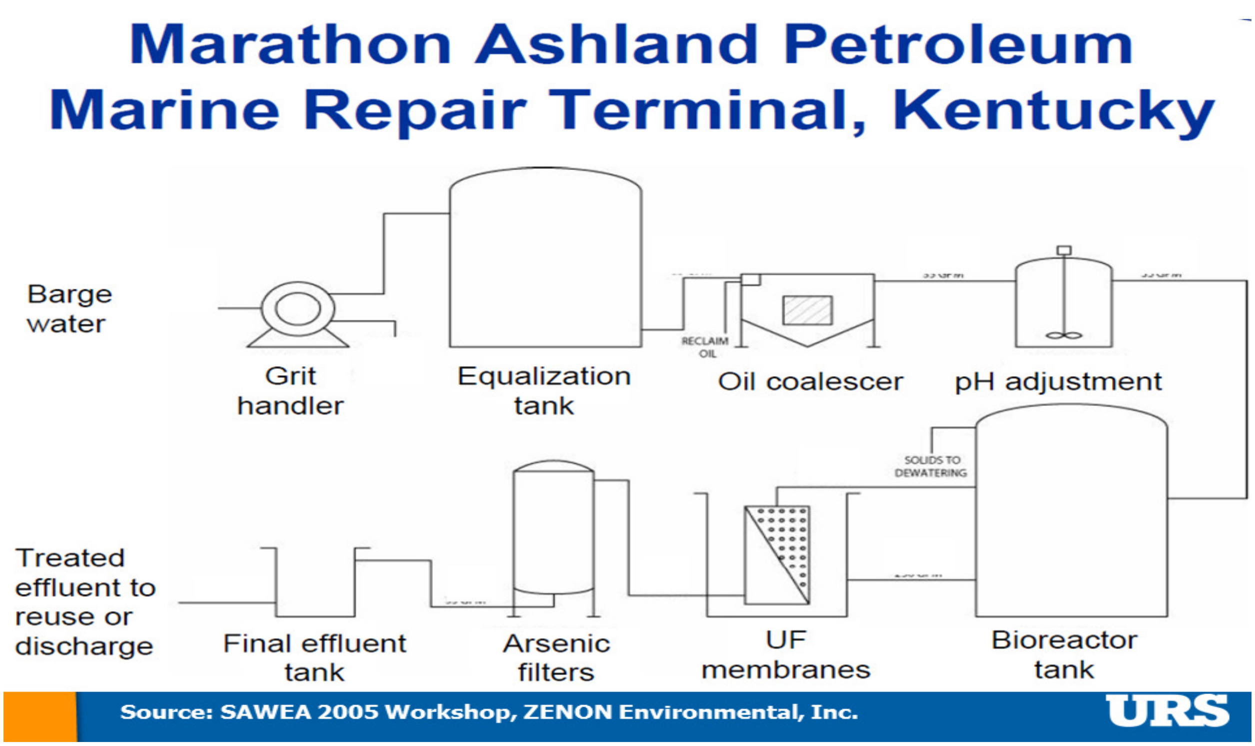


Figure 20 Example TFF Application in a Municipal Resource Recovery Center

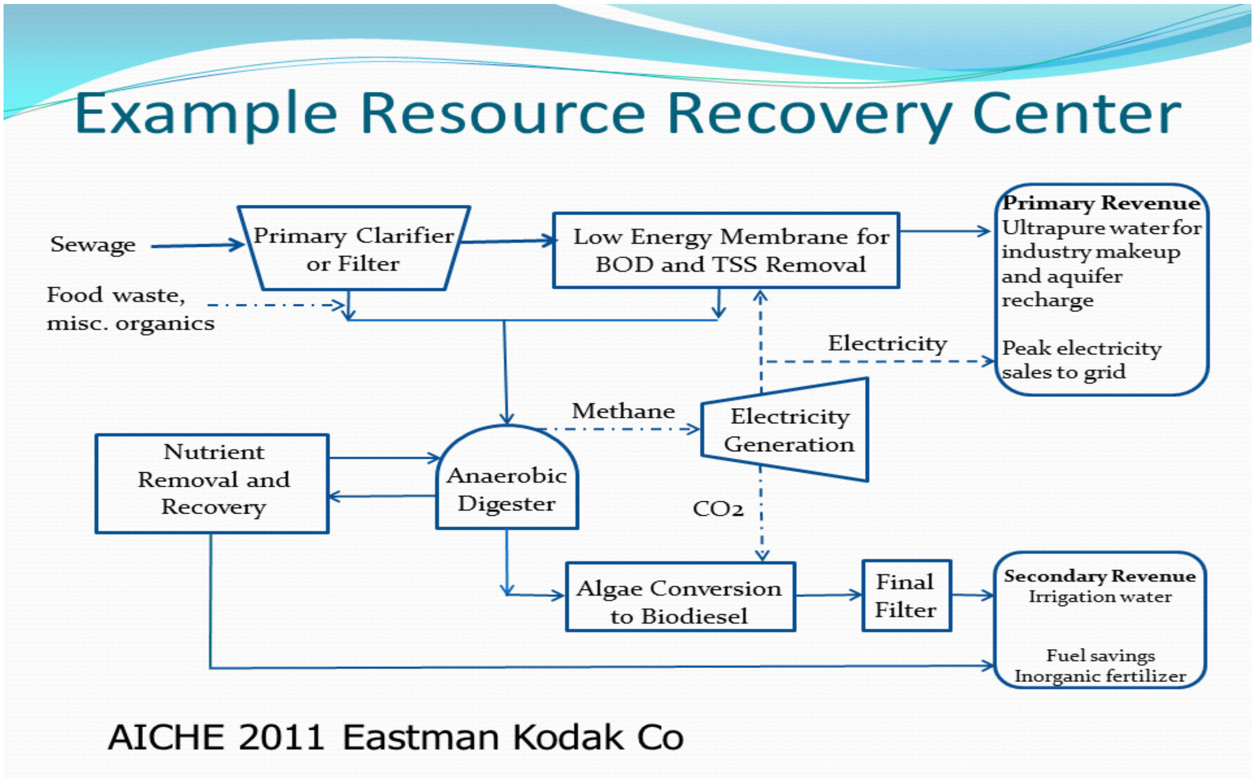
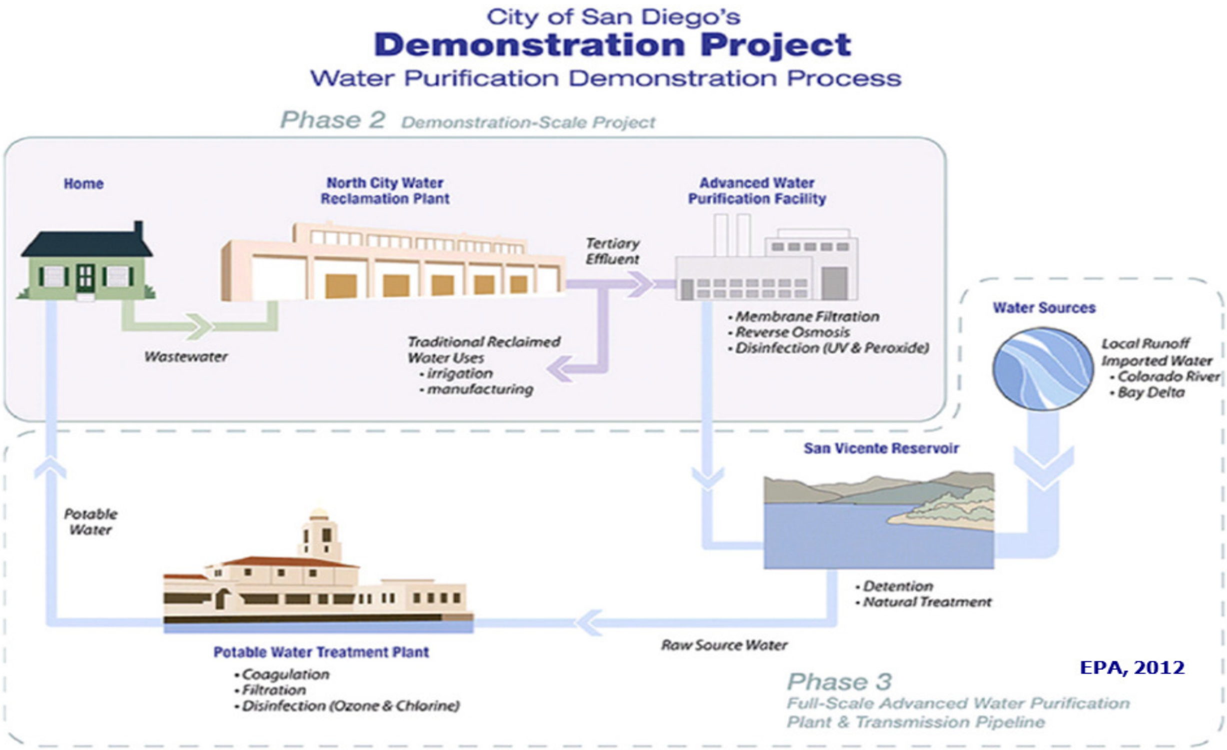


Figure 21 Water Purification TFF Application



Conclusions:

Factors To Be Considered during TFF Scaleup include the following

- Understanding of the process objectives
- Purity, yield, times, volumes, concentrations, etc.
- Select Correct Membrane
- Select Correct Device
- Collect Adequate Data to Select Proper Operating
- Conditions
- Flux vs. Crossflow
- Flux vs. TMP
- Flux vs. Concentration
- Collect Data for Multiple Runs to Prove Robustness

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