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Wastewater Recovery & Reuse – Part I

Presented at:

Saudi Arabia Water Environment Association

by

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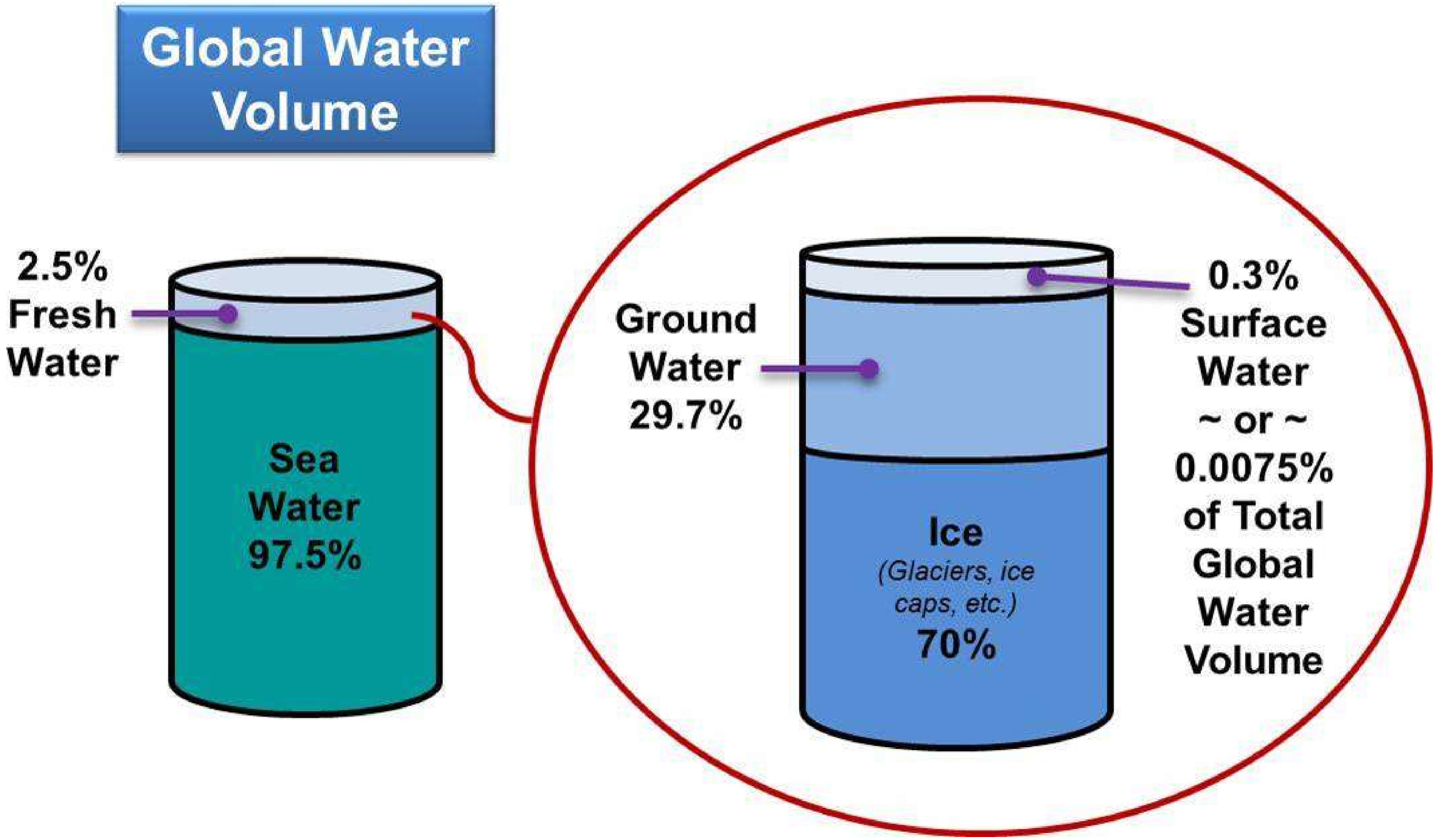
Introduction

Distribution of Global Water Supply (m^3 x 10^9)

	FRESH	SALINE	TOTAL
Rivers and streams	1,250	—	—
Freshwater lakes	125,000	—	—
Salt lakes and inland seas	—	104,000	—
Total surface water	**126,000**	**104,000**	**230,000**
Soil moisture and seepage	67,000	—	—
Underground water to 1/2 mile depth	4,200,000	—	—
Underground water below 1/2 mile	4,200,000	—	—
Total ground water	**8,467,000**	—	**8,467,000**
Glaciers and ice caps	29,180,000	—	—
Oceans	—	1,321,460,000	—
Total world water supply	**37,773,000**	**1,321,564,000**	**1,359,337,000**

Global Water Supplies



Wastewater Sources

Wastewater Sources

- Rainwater/Stormwater
- Residential Discharges
- Municipal Sewage
- Industrial/Commercial Discharges

Rainwater Harvesting

The Attributes of Harvested Rainwater

- 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 is both hardness and sodium-free.
- 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 water if groundwater quality is unacceptable.
- Provides a source if tap charges are too high for water supply connection.
- Reduces erosion in urban environments.

The Attributes of Harvested Rainwater (con't)

- 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 demands in the summer
- Provides water for cooling and air-conditioning plants
- Reduces the demands on groundwater
- Provides water for fire protection
- Saves money for the consumer in utility bills

Rainfall Quality

- Particles
- Liquids
- Salts
- Gases

A function of location

Water Contaminants

Class	Examples
Suspended solids	Dirt, clay, colloidal materials, silt, dust, insoluble metal oxides and hydroxides
Dissolved organics	Trihalomethanes, synthetic organic chemicals, humic acids, fulvic acids
Dissolved ionics (salts)	Heavy metals, silica, arsenic, nitrate, chloride, carbonates
Microorganisms	Bacteria, viruses, protozoan cysts, fungi, algae, molds, yeast cells
Gases	Hydrogen sulfide, methane, sulfur dioxide, carbon dioxide

Rainwater Harvesting 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 treated with technologies dictated by intended use and/or regulatory requirements.
- An optional approach is to include a “day tank” for internal storage, distribution and municipal water makeup.

Collection Surface Materials

Metals:

Aluminum

Galvanized Sheet Metal

Sheet Steel

NO LEAD/COPPER FLASHINGS

Ceramics:

Clay Tiles

Concrete Tiles

Slate Tiles

Composites:

Asphalt

Wood

Collection Surface Contaminants

Roofing Material	Contaminants
Aluminum	aluminum salts
Galvanized metal	lead, cadmium, zinc salts
Sheet metal	lead
Ceramic materials	mold, algae, bacteria, moss
Composite materials	mold, algae, bacteria, moss, dust, soot, petroleum compounds, gravel grit, copper, organics, fillers
Wood	mold, algae, bacteria, moss, wood preservatives

Other Components

Conveying System

Gutters

Downspouts

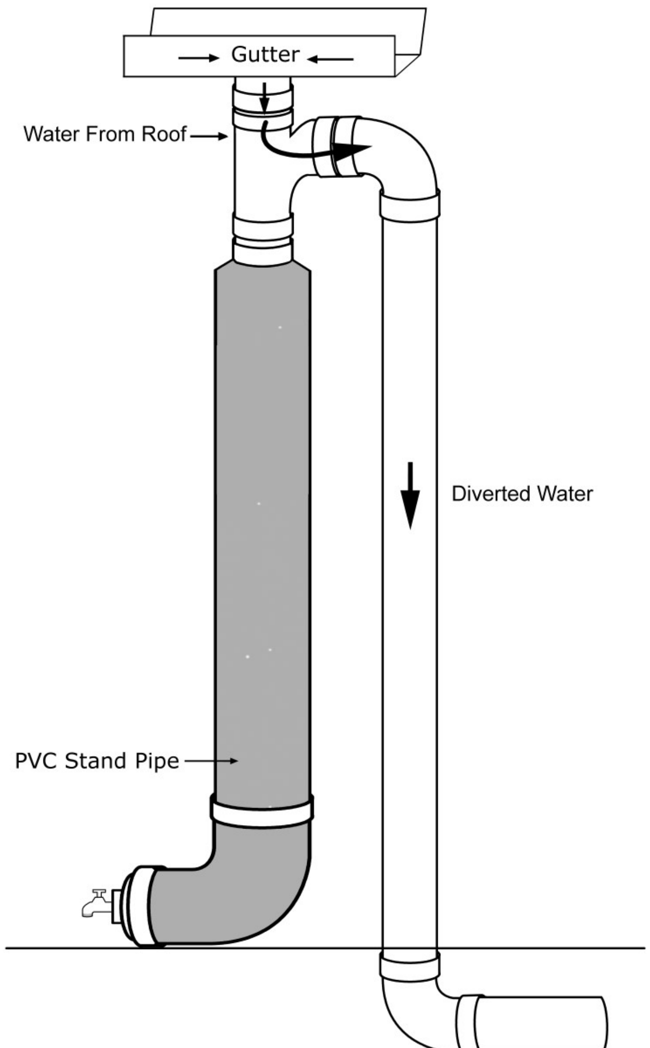
Siphonic Drains

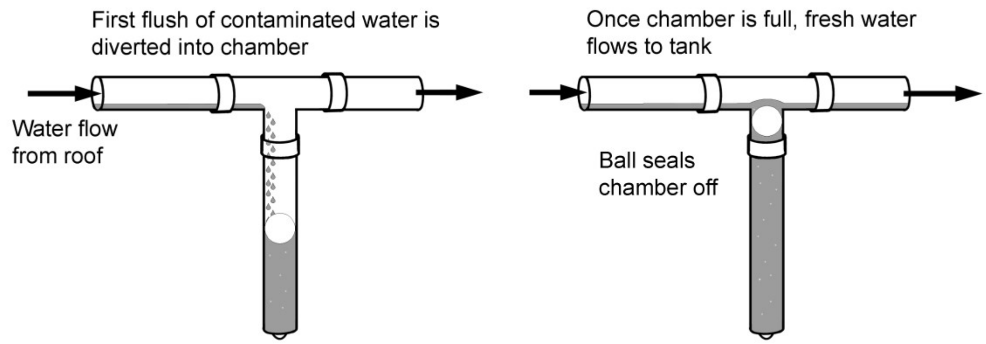
Materials of Construction

Diverters & Filters

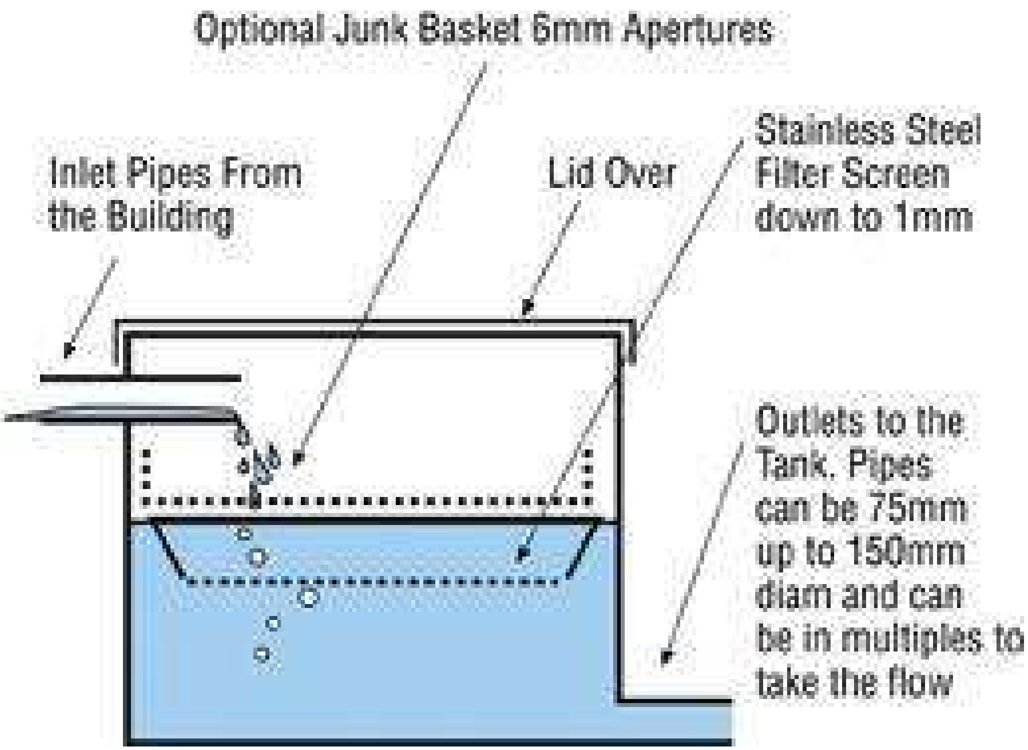
First-flush diverts 5-10% of flow

"First-Flush" Diverters





Roof Filter


Optional Junk Basket 6mm Apertures
Inlet Pipes From the Building
Lid Over
Stainless Steel Filter Screen down to 1mm
Outlets to the Tank. Pipes can be 75mm up to 150mm diam and can be in multiples to take the flow

Collection Tank

Characteristic	Above Ground	Below Ground
Installation cost	Low	High
UV resistant material	Yes	No (exposed surfaces only)
Opaque walls	Yes	No
Ease of inspection & maintenance	High	Low
Stored water temperature	Ambient	Cool

Collection Tank Materials

	Tank Materials	Strengths	Weaknesses	Relative Cost
Plastic	Fiberglass	commercially available minimal maintenance light weight	must be sited on smooth, solid footing UV-degradable solid, level footing, fittings, molded relatively fragile	2
	Polyethylene and polypropylene	commercially available minimal maintenance	UV-degradable fittings may leak	3
Metal	Galvanized steel tanks	commercially available light weight	possible corrosion (will not rust below ground)	1
Ceramic	Concrete	durable, immovable available "poured-in-place" or prefabricated neutralizes pH	potential to crack and leak	5
	Ferrocement	durable, immovable, versatile neutralizes pH	potential to crack and leak must be fabricated on site	4
	Concrete block, tile	durable, immovable keeps water cool in hot climates	difficult to maintain expensive to build must be fabricated on site	6
Wood	Redwood, cedar, cypress, etc.	aesthetically appealing	high maintenance will rot below ground must be fabricated on site	7

Relative cost: installed cost, with "1" being the lowest

Concrete Tanks

Tank Size Factors

Available collection area

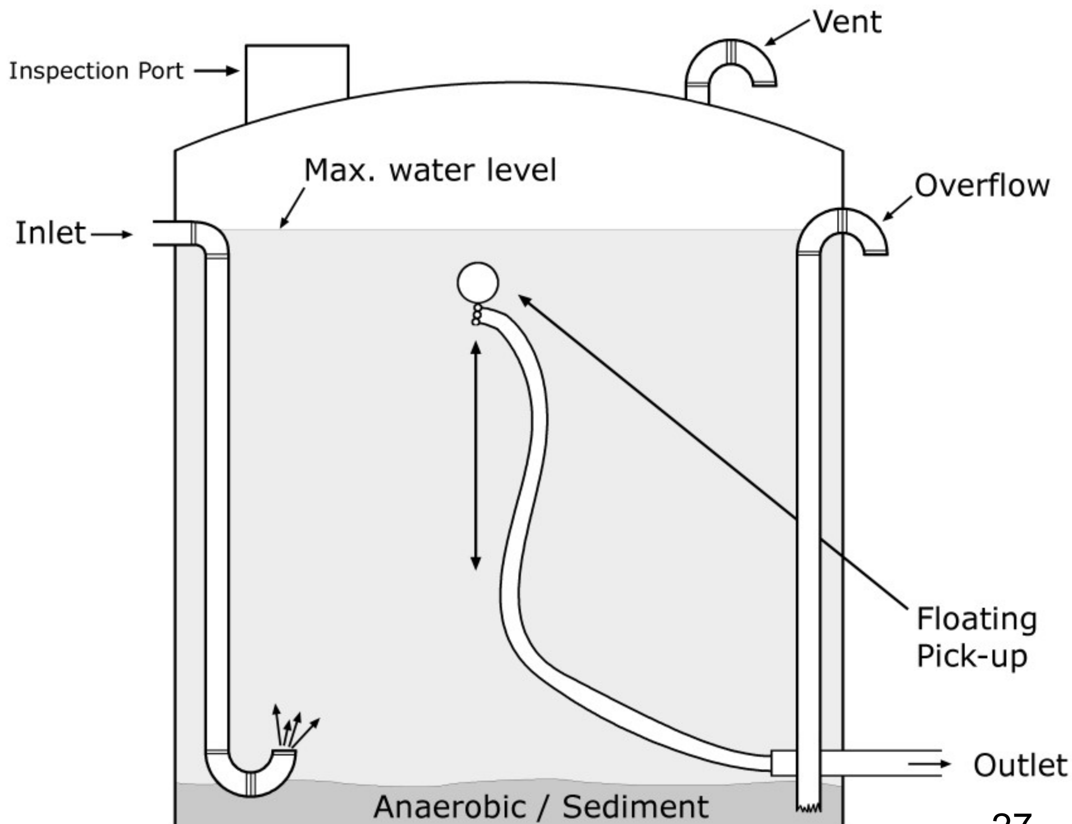
Rainfall patterns *(volume and frequency)*

Collected water use

Daily and instantaneous flow requirements

Water Going In and Out

- Inlet – side or top or bottom
- Outlet
- Overflow
- Inspection Port
- Vent



Opinion:

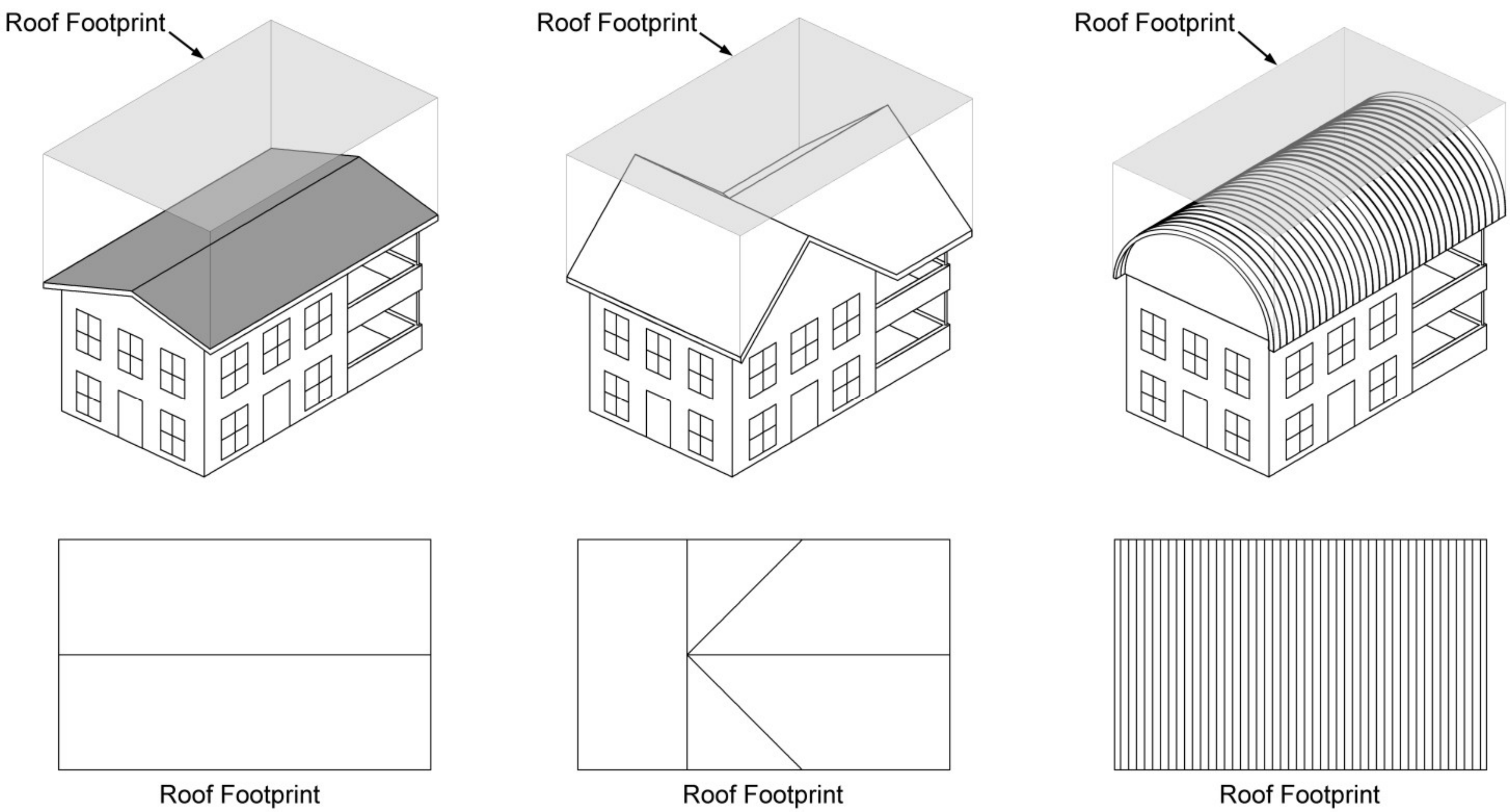
STORAGE TANKS MUST BE DISINFECTED CONTINUOUSLY

Surface Collection Volume

For every square foot of roof footprint,
1” of rainfall will deposit 0.62 gallons of water.

To account for first flush,
evaporation & water losses,
it is recommended to lower this figure
to 0.50 gallons/ft^2.

Footprint of the Building



Jet Pump – on demand pump

Submersible Pump

Pressure Tanks

Supply and Demand

Size of collection surface and rainfall frequency determine
SUPPLY

Usage determines
DEMAND

Demand determines
COLLECTION TANK SIZE

Minimum Indoor Water Quality Guidelines

Category of Use	Rainwater Quality for Nonpotable Indoor Use	Rainwater Quality for Potable Uses
Single Family Households	Total Coliforms <500 cfu/100 ml Fecal Coliforms <100 cfu/100 ml Water testing recommended annually	Total Coliform - 0 Fecal Coliform - 0 Protozoan Cysts - 0 Viruses - 0 Turbidity <1 NTU Water testing recommended every 3 months
Community or Public Water System	Total Coliforms <500 cfu/100 ml Fecal Coliforms <100 cfu/100 ml Water testing recommended annually	Total Coliform - 0 Fecal Coliform - 0 Protozoan Cysts - 0 Viruses - 0 Turbidity <0.3 NTU Water testing required monthly *In addition, the water must meet all other applicable public water supply regulations and water testing requirements*

CFU = Colony forming units

NTU = Nephelometric turbidity units

Indoor Domestic Demand

	Water Consumption using Conserving Fixtures	Assumptions from AWWA Residential End-Use Study
Toilets		
ULFT	1.6 gal/flush	6 flushes/person/day
Dual Flush	1 gal/flush - liquids 1.6 gal/flush - solids	6 flushes/person/day
Baths & Showers		
Showerhead	2.2 gal/min	5 minutes/person/day
Bath	50 gal/bath	NA
Faucets		
Personal hygiene, cooking, and cleaning of surfaces	2.2 gal/faucet/min	5 minutes/person/day
Appliances or uses which are measured on a per-use basis (not a per-person basis)		
Clothes Washer (Front-loading horizontal-axis)	18-25 gal/load	2.6 loads/week
Dishwasher	8 gal/cycle	0.7 cycles/day

Indoor Office Demand *

	Gallons/use	Uses/person	Gallons/person/day
Toilet/urinal	1.6	4	6.4
Lavatory sink	1.0	4	4.0
Shower	25	0.4	10.0

Total daily usage/person = 20.4 gallons

* *Does not include outdoor or cooling water usage*

Potential Water Uses

Nonpotable		Potable
• Landscape irrigation	• Building washing	• Drinking water
• Garden watering	• Cooling towers	• Cooking/culinary
• Vehicle washing	• Fire suppression	• Showering/bathing
• Toilet/urinal flushing	• Household cleaning	• Dishwashing
• Laundry	• Pool/pond filling	

Residential Installation

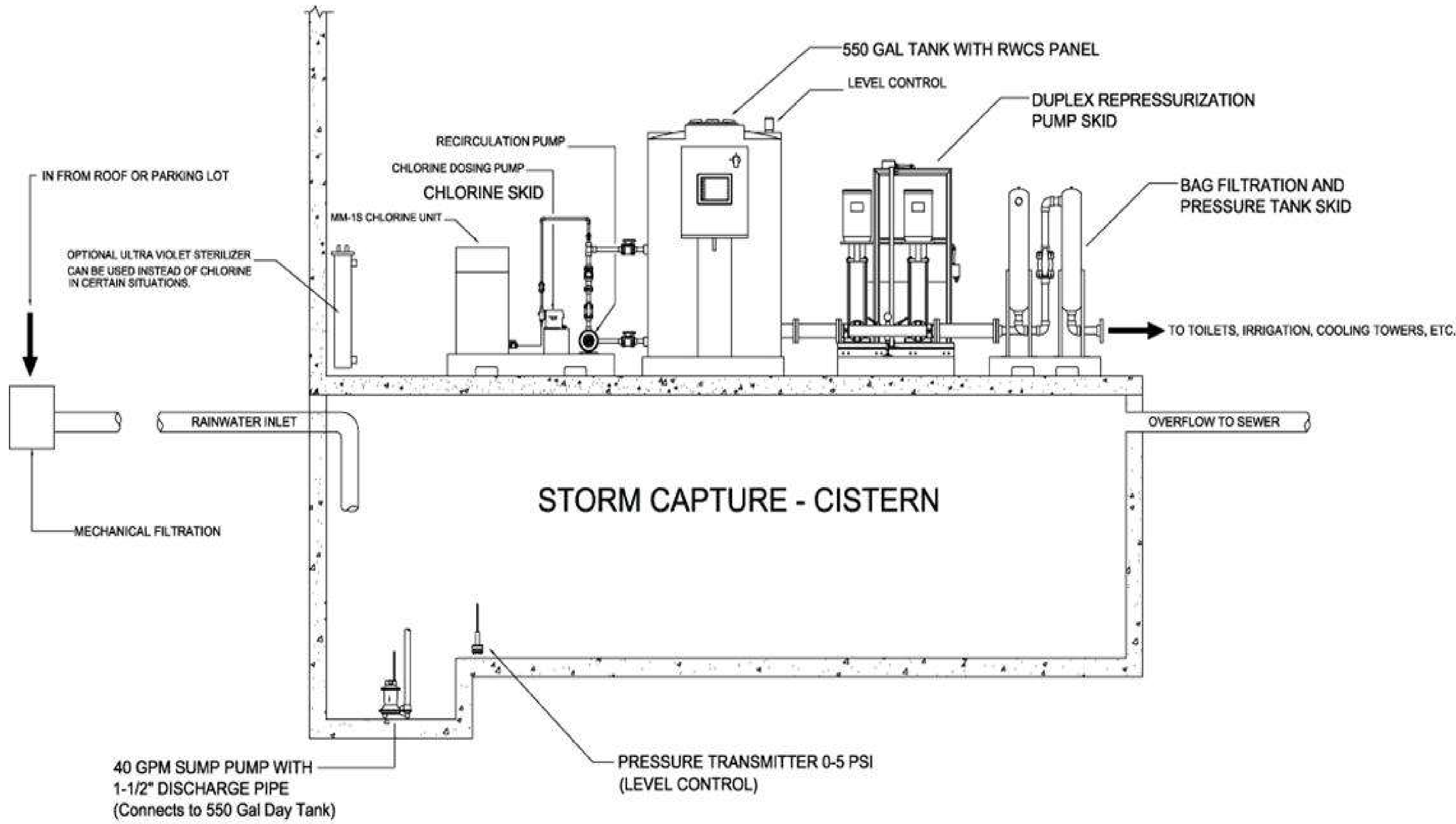
Industrial Installation

Pathogens in Harvested Rainwater

- Salmonella
- Campylobacter
- Legionella
- Clostridium
- Giardia Lamblia
- Cryptosporidium Parvum

Stormwater

Stormwater Collection



www.stormcapture.com

Graywater

Definitions

Graywater

Also called “greywater”, “gray water” and “greywater”, untreated wastewater from domestic activities:

- Bathing
- Showering
- Laundry
- Lavatory sinks

“Blackwater” not included:

- Toilets
- Urinals
- Dishwashers
- Kitchen sinks
- Garbage disposers

Blackwater

Toilet/Urinal
Kitchen Sink
Dishwasher
Disposer

Graywater

Bath/Shower
Lavatory Sink
Washing Machine

Indoor Wastewater Generation

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

Ranges of Significant Contaminants

Parameter	Unit	Range
BOD_5 (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*

Typical Sources of Graywater Contaminants

Ingredient	Concentration (mg/L)
Sunscreen	1500
Moisturizer	1000
Toothpaste	3250
Deodorant	1000
Na_2SO_4 (Sodium sulfate)	3500
$NaHCO_3$ (Sodium bicarbonate)	2500
Na_3PO_4 (Trisodium phosphate)	3900
Clay	5000
Vegetable Oil	700
Shampoo or Hand Soap	7200
Laundry Detergent	15000
Boric Acid	140
Lactic Acid	2800

NON-RESIDENTIAL GRAYWATER

Non-Residential Sources

Hospitals
Schools
Hotels
Office Buildings
Restaurants

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-Efficience Technologies for Mechanical Contractors: New Business Opportunities", Figure 1.

Testing Protocols

NSF is a Global Leader in Public Health and Safety

- Independent, Not-for-profit organization
- Developer of over 72 national consensus standards
- Steadfast ties with key associations and govt. agencies
- Service provider to over 12,000 companies in 100 countries

INDEPENDENTLY CERTIFIED™ NSF SYSTEM

Product Standards

NSF 350 *Onsite residential and commercial reuse treatment systems*

and

NSF 350-1 *Onsite residential and commercial graywater treatment systems for subsurface discharge*

Courtesy of NSF International

Product Test Conditions

- Installed per manufacturer's instructions.
- No restriction for seasons.
- Operated in accordance with manufacturer's instruction.
- Minimum six month evaluation.
- No service or maintenance during entire test.
- All test data reported.
- No allowance for discard of any data, except if test facility fails to provide an acceptable test.

NSF/ANSI STANDARD 350

Scope: Standard 350

- **Residential and commercial treatment systems**
- **Sources; graywater and combined wastewater**
  - Graywater: laundry and bathing, excluding toilet and kitchen.
- **Non-potable effluent use**
  - Indoor; toilet and urinal flushing.
  - Outdoor; subsurface discharge.

NSF 350 – Building Types

Residential (Class R) – Up to 1500 gpd

Commercial (Class C) - >1500 gpd

Commercial Laundry Water – All volumes

NSF/ANSI STANDARD 350-1

NSF/ANSI 350-1 applies to subsurface discharge only

NSF 350-1 – Building Types

Residential – Up to 1500 gpd

Commercial - >1500 gpd

Commercial Laundry Water – All volumes

Challenge Water - Bathing Water Only

Parameter	Required Range
TSS (Total Suspended Solids)	50-100 mg/L
BOD_5 (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

Bathing Challenge Water Constituents

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

Laundry Wastewater From:

- Hotels
- Hospitals
- Rental Uniform Companies

Challenge Water - Laundry Water Only

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

Laundry Challenge Water Constituents

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_2SO_4	4 g
$NaHCO_3$	2 g
Na_3PO_4	4 g

Both Bathing and Laundry Waters:

Mix bathing challenge water and laundry challenge water in ratio of 53:47

Challenge Water – Combined Sources

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)	10^3-10^4 cfu/100 mL

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*

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Treated Effluent Criteria

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	$\geq 0.5 - \leq 2.5$			
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*

Effluent Criteria

$CBOD_5$ - <25 mg/L

TSS - <30 mg/L

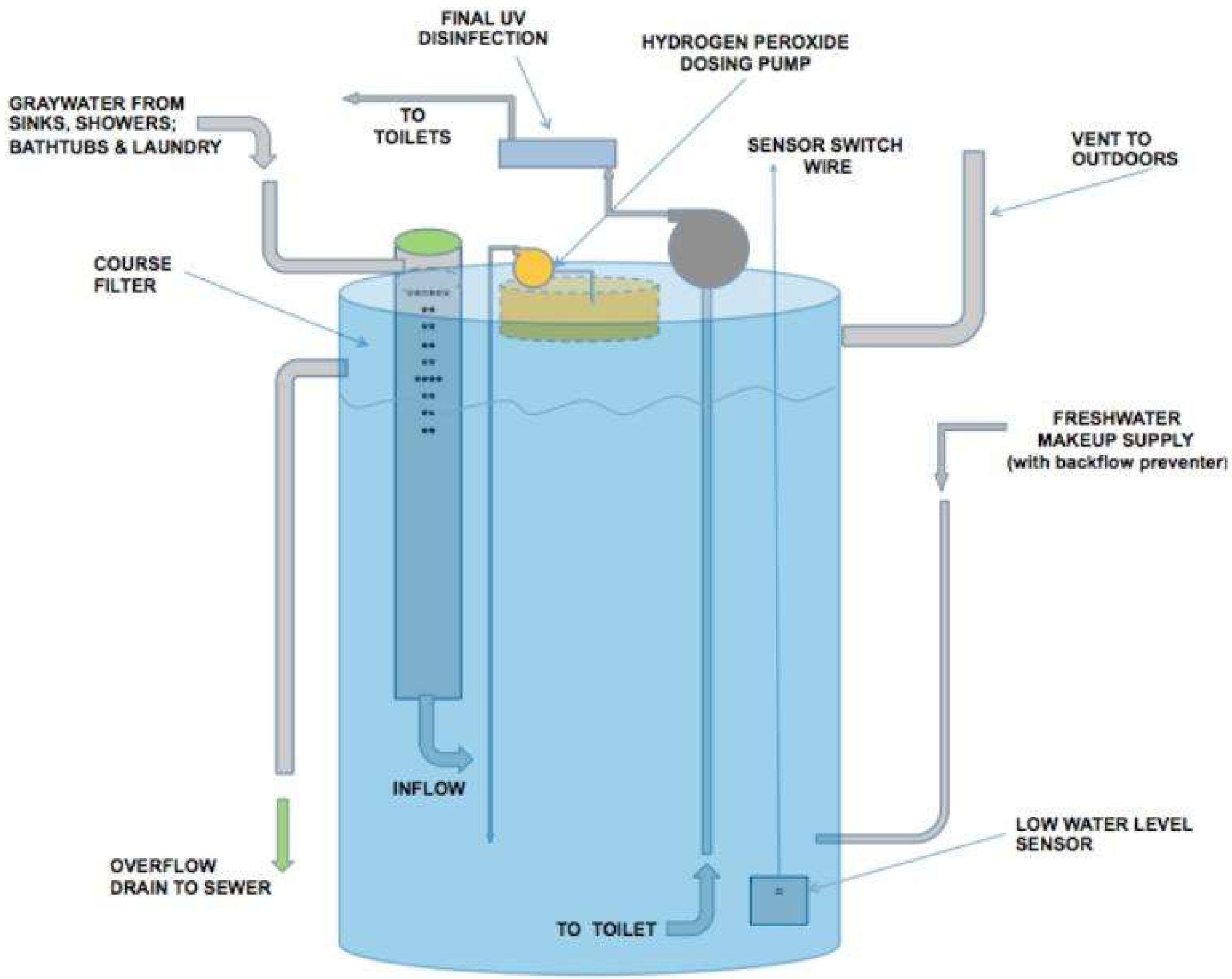
pH - 6-9

Technology Selection Factors

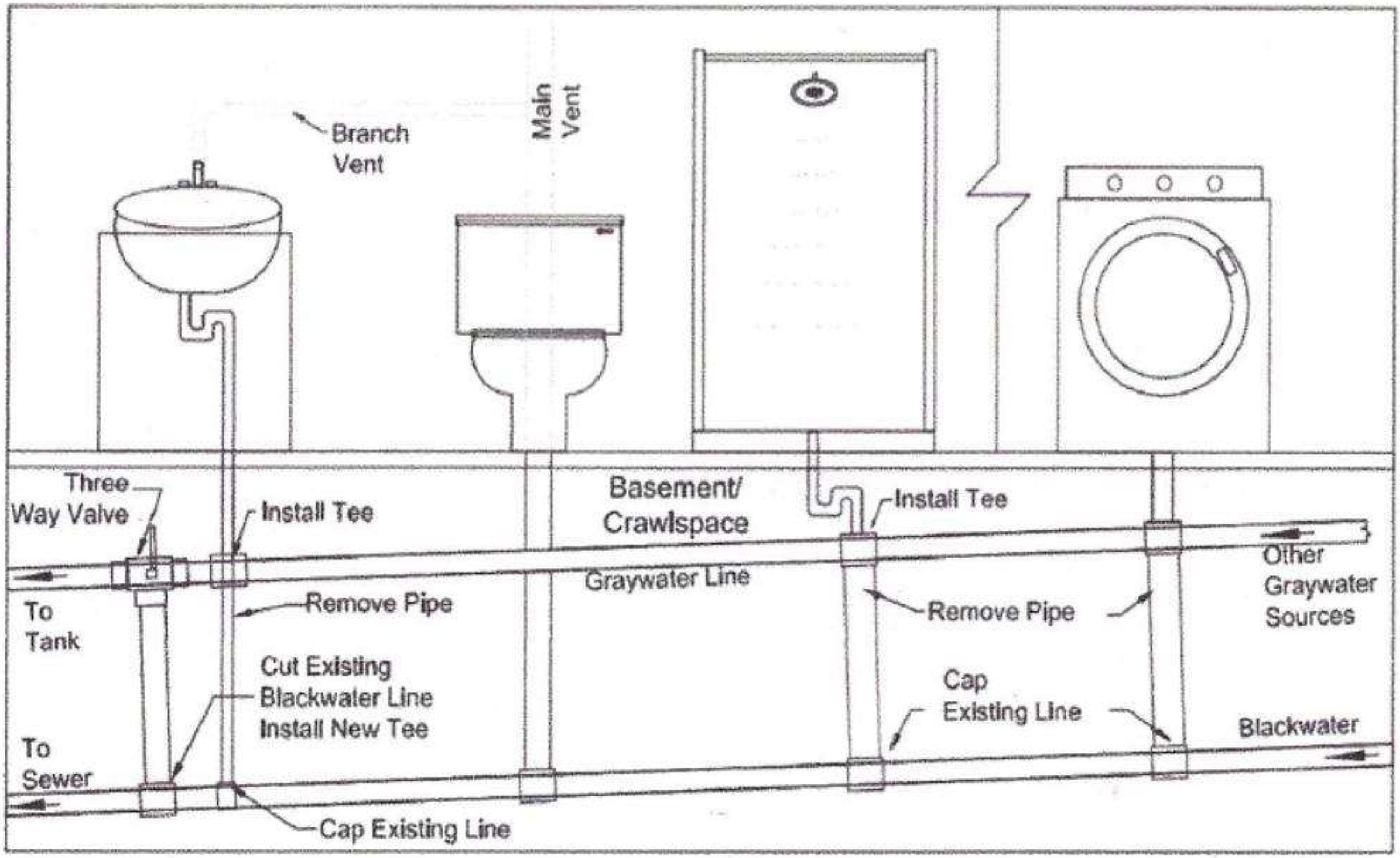
- Ultimate use of the recovered graywater.
- Specific contaminants in the graywater to be reduced.
- Total volume requirements.
- Regulations.

Example System

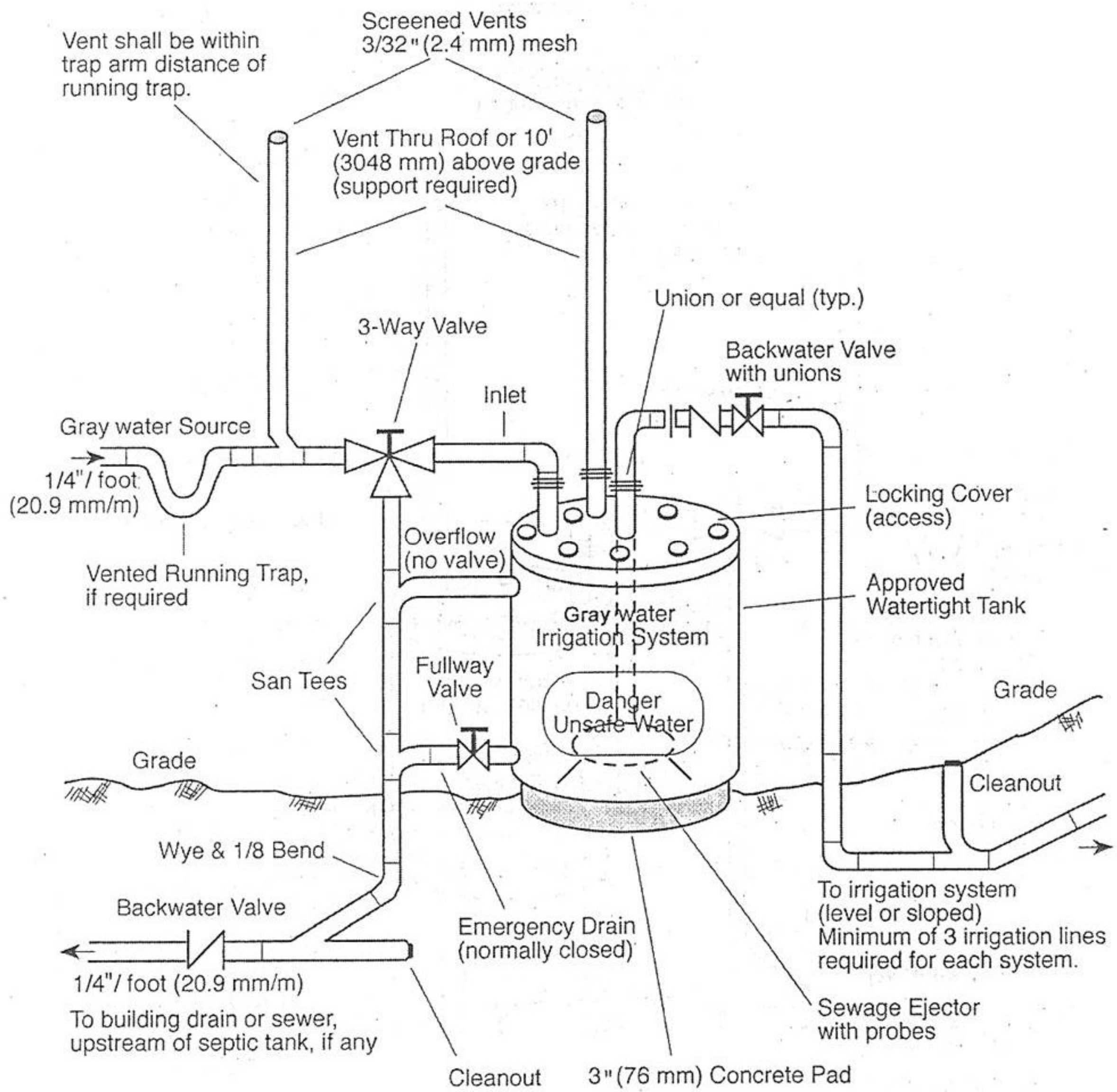
Example System



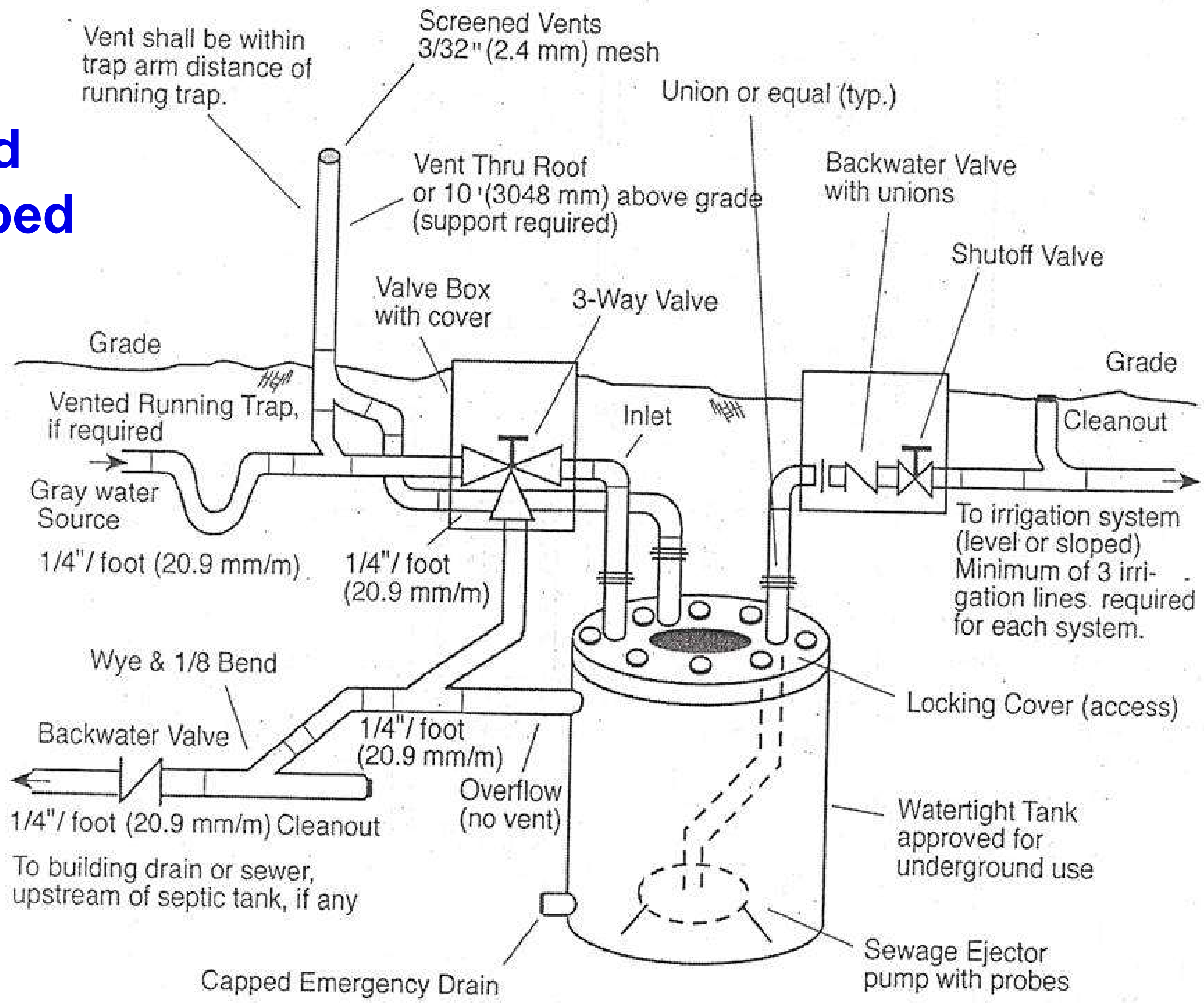
Design


Branch Vent
Main Vent
Three Way Valve
Install Tee
Basement/ Crawlspace
Install Tee
Graywater Line
Other Graywater Sources
To Tank
Remove Pipe
Remove Pipe
Cut Existing Blackwater Line Install New Tee
Cap Existing Line
To Sewer
Blackwater
Cap Existing Line

Graywater System Surface Mounted Tank – Pumped (conceptual)



Graywater Underground Tank – Pumped (conceptual)

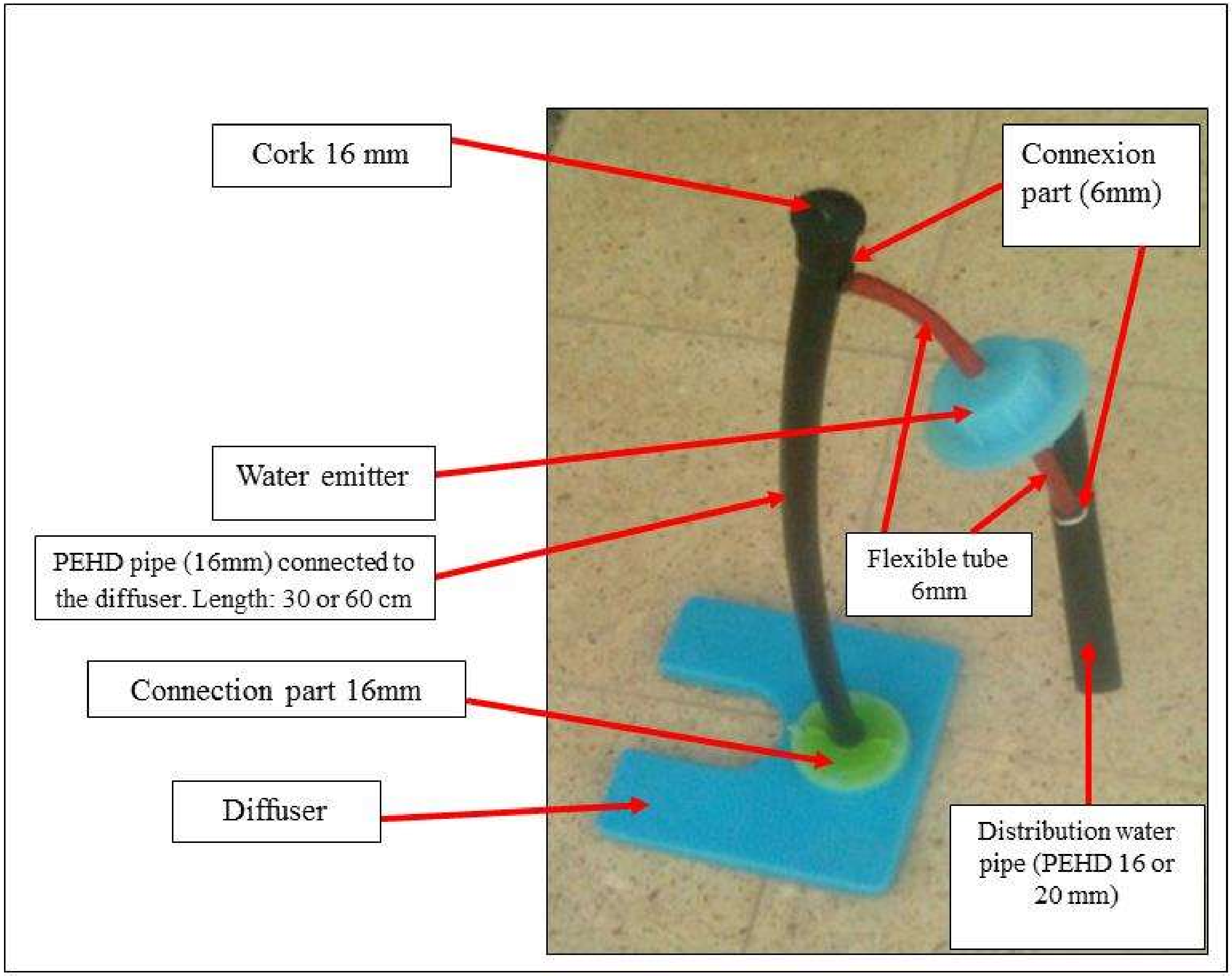


Broad Scope of Non-Potable Reuse Applications

- Use of treated effluent:
  - Irrigation
  - Toilet/urinal flushing
  - Vehicle washing
  - Fire protection
  - Laundry
  - Fountains
  - Dust control
  - Construction

Courtesy of NSF International

Subsurface Watering



Connection details of the buried diffuser 15/15 for trees and landscaping

Buried diffusers 30/15 for trees

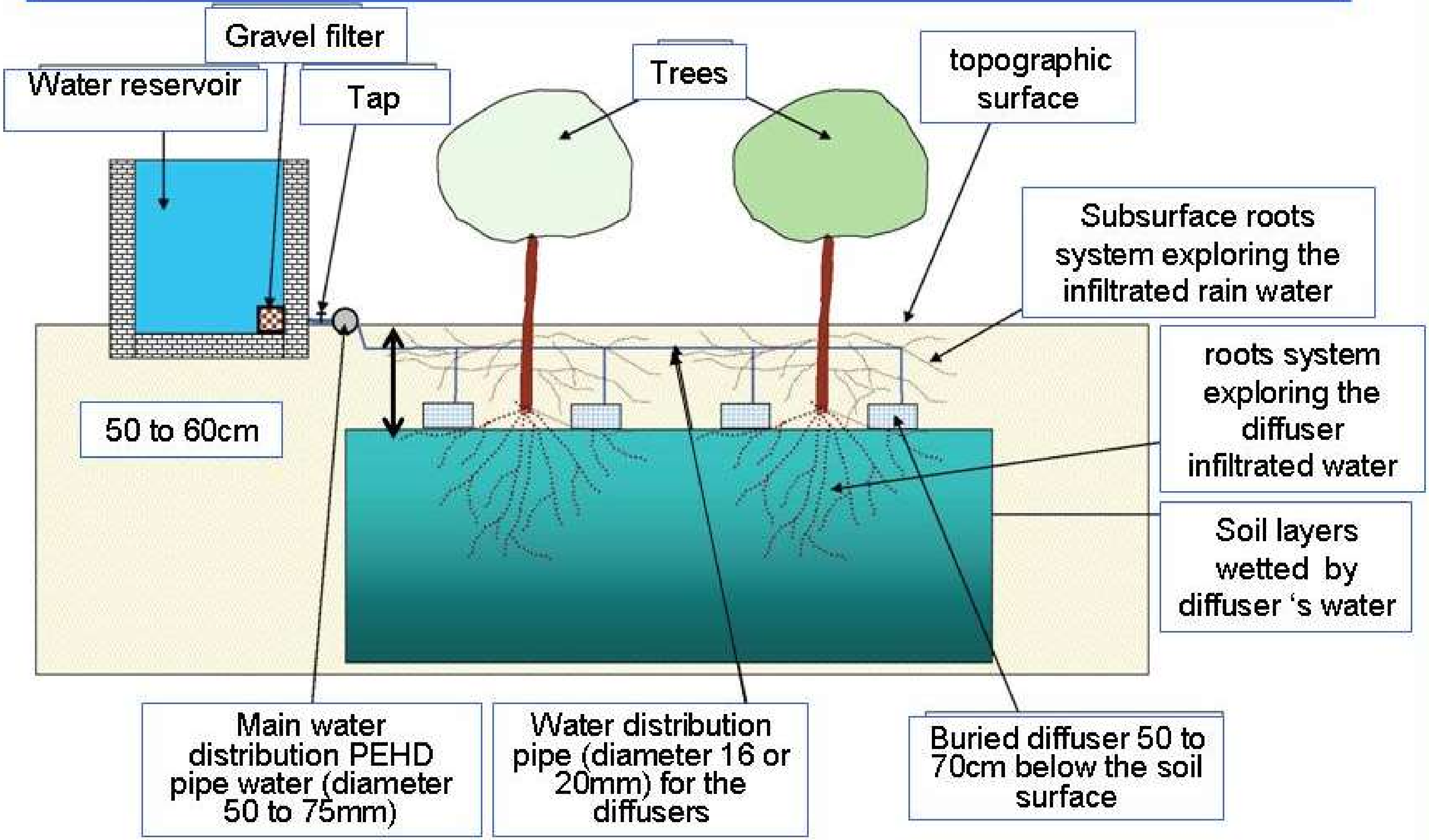
Courtesy of Chahtech

Installation of the buried diffusers for orange trees in Beni Khalled, Cap Bon North of Tunisia

Young orange tree in a private garden irrigated with buried diffusers

Courtesy of Chahtech

Gravity Irrigation of trees using buried diffusers connected to low pressure (0,2 bar) water distribution network using the water of a reservoir



Courtesy of Chahtech

For drip and subsurface irrigation, the only treatment usually required is filtration to 25µ

What is Drip Irrigation?

Drip Irrigation is a method of delivering water slowly, at low pressure, directly to the root systems of plants.

Sub Surface Drip Irrigation of Turf

Key Attributes

- ✓ Unaffected by wind
- ✓ No losses from evaporation
- ✓ No overspray or misting
- ✓ 90% efficient
- ✓ Low pressure
- ✓ Ideal for reclaimed water
- ✓ Encouraged by MWELO

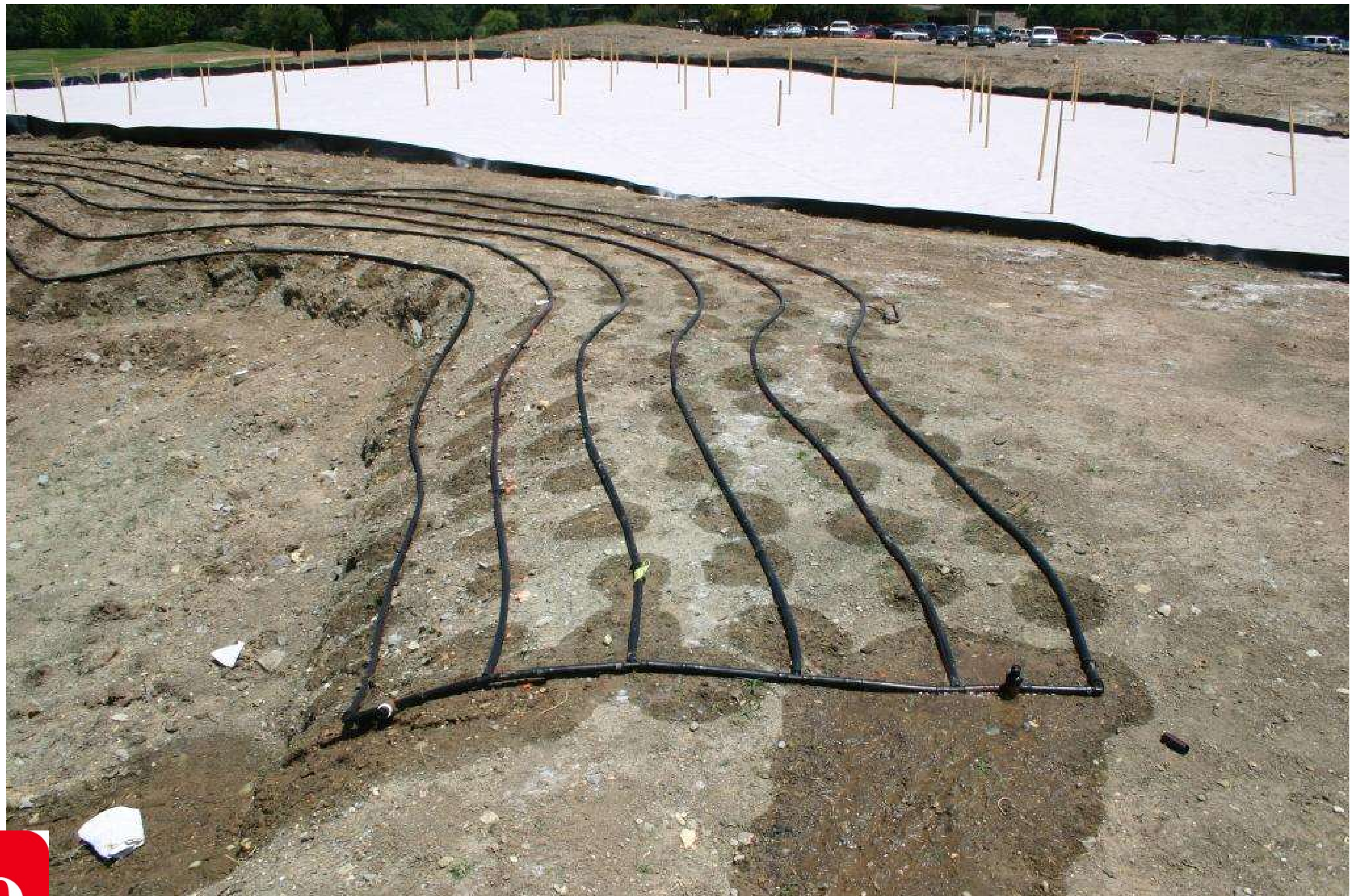
TORO®

Installation Procedure

- ✓ Prepare grade at -5 inches
- ✓ Provides better control of depth and spacing according to soil texture and emitter flow rate
- ✓ Install inlet and exhaust manifolds. Staple lines in place.
- ✓ Install air relief devices & flush valve (manual/auto)
- ✓ Install/Replace soil
- ✓ Install sod

TORO®

Golf Course Bunkers

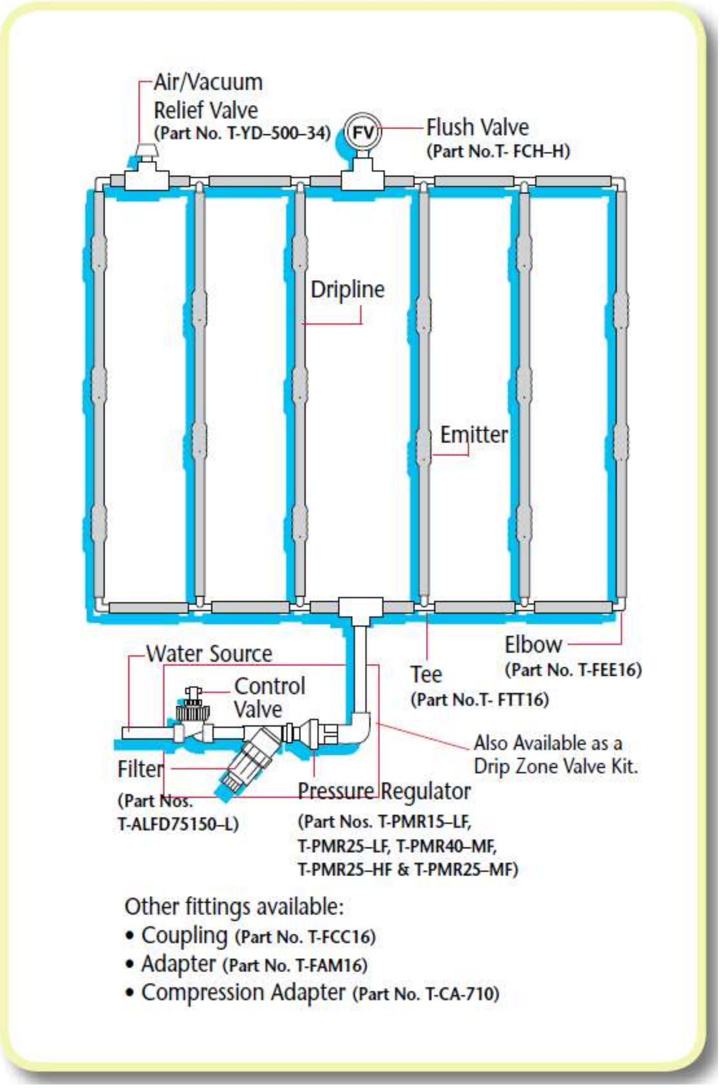


Agricultural Row Crop Applications

TORO®

Agricultural Permanent Crop Applications

Toro
DL2000 and Rootguard



TORO®

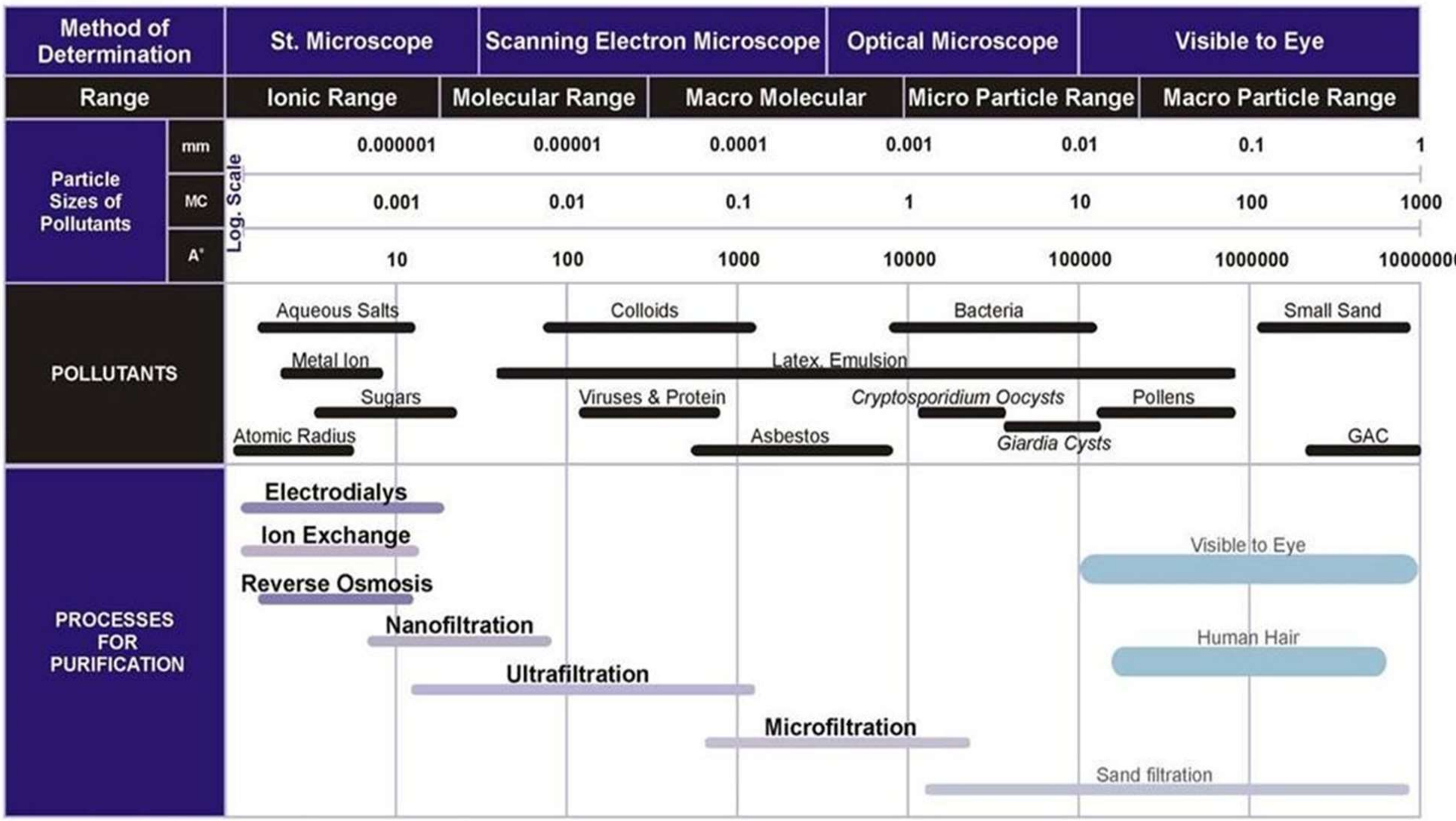
Industrial/ Commercial Discharges

Effluent likely to be unique to a specific manufacturing process

Industrial water reuse growing at > 14% per year in the U.S.

Treatment Technologies

Water Contaminants, Sizes and Treatment Technologies



1 Angstrom(A°) = 10^{-10}Meter(m) = 10^{-4}Microns(MC) = 10^{-7}Milimeter(mm)

Courtesy Val S. Frenkel, Ph.D., P.E., D.WRE., Kennedy/Jenks Consultants

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	—	—	X	—
CHEMICAL REDUCTION	—	—	X	—
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

Treatment Technologies	Suspended Solids Removal	Dissolved Organic Removal	Dissolved Salts Removal	Microorganism Removal
ELECTOLYTIC 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	—

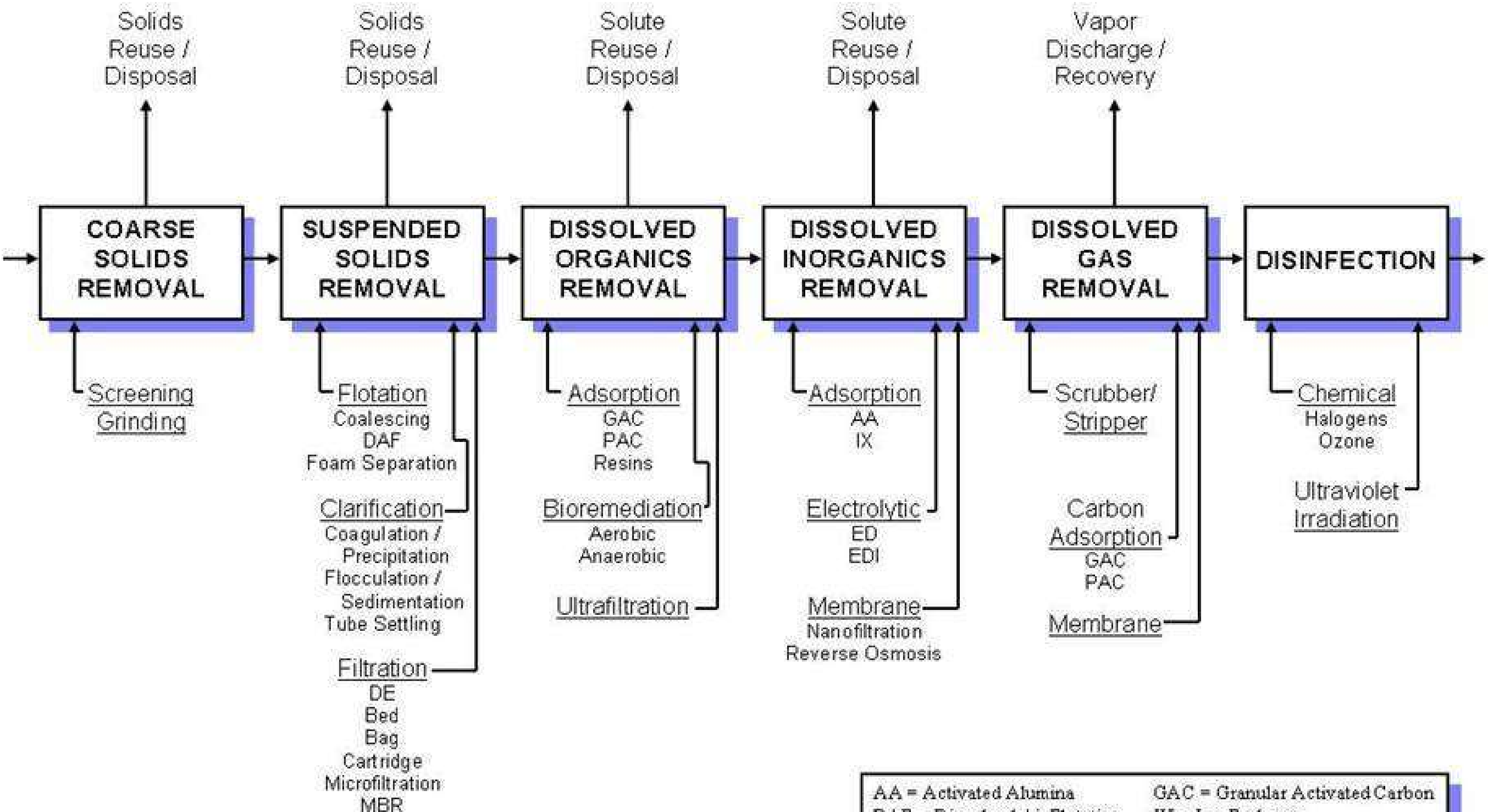
L = under certain conditions there will be limited effectiveness

Treatment Technologies

Treatment Technologies	Suspended Solids Removal	Dissolved Organic Removal	Dissolved Salts Removal	Microorganism Removal
MEMBRANE PROCESSES				
Microfiltration	X	—	—	X
Ultrafiltration	X	X	—	X
Nanofiltation	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

INDUSTRIAL WASTEWATER TREATMENT



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

Dissolved Organics Removal

- Activated Carbon
- Special Resins
- Ultrafiltration

Dissolved Salts Removal

- Reverse Osmosis
- Ion Exchange
- Distillation

It is Impossible to Make Water Completely Free of All Contaminants

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

Filtration Technologies

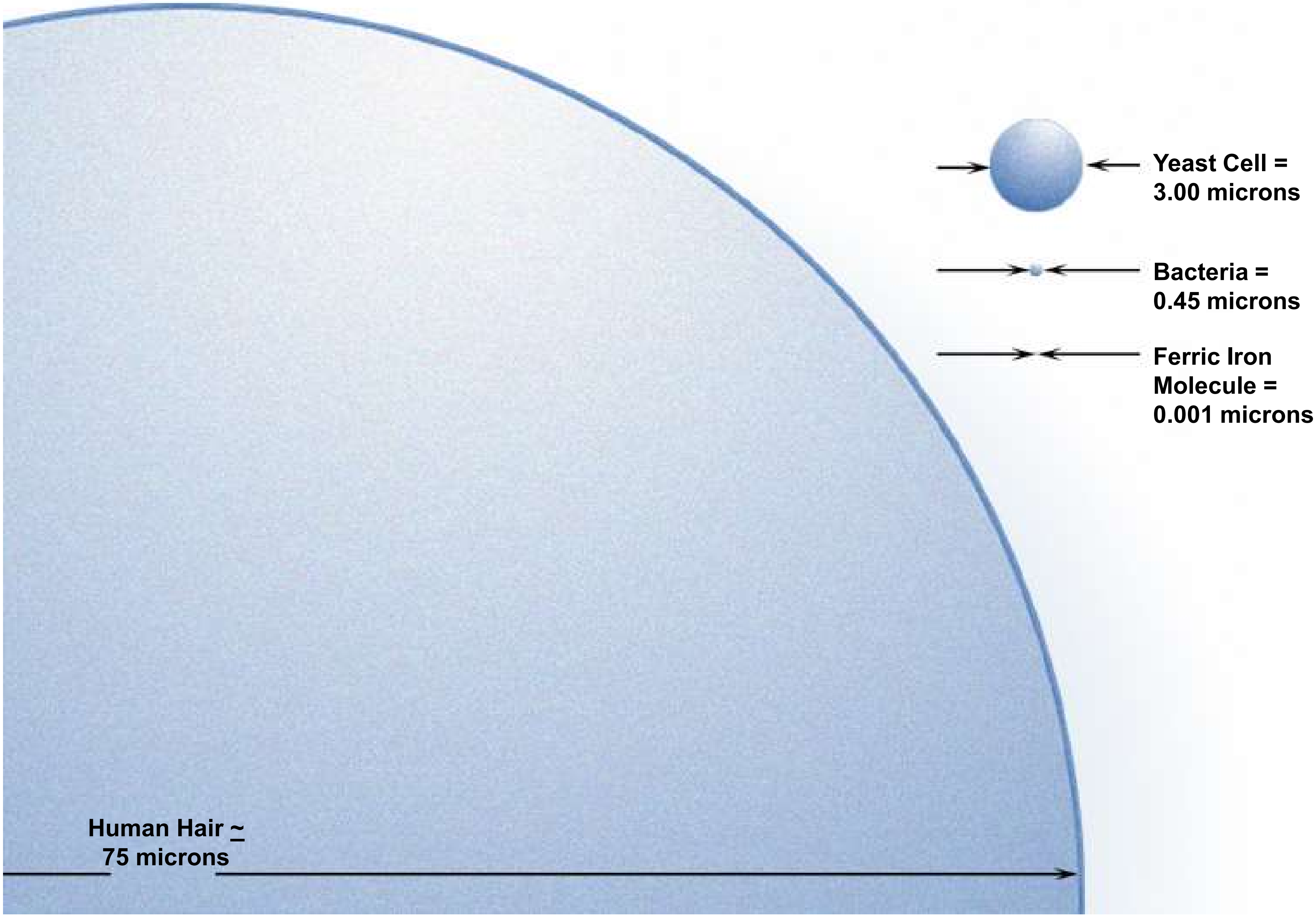
Particle

Non-Dissolved Solid (Suspended)

Greater than 0.1 micron (typically)

Non-Volatile

Comparative Size of Particles



Observable Issues

1) Scratchy, abrasive feeling water (washing, bathing, etc.)
2) Cloudy, muddy appearance

FILTRATION

Removal of Suspended Solids (primarily)

Filtration Mechanisms

Straining (sieving)

- Porosity of filter medium

Non-Straining

- Sedimentation / Impaction
- Bridging
- Attraction / Attachment
- Brownian Motion
- Stickiness

Detachment

Filter Requirements

- Efficient particle removal
- Minimal contaminant addition
- Easy installation
- Long-term chemical stability
- Long-term integrity
- High permeability

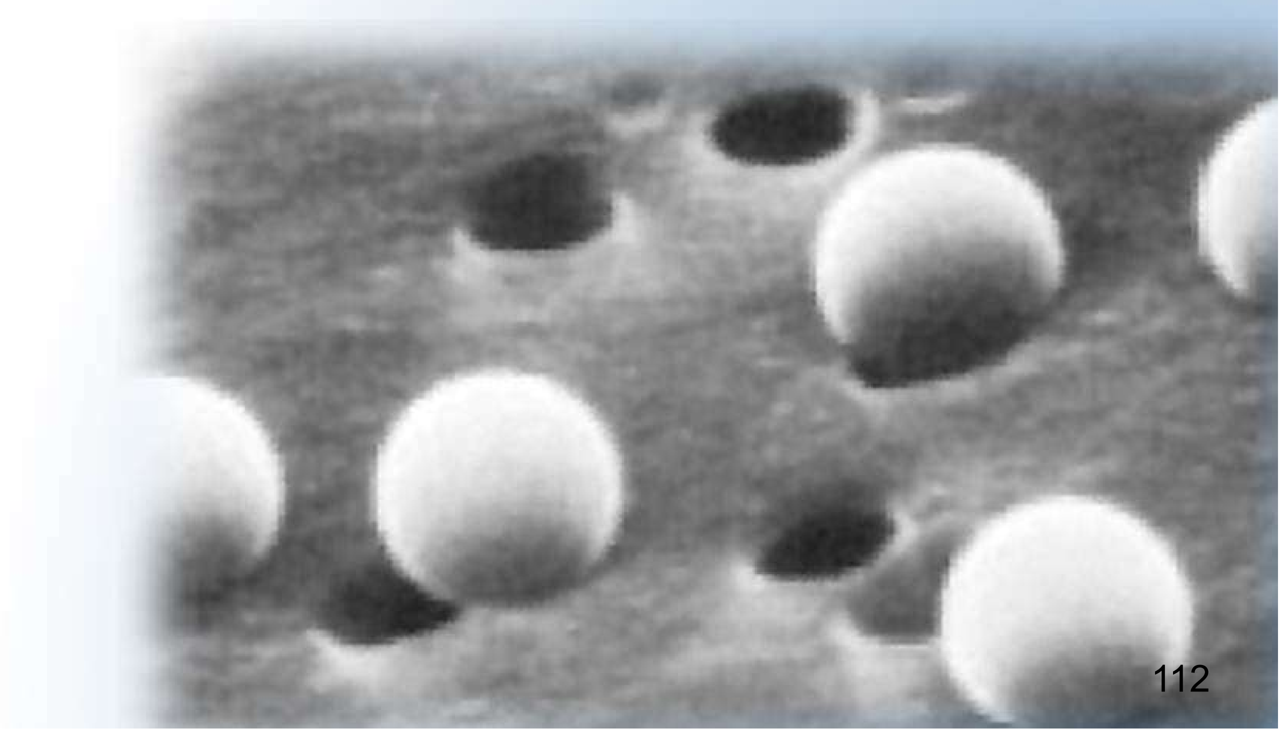
Suspended Solids Removal

- Media Filters
- Cartridge Filters
- Bag Filters
- Carbon and Ceramic Block Filters
- Microfiltration

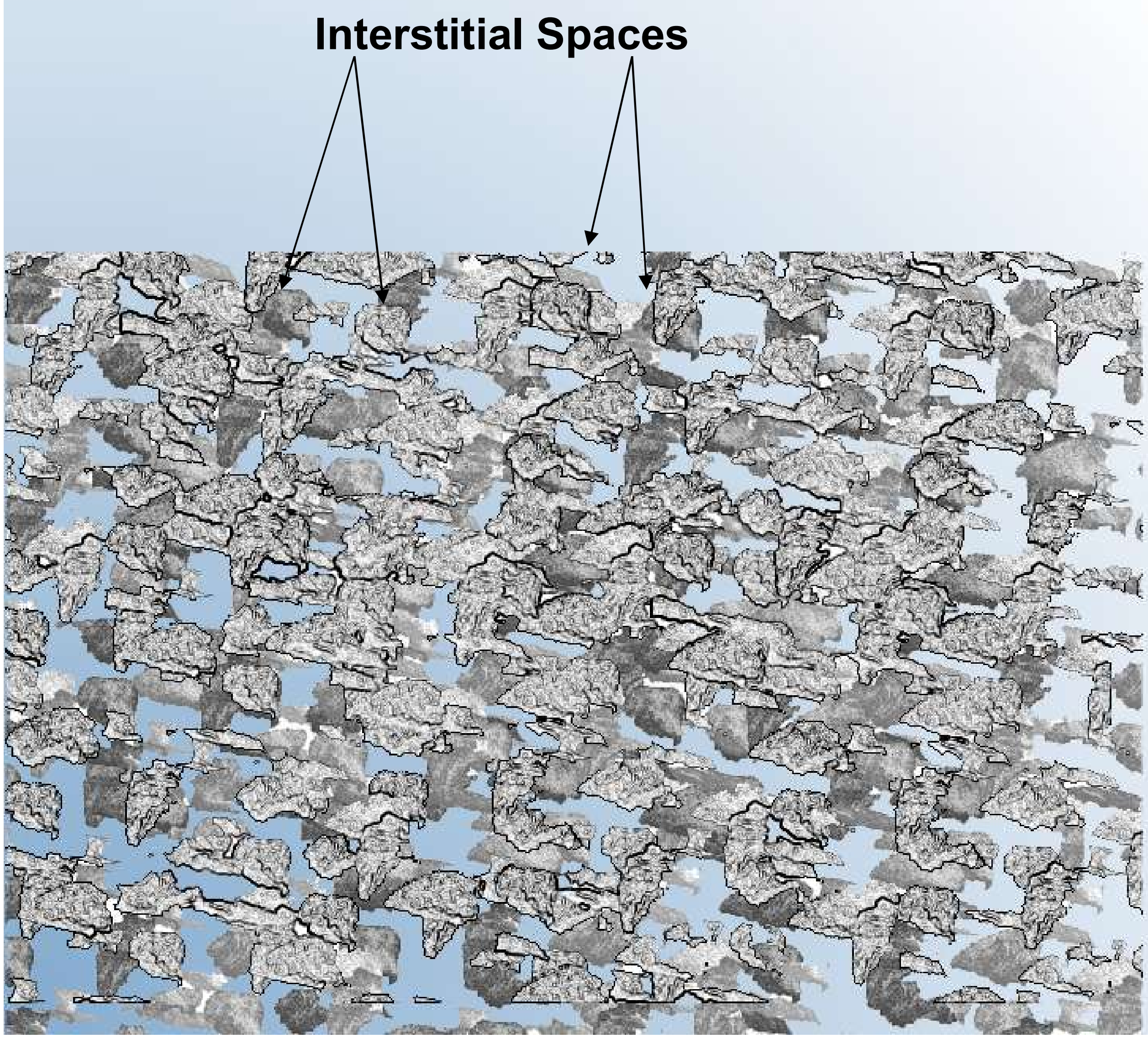
Straining

Pore Size

Particle Size



Interstitial Space



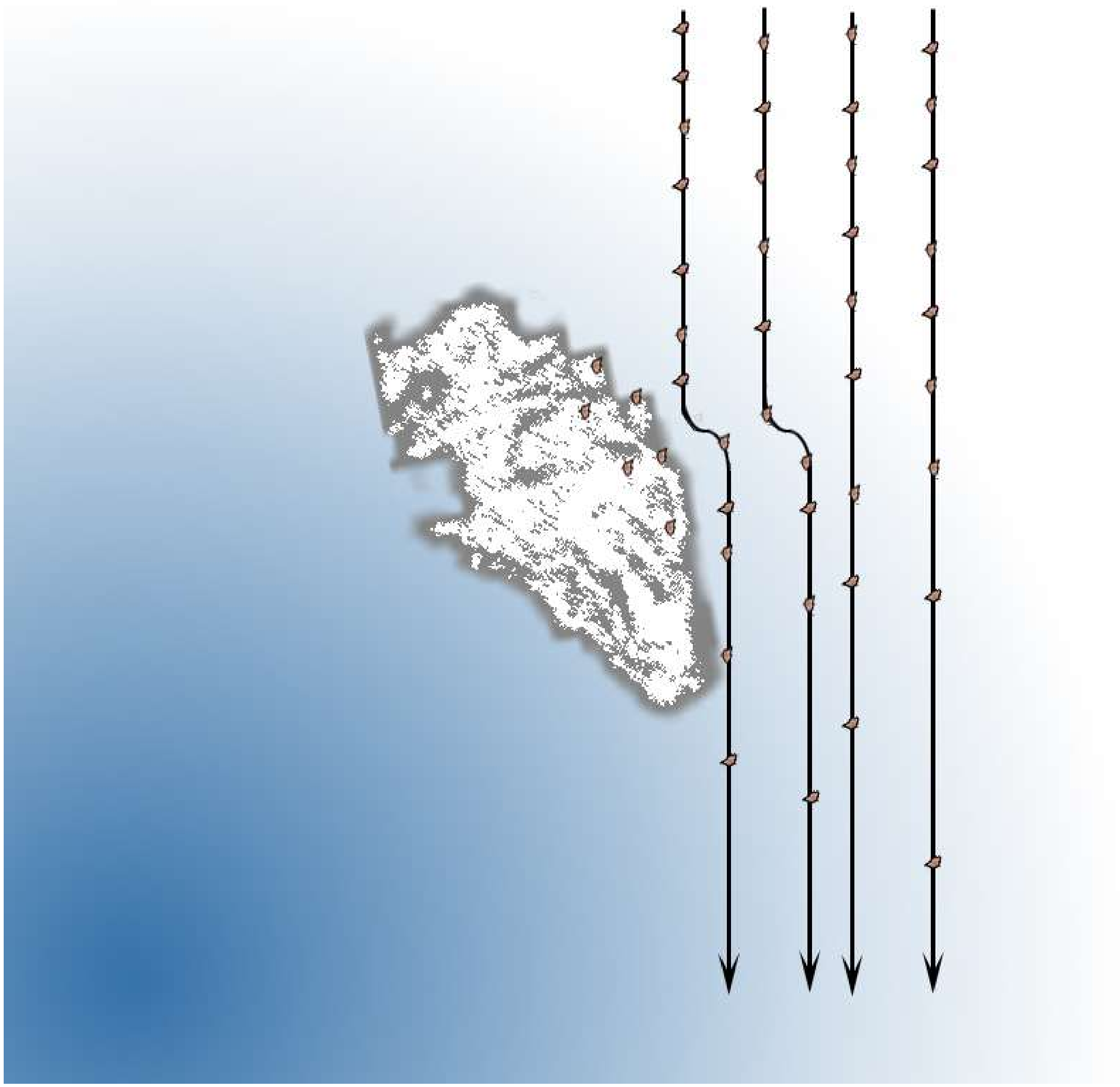
Space between media represents about 15.47% of volume

For 40/60 Mesh Filter Media:

(40 Mesh = 354 microns)

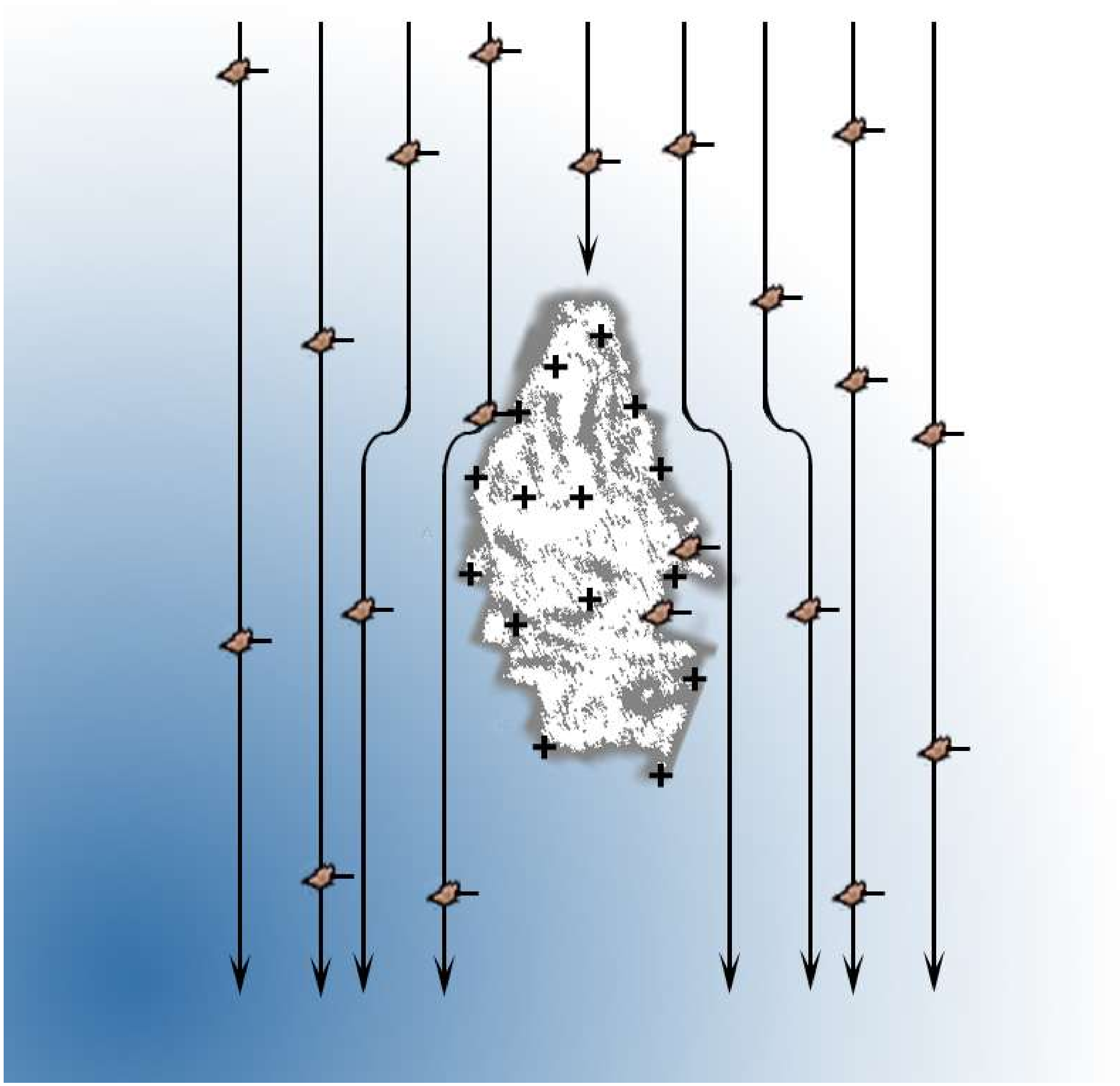
354 * 15.47% = 54 .76 microns

Sedimentation/Impaction



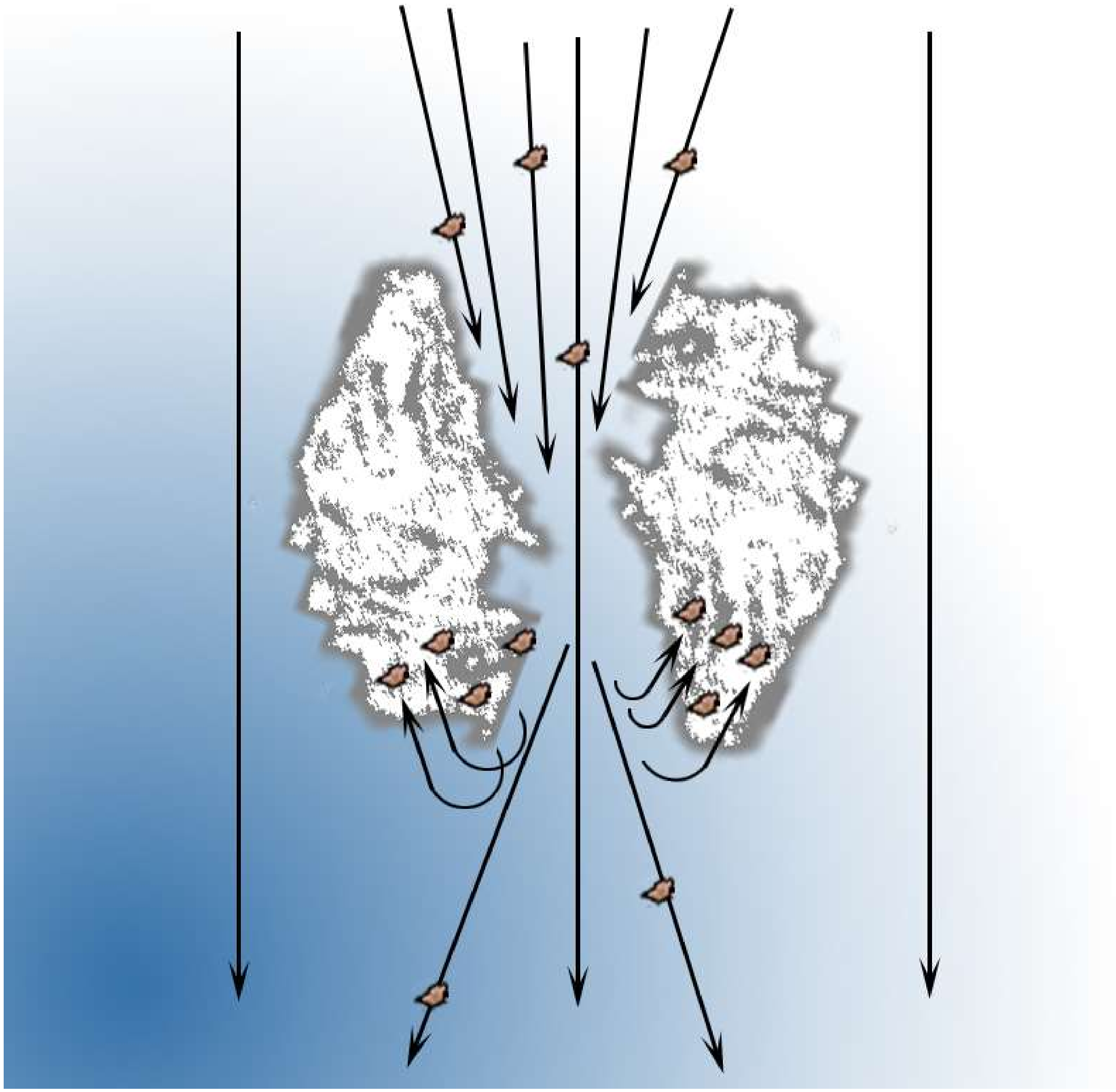
Particles impacting on filter media

Attraction/Attachment



Attraction through opposite charges on media and particles

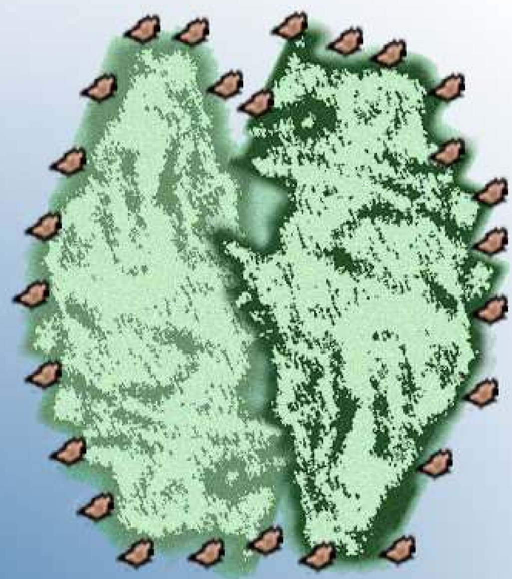
Brownian Motion



Turbulent conditions create random flow patterns.

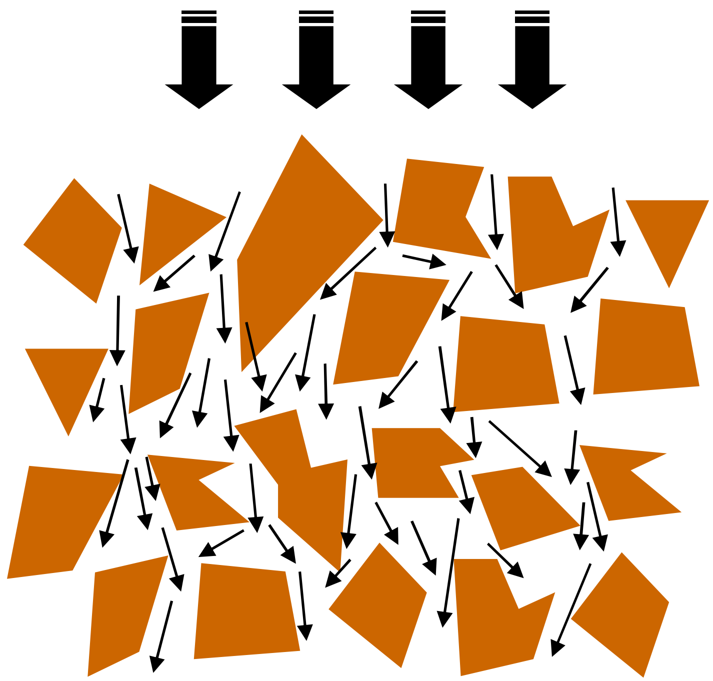
Deposits occur throughout the filter media

Stickiness



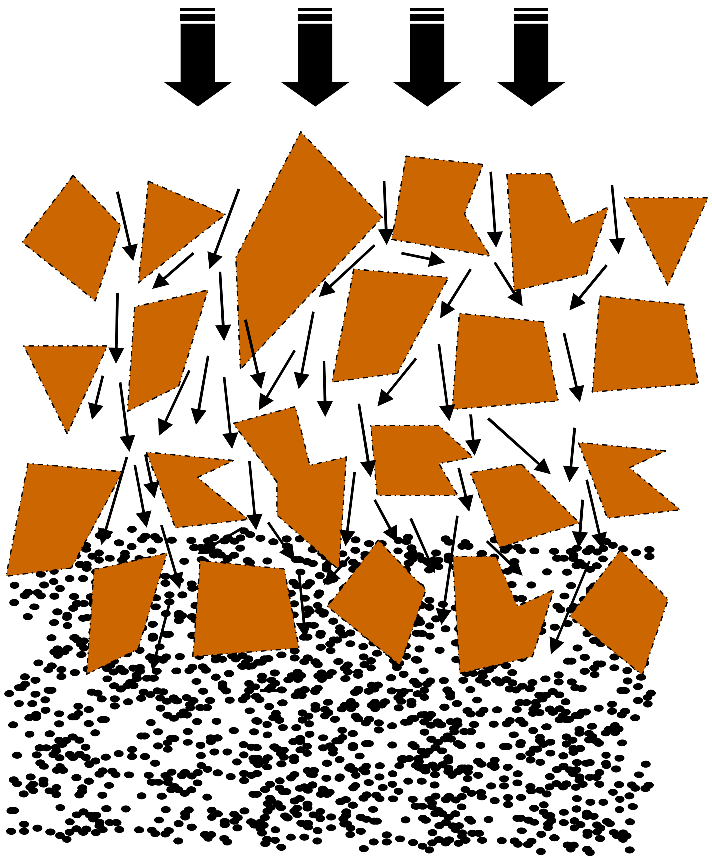
Biofilm adds to surface characteristics of most filter media

Hydrodynamic Flow Characteristics



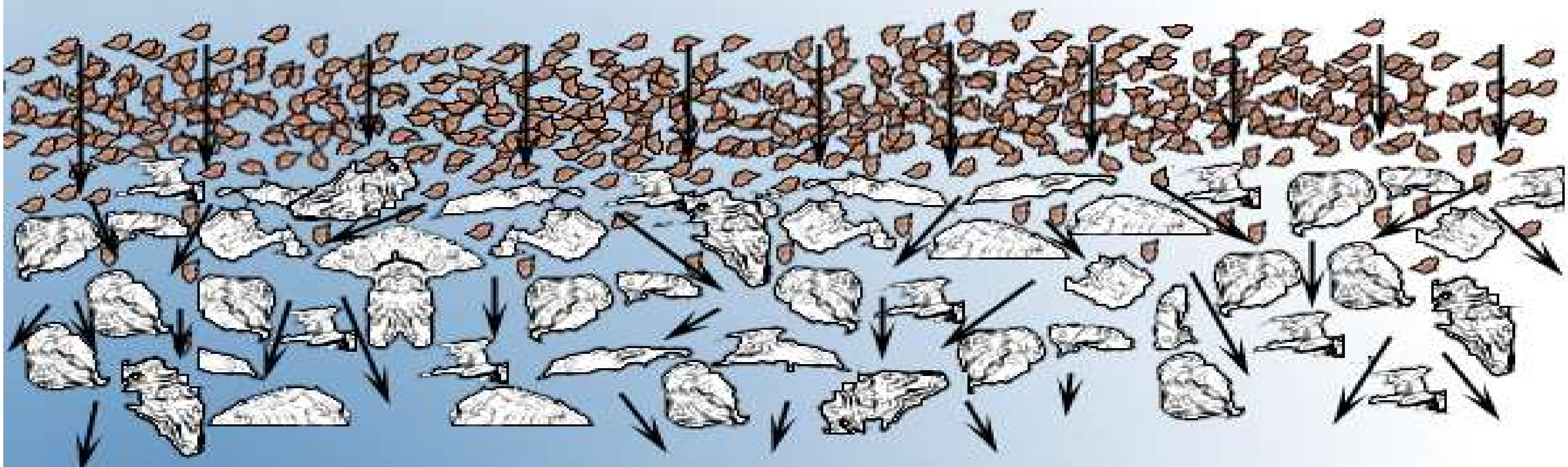
Flow velocity will increase as a fluid stream enters the interstitial spaces of a filter medium.

Detachment



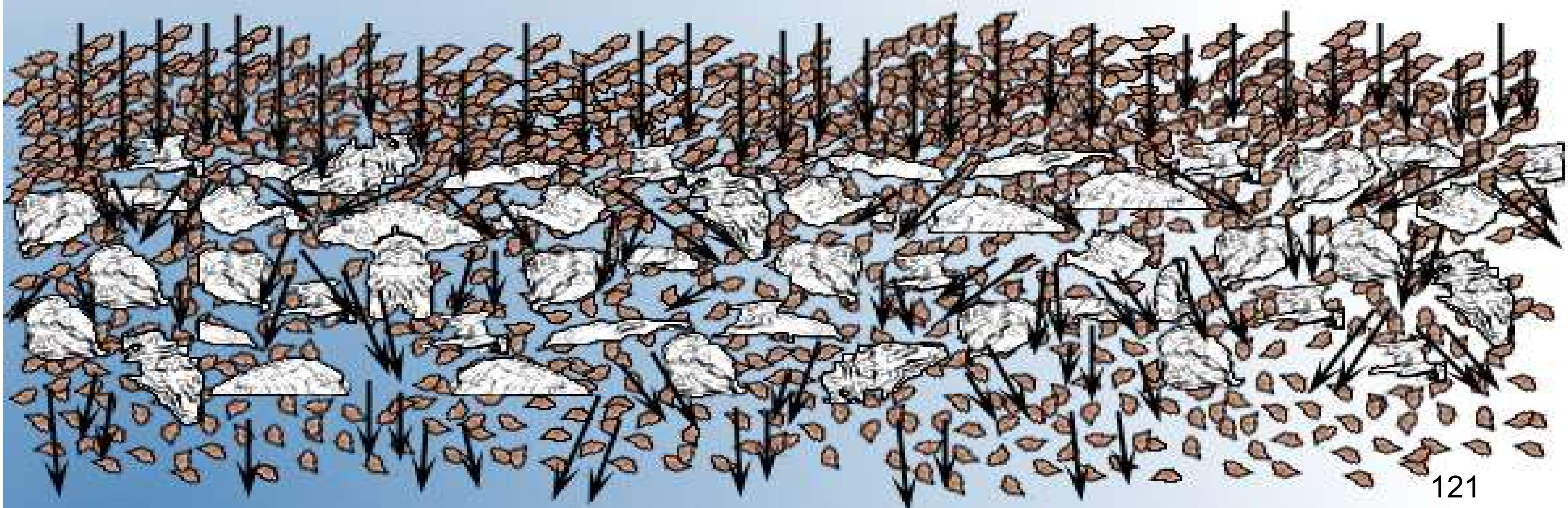
If flow velocities increase within interstitial spaces due to bridging or by increasing the flow rate through a filter, hydrodynamic shear forces will begin to dislodge deposited particles.

Filter Cake Formation

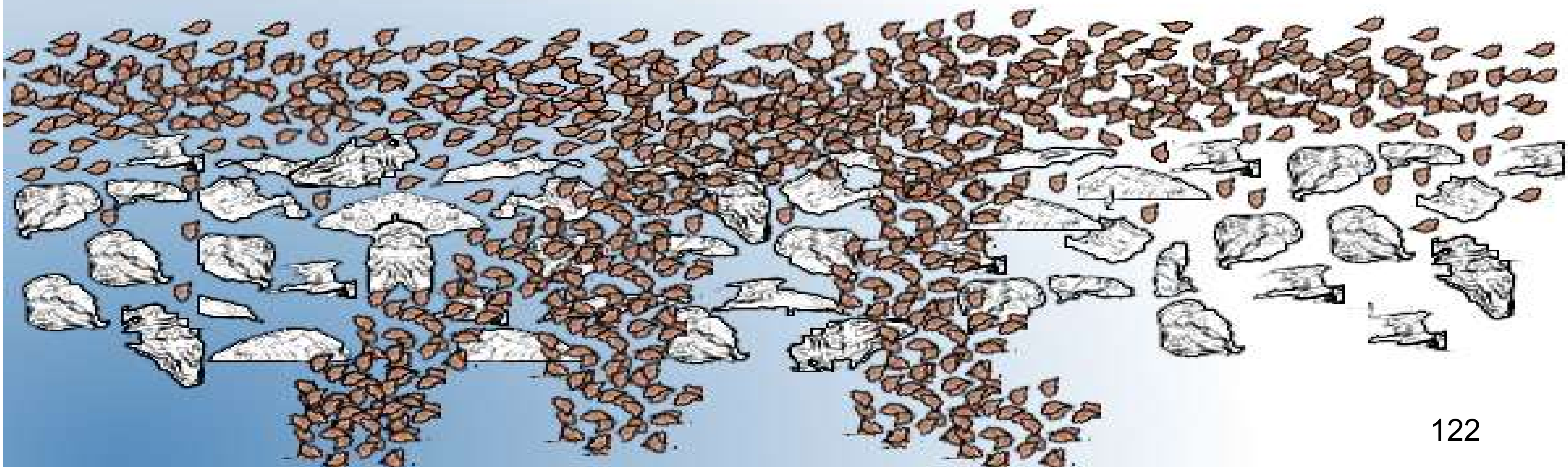


Release

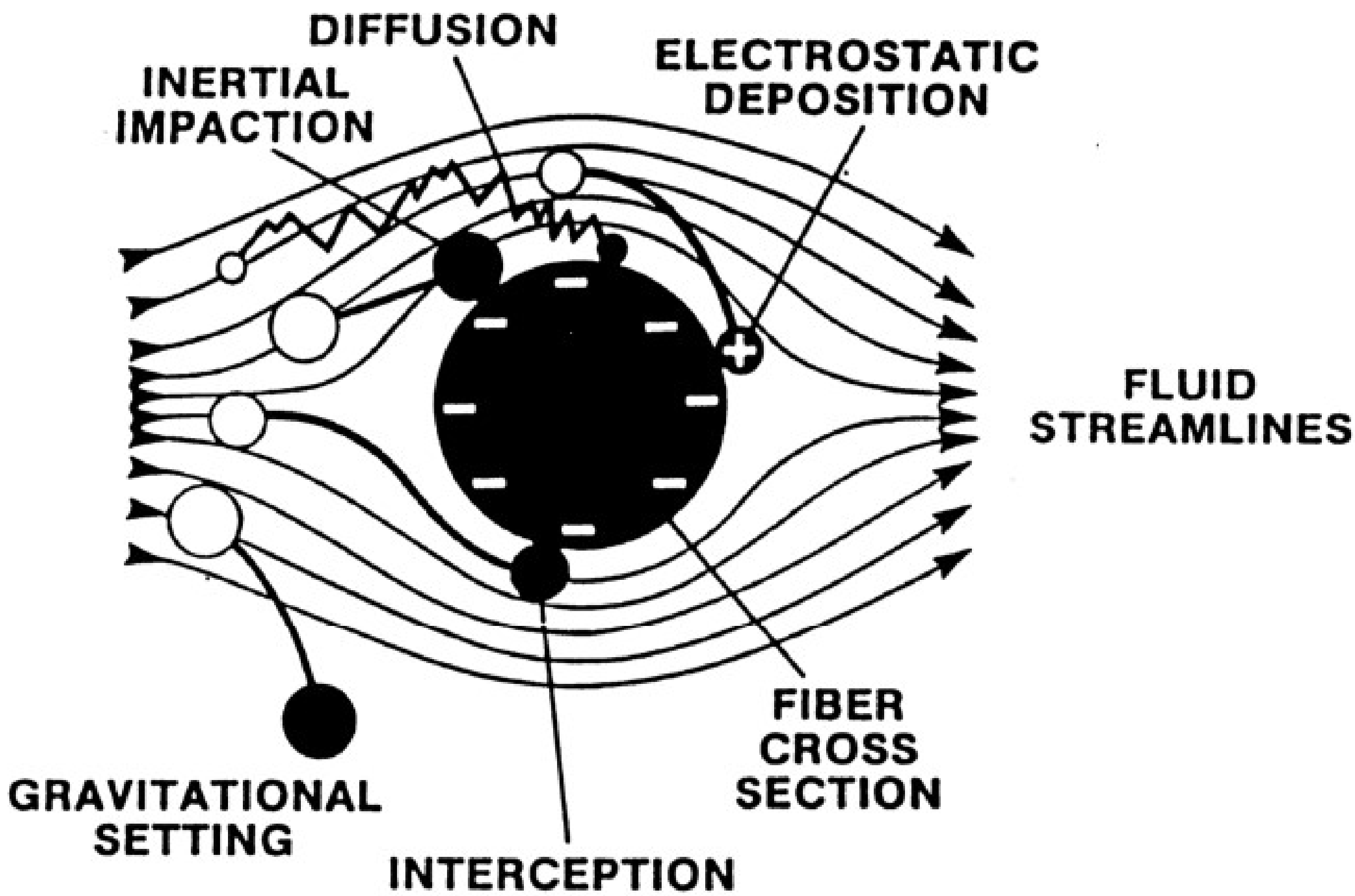
Once a filter cake is formed, it can be disrupted and forced through the filter media with increases or sudden fluctuations in head pressure.



Channeling - Filter Cake Release



Summary of Particle Capture Mechanisms



Bed Filters

Bed filters primarily utilize depth filtration wherein particles are captured within the body of the media

Bed Filter Design Factors

Tank Surface Area

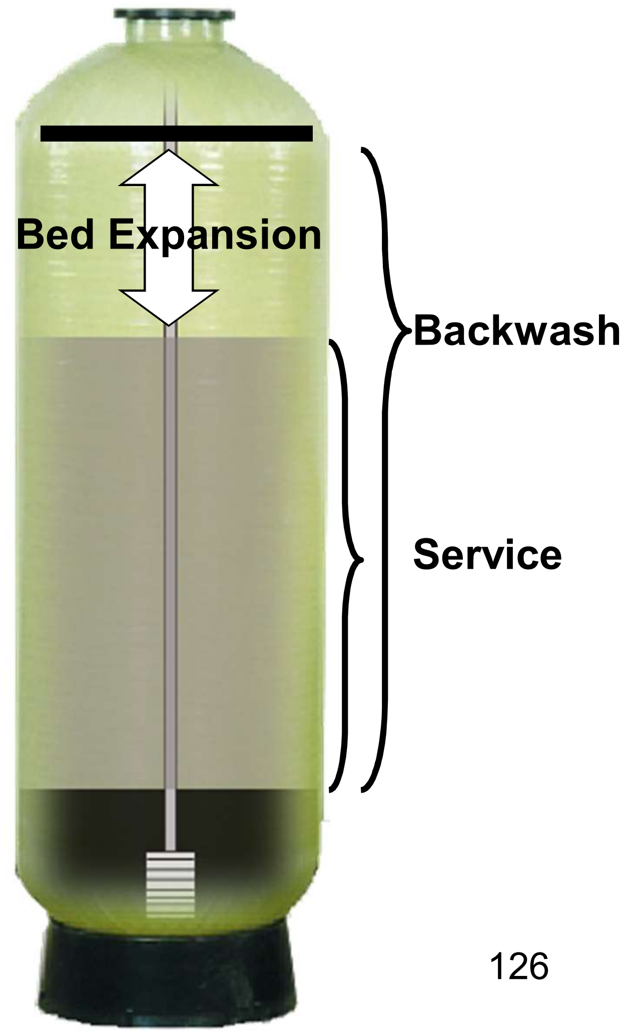
Media Depth

Service Flow

Backwash Flow

Bed Expansion (Freeboard)

Media Material

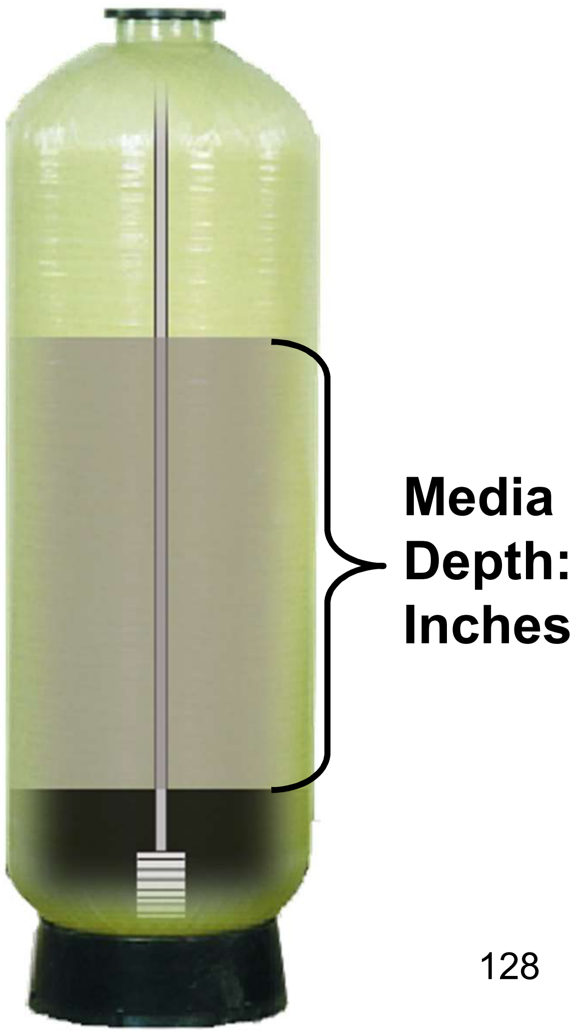


Bed Filter Design Factors

Tank Surface Area

Bed Filter Design Factors

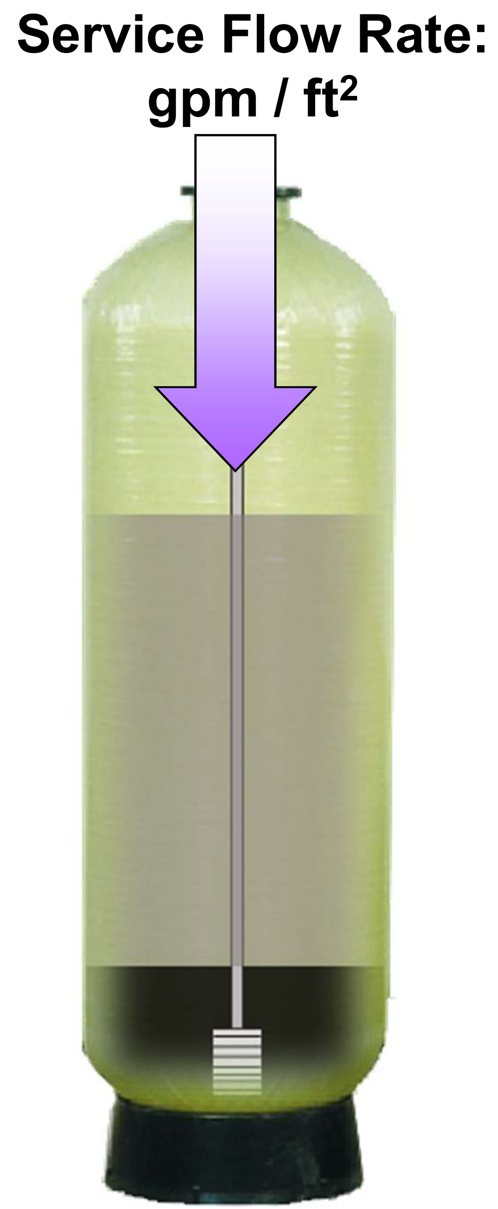
Media Depth



Cartwright Consulting Co.

Bed Filter Design Factors

Service Flow



Media Material

Media Surface
- Sand
- Anthracite Coal
- Garnet
- Others

Adsorption
- Activated Carbon
- Activated Alumina

Media Properties

Mesh Size

Particle size

Density

Uniformity Coefficient

Measurement of media sphereosity

1= Perfect Sphere

Surface Area

Effective surface area of media

Sand

45/50 Mesh Size

Service: 4 gpm/ft^2

Backwash: 25 gpm/ft^2

Uniformity: 1.6

Density: 100 lbs/ft^3

Anthracite Coal

20 Mesh Size

Service: 4 gpm/ft^2

Backwash: 18 gpm/ft^2

Uniformity: 1.5

Density: 55 lbs/ft^3

Garnet

Distributor Support
(under bedding)

Backwash: 30 gpm/ft^2
Uniformity: 2.0
Density: 150 lbs/ft^3

Media Summary

Media Surface	Uniformity Coefficient	Mesh Range	Density: Pounds / ft3	Service Flow Rate gpm/ft^2	50% Bed Expansion Backwash Rate gpm/ft^2	Use
Sand	1.6	45/55	100	4	25	20 micron particle removal
Anthracite Coal	1.5	20	55	4	18	15 micron particle removal
Aluminum Silicate	1.7	25	25	5	10	20 micron particle removal
Ceramic	1.1	20/80	55	10	5	5 micron particle removal
Garnet	2	50/60	150	10	30	Distributor underbedding

System Types

Single Medium

Muti-Media

Single Medium System

Multi Media System

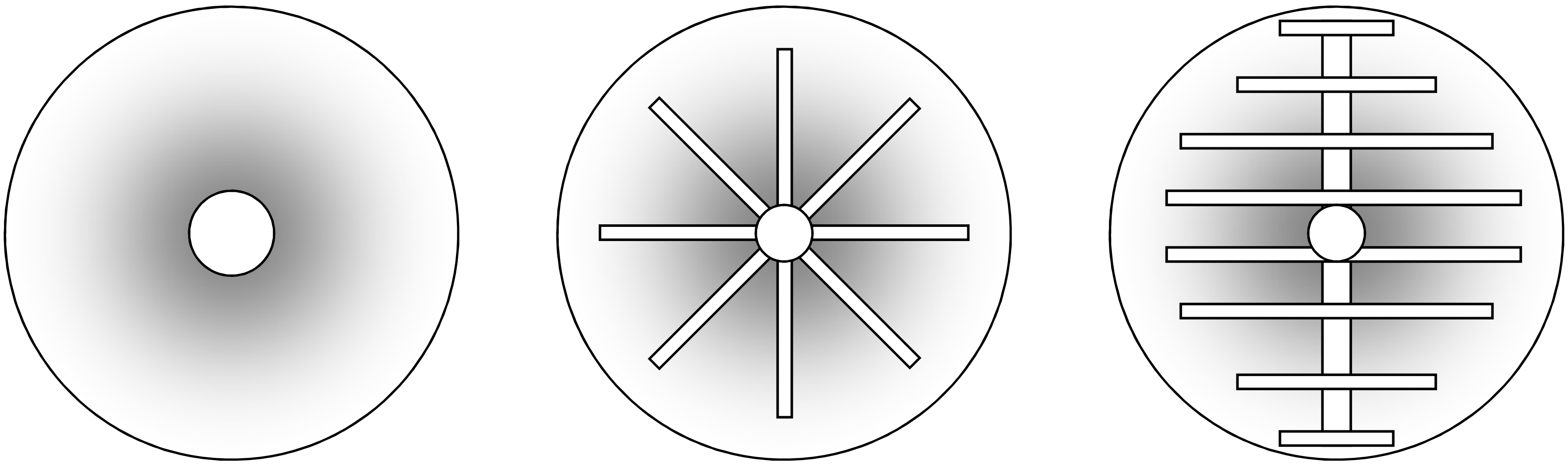
Multi Media System

Tank Construction

Fiberglass Reinforced

Steel, Lined

Distributor Designs



Basket

Hub & Lateral

Manifold

Backwash Cycle

Service

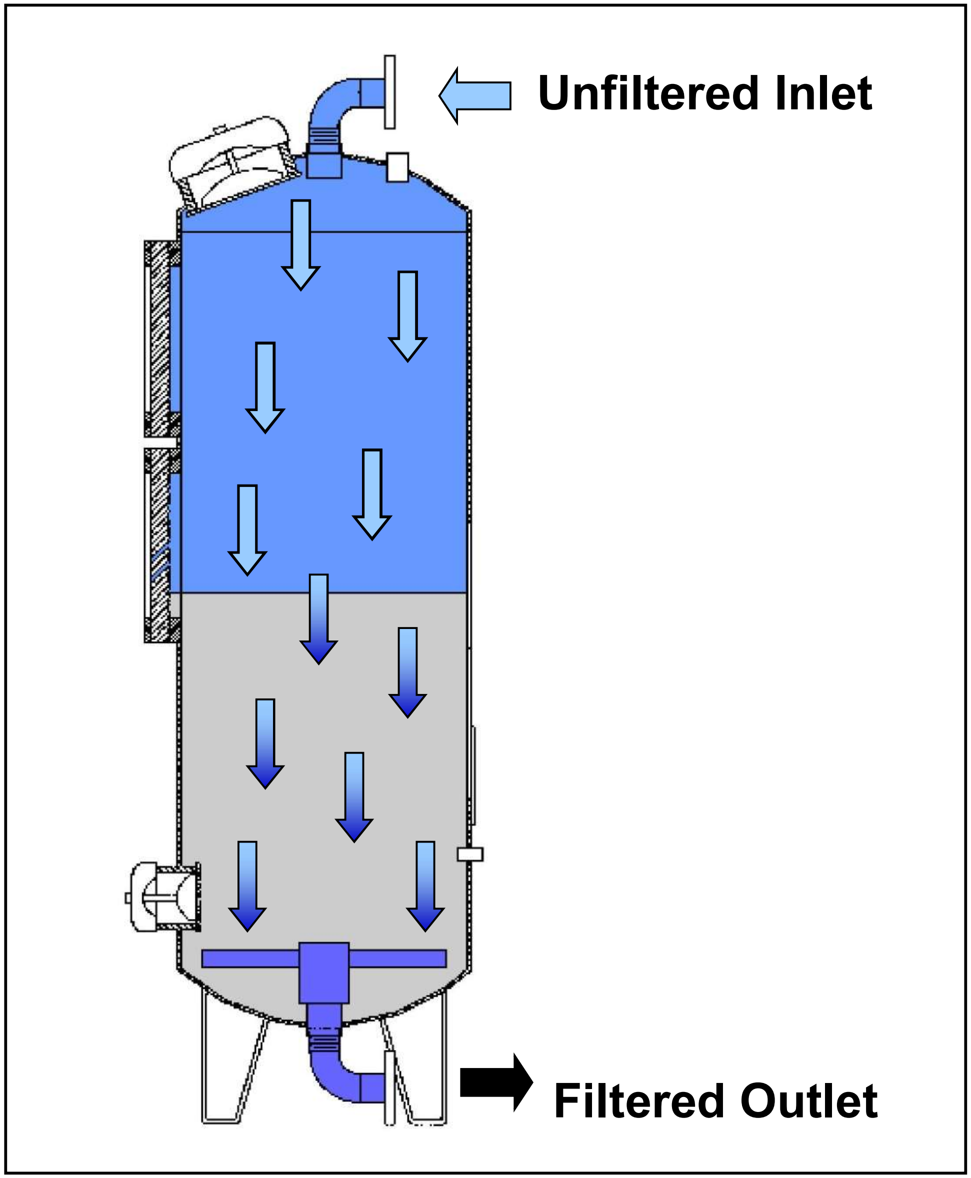
Backwashing

- Air
- Water
- Air + Water

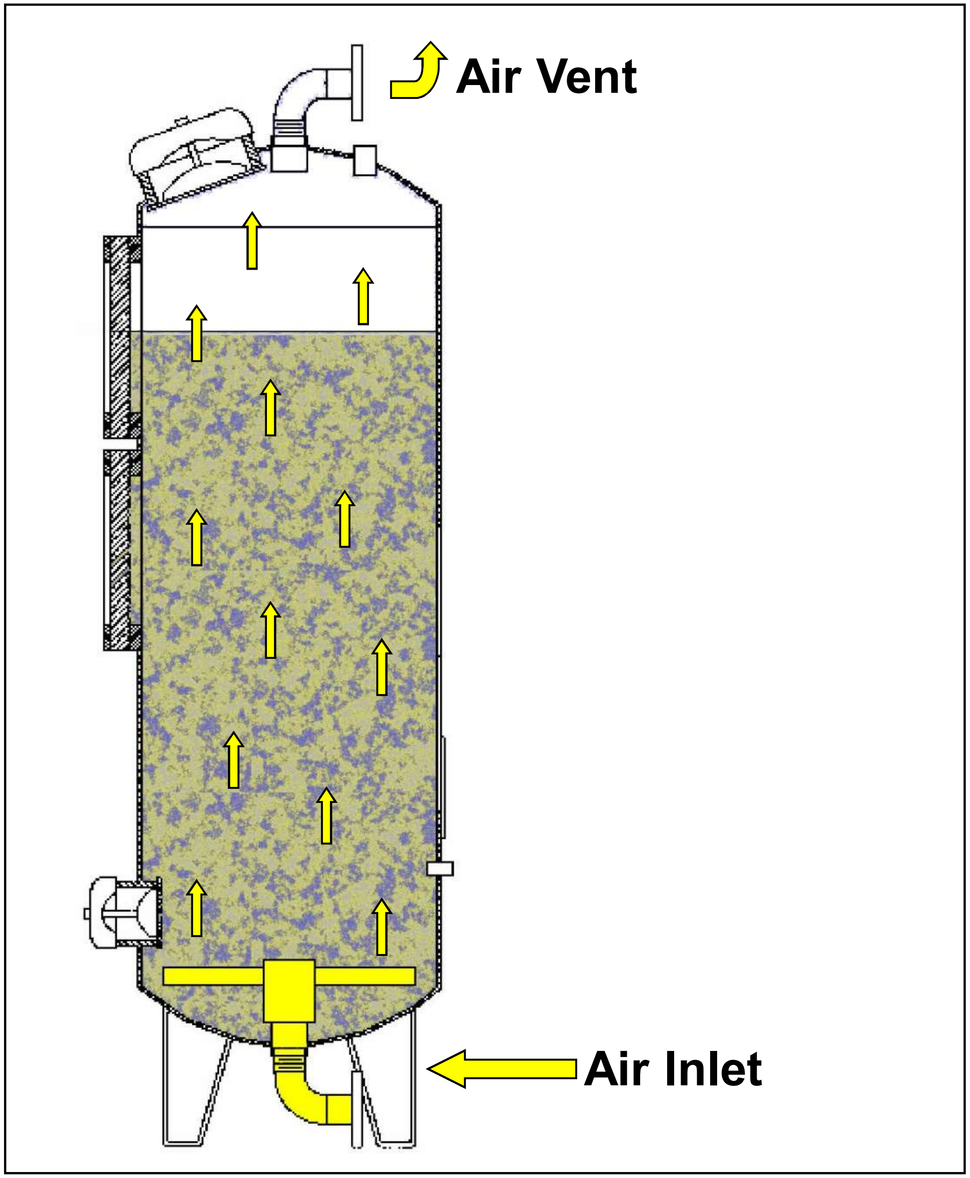
Settling

Down Rinse/Filter to Drain

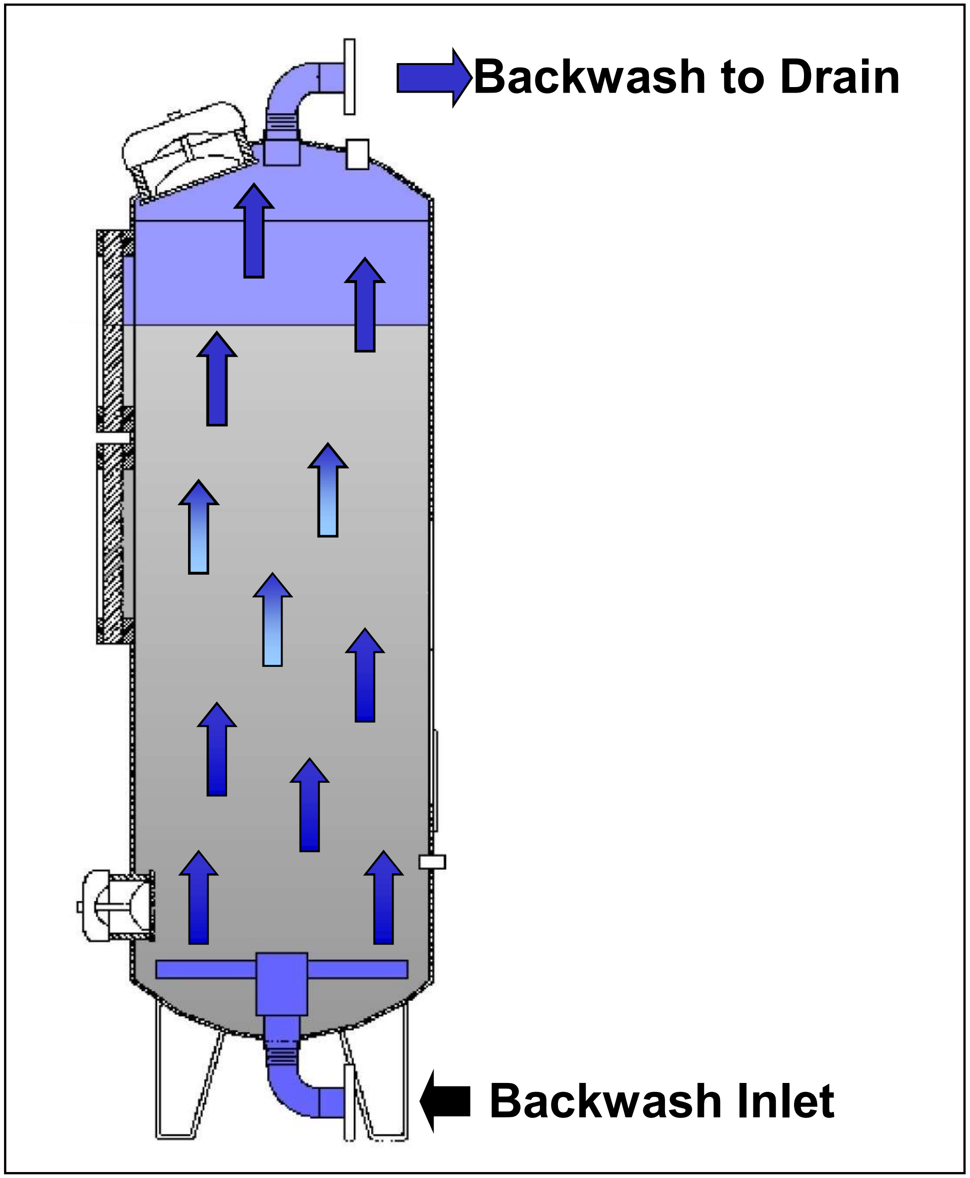
Service



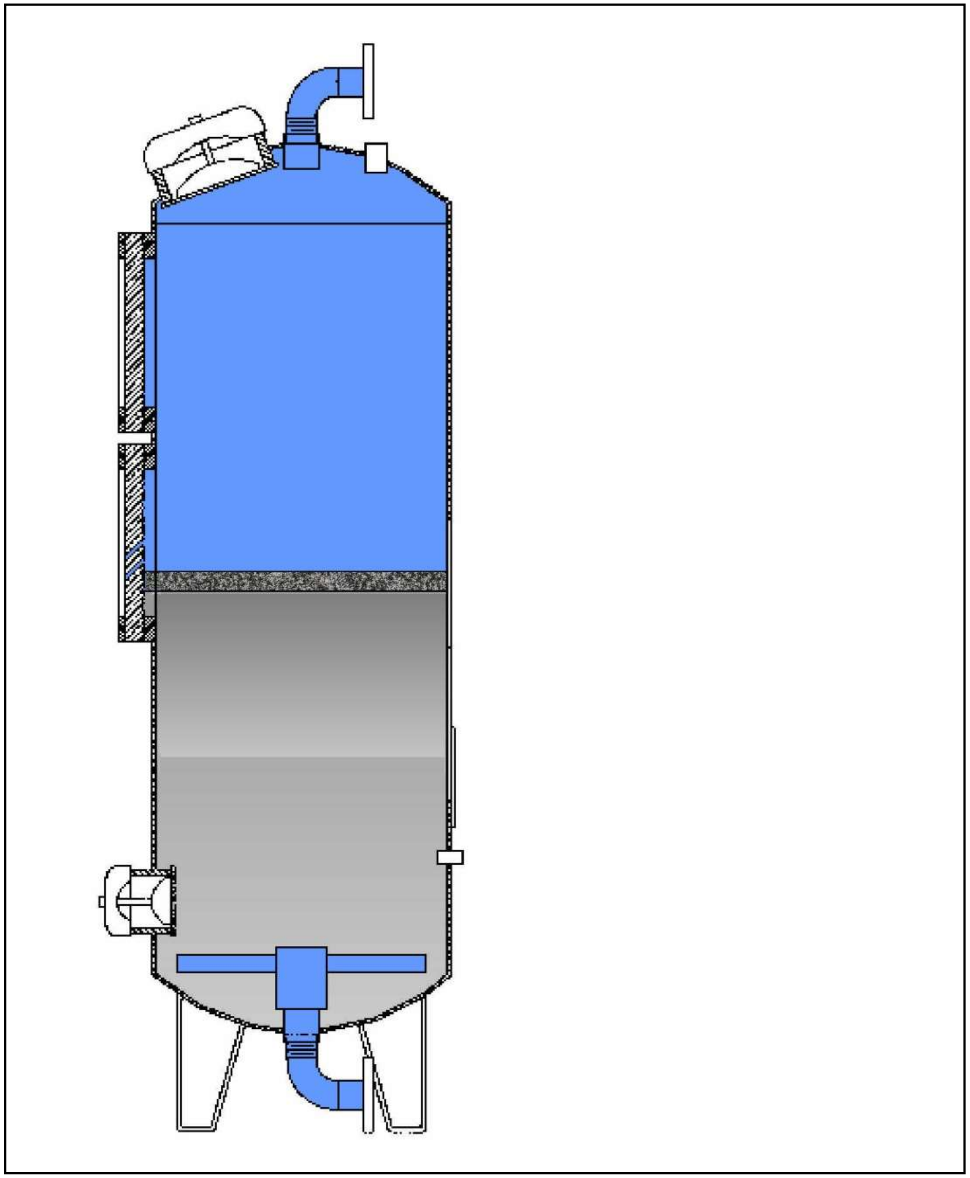
Backwashing with Air



Backwashing with Water



Settling



Backwash Controls

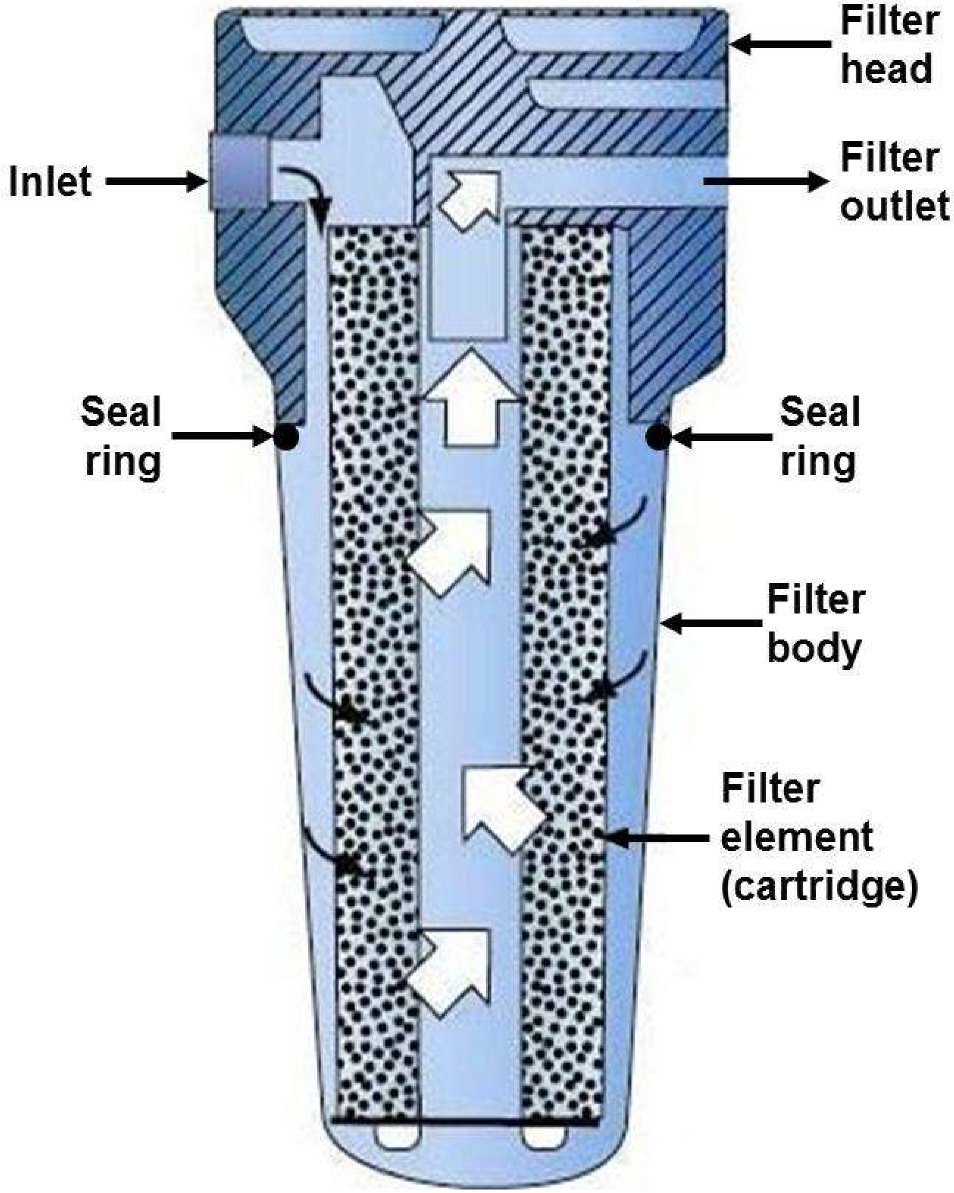
Time

Flow

Differential Pressure

Cartridge Filters

Cartridge Filter System



Cartridge Filters

Many choices of pore sizes

Numerous choices of materials

No backwash requirement

Simplicity of operation

Minimal space requirement

Low capital cost

High O&M Costs due to cartridge replacement

Cartridge Filters

Identifying Materials of Construction

- String Wound
- Cellulose
  - Poor tolerance to pH
  - Lowest Cost
- Microfiberglass
  - Low cost
  - Higher dirt holding capacity
- Polyester
- Polypropylene (PP)
  - Higher Purity
- Carbon Blocks
- Nano Fibers

Surface Filtration

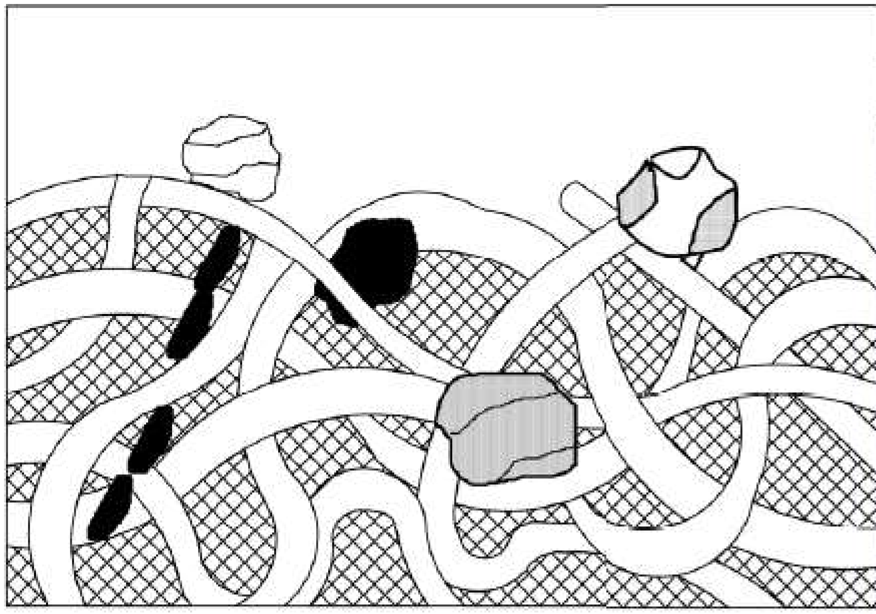
Sieving mechanism to hold back particles

Depth Filtration

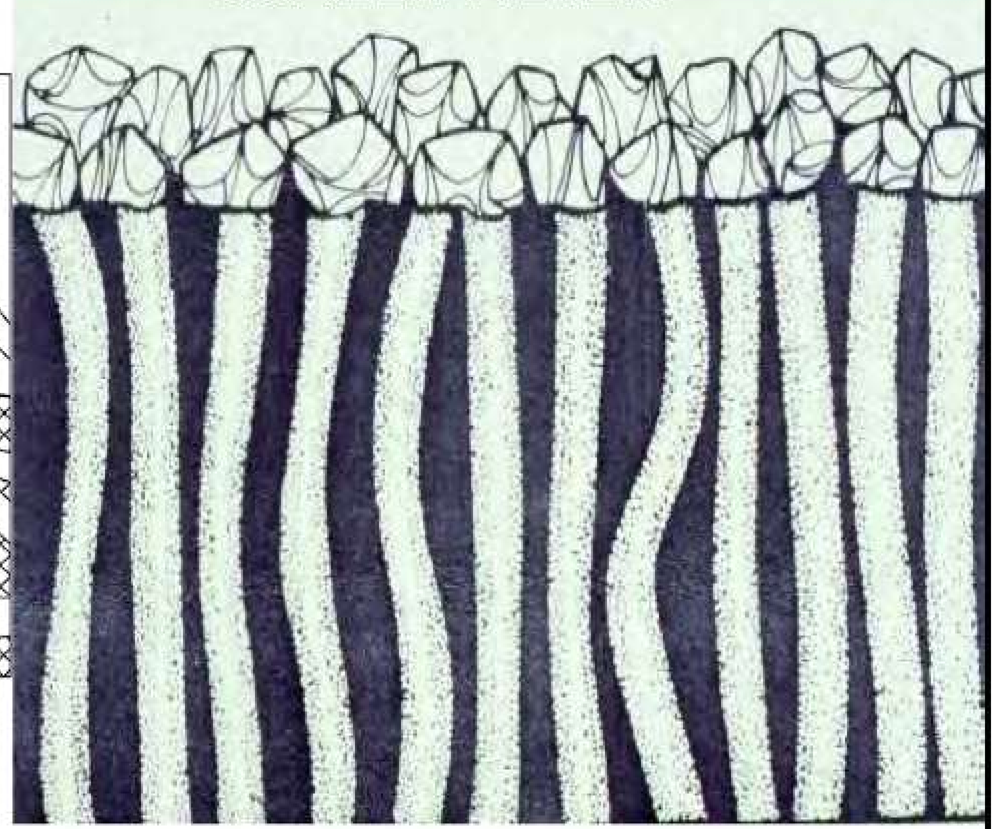
Particles captured
within the body of the media
by sieving and adsorption

Filtration Mechanisms

DEPTH FILTER



SCREEN FILTER



From: Millipore catalog

Bag Filter

Bag Filter

Surface-Active Technologies

What are They?

Media that promote the removal of contaminants by either causing a chemical reaction or adsorbing the contaminant on its surface (or both).

Surface-Active Media

Material	Application	Color	Density (lb./ft^3)	Service Flow (gpm/ft.^{2})	Backwash Flow (gpm/ft.^{2})
Birm®	Oxidation	Black	35-40	3.5-5.0	10-12
Manganese Greensand®	Oxidation	Black			
Greensand Plus®	Oxidation	Black	88	2-12	>12
MTM®	Oxidation	Dark Brown	45-50	2-5	8-10
Pyrolox®	Oxidation	Black	120	4-6	25-30
Calcite	pH Adjustment	White	90	3-6	8-12
Corosex®	pH Adjustment	White	75	5-6	10-12
Activated Carbon (coconut shell)	Chlorine Removal	Black	28	5	10-12

Oxidizing Media

Changes the solubility by modifying the valence of:

- Iron ($Fe^{2+} \rightarrow Fe^{3+}$)
- Manganese ($Mn^{2+} \rightarrow Mn^{3+/4+}$)
- Hydrogen Sulfide ($S^{2-} \rightarrow S^{o}$)

Oxidizing Media

In addition to oxidizing the contaminants, the media also filter out the insoluble solids

Birm

- MnO_2 coated aluminum silicate (pumicite)
- Dissolved oxygen >15% iron content
- pH >6.8
- Free Cl_2 <0.5 mg/L
- Iron and manganese removal only (no H_2S)
- No polyphosphate or oil present

Greensand Plus®

- MnO_2 coated silica sand
- Removes Fe, Mn and H_2S
- pH >6.2
- Cl_2 or $KMnO_4$ should be continuously added
- No polyphosphate or oil present

MTM®

- MnO_2 coated granular media
- Removes Fe, Mn and H_2S
- pH >6.2
- Cl_2 or $KMnO_4$ should be continuously added
- Lower backwash rate than Greensand Plus®

Pyrolox®

- Natural ore for removal of Fe, Mn and H_2S
- pH >6.5
- Cl_2 or $KMnO_4$ can be used
- No H_2O_2 can be used

pH Adjustment Media

CALCITE –

Naturally occurring $CaCO_3$ media.
Used to raise pH of acidic waters and to increase “potability.”

COROSEX® –

MgO to raise pH of acidic waters. More effective than calcite, but may increase pH too much.

Calcite

- pH Correction
- Weaker then Magnesium Oxide
- Sacrificial Media
- Increases pH, Alkalinity and Hardness
- Oxidizes about 1/3 of Iron

Monitoring Requirements

- Pressure drop – Typically 10 psi indicates the need for backwashing
- Utilize pre and post-filter pressure gauges or differential pressure gauge
- Can also measure for specific contaminant

Activated Carbon

How Does Activated Carbon Work?

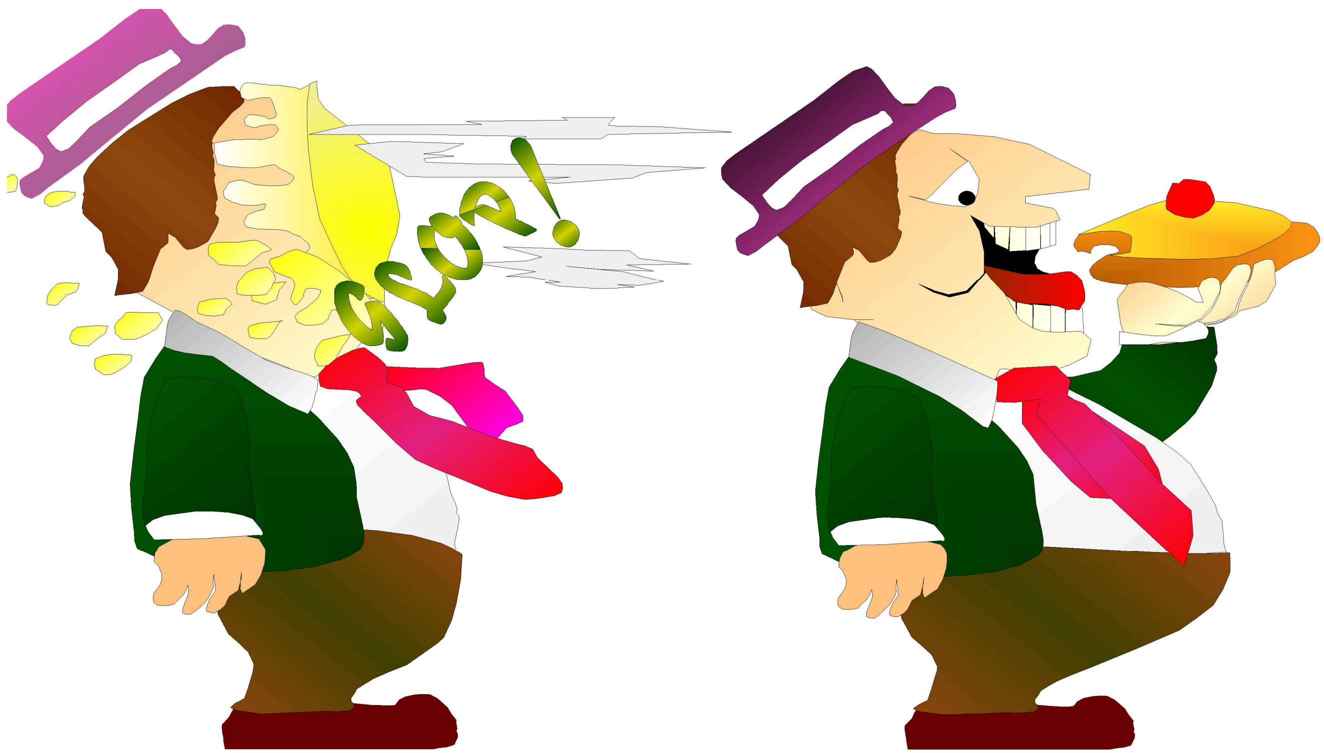
- ADsorption NOT ABsorption

  - ADsorption refers to the process in which a layer of molecules is attracted to the SURFACE of another substance. In ADsorption, the substance (ADsorbate) being adsorbed forms on the surface of the host (ADsorbent)

  - ABsorption refers to the assimilation or “taking up” one substance by another without specific reference to a surface. In ABsorption, the material goes INTO the bulk of the material.

Courtesy Calgon Carbon Corp

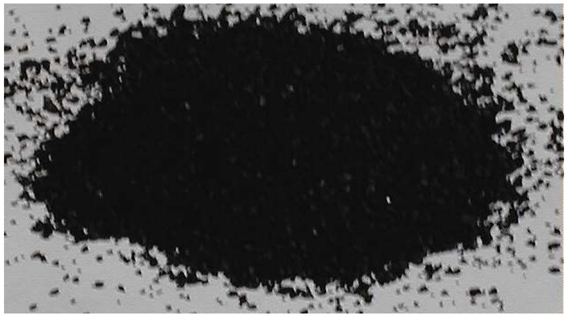
How Activated Carbon Works



ADsorption ABsorption

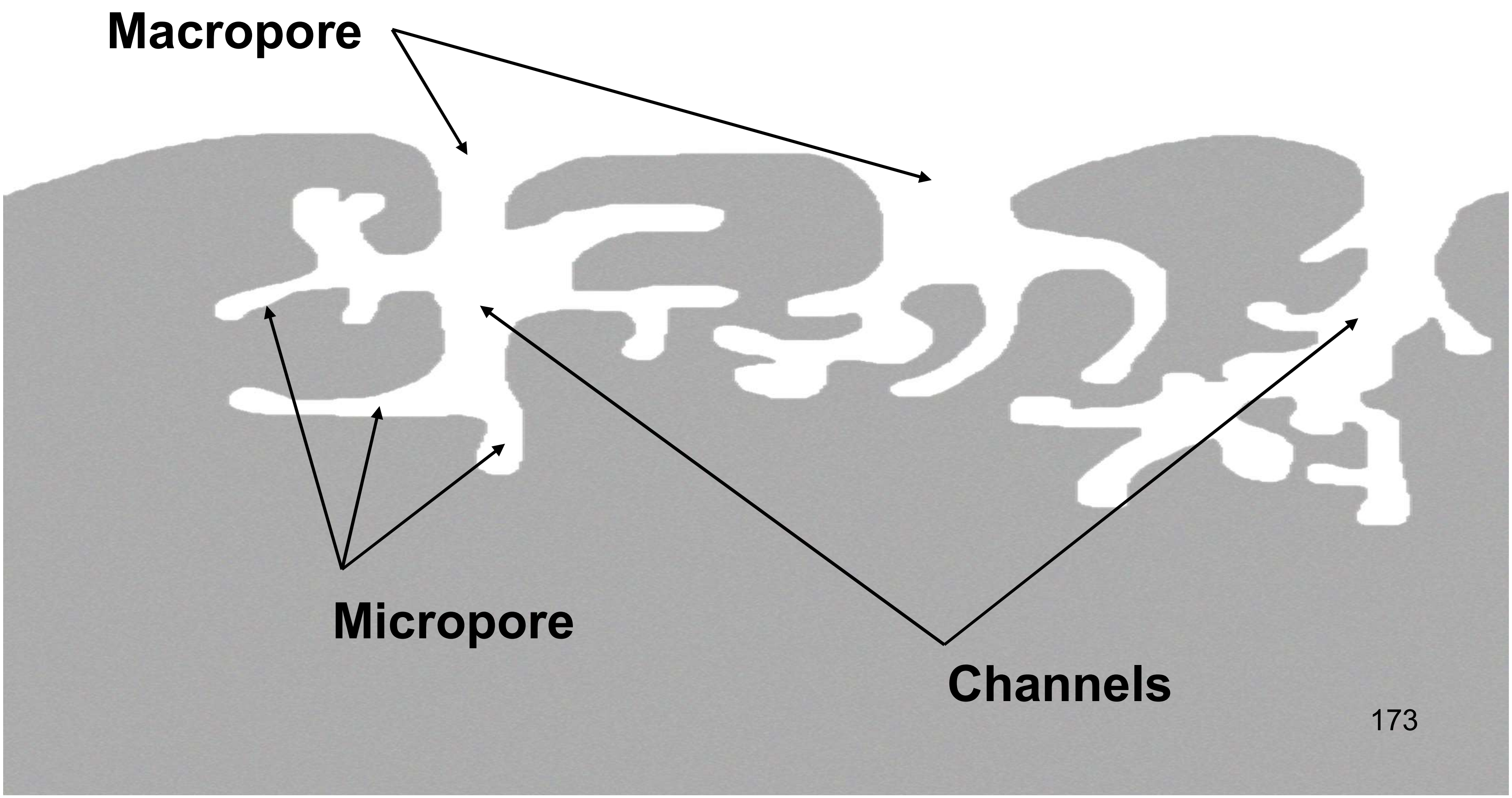
Courtesy Calgon Carbon Corp

Activated Carbon

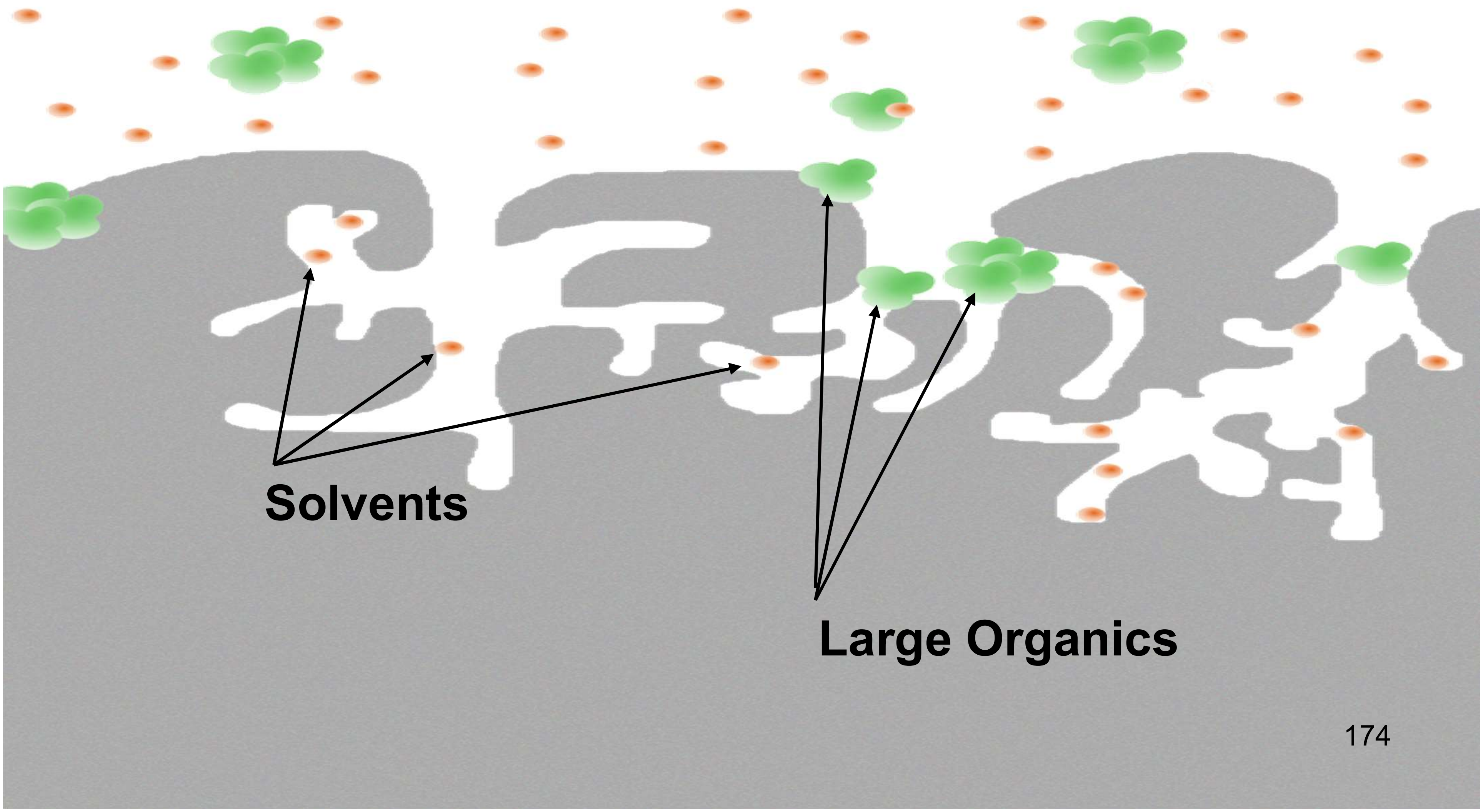


- Absorption - a substance penetrating into the carbon
- Adsorption - a substance adhering to the surface of the carbon

Activated Carbon Structure



Activated Carbon Structure



Carbon Types

Bituminous
Lignite
Wood
Coconut Shell

Raw Material Determines Characteristics

- Bituminous coal
  - Good overall mix of adsorption and transport pore structure
  - Good hardness/abrasion resistance
- Coconut
  - Tend to have more adsorption and less transport pore structure
  - Good hardness/abrasion resistance
- Wood/Lignite
  - Tend to have more transport structure
  - Lower hardness/abrasion resistance

Courtesy Calgon Carbon Corp

ACTIVATED CARBON FOR CHLORINE REMOVAL

Chlorine removal by oxidation/reduction

$$Cl_2 \longrightarrow 2Cl^-$$

Dechlorination

- Coconut and Coal based products well suited
- Dechlorination consumes activated carbon
  - Dechlorination oxidizes the carbon
  - $HOCl + C^* \Rightarrow CO^* + H^+ + Cl^-$
- Minimum contact time of 2.0 minutes for larger mesh, but carbon blocks have less than 1 minute EBCT for typical residential use
- GAC may require backwashing periodically
  - Coal/coconut GAC can be backwashed as required to maintain equipment flow and operating requirements
  - Carbon blocks will require disposal due to eventual pressure drop build up

ACTIVATED (CATALYTIC) CARBON FOR CHLORAMINE REMOVAL

Catalytic Carbon

- The removal mechanism for monochloramine is a two step reaction:

  (1) $NH_2Cl + H_2O + C^* \rightarrow NH_3 + H^+ + Cl^- + CO^*$

  (2) $NH_2Cl + CO^* \rightarrow N_2 + 2H^+ + Cl^- + H_2O + C^*$

  where C* = surface carbon and CO* = surface carbon oxides

- General performance guidelines:
  – Bituminous based carbon > coconut based carbon
  – Bituminous based carbon > lignite based carbon
  – Small mesh > large mesh

Monitoring

Monitoring Requirements

- Measure chlorine concentration in effluent
- ORP measurement also effective
- Pressure drop for backwashing

Membrane Technologies

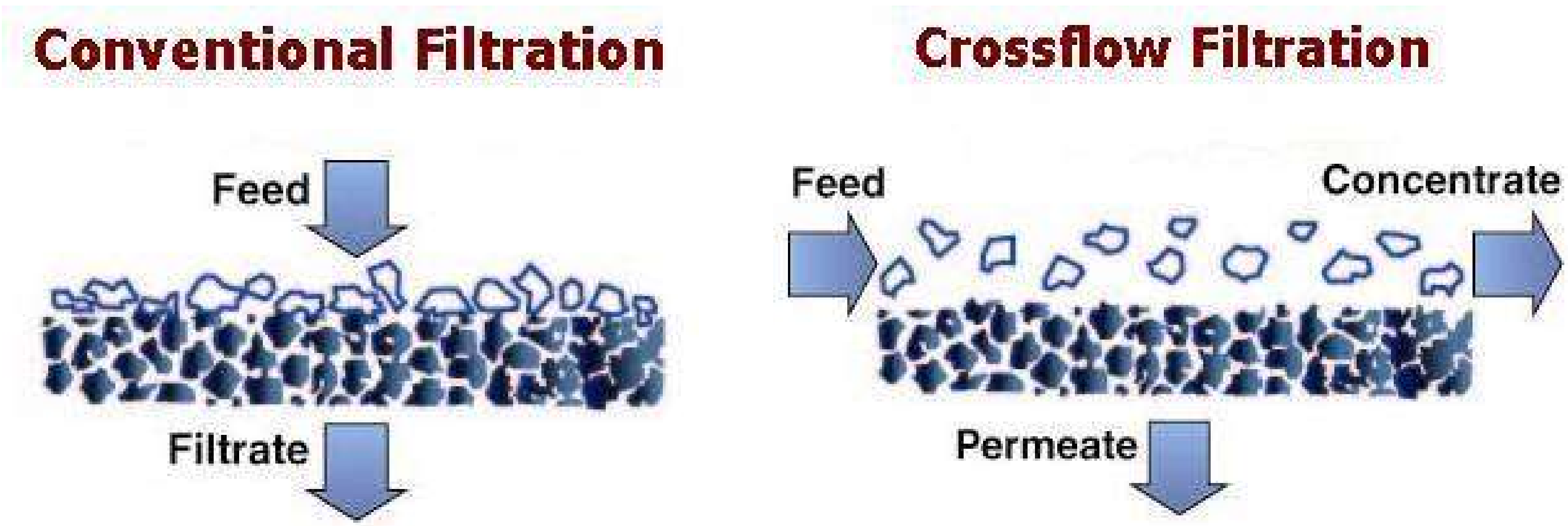
Membrane Technologies

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

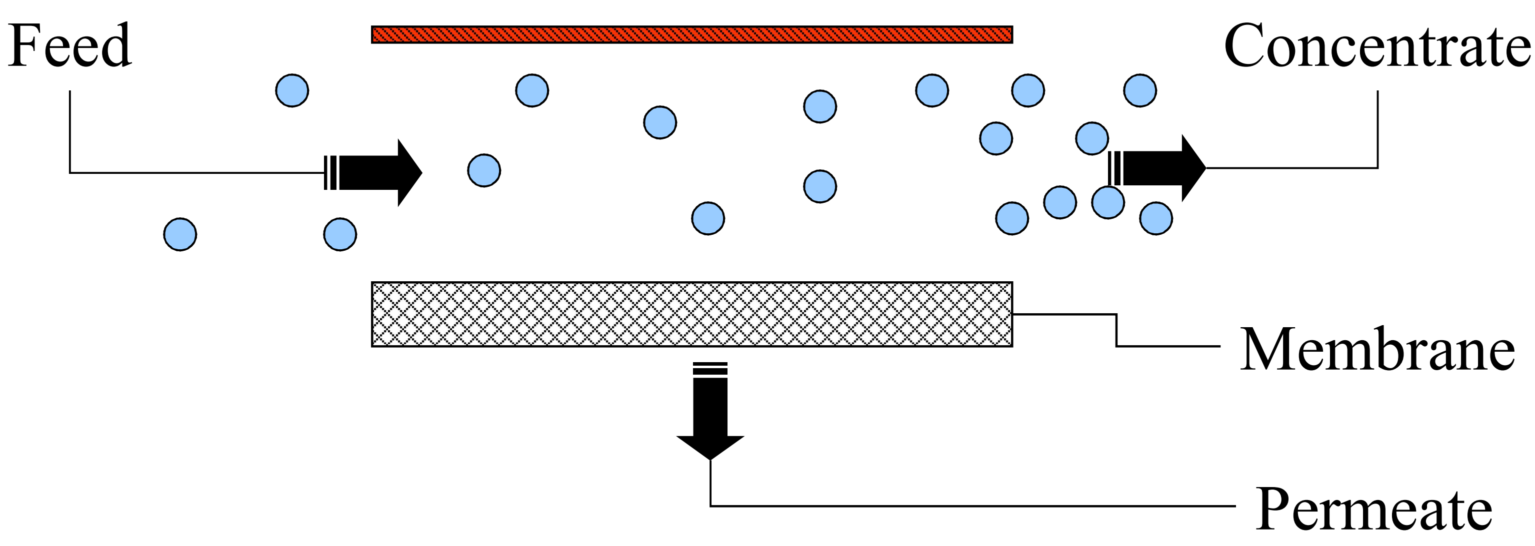
Membrane Technologies Advantages

- 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

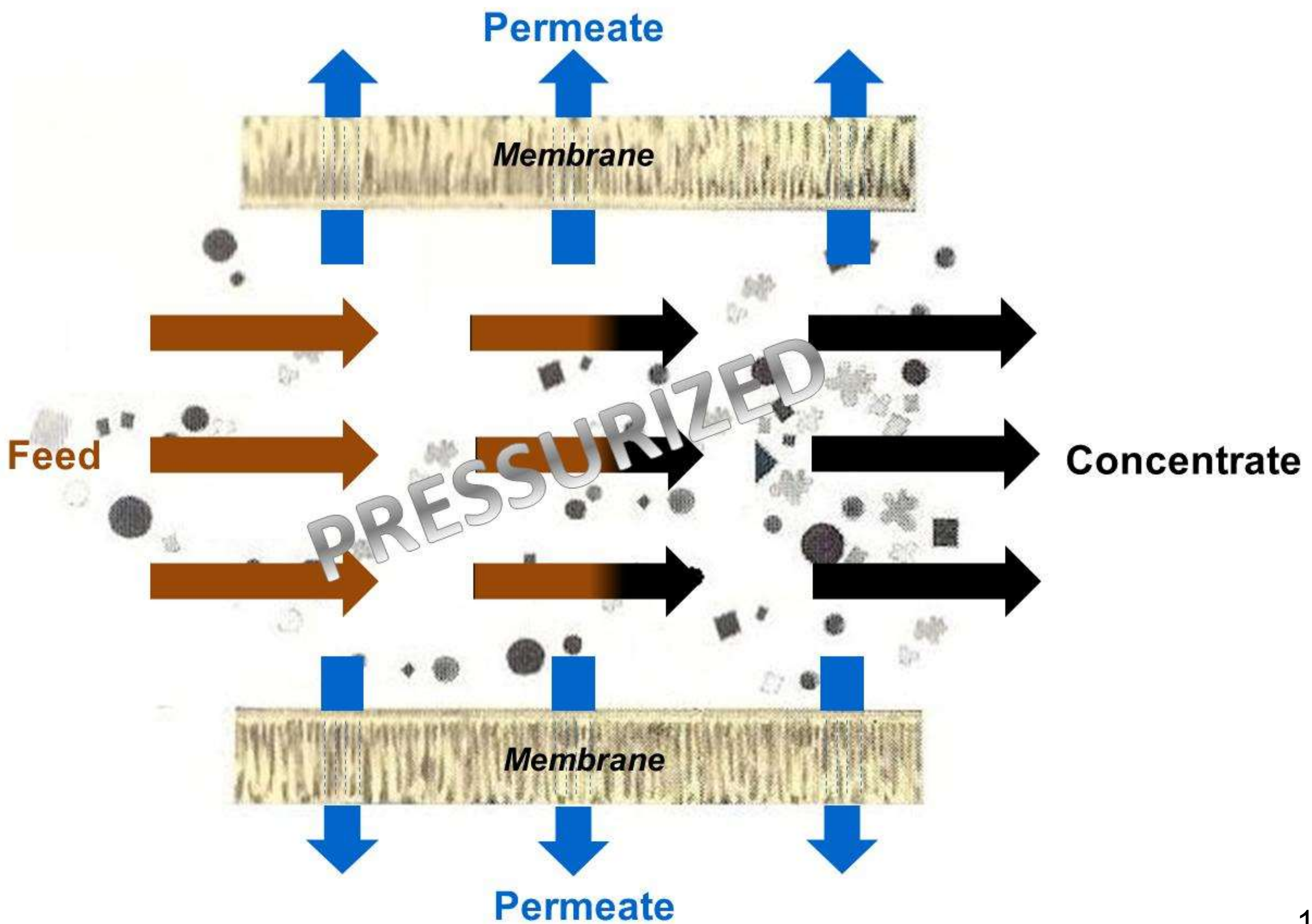
Conventional vs. Crossflow



Crossflow Filtration



Membrane Process

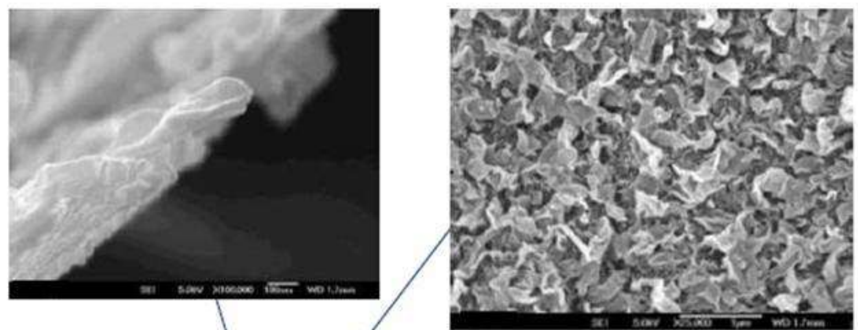


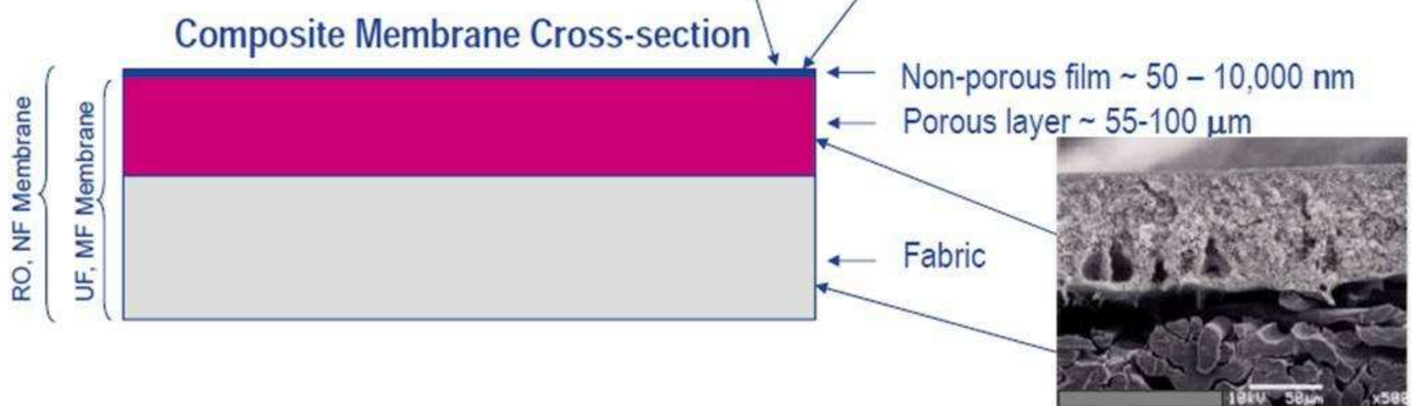
What is a Membrane?

Two classes of membranes:

- Porous (UF, MF)
- Non-porous (RO, NF)

Non-porous membranes typically comprise a thin film on a support



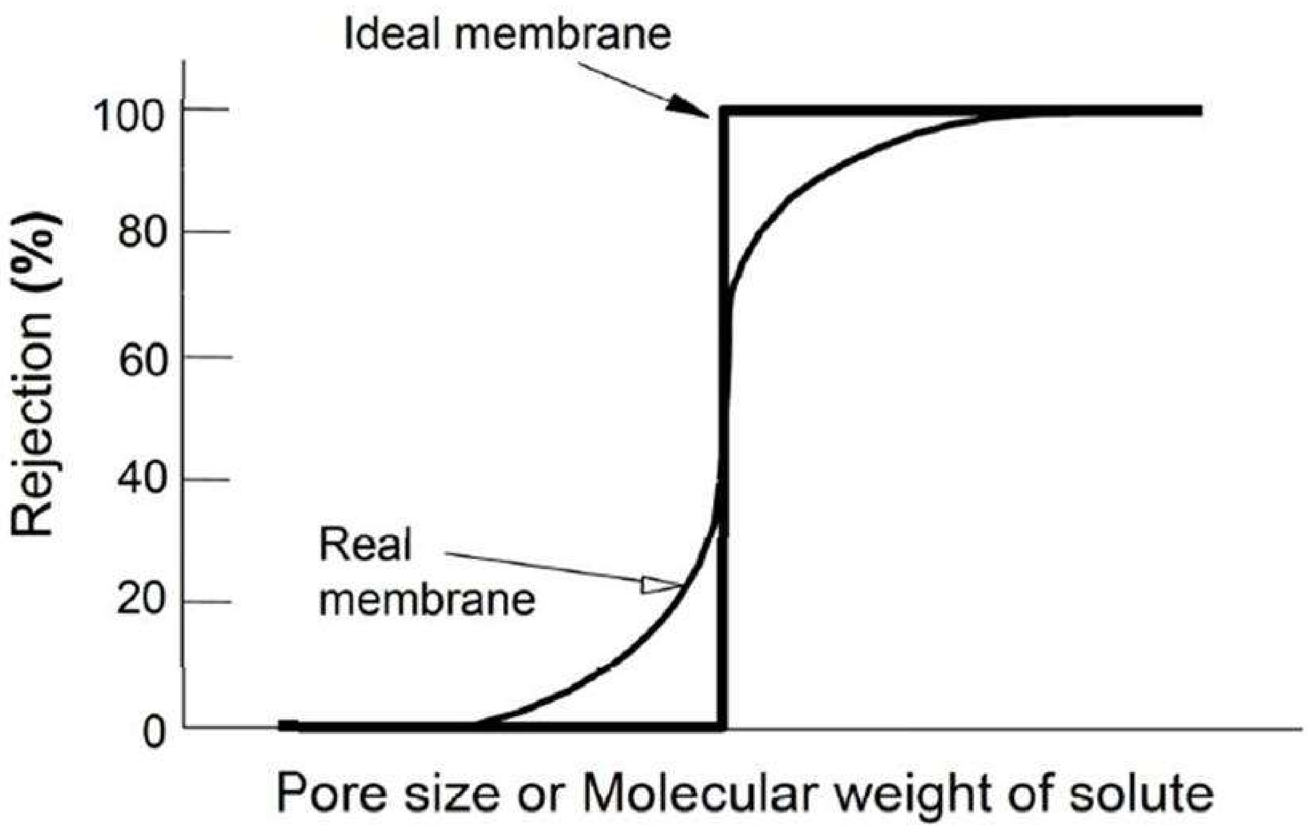


imagination at work

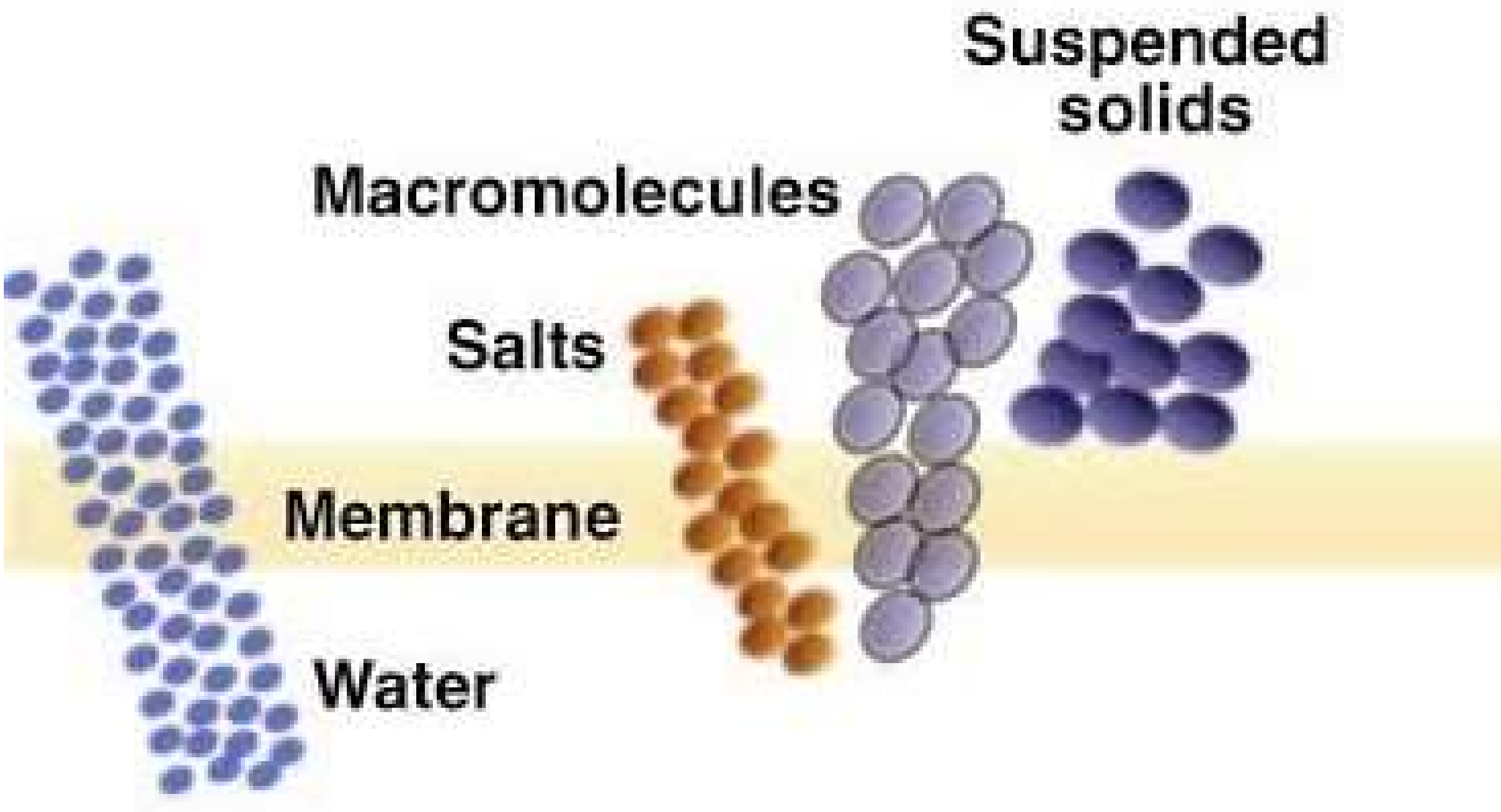
12 /
GE Proprietary
11 June 2009

Limitations of Membranes

Cannot get sharp separations



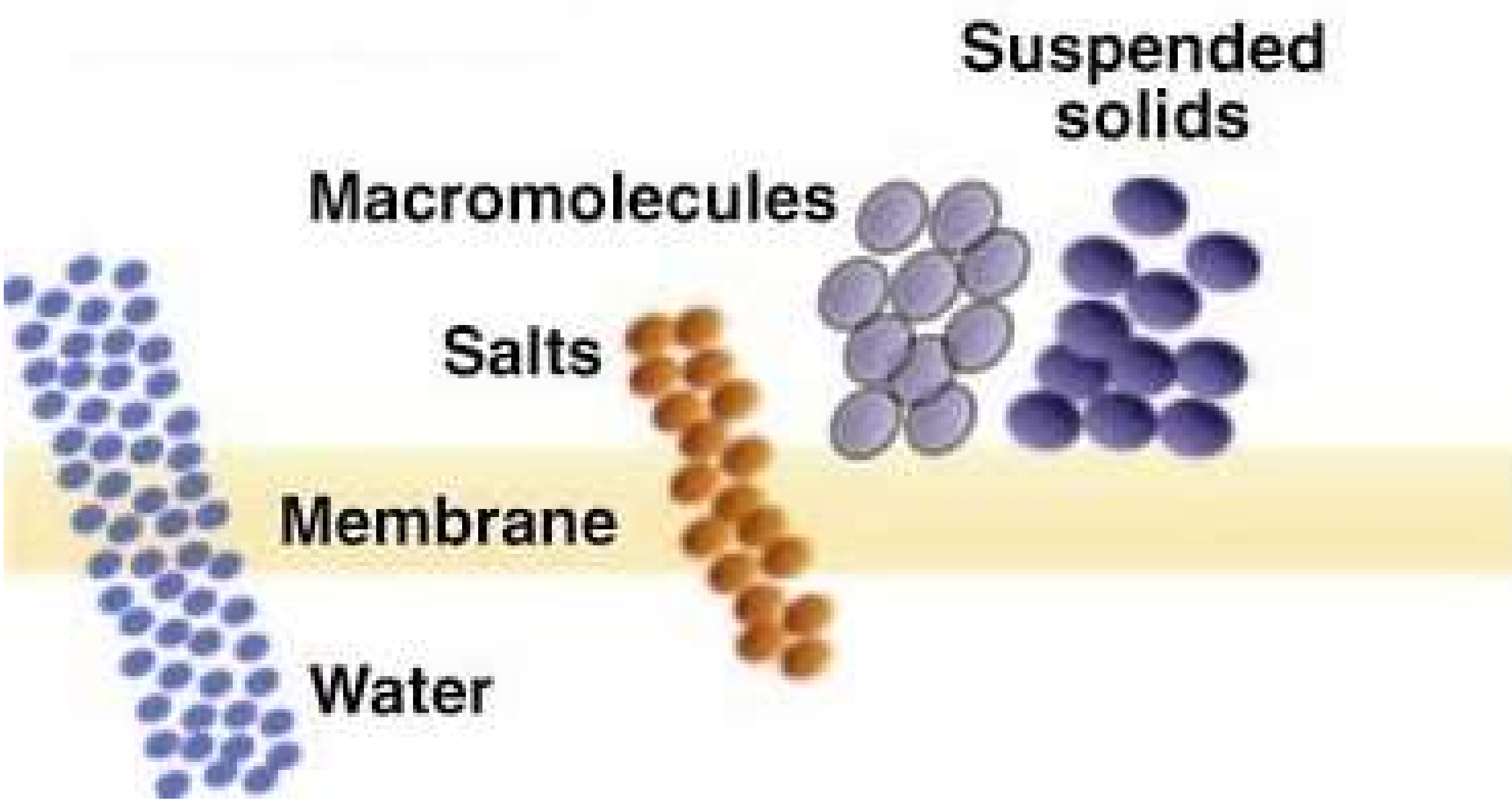
Microfiltration



Microfiltration (MF)

- Particle (suspended solids) removal only.
- Pore sizes in the submicron range (<1.0μ).
- Removal mechanism is sieving.

Ultrafiltration

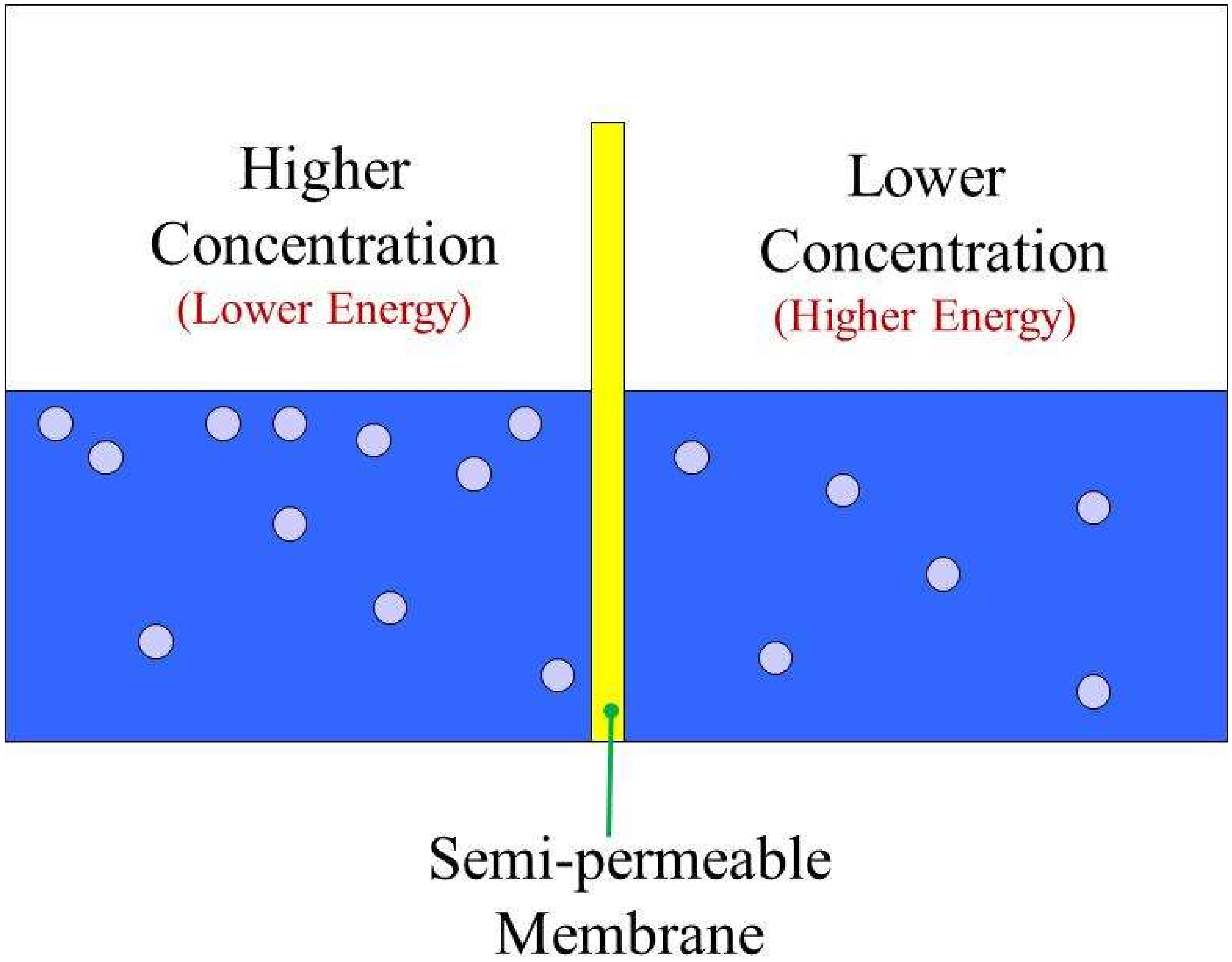


Ultrafiltration (UF)

- Dissolved organic (macromolecule) removal.
- Pore sizes in the submicron range, and generally smaller than MF.
- Removal mechanism is sieving.

MF and UF Membranes operate based on "sieving" – What is to big to pass through the pores is held back ("rejected")

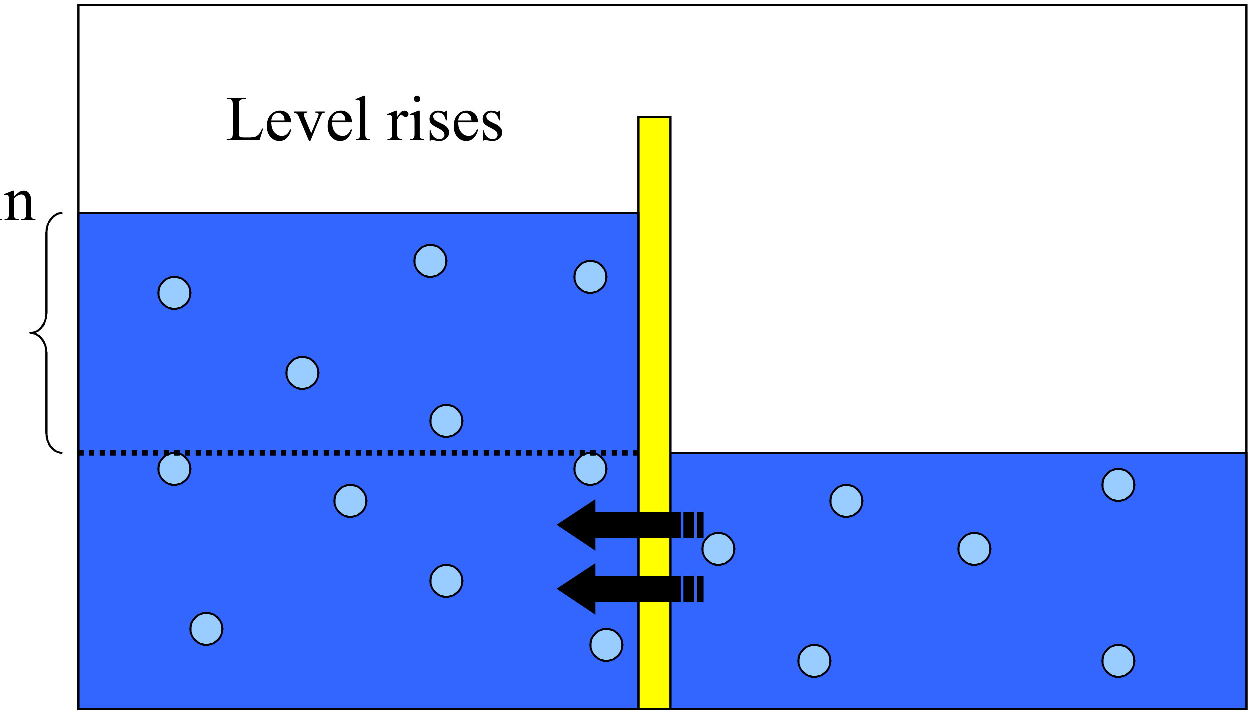
Osmosis



Higher
Concentration
(Lower Energy)
Lower
Concentration
(Higher Energy)
Semi-permeable
Membrane

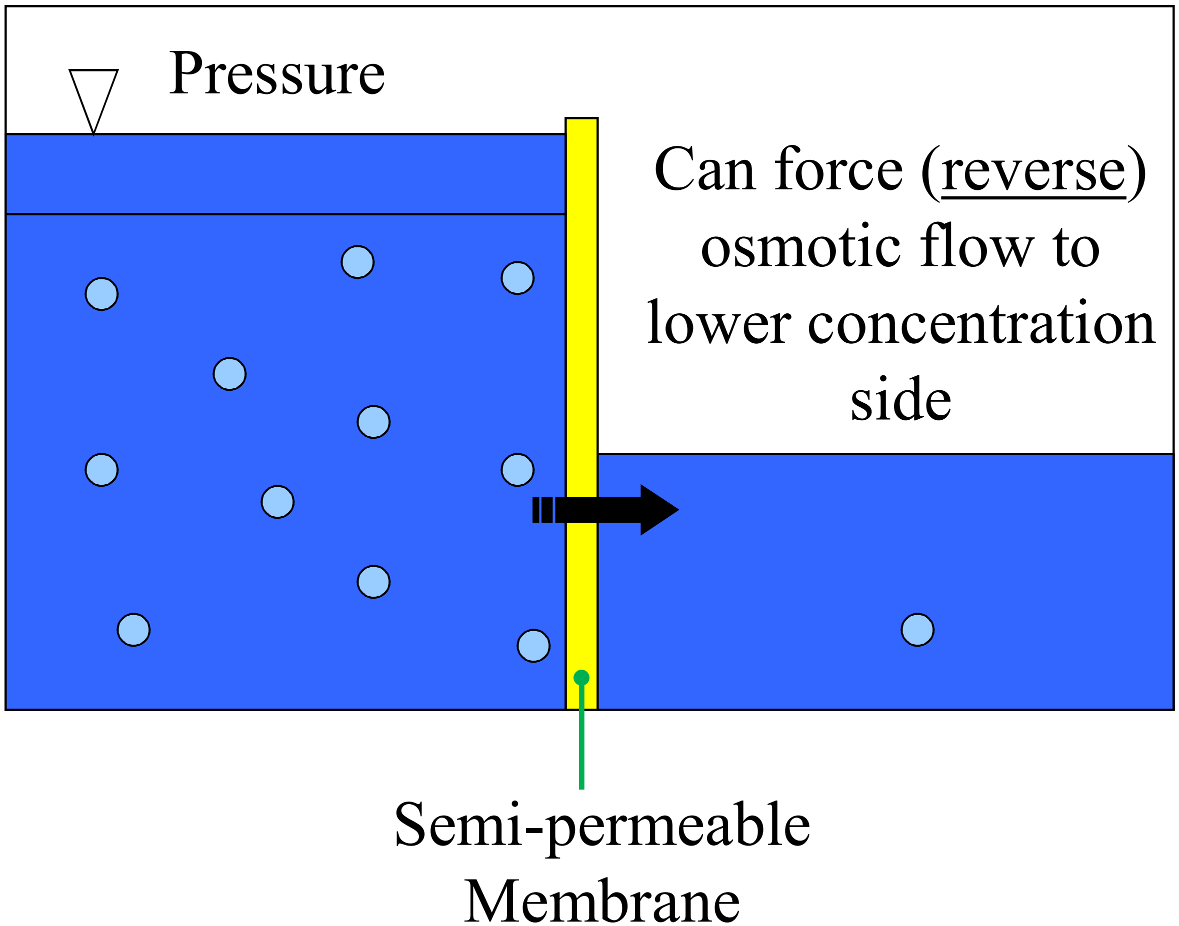
Osmosis

Difference in level is <u>Osmotic Pressure</u>

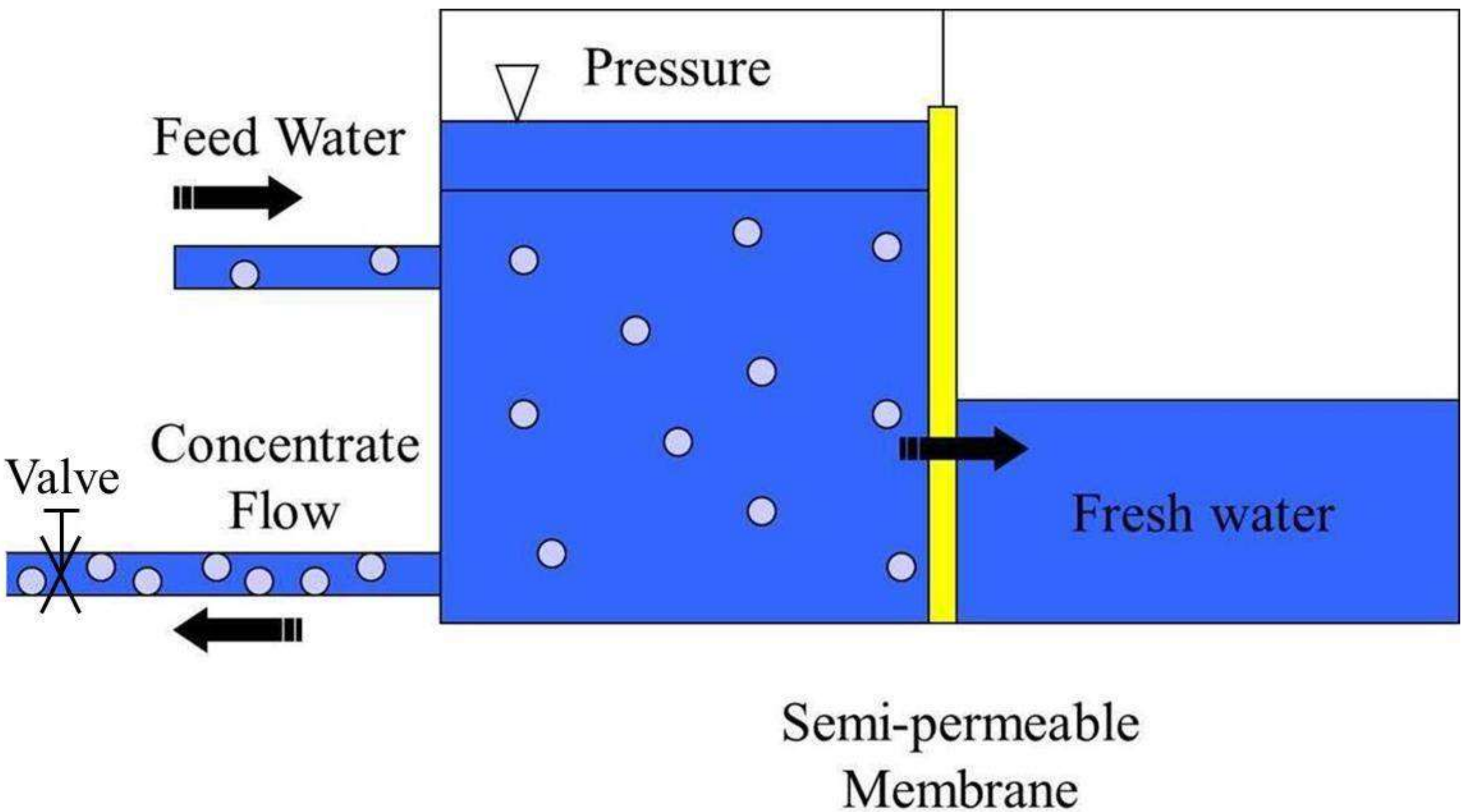


Water Flow

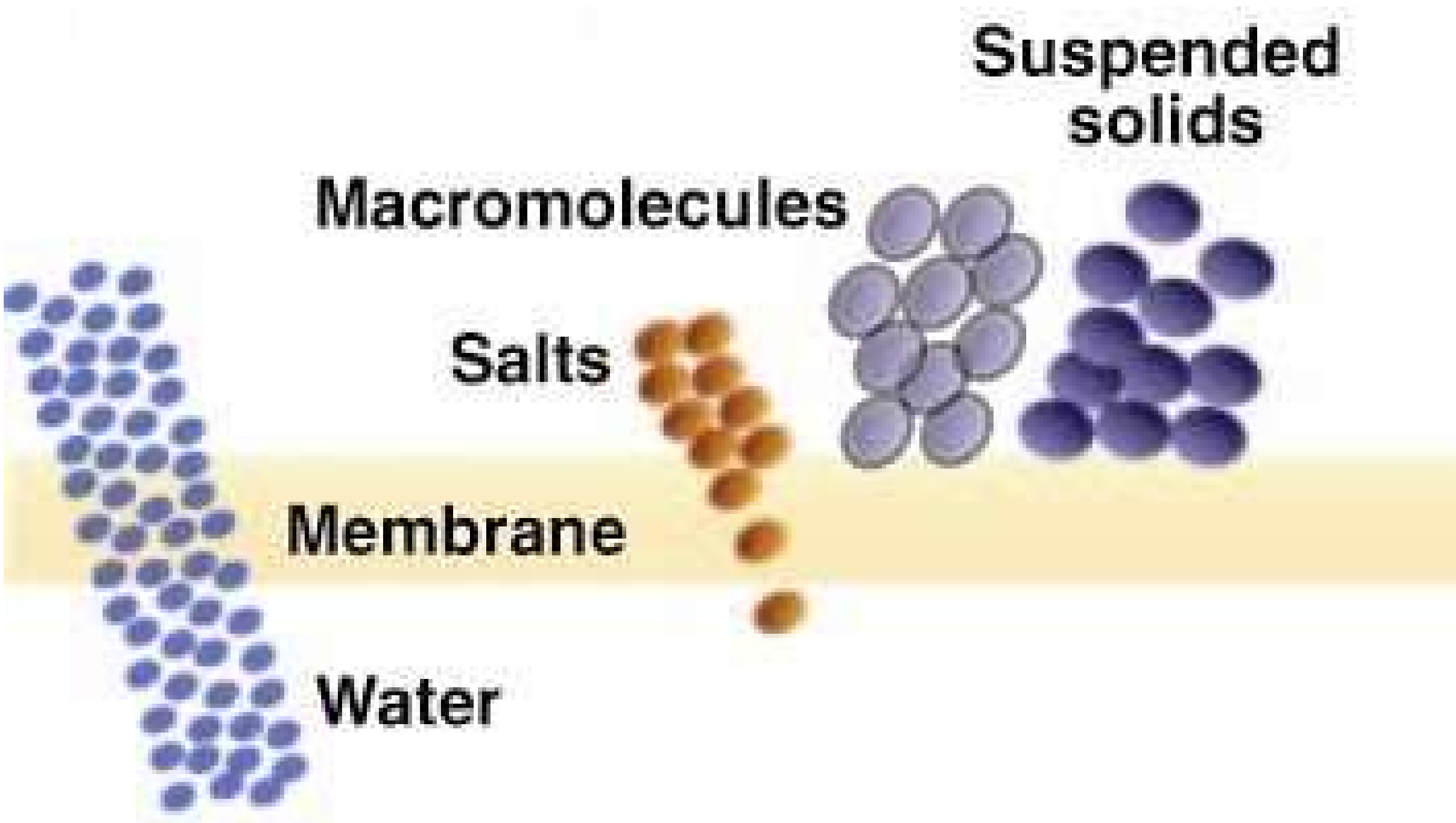
Reverse Osmosis



Reverse Osmosis Applied



Nanofiltration



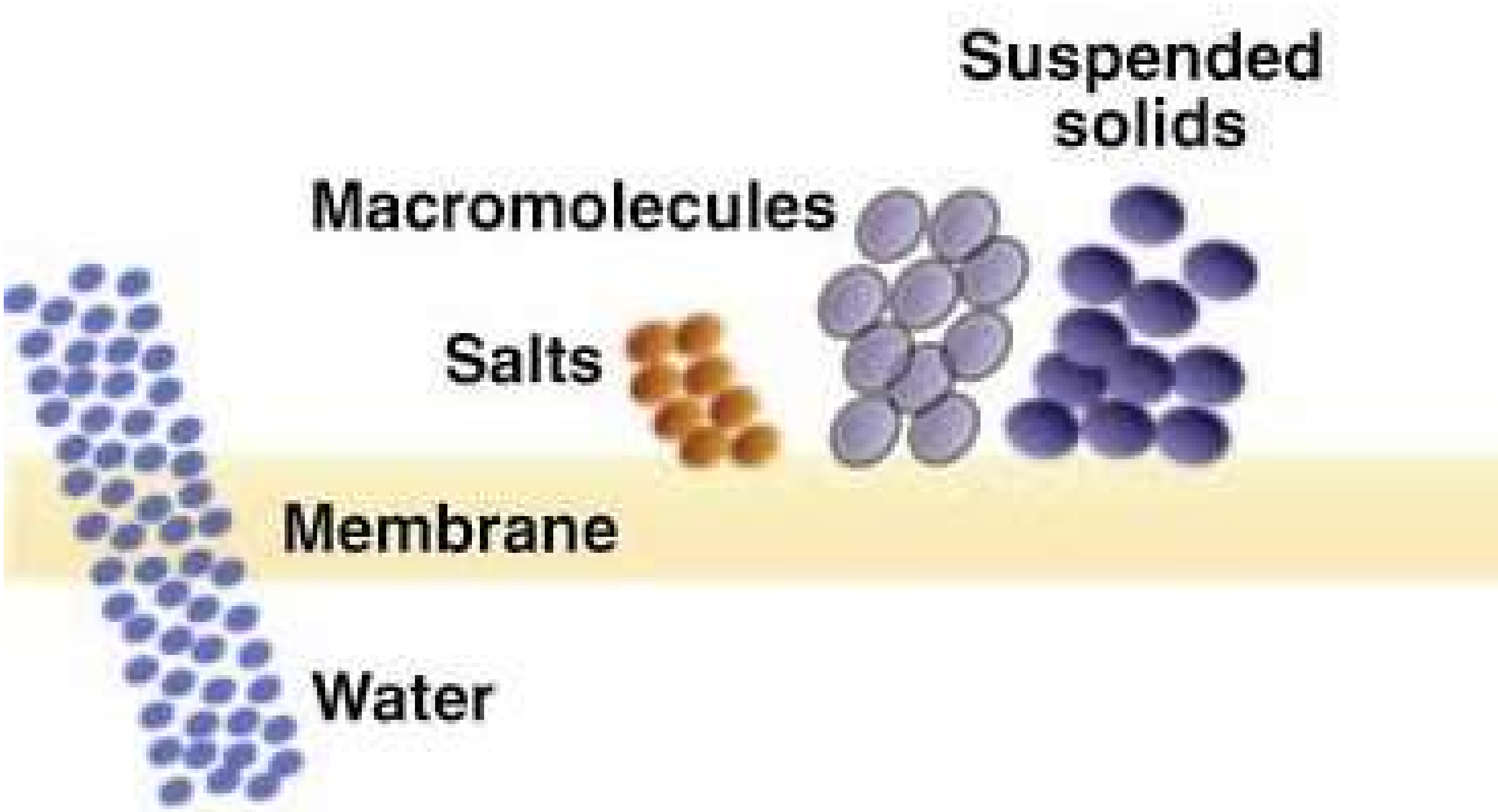
Nanofiltration (NF)

"Loose RO"
Rejects salts as with RO

- But -

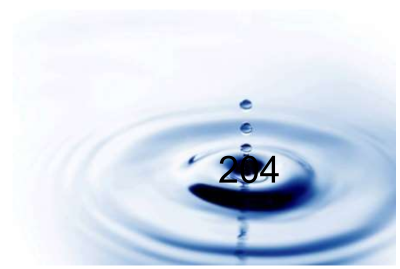
Rejects multivalent salts to a much higher degree than monovalent salts

Reverse Osmosis



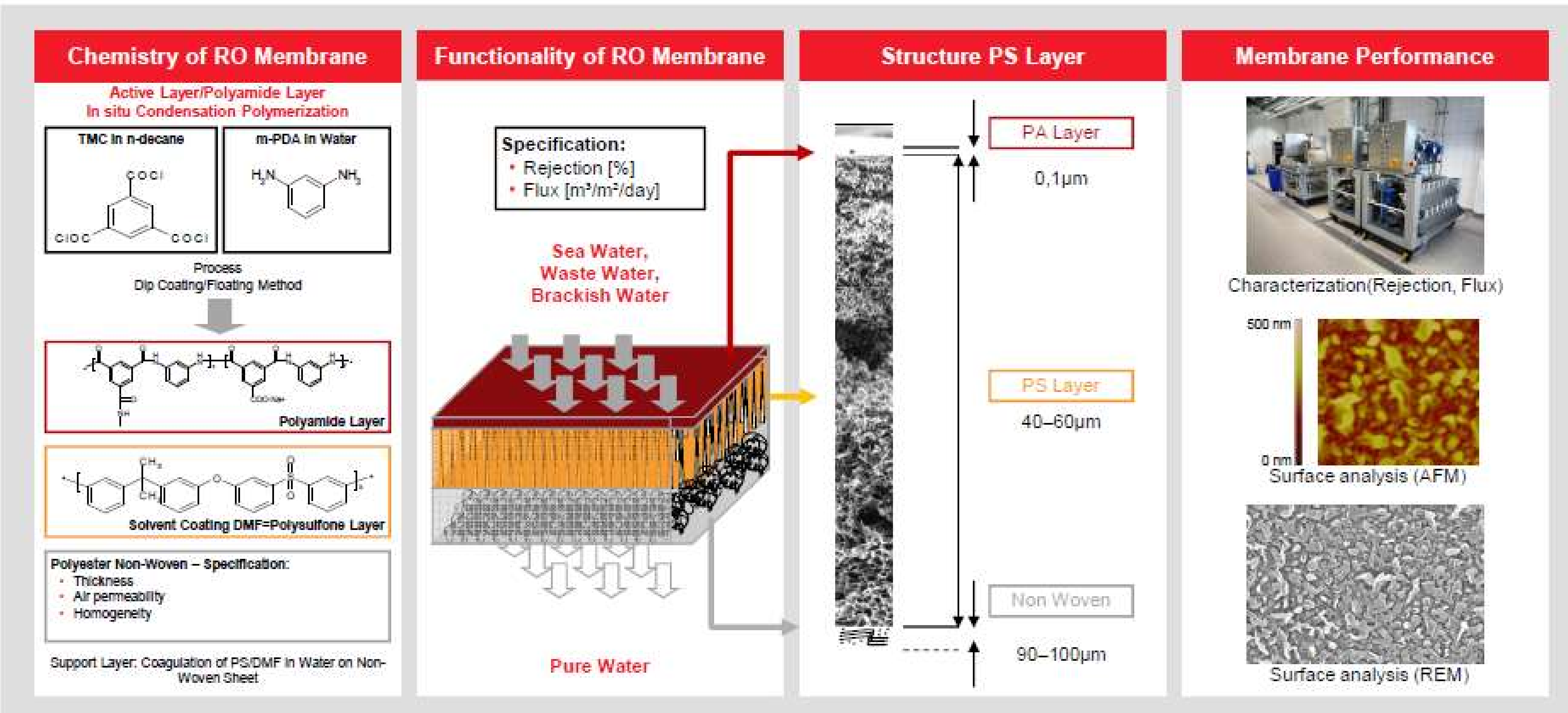
RO Removes dissolved organic contaminants by a process of SIZE EXCLUSION:

- What’s too big to go through the membrane is held back.
- Function of both the size and shape of the organic molecule.



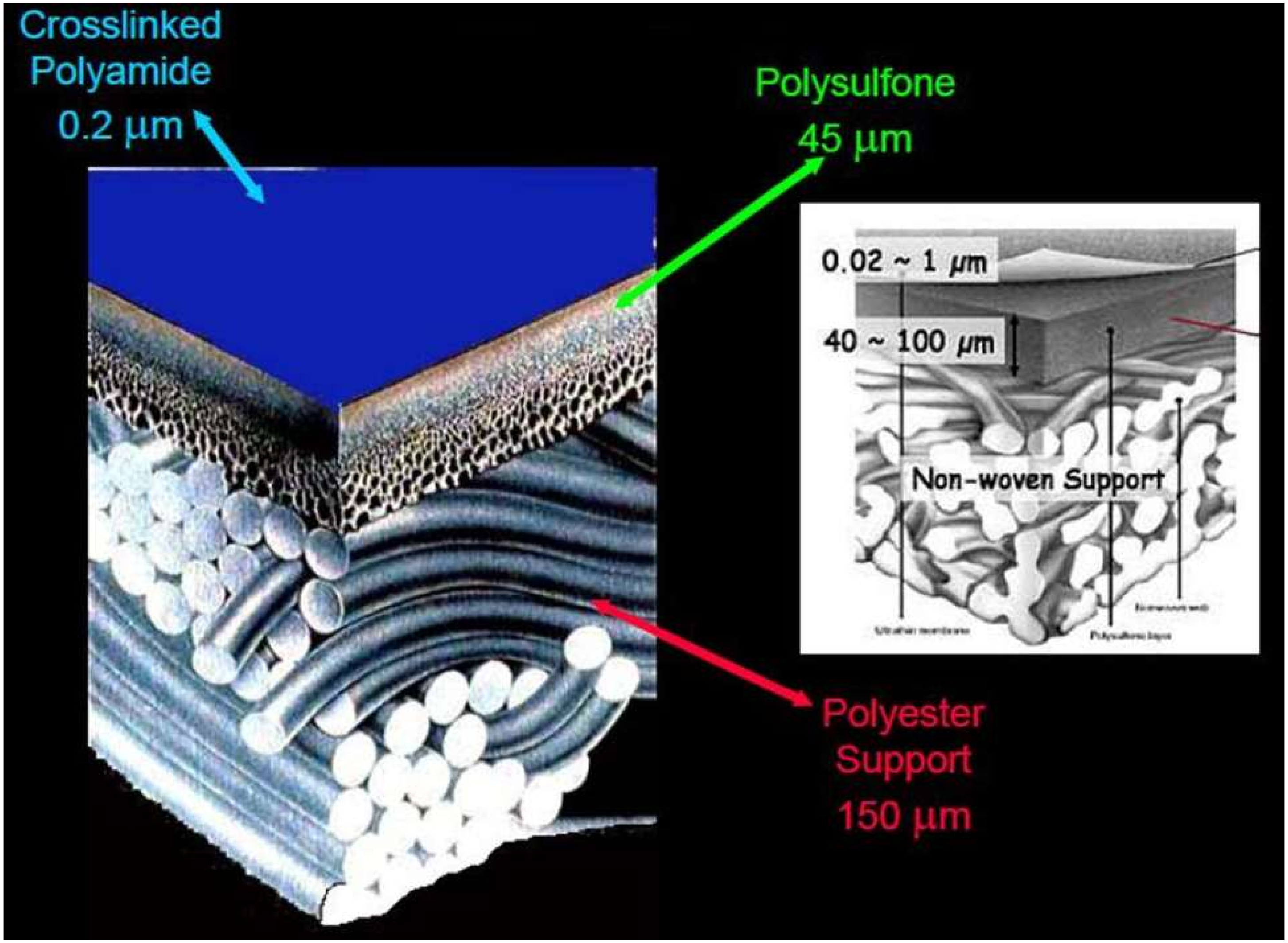
Dissolved organics with a molecular weight greater than ~100 Daltons are rejected by RO

Reverse Osmosis –
Membrane Chemistry and Functionality

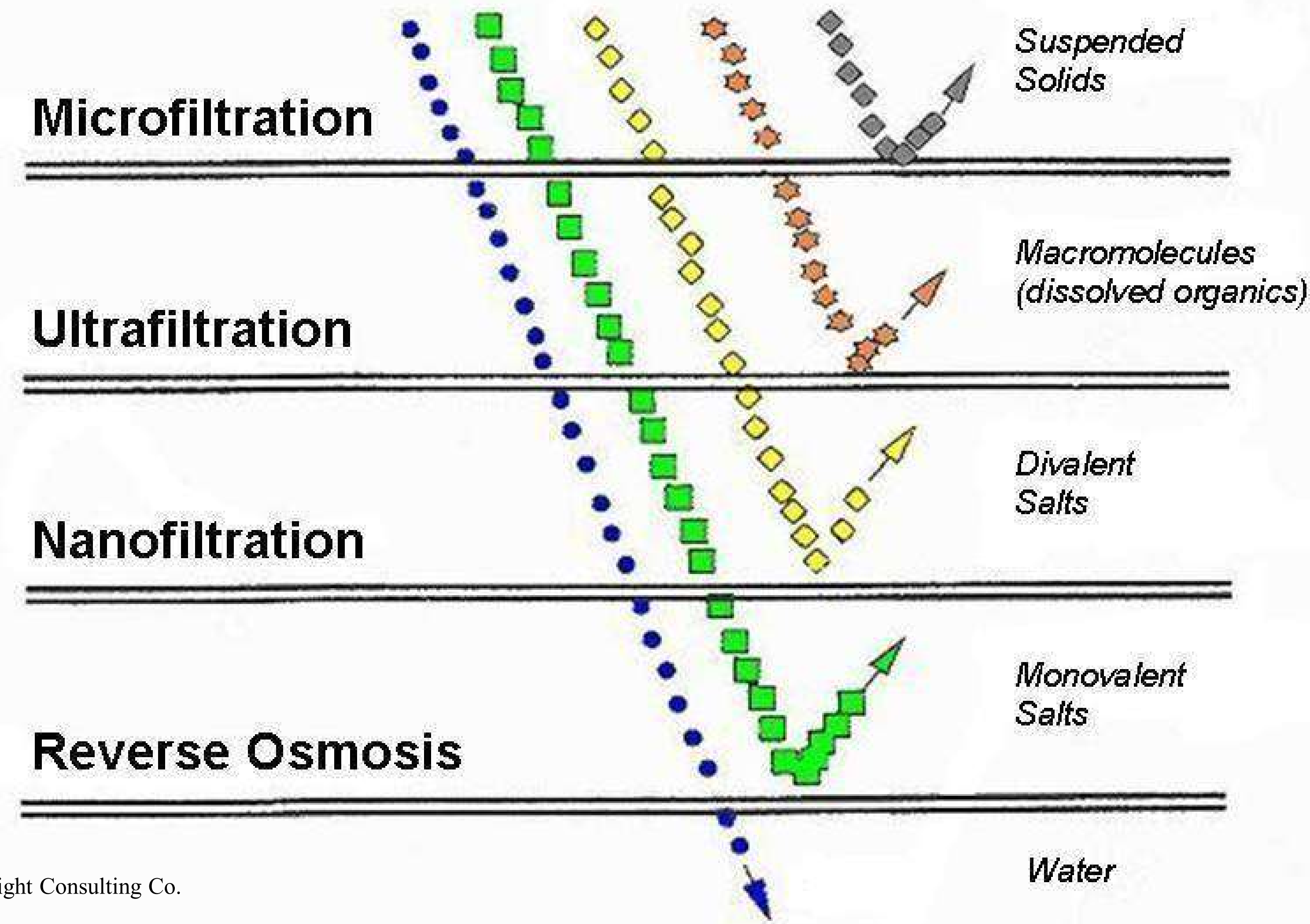


Membrane – Cross Section

Typical RO Membrane



Membrane Technologies



Membrane Technologies Compared

Feature	Microfiltration	Ultrafiltration	Nanofiltration	Reverse Osmosis
Materials of Construction	Ceramics, Sintered metals, Polypropylene, Polysulfone, Polyethersulfone, Polyvinylidene fluoride, Polytetrafluoroethyliene	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+%

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

Membrane Technologies Compared

Feature	Microfiltration	Ultrafiltration	Nanofiltration	Reverse Osmosis
Materials of Construction	Ceramics, Sintered metals, Polypropylene, Polysulfone, Polyethersulfone, Polyvinylidene fluoride, Polytetrafluoroethyliene	Ceramics, Sintered metals, Polypropylene, Polysulfone, Polyethersulfone, Polyvinylidene fluoride	Thin film composites, Cellulosics	Thin film composites, Cellulosics
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 Materials

Over 150 materials are available

POLYMERIC

Cellulose acetate
Polyamide
Poly(ether)sulfone
Polyvinylidene fluoride
Regenerated cellulose
Polyacrylonitrile
PTFE
Polypropylene
Polycarbonate

INORGANIC

Alumina
Zirconia
Titania
Stainless steel
Carbon composite
Silicon carbide
Nickel

Cellulose Acetate

First RO Polymer

- Moderate salts rejection (95-98%)
- Poor thermal stability (compaction)
- Poor bacterial resistance
- Limited pH stability (<8)
- Relatively resistant to oxidizing agents

Thin Film Composite

Vast majority of RO membranes are Thin Film Composite:

- High Rejection
- Excellent Thermal Stability
- Bacteria Resistant
- pH Stable

HOWEVER – They are chemically attacked by oxidizing agents:

- Chlorine compounds
- Hydrogen peroxide
- Potassium permanganate
- Others

Membrane Comparisons

Parameter	Cellulosic	Thin Film Composite
Bacteria	Some bacteria will attack	Very bacteria resistant
pH Range	4.0-8.0	2.0-11.0
Chlorine Tolerance	Excellent resistance	Poor resistance, 200-1000 ppm hrs.
% Rejection	92%-95%	95%-99%
Nitrate Rejection	0%-65%	40%-90%
Temperature Limit	87°F (31°C)	112°F (45°C)

Microfiltration & Ultrafiltration

Materials of Construction	Device Configuration			
	Hollow Fiber	Tubular	Plate & Frame	Spiral Wound
Polymeric				
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	–	–	–
Non-Polymeric				
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 & Reverse Osmosis

Materials of Construction	Device Configuration			
	Hollow Fiber	Tubular	Plate & Frame	Spiral Wound
Polymeric				
PS*	–	X	X	X
PES*	–	X	X	X
CA	–	X	X	X
TF	–	X	X	X
Non-Polymeric				
None	–	–	–	–

** Base polymer below TF polymer*

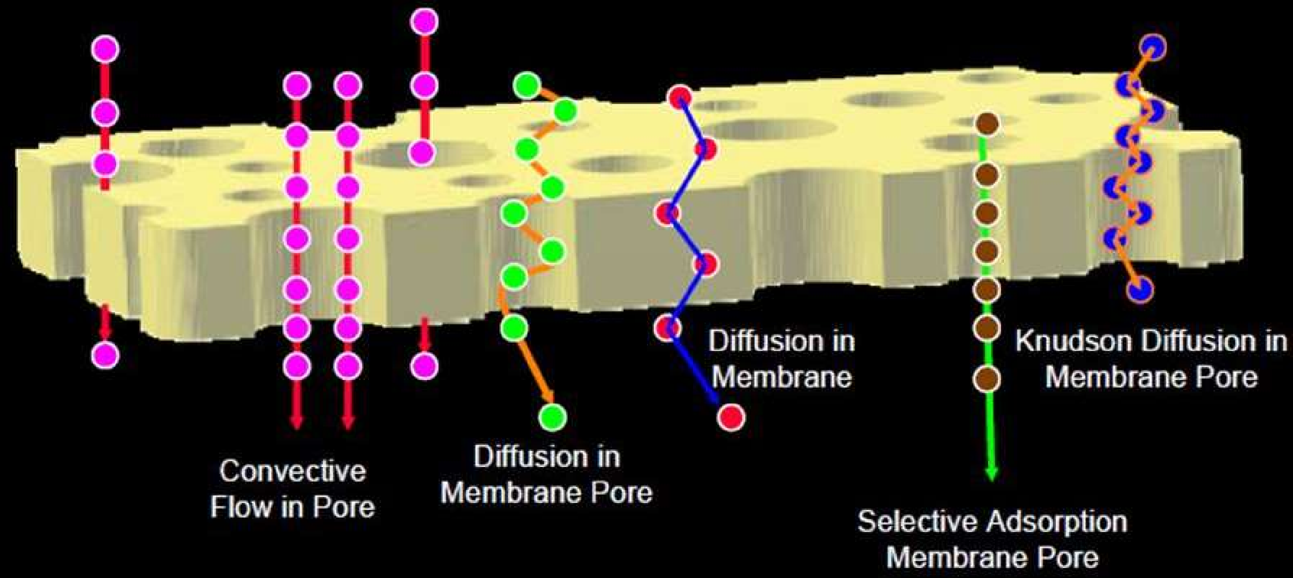
PS = Polysulfone

PES = Polyethersulfone

CA = Cellulose Acetate

TF = Thin Film Composite

Modes of Transport in Membranes



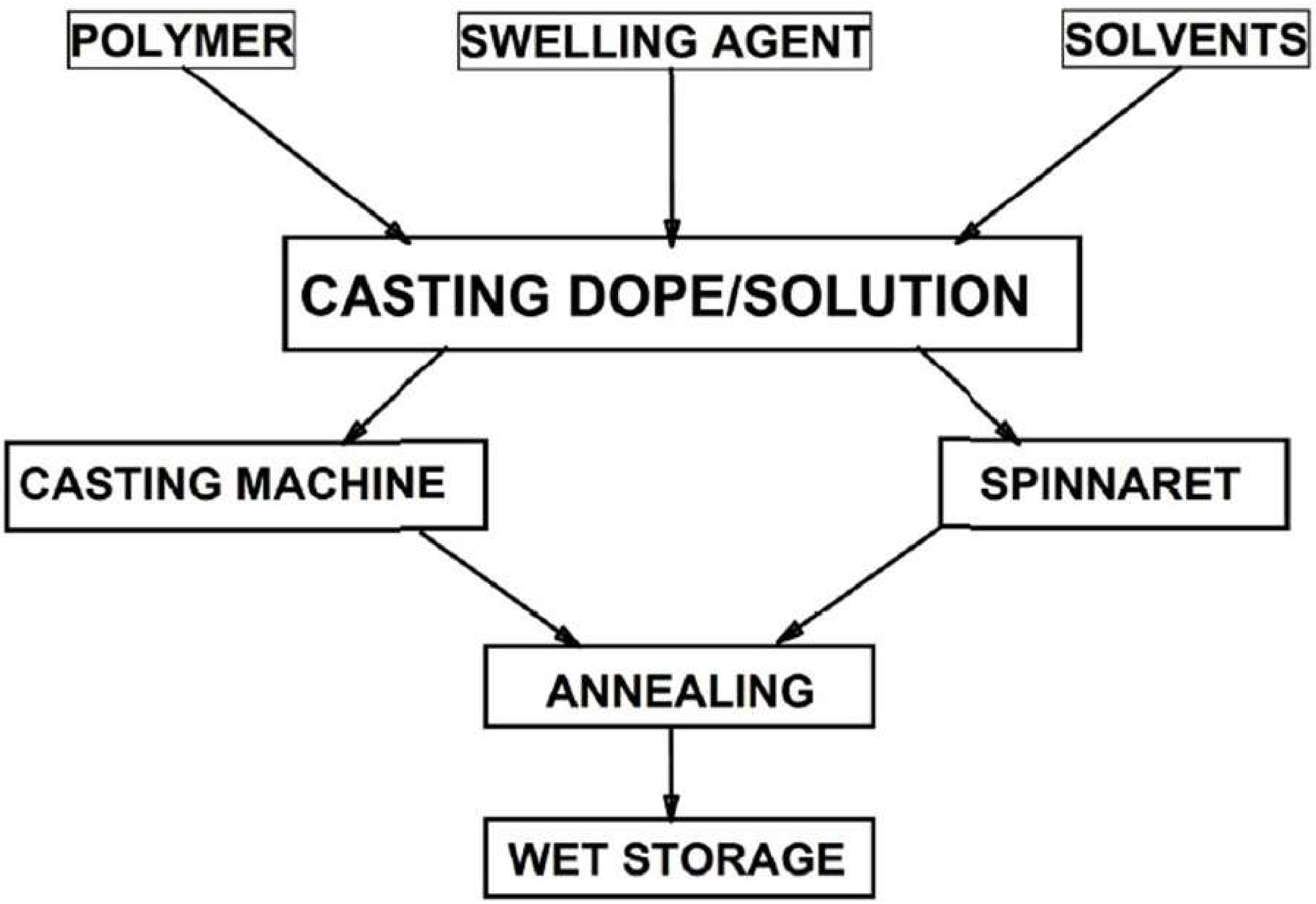
Knudson diffusion - Mean free path is long compared to pore size - many collisions with pore wall

Diffusion/Molecular diffusion - Mean free path is short compared to pore size or membrane extent
- Few or no collisions with pore wall

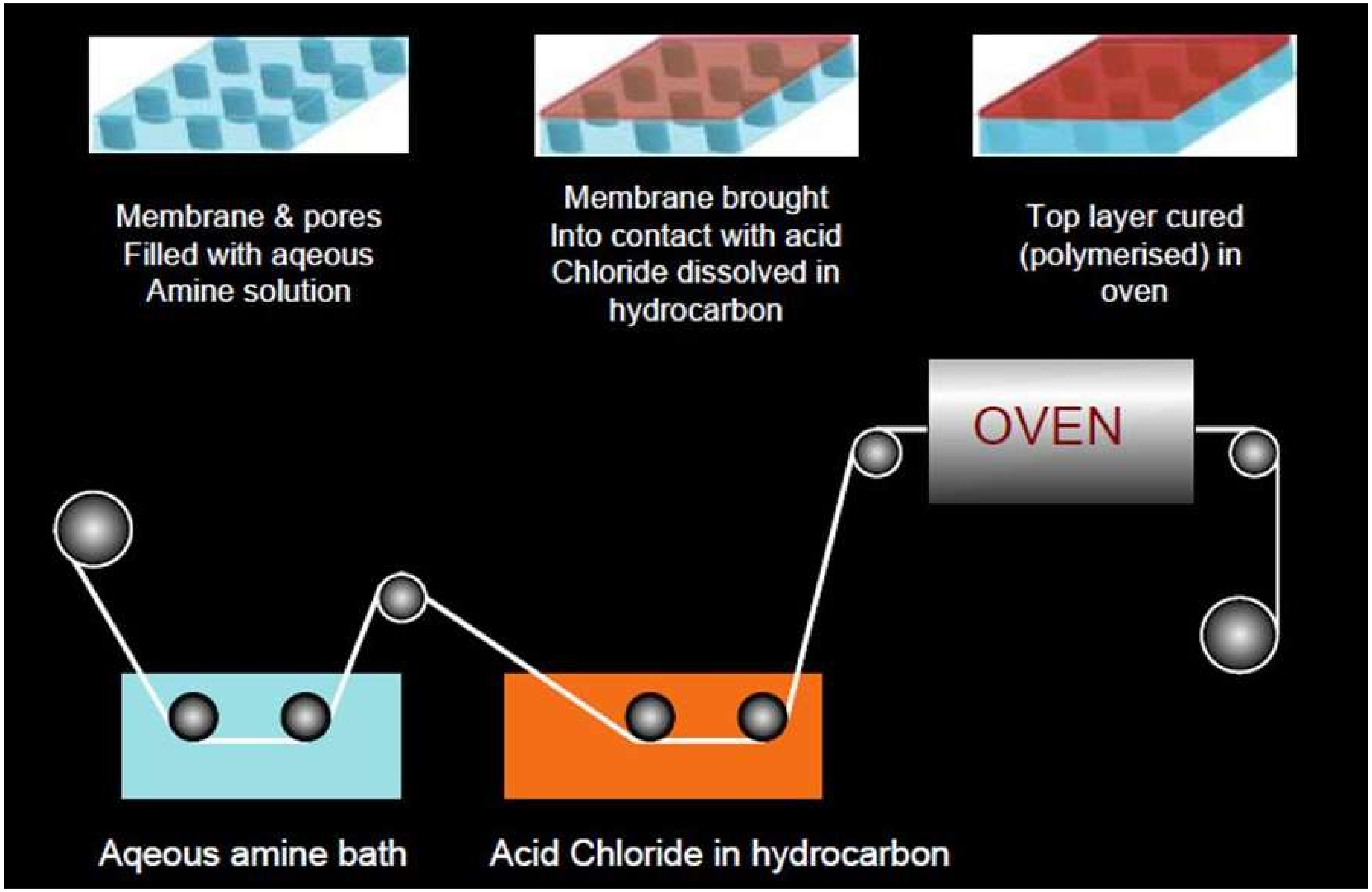
Selective adsorption- diffusion in which molecule adsobs to pore wall and hops from one adsorbtion site to another on its way through the pore.

Membrane Manufacturing

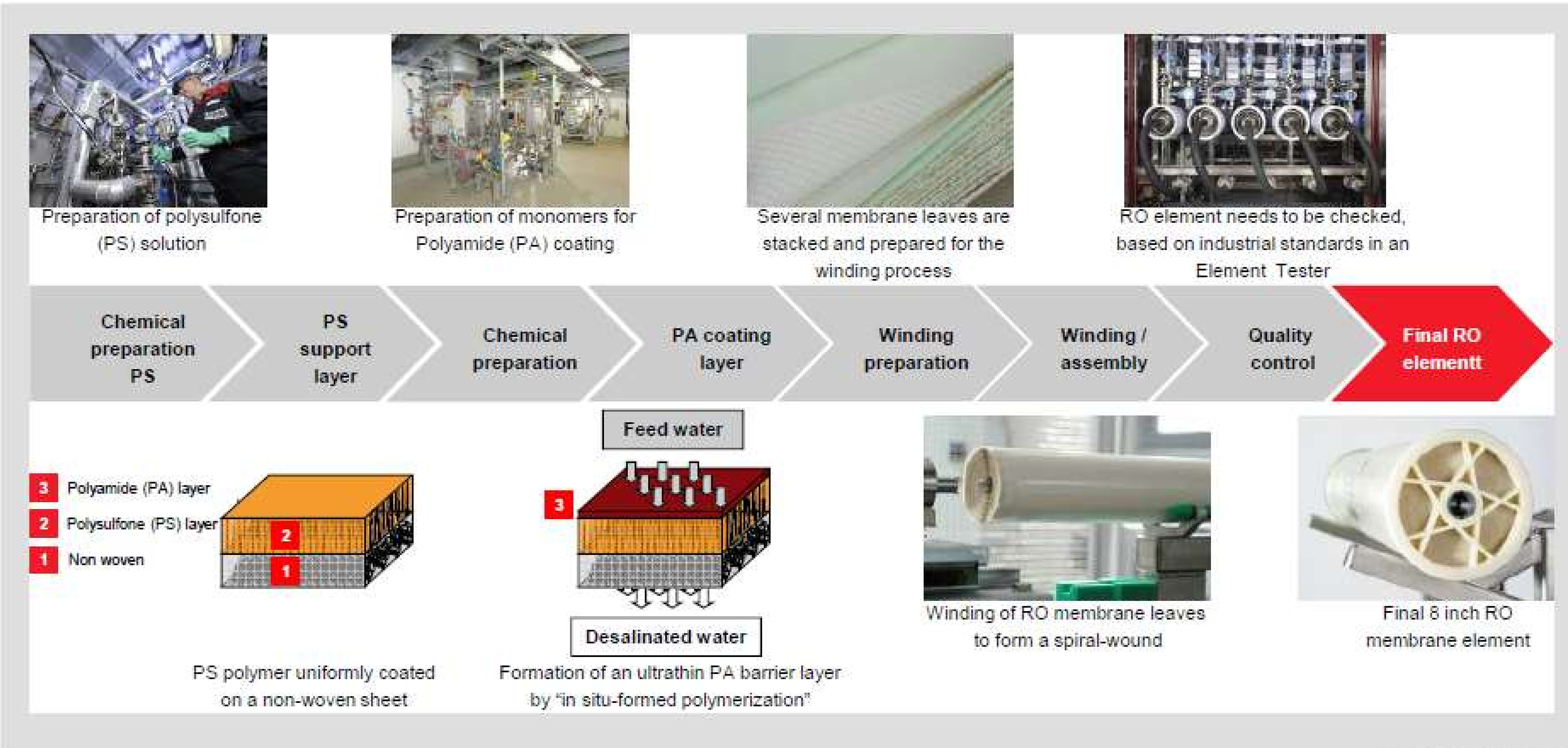
Manufacture of Polymeric Membranes



Casting a Thin Film Composite Membrane



State-of-the-art production process ensures premium quality reverse osmosis membranes



LANXESS

Membrane Element Devices

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

Membrane Element Devices

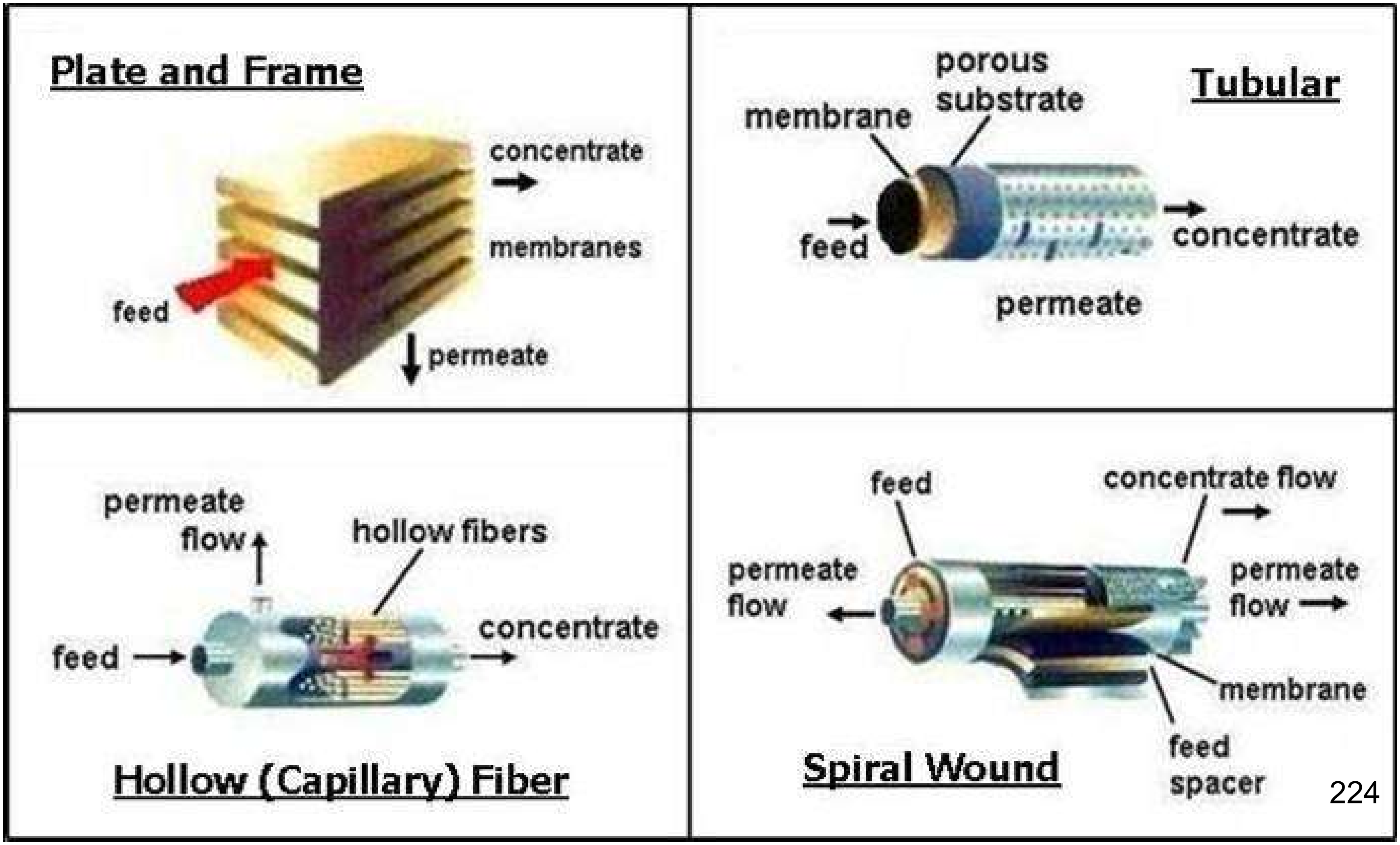


Plate
&
Frame

Plate & Frame

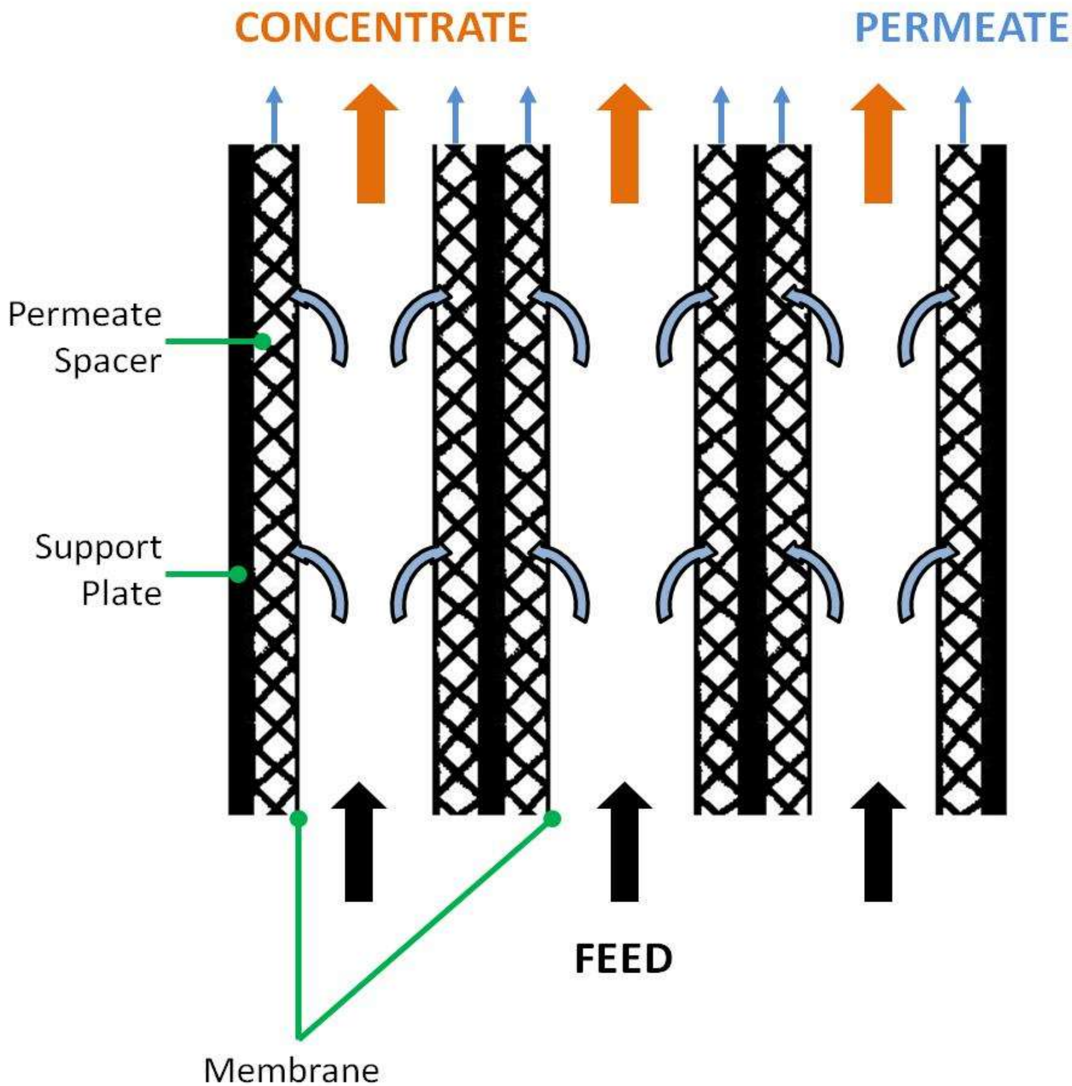
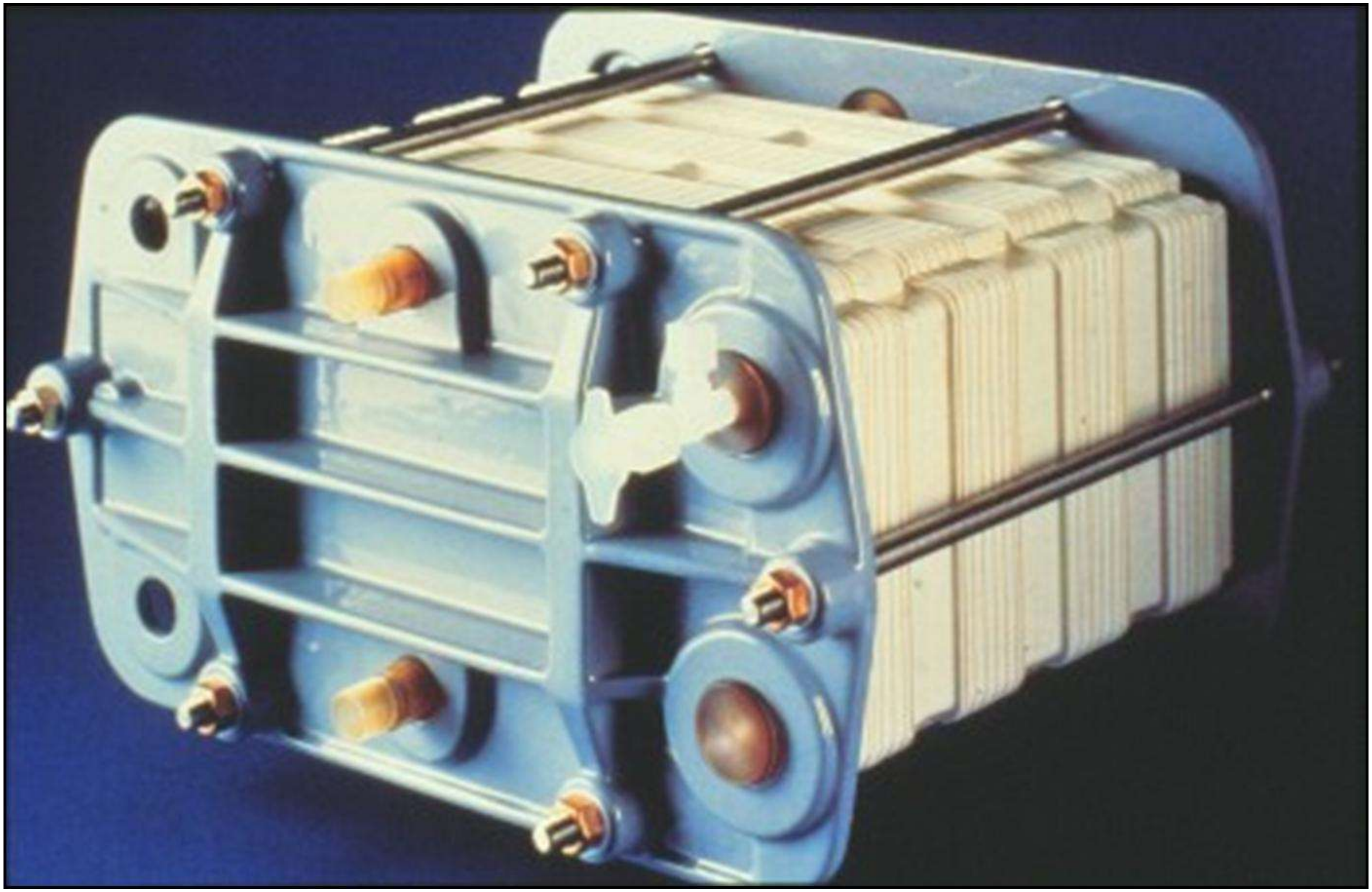
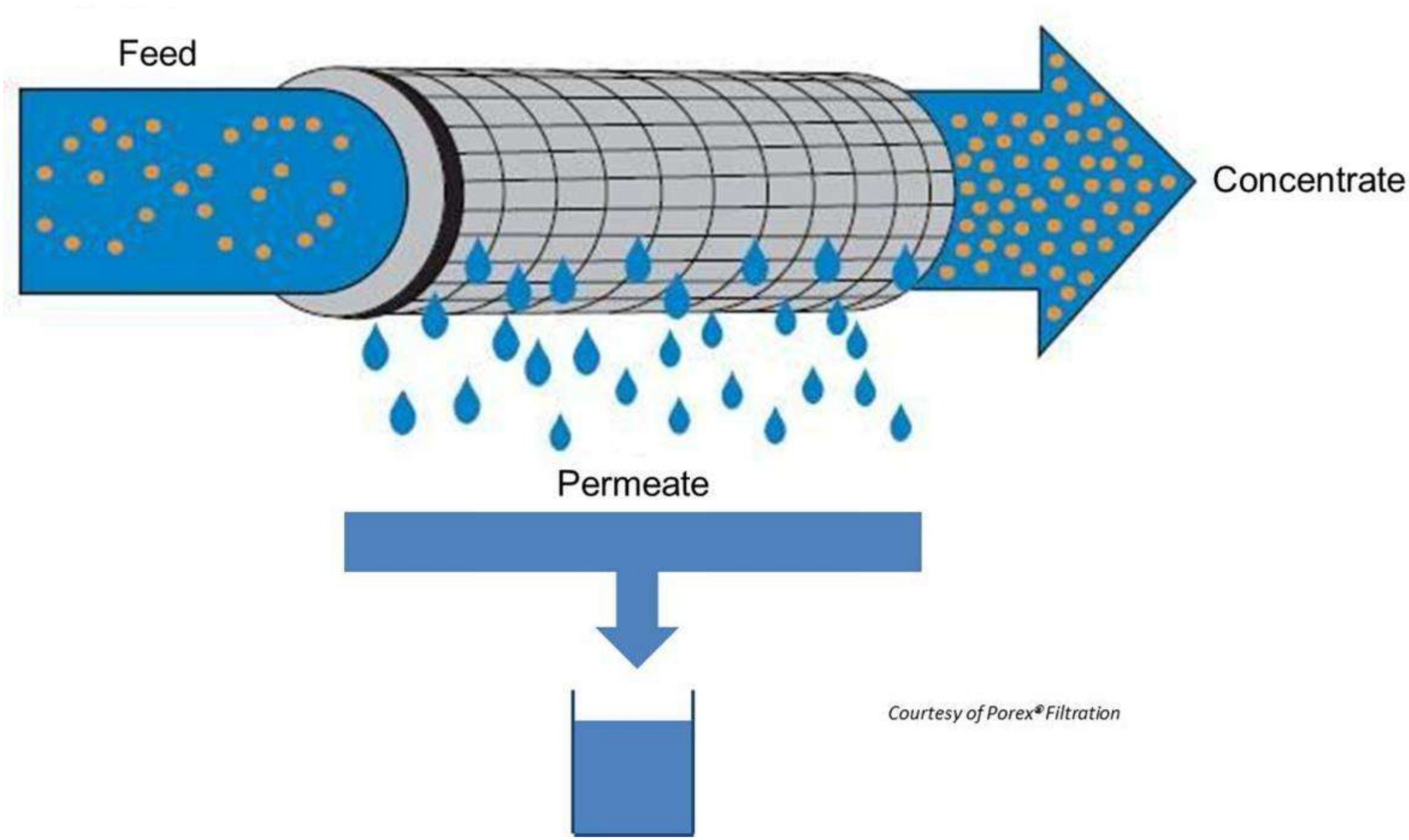

CONCENTRATE
PERMEATE
Permeate Spacer
Support Plate
FEED
Membrane

Plate & Frame



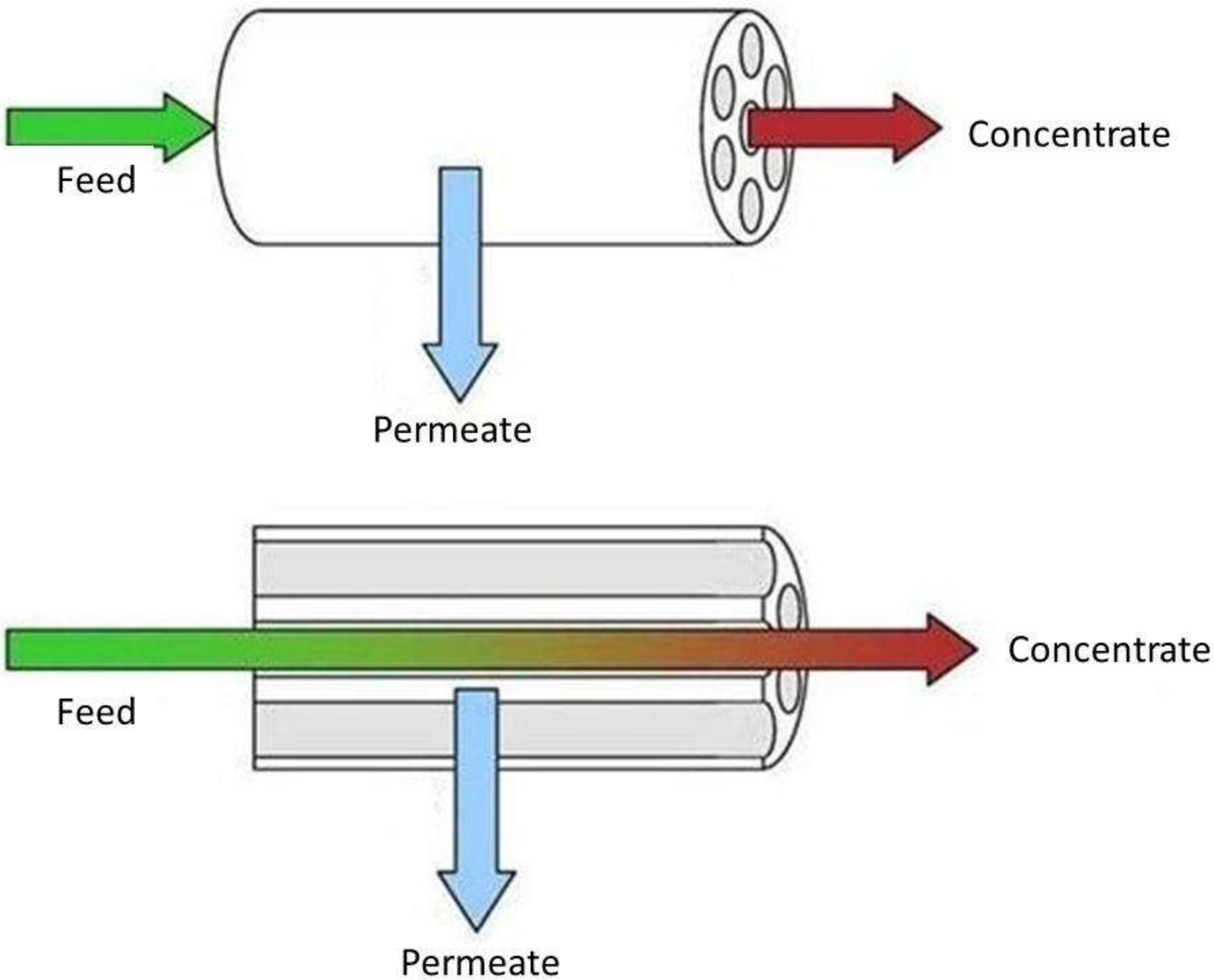
Tubular

Tubular



Tubular

Tubular

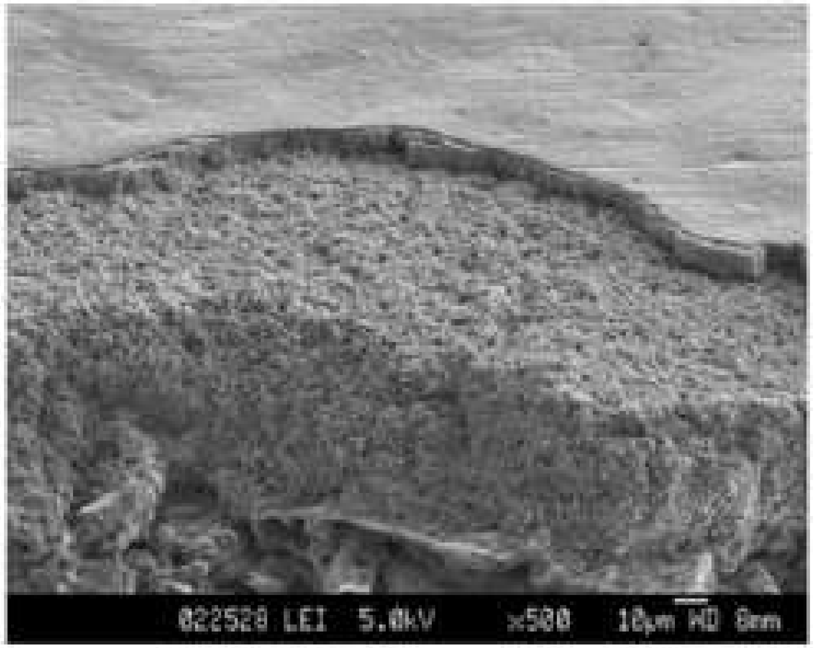


Ceramic Membrane

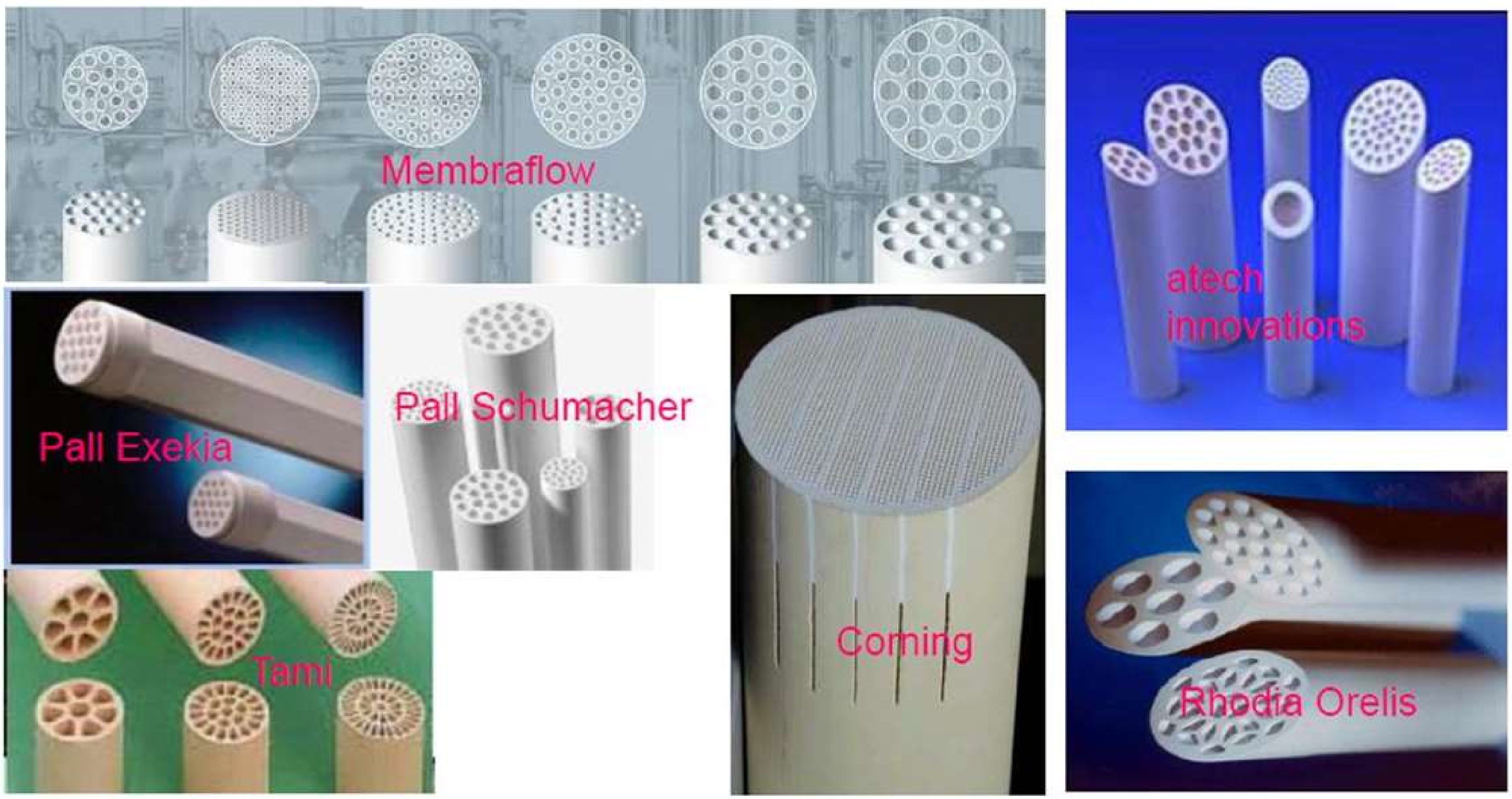
Ceramic membranes:

tubular, multi-channel

- Composite membrane consisting of
  a) porous support from pure α-Al_2O_3
  b) porous membrane layer from α-Al_2O_3, TiO_2 or ZrO_2



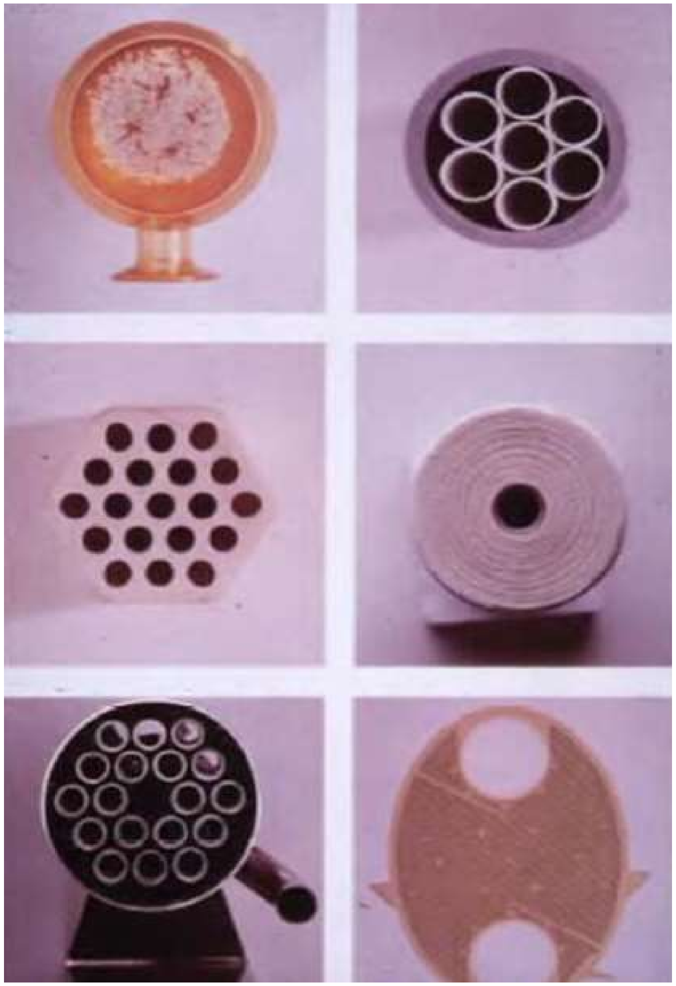
Multi-Channel Ceramic Elements



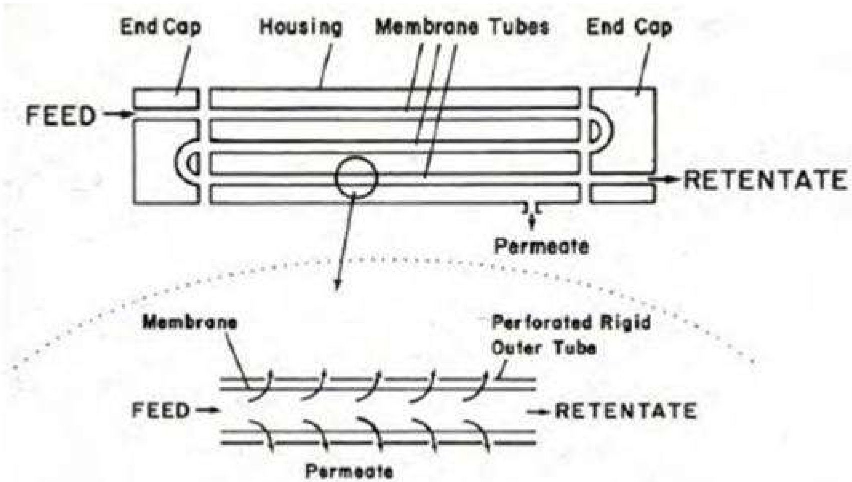
Courtesy of Mike Grigus

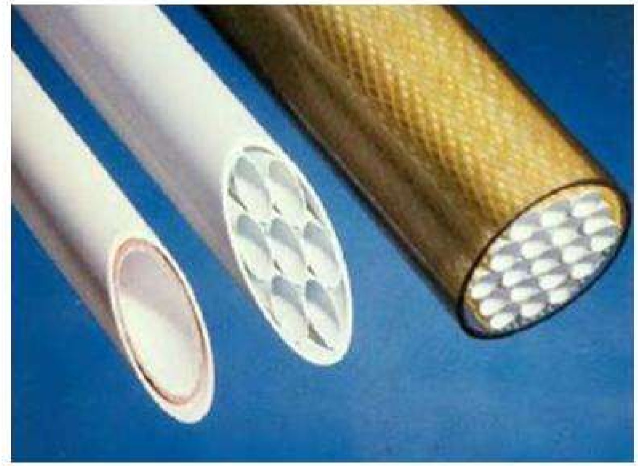
Membrane Elements

- Plate & Frame
- Tubular
- Hollow Fiber
- Spiral Wound



Membrane Elements

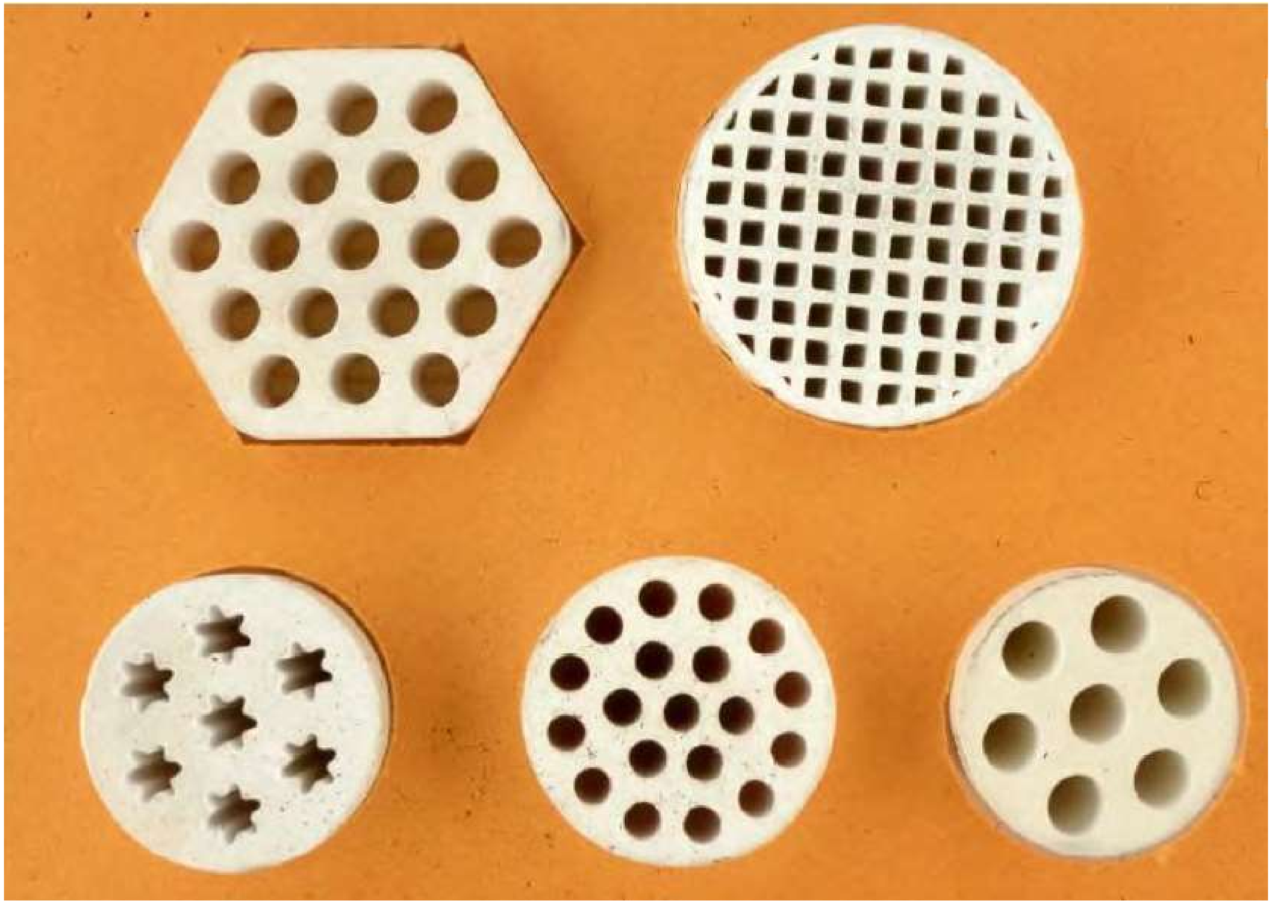




Multi-Channel Ceramic Elements

Courtesy of Munir Cheryan

Multi-Channel Ceramic Elements



Courtesy of Munir Cheryan

Graver Scepter

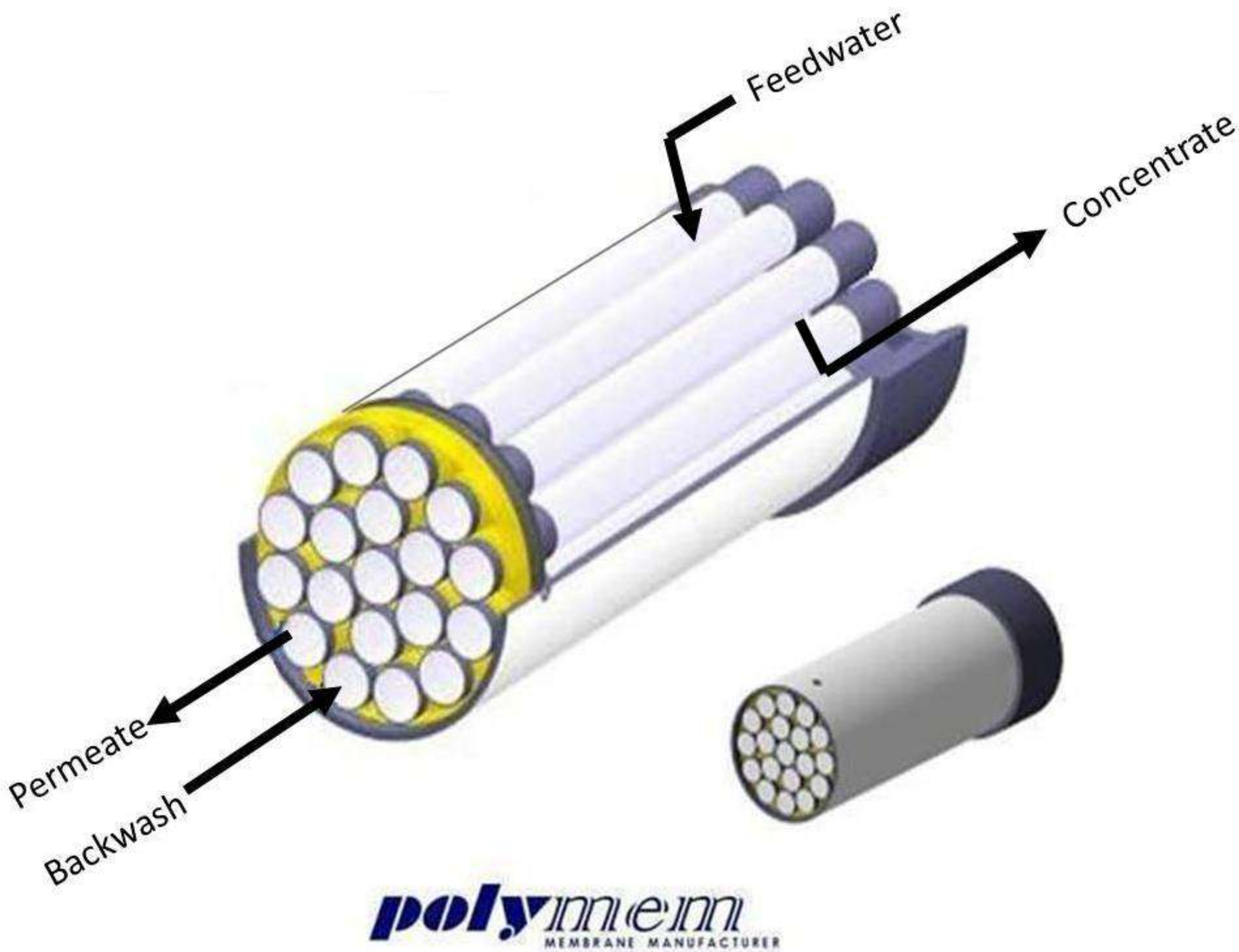
Courtesy of Munir Cheryan

Hollow (Capillary) Fiber

Hollow Fiber Membranes

Hollow fiber membranes are manufactured from the unsupported polymer – spinneret process.

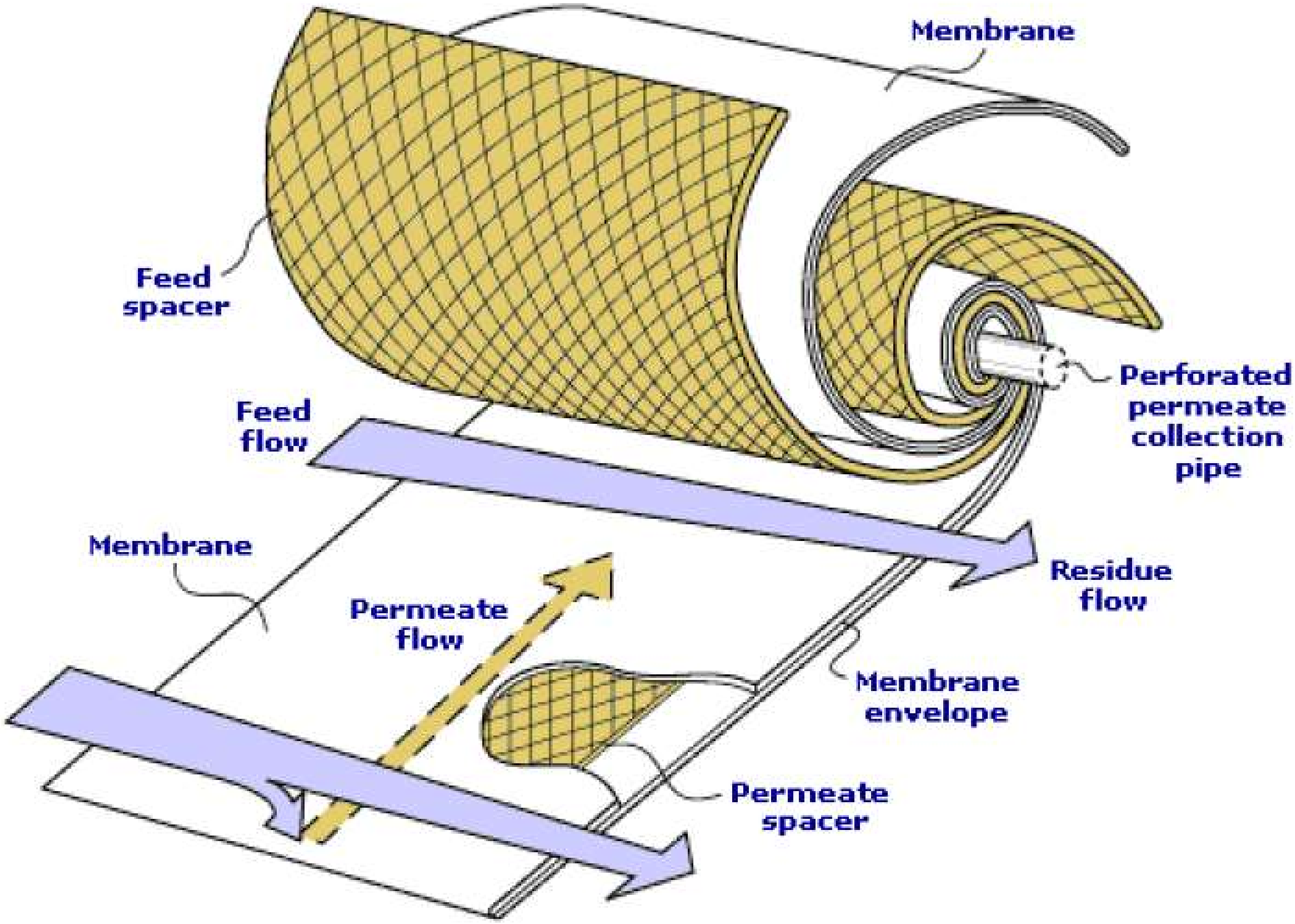
Hollow (Capillary) Fiber



Hollow (Capillary) Fiber

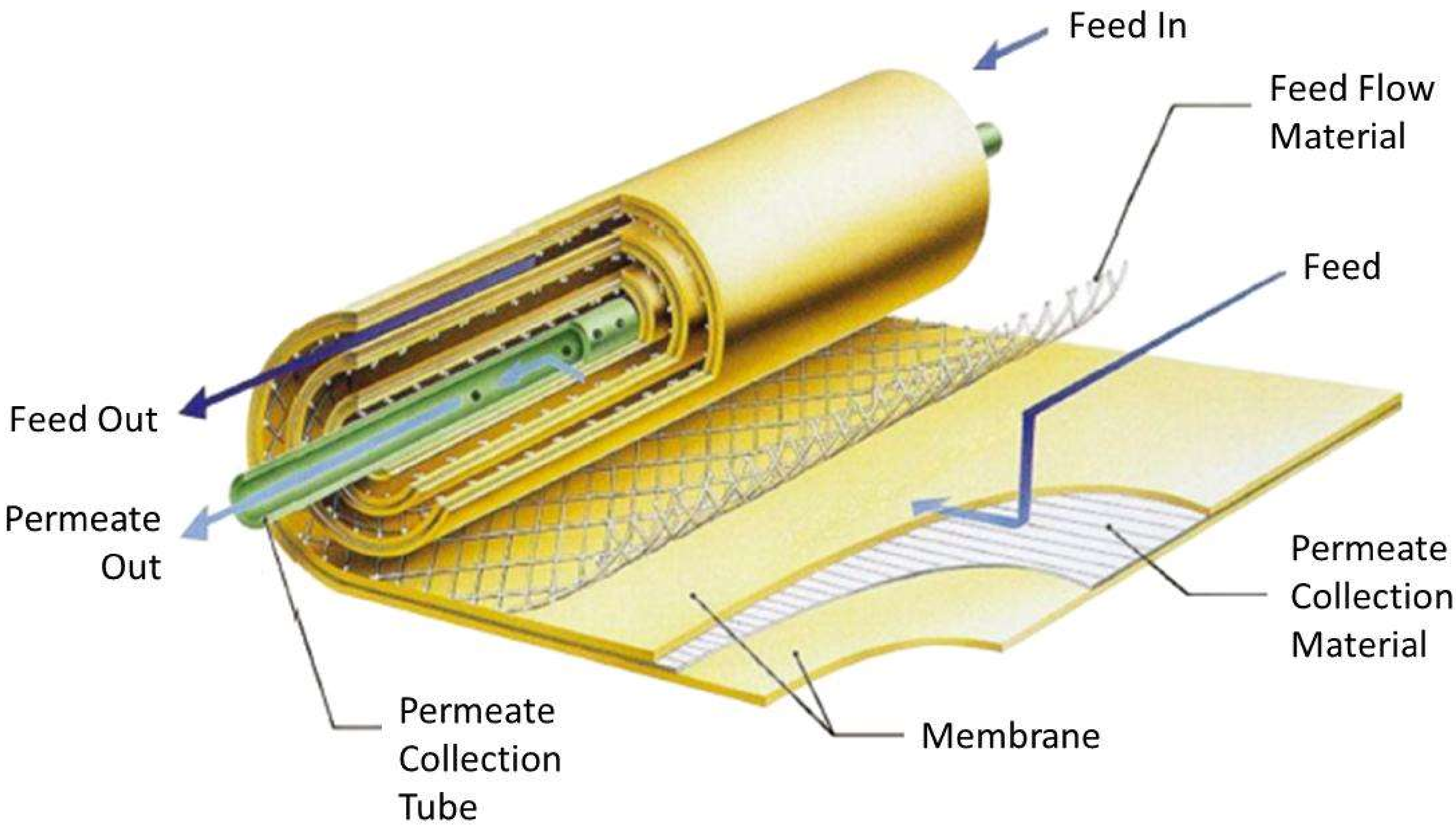
Spiral Wound

Spiral Wound



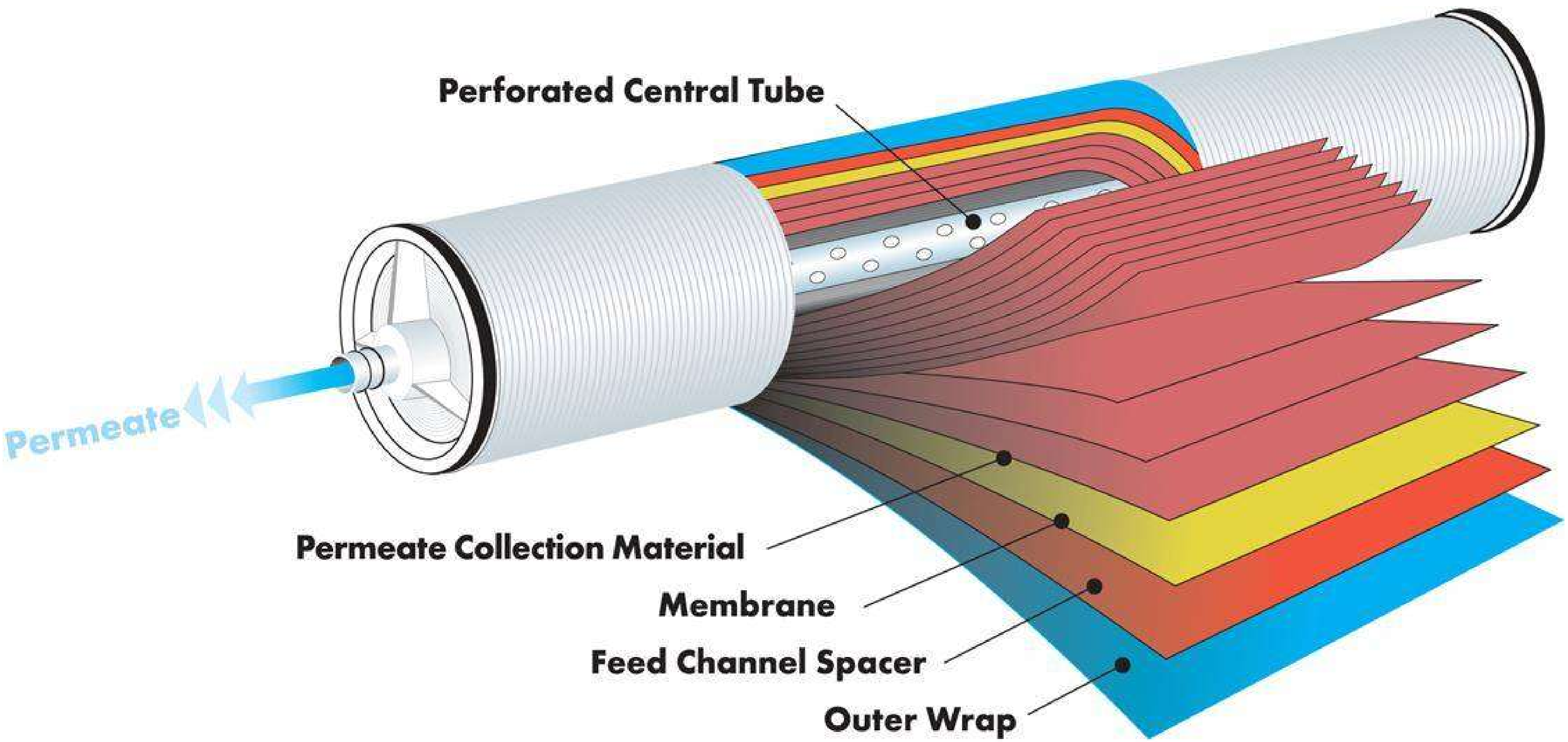
Courtesy of Mike Grigus

Spiral Wound



Courtesy of AmFor, Inc.

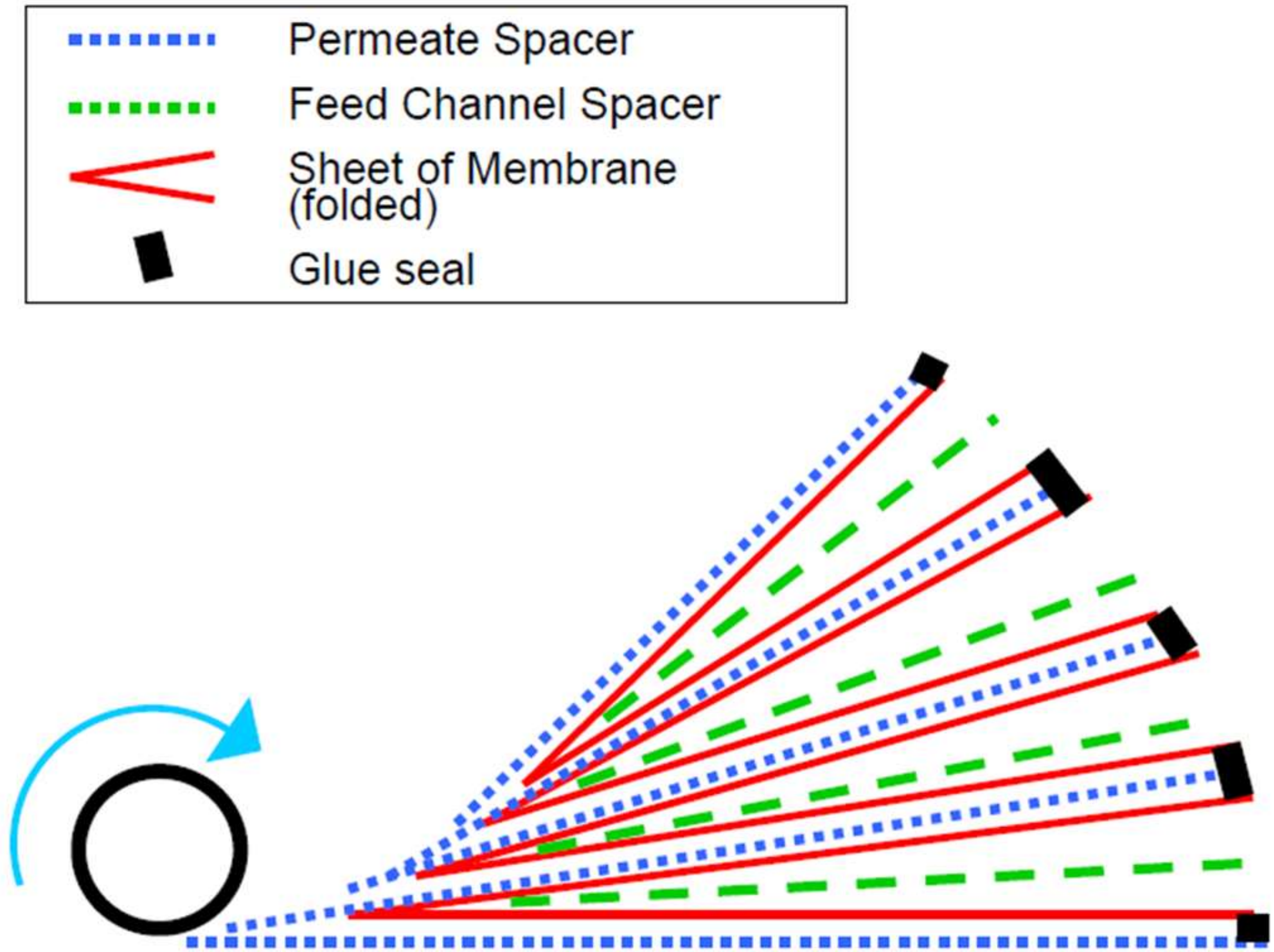
Spiral Wound



Courtesy of TriSep Corporation

Courtesy of Mike Grigus

Spiral Wound Element Construction

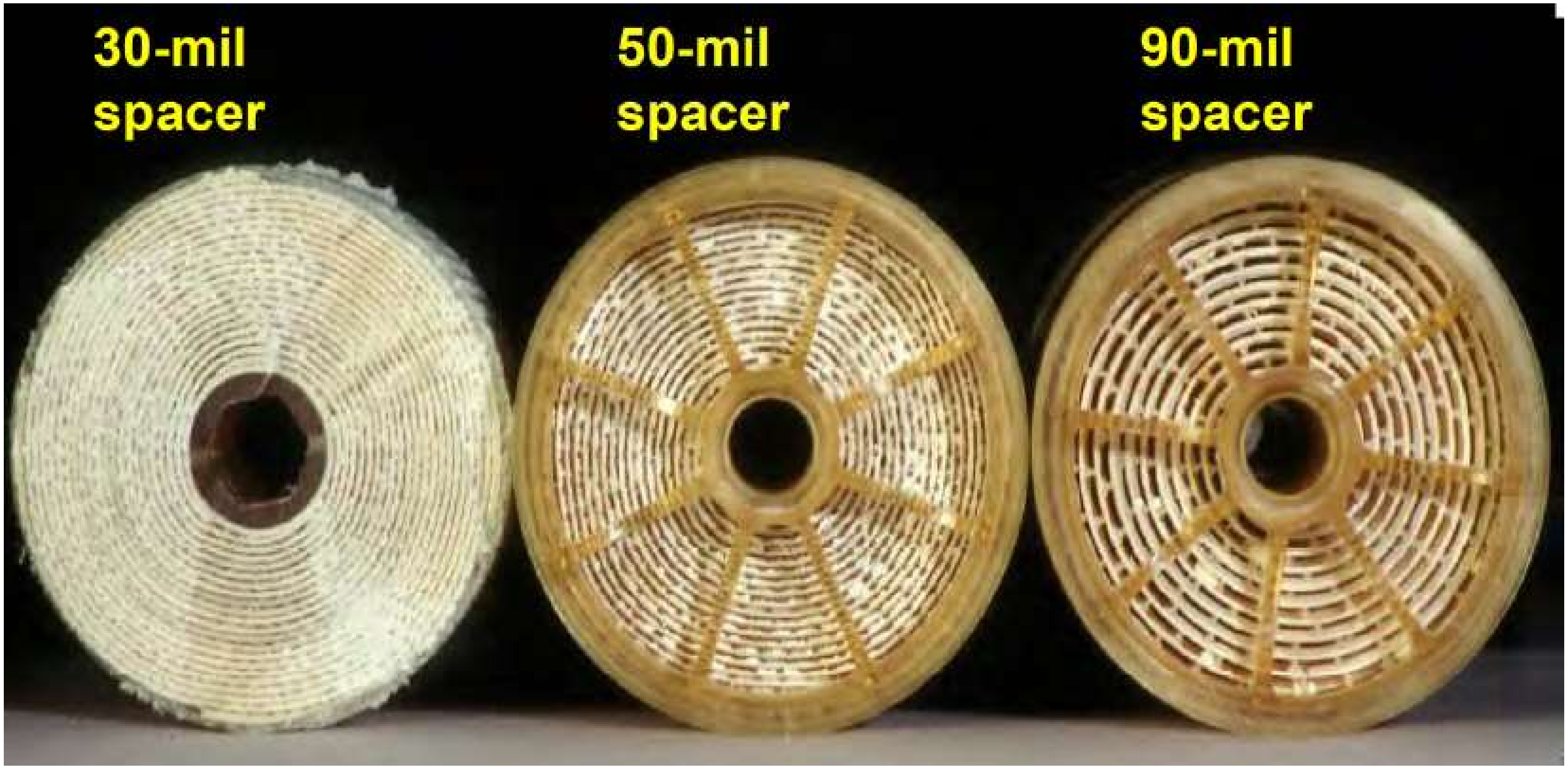


Courtesy of Mike Grigus

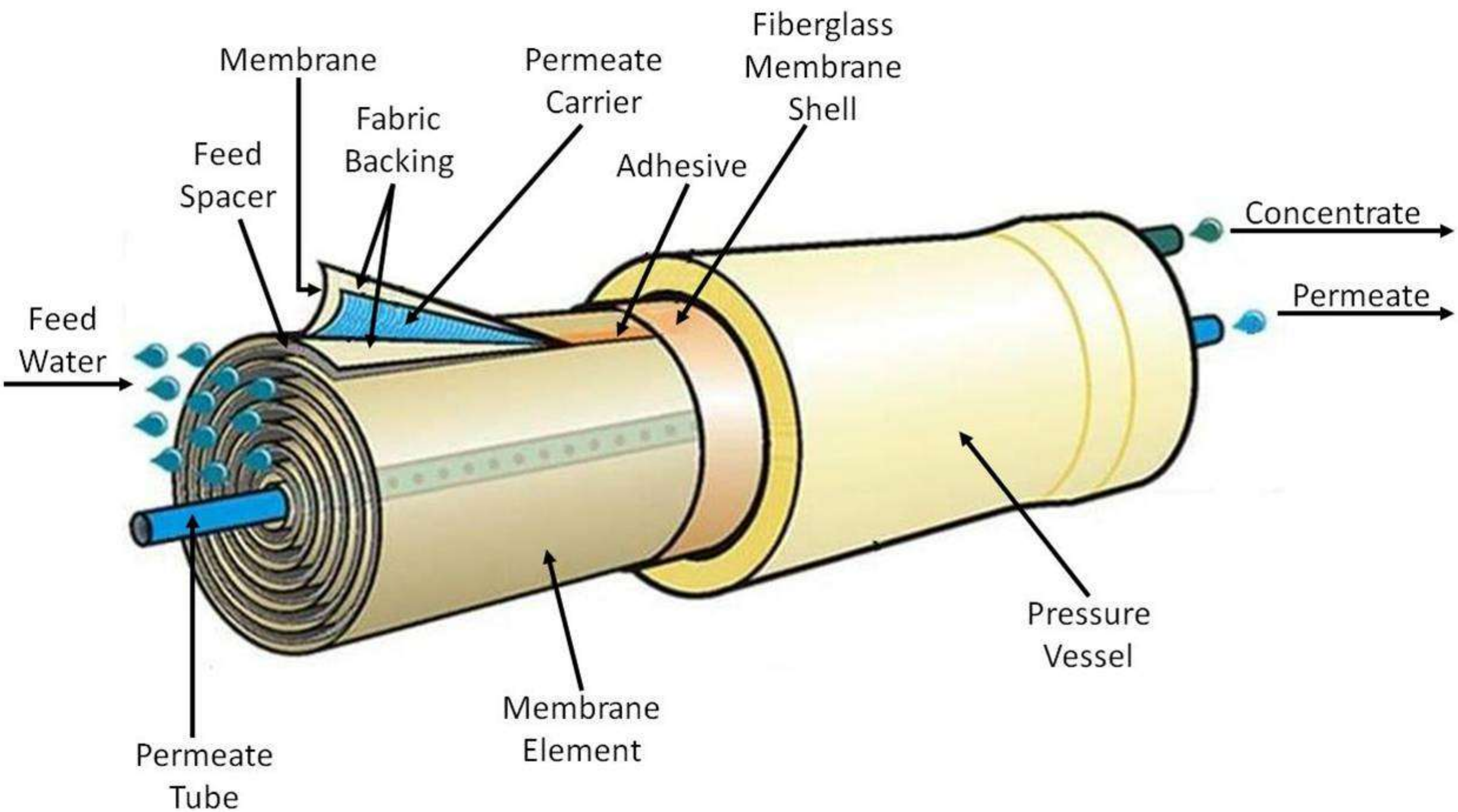
Spiral Element Sizes

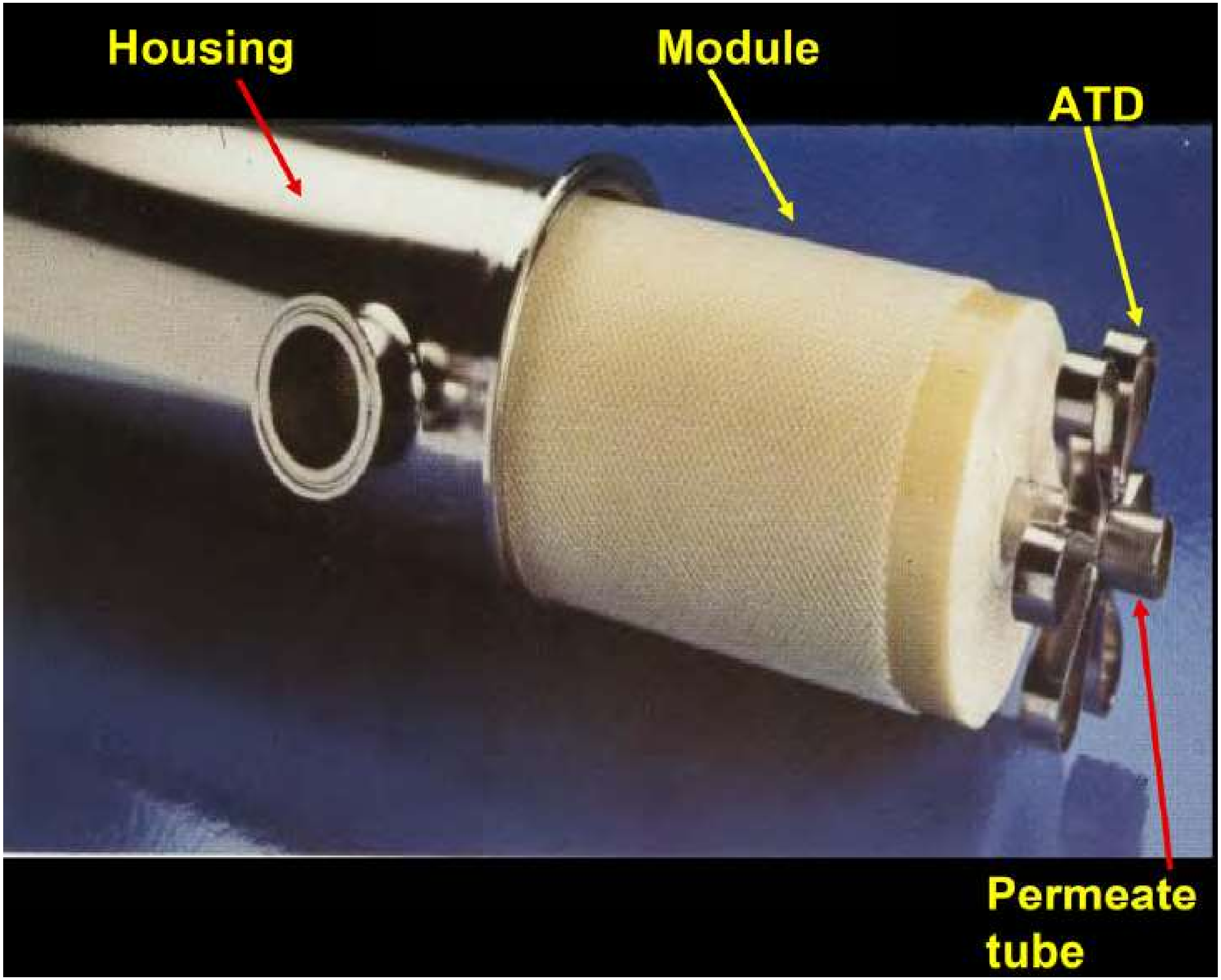
(2”∅, 4”∅, 8”∅, 16”∅)

Spacer Thicknesses

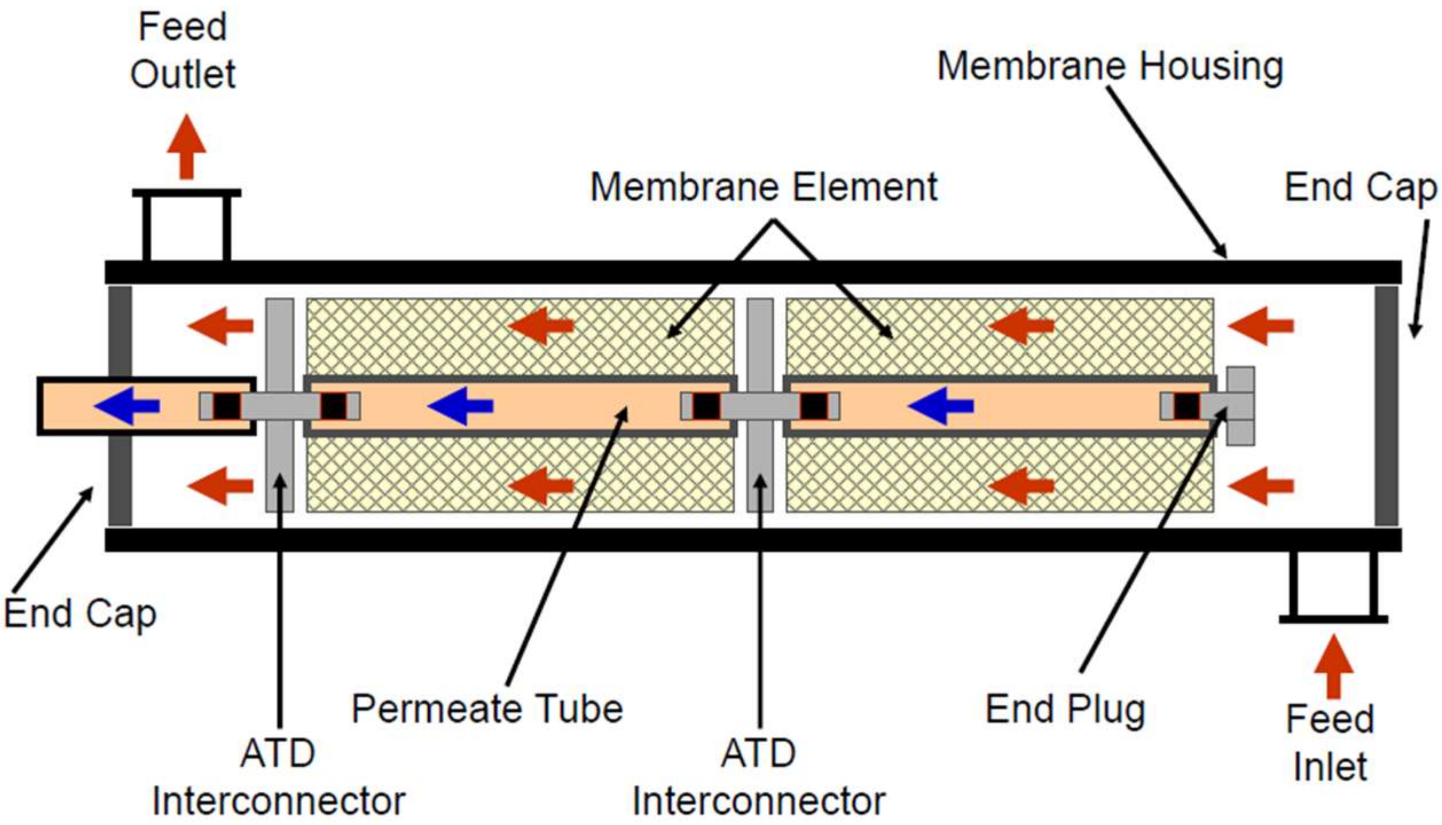


Spiral Wound




Housing
Module
ATD
Permeate
tube

Two Element, Spiral Membrane/Housing



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*

Factors to Consider in Membrane Element Selection

- **Size of suspended particles**
  - Free channel height >10X largest particle
- **Propensity for concentration polarization**
  - High Close spacing modules
  - Low High turbulence modules
- **Physical properties of feed**
  - Viscosity
  - TSS
- **Cleaning and sanitation**

System Design

Calculations

Temperature pressure (TMP1, P_T) = $\dfrac{P_i + P_o}{2} - P_p$

Pi = inlet pressure
P = outlet pressure

Pressure drop (ΔP) = $P_i - P_o$

(Cross-flow) Velocity = $\dfrac{\text{(Cross) flow rate}}{\text{Cross-sectional area}} = f(\Delta P)$

Energy consumption = Flow rate x ΔP

Flue (J) = $\dfrac{\text{Volume of permeate}}{\text{Membrane area x Time}} = \dfrac{\text{Liters}}{m^2 . h}$ = LMH

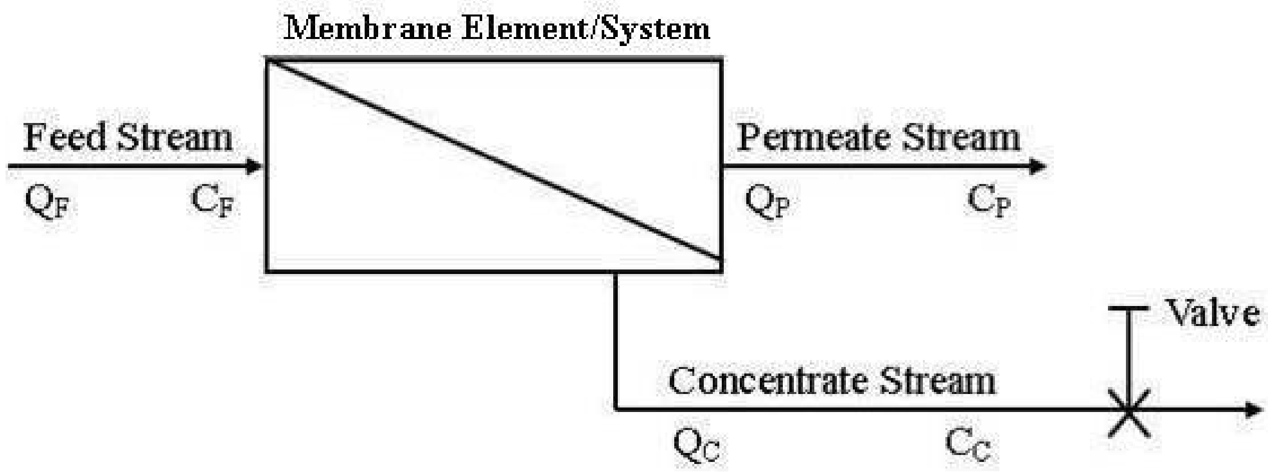
1 GFD (gallons/sq.ft./day) = 1.7 LMH

Rejection ® = 1 - C_p/C_c

Cp = permeate concentration
Cc = concentrate pressure

Rejection = 100% when Cp = 0

Membrane System Schematic



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

$$\text{Recovery} = \frac{Q_P}{Q_F} \times 100$$

(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)

Terminology

Feed $\equiv$ Influent

Concentrate $\equiv$ Brine $\equiv$ Reject

Permeate $\equiv$ Product $\equiv$ Dilute $\equiv$ Filtrate

Bank $\equiv$ Array

Definition of Flux

Flux = Total Permeate Rate ÷ Total Membrane Area
Specific Flux = Flux ÷ NDP (net driving pressure)

Rejection

Solute removal from the feed water

Percent Rejection

% Rejection: The degree of removal of solute by the membrane process.

For RO:

$$\text{Rejection (\%)} = \frac{\text{Feed Conductivity} - \text{Permeate Conductivity}}{\text{Feed Conductivity}} \times 100$$

- RO always rejects a **percentage** of salts.
- Therefore, permeate quality a function of feedwater quality.

If feedwater TDS ↑,
Permeate TDS ↑

Ion exchange technologies do not work this way; resins are more absolute.

Recovery

Definition of Recovery

% Recovery: The percentage of feedwater that passes through the membrane as product water (i.e. how efficiently water is converted into product water).

$$\text{Recovery (\%)} = \frac{\text{Permeate Rate}}{\text{Feed Rate}} \times 100$$

Part of system design

Effect of Recovery on Concentration

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

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

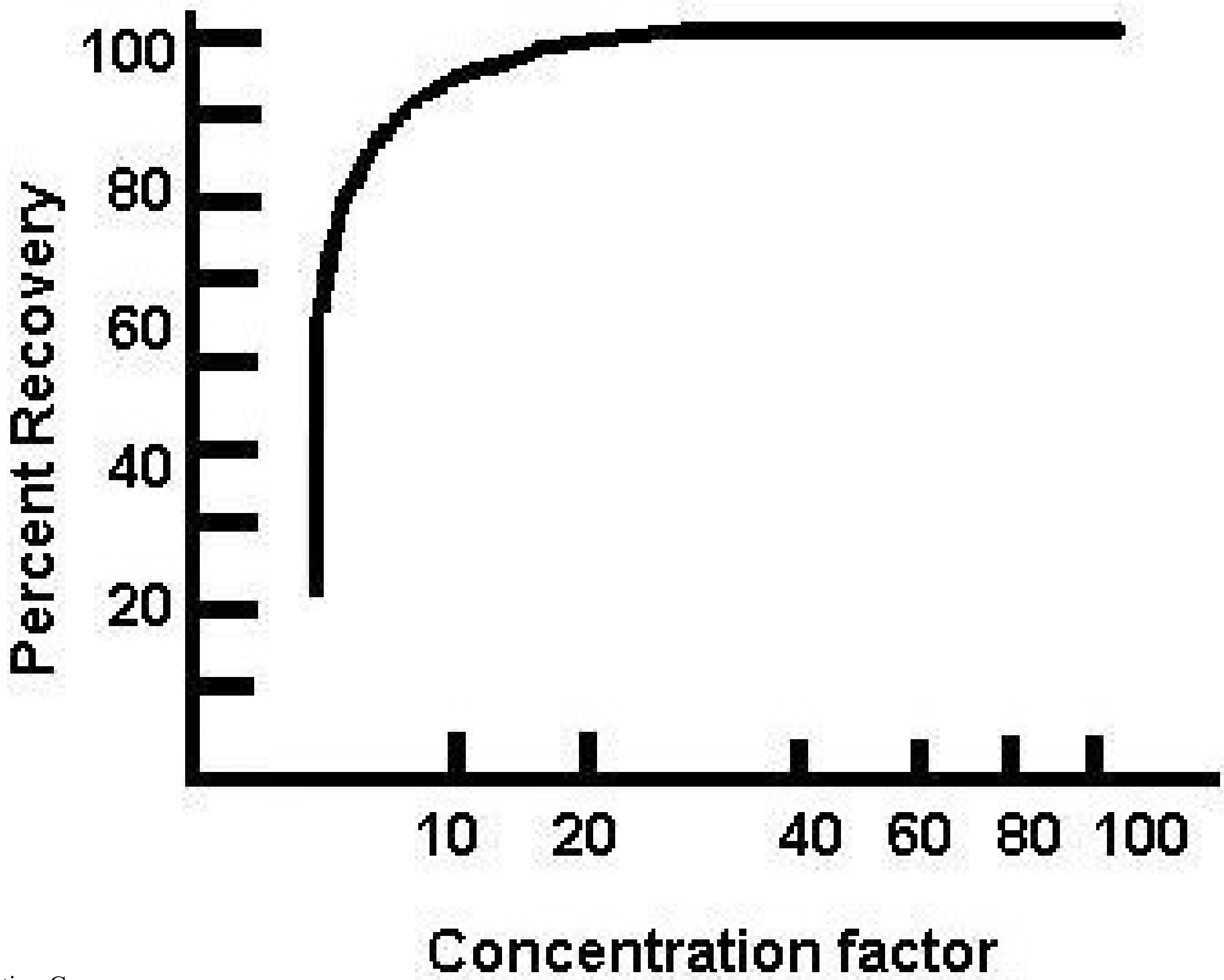
Percent Recovery	Concentration Factor
33%	1.5
50%	2
67%	3
75%	4
80%	5
90%	10
95%	20
97.5%	40
98%	50
99%	100

Definition of Concentration Factor

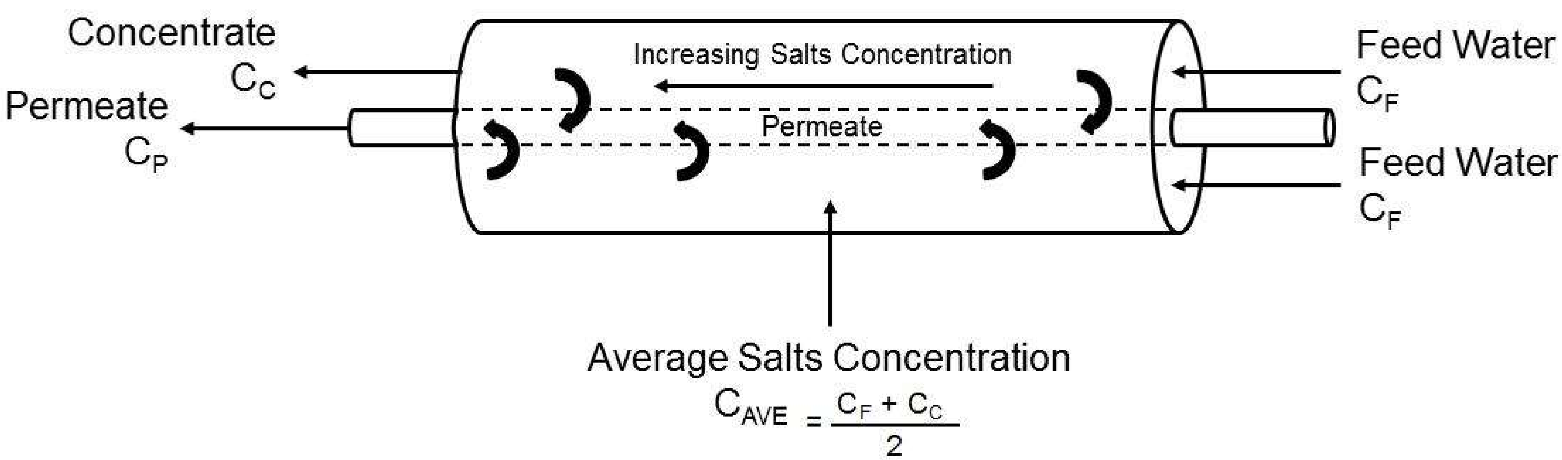
The degree to which contaminants in the concentrate stream are concentrated.

$$\frac{1}{1 - \text{Recovery}}$$

Effect of Recovery on Concentration Factor



Typical RO Spiral Membrane Element



High Recovery Advantages

- Lower flow rate
  (smaller diameter piping, etc.)

- Smaller high pressure pump

High Recovery Hazards

Precipitation – Fouling

For RO/NF – High π

For RO/NF – As Recovery ⬆

Permeate TDS ⬆

Discharge Issues

Water Temperature

Feedwater temperature will affect RO permeate rate:

As temperature $\downarrow$,
Permeate rate $\downarrow$

Colder water has a higher viscosity than warm water, so more pressure is required to force it through the membrane.

Temperature Correction Factors (Typical)

Temperature (t)		T_{cor}	Temperature (t)		T_{cor}	Temperature (t)		T_{cor}
°C	°F		°C	°F		°C	°F	
1	33.8	0.460	19	66.2	0.830	37	98.6	1.403
2	35.6	0.482	20	68.0	0.861	38	100.4	1.440
3	37.4	0.499	21	69.8	0.888	39	102.0	1.479
4	39.2	0.510	22	71.6	0.915	40	104.0	1.520
5	41.0	0.534	23	73.4	0.943	41	105.8	1.56
6	42.8	0.552	24	75.2	0.971	42	107.6	1.603
7	44.6	0.571	25	77.0	1.000	43	109.4	1.645
8	46.4	0.590	26	78.8	1.030	44	111.2	1.686
9	48.2	0.609	27	80.6	1.060	45	113.0	1.730
10	50.0	0.630	28	82.4	1.091	46	114.8	1.776
11	51.8	0.651	29	84.2	1.122	47	116.6	1.821
12	53.6	0.672	30	86.0	1.155	48	118.4	1.869
13	55.4	0.693	31	87.8	1.188	49	120.2	1.916
14	57.2	0.716	32	89.6	1.221	50	122.0	1.965
15	59.0	0.739	33	91.4	1.256			
16	60.8	0.760	34	93.2	1.292			
17	62.6	0.786	35	95.0	1.328			
18	64.4	0.810	36	96.8	1.364			

Summary
(so far)

- RO permeate quality function of feedwater quality.
- RO design must compensate for feedwater temperature.
- Removal of organics (non-ionic species) down to a molecular weight of ~100 Daltons

Osmotic Pressure

Osmotic Pressure (π)

The pressure, due to the effect of TDS in the feedwater, that must be overcome in order to generate product water flow.

π is a function of the specific salt, as well as its concentration.

Osmotic Pressure

$$\pi = 1.19\,(T + 273)\,\Sigma M_i$$

Where:

π = Osmotic Pressure (psi)

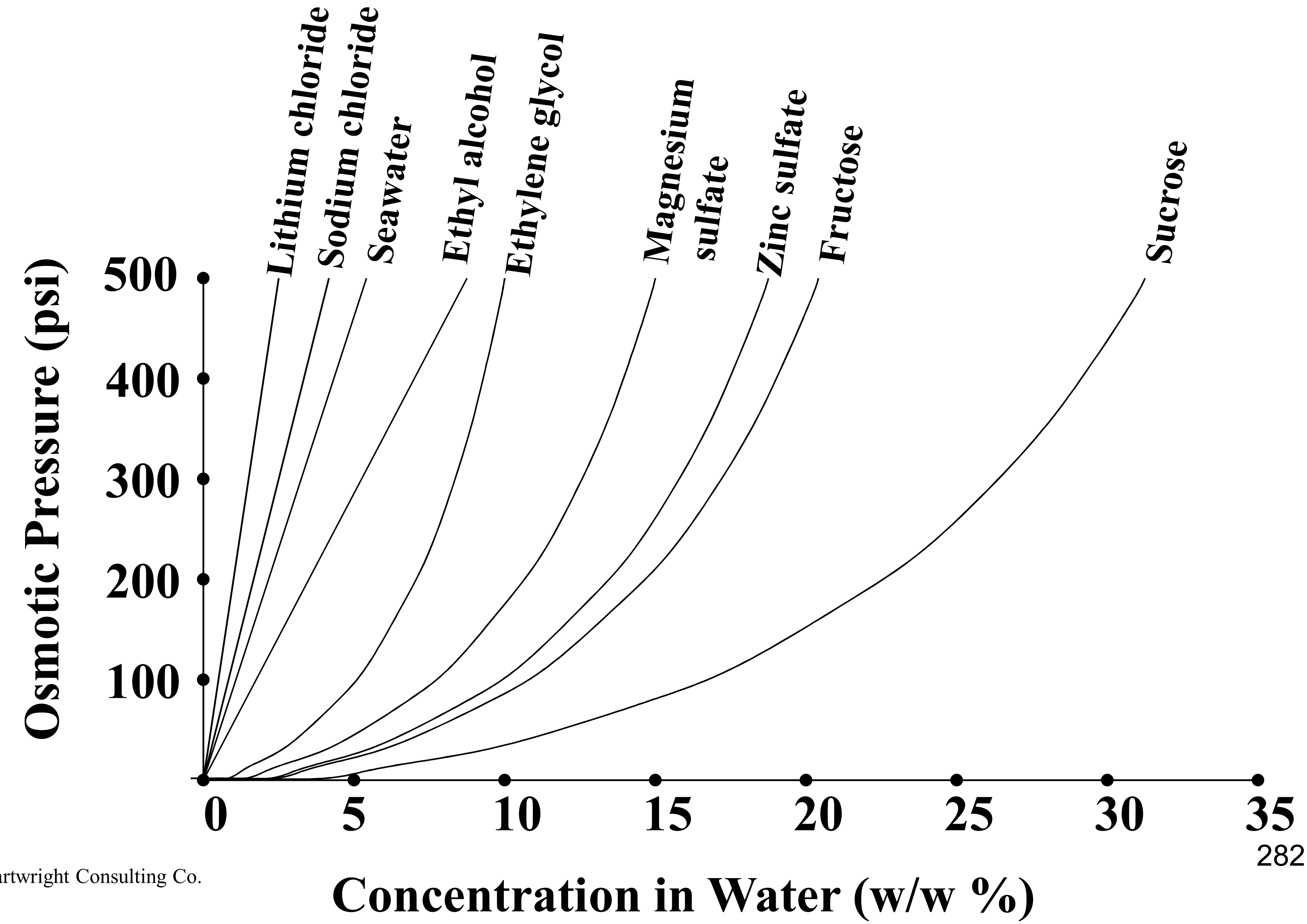
T = Water Temperature (^oC)

M_i = Molar Concentration of individual ions (gmol/L)

Typical Osmotic Pressure at 25°C

Compound	Conc. (mg/L)	Conc. (mol/L)	Osmotic Pressure (psi)	Osmotic Pressure (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_2SO_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

Solute Concentration as a Function of Osmotic Pressure



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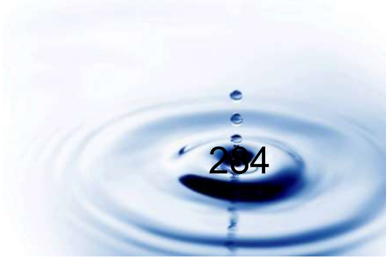
Osmotic Pressure Simplified Calculations

For monovalent salts: assume 1 psi of osmotic pressure per 100 mg/L of TDS.

For multivalent salts: assume ½ psi of osmotic pressure per 100 mg/L of TDS.

Flow Rate



Reynolds Numbers

Reynolds Number	Flow Characterization
<2300	Laminar
2300-4000	Transitional
>4000	Chaotic

Turbulent Flow

Reynolds Number

$$Re = \frac{QD_H}{vA}$$

Where: Q = Volumetric Flow Rate (m^3/sec)

D_H = Pipe Inside Diameter (m)

v = Kinematic Viscosity (m^2/sec)

A = Pipe Cross-sectional area (m^2)

Turbulent Flow (Chaotic Fluid Flow)
Reynolds Number >4,000

Laminar Flow (Smooth Fluid Flow)
Reynolds Number <2,300

Transition Flow
Reynolds Number >2,300 & <4,000

To Ensure Turbulent Flow in a Pipe, Water Velocity must be Above 3 m/sec (~10 ft/sec)

RO pump pressure directly affects permeate rate.

Applied Pressure

$$NDP = P_{op} - \pi - P_{bp}$$

Where: NDP = Net Driving Pressure

P_{op} = Applied Pressure

π = Osmotic Pressure

P_{bp} = Back Pressure

As pump pressure ↑, Permeate rate ↑

Membrane manufacturers specify the maximum recommended pump pressure. If the pressure is too high, the membrane will foul more quickly.

If the pressure is too low, the salts rejection will suffer. Most manufacturers recommend a minimum feed pressure of 30 psi (2 bar).

More System Design

System Design Criteria

- Feedwater Quality
- Permeate Quality Requirements
- Membrane Technology
  (MF, UF, NF, RO)
- Membrane Polymer
- Membrane Element Configuration
- Pretreatment Requirements

Feedwater Quality

General Parameters

- Total Solids Content
- Suspended (TSS)
- Dissolved Organic (TOC, MBAS, COD, BOD)
- Dissolved Inorganics (TDS)

Feedwater Quality (cont.)

Chemicals of Concern

- Oxidizing Chemicals
- Organic Solvents
- Saturated Solutes

Feedwater Quality
(cont.)

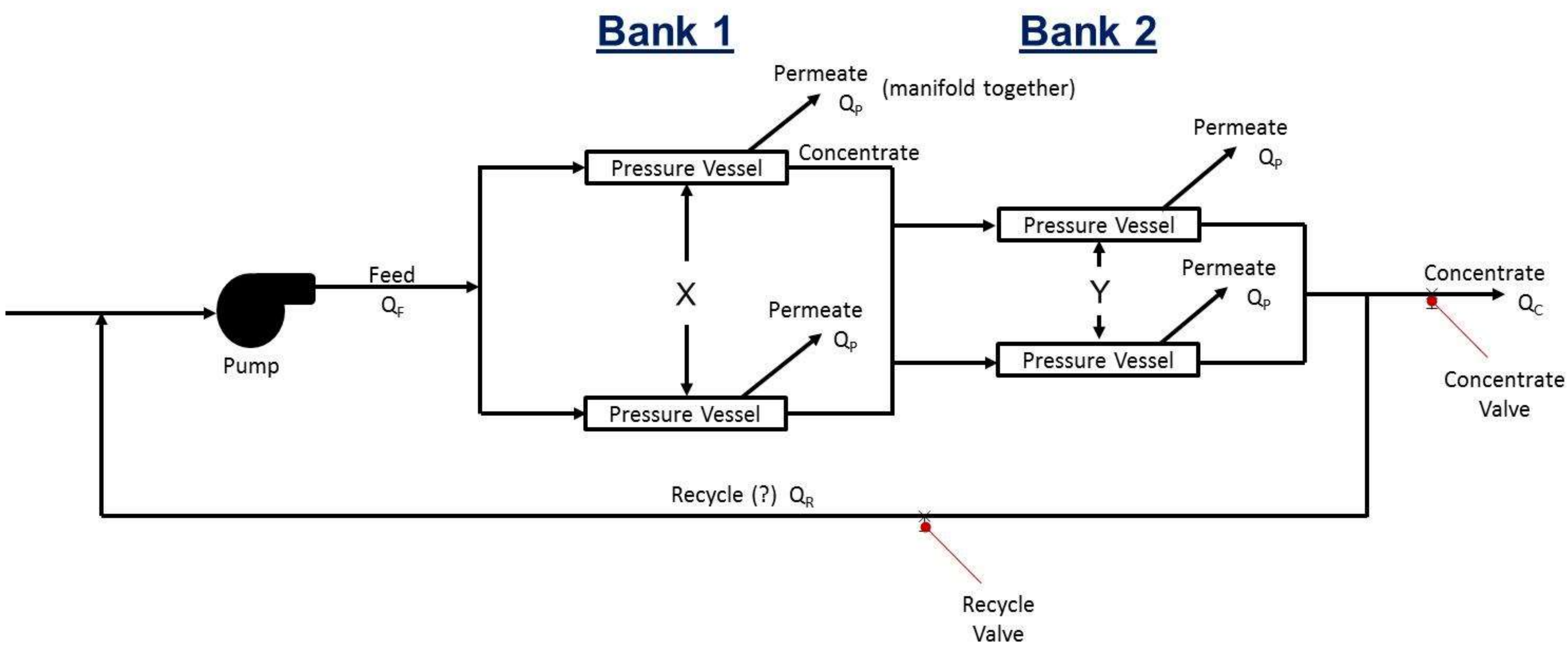
Other Factors

- pH
- Operating Temperature
- Osmotic Pressure as a Function of System Recovery
- Variation in Chemistry as a Function of Time

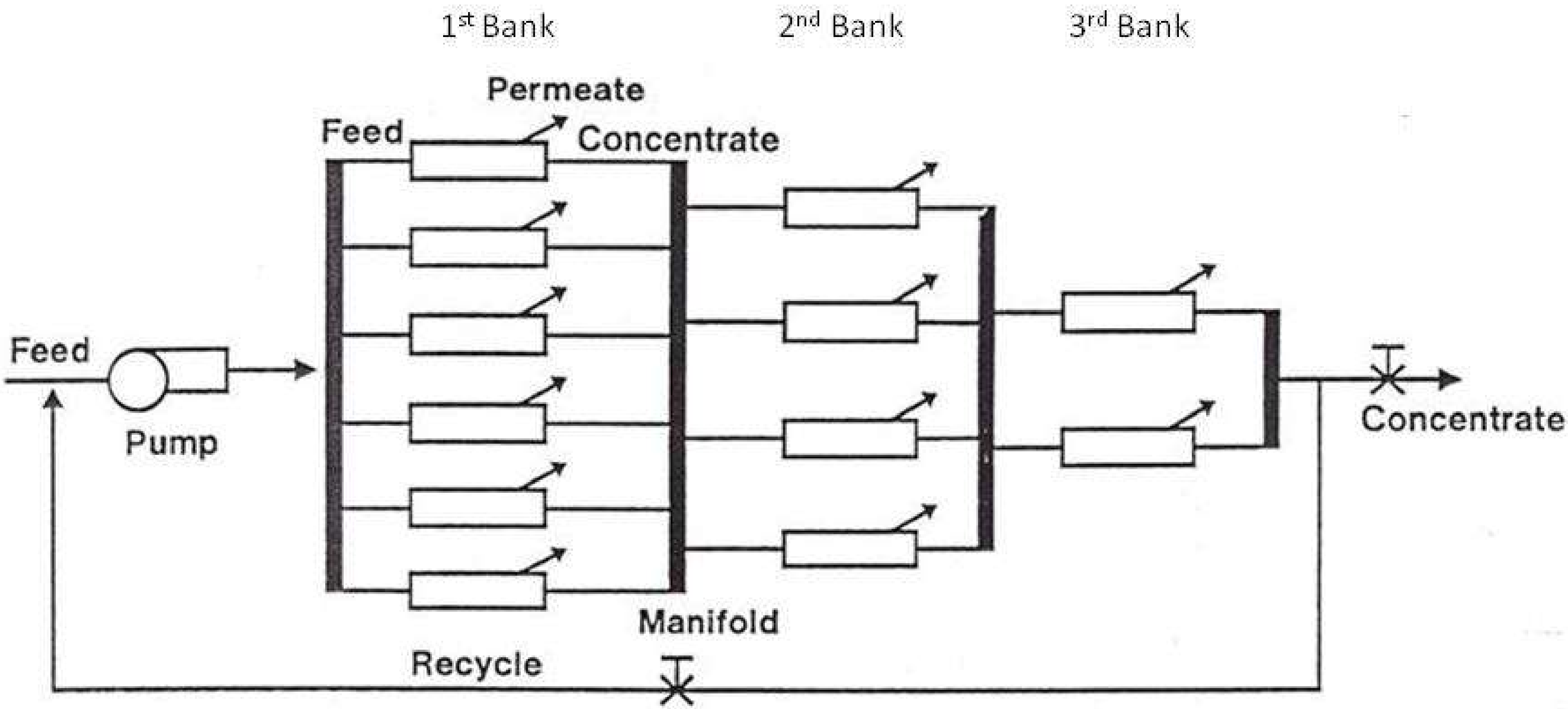
System Design Factors

- Optimum Membrane Element Configuration
- Total Membrane Area
- Specific Membrane Polymer
- Optimum Pressure
- Maximum System Recovery
- Flow Conditions (turbulent, etc.)
- Membrane Element Array
- Pretreatment Requirements

Membrane Element Array



Membrane Element Array



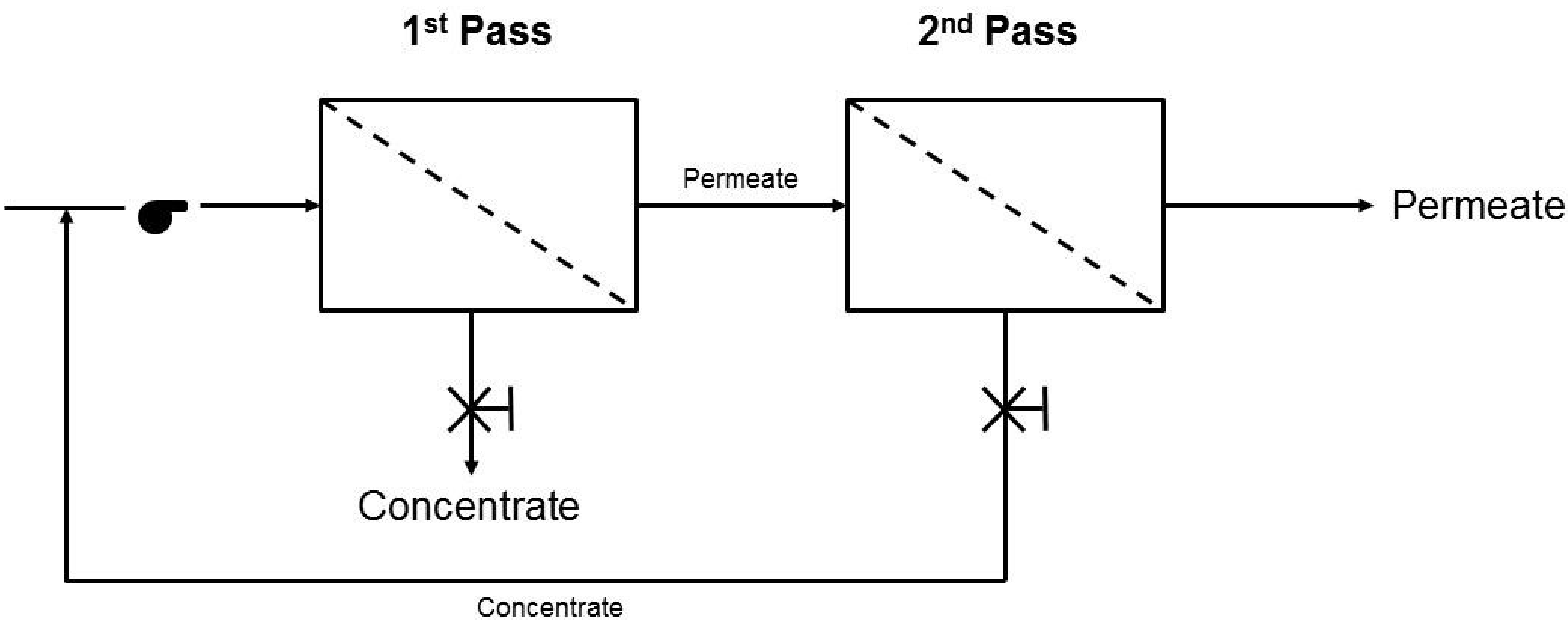
System Design Criteria

Each membrane housing (pressure vessel) may contain as many as 7 spiral elements

Two-Pass RO

For applications requiring permeate <10 ppm TDS (e.g. pharmaceutical, cosmetic, etc.), two-pass RO is often employed

Two-Pass RO


1st Pass
2nd Pass
Permeate
Permeate
Concentrate
Concentrate

RO Limitations

For most industrial applications, the highest ionic purity of water possible is 18,000,000 Ω-cm resistance (18 MΩ-cm).

Approximately 0.03 ppm TDS

RO Limitations

On a practical basis, RO only CANNOT produce 18 MΩ-cm quality water.

RO Limitations

Looking at the numbers:

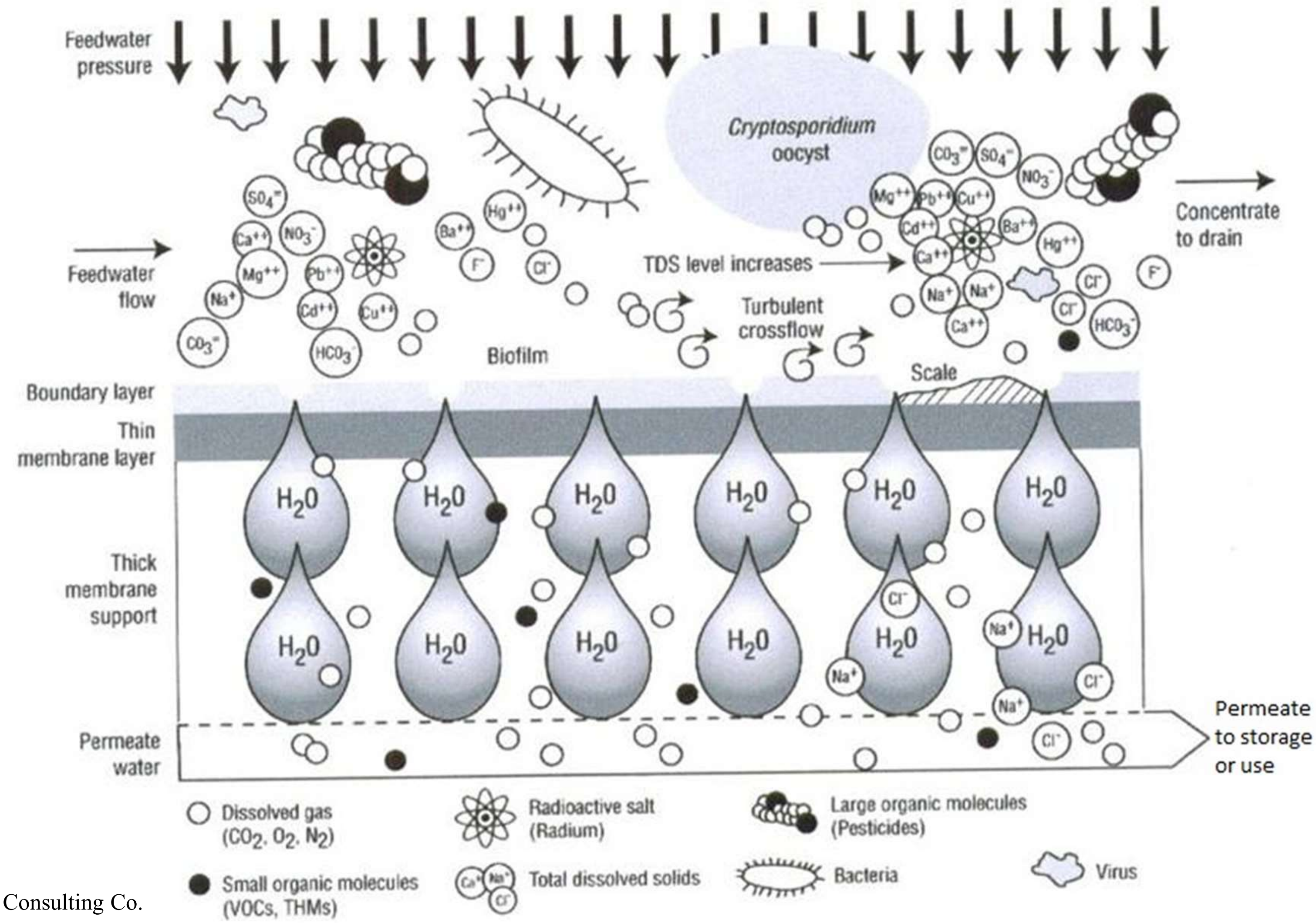
Assuming a membrane with 99.5% salts rejection treats water with a TDS of 500 ppm; permeate quality = 2.5 ppm (approximately 200,000 Ω-cm)

RO Limitations

To produce 18 MΩ-cm quality water, the best approach is RO followed by either mixed bed IX or EDI

Membrane Fouling

RO Membrane Process



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Fouling –
The bane of all membrane systems

MEMBRANE FOULING CANNOT BE PREVENTED but it can be MINIMIZED

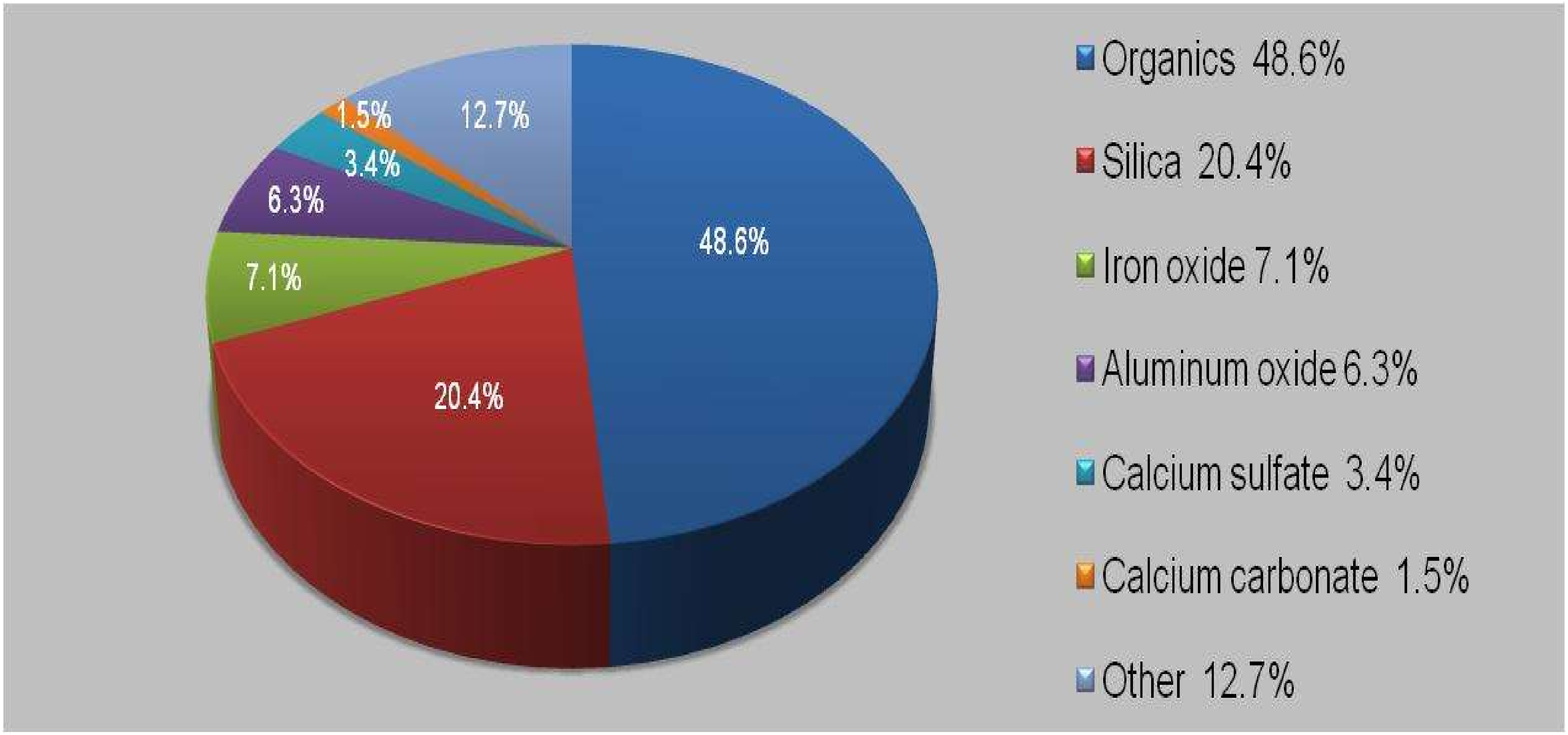
Fouling

- **Plugging** - Particulate materials (suspended solids)
- **Scaling** - Precipitated materials
- **Organic Fouling** - Coating and plugging by organics
- **Microorganisms** - Bacterial biofilm

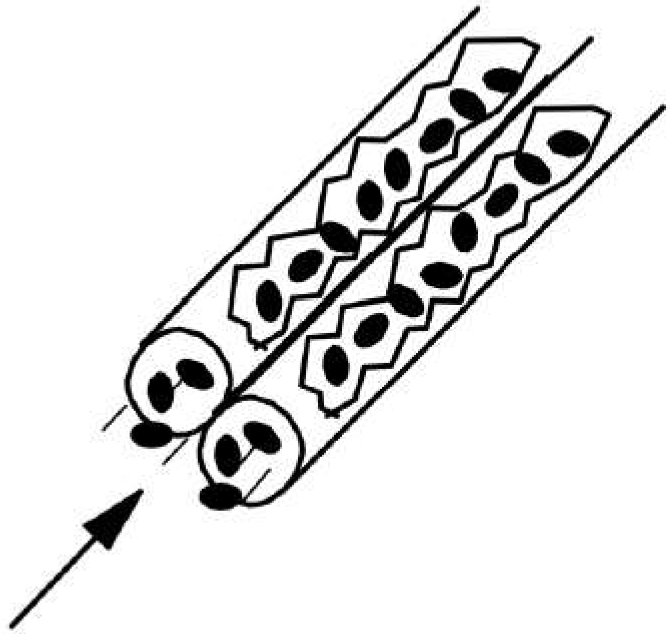
Fouling Summary

Foulant	Primary Mechanism	Examples
Suspended Solids (plugging)	Filtration	Dirt, clay, silt, dust, hydrous metal oxides, *e.g.* $Fe(OH)_3$
Inorganic Salts (scaling)	Concentration effects, Adsorption	$CaCO_3$, $MgCO_3$, $BaSO_4$, $CaSO_4$, SiO_2, and other salts
Organics (plugging)	Adsorption, Film Formation	Oils, grease, surfactants, coagulants, antiscalants, humic and fulvic acids
Microorganisms (Biofouling)	Adhesion, Adsorption, Biofilm Formation	Bacteria

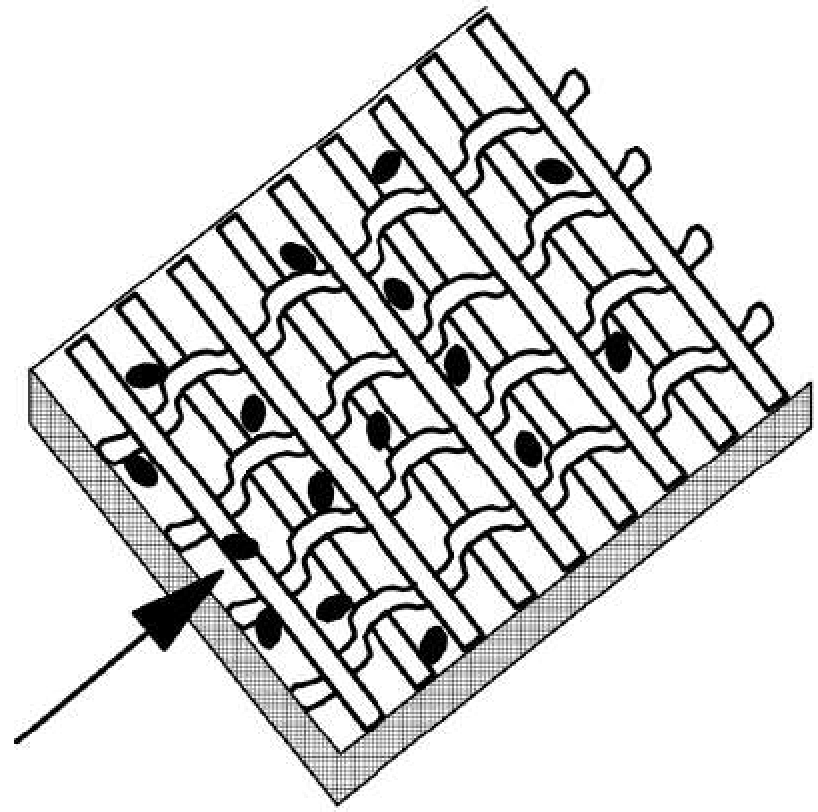
Typical Fouling Constituents on Membrane Surface



Suspended Solids



Tubular and hollow fiber modules



Flat sheet and spiral modules with spacers

Fouling

OILS

Free oil – Water insoluble, immiscible, forms impermeable film on membrane surfaces.

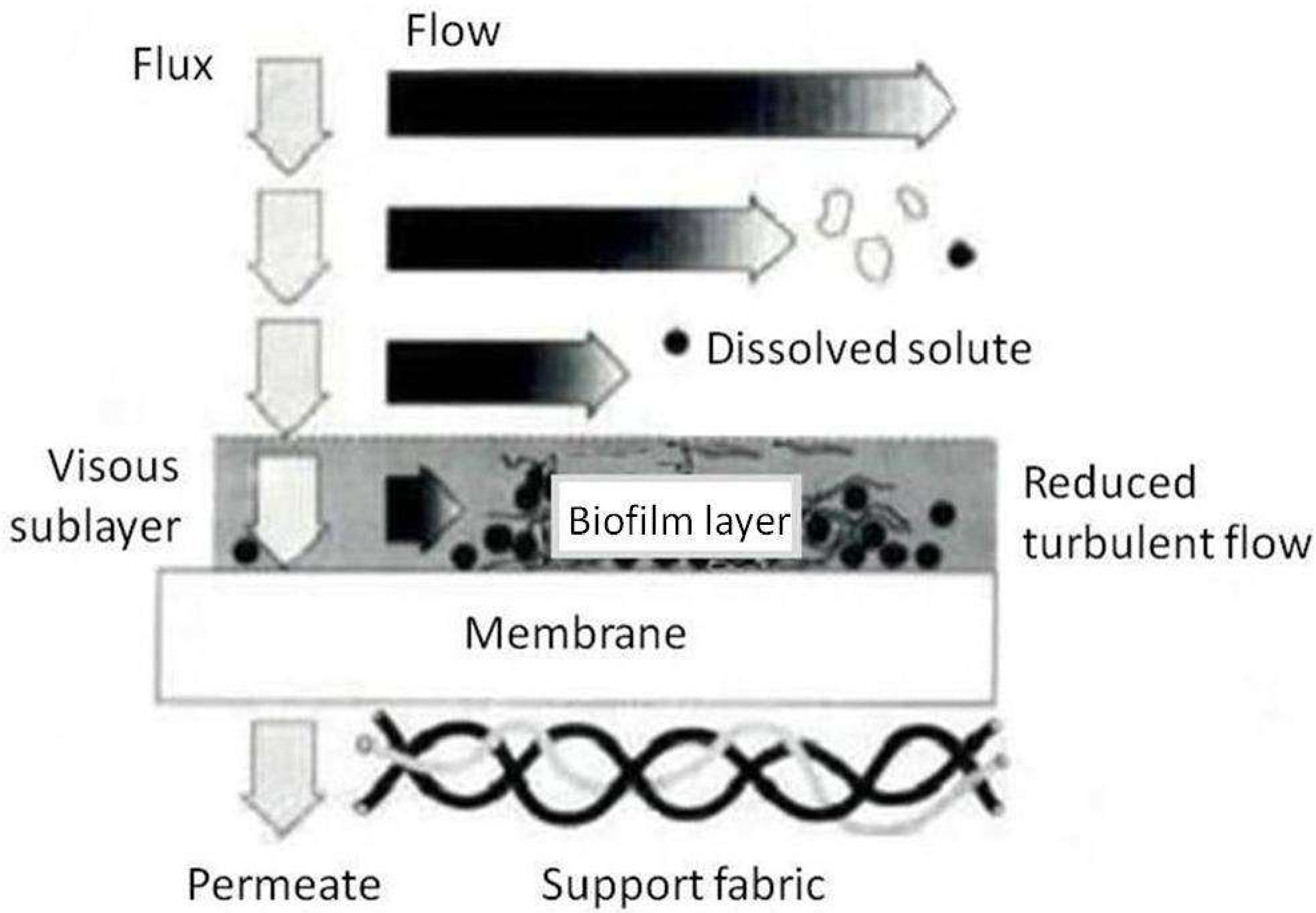
Emulsified – Discrete droplets from: Chemical addition and Mechanical agitation, can be removed by MF

Dissolved – Water soluble organics can be removed by UF.

Oily Wastes

- Free Oils – No!
- Emulsified Oils – MF
- Dissolved Oils - UF

Biofilm Formation on a Membrane



Concentration Polarization

Concentration polarization is defined by the following equation:

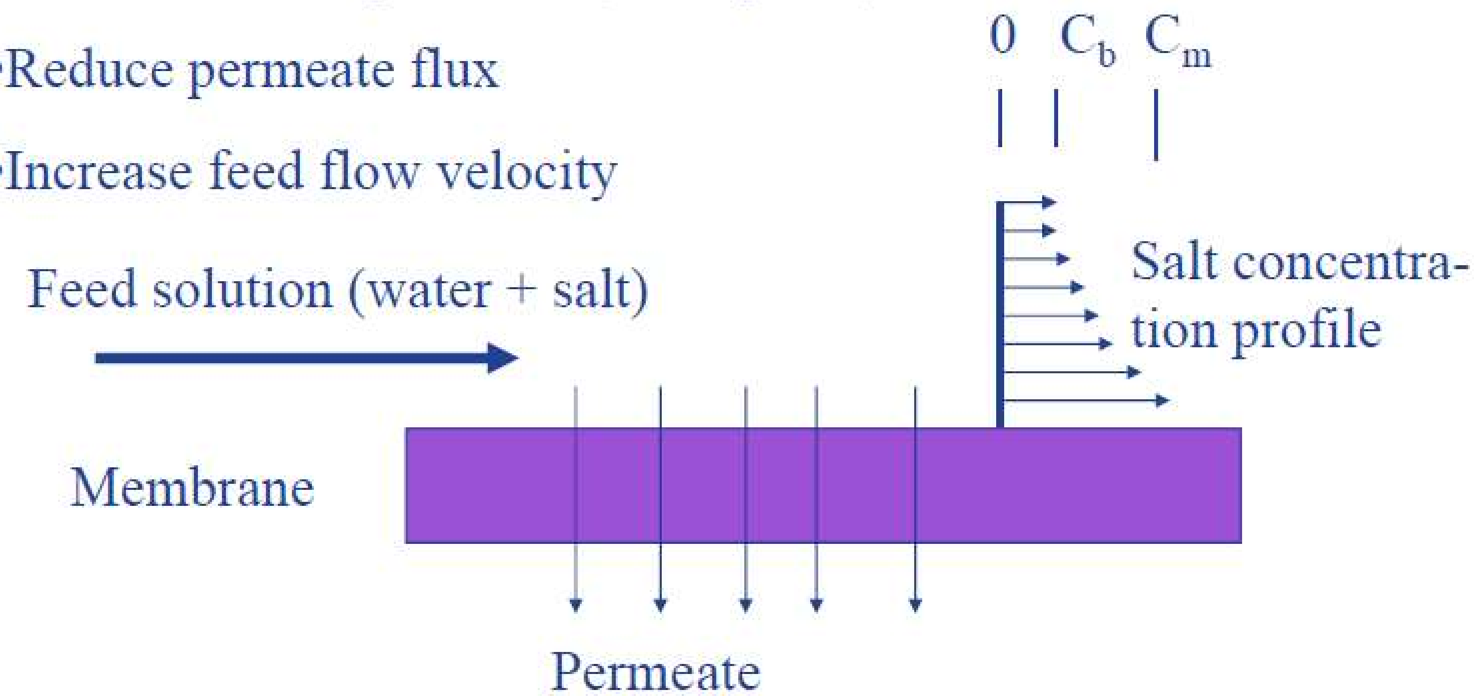
$$C_m/C = B = e^{K(Fp/Fb)}$$

Where: C_m = Concentration at the membrane surface
C = Average bulk concentration
B = Concentration polarization
K = A proportionality constant
F_p = Product flow
F_b = Average brine flow

Concentration Polarization

To Reduce Polarization Modulus, C_m/C_b

- Add turbulence promoter,(feed spacer)
- Reduce permeate flux
- Increase feed flow velocity



Fouling Mitigation

- Pretreatment
- System Design
- Membrane Polymer
- Membrane Device Configuration
- Chemical Addition
- System Operation

Membrane Element Cleaning Capability

Element Configuration	Available MembraneTechnology				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)

Pretreatment Technologies

Foulant	Recommended Pretreatment
Suspended solids	Filtration Granular media Cartridge Bag MF Coagulation followed by filtration
Inorganic salts (scaling)	pH adjustment Softening Antiscalant addition
Organics	Filtration UF Adsorption Activated carbon Organo clays Special resins Coagulation followed by filtration Oil/water separation Skimmers Dissolved air flotation
Microorganisms	Disinfection Chemical addition Ozonation Ultraviolet irradiation Filtration

Membrane Polymers Properties

Surface roughness

Polyolefin

Fluorinated

Thin film composite

Charge

Monitoring

To accurately measure permeate flux over time, factor in the effects of temperature and pressure.

Resulting data are known as ***NORMALIZED*** flux rates.

Normalized Flux

- Usually use membrane element design data from manufacturer (permeate rate at a specific pressure and temperature)

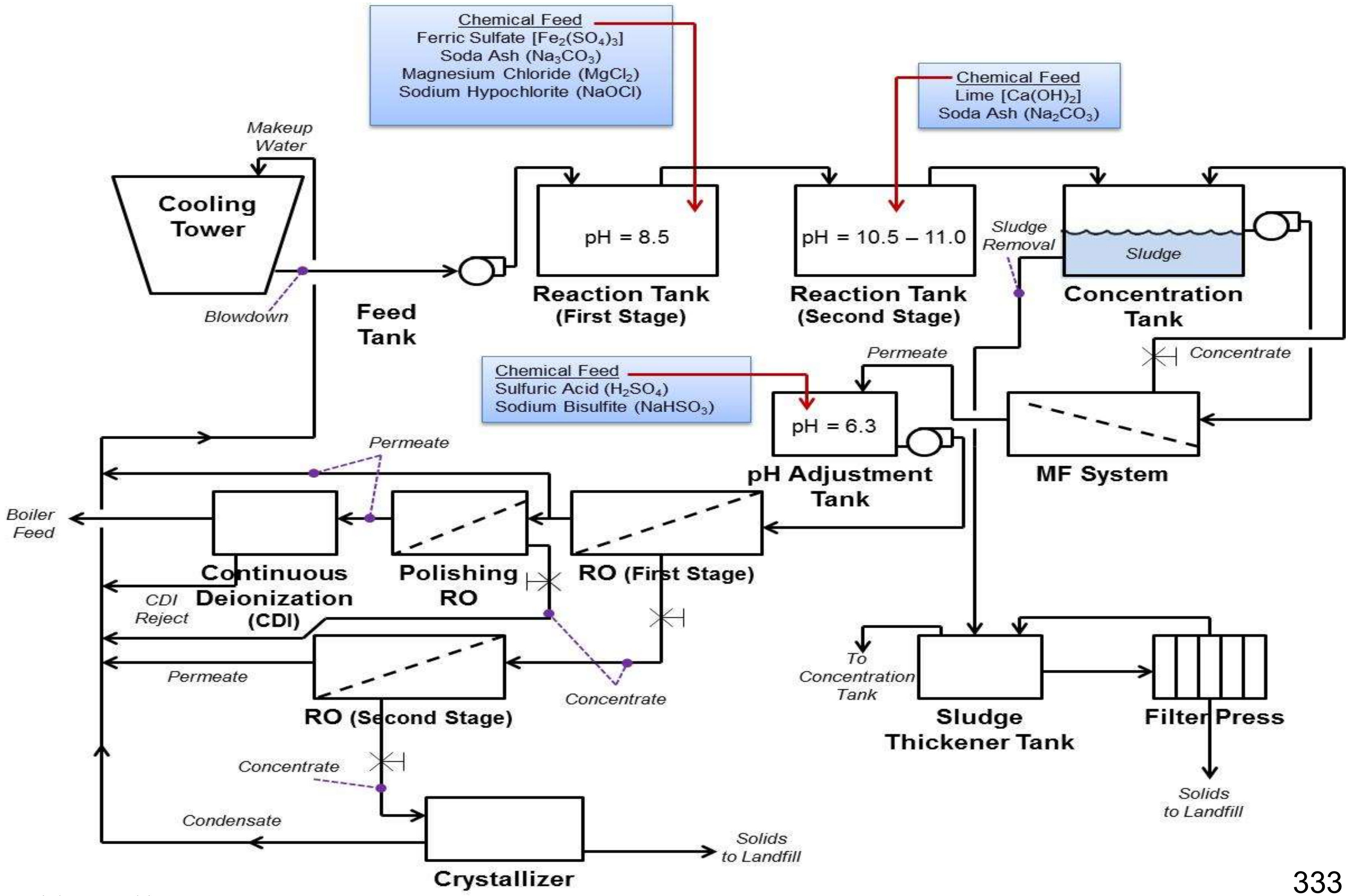
- For brackish water elements design data are:
  Pressure = 225 psi (15.5 bar)
  Temperature = 77^{o}F (25^{o}C)

- Pressure conversion – direct ratio of element design pressure to actual operating pressure
- Temperature conversion based on temperature correct factor (TCF) from element manufacturer

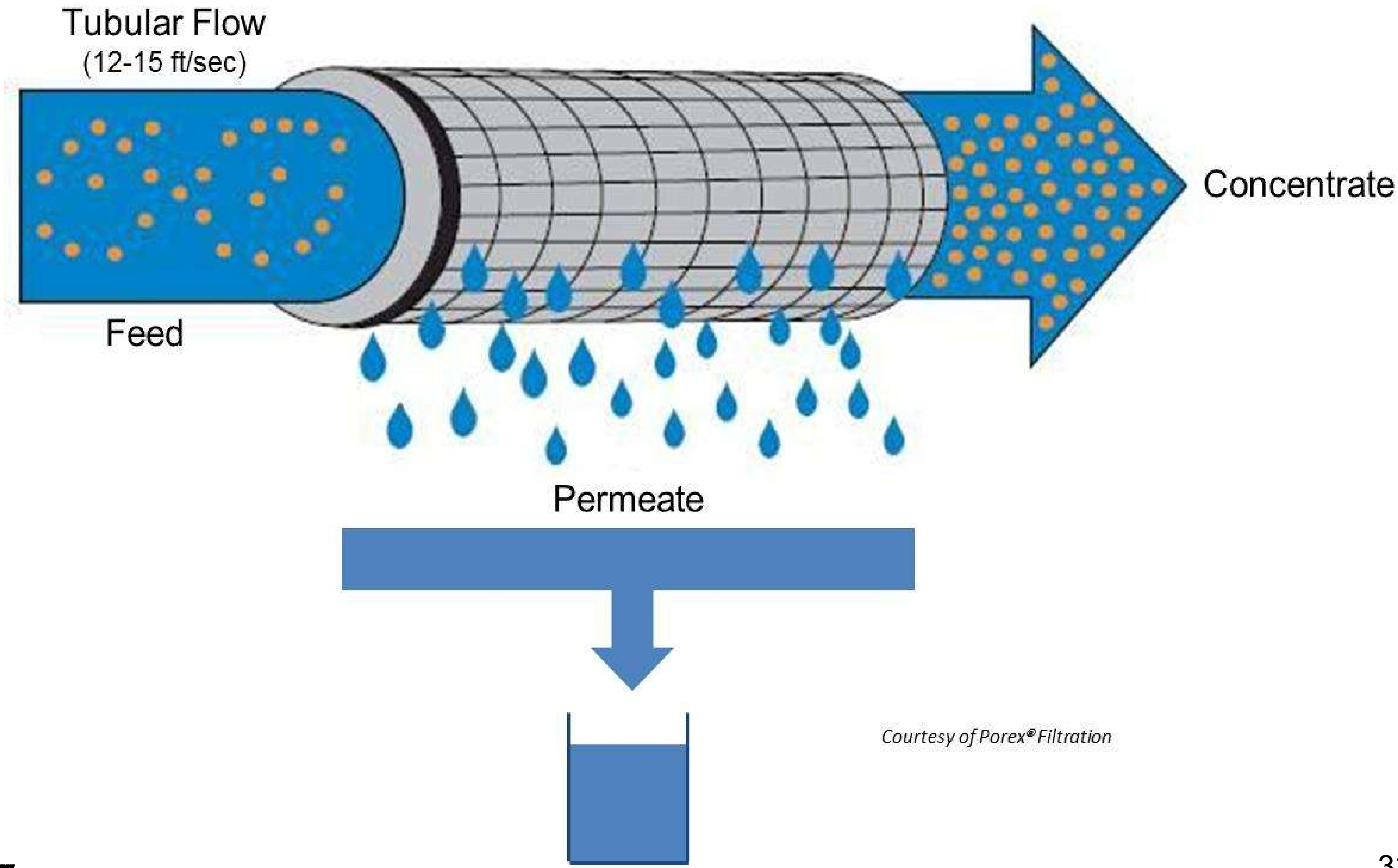
Case Histories

Zero Liquid Discharge of Cooling Tower Blowdown

Cooling Tower Blowdown Treatment System

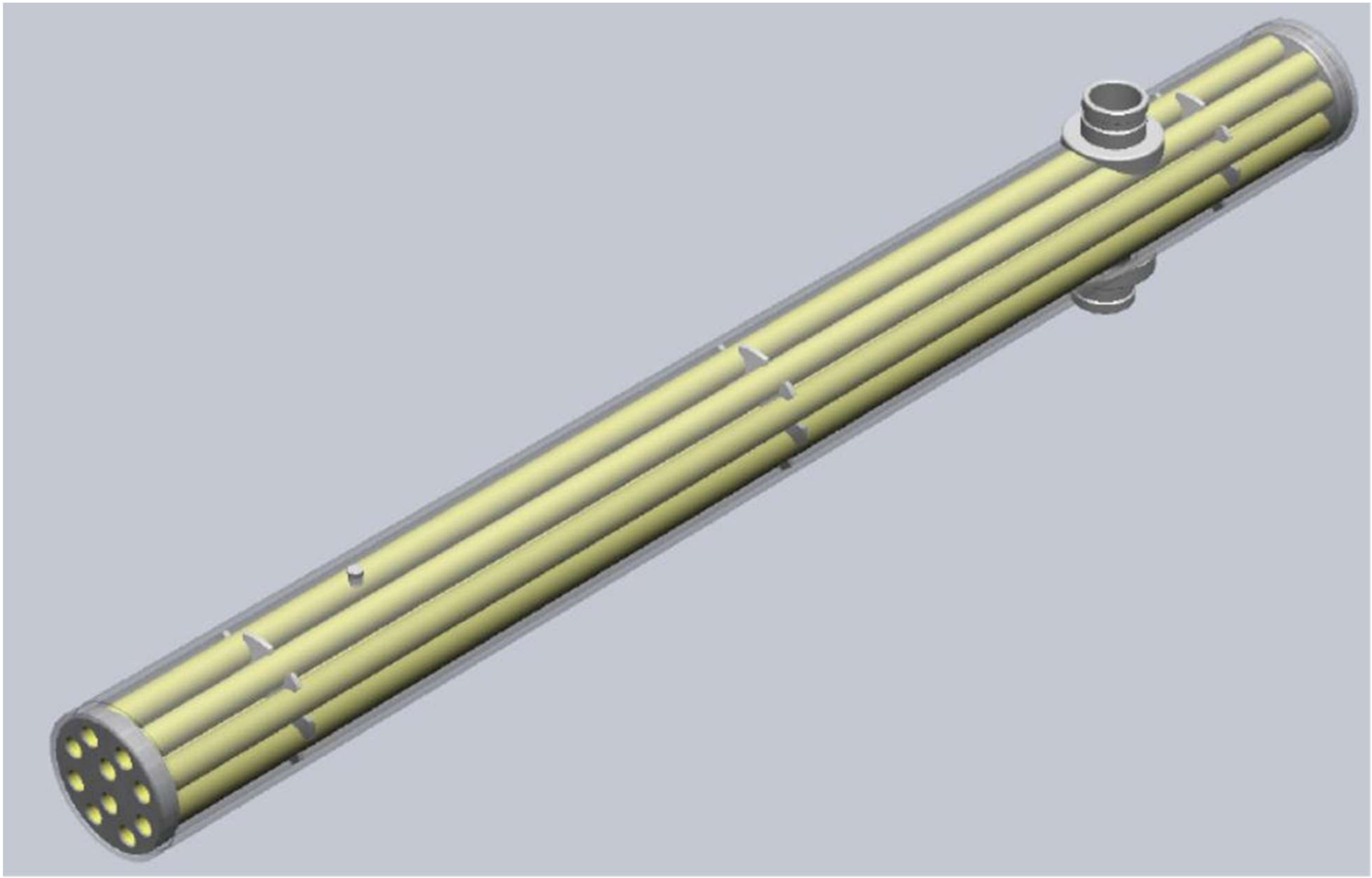


Tubular MF

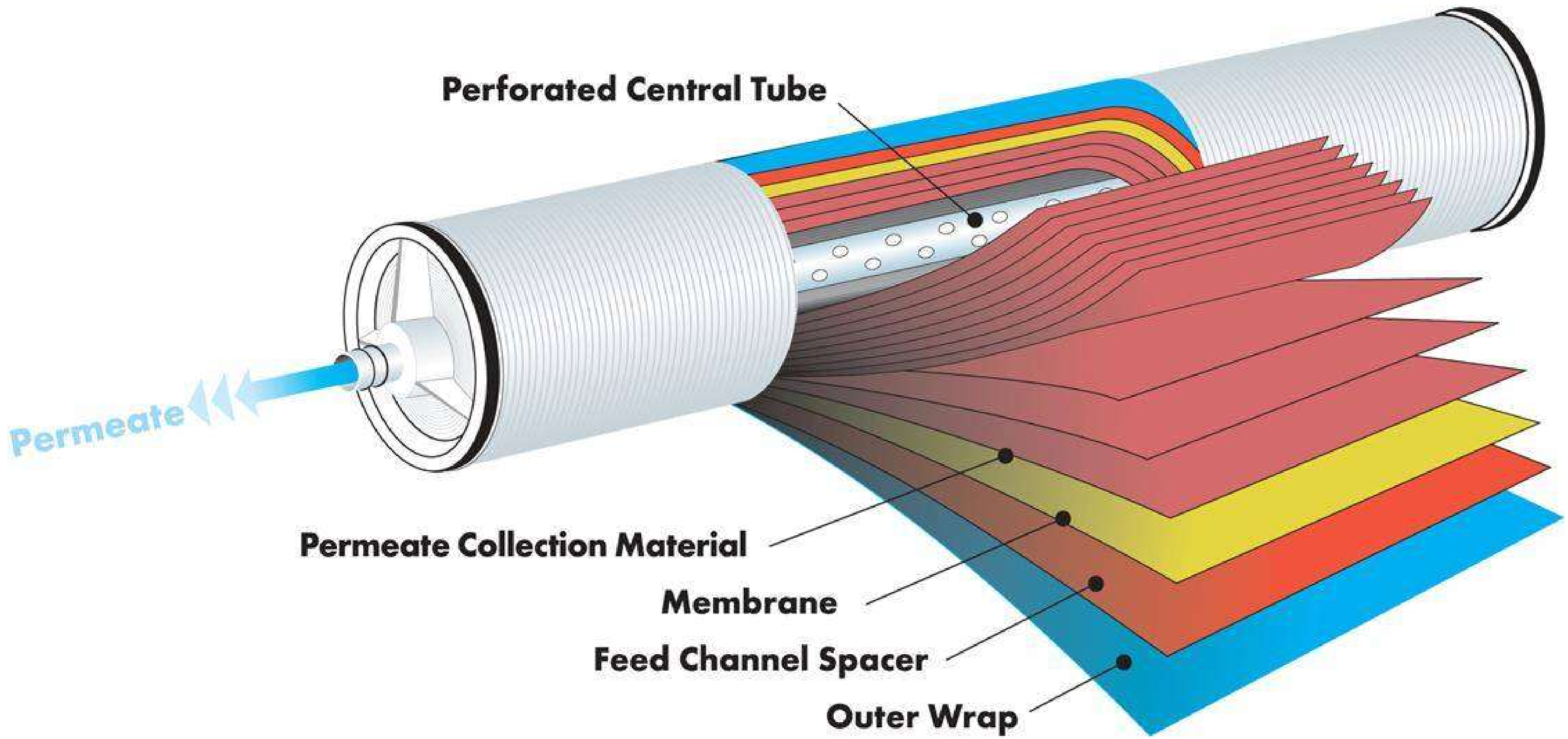


Courtesy of Porex® Filtration

Tubular MF

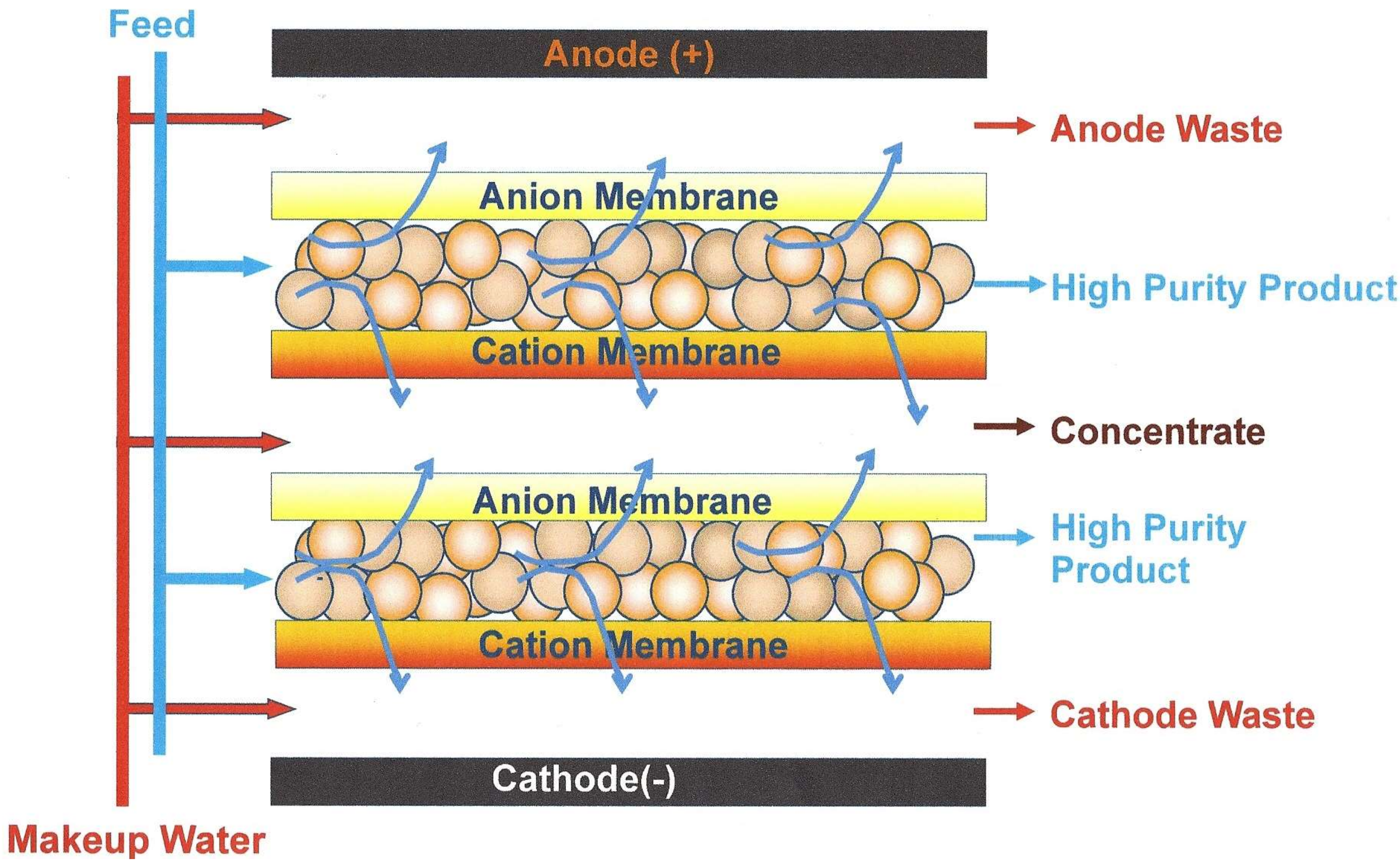


Spiral Wound Membrane Element



Courtesy of TriSep Corporation

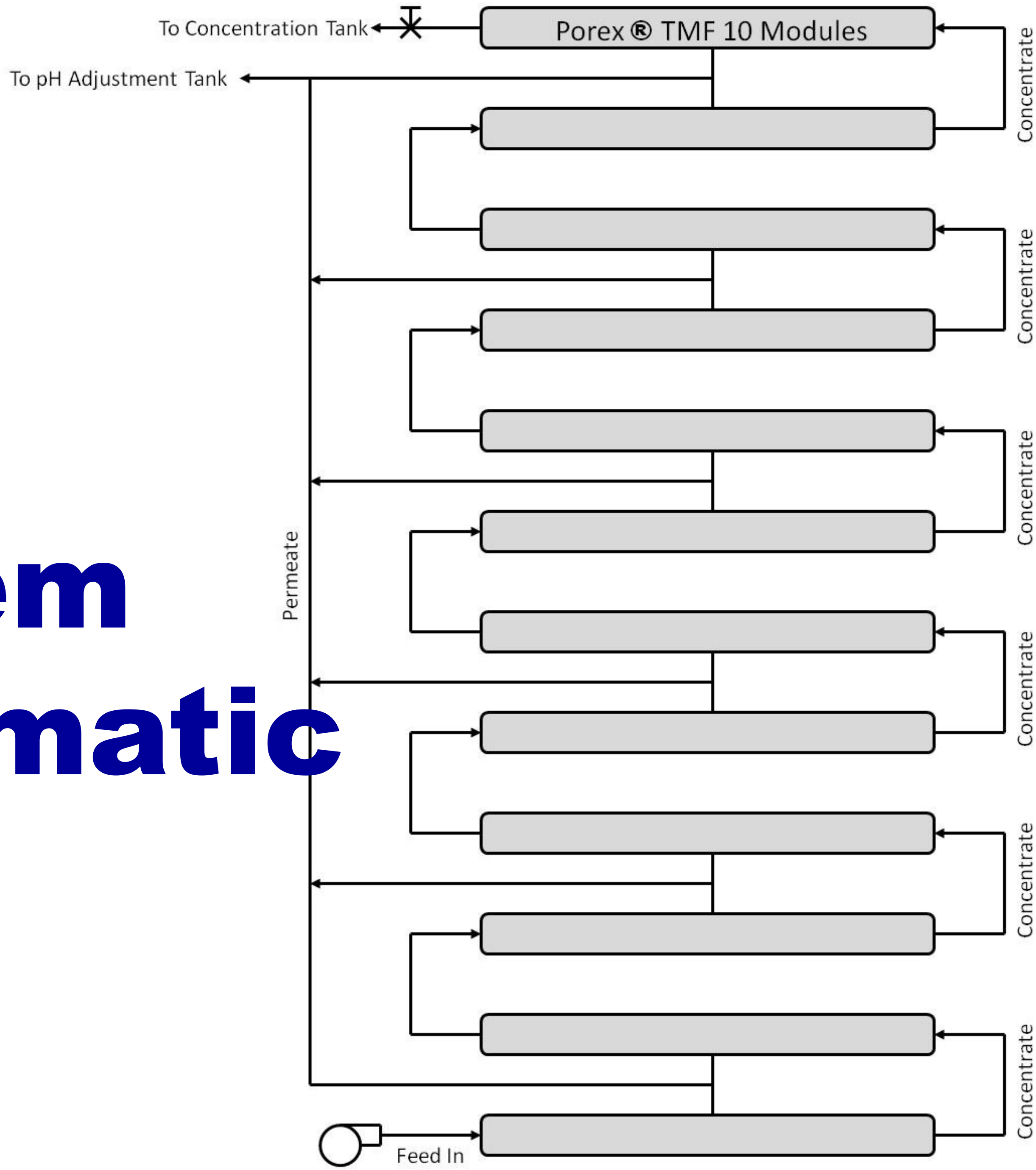
Continuous Deionization (CDI)



Porex® Module Specifications

Modules	
Housing Diameter	6" Schedule 40
Permeate Port (Qty 2)	2.875"∅ x 1.89" L pipe stub
Concentrate Ports	6"∅ 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

MF System Schematic



MF System Performance

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

RO 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%

Fouling

Membrane Element Backwashing/Backpulsing

Element Configuration	Backwashable?
Tubular MF	Yes
Spiral Wound RO	No

To Minimize MF Fouling

- High Velocity (12-15 ft/sec)
- Chlorine Addition
- Backpulsing

Cleaning

MF Acid Cleaning

- <u>15 minutes</u> - 3-5% HCl Recirculation
- <u>45 minutes</u> - Soak
- <u>45 minutes</u> - Recirculation with Rinse Water

MF Caustic Cleaning

NaOH + Bleach (12-15% NaOCl)
pH 12-13

- 30 minutes - Recirculation
- 150 minutes - Soak
- 30 minutes - Recirculation with Rinse Water

RO Cleaning

<6 months

Conclusions

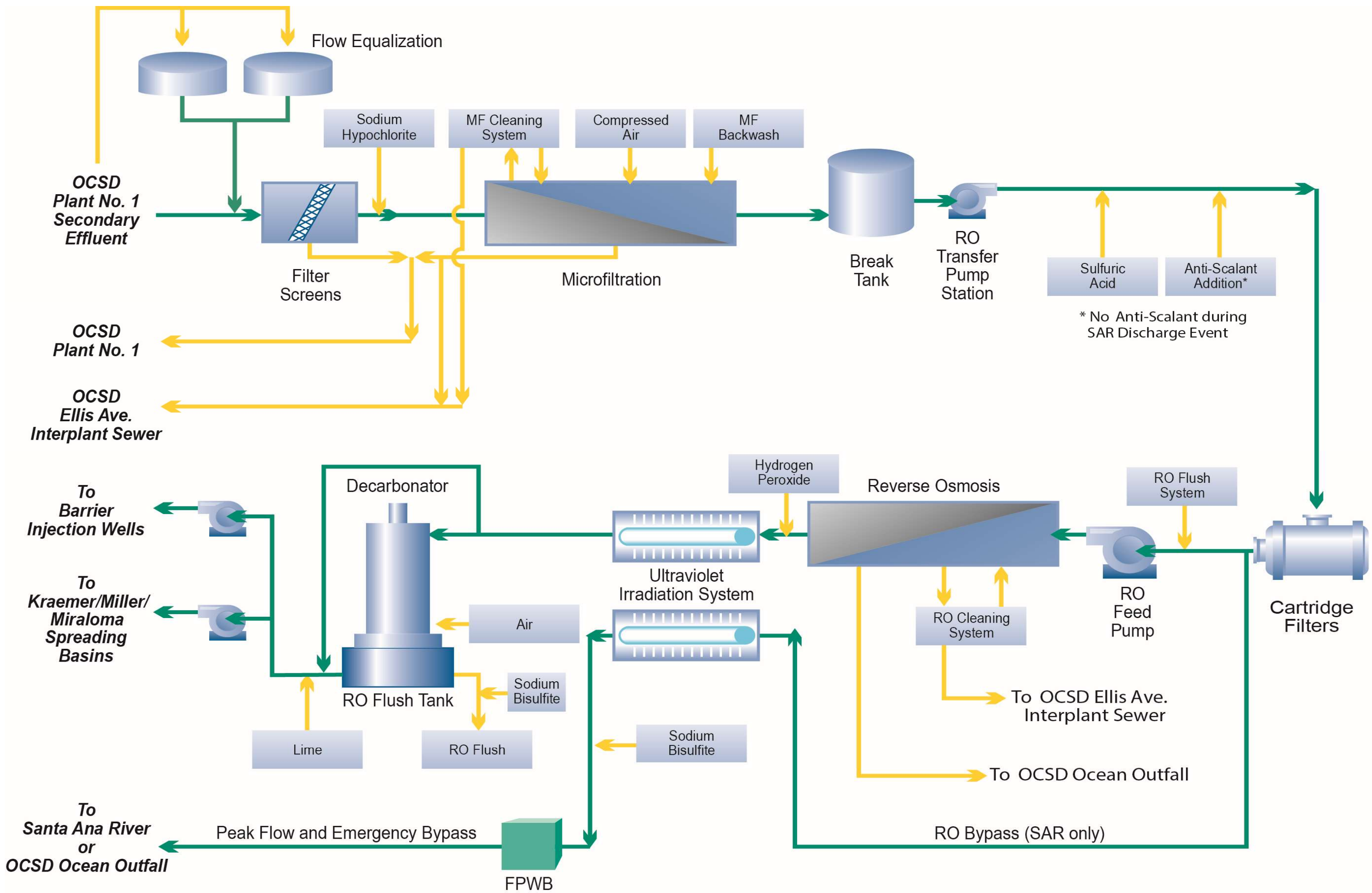
- ✓ **MF Protects Spiral RO Membranes:**
  Low Cleaning Frequency
  High System Recovery

- ✓ **MF Facilitates Zero Liquid Discharge**

- ✓ **MF Eliminates Traditional Clarification**

Orange County Ground Water Replenishment System

Orange County Ground Water Replenishment System



Microfiltration System

- 144 MGD Evoqua CS Microfiltration System
- Tiny, straw like hollow fiber polypropylene membrane
- Removes bacteria, protozoa, and suspended solids
- 0.2 micron pore size
- Backwash every 22min, CIP every 21 days (no maintenance washes)

Reverse Osmosis System

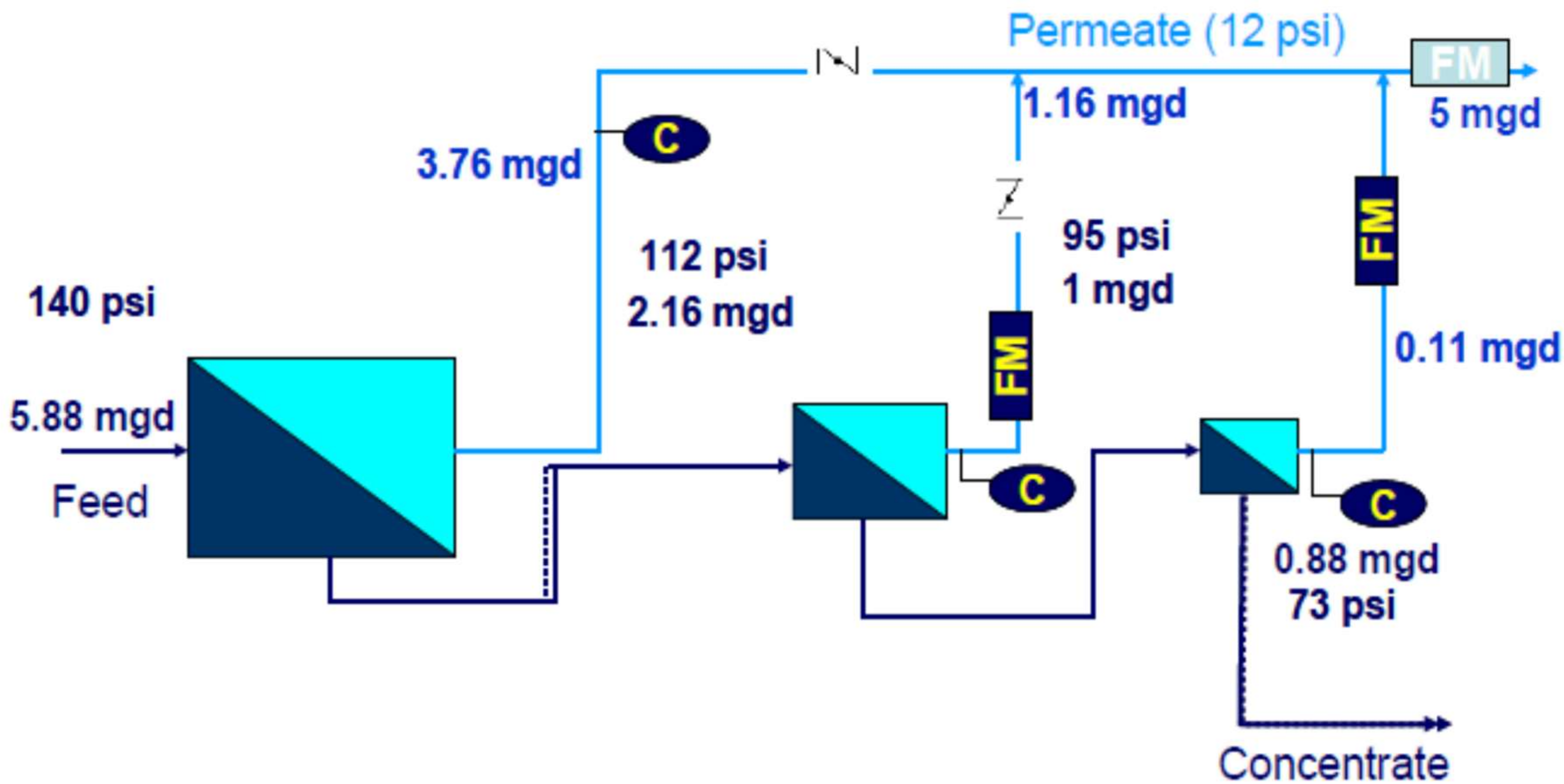
- 100 MGD Reverse Osmosis System
- 3 stage: 78-48-24 array
- 21, 5 mgd units, 12 gfd flux
- Hydranautics ESPA-2, CSM FLR and Dow XFRLE Membranes
- Recovery Rate: 85%
- Removes dissolved minerals, viruses, and organic compounds (incl. CECs)
- Pressure range:
  150 – 220 psi

Advanced Oxidation Disinfection

GWRS
GROUNDWATER REPLENISHMENT SYSTEM

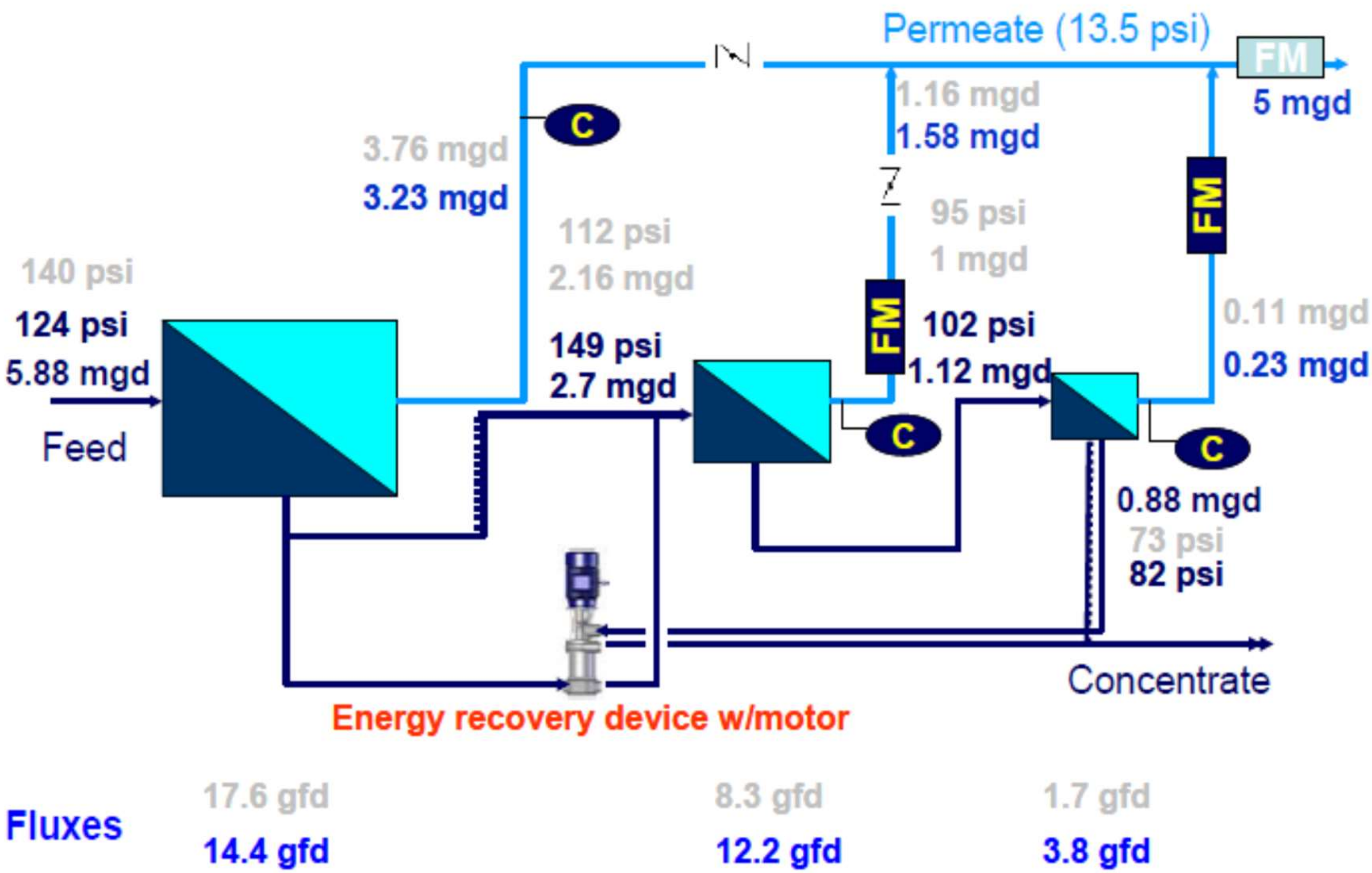
- 100 MGD Trojan UVPhox System
- Low Pressure – High Output lamp system
- Destroys trace organics
- Uses Hydrogen 3 mg/L Peroxide to create an Advanced Oxidation Process
- 13, 8.75 mgd trains (1 acts as standby)
- 6 reactors per train housed in 3 vessels
- 432 lamps per train (5616 total lamps)

Schematic of Existing RO Units without ERD



Fluxes	17.6 gfd	8.3 gfd	1.2 gfd

Schematic of New RO Units with ERD



Project Funding and Timing

GWRS
GROUNDWATER REPLENISHMENT SYSTEM

- Capital Cost: approximately $481 million
  - Split equally between OCWD and OCSD
- Expandable to 130,000 afy (438,500 m^3/day)
- Operational since January 2008

Food Processing Wastewater Recovery & Reuse

Background

Bakery Wastewater → 15,000 gpd

BOD → 50,000 mg/L

TSS → 5,000 mg/L

POTW Limits: 250 mg/L BOD

250 mg/L TSS

Hauling/Treatment Charges → $50,000/month

Conceptual Design

Prescreening – large suspended solids
Microfiltration – almost all suspended solids
Reverse osmosis – polish for discharge or reuse
Evaporation – concentrate disposal

Prescreen Testing

Vibrating screen vs. automatic backwashing filter

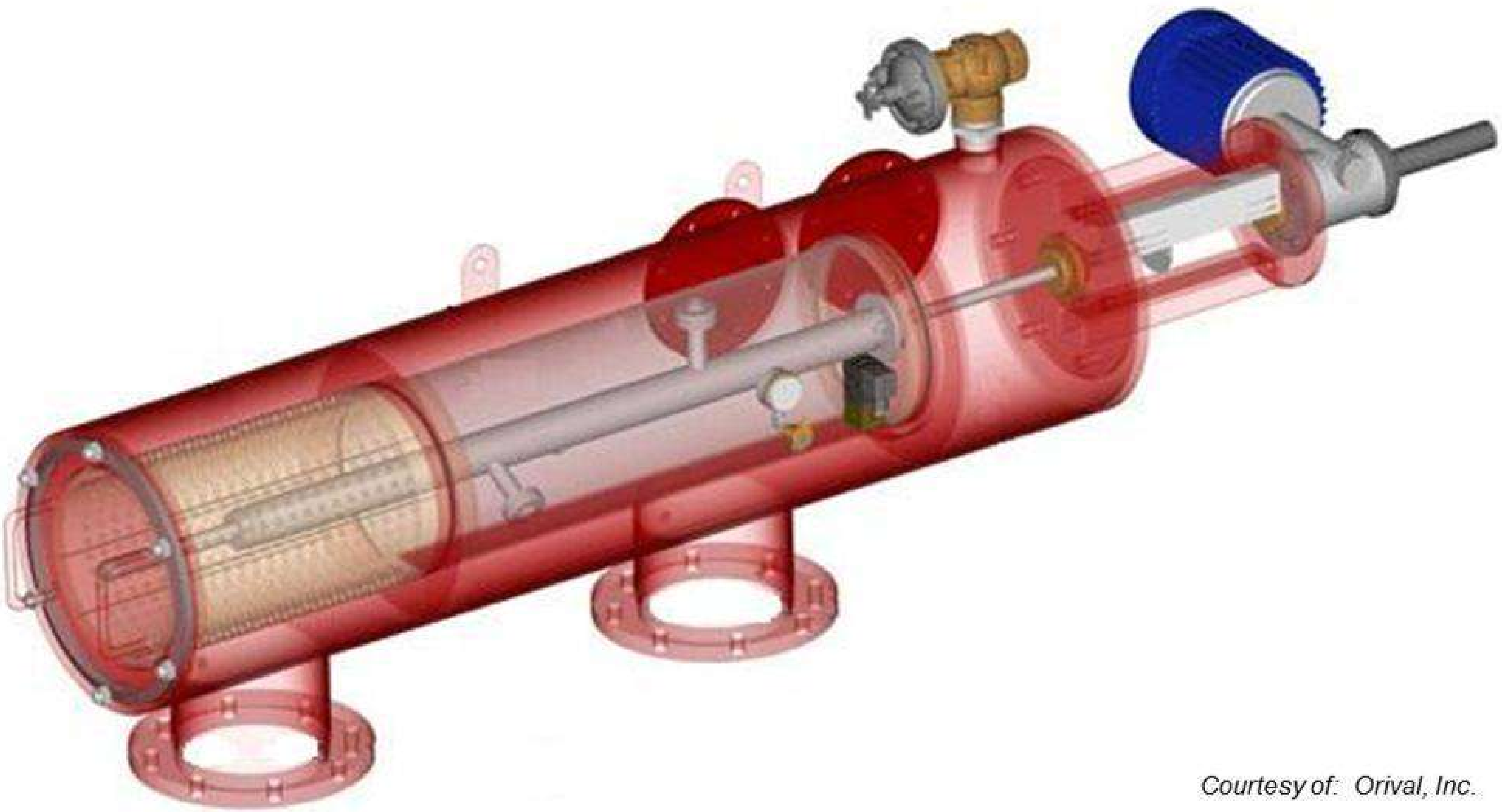
100μ automatic backwashing continuous filter selected

Prescreen Testing

Collected filtrate

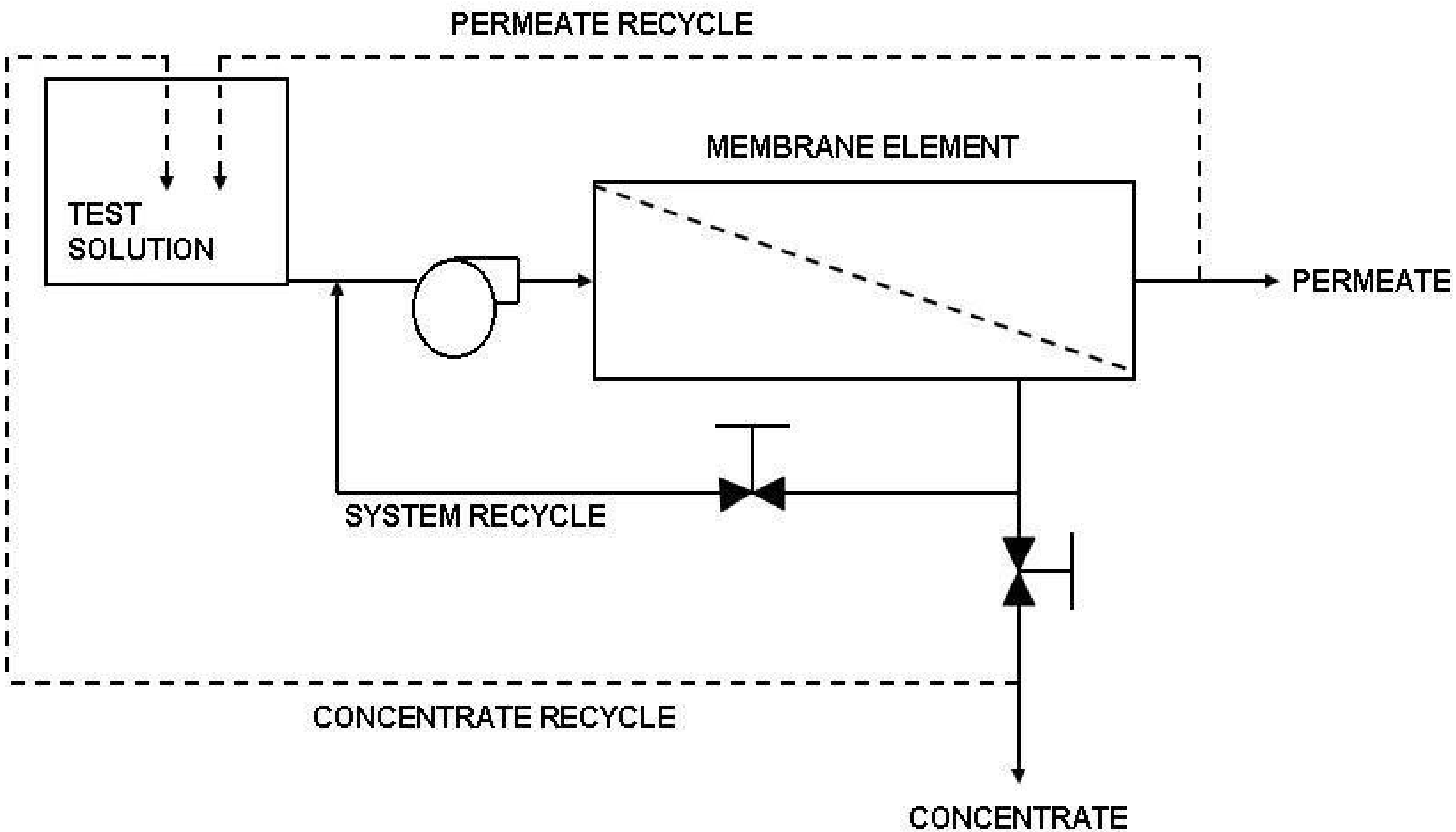
Observed settled solids

Continuous Filter



Courtesy of: Orival, Inc.

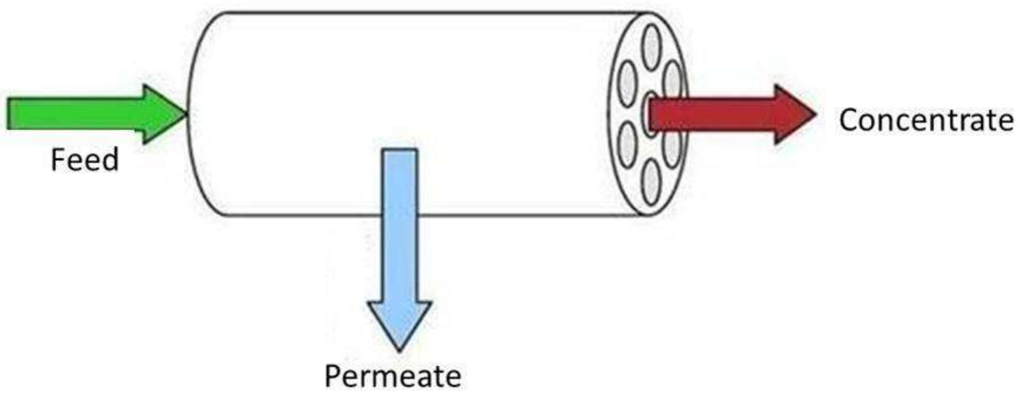
Microfiltration Testing

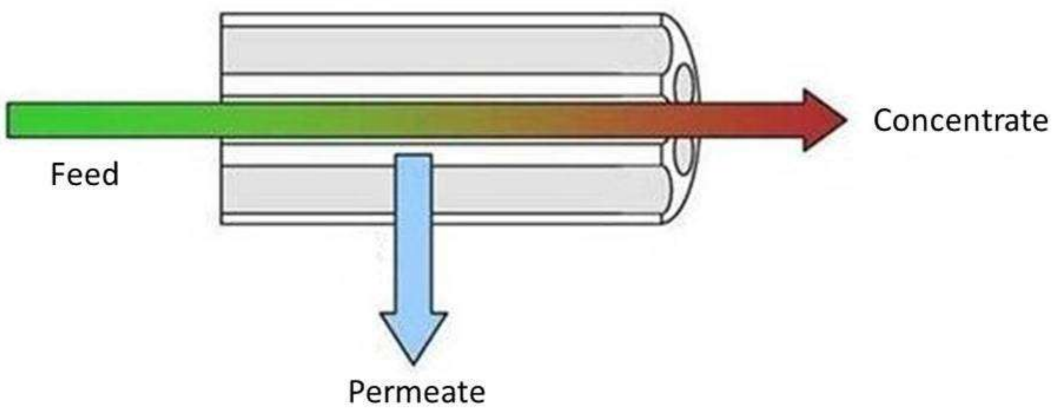


Ceramic MF Membrane

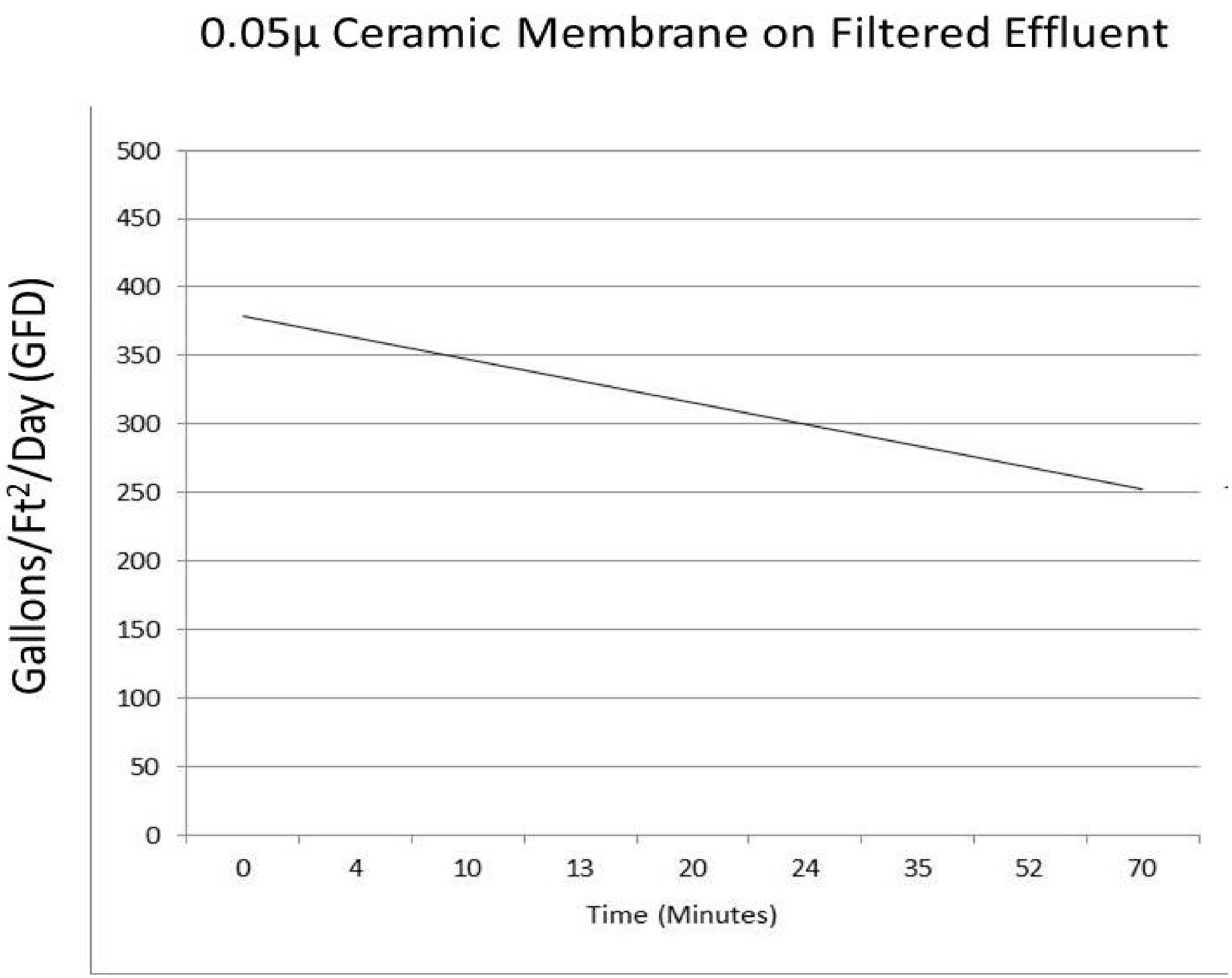
Silicon Carbide
0.05μ Pore Size

Ceramic MF Membrane





Permeate Rate

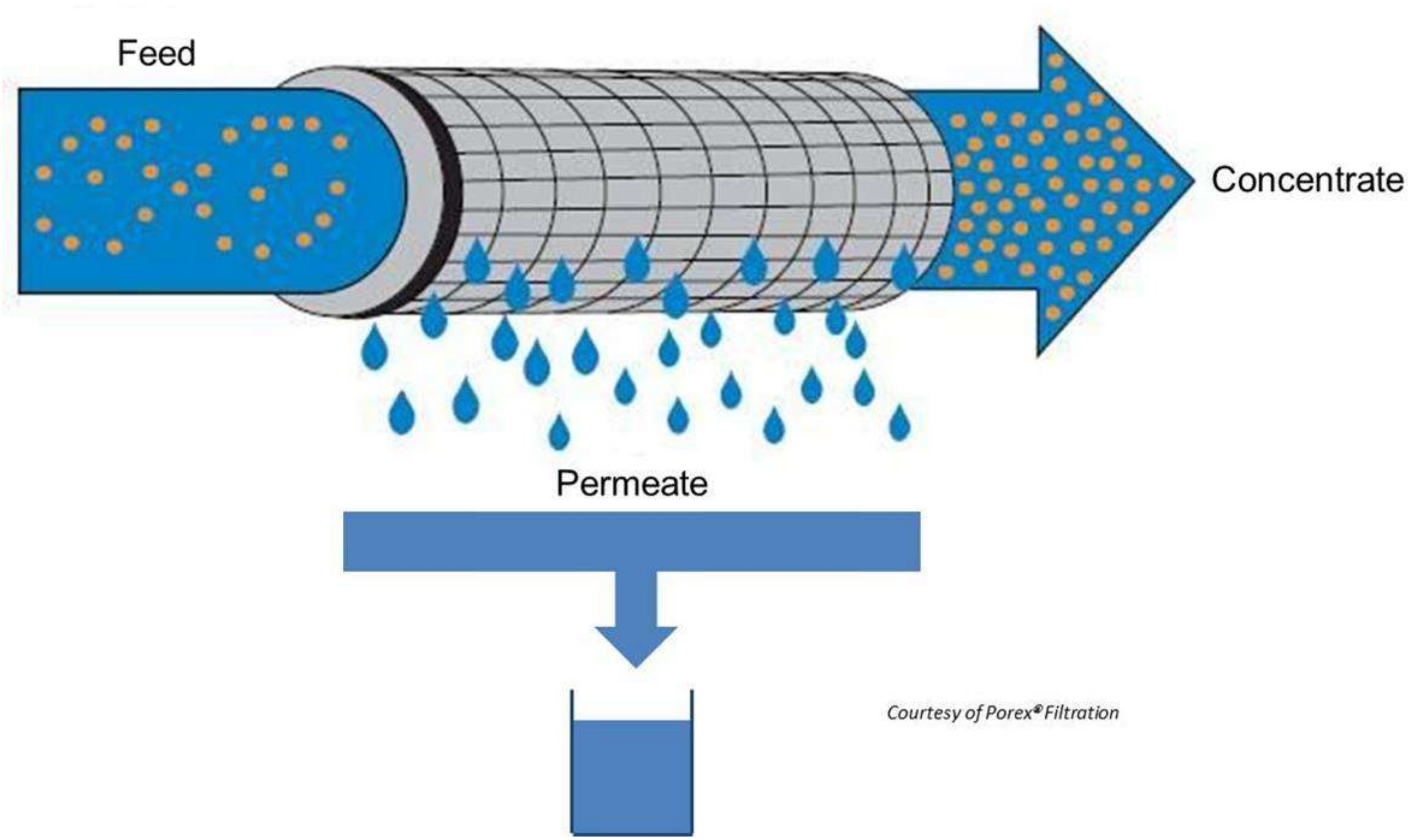


Polymeric MF Membrane

PVDF Material

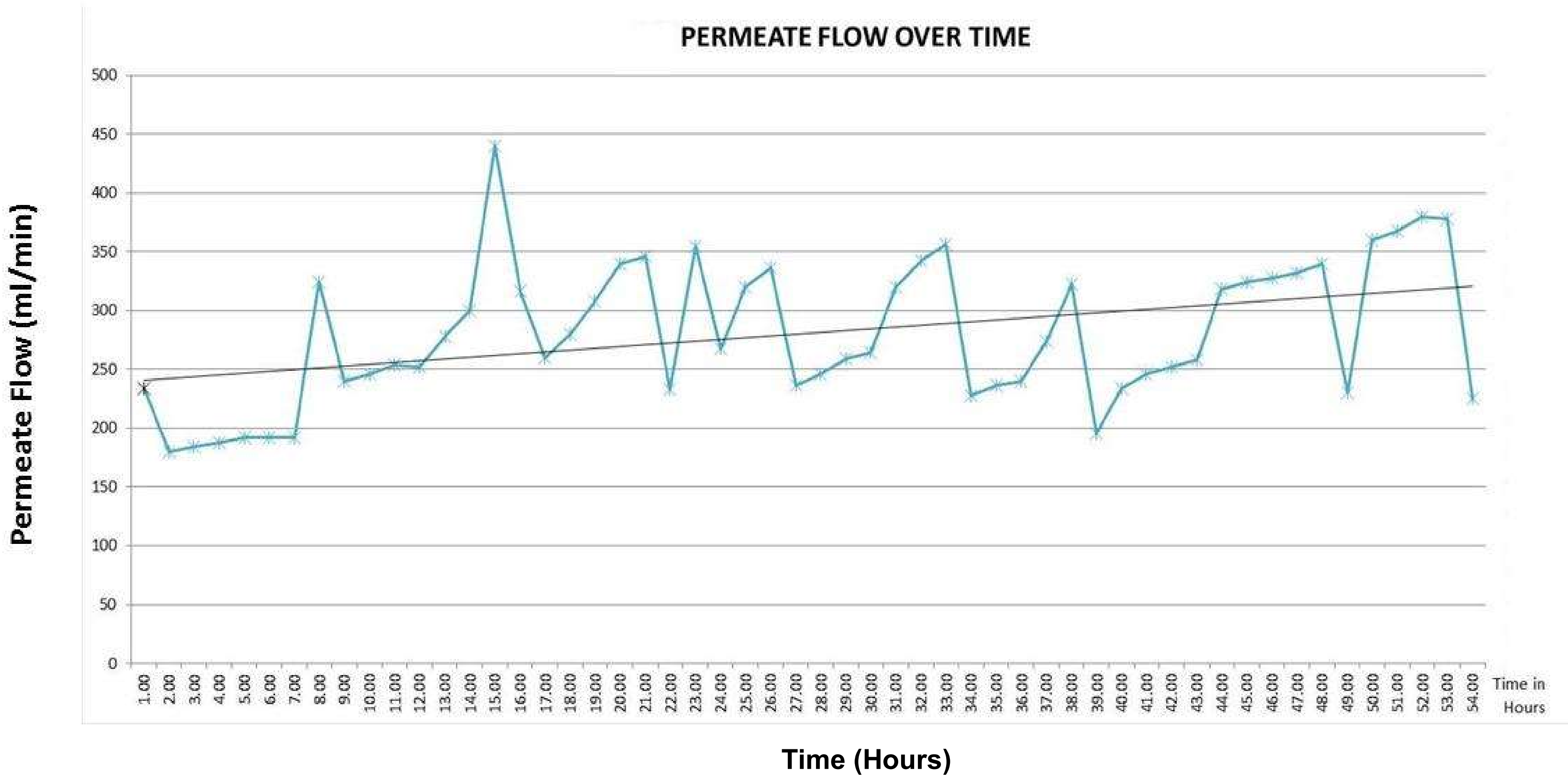
0.05μ Pore Size

Polymeric MF Tubular Membrane

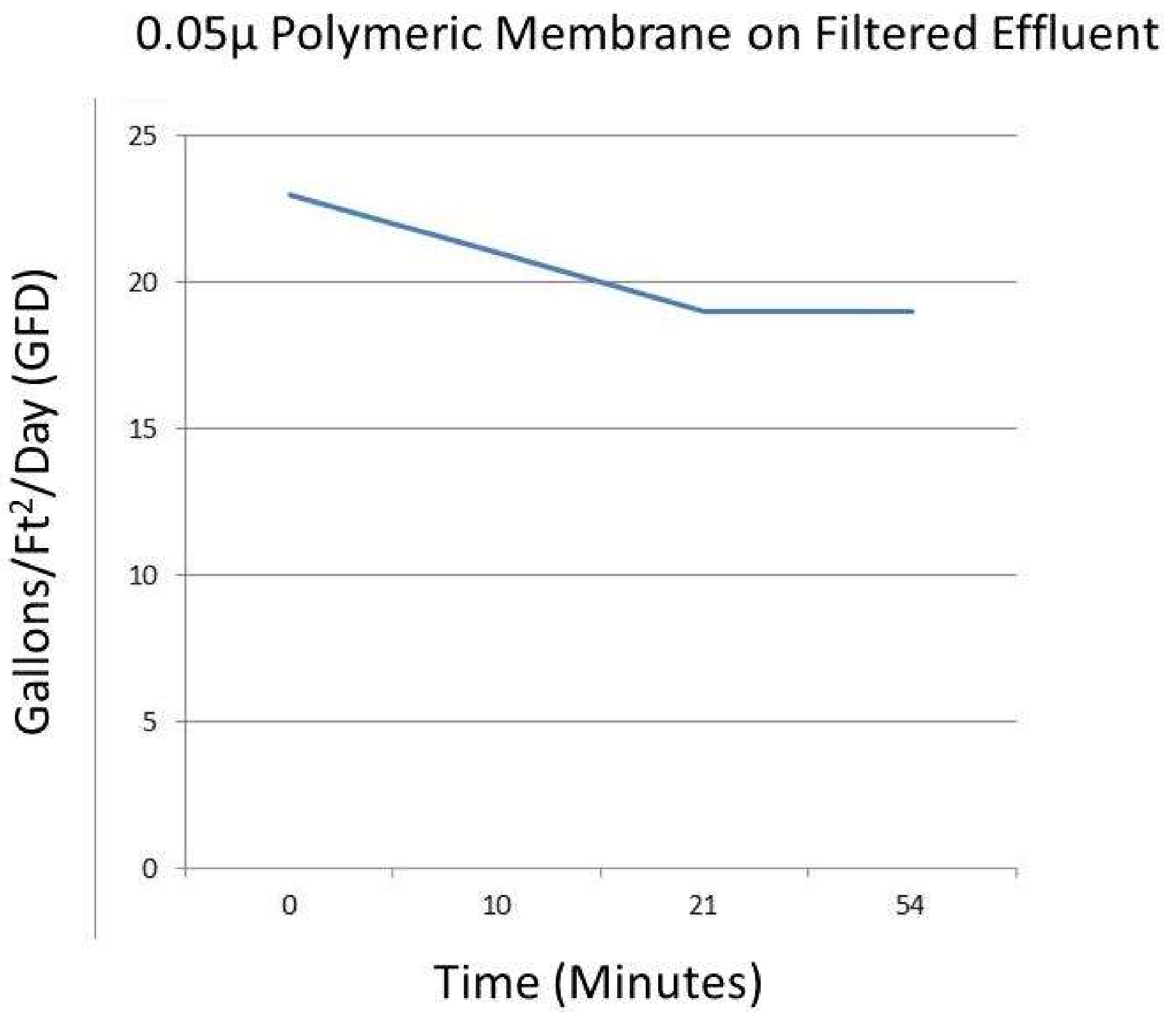


Courtesy of Porex® Filtration

Permeate Flow



Flux Rate



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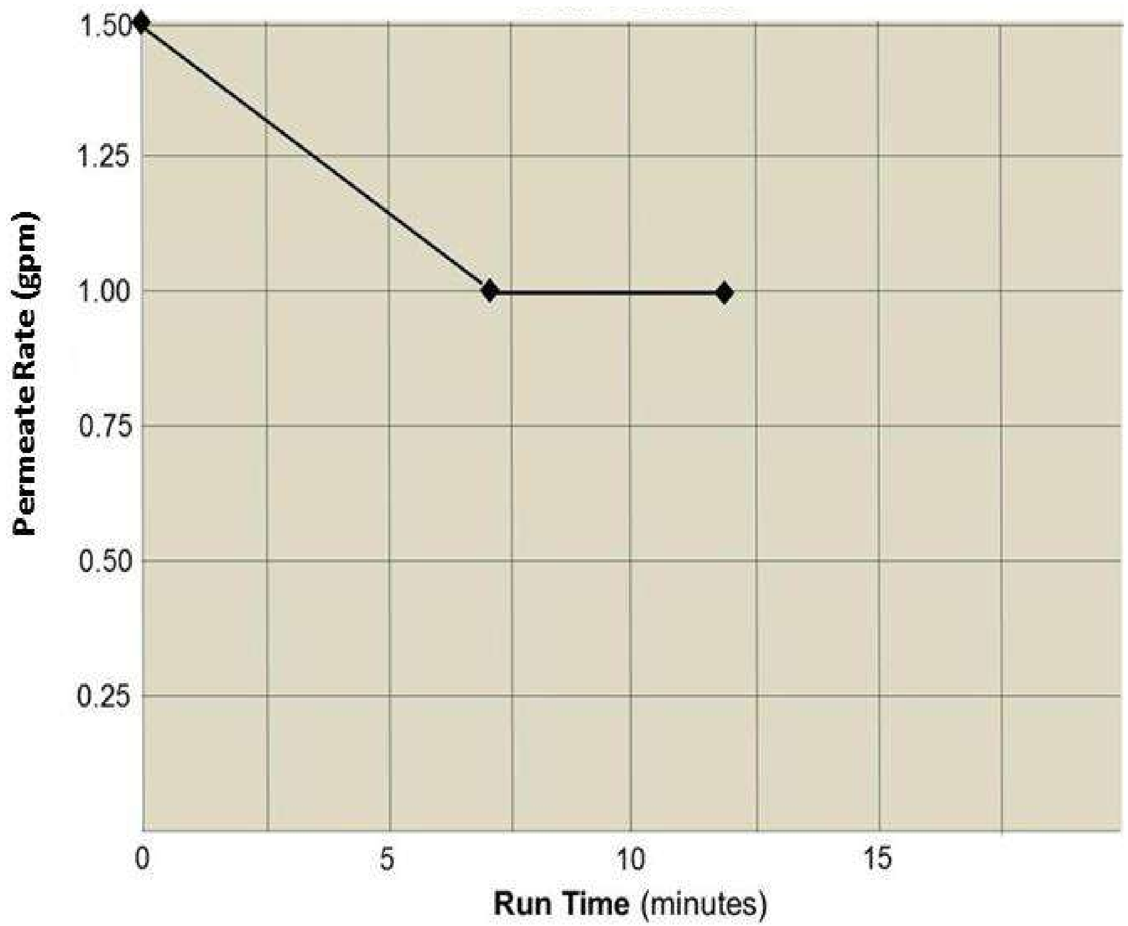
Applications Testing Results

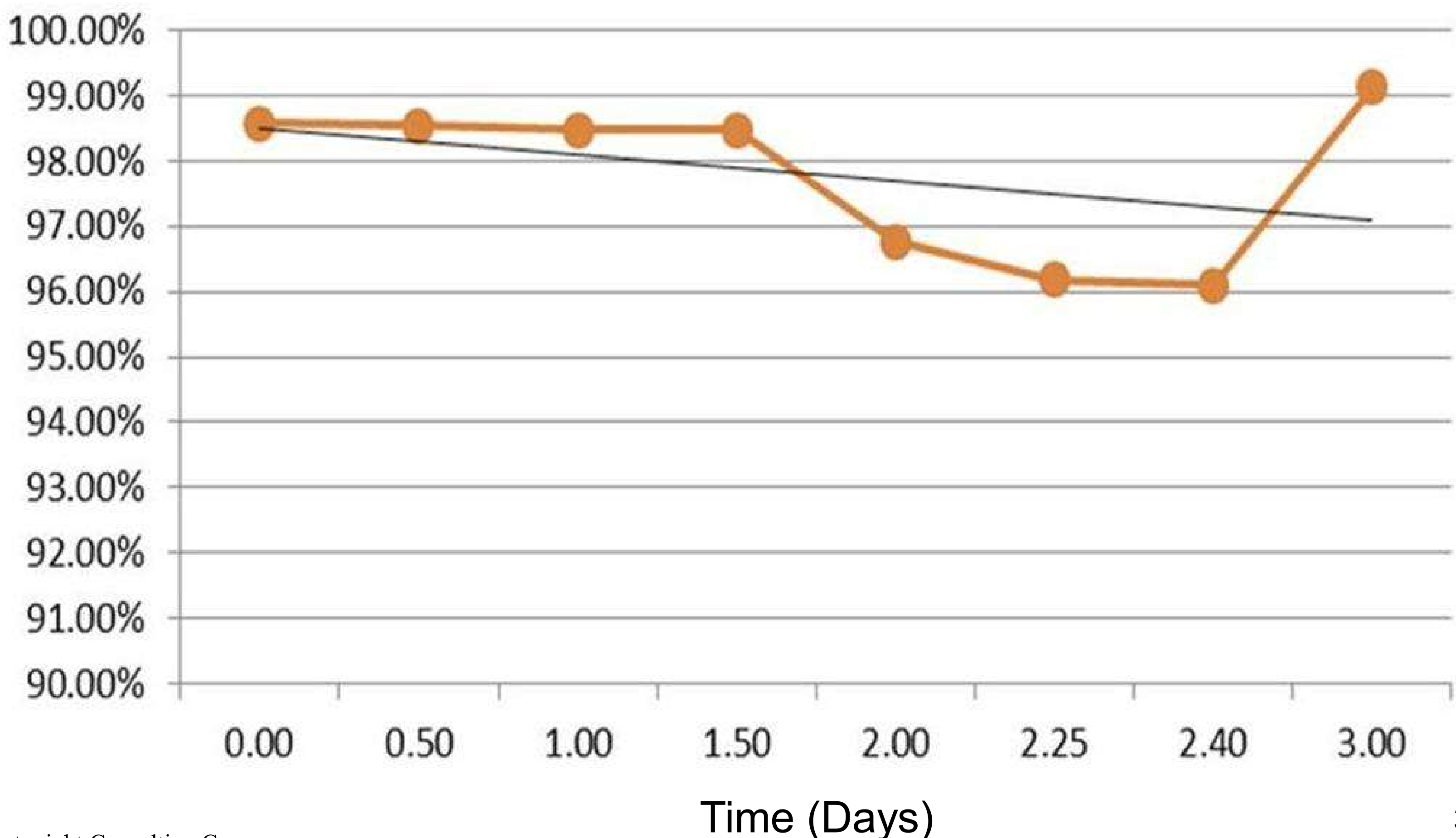
- Continuous Automatic Backwashing Filter
- Polymeric MF Tubular Membrane

Polish with RO Standard Thin Film Membrane

RO Treatment of MF Permeate



Percent Rejection – RO Unit



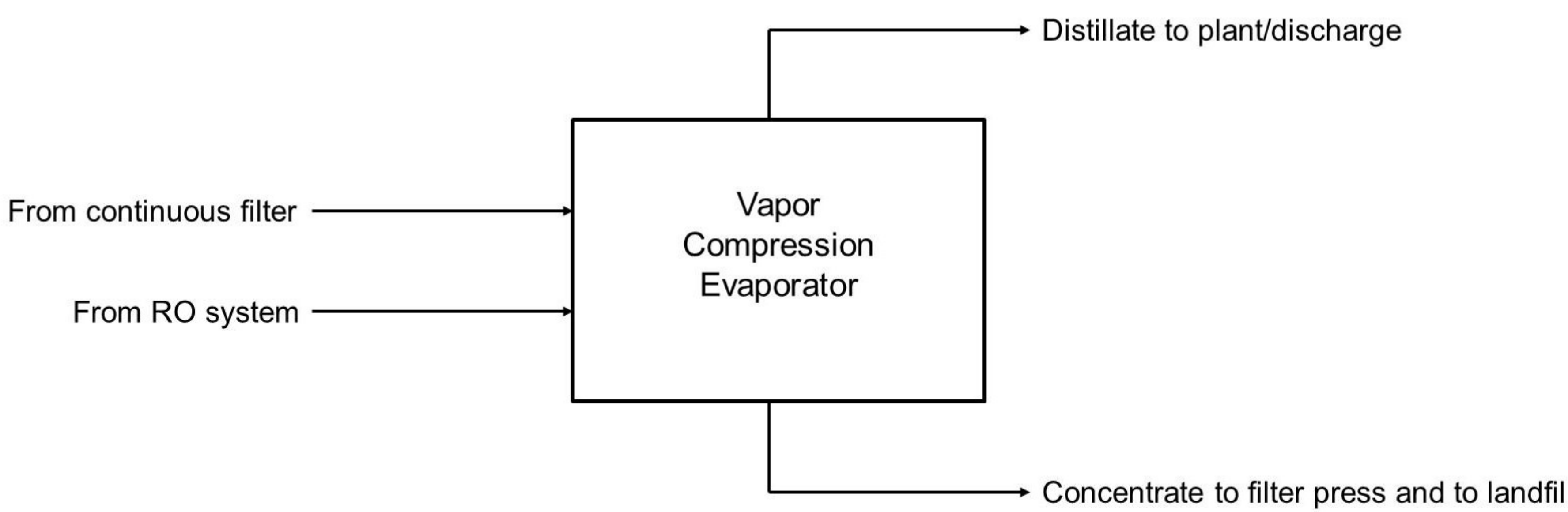
Concentrate Treatment

Prescreen filter solids to Vapor Compression Evaporator

MF concentrate back to feed tank

RO concentrate to Vapor Compression Evaporator

Vapor Compression Evaporator

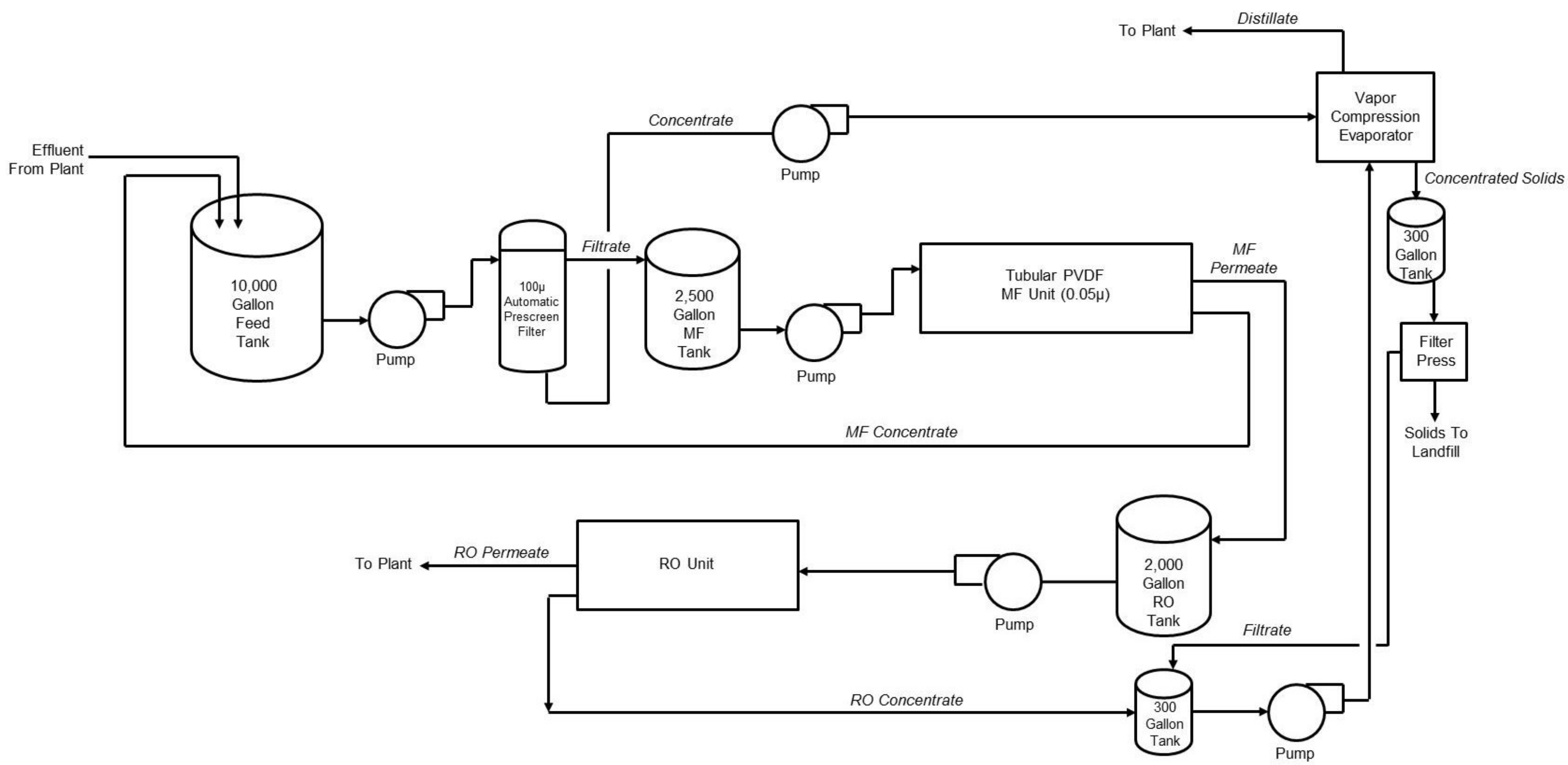


Results

	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

Total Treatment System



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Prescreen Filter

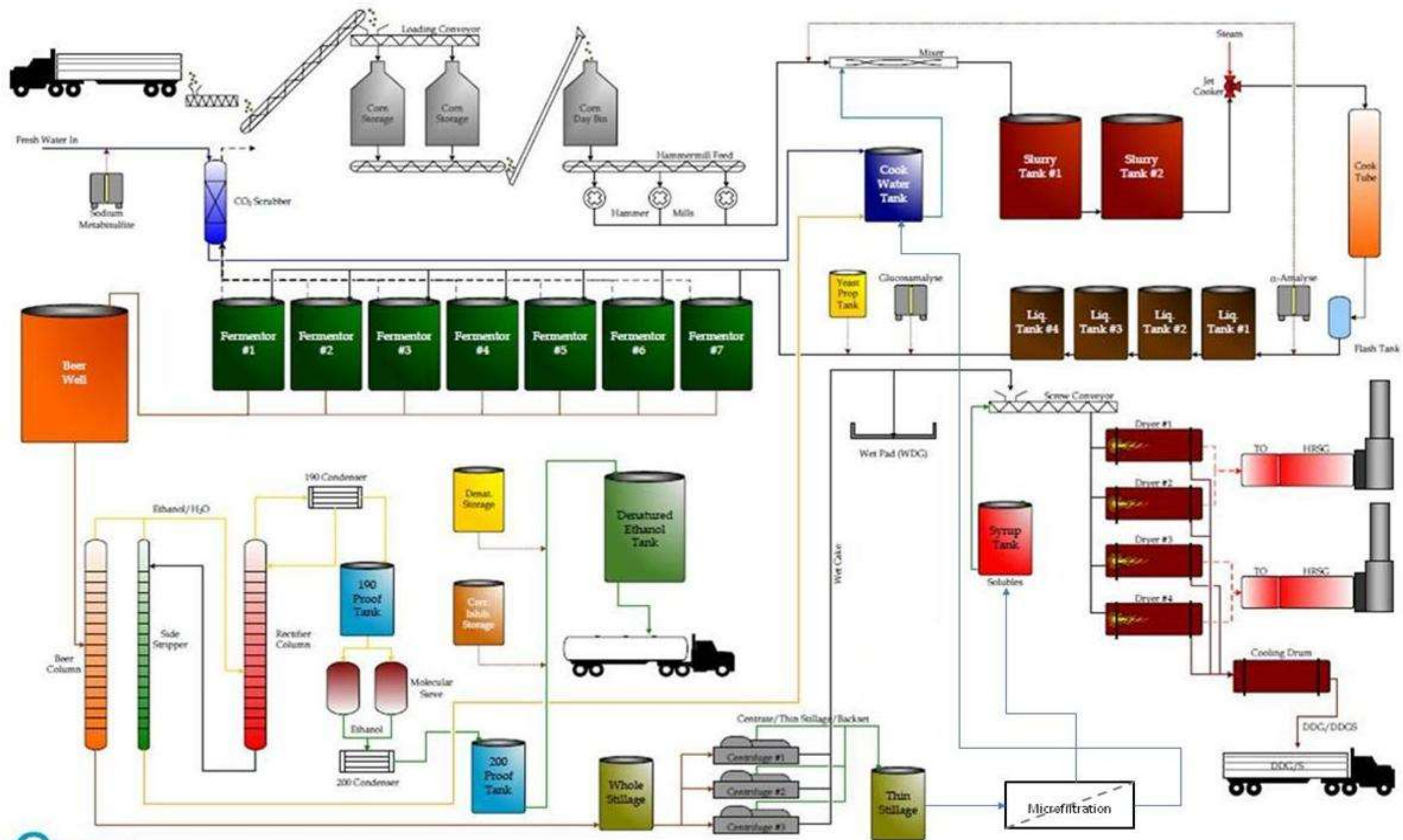
MF Unit

Overview of System

RO Unit

Ethanol Plant Thin Stillage Treatment

Total Treatment System



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1/952-854-4911