Introduction to Membrane Filtration & Fluoridation Technologies

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Introduction to Membrane and Fluoridation Technologies

7 Contact Hours
9 CC10 Hours

Membrane and Fluoridation technologies will be explored in this one day course. Discussion will include with an up-close look at the membrane filtration treatment methods. Membrane processes and parameters will be introduced followed by operational and maintenance techniques. The uses of membrane filters to remove fluoride will be discussed in depth. Participants will review Fluoride applications and the evaluation methods used for determining performance. The operator will also review safe handling techniques of Fluoride and review how to properly store this treatment agent. Actual facilities will be topics of classroom discussion and demonstrations.

1.Identify the various membrane types and their configurations;
2.Perform basic mechanical and operational adjustments;
3.Explain the processes of membrane filter(s) and the parameters of each type;
4.Discuss and demonstrate safe operation, handling and storage of fluoride chemical agents;
5.Determine proper chemical dosing by using basic calculations; and
6.Perform basic mechanical and operational adjustments to fluoride feed equipment.

8:00 AM to 8:30 AM	Introduction Hand out materials
8:30 AM to 10:00 AM	Membrane Types and Configurations
10:00 AM to 11:00 AM	Membrane Filtration Feed Equipment
11:00 AM to 11:30 AM	Contaminant Removal
11:30 AM to 12:00 PM	Different Forms of Fluoride
12:00 PM to 1:00 PM	LUNCH
1:00 PM to 2:00 PM	Fluoride Feed Equipment
2:00 PM to 2:30 PM	Fluoride Safety
2:30 PM to 3:00 PM	Facility Discussion
3:00 PM to 3:30 PM	Dosage Calculations
3:30 PM to 4:00 PM	Review Final Exam

MCET
environmental, health, and safety training

Maryland Center for Environmental Training
at the
COLLEGE of SOUTHERN MARYLAND

Membrane Filtration and Fluoridation

Process Training Sessions

Before class starts, please:

- **Sign in** on Attendance Sheet

During classes, please:

- **Asks questions**
- Feel free to get up and leave the classroom at any time (i.e., rest rooms, phone calls, etc.)
- **Answer questions** on worksheets and exercises

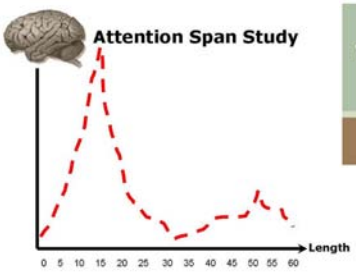
Housekeeping

- 1- day class
- Start class – 8:00 am
- 10-minute Breaks – every hour
- Lunch – 11:30 am ~ 12:30 am
- End class ~ 3:00 to 4:00 pm

Instructor Expectations

- Begin and end class on time
- Be interactive – ask questions; participate at your own comfort level
- Share experiences and needs
- Less lecture, more discussions
- Keep it simple
- ***Make this an enjoyable and informative experience!***

Student Attention Span - Lectures



How this Class is Structured

- This 1-day class will be more class discussion, less lecture
- The workshop will be structured around three teaching components:
  - Establishing rapport (Trainer as facilitator)
  - Stimulating student interest (Trainer as motivator)
  - Structuring classroom experiences (Trainer as designer)

Discussions

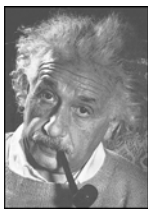
- Student involvement in class discussions is encouraged:
  - To keep students attentive
  - To help students retain information

The Guiding Expectation

"Things should be made as simple as possible -- but no simpler."

Albert Einstein

www.physik.uni-frankfurt.de/~jr/physpiceinstein.html



Ground Rules

- Discussion is encouraged - ask questions; share experiences
- Use terms we all can understand
- Everyone is different, so please show respect for others in the room
- Express opinions - of things, not people
- Maintain confidences

Ice Breaker and Discussion

- Let's introduce ourselves:
  - Name
  - County, City, or Town of plant location
- Facilitated discussion:
  - If filtering with membranes, how well are the filters working?
  - If fluoridating, how well is the process working?
  - Is there room for improvement?

(Allow 20 to 30 minutes for reflection and discussion)

Introduction

Objectives, Focus, and Agenda

Learning Objectives

1. To inform operators on equipment components and process operational concepts of:
   - Membrane Filtration
   - Fluoridation
2. To identify monitoring strategies and process adjustments to enhance:
   - Process control
   - Process efficiency

Agenda

- Membrane Filtration
  - Classifications and configurations
  - Applications
  - Troubleshooting
- Fluoridation
  - Introduction and history
  - Regulatory framework
  - Chemicals and chemical feeders

Objectives

- To discuss the fundamentals of membrane filtration for particle removal
- To discuss water fluoridation

Participant Focus

- What makes a membrane work?
  - Pore size - density and distribution
    - Small pores = Better separation
    - More pores = Better flow per area (flux)
    - Close distribution of pore size = Consistent separation
- Manufacturing membranes to a consistent quality standard is difficult – a few large pores can ruin separation performance

Participant Focus

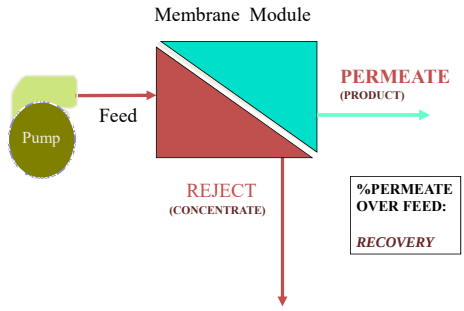
- What makes a membrane work?
  - Permeability (flux per unit pressure at set temperature)
    - Flux (flow per unit area), gals/day/ft^2
  - Trans-membrane pressure (TMP)
    - Higher delta Pressure = More flow
  - Temperature
    - Lower temperature = Lower flow (viscosity or diffusion driven)
  - Water quality = more “solids”, less flow

Membrane Filtration

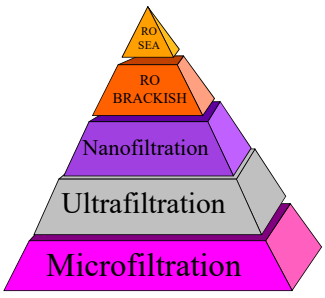
Objectives

- How does membrane filtration fit into the water treatment process?
- What are the advantages and disadvantages of membrane filtration?
- What equipment is used during membrane filtration?

SIMPLIFIED SCHEMATIC

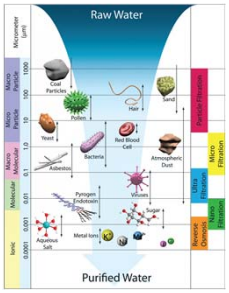


There are five basic membrane systems.



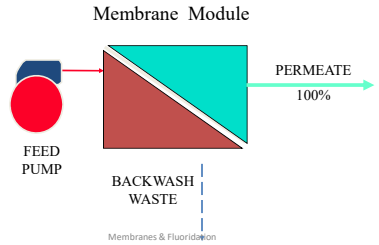
Why use Membranes?

- Removal of pathogens, not inactivation
- One step particle removal > 4 log (99.99%)
- Back washable with air/water- keeps flux high
- Membrane integrity – ensures safe water
- Compact footprint – saves real estate
- Easily expanded – modular concept



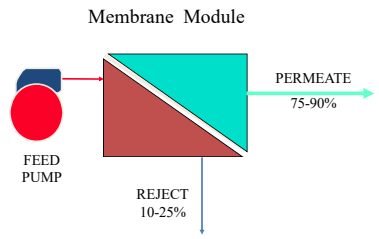
TWO DIFFERENT MODES OF OPERATION

DEAD END WITH FREQUENT BACKWASH

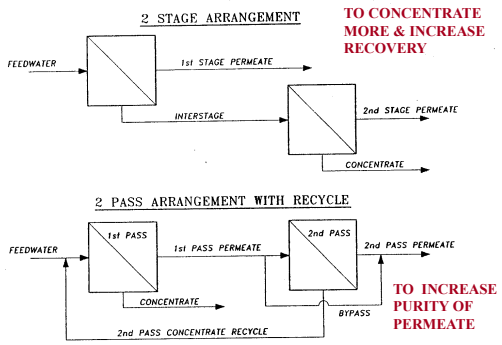


TWO DIFFERENT MODES OF OPERATION

CONTINUOS CROSS FLOW



STAGES & PASSES



WHICH ONE TO USE?

DEPENDS ON MANY CRITICAL FACTORS:

- Size, type & conc. of contaminant
- Polyamide memb. will be damaged by cl_2
- Biological degradation concerns
- ph, temp, flux & other design factors
- Availability for configuration

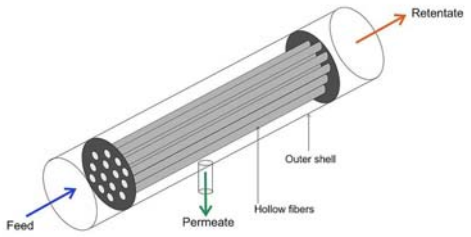
Membrane Filter Applications

- Drinking water supply
- Tertiary filtration of secondary sewage effluent
- Membrane bioreactor (MBR) after aeration
- Reuse and desalination - pretreatment for Reverse Osmosis

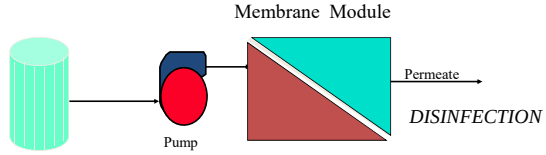
UNIQUE FEATURES OF MEMBRANES

- It's a barrier
- It's modular
- Easy to operate
- Can be made attractive

Membrane Filter Cartridge

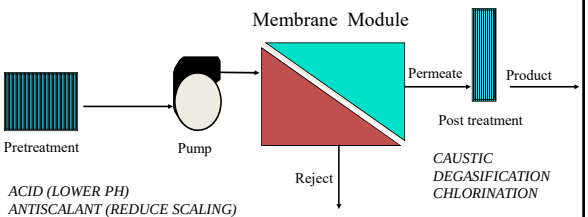


PRE/POST TREATMENT MF / UF



50-200 u
SCREEN

PRE/POST TREATMENT RO



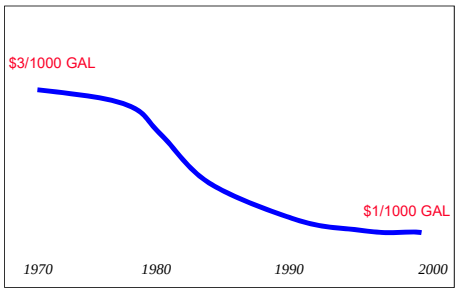
Residential Reverse Osmosis System

EVEN SEAWATER IS BECOMING AFFORDABLE

LOCATION	SALINITY	MGD	$M
► TAMPA	26,000	25	94
► TRINIDAD	34,000	28	120
► LARNACEA	35,000	10	40
► ISRAEL			36 (1ST OF 5)

$2-$3/K GAL

BRACKISH WATER REVERSE OSMOSIS
Cost Reduction



OTHER REASONS FOR GROWTH

FRESH WATER SOURCES LONG DISTANCE AWAY

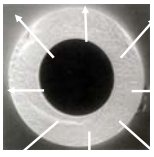
NATIONAL SECURITY/CONFLICTS/INDEPENDENCE
(22 COUNTRIES DEPEND ON OTHERS FOR WATER)

NON-SMART GROWTH
(50% POP. INCREASE IN FL/TX/CA IN NEXT 20 YEARS)

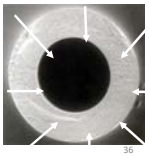
SOMETIMES CHOSEN BECAUSE OF SMALL FOOTPRINT & AESTHETICS

Direction of Permeate flow

- Inside to Outside (e.g. Koch, Norit X Flow) - Pressure
  - Higher cross flow velocity = good flux
  - Better protection for separation layer
  - Need fine pre-strainers to prevent blockage



- Outside to Inside (e.g. Pall, Memcor, Zenon) - Vacuum
  - High compressive strength
  - Larger surface area to fluid
  - High solids tolerance

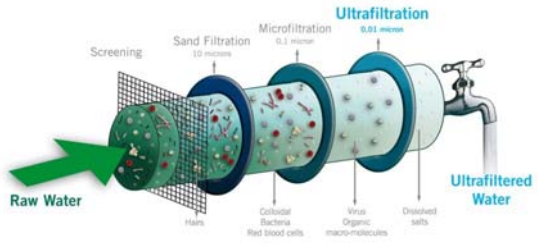


Direction of Permeate flow

- Vacuum
  - Uses less energy
  - Higher solids loading
  - Uses 5x less valves
  - Scales up more easily
  - More competitive

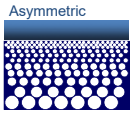
- Pressurized
  - Operates at higher flux
  - Less waste
  - Lower capital cost
  - Low head room
  - No crane needed

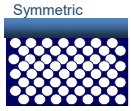
Membrane Filter (MF)

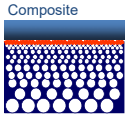


Membrane Structure

- Asymmetric
  - Most common type
  - Thin film for separation
  - Porous support sub-structure
- Symmetric
  - Homogeneous structure
  - Strong
  - Can plug – difficult to clean
- Composite (mainly RO)
  - Diffused layer on substrate







Types of Membrane Configuration

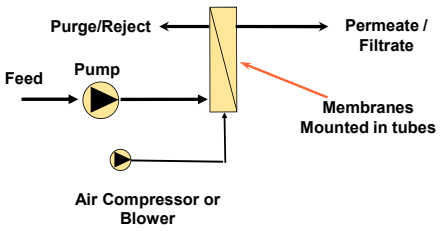
- Spiral
  - Suited to UF, NF and RO
  - Needs good pretreatment
  - Not suited for MF
- Flat Sheet
  - High solids applications – MBR
  - Special processes – e.g. pharmaceutical

- Tubular
  - High solids applications
  - Special processes - dairy
- Hollow Fiber
  - Mainly MF/UF but some RO

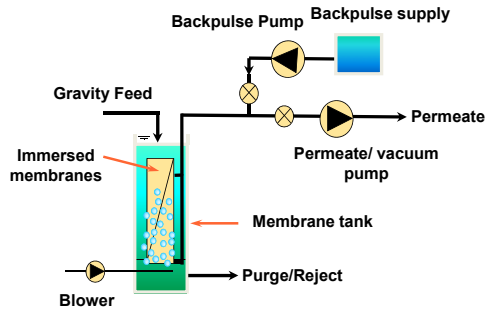
Membrane Hollow Fiber

- Well suited to MF/UF applications
- High solids tolerance
- Back washable
- Easier to chemically clean (PVDF)
  - Oxide (Cl_2) tolerant
  - Acid tolerant
- Flow path
  - Outside to Inside
  - Inside to Outside

Pressurized MF Schematic

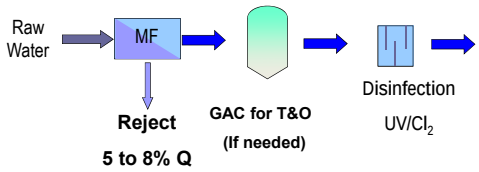


Vacuum MF Schematic



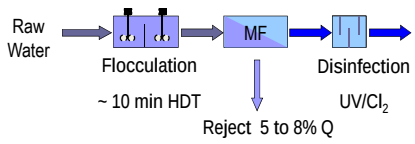
Where does MF fit?

Microfiltration of Surface or Ground Water Under Influence



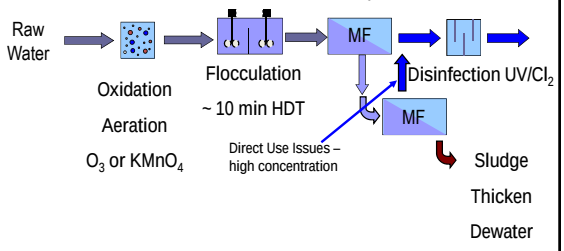
Where does MF fit?

Coagulation + Microfiltration for color and TOC Removal



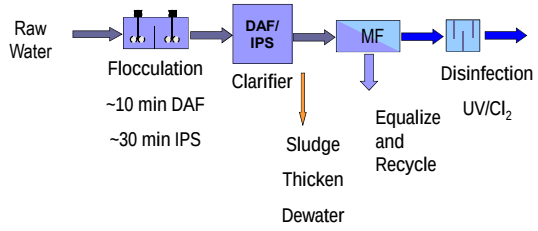
Where does MF fit?

Oxidation + Coagulation + Microfiltration
+ Residuals Concentration by MF



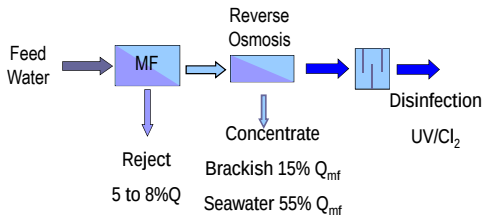
Where does MF fit?

Clarification + Microfiltration for color and TOC Removal



Where does MF fit?

Pre-treatment for Reverse Osmosis



Water Filtration

Contaminant Removal

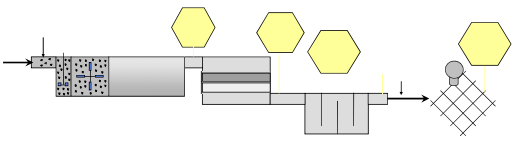
"Top 10" Global Challenges [1]
for the New Millennium

1. **Energy**
2. **Water**
3. Food
4. Environment
5. Poverty
6. Terrorism and War
7. Disease
8. Education
9. Democracy
10. Population

1. Richard E. Smalley, Nobel Laureate, Chemistry, 1996, *Materials Research Society Bulletin*, June 2005

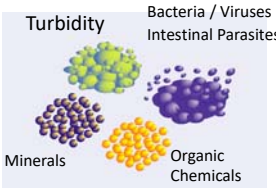
Water Treatment

- Water treatment strategies focus on multiple barrier approaches to assure safe drinking water
  - Turbidity removal (Sedimentation + filtration)
  - Disinfection: Bacteria and Virus Inactivation (Effluent + distribution)



Enhanced Turbidity Removal

Filtration is the **last** physical barrier preventing contaminants into the water distribution system. Any malfunction in the treatment process could result in unsafe drinking water and water quality problems.



Common Contaminants of Concern

- Particles - Turbidity
- Pathogens:
  - Cryptosporidium
  - Giardia
  - Bacteria and viruses
- Organic matter:
  - Total or dissolved organic carbon (TOC or DOC)
  - Color
  - Precursor to disinfection byproducts (DBPs), if using chemicals for disinfection

Turbidity

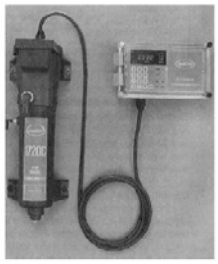
- Turbidity is normally gauged with an instrument that measures the amount of light scattered at an angle of 90° from a source beam
- The units of turbidity are usually in Nephelometric Turbidity Units (NTU).

Bench-top Turbidimeter

- Measurement of "cloudiness" in the water
- Expressed in NTU (Nephelometric Turbidity Units)
- Basis for regulatory compliance and process control
- Turbidimeters must be calibrated to maintain accuracy

Bench-top Turbidimeter & Primary Standards

ON-LINE TURBIDIMETERS

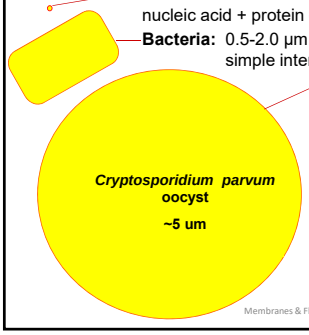


Classes of Microorganisms: The Microbial World

Viruses: smallest (0.02-0.3 µm diameter); simplest: nucleic acid + protein coat (+ lipoprotein envelope)

Bacteria: 0.5-2.0 µm diameter; prokaryotes; cellular; simple internal org.; binary fission.

Protozoa: most >2 µm - 2 mm; eucaryotic; uni-cellular; non-photosynthetic; flexible cell membrane.; wide sizes and shapes; hardy cysts and oocysts; flagellates amoebae, ciliates, sporozoans (*Cryptosporidium* sp.) and microsporidia.



Particles

- Turbidity is a regulated parameter
- Surrogate for Giardia and Cryptosporidium
- Interfere with disinfection
- Affects coagulant dose (for some waters)
- Impact on water treatment costs:
  - Coagulant demand
  - Filter run length
  - Residuals handling and disposal

Colloids

- Small particles
  - No definite size range
  - Generally 1 nm - 10 μm
  - Can be smaller or larger
- In water they are also called “aqua sols”
- Particles can be either organic or inorganic

Types of particles

- Inorganic
  - Clays
  - Metal oxides and hydroxides
    - $Al(OH)_3$ floc in coagulation
    - $Fe(OH)_3$ floc from oxidation of FeII & coagulation
    - MnO_2 from oxidation of MnII
    - SiO_2 (silica)
  - Carbonates
    - $CaCO_3$ and $CaMgCO_3$

Types of particles

- Organic particles:
  - Microoganisms
    - Virus
    - Bacteria
    - Algae
    - Protozoa (*Giardia* & *Cryptosporidium*)
  - Organic debris
  - Humic substances

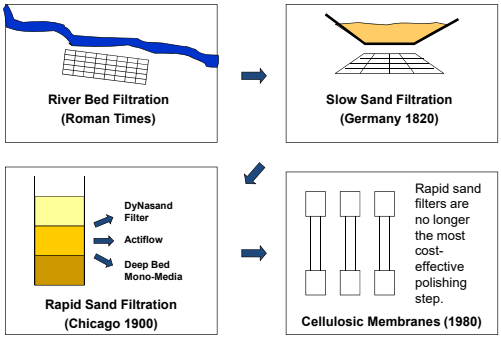
Enhanced Turbidity Removal

Filtration

What is Water Filtration?

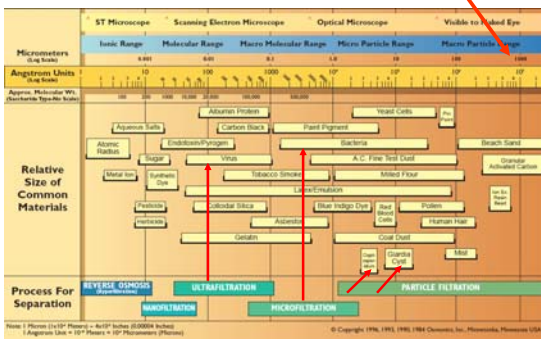
- Process Description:
  - Removal of turbidity and other suspended matter by passing water through a granular porous medium such as sand, anthracite coal, or a membrane.
- Goes back thousands of years; seriously began in 1850 (Europe); 1890 (US)

Evolution of Water Filtration Technology



Filtration Spectrum

Log Scale in Microns (1.0 mm)



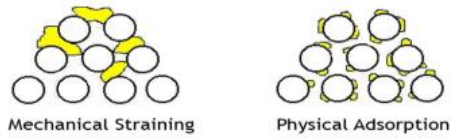
Types of Water Filters

- Typically, filters are classified as one of two general types:
  - Depth filters
    - Granular media filters, sand and anthracite coal
    - Removal mechanisms; adsorption to and interception on media particles
  - Screen filters
    - Membrane filters
    - Having a defined pore size
    - Removal mechanism; straining

Types of Water Filters

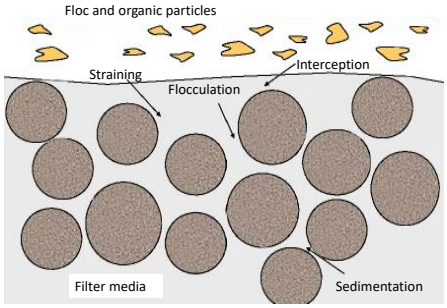
- Granular media, depth filters
  - Slow sand filters
  - Rapid sand filters
  - High-rate, multimedia filters
- Membrane, screen filters
  - Micro-, ultra-, nano-, and RO
- Cake filtration
  - Diatomaceous earth filters

Filtration Attachment Mechanisms



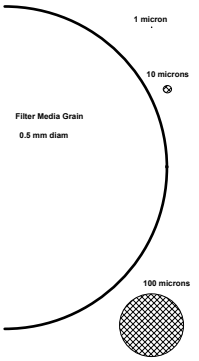
Filtration Attachment Mechanisms

Depth Filter



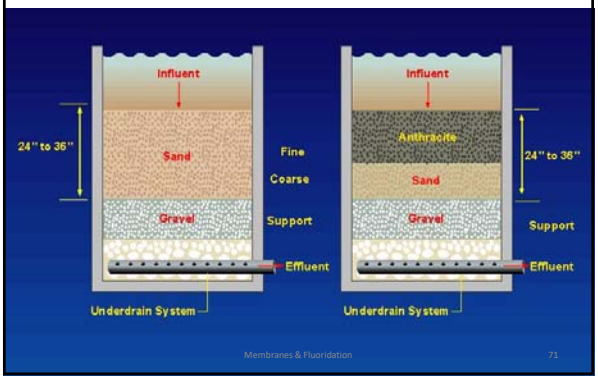
Relative Size of Particles and Filter Media

Soil	1-100 µm
Cryptosporidium oocysts	5 µm
Bacteria	0.3 – 3 µm
Viruses	0.005 – 0.1 µm
Floc particles	100 - 2000 µm
Visible particle w/ 20:20 vision	37 µm

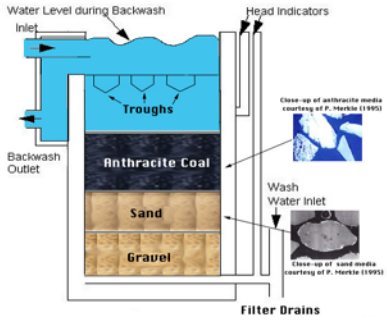


Filter media pores range from 50 to 400 µm depending on media size

Single and Dual Media Filters



Dual Media Filters



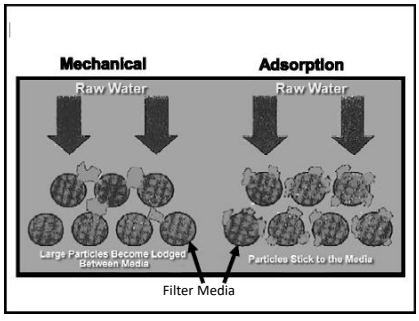
Multimedia Filters

Conventional Filtration versus Membranes

DEPTH FILTRATION	MEMBRANE FILTRATION
PARTICLE ATTACHMENT	
PROBABILITY OF CAPTURE	BARRIER BY MECHANICAL RETENTION
99.6%	99.99%

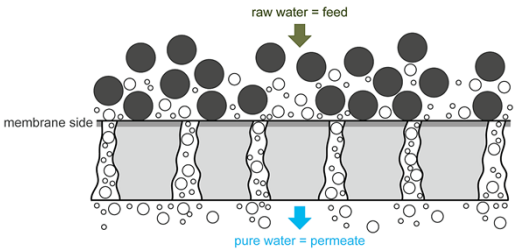
Filtration Attachment Mechanisms

Depth Filter



Filtration Attachment Mechanisms

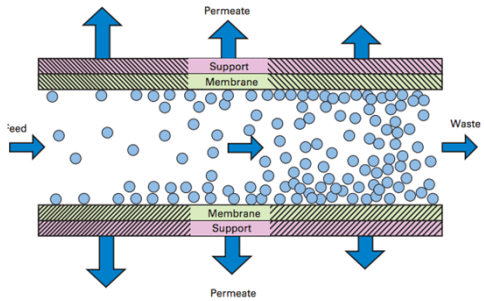
Screen Filter - Membranes



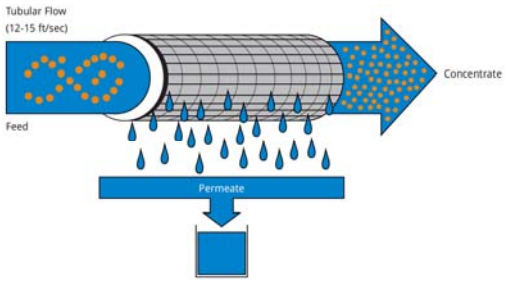
WHAT IS MEMBRANE ?

- A semi-permeable thin layer of material capable of screening out contaminants as a function of their physical / chemical properties
- Despite variations in configurations and types, they are all pressure or vacuum driven except “EDR”, which is Electrical Potential Driven

Membrane Filtration

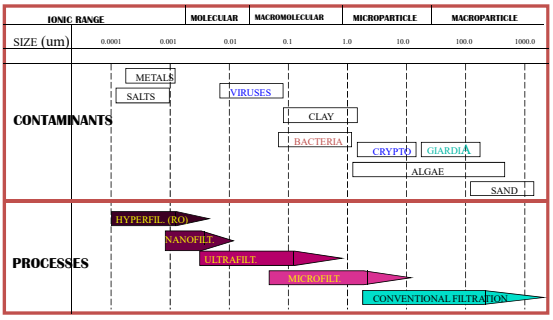


Membrane Filtration

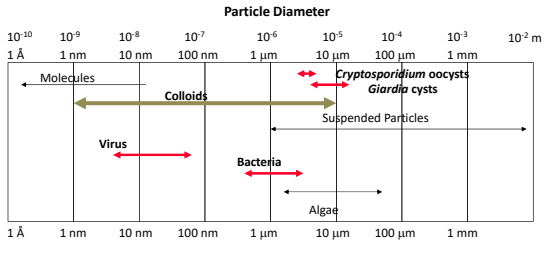


Membrane Filter System

FILTRATION PROCESSES

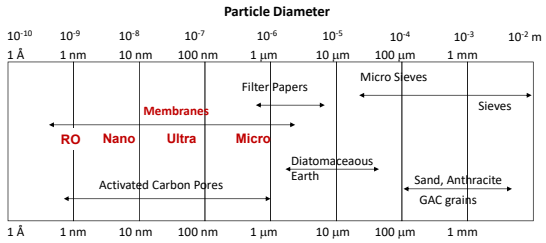


Particle Size



(After Stumm, ES&T, Vol. 11, p. 1066, 1977)

Size Spectrum of Granular Filter Media



(After Stumm, ES&T, Vol. 11, p. 1066, 1977)

Filtration

Depth (Gravity) Filters

Gravity/Granular Media Filtration

- Gravity filtration through beds of granular media is the most common method of removing colloidal impurities in water processing
- During filtration, adsorbtion and interstitial removal results in accumulation of deposits in the upper portion of the filter media

Gravity/Granular Media Filtration

- Because of the reduction in pore area, the velocity of water through the remaining voids increases, shearing off pieces of captured floc and carrying impurities deeper into the filter bed
- As a result, the effective zone of removal passes deeper and deeper into the filter during the filter run

Granular Media Filtration

- Eventually, clean bed depth is no longer available, and breakthrough occurs, carrying solids out in the underflow and causing termination of the filter run

Typical Filter Run

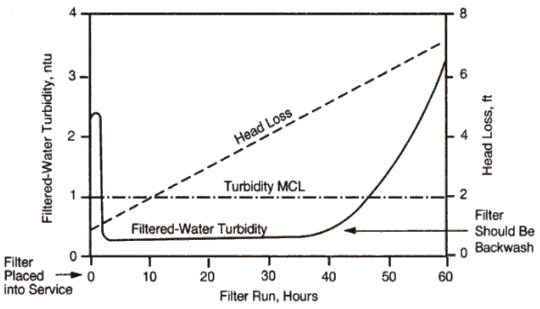
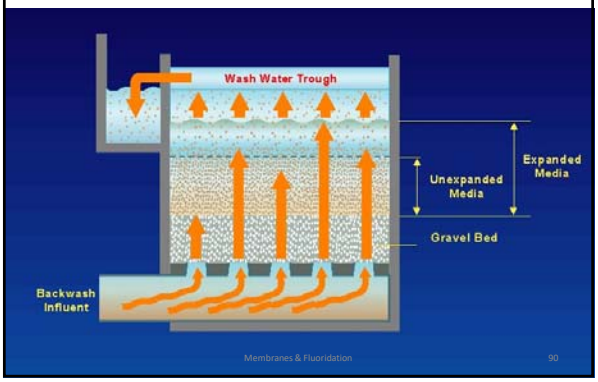


Figure 6-27

Filter Operation

- As the filter begins to clog from accumulated solids, less water will pass through it
- At some point cleaning is required
- Filter operation before cleaning is usually from a few hours to 2 days
- Cleaning is accomplished by reversing the flow of water to the filter, or backwashing

Filter Bed Expansion

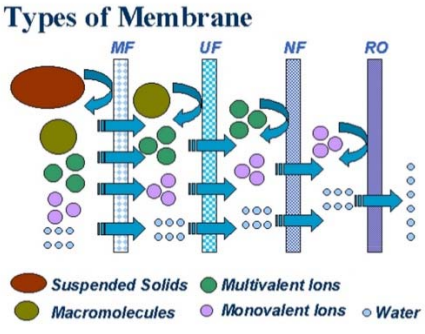


Filtration

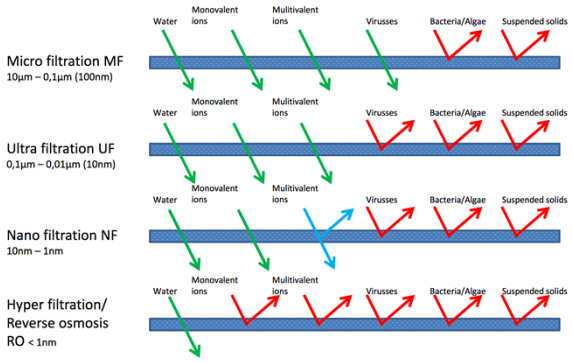
Screen (Membrane) Filters

Membrane Filter Technology

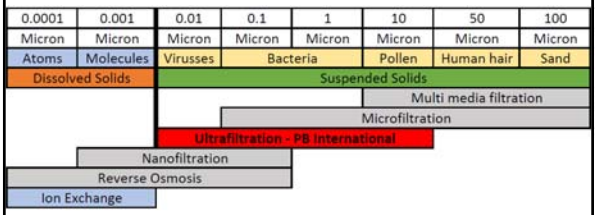
- There are four general categories of membrane filtration systems
  - Microfiltration
  - Ultrafiltration
  - Nanofiltration
  - Reverse Osmosis



Comparison membrane techniques



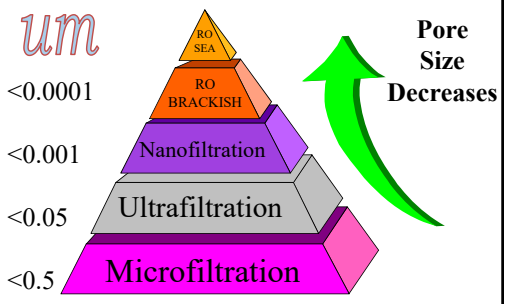
Membrane Filter Technology



Membrane Filter Technology

Filter type	Pore Size, µm	Operating Pressure		Materials Removed
		psi	bars	
Microfilter, MF	**1.0-0.01**	**<30**	**1-2**	**Clay, bacteria, large viruses, suspended solids**
Ultrafilter, UF	**0.01-0.001**	**20-100**	**1.5-7**	**Viruses, proteins, starches, colloids, silica, organics, dye, fat**
Nanofilter, NF	**0.001-0.0001**	**50-300**	**3.5-20**	**Sugar, pesticides, herbicides, divalent anions**
Reverse Osmosis, RO	**< 0.0001**	**225-1,000**	**15-70**	**Monovalent salts**

PORE SIZES



How do they compare?

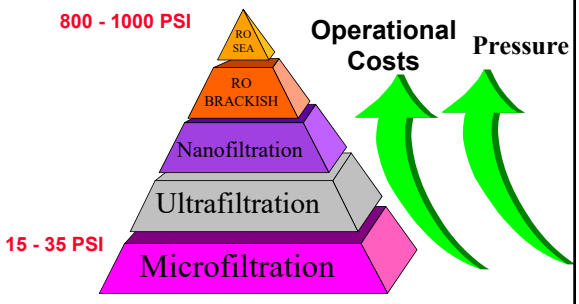
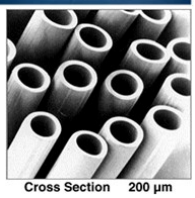


Table I.9 Flux range and pressures in various pressure driven membrane processes.

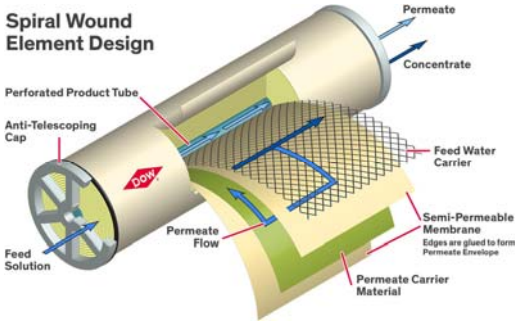
membrane process	pressure range (bar)	flux range ($l.m^{-2}.h^{-1}.bar^{-1}$)
microfiltration	0.1 - 2.0	> 50
ultrafiltration	1.0 - 5.0	10 - 50
nanofiltration	5.0 - 20	1.4 - 12
reverse osmosis	10 - 100	0.05 - 1.4

Hollow Fiber



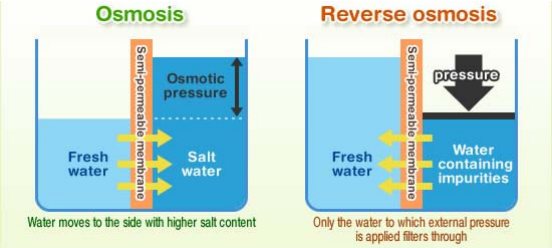
Cross Section 200 µm

Spiral Wound Element Design



Graphic of spiral wound element courtesy of Dow.

Osmosis vs. Reverse Osmosis



DEFINITIONS & TERMINOLOGY

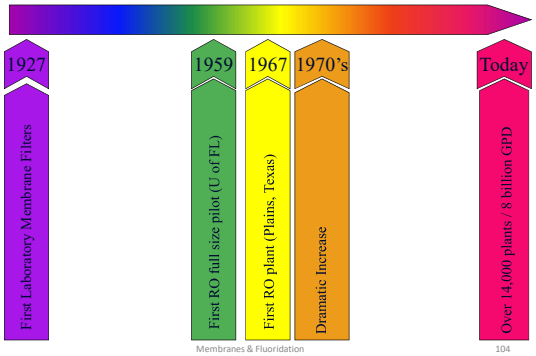
RECOVERY: (PERMEATE FLOW / FEED FLOW)*100

FLUX: PERMEATE FLOW / MEMBRANE SURFACE AREA, GALLONS PER DAY PER SQUARE FOOT(GPD/SF)

CONCENTRATION POLARIZATION: CONCENTRATION

TMP: TRANS-MEMBRANE PRESSURE

History of Membrane Processes



EXAMPLES OF LARGE PLANTS

LOCATION	*TYPE*	*MGD*
• CAPE CORAL, FL	BWRO	15
• SARASOTA, FL	EDR	12
• SCOTTSDALE, AZ	MF	18.5
• DEL RIO, TX	UF	28
• PITTSBURGH, PA	MF	20
• SAN JOSE, CA	MF	6
• JEDDAH	SWRO	15
• FRANCE	UF	15
• FORT MYERS, FL	NF	12
• BAHRAIN	UF/SWRO	10
• TAMPA BAY, FL	SWRO	25
• SAN DIEGO, CA	SWRO	50
• NEWPORT NEWS, VA	BWRO	6
• CHESAPEAKE, VA	CONV/RO	8

SOME MEMBRANE MANUFACTURERS

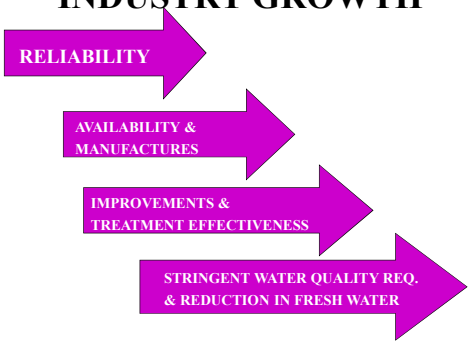
- IONICS
- OSMONICS / DESAL
- DUPONT/DOW
- FILMTEC
- KOCH
- TRISEP
- MEMCOR
- PALL
- FLUID SYSTEMS
- HYDRANAUTICS
- AQUASOURCE
- ZENON

DRAMATIC GROWTH IN 50 YEARS

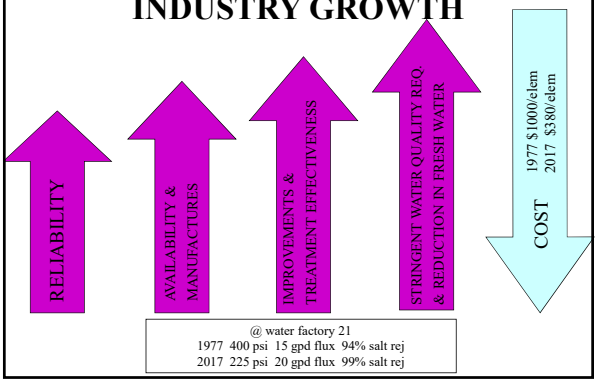
NUMBER OF MEMBRANE PLANTS WORLD-WIDE

- 1970 <10
- 1980 100
- 1990 1000
- 2000 5000
- 2017 >14000

REASONS FOR DRAMATIC INDUSTRY GROWTH



REASONS FOR DRAMATIC INDUSTRY GROWTH



MEMBRANE COSTS

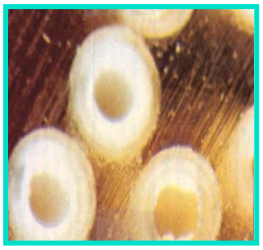
TYPE COST*	PRESSURES psi	EQUIPMENT COST $M/MGD	O&M COST $/KGAL	WATER $/KGAL
MF	10- 30	0.5 - 1	0.3 - 0.4	0.4 - 0.6
UF	20- 75	0.5 - 1.1	0.3 - 0.6	0.4 - 0.7
NF	80 - 150	0.8 - 1.2	0.4 - 0.7	0.6 - 0.9
BWRO	200 - 700	0.9 - 1.5	0.8 - 1.5	1.0 - 2.0
SWRO	700 - 1200	2.0 - 6.0	2.0 - 4.0	2.0 - 4.0

** INCLUDES MEM. REPLACEMENT, LABOR, CHEMICALS, POWER & CAPITAL COST RECOVERY.*

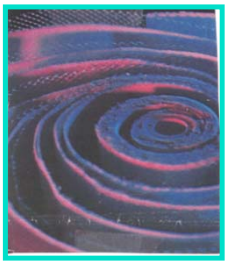
Membrane Materials

- Cellulose Acetate (CA)
- Poly(ether)sulphone (PS or PES)
- Polypropylene (PP)
- Polyamide (PA)
- Polyvinylidienefloride (PVDF)
- Combinations
  - Thin film composites (TFC) e.g. PA on PS
  - Mixtures as solutions or matrices e.g. PVDF +CA

CLOSE - UP VIEW

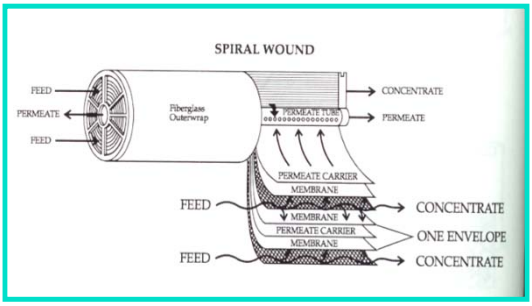


HOLLOW FIBER

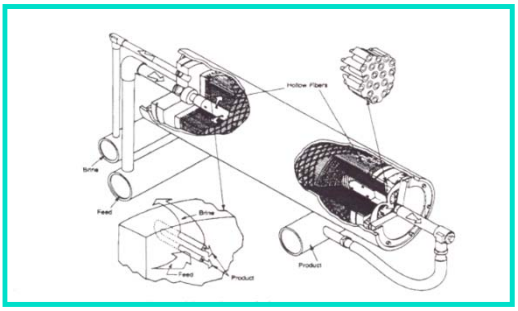


SPIRAL WOUND

SPIRAL WOUND SYSTEM



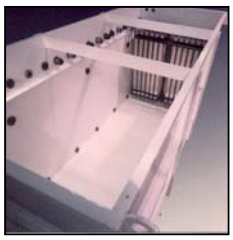
HOLLOW FIBER SYSTEM



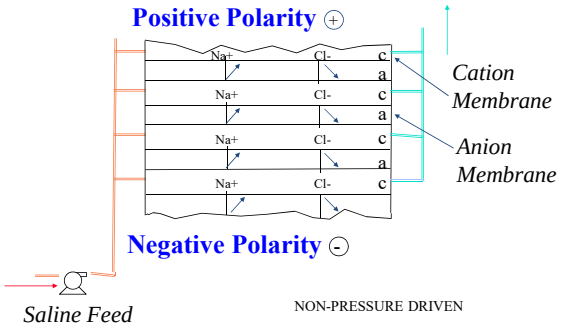
RO/NF Equipment

- Membrane elements
- Pressure vessels
- RO Skids
- Feed pumps
- Piping
- Instrumentation
- Pre/Post treatment

SUBMERGED MEMBRANES ARE THE ANSWER FOR TOUGHER RAW WATERS



EDR requires ion to be charged & is electrical Potential driven



NON-PRESSURE DRIVEN

SOME EXAMPLES

CURRITUCK, NORTH CAROLINA

0.2 MGD

EXPAND TO 0.5

NF SOFTENING

W/ CONV TO BW RO

90% RECOVERY

155 PSI

KILL DEVIL HILL PLANT, NC

3.0 MGD

EXPANDABLE TO 8

FEED TDS: 3,800

3 TRAINS

HARLINGEN , TEXAS

4 MGD RO

3 SKIDS

WASTEWATER PURIFICATION FOR INDUSTRIAL SALE

CITY OF FREDERICK EMERGENCY UF PLANT

1 MGD CAPACITY

HIGH COLIFORM

HIGH TURBIDITY

LEASE (TEMP. PLANT)

EXTREMELY FAST SCHEDULE

JUPITER ISLAND, Florida - BWRO

2MGD (EXPAND TO 4MGD) BWRO

HIGH H_2S

SIGNIFICANT POST TREATMENT

2 STAGE, 80% RECOVERY

FORT MYERS, FLORIDA

12 MGD

EXPAND TO 20

3-4 MGD SKIDS
NF SOFTENING
90% RECOVERY
155 PSI, W/BWRO
CONVERSION
PLANNED

COURTESY OF BOYLE ENGINEERING

PITTSBURGH 25 MGD POST TREATMENT






HOLLOW FIBER, 8 RACKS

VERO BEACH, FLORIDA

6 MGD

EXPAND TO 10

3-2 MGD SKIDS

LOW PRES. BWRO

85% RECOVERY

175 PSI

MARCO ISLAND, Florida - RO

RECENTLY EXPANDED TO 6 MGD

10,000 TDS FEED WATER

SUFFOLK, VIRGINIA

3.8 MGD

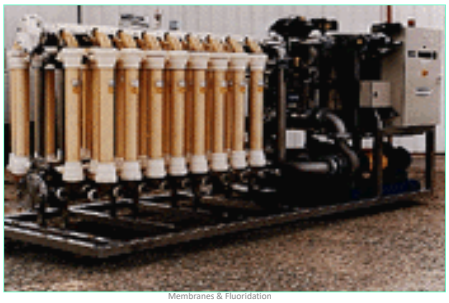
EDR PLANT

TDS REDUCTION & NATURAL FLUORIDE REMOVAL

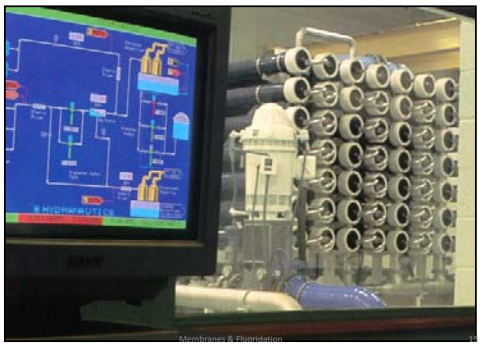
WELL BEYOND MUNICIPAL & CONVENTIONAL APPLICATIONS

- TARGETING SPECIFIC CONTAMINANTS (NITRATE, RADIUM, ARSENIC, ETC.)
- INDUSTRIAL RECOVERY/REUSE
- ULTRA PURE WATER
- PHARMACEUTICAL
- FOOD INDUSTRY
- COOLING TOWER/POWER INDUSTRY
- ELECTRONICS & COMPUTER
- LABORATORIES
- …….. MUCH MORE

FULLY AUTOMATED PACKAGED PLANTS AVAILABLE



EASY TO OPERATE



SMALL FOOTPRINT (12,000 SF BLDG)
25 MGD MF PLANT

CAN BE MADE ATTRACTIVE

10 MGD CAPACITY, VERO BEACH FLORIDA

OPERATIONAL ISSUES

CAREFUL SELECTION & OPERATION IS CRUCIAL

- Requires detailed evaluation & piloting
- May require pretreatment
- Potential fouling/scaling if not properly selected
- Requires operator training & knowledge

SCALING CONCERNS

PRECIPITATION OF SUPER SATURATED CARBONATES, SULFATES, SILICATE, ETC. RESULTS IN TMP INCREASE

IN 70's & 80's USED TO BE A BIG PROBLEM. BUT WE NOW CAN PREDICT IT & CONTROL IT.

- *ALTERING pH & ADDING SCALE INHIBITORS*
- *WELL DESIGNED BRINE SPACERS*
- *ADEQUATE FLUSHING VELOCITIES*
- *OPTIMIZATION OF HYDRAULICS IN THE SYSTEM*
- *EFFECTIVE CLEANING*

FOULING CONCERNS

PHYSICAL DEPOSITS (SUCH AS CLAY, SILT, METAL OXIDES, BIOLOGICAL SLIME, ALGAE, ETC.) ON THE SURFACE & INTO MEMBRANE PORES CAUSES INCREASE IN TMP & POOR WATER QUALITY

ORGANIC & PARTICULATE FOULING CAN BE CONTROLLED BY MEMBRANE SELECTION AND OPTIMIZED OPERATION/CLEANING PROCEDURES

Optimized Pretreatment selection, design & operation is the key to fouling prevention

HOW TO PREVENT FOULING AND SCALING ?

- CONTINUOUSLY MONITOR RAW WATER
- KEEP PRE-TREATMENT CLEAN
- MONITOR FEED WATER CHANGES
- FLUSH SYSTEM IF NOT IN USE
- FOLLOW CLEANING PROCEDURES
- PERFORM TREND ANALYSIS
- CONDUCT PROFILING (sample each vessel)
- PERFORM PROBING (if necessary)
- ROUTINE SDI TESTING

Plant Process & Equipment

- Pre-treatment
- Post treatment
- Controls & instrumentation

Custom Plant Designs

OPERATIONAL CHARACTERISTICS

	FLUX	PERM. CONC.
FEED TEMP*.	↑ ↑	↑
FEED PRESSURE	↑ ↑	—
FEED CONC.	↑ ↓	

** ABOUT 3% PER DEGREE CELSIUS*

A FEW OTHER SIDE ISSUES TO KNOW

CHLORINE TOLERANT MEMBRANES

Industry has finally realized most surface water systems require chlorine at the head works for oxidation, disinfection & bio-growth control

Need more chlorine tolerant membranes with higher flux rates

APPLICATION / INNOVATIONS

There is a great demand on conventional plant filtration upgrades, which likely means membranes upgrades that are:

- Tough
- Chemical tolerant
- High flux
- Low energy

CLEANING

- Clean when 10-15% drop in normalized flow
- If more than 30% drop, may be impossible to fully restore performance
- Always follow manufacturer's recommendations
- Chemical is mixed & heated in a tank
- Feed at a recommended rates
- Flush
- Put back online

CLEANING CHEMICALS

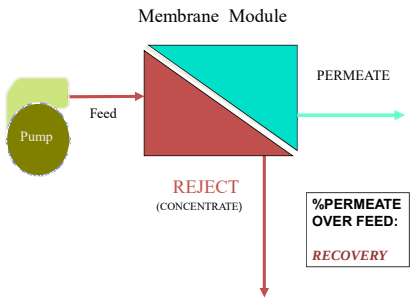
- Depends on type & degree of fouling and scaling
- Contact manufacturer or third-party specialty RO cleaning firms
- Generally low pH followed by high pH (exception is for oil deposits which is reversed)
  - Low pH – dissolve scaling
  - High pH – organic removal
- Sometimes skids are soaked with permeate for a few hours before cleaning

CLEANING REMEDIES

- CARBONATE SCALE:
  - Easy to remove if detected early, low ph with citric acid
- ORGANIC FOULANTS:
  - If detected early and have not been absorbed to membrane surface, normal cleaning is sufficient
- MICROBIAL DEPOSITS:
  - Clean, flush, sanitize piping, and pre-treatment
- SULFATE SCALE:
  - Much more difficult, especially barium and strontium sulfates. best is to prevent from happening

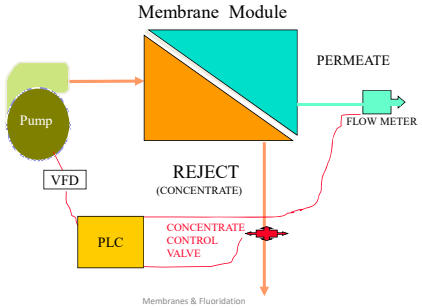
OVERALL SYSTEM CONTROL

SIMPLIFIED SCHEMATIC

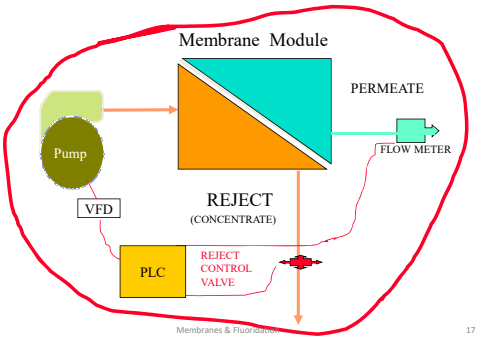


SIMPLE 3 STEP CONTROL

PERMEATE FLOW IS SET
CCV MODULATES TO ACHIEVE DESIGN RECOVERY
FEED PUMP VFD KEEPS UP WITH PRESSURE TO GIVE CONSTANT PERMEATE FLOW



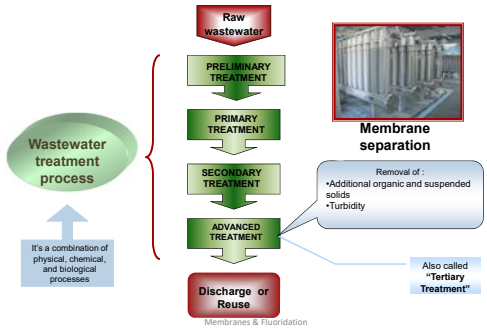
UPSTREAM SEES ONE GIANT CONTROL VALVE



Water Reuse

Using Membrane Filters

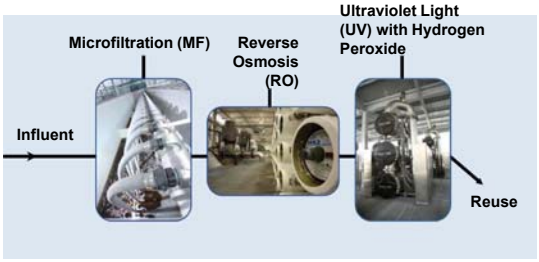
Role of Enhance Solids Removal



Reuse Regulations and Rules

- EPA Suggested Guidelines
  - pH = 6-9
  - $BOD_5 \leq 10$ mg/L
  - **Turbidity ≤ 2 NTU**
  - E. coli = NONE
  - Residual $Cl_2 \geq 1$ mg/L
- Filtration effectiveness evaluated by ***turbidity***
  - NTU: nephelometric turbidity units
  - Particle counts

Wastewater Purification Process



California Water Recycling Criteria

- Media Filtration
  - 5 gpm/ft^2 maximum
  - **≤ 2 NTU average daily turbidity**
  - ≤ 5 NTU 95% of time in any 24-hour period
  - 10 NTU maximum
  - Coagulation required unless secondary effluent ≤ 5 NTU
- Membranes
  - **≤ 0.2 NTU 95 % of time in any 24-hour period**
  - 0.5 NTU maximum

Typical Reuse Water Quality

Constituent	After BNR plus disinfection	After BNR plus depth filtration and disinfection	After BNR plus microfiltration, RO, and disinfection
TSS, mg/L	5-20	1-4	≤ 1
BOD_5, mg/L	5-20	1-5	0-2
TN, mg/L	2-12	2-12	≤ 1
NO_3, mg/L	1-10	1-10	≤ 1
TP, mg/L	0.1-0.5	0.1-0.5	≤ 0.5
Turbidity, NTUs	2-6	≤ 2	0.1 - 0.5
Microbiology, MPN/100 mL			
Bacteria	2.2-240	≤ 2.2	≈ 0
Protozoan	5-10	≤ 1	≈ 0
Viruses	100-10000	≤ .0001	≈ 0

Wastewater Reclamation/Reuse

Increasing Water Sources

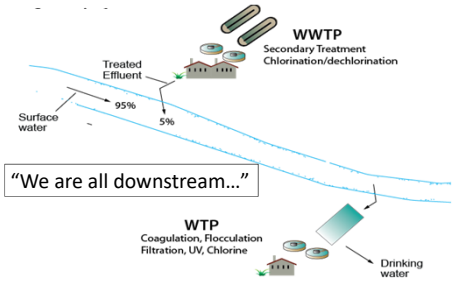
- Improve current usage:
  - Promote water conservation
  - Repair and improve water distribution systems
- Getting water out of waste:
  - **Reclamation of wastewater for reuse**
  - Desalination of brackish and sea waters

What is Water Reuse/Recycling?

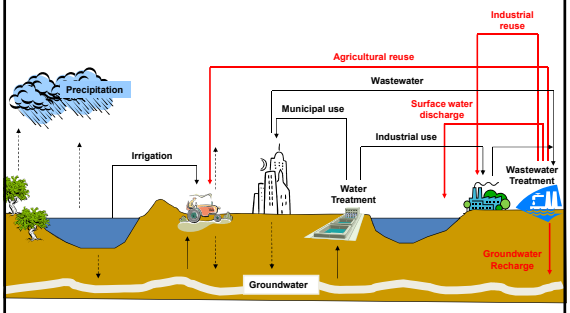
Non-Potable
- Irrigation—Golf, Residential, etc.
- Cooling Towers, Boiler Feed
- Wetland Restoration

Potable
- Indirect
  - Seawater Intrusion Barrier
  - Groundwater Replenishment
  - Aquifer Storage/Recovery
  - Reservoir Augmentation
- Direct
  - Pipe-to-Pipe

De facto Reuse is Common



Wastewater Reclamation and Reuse



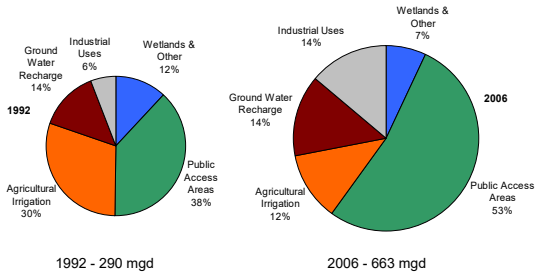
Major Users of Reclaimed Water

- Agriculture
- Golf courses
- Residential landscapes
- Ground water recharge
- Industrial

Reclaimed Water - Florida

- Highly treated wastewater
- Good source of water for irrigation and industrial uses
- Has been known about for many years
- Became more widely used in Florida in the 1980's and 1990's
- Florida is now one of the largest users of reclaimed water in the U.S.

Reclaimed Water 1992-2006



1992 - 290 mgd

2006 - 663 mgd

California - Carson Regional Water Recycling Plant

- LA Water District
- Capacity = 5.0 MGD
- Nitrification
- Microfiltration and RO
- Effluent - process water for an oil refinery

California – Santee Water Reclamation Facility

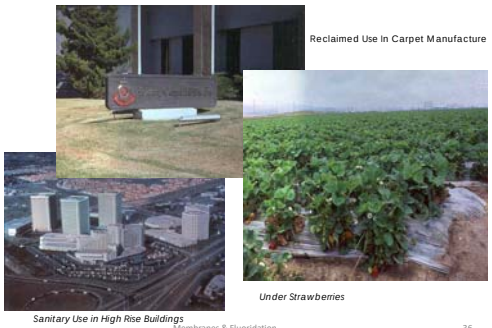
- 2.1 MGD
- Biological nutrient removal process
- Denitrification filters
- Effluent - multiple uses

California - Michelson Water Recycling Plant

- Irvine Ranch Water District (IRWD)
- Capacity = 30 MGD
- Effluent – multiple uses

IRWD Landscape Reclaimed Water Uses

IRWD Other Reclaimed Water Uses



Africa - Windhoek, Namibia

Natural Beauty … but not Enough Water

Windhoek's Wastewater Reclamation Plant for Potable Use

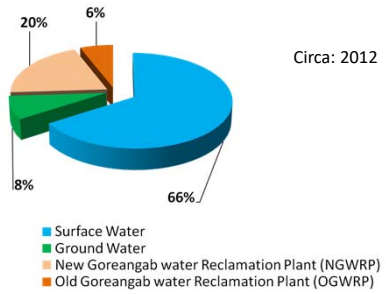
Goreangab Reclamation Plant (Windhoek)

The only wastewater reclamation plant in the world producing water for **direct** potable reuse

Windhoek's Goreangab Water Reclamation Plant

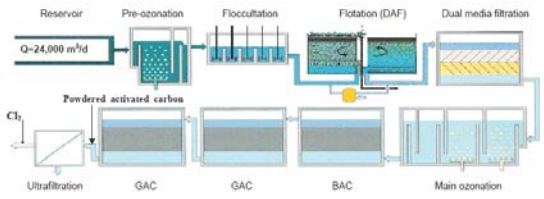
- Namibia, 1968
- Initially met 25% of city's water demand
- Now can provide up to 50% of the potable supply

Windhoek Water Sources



Circa: 2012

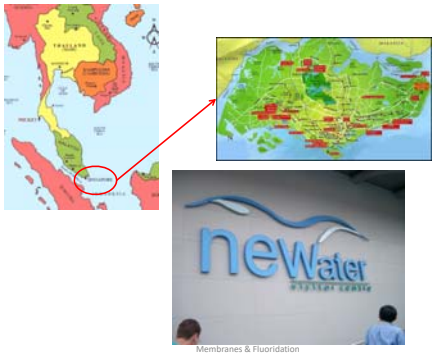
The Treatment Scheme: A Multiple Barrier Approach



Most Important: Public Acceptance and Trust in the Quality of Water

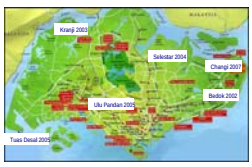
- Breaking down the psychological barrier (the **"yuck factor"**) is not trivial
  - Rigorous monitoring of water quality after every process step
  - Final product water is thoroughly analyzed (**data made available to public)**
- The citizens of Windhoek have a genuine pride in the reality that their city leads the world in the reclamation of wastewater for **direct** reuse

NEWater Singapore

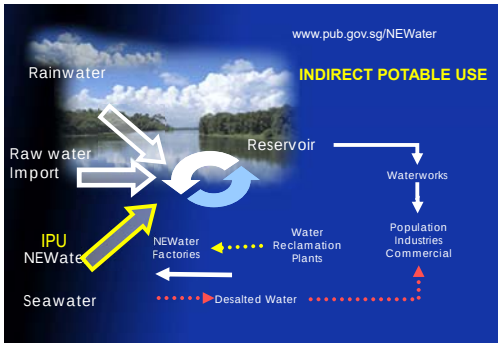


NEWater Singapore

- NEWater satisfies 30% of potable water demand
- Goal: > 50% of potable water demand
- 5 NEWater plants
- >100 mgd production



NEWater Singapore



2000 - Demonstration Plant, Bedok District, Singapore

- Studies show MF/RO as preferred process
- Full scale demonstration plant
  - 2.5 MGD
  - Microfiltration, RO, UV
- 2-year study of 191 parameters including:
  - Physical/chemical analysis
  - Pesticide/herbicide analysis
  - Radionuclides
  - Synthetic and natural hormones
  - Microbiological

Public Consultation and Outreach

Singapore's Prime Minister
Goh Chok Tong

Ubiquitous Bottled Water

NEWater Visitor Centre

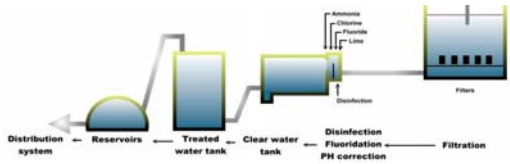
Fluoridation

Objectives

- What are the advantages and disadvantages of fluoridation?
- How does fluoridation fit into the water treatment process?
- What chemicals and equipment are used to fluoridate water?

Fluoridation

- After filtration, a fluoride chemical can be added to treated drinking water supplies
- Optional, not mandatory



Water Fluoridation

- **Fluoridation** is the process of adjusting the concentration of fluoride in public water supplies for the prevention of dental decay
- Fluoride has been added to drinking water in the United States since about 1945 and it has been estimated that every dollar spent on fluoridation has saved $50 in dentists' bills.

Water Fluoridation

- Discovered through comparisons of the teeth of children from areas that have different concentrations of natural fluoride in their drinking water.

Water Fluoridation

- The goal of water fluoridation is to control the amount of fluoride each customer ingests per day
- Ambient temperatures determine customer water consumption
- People tend to drink more water when it's hot, so the optimal fluoride concentration in warm climates will be lower than in cool climates

Water Fluoridation

- Sodium fluoride (NaF) was the first chemical to be used for water fluoridation in the US
- Original fluoride concentrations of 0.7 to 1.2 mg/L were set based on regional temperatures

Water Fluoridation

- Fluoride in water has been proven to prevent tooth decay among children and to prevent root tip rot
- Fluoride acts by strengthening the tooth enamel and by making the enamel more resistant to decay
- This is a long-term process, with results usually being noticeable only after about 4 to 6 years.

Fluorosis and Other Problems

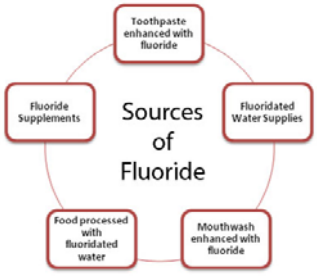
- Although fluoride is safe at the concentrations used in water treatment, an excess amount of fluoride in water can result in mottled brown stains on teeth
- These stains are known as **fluorosis**
- Fluorosis results from fluoride concentrations of 2 to 13 ppm in drinking water

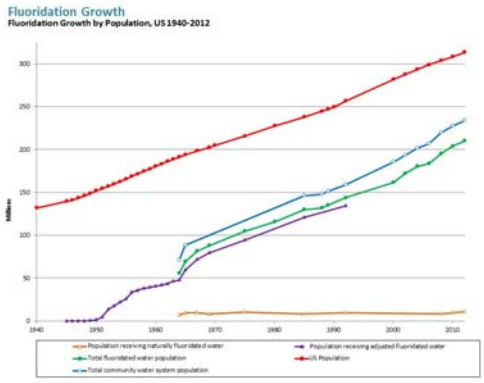
Fluorosis and Other Problems

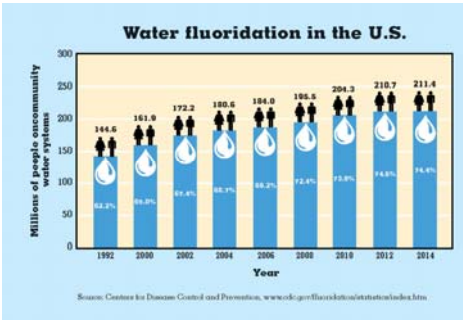
- Although fluorosis is only an aesthetic problem, treatment plants strive to prevent fluorosis by setting the fluoride concentration at ~0.7 mg/L
- Fluoride levels above 4 mg/L exceed Maximum Concentration Levels (MCLs) established under the Safe Drinking Water Act, e.g., 1986 Fluoride Rule

Other Sources of Fluoride

- Toothpaste
- Mouthwash
- Food
- Supplements





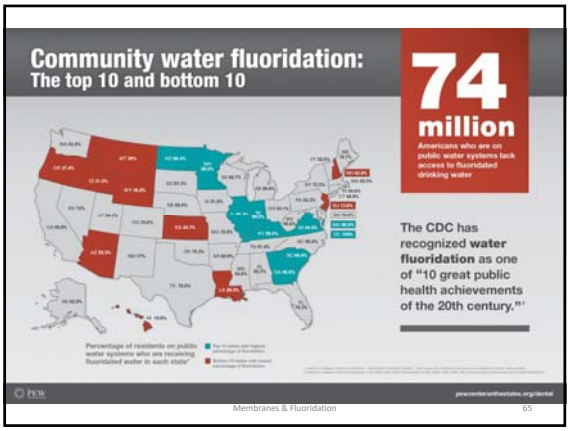


Fluoride is an Ion naturally found in nature

- A small amount of fluoride is essential in a diet for proper tooth and bone formation

Fluoridation Endorsements

- More than 100 scientific, professional, and medical associations have recognized the benefits and safety of water fluoridation including:
  - American Dental Association
  - American Water Works Association
  - Public health groups worldwide



Annual Average of Maximum Daily Air Temperature,* °F	(°C)	Recommended Control Limits of Fluoride Concentration, *mg/L* Lower	Optimal	Upper
53.7 and below	(12.0 and below)	0.9	1.2	1.7
53.8–58.3	(12.1–14.6)	0.8	1.1	1.5
58.4–63.8	(14.7–17.6)	0.8	1.0	1.3
63.9–70.6	(17.7–21.4)	0.7	0.9	1.2
70.7–79.2	(21.5–26.2)	0.7	0.8	1.0
79.3–90.5	(26.3–32.5)	0.6	0.7	0.8

Each individual State Health Department uses CDC information to establish optimal fluoride levels

Fluoridation Chemicals

- Dry chemicals:
  - Sodium Fluoride (NaF)
  - Sodium Fluorosilicate (Na_2SiF_6)
- Liquid Chemical:
  - Fluorosilicic Acid (H_2SiF_6)

Sodium Fluoride (NaF)

- NaF:
  - Is a white, odorless material available either as a powder or as various size crystals with a specific gravity of 2.79

Sodium Fluoride (NaF)

- Sodium fluoride was the first chemical used for fluoridation and is still used in small installations
- Saturators are commonly used for making 4.0% NaF solutions
- Sodium fluoride is not generally used in large plants because of the high cost of chemicals and bulky saturators

Sodium Fluoride (NaF)

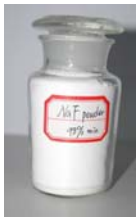
- When added to water, sodium fluoride(NaF) dissociates into sodium and fluoride ions:

$$NaF \leftrightarrow Na^{+} + F^{-}$$

- The pH of a sodium fluoride solution varies with the type and amount of impurities present
- Solutions prepared from common grades of sodium fluoride have a pH near neutrality (approximately 7.6)

Sodium Fluoride (NaF)

- Sodium fluoride is available in purities ranging from 97 to over 98 percent



Sodium Fluorosilicate (Na_2SiF_6)

- Na_2SiF_6, as known as sodium silicofluoride, is a white, odorless, crystalline material with a specific gravity of 2.68

Sodium Fluorosilicate (Na_2SiF_6)

- When sodium fluorosilicate is dissolved in water, virtually 100 percent dissociation occurs:

  $Na_2SiF_6 \leftrightarrow 2Na^+ + SiF_6^=$

- Fluorosilicate ions ($SiF_6^=$) may react in two ways, most common is hydrolysis of $SiF_6^=$ releasing fluoride ions and silica (SiO_2):

  $SiF_6^= + 2H_2O \leftrightarrow 4H^+ + 6F^- + SiO_2\downarrow$

- Silica is very insoluble in water

Sodium Fluorosilicate (Na_2SiF_6)

- Alternatively, $SiF_6^=$ dissociates very slowly, releasing fluoride ions and the gas silicon tetrafluoride (SiF_4):

  $SiF_6^= \leftrightarrow 2F^- + SiF_4\uparrow$

- Silicon tetrafluoride reacts with water to form hydrogen fluoride, silicic acid and silica:
  - $SiF_4\uparrow + 3H_2O \leftrightarrow HF + H_2SiO_3$
  - $SiF_4\uparrow + 2H_2O \leftrightarrow 4HF + SiO_2\downarrow$
  - $HF \leftrightarrow H^+ + F^-$

Sodium Fluorosilicate (Na_2SiF_6)

- Solutions of sodium fluorosilicate are acidic, with saturated solutions usually exhibiting a pH of between 3 and 4
- Sodium fluorosilicate is available in purities of 98 percent or higher

Fluorosilicic Acid (H_2SiF_6)

- **Fluorosilicic acid (H_2SiF_6)**, also known as hexafluorosilicic, silicofluoric, or hydrofluorosilicic acid is available commercially as a 20 to 35 percent aqueous solution
- **Fluorosilicic acid** is the most used fluoridating chemical

Fluorosilicic Acid (H_2SiF_6)

Fluorosilicic Acid (H_2SiF_6)

- **Fluorosilicic acid (H_2SiF_6)** solutions of 20 to 35 percent have a low pH (1 to 2), is a straw-colored, transparent, fuming, corrosive liquid having a pungent odor and an irritating action on the skin
- The liquid may be fed directly into the raw water or may be diluted

Fluorosilicic Acid (H_2SiF_6)

- **Fluorosilicic acid (H_2SiF_6)** is a popular choice in many water treatment plants because it is usually the least expensive fluoridation chemical and is the easiest to feed
- However, it can be expensive to ship since it is a liquid

Fluorosilicic Acid (H_2SiF_6)

- **Fluorosilicic acid (H_2SiF_6)** solutions of 20 to 35 percent have a low pH (1 to 2), is a straw-colored, transparent, fuming, corrosive liquid having a pungent odor and an irritating action on the skin
- Fluorosilicic acid dissociates in solution virtually 100 percent

Fluorosilicic Acid (H_2SiF_6)

- **Fluorosilicic acid's (H_2SiF_6)** chemistry is very similar to that of sodium fluorosilicate (Na_2SiF_6)
  - $H_2SiF_6 \leftrightarrow 2HF + SiF_4\uparrow$
  - $SiF_4\uparrow + 2H_2O \leftrightarrow 4HF + SiO_2\downarrow$
  - $SiF_4\uparrow + 3H_2O \leftrightarrow 4HF + H_2SiO_3$
  - $HF \leftrightarrow H^- + F^+$

Fluorosilicic Acid (H_2SiF_6)

- Fluorosilicic acid should be handled with great care because of its low pH
- It will cause a "delayed burn" on skin tissue
- Fluorosilicic acid fumes are lighter than air and will rise instead of settle to the floor

Item	Sodium Fluoride, NaF	Sodium Fluorosilicate, Na_2SiF_6	Fluorosilicic Acid, H_2SiF_6
Form	Powder or crystal	Powder or very fine crystal	Liquid
Molecular weight	42.00	118.1	144.08
Commercial purity, %	97–98	98–99	20–30
Fluoride ion, % (100% pure material)	42.25	60.7	79.2
Pounds required per mil gal for 1.0 ppm F at indicated purity	18.8, 98%	14.0, 98.5%	35.2, 30%
pH of saturated solution	7.0	3.5–4.0	1.2 (1% solution)
Sodium ion contributed at 1.0 ppm F, ppm	1.17	0.40	0.00
F ion storage space, ft^3/100 lb	22–34	23–30	54–73
Solubility at 77°F, g/100 mL water	4.0	0.762	Infinite
Weight, lb/ft^3	65–90	85–95	10.5 lb/gal, 30%
Shipping containers	100-lb bags, 125–400-lb fiber drums, bulk	100-lb bags, 125–400-lb fiber drums, bulk	13-gal carboys, 55-gal drums, bulk

Chemical Feed Systems

- Dry feed systems
- Solution feed systems
- In general, solution feeders are more expensive than dry feeders and are used in smaller systems
- Dry feeders are used in large treatment plants
- In both cases, the chemicals are added to water in a liquid form

Chemical Feed Systems

- Equipment used to feed fluoride into water comes in two categories:
  - Dry feeders
  - Solution feeders
- The distinction is whether the chemical is measured as a liquid (in **solution feeders**) or as a solid (in **dry feeders)**

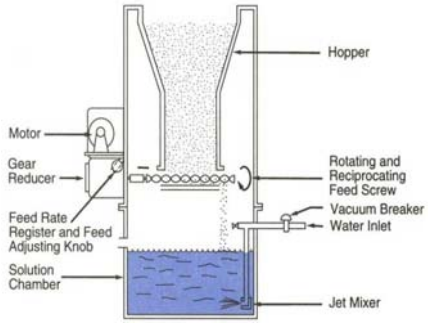
Dry Feeders

- Volumetric
- Gravimetric

Dry Feeders

- Volumetric
  - Delivers a set volume of chemical with each revolution of a screw
  - Varying the speed of the screw varies the feed rate
  - Less expensive
  - Less accurate

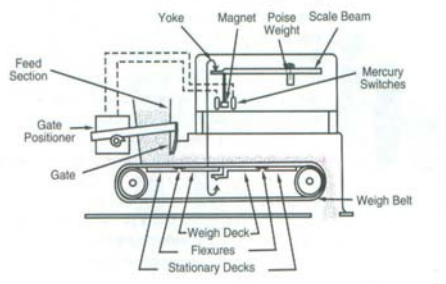
Volumetric Dry Feeder



Gravimetric Feeders

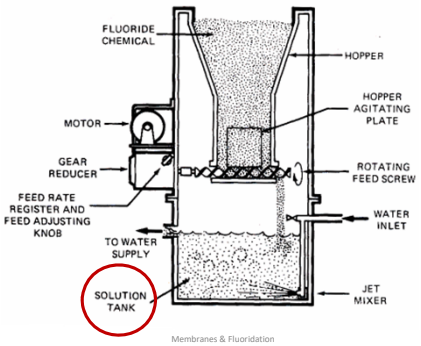
- Delivers a certain weight of chemical for each revolution of a conveyor belt
- Feeds a predetermined weight
- Very accurate
- More expensive.

Gravimetric Feeders

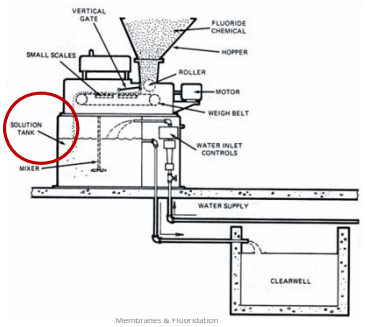


Both types of dry feeders discharge into a solution tank. Tanks must have a mixer to properly dissolve the chemical.

Solution Tanks



Solution Tanks



Solution Feeders

- Sodium Fluoride solution from a saturator
- Commercially prepared Fluorosilicic Acid from a tank or drum
- Metering pumps (Diaphragm or peristatic)
  - Feed a constant rate at a constant speed
  - Controlled by flow rate or manually set

Diaphragm-Type Metering Pump

Speed Control

Manual / Flow Pace Selector

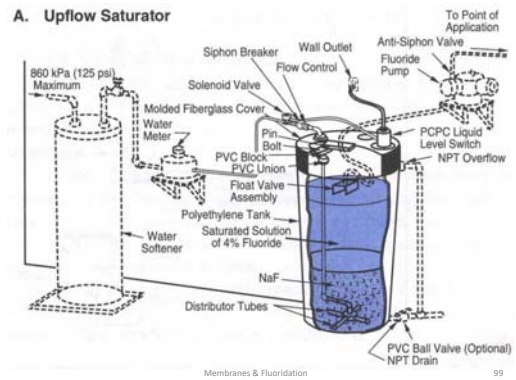
Stroke Control

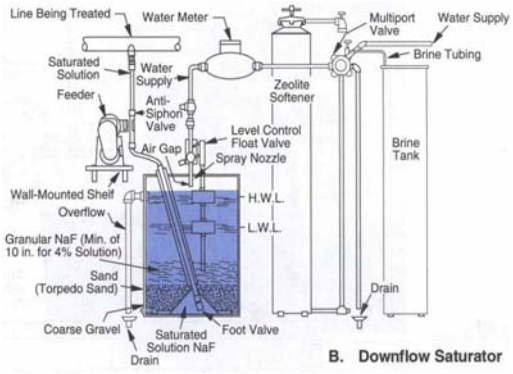
Saturators

- A saturator feed system is unique to fluoridation
- It's based on the principle that a saturated fluoride solution (4%) will result if water can trickle through a bed containing a large amount of sodium fluoride (NaF)
- A small pump is used to feed the saturated solution into the water being treated

Saturators

- Saturators can either be up-flow, with water flowing from the bottom to the top of the saturator, or downflow, in which water flows down through the saturator
- Up-flow saturators are preferred because they are easier to clean and maintain



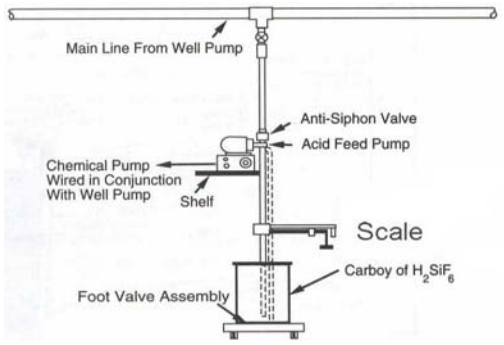


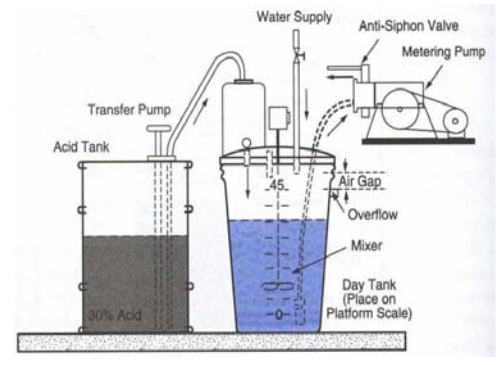
Saturators create a fluoride solution of 4 percent. This known concentration can be fed to a water supply by a chemical feed pump.

Keep at least 6 inches of chemical in the saturator, 10 inches for higher flow systems.

Acid Feed System

- Simplest installation
- Fed right from the shipping container
- Larger Systems - Truck unloads to storage tank; operator transfers to day tanks
- Small Systems - Carboys





Backflow or Back Siphonage

- Must have protection against backflow or back siphonage when a concentrated chemical is connected to a water system

Monitoring

- As a reminder, excess fluoride concentrations in water can cause illness
- The operator should monitor the fluoride concentration once a shift, or at least once per day to prevent overfeeding

Monitoring

- Underfeeding is less of a problem than overfeeding and fluoridation equipment can be shut down for cleaning and maintenance for short periods without shutting down the entire water treatment plant

Fluoride Chemical Safety

- Three pathways of overexposure
  - Ingestion
  - Inhalation
  - Bodily contact
- Safety equipment
  - Goggles
  - Respirator or mask (approved by NIOSH)
  - Rubber gloves
  - Rubber aprons
  - Rubber boots

Fluoride Chemical Safety

- Treatment plant operators must use proper handling techniques to avoid overexposure to fluoride chemicals
- Dusts are a problem when sodium fluoride and sodium fluorosilicate are used
- The use of personal protective equipment (PPE) should be required when any fluoride chemical is handled or when maintenance on fluoridation equipment is performed

Fluoride Chemical Safety

- Solid forms of fluoride are the most problematic to operators, since inhaling fluoride dust is very dangerous
- A dust collector should be used, and a respirator should be worn when handling fluoride powders

Fluoride Chemical Safety

- Liquid forms, such as fluorosilicic acid (H_2SiF_6), can also be dangerous
- Fluorosilicic acid produces poisonous fumes which must be vented, and which are irritating to the skin
- The liquid itself can cause burns when allowed to touch skin

Fluoride Chemical Safety

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Fluoride Chemical Safety

- The most extreme safety problem when dealing with fluoride is fluoride poisoning, which can be fatal.
  - However, fluoride poisoning occurs only when a large amount of fluoride - approximately one tablespoon - is ingested
  - This is an amount much larger than would normally be inhaled while handling dry fluorides.

Fluoride Chemical Safety

- Accidental ingestion of fluoride chemicals can occur through contaminated food and drink
- The operator should always wash his hands after handling fluoride chemicals and should not eat, drink, or smoke in areas where fluorides are used or stored

Summary

Comments and Conclusions

Summary

- The purpose of water fluoridation is to prevent dental disease
  - Recommended fluoride concentration is 0.7 mg/L
- Water fluoridation is the safest, most effective and most economical public health measure for preventing and reducing dental cavities
- EPA's 1986 Fluoride Rule set drinking water guidelines of less than 4 mg/L to protect against skeletal fluorosis

Summary

- A membrane is a thin layer of semi-permeable material that separates substances when a driving force is applied across the membrane
- Membrane processes are increasingly used for removal of bacteria, microorganisms, particulates, and natural organic material in water and wastewater treatment processes

Summary

- As advancements are made in membrane manufacture and module design, capital and operating costs continue to decline
- The membrane processes discussed here are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO)
- Applications include upgrades to drinking water treatment, tertiary filtration of sewage effluent for reuse, and desalination

Questions?

Thank You

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"Anyone who can solve the problems of water will be worthy of two Nobel prizes – one for peace and one for science."

- John F. Kennedy