Assessment of Membrane Fouling and Standardization of Testing Methods for Membranes

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(RO/NF Applications for Drinking Water Treatment)

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Overview

- Membrane Applications for Water Treatment in America
- Membrane Fouling
- Membrane Performance Assessment
- Concluding Remarks

BACKGROUND

Applications of Membrane Processes for Drinking Water Treatment in America

Potable Water Treatment

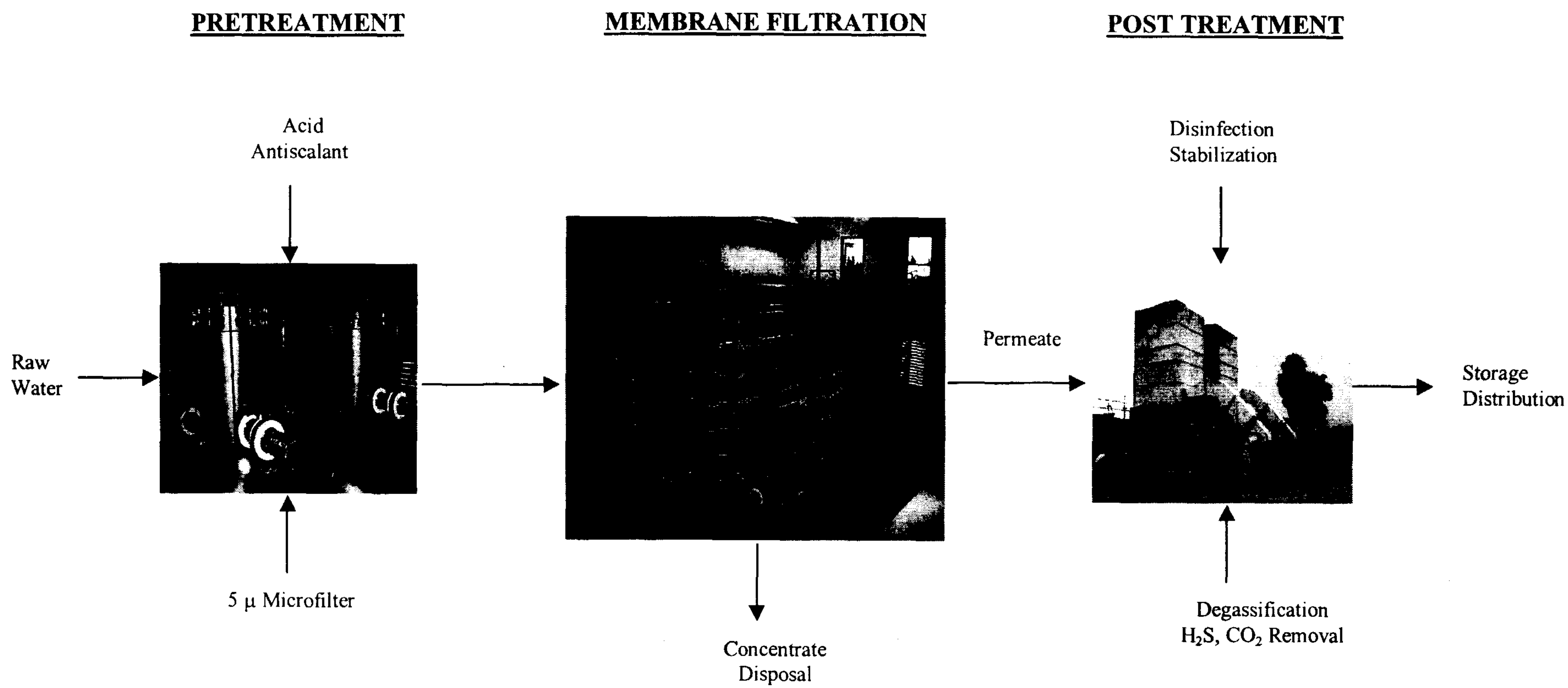
- ❑ Increasing Water Consumption
- ❑ Decrease in Source Water Quality
- ❑ Stringent Drinking Water Regulations
- ❑ Great Demand for Advanced Drinking Water Treatment for Low Quality Source Waters

***Membrane:** Versatile Alternative to Augment Water Supplies and Comply with Stringent Regulations*

Membranes for Drinking Water Treatment in America

- ❑ RO/NF processes for brackish water treatment and softening (e.g. groundwater)
- ❑ MF/UF processes for replacing conventional water filtration
- ❑ Seawater desalination
- ❑ Advanced integrated membrane system (IMS) for low quality water treatment (e.g. surface water)

Typical Membrane Facility



Applications of Membrane Processes in Florida

City	Year	Capacity (MGD)	Process	Membrane	Recovery (%)
Cape Coral	1992	16.8	RO	Fluid	80
Dunedin	1991	9.5	NF/RO	Hydra	83
Fort Myers	1992	12	NF	Hydra	88
Hollywood	1995	18	NF/RO	Hydra	85/75
Jupiter	1997	9	RO	Hydra	75
Marco Island	1997	5	RO	Fluid	75
Melbourne	1995	6.5	RO	Hydra	85
Naples	1993	12	NF/RO	Hydra	90
Palm Coast	1991	2	NF	Dow	80
Pine Island	1993	1.6	RO	MSC	85
Plantation	1998	16	NF	Hydra	85
Sanibel	1994	4.7	RO	Dow	80

S Hong, J. Taylor, and T. Tak, "Application of Membrane Technologies for Drinking water Treatment in Florida", *Korean Membrane Journal*, 2 (2000) 26-35

Membrane Processes for Low Quality Source Waters

- Regulated more strictly due to poor water quality (e.g. surface water treatment rule and disinfection by product rule)
- Greatly limited by significant fouling potential
- Requires advanced pretreatment processes to reduce fouling: *Integrated Membrane Systems (IMS)*

IMS Pretreatment Processes

- ❑ Conventional Pretreatment: Acid/Antiscalant Addition for Scaling Control
- ❑ Advanced Pretreatment: Various Unit Processes for Particle, Organic and Biofouling Control

(Advanced) Pretreatment Process	Fouling Mechanism			
	Particles	Scaling	Biological	Adsorption
Acid/antiscalant addition*	No	Yes	No	No
Coagulation/Sedimentation/Filtration	Yes	No	No	Yes
Soil Filtration	Yes	No	Yes	Yes
Slow Sand Filtration	Yes	No	Yes	Yes
Biologically Activated Carbon Filtration	Yes	No	Yes	No
Microfiltration	Yes	No	Yes	No
Ultrafiltration	Yes	No	Yes	No
Oxidation-Filtration	Yes	No	Yes	No
Disinfection	No	No	Yes	No

MEMBRANE FOULING

Standard Monitoring Techniques for Membrane Fouling

Membrane Fouling

- Deterioration of membrane performance (reduced flux and selectivity) due to accumulation of substances on the membrane surface and/or within the membrane pore structure
- A major operational problem in membrane separation processes
- *No standard fouling potential assessment* methodologies established yet
- Lack of knowledge and experience in control of membrane fouling

Factors Affecting Fouling

- ☐ Feed Water Quality (e.g. foulant concentration and properties, feed solution chemistry)
- ☐ Membrane Characteristics (e.g. surface roughness, charge and hydrophobicity)
- ☐ Physical Operating Conditions (e.g. flux, recovery, operating pressure, module hydrodynamics)

S. Hong and M. Elimelech, "Chemical and Physical Aspects of Natural Organic Matter (NOM) Fouling of Nanofiltration Membranes", *Journal of Membrane Science*, 132 (1997) 159-181.

Foulants in Source Waters and Resulting Fouling Mechanisms

In typical RO/NF processing natural waters,

- **Colloidal and Suspended Matter**
  (Particle Fouling)
- **Sparingly Soluble Salts**
  (Precipitation Fouling)
- **Natural Organic Matter**
  (Adsorptive Organic Fouling)
- **Biological Growth**
  (Biofouling)

Standard Monitoring Requirements for Particle Fouling

- ❑ Fouling Indices
  - Silt Density Index (SDI): ASTM D-4189-82
  - Modified Fouling Index (MFI)
- ❑ Feed Water Particle Quality Monitoring
  - Turbidity
  - Particle Counts
- ❑ Multi-stage Water Productivity Monitoring
  - Specific Flux (Kw): 1st Stage Kw > 2nd Stage Kw
- ❑ Additional Feed Water Quality Monitoring
  - Dissolved Oxygen (DO)

Standard Monitoring Requirements for Scaling

- ❑ **Limiting Salt Determination based on Feed Water Quality (Ion) Analysis**
- ❑ **Mass Balance on Primary Ions Causing Precipitation (e.g. calcium and sulfate)**
- ❑ **Multi-stage Water Productivity Monitoring**

  Specific Flux (Kw): 1st Stage Kw < 2nd Stage Kw

Standard Monitoring Requirements for Organic Fouling

- ❑ Water Productivity Monitoring

  Specific Flux (Kw) under Various Pretreatment Processes

- ❑ Feed Water Organic Quality Monitoring

  TOC or DOC

  UV254

  SUVA

SUVA (L/mg-m)	Potential Adsorption Fouling
<2	Low
2 to 3	Medium
>3	High

Standard Monitoring Requirements for Biofouling

- **Feed Water Biological Quality Monitoring**
  - **Heterotrophic Plate Counts (HPC)**
- **Feed Water Nutrient Monitoring**
  - **Assimilable Organic Carbon (AOC)**
  - **Biodegradable Dissolved Organic Carbon (BDOC)**
- **Additional Feed Water Monitoring**
  - **Dissolved Oxygen (DO)**

I. Escobar, S. Hong, and A. Randall, "Removal of Assimilable Organic Carbon (AOC) and Biodegradable Dissolved Organic Carbon (BDOC) by Reverse Osmosis and Nanofiltration Membranes", *Journal of Membrane Science*, 175 (2000) 1-17.

MEMBRANBE PERFROMACNE ASSESSEMT

Standard Procedures for Performance Evaluation of Membrane Processes

Evaluation of Membrane Processes for Water Treatment

- Membrane performance is feed-water-specific and differ from application to application and site to site
- Pilot-scale field evaluation should be conducted to accurately assess membrane performance and fouling behavior
- Standardization of membrane pilot investigation begins to realize (e.g. AwwaRF IMS protocol by Taylor)
- Membrane characterization is also important to understand membrane performance and fouling mechanisms

Preliminary Bench-scale Membrane Evaluation

- **Bench-scale filtration experiments is generally performed to select membranes for pilot study**
- **Membrane selection criteria should be established based on water quality objectives and productivity predictions**
- **Example guideline for membrane screening (St Johns river water project by UCF and CH2M Hill)**
  1. High Organic Rejection: Less than 0.5 mg/L TOC in Permeate
  2. High Inorganic Rejection: 90 to 95% rejection of TDS, Cl^- and Br^- predicted using solution diffusion model at 85% recovery and 15 gsfd operating flux.
  3. Productivity: Normalized water mass transfer coefficient (Kw) > 0.10 gsfd and 15% Kw loss predicted over a ninety day period

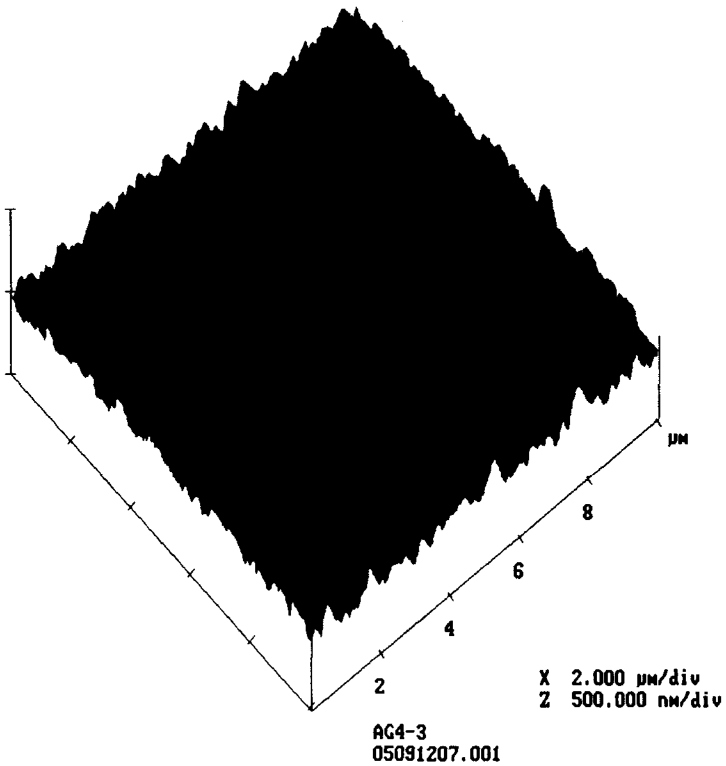
Membrane Characterization

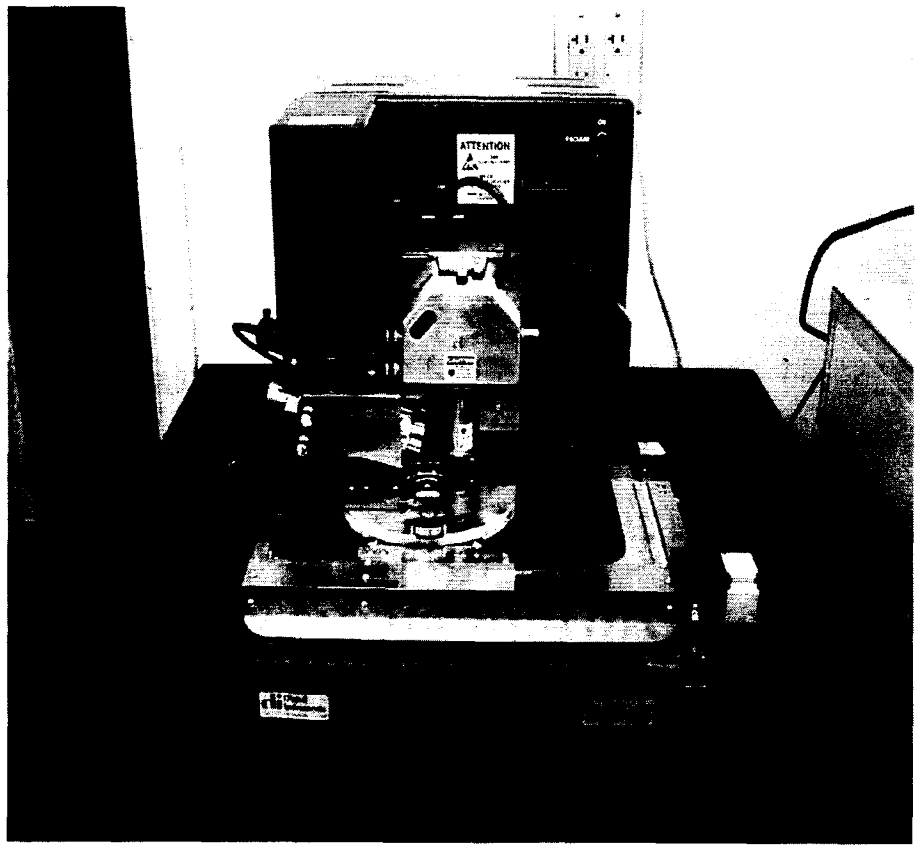
The extent of membrane fouling is greatly affected by membrane surface properties. However, standardization of membrane characterization techniques and procedures have not been established yet.

- **Roughness (Atomic Force Microscopy)**
  - **Average Roughness**
  - **Surface Area Difference**
- **Charge (Streaming Potential Analysis)**
  - **Zeta Potential**
- **Hydrophobicity (Goniometer)**
  - **Contact Angle Measurement**

E. M. Vrijenhoek, S. Hong, and M. Elimelech, "Influence of Membrane Surface Properties on Initial Rate of Colloidal Fouling of Reverse Osmosis and Nanofiltration Membranes", *Journal of Membrane Science*, 188 (2001) 115-128

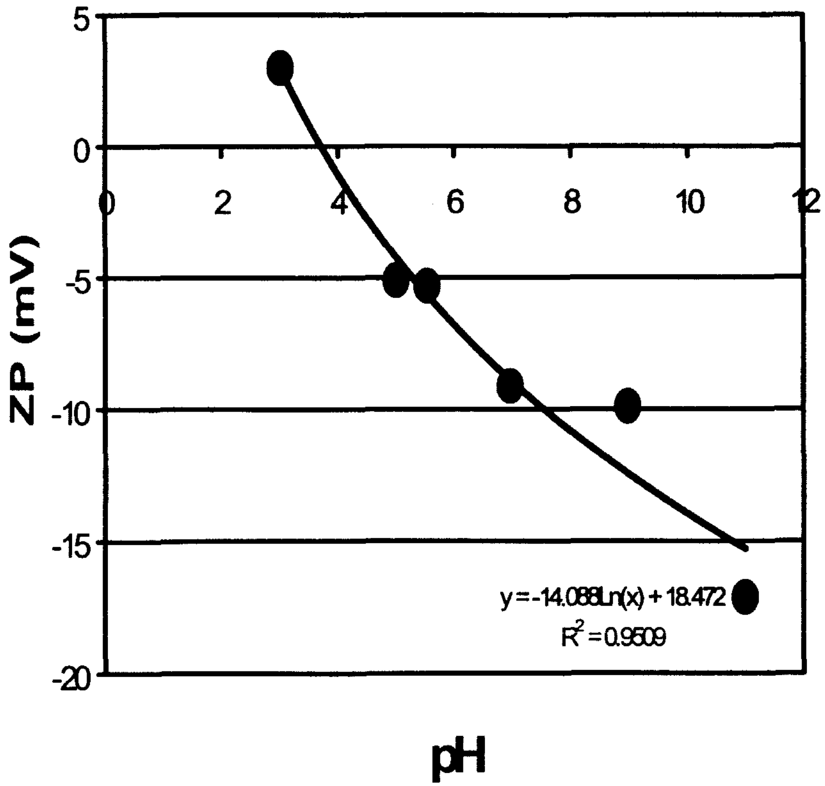
Membrane Surface Roughness

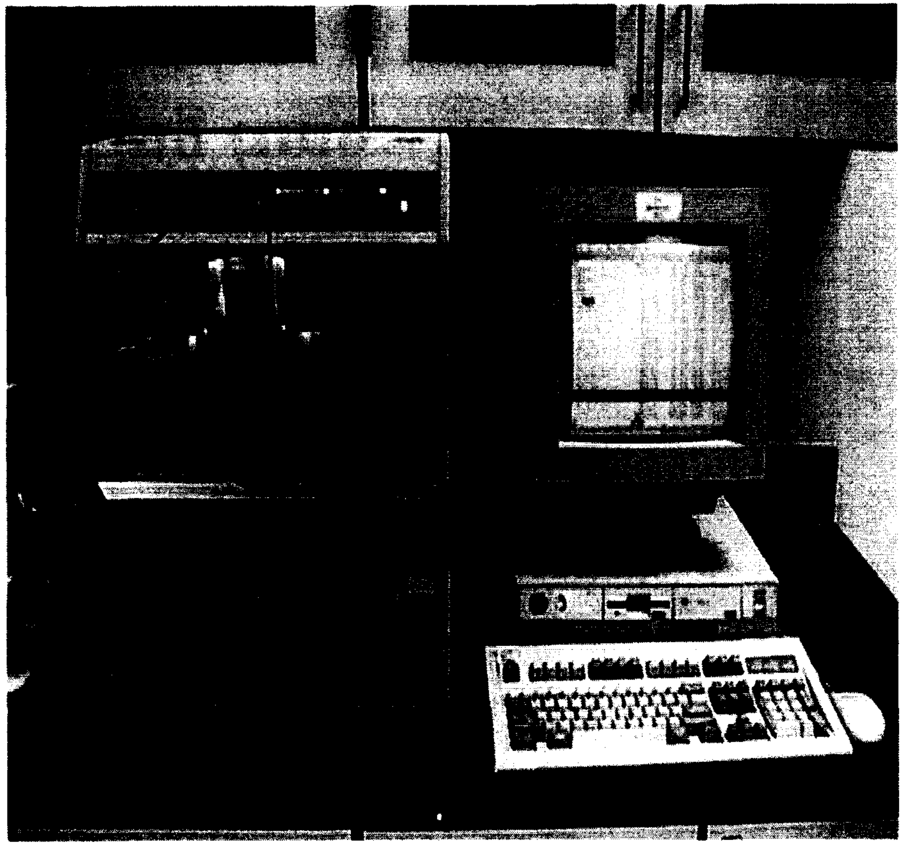




NanoScope™ Digital Instruments (DI)

Membrane Surface Charge





BI-EKA, Brookhaven Instruments Co.

Pilot-scale Performance Evaluation

- ❑ Membrane selection and characterization (4 in diameter and 40 in long module)
- ❑ Pretreatment design and operation
- ❑ Pilot-scale field evaluation

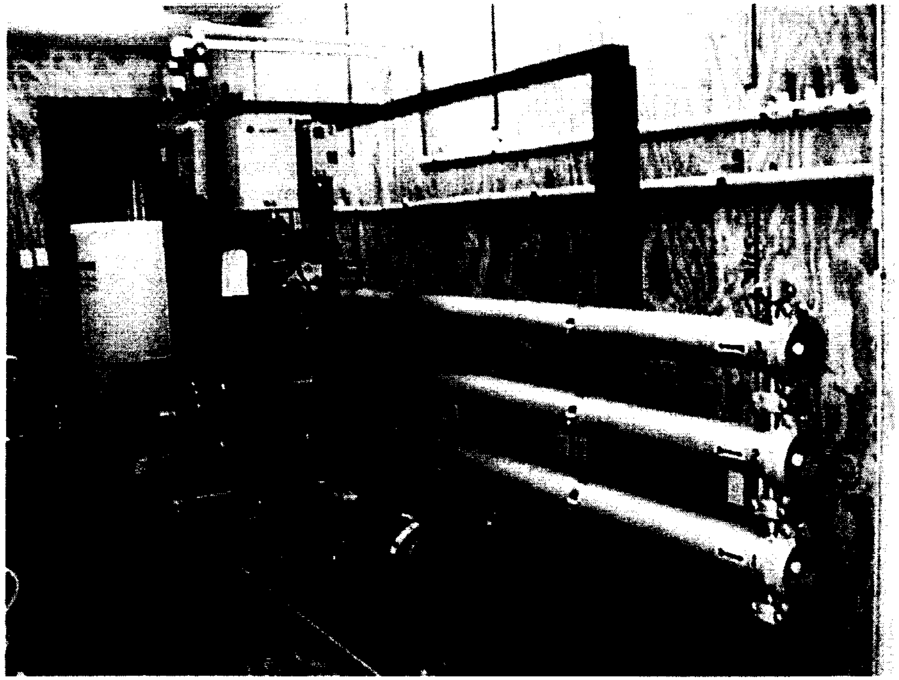
  75 to 85% recovery

  12 to 20 gsfd operating flux

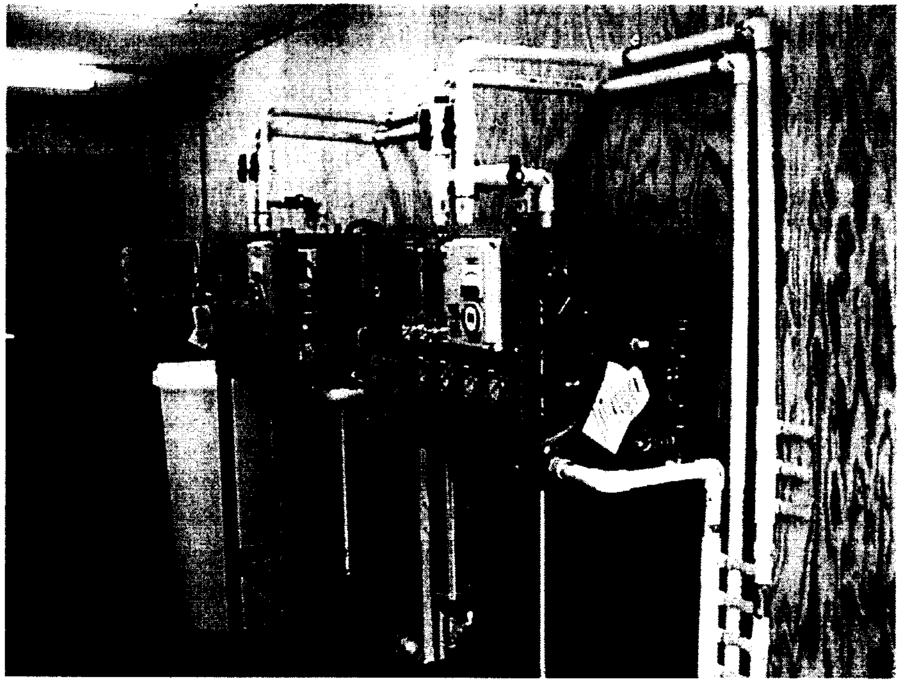
  1000 to 2000 hrs of operating time

  chemical cleaning efficiency
- ❑ Process Optimization (e.g. flux and recovery)
- ❑ Data analysis and prediction for full-scale operation

Typical Pilot Membrane Filtration System

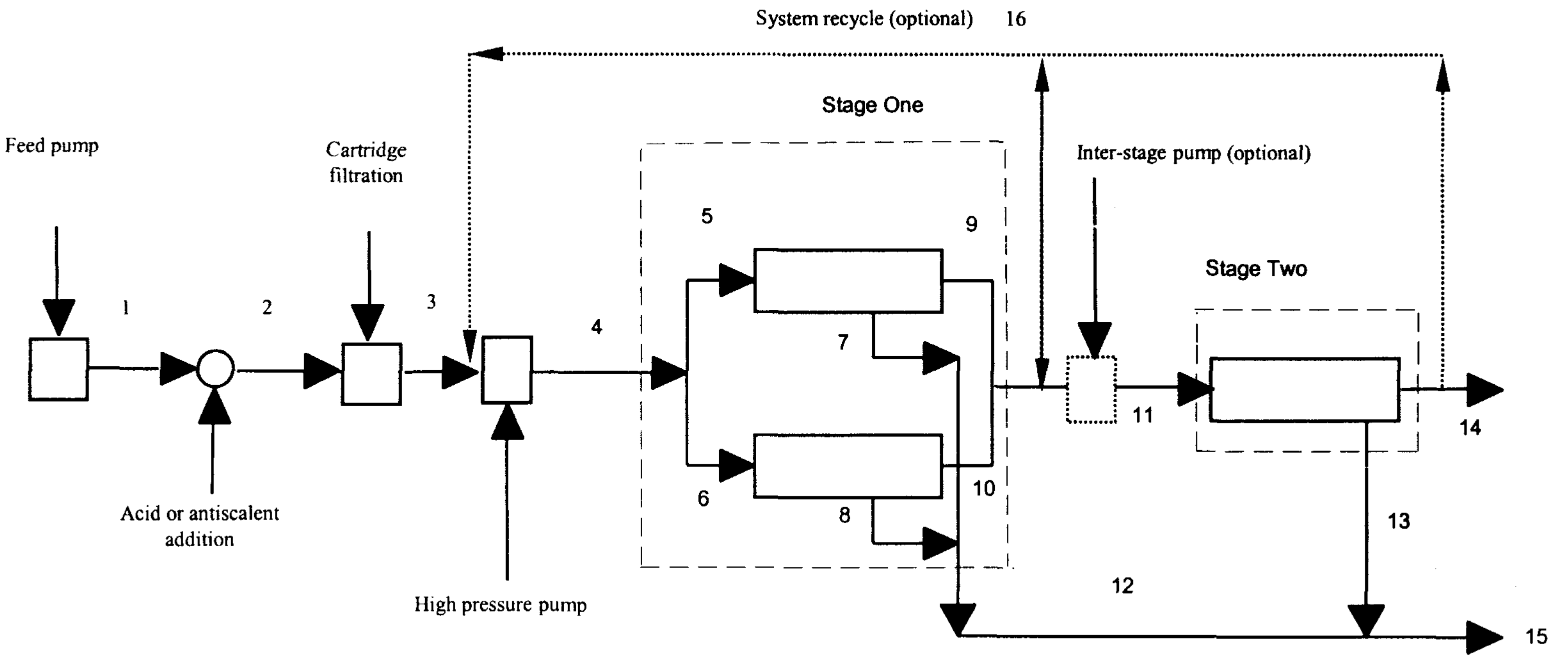


Two Stage RO System
(High Recovery)



Single Element RO Systems
(Low Recovery)

Pilot Scale Monitoring Points



Two-Stage High Recovery System

Typical Monitoring Parameters and Frequency for Pilot Study

Parameter	Location Number 1	2	3	4*	5	6	7	8	9	10	11	12	13	14	15	16
Flow rate												D	D	D	D	D
Pressure		D	D	D							D	D	D	D	D	
Temperature				D												
Direct flow measurement														D	D	
Conductivity	D		D	D							D	D	D	D	D	
PH	D		D	D							B	B	B	D	B	
TDS			B	B							B	B	B	B	B	
Sodium			B	B							B	B	B	B	B	
Chloride			B	B							B	B	B	B	B	
Sulfate			B	B							B	B	B	B	B	
Total Hardness			B	B							B	B	B	B	B	
Calcium Hardness			B	B							B	B	B	B	B	
Alkalinity			B	B							B	B	B	B	B	
Turbidity			B	B							B	B	B	B	B	
UV_{254}			B	B							B	B	B	B	B	
TOC			B	B							B	B	B	B	B	
Bromide			B												B	
SDS – THM4			B												B	
SDS – HAA6			B												B	
SDS - Chlorine demand			B												B	
AOC			B												B	
BDOC			B												B	
Attached Cell Growth			B								B			B	B	
Particle Counts			B								B	B	B	B		
HPC			B								B	B	B	B		

D - daily (once per shift)
B - biweekly
* - The water quality parameters at location 4 only need to be monitored if concentrate recycle is used.

Pilot Performance Data Analysis

Water Quality Modeling

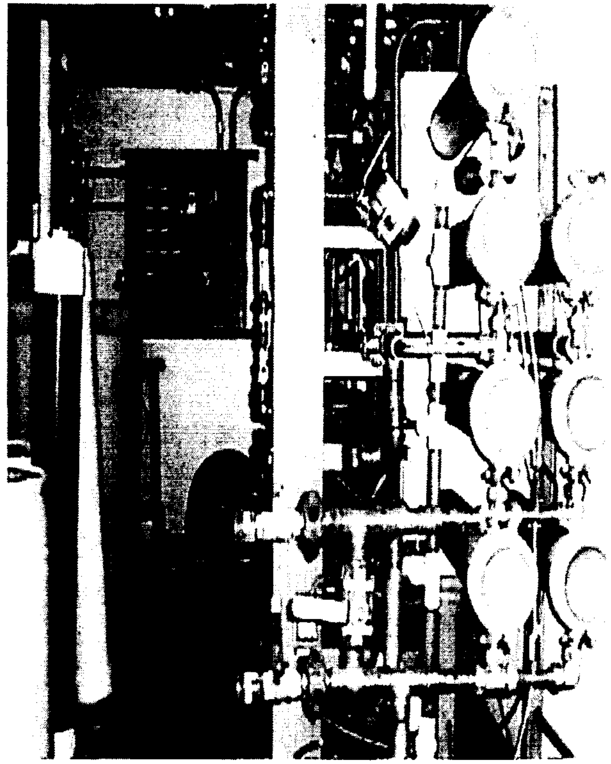
$$C_{p,i} = \frac{k_{i,i} C_{f,i}}{k_{W,i} \Delta P_i \left(\frac{2-2r_i}{2-r_i} \right) + k_{i,i}} = Z_i C_{f,i}$$

Water Productivity Modeling

$$K_w = \frac{1}{R_T} = \frac{1}{(R_m + R_a + R_b + R_s + R_p)} \cong \frac{1}{(R_m + R_x)}$$

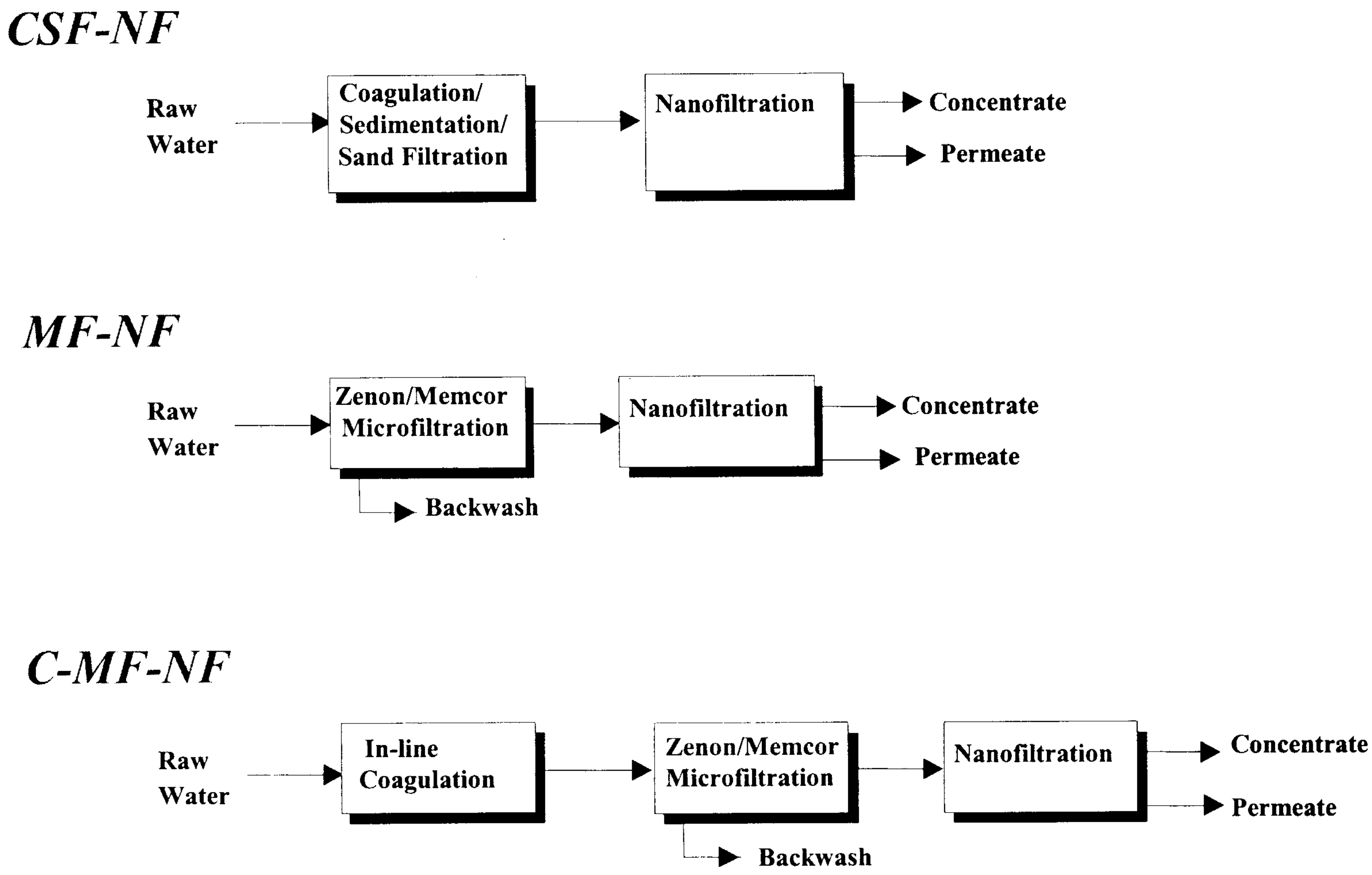
Case Study: Tampa Bay Membrane Pilot Investigation

- Highly Organic Surface Water Obtained from Hillsborough River, Tampa, FL (TOC=20 mg/L)
- LPRO Membrane:
  CALP: Cellulose Acetate (*Fluid Systems*)
  LFC1: Polyamide TFC (*Hydranautics*)
- Two 2-1 Array Pilot Systems
- Advanced Pretreatment Processes due to High Fouling Potential

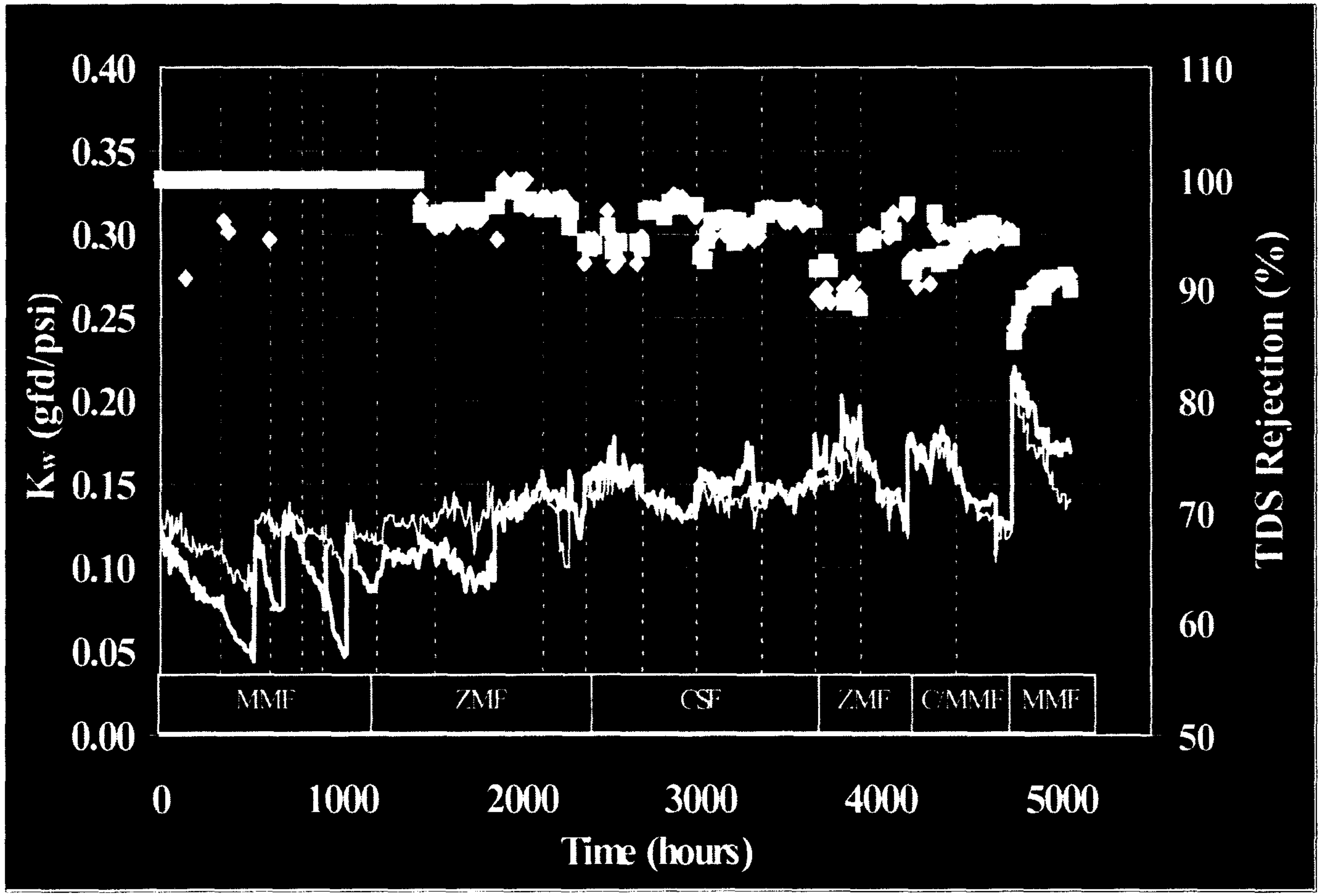


S. Hong, S. Beverly, S. Seal, R. Reiss, J. Taylor, and C. Hobbs, "Identification of Low Pressure Reverse Osmosis Membrane Failure by X-Ray Photoelectron Spectroscopy", Proceedings of *American Water Works Association (AWWA) 2000 Annual Conference*, June 11 – 15, 2000, Denver, Colorado.

Membrane Process Trains



PA Membrane Performance



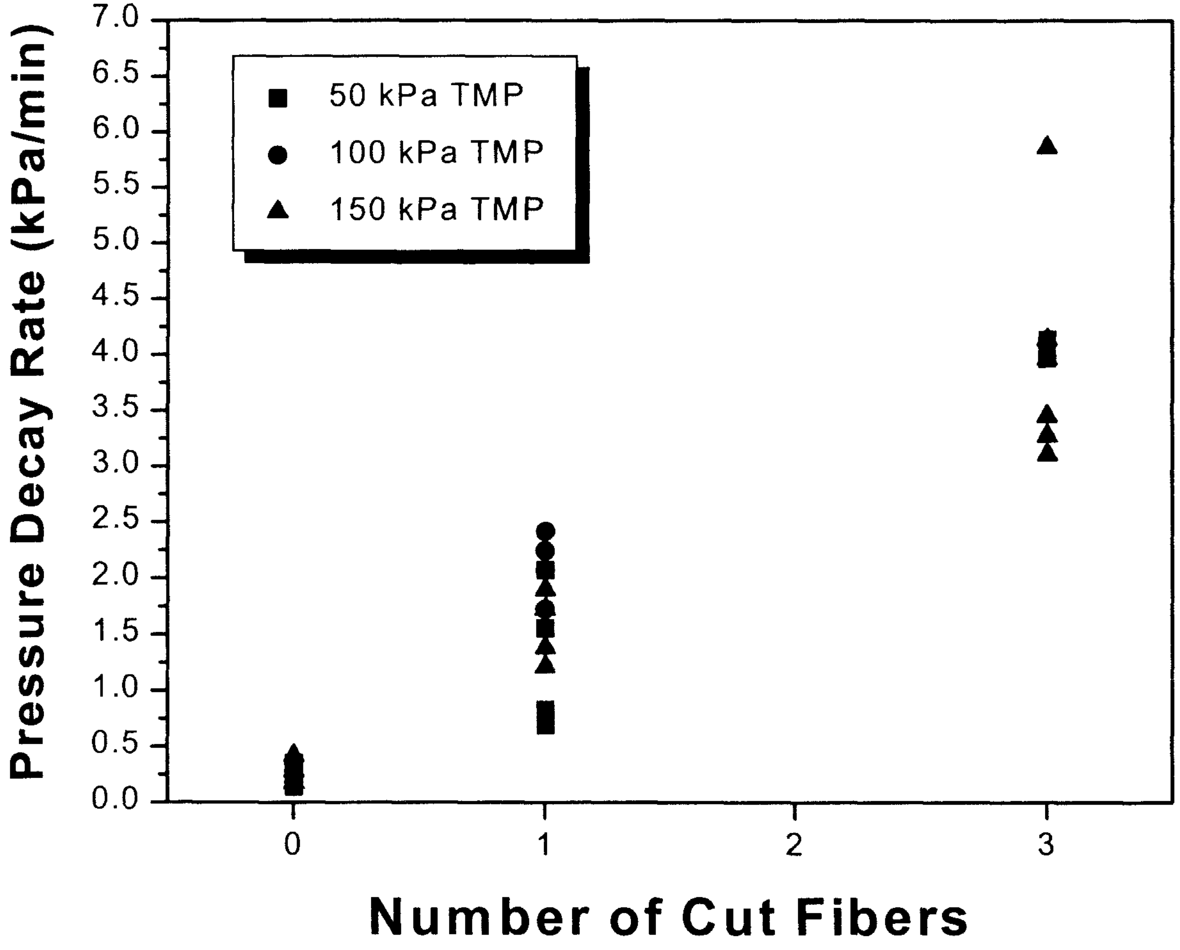
The monochloramine was also effective to minimize the biofouling of PA membrane, but caused gradual deterioration of membrane integrity

MF/UF Integrity Monitoring

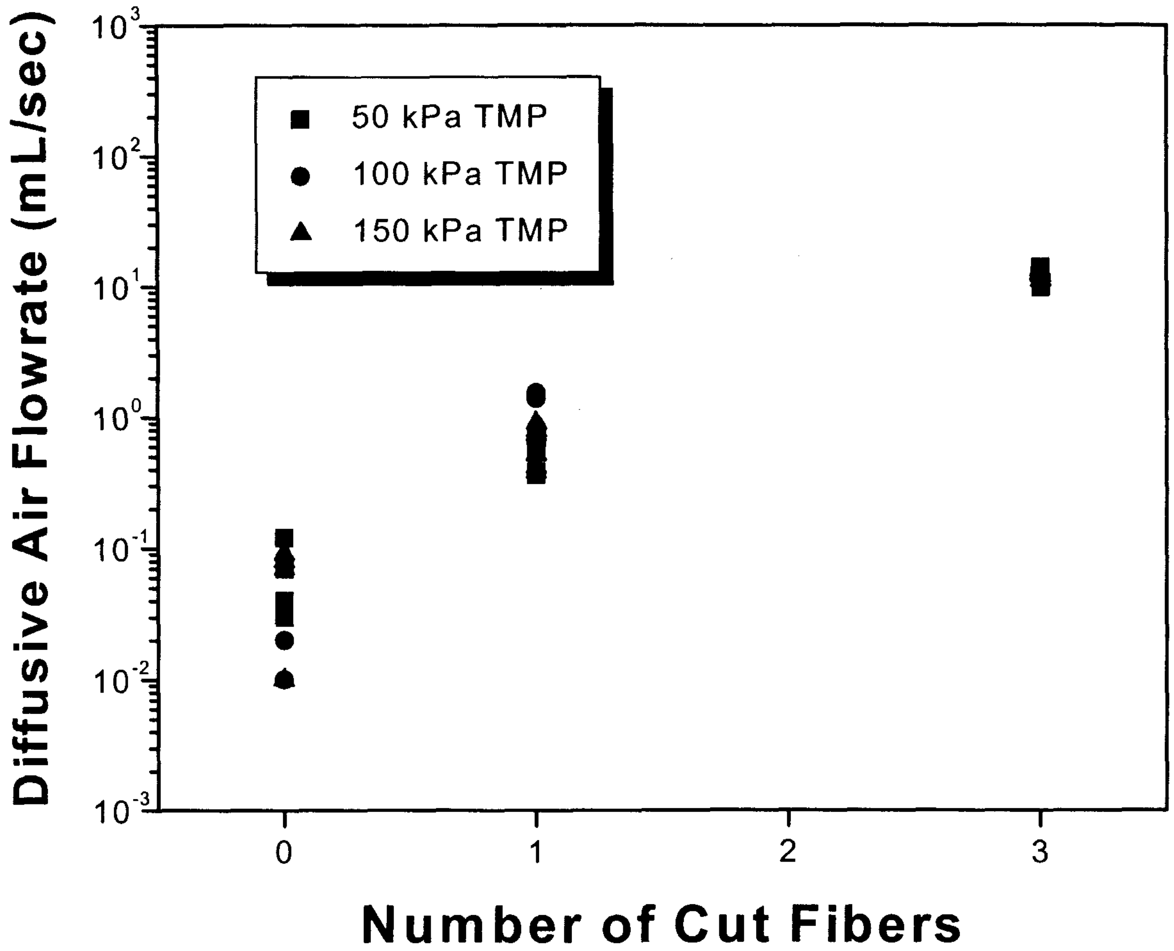
- **Integrity monitoring will be required for full-scale MF/UF processes to ensure microbial removal**
- **Indirect Methods**
  - **Measure a Surrogate Parameter to Determine the Condition of the MF Membrane.**
  - **Examples: Turbidity, Particle Counting**
- **Direct Methods**
  - **Evaluate the Integrity of the Membrane itself**
  - **Examples:** ***Pressure Decay Test (PDT)***
    Diffusive Air Flow Test (DAF)

S. Hong, F. Miller, and J. Taylor, "Assessing Pathogen Removal Efficiency of Microfiltration by Monitoring Membrane Integrity", Proceedings of *1st World Water Congress of the International Water Association (IWA)*, July 3 – 7, 2000, Paris, France.

PDT Sensitivity



DAF Sensitivity



CONCLUDING REMARKS

Standardization of Membrane Testing Methods in America

- Despite its importance, standardization of membrane performance testing methods at both bench and pilot-scale is not established in U.S.
- Only a few testing methods such as SDI have been standardized for fouling assessment.
- Standard protocols for membrane characterization are not developed yet. Thus, direct comparison of testing results from various measurements can not be made.