

# **New Techniques for Real-Time Monitoring of Reverse Osmosis (RO) Membrane Integrity**

April 10, 2014



WaterReuse Research Foundation Webcast Series

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## WATEREUSE RESEARCH FOUNDATION

### New Techniques for Real-Time Monitoring of Membrane Integrity for Virus Removal

WRF-09-06b



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## WaterReuse 09-06b report published in 2014





# Overview

- Introductions
- Current Status of MIT for RO/NF
- Objectives and Research Methods
- Theoretical Concept of newly Proposed PM-MIMo
- Practical Testing of Newly Proposed PM-MIMo
- Summary of Research Result





# Introductions

## **Principal Investigator**

Val S. Frenkel, Ph.D., P.E., D.WRE., *EKI*

## **Co-Principal Investigator**

*Prof. Yoram Cohen, Ph.D., UCLA*

## **Research Project Team**

- Anditya Rahardianto, Ph.D., *UCLA*
- Sirikarn Surawanvijit, *UCLA*
- John Thompson, *UCLA*
- Gregg Cummings, P.E., *PARSONS*





# Introductions

## **Project Advisory Committee**

- Michelle Chapman, *U.S. Bureau of Reclamation (USBR)*
- Bob Hultquist, *California Department of Public Health (CDPH)*
- Kevin Alexander, *Hazen & Sawyer*
- Zia Bukhari, *American Water*





# Introductions

## **Participating Organizations**

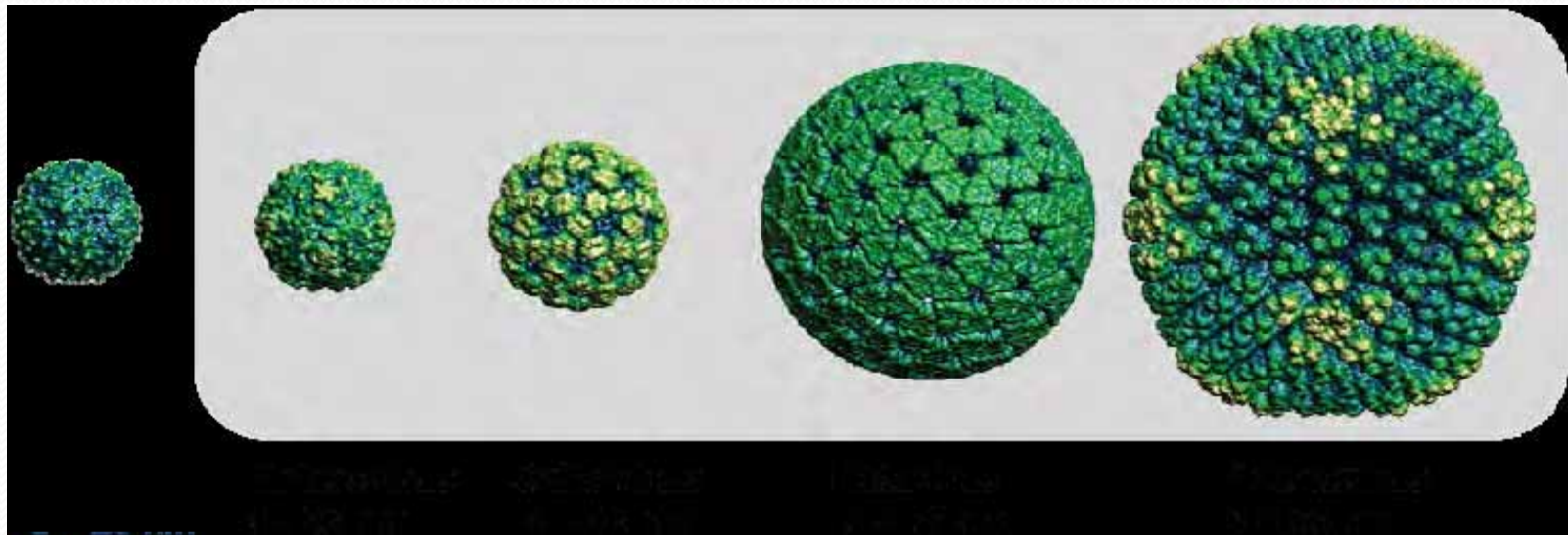
- Kennedy/Jenks Consultants (California)
- UCLA Water Technology Research (WaTeR) Center (California)
- El Paso Water Utilities (Texas)
- East Bay Municipal Utilities District (California)
- Tampa Bay Water (Florida)

# Abbreviations

- RO Reverse Osmosis
- NF Nanofiltration
- Q Flow
- PM-MIMo Pulsed-marker membrane integrity monitoring
- MIM Membrane Integrity Monitoring
- MIT Membrane Integrity Testing
- PFRO Plate-and-Frame Reverse Osmosis
- SPRO Spiral-Wound Reverse Osmosis



# Viruses



**MS2**  
d = 28nm

**Enterovirus**  
d = 32 nm

**Calicivirus**  
d = 42 nm

**Rotavirus**  
d = 77 nm

**Adenovirus**  
d = 95 nm

**Depiction of surfaces of common waterborne enteric virus capsids (grey background) and their typical surrogate (MS2) bacteriophage**

# Regulations

According to the U.S. Environmental Protection Agency (EPA) Surface Water Treatment Rule (SWTR), inadequately treated water may contain disease-causing microorganisms, which include bacteria, viruses, and parasites (California Department of Public Health, 2009a). In 1986, SWTR established requirements for removal and inactivation of these pathogens from the surface water systems. These regulations are on the basis of a minimum log removal value (LRV):

$$LRV = \log_{10} \left( \frac{C_f}{C_p} \right)$$

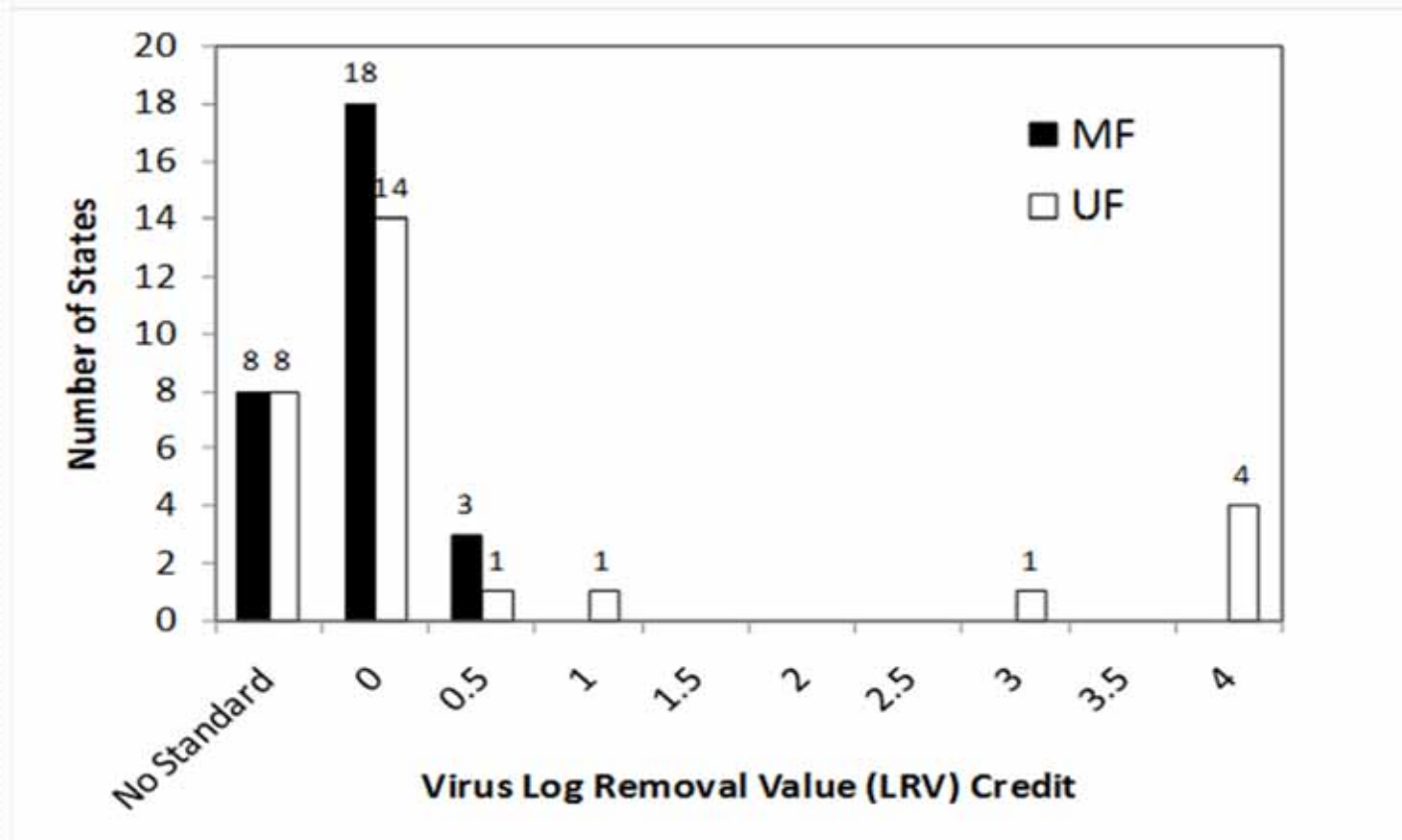
where  $C_f$  and  $C_p$  are the concentrations of the pathogen or microorganism in the feed and permeate streams, respectively. Under SWTR, LRVs in water treatment processes are regulated as follows (U.S.EPA, 2001):

- 99 % (2-log) removal and/or inactivation of Cryptosporidium
- 99.9% (3-log) removal and/or inactivation of Giardia
- 99.99% (4-log) removal and/or inactivation of viruses

In California, 4-log removal and/or inactivation of Cryptosporidium and 99.999% (5-log) removal and/or inactivation of viruses are required for disinfected recycled water (California Department of Public Health, 2009b).



# Regulations

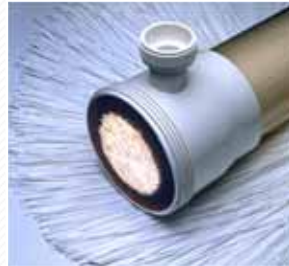


**Summary of state virus removal credit for MF and UF**

# CDPH Pathogen Removal Credits

	Conventional Clarification – Filtration	CDPH MF Membrane Filtration	CDPH UF Membrane Filtration
<b><i>Giardia</i> Removal Credit</b>	2.5-log	4-log	4-log
Required <i>Giardia</i> Inactivation	0.5-log	0.5-log for multi-barrier	0.5-log for multi-barrier
<b>Virus Removal Credit</b>	<b>2-log</b>	<b>0.5 to 2.5-log</b>	<b>3.5 to 4 log</b>
Required Virus Inactivation	2-log	2 to 3.5-log for multi-barrier	2-log for multi-barrier

# Membrane Technologies

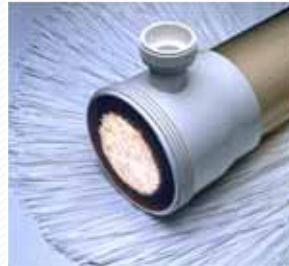


- **Microfiltration (MF)** - separates particles from 0.1 to 0.5 microns
- **Ultrafiltration (UF)** - rejects materials from 0.005 to 0.05 microns (1,000 – 500,000 Daltons MWCO)
- **Nanofiltration (NF)** - rejects materials from 0.0005 to 0.001 microns (200 – 1,000 Daltons MWCO)
- **Reverse Osmosis (RO)** – rejects species ranging in molecular size down to 10 Daltons MWCO





# Membrane Technologies



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# MIT Methods: Indirect, Direct

## Indirect MIT:

*Turbidity*

*Conductivity*

*Particle Counting (Particle Size Distribution – PSD)*

*Sulfate Concentration (sensitivity up to 3 LRV)*

*TOC Concentration (sensitivity up to 4 LRV)*

# MIT Methods: Indirect, Direct

## Indirect MIT:

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*Conductivity*

*Particle Counting (Particle Size Distribution)*

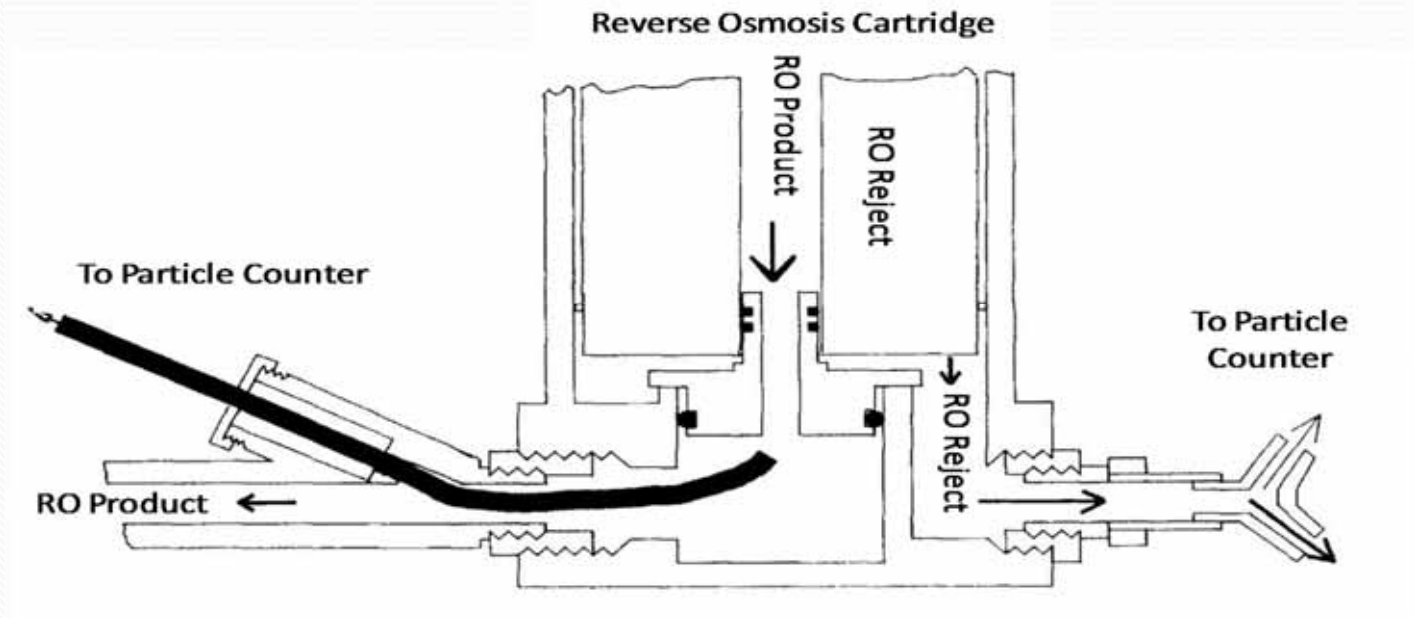
*Sulfate Concentration (sensitivity up to 3 LRV)*

*TOC Concentration (sensitivity up to 4 LRV)*

*Indirect MIT methods are inaccurate: dependent on RO/NF feed water quality and on membrane system operating conditions*

# Indirect MIT

An experimental setup for testing membrane integrity of an RO membrane cartridge via particle counting



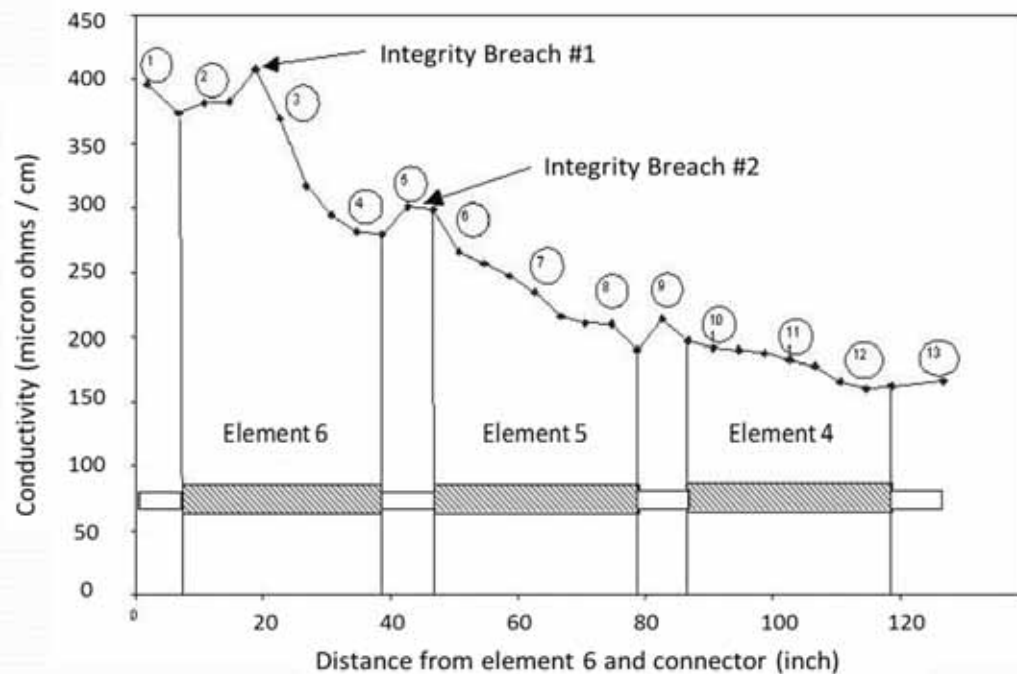
Membrane	LRV	Median Particle Load (particles/mL)	
		RO Reject	RO Product
CA1	1.61–1.90	$3.1 \times 10^3$	60
CA1	1.53–1.87	$5.6 \times 10^3$	155
CA2	3.70–3.97	$3.2 \times 10^3$	0.48
PS	4.47–4.76	$5.0 \times 10^3$	0.13
PA	3.67–3.93	$3.2 \times 10^3$	0.44
CA2	4.61–4.83	$5.2 \times 10^3$	0.09

Log Removal of Particles by Different Types of RO Membranes<sup>(a)</sup>  
as Determined via Laser Diffraction Particle Counter

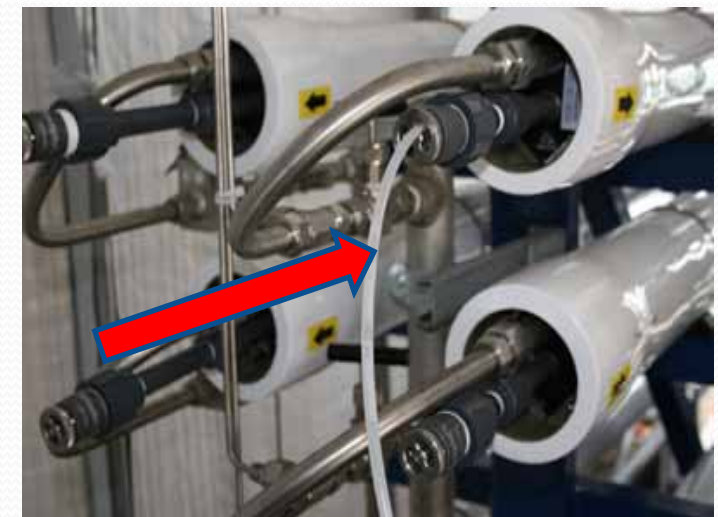


# MIT Methods: Indirect, Direct

## Indirect MIT: Axial Probing



Conductivity probing data in Stage 2 of a 2-stage RO system, indicating multiple suspected integrity breaches





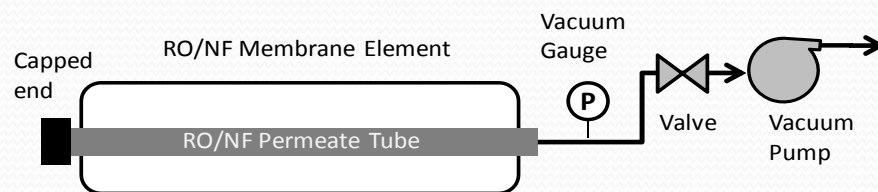
# MIT Methods: Indirect, Direct

## Direct MIT:

*Pressure Methods (off-line pressure decay test)*

*Vacuum Methods*

*Marker Based Methods (biological, non-biological markers, fluorescent-tagged bacteriophages, nanoparticles molecular dyes and macromolecules )*



Schematic of vacuum-hold test for an RO membrane element

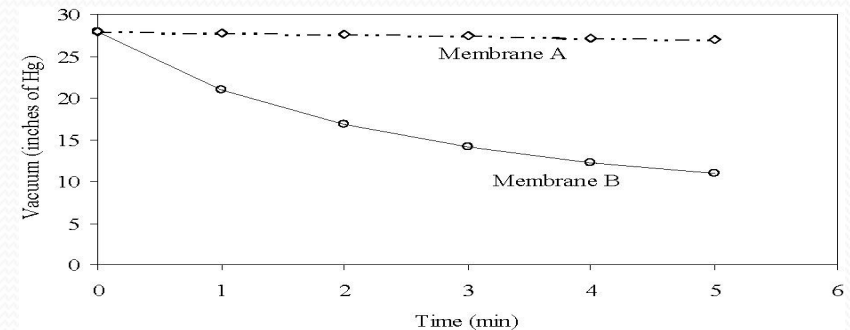


Illustration of vacuum decay test profile for an intact (membrane A) versus a compromised (membrane B) membrane

# MIT Marker Based Methods:

Phages:

MS2 bacteriophages,

PRD1 bacteriophages,

QB coliphages

T4 coliphages

# MIT Marker Based Methods:

Phages:

MS2 bacteriophages,

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QB coliphages

T4 coliphages

*Phages as surrogates for testing are biological in nature, and can undergo biological inactivation and grow in water systems*

# MIT Marker Based Methods:

Fluorescent-tagged Nanoparticles (1 – 100 nm):

Gold (Au)

Silver (Ag)

Copper (Cu)

Silica (Si)

Polystyrene (PS) microspheres



# MIT Marker Based Methods:

Fluorescent-tagged Markers Selection Based on:

*Toxicological effects*

*pH dependency*

*Salinity dependency*

*Temperature dependency*

*Photochemical decay*



# MIT Marker Based Methods:

Fluorescent-tagged Nanoparticles (1 – 100 nm):

Gold (Au)

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Copper (Cu)

Silica (Si)

Polystyrene (PS) microspheres



**High cost, for gold \$45–\$120/mL**

# MIT Marker Based Methods:

## Fluorescent Molecular Dyes

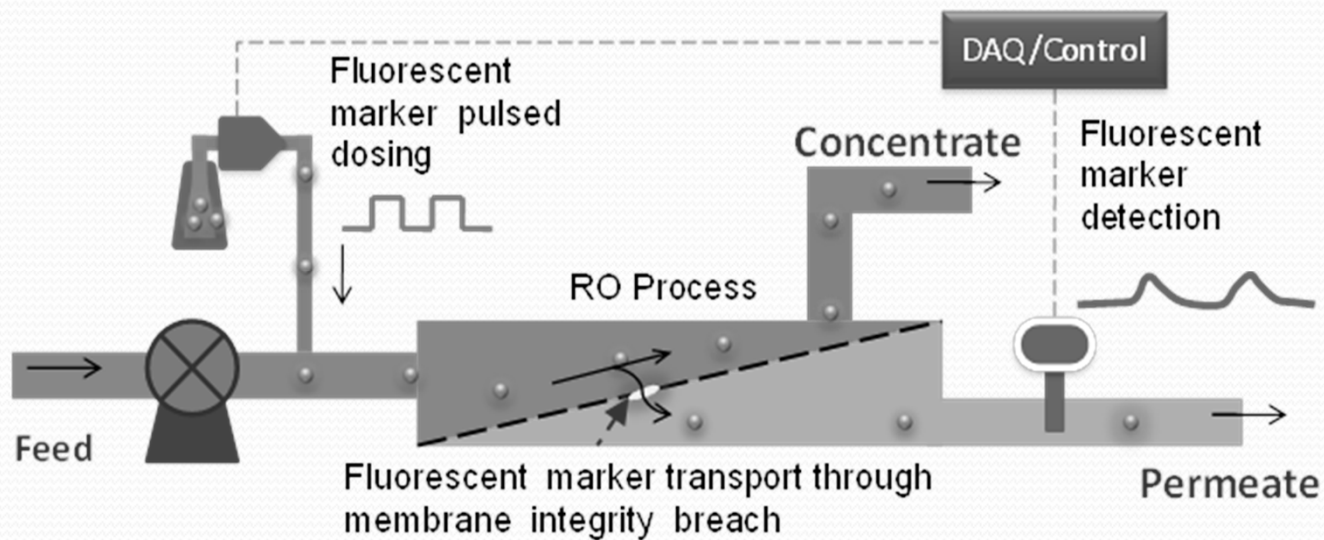
Fluorescent Dyes	Ex/Em <sup>(a)</sup> (nm)	Chemical Formula	Mol Wt	Solubility in Water (mg/mL)
Rhodamine WT	554/580	$C_{29}H_{29}N_2NaO_5$	480.55	Very soluble
Rhodamine B	554/576	$C_{28}H_{31}ClN_2O_3$	479.02	50
Rhodamine 6G	526/552	$C_{28}H_{31}ClN_2O_3$	497.02	20
Sulforhodamine B	554/576	$C_{27}H_{29}N_2NaO_7S_2$	580.65	10
Amidorhodamine G	530/551	$C_{25}H_{25}N_2NaO_7S_2$	552.59	Very soluble
Fluorescein	490/520	$C_{20}H_{12}O_5$	332.31	0.3
Uranine	491/512	$C_{20}H_{10}Na_2O_5$	376.28	40
Eosin B	516/538	$C_{20}H_6Br_4Na_2O_5$	691.88	40
Pyranine	455/512	$C_{16}H_7Na_3O_{10}S_3$	524.39	178
Tinopal CBS-X	346/435	$C_{28}H_{20}Na_2O_6S_2$	562.57	25
Erythrosine	525/547	$C_{20}H_6I_4Na_2O_5$	879.87	20
Sodium naphthionate	320/430	$C_{10}H_8NNaO_3S$	245.23	240
Lanaperl fast yellow	469/508	$C_{25}H_2ON_5NaO_6S_2$	549.55	Very soluble
Lissamine FF	432/508	$C_{19}H_{13}N_2NaO_5S$	404.38	40
Bengal rose	518/535	$C_{20}H_2Cl_4I_4Na_2O_5$	1017.67	100
Fluorescent brightener 28	349/430	$C_4O_4H_{42}N_{12}Na_2O_{10}S_2$	960.96	Very soluble

### Commonly Used Fluorescent Molecular Dyes for Tracers in Water Systems

Ex/Em = Wavenumbers for fluorescence excitation (Ex) and emission (Em) peaks



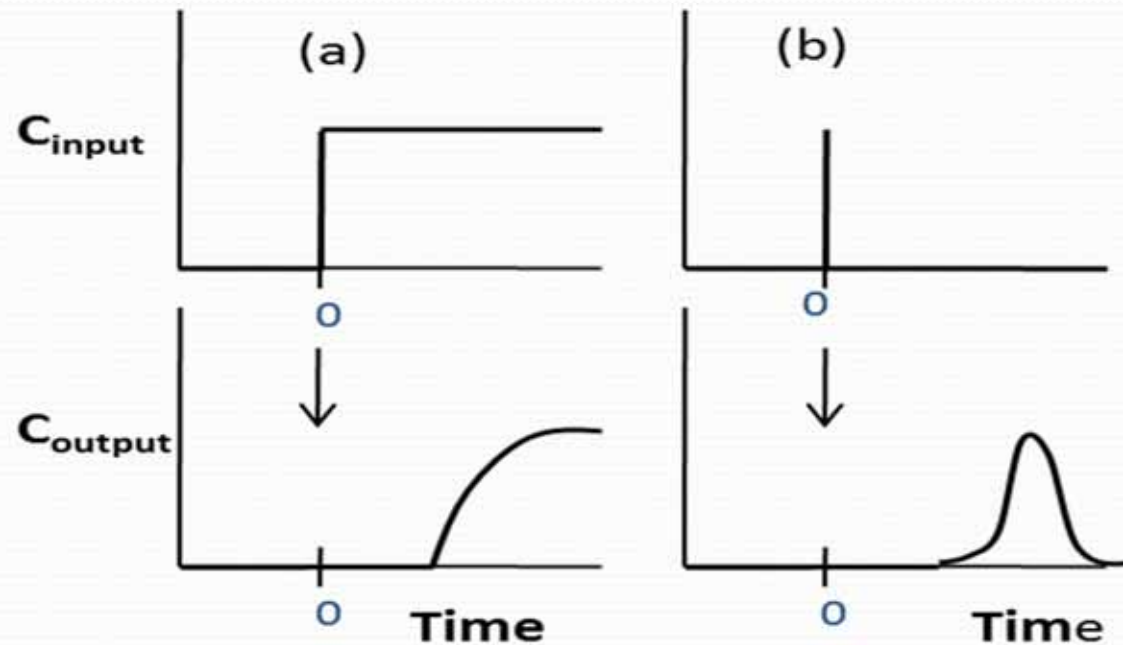
# Membrane Technologies



Pulsed-marker membrane integrity monitoring (PM-MIMo) scheme

*PM-MIMo™ , UCLA Patent pending technology*

# Membrane Technologies



*Schematic Illustration of dynamic response curves of marker step (left) and impulse (right) inputs in a laminar flow channel*

$C_{input}$  and  $C_{output}$  refer to the marker concentrations in the RO feed and permeate streams, respectively

# MIT Marker Based Methods:

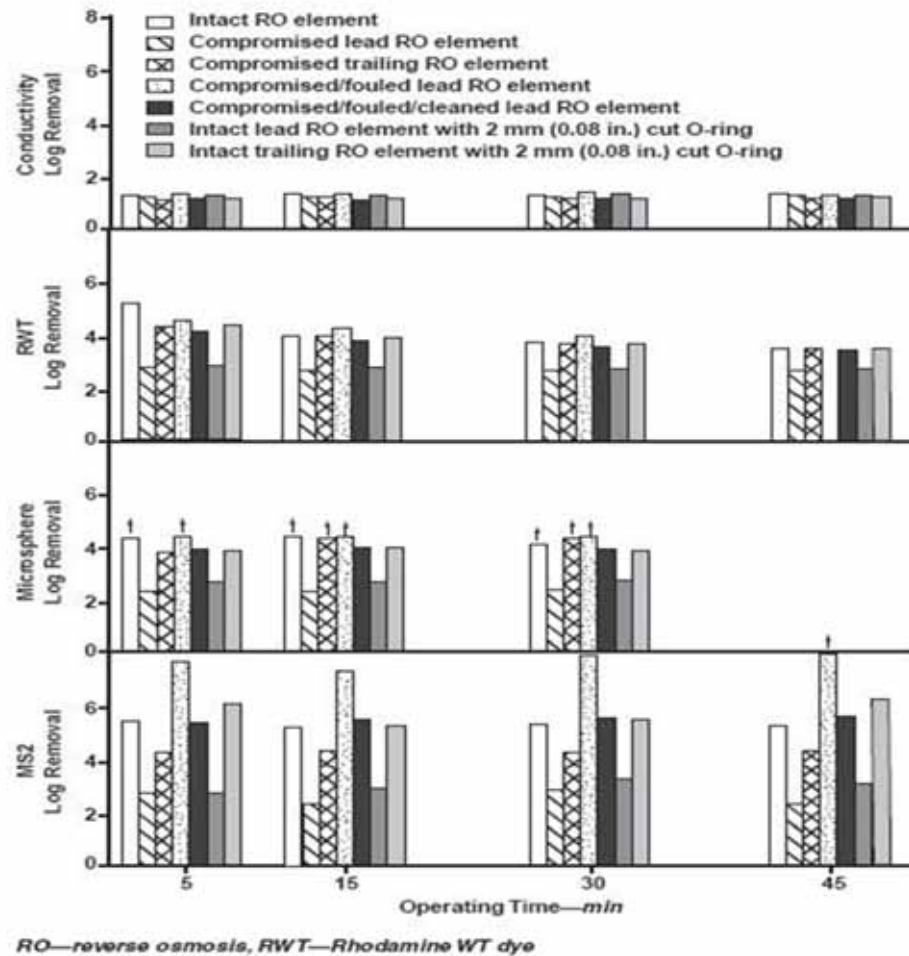
Fluorescent-tagged Markers Selection Based on:

- *Toxicological effects*
- *pH dependency*
- *Salinity dependency*
- *Temperature dependency*
- *Photochemical decay*





## MIT Marker Based Methods:



Performance of RO MIT for intact and compromised membranes on basis of 4 different testing methods

NOTE: MVTU = multi-vessel testing unit

# MIM Marker Based Methods:

## Fluorescent-tagged Markers Selection Criteria:

Sensitive for detecting nano-sized ( 1 nm – 100 nm) contaminants at low concentration levels

Capable of detecting membrane breach in (near) real\_time to enable timely corrective actions

Informative regarding breach characteristics

Cost effective for municipal applications

# MIT Marker Based Methods:

## Constant Marker Concentration Approach (Current):

High cost of markers

Temporal variations in water quality

LRV of the marker for a constant feed marker concentration (between intact and compromised membranes) may be insufficient for assessing the extent and characteristics of membrane breaches



# MIT Marker Based Methods:

## Fluorescent-tagged Markers Selection Criteria:

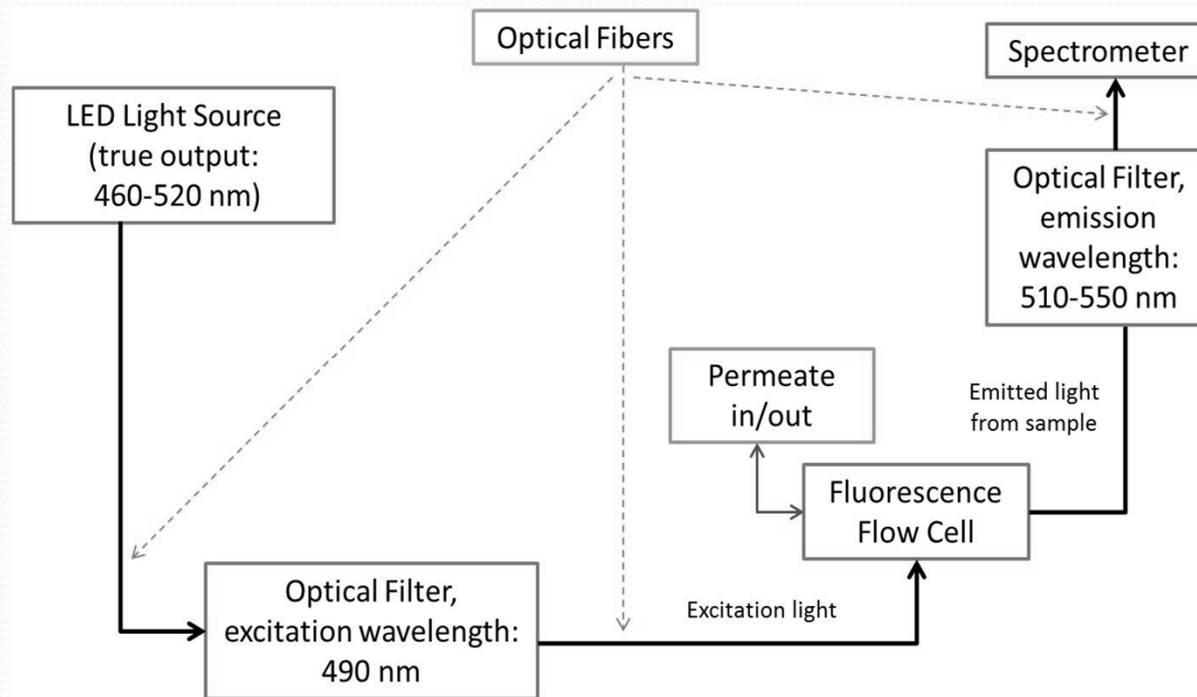
Characteristics	Description
<b>Sensitive</b>	<ul style="list-style-type: none"><li>· Detect low concentrations of target species in permeate from a single or multiple element breaches within a full-scale membrane train</li><li>· Quantify the range of target species LRV</li></ul>
<b>Real-time</b>	<ul style="list-style-type: none"><li>· System shutdown is not required</li><li>· Normal filtration continues during integrity monitoring</li></ul>
<b>Comprehensive</b>	<ul style="list-style-type: none"><li>· Characterize the extent of breach</li><li>· Provide useful information to identify membrane breach location for corrective actions</li></ul>
<b>Cost-Effective</b>	<ul style="list-style-type: none"><li>· Does not require significant additional equipment or overhauls for existing plants</li><li>· Expensive or rare/specialty chemicals are not required</li></ul>

# PM-MIM Marker Based Methods



**2.5 - ppm fluorescent marker solution from left to right:  
eosin B, uranine, rhodamine WT, fluorescein, and lissamine green B**

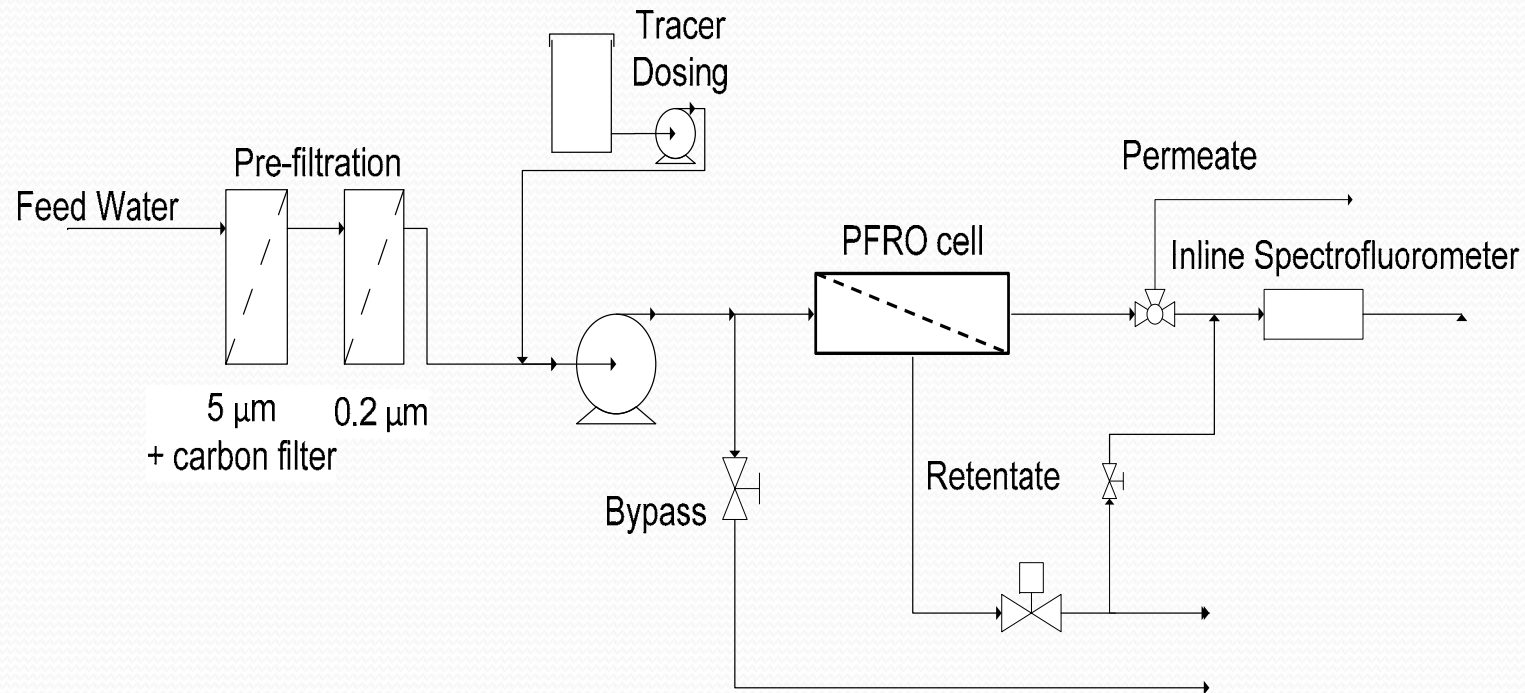
# PM-MIMo Spectrofluorometer



Schematic representation of PM-MIMo spectrofluorometer system



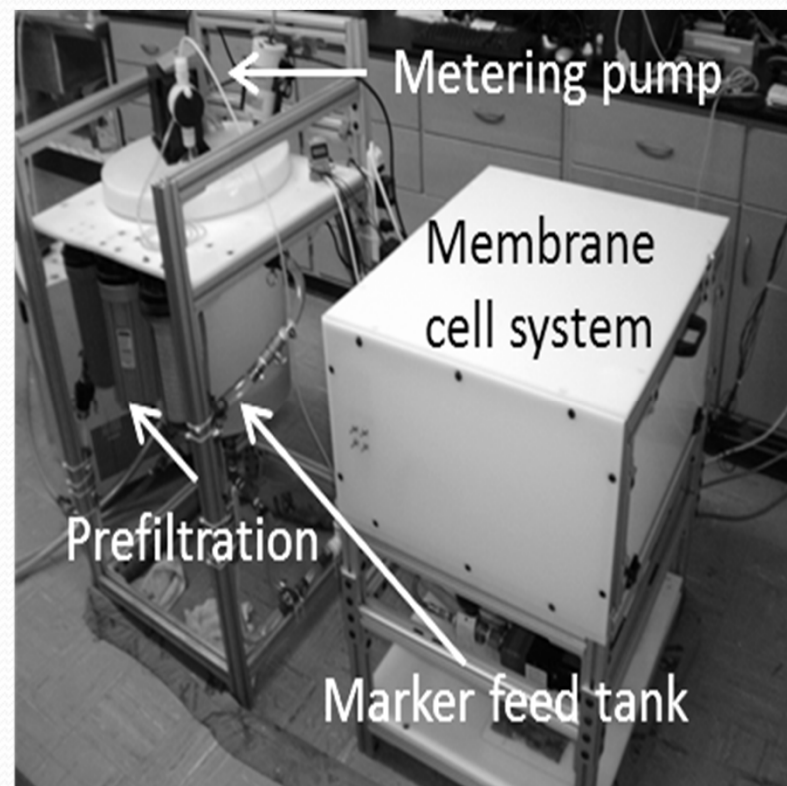
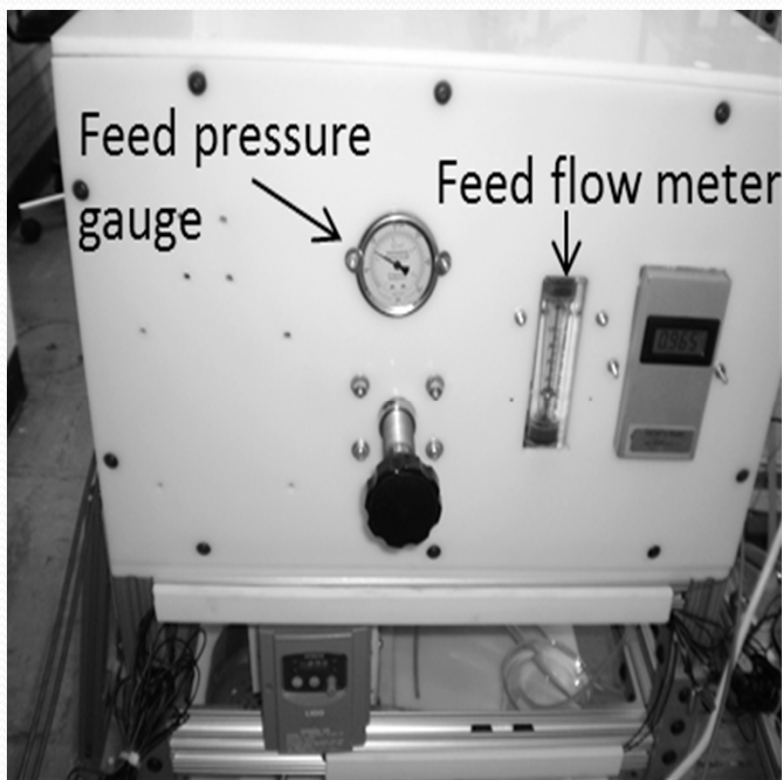
# PM-MIMo Experimental System



Schematics of the experimental PFRO-ISPf system



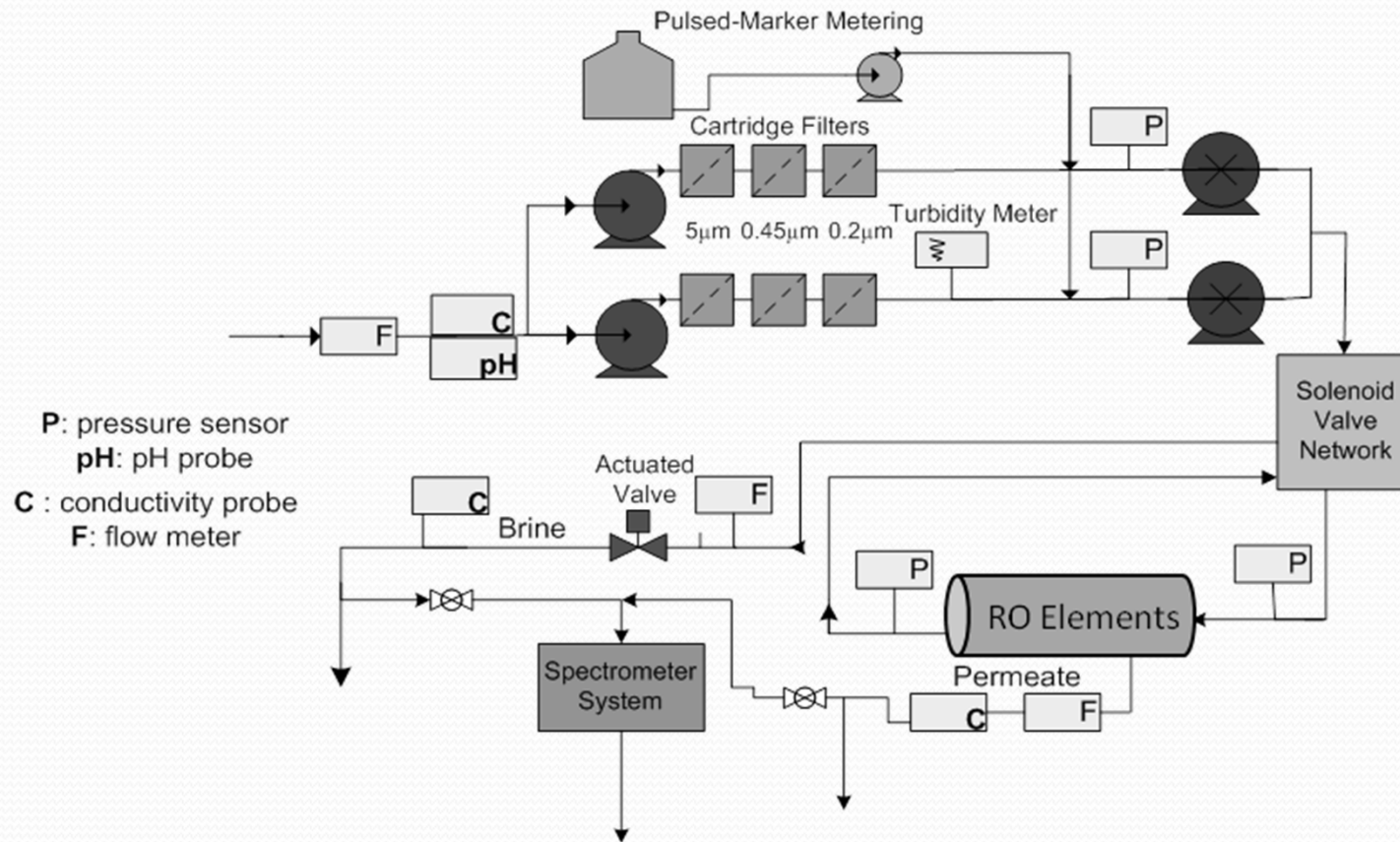
# PM-MIMo Experimental System



Photographs of the PFRO membrane system.



# PM-MIMo Experimental System



Schematic of the UCLA M3 system integrated with the PM-MIMo system





# MIM Marker Based Methods:

## 5 Markers Screened for:

- Determine the fluorescence spectra of the markers
- Quantify the minimum detection limit
- Develop concentration calibration curves
- Evaluate the impact of pH and chlorine concentration on the fluorescence signal stability

# Fluorescent Markers Commonly Used

Fluorescent Marker	Chemical Formula	Mol Wt	Prescreening Criteria		
			Non-toxic	Commercially Available	Insensitive to UV Light
Rhodamine WT	$C_{29}H_{29}N_2NaO_5$	480.55	Y	Y	Y
Rhodamine B	$C_{28}H_{31}ClN_2O_3$	479.02		Y	Y
Rhodamine 6G	$C_{28}H_{31}ClN_2O_3$	497.02		Y	Y
Sulforhodamine B	$C_{27}H_{29}N_2NaO_7S_2$	580.65		Y	Y
Sulforhodamine 101	$C_{31}H_{30}N_2O_7S_2$	606.71		Y	Y
Amidorhodamine G	$C_{25}H_{25}N_2NaO_7S_2$	552.59	Y		
Fluorescein	$C_{20}H_{12}O_5$	332.31	Y	Y	Y
Uranine	$C_{20}H_{10}Na_2O_5$	376.28	Y	Y	Y
Eosin B	$C_{20}H_6Br_4Na_2O_5$	691.88	Y	Y	Y
Pyranine	$C_{16}H_7Na_3O_{10}S_3$	524.39	Y	Y	
Tinopal CBS-X	$C_{28}H_{20}Na_2O_6S_2$	562.57	Y		N/A
Erythrosine	$C_{20}H_{14}Na_2O_5$	879.87	Y		N/A
Sodium naphthionate	$C_{10}H_8NNaO_3S$	245.23	Y	Y	N/A
Lanaperl fast yellow	$C_{25}H_2ON_5NaO_6S_2$	549.55	N/A	Y	N/A
Bengal rose	$C_{20}H_2Cl_4I_4Na_2O_5$	1017.67	Y	Y	N/A
Brightener 28	$C_4OH_{42}N_{12}Na_2O_{10}S_2$	960.96	N/A	Y	Y
Amino G acid	$C_{10}H_9NO_6S_2$	303.32	Y	Y	N/A
Amidoflavine	$C_{24}H_7NO_2$	341.28	N/A		Y
Leucophor PBS	$C_{29}H_2N_2O_2$	428.48	N/A	X	Y

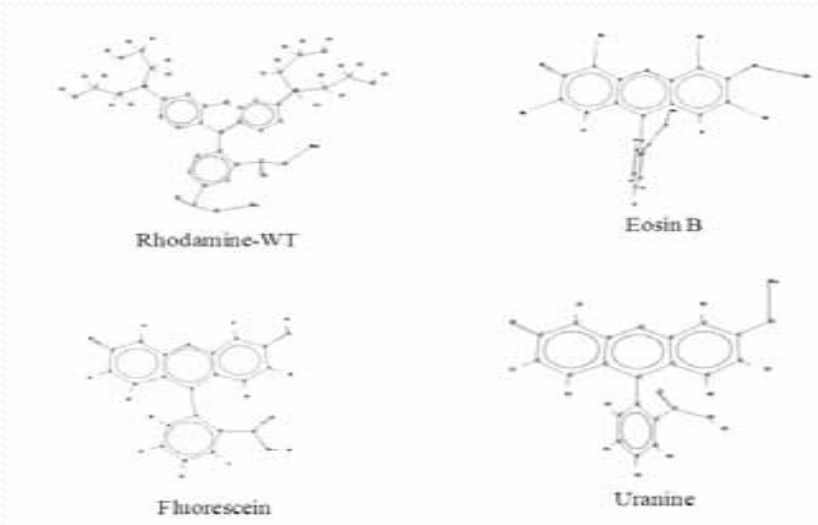
## Commonly Used Fluorescent Molecular Markers in Water Tracing Applications

Y - marker meets the specific screening criterion; N/A, A - information lacking to evaluate the criterion.

# Fluorescent Markers Shortlisted

Marker	Diameter (nm)	MW (g/mol)	Density (g/cm <sup>3</sup> )	Molar <del>ar</del> Vol (cm <sup>3</sup> /mol)	Estimated Diffusivity (10 <sup>-6</sup> cm <sup>2</sup> /s) <u>of Marker from:</u>		
					Scheibel	Wilke and Chang	Haeyduk and Laudie
Fluorescein	1.16	332	1.04	319	4.67	4.43	4.45
Eosin	1.22	692	0.90	769	3.12	2.61	2.65
Uranine	1.15	376	1.51	249	5.28	5.13	5.14
R-WT	2.01	566	1.19	476	3.86	3.48	3.51

## Molecular Properties and Aqueous-Phase Diffusivity of the Candidate Markers



Molecular structures of candidate molecular markers



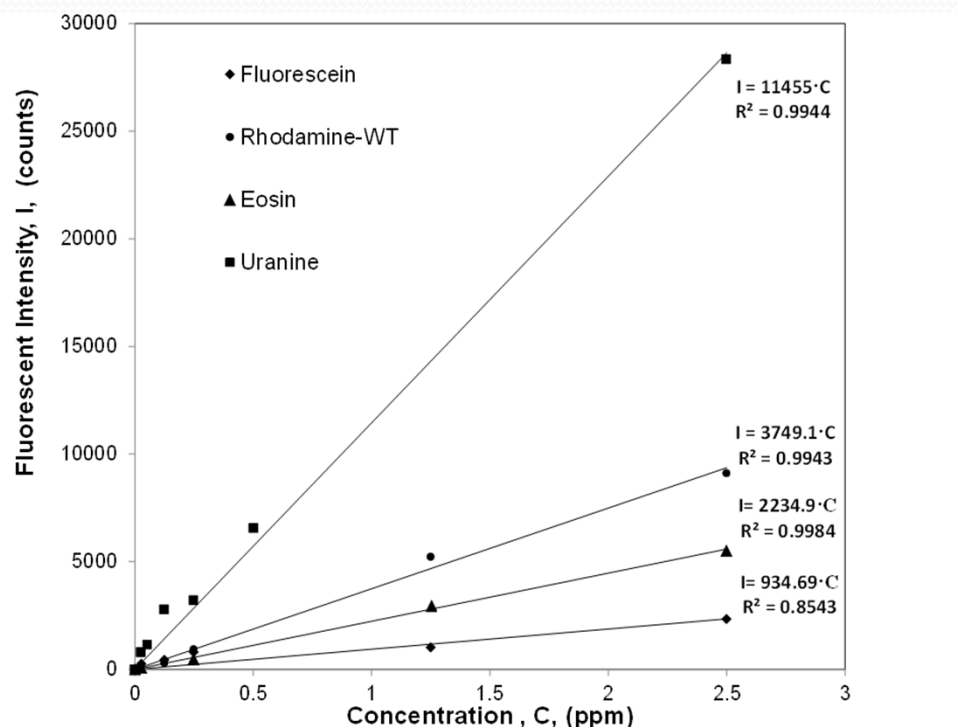
# Fluorescent Markers Shortlisted

Marker	Optimum Excitation-Emission Wavelength (nm)
Rhodamine WT	530/580
Uranine	485/520
Fluorescein	485/510
Eosin	485/534

Optimal Fluorescence Excitation and Emission Wavelengths for the Candidate Markers

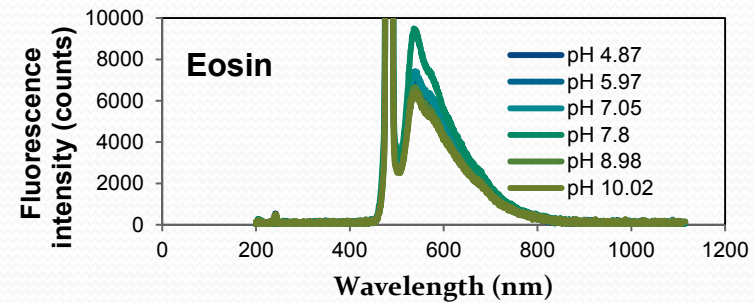
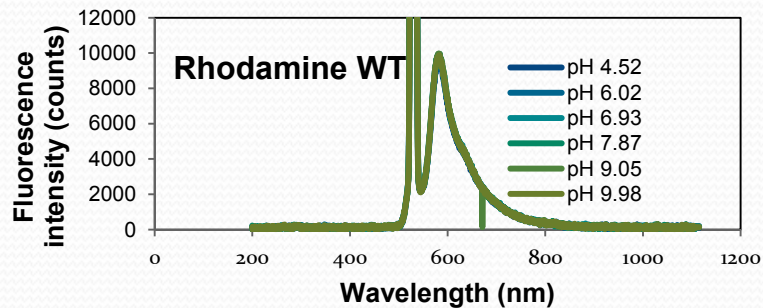
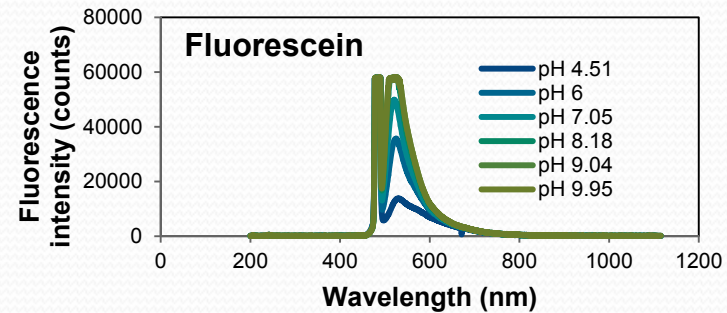
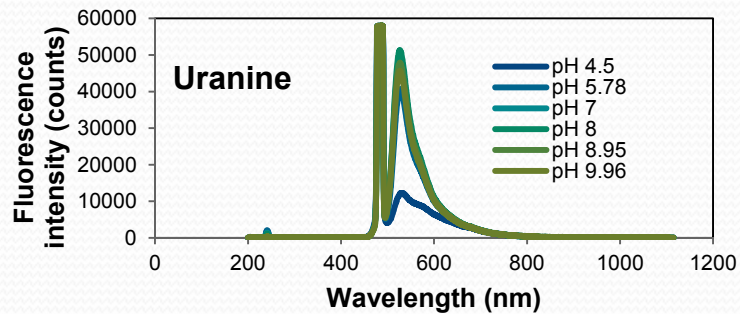
Marker	Detection Limit (ppm)
Rhodamine WT	0.25
Uranine	0.01
Fluorescein	0.125
Eosin	0.25

Detection Limit of Candidate Markers



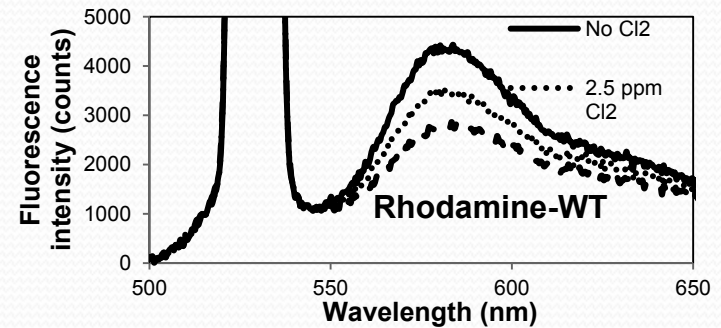
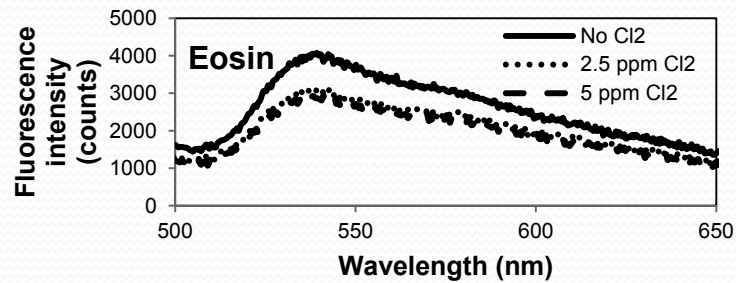
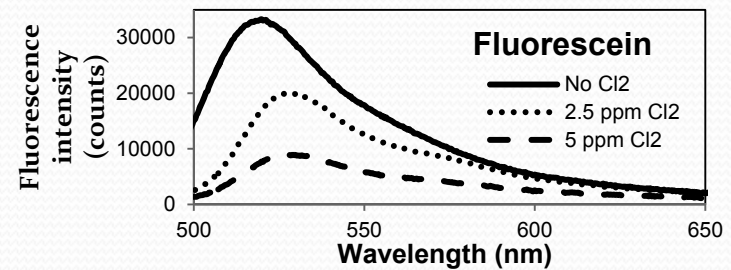
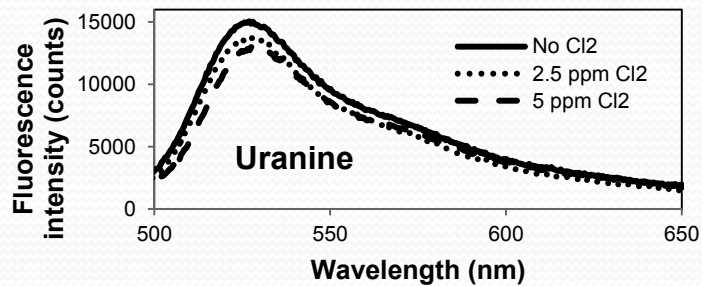
**Fluorescent- concentration calibration curves of the candidate molecular markers**

# Fluorescent Markers Shortlisted



pH effect on fluorescence intensity of candidate markers at concentration of 2.5 ppm in water

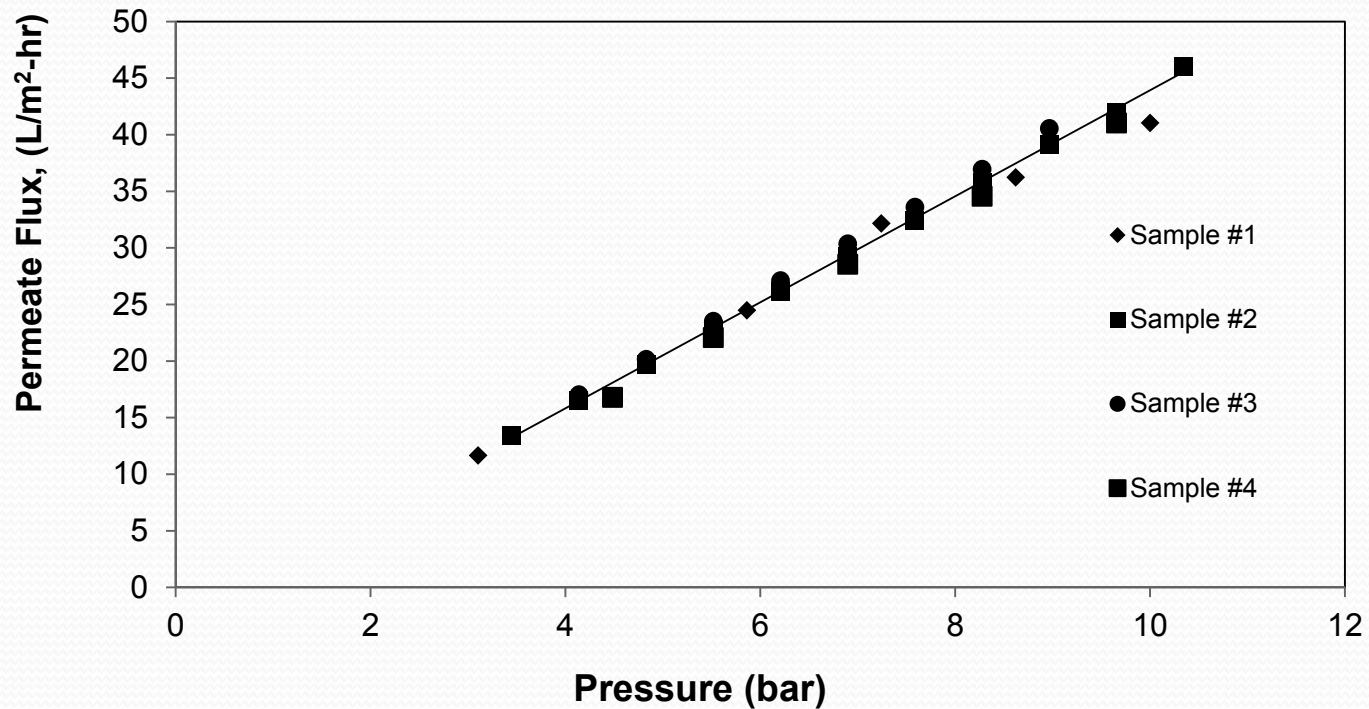
# Fluorescent Markers Shortlisted



Impact of chlorine concentration on fluorescence intensity of the candidate markers



# Membrane Permeability: PFRO – ESPA2



Flux versus transmembrane pressure for determination of water permeability of different ESPA2 membrane coupons

# Membrane Permeability

Membrane or Value	Membrane Water Permeability (LMH/bar)
Sample No. 1	4.33
Sample No. 2	4.68
Sample No. 3	4.87
Sample No. 4	4.65
Avg. Permeability	4.63
SD	0.22

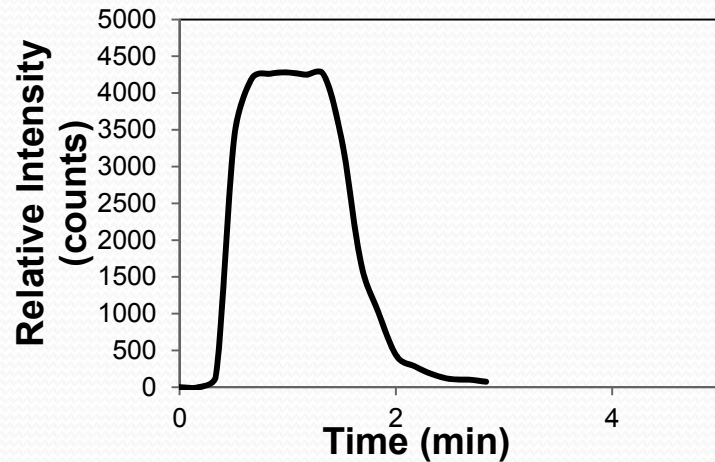
Permeability of Intact ESPA2 RO Membrane Coupons



Membrane Source or Value	Observed NaCL Rejection for 500 ppm solution
Sample No. 1	97.65%
Sample No. 2	98.50%
Sample No. 3	97.69%
Sample No. 4	96.80%
Mean	97.66%
Standard Deviation - SD	0.69%

Observed Salt Rejection of Intact ESPA2 RO Membranes

# Fluorescent Marker Selected - URANINE



Marker input resulting from injection of uranine to achieve uranine concentration of 40 ppm in the RO feed stream for 60 s

$\Delta P$ (psi) or ppb Value	$J_v$ ( $m^3/m^2$ s)	$R_{obs}$ (%)	LRV
90	$8.33 \times 10^{-6}$	99.984	3.80
100	$9.73 \times 10^{-6}$	99.989	3.96
110	$1.06 \times 10^{-5}$	99.993	4.15
120	$1.18 \times 10^{-5}$	99.994	4.22
<b>At minimum detection limit (2.45 ppb)</b>		99.996	4.40

**Uranine Rejection by Intact RO Membrane<sup>a</sup> Following a 60-s Pulse of 40-ppm Uranine Concentration in the RO Feed Stream<sup>b</sup>**

<sup>a</sup>ESPA2 (Hydraulics).

<sup>b</sup>RO feed flow rates of 1 L/min and 600-ppm uranine solution injection feed flow rate of 186 mL/min. Experimental conditions:  $C_f = 40$  ppm, feed cross-flow velocity = 18.4 cm/s.



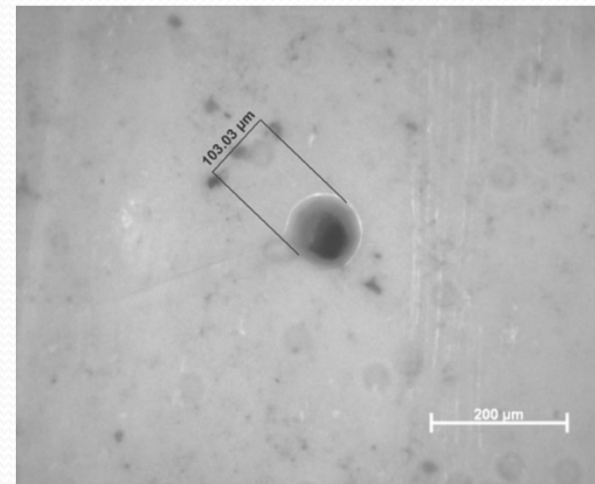
# Membrane Breach - Pinholes

## Characteristics of Membrane Breaches

Extent of Membrane Breach	Approx. Breached Surface Area (mm <sup>2</sup> )
Single small pinhole (70 μm)	$3.85 \times 10^{-3}$
Single large pinhole (104 μm)	$8.49 \times 10^{-3}$
Double large pinhole (104 and 103 μm)	$16.8 \times 10^{-3}$



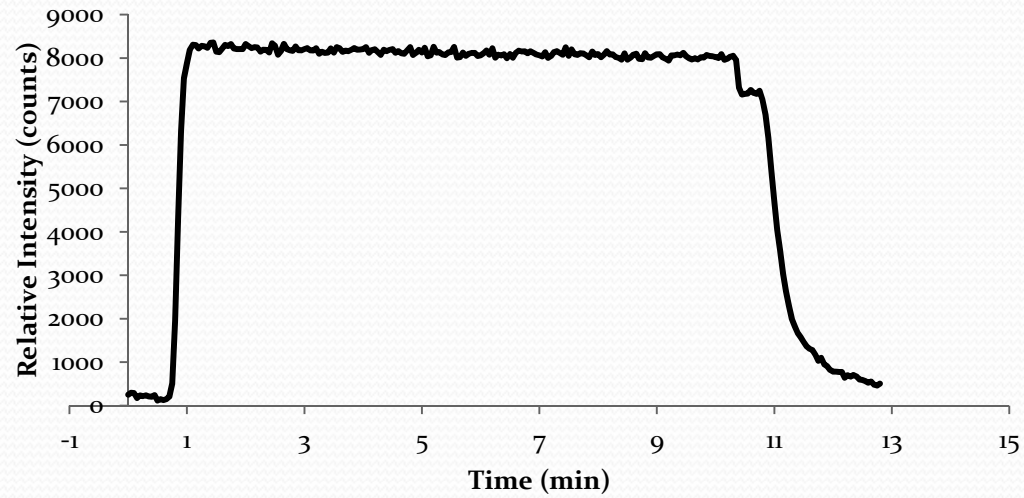
Large pinhole No. 1:  
104 μm diameter



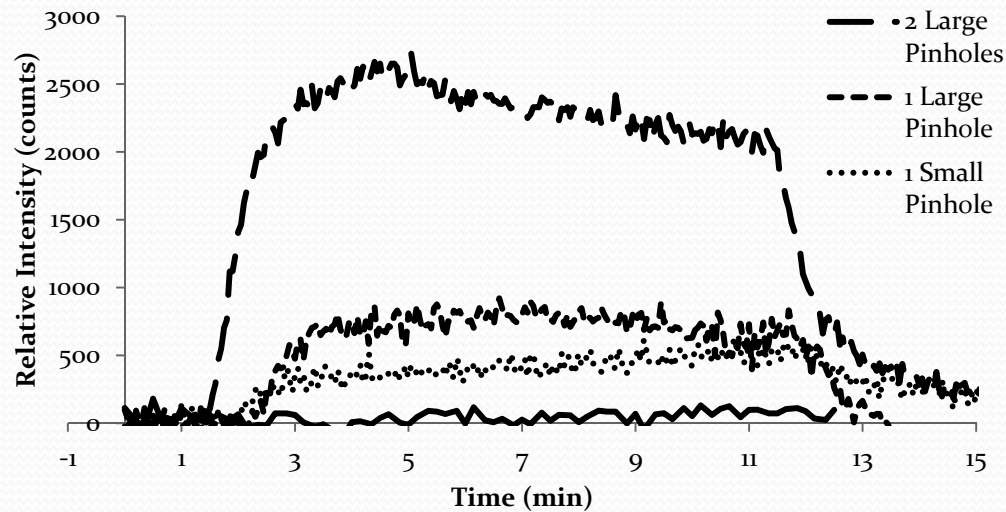
Large pinhole No. 2:  
103 μm diameter

# PM-MIMo Experiment: Intact vs. Impacted Membrane

Feed  
Marker  
Input  
Uranine – 10 mg/l



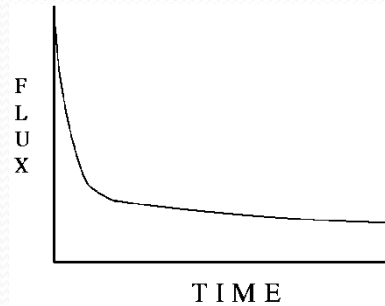
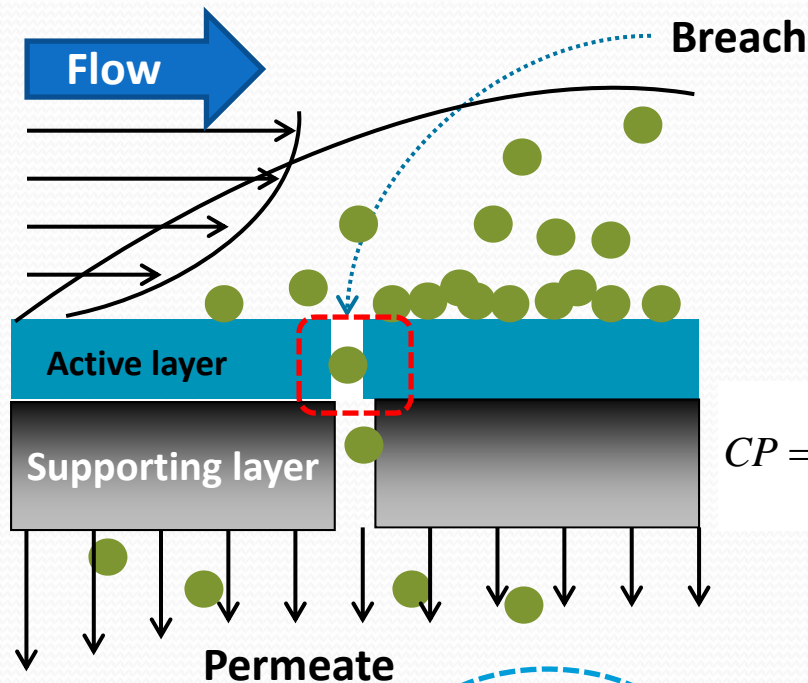
Permeate  
Marker  
Response



Step input and response data obtained from a continuous dosing of uranine to achieve 10 ppm marker concentration in the RO feed stream

PFRO was operated at 100 psi and cross-flow velocity of 18.4 cm/s

# Marker Transport



## Concentration Polarization

$k_f$ : average feed-side mass transfer coefficient; determines level of solute transport across the membrane/ fluid concentration boundary layer

$$CP = \frac{(C_m - C_p)}{(C_b - C_p)} = \exp\left(\frac{J_v}{k_f}\right)$$

$$J_s = B(C_m - C_p) + (1 - \sigma) \frac{1}{2} J_v (C_m + C_p)$$

## Solution diffusion

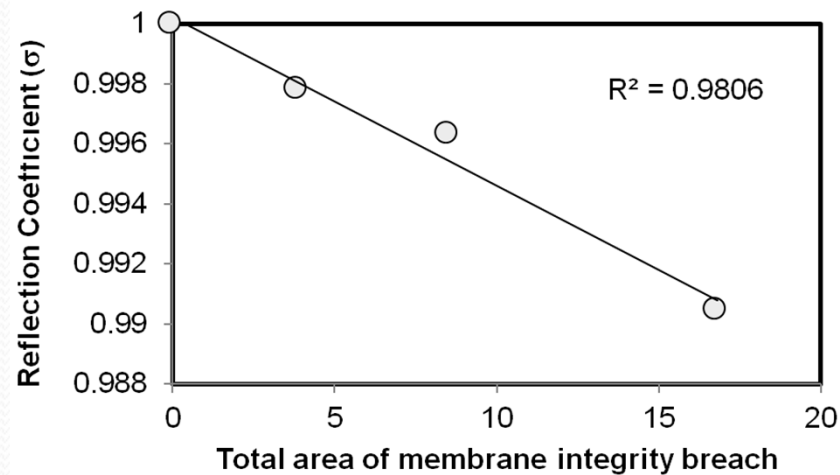
$B$ : solute transport parameter; determines solute potential for passing through RO membranes via solution-diffusion mechanism

## Convective transport

$\sigma$ : reflection coefficient; If  $\sigma$  decreases ( $<1$ ) relative to intact membrane, this would suggest possible membrane integrity breach and thus degradation of permeate quality



## PM-MIMo Experiment: Reflection Coefficient vs. Size of Breach

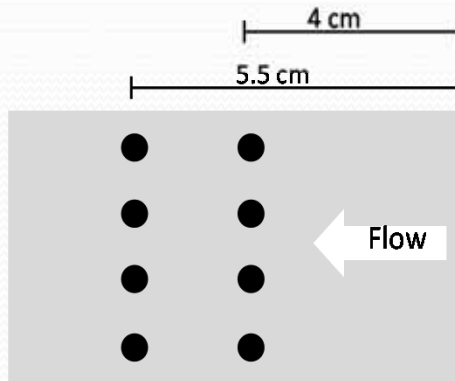


$$J_v = L_p(\Delta P - \sigma \Delta \pi)$$

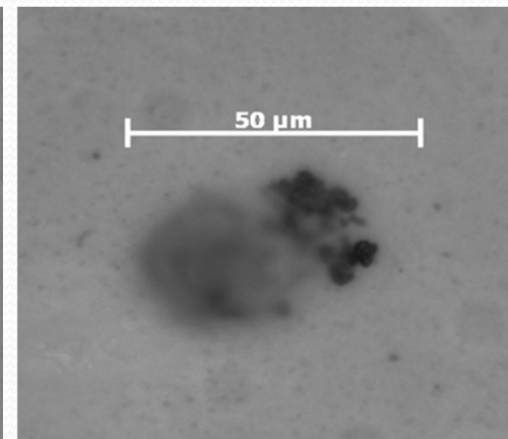
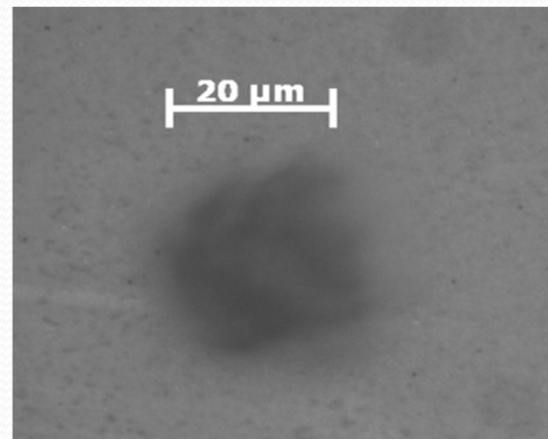
**Relationship between reflection coefficient of uranine transport through ESPA2 membrane with the total area of membrane integrity breach (pinholes)**

*Note:* PFRO was operated at 100 psi and cross-flow velocity of 18.4 cm/s; uranine was continuously dosed to achieve a 10-ppm concentration in the RO feed.

# PM-MIMo Experiment: Size and Location of Breach



Micrographs of pinholes located 4 cm (left) and 5.5 cm (right) away from the PFRO channel inlet



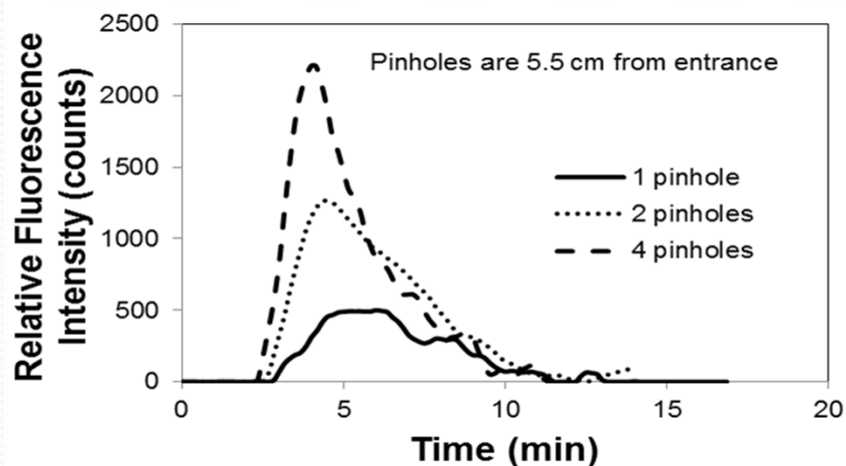
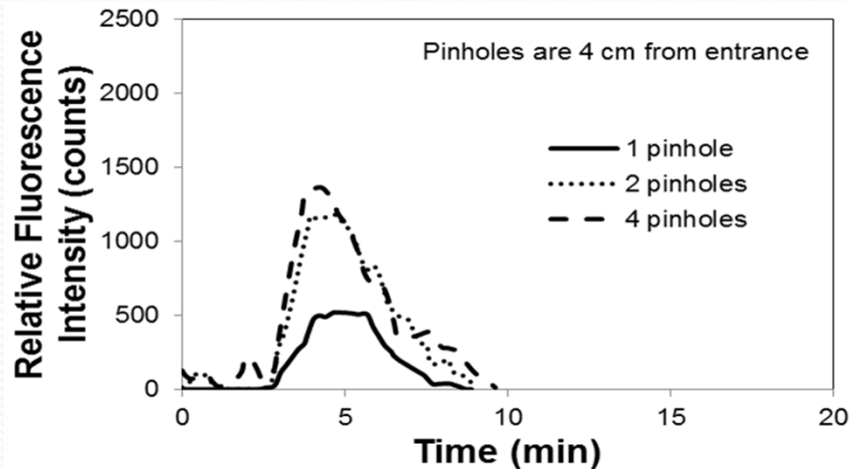
Depiction of pinhole locations on the membrane coupon

Pinhole Location	No. of Pinholes	Approx. Breached Area (mm <sup>2</sup> )
4 cm from entrance	1	$1.96 \times 10^{-3}$
	2	$3.92 \times 10^{-3}$
	4	$7.85 \times 10^{-3}$
5.5 cm from entrance	1	$3.14 \times 10^{-3}$
	2	$6.28 \times 10^{-3}$
	4	$1.26 \times 10^{-3}$

Size of Membrane Integrity Breaches

# PM-MIMo Experiment: Size and Location of Breaches

Size of Membrane Integrity Breaches



Pinhole Location	No. of Pinholes	Approx. Breached Area (mm <sup>2</sup> )
4 cm from entrance	1	$1.96 \times 10^{-3}$
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	4	$7.85 \times 10^{-3}$
5.5 cm from entrance	1	$3.14 \times 10^{-3}$
	2	$6.28 \times 10^{-3}$
	4	$1.26 \times 10^{-2}$

**Marker fluorescence intensity–time profiles for the RO permeate,**

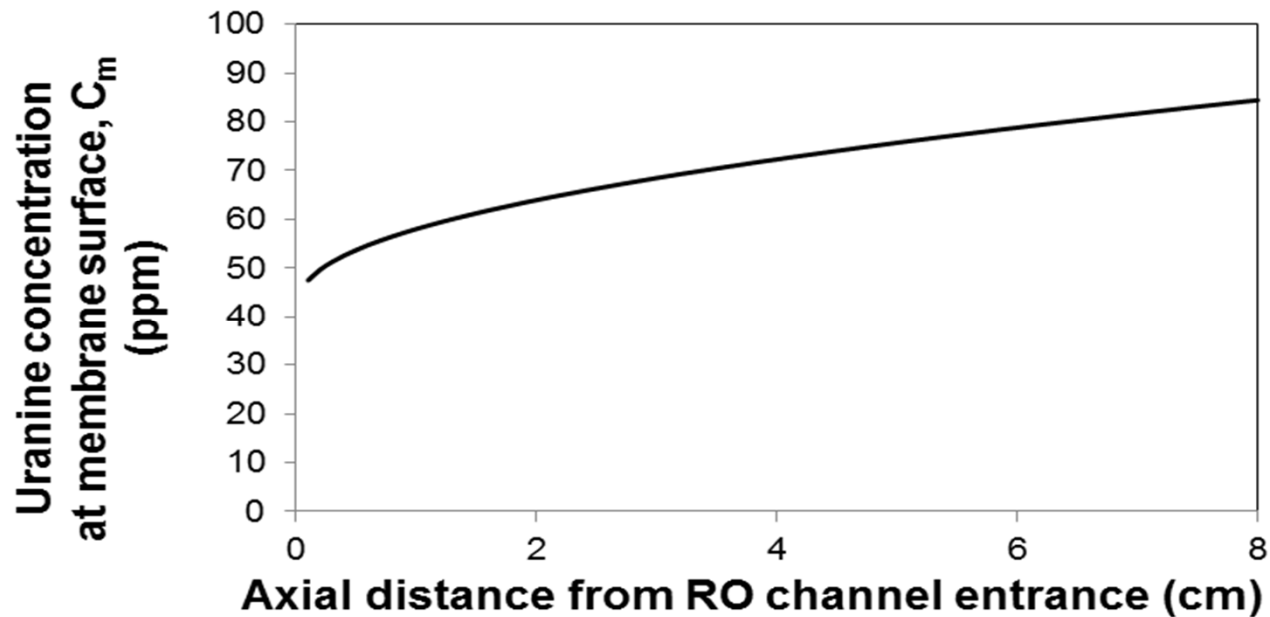
**for membranes with pinholes, in response to marker injection to the RO feed**

*Notes:* PFRO was operated at 100 psi at a cross-flow velocity of 18.4 cm/s; uranine dosing was set to attain a concentration of 40 ppm in the RO feed for a duration of 60 s.

Fluorescence intensity for the marker in the permeate stream, for the intact membrane, was below relative intensity of 180 counts.



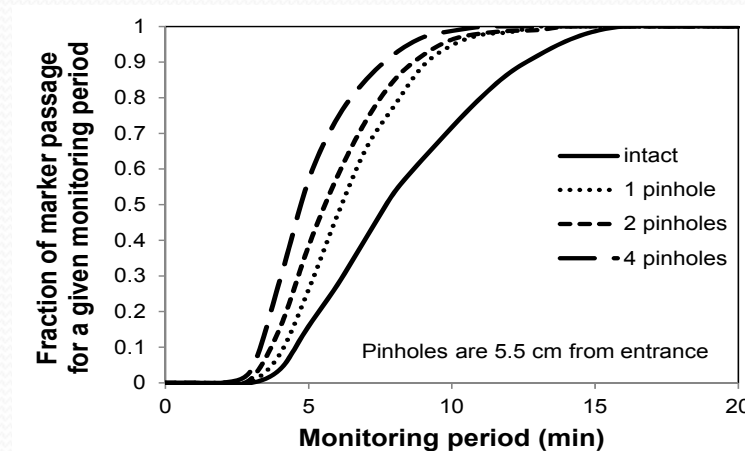
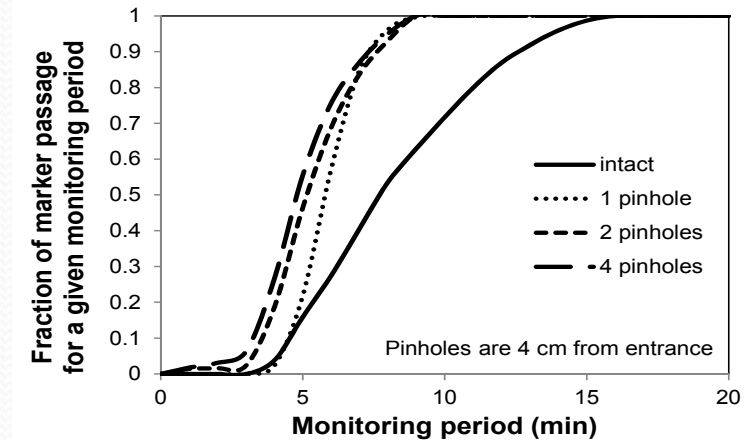
## Illustration of the Effect of Concentration Polarization on Marker Concentration at the Membrane Surface



**Estimated marker concentration at the membrane surface ( $C_m$ ) corresponding to a 40 ppm uranine marker concentration in the RO feed.**

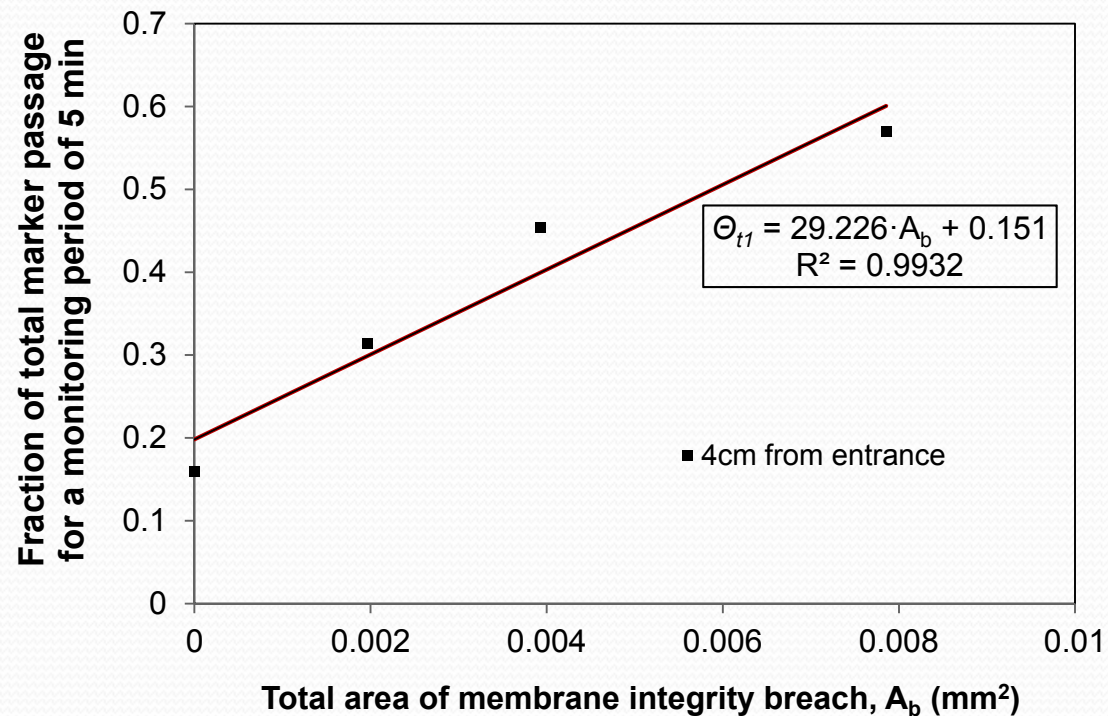
*Notes:* Permeate flux of  $9.8 \times 10^{-6} \text{ m}^3/\text{m}^2 \text{ s}$  at transmembrane pressure of 100 psi and cross-flow velocity of 18.4 cm/s.

# PM-MIMo Experiment: Size and Location of Breach



Fraction of marker passage through the RO membranes after a given monitoring period at distances of (a) 4 cm and (b) 5.5 cm from the channel entrance for different membrane breached areas

## Correlation of Total Marker Passage through the membrane with Area of Integrity Breach

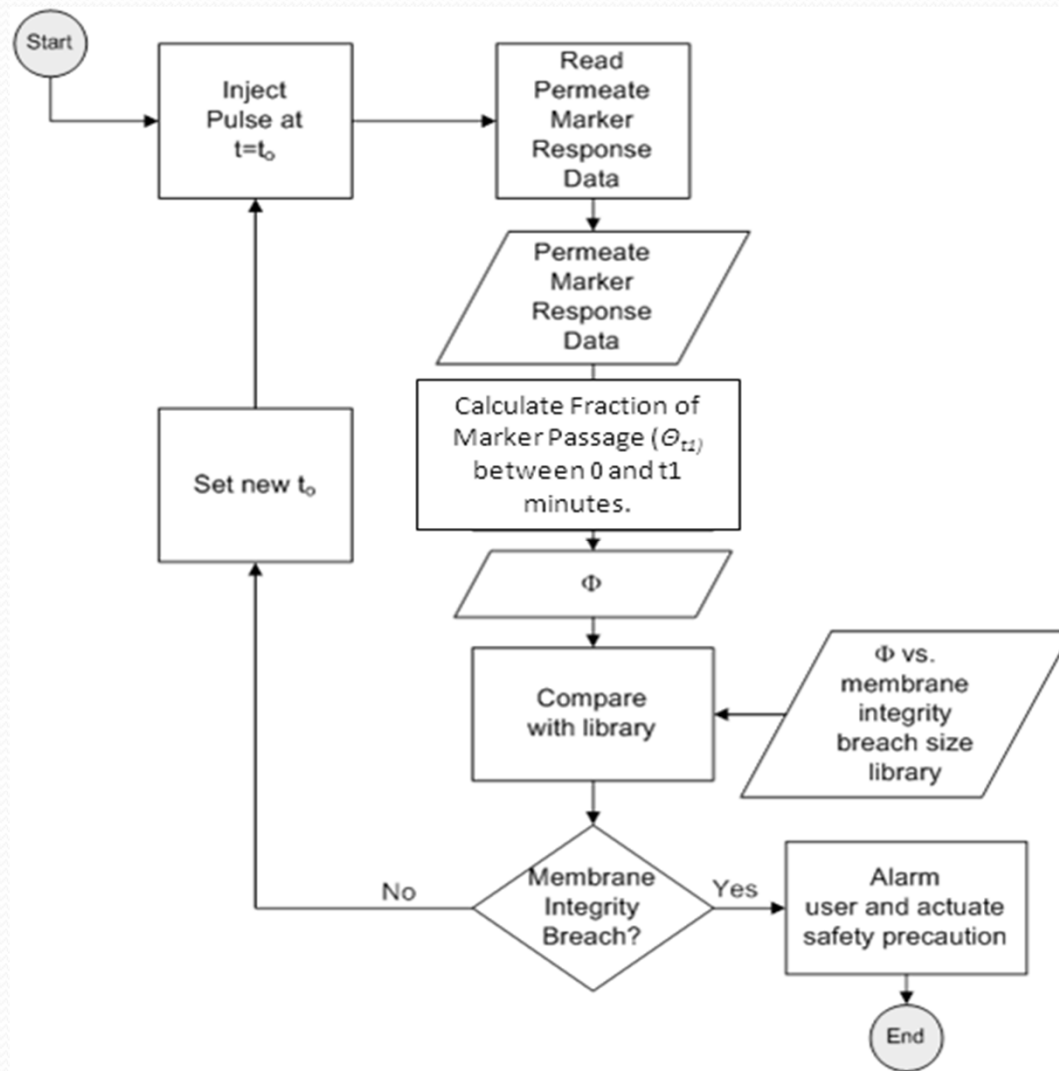


**Relationship between the FTMP through the membrane and the total area of membrane integrity breach.**

*Note:* Monitoring period of 5 min from the commencement of marker feed injection; 60 s of marker injection to achieve 40-ppm marker RO feed concentration.



# Schematic of Proposed PM-MIMo Protocol

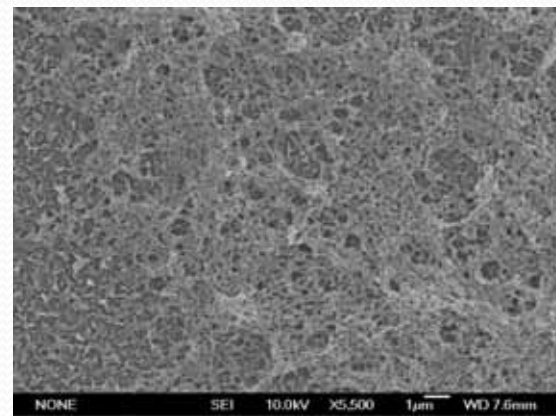
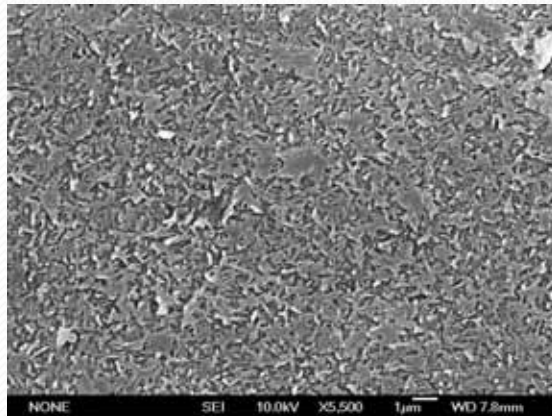


# Membrane Breach – Oxidation by NaOCl

Test	Membrane Exposure Conditions			Normalized Membrane Permeability <sup>a</sup>	Normalized Salt Rejection	Contact Angles (°)
	NaOCl Conc (ppm)	Exposure Time (h)	NaOCl Dose (ppm-h)			
1	0	0	0	1	1	69.00
2	20	8	160	1.043	1.003	66.78
3	40	4	160	1.245	1.006	64.10
4	80	2	160	1.326	0.998	60.75

## Effect of Membrane Exposure to NaOCl Solutions on Membrane Permeability and Salt Rejection

<sup>a</sup>The normalized permeability and salt rejection are the ratios of these values relative to those for the intact membrane.



SEM images of the surface of commercial ESPA2 polyamide RO membranes before and after exposure to 80 ppm NaOCl solution for 2 h.

## Membrane Breach – Oxidation by NaOCl

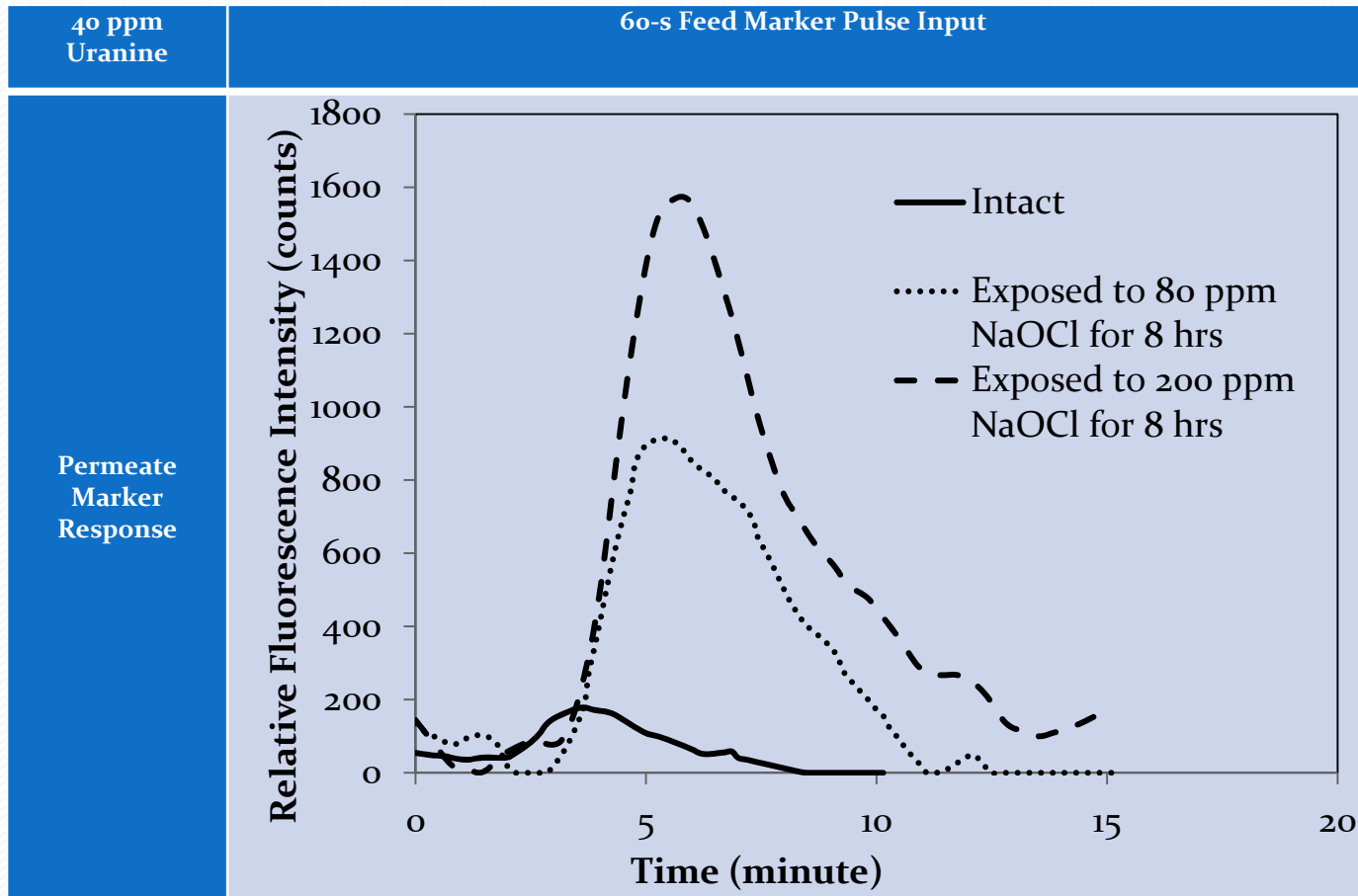
$J_v$ ( $m^3/m^2 s$ )	$R_{obs}$ (%)			Marker LRV		
	Intact Membrane	80-ppm NaOCl for 8 h	200-ppm NaOCl for 8 h	Intact Membrane	80-ppm NaOCl for 8 h	200-ppm NaOCl for 8 h
$8.33 \times 10^{-6}$	99.984	99.946	99.912	3.80	3.26	3.06
$9.73 \times 10^{-6}$	99.989	99.952	99.933	3.96	3.32	3.17
$1.06 \times 10^{-5}$	99.993	99.980	99.945	4.15	3.70	3.26
$1.18 \times 10^{-5}$	99.994	99.985	99.949	4.22	3.82	3.29

### Effect of Permeate Flux on Marker Rejection and LRV for Intact and Compromised RO Membranes

*Notes:* Marker was injected at a flow rate of 185.7 mL/min (marker concentration of 600 ppm) into the RO feed stream with a flow rate of 2.6 L/min in order to achieve a marker concentration of 40 ppm in the RO feed stream. The cross-flow velocity in the PFRO channel was 18.4 cm/s.

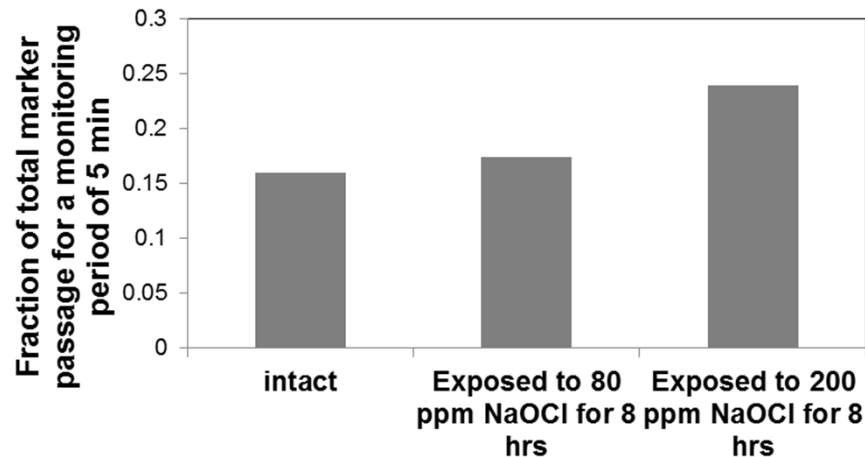


# Membrane Breach – Oxidation by NaOCl



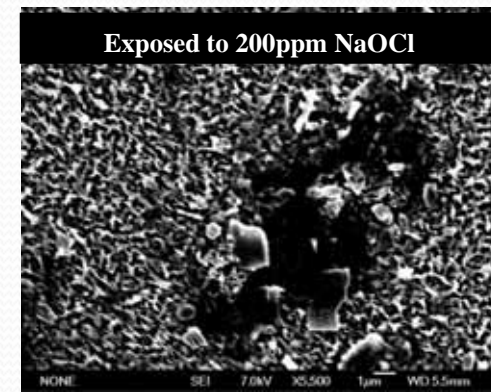
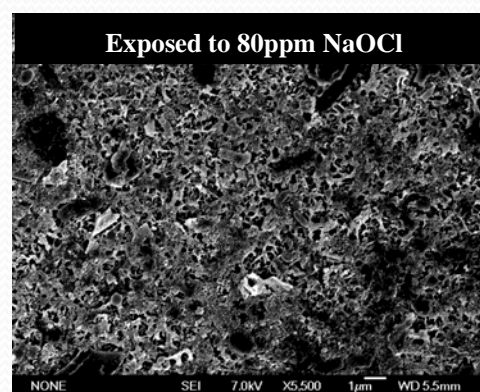
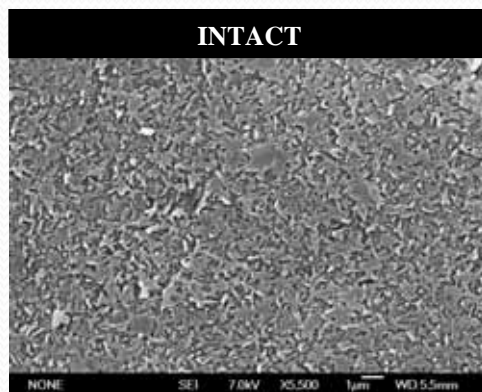
**Marker fluorescence intensity–time profiles for the RO permeate, for membranes exposed to 80 and 200 ppm NaOCl for 8 h, in response to marker injection to the RO feed to attain 40 ppm feed concentration to the PFRO cell for a pulse period of 60 s. Note: PFRO was operated at 100 psi and cross-flow velocity of 18.4 cm/s.**

# Membrane Breach – Oxidation by NaOCl



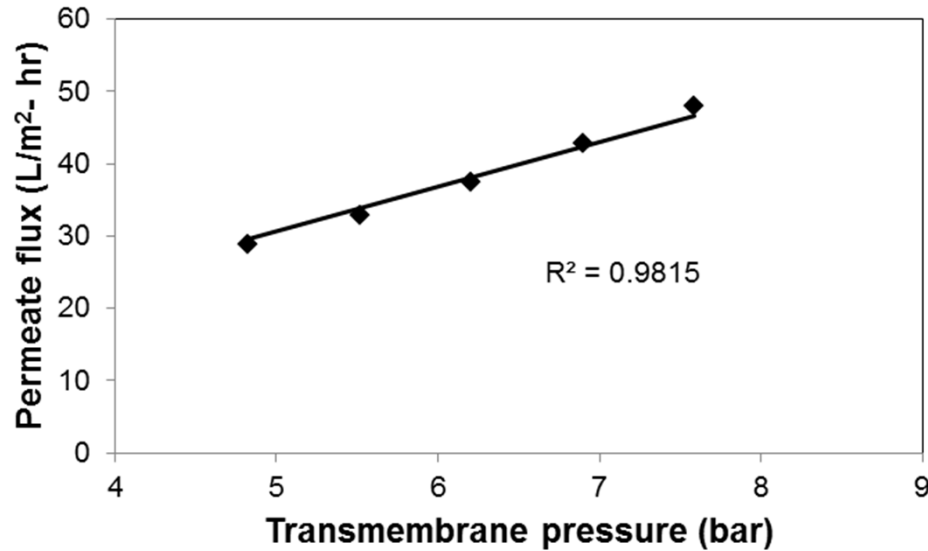
**FTMP detected in the permeate for intact ESPA2 membranes and membranes exposed to 80 and 200 ppm NaOCl for 8 h.**

*Notes:* Monitoring period of 5 min; uranine dosing to achieve 40 ppm marker concentration in the RO feed for a 60 s pulse. PFRO was operated at transmembrane pressure of 100 psi and channel cross-flow velocity of 18.4 cm/s.



SEM images of the commercial ESPA2 polyamide RO membranes before and after 8 - hr exposure to 80 - and 200 - ppm NaOCl solutions

# Membrane Permeability: SPRO – XLE-2540



**Flux versus transmembrane pressure for determination of water permeability of the XLE-2540 membrane**  
 (Note: Cross-flow velocity = 20.95 cm/s in the PFRO system)

Transmembrane Pressure, psi	Permeate Flux, L/m <sup>2</sup> -h	Observed Salt Rejection, %
160	45.7	96.0
157	38.3	96.2
152	36.9	96.3
149	35.4	96.1
146	34.0	95.8
Mean		96.1
SD		0.2

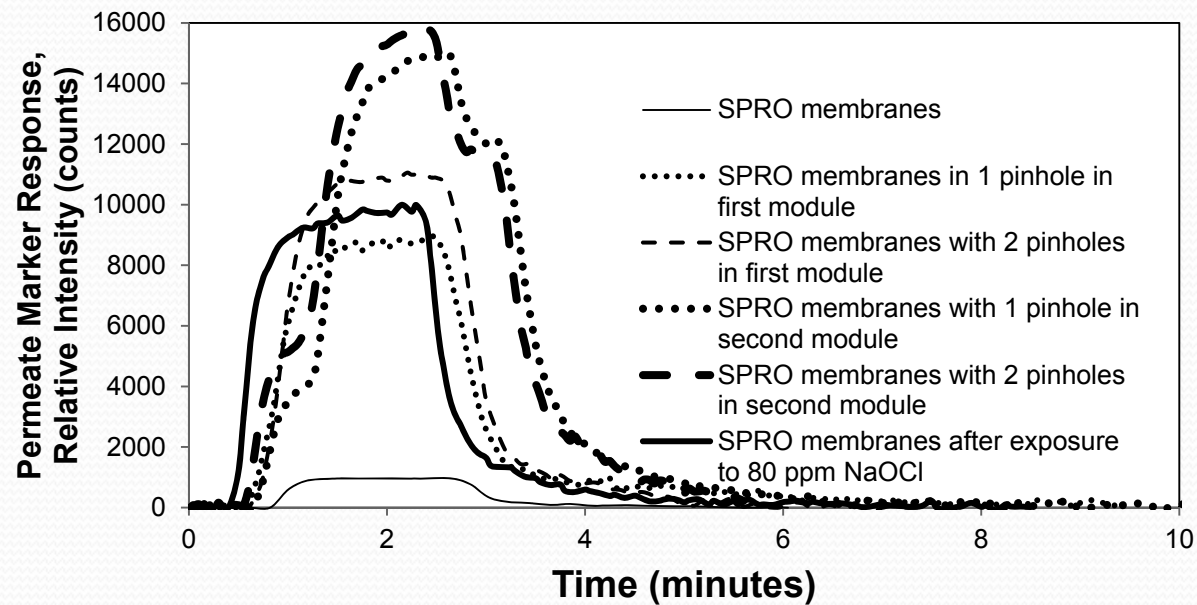
**Observed Salt Rejection for the XLE-2540 Membrane as Determined in the SPRO Membrane System at Various Transmembrane Pressures**  
 (Note: Cross-flow velocity = 12.12 cm/s)



# Marker Response Intensity in SPRO

Permeate Flux (m/s)	$C_m$ (ppm)	$C_p$ (ppb)	Observed Rejection ( $R_{obs}$ )
$2.27 \times 10^{-5}$	31.1	9.85	99.951
$2.09 \times 10^{-5}$	30.1	10.30	99.948
$1.91 \times 10^{-5}$	29.1	10.87	99.946

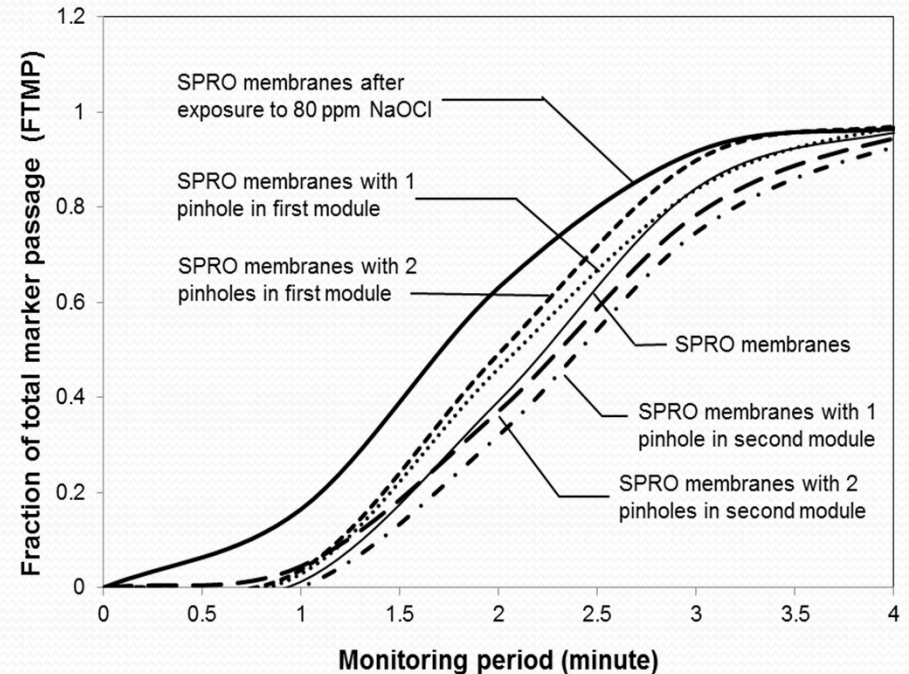
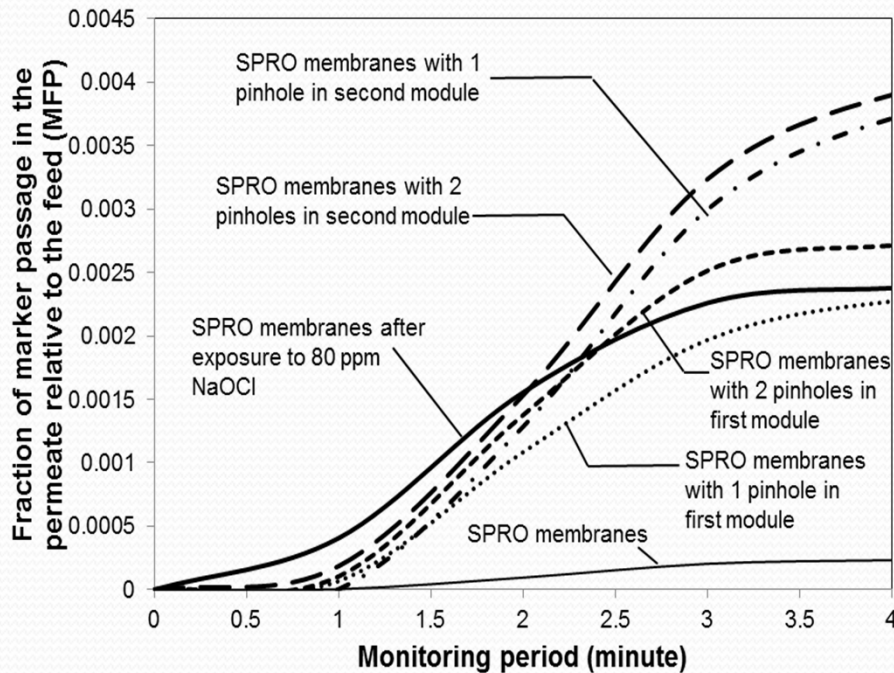
**Observed Uranine Rejection for Different Permeate Fluxes for the Flat-Sheet XLE-2540 Membrane** (Note: Uranine concentration in the RO feed stream is 20 mg/L)



**RO permeate marker fluorescence intensity–time profiles in response to marker injection into the SPRO feed.**

Note: The SPRO system was operated at 160 psi at a cross-flow velocity of 12.12 cm/s; uranine dosing was set to attain SPRO marker feed concentration of 20 ppm for 2 min.

# Marker Passage in SPRO



**Marker feed passage (MFP) at various monitoring times (Equation 15c).** (Notes: SPRO system was operated at 160 psi at a cross-flow velocity of 12.12 cm/s. Uranine dosing was set to attain a 20-ppm concentration in the SPRO feed for a pulse duration of 2 min. MFP is the passage fraction of the total injected marker feed over the designated monitoring period)

**FTMP to the permeate stream at various monitoring** (Notes: SPRO system was operated at 160 psi at a cross-flow velocity of 12.12 cm/s. Uranine dosing was set to attain a concentration of 20 ppm in the SPRO feed for a pulse duration of 2 min)



# PM-MIMo Experiment: Impact Caused by Convection

Uranine Rejection by Intact XLE-2540 RO Membranes in a PFRO Cell Following a Steady-State 10-min 20-ppm Pulse of Uranine in the RO Feed

$\Delta P$ (psi)	$J_v$ ( $m^3/m^2 s$ )	Marker $LRV_{total}$	Marker $LRV_{diff}$	Marker $LRV_{conv}$
90	$1.91 \times 10^{-6}$	3.26	3.27	5.11
100	$2.09 \times 10^{-6}$	3.29	3.29	5.11
110	$2.27 \times 10^{-6}$	3.31	3.31	5.08

Membrane Condition	Reflection Coefficient ( $\sigma$ )	Marker $LRV_{total}$	Marker $LRV_{diffusion}$	Marker $LRV_{convection}$
Intact flat-sheet XLE membrane <sup>b</sup>	0.999989	3.15	3.15	5.19
SPRO system	0.9997	3.05	3.15	3.74
SPRO system with 1 pinhole in the 1st membrane module	0.9882	2.10	3.15	2.14
SPRO system with 2 pinholes in the 1st membrane module	0.9848	2.00	3.15	2.03
SPRO system with 1 pinhole in the 2nd membrane module	0.9797	1.88	3.15	1.90
SPRO system with 2 pinholes in the 2nd membrane module	0.9780	1.84	3.15	1.86
SPRO system after exposure to 80-ppm NaOCl solution for 8 h	0.9867	2.05	3.15	2.08

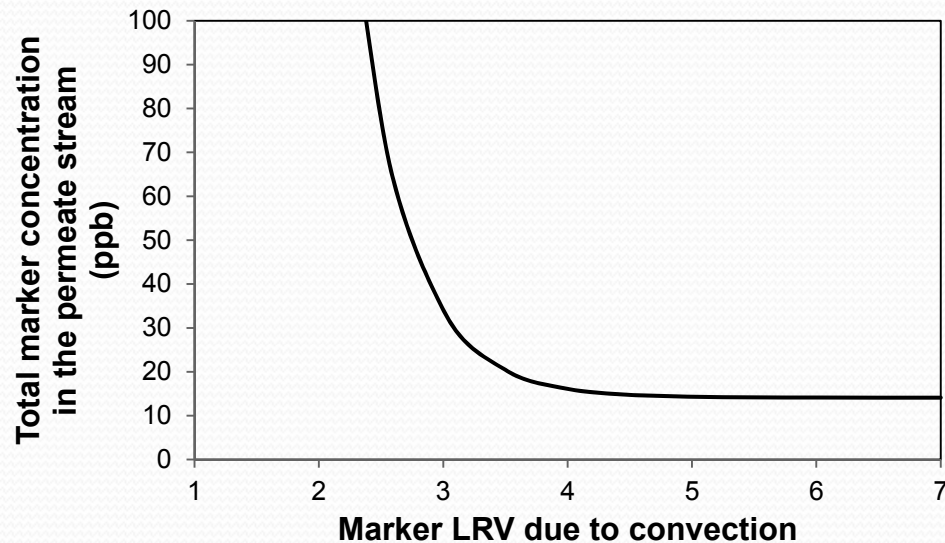
## Impact of Membrane Breaches on Reflection Coefficient and Marker LRV Determined on the Basis of a 2-min Pulse Dosing of Uranine to Achieve 20 ppm Uranine Concentration in the SPRO Feed

Note: The SPRO system was operated at 160 psi and feed flow rate of 6.8 L/min (average cross-flow velocity of 12.12 cm/s); The marker  $LRV_{diff}$  and  $LRV_{conv}$  were estimated under the SPRO operating conditions using  $B$  and  $\sigma$  values determined from the PFRO experiment (Table 9.2). Experimental conditions:  $C_f = 20$  ppm, feed cross-flow velocity = 12.12 cm/s.

<sup>a</sup>Section 9.3.



# PM-MIMo Experiment: Impact Caused by Convection



**Total marker concentration in the permeate stream in response to marker LRV due to convection of the SPRO membrane system.**

*Note:* The example is for SPRO system operation at 160-psi feed pressure and cross-flow velocity of 12.12 cm/s with uranine RO feed concentration of 20 ppm in the SPRO feed for a pulse period of 2 min. Total permeate concentration for a given LRV due to convective transport was calculated



## Summary

- With more reliance on high pressure membranes when providing water for drinking purposes, IPR and DPR the MIT/MIM of RO and NF membranes need to be well established and adopted by the industry
- Current direct MIT and MIM methods and technologies are not in the stage to meet the industry needs and not well adapted by the industry
- The newly developed PM-MIMo approach is very promising to fill the industry gap to monitor RO/NF membranes integrity and PM-MIMo approach can be utilized to detect and provide information on the characteristics of various types of membrane integrity breaches in the SPRO membrane system via real-time monitoring
- The PM-MIMo approach is sensitive to minor breaches and should be able to demonstrate greater than 4 LRVs of the marker through the intact membranes of the SPRO system
- The PM-MIMo approach clearly has potential for use as a real-time integrity monitoring technique for full-scale applications
- Field studies by UCLA are now underway demonstrate the accuracy, versatility, and robustness of this (patent pending) PM-MIMo technology







## Questions?

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