Pulsed-Power Electromagnetic Effects on Crystallization During Desalination

Xiaoyun Lu[1], Jeff Harvey[1], Hengyi Ju[1], Todd Murray[1], Katie Guerra[2], and John Pellegrino[1]

[1]University of Colorado at Boulder, Boulder, USA
[2]Bureau of Reclamation, Denver, USA

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Overview

- **Background**
  - Reverse osmosis (RO) Desalination and Scaling
  - Electromagnetic Field Effects on Electrolyte Crystallization
  - Electromagnetic field generator
- **Initial Study Results**
  - Pilot-scale plant
  - Bench-scale cross-flow system
- **Crystallization Characterization**
  - Acoustic Spectroscopy
- **Significance and Future Work**

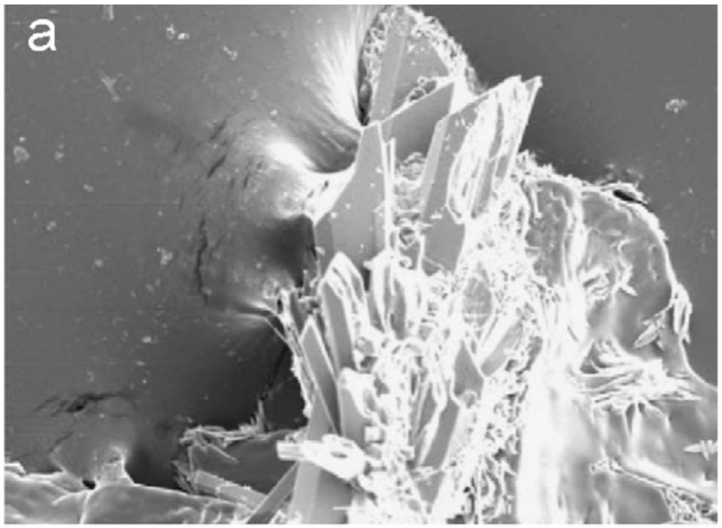
Background

- Reverse osmosis (RO) membrane desalination is a well-known pressure-driven water purification process.
- Scaling due to crystallization of sparingly soluble salts on the membrane surface causes flux decline, low water recovery rate, and short membrane lifetime.
- Strategies for scaling mitigation:

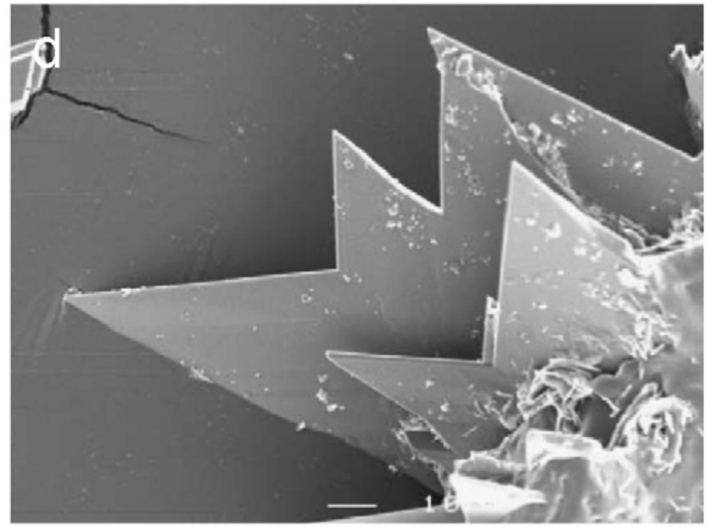
- Chemical methods: antiscalant, pH adjustment, ion exchange: solution chemistry, expensive
- Non-chemical methods

- Mechanical cleaning: down time, membrane lifetime
- *Electronic or magnetic pretreatment*

Electromagnetic(EM) Mechanism



With Magnetic Field

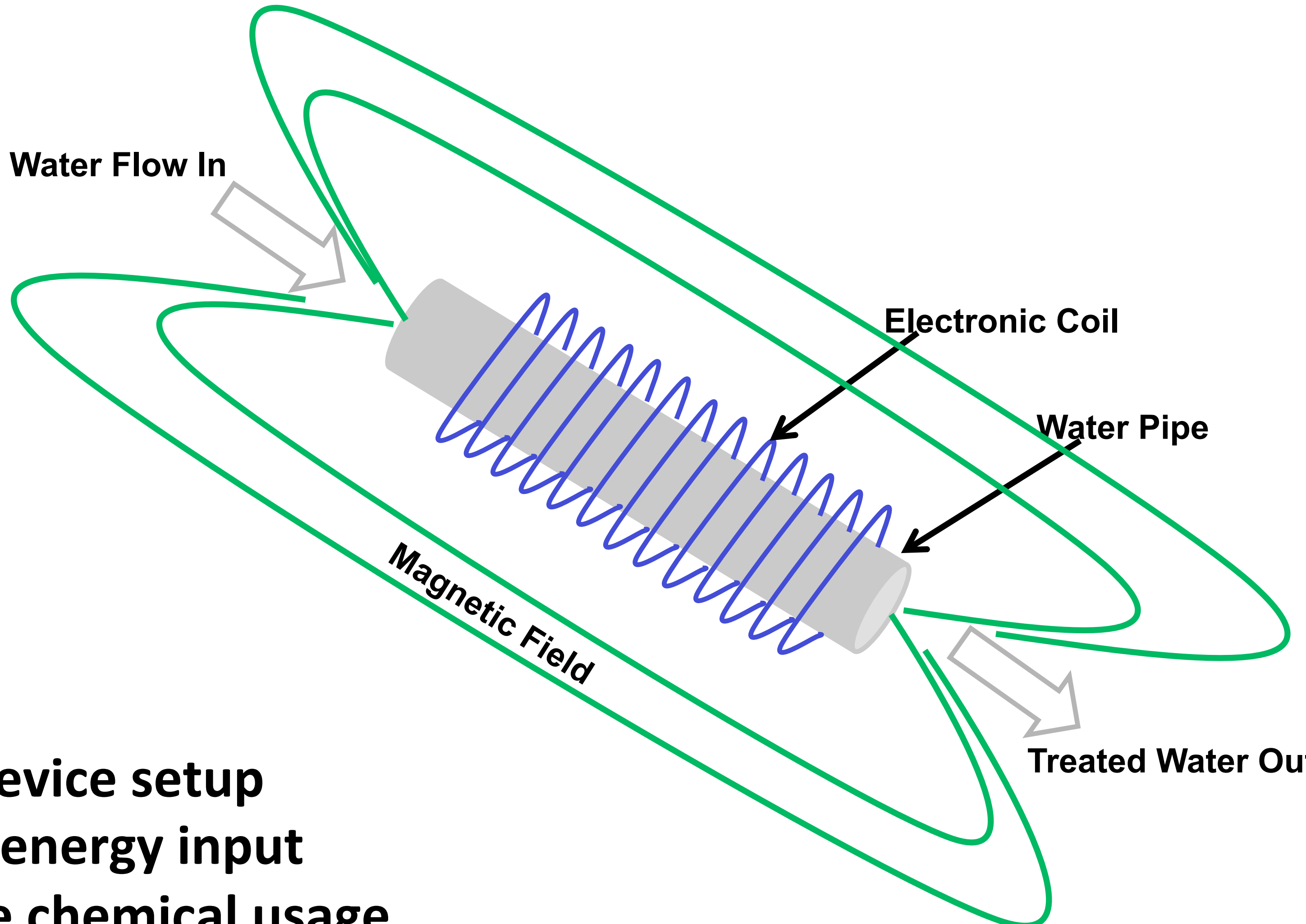


Without Magnetic Field

- **EM affects crystallization kinetics and morphology of various electrolytes.**
- **EM field treatment prevents or eliminates chemical scale.**
- **Incorporation of an EM field in a RO desalination system could be an feasible approach to prevent membrane scaling.**

Golriz et.al. Journal of Crystal Growth, 303 (2007) 381-386
Liburkin et.al. Glass and Ceramics, 43 (1986) 116-119

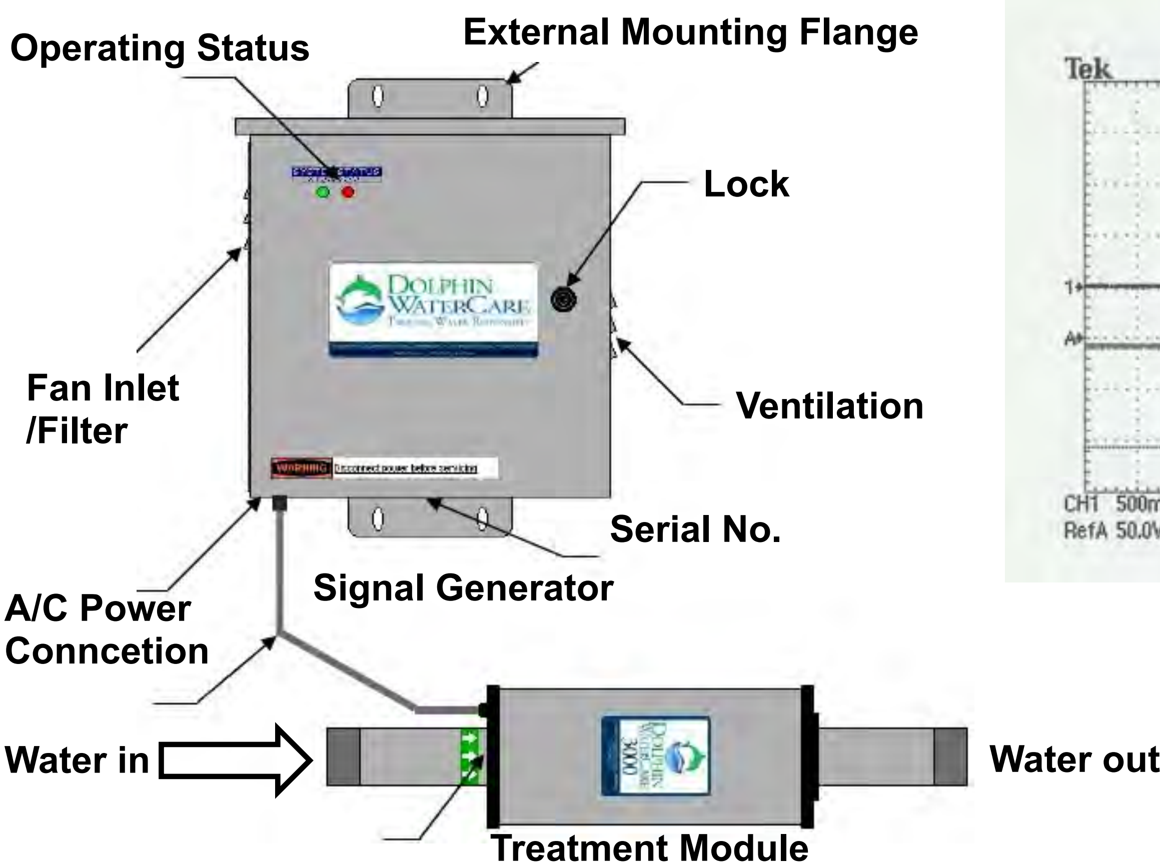
Electromagnetic Field Benefit

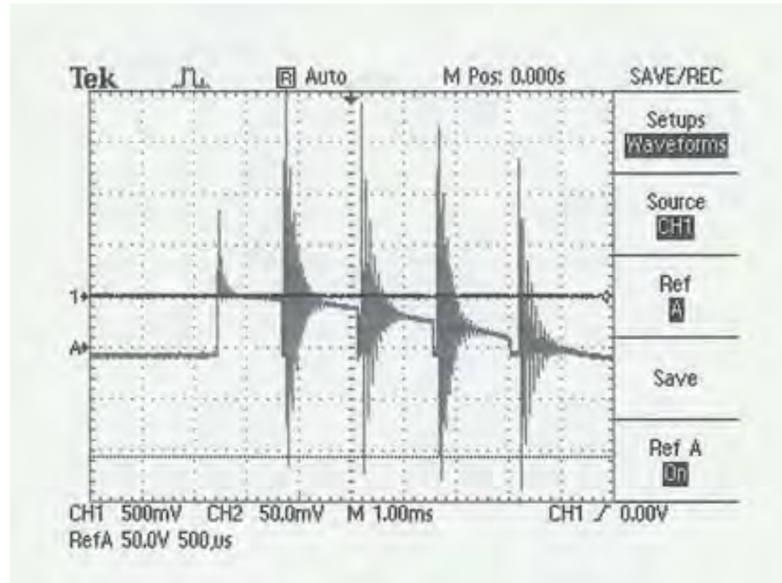


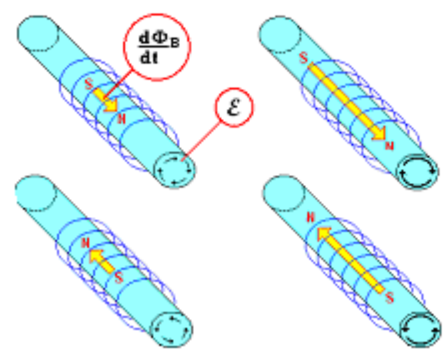
- Simple device setup
- Minimal energy input
- Eliminate chemical usage
- Eliminate disposal costs, pollution possibility

EM Field Generator

Dolphin System – Clearwater System Corporation

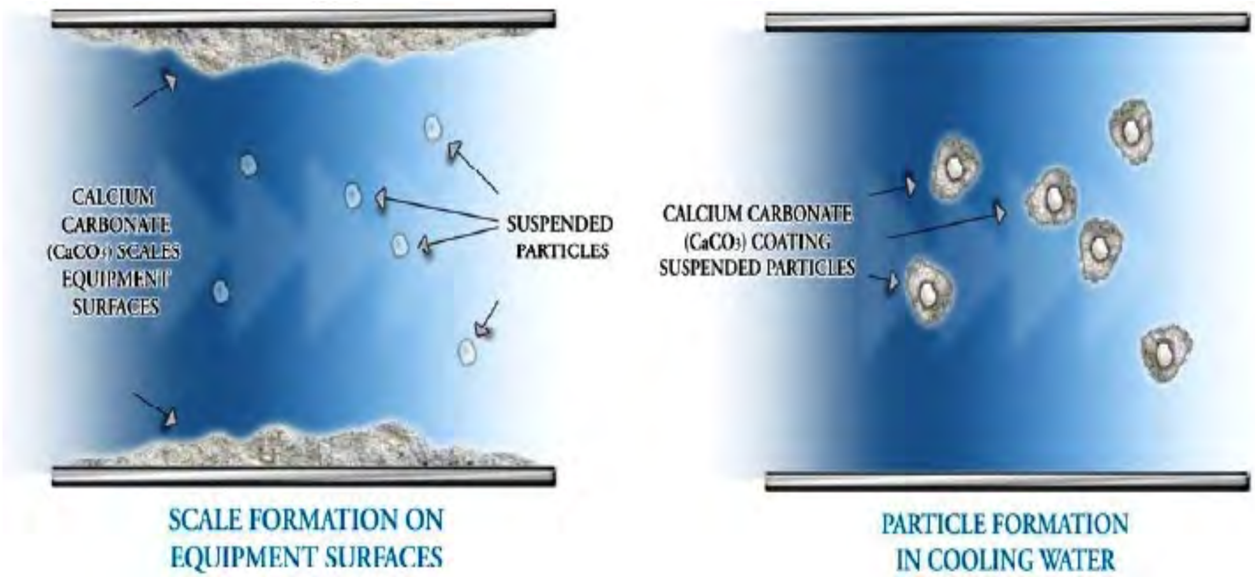






http://www.clearwater-dolphin.com/operating_principles.htm

Dolphin System



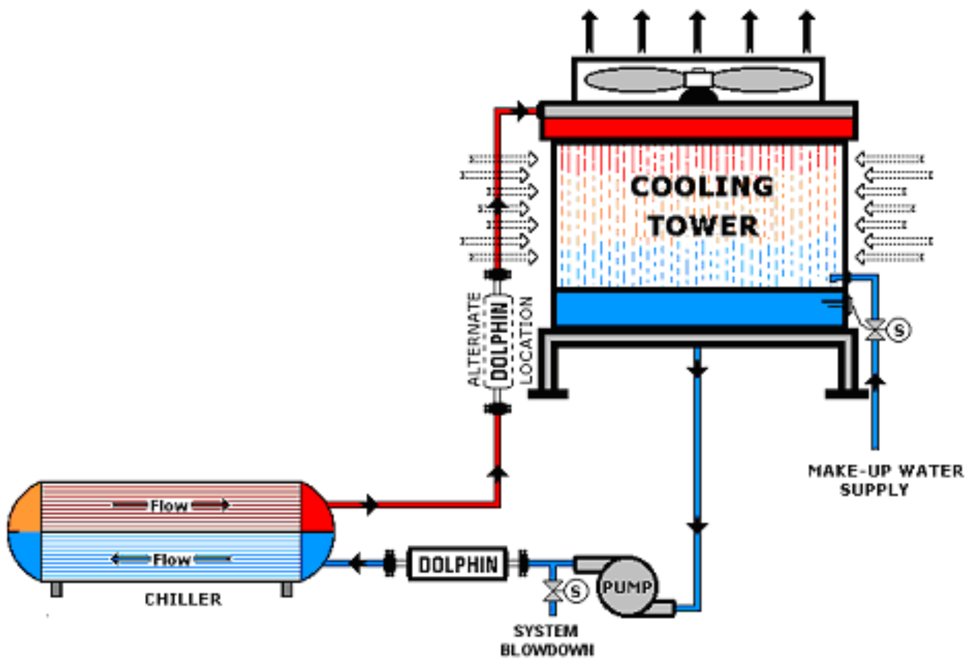
- Dolphin system removes the static electric charge on the small suspended particle surface .
- The suspended particles act as seeds for precipitation of sparingly soluble salts.
- The aggregation occur s in bulk solution instead of scaling on the membrane surface.

Typical Surface Scale
Chemical Treatment

Bulk Solution Precipitation
Pulsed EM Treatment

http://www.clearwater-dolphin.com/operating_principles.htm

Dolphin System Application

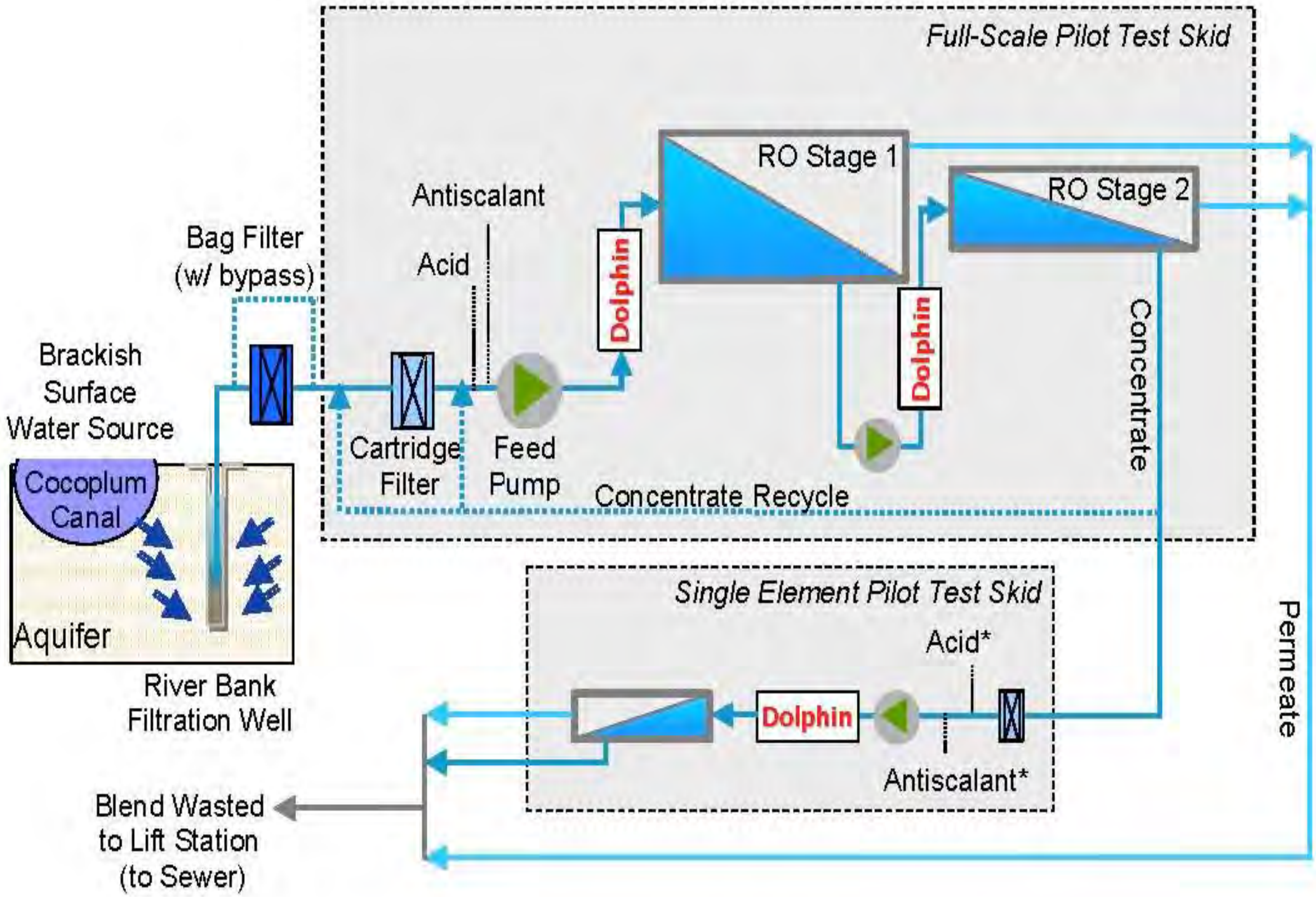


- Significant cleaning of the plate-and-frame heat exchanger
- Consistently low bacteria levels
- Less corrosion results
- Eliminate of nearly all chemical treatment

Dolphin Water Treatment Study Report prepared by BWI Solutions Inc. 2004
http://www.clearwater-dolphin.com/cooling_towers.htm

Initial Study - Pilot Scale

Full scale pilot plant in Northport, Florida by Carollo Engineering



Initial Study - Pilot Scale

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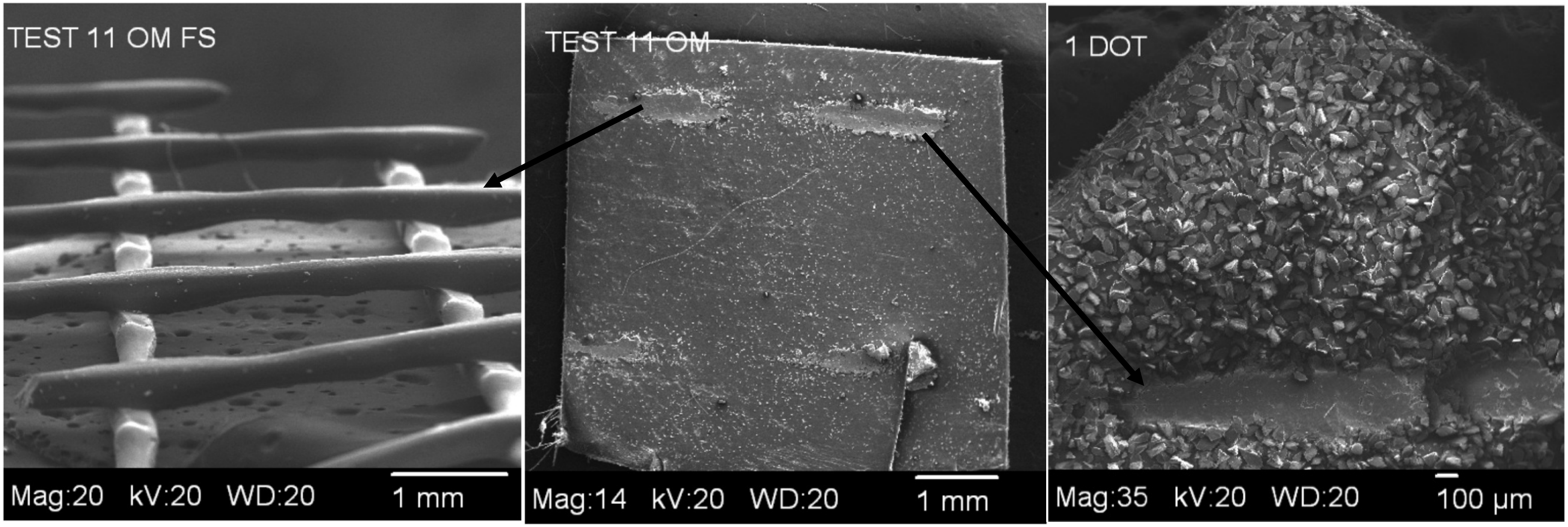
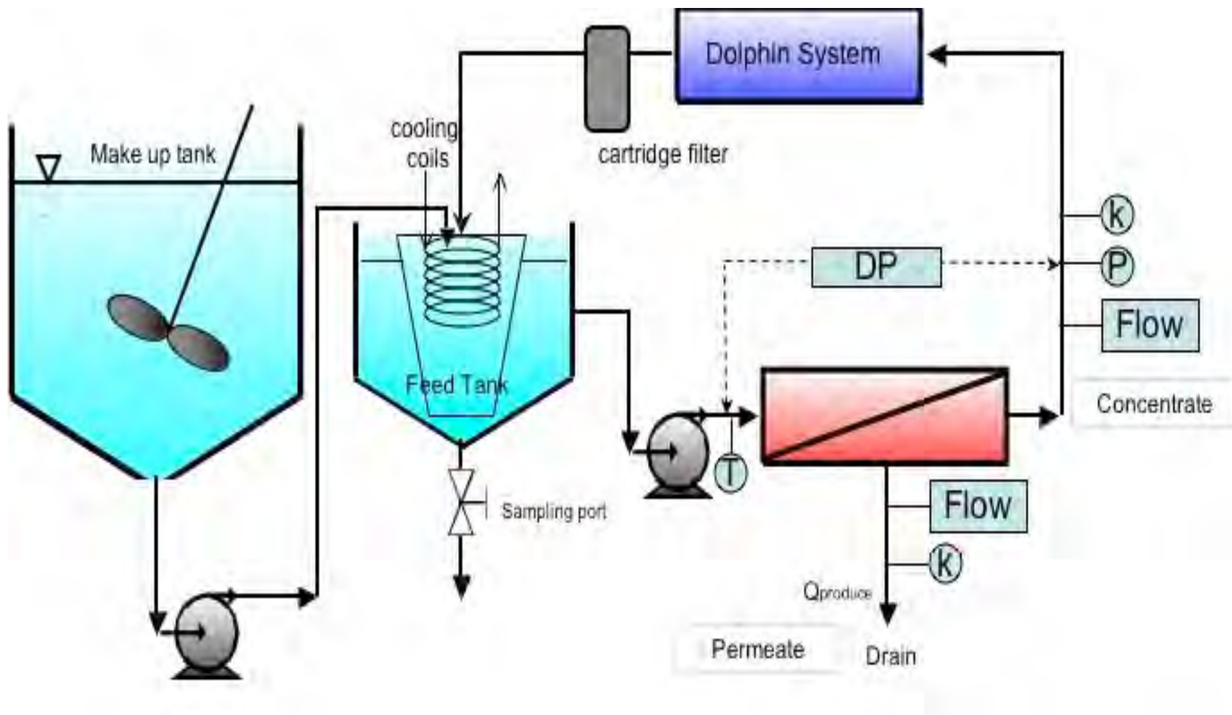


- **The membrane is not fouled from sparingly soluble salts**
- **Pressure difference was caused by the back pressure created by concentrate blockage**
- **Concentrate blockage initiates at the intersections of spacer fibers**

Initial Study - semi-pilot scale

2.5" element pilot scale plant in Bureau of Reclamation, Denver



K: Conductivity meter
P: Pressure transducer
Flow: Flow meter
T: Thermal couple

Species	Composition
H_2O	1 kg
NaOH	0.4 mg
$NaHCO_3$	100 mg
$CaCl_2$	0.475 g
Mg SO_4	0.12 mg
KCl	1.0 g
$FeCl_2$	0.38 mg
NaCl	20.6 g

Concentration: ~11000 ppm

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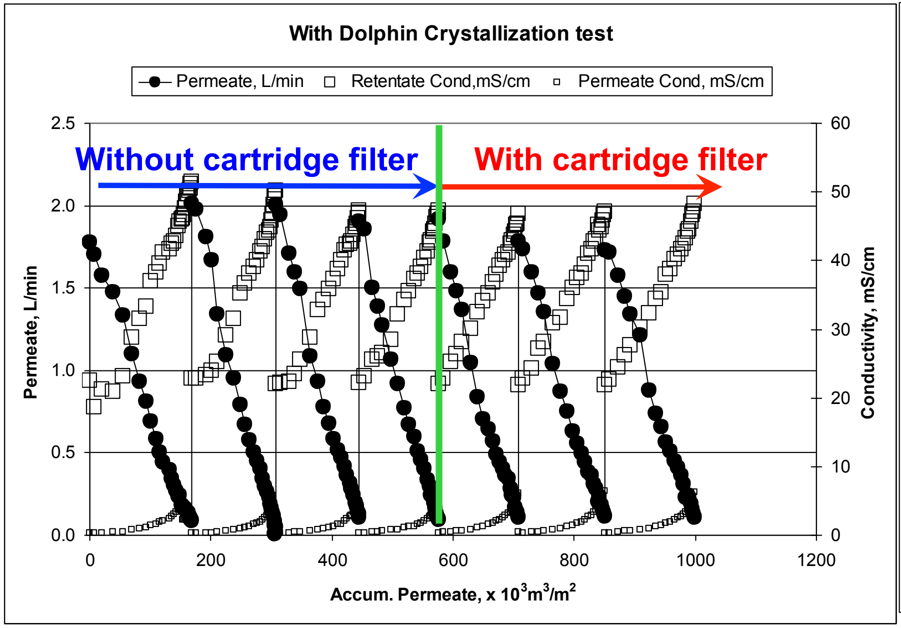
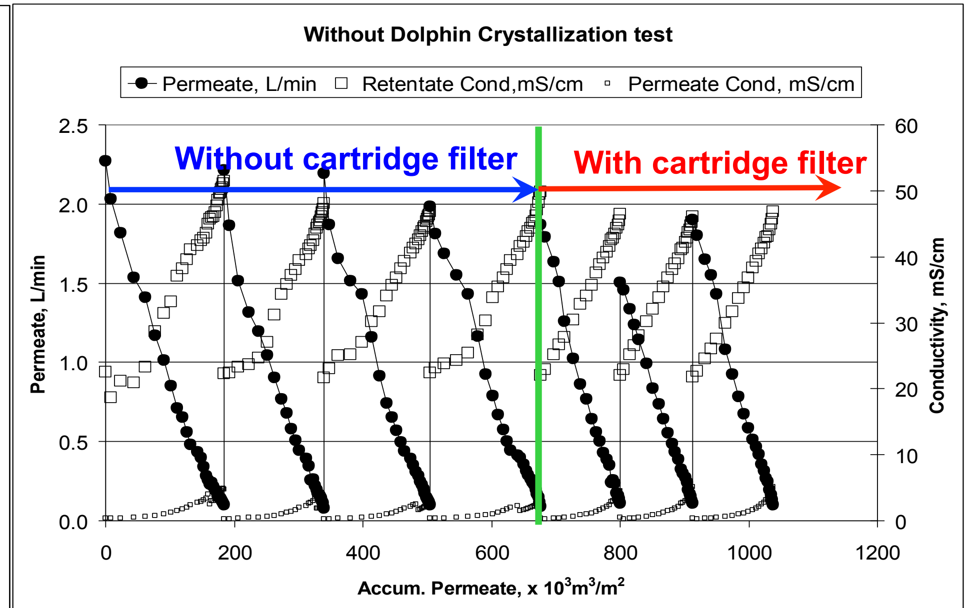




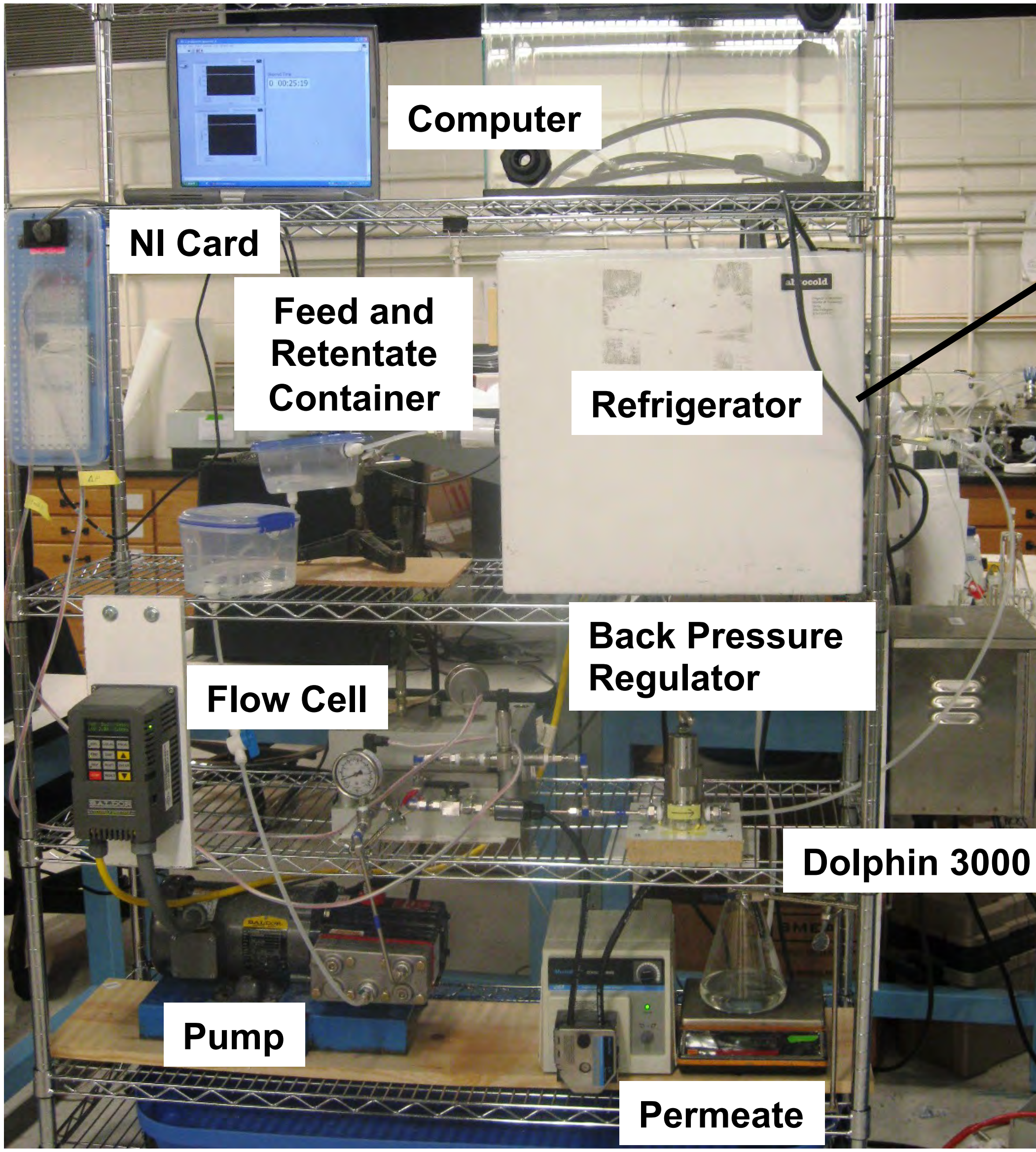
Productivity (m^3/m^2)	With Dolphin	Without Dolphin
1st – 4th cycle	575	676
5th-7 th cycle	421	360

Interpretation:

With Dolphin: smaller colloidal crystals may be formed that do not settle easily in the feed tank, instead, they precipitated on the membrane surface.

Without Dolphin: larger sized crystals may be formed that could act as seeds for precipitating salt in the feed tank.

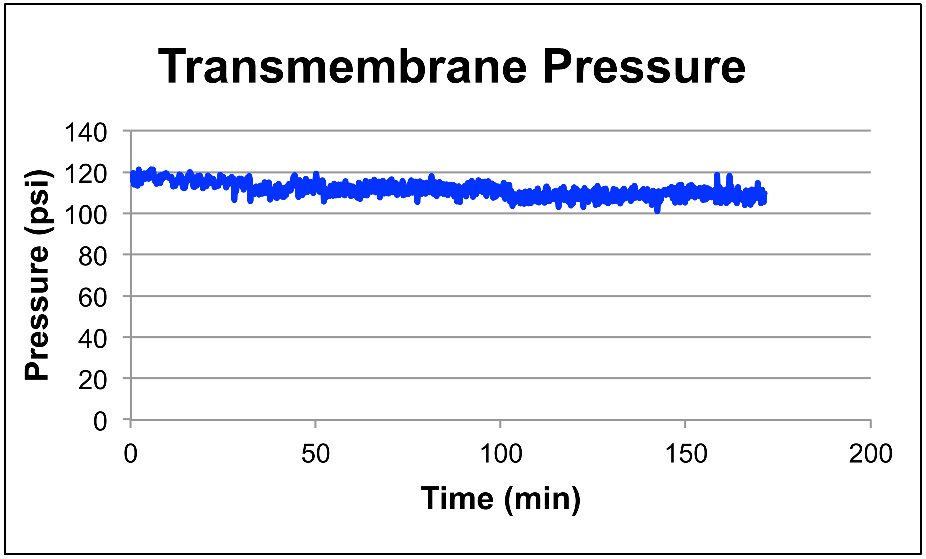
Bench-scale RO setup

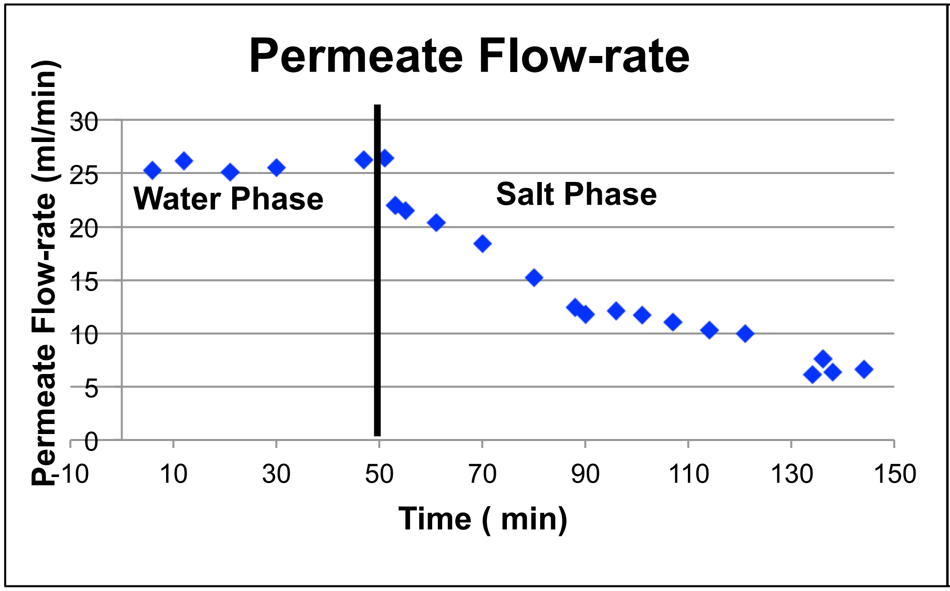


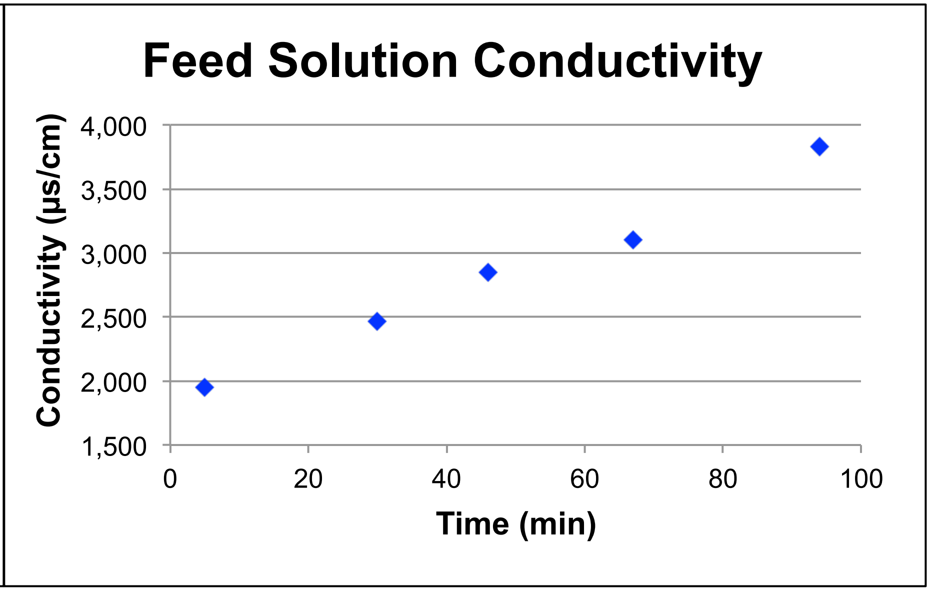
Experimental design

- **Controlled Parameters**
  - Concentration: 1.85 gL^{-1} $CaSO_4$
  - Temperature: 23ºC
- **Experimental Variable:**
  - Pressure: 50 - 300 psi
  - Cross-flow velocity: 10 - 21 cm/s
  - Control experiments: without PP-EM field
- **Real-Time Response Variables**
  - Permeate flow-rate
  - Conductivity
  - Membrane salt rejection
- **Post-Mortem Characterization**
  - Gravimetric measurements
  - Light microscopy image: surface area coverage
  - Scanning electronic microscope (SEM)

Experimental results



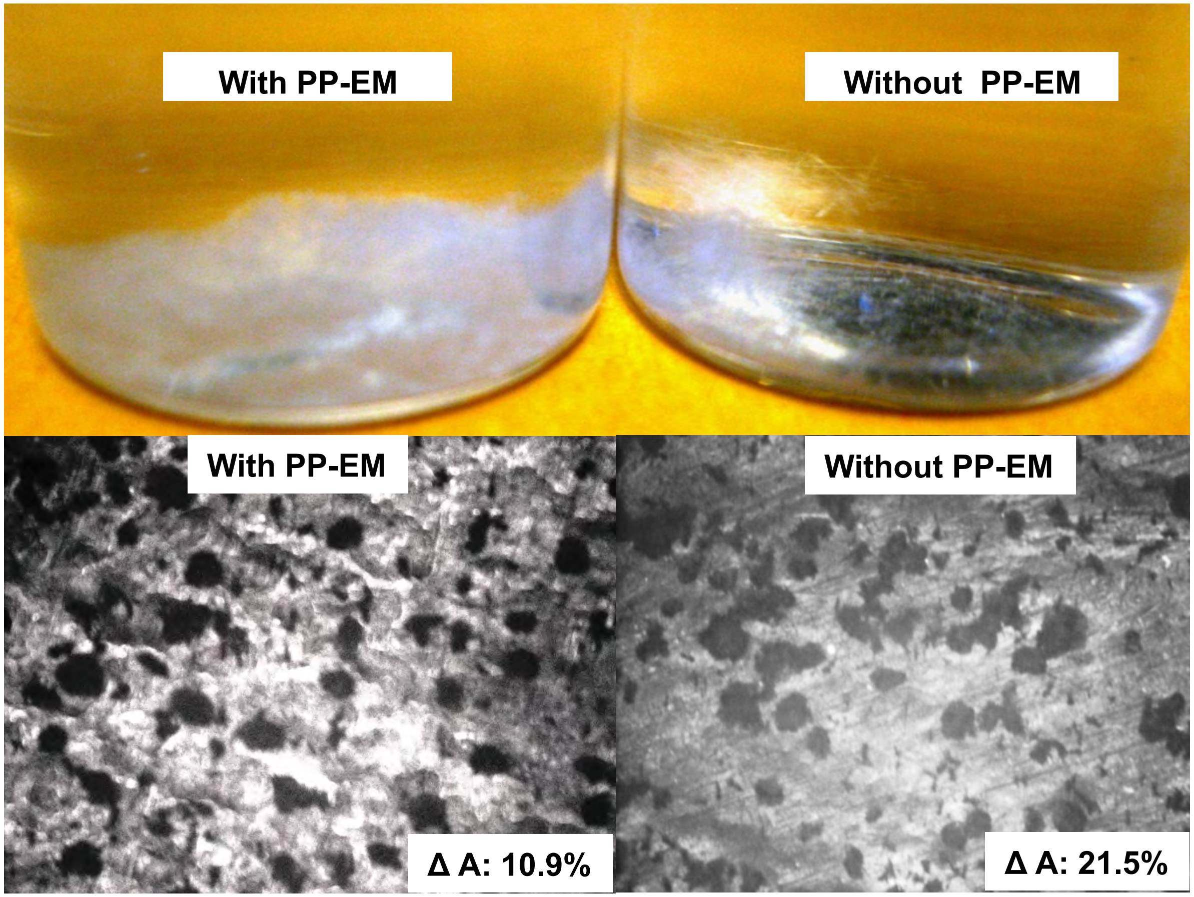




Experimental results

Tests (PP-EM on/off)	Test 1/Test 2	Test 3/Test 4	Test 5/Test 6	Test 7/Test 8
Pump Speed	327 rpm	89 rpm	327 rpm	89 rpm
Pressure	300 psi	110 psi	50 psi	300 psi
Test Period	1.5 HR	3 HR	4.5 HR	11 HR
Flow Velocity	32 cm/s	10 cm/s	32 cm/s	10 cm/s
Permeate Flow-rate	21 - 8 ml/min	9 - 6 ml/min	5 - 4 ml/min	17 - ~0 ml/min
Post-mortem Gravimetric	Test 1: 12.8% Test 2: 13.5%	Test 3: 5.7% Test 4: 9.4%	Test 5: 7.7% Test 6: ~0%	Test 7: 13.8% Test 8: 16.7%
Visual Observation	Test 1: trace amount of precipitation Test 2: small amount of precipitation	Test 3: Clear precipitation in bulk solution Test 4: small amount of precipitation	Test 5: small amount of precipitation Test 6: trace amount of precipitation	Test 7: trace amount of precipitation Test 8: trace amount of precipitation

Experimental results



- The bulk solutions treated with PP-EM field showed significant more precipitation than the one without utilizing PP-EM field.
- More scaling on the membrane surface when not utilizing PP-EM.

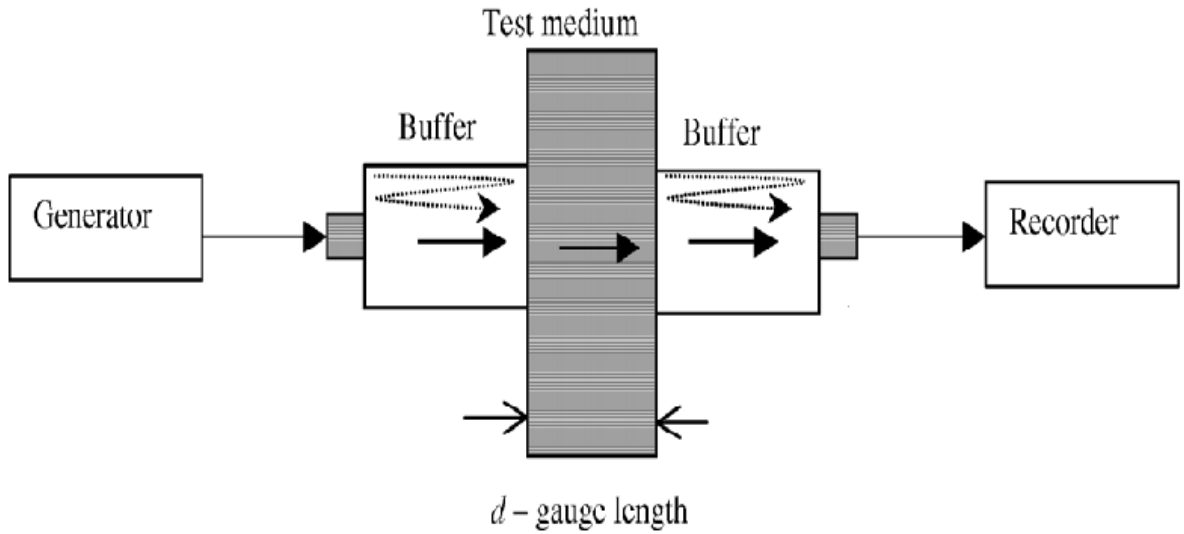
Feed solution modification

As a sparingly soluble salt, utilizing $CaSO_4$ directly may cause nucleation easily

$CaCl_2$ + Na_2SO_4 ----> 2 NaCl + $CaSO_4$

Tests (PP-EM on/off)	Test 9/Test 10	Test 3/Test 4
Pump Speed	89 rpm	89 rpm
Pressure	110 psi	110 psi
Test Period	3 h	3 h
Flow Velocity	10 cm/s	10 cm/s
Permeate Flow-rate	9 – 8 (11%) ml/min	9 – 6 (33%) ml/min
Post-mortem Gravimetric	Test 9: 0.4% Test 10: /	Test 3: 5.7% Test 4: 9.4%
Visual Observation	Test 9: trace amount of precipitation Test 10: trace amount of precipitation	Test 3: clear precipitation in bulk solution Test 4: small amount of precipitation

Acoustic spectroscopy

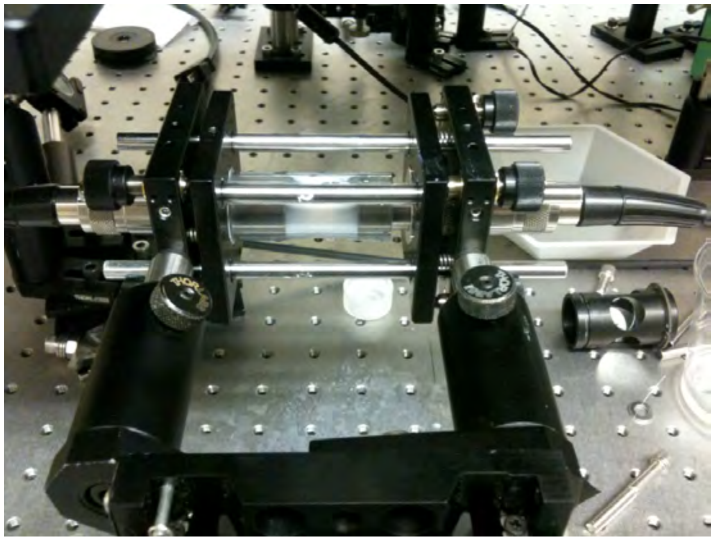


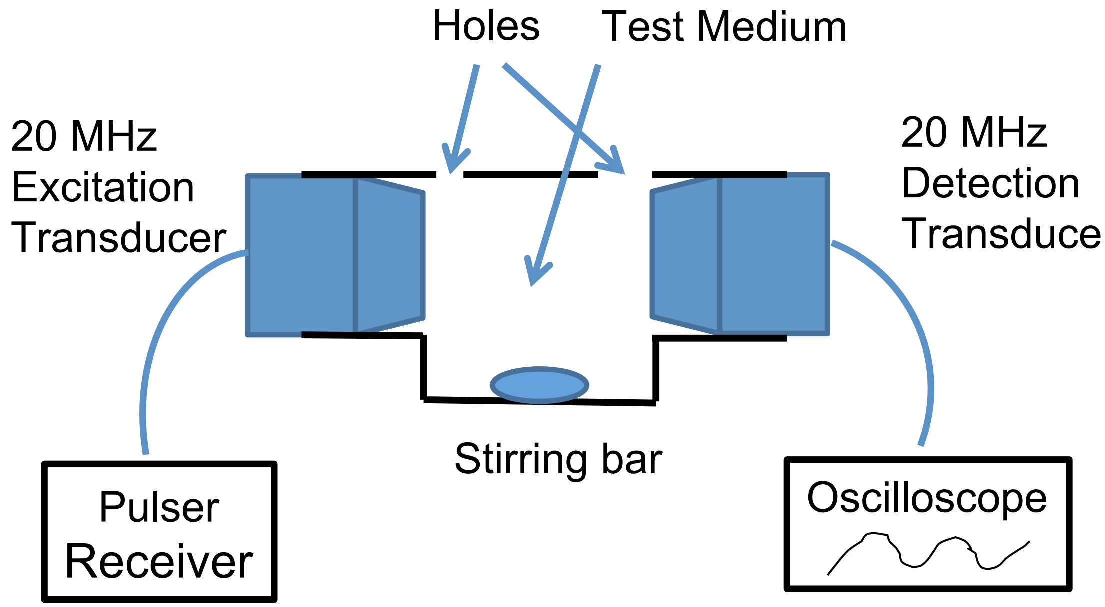
$$X_0\,(\omega) = \exp\,[-\,\alpha 0\,(\omega)\,d]$$

- **Acoustic spectroscopy has been applied as a non-destructive method in characterization of particle size distribution in aqueous suspensions by measurement of the ultrasonic signal attenuation coefficient as a function of frequency.**

Challis et.al., IEEE transactions on ultrasonic, ferroelectrics, and frequency control, 52 (10), 1754-1768, 2005
Cocker, et.al., Journal of acoustical society of America, 90 (2), 730-740, 1991
Goetz, et.al., Langmuir, 16, 7597-7604, 2000

Acoustic system setup





- The two transducers are held with kinematic mounts so their tilting angle can be adjusted.
- The distance between two transducers is measured precisely under an optical microscope.
- A short pulse is generated by the pulser/receiver, and the acoustic signal is recorded by the oscilloscope.

Theoretical function

$$S(\omega) = H(\omega) X(\omega)$$

$S(\omega)$: detected acoustic signal in the frequency domain

$H(\omega)$: the system transfer function

$X(\omega)$: frequency response of the test liquid

- Calibration of the system to obtain $H(\omega)$: liquid with known acoustic properties

$$X_0(\omega) = \exp[-\alpha 0(\omega) d]$$

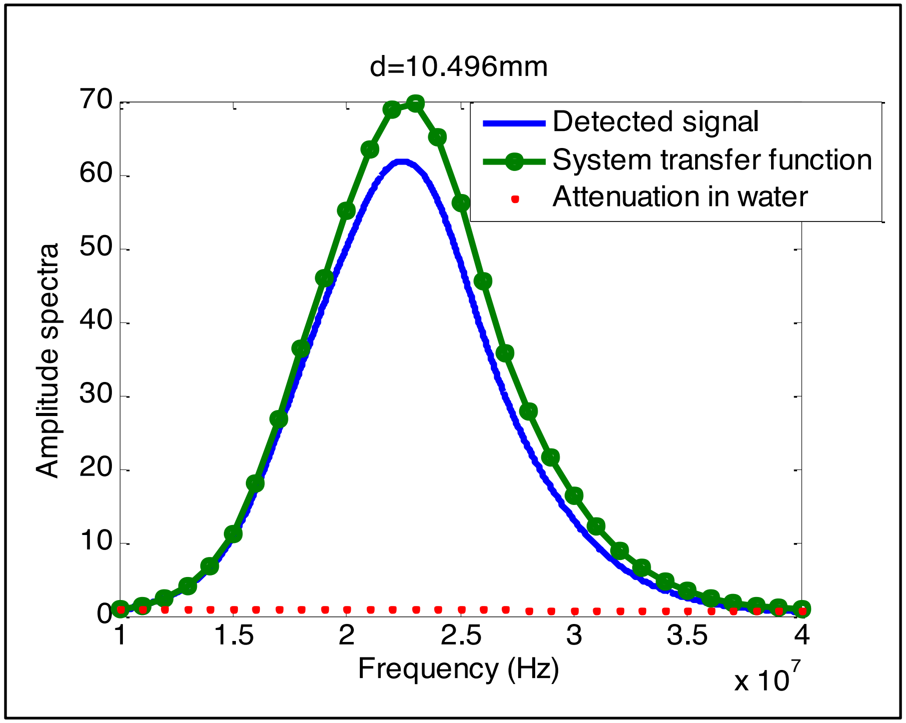
$\alpha 0(\omega)$: attenuation coefficient of aqueous solution

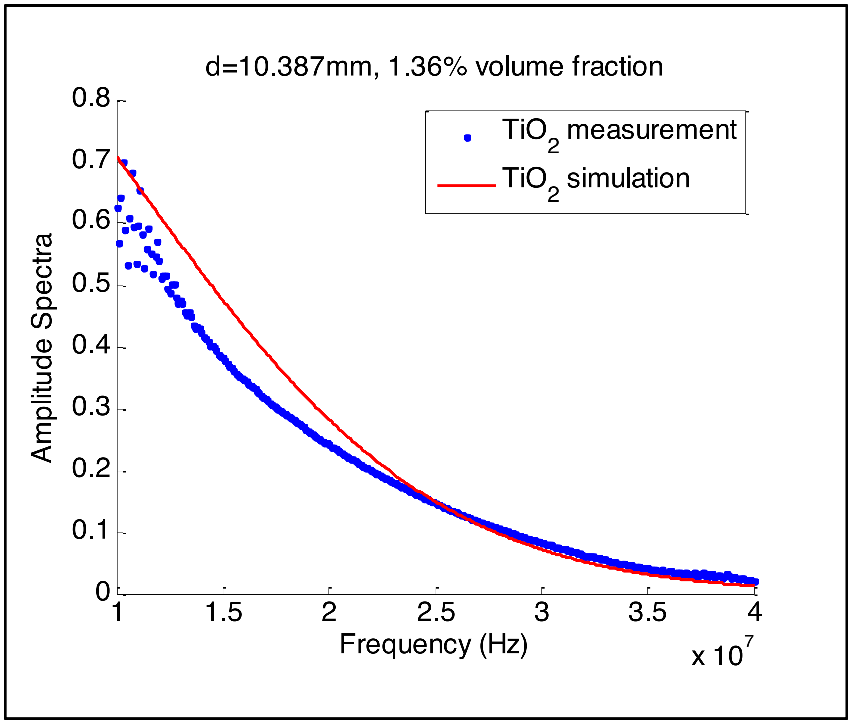
d: distance between two transducers surfaces

$$H(\omega) = S_0(\omega)/X_0(\omega)$$

- Measurement of attenuation spectrum to obtain $X(\omega)$

Acoustic Study Results

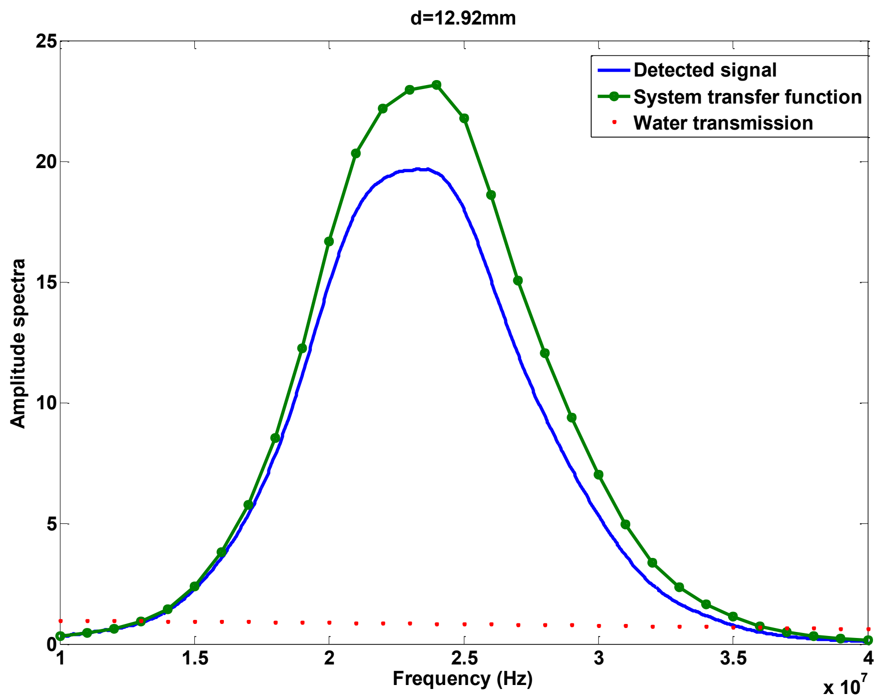


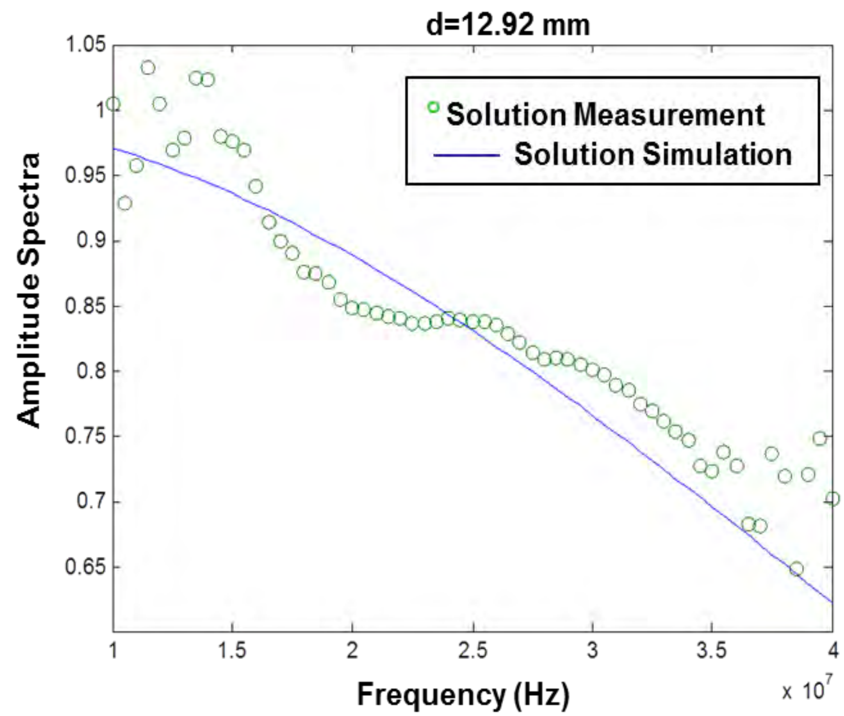


Acoustic study results

$CaCl_2 + Na_2CO_3 \longrightarrow 2\,NaCl + CaCO_3$

The solubility of $CaCO_3$ in DI water at ambient temperature: 0.0147 g L^{-1}



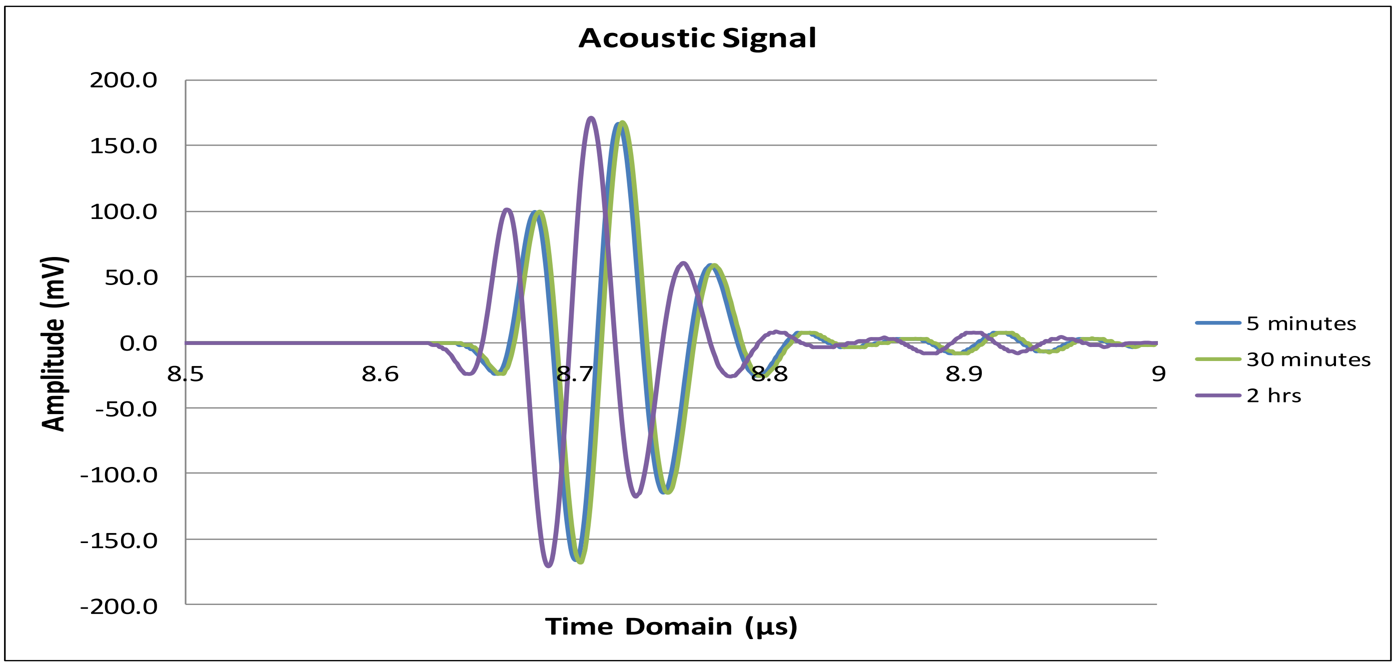


Acoustic study results

$CaCl_2 + Na_2CO_3 \text{ ----> } 2\ NaCl + CaCO_3$

Time (min)	pH	Conductivity (µs/cm)
0	9.2	2290
5	8.4	1900
10	8.2	1900
20	8.2	1900
30	8.2	1870
120	7.9	1840
1200	7.9	1840

The solubility of $CaCO_3$ in DI water at ambient temperature: 0.0147 g L^{-1}



Significance

- Initial study in both pilot and bench scale RO desalination system utilizing PP-EM field verified possible effects of electromagnetic field on precipitation of scarcely soluble salts crystallization in bulk solution.
- Initial study indicated possibility to mitigate scaling during RO process by utilizing PP-EM field.
- A possible real-time crystallization characterization methodology, acoustic spectroscopy, has been developed.

Future Work

- Replicates of the current tests
- More systematic tests with the bench-scale cross-flow RO system with variable testing conditions and complex feed solutions
- Install acoustic spectroscopy system into the RO flow system for real-time solution property monitoring

Acknowledgements

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Clearwater Systems LLC