This presentation premiered at WaterSmart Innovations

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Comparative Techno-Economic and Environmental Assessment of Ozone-Membrane Distillation for Brine Concentrate Management

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Water Reuse a Means to Secure Potable Water Supply

Water Demand 1985–2010 Mm³

Lake Mead, Colorado, 2015. (Jae C. Hong / AP Photo)

Wildfire in Tucson Arizona 2020
Danielle & Ryan McCrory Photography

Water Yield 1985–2010 Bm³

USA Population Census.Gov

U.S. Drought Monitor

August 25, 2020
(Released Thursday, Aug. 27, 2020)
Valid 8 a.m. EDT

Water Yield 1985–2010 Bm³

Lake Mead, Colorado, 2015. (Jae C. Hong / AP Photo)

Wildfire in Tucson Arizona 2020
Danielle & Ryan McCrory Photography
Why Membrane Distillation?

• Higher energy efficiency (GOR) and lower energy consumption

• Lower Specific Electrical Energy compared to RO at high concentrations
• Viable when low-grade heat or renewable energy is available
Water Reuse RO Concentrate

- High TDS: 3-35g/L
- Rich in Organic Matter: >20 mg/L\[^1\]
- High disposal cost: ~33% of desalination\[^2\]
- Environmental effects: salinity, organics, chemicals and temperature

\[^1\]Orange County Water District brine concentrate analyses (Ersever, 2013)
Conventional Concentrate Management Systems

80% RECOVERY

Concentrated Brine

Discharge to Water Body
Discharge to Sewer System
Evaporation pond
Deep Injection Well
Brine concentration + Crystallization
Ozone-Membrane Distillation (MD)

- Lower Specific Electrical Energy compared to RO at high concentrations
- Viable when low-grade heat or renewable energy is available
- Maximizes water recovery

RO + Ozone MD = 94% water recovery
Project Goals

- **Develop** a comparative techno-economic assessment of conventional brine management and the proposed Ozone-MD system.

- Determine key **performance variables** that influence system capital and operation and management cost, energy requirements, and environmental impacts.

- **Identify** improvement opportunities, evaluate economy of scales, and assess the feasibility for implementing the novel brine management technology.
Boundaries and General Variables

- Evaporation Pond
- Deep Injection Well
- Brine Concentrator - Crystallizer
- Ozone-MD

- Slurry
- Salts
- Distillate
- Brine

- Infrastructure
- Operation and Management
- Energy requirements
Methods

Design Systems

Identify cost factors

Assessment

Develop Phyton Based Cost Model

Sensitivity Analysis
Concentrate Management Systems Modeled After Experimental Conditions

Using real RO concentrate from a pilot scale RO system with the following properties:

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity (mS/cm)</td>
<td>4.2</td>
</tr>
<tr>
<td>TDS (mg/L)</td>
<td>2400</td>
</tr>
<tr>
<td>Total organic carbon (mg/L)</td>
<td>23</td>
</tr>
<tr>
<td>Recovery</td>
<td>80%</td>
</tr>
</tbody>
</table>

Pilot-scale UF-RO system at WEST Center, University of Arizona
## Baseline Design Criteria for Concentrate Management Systems

<table>
<thead>
<tr>
<th>System</th>
<th>Variable</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Concentrate Volume</td>
<td>3,785 (1)</td>
<td>m³ (MGD)</td>
</tr>
<tr>
<td></td>
<td>Concentrate Salinity</td>
<td>3 to 35</td>
<td>g/L</td>
</tr>
<tr>
<td></td>
<td>Plant Lifetime</td>
<td>20</td>
<td>Years</td>
</tr>
<tr>
<td></td>
<td>Availability</td>
<td>95</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>Recovery</td>
<td>70</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>Concentrate pumping distance*</td>
<td>1.6 to 32 (1-20)</td>
<td>km (miles)</td>
</tr>
<tr>
<td>Evaporation Ponds</td>
<td>Liner Thickness</td>
<td>60 to 100 (2.4 to 3.9)</td>
<td>mm (inches)</td>
</tr>
<tr>
<td></td>
<td>Pond depth</td>
<td>1.2 to 3.7 (4 to 12)</td>
<td>m (ft)</td>
</tr>
<tr>
<td>Deep Injection Well</td>
<td>Well depth</td>
<td>762-3048 (2,500 to 930)</td>
<td>m (ft)</td>
</tr>
<tr>
<td></td>
<td>Injection velocity</td>
<td>2.4 to 3 (8 to 10)</td>
<td>m/s (ft/s)</td>
</tr>
<tr>
<td>Brine Concentrator</td>
<td>Recovery</td>
<td>70 to 99</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>Temperature gradient hot side (MD)</td>
<td>50 to 80 (122 to 176)</td>
<td>ºC (°F)</td>
</tr>
<tr>
<td></td>
<td>Temperature gradient cold side (MD)</td>
<td>30 to 40 (86 to 104)</td>
<td>ºC (°F)</td>
</tr>
<tr>
<td></td>
<td>Concentrate feed flow rate to MD</td>
<td>0.5 to 1.5 (2.2 to 6.6)</td>
<td>m³/hr (gpm)</td>
</tr>
<tr>
<td></td>
<td>Membrane cost</td>
<td>60**-280</td>
<td>USD/7.2 m²</td>
</tr>
</tbody>
</table>

*Deep Well Injection and Evaporation Ponds

**Mass production
Financial Assumptions for Cost Model

<table>
<thead>
<tr>
<th>Financial Assumptions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interest Rate %</td>
<td>10</td>
</tr>
<tr>
<td>Inflation Rate %</td>
<td>3</td>
</tr>
<tr>
<td>Amortization Factor %</td>
<td>12</td>
</tr>
<tr>
<td>Land Cost $/m^2 [3]</td>
<td>1.4</td>
</tr>
<tr>
<td>Electricity $/kWh [4]</td>
<td>0.07</td>
</tr>
<tr>
<td>Natural gas $/m^3 [5]</td>
<td>0.14</td>
</tr>
<tr>
<td>Liner Cost $/m^2</td>
<td>3-15</td>
</tr>
<tr>
<td>Regenerated water $/m^3 [6]</td>
<td>0.67</td>
</tr>
<tr>
<td>Indirect Cost %</td>
<td>10</td>
</tr>
<tr>
<td>Land clearing $/Acre</td>
<td>1000-4000</td>
</tr>
</tbody>
</table>

- Levelized cost of disposal (LCCD) will be compared between systems.
- LCCD: net present cost of 1m³ of concentrate disposed of by the system over its lifetime

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Results
Higher evaporation rate and lower rainfall provide better conditions for evaporation ponds, lowering disposal cost.

Lower evaporation rates require larger evaporative areas.
Effect of Pumping Distance on Deep Injection Well Disposal Costs

- Increase in pumping distances results in higher energy requirements.
Brine Concentrator + Crystallizer Thermal Source Effect on LCCD

- Using methane as the thermal source for the brine concentrator reduces costs significantly and allows to use smaller systems at full capacity.
Increase in flux increases energy requirements, making thermal source the key cost component for O&M
Levelized cost of disposal / m³

LCCD is lowest for evaporation ponds due to low O&M requirements.

Conversely high energy requirements and equipment cost for evaporative crystallization make this option the highest LCCD.
## General Observations

<table>
<thead>
<tr>
<th>System</th>
<th>Cost of disposal ($/m^3)</th>
<th>Resource recovery</th>
<th>Energy consumption</th>
<th>Modularity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozone-MD</td>
<td>$ $</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Evaporation Pond</td>
<td>$</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Deep Injection Well</td>
<td>$ $ $</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Brine concentrator + Crystallizer</td>
<td>$ $ $ $</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
Ozone-MD is placed second when considering methane as a thermal source. The levelized costs of disposal are competitive to those of conventional concentrate management systems.

Ozone-MD is a viable option when value is placed on resource recovery. Which is of vital importance for water-stressed regions.

There is no one size fits all solution when selecting concentrate management systems. Best scenario conditions are site dependent.
Acknowledgements

Dr. Kerri Hickenbottom
Dr. Andrea Achilli

HER-ART Lab Group Members
Bianca Souza Chaves
Jeb Shingler
Luke Presson
Mikah Inkawhich
Mohammed Alhussaini
Mukta Hardikar
Zachary Binger

Southern Nevada Water Authority
Universities Council on Water Resources
General Observations

- Evaporation pond LCCD is the lowest at $0.52/m^3$, however this system is highly limited by region-specific conditions.

- LCCD for DIW, rapidly increases with pumping distance. If the pumping distance is more than 30 km, the best-case scenario costs double.

- The best-case scenario for Ozone-MD using methane as a heat source places the system LCCD second to the evaporation ponds. When considering the market price of recovered water, ozone-MD costs are competitive to those of evaporation ponds.
Ozone-MD system Model

Input variables

<table>
<thead>
<tr>
<th>Feature</th>
<th>Range</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed Flow Rate</td>
<td>500-1500</td>
<td>L/hr</td>
</tr>
<tr>
<td>Salinity</td>
<td>3-35</td>
<td>g/L</td>
</tr>
<tr>
<td>Tf,m</td>
<td>50-80</td>
<td>°C</td>
</tr>
<tr>
<td>Td,m</td>
<td>30-40</td>
<td>°C</td>
</tr>
</tbody>
</table>

Jw = flux

\[
J_w = \frac{1}{R} \left( P_{f,m}(T_{f,m}, S_{f,m}) - P_{d,m}(T_{d,m}, S_{d,m}) \right)
\]

Jw = flux

(Pf,m)= Water vapor pressure on feed side
(Pd,m)= Water vapor pressure on DI side
R= mass transfer resistance
(Tf,m and Td,m)= Temperature at membrane surface
(Sf,m and Sd,m)= Salinity at the membrane surface
Ozone-MD liner thickness sensitivity effect on cost

Liner Cost as a Function of acreage

Liner cost vs. Evaporative area with 4ft depth
Fractional contribution to cost of capital and O&M components for Ozone-MD

LCCD is $0.73/m^3

Membrane modules make up 21-35% of the capital cost.
Evaporation Pond

Fractional Contribution to Cost for Capital and O&M costs of Evaporation Pond Systems

Levelized cost of concentrate disposed (LCCD) is $0.52/m³

Biggest contribution is liner at 39 to 50% of capital costs
LCCD is $1.07/m^3$

Biggest effect on cost is for installed casing which contributes up to 22% of capital cost.
Effect of pumping distance on DIW LCCD

LCCD of DIW according to pumping distance

- 0.5 miles
- 2.5
- 7.5 Miles
- 20 Miles

Well depth (m)

LCCD ($/m³)
Brine Concentrator + Crystallizer

Capital and O&M costs for Brine Concentrator + Crystallizer

Working at 70% Capacity

Working at 99% Capacity

LCCD is $3.35/m³

Evaporator and installation costs are 56-74% of capital cost