Initial Cost Analysis of a Desalination Process Utilizing Hydrotalcite and Permutite for Ion Sequestration

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Abstract

An initial cost analysis of a proposed desalination process was performed. The proposed process utilizes tailored inorganic ion exchangers, hydrotalcite and permutite, to sequester anions and cations from a brackish water solution. Three different process scenarios were considered: 1) disposal of the spent exchangers as dry waste 2) conventional chemical regeneration, and 3) acid regeneration of permutite coupled with thermal (550 °C) regeneration of hydrotalcite. Disposal of the resin and conventional regeneration are not viable options from an economic standpoint. Applying limited data and optimistic assumptions to the third scenario yielded an estimate of $2.34/kgal of product water. Published values for applying conventional reverse osmosis to similar water streams range from $0.70 to $2.65/kgal. Consistent with these baseline values, the Water Treatment Estimation Routine, WaTER, developed by the United States Department of the Interior, Bureau of Reclamation produced a cost estimate of $1.16/kgal for brackish water reverse osmosis.
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Introduction:
An initial cost analysis has been performed on a proposed desalination process for brackish water. The proposed process, described elsewhere [1], utilizes tailored inorganic ion exchangers, hydrotalcite and permutite, to sequester anions and cations respectively, from a brackish water solution. Figure 1 outlining the process was provided to the authors of this report by the process developers. Based on Figure 1, and additional discussions with the developers, three different process scenarios were considered: 1) disposal of the spent exchangers as dry waste 2) conventional chemical regeneration of the exchangers, and 3) acid regeneration of permutite coupled with thermal (550 °C) regeneration of hydrotalcite. This report outlines the approach and principal results of the analysis.

**Figure 1.** Basic flow chart of proposed desalination process [2].

**Scenario 1: Resin Disposal**
Conventional wisdom asserts that ion exchange is only applicable to desalination in cases where high purity water is required (e.g. to avoid scaling in boilers), and only then after the majority of ions have been removed by other methods. The reasoning here is that the use of relatively high value products (organic resins and chemical regeneration solutions) to produce a relatively low value product (fresh water) should be avoided, if possible. However, one of the basic premises of the proposed process is that the hydrotalcite and permutite exchangers have geological analogs, and therefore might be synthesized from naturally occurring mineral deposits at a cost significantly lower than conventional organic ion exchange resins. The table below, provided by the developers [2], suggests some potential precursors to the ion exchange materials and their approximate costs. For
comparison, prices for commercial organic cation exchange resins range from $1.20-2.40/lb, while prices for anion resins range from $3.60-7.20/lb [3].

Table 1: Approximate costs of natural or near-natural synthetic precursors.

<table>
<thead>
<tr>
<th>Precursor/Resin</th>
<th>Description</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bauxite Ore</td>
<td>(45% by weight Al$_2$O$_3$ – w/o shipping)</td>
<td>$0.016 – 0.032/lb Al$_2$O$_3$</td>
</tr>
<tr>
<td>Diatomaceous Earth</td>
<td>(Diatomite – 95%+ SiO$_2$)</td>
<td>$0.128/lb</td>
</tr>
<tr>
<td>Silica Fume</td>
<td>(95%+ SiO$_2$ – amorphous, very fine grained)</td>
<td>$0.20/lb</td>
</tr>
<tr>
<td>Silica Sand</td>
<td>(95%+ SiO$_2$)</td>
<td>$0.02 – 0.03/lb</td>
</tr>
<tr>
<td>Magnesia Ore</td>
<td>(90% MgO)</td>
<td>$0.147/lb</td>
</tr>
</tbody>
</table>

The feasibility of fabricating the exchangers from “dirt” and disposing of the spent material after use is examined in Figure 2. Figure 2 postulates a hypothetical IX material with a high capacity (5 meq/g) and ideal exchange properties (100% selective). The lines in the figure represent target costs for the material per 1000 gallons of desalted water (assuming complete salt removal). The shaded areas represent price ranges for various materials taken from Table 1.

**Figure 2.** Maximum allowable resin cost to meet a target cost for desalting NaCl brine at an ion exchange capacity of 2.5 meq/g (disposable resin scenario). Price ranges for various materials are included for comparison.

Brackish water can generally be desalted via conventional reverse osmosis (BWRO) at a cost of $1-2/kgal (published values range from $0.70 to $2.65/kgal) [4]. Using $1-2 as a target cost for the synthetic precursors in Figure 2, it is clear that disposal of the ion
exchanger will be uneconomical at any brine concentration of interest. That is, the costs of even the least expensive possible precursors (silica and bauxite) begin to exceed the allowable cost at very low brine concentrations. For example, $2/kgal (for the precursor alone) is exceeded at a concentration of <3000 ppm. Thus, disposal of the spent exchanger appears to be uncompetitive with BWRO, even if very inexpensive precursors are utilized to fabricate the exchangers.

**Scenario 2: Chemical Regeneration**

The conventional reasoning applied to resin disposable is also applicable to chemical regeneration. That is, unless there is a compelling reason to generate high purity water, it does not make good economic sense to use relatively high value products (acid and base solutions) to produce a relatively low value product (fresh water). Figure 3 illustrates this point; the cost of the regenerant solutions exceeds $2/kgal at brine concentrations of only 2000 ppm. Figure 3 also shows that most of the total costs are attributable to the base, NaOH.

![Figure 3. Reagent cost for regenerating ion exchange resins used for treating varying brine concentrations. H$_2$SO$_4$ - $49/ton ($0.02/lb); NaOH - $360/ton ($0.18/lb). Figure taken from [4].](image)

**Scenario 3: Acid Regeneration Couple with Thermal Regeneration**

This proposed scenario couples acid regeneration of the permutite cation exchanger with high temperature (550 °C) thermal regeneration of the hydrotalcite anion exchanger. During the envisioned thermal treatment, the hydrotalcite would change phases, liberating acid gasses (e.g. HCl) in the process. The hydrotalcite would be recovered upon rehydration. The acid gasses would be trapped or scrubbed and could conceivably be used to regenerate the permutite cation exchanger [2]. However, since the major cost
associated with chemical regeneration is the price of the base, the main opportunity for savings lies in replacing NaOH with the thermal treatment.

To facilitate the cost estimation process, the Water Treatment Estimation Routine, WaTER, developed by the United States Department of the Interior, Bureau of Reclamation was used [5]. WaTER is an Excel® spreadsheet program developed to address the problems of arriving at water treatment plant costs. The program is based on production capacity, a water analysis and uses a set of generalizations to specify equipment for a particular water treatment process. The program was adapted from the U.S EPA 1979 report, *Estimating Water Treatment Costs, Vol.2, Cost Curves Applicable to 200 mgd Treatment Plants* (EPA-600/2-79-1626, August 1979). To complete the analysis, the WaTER ion exchange routine was modified to accommodate thermal regeneration of the Hydrotalcite resin.

The following assumptions were used in the analysis:

- Brackish water supply similar to Tularosa Basin water
  - Total Dissolved Solids – 3070 mg/L
  - High sulfate concentration – 1100 mg/L
  - Alkalinity as Bicarbonate – 125 mg/L
  - Silica fairly low – 12 mg/L
  - Calcium – 110 mg/L
  - Magnesium – 80 mg/L
  - Anion/Cation equivalence – 0.0479 eq/L
- 5 mgd plant capacity (capital costs of RO plants decrease as capacity increases up to about 5 mgd [6]) operating at 95% availability.
- Ion exchange vessels sized at 20% excess volume using a 2 vessel train for each sequestering process.
- Cation exchange using Permutite with an ion exchange capacity of 2 meq/g at 100% selectivity.
- Anion exchange using Hydrotalcite with an ion exchange capacity of 2.5 meq/g at 100% selectivity.
- 1.5 specific gravity for both materials.
- Each exchange process operated on a service cycle of 2 days with an infinite regeneration capacity.
- Initial cost of resins based only on raw material costs with no other manufacturing costs factored in [7].
- Costs associated with waste streams and material handling of the hydrotalcite during the thermal regeneration step were not factored into the cost analysis.

**Ion exchange calculations:**

The ion exchange requirement was based on a total ion equivalence of 0.0479 eq/L. This ion equivalence was based on the water analysis specification given in the WaTER program (Table 2).
Table 2: Tularosa Basin water as specified in WaTER.

**WATER ANALYSIS**

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<tr>
<th>Component</th>
<th>Water Analysis</th>
<th>Units</th>
<th>MCL (mg/L)</th>
<th>Amount Over MCL</th>
<th>Valence Charges</th>
<th>Molecular Wt.</th>
<th>Equivalent Weight</th>
<th>Moles/Liter</th>
<th>Equiv./Liter</th>
<th>Ionic Strength mg/L as CaCO₃</th>
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</table>

Exchange capacity calculations for Hydrotalcite:

Hydrotalcite - 2.5 meq/g exchange capacity (2.5 eq/kg)

Exchange capacity in eq/L = (2.5 eq/kg) * (1.5 kg/L) = 3.75 eq/L

Amount of Hydrotalcite per liter of water treated

\[
\text{Amount of Hydrotalcite per liter of water treated} = \left( 0.0479 \text{eq/L} \right) \times 0.019 \text{ kg/L of treated water} \\
\]

Amount of Hydrotalcite required for producing 5 mgd:

\[
(5 \text{ mgd}) = 1.894 \times 10^7 \text{ L/day} \\
(1.894 \times 10^7 \text{ L/day}) \times (0.019 \text{ kg/L}) = 3.589 \times 10^5 \text{ kg/day} \\
= 7.92 \times 10^5 \text{ lb/day}
\]
Raw material requirements and costs based on a Hydrotalcite formula of $\text{Mg}_3\text{Al(OH)}_8\text{Cl}_2$:

- Magnesia Ore – 3 moles/mole of Hydrotalcite
  - 90% purity @ $0.147/\text{lb}$
- $\text{AlCl}_3$ – 1 mole/ mole Hydrotalcite
  - 98.5% purity @ $0.495/\text{lb}$
- $\text{NH}_4\text{OH}$ – 8 moles/mole Hydrotalcite
  - 29% purity @ $0.58/\text{lb}$

Hydrotalcite cost:
$\text{Hydrotalcite cost:}$
$\text{Cost = } 1.28/\text{lb or } 5442/\text{m}^3 \text{(assumes 1.5 sp. gr.)}$

Exchange capacity calculations for Permutite:

- Permutite - 2 meq/g exchange capacity (2 eq/kg)
- Exchange capacity in eq/L = (2 eq/kg)*(1.5 kg/L) = 3.0 eq/L
- Amount of Permutite per liter of water treated –

\[
\frac{.0479\text{eq/L}}{2.0 \text{ eq/kg resin}} = 0.024 \text{ kg/L of treated water}
\]

Amount of permutite required for producing 5 mgd

- ($5 \text{ mgd}) = 1.894 \times 10^7 \text{ L/day}$
- $(1.894 \times 10^7 \text{ L/day})*(0.024 \text{ kg/L}) = 4.55 \times 10^5 \text{ kg/day}$
- $= 1.00 \times 10^5 \text{ lb/day}$

Raw material requirements and costs based on a Permutite formula of $\text{Si}_0.772\text{Al}_0.228\text{O}_{1.886}$:

- $\text{SiO}_2/\text{NaO}$ – 1.078 moles/mole of Hydrotalcite
  - 99.99% purity @ $0.1385/\text{lb}$
- $\text{Al(NO}_3)_3$ – 0.32 mole/ mole Hydrotalcite
  - 99.99% purity @ $2.25/\text{lb}$

Permutite cost:
$\text{Permutite cost:}$
$\text{Cost = } 0.65/\text{lb or } 2148/\text{m}^3 \text{(assumes 1.5 sp. gr.)}$
**Regeneration of Resins:**

Regeneration of the Permutite resin was based on sulfuric acid addition and the Hydrotalcite regeneration was based on drying at 100 °C followed by thermal regeneration at 550 °C.

Permutite regeneration by $\text{H}_2\text{SO}_4$:

Equivalent volume of Permutite (eq/m$^3$)

$$= (2\text{meq/g})*(1.5\text{g/ml})*(eq/1000 \text{ meq})*(10^6\text{ml/m}^3) = 3,000 \text{ eq/m}^3$$

Equivalence and mass of $\text{H}_2\text{SO}_4$ needed for regeneration

5mgd water produced = $1.894 \times 10^7$ L/day

Ion equivalence of water = 0.0479 eq/L (from data analysis report)

$\text{H}_2\text{SO}_4$ eq = ($1.894 \times 10^7$ L/day)*(.0479) = $9.07\times10^5$ eq $\text{H}_2\text{SO}_4$/day

$\text{H}_2\text{SO}_4$ = ($9.07\times10^5$eq /day)*(1 mol/2 eq) = $4.5\times10^5$ mols $\text{H}_2\text{SO}_4$/day

$$= 4.45\times10^5 \text{ kg H}_2\text{SO}_4$/day

Total $\text{H}_2\text{SO}_4$ required per m$^3$ of resin:

Eq wt of $\text{H}_2\text{SO}_4$ = (98g/mol)*(1mol/2eq)*(1 kg/1000g) = 0.0485 kg/eq

(3,000eq/m$^3$ resin)*(0.00485) = 146 kg $\text{H}_2\text{SO}_4$/m$^3$ resin

Thermal regeneration of Hydrotalcite:

The specific heat for drying the hydrotalcite (to 100 °C) was assumed to be similar to an integrated value reported for zeolite powder, 577 J/g (0.547 BTU/g) [8]. For further heating to 550 °C, a specific heat of 0.257 cal/g/C (0.00102 BTU/g/C) was assumed based on values published for silica [9].

The total weight of Hydrotalcite regenerated per service cycle is $7.25\times10^8$ g or ~ 800 tons. Then, the energy to dehydrate bed per service cycle at a heater efficiency of 70% is:

$$(7.25\times10^8\text{g})*(0.547 \text{BTU/g})/(0.7) = 5.666\times10^8 \text{ BTU} = 5666 \text{ therms}$$

The cost to dehydrate resin at $0.65/therm [10] is:
(5666 therms) * ($0.65/therm) * (1 service cycle / 10,000,000 gallons) * (1000 gallons / kgal) = $0.37/kgal of water produced

Energy to heat from 100°C to 550°C at 70% efficiency:

\[
(7.25 \times 10^8 \text{g}) \times (0.00102 \text{BTU/g/C}) \times (550 - 100) / 0.7 = 4.755 \times 10^8 \text{BTU} = 4755 \text{ therms}
\]

Cost to heat Hydrotalcite from 100°C to 550°C at $0.65/therm:

\[
(4755 \text{ therms}) \times ($0.65/\text{therm}) \times (1 \text{ service cycle} / 10,000,000 \text{ gallons}) \times (1000 \text{ gallons} / \text{kgal}) = $0.31/ \text{kgal of water produced}
\]

Total heat requirement assuming a 24hr operation:

\[
(4.755 \times 10^8 \text{ BTU} + 5.666 \times 10^8 \text{ BTU}) / 24 = 4.34 \times 10^7 \text{ BTU/hr}
\]

Cost estimates for using an industrial furnace for dehydrating and heating the hydrotalcite to 550 °C, are based on fluidized bed incinerator costs [11]. Other operations, e.g. sludge drying, cement kiln, rotary kiln, high temperature steam heating and thermal regeneration of granular activated carbon ($0.11 - 0.21/lb, $17.6 – 33.6/kgal [12]) were also considered.

From [11],
Capital cost = $112,000 / 10^6 \text{ BTU/hr furnace capacity}
Annual O&M cost = $46,500 / 10^6 \text{ BTU/hr furnace capacity}

Thus,
Capital cost = ($112,000 / 10^6 \text{ BTU/hr}) \times (43.4 \times 10^6 \text{ BTU/hr}) = $4,860,000
Annual O&M = ($46,500 / 10^6 \text{ BTU/hr}) \times (43.4 \times 10^6 \text{ BTU/hr}) = $2,018,000

_WaTER Program Calculations:_
From the above, the primary inputs to the WaTER program were:
- Plant production capacity of 5 mgd at 95% plant availability
- Total Cation/Anion eq/L – 0.0479 eq/L
- Permutite cost - $0.65/lb at 3 eq/L for a bed cost of $2148/m³
- Hydrotalcite cost - $1.28/lb at 3.75 eq/L for a bed cost of $5442/m³
- Two day run cycle with a service flow rate of 20L/hr/L of resin
- Regeneration chemical loading rate – 146 kg H₂SO₄/m³ resin
- Standard operation and maintenance cost (i.e., chemical cost, electrical cost, gas cost, backwash water cost)
- Capital cost of the fluidized-bed furnace used for thermal regeneration of the Hydrotalcite resin - $4.865 \times 10^6
- Thermal regeneration system O&M - $2.017 \times 10^6/yr
The cost estimate generated from these inputs is shown in Figure 4. Additional details pertaining to the costs calculated by the program are shown in Figures 5 and 6.

Figure 4. Block diagram generated by modified WaTER program showing costs for scenario 3.

The estimate of $2.34/kgal of water produced generated by the program should be viewed as an optimistic “best-case” number since the analysis did not include a number of expected costs, and assumed best case performance. Specifically, the cost of permutite and hydrotalcite was based only on raw material costs. Manufacturing costs were not considered and synthetic yields were assumed to be 100%. Also, the assumptions of infinite regeneration capacity without loss of performance and 100% selectivity are unreasonable best-case scenarios. Periodic bed replacement, and an excess of material in the bed would be required in a real system. There are also a number of issues with the thermal regeneration of the hydrotalcite that were not considered. First, regeneration was considered to be 100% effective at 550 °C. To the best of our knowledge, this has not yet been demonstrated. Also, no costs were included for handling the solids during the regeneration step. In addition, the hydrotalcite will undergo a phase change during the regeneration that will likely lead to physical degradation of the particulate form required for column operations. An additional step to convert the material back into a suitable pelletized form would likely be required. Finally, the waste issues of the process were not addressed, e.g. costs have not been included for acid gas scrubbing (nor has any benefit been claimed for acid reclamation).
### Cost

<table>
<thead>
<tr>
<th>Process</th>
<th>Parameter</th>
<th>Units</th>
<th>Total</th>
<th>$/m³</th>
<th>Cap</th>
<th>$/kgal</th>
<th>$/m³</th>
<th>$/kgal</th>
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</thead>
<tbody>
<tr>
<td>Cation Ion Exchange-Permutite</td>
<td>$/m³ Cation Exchange Resin</td>
<td></td>
<td>$1.973</td>
<td>$/lb = 0.60</td>
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<tr>
<td>Cation Resin Volume</td>
<td>m³</td>
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<td>725 m³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>To Remove Cation Equivalents/L</td>
<td></td>
<td></td>
<td>4.79E-02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Cation Ion Exchange Permutite

**Desired Flow Rate:** 219.0 L/s

**Equi-L. Cation:** 0.46 m³/m³

**Service Flow Rate:** Range = 16 - 40

**Cation Equiv/Liter of Resin:** 3.00 equiv/L

**Desired Run Cycle:** 2 days

**Medium:** Cation

**Vessel:**
- Aspect ratio: 3
- Bed area: 29.55 m²
- Base pressure vessel correlation: 0.562
- Number of Vessels (Reality check): Height is 24.5 m
  - log($) = b + m*log(m³)
  - b = 0.466
  - m = 0.562
- Cost factor for operating pressure:
  - Tank cost at base pressure: $117,061
  - TOTAL TANK COST (vessels): $457,643

**Regeneration (with H₂SO₄):**
- H₂SO₄ required: 146,626 kg
- Chemical cost per kg H₂SO₄: $0.02
- TOTAL CHEMICAL COST PER YEAR: $2,932.17
- Chemical concentration: 2%
- Regeneration fluid recy: 625 m³
- STORAGE TANK COST: $156,900

**Backwash Water:**
- Resin Bed Expansion: 20%
- Total vol. of backwash water (m³): 1400 m³
- Visc. of backwash water per year: 2074.17 m³

**Pumping:**
- Height Difference: 25 m
- Pipe Diameter: 0.73 ft
- Length of Pipe: 32.81 ft
- Number Transfer Pumps: 2
- Pressure Differential: 14.5 psi
- Capacity per Pump: 0.461 m³/s
- Size: 246.0 hp

**Operation & Maintenance:**
- Annual Cost: $1,218,653

**Regeneration/Backwashing Pump:**
- Filter area (m²): 29.55
- Applicable Range: 13-2600 m²

**Total Construction Cost:** $2,932,175

**Total Annual Cost:** $1,218,653

**Figure 5. WaTER Program Results for Permutite Resin.**
Anion Ion Exchange Thermal Regeneration

<table>
<thead>
<tr>
<th>Process Parameter</th>
<th>Units</th>
<th>Cost/m³</th>
<th>Construction Cost</th>
<th>Operating Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anion Equivalents/L Resin</td>
<td>3.75</td>
<td>$4,225</td>
<td>$9410</td>
<td>$497</td>
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<tr>
<td>Anion Volume:</td>
<td>m³</td>
<td></td>
<td>$1,882</td>
<td>$497</td>
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<tr>
<td>To Remove Anion Equivalents/L:</td>
<td>4.79E-02</td>
<td></td>
<td>$2838</td>
<td>$497</td>
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</tbody>
</table>

Anion Ion Exchange With Thermal Regeneration Hydrotalcite

<table>
<thead>
<tr>
<th>Desired Flow Rate</th>
<th>229.0 L/s</th>
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</thead>
<tbody>
<tr>
<td>E q u i v / L , A N I O N</td>
<td>4.79E-02</td>
</tr>
<tr>
<td>SERVICE FLOW R A T E</td>
<td>16 - 40</td>
</tr>
<tr>
<td>A N I O N E Q U I V / L</td>
<td>3.75</td>
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<td>D es i r e d Run Cycle:</td>
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<tr>
<td>A N I O N</td>
<td>4.79E-02</td>
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Vessel: 580 m³

<table>
<thead>
<tr>
<th>Process</th>
<th>Units</th>
<th>Cost/m³</th>
<th>Construction Cost</th>
<th>Operating Cost</th>
</tr>
</thead>
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<tr>
<td>Resin</td>
<td>580 m³</td>
<td>$4,225</td>
<td>$9,410,208</td>
<td>$497</td>
</tr>
</tbody>
</table>

Total Annual Cost $: 16,837,781

Figure 6. WaTER Program Results for Hydrotalcite Resin.

Summary:
Reverse osmosis is the current state-of-the-art desalting technology for brackish water and can generally be performed at a cost of $1-2/kgal. The WaTER program gives an estimate of $1.16/kgal for RO treatment of the Tularosa Basin water considered here. Scenarios wherein permutite and hydrotalcite ion exchangers are used in a once-through process and disposed of, or are chemically regenerated, are non-competitive with RO on a cost basis. Other factors such as costs and regulations associated with waste disposal may influence the decision to consider these options, in which case additional analysis should be performed. Specifically, the use of these (and other currently commercially available) inorganic exchangers should be compared to the use of commercial organic ion exchange resins, wherein final disposal options include burning the resin to yield a dry salt product. The scenario where acid regeneration of the permutite is combined with high temperature thermal regeneration of the hydrotalcite also appears to be non-competitive with RO as a cost of $2.34/kgal was calculated using very optimistic assumptions. Refinements to the calculation would be expected to significantly increase the cost estimate. A low temperature, in-situ regeneration process that limits materials...
handling and heat loads, such as the hot water regeneration employed in the Sirotherm process [13-19], would be preferable.

References:

2. J. Krumhansl, Sandia National Laboratories, Dept. 6118, personal communications
7. J. Krumhansl, Sandia National Laboratories, Dept. 6118, and J. Pless, Dept. 6245, personal communications.
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