Water Recovery from Brine in the Short and Long Term: A KSC Approach

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How did we come to these designs?

• KSC has spent many years researching Hollow Fiber Membrane Bioreactors as well as research encompassing:
  – Alternate ammonia removal
  – Advanced oxidation
  – Brine purification technologies

• KSC-ISRU has built an electrolysis cell for the removal of acids in ISRU mining brines

• Our goal is to combine all such technologies
Hollow Fiber Membrane Bioreactors

Two-Stage HFMB system for Carbon Oxidation and Nitrification

• KSC has mainly ~1-L and sub-liter bioreactors using silastic tubing with, in most cases, a U-channel design to allow easy construction and operation
• Reactor set-ups have included:
  – Combined-stage bioreactors that perform carbon oxidation, ammonia oxidation, and denitrification
  – Multi-staged reactors perform carbon oxidation and nitrification reactions separately
• We have also worked on bioreactor automation, flow improvements, biofilm attachment, reactor rapid start-up, and reactor dormancy studies
Advanced Ammonia Removal

- Magnesium phosphate dibasic trihydrate (MgHPO₄·3H₂O) or MP reacts with ammonia, exclusively, to produce struvite
- The resulting struvite (MgNH₄PO₄·6H₂O) or MAP is treated using heat and/or vacuum to regenerate the MP
- Cycle can be repeated indefinitely and only requires base and vacuum (heat makes it faster)
- Has many-fold higher selectivity than cation exchange resins and 2-4x ion capacity with higher expected lifecycles

Left: Fluidized Bed Test Stand
Above: Plug Flow Test Stand (Mock Up)
Advanced Catalytic Oxidation

- Uses ozone or hydroxyl molecules to rapidly oxidize contaminants (e.g., urea, ammonia, nitrate)
- Other Benefits:
  - Reduces Total Organic Carbon (TOC)
  - Reduces microbial loads by many logs (orders of magnitude)
- Benefits of Ozone:
  - Can be generated via UV light, cavitation, or by corona discharge
  - Does not persist in the system beyond the unit operation (low half life)
  - Takes low amounts of energy to form
- The reaction of ozone with relevant contaminants is not well documented
  - Limited testing at KSC several years ago showed promising, successful destruction of contaminants
- Ozone-based systems can be challenge due to two-phase flow, but there are ways around it
Originally designed for fertilizer recovery and increased water recovery

Pre-treated ECLSS brine (removed urea/carbon) is sequentially treated to remove hardness, polyvalent ions, and, optionally, nitrate

– Resulting sodium/potassium chloride stream is then deionized, producing pure water and either a concentrated brine stream or separate acid and base streams
– Acid and base streams can be used to continuously regenerate the ion exchange resins
  • Spent regenerate contains fertilizer components (i.e., $K_3PO_4$, $KNO_3$, $K_2SO_4$)

KSC built and tested an electrostatic separator to enrich dry sodium/potassium salt streams

Without fertilizer recovery, only the first ion exchange resin needs to be used to prevent membrane fouling, but the other ions will persist in the brines
ISRU Acid Removal

- The above test stand was used to deionize 2% HF from acid streams generated by ISRU.
- Water quality was extremely high, but only 50% recovery was noted at lower amperage.
- We expect 80-90% recovery (per stage) once we use a higher amperage (60 instead of 6) power supply running at 3-5 volts.
- Treatment time for 1L of fluid for a test stand this size was well under an hour.
Long-Term Multi-Redundant System

60 L/day mixed ISS Wastewater
No pre-treatment

- Uses 4 modular HFMBs, 2 carousel absorbers, and 2 membrane electrolyzers
- Designed to survive up to 3 HFMB failures or 2 HFMB and struvite failure by increasing consumable use until repairs or replacements are made
- Cascading electrolyzers first concentrate brine and produce water, then produce concentrated acid and base from brine concentrate
  - If 1 electrolyzer fails, the other can become the first stage while still yielding 80-90% water recovery
- Base consumed the nitrifying HFMBs and/or struvite columns
- Acid consumed (along with some base) by IRC 747 columns
- Energy required for electrolyzers
- Vacuum and/or heat required for struvite columns

Urea Hydrolysis HFMB 60L

Nitrification HFMB pH 8 60L

Nitrification HFMB pH 7 60L

Nitrification HFMB pH 6 60L

Struvite Column 1L

IRC 747 Column 1L

Electrolysis Cell 4L

~1L Base
~1L Acid

IRC 747 Column 1L

Electrolysis Cell 4L

~58L H₂O

~1L Base
~1L Acid
Long-term Multi-Redundant System Excluding Biological Reactors

- Replaces the carbon/ammonia removal train with a single (or dual, redundant) Advanced Catalytic Oxidation (ACO) unit.
- Similar to the previous design
  - Much smaller and more “mechanical”
  - Should have a similar consumable loop
- ACO unit:
  - Should be able to break down urea to ammonia/nitrate/N₂
  - Depending on the ratio, it will potentially require more unit ops
- We have two competing ACO technologies:
  - Both require some modification for μ-gravity use
  - Also have a third design that is a hybrid of the two
Proposed Testing

- Test multiple influent streams for KSC’s current electrolysis cell to determine processing capabilities
- Calculate mass and energy balances (wh/L treated, residence, removal rates, etc.)
- Examine performance over time and assess possible membrane fouling agents
- Figure out any “blockers” and remove them using ersatz mixtures formulated without them
  - Also includes testing of alternate unit operations capable of removing species in question
- This cell currently exists at KSC and, if funded, we would build another one at low costs (cost of headers and machining)

1L batch mixed ISS Wastewater
Variable pre-treatments*
Variable N-fate**
Ion removal†

Electrolysis Cell 1L

Concentrated Brine
H₂O

*: chromic acids, organic acids, none
**: urea, ammonia, nitrate, mixture
†: hardness, poly-valents, C, N
Further Testing Capabilities

1L batch mixed ISS Wastewater
Variable pre-treatments*
Variable N-fate**
Ion removal†

Advanced Catalytic Oxidation 3L

Unknown Effluent Stream (to be assessed)
Test Variables:
Residence Time
Recycle Ratio
“Enhanced Oxidation” methods

- Effluent Stream from ACO unit should be assessed to determine compatibility with electrolysis cells
  - May be the only viable physical chemical method capable of removing urea and other organics
  - Such compounds will likely foul/prevent water recovery from the electrolyzer or any other brine dewatering system
- As with the electrolyzer, pretreatment regimes, N-fate, and ion concentrations can be tested to determine full capabilities
- KSC currently owns an ozone test stand can also procure/build the other 2 designs
- Based on testing results, it may be possible to combine units to make a high-fidelity test stand and add other required unit ops (hardness removal, maybe some sort of N-removal, etc.)

*: chromic acids, organic acids, none
**: urea, ammonia, nitrate, mixture
†: hardness, poly-valents, C, N
Questions?