

Silver Electrolysis for Disinfection of Spacecraft Potable Water: 2023 Update

ICES-2023-41

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Background

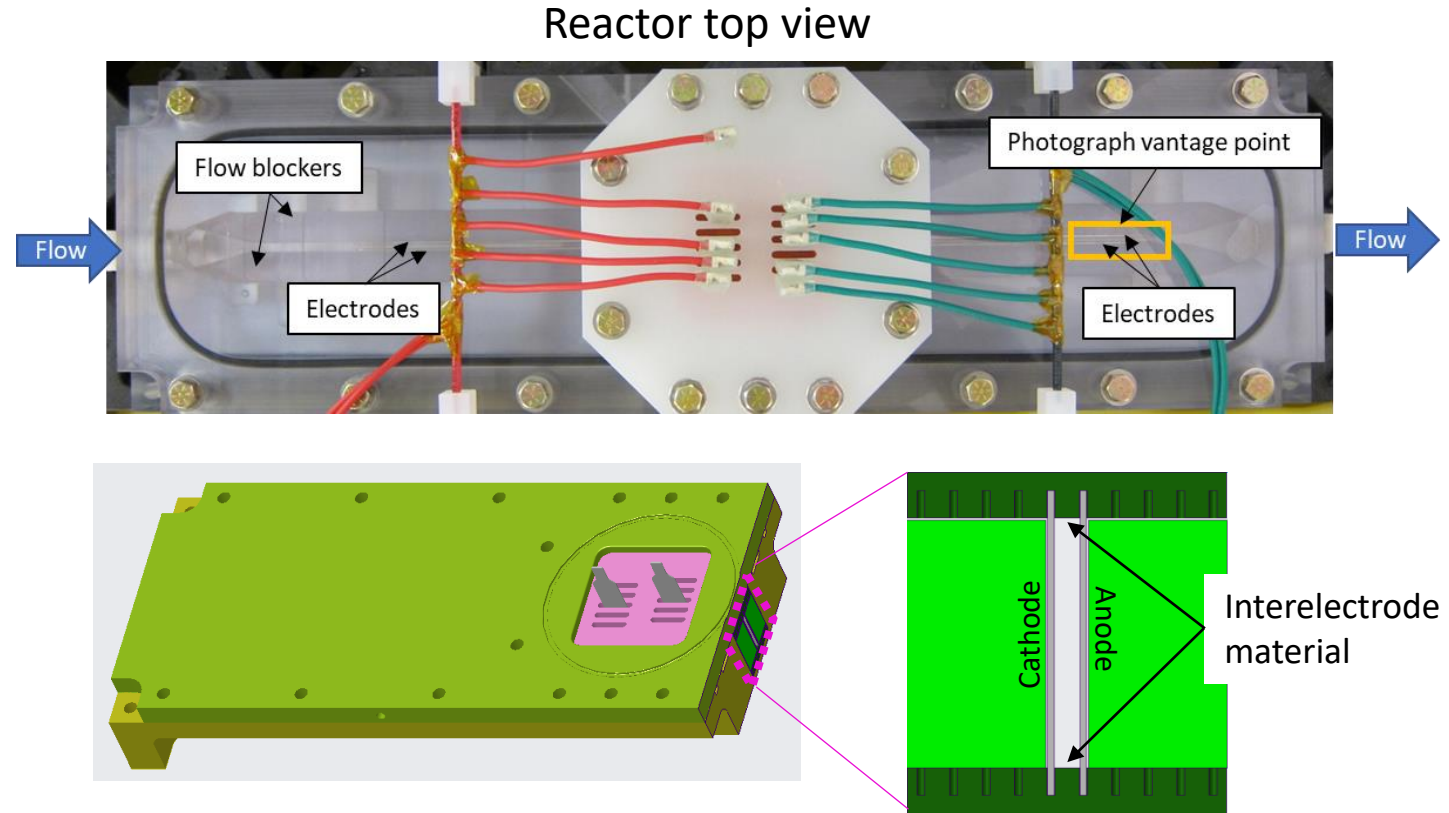
- Goal to replace iodine with ionic silver as residual biocide in future water recovery systems
- Requires inline method for silver ion introduction
- Silver electrolysis (anodic dissolution of silver) is a promising candidate
- Previous testing demonstrated feasibility and advantages of technology (see ICES-2022-20)
- Previous testing also uncovered fault condition that occurs in certain reactor configurations/modes of operation: “electrode bridging”
 - Silver deposits form alternate conduction pathway -> diminishes silver ion output
- The past year’s efforts focused on:
 - Testing to determine strategies for preventing the electrode bridging fault
 - Testing to better understand the role of dissolved oxygen in the cathode reaction
 - Preliminary multiphysics modeling of the silver electrolysis reactor
- These efforts are directed toward development of next gen prototype

Agenda

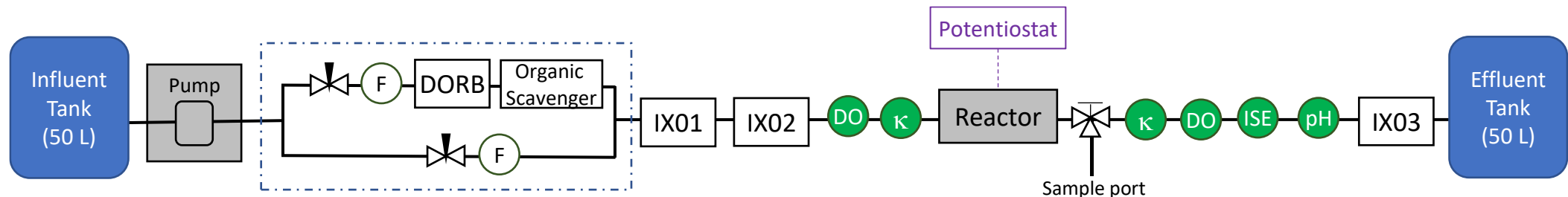
- Test Article/Test Rig description
- Fault Prevention Test
- Dissolved Oxygen Test
- Preliminary Modeling
- Conclusions and Future Work

Test Article (Reactor) and Test Rig

- Reactor enables:
 - Removable electrodes
 - Varied # of electrodes/spacing
 - View into electrode channel(s)
- Test Rig provides:
 - Water quality expected of spacecraft potable water
 - Control of dissolved oxygen (DO) concentration (dashed box)
 - Inline sensors and sample port



Test Rig Schematic



Fault Prevention Test

Purpose: investigate electrode bridging and develop prevention strategies

Test setup: reactor in two-electrode configuration, flowrate 33 mL/min, target silver concentration of ~400 ppb

Baseline test case includes no prevention measures (worst case)

- Subsequent cases include only one prevention measure at a time

Operated until reactor failure or successful completion of 146 hrs (1 crew-yr)

Three test cases of interest:

1. Baseline test case

- 0.33 mA (3.8 $\mu\text{A}/\text{cm}^2$)

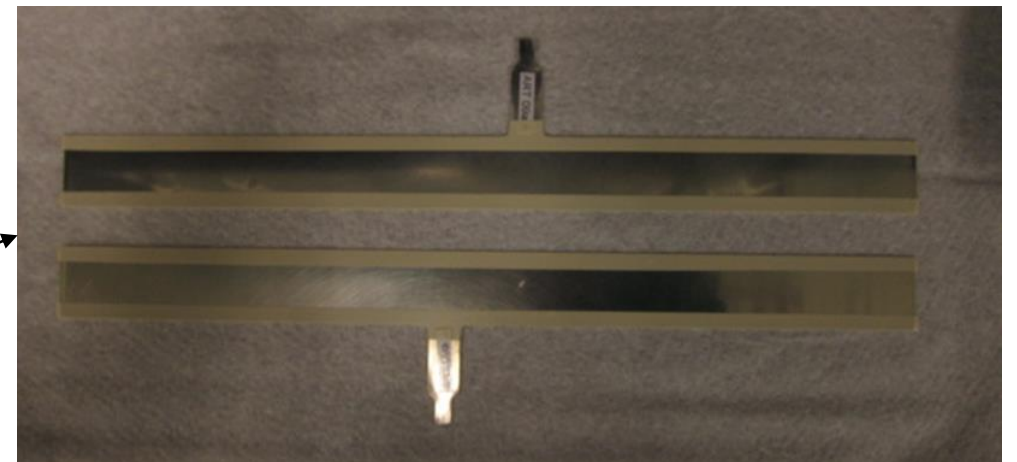
2. Baseline with polarity reversal

- 0.7 mA (8.2 $\mu\text{A}/\text{cm}^2$)

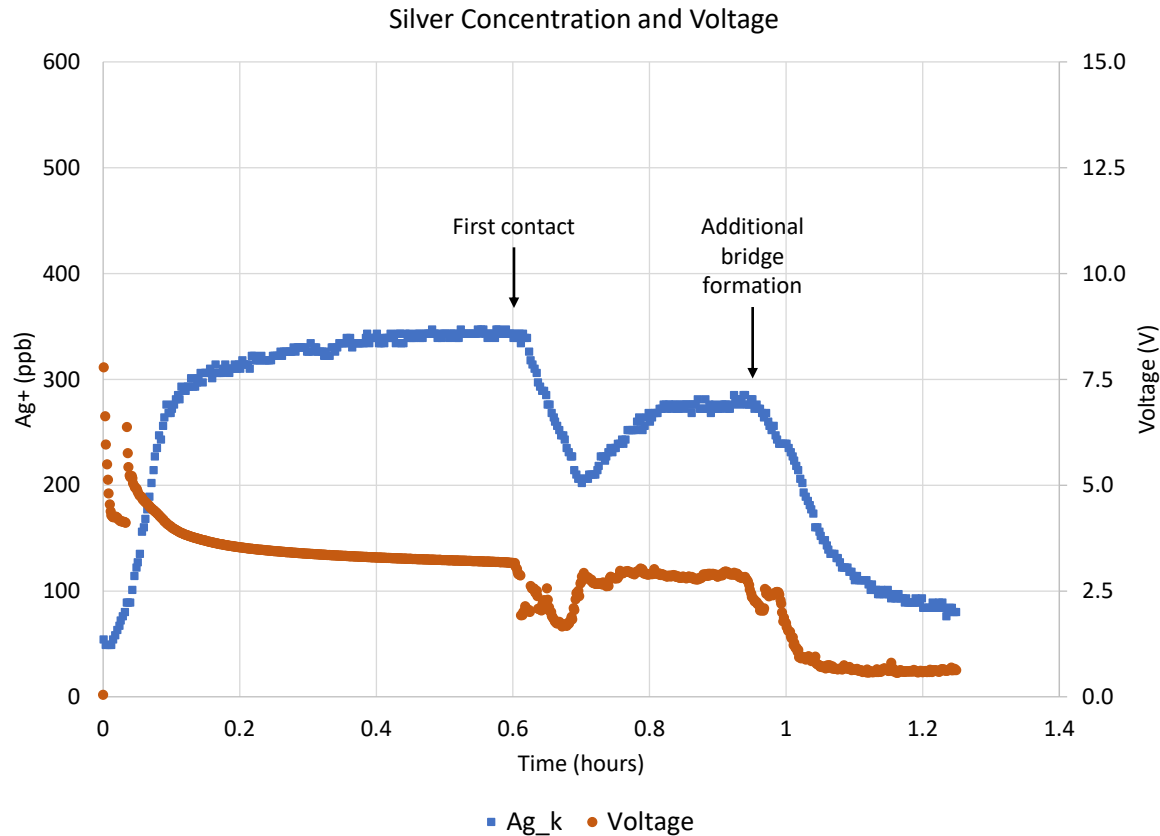
3. Baseline with masked electrode edges

- 0.33 mA (5.5 $\mu\text{A}/\text{cm}^2$)
- (no polarity reversal)

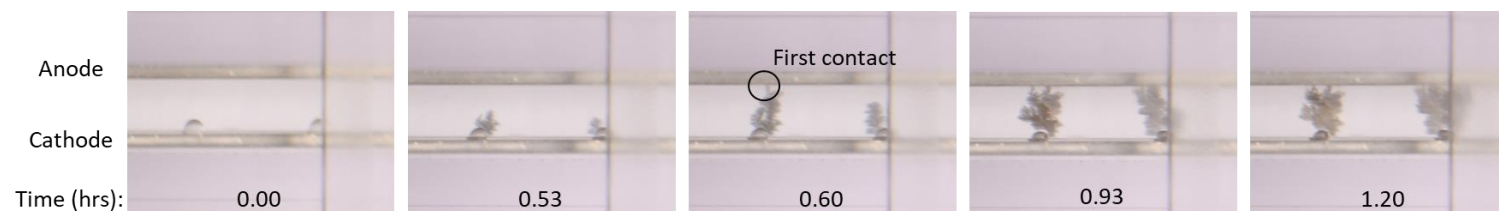
Electrodes with masked edges



Baseline Test Case

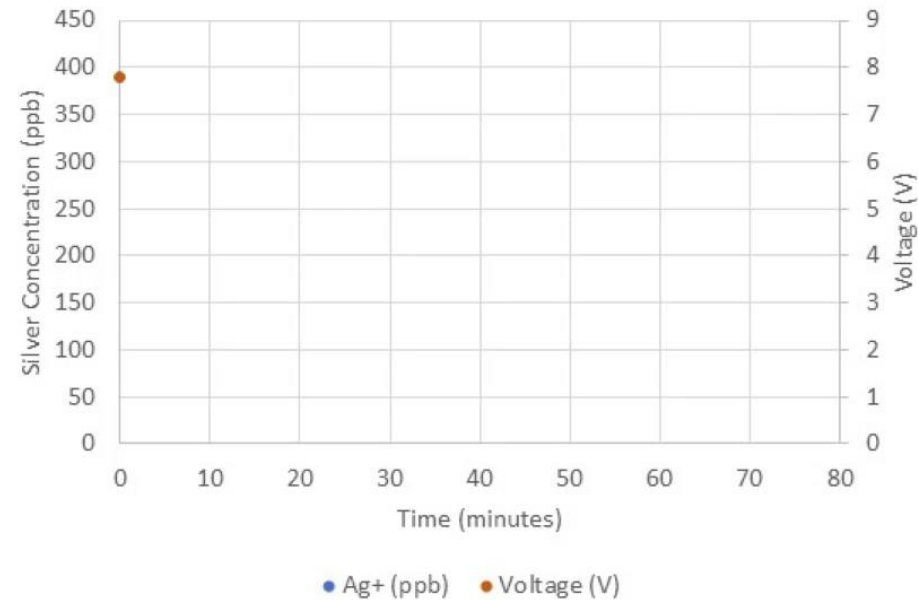


- No preventive measures employed
- Bridging fault observed within 1hr
 - Silver concentration and voltage drop when electrode gap is bridged
 - Confirmed mechanism: cathodic deposition that grows along interelectrode material
- Current efficiency ~50%



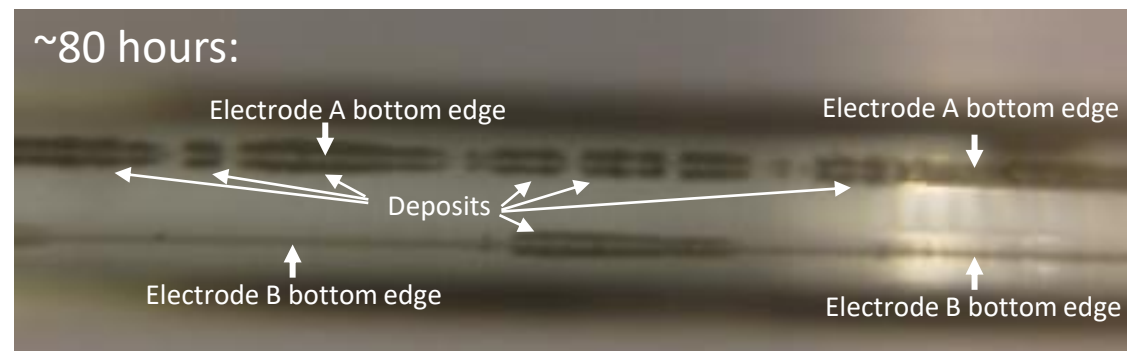
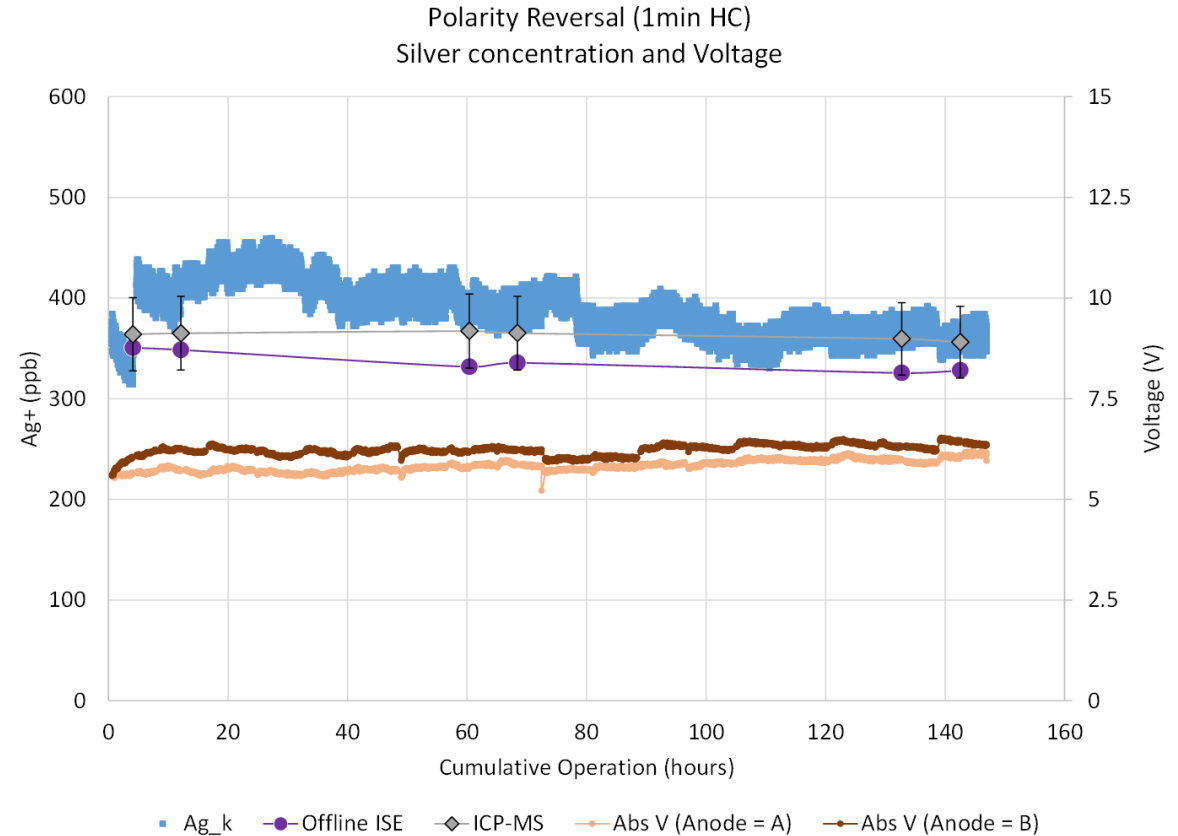
Baseline Test Case:

Time-lapse of electrode bridging fault (100x speed)

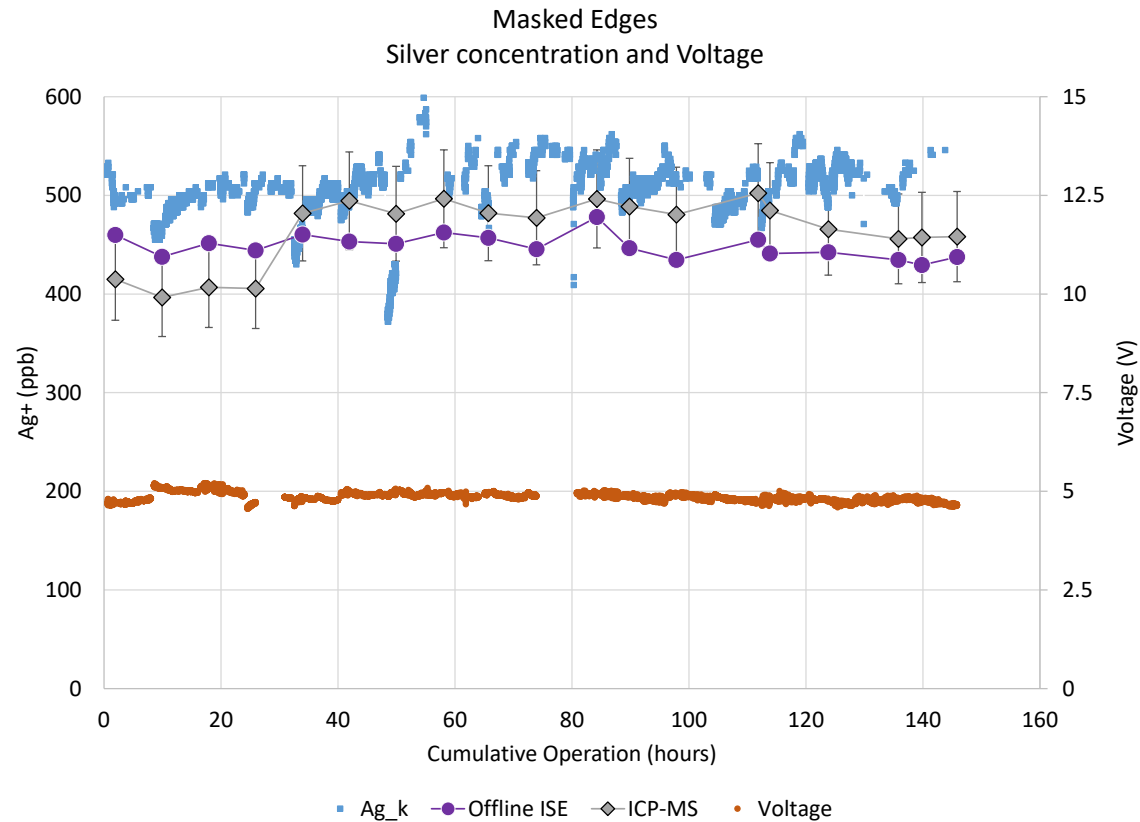


Polarity Reversal

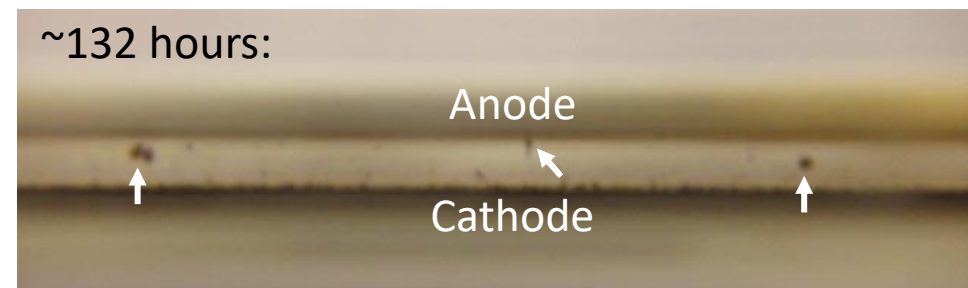
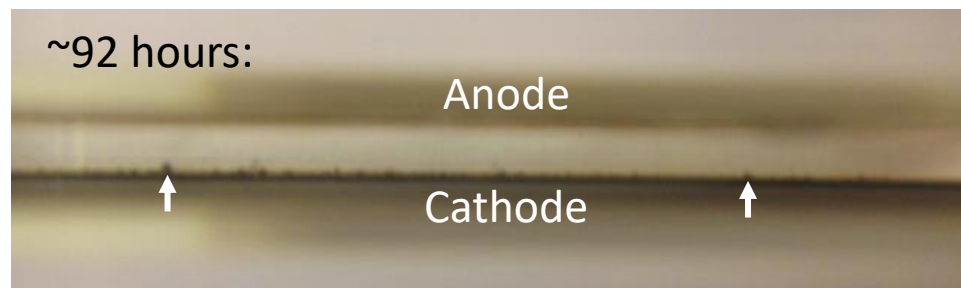
- Polarity Reversal key points:
 - On a regular interval (every “half-cycle”, HC), the direction of current is reversed; anode becomes cathode, vice versa
 - Keeps electrodes clean and prevents electrode bridging by re-dissolving fringes of silver deposits
 - Easy to implement in any design scheme
 - Previous testing (“Feasibility Test”) used a 30min HC, which was too long; this test used a 1min HC
- System operated for 1 crew-year (146 cumulative hours) with no indication of bridging or other performance degradation
- Polarity reversal prevented deposits from growing perpendicular to electrodes. Deposits formed along electrode edges, but did not grow across gap and reached steady-state at ~80hrs
 - Deposits had no impact on performance or water quality
 - Could possibly be eliminated by increased reversal frequency and/or use of alternate interelectrode material
 - Can be eliminated by combining with other technique



Masked Edges



- Masked edges:
 - Prevent high silver concentration in corners of fluid channel
 - Separate active surface of electrode from interelectrode material and from regions of low fluid velocity
- Operated in constant polarity (no reversal)
- System operated for 1 crew-year (146 cumulative hours) with no indication of bridging or other performance degradation
 - 25% increase in current efficiency over baseline test case
- Flakes observed at cathode
 - Silver dendrites that break off/settle
 - First hint of flake formation at ~36hrs
 - Undesirable, but fully preventable with polarity reversal

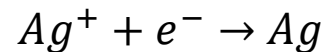
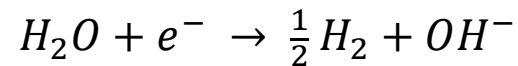
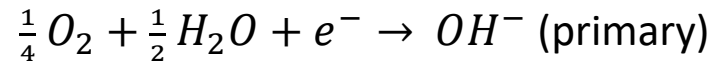


Fault Prevention Test Summary

- Confirmed intuitions / gained insights about electrode bridging fault:
 - Result of cathodic silver deposition that grows dendritically across electrode gap
 - Occurs in regions with combination of high local silver concentration, low fluid velocity, and contact with substrate (interelectrode material)
- Both techniques (edge masking and polarity reversal) very effective
 - At least one crew-year of no-fault operation
 - Combination of these techniques expected to yield optimal performance
- Polarity reversal should be considered for any design concept
 - May provide, by itself, sufficient protection against bridging fault
 - Prevents flaking and significant changes of surface morphology
- Ongoing work: test alternate interelectrode materials
- Additional testing of techniques to be performed on next generation prototype

Dissolved Oxygen Test Background/Setup

- Primary cathode reaction expected to be dissolved oxygen reduction, but other reactions possible:

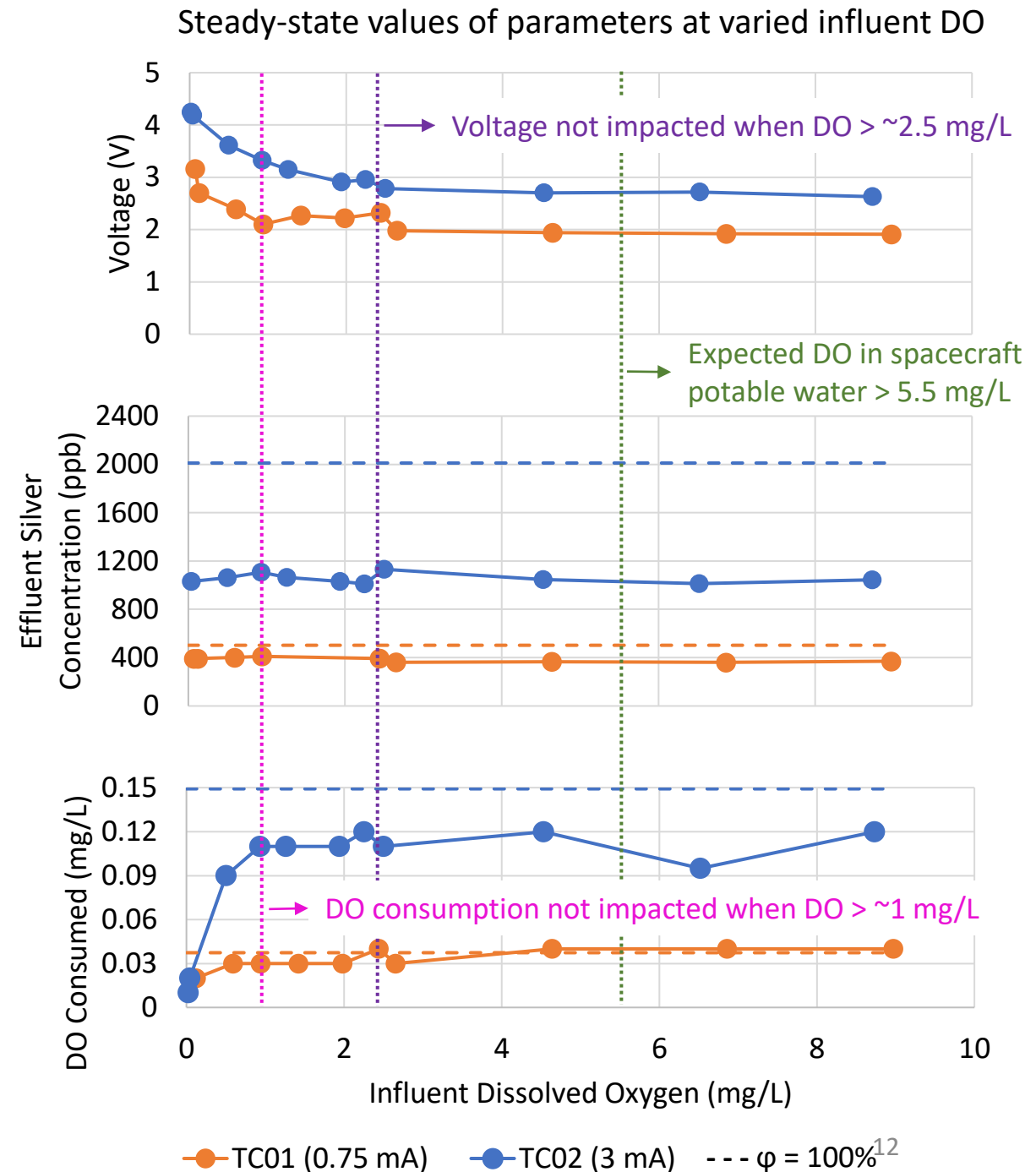


- Cathode reaction expected to depend on influent DO concentration
- Minimum DO concentration in spacecraft water expected to be ~5.5 mg/L

- Purpose: investigate cathode reaction to better understand reactor electrochemistry
- Test conditions:
 - Reactor in 10 electrode configuration
 - Flowrate: 100 mL/min
 - Two test cases: 0.75 mA, 3 mA
 - Both test cases comprised multiple steps at varying influent DO concentration (from 8.97 mg/L down to 0.02 mg/L)
- Steady-state value of Voltage, Silver Concentration, and DO Consumption plotted against Influent DO concentration

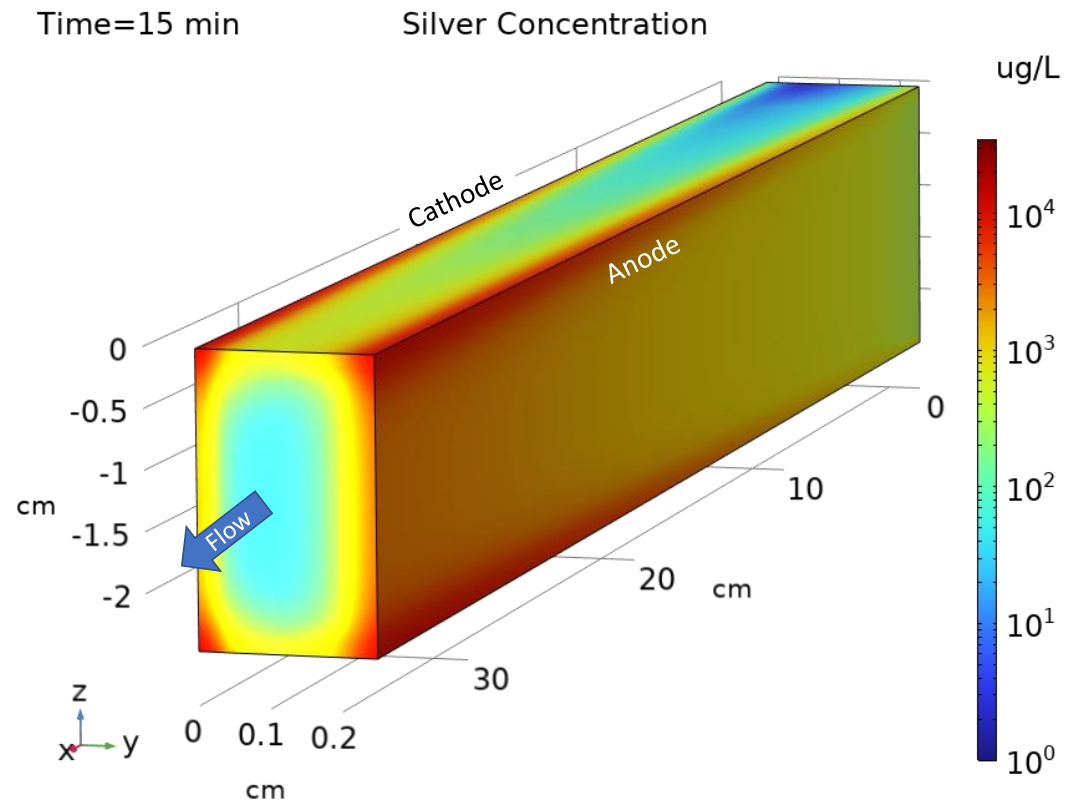
Dissolved Oxygen Test Results

- DO reduction is primary cathode reaction
- When influent DO concentration is in expected range, reactor performance is not impacted
 - Voltage not impacted above ~ 2.5 mg/L
 - Current efficiency not impacted at all
 - DO consumption not impacted above ~ 1 mg/L
- Below influent DO of 1 mg/L, another reaction is occurring, which is assumed to be hydrogen evolution
 - Not concerning: even if 100% of cathodic current were hydrogen evolution, rate of production would still be very low
 - Ongoing testing is investigating this further to better understand division of current between the three possible cathode reactions



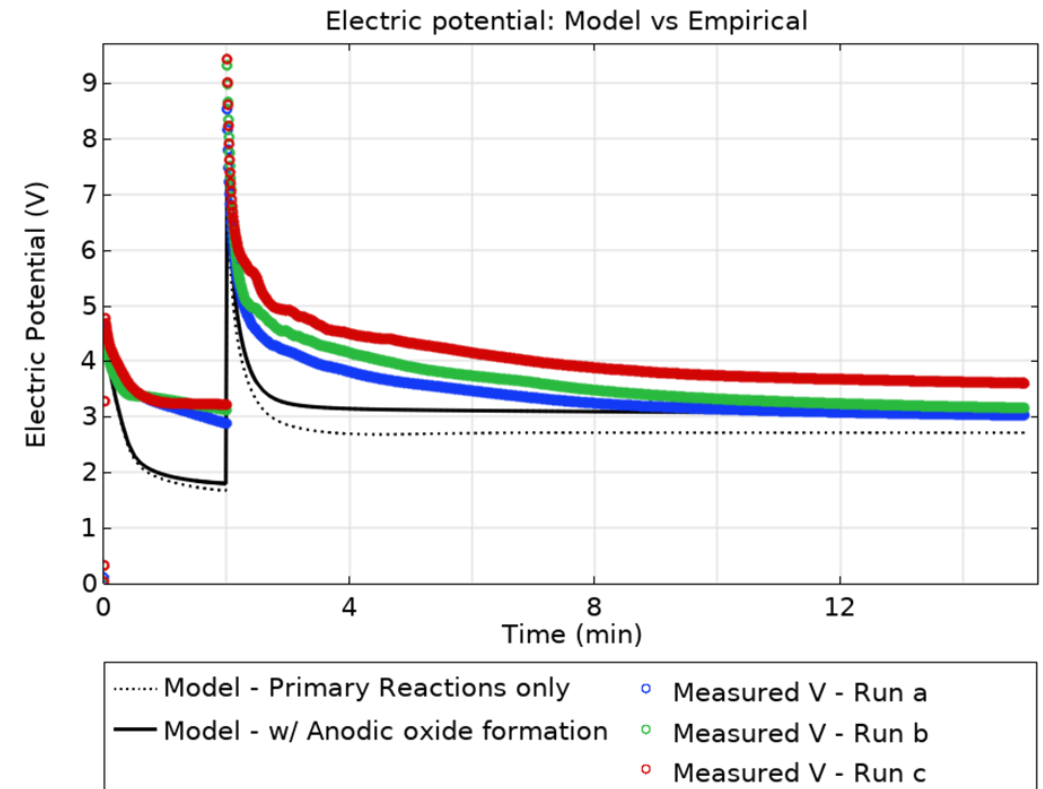
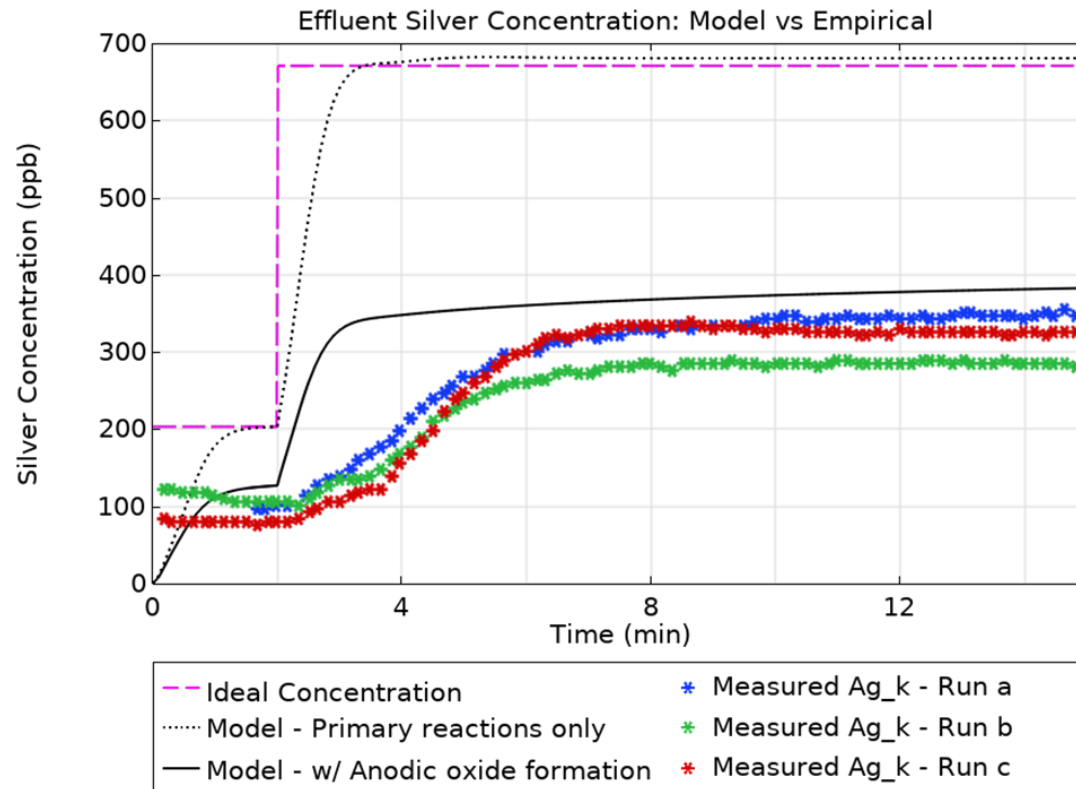
Preliminary Modeling

- Combines fluid flow, mass transport, and electrochemistry
- So far, includes single rectangular electrode channel with subset of reactions
 - Primary anode/cathode reactions plus anodic oxide formation
- Input parameters (flowrate, current, cell geometry) match baseline case from Fault Prevention Test



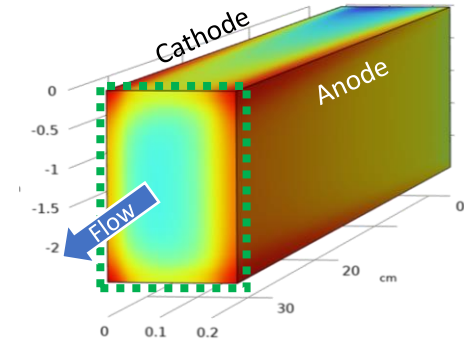
Preliminary Modeling

Comparison with Empirical Data

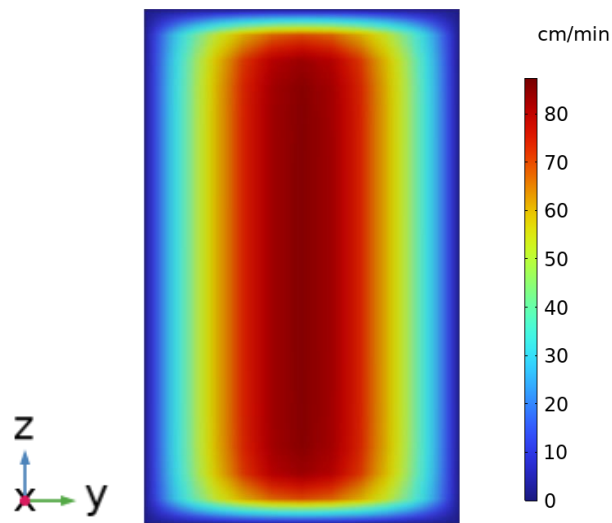


Preliminary Modeling

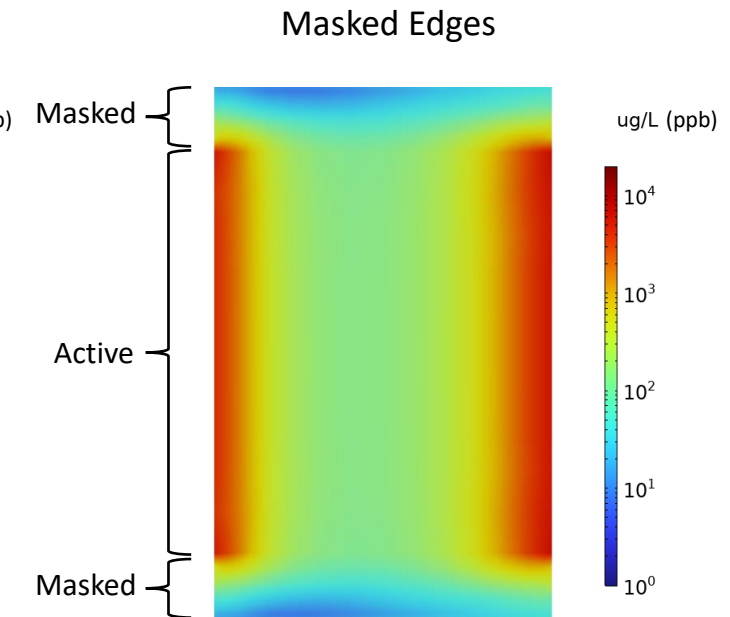
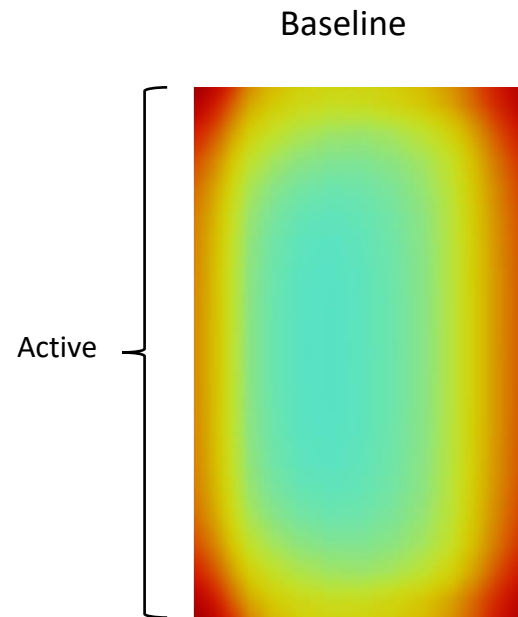
Steady-State $[Ag^+]$ Distribution in Alternate Configurations



Fluid Velocity Magnitude



Silver Concentration



Conclusions and Future Work

- Fault Prevention Test
 - Electrode bridging fault is preventable
 - Combination of techniques expected to yield best results
 - Test of alternate materials is ongoing
 - Future work: long-duration test of best configuration
- DO Test
 - Dissolved oxygen reduction is predominant cathode reaction
 - Cathode reaction does not impact reactor performance in expected range of influent DO concentration
 - Hydrogen production very low; ongoing testing to determine regime in which it occurs
- Modeling
 - Model provides realistic representation of reactor multiphysics
 - Future work: include additional reactions and validate against multiple sets of data
 - Continue using model for design optimization while reducing test time
- Development of next generation prototype to demonstrate reactor performance in a flight-like configuration

Acknowledgments

- Exploration Capabilities, Life Support Systems Project
- Countless colleagues for their advice, sample analysis, assistance with design/development, and editorial suggestions
- Specific thanks to Moses Navarro, Andrew Lin, Zac Colovos