Enhanced Depolarized Electro-Membrane System (EDEMS) for Direct Capture of Carbon Dioxide from Ambient Air

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National Energy Technology Laboratory

Carbon Management and Natural Gas & Oil Research Project Review Meeting

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Project Overview

Overall Project Objective

– Develop hybrid electrochemical - membrane process to directly capture CO_2 from air, recondition the capture solvent, and release captured CO_2 in concentrate form

Funding: DOE $699,509 and UKRF Cost Share $174,904

Overall Project Performance Dates: 10/1/2020 – 03/31/2022

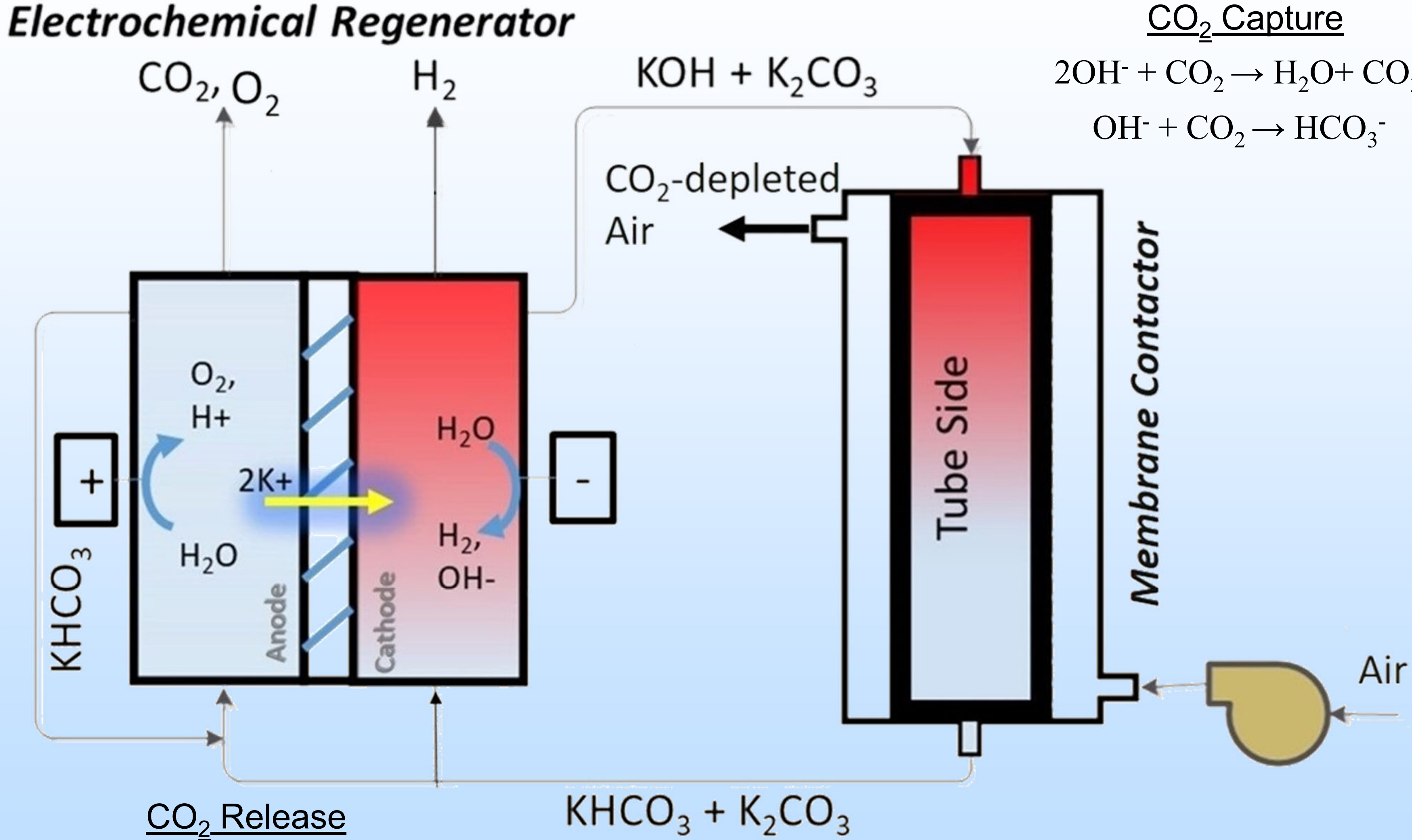
Project Participants: University of Kentucky and ALL4

Project Overview

Project Objectives:

- Develop an inorganic membrane contactor including a patterned surface, and demonstrate its effectiveness and stability for ambient CO_2 removal with caustic solvent
- Demonstrate the effectiveness and stability of a depolarized electrochemical reactor for solvent regeneration at low applied voltages
- Integrate and demonstrate the enhanced depolarized electro-membrane system (EDEMS) for >50% CO_2 capture from a >2 L/hour influent air with ~400 ppm CO_2

Technology Background



<u>CO_2 Capture</u>

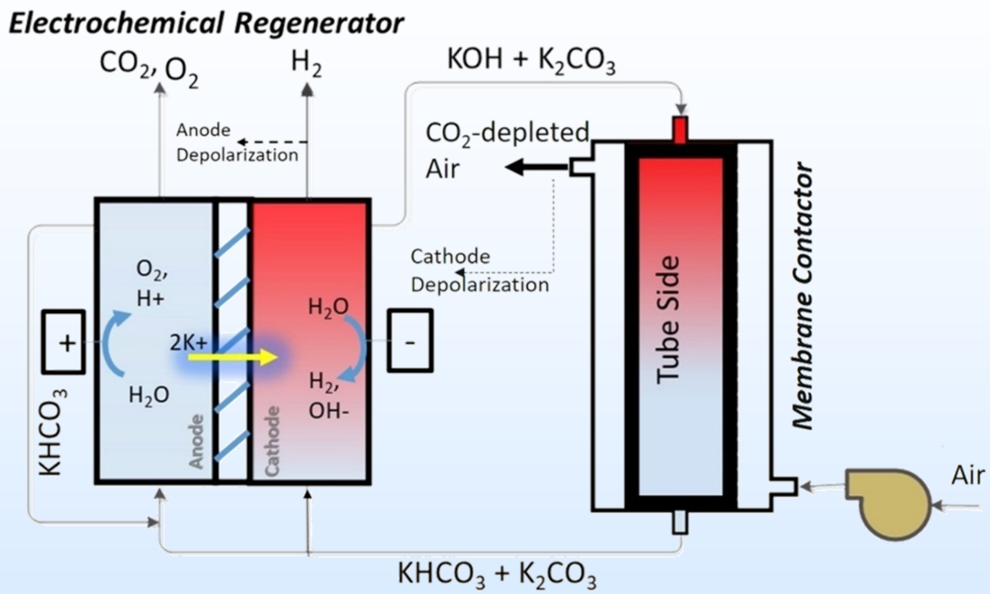
$2OH^- + CO_2 \rightarrow H_2O + CO_3^-$

$OH^- + CO_2 \rightarrow HCO_3^-$

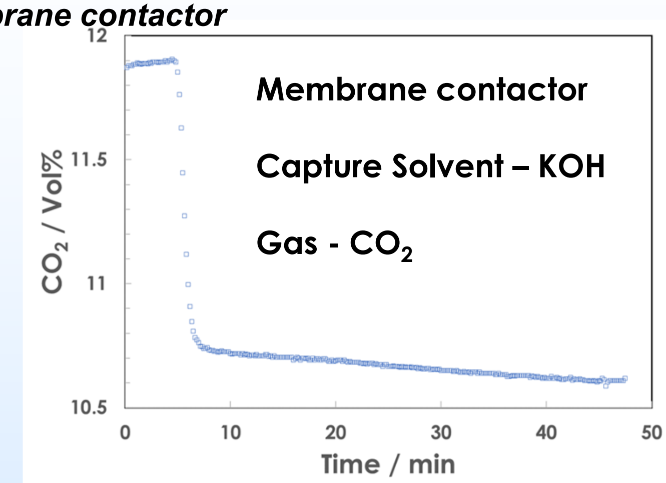
<u>CO_2 Release</u>

$H^+ + HCO_3^- \rightarrow CO_2 + H_2O$

Technology Background



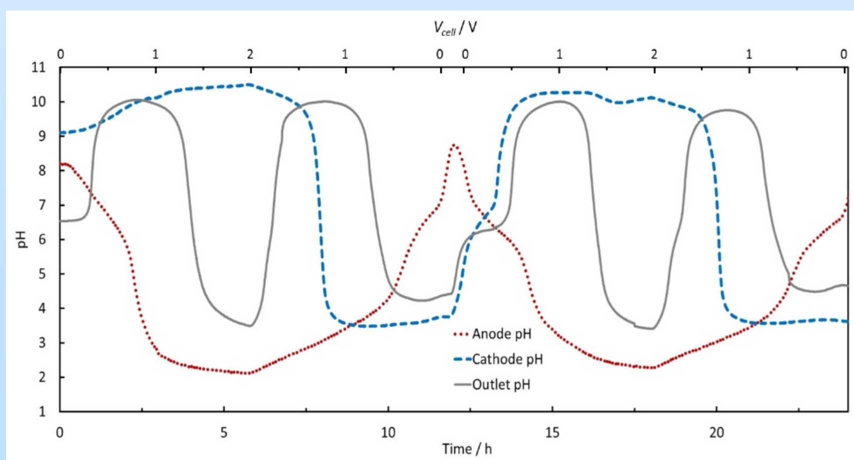
Preliminary data: Capture performance of large membrane contactor



Key Benefits

- Provide stable performance facilitated by the depolarized electrochemical cell and stable hydrophobic contact absorber to reduce the capital cost and energy requirement by up to 30% by intensifying the electrochemical and CO_2 release reactions
- Provide reduced pressure drop capture process coupled with fast kinetics capture solvent regenerated by electrochemical process
- Mitigate water loss compared to direct contact absorber
- Employ depolarization to reduce capture cost or to provide energy storage media

Preliminary data: pH response of electrochemical desalinator



Project Scope

a. Work plan

- Inorganic membrane contactor development with surface patterning; then performance and stability comparison to commercial contactor with caustic capture solvent (Task 2)
- Development of electrochemical reactor sub-system and demonstration of depolarization to reduce voltage requirement and enhance CO_2 up-concentration (Task 3)
- Integrate sub-systems, and demonstrate continuous DAC capture for 12-24 hours (Task 4)

b. Project Milestones

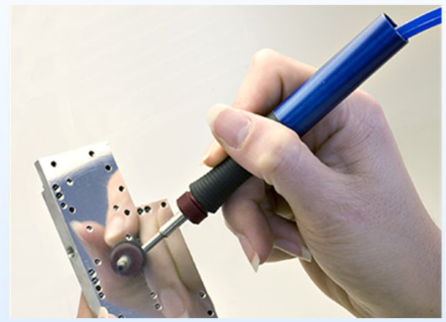
- 50% CO_2 capture efficiency for DAC using patterned superhydrophobic membrane absorber for 12-24 hours
- Depolarized Electrochemical Cell with capture solvent regeneration at <3.5 V, 1 A
- EDEMS for DAC at >2 L/hr influent air for >50% CO_2 capture for 12-24 hours

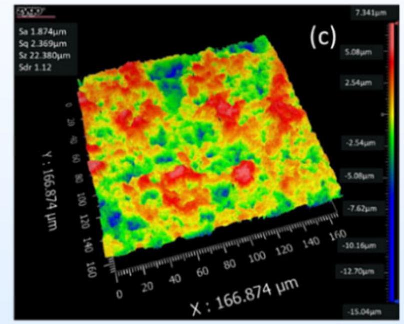
c. Project success criteria

- Produce patterned membrane contactor with 10-25% improved membrane area compared to un-patterned membrane
- Depolarized electrochemical cell achieves > 50% faradaic efficiency at 1 Amps
- EDEMS achieves >50% CO_2 capture efficiency at < 3.5 V DEC

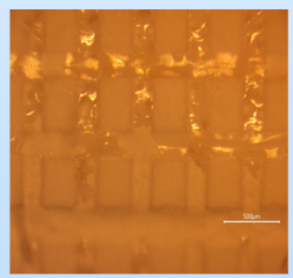
Patterning of Inorganic Membrane

Microblasting
COMCO-Inc

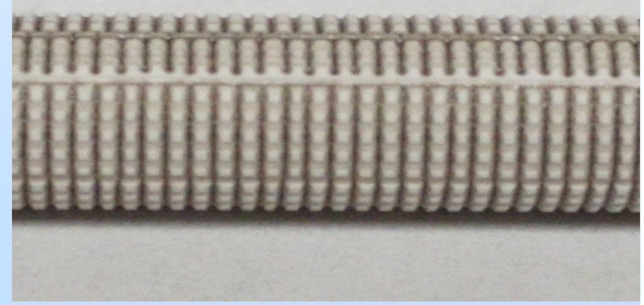




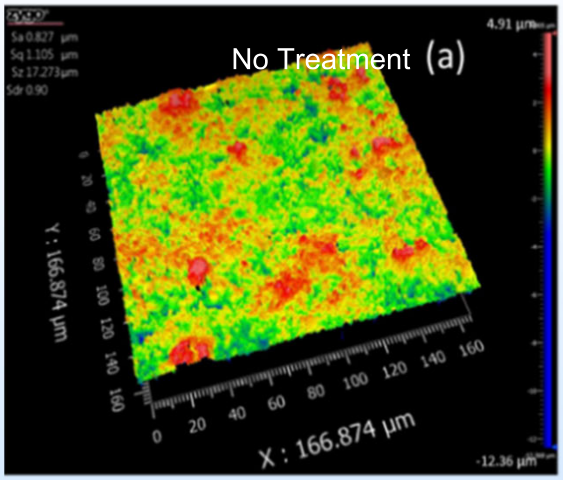
Laser Patterning

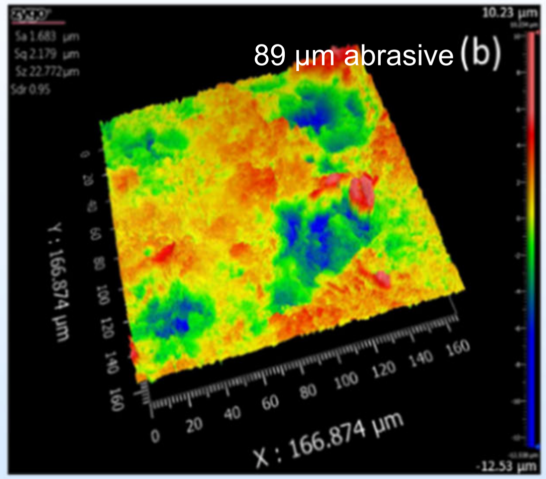


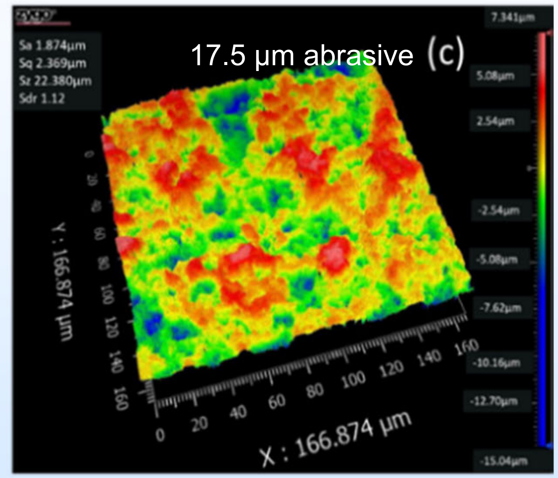
500µm Grid on Dry 0.5µm Alumina Tube



Microblasting Approach



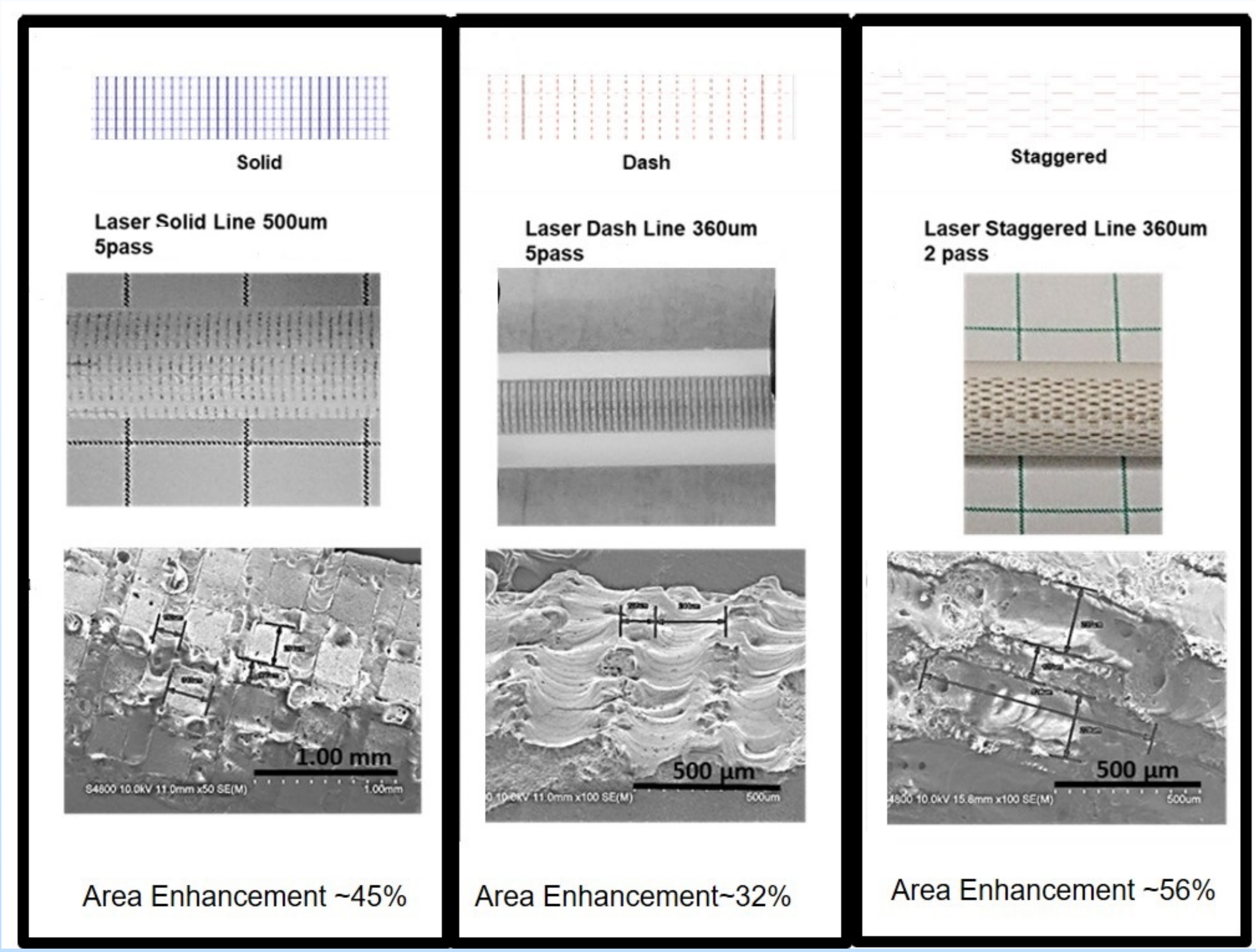




Abrasive, Aluminum Oxide (µm)	10.0	17.5	50.0	89.0	No Treatment
SDR, Developed interfacial area ratio (%) *vs.* geometrically smooth surface	90.0	112.0	88.0	95.0	90.0
Area Enhancement (%)	None	24.4	None	5.6	None

Laser Patterning Approach

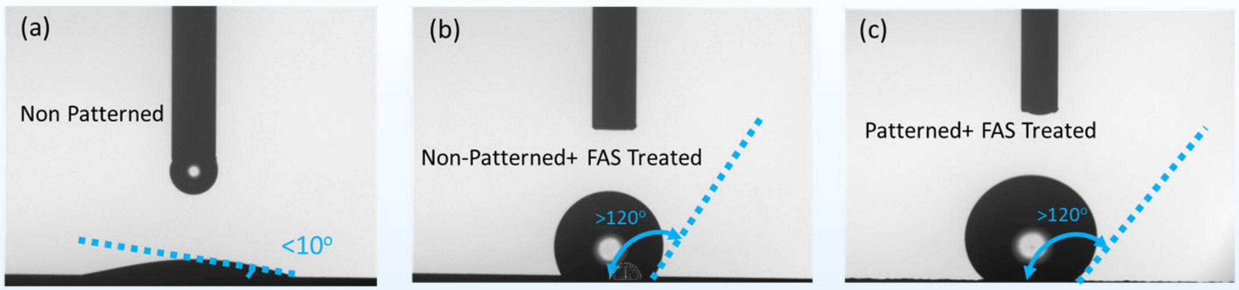
Surface area acquired with Mountains SEM Software

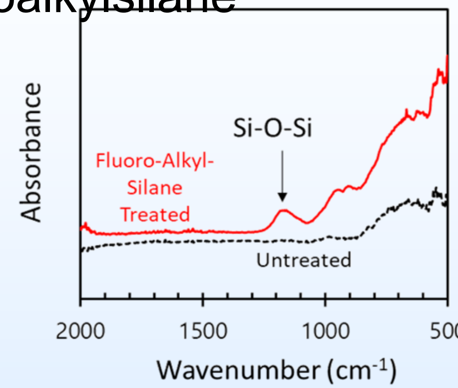


<u>Satisfied Success Criteria of 10-25% Area Enhancement</u>

Contactor Preparation and Stability

Tubular Membranes Treated with Fluoroalkylsilane



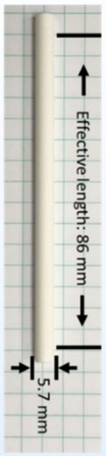


Stability of Planar Membranes Treated with Flouroalkylsilane

Alumina disk with an effective pore size of 2.5 µm	**Contact Angle (°)**	**Contact Angle after 72hours in 2.5wt% KOH at ~23°C (°)**	**Contact Angle after 120hours in 2.5wt% KOH at ~23°C (°)**	**Contact Angle after 12 days in 2.5wt% KOH at ~23°C (°)**	**Contact Angle after additional three weeks in 2.5wt% KOH at ~23°C (°)**
Laser Patterned	131	123	123	113	104
Unpatterned	143	98	91	83	61
PP membrane, 0.2 µm	135		127		120
PP membrane, 0.45 µm	132		126		115

Contactor Testing

Alumina membrane coated with Flouroalkylsilane

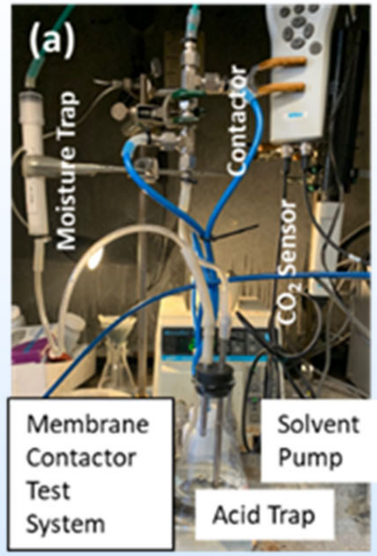


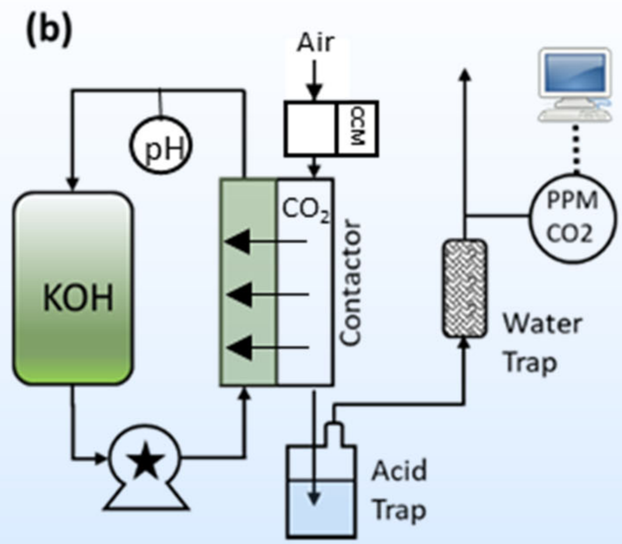
Membrane

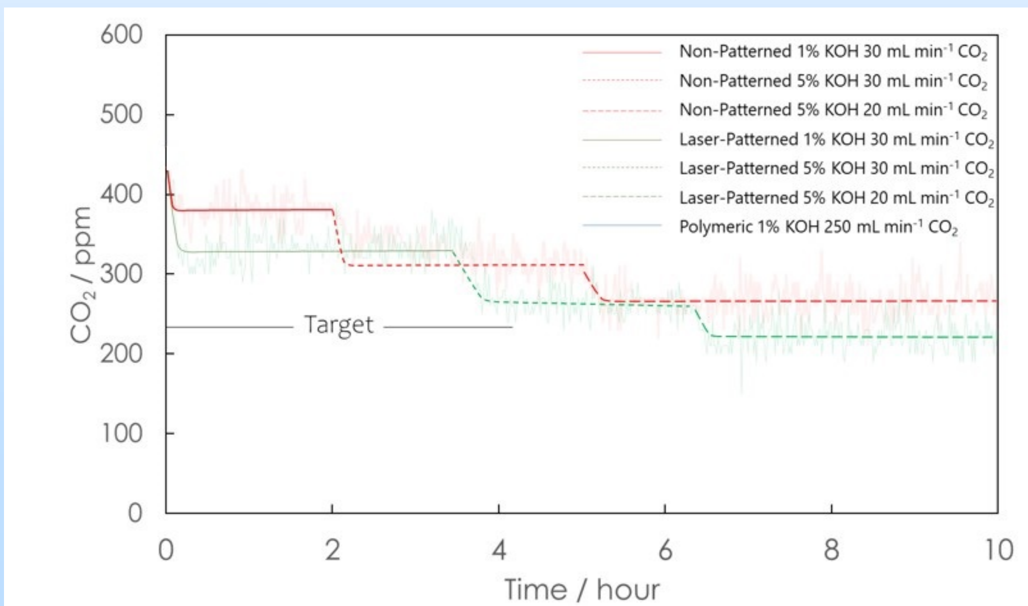
FAS Coated Patterned Membrane

~33% Area Enhancement

Membrane Cell





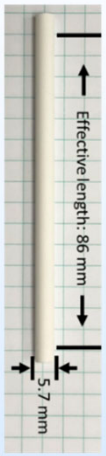


Capture improved with:

1. Increased gas residence time
2. Increased concentration of capture solvent
3. Interfacial enhancement

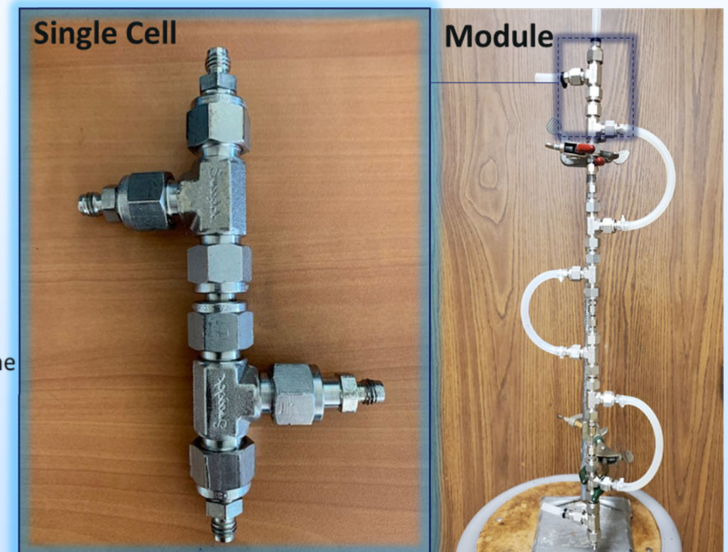
Bundled Contactor Testing

Alumina membrane coated with Flouroalkylsilane

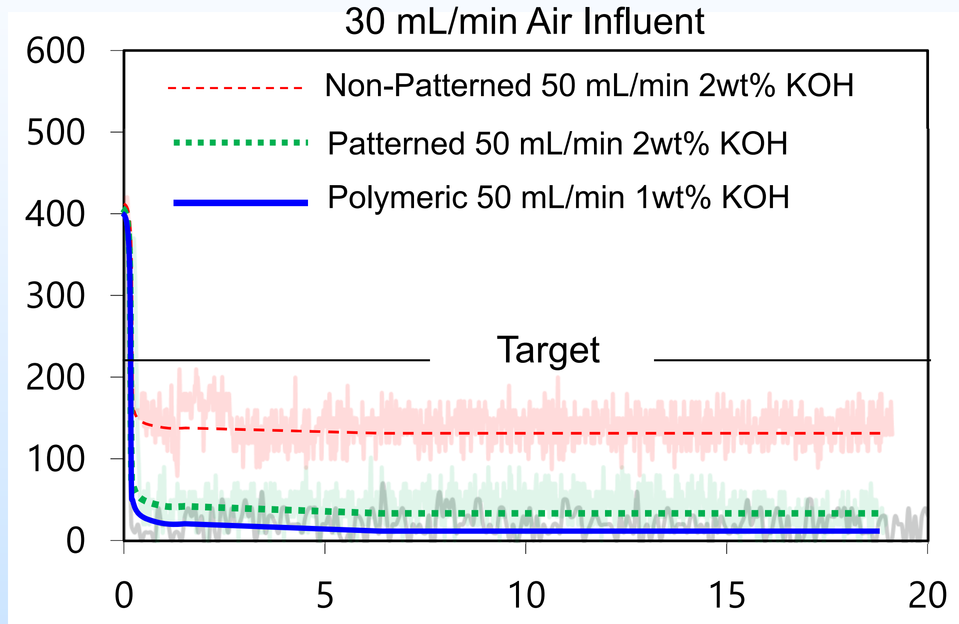


Membrane

FAS Coated Patterned Membrane
~45% Area Enhancement

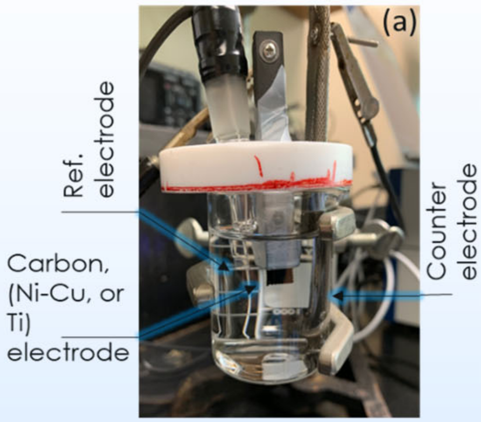


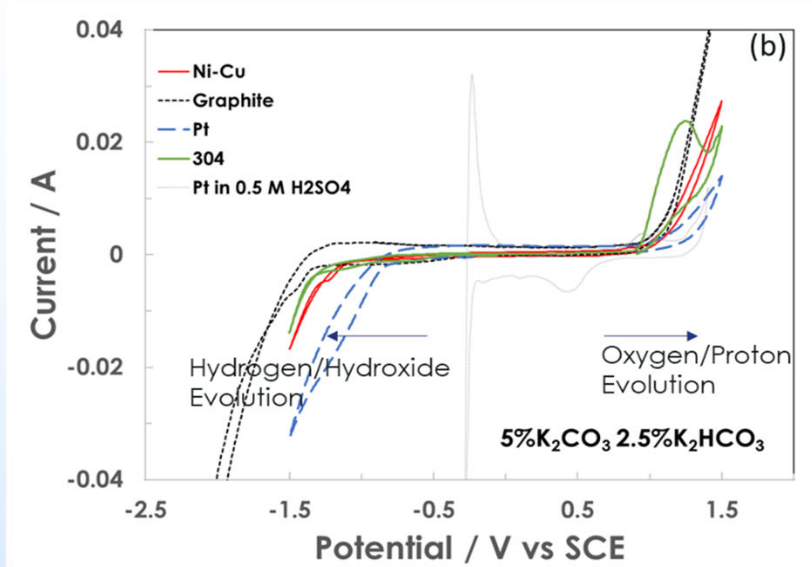
Four Membranes in Series



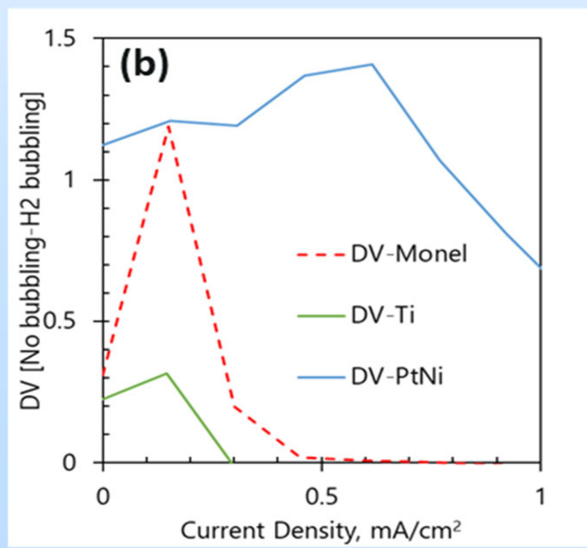
Achieved >90% CO_2 capture using laser-patterned inorganic membrane contactor bundle (1.3E-06 mol/m^2-s) and performance similar to polymeric membrane (1.0E-06 mol/m^2-s)

Electrodes for Electrochemical Regenerator



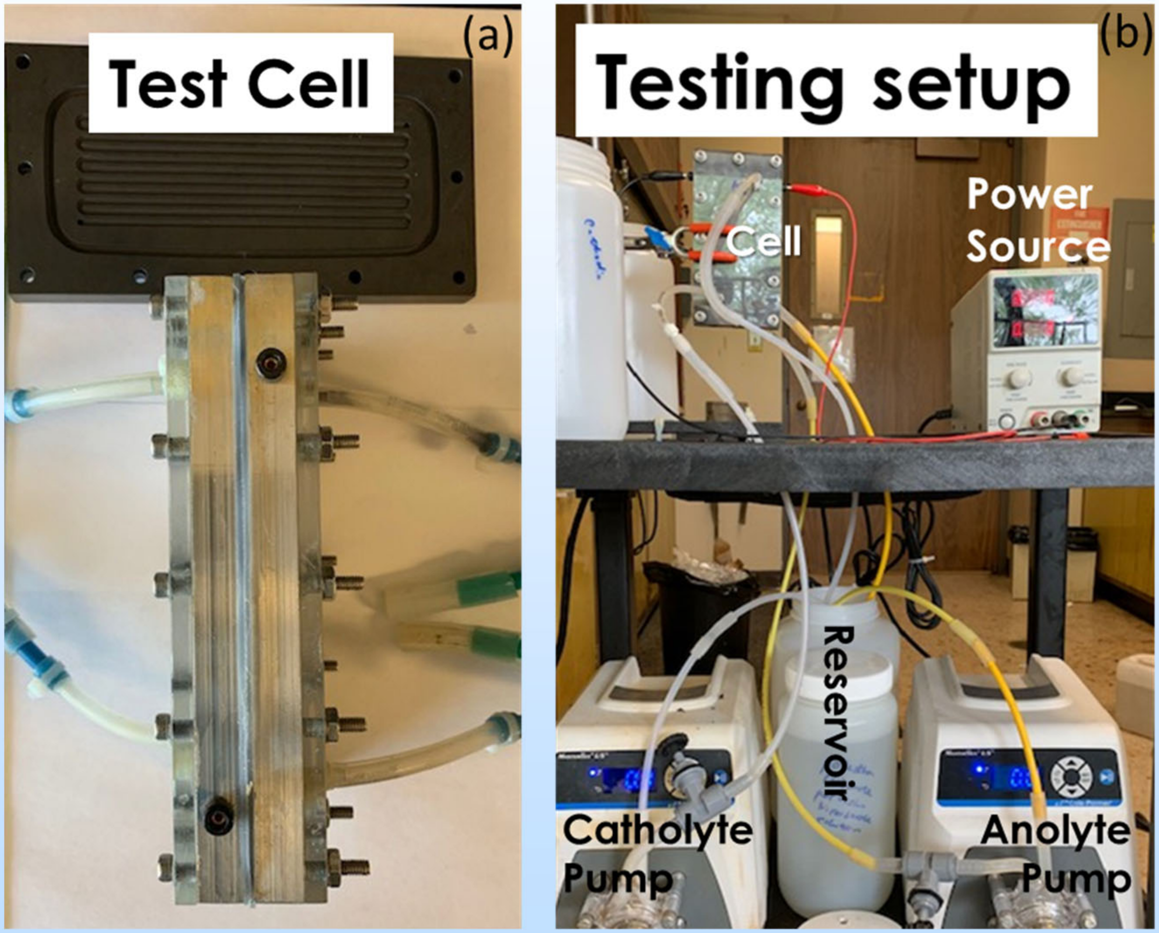


<u>Monel (Ni-Cu) and graphite are adequate for OER, but key concern with graphite at high voltage operation due to carbon oxidation</u>



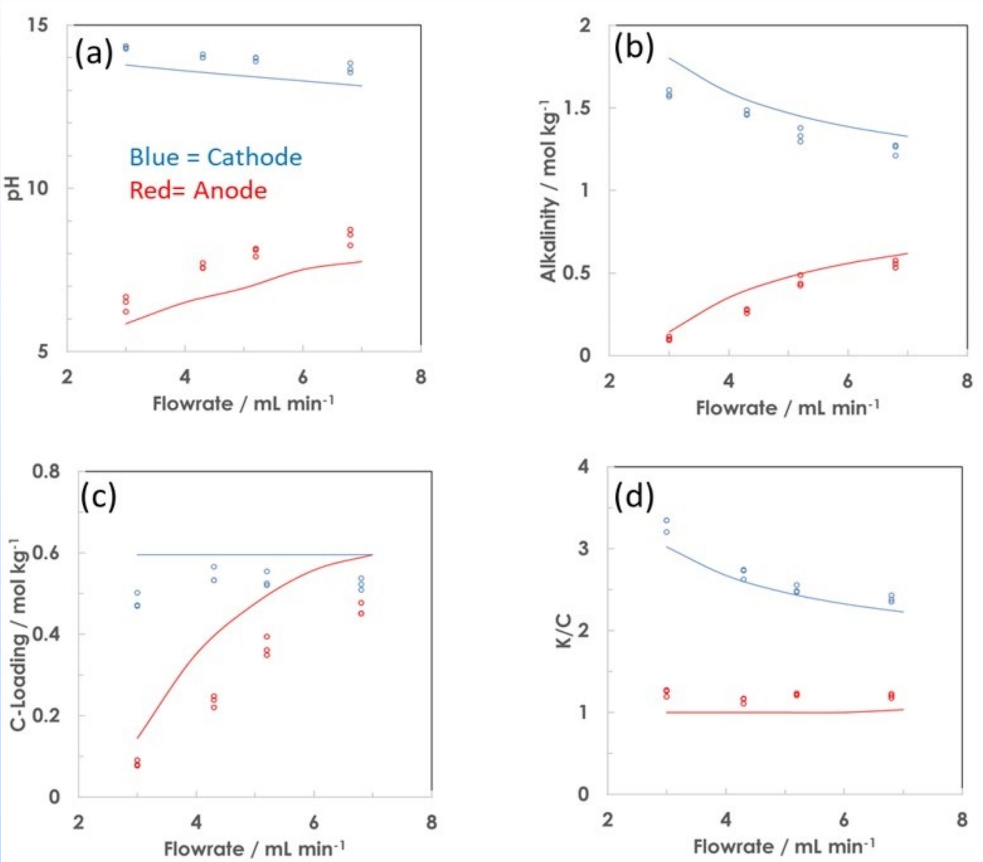
<u>Pt-based catalyst preferred for depolarized operation</u>

Electrochemical Test Station

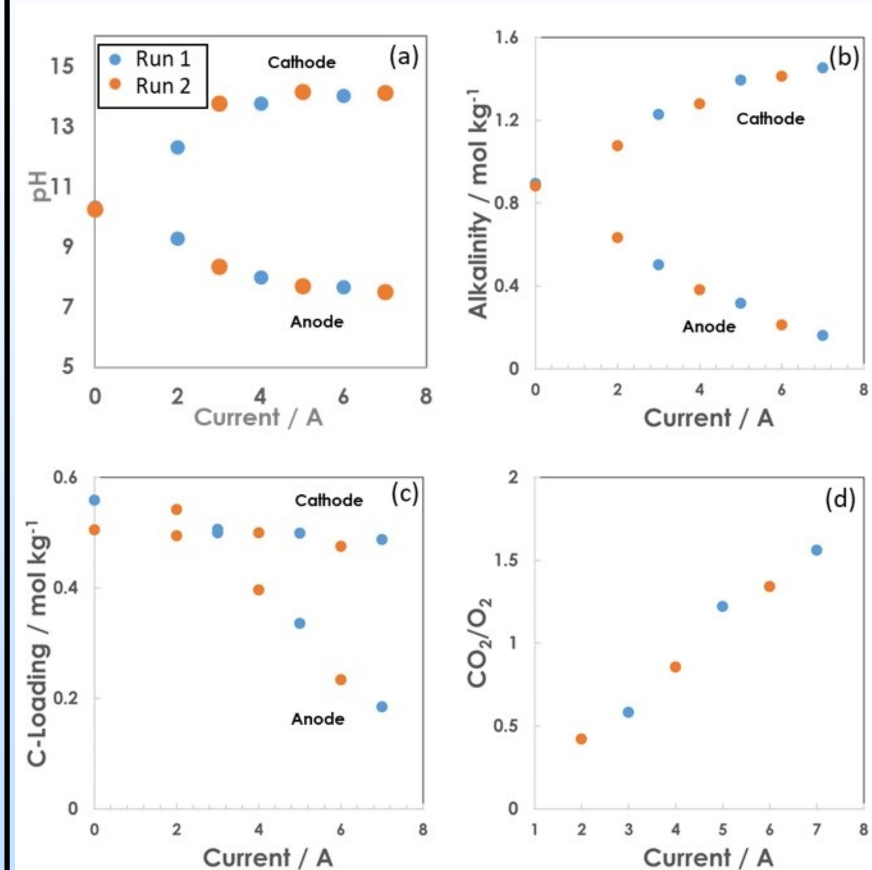


Parametric Effects on Electrochemical Performance

$5\% \ K_2CO_3 + 2.5\% \ KHCO_3$



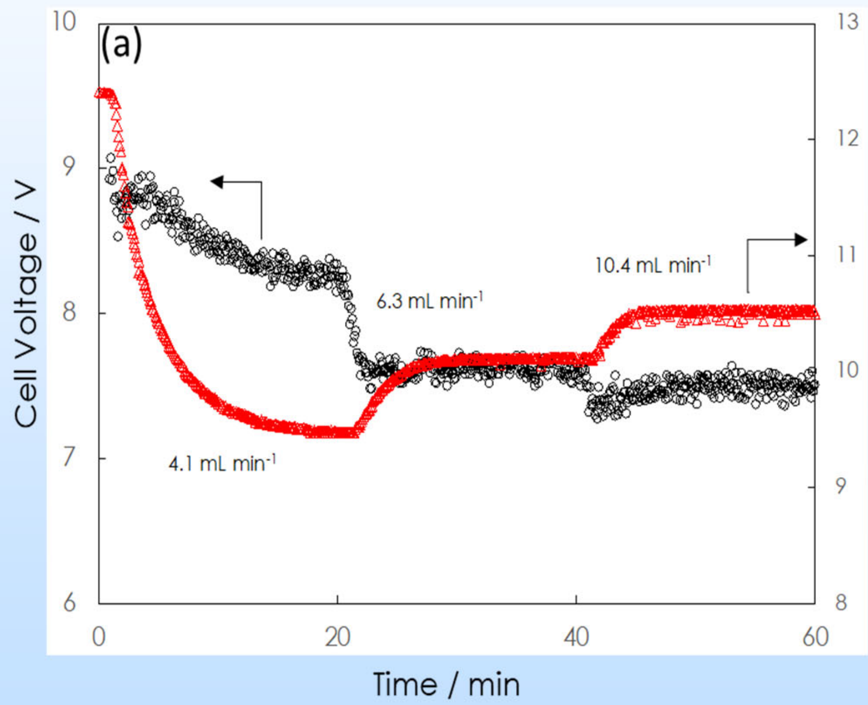
5 Amp Constant Current

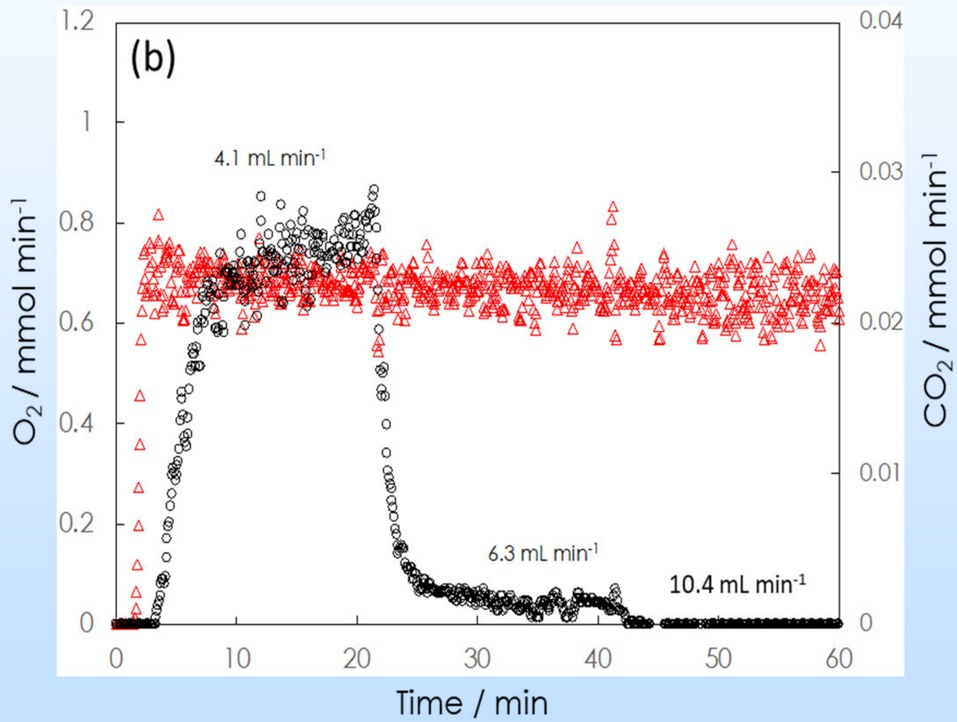


4.3 mL/min Anolyte/Catholyte Circulation

Parametric Effects on Electrochemical Performance – Gas Analysis

Effect of flow rate on pH and voltage, effluent O_2 and CO_2 response during polarization at 4A and 10wt% K_2CO_3 as solvent

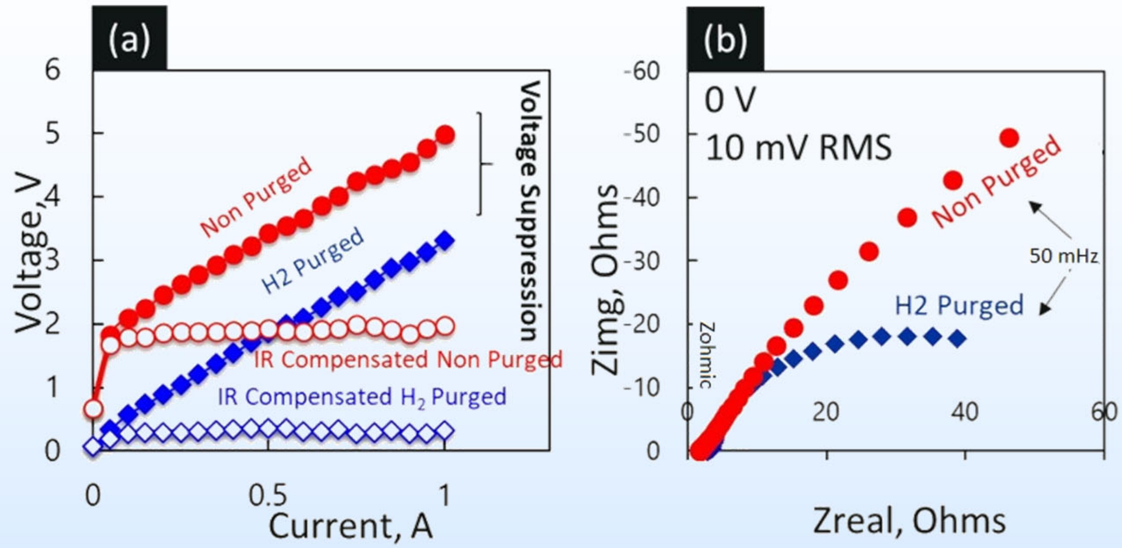




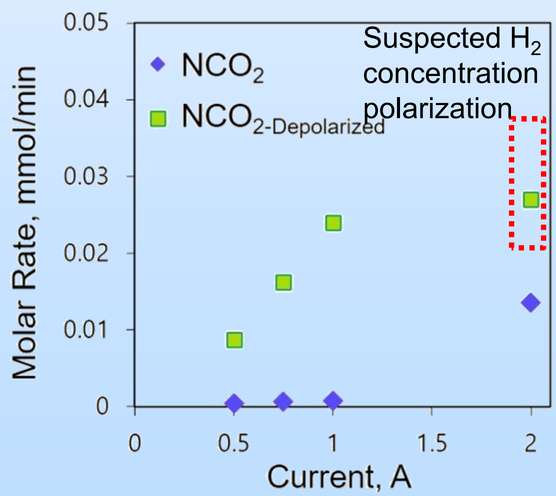
<u>Oxygen production is commensurate with current and CO_2 release is pH dependent</u>

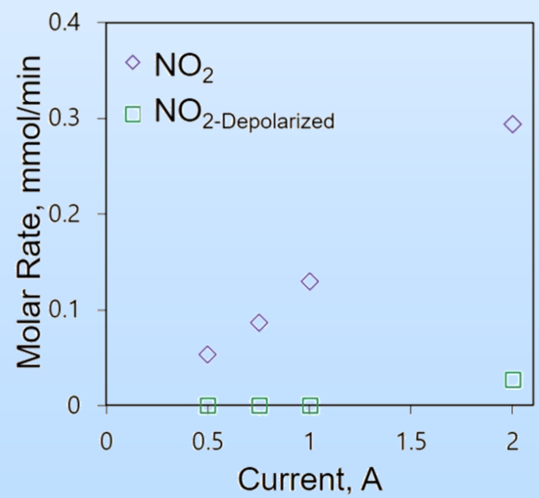
Depolarized Operation of Electrochemical Cell

10 mL/min Anolyte / Catholyte
Monel Cathode
Pd/C catalyst on Monel Anode
1 wt% Na_2CO_3



5 mL/min Anolyte / Catholyte
Monel Cathode
Pt/C catalyst on Monel Anode
5 wt% K_2CO_3
Non-Depolarized @1A, 3.6V
Depolarized@1A, 2.5V

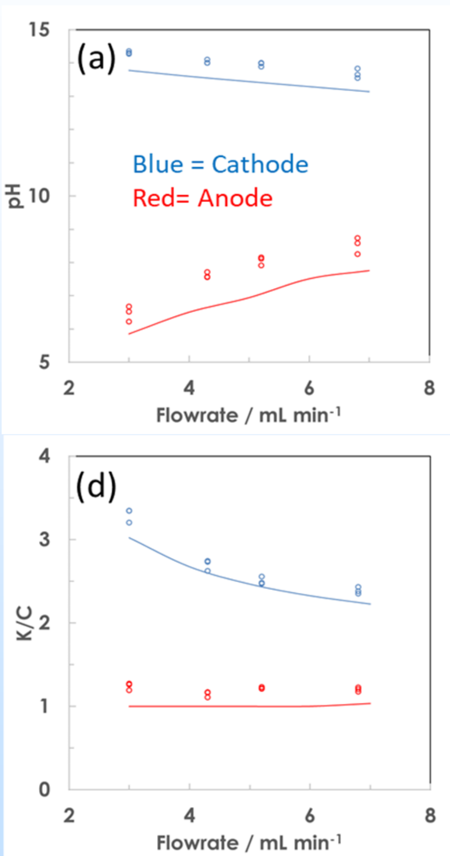


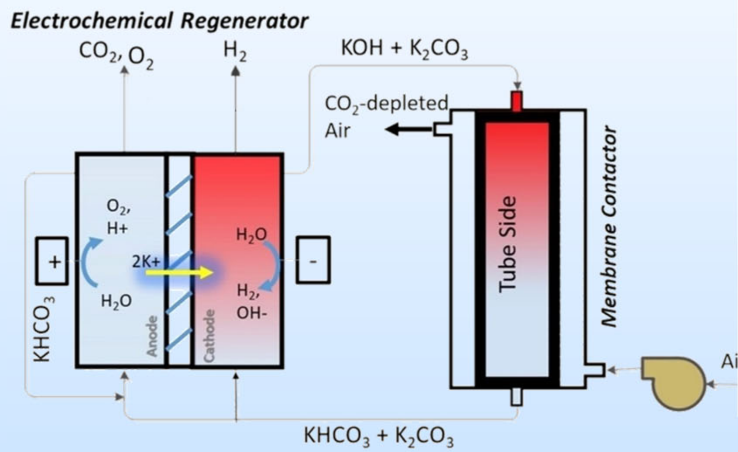


<u>Depolarization suppresses >1 Volts</u>

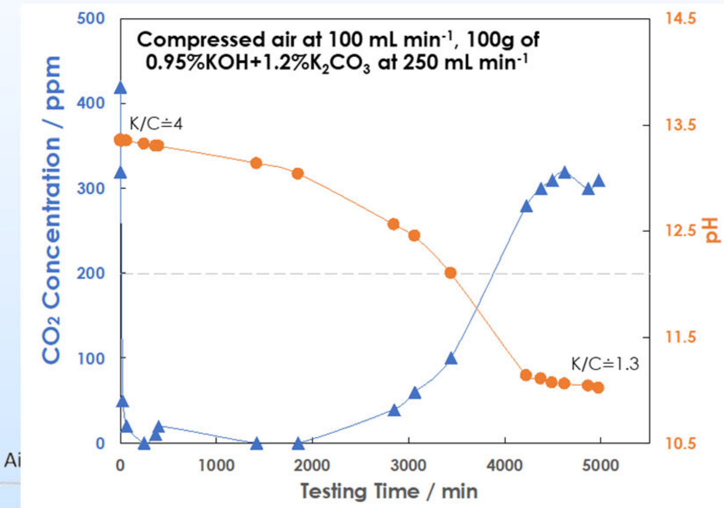
Next Step: Process Integration

Electrochemical Regenerator





Contactor Performance



<u>Matching regenerator and contactor performance for continuous operation including exploring new configurations for more efficient capture</u>

Summary

(1) Depolarized operation is a promising technique to reducing the energy requirement for DAC while simultaneously mitigating the complexities of downstream CO_2 purification.

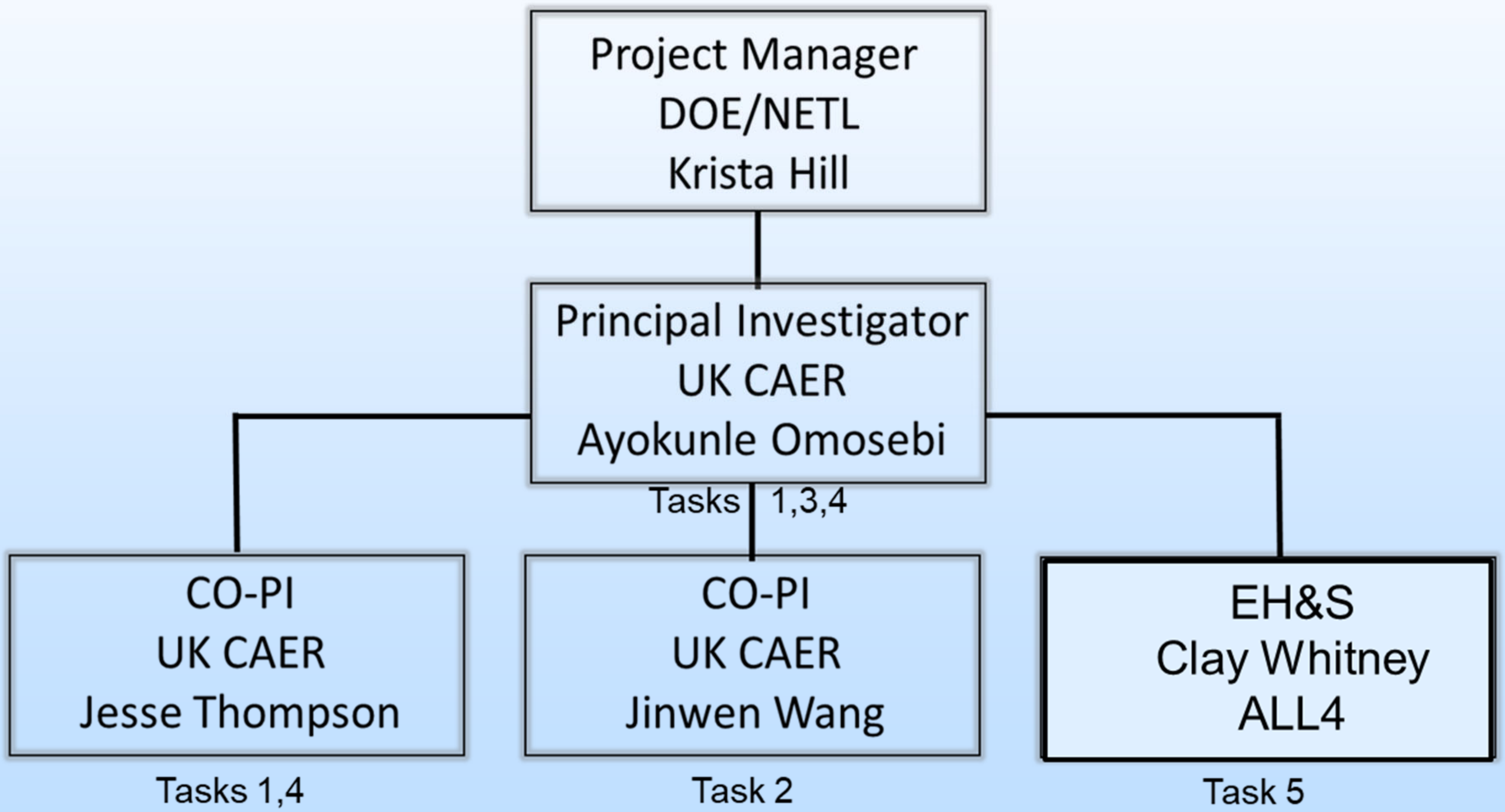
(2) Interim results show the patterned inorganic membrane as a stable and effective contactor for DAC with capture facilitated by K/C >2 solvent

(3) Electrochemical regeneration performance and energy requirement strongly dependent on solvent concentration/speciation, flow rate and current including the interplay of bubble dynamics and their convection

Acknowledgements

- DOE-NETL: Krista Hill
- UK CAER: Lisa Richburg and Kunlei Liu

Appendix - Organization Chart



Appendix - Gantt Chart

	Task Name	Start	End
1	**Project Management and Planning**	10/1/2020	3/30/2022
1.1	Project Management Plan	10/1/2020	3/30/2022
1.2	Initial Technology Maturation Plan	10/1/2020	3/30/2022
2	**Effectiveness of Micropatterned Superhydrophobic Membrane Absorber for DAC**	10/1/2020	7/30/2021
2.1	Procurement, Preparation and Patterning of Membrane Absorber	10/1/2020	12/21/2020
2.2	Superhydrophobic Modification of Micropatterned Membrane Absorber	12/21/2020	2/19/2021
2.3	Installation and Integration of Membrane Absorber	2/19/2021	4/20/2021
2.4	Membrane Absorber Performance Evaluation	4/20/2021	7/30/2021
3	**Development of the Electrochemical Regenerator**	10/1/2020	7/30/2021
3.1	Batch Mode Evaluation of DEC	10/1/2020	1/11/2021
3.2	Potential distribution of DEC	1/11/2021	2/10/2021
3.3	Flow cell design and integration	2/10/2021	4/12/2021
3.4	Performance and stability of continuous DEC	4/12/2021	7/30/2021
4	**Evaluation of EDEMS for DAC**	6/1/2021	3/30/2022
4.1	Development, Integration, and Commissioning of the EDEMS	6/1/2021	8/31/2021
4.2	Parametric Evaluation of the EDEMS	9/1/2021	11/30/2021
4.3	Stability of the EDEMS	12/1/2021	3/30/2022
4.4	Update State Point Data Table	9/1/2021	3/30/2022
5	**Process Design and Environmental, Health and Safety (EH&S) Assessment**	1/1/2022	3/30/2022
5.1	Process Design	1/1/2022	3/30/2022
5.2	EH&S Risk Assessment	1/1/2022	3/30/2022