AIR2**CO2** Contactor: Advanced Integrated Reticular Sorbent-Coated System to Capture CO_2 using an Additively-Manufactured Contactor

DEFE0032126

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Project Overview

$2.0 MM program ($1.5 MM DOE + $0.5 MM GE cost share)

36-month program: 10/1/2021 to 9/30/2024

BP1: 10/1/2021-5/31/2023

BP2: 6/1/2023-9/30/2024

Project Participants:

- GE Vernova Advanced Research
- University of California, Berkeley (BP1 only)
- University of South Alabama (BP1 only)

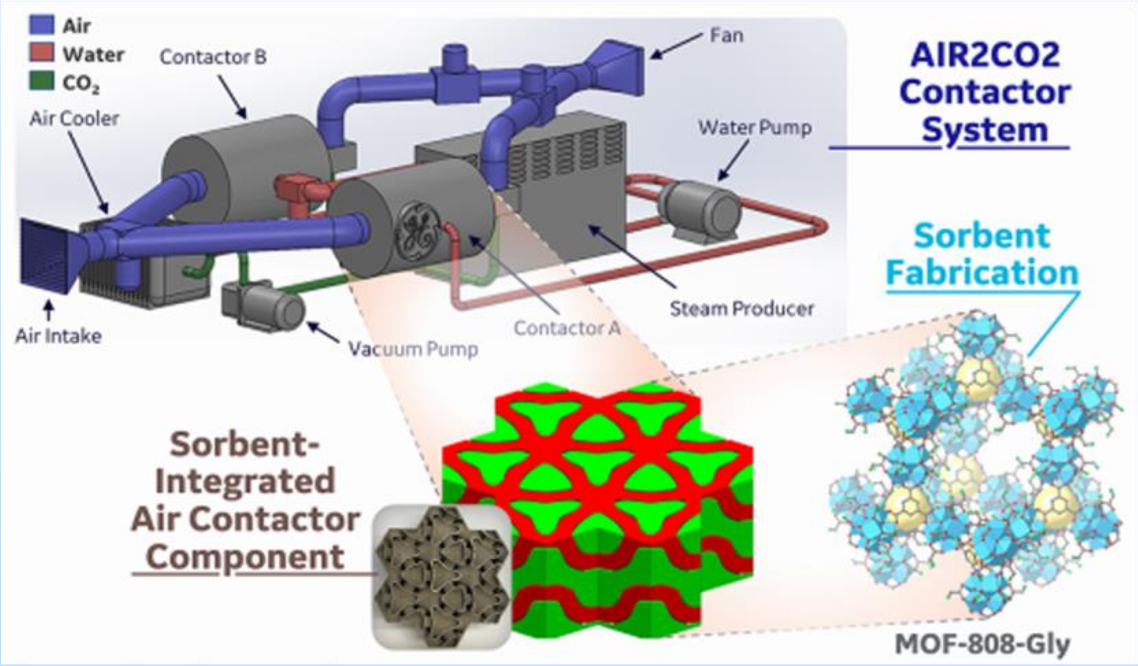
Overall Project Objective:

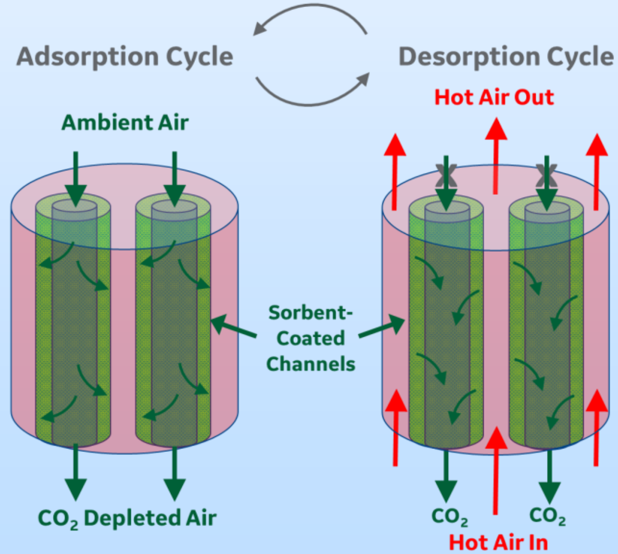
Demonstrate feasibility (TRL3) of a bench-scale, sorbent-integrated system that integrates a low pressure drop, additively-manufactured contactor and an advanced sorbent to capture and release atmospheric CO_2.

Technology Background

AIR2CO2 Contactor relies on integration of three key innovations:

1. Model-directed design and fabrication of an additively-manufactured, two-channel trifurcating air contactor that exhibits low pressure drop and high surface area-to-weight ratios,
2. Modular, scalable, indirect-heated system that enables alternating adsorption and desorption of CO_2, and
3. Tailored reticular sorbent-binder composite that exhibits high capacities, rapid sorption kinetics, and robust cycle performance at low CO_2 concentrations.





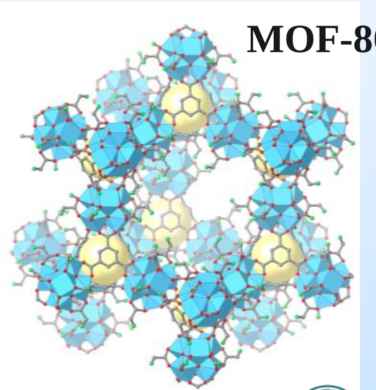
AIR2CO2 Contactor Technical Approach & Key Milestones

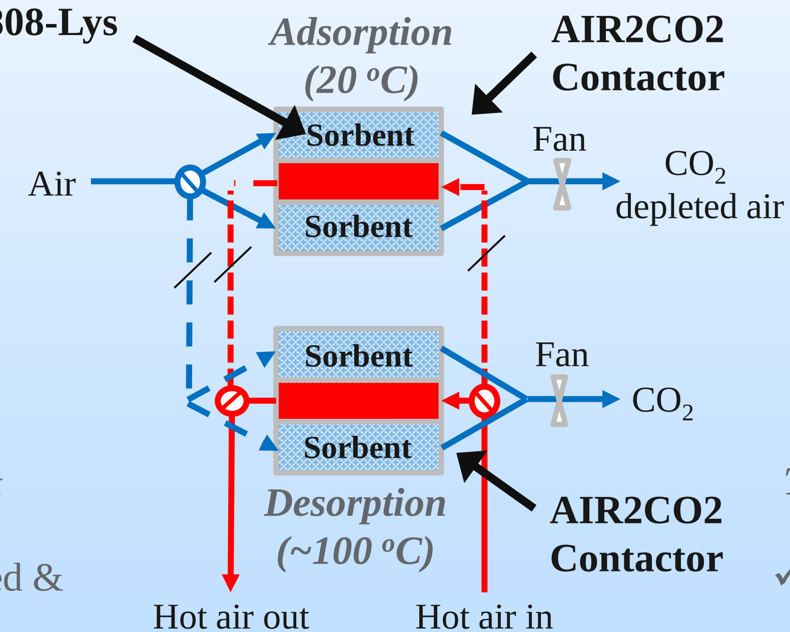
AIR2CO2 Contactor Modeling

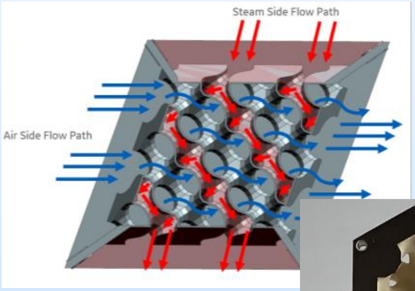
- ✓ AIR2CO2 contactor geometry determined
- ✓ AIR2CO2 engineered system model developed

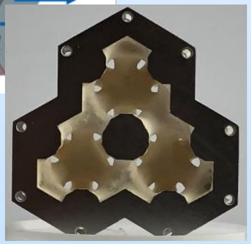
Sorbent Integration into AIR2CO2 Contactor System

- ✓ Low pressure drop AIR2CO2 contactor
- ✓ Sorbent-binder composite on AIR2CO2 Contactor demonstrated (retains >80% sorbent capacity)
- ✓ Bench-scale AIR2CO2 contactor system demo









Sorbent Synthesis & Characterization

- ✓ Sorbent material optimized & downselected
- ✓ GE MOF sorbent fabricated for system integration

Techno-economic & Macroeconomic Analyses

- ✓ AIR2CO2 Contactor capital and operating cost models developed

Project Risks & Mitigation Strategy

Perceived Risk	Mitigation/Response Strategy
Technical/Scope Risks:	
Insufficient **sorbent capacity**, slow CO_2 capture/release **kinetics** & thermal/hydrolytic **instability**	**AIR2CO2 Contactor is sorbent agnostic**… 1) optimize MOF-808-Lys synthesis, contactor surface area & coating thickness to maximize capacity, kinetics & stability; 2) **employ alternative MOF materials.**
Sorbent and contactor scalability	**Evaluate GE & external sorbent materials & engage external supply chain. Explore alternative contactor geometries and materials of construction, leveraging GE experience in fluid contactors.**
System integration challenges: 1) Lack of composite uniformity; 2) Heat management & sorption kinetics/mass transport mismatch lead to high system energetics	Iterate on 1) coating processes, MOF-binder formulations and contactor parameters to optimize adhesion, thickness, and thermal transfer & 2) system modeling and experimental validation with systematic scaling and demonstration to enable robust process design and reduce operational risk
Suboptimal AIR2CO2 contactor design results in **large pressure drops & high steam duty**	**Leverage GE heat exchanger expertise to iteratively balance thermal mass, surface area, wall thickness and hydraulic diameters**
Management, Planning, and Oversight Risks:	
Ineffective selection of sorbent materials, contactor designs & coating processes	Expand TRL3 material selection options & leverage Six Sigma statistical tools and detailed success criteria to downselect and advance technologies
EH&S Risks:	
Potential for sorbent decomposition results in downstream extractables/contaminants	Perform sorbent life cycle studies and analyze possible by-products of side reactions
External Factor Risks:	
Supply chain challenges hinders partnering & supply chain	Proactively work with vendors and sourcing to ensure timely delivery

Sorbent System Testing

Sorbent & Film Properties

Chemical & Structural Analysis

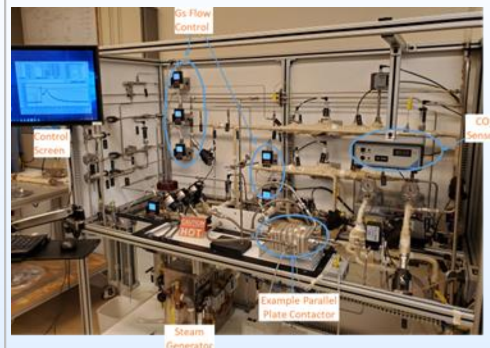
Benchtop XRD System

Surface area analysis

Sorption Properties: Thermodynamics & Kinetics

Structure-property-performance

Dynamic System Performance



<u>CAT-1</u>

- T_{ads} = 5-30°C;
- T_{des} = 100-120°C
- 1-30 SLPM
- <100-1000 mbar
- Up to 80%RH achievable

<u>1 kg CO_2/day DAC Demo</u>

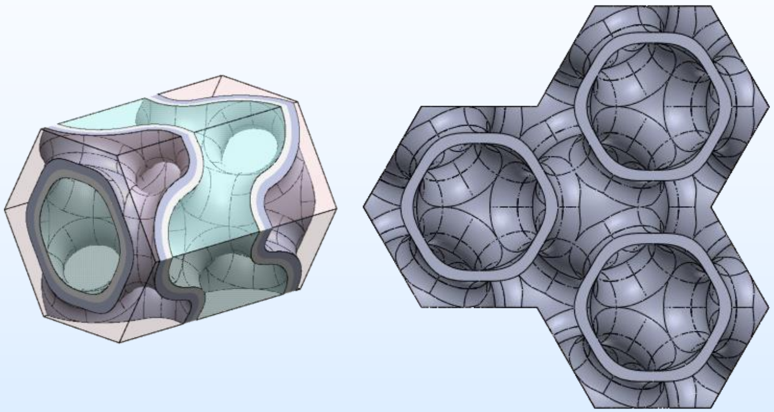
- T_{ads} = 5-30°C;
- T_{des} = 60-125°C
- 2000-9000 SLPM
- <100-1000 mbar
- Up to 80%RH achievable

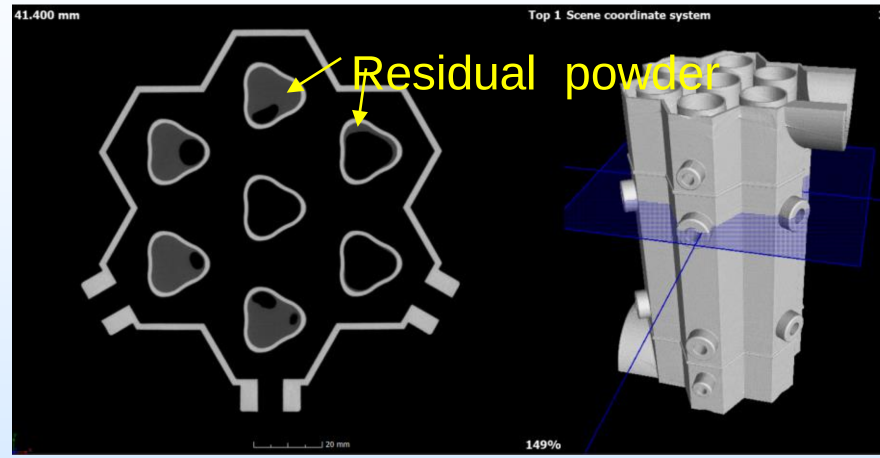
- Fundamental mass transfer understanding informs coated contactor & system process and design
- Component characterization & module testing
- Input data to develop and refine TEA models

System testing and validation

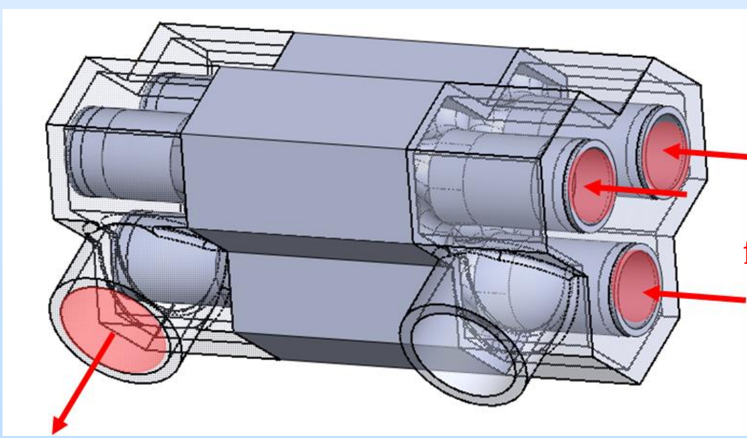
AIR2CO2 Contactor System Geometry Modeling

AIR2CO2 Contactor Additive Design & Fabrication





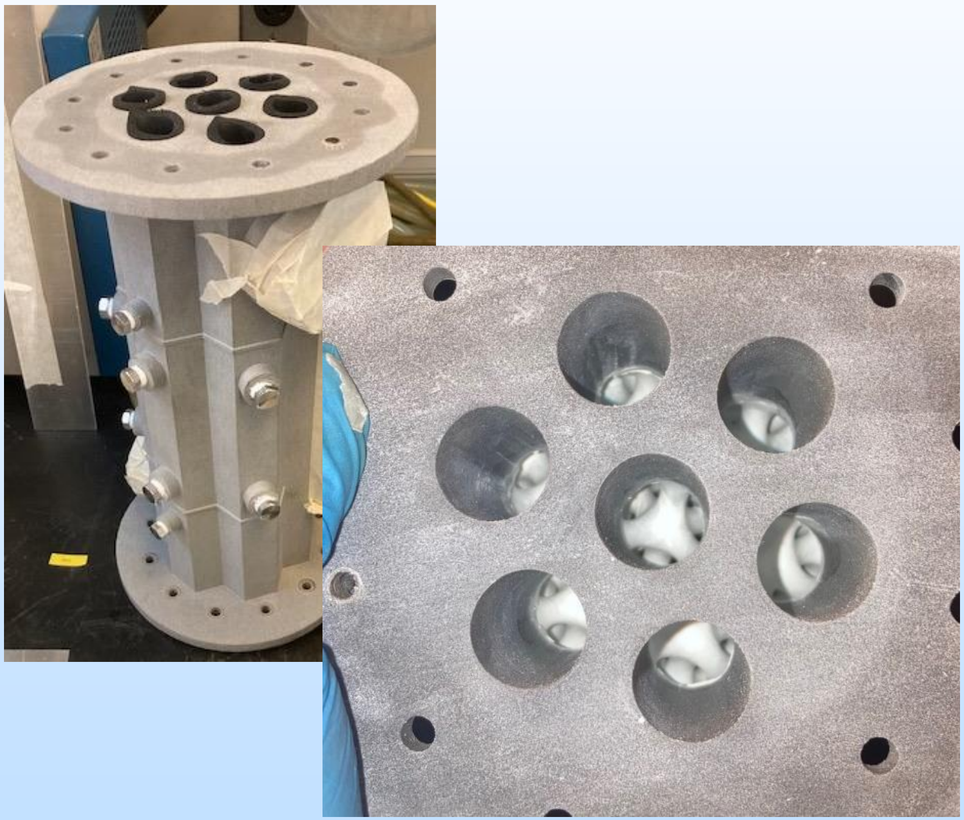
Powder removed from parts to enable two-channel flow



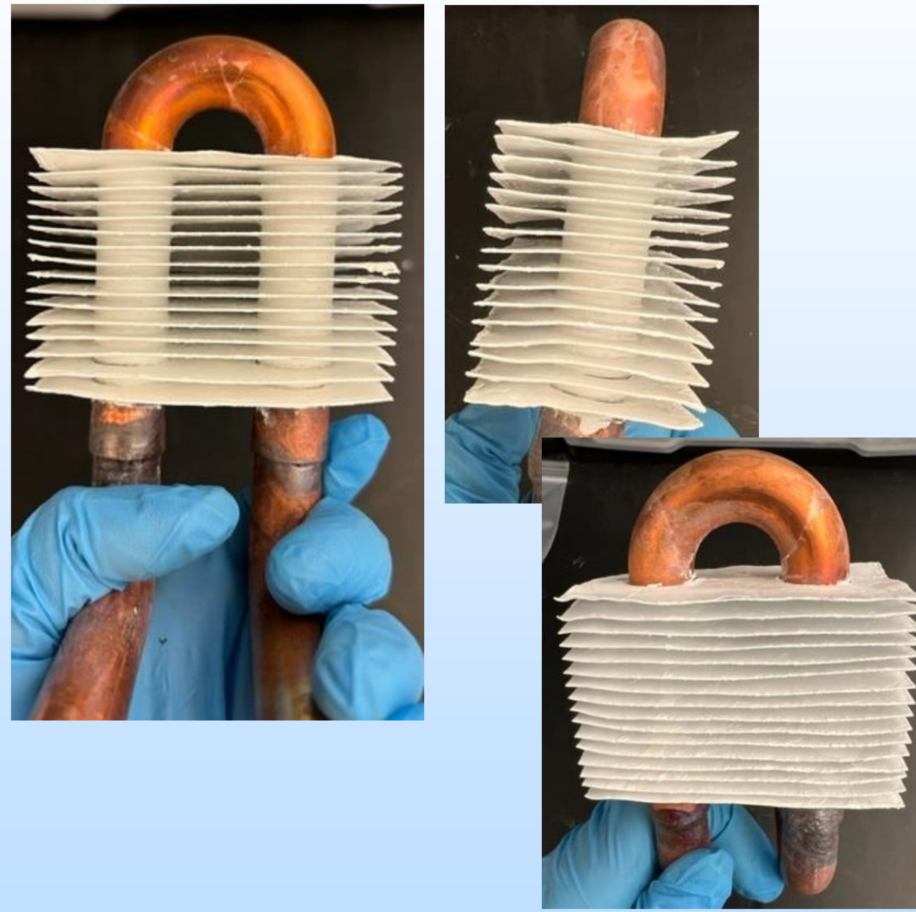
Contactor designs finalized, fabricated, and scaled

Sorbent (GE115) Integration into AIR2CO2 Contactor System

AIR2CO2 Additive Contactor



Fin-in-Tube Contactor

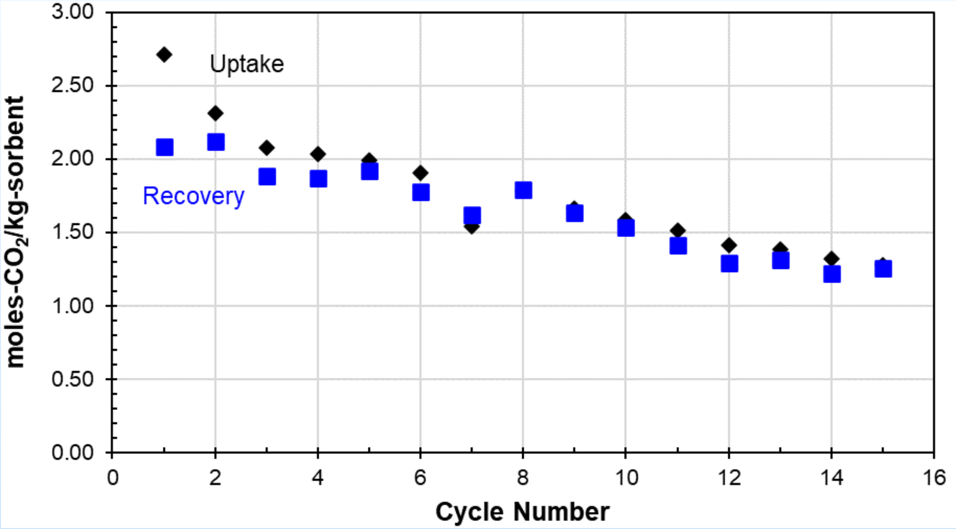


Uniform coatings achieved that retain >80% of the native sorbent capacities

GE115 Cycling Performance… From BP1 to BP2

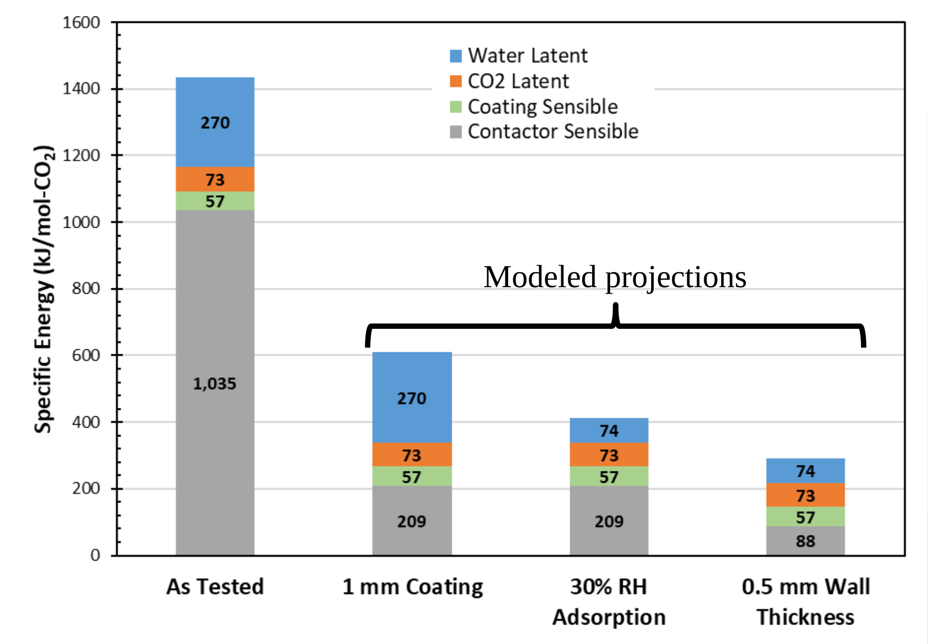
Cycling CO_2 Capacities

Adsorption: DAC, 25 °C, 50% RH, 20 SLPM
Desorption: 120 °C, 1 SLPM N_2 sweep



- 53% capacity drop after 15 cycles
- Employ Gen 2 GE sorbents with improved chemical and thermal stability

AIR2CO2 Contactor Alpha-Prototype Steam Duty

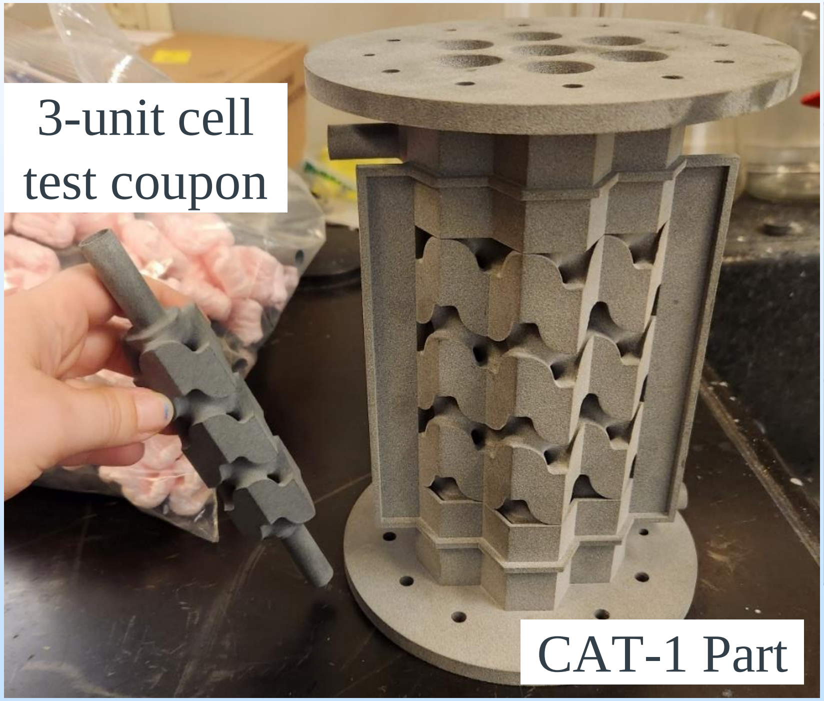


- Maximize coating capacity, kinetics & thickness
- Effectively manage water
- Minimize contactor thermal mass (1.2 mm down to 0.5-1.0 mm)

Driving towards BP2 targets through multi-parameter learnings & optimization

Next Generation Additive Contactor Design & Fabrication

Leak Testing – determine minimum wall thickness without leaking



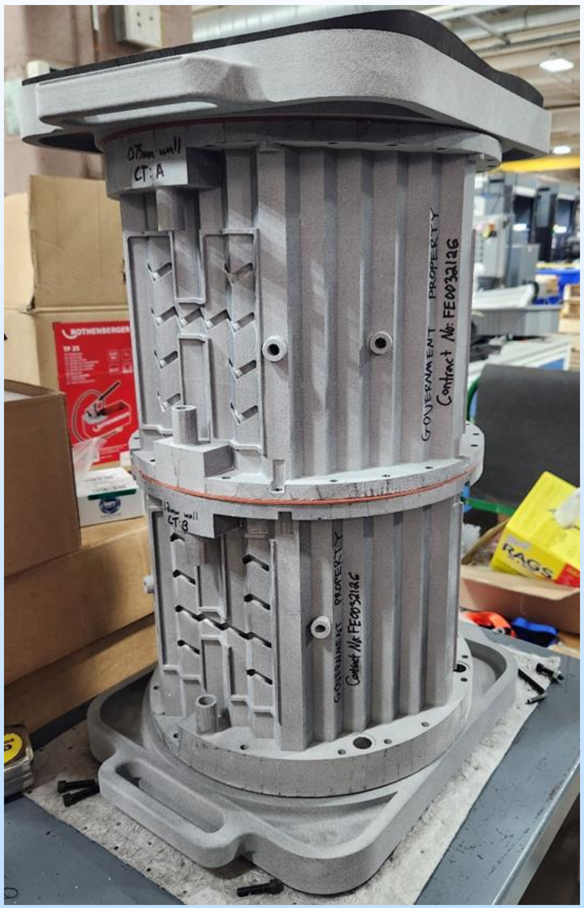
Type	Hydraulic Diameter (mm)	Wall Thickness (mm)	Test Result
3-unit cell test coupons	10	0.50	FAILED
		0.75	PASSED
		1.0	PASSED
		1.2	PASSED
CAT-1 Parts	10	0.75	FAILED
		1.0	**PASSED**
		1.2	**PASSED**

Leak test performed with part submerged in water with nitrogen gas applied at 15 psi.

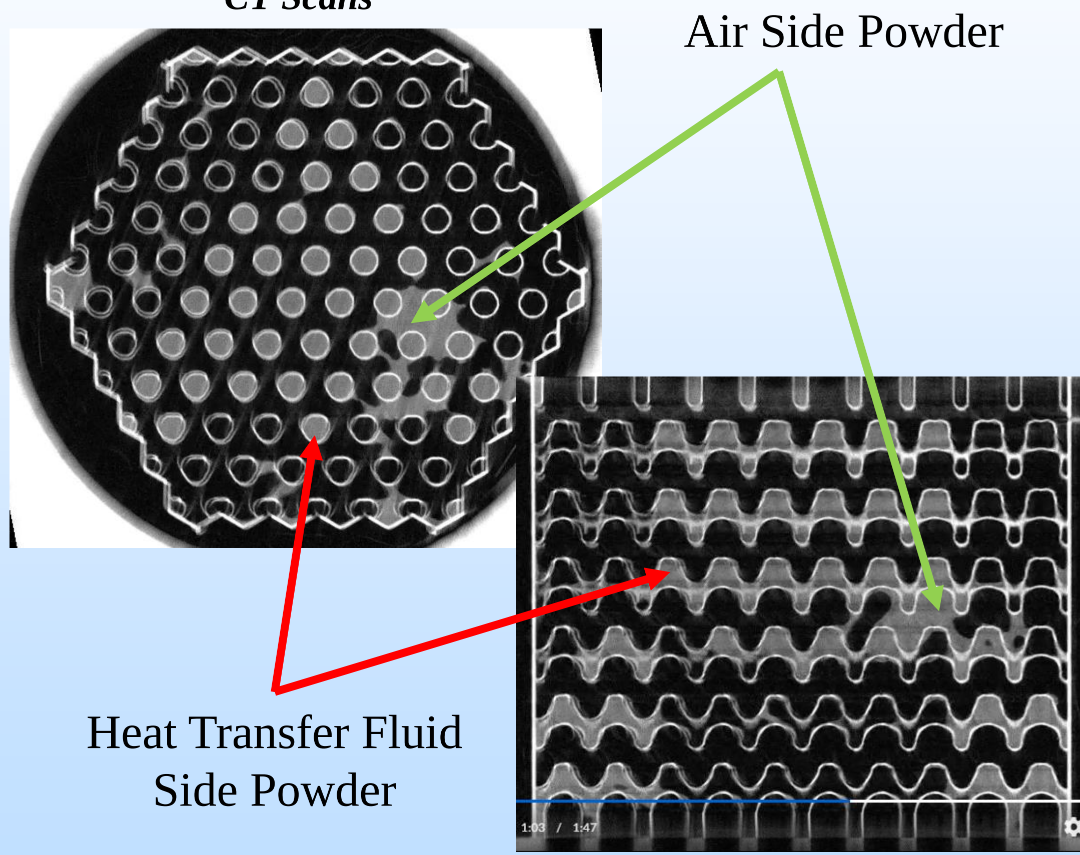
1.0 mm wall thickness passes CAT-1 part leak tests…
AIR2CO2 Contactors fabricated at 1.0- and 1.2-mm wall thicknesses

Next Generation Additive Contactor Depowdering

Depowdering required for free fluid flow… and good heat transfer



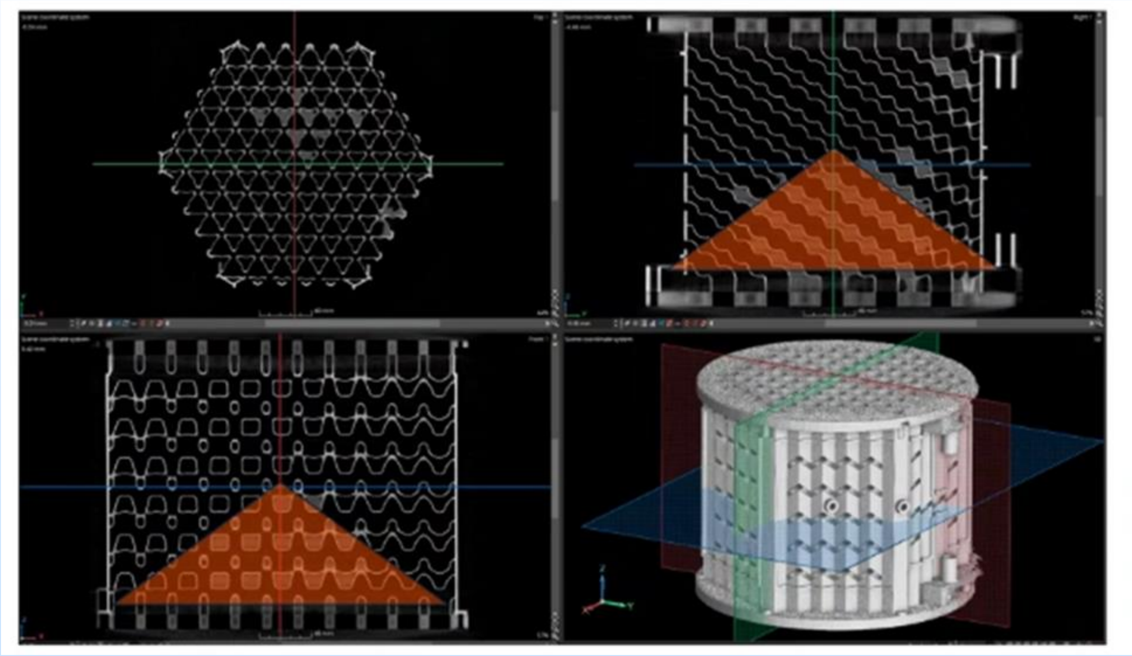
CT Scans

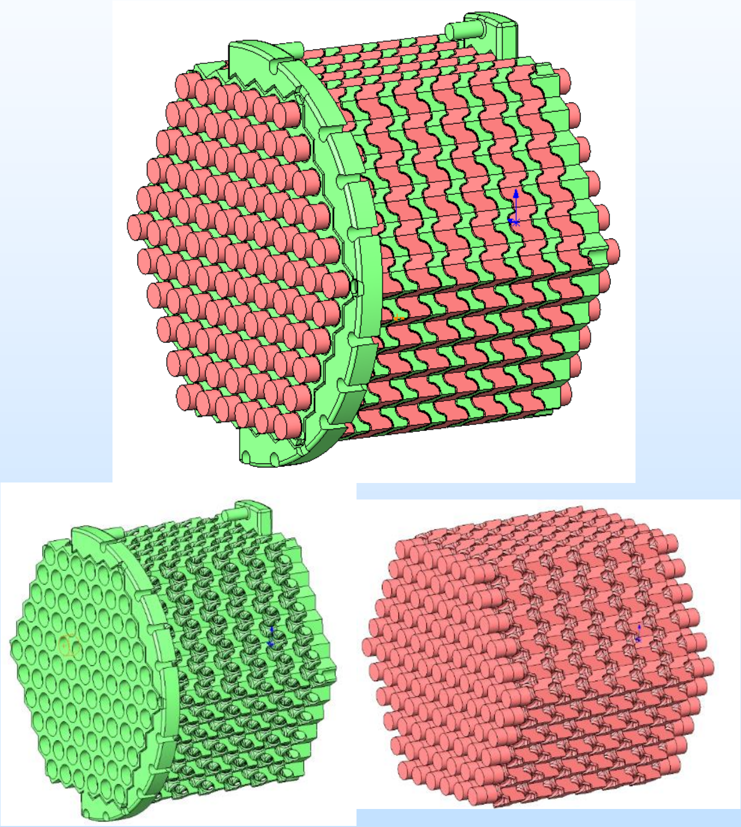


Slight redesign needed to ensure full depowdering & retain fluidic independence

Next Generation Additive Contactor Depowdering

Design drives ease of depowdering

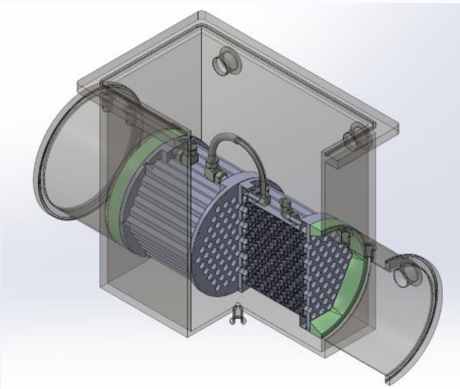


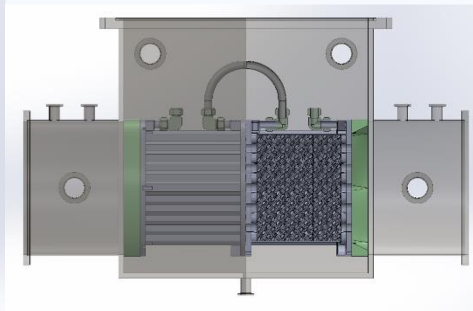


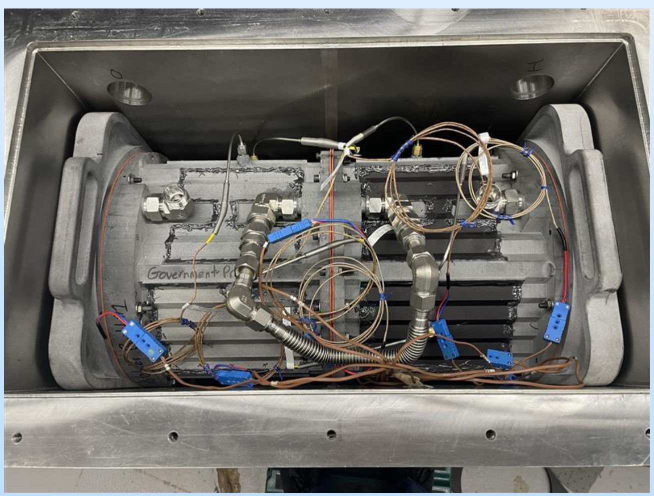
Slight redesign needed to ensure full depowdering & retain fluidic independence

Next Generation Additive Contactor Design & Fabrication

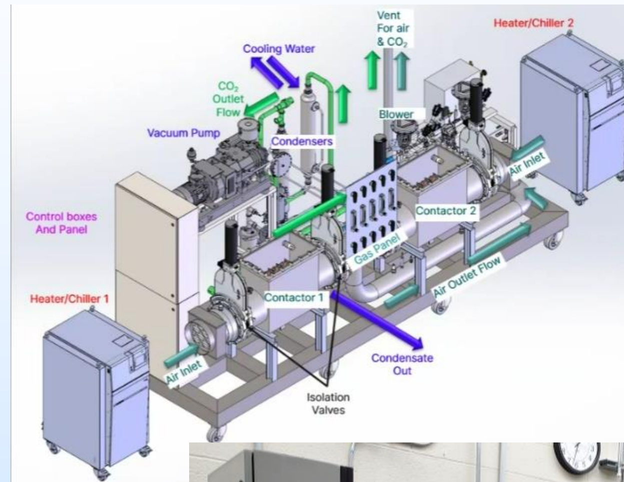
AIR2CO2 Contactor Additive Design

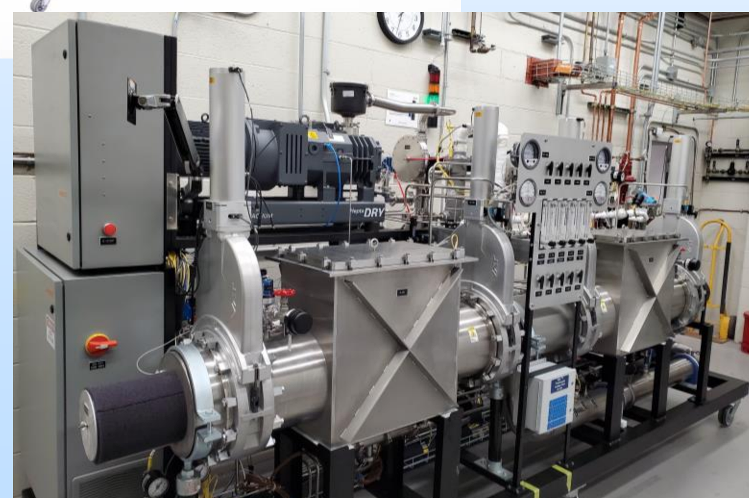






1 kg CO_2/day DAC Demo

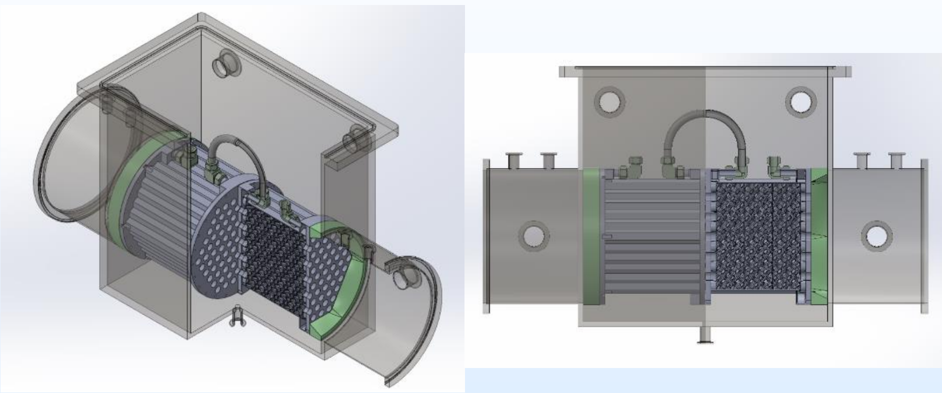




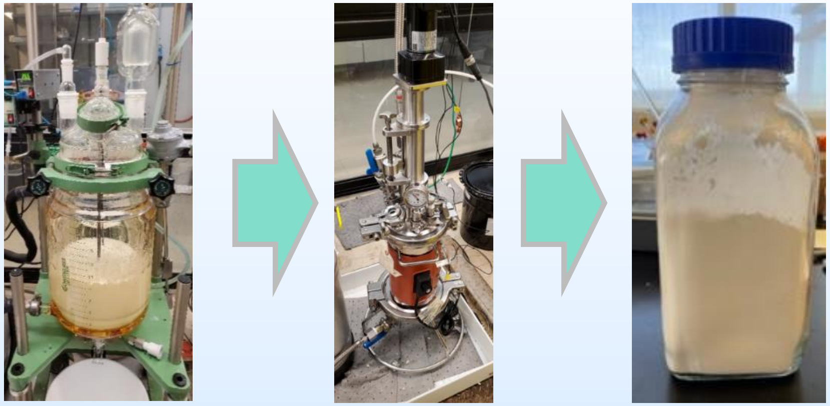
AIR2CO2 Contactors fabricated at 1.0- and 1.2-mm wall thickness & integrated into the 1 kg CO_2/day DAC Demo

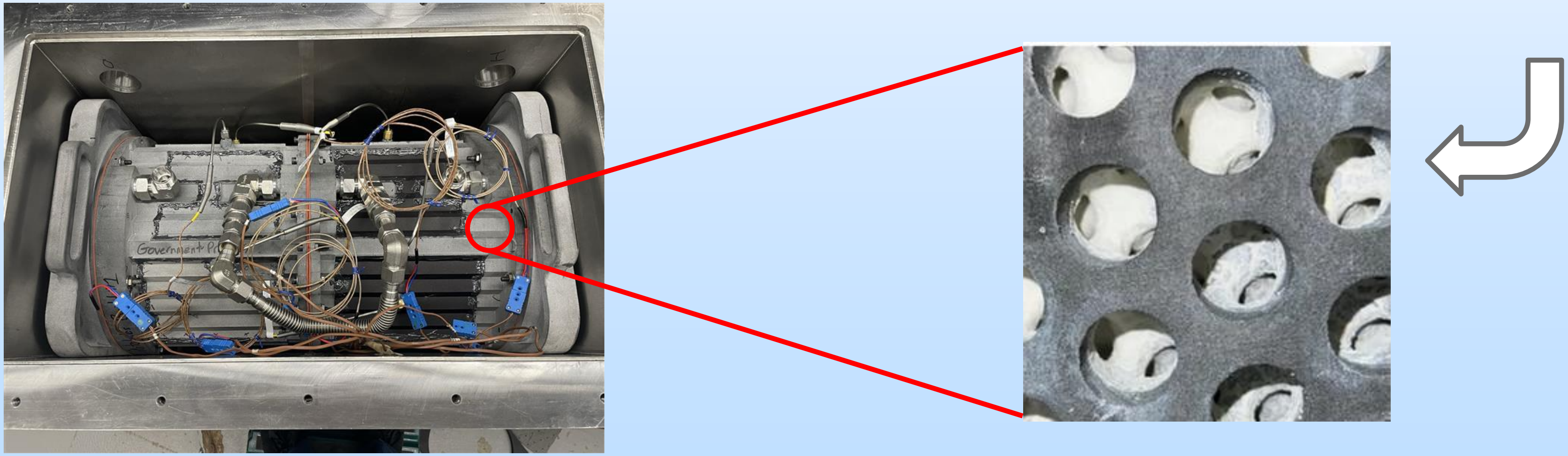
Gen 2 Sorbent (GE292) Integration into AIR2CO2 Contactor System

AIR2CO2 Contactor Additive Design



GE Gen 2 MOF Scale-up & Coating



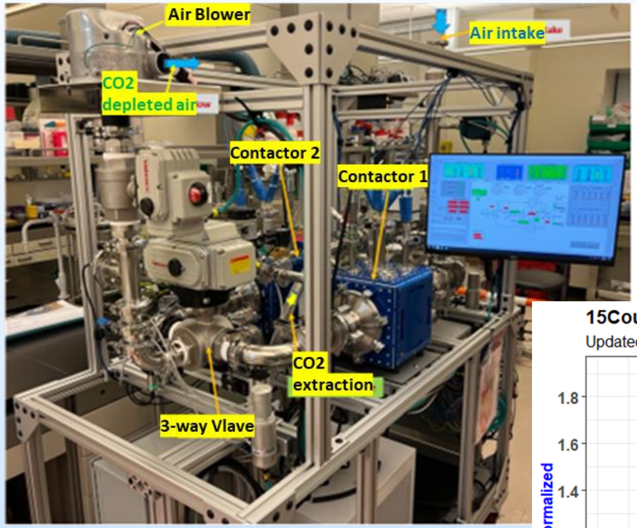


Robust coatings achieved that retain >90% of the native sorbent capacities

Gen 2 Sorbent (GE292) Cyclability

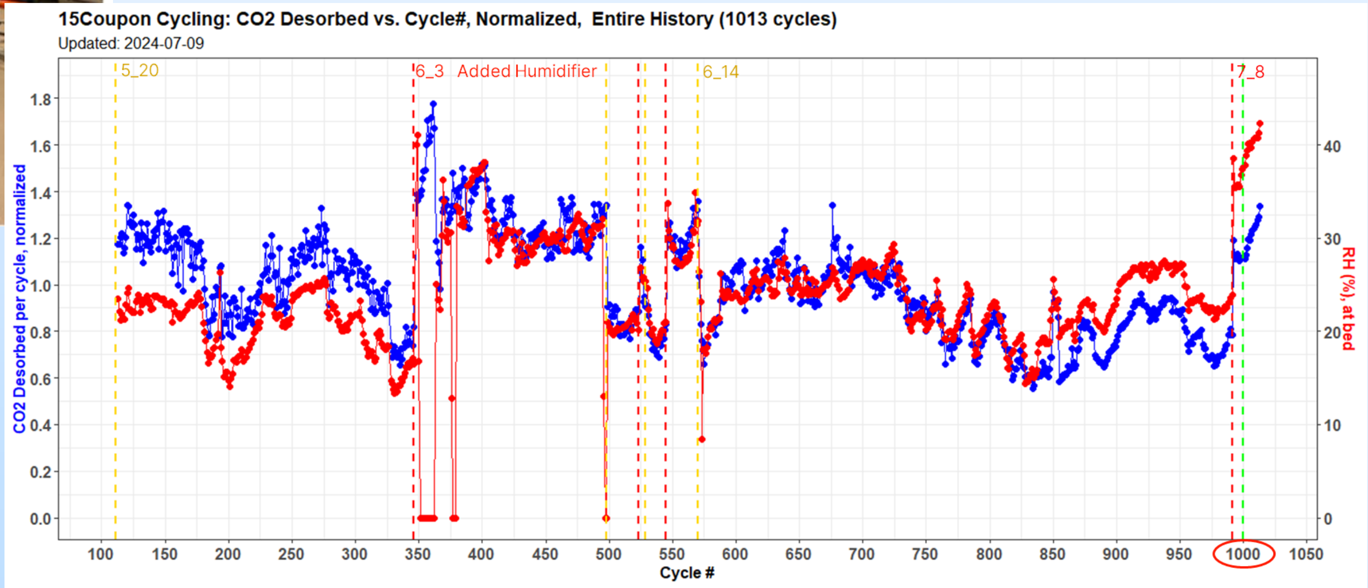
Leveraging government partnerships to accelerate technology development

DAC-EMP Rig



- Cycling Conditions: (30min adsorption ambient air) + [15min @120°C under vac (<100mBar) +15min N_2 purge cooling]
- Uptake =f[RH(%)] applied for RH-response correction before normalization

- Integrated System for Electromicrobial Production of Butanol from Air-Captured CO_2
- ARPA-E Award No. DE-FOA-00002459
- Equipment transferred to AIR2CO2 Contactor project

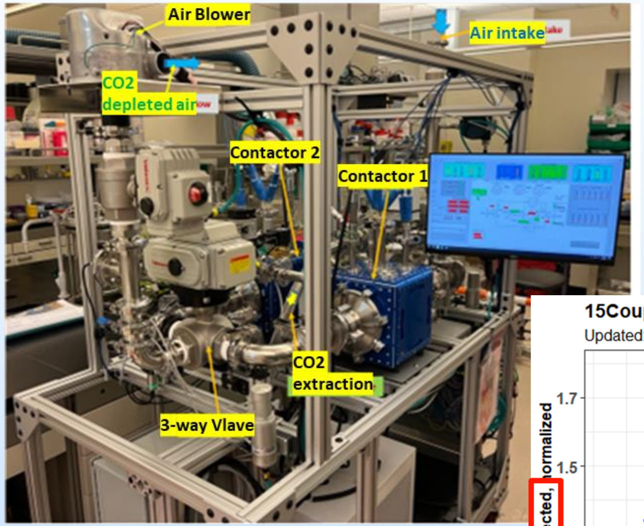


CO_2 cycling performance mirrors ambient relative humidity

Gen 2 Sorbent (GE292) Cyclability

Leveraging government partnerships to accelerate technology development

DAC-EMP Rig



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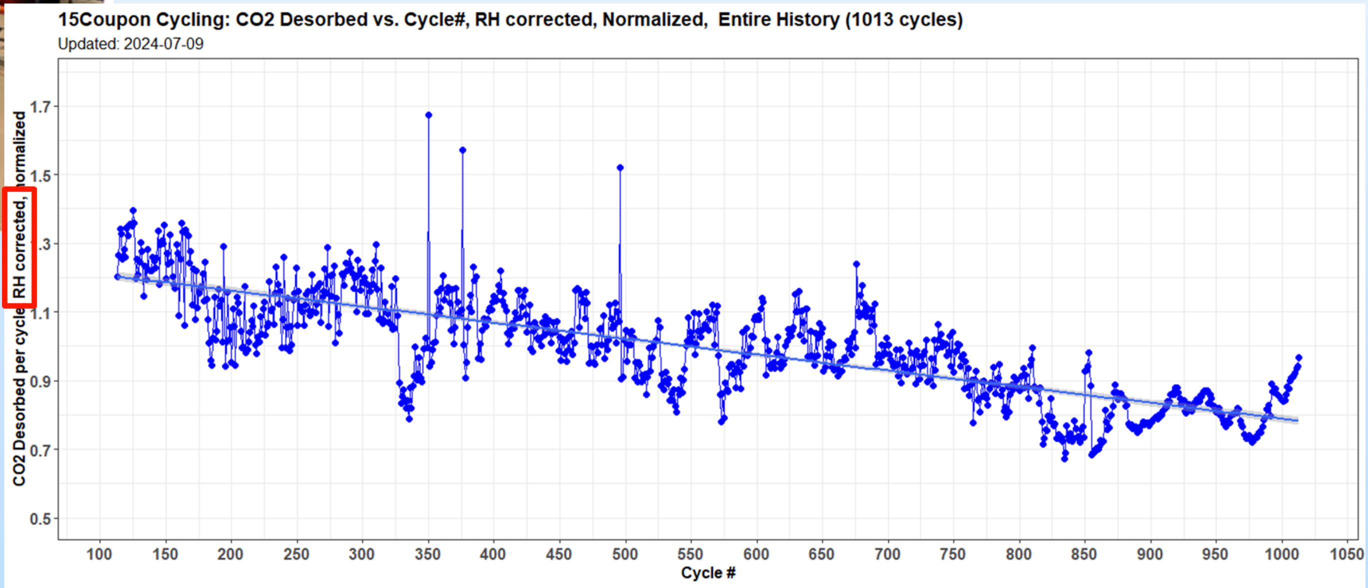


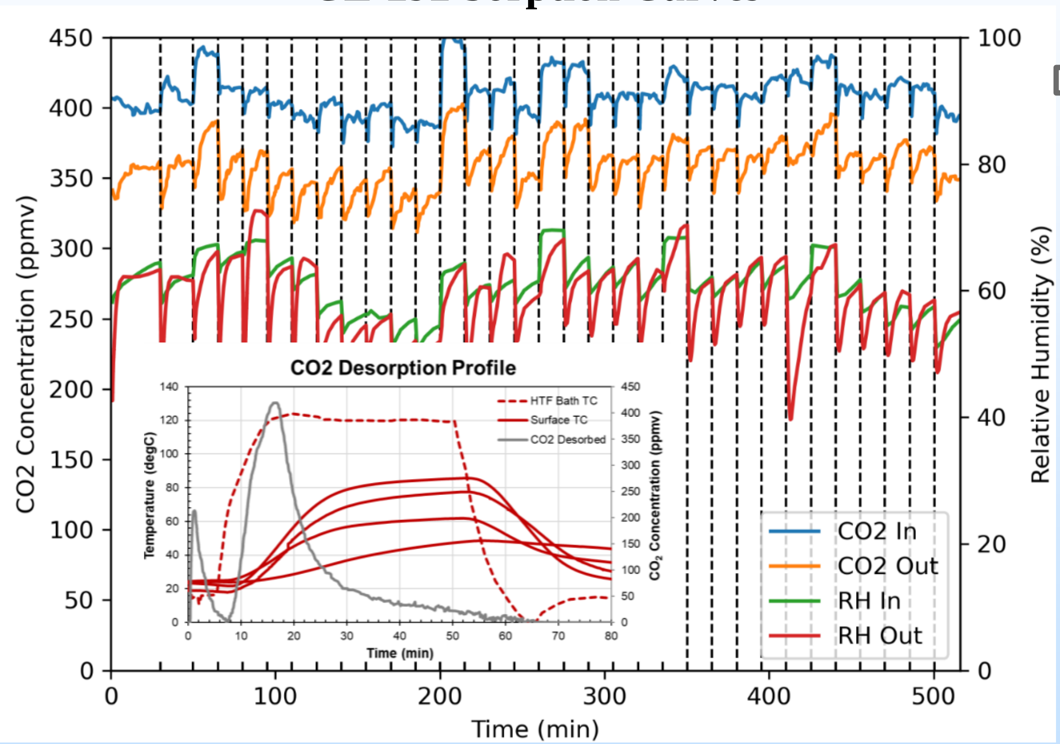
- Integrated System for Electromicrobial Production of Butanol from Air-Captured CO_2
- ARPA-E Award No. DE-FOA-00002459
- Equipment transferred to AIR2CO2 Contactor

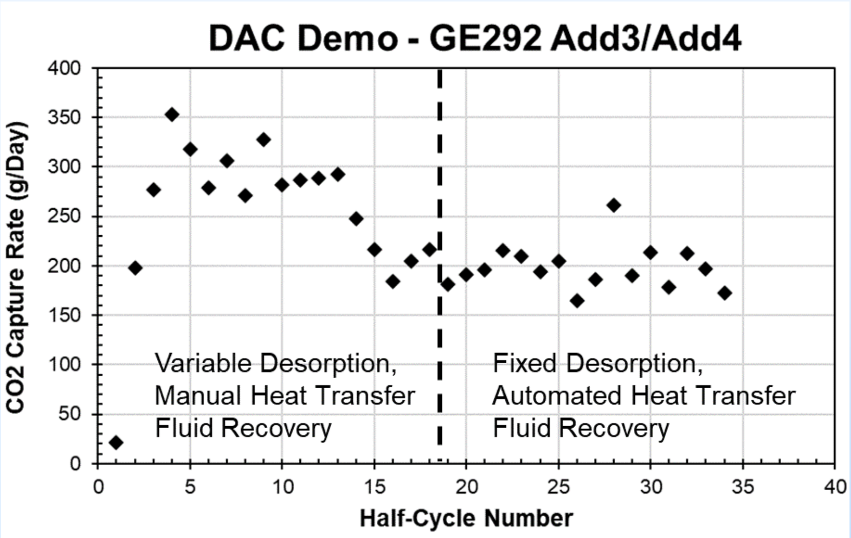
0.04% decay rate observed over >1000 cycles

AIR2CO2 Contactor: Summary of Coated Parts Testing

Adsorption-Desorption Cycling in the 1 kg CO_2/day DAC Demo Rig

GE-292 Sorption Curves





Adsorption: 400-450 ppmv CO_2, 22 °C, 50-70% RH, 5000 SLPM
Desorption: 85 °C (max internal), 100 SLPM N_2 sweep

Cycling of GE292-coated AIR2CO2 Contactors ongoing

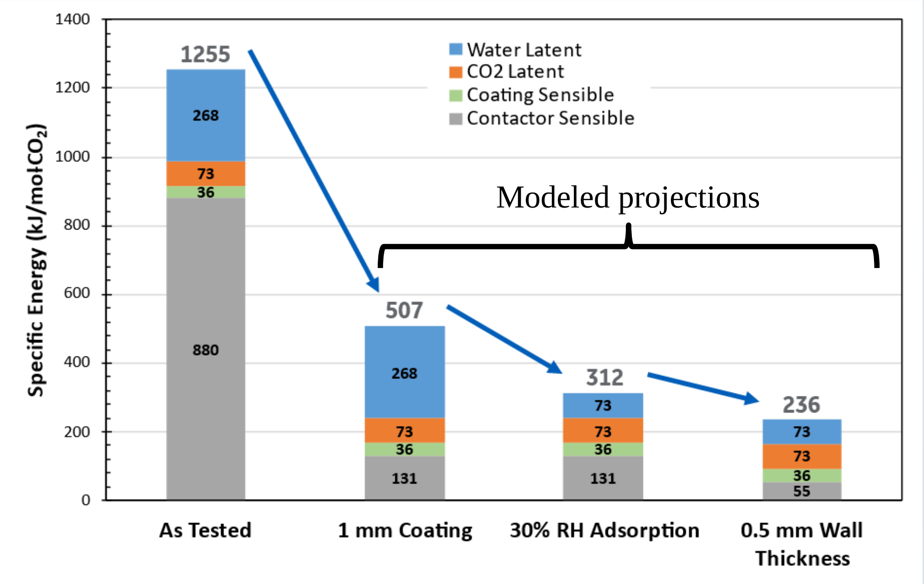
Progress Against Success Criteria

Parameters	BP1: GE115	BP2: GE292	BP1 Target	Project Target
CO2 Capture Efficiency %	67.5[1]	13.2[1]	50	70
Space Velocity, Hr-1	80,043	257,130	50,000	150,000
Pressure Drop, Pa	235[2]	235[2]	500	150
Capacity Fade/Cycle %/cycle	3.52	0.04	0.005	0.0001
Steam Duty, kJ/mol CO2	1435	1255	275	172
Overall Volumetric Productivity (gmol CO2/ hr V(l))	0.44[1]	0.26[1]	1	2
Overall Gravimetric Productivity (g-CO2/ hr g-Sorbent)	0.056[1]	0.063[1]	-	-

[1] Efficiency and productivity values taken at 15 minutes

[2] Pressure drop extrapolated to 1 tonne-CO_2/day system with 0.3 m length in flow direction

Steam Duty

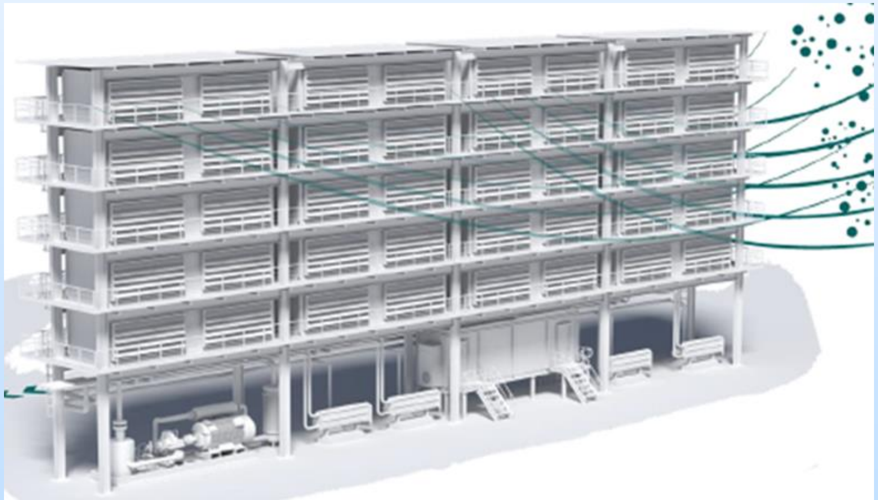


- Employ Gen 2 GE sorbents with improved chemical and thermal stability
- Improve coating capacity
- More effectively manage water
- Minimize contactor thermal mass… additive leakage rates required thicker walls, which hindered heat transfer

Driving towards BP2 targets through multi-parameter learnings & optimization

Plans for future testing/development/ commercialization

a. AIR2CO2 Contactor: conclude adsorption-desorption bench-scale proof-of-concept testing of coated, additively-printed parts; refine techno-economics and life cycle analysis
b. Post-AIR2CO2 Contactor: 10 tonne CO_2/year demonstration
c. Scale-up potential: Demonstration scale with full size contactor. Supply chain development – sorbent scale-up, contactor fabrication, sorbent-binder formulation & coating



AIR2CO2 Contactor Summary

Sorbent & System Performance Achieved:

1. Sorbent-agnostic contactor design achieved low pressure drop targets
2. Coating formulations demonstrate >80% of native sorbent sorption performance and excellent adhesion to additively-printed contactors
3. Modeling and experimental validation shown across length scales… kinetics & mass transfer understanding enables robust AIR2CO2 Contactor process design, reduces operational risk and informs techno-economic analyses (capital and operating models)

Significant accomplishments & future activities:

- ✓ Climate Action @ GE (CAGE) lab-scale dynamic testing and Prototype Development Lab (PDL) established. Modular 1 kg CO_2/day system designed and constructed.
- ✓ Next generation sorbent architectures and advanced coating formulations enable high capacity, robust coated coupons and contactors
- ✓ Additively-manufactured, two-channel trifurcating air contactor geometry with low thermal mass determined through iterative model-directed design, fabrication & testing
- ✓ Indirect-heated AIR2CO2 Contactor engineered system design finalized and alpha-prototype demonstrated
- ✓ Modular, scalable, sorbent-coated AIR2CO2 Contactor designed, fabricated, and tested on 1 kg CO_2/day engineered prototype system

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Marissa Dannible

Jake Dean
Alex Sapone
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Prof. T. Grant Glover
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Appendix

Organization Chart

<u>GE Research</u> – contactor design & fabrication, coating development, system modelling, fabrication & performance testing


Dr. David Moore, PI


Dr. William Gerstler


Dr. Mark Doherty


Dr. Donald Whisenhunt


Ms. Dana Capitano


Ms. Hannah Bower


Mr. Steven Barone


Dr. Jenny Ardelean

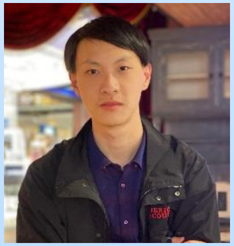

Mr. Travis O'Neil


Mr. Marcus LaPorte

<u>UC Berkeley</u> – sorbent development & characterization, powder performance testing


Prof. Omar Yaghi
Co-PI


Mr. Oscar Chen


Mr. Haozhe Li


Dr. Chuanshuai Li

<u>Univ. S. Alabama</u> – system modelling, CO_2 sorption kinetics measurements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Co-PI


Mr. Thomas
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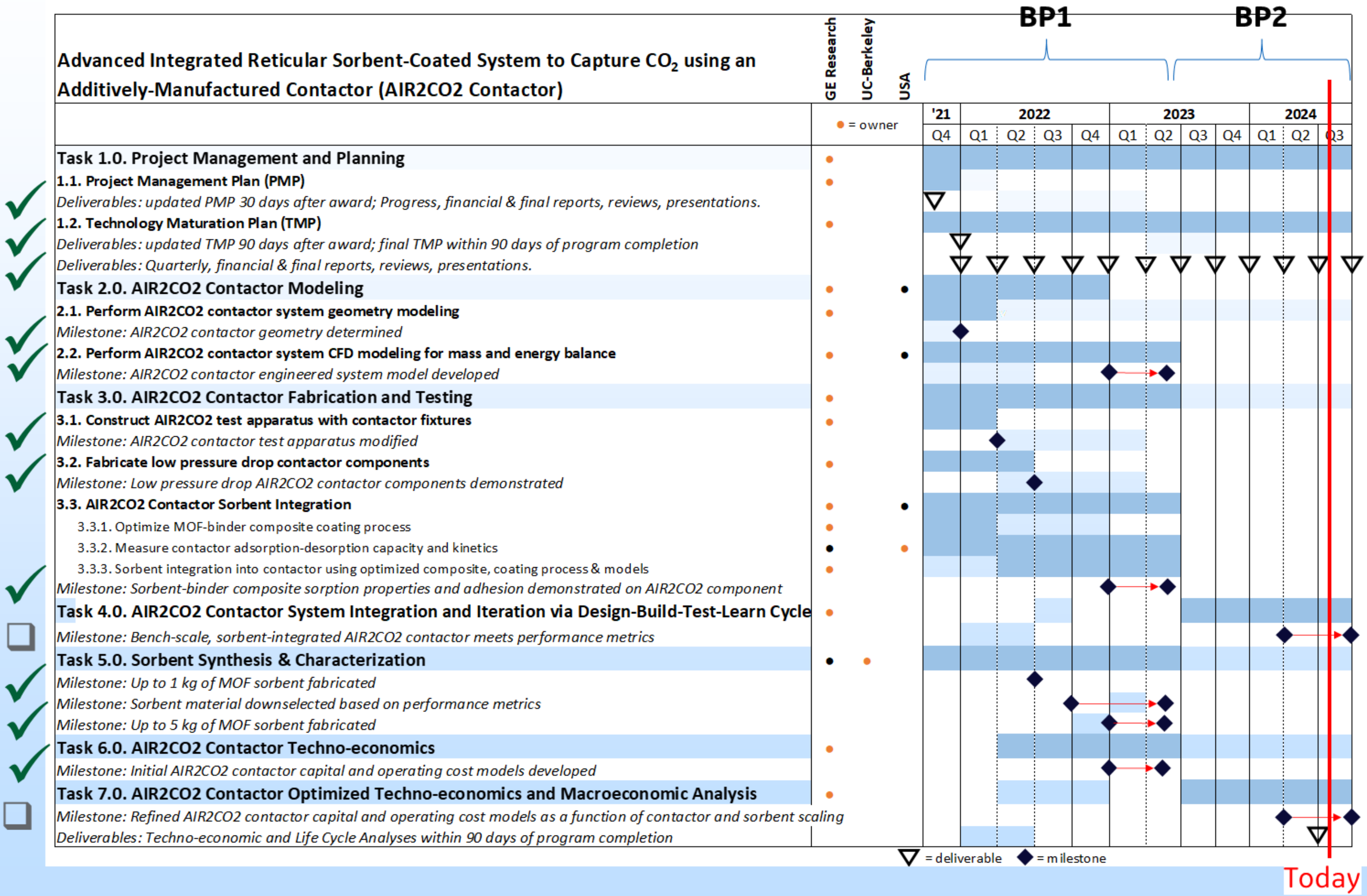
Gantt Chart


BP1
BP2
Advanced Integrated Reticular Sorbent-Coated System to Capture CO_2 using an Additively-Manufactured Contactor (AIR2CO2 Contactor)
GE Research
UC-Berkeley
USA
● = owner
'21
2022
2023
2024
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Task 1.0. Project Management and Planning
1.1. Project Management Plan (PMP)
Deliverables: updated PMP 30 days after award; Progress, financial & final reports, reviews, presentations.
1.2. Technology Maturation Plan (TMP)
Deliverables: updated TMP 90 days after award; final TMP within 90 days of program completion
Deliverables: Quarterly, financial & final reports, reviews, presentations.
Task 2.0. AIR2CO2 Contactor Modeling
2.1. Perform AIR2CO2 contactor system geometry modeling
Milestone: AIR2CO2 contactor geometry determined
2.2. Perform AIR2CO2 contactor system CFD modeling for mass and energy balance
Milestone: AIR2CO2 contactor engineered system model developed
Task 3.0. AIR2CO2 Contactor Fabrication and Testing
3.1. Construct AIR2CO2 test apparatus with contactor fixtures
Milestone: AIR2CO2 contactor test apparatus modified
3.2. Fabricate low pressure drop contactor components
Milestone: Low pressure drop AIR2CO2 contactor components demonstrated
3.3. AIR2CO2 Contactor Sorbent Integration
3.3.1. Optimize MOF-binder composite coating process
3.3.2. Measure contactor adsorption-desorption capacity and kinetics
3.3.3. Sorbent integration into contactor using optimized composite, coating process & models
Milestone: Sorbent-binder composite sorption properties and adhesion demonstrated on AIR2CO2 component
Task 4.0. AIR2CO2 Contactor System Integration and Iteration via Design-Build-Test-Learn Cycle
Milestone: Bench-scale, sorbent-integrated AIR2CO2 contactor meets performance metrics
Task 5.0. Sorbent Synthesis & Characterization
Milestone: Up to 1 kg of MOF sorbent fabricated
Milestone: Sorbent material downselected based on performance metrics
Milestone: Up to 5 kg of MOF sorbent fabricated
Task 6.0. AIR2CO2 Contactor Techno-economics
Milestone: Initial AIR2CO2 contactor capital and operating cost models developed
Task 7.0. AIR2CO2 Contactor Optimized Techno-economics and Macroeconomic Analysis
Milestone: Refined AIR2CO2 contactor capital and operating cost models as a function of contactor and sorbent scaling
Deliverables: Techno-economic and Life Cycle Analyses within 90 days of program completion
▽ = deliverable
◆ = milestone
Today