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

DEFE0032126

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GE Vernova Advanced Research

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Project Overview

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

30-month program: 10/1/2021 to 3/30/2024

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

BP2: 6/1/2023-3/30/2024

Project Participants:

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

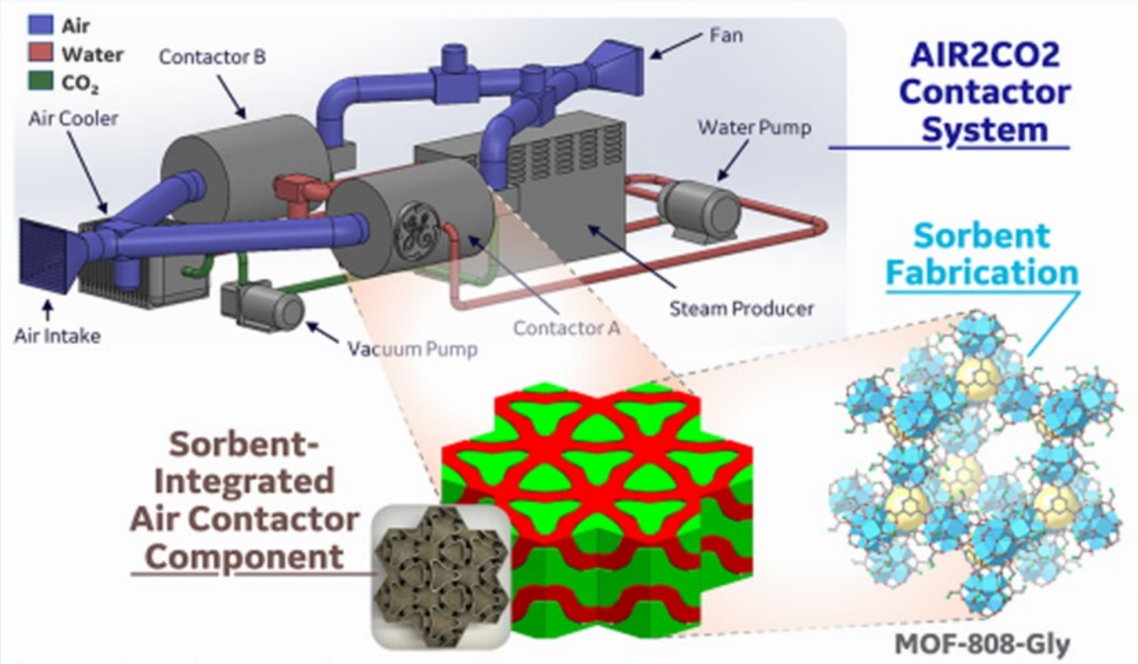
Overall Project Objective:

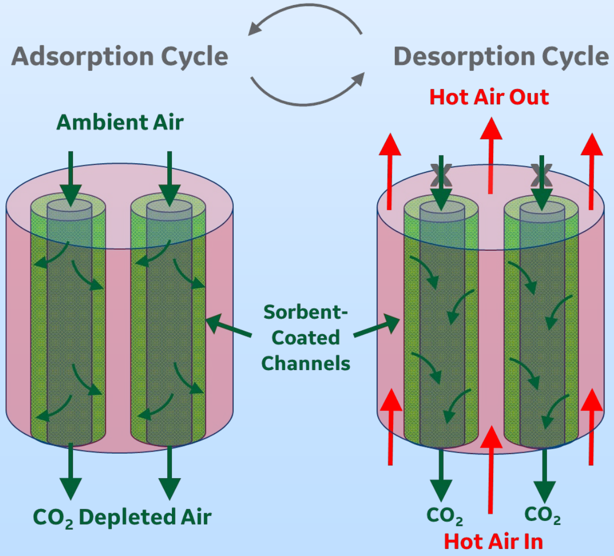
Demonstrate feasibility (TRL3) of a bench-scale, sorbent-integrated system that integrates a low pressure drop, additively-manufactured contactor and an advanced sorbent to capture and release atmospheric CO_2.

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.





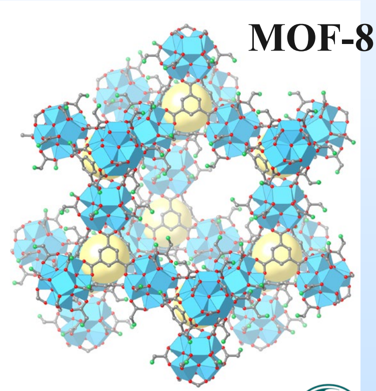
AIR2CO2 Contactor Technical Approach & Key Milestones

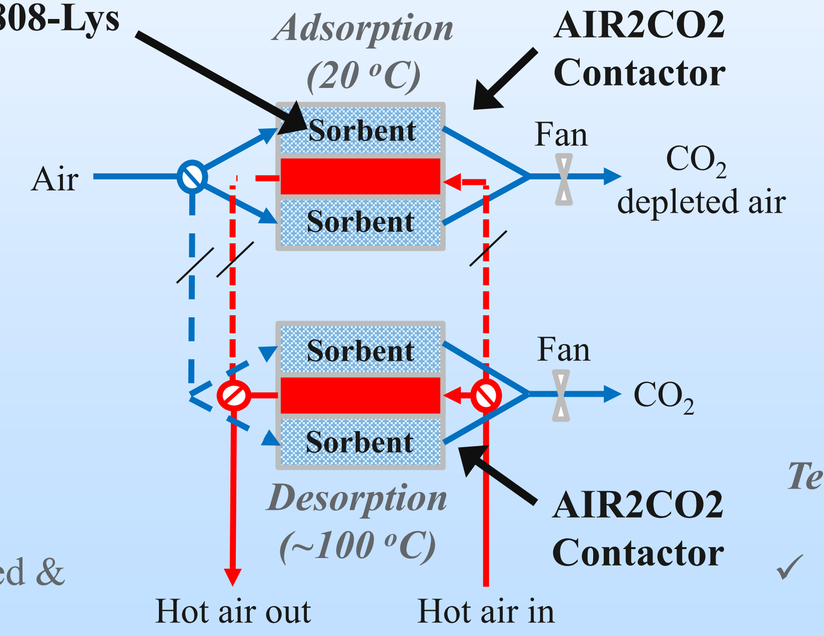
AIR2CO2 Contactor Modeling

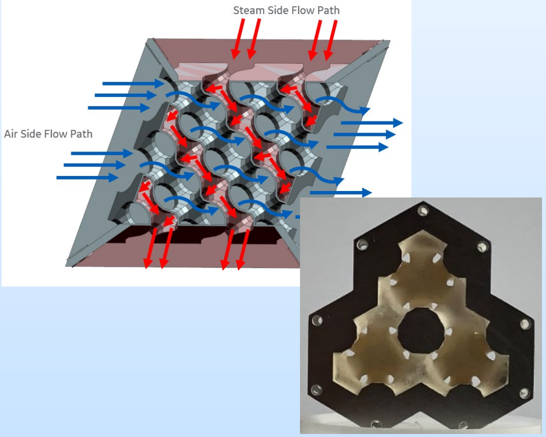
- ✓ AIR2CO2 contactor geometry determined
- ✓ AIR2CO2 engineered system model developed

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 (currently under construction)







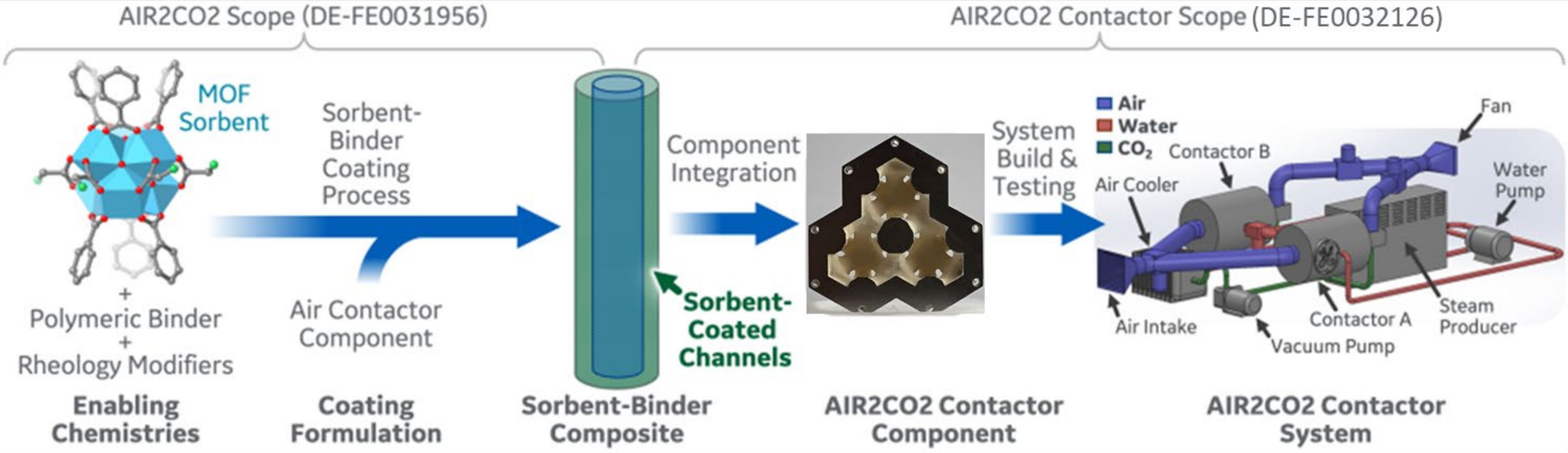
Sorbent Synthesis & Characterization

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

Techno-economic & Macroeconomic Analyses

- ✓ AIR2CO2 Contactor capital and operating cost models developed

AIR2CO2 Contactor System Integration & Success Criteria



AIR2CO2 Scope (DE-FE0031956)

AIR2CO2 Contactor Scope (DE-FE0032126)

MOF Sorbent

\+ Polymeric Binder + Rheology Modifiers

Sorbent-Binder Coating Process

Air Contactor Component

Component Integration

Sorbent-Coated Channels

System Build & Testing

Enabling Chemistries

Coating Formulation

Sorbent-Binder Composite

AIR2CO2 Contactor Component

AIR2CO2 Contactor System

KEY PARAMETERS:

CO_2 Sorption Capacity, CO_2 Sorption Kinetics

Solids Loading, Slurry Stability & Viscosity

Thickness, Adhesion, Porosity, Structural Integrity

Pressure Drop, CO_2 Sorption Capacity, CO_2 Sorption Kinetics, Sorbent System Stability and Lifetime

Success Criteria:

Parameters	BP1 Target	Project Target
CO_2 Capture Efficiency, %	50	70
Space Velocity, hr^{-1}	50,000	150,000
Pressure Drop, Pa	500	150
Capacity Fade/Cycle, %/cycle	0.005	0.0001
Steam Duty, kJ/mol CO_2	275	172
Overall Volumetric Productivity $(gmol_{CO2}/(hr^* V_L)$	1	2

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 Additive and GE Aviation heat exchanger expertise to iteratively balance 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

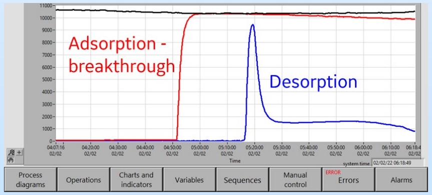
Sorbent System Testing

Sorbent & Film Properties

Chemical & Structural Analysis

Benchtop XRD System

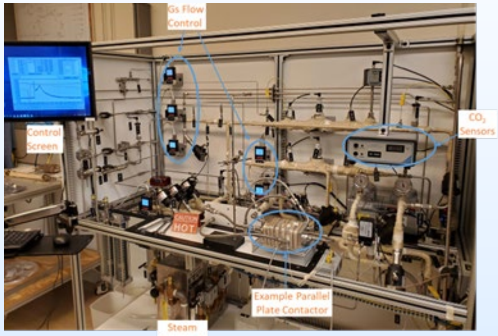
Surface area analysis



Sorption Properties: Thermodynamics & Kinetics

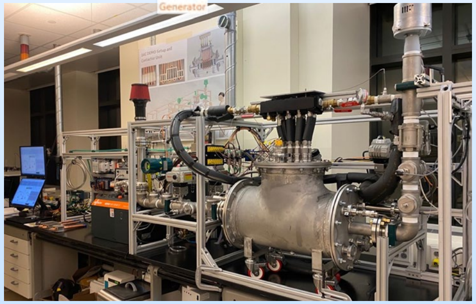
Structure-property-performance

Dynamic System Performance



CAT-1

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



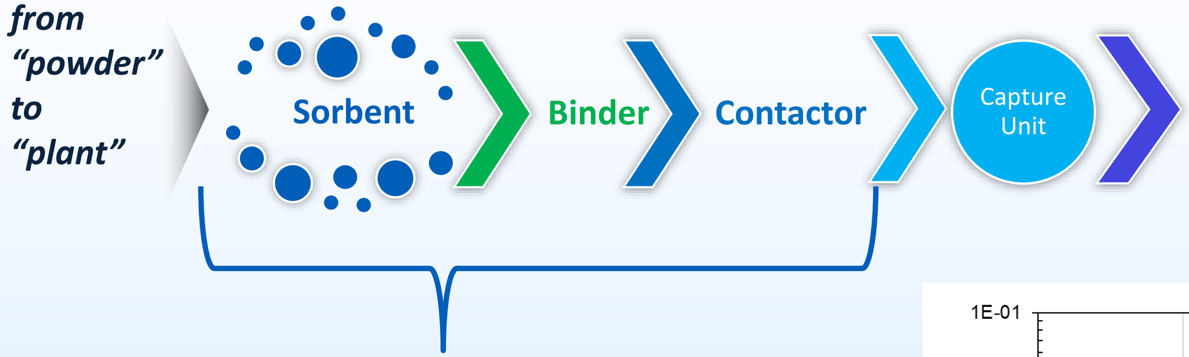
DAC Prototype Rig

- T_{ads} = 5-30°C;
- T_{des} = 100-120°C
- 20-1200 SLPM
- 25-1000 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

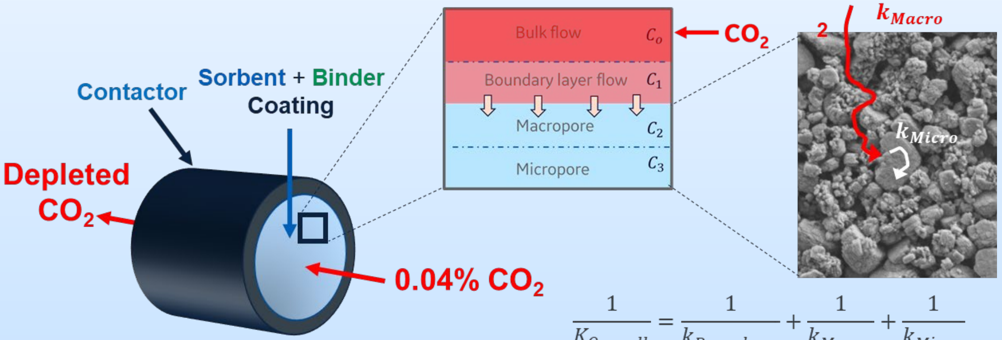
Dynamic Sorbent System Testing



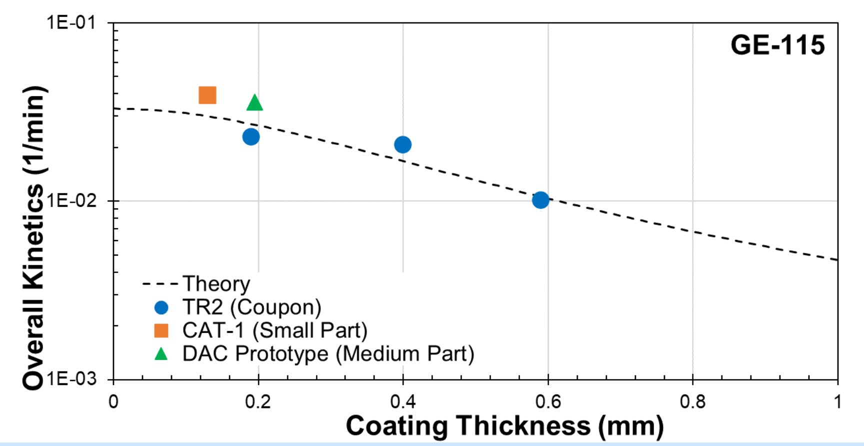
DAC Plant Performance

- CAPEX
- OPEX
- Efficiency

Mass Transfer Resistances



$$\frac{1}{K_{Overall}} = \frac{1}{k_{Boundary}} + \frac{1}{k_{Macro}} + \frac{1}{k_{Micro}}$$



How quickly CO_2 saturates the sorbent

$$\boldsymbol{R_{AC}} \equiv \frac{pL\rho_s T_s N_0 \boldsymbol{K_{Overall}}}{A_f V C_0} = \frac{Adsorption\ Rate}{Convection\ Rate}$$

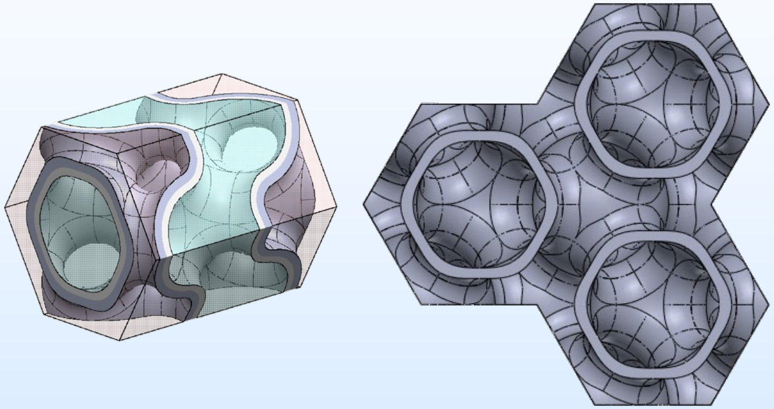
Process Design

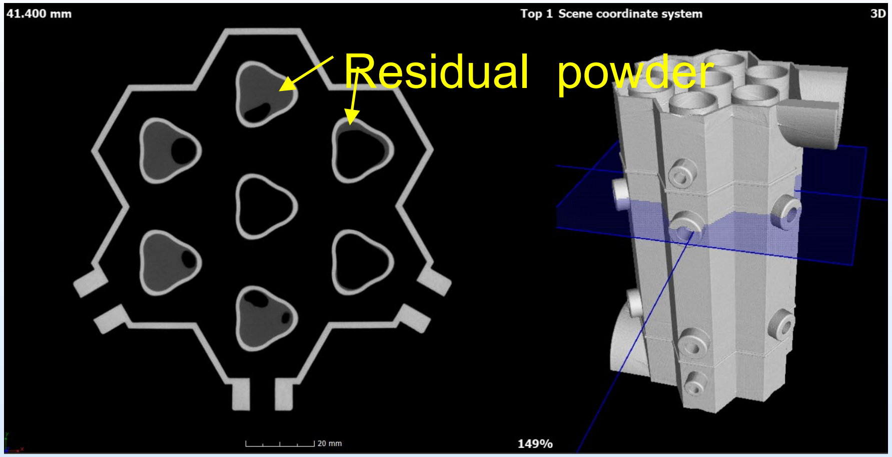
- Capture Unit Design & Scalability
- System Process Development

Kinetics & mass transfer understanding enables robust process design and reduces operational risk

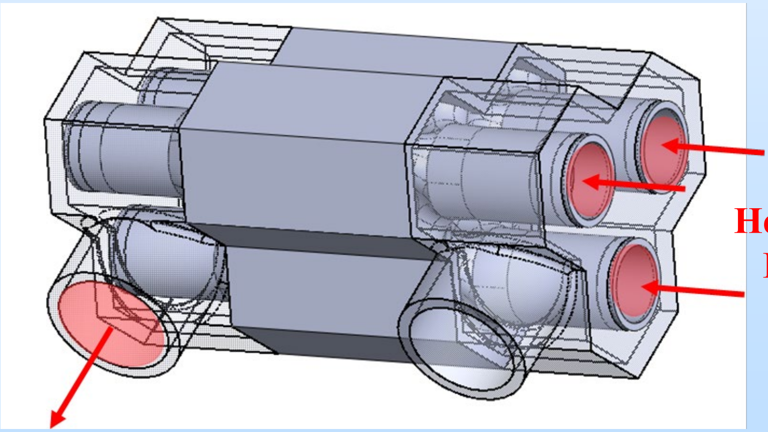
AIR2CO2 Contactor System Geometry Modeling

AIR2CO2 Contactor Additive Design & Fabrication





Powder removed from parts to enable two-channel flow



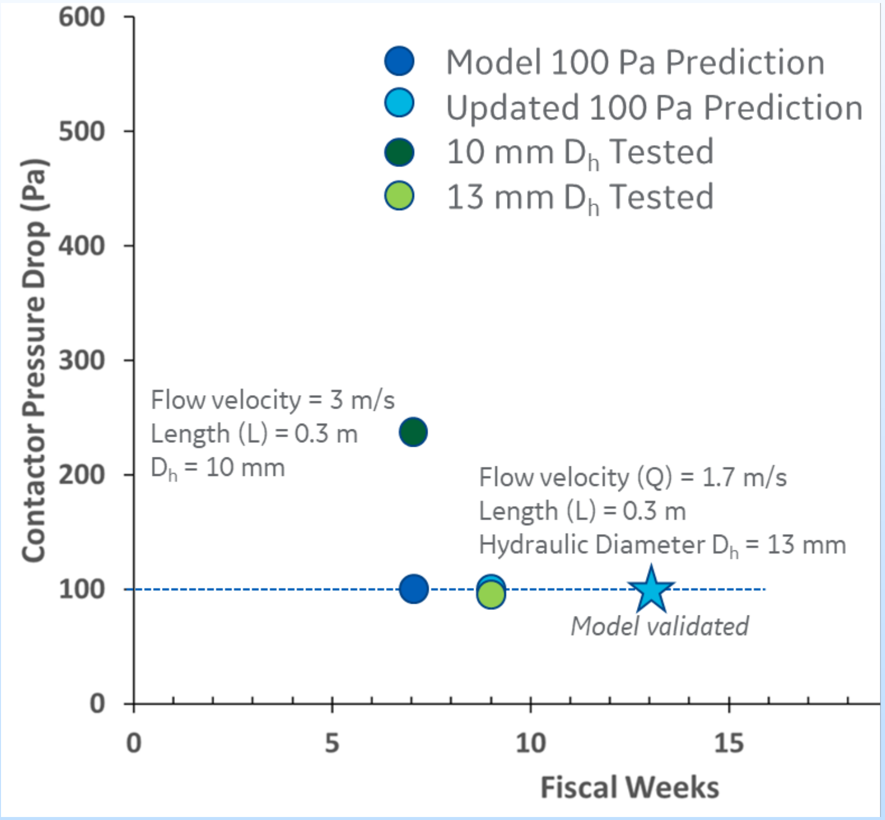
Steam or Heated Air for Desorption

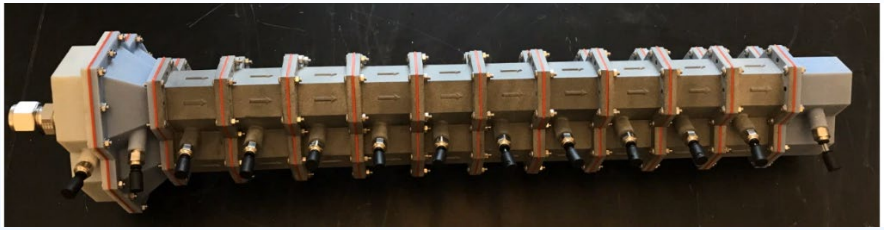
Contactor designs finalized and fabricated for BP1 activities

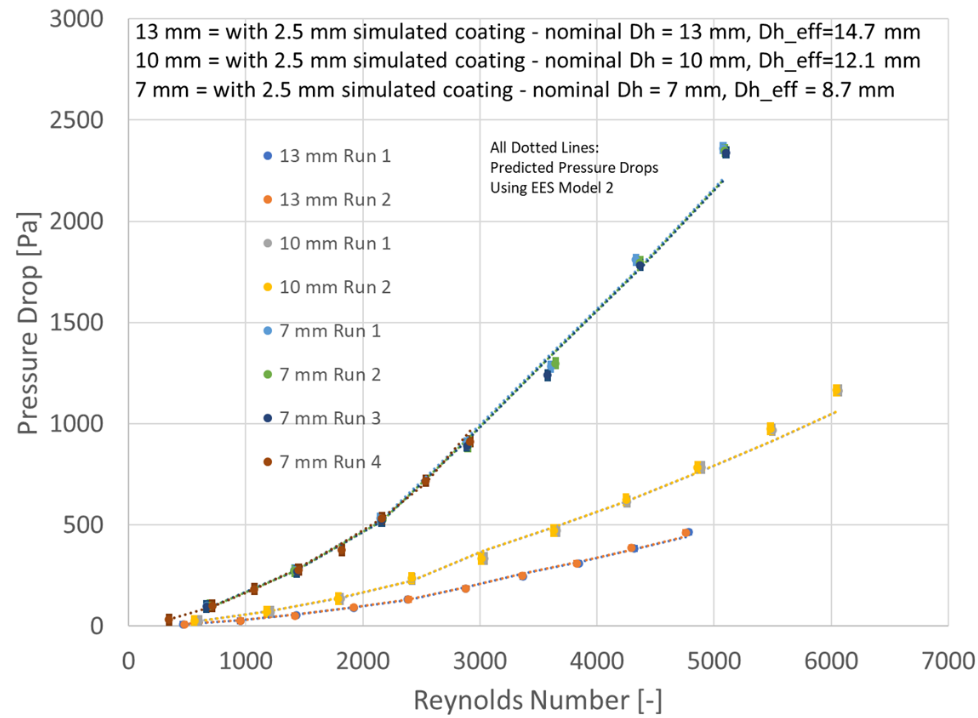
Additive Contactor Design, Fabrication & Testing

Blasius Pressure Drop Equation

$$\Delta P = 0.241\frac{\rho^{0.75}\, L\, Q^{1.75}\mu^{0.25}}{\pi D_h^{4.75}}$$



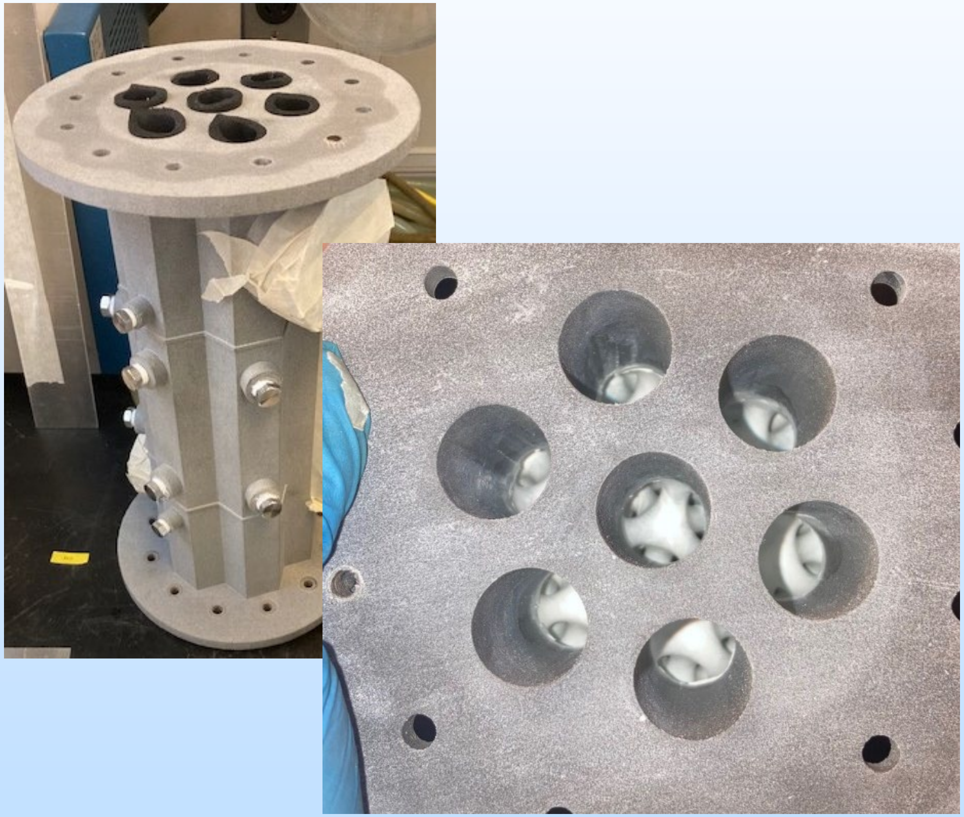




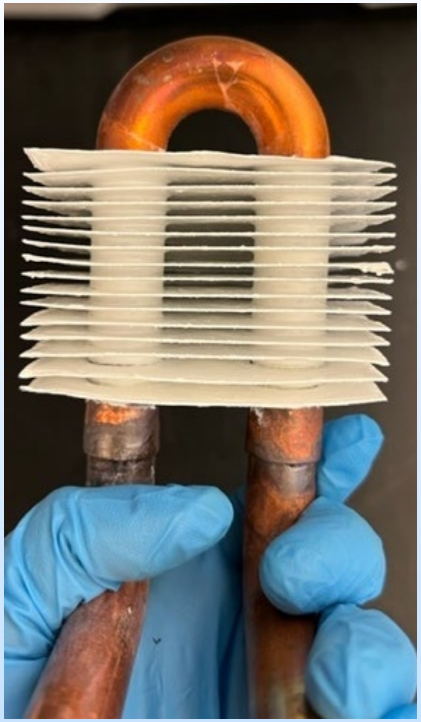
Contactor design & models optimized to achieve pressure drop targets

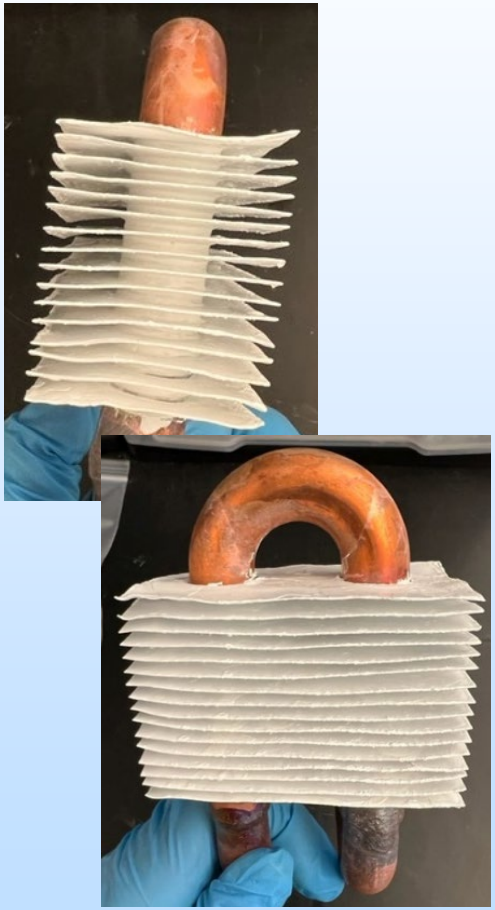
Sorbent (GE115) Integration into AIR2CO2 Contactor System

AIR2CO2 Additive Contactor



Fin-in-Tube Contactor



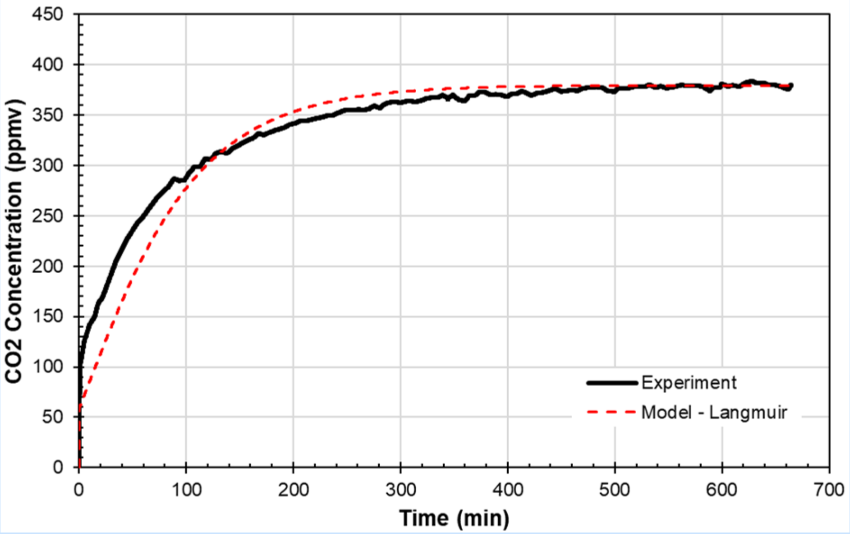


Uniform coatings achieved that retain >80% of the native sorbent capacities

GE-115 Model Fit & Cycling Performance

CO$_2$ Adsorption Breakthrough and Model Fit

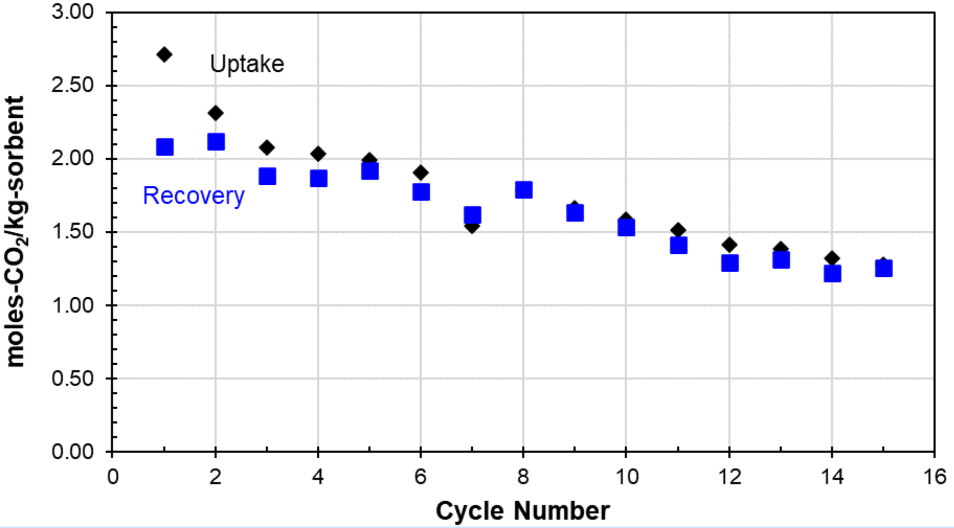
Adsorption: DAC, 25 °C, 50% RH, 10 SLPM
Desorption: 120 °C, 1 SLPM N$_2$ sweep



		Ki (1/s)	
Capacity (mol/kg)	Coating Thickness (mm)	Freundlich (TR2)	Langmuir (Optimized)
2.71	0.16	3.8x10^{-4}	2.8x10^{-4}

Cycling CO$_2$ Capacities

20 SLPM feed gas used for continued cycling (Cycles 2-15)



- Mass balance discrepancy, particularly in early cycles, indicates incomplete desorption
- 53% capacity drop after 15 cycles

Reasonable model fit. Gen 2 GE sorbents with improved life will be employed.

AIR2CO2 Contactor: Summary of Coated Parts Testing

Contactor	GE-115 Capacity (mol/kg)	Coating Thickness (mm)	K_i (1/s)	Volumetric Productivity ($mol_{CO2}/(L*hr)$)		Gravimetric Productivity ($kg_{CO2}/(kg_s*hr)$)		Capture Efficiency (%)	
				15 min	30 min	15 min	30 min	15 min	30 min
Additive	2.71	0.16	2.76×10^{-4}	0.44	0.40	0.054	0.049	67.5	61.7
Fin and Tube	2.41	0.13	6.5×10^{-4}	0.86	0.70	0.13	0.11	59.6	48.3

Adsorption: DAC, 25 °C, 50% RH, 10 SLPM
Desorption: 120 °C, 1 SLPM N_2 sweep

How quickly CO_2 saturates the sorbent

$$\boldsymbol{R}_{AC} \equiv \frac{pL\rho_s T_s N_0 \boldsymbol{K}_i}{A_f V C_0} = \frac{Adsorption\ Rate}{Convection\ Rate}$$

To maximize productivity…use best material (capacity, kinetics) and operate in adsorption limit (↓R_{AC})

BP1 productivity & efficiency targets met with fin and tube coated contactors

Progress Against Success Criteria & Next Steps

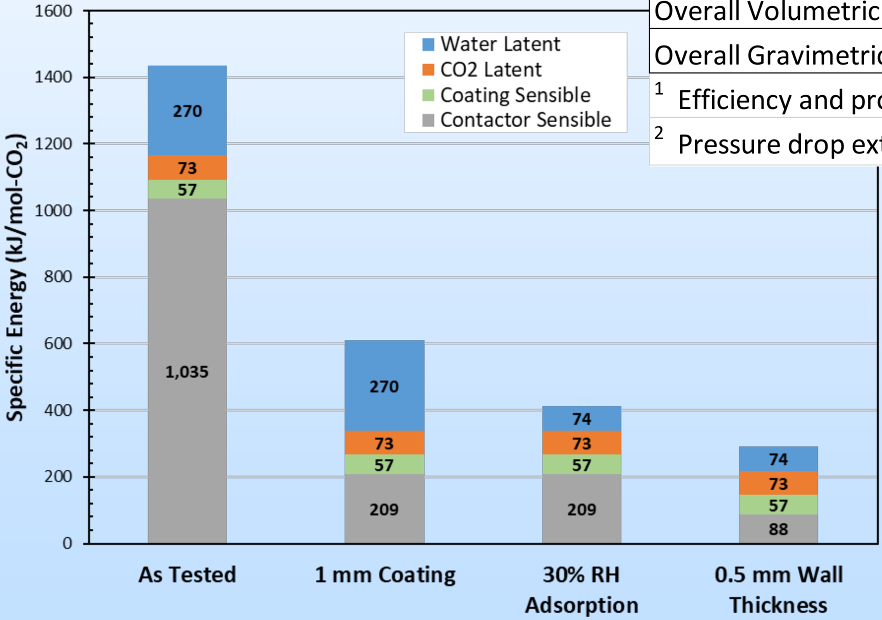
GE-115 Additive Contactor Performance

Parameters	Current - GE-115	BP1 Target	Project Target
CO2 Capture Efficiency %	67.5[1]	50	70
Space Velocity, Hr-1	80,043	50,000	150,000
Pressure Drop, Pa	235[2]	500	150
Capacity Fade/Cycle %/cycle	3.52	0.005	0.0001
Steam Duty, kJ/mol CO2	1762	275	172
Overall Volumetric Productivity (gmol CO2/ hr V(l))	0.44[1]	1	2
Overall Gravimetric Productivity (g-CO2/ hr g-Sorbent)	0.056[1]	-	-

[1] Efficiency and productivity values taken at 15 minutes into first 10 SLPM cycle

[2] Pressure drop extrapolated to 1 tonne-CO$_2$/day system with 0.3 m length in flow direction

AIR2CO2 Contactor Alpha-Prototype Steam Duty



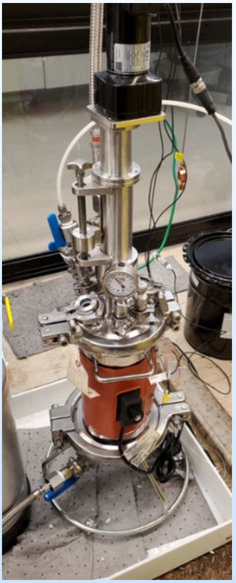
- Employ Gen 2 GE sorbents with improved chemical and thermal stability
- Maximize coating capacity, kinetics & thickness
- Effectively manage water
- Minimize contactor thermal mass

Driving towards BP2 targets through multi-parameter understanding & optimization

Sorbent & Film Fabrication

GE Gen 2 MOF Scale-up

Synthesis



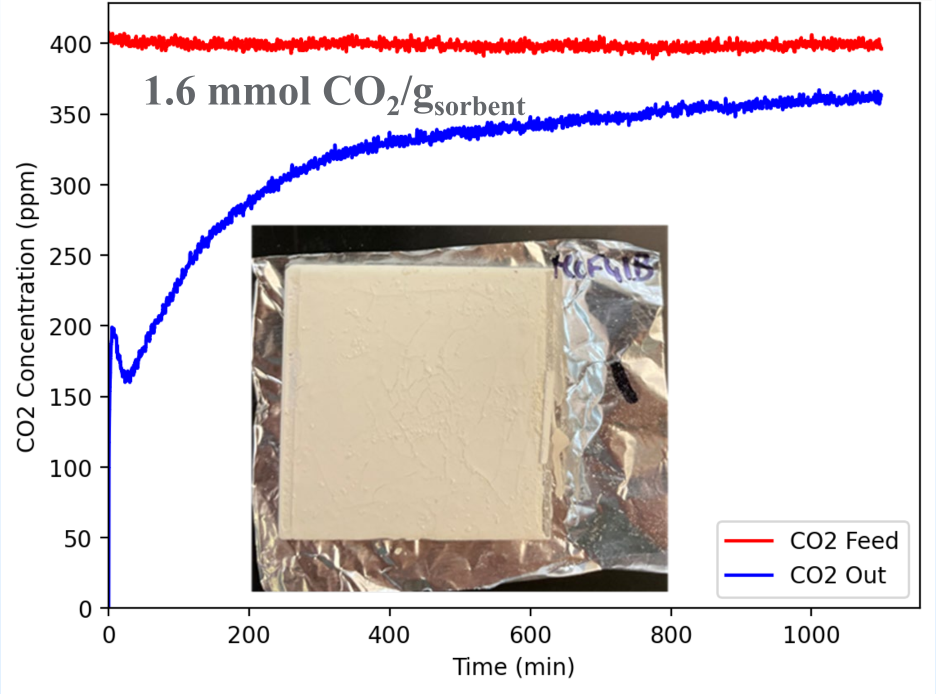
Purification & Isolation

Product

>300 grams of GE MOF scaled up

Sorbent Film Performance

Adsorption Conditions: 50% RH, 25°C, 0.04 kPa CO_2

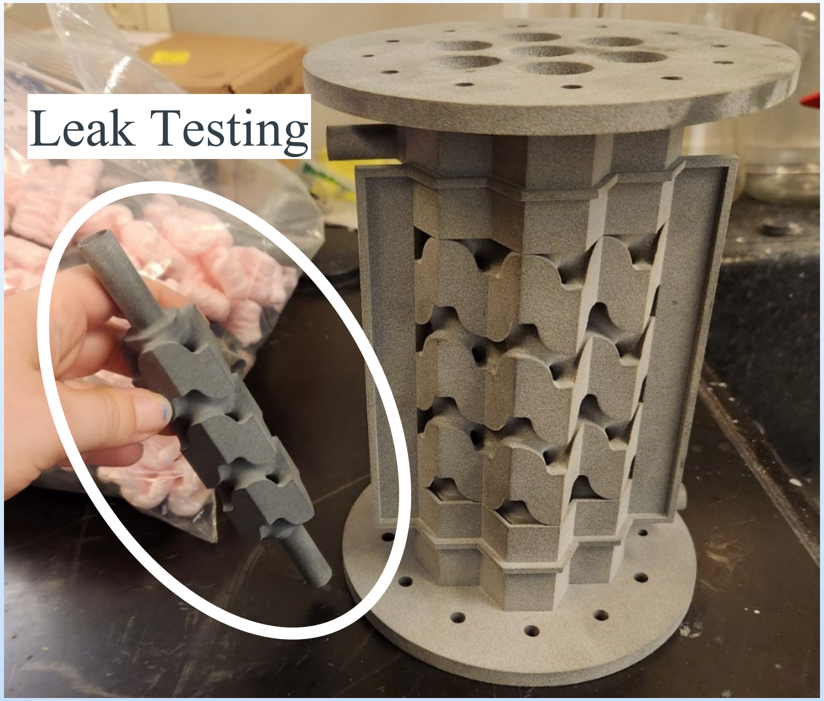


Adherent sorbent films with promising capacities

Successfully scaled MOF sorbents and demonstrated robust, high-performance films

Next Generation Additive Contactor Design & Fabrication

Leak & Performance Testing



Type	Purpose	Hydraulic Diameter (mm)	Wall Thickness (mm)
Leak Testing	Determine minimum wall thickness without leaks	10	0.50 - FAILED 0.75 - PASSED 1.0 - PASSED 1.2 - PASSED
Performance Testing	Measure adsorption metrics in CAT-1 rig	10	1.2

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

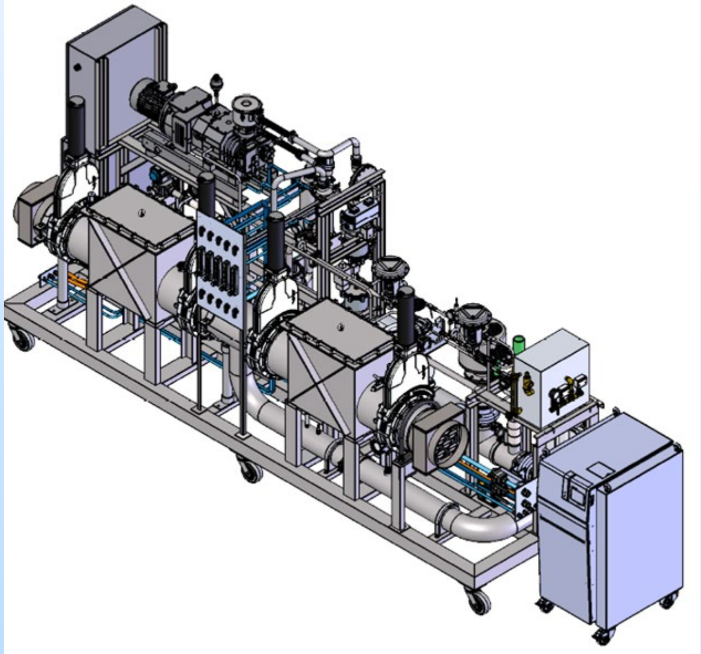
Contactor wall thickness of 0.75 mm chosen for additive contactor design

Plans for future testing/development/commercialization

a. AIR2CO2 Contactor: Alternating adsorption-desorption bench-scale proof-of-concept testing of coated, additively-printed parts; techno-economics; up to 1 kg CO_2/day demo

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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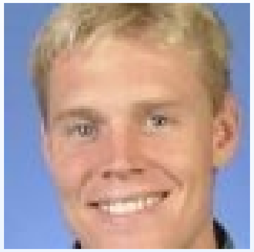
Appendix

Organization Chart

GE Research – contractor design & fabrication, coating development, system modelling, fabrication & performance testing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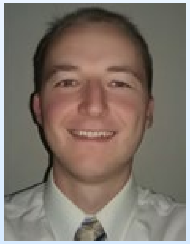
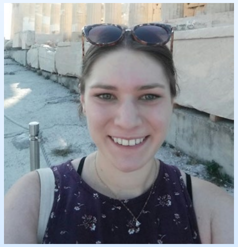
Dr. Bin Xu


Dr. Michael Radetic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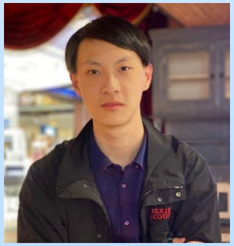
Mr. Travis O'Neil


Dr. Alex Antonio

UC Berkeley – sorbent development & characterization, powder performance testing


Prof. Omar Yaghi
Co-PI


Mr. Oscar Chen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Univ. S. Alabama – system modelling, CO_2 sorption kinetics measurements


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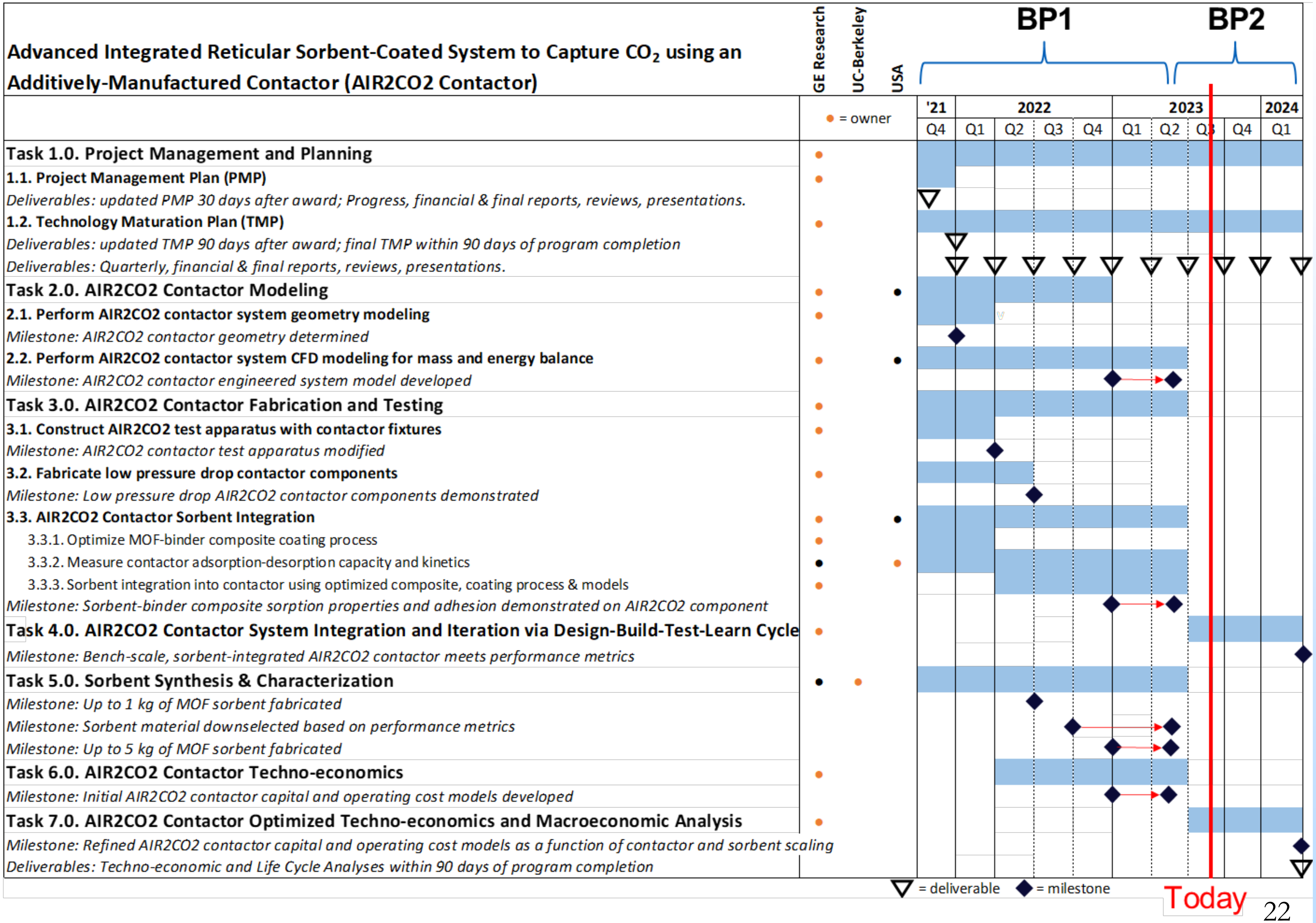
Gantt Chart



Advanced Integrated Reticular Sorbent-Coated System to Capture CO_2 using an Additively-Manufactured Contactor (AIR2CO2 Contactor)

🟠 = owner

		GE Research	UC-Berkeley	USA
	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			