Bench-Scale Development of a Novel Direct Air Capture Technology Using High-Capacity Structured Sorbents

DE-FE0032118

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Susteon Inc.

U.S. Department of Energy

National Energy Technology Laboratory

Carbon Management Project Review Meeting

August 15 - 19, 2022

Project Overview

Total Funding: $1,903,876

DOE Funding: $1,500,000

Cost Share: $403,876

Overall Project Performance Dates:

BP1: 10/01/2021 – 09/30/2022

BP2: 10/01/2022 – 09/30/2023

Project Participants:

Susteon Inc. (Prime)

Columbia University (Professor Robert Farrauto)

Cormetech

TotalEnergies

SoCalGas

DOE Project Manager: Mr. Dustin Brown

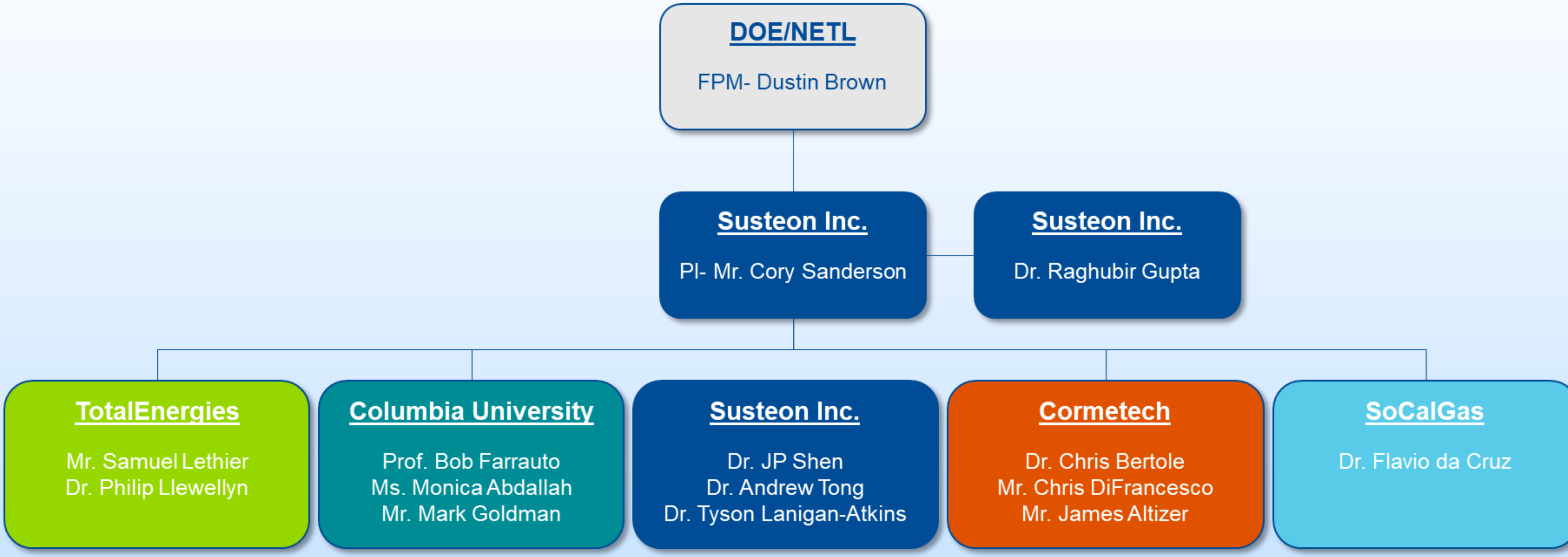
Project Objectives

The overall objective of the project is to lower the cost of DAC through development of a structured material system which will be regenerated with low-carbon electricity (TRL 3 to TRL 4).

Technical Objectives

- Increase CO_2 capacity and absorption rate to lower capital costs
- Regenerate directly with electricity
- Develop a washcoating synthesis process for structured supports for low-pressure drop
- Design and build a 1 kg/day CO_2 bench-scale unit
- Perform parametric and long-term testing to obtain engineering data needed for a pilot system design for next step of technology development
- Develop a process model to accurately represent the DAC process
- Perform and refine a technoeconomic assessment (TEA) to evaluate the commercial potential of an N^{th} of a kind large-scale DAC facility

Project Team



SMS short and long-term testing

Bench-scale testing, Process Model, TEA/LCA

Substrate supply, heating and sorbent material integration to SMS

Susteon's Vision for DAC

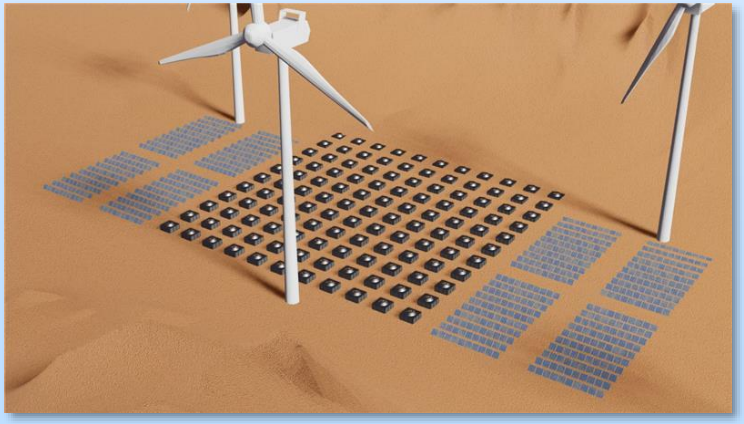
Our Solution

Core Innovations:
- Non-amine sorbent for CO_2 capture
- An integrated selective heating mechanism
- A low pressure drop support

Resulting in:
- A pathway to < 2,000 kWh/ton of CO_2
- CapEx target <~$600/ton-yr

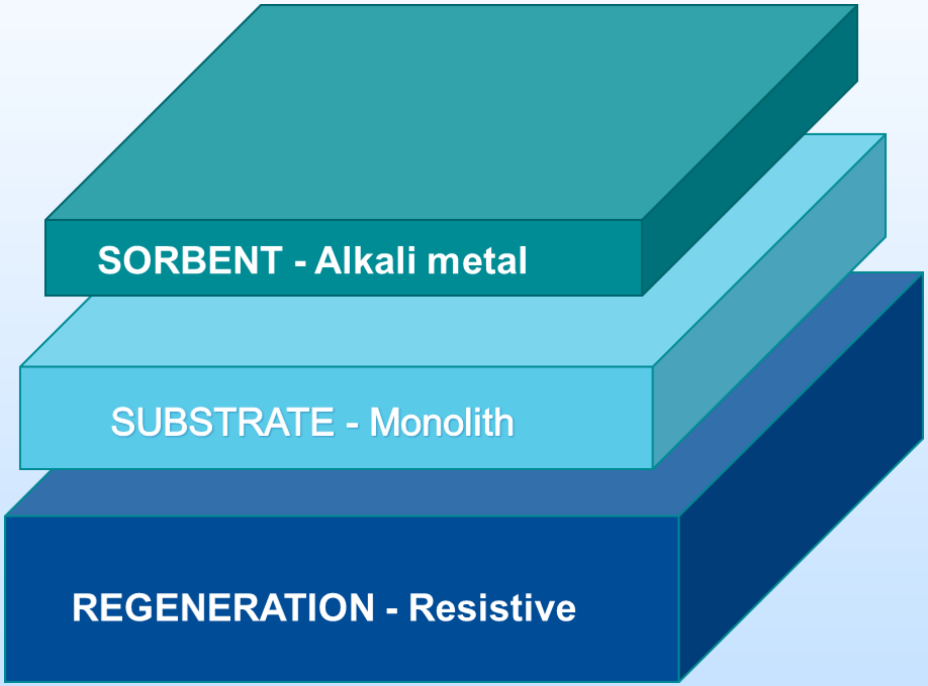
Key Differentiators

1. Abundantly available, low-cost capture agent (alkali metal based)
2. Low energy of desorption by controlling the chemistry
3. Fast kinetics of adsorption and desorption
4. Beneficial effect of moisture in ambient air
5. Innovative heating to minimize heat losses
6. Scalability using existing supply chain



Structured Material System (SMS) Concept

- Adsorption with alkali metal sorbent is different with 400 ppmv CO_2 in air compared to high concentrations of CO_2 in point sources.
- Humidity in air plays a critical role in CO_2 capture from air.
- Our SMA integrates the sorbent, regeneration method, and substrate into an optimized form, which;
    - Lowers capital utilization by enabling fast CO_2 adsorption rates and high capacity
    - Lowers the energy utilization by reducing pressure drop during adsorption and energy losses during desorption
    - Powered by low-carbon electricity for maximum net removal efficiency (no steam needed)



Technical Approach

- **Optimize structured material system** Na_2CO_3 on alumina support with the key objectives of (1) maximizing CO_2 capture capacity (2) maximizing CO_2 capture kinetics (3) maintain high dynamic capture capacity between cycles (4) good adsorbent stability (5) low desorption energy
- **Support the sorbent on a low-pressure structured support** such as monoliths to minimize the energy consumption due to pressure drop with a target of <250 kWh/ton of CO_2 captured. Coating of a uniform layer of Na_2CO_3 and alumina will require optimization of the coating process.
- **Develop a design for heating of sorbent** to initiate CO_2 desorption.
- **Design an efficient process cycle** for adsorption, heating, and desorption to maximize capital productivity and minimize the overall capex and opex for the process.

Project Success & Milestones

Project Success Criteria

- Complete at least 100 cycles of bench-scale system (1 kg/day CO_2 capture), continuous testing of the DAC process cycle to show less than 5% decrease in system CO_2 capacity as measured from 5^{th} to last cycle.
- Process model which accurately predicts performance (adsorption/desorption rate, capacity, desorb heating requirements) within 5% of experimental results
- Attainment of the targeted TRL 4 on successful completion of bench-scale testing
- Final TEA showing progress towards DAC cost reduction to < $250/ton CO_2
- LCA showing GHG removal efficiency of >50%.

Project Success & Milestones

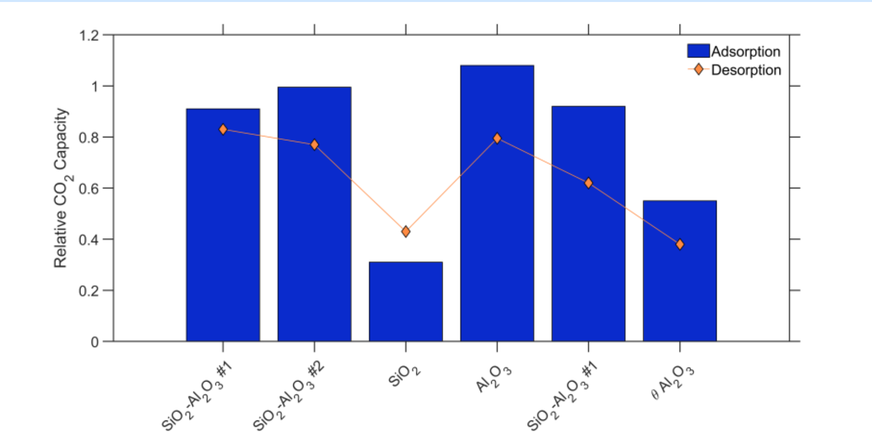
Task/Subtask	Milestone Title & Description	Planned Completion Date	Actual Completion Date	Verification method
Task 1	Updated Project Management Plan	10/31/2021	10/22/2021	Submission of revised PMP
Task 1	Kickoff meeting	11/1/2021	11/1/2021	Presentation and PMP
Subtask 1.2	Technology Maturation Plan (TMP), Initial	12/31/2021	2/1/2022	Submission of initial TMP
Task 2	Demonstrate functionality of integrated structure material sorbent	5/31/2022	3/21/22	Quarterly Reports
Task 3 (Go/No-Go)	A CO_2 working capacity on SMS of 2.5 wt% in Bench-Scale System over 10 cycles	9/30/2022	7/15/22	Quarterly Reports
Task 4	Less than 5% capacity fade after 10 cycles	1/31/2023		Quarterly Reports
Task 5	Process model which accurately predicts performance (adsorb/desorb rate, capacity, desorb heat) within 5% validated against experimental results to date	5/31/2023		Quarterly Reports
Subtask 6.1	Techno-Economic Analysis	9/30/2023		Submission of final TEA
Subtask 6.2	Life Cycle Analysis	9/30/2023		Submission of final LCA
Subtask 1.2	Technology Maturation Plan (TMP), Final	12/31/2023		Submission of final TMP

Sorbent Washcoat Optimization

Effects of Support

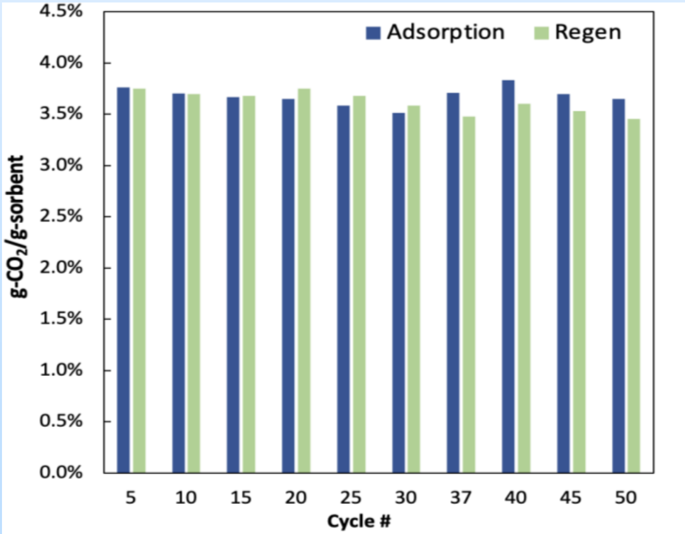
- Synthesized granules of alkali metal (Na and K) sorbents dispersed on different supports
- Investigated - material type, particle size, porosity, acidity, surface area
- Samples were tested to evaluate the performance
    - CO_2 capture capacity
    - Sorption kinetics
    - Stability

Determined a support material for washcoating



Washcoat Loading

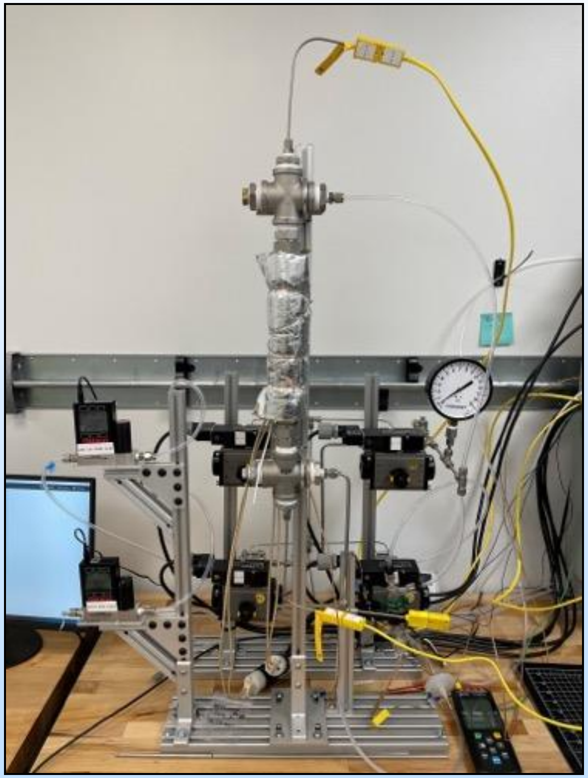
- High porosity cordierite monolith with thin walls was loaded with **2.39 g/inch³** of washcoat
- Coated monolith was tested for 50 cycles to demonstrate high washcoat stability

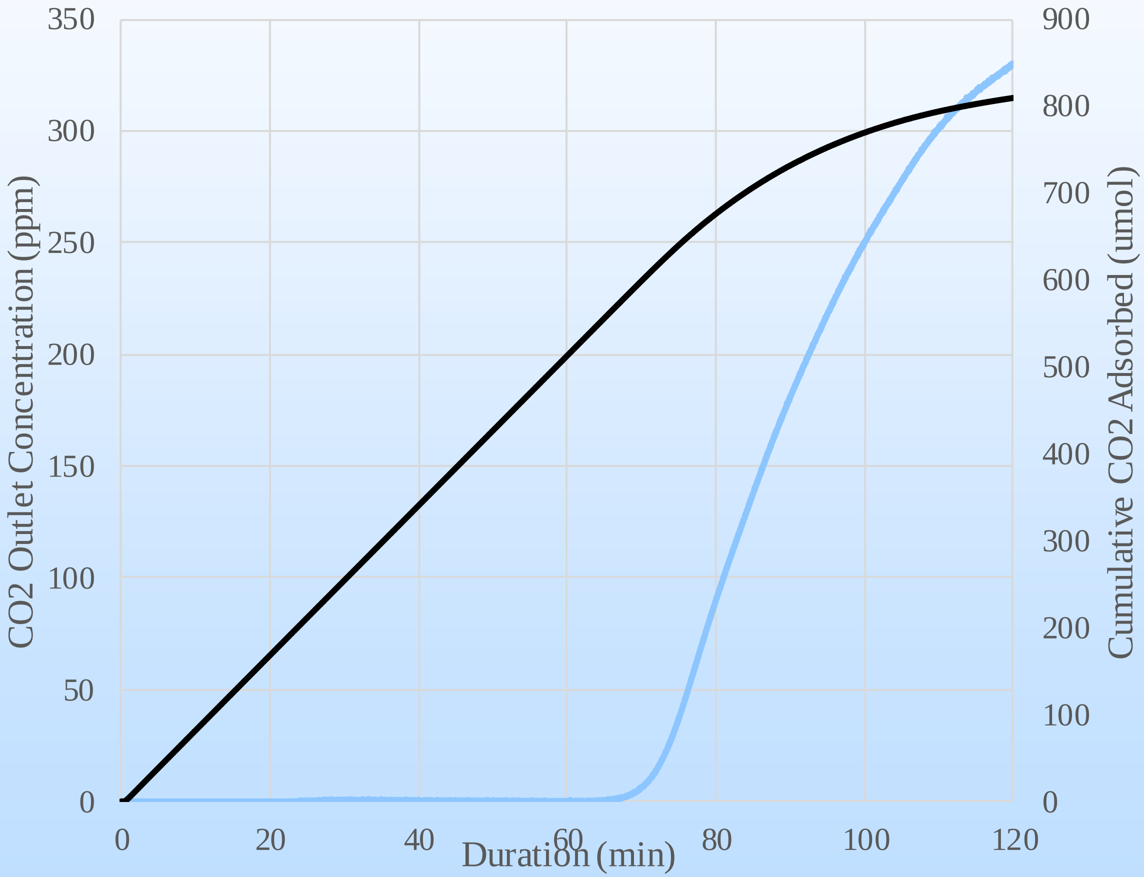


(b)

Sorbent Performance

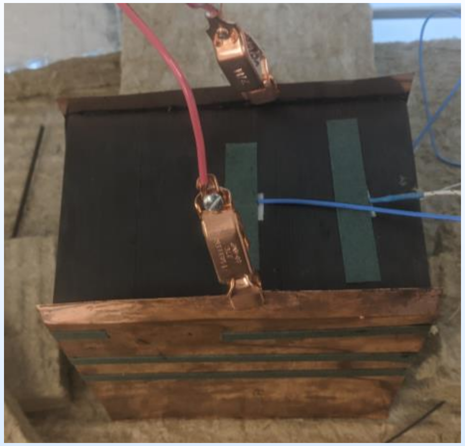
Adsorption of CO_2 from humid air, breakthrough and cumulative





Desorption Method Optimization

- Coated cordierite monoliths with a layer of carbon to impart electrical conductivity and test their Joule heating performance
  - Explored different carbon precursors and used different loadings (g/in^3) to achieve target resistance and heating performance
- Developing a coating procedure for achieving target resistivity, long term stability, and low-cost
  - Process is scalable using commercially available materials
- Characterized coated samples for their electrical resistance durability and heating performance

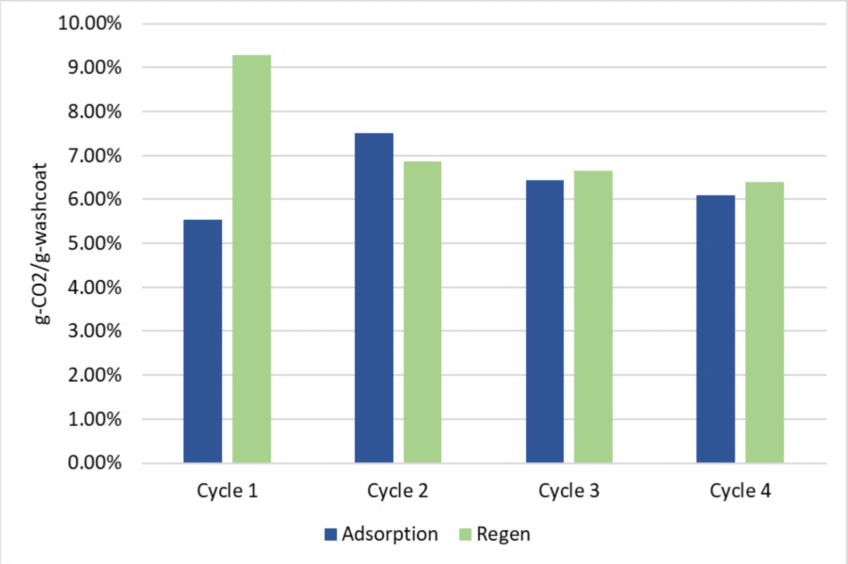


Key results:

- Determined appropriate coating and monolith materials for bench-scale unit
- Identified key parameters for improving coating uniformity
- Identified optimum loading (g/in^3) for the resistive layer
- Resistively heated full-size monolith to 120°C
- Incorporated flow-through electrodes

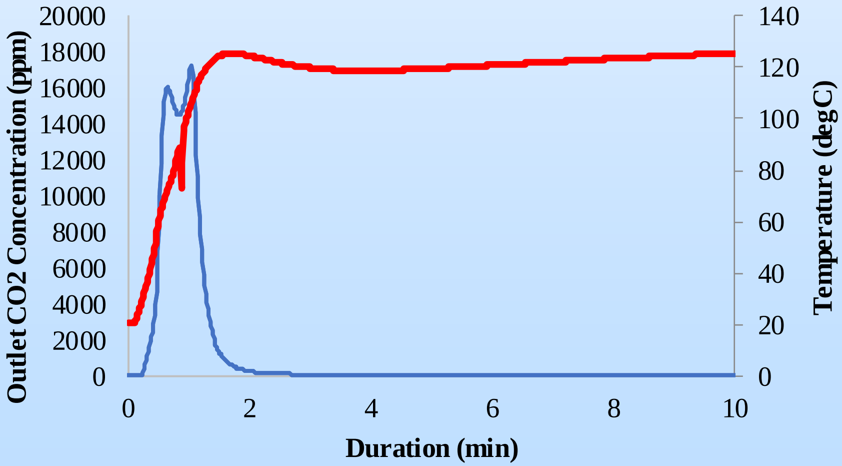
Integrated Structured Material System Testing

- Created integrated structured material samples with cordierite monolith coated with a conductive layer and sorbent
- Sample had a washcoat loading of 2.91 g.
- Performed cyclic adsorption and desorption testing of integrated structured material in a lab reactor
- Regeneration achieved via direct resistive/Joule heating



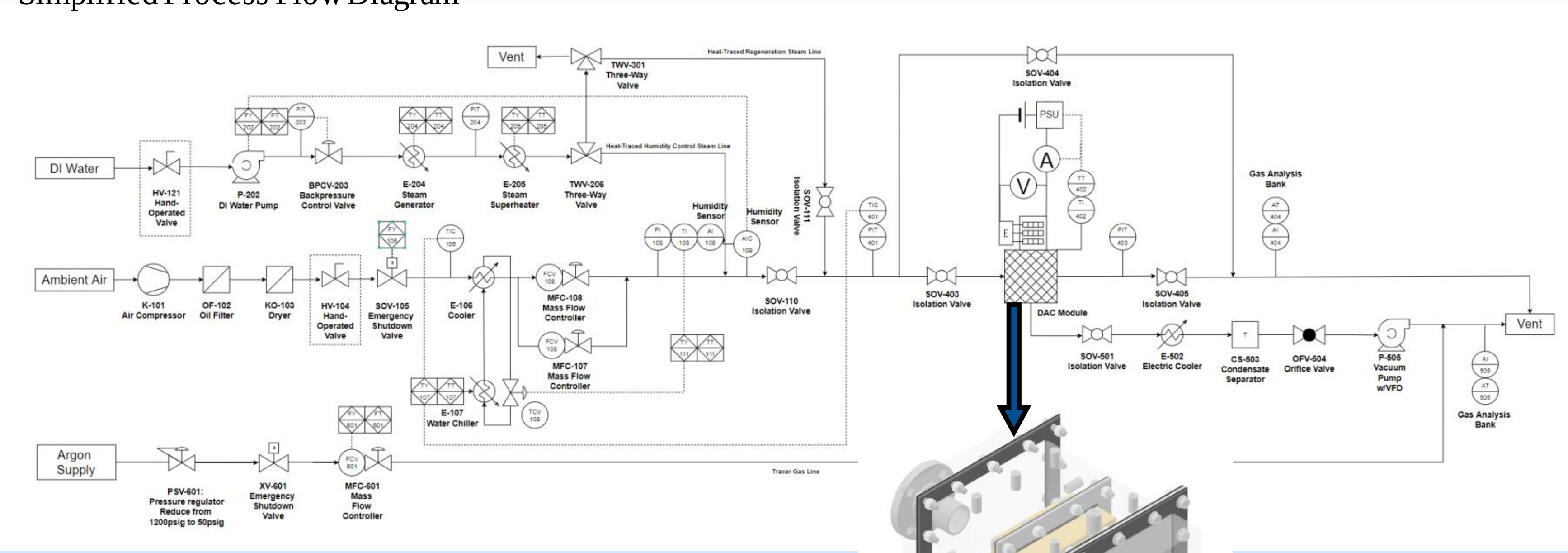
Stage	Time (min)	Temperature (°C)	Gas (mL/min)
Adsorption	60	Ambient	1000 (humid air)
Purge	10-20	Ambient	500 (N_2)
Desorption	3-10	~120°C	500 (N_2)

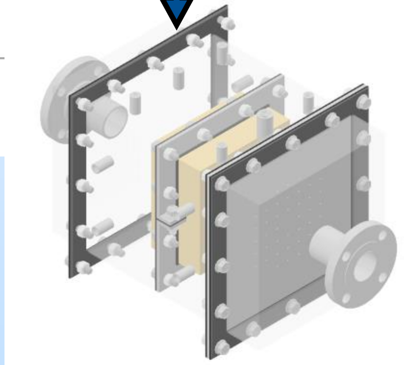
Cyclic testing reactor conditions



Bench-Scale Design & Fabrication

Simplified Process Flow Diagram





<u>Project Schedule</u>

FY22Q1: Design & Procurement

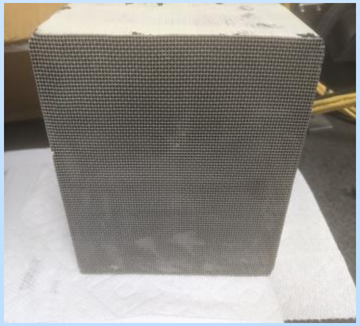
FY22Q1: Fabrication & Assembly

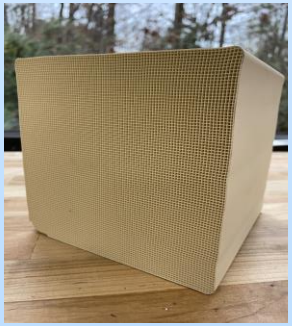
FY22Q3: Commissioning

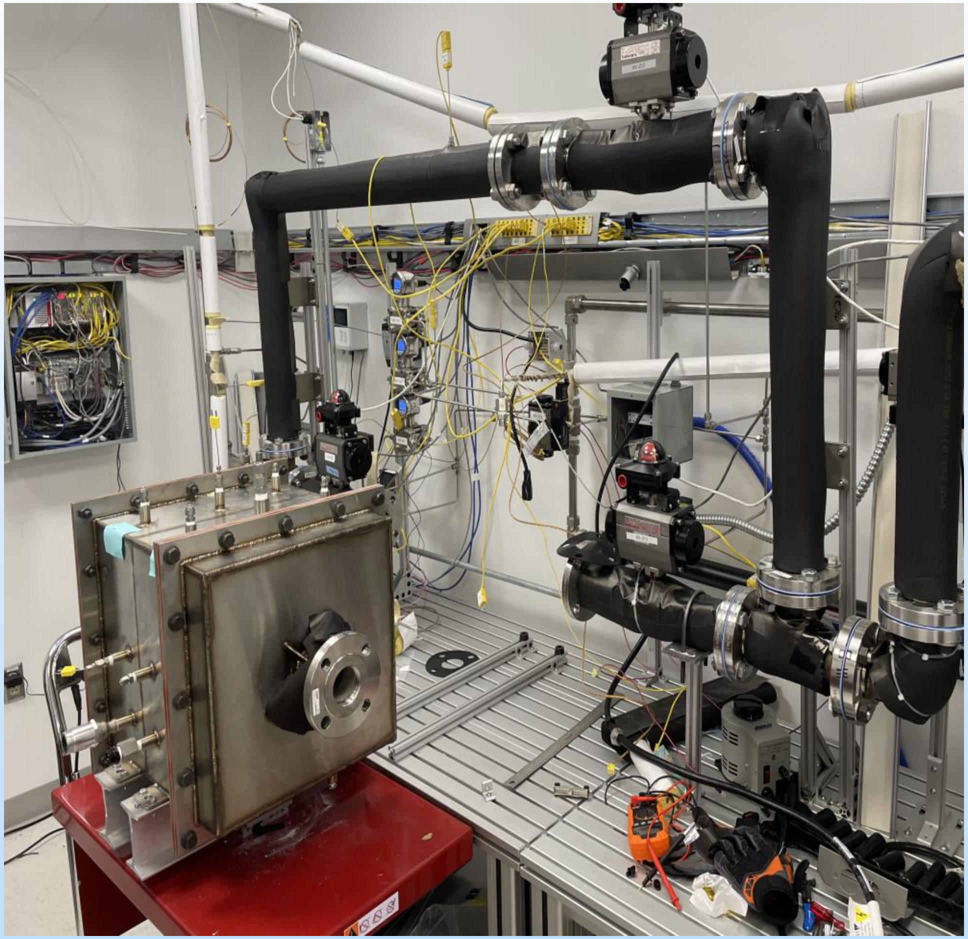
FY22Q4: Testing

Bench-Scale Unit

- Designed for 1-2 kg/day of CO_2 from ambient air
- Highly instrumented to obtain high-fidelity mass/energy balances
- All major process components representative of a scaled-up system included
- Full-scale four monolith bricks (150 mm cubes) can be tested
- System fully commissioned in Spring 22
- Fully operational and providing engineering data for 1 ton/day pilot plant



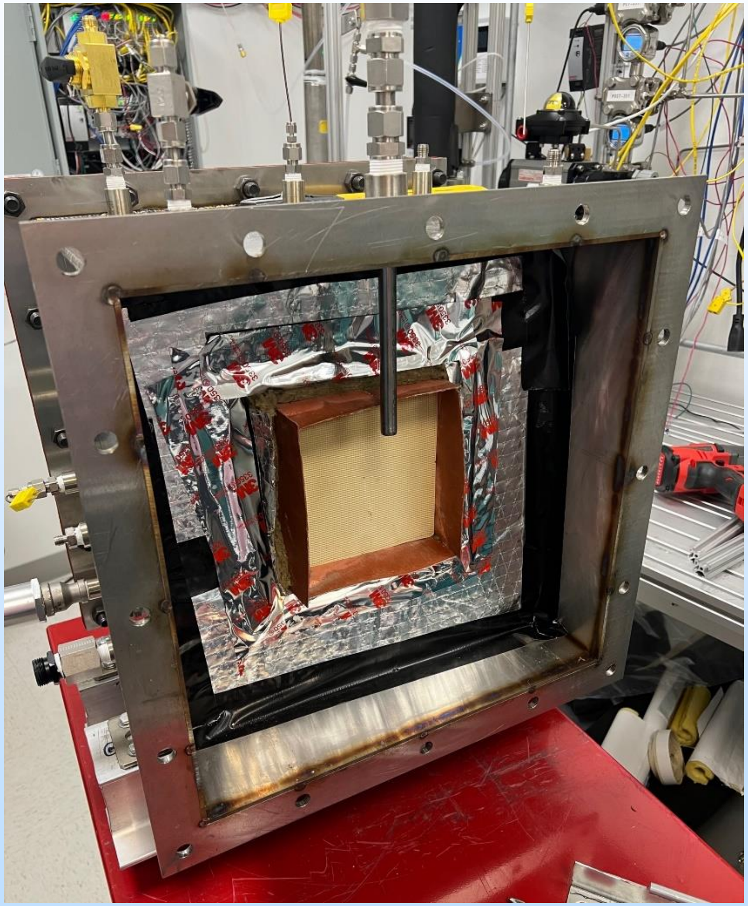




Bench-Scale Testing

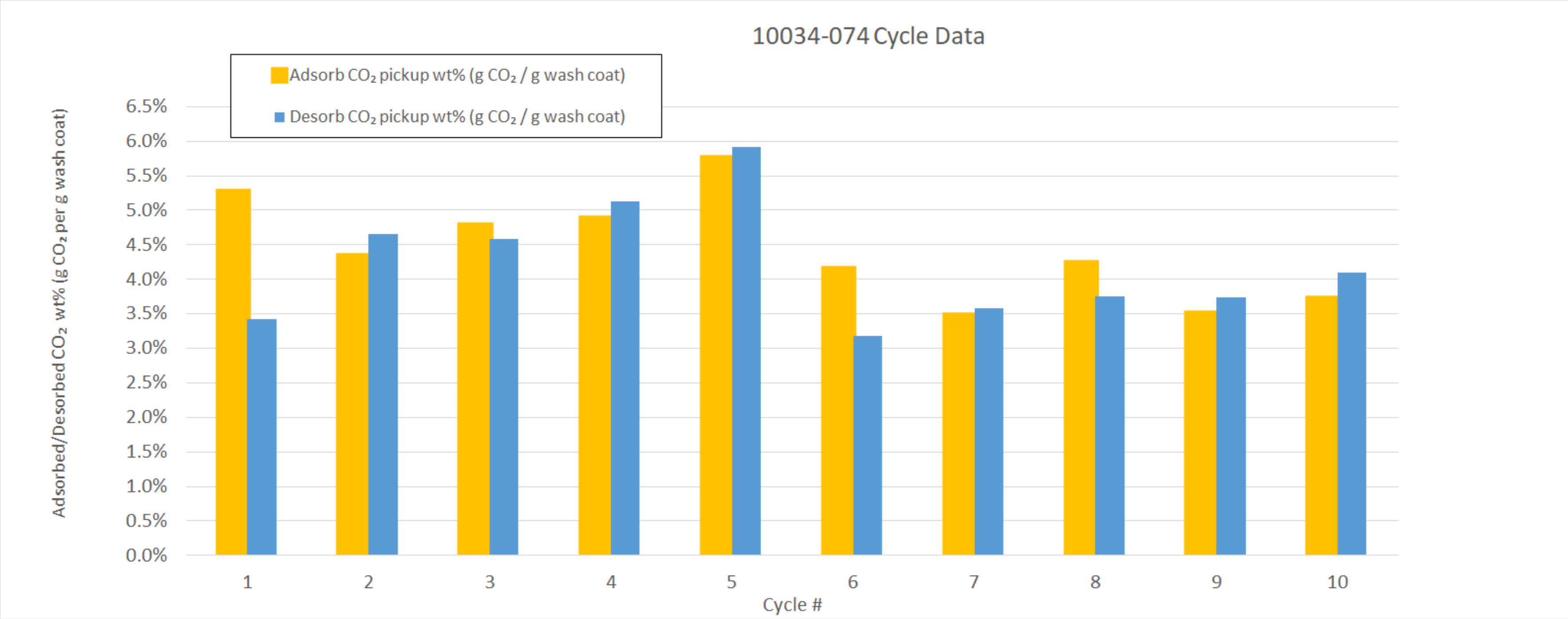
- Coated a full-size (150 mm LxWxH) cordierite monolith with sorbent using an optimized method
- Performed cyclic adsorption/desorption testing

Stage	Time (hr)	Temperature (°C)	Gas (SLPM)
Adsorption	2-3	Ambient	125-500 humid air
Purge	0.75	Ambient	0.1 bar
Desorption	6-12	~75-110°C	1.8 N_2 @ 0.2 bar



Bench-Scale Testing

BP1 Success #2- CO_2 working capacity on SMS of 2.5 wt% in bench-scale system over 10 cycles



Cyclic testing performed at varying WHSV, but fixed humidity of 40% RH

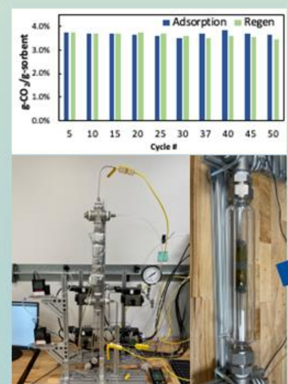
Project Schedule

Project Timeline	Start Date	End Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
			Months from Project Start Date																							
Task 1.0 - Project Management and Planning																										
Subtask 1.1 Project Management Plan	1-Sep-21	31-Aug-23																								
Subtask 1.2 Technology Maturation Plan	1-Sep-21	31-Aug-23																								
Milestone 1a: Initial TMP within 90 days of Project Start		30-Nov-21			★																					
Milestone 1b: Final TMP within 90 days of Project Close Out		30-Nov-23																								★
Task 2.0 – Laboratory Studies of Structured Materials																										
Subtask 2.1 – Evaluation of Various Monolith Materials	1-Sep-21	31-Oct-21																								
Subtask 2.2 – Desorption Layer and Sorbent Washcoat Coating Studies	1-Oct-21	31-Dec-21																								
Subtask 2.4 – Structured Material Characterization	1-Dec-21	28-Feb-22																								
Subtask 2.5 – Structured Material Testing in Lab-Scale Reactor	1-Feb-22	30-Apr-22																								
Milestone 2: Demonstrate Functionality of Integrated Structured Material Sorbent		30-Apr-22								★																
Task 3.0 – Bench-Scale Design, Fabrication, and Testing																										
Subtask 3.1 – Design and Construction of th Bench-Scale System	1-Sep-21	31-Dec-21																								
Subtask 3.2 – Coating of the SMS for Bench-Scale Testing by a Commercial Vendor	1-Jan-22	30-Mar-22																								
Subtask 3.3 – Characterization of Commercially Manufactured SMS	1-Apr-22	31-May-22																								
Subtask 3.4 – Structured Sorbent System Bench-Scale Testing	1-Jun-22	31-Aug-22																								
Milestone 3: A CO2 Working Capacity on SMS of 2.5 wt% in Bench-Scale System over 10 cycles.		31-Aug-22												Go/ No- Go												
Task 4. Long-Term Testing																										
Subtask 4.1 – Accelerated degradation Testing at Lab-Scale	1-Sep-22	31-Dec-22																								
Subtask 4.2 – Long-term Testing at Bench-Scale	1-Sep-22	31-Dec-22																								
Milestone 4: Less than 5% capacity fade after 100 cycles		31-Dec-22																★								
Task 5. Process Design & Modeling																										
Subtask 5.1 – Process Model Development and Validation	1-Nov-22	31-Jan-23																								
Subtask 5.2 – Desorption Optimization	1-Dec-22	31-Jan-23																								
Subtask 5.3 – Process Cycle Design	1-Jan-23	30-Apr-23																								
Milestone 4: Process model which accurately predicts performance (adsorb/desorb rate, capacity, desorb heat) within 5% validated against experimental results to date.		30-Apr-23																				★				
Task 6. Techno-Economic Analysis & Life-Cycle Assessment																										
Subtask 6.1 – Techno-Economic Analysis (TEA)	1-Apr-23	31-Aug-23																								
Subtask 6.2 – Life Cycle Analysis	1-May-23	31-Aug-23																								
Milestone 6: High-fidelity TEA and LCA to assess the cost of CO2 capture and impact on GHG emissions from the proposed technology compared to SOTA.		30-Nov-23																								★

Technology Development Roadmap

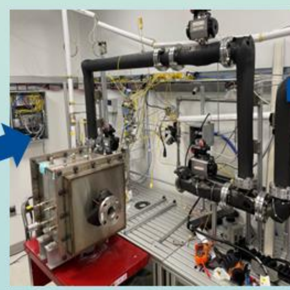
Laboratory Testing
(3 g/day)
TRL-2

- Verified sustained performance of structured sorbent
- Proof of concept resistive layer coating showing high CO_2 desorption rates



Bench Component Testing
(Intermittent 2 kg/day)
TRL-2 → TRL-3

- Optimize sorbent and heating material washcoat synthesis on selected structured sorbent
- Verify performance of structured sorbent for adsorption and desorption



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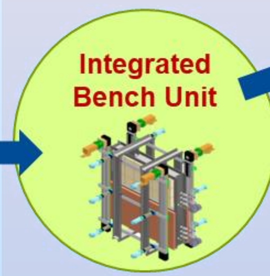
Integrated Bench Testing
(2 kg/day)
TRL-3 → TRL-5

Validate continuous operation with SMS sealing design and CO_2 production under real environment condition



DAC Pilot Plant Demonstration
(1 ton/day)
TRL-5 → TRL-7

Pre-commercial form factor with continuous testing for new SMS

DAC Commercial Demonstration Plant
(10 ton/day)
TRL-8

Summary

Task 2

- Evaluated multiple low pressure drop substrates for sorbent loading performance and heating material integration
- Identified optimal support material to achieve sorbent dispersion and maximum adsorption rate
- Performed several iterative washcoat loading tests with various substrates, supports, heating material integration, and sorbent slurry conditions
  - **Achieved BP1 target of 2.0 g/in^3 washcoat loading on electrically heatable SMS**
- Conducted cyclic adsorption and desorption testing on (1) SMA with sorbent only, (2) SMA with heating material only, and (3) fully integrated SMA with sorbent and heating material
  - Results from testing achieved BP1 targets for capacity fade and CO_2 recovery
  - **Achieved BP1 target demonstrating integrated SMA which captures and releases CO_2 with electric heating**

Task 3

- Completed design, fabrication, and assembly of bench-scale reactor system
- Completed commissioning of bench-scale system, verifying instrument and analyzer calibrations, confirming system is leak tight, and mass balance closure
- Performed initial coating of full size SMA with sorbent only to date
- Ran many adsorption/desorption cycles on initial coated SMA in bench-scale system
  - **Achieved BP1 target of 2.5 wt% over 10 cycles**

Acknowledgments

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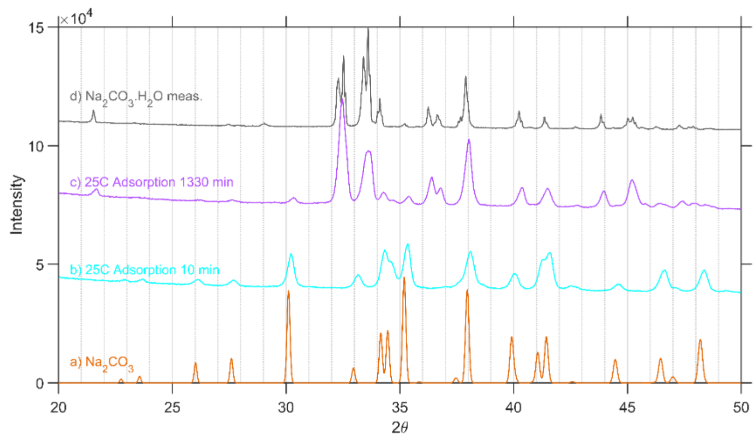
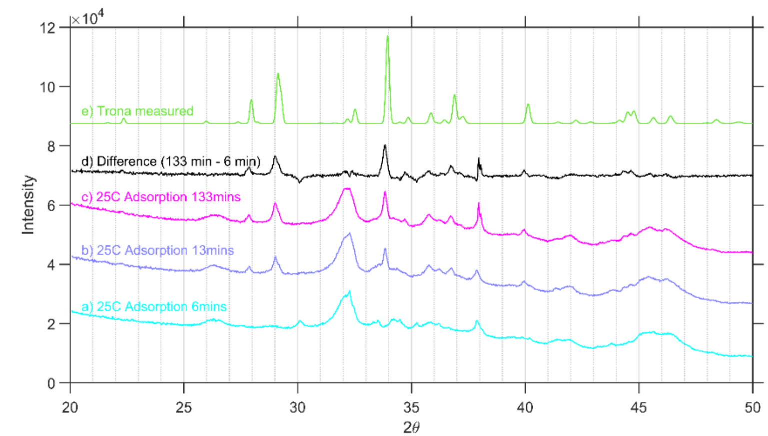
Appendix

Structured Material Characterization and Testing

Adsorption Mechanism

- In situ adsorption (400 ppmv CO_2 in humid air) and heating (regeneration) XRD
- Adsorption on pure Na_2CO_3 leads to slow formation of hydrates, predominantly $Na_2CO_3.H_2O$
- Adsorption on Na_2CO_3 dispersed on alumina support leads to rapid formation of Trona
- $3Na_2CO_3 \bullet H_2O(s) + CO_2(g) + 2\ H_2O(g) \leftrightarrow 2Na_2CO_3 \bullet NaHCO_3 \bullet 2H_2O(s)$
- **Fundamentally different process compared to Na_2CO_3/K_2CO_3 adsorption from >1% CO_2 streams**





Structured Material Characterization and Testing

Desorption Mechanism

- Upon heating, trona formed during carbonation regenerates back to Na_2CO_3 phase
- This confirms we can cycle between Na_2CO_3 and trona with intermediate hydrate phases
- This work is continuing to get the measurements on heat of adsorption/regeneration and precise role of water in air.