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

DE-FE0032118

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2023 Carbon Management Research Project Review Meeting
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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)
- Sustaera
- Cormetech
- TotalEnergies
- SoCalGas

DOE Project Manager: Mr. Zachary Roberts

Project Objectives

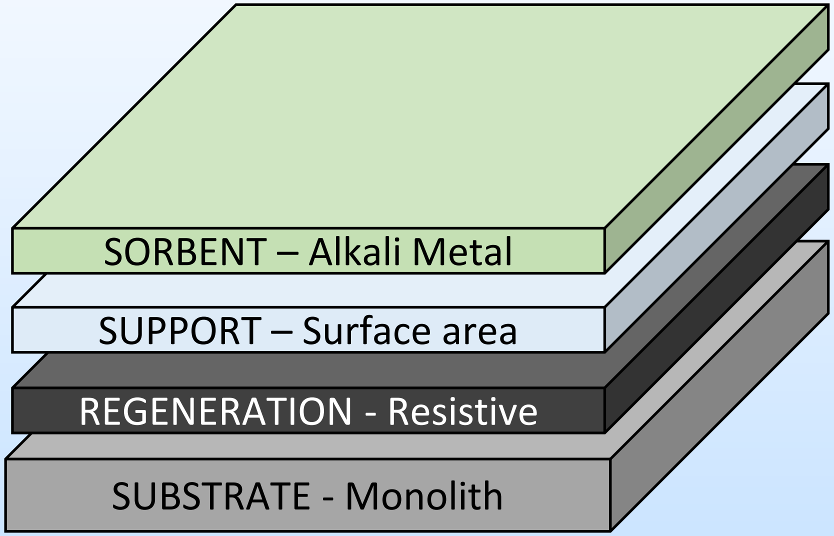
The overall objective of the project is to lower the cost of DAC through development of a structured material system which will be regenerated with low-carbon electricity (TRL 3 to TRL 4).

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

Structured Material Assembly (SMA) Concept

- Adsorption with a 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;
  - Increases productivity by enabling fast CO_2 adsorption rate and fast regeneration
  - 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)



SORBENT – Alkali Metal

SUPPORT – Surface area

REGENERATION - Resistive

SUBSTRATE - Monolith

Technical Approach

- **Optimize structured material system:** Promoted 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 working 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. Optimize the coating process to obtain a uniform layer of sorbent and support on a substrate
- **Develop a design for heating of sorbent** to initiate CO_2 desorption.
- **Design an efficient process cycle** for adsorption, heating, and desorption to maximize sorbent 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 CO_2 capacity
- Process model which accurately predicts performance (adsorb/desorb 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%.

Sorbent Washcoat Optimization

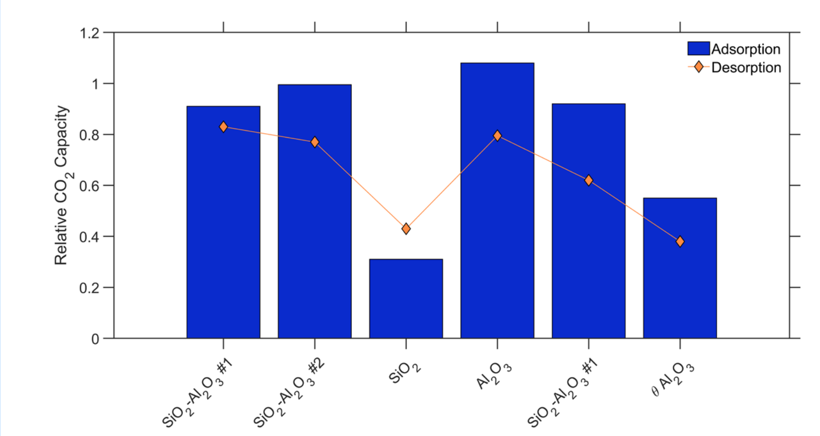
Effects of Support

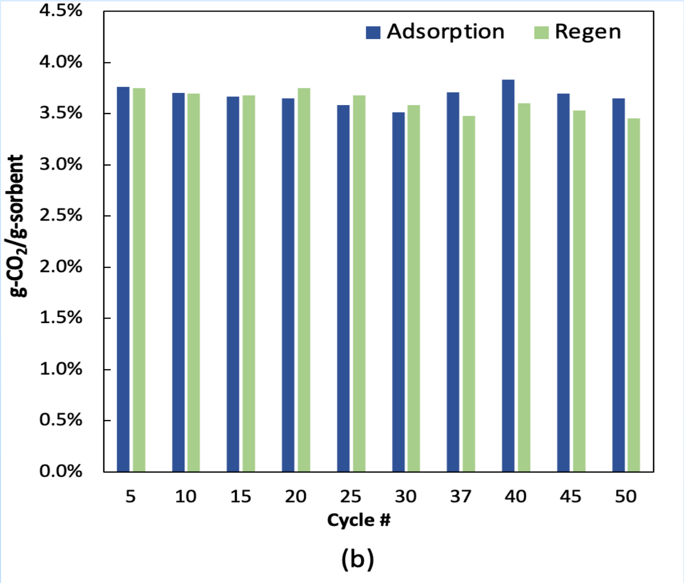
- Synthesized granules of alkali metal (Na and K) sorbents dispersed on different supports
- Investigated: sorbent compositions, particle size, porosity, acidity, surface area
- Samples were tested to evaluate
  - CO_2 capture capacity
  - Sorption kinetics
  - Stability

Washcoat Loading

- High porosity cordierite monolith with thin walls was loaded with **2-3 g/in^3** of washcoat
- Coated monolith was tested for 50 cycles to demonstrate high washcoat stability

Determined a support material for washcoating

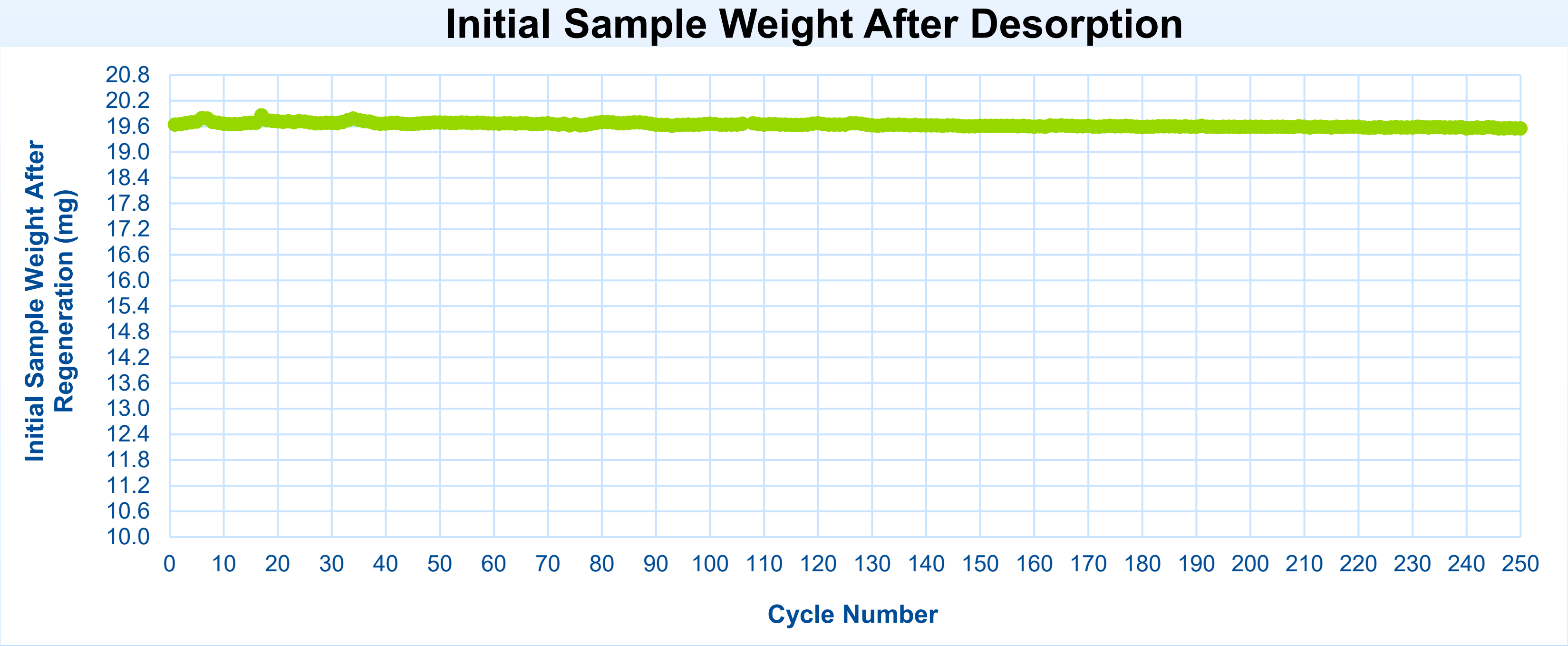




(b)

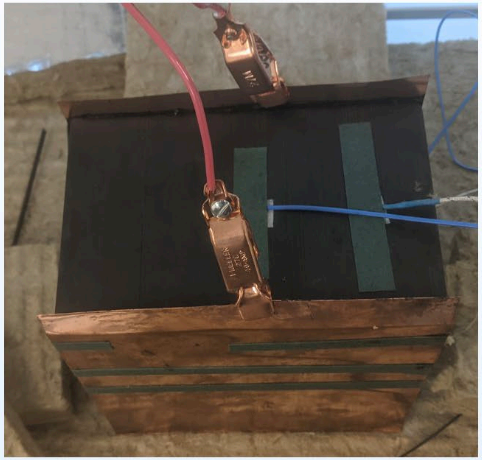
Sorbent Stability

- 250 cycle aging test performed in TGA on sorbent granules to confirm sorbent stability
- No degradation in sample observed



Desorption Method Optimization

- Coated cordierite monoliths with a layer of carbon to impart electrical conductivity and test Joule heating performance
    - Explored different carbon precursors and used different loadings (g/in^3) to achieve target resistance and heating performance
- Developed 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



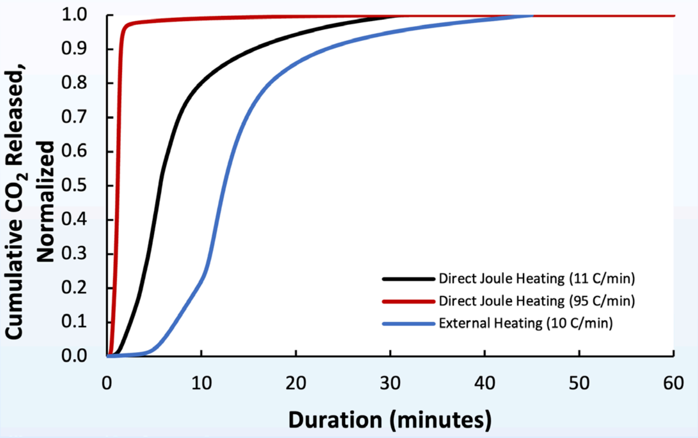
Key results:

- 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 up to 120ºC
- Incorporated flow-through electrodes

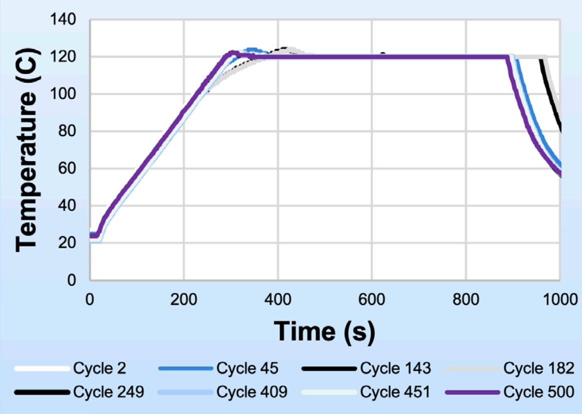
Heating Layer Performance

- Capable of rapid heating, >95°C/min
- Results in rapid rate of CO_2 desorption
- 500 heating and cooling cycles performed on ¾" core SMA samples
- Power input consistent through all cycles
- No significant change in heating layer electrical properties

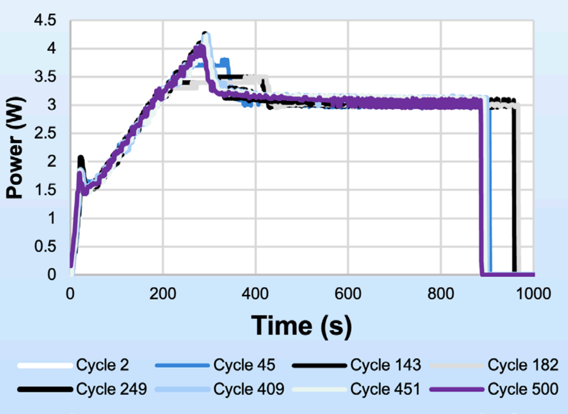
SMA Core Sample Testing



Temperature Profile



Power Input Profile

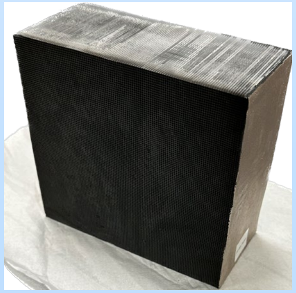


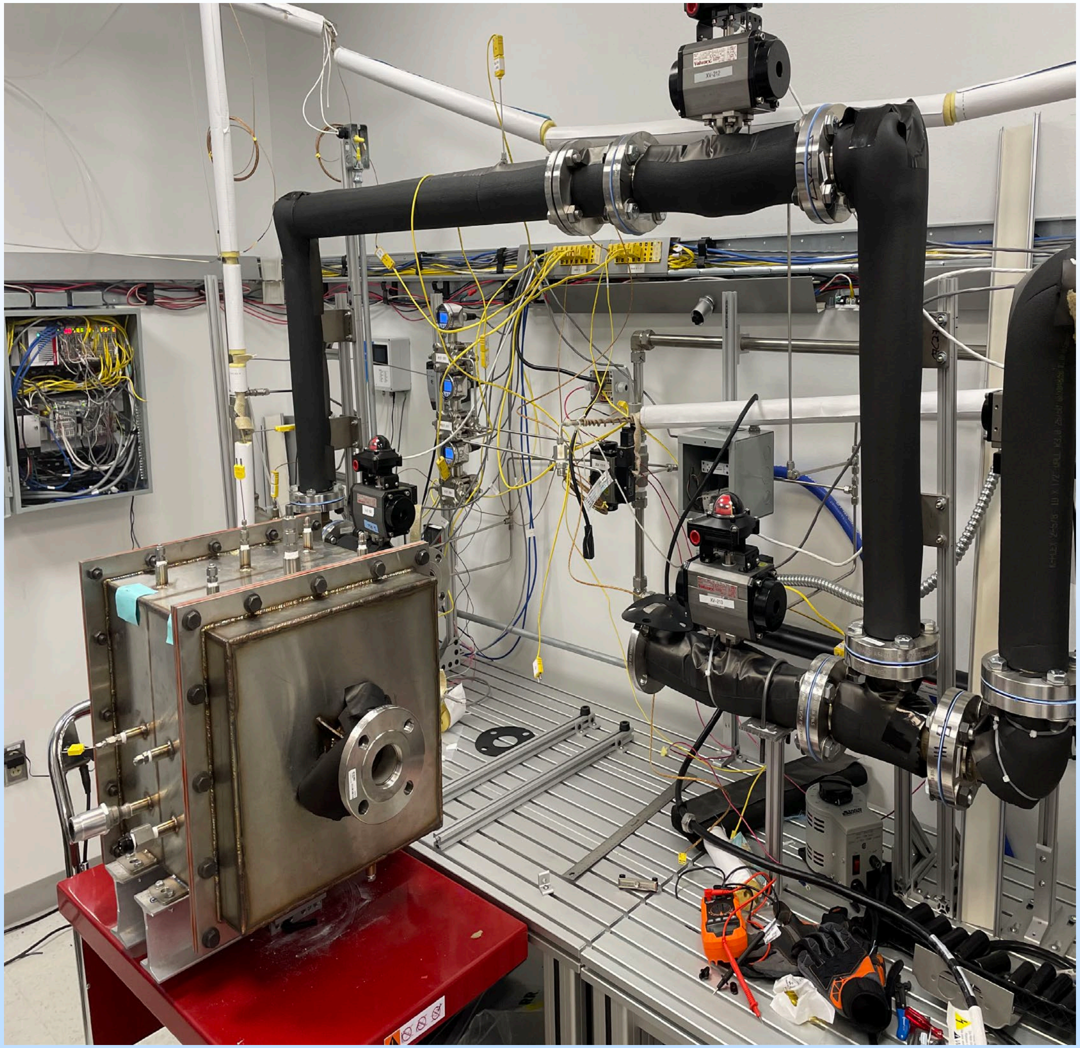
Bench-Scale Unit: Design

- 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
- Full-scale four monolith bricks (150 mm cubes) can be tested
- System fully commissioned in Spring 22.

Bare Monolith

Integrated SMA

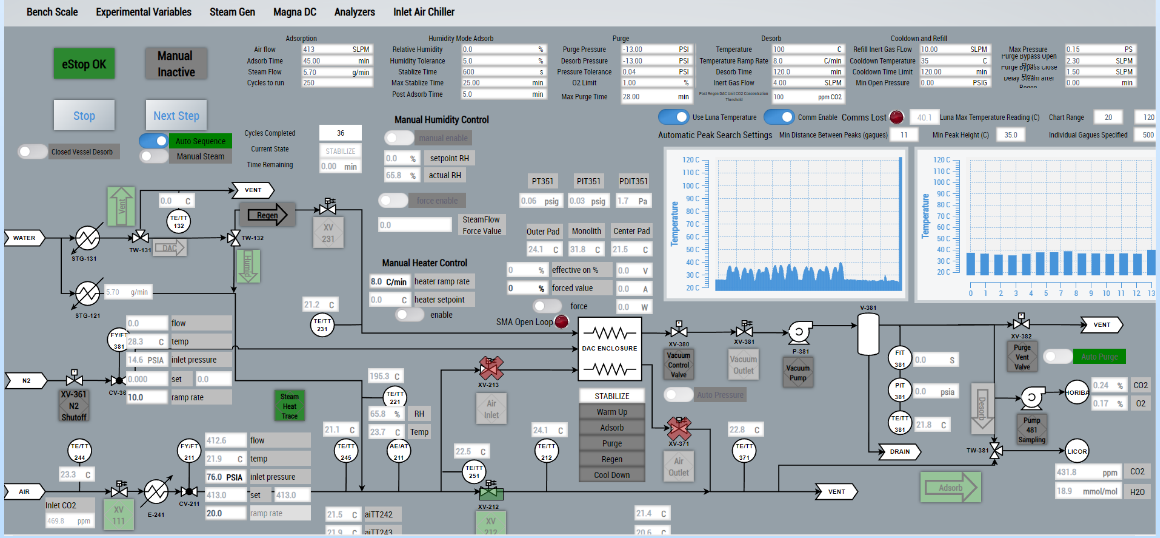




Bench-Scale Unit: Capabilities

- Capture CO_2 from ambient air (not from cylinder gas)
- Test up to 4 SMAs
- Fully automated, 24/7 unit operation
- Customizable control sequencing and sequence conditions
- Online data acquisition, computing, and monitoring

Sample HMI Screen



Adsorption

Air flow	413	SLPM
Adsorb Time	45.00	min
Steam Flow	5.70	g/min
Cycles to run	250	

Humidity Mode Adsorb

Relative Humidity	0.0	%
Humidity Tolerance	5.0	%
Stablize Time	600	s
Max Stablize Time	25.00	min
Post Adsorb Time	5.0	min

Purge

Purge Pressure	-13.00	PSI
Desorb Pressure	-13.00	PSI
Pressure Tolerance	0.04	PSI
O2 Limit	1.00	%
Max Purge Time	28.00	min

Desorb

Temperature	100	C
Temperature Ramp Rate	8.0	C/min
Desorb Time	120.0	min
Inert Gas Flow	4.00	SLPM
Post Regen DAC Unit CO2 Concentration Threshold	100	ppm CO2

Cooldown and Refill

Refill Inert Gas FLow	10.00	SLPM
Cooldown Temperature	35	C
Cooldown Time Limit	120.00	min
Min Open Pressure	0.00	PSIG
Max Pressure	0.15	PS
Purge Bypass Open Flow	2.30	SLPM
Purge Bypass Close Flow	1.50	SLPM
Delay Steam after Regen	0.00	min

Cycles Completed: 36
Current State: STABILIZE
Time Remaining: 0.00 min

Manual Humidity Control
setpoint RH: 0.0 %
actual RH: 65.8 %
SteamFlow Force Value: 0.0

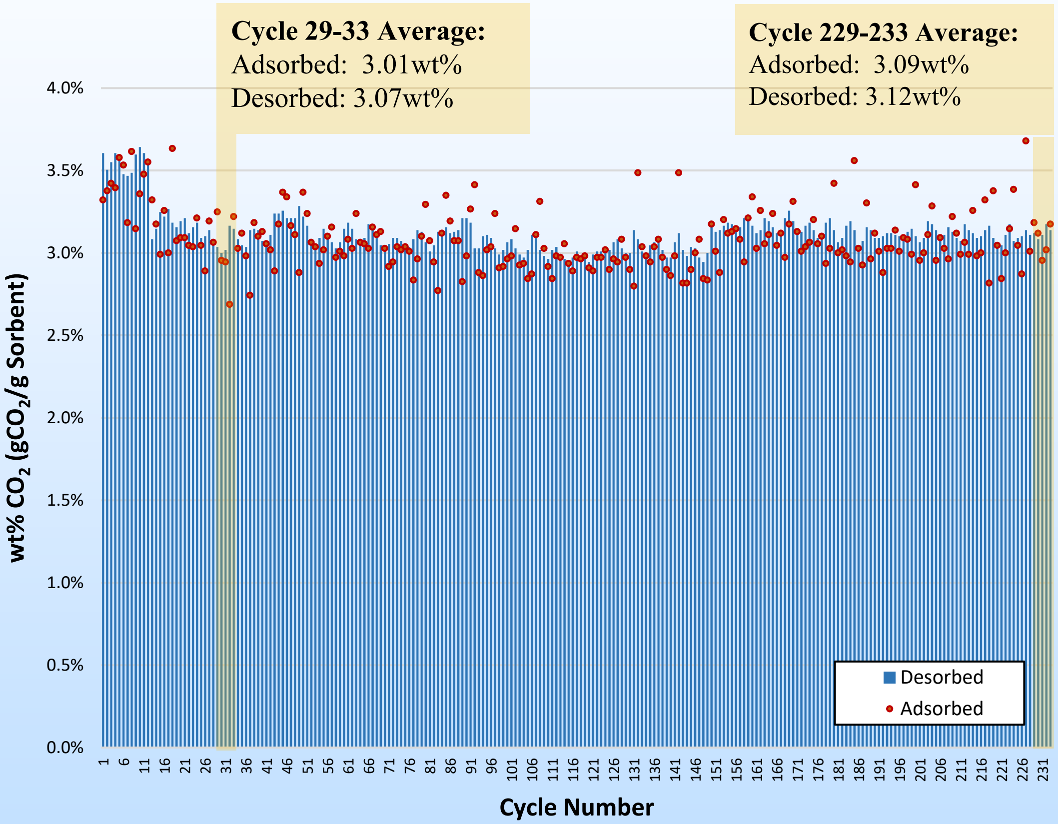
PT351: 0.06 psig
PIT351: 0.03 psig
PDIT351: 1.7 Pa

Use Luna Temperature
Comm Enable
Comms Lost
Luna Max Temperature Reading (C): 40.1
Chart Range: 20 120

Automatic Peak Search Settings
Min Distance Between Peaks (gagues): 11
Min Peak Height (C): 35.0
Individual Gagues Specified: 500

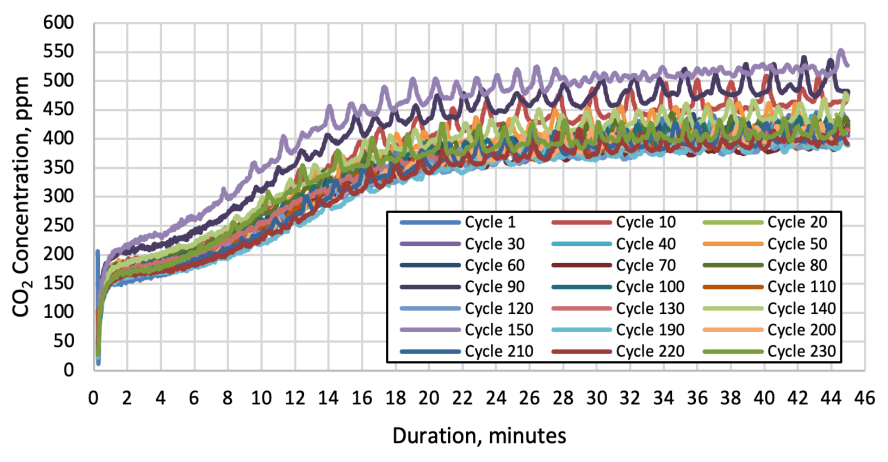
Bench-Scale Unit Test Results

- No operational issues observed throughout this long-term testing
- No discernable capacity fade observed after cycle 30
- SMA stable after >300 cycles of operation
- Completed Success Criteria: Complete at least 100 cycles of bench-scale system, continuous testing of the DAC process cycle to show less than 5% decrease in system CO_2 capacity

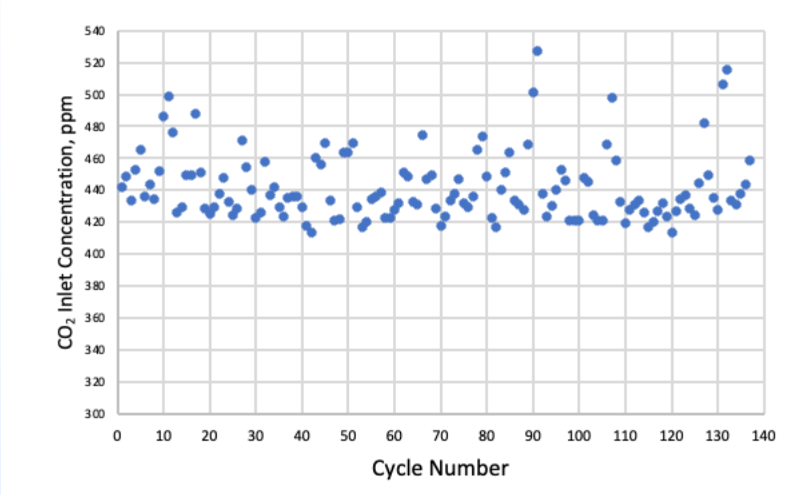


Bench-Scale Unit Test Results

CO_2 Breakthrough Profiles During Adsorption Step



CO_2 Outlet Concentration During Adsorption

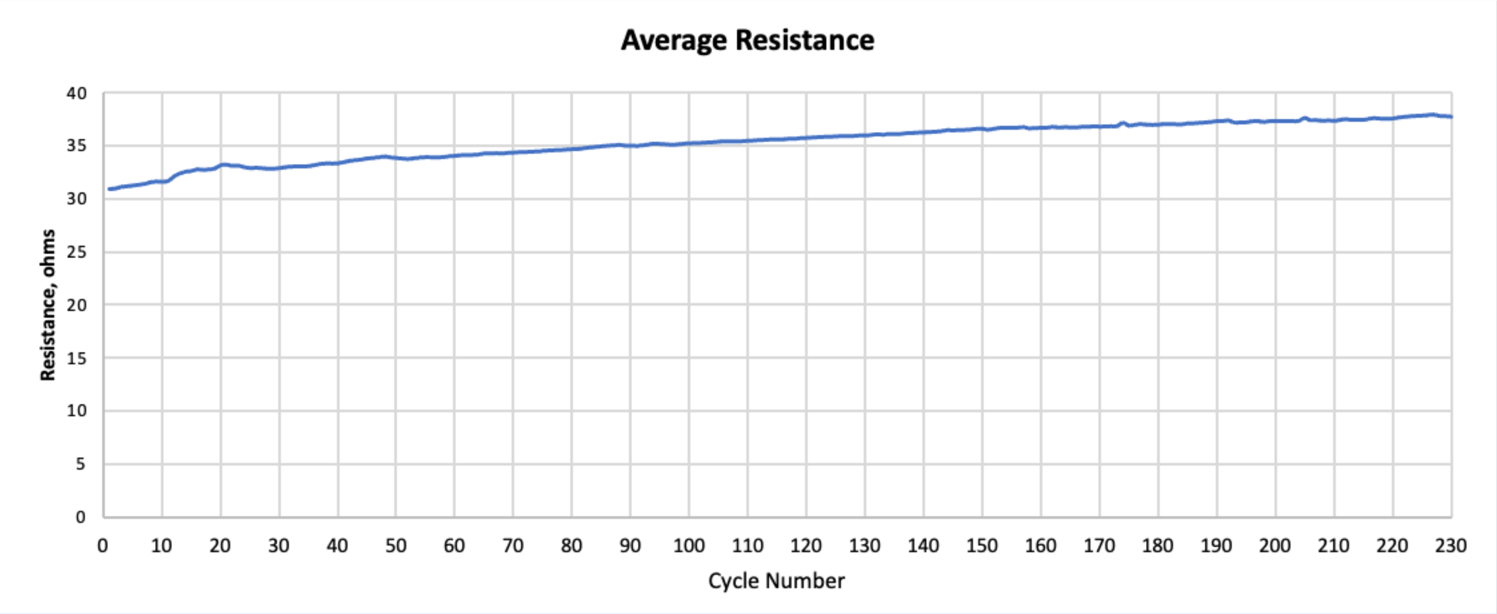


CO_2 Inlet Concentration During Adsorption

- Some air bypass around SMA observed
- No observable changes in breakthrough profiles from cycle to cycle
  - Concentrations (shift in on y-axis) due to variable day-to-day CO_2 concentration in air feed
- No observable pressure drop across SMA, <0.012 inH_2O

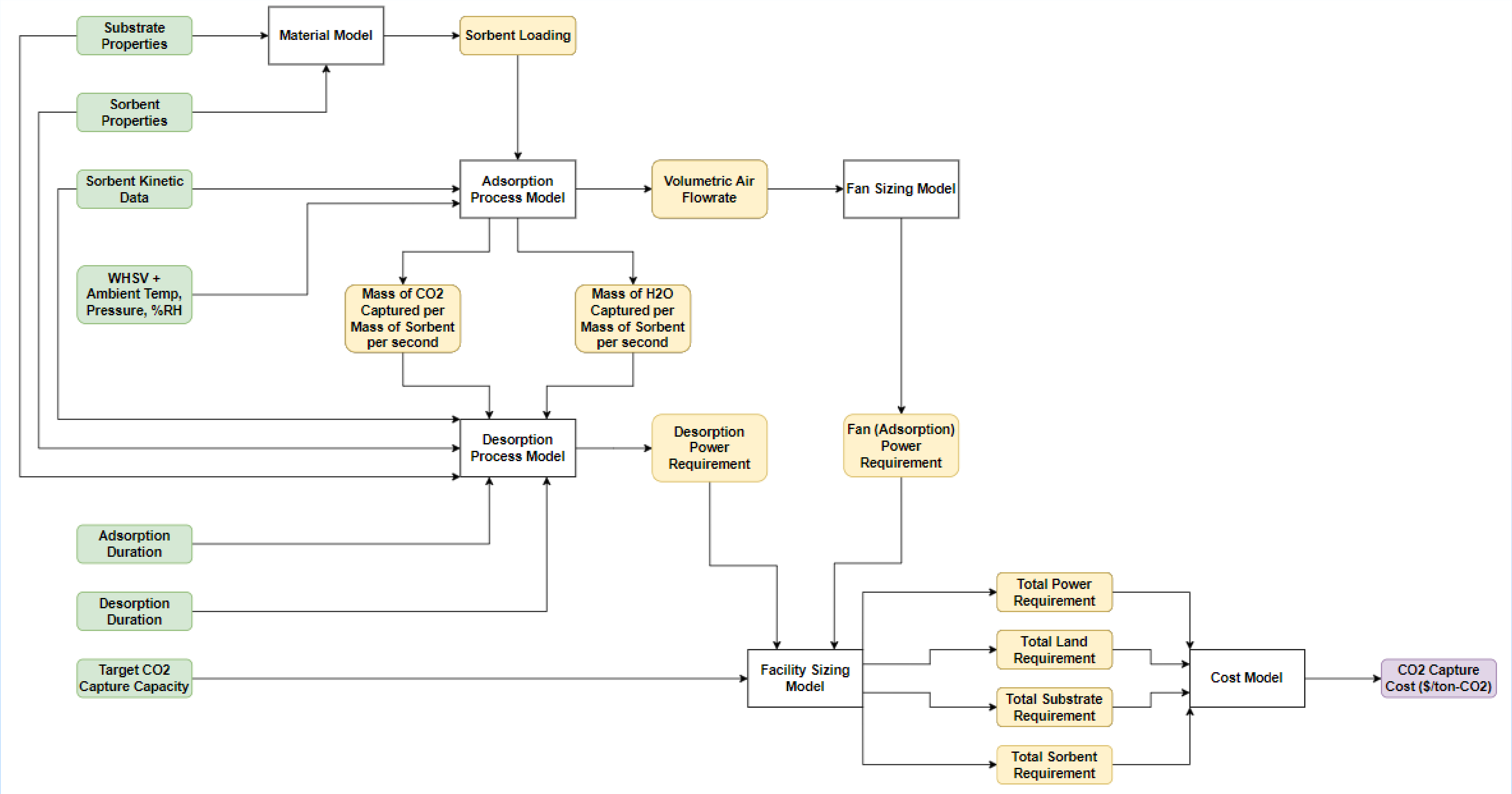
Bench-Scale Unit Test Results

Sustained Electrical Properties of SMA



- SMA resistance stabilizing, consistent with 500 cycle core sample rapid heating test
- Observed resistance increase is manageable for a commercial unit design

Process Model Development



Finalizing process model and technoeconomic assessment

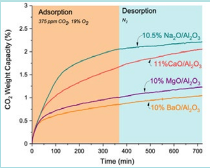
Technology Development Roadmap

Scale

TGA Testing

SC0020795

- Na-Based Sorbent Material Selected
- Proof of concept of on reaction pathway



Laboratory Testing

(3 g/day)

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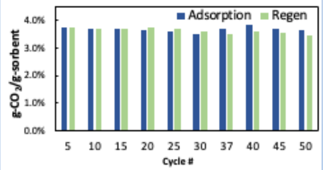
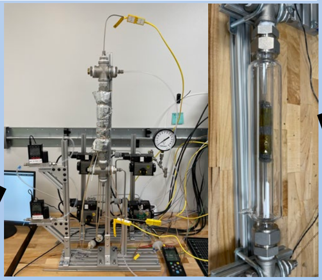
- Verified sustained performance of structured sorbent
- Proof of concept resistive layer coating showing high CO_2 desorption rates





Bench Component Testing

(Intermittent 1 kg/day)

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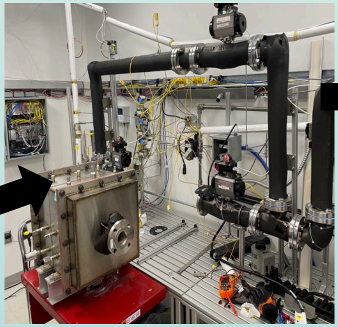
- Optimize sorbent and heating material wash coat synthesis on selected structured sorbent
- Verify performance of structured sorbent for adsorption and desorption



Integrated Bench Testing

(1 TPY)

FE0032243

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

Integrated Bench System Testing

DAC Unit Demonstration

(10-30 ton/day)

- Demonstrate full scale DAC unit
- Fits DOE DAC Hub target

Progress

Acknowledgements

Project Sponsor

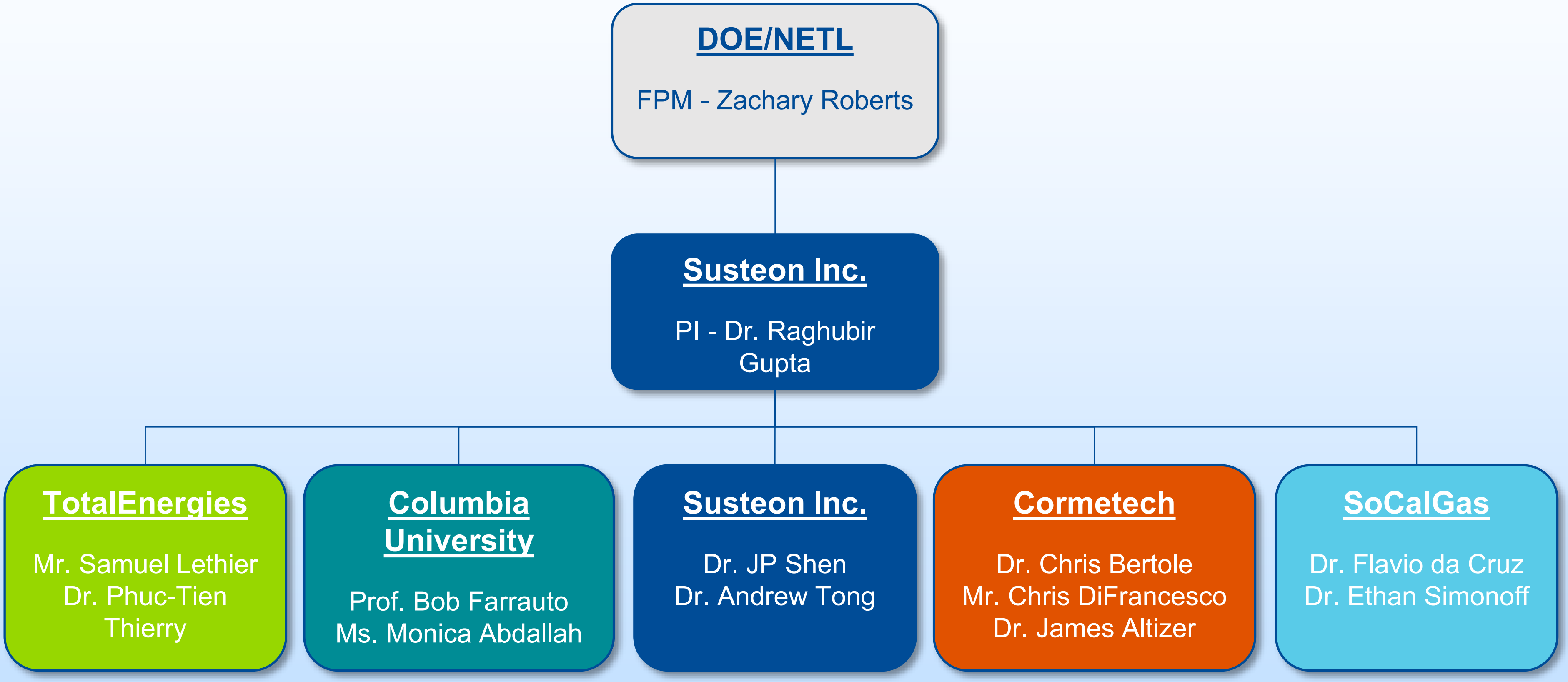
- National Energy Technology Laboratory: This material is based upon work supported by the Department of Energy under Award Number **DE-FE0032118**

Project Partners

- Columbia University (Professor Robert Farrauto)
- Sustaera
- Cormetech
- TotalEnergies
- SoCalGas

Appendix

Organization Chart



DOE/NETL

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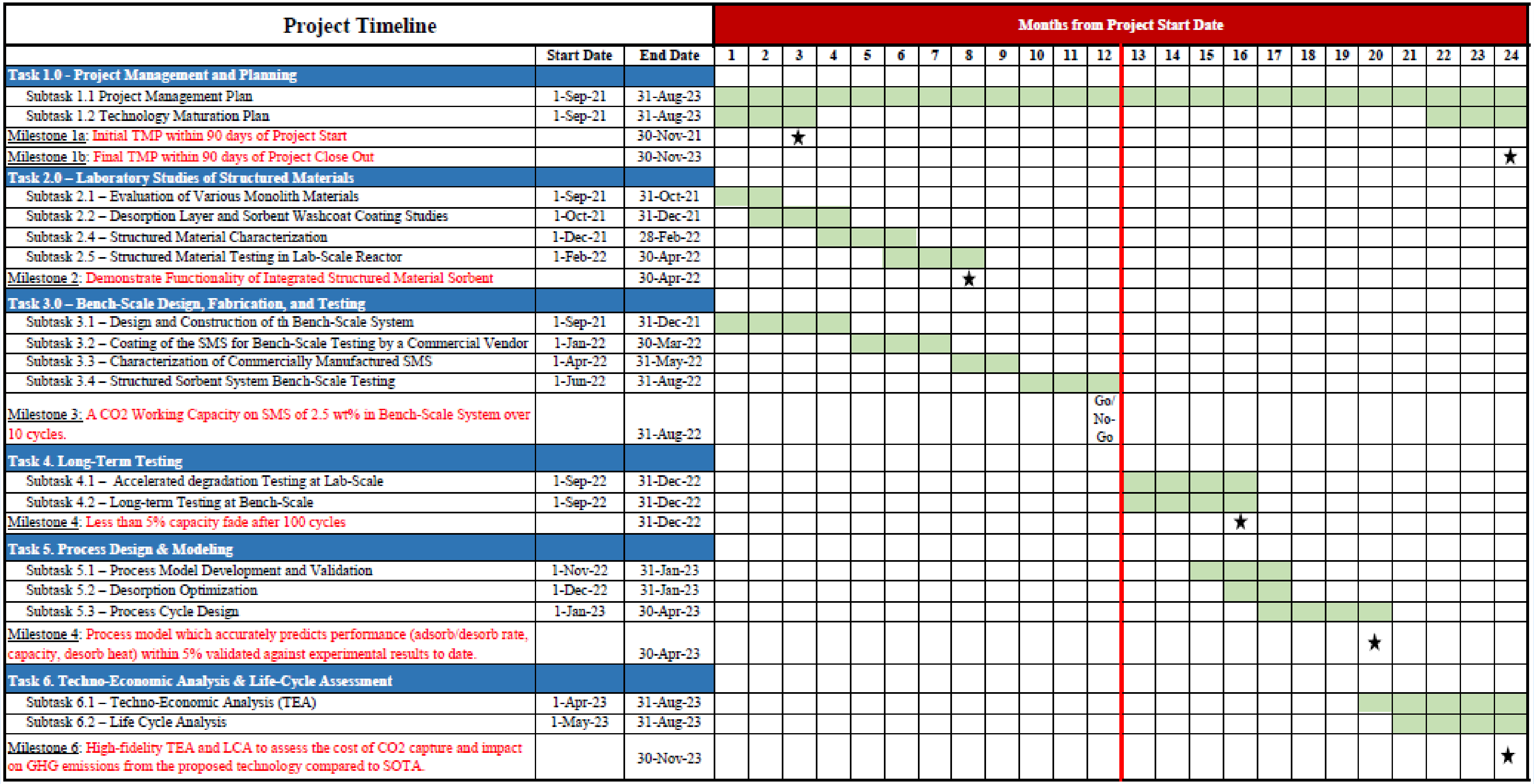
Gantt Chart



Project Timeline			Months from Project Start Date																							
	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
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																								★