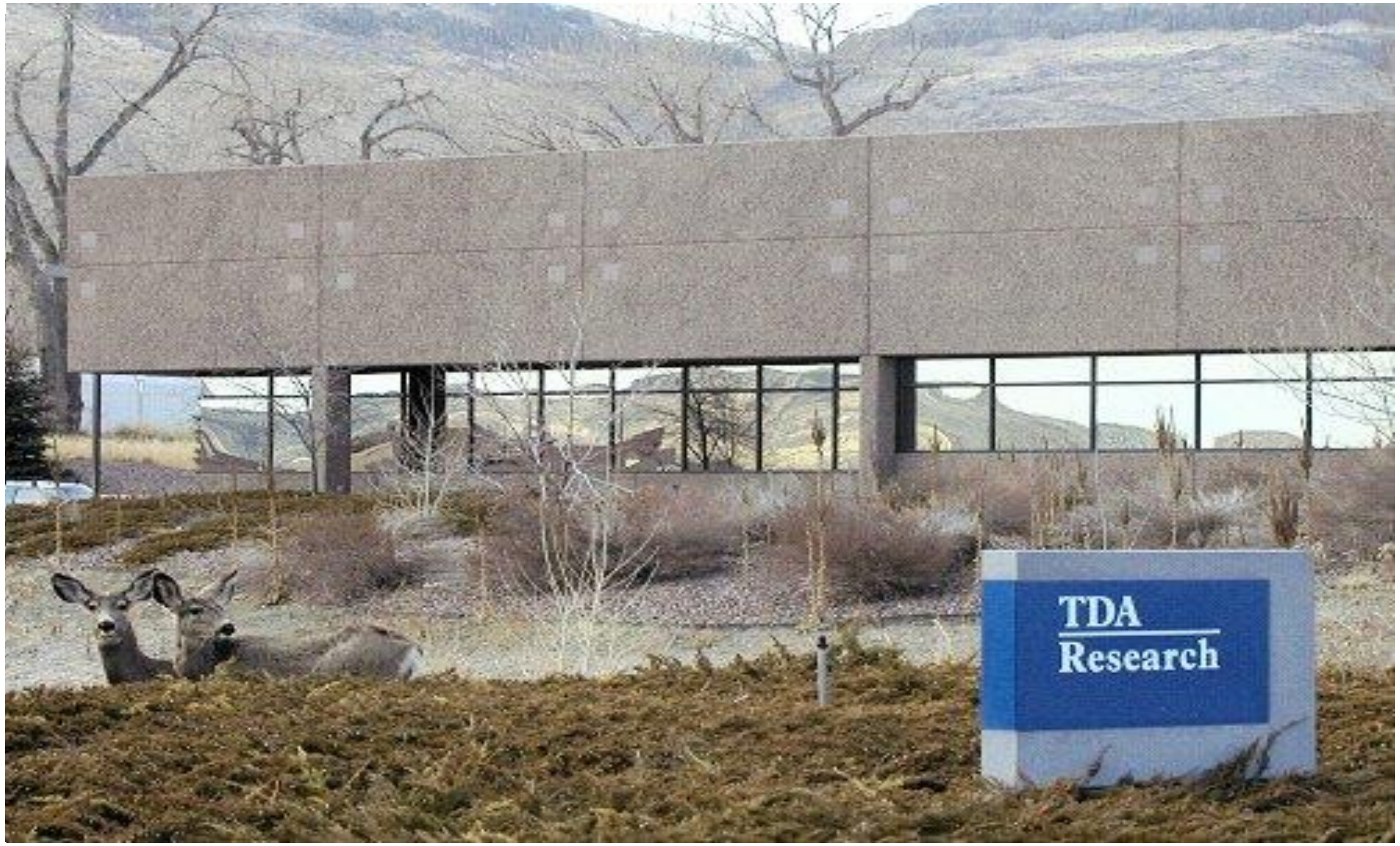
3D Printed Engineered Structures for High Performance Direct Air Capture System

Contract No. FE0032260



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Carbon Management Review Meeting

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Project Team and Objectives

- To design and construct an engineered sorbent structure for capturing CO_2 from ambient air via a rapid temperature swing adsorption (RTSA)
- Unit cell will be a 3D printed monolith with integrated heating
  - Low pressure drop
  - Enhanced heat transfer to ensure high CO_2 productivity in the TSA cycle (kg CO_2 removed per kg sorbent per unit time)

Project Duration

- Start Date = September 2023
- End Date = March 2027

Budget

- Project Cost = $3,749,956
- DOE Share = $2,999,956
- TDA & partners = $750,000

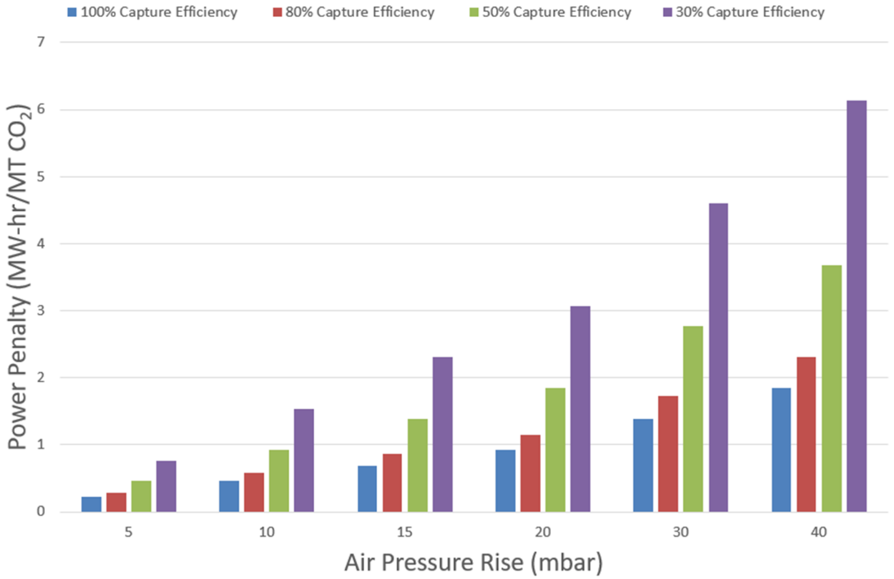
BP	Period	Main Activity
1	Year 1	Preparation of Small Test Articles
		Optimization of Paste Properties
		Screening Tests
2	Year 2	Preparation of Larger Test Articles
		Large scale Evaluations
		Long-term Cycling
3	Year 3	Module Design
		Techno-economic Assessment
		Life Cycle Analysis

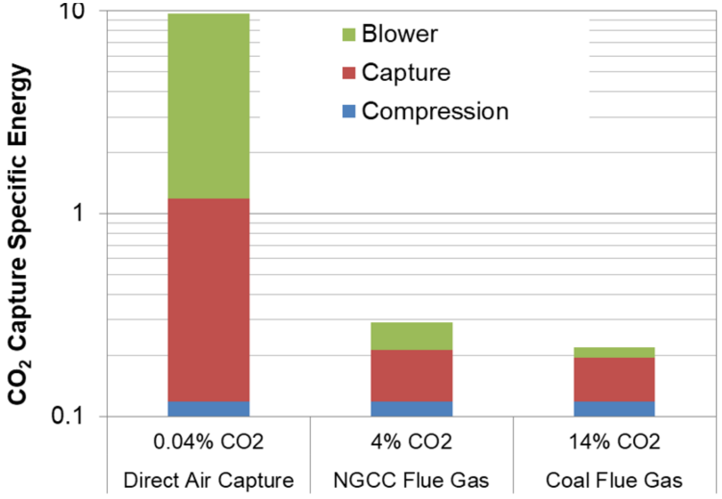
Introduction

- **Sorbent-based DAC systems have to address two key challenges that stem from the low concentration (400-500 ppmv) of CO_2 in air:**
  - Need to circulate large volumes of air
  - A rapid cycle sequence that increases the CO_2 productivity (ton CO_2 removed per ton sorbent per hr)

- **A cost-effective gas-solid contactor must achieve a low pressure drop**
- **An effective heat integration/management system is needed to ensure a rapid cycle to reduce the sorbent inventory**

Energy Penalty for Moving Air





A fixed pressure drop is assumed in all contactors

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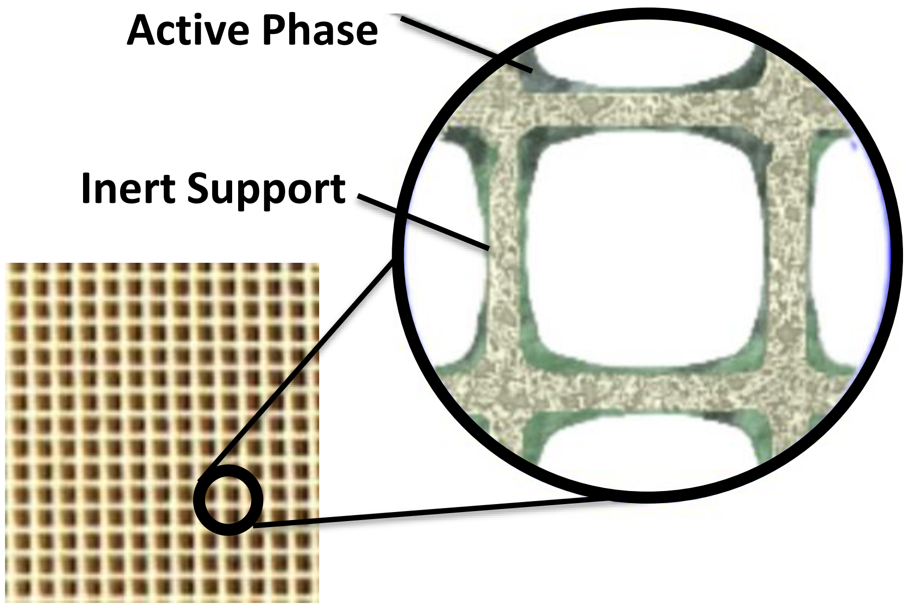
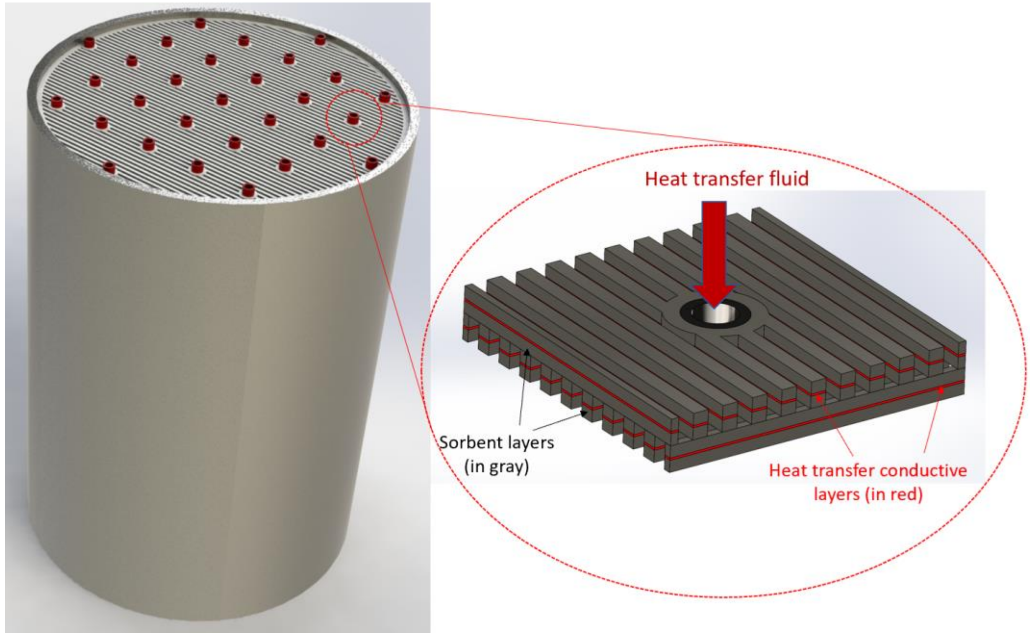
Approach

- A new gas-solid contactor is designed based on 3D printed monoliths where the entire monolith is made out of the reactive phase
  - Low pressure drop due to the presence of open flow channels
  - High active material loading (high volumetric capacity)
  - Possibility to integrate electric heaters using conductive paste to allow rapid heating



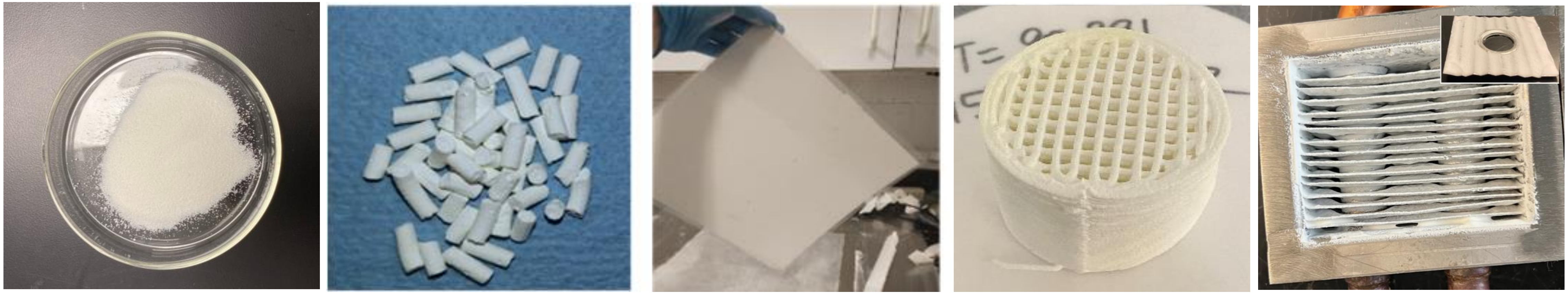
Conventional Monoliths



TDA's Monolith

TDA's Sorbent for DAC

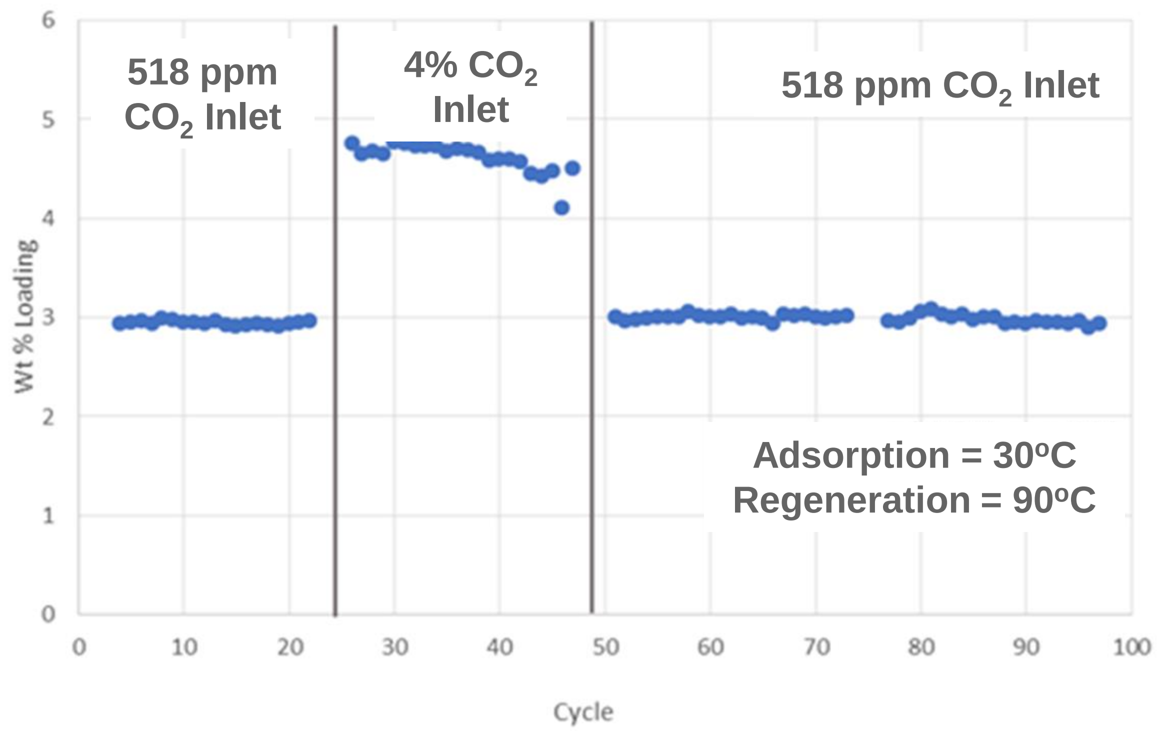
- **TDA has been developing a new polymer sorbent for DAC and life support applications (DE-SC-00020846, 80NSSC18C0135, N00178-18-C-8009)**
  - **Sorbent has very high CO_2 uptake in dilute gas streams (e.g., 400 ppm CO_2 in air; 2,500 ppm spacecraft cabin; up to 5,000 ppm in submarines)**
  - **The sorbent maintains its stability at high temperatures**
- **The sorbent can be prepared in the form of pellets, laminates and 3D printed monoliths; in this project it will be applied as a 3D printed monolith**

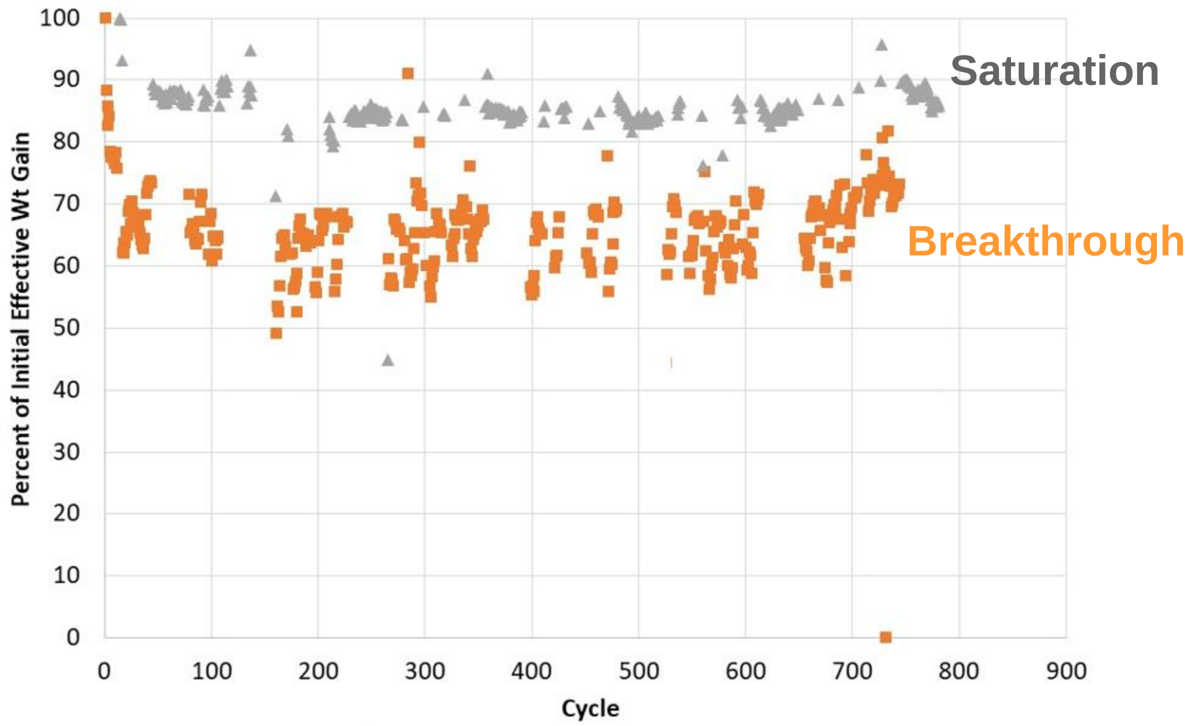


(a) (b) (c) (d) (e)

Various forms of polymer sorbent: (a) powder (b) pellets (c) single laminate layer (d) 3D printed monolith (e) applied as a coating on HEX surfaces

Temperature & Cyclic Stability





- **High stability under TSA/VTSA cycling**
- **High working capacity**
  - **~3% wt. CO_2 uptake at a 60°C swing**
- **Stable operation for ~800 cycles under DAC conditions (over 10,000 cycles has been demonstrated for the Navy application)**

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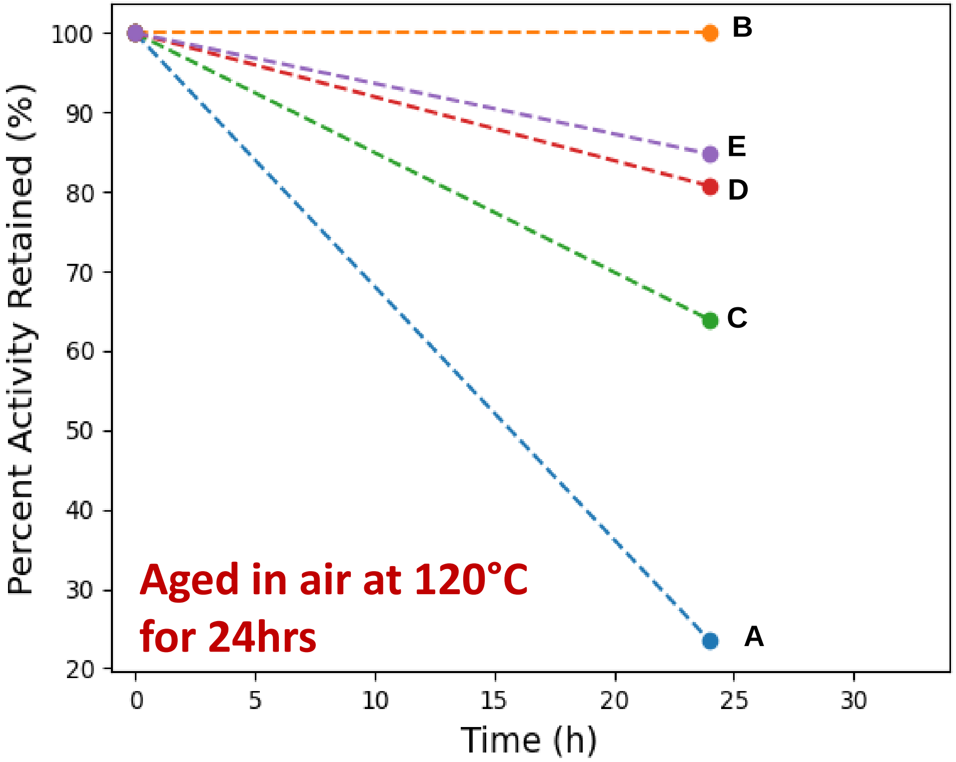
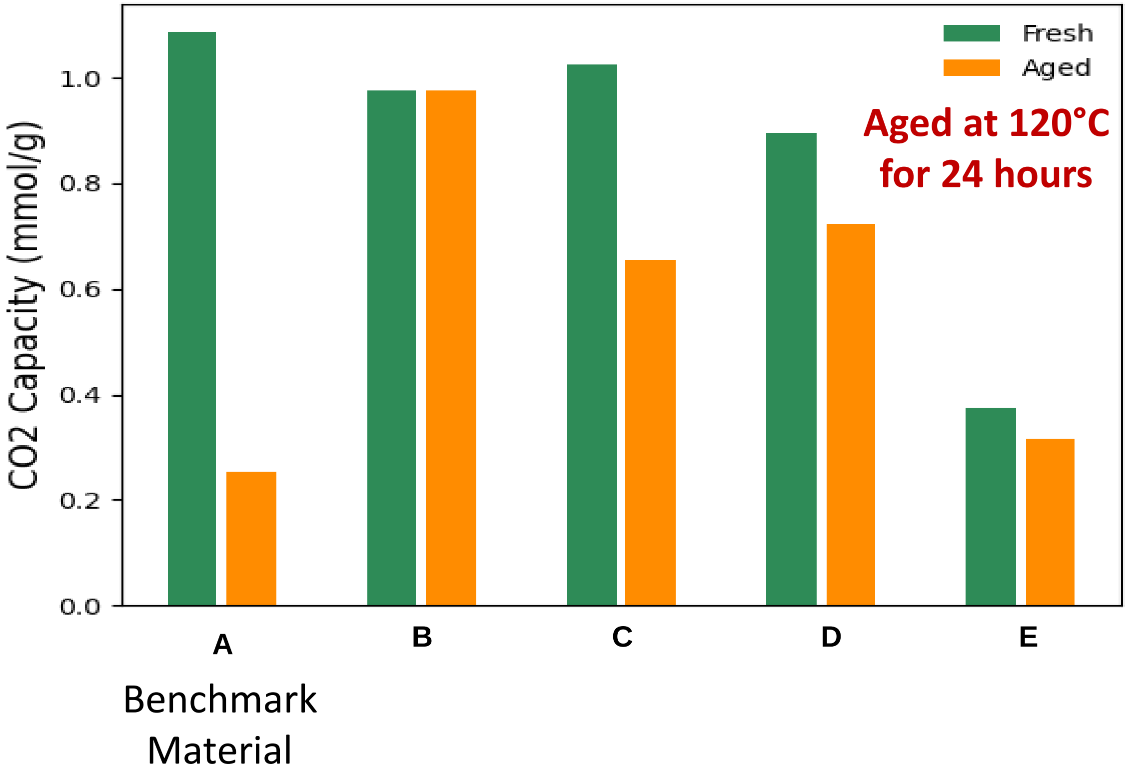
High Temperature Oxidative Stability





- TDA identified several formulations that can provide high temperature oxidative stability
- An aggressive test method is developed to accelerate aging effects in air for 24 h at 120°C under dry conditions
- CO_2 uptake performance is tested before and after the aging test in a 5 min concentration swing cycle at 60°C

3-D Printing Process

Printing

<u>Paste 3D Printer</u>

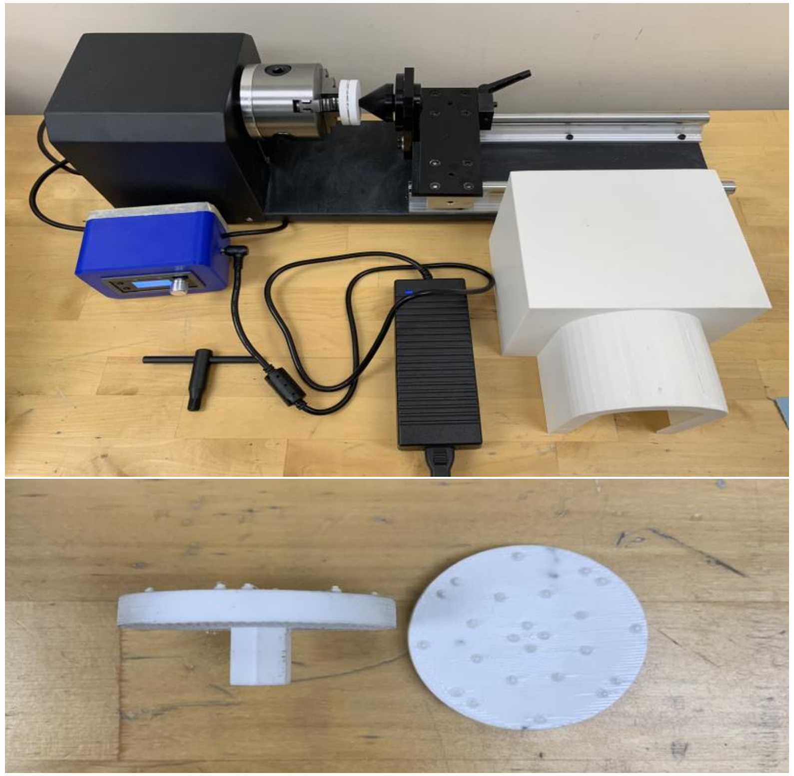
- Liquid Deposition Modeling
- 1.6mm nozzle diameter
- Screw extrusion
- 10 x 10 x 10” build volume

Drying

<u>Custom Drying Chamber</u>

- Adjustable top vent
- Controlled and repeatable drying rate
- Removable cover

Post Processing (Sanding)



<u>Low-Speed Lathe</u>

- Sanding grips to hold the dried monolith, clamped to the lathe
- Shape, dimension, and surface roughness is controlled

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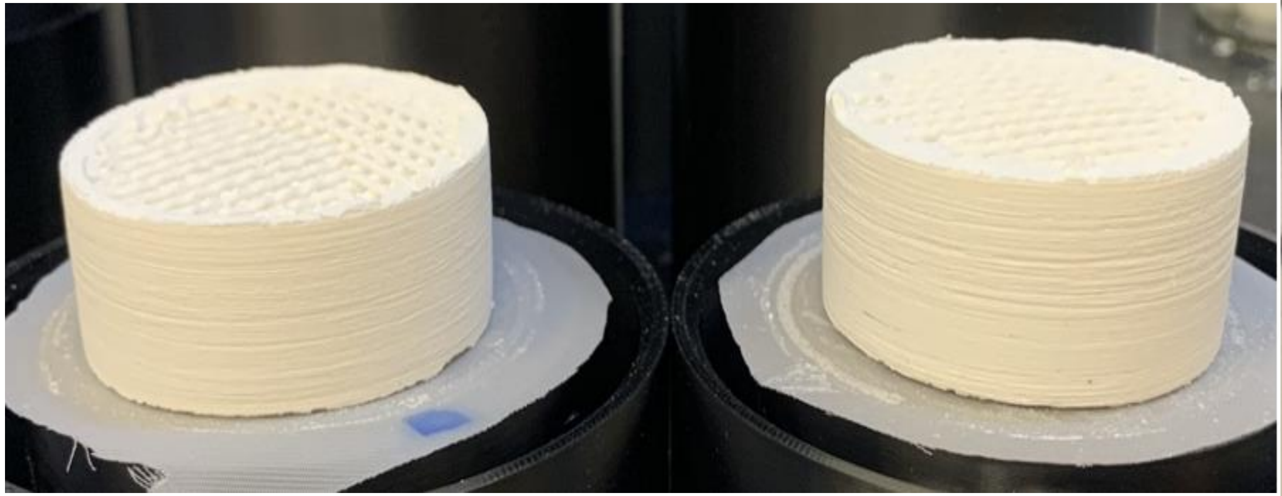
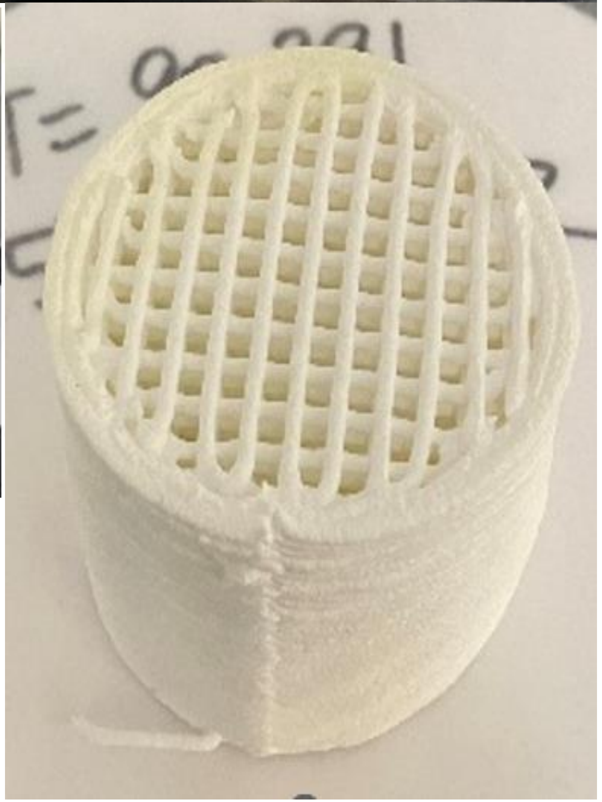
3D Printed Sorbent Samples

Early Preparations

Recent Preparations





- Critical parameters (for mechanical strength) include binder type and composition, paste rheology, printing rate and drying conditions

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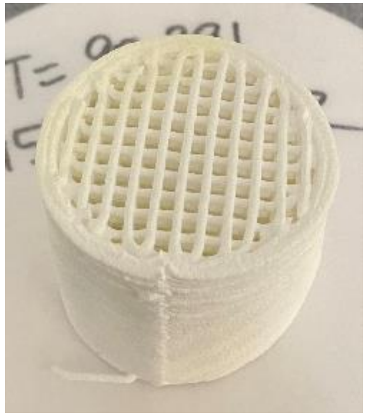
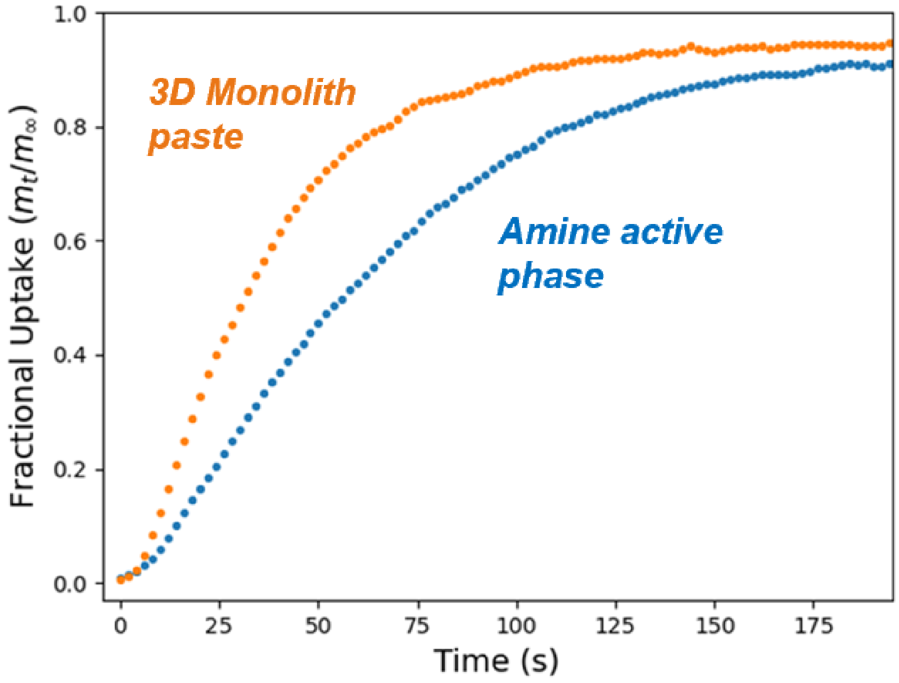
3D Printed Sorbent – Evaluation in the TGA

TDA Standard 60-cycle Test

3D Printed Sorbent CO_2 Uptake	CO_2 Uptake wt.%						
	60°C		80°C		100°C		60°C
Cycled in 4% CO_2/4%O_2/N_2 AND N_2	15/15 min	5/5 min	15/15 min	5/5 min	15/15 min	5/5 min	5/5 min
3D Print Monolith Section	5.74	5.38	2.00	2.05	0.52	0.62	5.46
Baseline Sorbent	6.94	4.94	2.90	2.94	0.78	0.77	5.11



- 5/5 min cycles (kinetic regime) showed ~10% reduction in CO_2 uptake while 15/15 min cycles (saturation) resulted in 18% reduction
- Binder acts as a diluent but did not degrade the amine
- Binder enables better dispersion of the active phase which led to the improved performance during short cycle time tests
- Stability was intact through the 60-cycle test

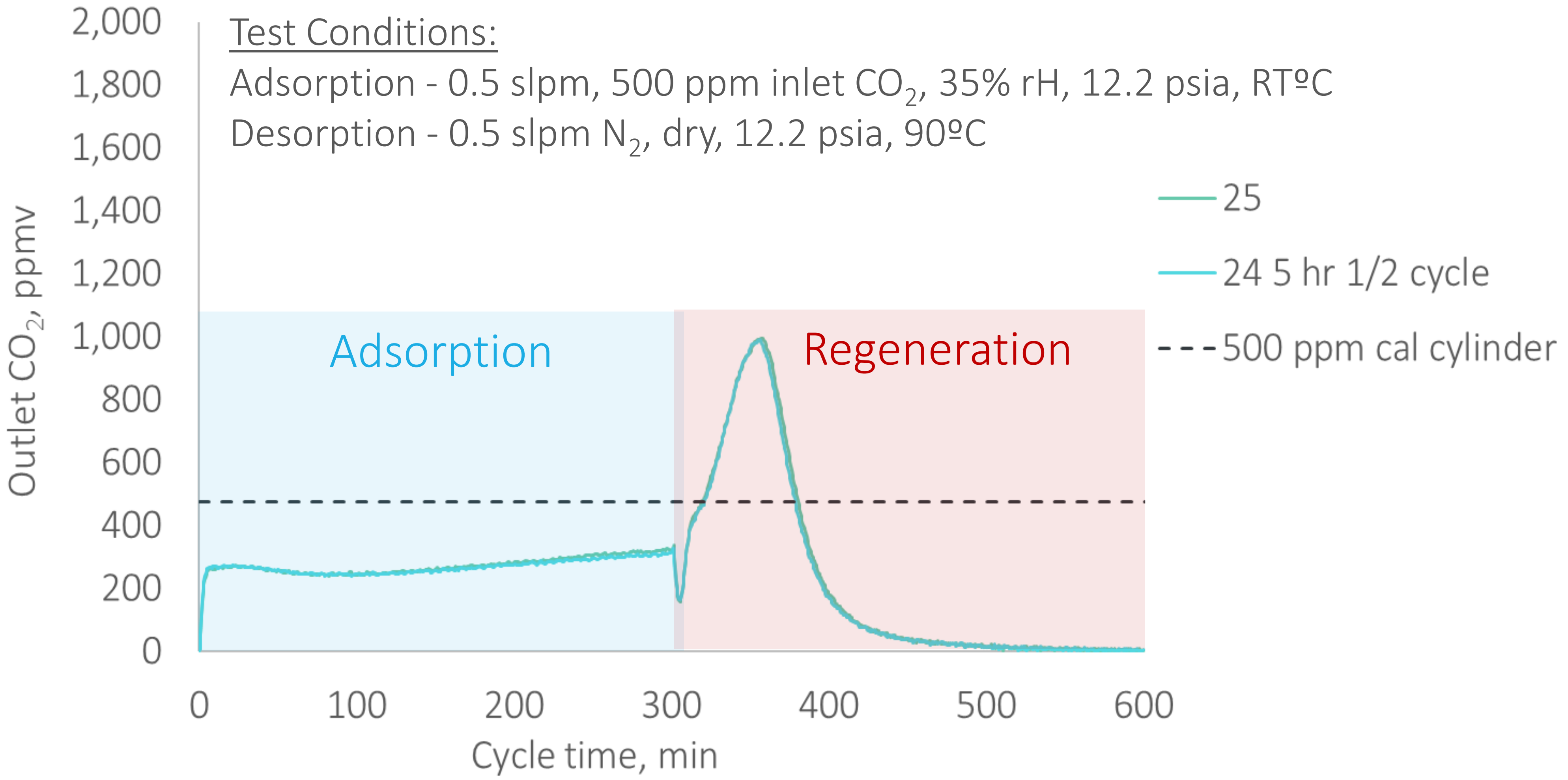


Bench Scale Sorbent Module for CO_2 Uptake

Bench Scale Test Cell
- ~100 mL Volume
- 2" x Ø1.87" Tri-clamp Spool
- Monolith Diameter: 43.8 mm, Height: 40-90 mm, Channel spacing 4 mm
- Non-porous polymer tape around the monolith to prevent gas channeling

Bench Scale Test System
- Electronic mass flow controllers to introduce air, N_2, O_2
- Water is introduced using a sparger
- Thermal swing and thermal/vacuum swing simulations
- Automated operation

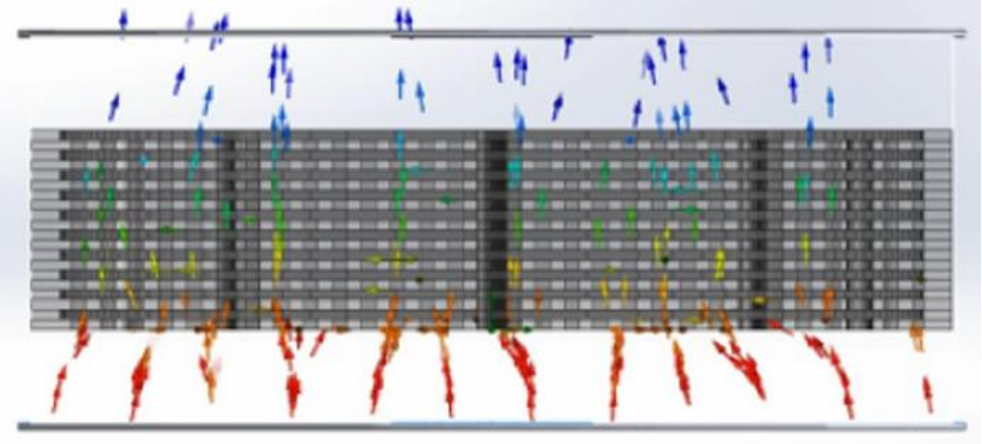
Bench Scale Test Results (Preliminary)



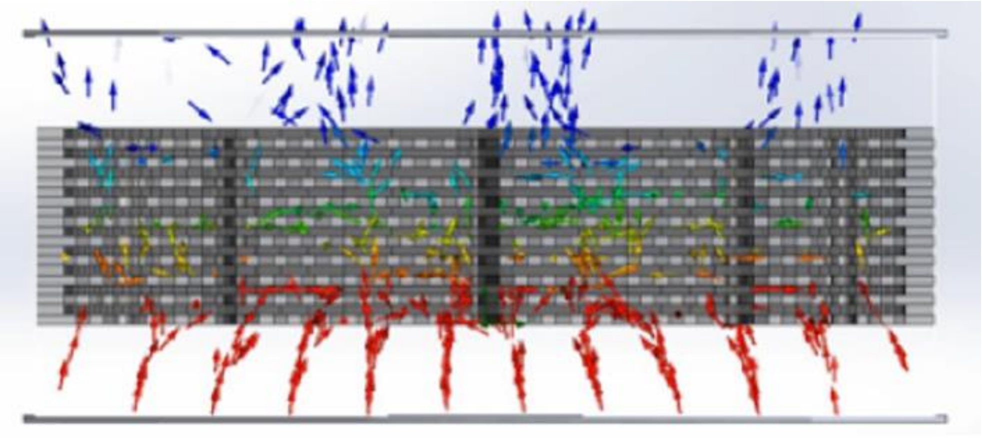
3D Printed DAC Printing Geometries

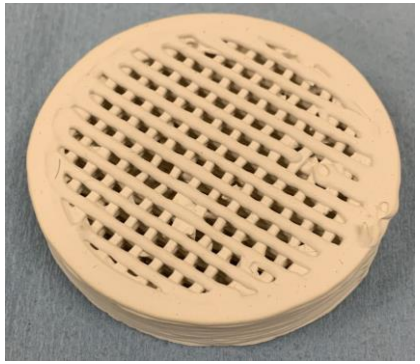
Advanced channel configurations could allow better flow distribution

Straight Channel Configuration



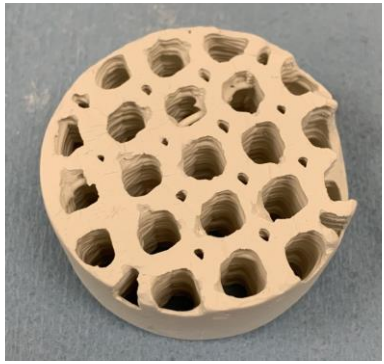
Staggered Channel Configuration



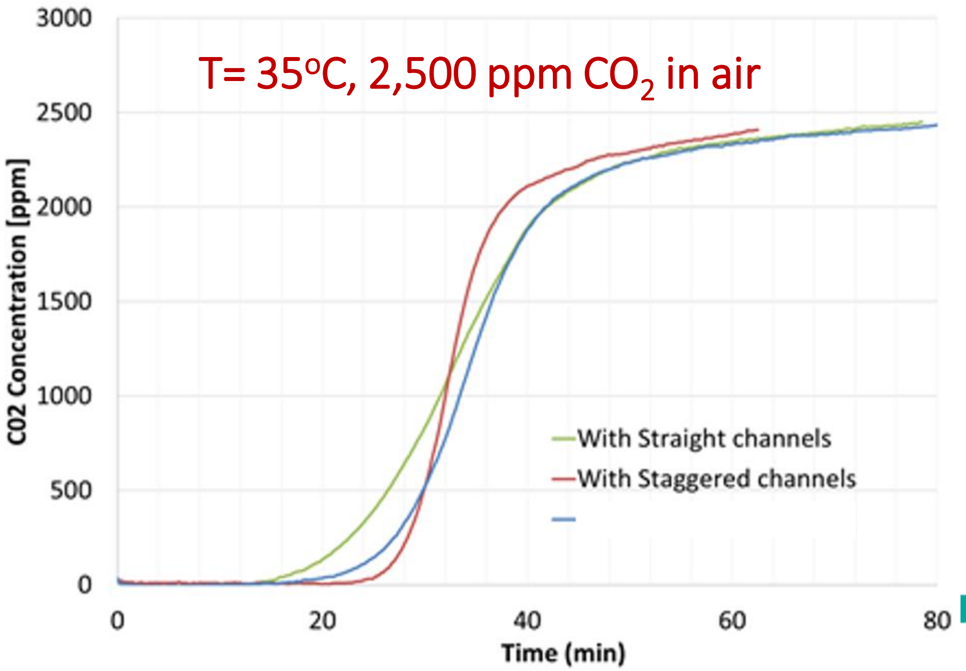


Standard Rectilinear

Gyroid Infill



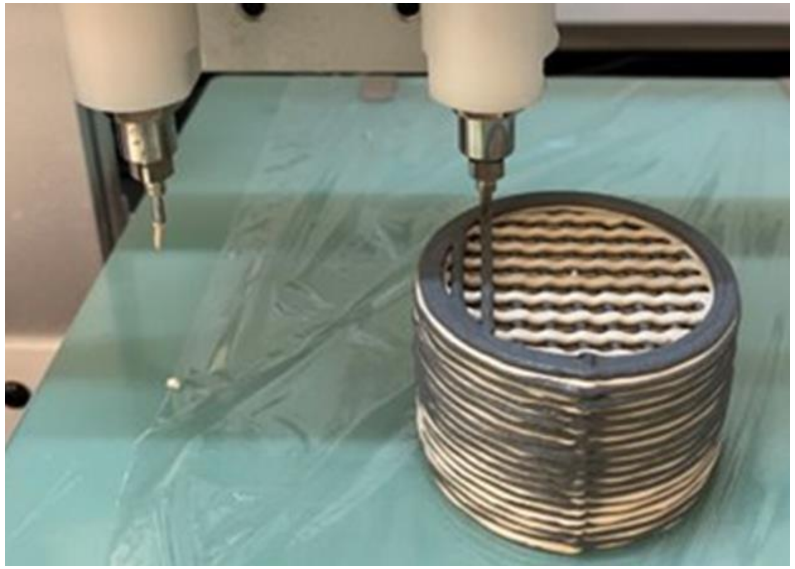
Repeating Circles



Heat Transfer Improvements

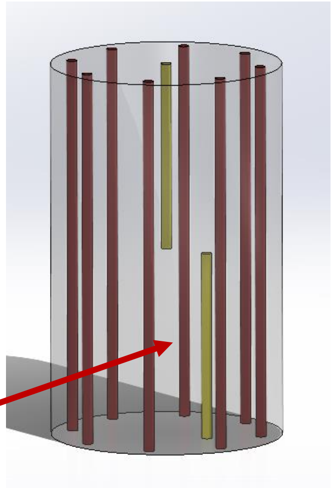
- Thermally conductive pastes may be used to improve the heat transfer rate
- These can be directly mixed with the active phase or can be printed in alternating layers using the dual-head printer
- Thermally conductive paste will be in direct contact with the heating elements that allows rapid heating
- Safe electrification of the DAC module/process

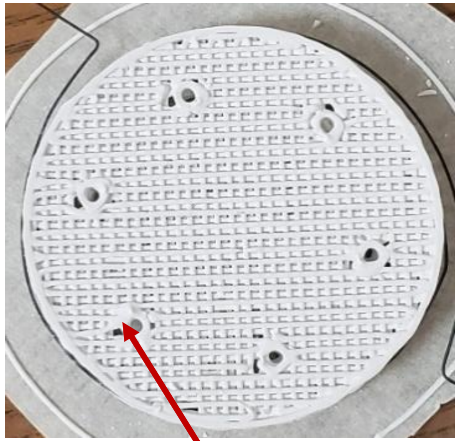
Graphite/sorbent mixture



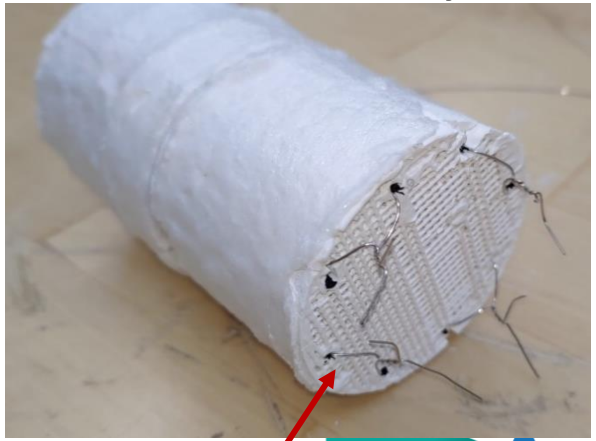
Integrated thermal conductive layers

Wire heaters





Conductive paste potting

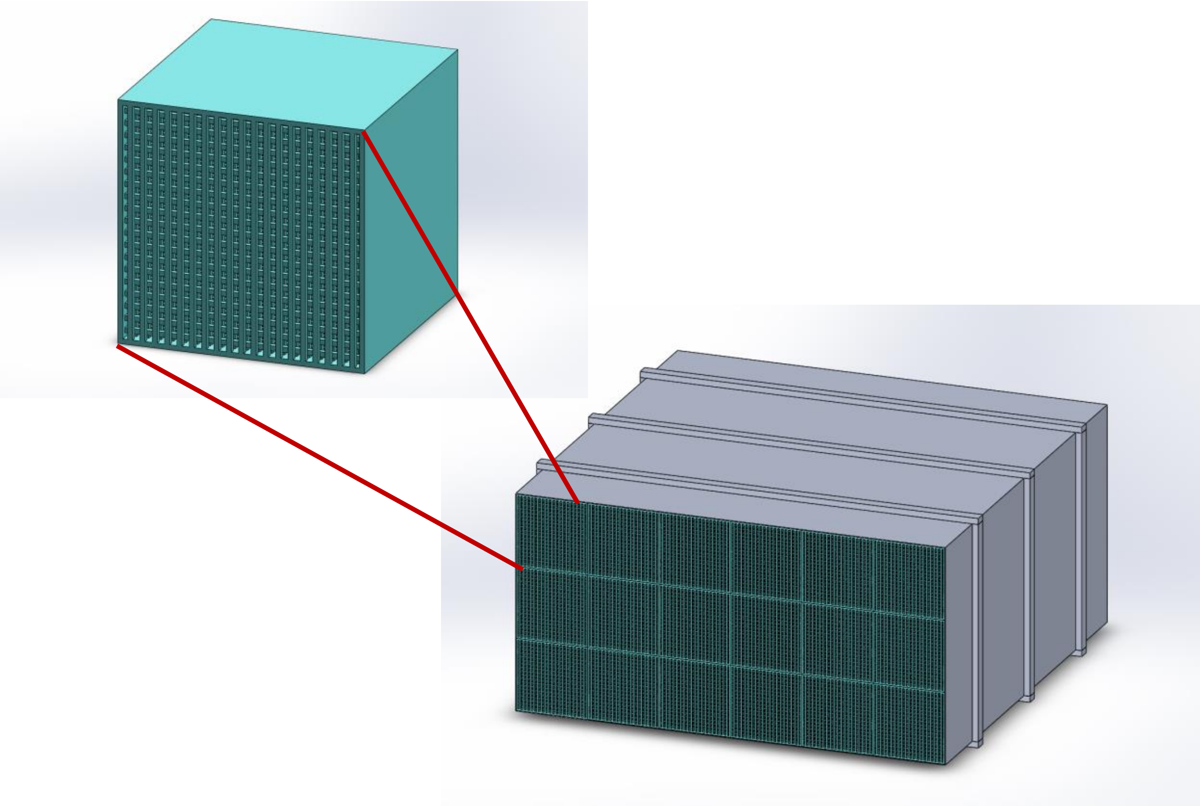


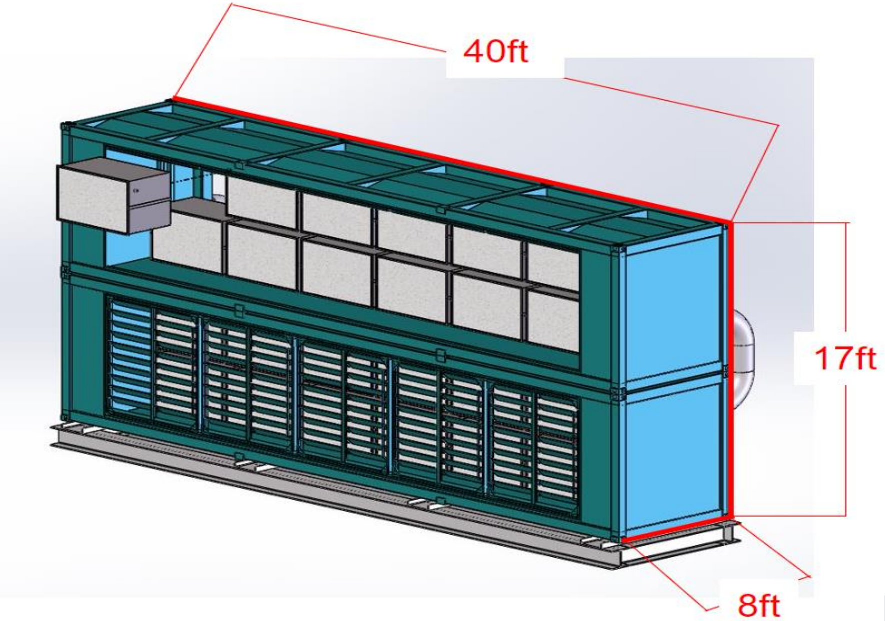
Wire heaters

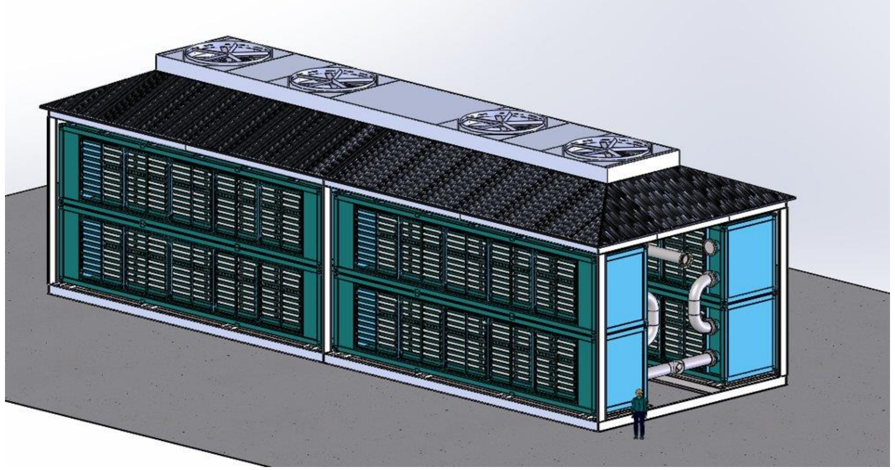
System Design

Shipping Container Modules (40' x 8' x 8.5’)

- 1 ft x 3 or 6 ft Sorbent Cube Cell to form a sub-module
- Multiple Sub-modules per Shipping Container







Future Work

Task 1. Project Management

Budget Period 1

Task 2. Preparation of Sorbent Material

Task 3. Preparation of Structured Sorbents

Task 4. Evaluation of Test Articles

Task 5. Design of the Sorbent Module

Task 6. Initial Techno-Economic Analysis

Budget Period 2

Task 7. Preparation of Larger 3D Structures

Task 8. Fabrication of the Test Unit

Task 9. Multiple Cycle Testing

Task 10. Process Simulation/Optimization

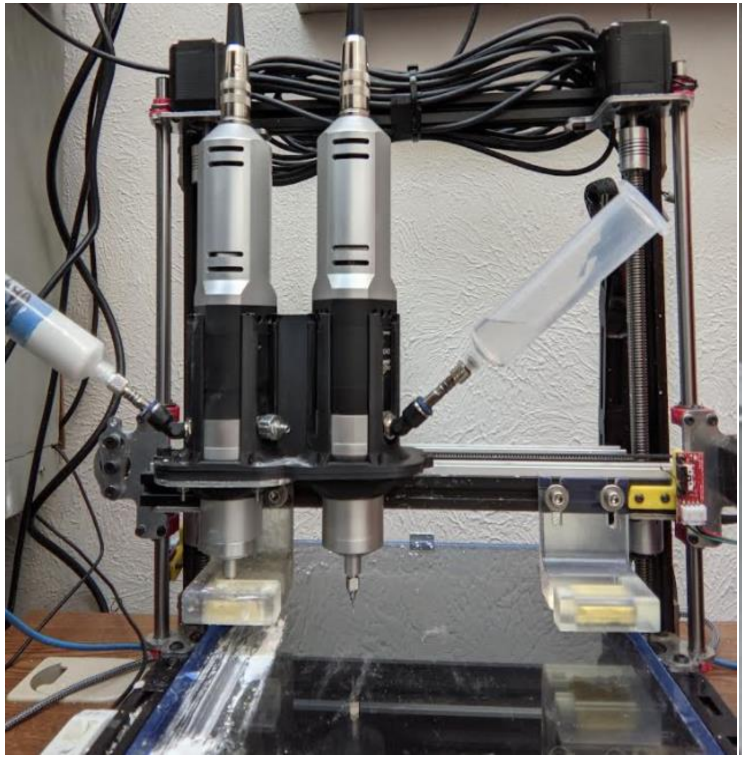
Budget Period 3

Task 11. Evaluation at Structured Sorbent

Task 12. Process Simulation/Sensitivity Analysis

Task 13. Final TEA

Task 14. EH&S, TGA and TMP



Double-headed 3D printer Mendel 2.0

4” x 8” 3D printed ceramic monolith

Acknowledgements

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Mr. Sai Gollakota

Collaborator
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