Transformational Sorbent-Based Process for Direct Air Capture (DE-SC002740)

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Executive Summary

InnoSepra's direct air capture process utilizes physical sorbents with low heats of adsorption (~0.8 GJ/MT)

- >4-wt% CO_2 capacities at the CO_2 concentration in air, ~400-ppm
- Very long-sorbent life (>5 years) and low sorbent cost (<$3/lb)
- Regenerable at low temperatures (<125^{o}C)
- Can be quickly scaled up to very large quantities needed for commercial scale direct air capture
- Potential for up to 50% reduction in the energy needed for Direct Air Capture, <4 GJ/MT
- Potential for up to 50% reduction in the capture cost, <$200/MT

During this Phase II SBIR project InnoSepra is

- Producing and testing the sorbents for direct air capture identified in another DOE project (FE0031953) at the lab scale
- Scaling up the technology for semi-bench scale testing
- Developing an engineering design to carry out a techno-economic analysis for a commercial scale DAC system

Presentation Outline

- Current Approaches for Direct Air Capture
- Background on the Proposed Technology
- Project Objectives and Overview
- Research Plan and Project Scope for the Phase II SBIR Project
- Phase II Work
- Summary

Current Approaches for Direct Air Capture

- A number of technologies have been proposed for direct air capture at close to ambient temperature. Among the proposed technologies two main technologies for Direct Air Capture include:
  - Reactive absorption on alkali metal hydroxides (Carbon Engineering)
  - Reactive sorbents based on impregnated amines (Climeworks, Global Thermostat, Silicon Kingdom Holdings, and a number of DOE funded projects)
- No technology for direct air capture using physical sorbents (this project) have been proposed

Current Approaches for DAC (Contd.)

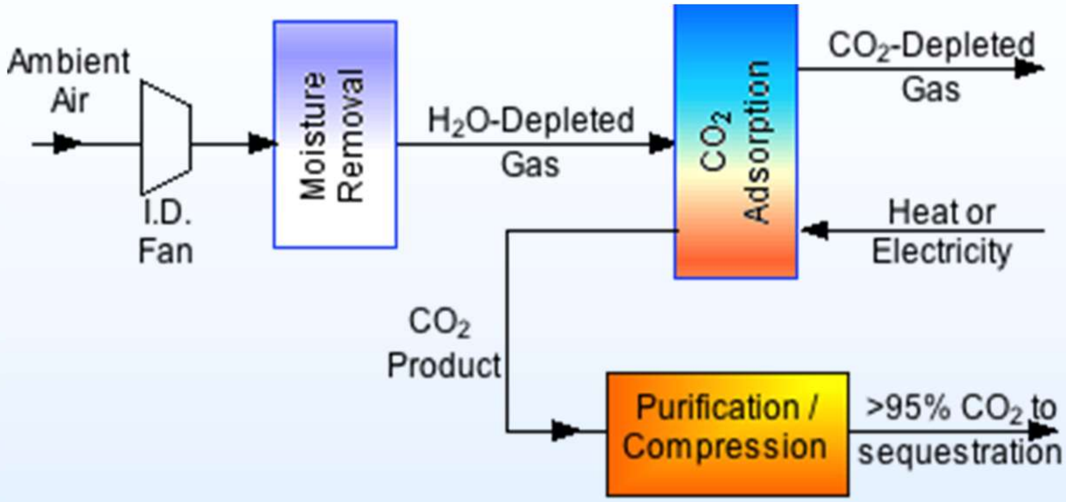
- Carbon Engineering uses an absorption system with a number of steps (Liu et al., Sust. Energy Fuels, 2020)
  - Reaction with NaOH to convert CO_2 to Na_2CO_3
  - Regeneration of Na_2CO_3 by reaction with $Ca(OH)_2$

    $Na_2CO_3 + Ca(OH)_2 \text{ ------}\rightarrow CaCO_3 + 2NaOH$
  - Calcination of $CaCO_3$ to produce lime at >900^oC in a kiln;

    $CaCO_3 + \text{Heat} \text{ -------}\rightarrow CaO + CO_2$
  - Hydration of CaO to produce $Ca(OH)_2$;

    $CaO + H_2O \text{ ----}\rightarrow Ca(OH)_2$
- Global Thermostat and Climeworks use amine-impregnated sorbents with either indirect regeneration or direct steam regeneration (Eisenberger, U.S. patents 8,500,855 & 10,413,866; Gebald et al., Environ Sci Technol, v48, p2497, 2014)
  - A very significant amount of energy needed for physisorbed water (2-8 moles of water adsorbed per mole of CO_2), the estimated thermal energy needed is between 100 to 400 kJ/mol of CO_2; Gebald et al., 2014, p2502)

Technology Background



- Based on physical sorbents in structured form
- Base materials with high CO_2 capacity (>4-wt% at p_{CO2} = 0.04 kPa), low heats of adsorption (40-44 kJ/mol of CO_2)
- Chemical modification of base materials to improve capacity and selectivity during another DOE project
- Materials are low cost, easily scalable to quantities needed for commercial use (thousands of tons), very stable (>5 year life)
- Key innovation is **the novel combination of process** (leveraging prior developments) **and materials** (low energy consumption) that provides performance similar to or better than reaction-based processes with much lower regeneration energy and capital requirement

InnoSepra Process for Direct Air Capture

- The compressed air after the I.D. Fan is dried in a moisture removal unit.
  - The process works with any ambient humidity (0-100%). No impact of ambient humidity on performance.
- The CO_2 from the moisture depleted gas is adsorbed in the CO_2 adsorption unit.
- The CO_2 is desorbed through a combination of heat & electricity. The product CO_2 stream is very dry. No impact of oxygen in feed or co-adsorbed oxygen present during regeneration on sorbent life.
- The CO_2 produced from this process is further purified to pipeline quality gas.

Project Objectives

The Overall Objectives of various DAC projects

- Demonstrate the effectiveness of InnoSepra's DAC technology for pipeline quality CO_2 with a potential energy consumption of <4 GJ/MT, and a capture cost of <$200/MT at a sufficiently large scale by 2028 or sooner

Specific Project Objectives

- To demonstrate the potential of the proposed transformational process to reduce the energy requirement for CO_2 capture to below 4 GJ/MT based on semi-bench scale testing
- Identify means to scale up the technology including the materials for commercial scale direct air capture
- Determine projected energy requirement based on semi-bench scale testing and a techno-economic analysis for a commercial scale DAC plant

Project Overview

- During this project InnoSepra is using the materials developed in another project and testing them at both the lab scale and the semi-bench scale to show that the process has a potential for a significant reduction in both the capital cost and the energy required for direct air capture compared to current state-of-the-art technologies
- Starting TRL: 3
- End of the Project TRL: 4
- DOE Project Manager: Zachary Roberts
- Total DOE funding: $1,600,000
- Project Dates: 09/01/2021 to 03/31/2024

Project Scope

Materials Development & Lab testing

- Fabrication of Adsorption Test Modules, Sorbent Production
- Fabrication of Rotating Wheel Adsorber System for Air Drying
- Fabrication of Test Unit for CO_2 Capture
- Semi-Bench Scale Testing for Moisture Removal
- Lab Scale Testing for CO_2 Capture
- Model Development and Process Simulation

Semi-Bench Unit Fabrication & Testing, Techno-economic Analysis

- Design and Fabrication of semi-bench scale test unit
- Installation and testing of semi-bench scale unit
- Conceptual Design of a 250 TPD Direct Air Capture System
- Techno-Economic Analysis for a 250 TPD Direct Air Capture System
- Final Project Report

Project Deliverables

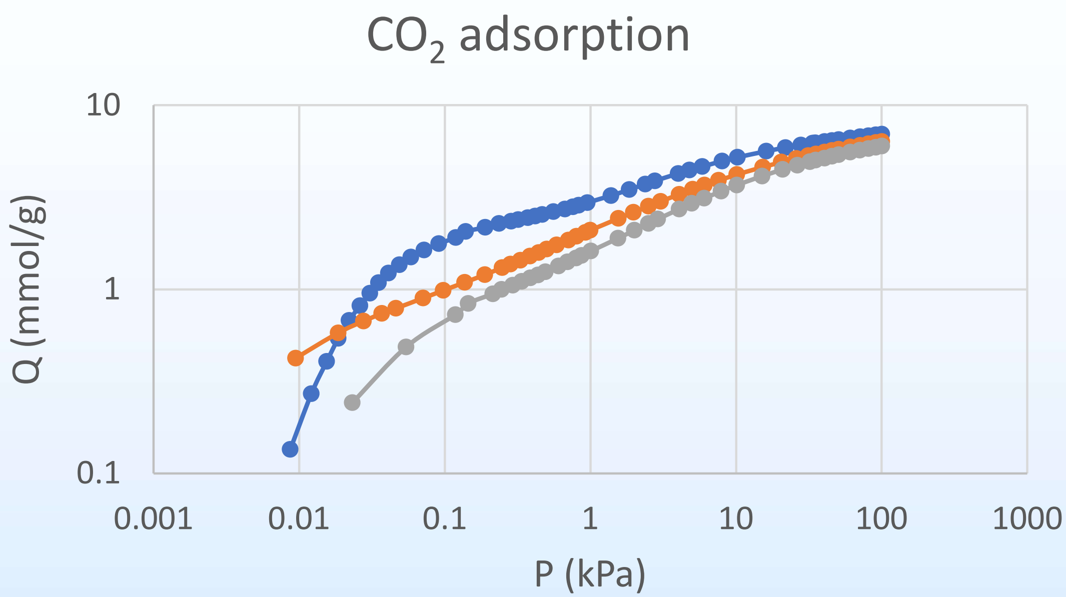
- Produce best sorbents for CO_2 enrichment identified in FE31953 for lab and field testing
- Process simulation of Direct Air Capture using laboratory and field test data
- Quantify the technical and economic benefits of the proposed Direct Air Capture based on process simulation, engineering design, and a techno-economic analysis
- Identify pathways for materials fabrication at large scale and further process scale up

Characterization of Materials for CO_2 Removal
(p_{CO2} = 400 ppm, p_{N2} = 100%)

Sorbent type (Powder)	Q (wt % at 25°C)	
	CO_2	N_2
Starting Material (Matl A)	1.25	0.99
Modification 1 (Matl B)	2.83	0.97
Modification 2	4.02	1.56
Modification 3	**7.44**	**2.82**
Modification 4 (Matl C)	5.28	4.26

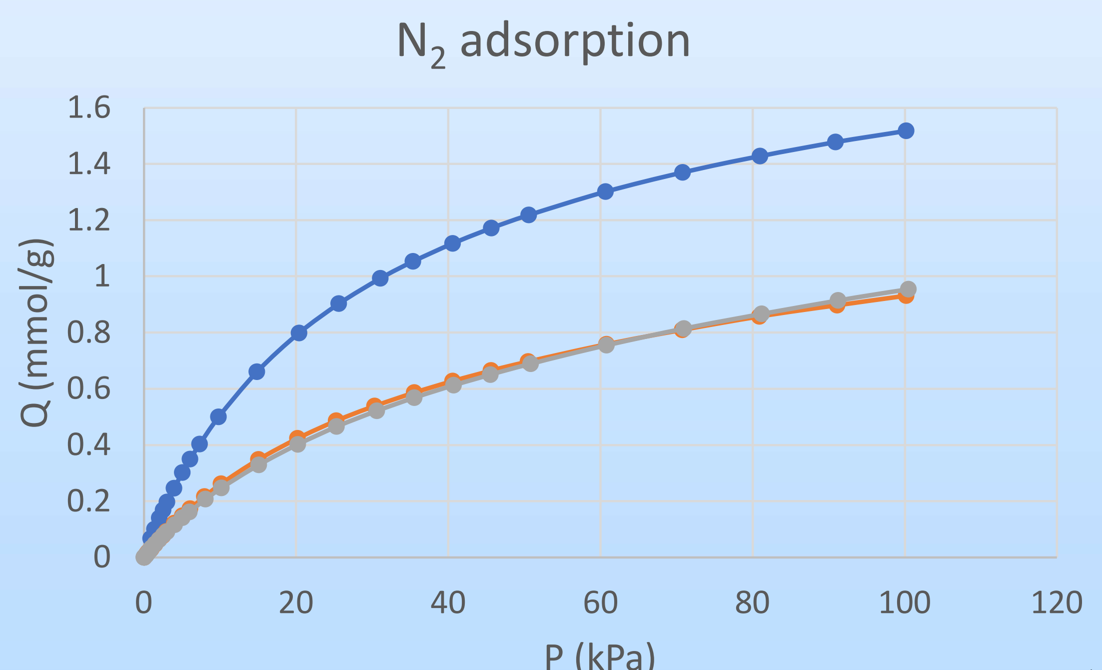
*Isotherm measurements using Micromeritics ASAP 2000 Sorption Balance. Equilibrium capacity over 5-wt% under DAC conditions.

Material C was Identified in FE31953



CO_2 and N_2 Isotherms on Material B – 25°C

Powder
Lab laminate
Commercial laminate



Moisture Removal Testing

Semi-bench scale testing for moisture removal

- **Moisture removal dessiccant wheels from Novelaire and Munters were tested**
- **Feed flows: 5-40 scfm**
- **Feed temperatures: ambient (20-30^{o}C)**
- **Regen flows: 5-40 scfm**
- **Regen temperatures: ambient (20-30^{o}C)**

Rotating Wheel Dehumidification Unit

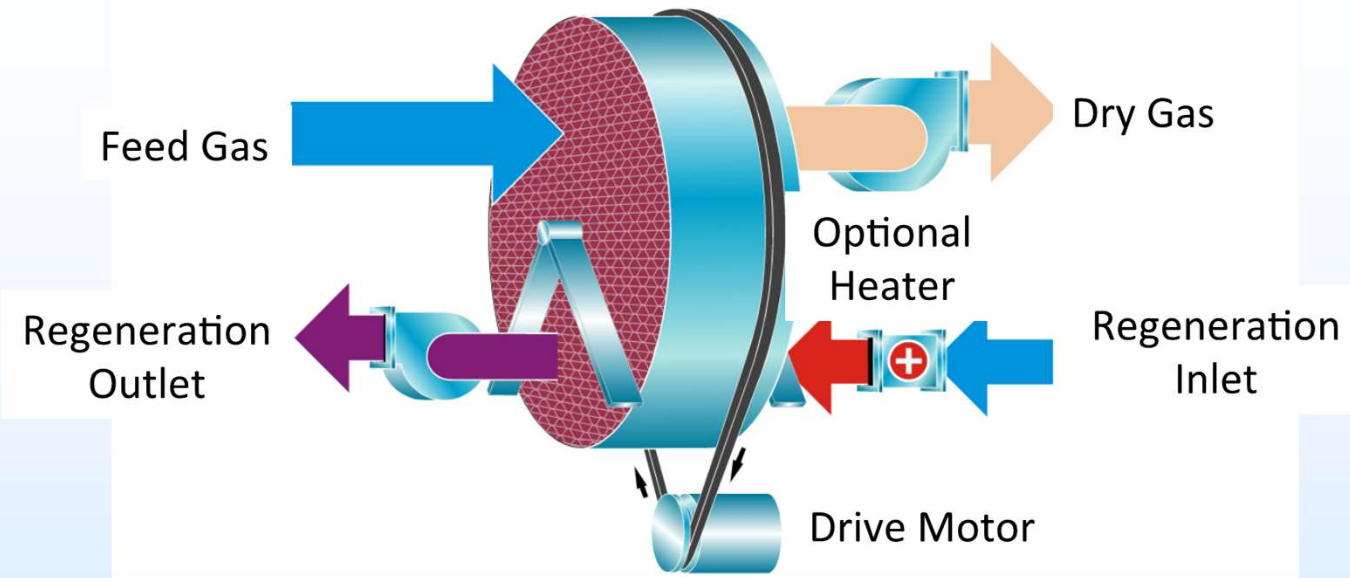


Figure 2: Rotating wheel dryer for feed dehumidification

- A rotating bed dryer unit was fabricated

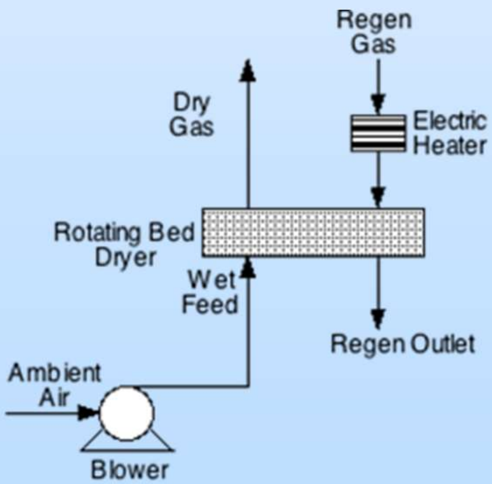
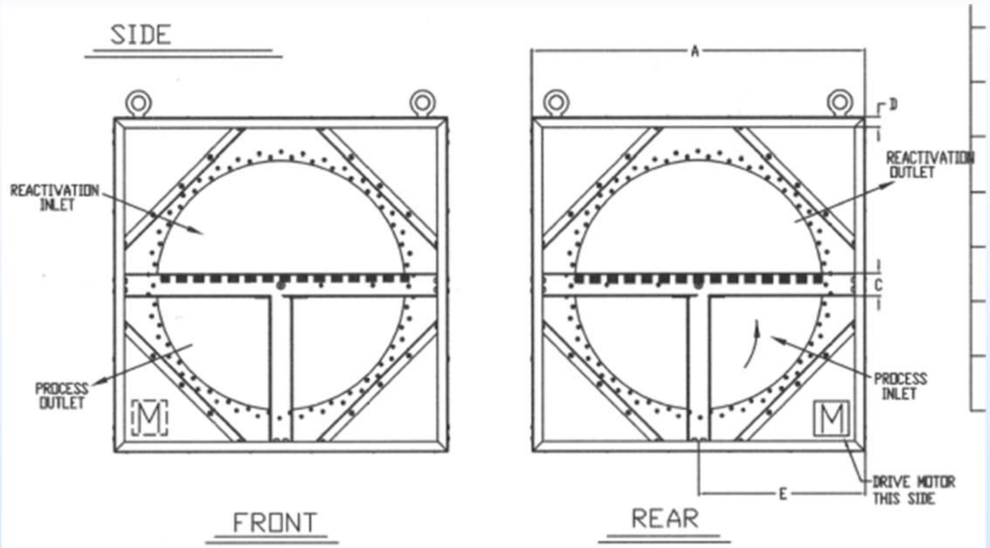


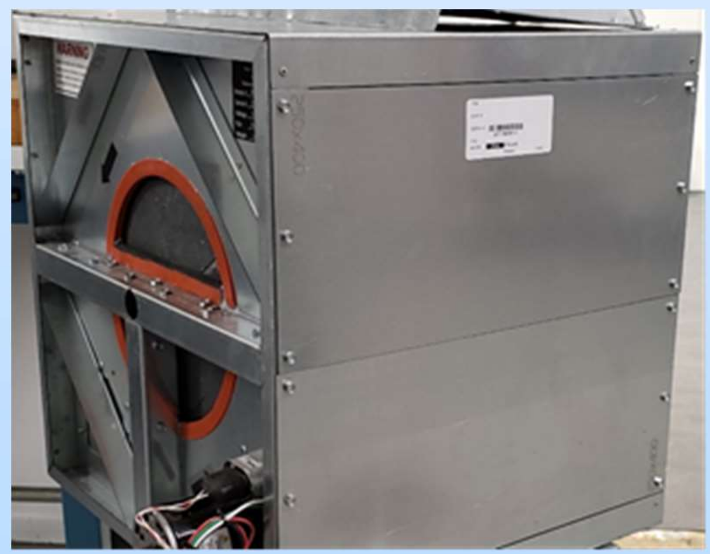
Figure 6. Lab Scale Air Drying Unit

Moisture Removal Process

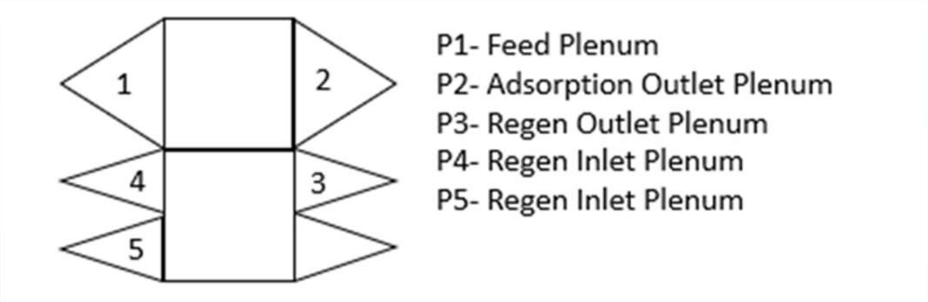
NovelAire Desiccant Wheel



Wheel diameter = 10 inches
Wheel depth = 16 inches

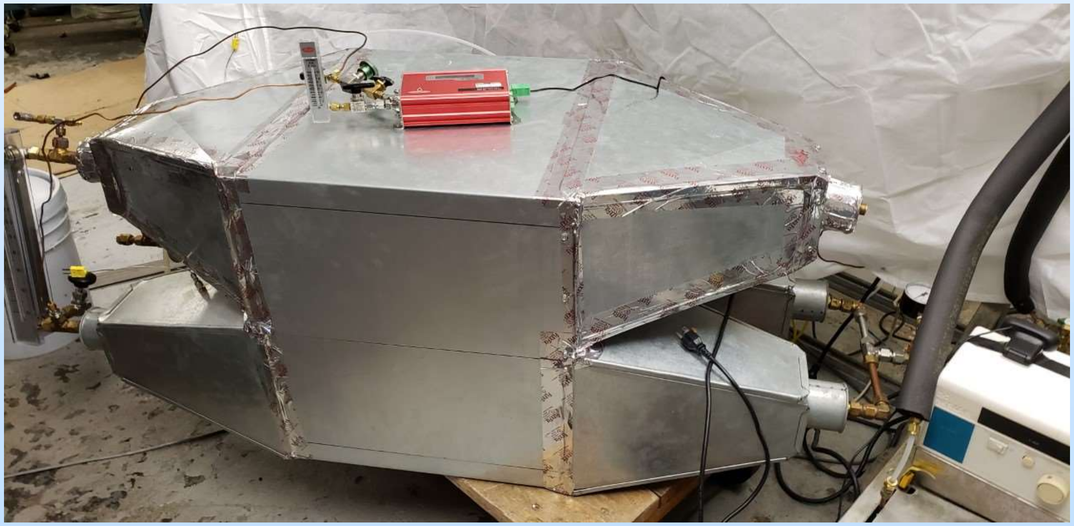


Moisture Removal Process

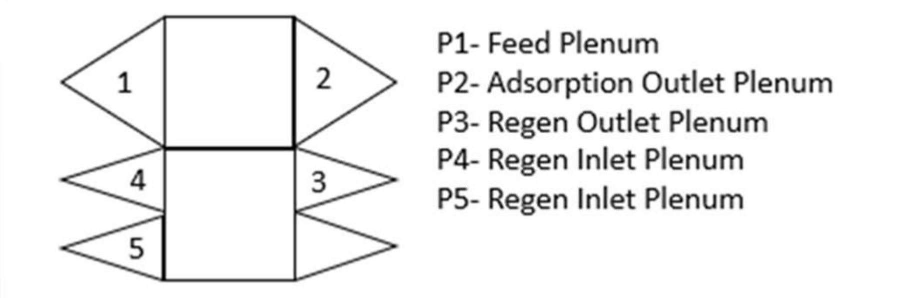


NovelAire desiccant wheel with plenums

The wheel is configured with 3 sections:
50% process air,
25% hot regen,
25% cold regen



Measurement of Pressure Drops



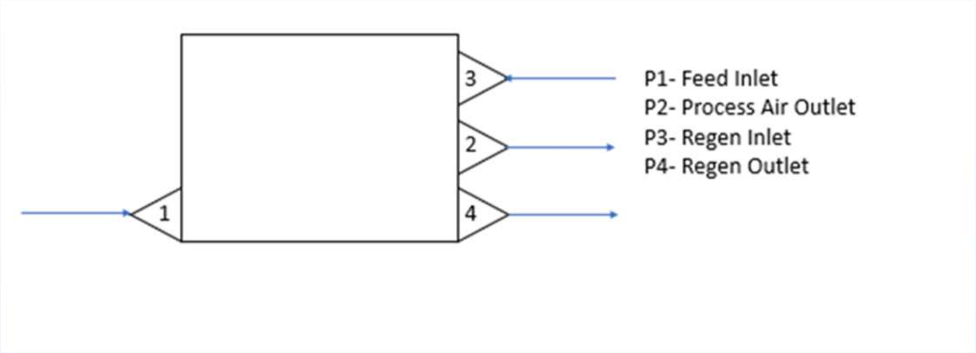
Wheel rotation = 18 rph

Branch	Flow In	Flow Out	Flow In	Flow Out	P1	P2	P3	P4	P5
	cfm	cfm	Location		in H2O	in H2O	in H2O	in H2O	in H2O
Adsorption	40	<2	1	2	1.65	0	0.9	0.95	N/A
Adsorption	40	12.5	1	2	2.75	0.05	2.25	2.25	N/A
Regeneration	40	<2	3	4 & 5	0.95	0	1.2	0.85	0.9
Adsorption	38	15	1	2	0	1.9	2.5	2.5	2.5
Adsorption	38	15	2	1	0	1.9	2.5	2.5	2.5

- Pressure drops as high as 2.7 inches water were measured
- Extensive testing was carried out but both internal and external leakages did not allow to close the mass balance

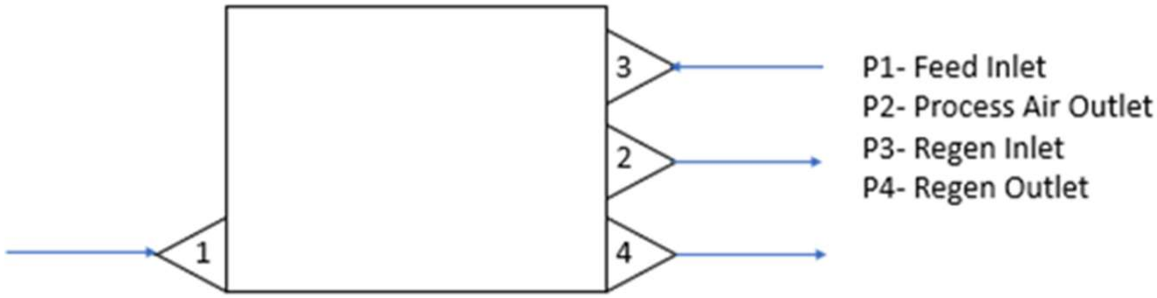
Moisture Removal Process

Munters Desiccant Wheel



The wheel is configured with 2 sections:
75% process air, 25% regen

Measurement of Pressure Drops



Process in P1			Process out P2		Regen in P3			Regen out P4	
Flow cfm	Temp. deg. C	Press. in H2O	Temp. deg. C	Press. in H2O	Flow cfm	Temp. deg. C	Press. in H2O	Flow deg. C	Press. in H2O
10	28.4	0.75	27.4	0.3	5	45-60	0.35	22.6	0.2
15	29.4	1.65	28.9	0.6	5	45	0.8	27.7	0.65
20	32.4	2.5	29.4	0.85	5	45	1	27.9	0.85
10	29.7	1.2	29	0.55	10	45	0.95	28.9	0.8
15	32.2	2.2	33.4	0.85	10	45	1.35	30.4	1.1
20	32.2	3	34.1	1.05	10	45	1.35	30.8	0.85

- Pressure drop across the process side of the wheel varies between 0.5 and 2.0 inches water, as the flowrate increases from 10 to 20 cfm
- Regen side pressure drop varies between 0.15 and 0.50 inches water

Measurement of Wheel Performance

Wheel rotation was varied between 7 and 14 rph

Process in P1			Process out P2		
Flow cfm	Temp. deg. C	Humidity ppm	Flow cfm	Temp. deg. C	Humidity ppm
6	33	10,236	3.5	46	501
10	35	10,236	6	48	1,813
6	34	10,236	3.5	51	605
6	33	12,122	4	47	952
6	33	12,535	4	51	605
10	36	11,722	6.5	35	3,441
6	35	11,334	4	58	1,136
6	36	12,203	4	59	796
6	35	12,450	4.5	45	727
5	30	12,122	3.25	45	379
5	27	13,218	3.25	37	296
4.5	27	12,122	3	29	294
4	27	12,203	2.5	27	81
3.5	28	12,203	2.25	26	80

- It is possible to dry feed air to below 100-ppm moisture. However, this leads to a significant drop in productivity
- Further studies are underway to improve the performance

CO_2 Capture Testing
Breakthrough Testing with Beaded Material

Feed 400 ppm CO2 in N2

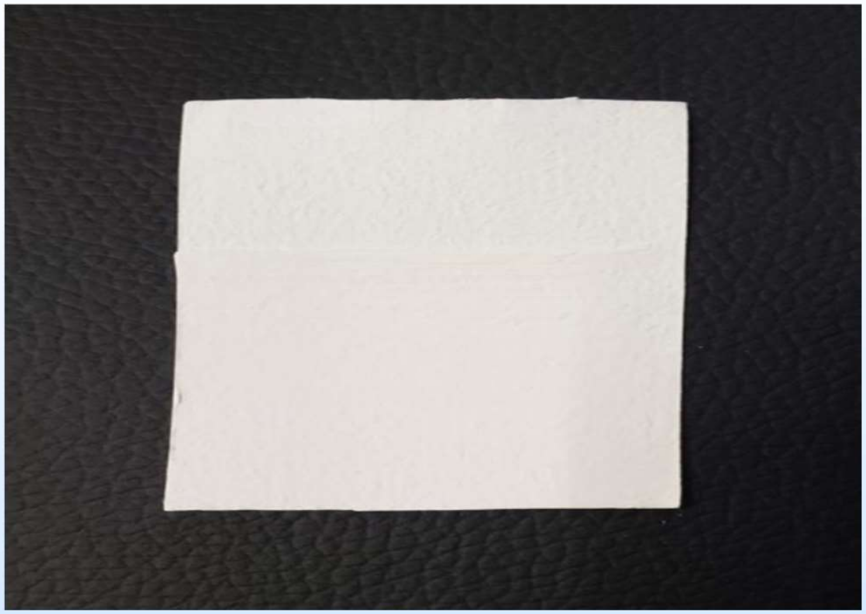
Adsorbent

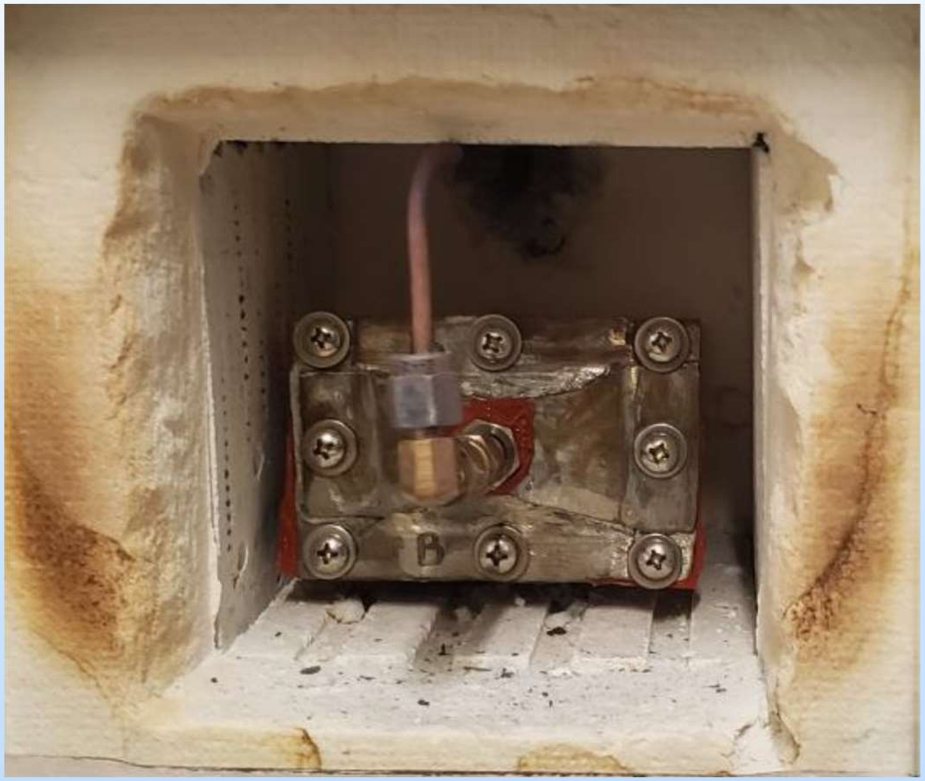
Capacity calculated from time to reach 200 ppm

T (oC)	Capacity (wt%)		
	F = 30 lpm	F = 20 lpm	F = 10 lpm
0	4.06	3.57	3.93
25	2.63	2.17	1.82
50	1.61	1.13	1.27
75	0.93	1.00	0.72
100	0.71	0.51	0.48

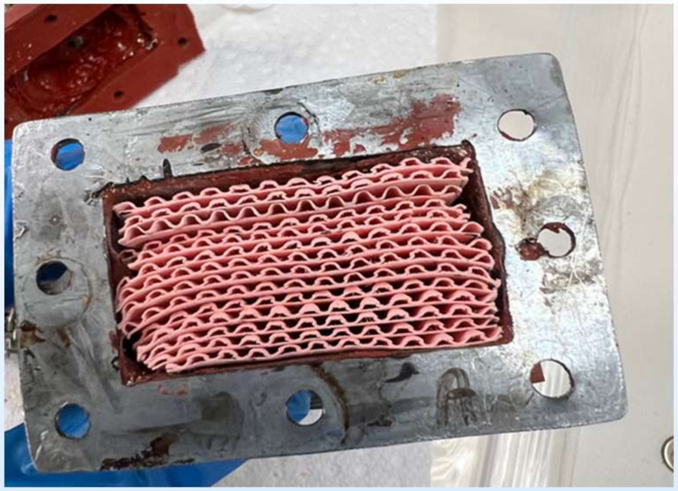
Preparation of Laminate Sorbents for CO_2 Removal

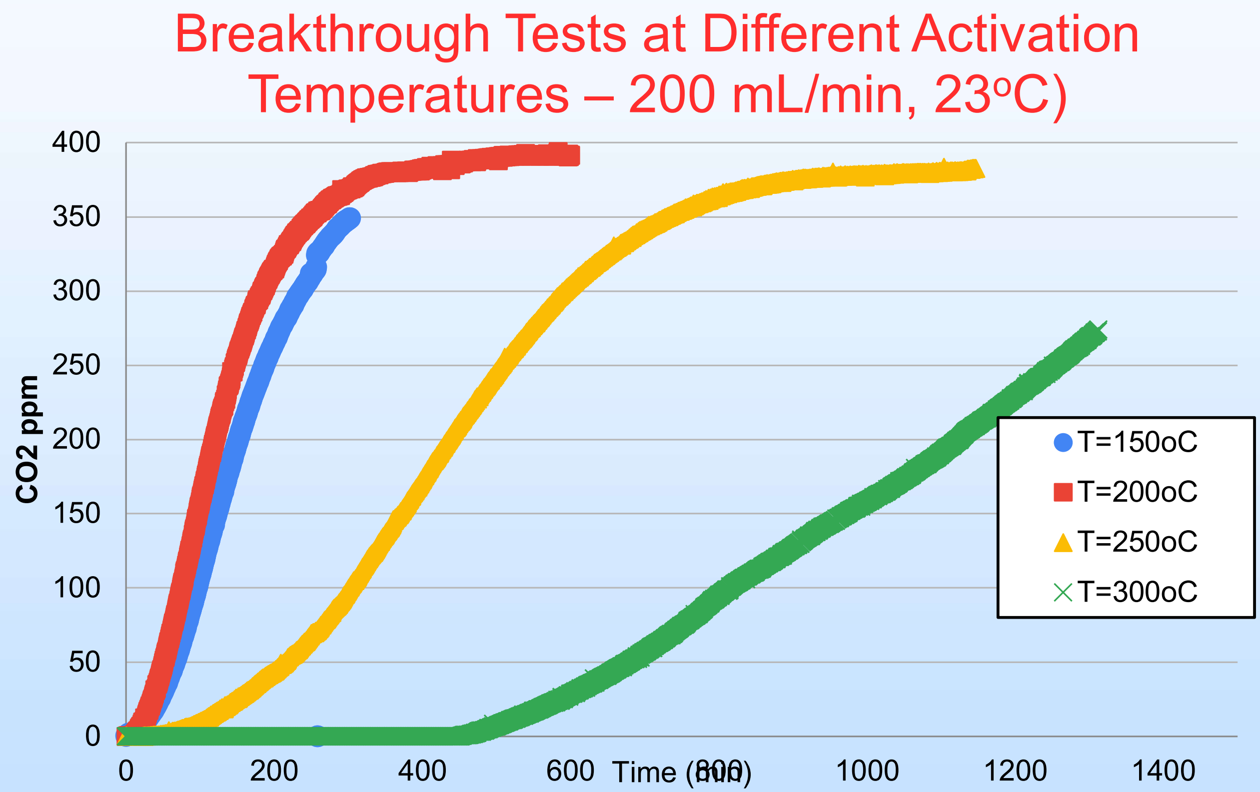
- Both in house development, and work with external partners to produce handsheets and sorbent structures





Testing of Commercial Laminates (Corrugated) - Material C

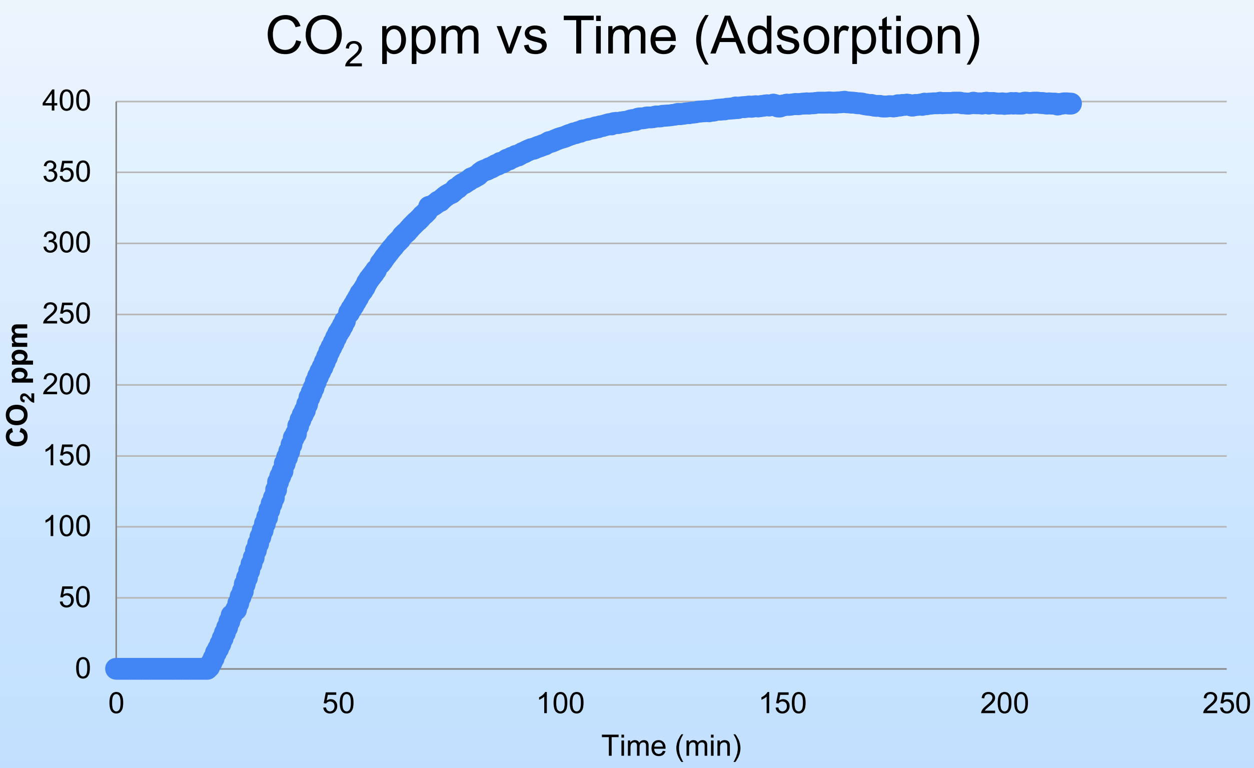




- Optimization of binder formulation and activation temperature to achieve high capacity and high adsorption rates
- Breakthrough capacity of about 2.5-wt% for >300°C activation

Laminate Structured Unit with Material C

Structure diameter = 5 in.
Structure height = 8 in.
Flow rate = 21 liters/min
Temperature = 23°C



Summary of Sorbent-Based Process Development

- Sorbents identified in FE31953 show isotherms capacities higher than 5-wt% for a p_{CO2} of 0.04 kPa (400-ppm CO_2 in air) at 25^{o}C
- Breakthrough capacities are between 2.5 and 4.0-wt%
  - The materials with the highest isotherm capacities do not necessarily have the highest breakthrough capacities
  - N_2 coadsorption can be significant and needs to be considered
- Rotating dryer beds from NovelAire and Munters tested at different flow conditions
- Commercially fabricated laminate structured beds show promising results and its performance being optimized through binder/activation temperature combination

Estimation of Regeneration Energy Required

- Model development for DAC System and Process Simulation
  - **An adsorption process model for the CO_2 capture part of the process was developed**
  - **An ASPEN model combining the CO_2 capture and final upgrading was developed**
  - **Energy requirement for the process was determined based on lab scale testing**
  - **The energy requirement will be updated after scale up testing**

Energy Needed for CO_2 Capture Based on Process Simulation

Product Flow	100	ton/day of CO_2
Full Cycle Time	30	min
Each cycle need to desorb	2.08	tons of CO_2 per cycle
Adsorption capacity	3.5	wt %
Amount of sorbent	59.5	ton adsorbent per bed
Regeneration Temperature	120	^{o}C
Heat needed for sorbent	6.0	GJ
Heat need to desorb CO_2	2.0	GJ
CO_2 sensible heat	0.20	GJ
TOTAL HEAT REQUIRED	8.2	GJ per cycle
TOTAL HEAT REQUIRED	3.9	GJ/ton of CO_2
Assume all the heat is suppliued by steam		
Steam flowrate	7,300	kg steam/hr
	7.30	ton steam/hr
	1.75	ton steam/ton of CO_2

Plans for Future Testing / Development

- Build larger CO_2 capture modules using Material C
  - An initial batch of material (more than 700-ft, 8” tall) was made. Needs to be optimized to improve CO_2 capacity.
- Flow testing with larger module
  - Using dry air from stage 1
- Update process model and the energy required for DAC
- Update initial techno-economic analysis
- Pilot scale testing in a future project

Summary

- The InnoSepra DAC Process utilizing low-cost InnoSepra DAC materials has the potential for a significant reduction in the energy required for direct air capture
- Process simulation indicates that it is possible to obtain high purity CO_2 (>95% purity) with physical sorbents while meeting the EOR/sequestration product specifications
- The process modeling indicates that the process has the potential to reduce the energy required by more than 50% over current DAC processes (<4 GJ/MT))
- The low energy requirement coupled with low material cost can lead to a CO_2 removal cost below $200/MT
- Ability for quick deployment after pilot scale validation

Project Schedule

Project Gantt Chart

Task

1. Procurement of Sorbents
2. Lab Unit for Moisture Removal Testing
3. Lab Unit for CO2 Capture Testing
4. Lab Testing of Moisture Removal
5. Lab Testing for CO2 Enrichment
6. Process Model Development
7. Engineering Design for Bench Unit
   Engineering design complete
8. Field Testing of Bench Unit
   Field testing complete
9. Techno-economic Analysis
9. Final Report