MIL-101(Cr)-Amine Sorbent Evaluation Under Realistic Direct Air Capture Conditions

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U.S. Department of Energy

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Project Overview

- Funding
  - DOE Funds: $755,166 (79.73%)
  - Cost share (ZCP Sorbent Development, LLC): $191,482 (20.23%)
- Funding Period: 10/01/2020-03/31/2022 (**no cost extension to 9/2022**)
- Project Participants:
  - Georgia Institute of Technology
  - ZCP Sorbent Development, LLC

	FY 2021		FY 2022		Total	
	DOE Funds	Cost Share	DOE Funds	Cost Share	DOE Funds	Cost Share
Applicant	$548,435		$206,731		$755,166	
Sub-recipient A, if proposed		$138,000		$53,482		$191,482
Total ($)	$548,435	$138,000	$206,731	$53,482	$755,166	$191,482
Total Cost Share %	20.10%		20.55%		20.23%	

Project Overview

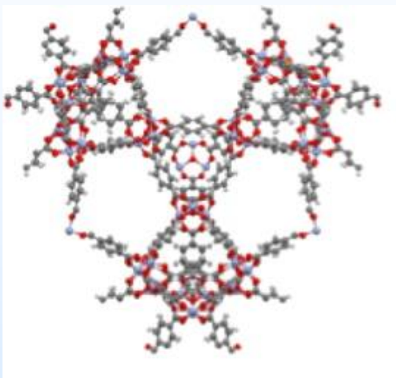
- Overall Project Objectives

  - Explore DAC performance of amine functionalized MIL-101(Cr) MOFs and build models of their adsorption behavior over a wide range of temperatures (-20 ^{o}C to 25 ^{o}C) and relative humidities (0% – 100%).

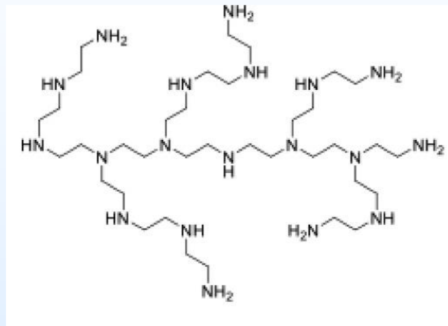
  - Develop and test the sub-ambient DAC materials in the forms of composite polymer/MOF <u>fibers</u> and on the surface of or within <u>monoliths</u>. (advance from TRL 2 to TRL 3)

Technology Background

PEI impregnated MIL-101(Cr) MOFs for ambient DAC (Darunte et al., 2016) 25 °C

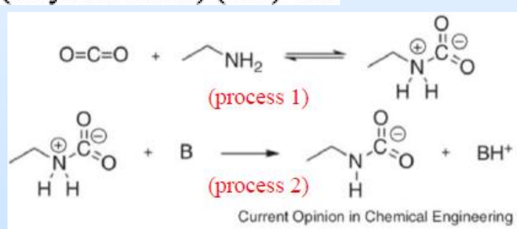


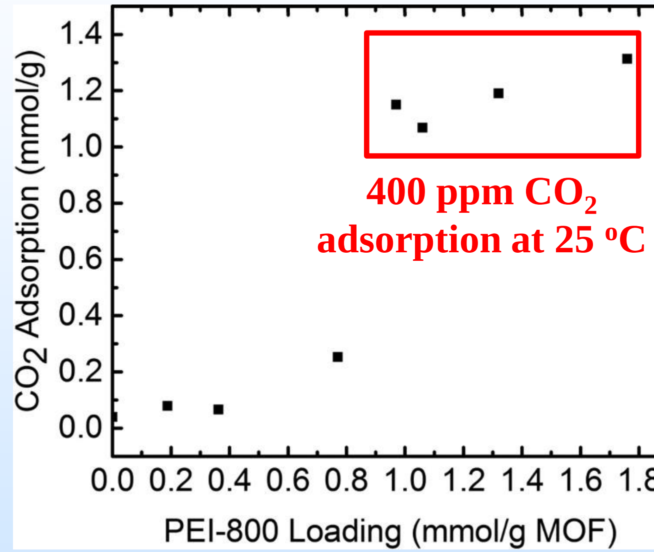
MIL-101(Cr)



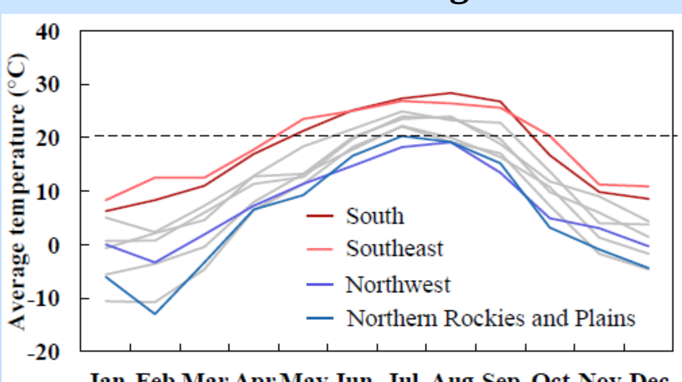
Poly (ethylene imine) (PEI)-800

DAC at 25 ºC





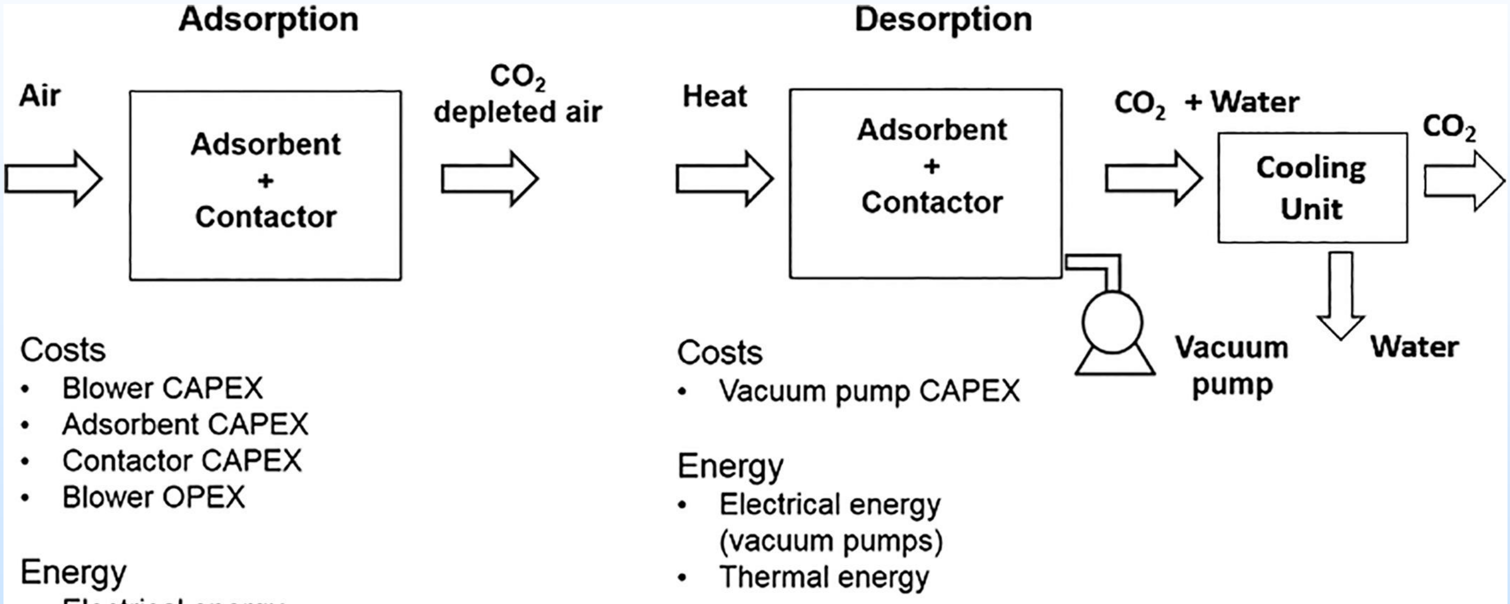
Average monthly temperatures for US Climate regions



Aim to investigate the CO_2 adsorption capabilities of MIL-101(Cr)-amine sorbents over wide range of adsorption temperature (-20 to 25 ºC) and RH (0 to ~100%) conditions.

Technology Background

Sub-ambient DAC cycles with small T swing (e.g. -20 ºC to 25 ºC)



Sinha et al. *AIChE J*. **2019**, 65, e16607

- T/VSA using solid sorbents in a structured contactor (fibers or monoliths)
- Heat delivery mode TBD

Innovation: design of sorbents/processes for operation in practical, temperate outdoor adsorption temperature range of -20 to 25 °C, in all humidities.

Technology Background

Sub-ambient DAC cycles with small T swing (-20 ^{o}C to 25 ^{o}C; ΔT ~ 45 ^{o}C)

State-of-the-art at project start:

- 99% of all published DAC studies conducted at T $\geq$ 25 °C
- >50% of all published DAC studies conducted in absence of humidity
- Warm DAC gives improved kinetics, but requires handling of large water sorption loads

Proposed Innovation:

- Practical, outdoor DAC requires operation at <u>cooler/colder temperatures</u> & in all humidities
- Cool/cold operation may allow for <u>more physisorption</u> as well we <u>less water sorption</u> due to lower humidity, both offer potential for <u>lower desorption energies.</u>

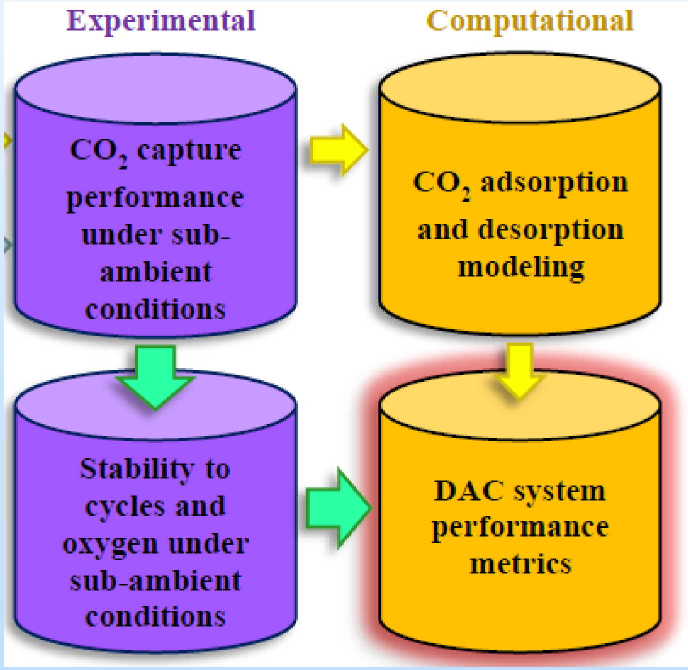
Kong et al., Korean J. Chem. Eng. 2022, 39, 1-19

Experimental Design & Work Plan

Characterization of MIL-101(Cr) powder, monolith, and fiber sorbents

Equipment for lab-scale experiments	Expected experimental conditions	Information acquired
Thermo-gravimetric System (TGA)	-20 to 25 ^oC, dry gas feed	CO_2 equilibrium adsorption and desorption capacities, adsorption and desorption kinetic profiles
Volumetric System (SAP)	-20 to 25 ^oC, dry gas feed	CO_2 adsorption isotherms
Fixed bed breakthrough System + MS and IR detectors	-20 to 25 ^oC, humid gas feeds with relative humidity between 0 and ~80%	Breakthrough & equilibrium capacities, adsorption and desorption kinetic profiles

Integration of lab-scale sub-ambient CO_2 adsorption testing with analytical computational studies



Project Success Criteria

Milestone	Decision Point	Date	Success Criteria
2	Development of MIL101(Cr)-based fibers and monolith sorbents. MIL-101(Cr) sorbent macrostructures, with at least two different compositions, successfully fabricated and structurally characterized.	Month 9 ↓ **Month 24 (extended)**	Successful synthesis of MIL-101(Cr)-amine fiber and monolith sorbents.
3	Evaluation of performance and stability of powder MIL-101(Cr)-based sorbents at sub-ambient conditions.	Month 18 ↓ **Month 21 (extended)**	**1-2 MIL-101(Cr)-based powder sorbents** identified as promising sorbents at sub-ambient conditions: good compromise between **CO_2 capacity, kinetics and stability** (towards multiple cycles and oxygen).
4	Translation of best performing powder MIL-101(Cr)-amine sorbents to fiber and monolith forms.	Month 18 ↓ **Month 24 (extended)**	Performance of fiber or monolith is at least 75% of the powder performance.
5	Employing models of adsorption and desorption behavior to estimate DAC system performance metrics.	Month 18 ↓ **Month 24 (extended)**	**Adsorption and desorption models** represent experimental data and estimated DAC system metrics allow **assessment of suitability for next stage of process development**.

Project Risks & Mitigation Strategies

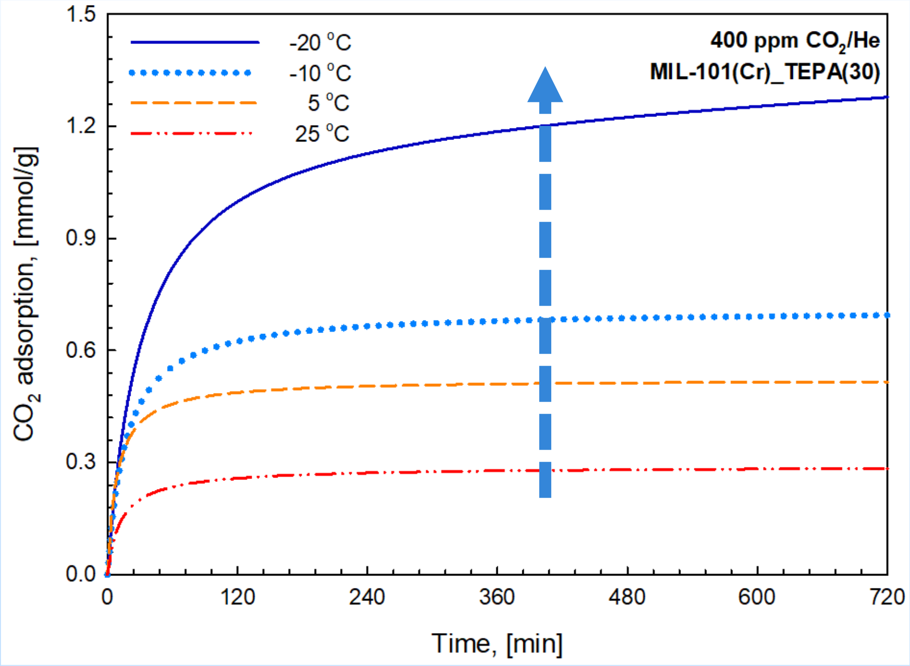
Perceive Risk	Risk Rating			Mitigation/Response Strategy
	Probability	Impact	Overall	
	(Low, Med, High)			
Financial Risks:				
Existing equipment failure, replacement funds not in budget	Low	Med	Low	Many experiments will be carried out on existing equipment that is regularly maintained and failure is unlikely.
Cost/Schedule Risks:				
Delayed hiring of personnel	Med	High	Med	PIs will seek applications for project before notification of award. PIs will seek applicants already at Georgia Tech. (Delays due to slow worker approval)
Delayed delivery of new equipment	Med	High	Med	If new equipment is delayed, existing equipment will be retrofitted with chillers to begin work on the project and limit delays. (Delays due to slow equipment delivery)

Perceive Risk	Risk Rating			Mitigation/Response Strategy
	Probability	Impact	Overall	
	(Low, Med, High)			
Technical/Scope Risks:				
Unable to grow MIL-101(Cr) on monolith materials	Low	Med	Low	Previous literature indicates MIL-101(Cr) can be grown on alumina; work can continue if no other monolith materials enable MIL-101(Cr) growth. (Unable to grow due to low compatibility between MIL-101(Cr) and cordierite monolith). Extrusion and **3D printing** of MIL-101(Cr) monoliths is also feasible.
Amine-MIL-101(Cr) sorbents not stable at low T	Med	Med	Med	Additional amines can be investigated. Previous work has found PEI-MIL-101(Cr) to be stable for adsorption at room temperature and work could continue with PEI only.
Management, Planning, and Oversight Risks:				
Team collaboration and communication is poor	Low	Med	Low	Jones, Lively, and Realff work together in the same building at Georgia Tech and have successfully worked together before.
ES&H Risks:				
Accident associated with experimental testing	Low	High	Low	Laboratory designed for adsorption experiments. Gas cylinder management is already in place. Liquid nitrogen is already used and all experimentalists receive proper training.

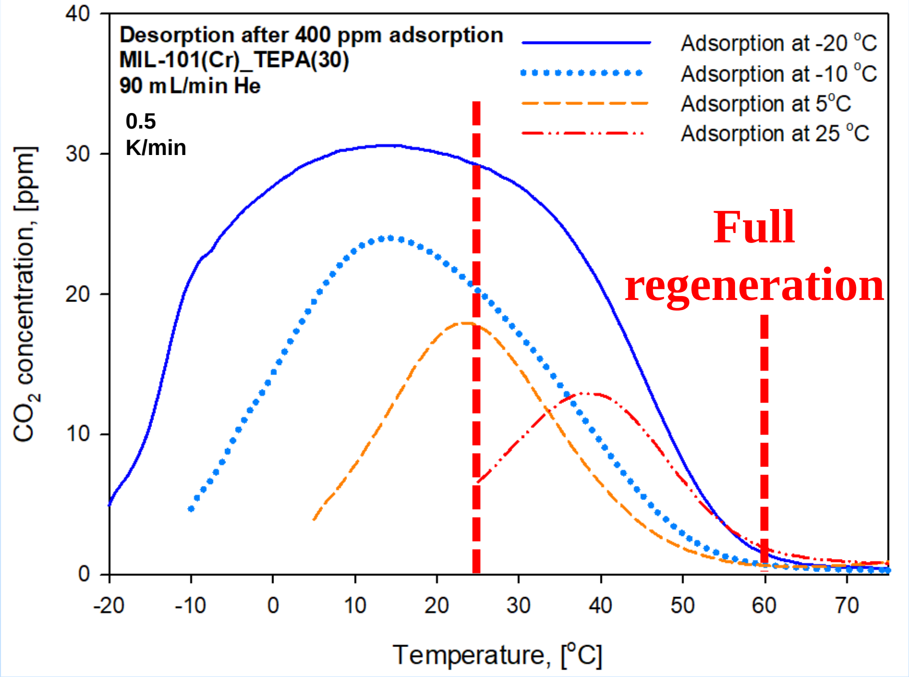
Development of Powder MIL-101(Cr) Sorbents at Sub-ambient Conditions

MIL-101(Cr)_TEPA(30) (400 ppm CO_2 capture at -20 °C)

By TGA/DSC



CO_2-Temperature Programmed Desorption



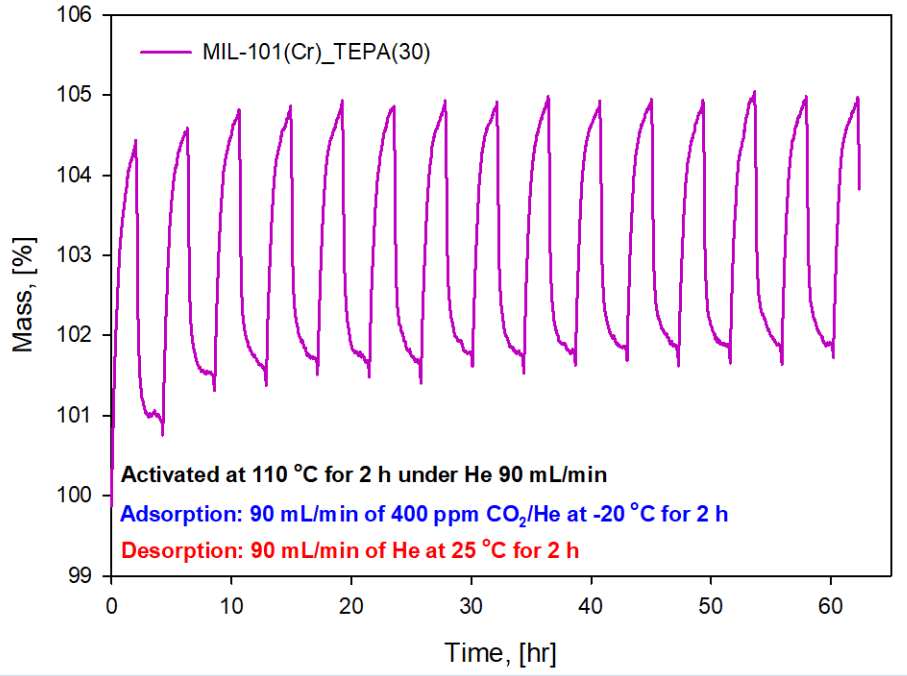
The amount of weak chemisorption became more significant at lower temperature conditions (thermodynamic effect).

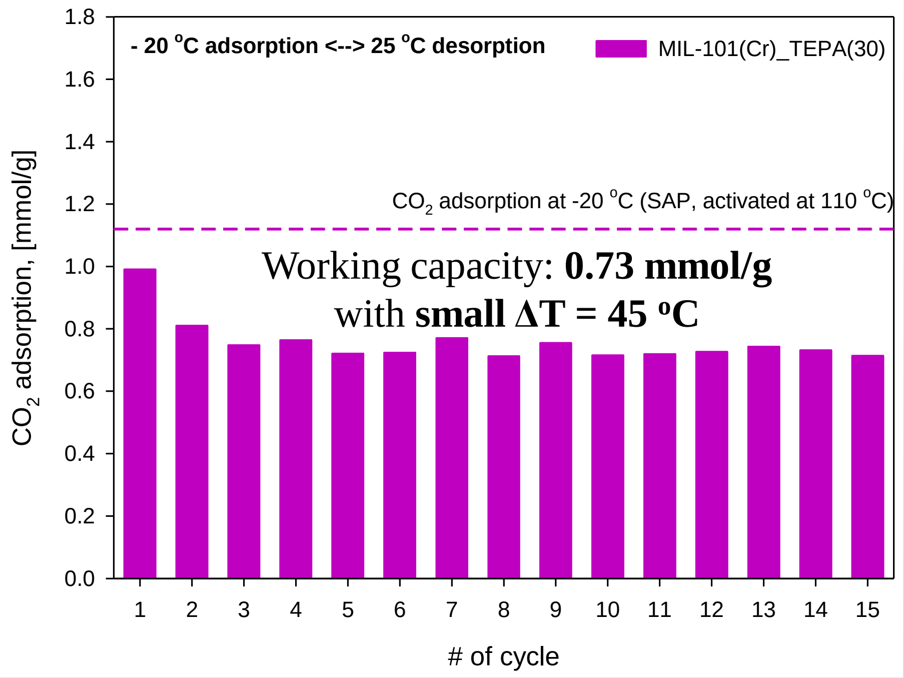
Rim et al., JACS Au, 2022, 2, 380-393.

Development of Powder MIL-101(Cr) Sorbents at Sub-ambient Conditions

Cyclic test (400 ppm CO_2 capture at -20 °C (2 h), desorption at 25 °C (2 h))

30 wt% TEPA impregnated MIL-101(Cr) powders



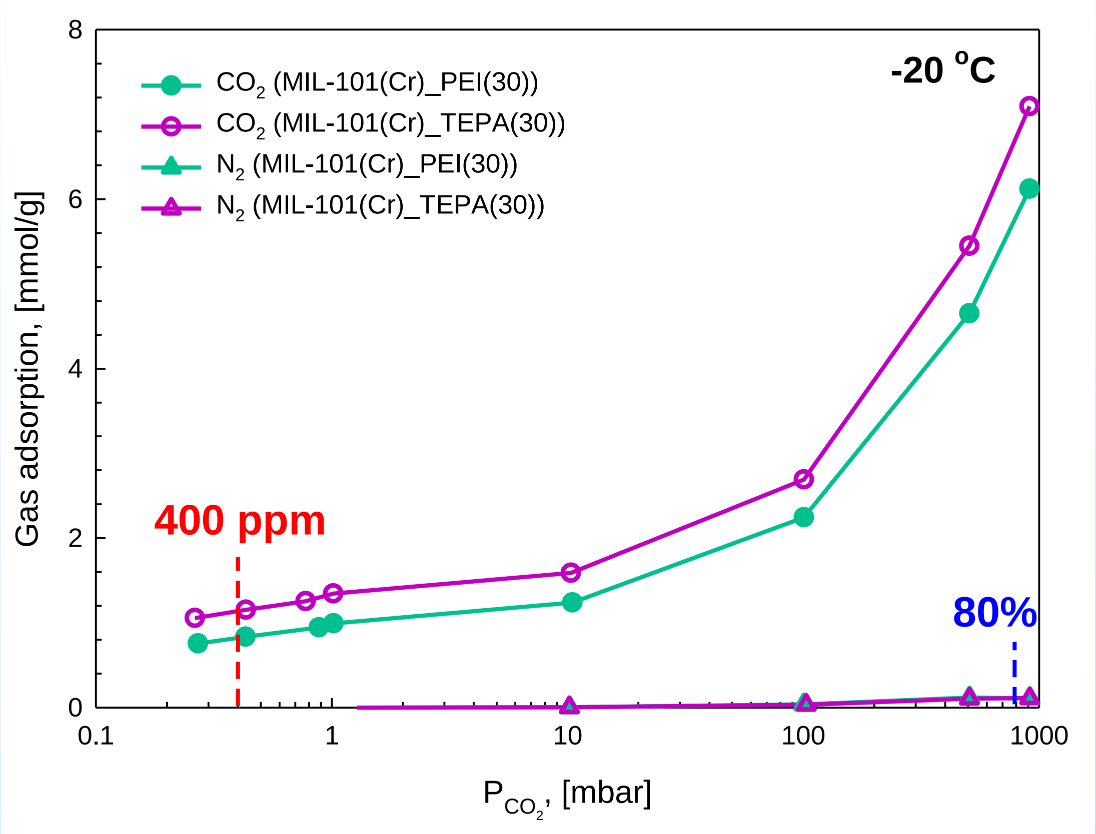


Significant energy savings may be realized for ***sub-ambient DAC*** via utilization of small T swings enabled by this ***weak chemisorption mechanism***.

Rim et al., JACS Au, 2022, 2, 380-393.

Development of Powder MIL-101(Cr) Sorbents at Sub-ambient Conditions

Single gas (CO_2 and N_2) adsorption isotherm of 30 wt% amine impregnated MIL-101(Cr) at -20 °C



Selectivity:

10 – 14
(mol CO_2 /kg / mol N_2 /kg)

20,000 – 30,000
(mol CO_2 /kg * x_{N2} / mol N_2 /kg * x_{CO2})

Selective 400 ppm CO_2 capture over 80% N_2 at -20 °C

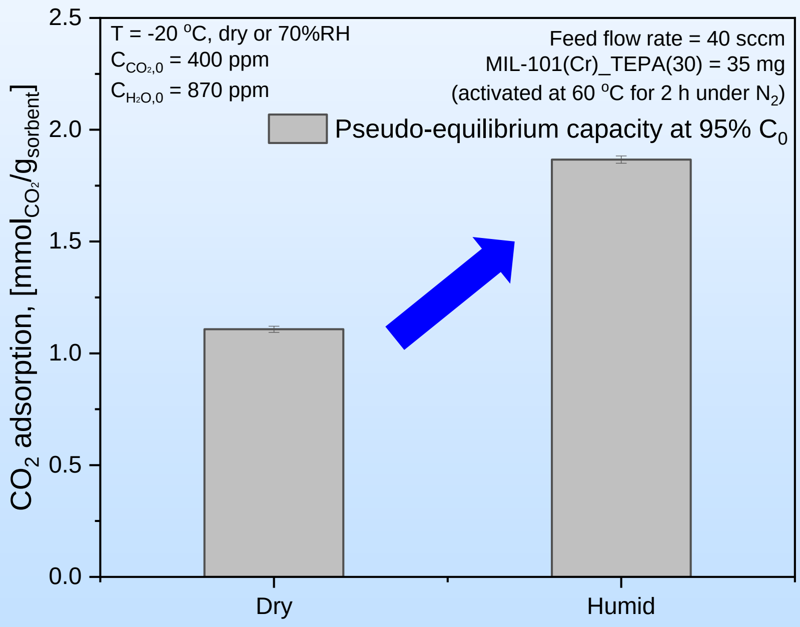
Rim et al., JACS Au, 2022, 2, 380-393.

Development of Powder MIL-101(Cr) Sorbents at Sub-ambient Conditions

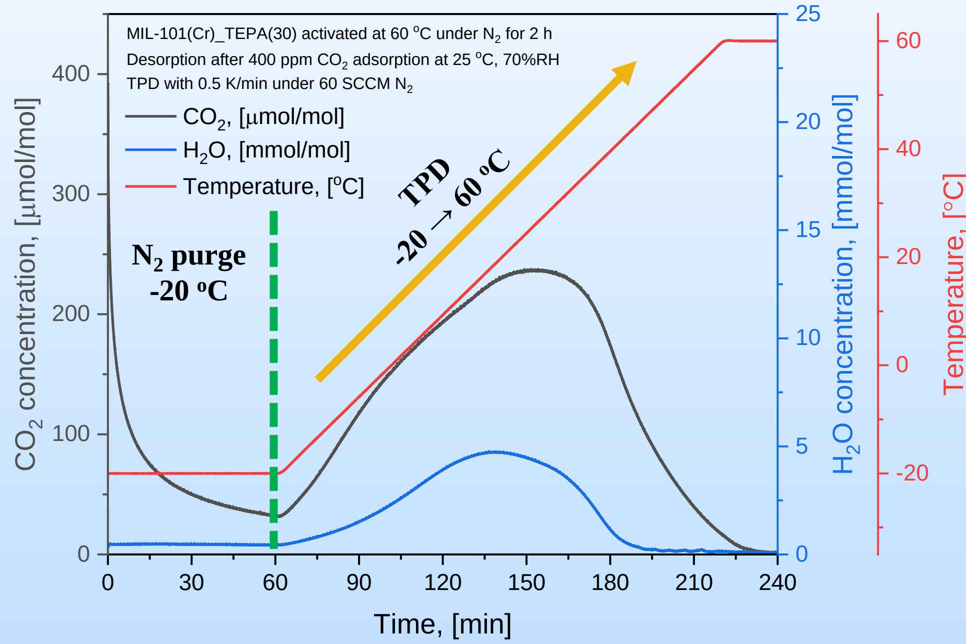
Sub-ambient DAC fixed bed test (dry and 70%RH at -20 ^oC)

MIL-101(Cr)_TEPA(30), weak chemisorption dominant

CO_2 capture capacity (breakthrough experiments)



CO_2/H_2O-TPD (0.5 ^oC/min)



Moisture has positive effect on capacity of sub-ambient DAC with MIL-101(Cr)_TEPA(30)

Rim et al., JACS Au, 2022, 2, 380-393.

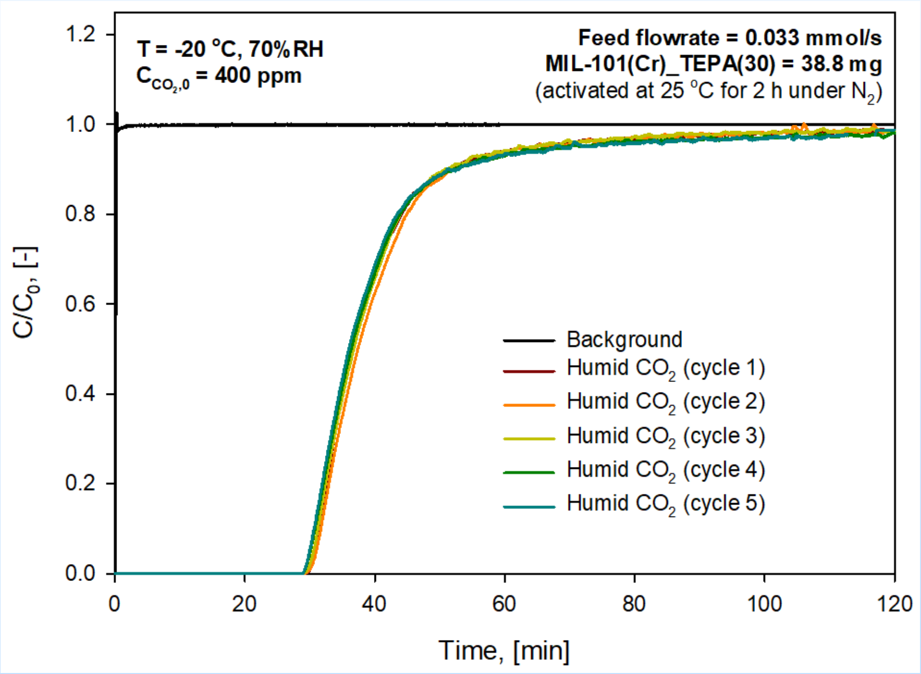
Development of Powder MIL-101(Cr) Sorbents at Sub-ambient Conditions

Cyclic fixed-bed tests under humid conditions (70% RH at -20 ºC)

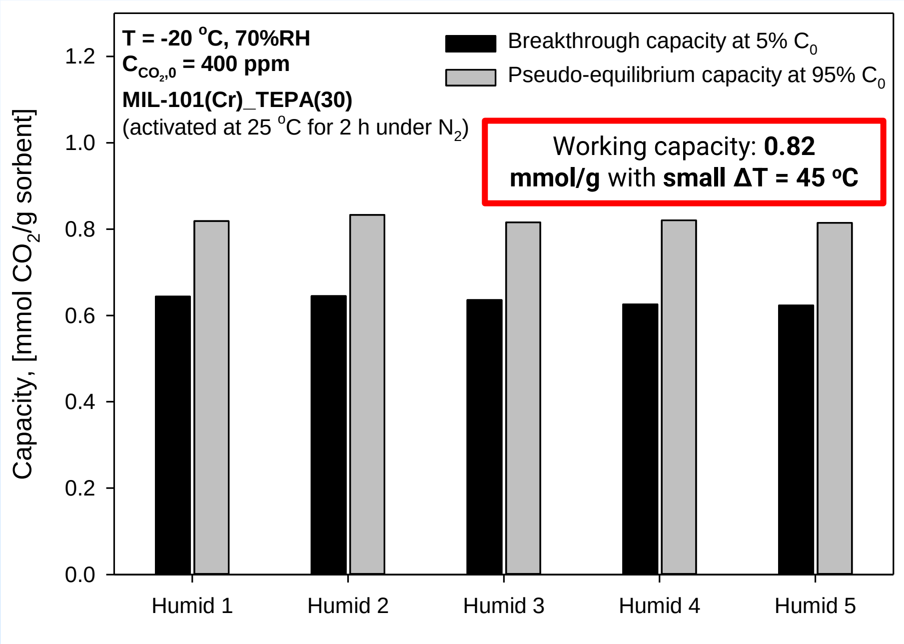
400 ppm CO_2 adsorption at -20 ºC (2 h), desorption at 25 ºC (2 h)

MIL-101(Cr)_TEPA(30)

CO_2 breakthrough curve



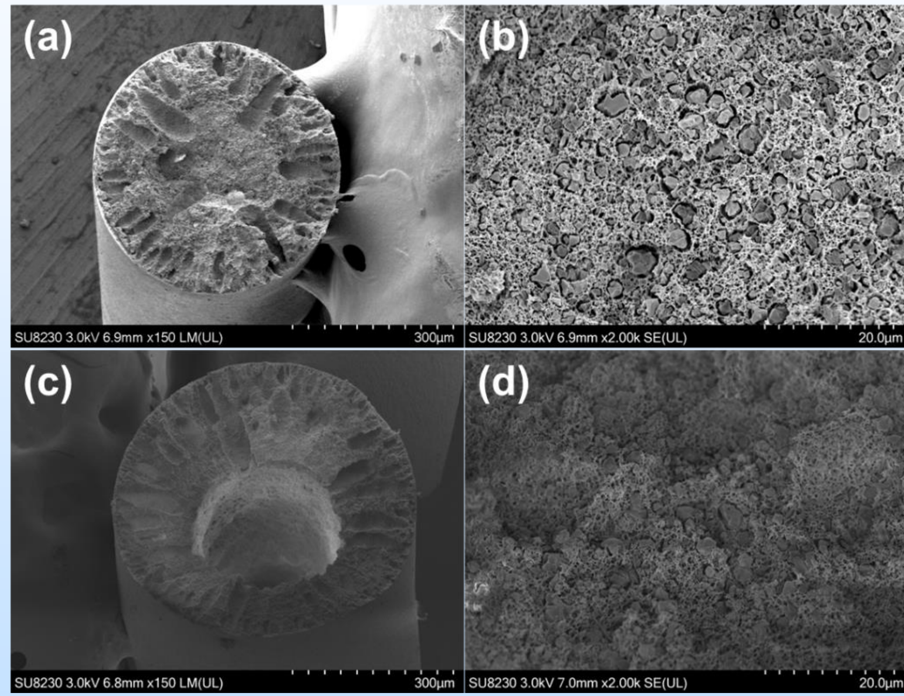
CO_2 capture capacity



30 wt% TEPA impregnated MIL-101(Cr) powders (weak chemisorption dominant) can be effectively regenerated at 25 ºC even under humid conditions.

Development of Amine MIL-101(Cr)-amine Fiber Sorbents

MIL-101(Cr)/CA fiber spinning

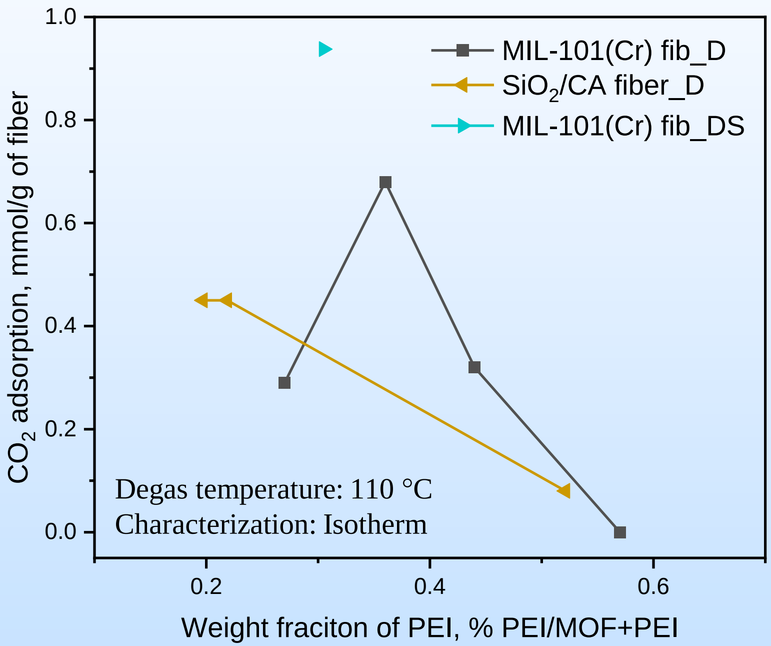


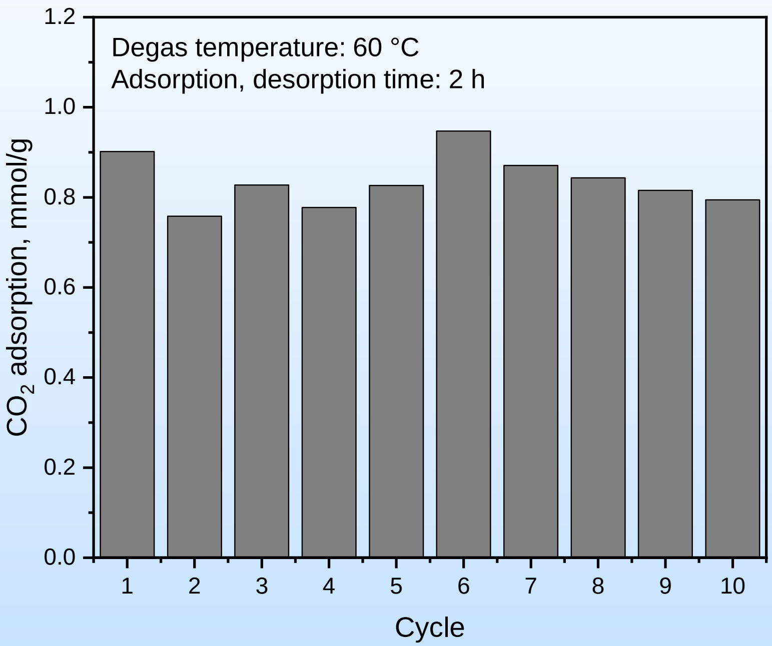
Successful fabrication of 50 wt% MIL-101(Cr) fibers of ~ 500 μm diameter
High permeance (164,000 GPU) compared to previously reported SiO_2/CA fibers[1]

[1] Labreche, Ying, et al. *Chem. Eng. J.* **2013**, 221, 166-175.

Development of Amine MIL-101(Cr)-amine Fiber Sorbents

PEI infused MIL-101(Cr)/CA fiber at -20 °C 400 ppm CO_2





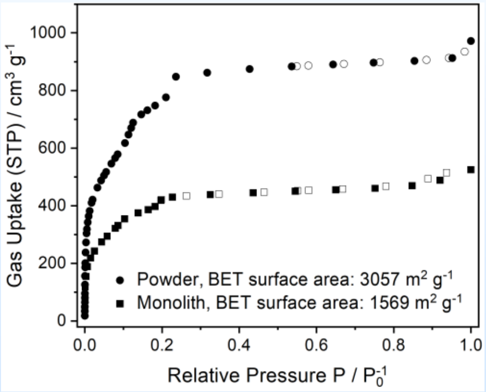
Highest CO_2 adsorption capacity by PEI-MIL-101(Cr) fibers with dual solvent (DS)

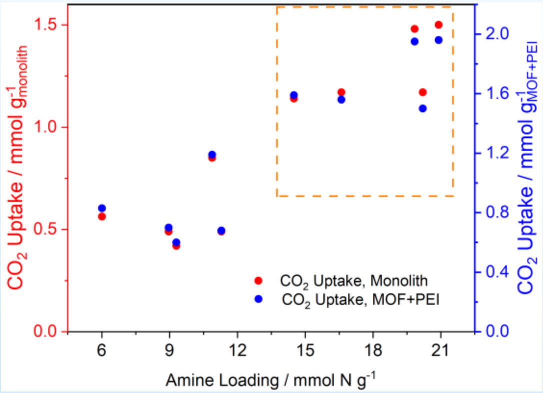
Stable performance during cycles under dry conditions with mild desorption temperature

The PEI-MIL-101(Cr) fibers will be tested under humid conditions in fiber module system.

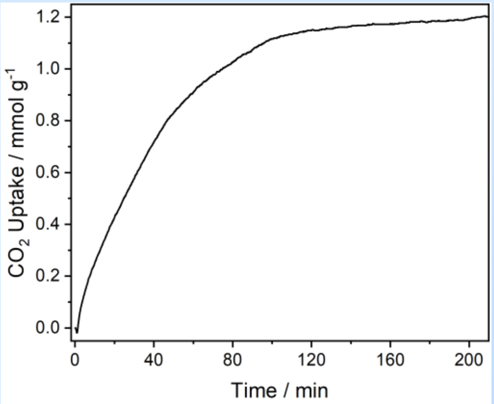
Development of MIL-101(Cr)-PEI 3D-Printed Monolith Sorbents

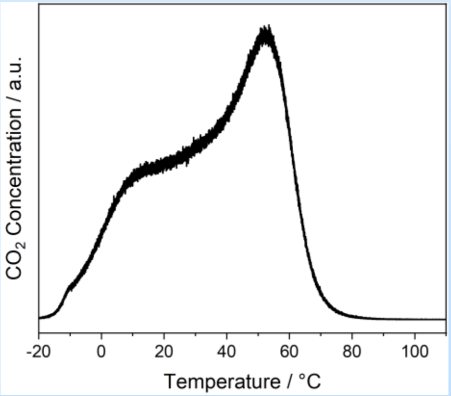
- Reduction in BET surface area of the monolith proportional to MIL-101 loading
- CO_2 uptake at 400 ppm and -20 °C increased with increased PEI loading





before PEI loading



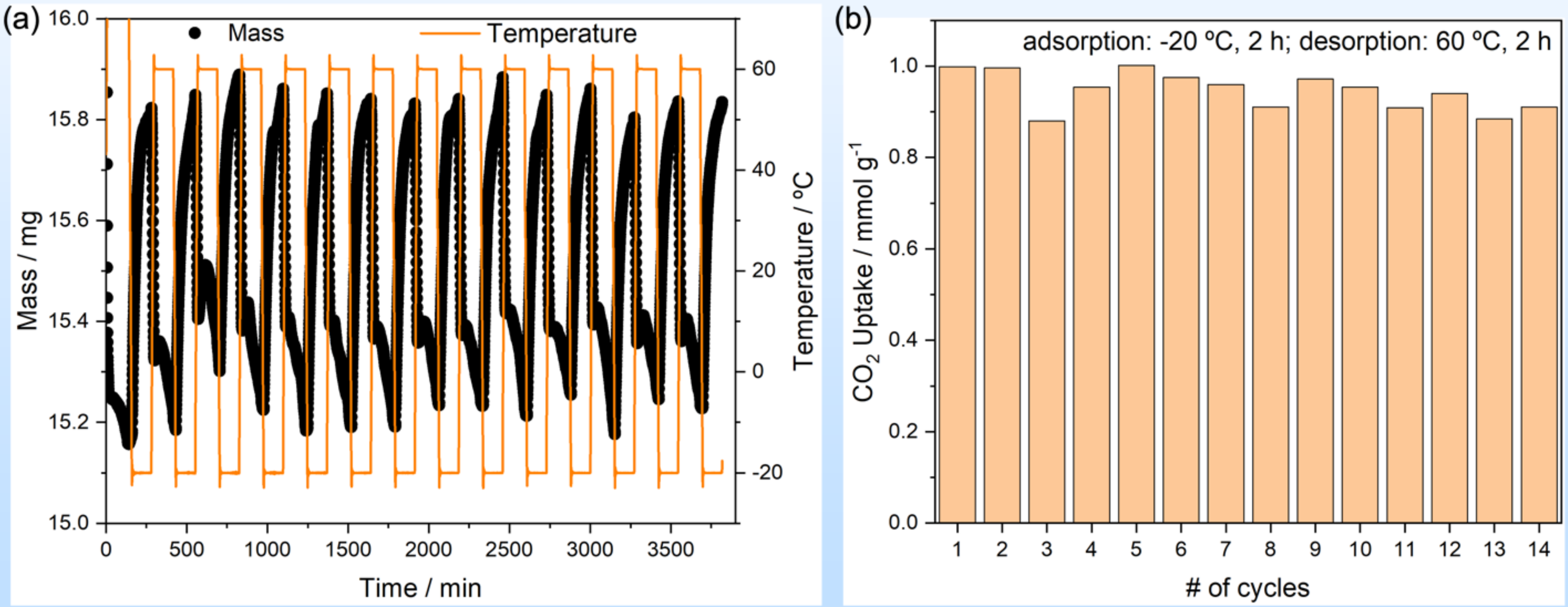


after PEI loading

Sub-ambient CO_2 uptake kinetics Temperature-programmed desorption

Development of MIL-101(Cr)-PEI 3D-Printed Monolith Sorbents

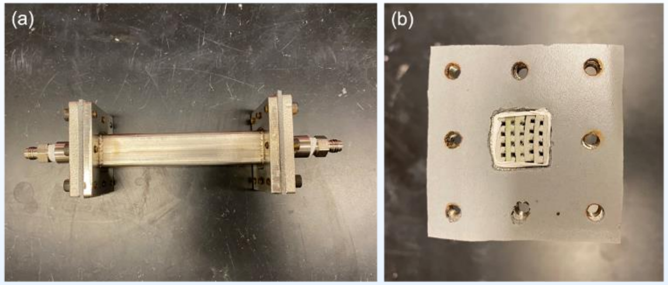
- Cyclic adsorption experiments: -20 °C in 400 ppm CO_2, 2 h; 60°C in He, 2 h
- 60 °C is enough to regenerate CA/MIL-101-PEI (PEI content: 14.5 N mmol/g MOF)
- Average working capacity: 0.95 mmol g(monolith)$^{-1}$

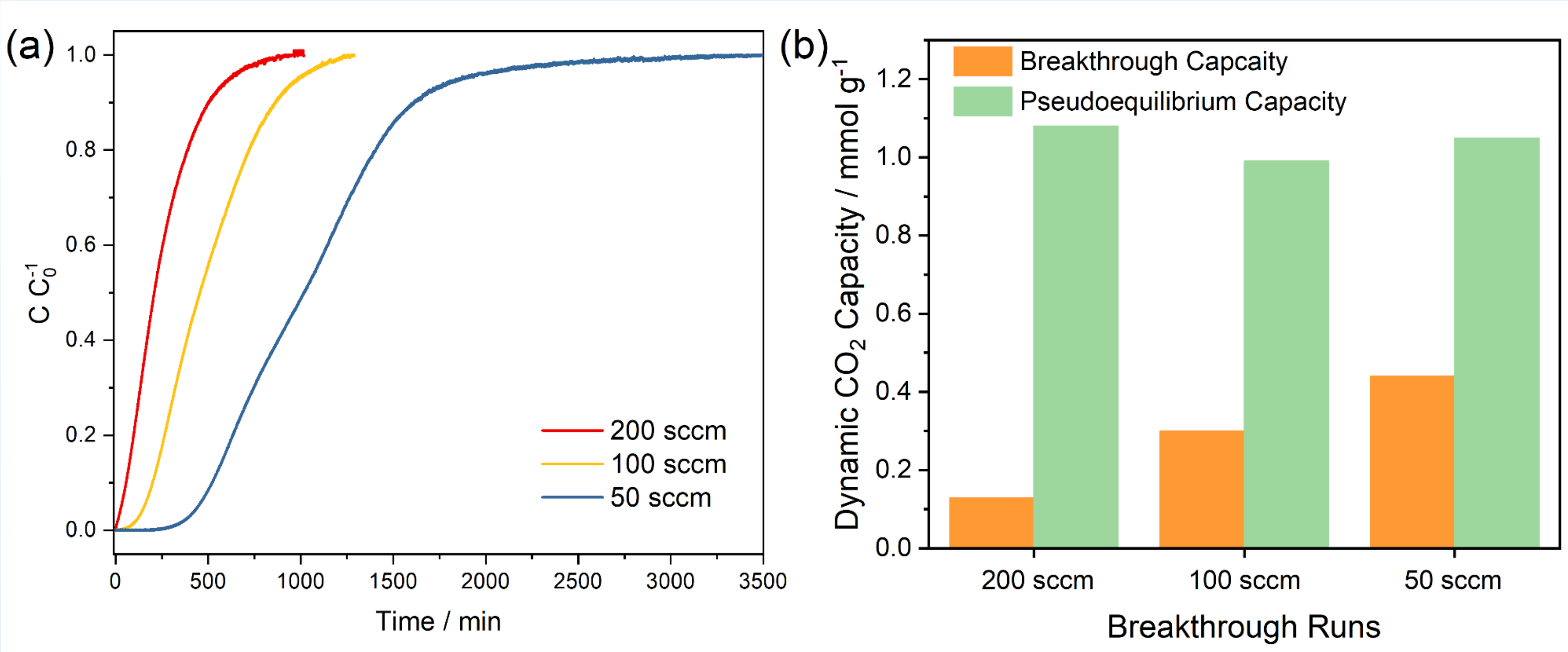


Cyclic sorption results

Development of MIL-101(Cr)-PEI 3D-Printed Monolith Sorbents

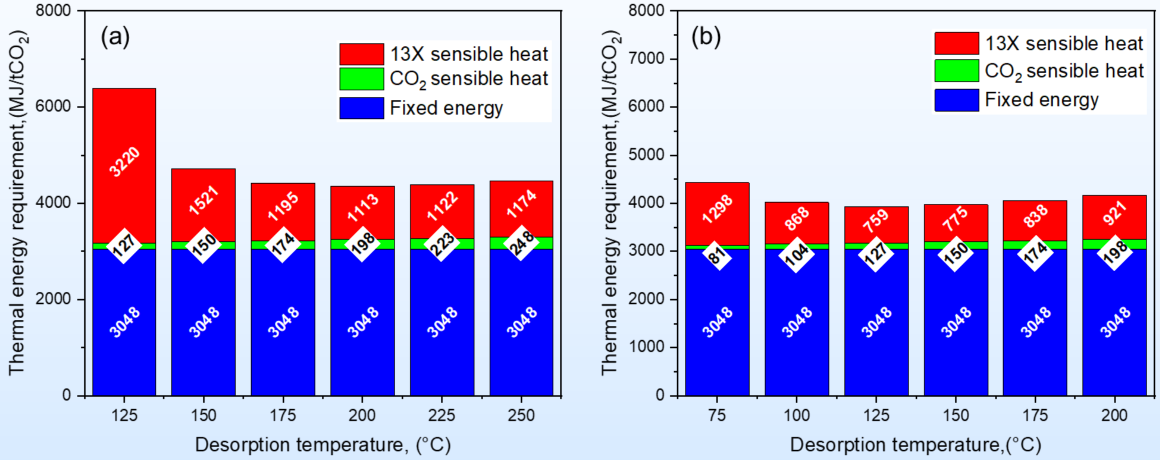
- Breakthrough curves of dry 400 ppm CO_2 at -20 °C
- Pseudo-equilibrium CO_2 sorption capacity comparable to TGA and gas sorption isotherm results



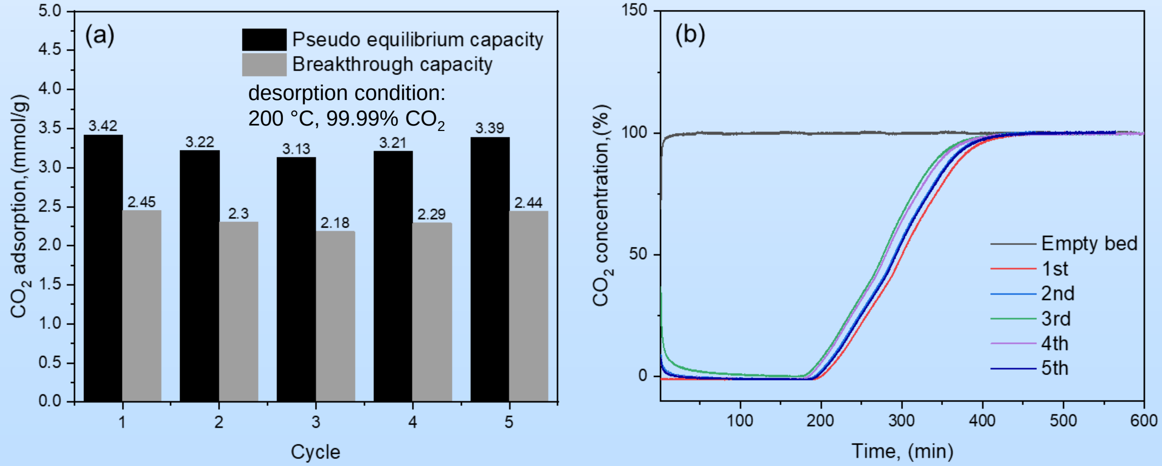


Development of Zeolite Powder Sorbents at Sub-ambient Conditions

13X zeolite TSA process at -20 °C 400 ppm CO_2

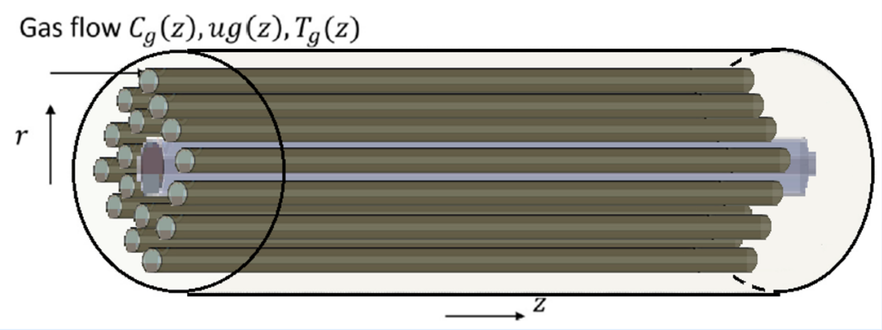


Song et al., Ind. Eng. Chem. Res. 2022, in press.



Thermal energy prediction using TSA and TVSA process (4.36 GJ/tCO_2 for TSA)
Stable performance of 13X during cyclic TSA experiments in fixed bed system

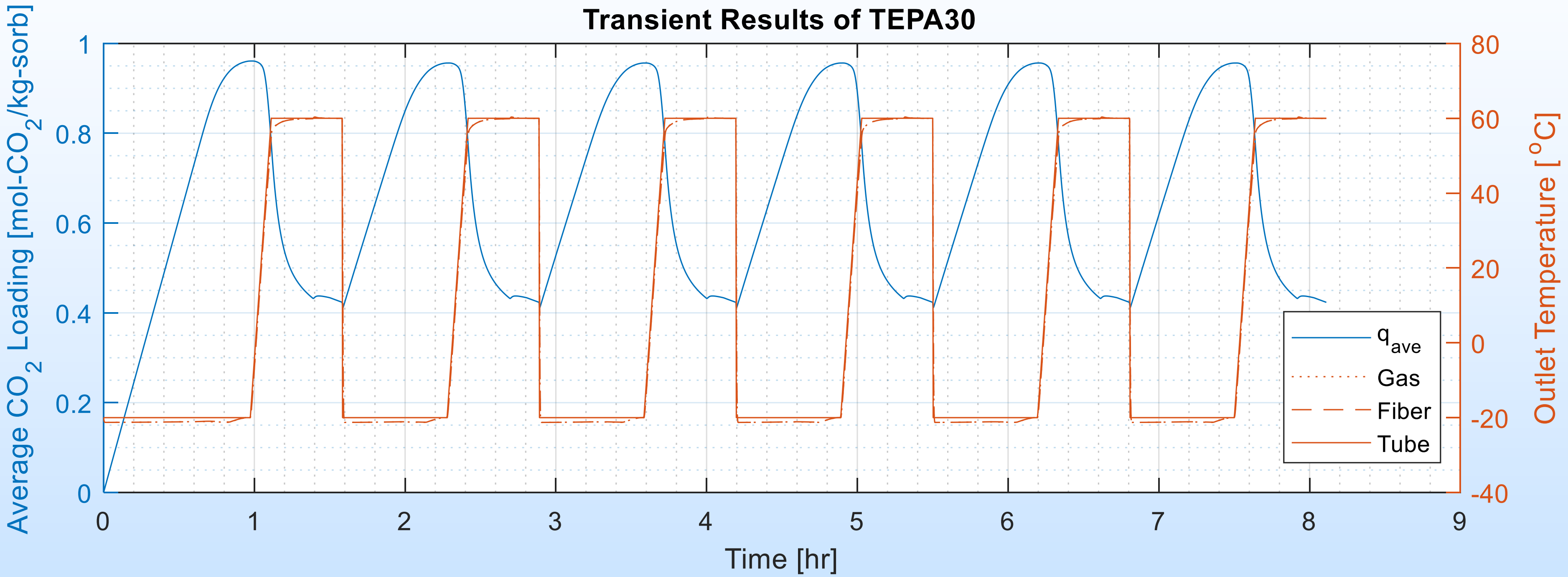
System Modeling Approach



- The DAC system contains multiple fibers (gray) to adsorb the CO_2, a centered tube (blue) to control the temperature. Air flows through the gas phase (white) and CO_2 is adsorbed onto the fibers

- A complete cycle includes adsorption (~34 min), vacuum (~1 min), desorption (~17 min), and compression (~1 min) steps.
- Mass transfer includes the gas phase, pore phase, and the fiber phase
- Energy balance includes the gas phase, fiber phase, and the tube phase
- Momentum balance includes the gas phase only
- Model equations are developed from the equation of motion and equation of energy for each phase individually
- Langmuir plus linear isotherm (low and high pressure) describes the CO_2 equilibrium of sorbents

Cycle results 30% TEPA, air at -20 °C



- Ambient temperature is -20 °C, and the desorption is at 60 °C
- Sorbent used is MIL-101(Cr)_30wt% TEPA
- Each cycle takes around [40 - 50] minutes.
- The cyclic steady-state is reached after two cycles of simulation
- The swing capacity is 0.7 mol-CO_2/kg-sorbent after two cycles

Performance Metrics

Ambient Temperature: -20 (^oC); Desorption Temperature: 60 (^oC)				
Material	Cyclic Duration (min)	42	47	52
PEI30	Swing Capacity (mol-CO_2/kg-sorb)	0.50	0.51	0.51
	Production (Ton-CO_2/kg-sorb/Year)	0.27	0.25	0.23
TEPA30	Swing Capacity (mol-CO_2/kg-sorb)	0.52	0.53	0.54
	Production (Ton-CO_2/kg-sorb/Year)	0.28	0.26	0.24

- Shorter cycles lead to
  - Decreased swing capacity
  - Increased production rate

Project Schedule (Key Milestones)

Task/ Subtask	Milestone Title & Description	Planned Completion Date
1	Project Management Plan	Month 1
3.2/4.2/**6.2**	Development of MIL-101(Cr)-based fibers and monolith sorbents. MIL-101(Cr) sorbent macrostructures, with at least two different compositions, successfully fabricated and structurally characterized.	Month 9 ↓ **Month 24 (extended)**
5/8	Evaluation of **performance and stability** of powder MIL-101(Cr)-based sorbents at sub-ambient conditions. CO_2 capacities will be measured for at least **three sorbent powder types**. Cyclic stability and rate of oxidative degradation will be measured for at least 1 sorbent at 3 different conditions.	Month 18 ↓ **Month 21 (extended)**
9	Translation of most promising powder MIL-101(Cr)-based sorbents to **fiber and monolith forms**. Developed macrostructures should have CO_2 capacity of at least 75% of the powder sorbent capacity.	Month 18 ↓ **Month 24 (extended)**
10	Employ **models of adsorption and desorption behavior** to estimate DAC system performance metrics; report swing capacity and energy consumption per ton CO_2.	Month 18 ↓ **Month 24 (extended)**

Plans for future testing/development/ commercialization

Tasks for future scale-up & testing:

a. This project

   -- assess preferred mode of incorporation into structured contactors (**fiber** vs. monolith vs. **3DP monolith**)

   -- use process model to assess preferred operational conditions

b. After this project

   -- assess preferred modes of desorption (T, V, heating modes, etc.)

   -- use technoeconomic model to find cost minima

Plans for future testing/development/ commercialization

Tasks for future scale-up & testing:

c. Scale-up potential

-- sorbent components all commercially available at small scale; assess & develop supply chains for sorbent

-- build and test automated low temperature DAC rig

Summary Slides

MIL-101(Cr) powder sorbents

a. Amine impregnated MIL-101(Cr) powders showed promising CO_2 uptake even at -20 °C due to enhanced weak chemisorption at cold temperatures.

b. MIL-101(Cr)_TEPA(30) is a preferred sorbent (among the samples we tested) for sub-ambient DAC due to promising adsorption capacity (1.12 mmol/g at -20 °C) and low regeneration temperature, 25 °C (weak chemisorption dominant).

c. Sub-ambient DAC capacity of MIL-101(Cr)_TEPA(30) was enhanced under humid conditions and stable working capacities (0.82 mmol/g) were obtained over 5 small humid temperature swing cycles (-20 °C <---> 25 °C) showing promising stability to humidity.

d. This work suggests that significant work on DAC materials that operate at low, sub-ambient temperatures is warranted for possible deployment in temperate and polar climates.

MIL-101(Cr) based fiber sorbents

a. PEI infused MIL-101(Cr)/CA (cellulose acetate) fiber sorbents with dual solvent method showed promising 400 ppm CO_2 uptake (0.94 mmol/g) at -20 ^{o}C.
b. PEI infused MIL-101(Cr)/CA fiber sorbents will be tested under humid conditions in fixed bed system.

MIL-101(Cr) based 3D-printed monolith sorbents

a. CA/MIL-101/PEI monoliths have been prepared by a 3D printing technique called solvent-based additive manufacturing (SBAM).
b. They show hierarchical porosity and comparable CO_2 uptake performance (in terms of MIL-101/PEI content) at sub-ambient conditions with powder sorbents.

DAC modeling

a. MIL101(Cr)_30% TEPA has higher swing capacity and production rate than MIL101(Cr)_30% PEI at -20 °C air temperature.
b. Cycle duration optimization leads to decreased swing capacity and increased production rate.
c. Simulation performance is sensitive to isotherm parameterization and input parameters, requires careful initialization.
d. Future plans: improve the production rate by productivity optimization, and complete TEA and LCA calculations.

Thanks to:

U.S. DEPARTMENT OF ENERGY | Fossil Energy and Carbon Management

Lively Group, Realff Group
David Elenowitz & Zero Carbon Partners

Jones Group:

- DAC Technology Knowledge Gaps

Kong et al., *Korean J. Chem. Eng*. **2022**, 39, 1-19.

- MIL-101(Cr)-Amine sorbents at cold T.

Rim et al., *JACS Au* **2022,** 2, 380-393.

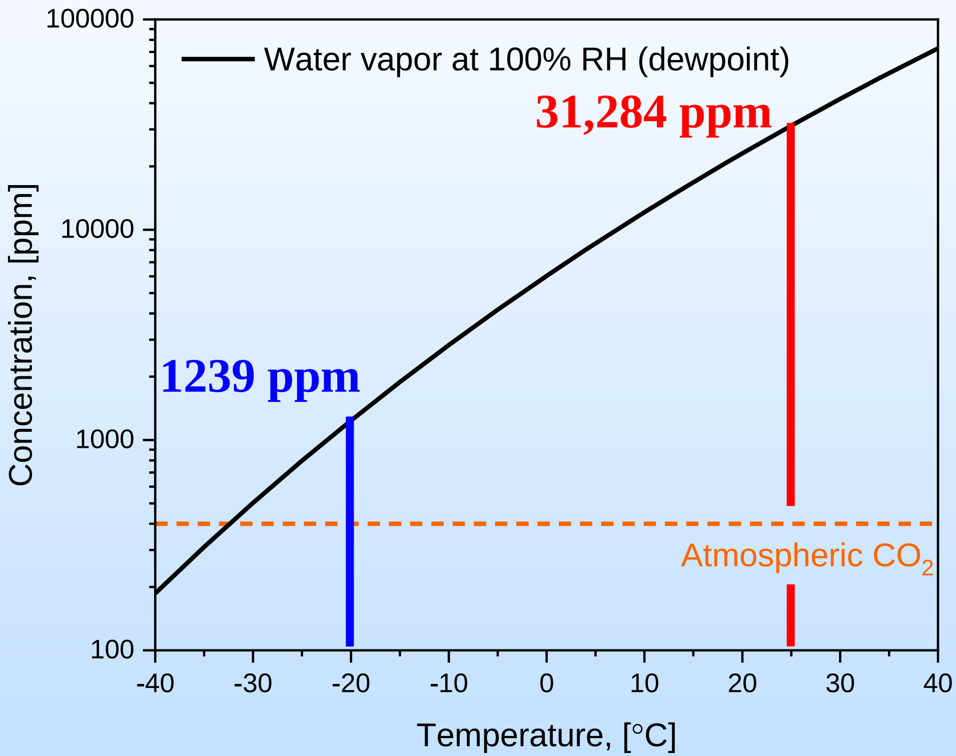
- Zeolites at cold temperatures

Song et al., *Ind. Eng. Chem. Res.* **2022,** in press.

Appendix

Aim to investigate the **CO_2 adsorption capabilities** of **amine-MIL-101(Cr)** sorbents over **wide range of adsorption temperature (-20 to 25 ^{o}C)** and **RH (0 to ~70%)** conditions.

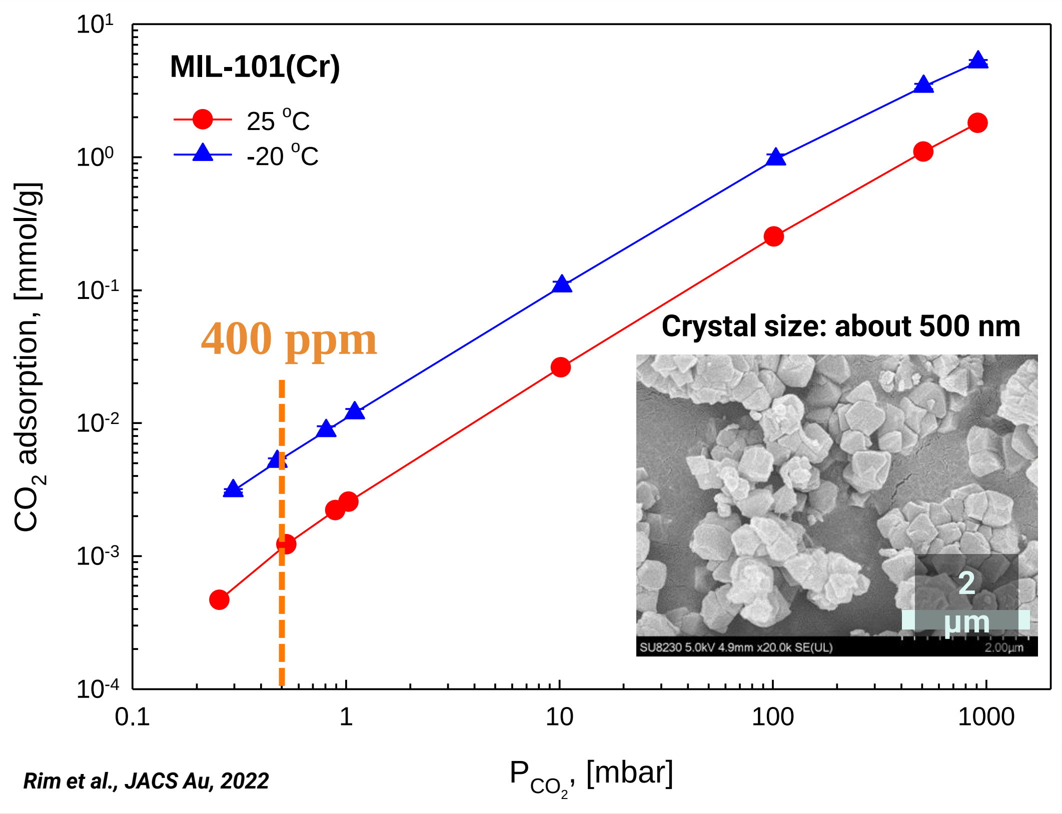
Absolute moisture concentration at dew point



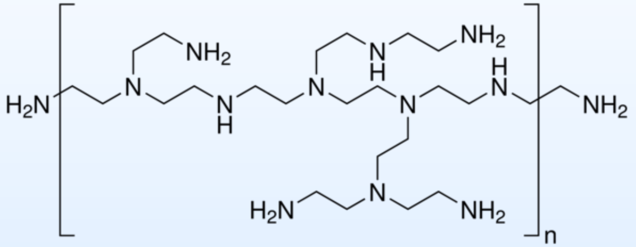
Kong et al., Korean J Chem Eng, 2021

Appendix

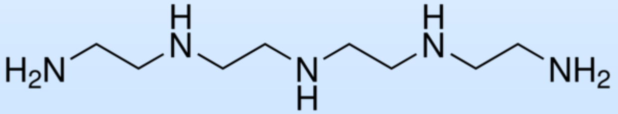
CO_2 adsorption isotherm



Impregnation with



Poly(ethyleneimine)
(PEI, branched, MW 800)



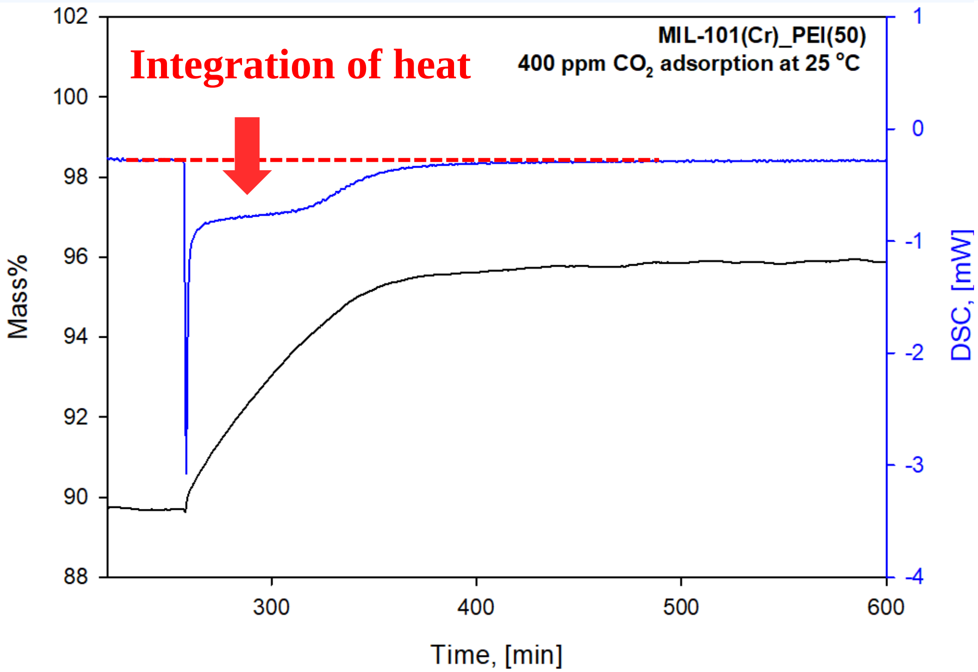
Tetraethylenepentamine
(TEPA)

Loadings: 10, 30, and 50 wt% of PEI or TEPA

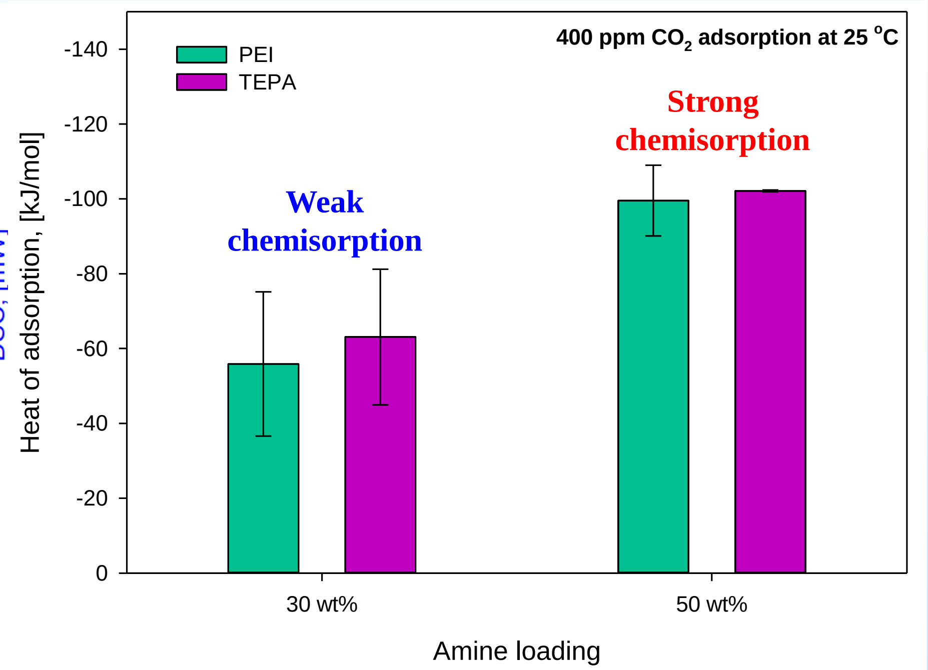
Appendix

Heat of adsorption at 25 °C

Measurement of heat of adsorption by TGA/DSC



Heat of adsorption



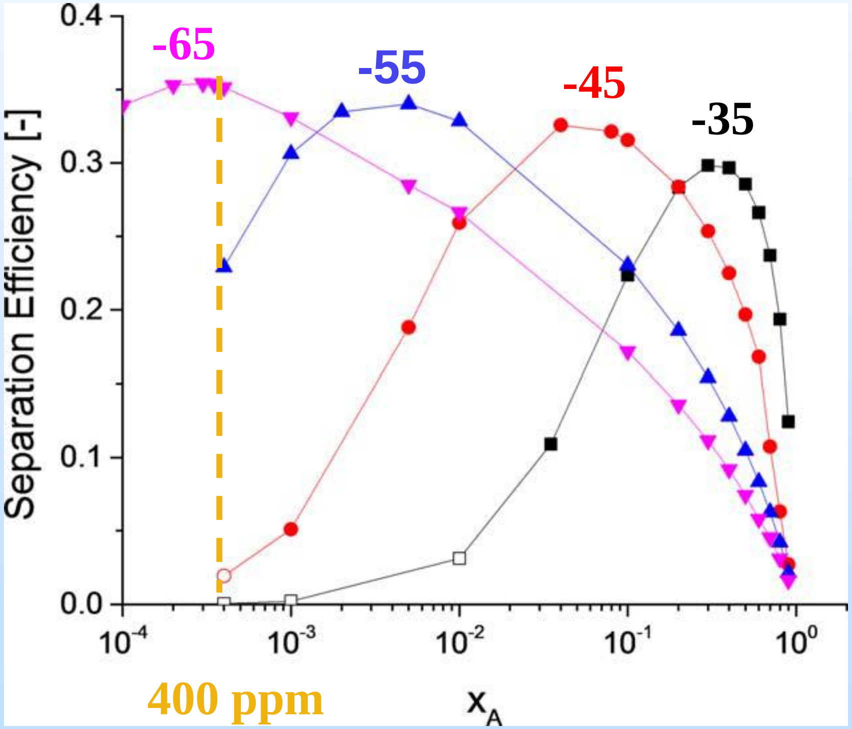
30 wt% loading: weak chemisorption dominant (-40 ~ -65 kJ/mol)
50 wt% loading: strong chemisorption dominant (-95 ~ -110 kJ/mol)

Rim et al., JACS Au, 2022

Appendix

Thermodynamic Separation Efficiency

Heat of adsorption (kJ/mol)

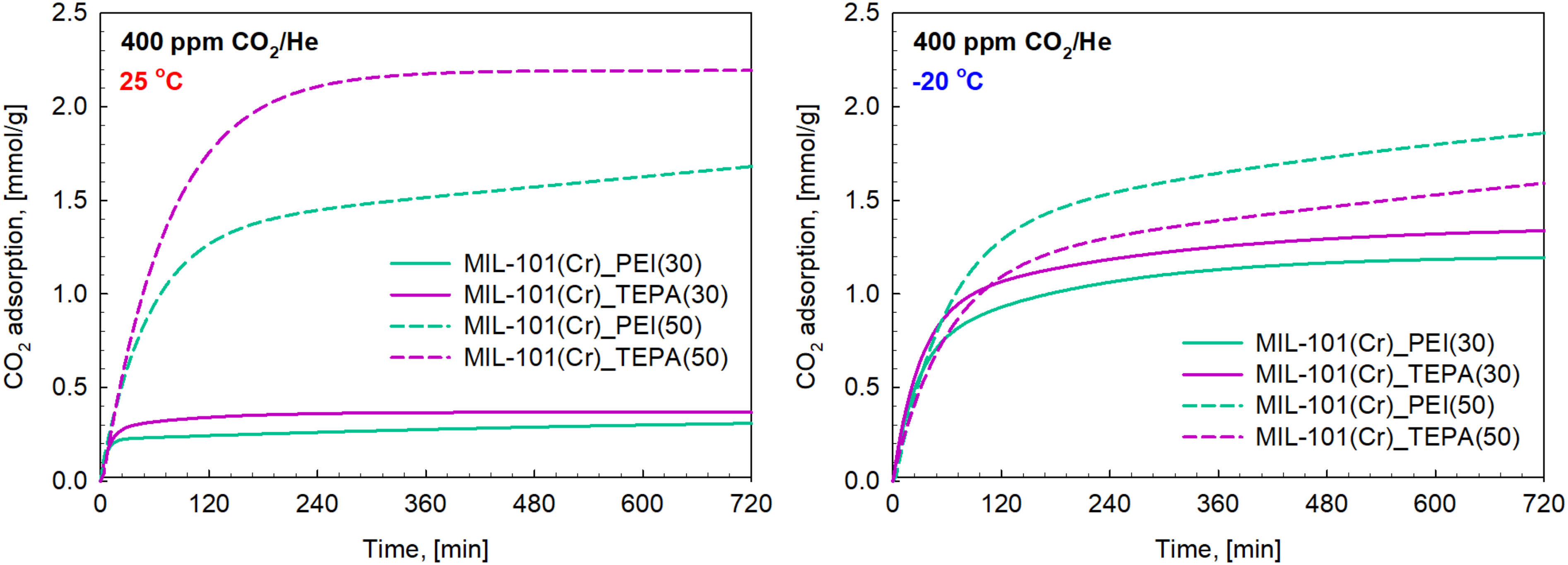


Lively and Realff, *AIChE J.*, 2016

TSA- for DAC, optimal sorbent has elevated ΔH_{ads} > 55 kJ/mol = Chemisorption

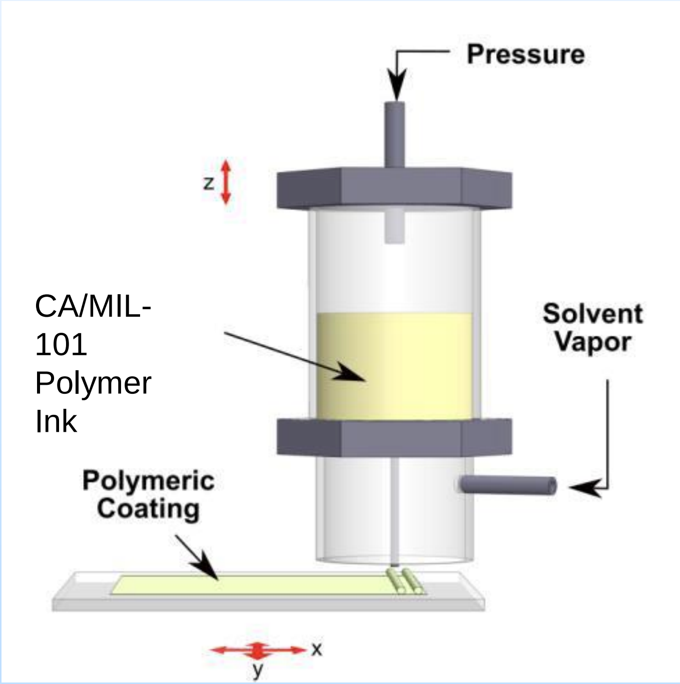
Appendix

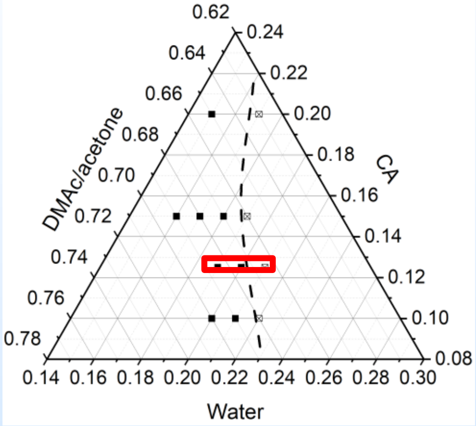
CO_2 Adsorption Kinetics (TGA/DSC)



Development of MIL-101(Cr)-PEI 3D-Printed Monolith Sorbents

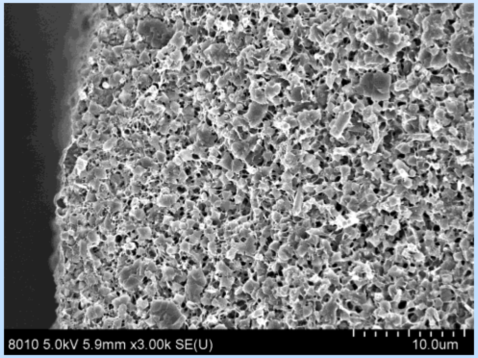
- Solvent Based Additive Manufacturing
- Cellulose acetate (CA) selected
- Dimethyl acetamide (DMAc) and acetone as solvent
- water as nonsolvent



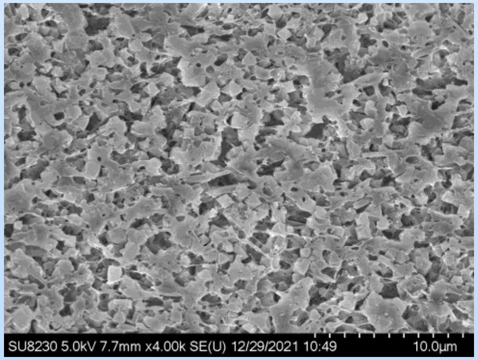


Phase diagram

As printed monolith

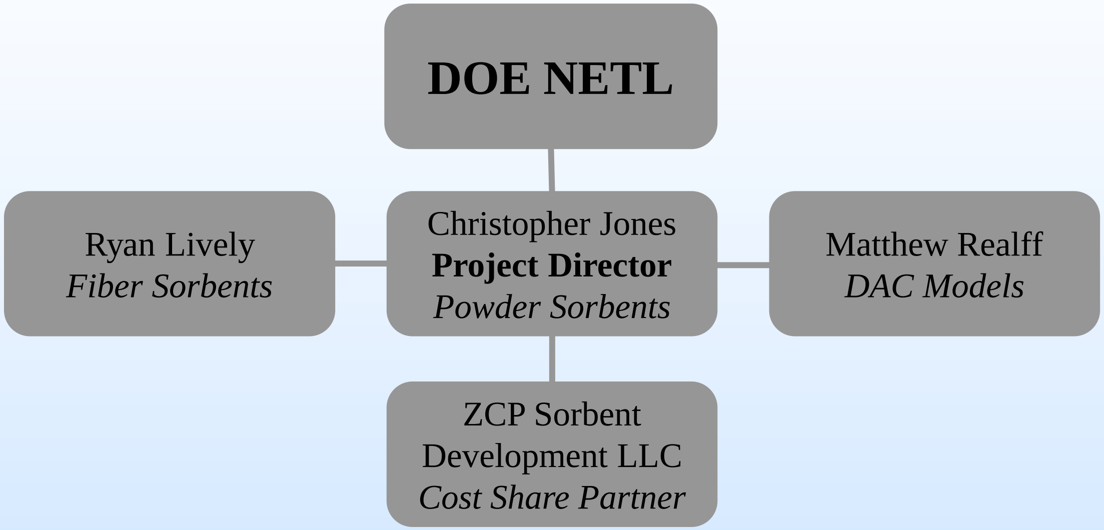


Cross Section



Surface

Organization Chart



- School of Chemical & Biomolecular Engineering, Georgia Institute of Technology
  - **Primary PI, Christopher Jones**: project director and communicate with DOE, developing MOFs powder sorbents and supporting MOFs on monolithic contactors for DAC
  - **Co-PI, Ryan Lively**: designing and fabricating MOFs bearing fiber sorbents for DAC, process development
  - **Co-PI, Matthew Realff**: DAC modeling and techno-economic/life cycle analysis
- ZCP Sorbent Development, LLC
  - Provide cost share by directly funding personnel in the project

Gantt Chart

Task	Team Member	Task Description	M	Year 1 Q1	Year 1 Q2	Year 1 Q3	Year 1 Q4	Year 2 Q1	Year 2 Q2	Year 2 Q3	Year 2 Q4	Task Start Date	Task End Date
1	**CWJ**	**Project Management, Planning and Reporting**	M1										
2	**CWJ**	**Development of MIL-101(Cr) powder sorbents**											
2.1		Synthesis of sorbent powder samples										10/01/20	02/28/21
2.2		Baseline testing of powder sorbents										11/01/20	02/28/21
3	**RPL**	**Development and preliminary testing of MIL-101(Cr)-amine fiber sorbents**											
3.1		Preparation of MIL-101(Cr) fibers										10/01/20	02/28/21
3.2		Preparation and characterization of amine loaded MIL-101(Cr) fibers	M2									02/01/21	04/30/22
3.3		Preliminary testing of CO_2 adsorption performance over MIL-101(Cr)-based fiber sorbents										06/01/21	04/30/22
4	**CWJ RPL**	**Development and preliminary testing of MIL-101(Cr)-amine monolith sorbents**											
4.1		Synthesis of MIL-101(Cr) on monolith supports										10/01/20	04/31/21
4.2		Preparation and characterization of amine loaded MIL-101(Cr) monoliths	M2									02/01/21	07/31/22
4.3		Preliminary testing of CO_2 adsorption performance over MIL-101(Cr)-amine monolith sorbents										06/01/21	07/31/22
5	**CWJ**	**Development of powder MIL-101(Cr)-based sorbents at sub ambient conditions**											
5.1		CO_2 adsorption testing of powder MIL-101(Cr)-based sorbent at sub-ambient conditions										12/01/20	10/31/21
5.2		Stability of powder MIL-101(Cr)-based sorbents to humidity	M3									03/01/21	11/30/21

M indicates milestone.

- Work in progress; - To be completed (original schedule); - To be completed (extended schedule); -To be completed (no cost time extension)

Task	Team Member	Task Description	M	Year 1 Q1	Year 1 Q2	Year 1 Q3	Year 1 Q4	Year 2 Q1	Year 2 Q2	Year 2 Q3	Year 2 Q4	Task Start Date	Task End Date
6	CWJ RPL	**Development of MIL-101(Cr)-amine monolith sorbent via 3D printing**											
6.1		Development of 3D printing procedure for MIL-101(Cr) monoliths										10/01/20	03/31/22
6.2		Testing of CO_2 adsorption performance for 3D printed MIL-101(Cr)-amine monolith sorbents										05/01/21	08/31/22
6.3		Investigation of effect of monolith properties on CO_2 adsorption performance										09/01/21	09/30/22
7	MJR	**Build models of the adsorption and desorption behavior of MIL-101(Cr)-amine materials**											
7.1		Model equilibrium adsorption behavior										02/01/21	03/31/22
7.2		Model kinetics of adsorption behavior										02/01/21	03/31/22
7.3		Model equilibrium desorption behavior										02/01/21	03/31/22
7.4		Model kinetics of desorption behavior										02/01/21	03/31/22
8	CWJ	**Measuring stability of MIL-101(Cr)-based sorbent powders at sub-ambient conditions**											
8.1		Stability of amine-MIL-101(Cr) sorbents to cyclic operation at sub ambient conditions										10/01/21	03/31/22
8.2		Stability of amine-MIL-101(Cr) sorbents to oxygen	M3									10/01/21	06/30/22
9	CWJ RPL	**Translation of best performing powder MIL-101(Cr)-amine sorbents to fiber and monolith forms**											
9.1		Synthesis and testing of best powder sorbent samples into fiber form										09/01/21	06/30/22
9.2		Synthesis and testing of best powder sorbent samples into monolith form	M4									09/01/21	09/30/22
10	MJR	**Estimate DAC system performance metrics**											
10.1		Determine estimated swing capacity and productivity of adsorbents										10/01/21	09/30/22
10.2		Determine estimated energy consumption per ton CO_2										10/01/21	09/30/22
10.3		Determine the system cost and life cycle energy inventory for 1 Mton of CO_2 scale system	M5									10/01/21	09/30/22

M indicates milestone.

- Work in progress; - To be completed (original schedule); - To be completed (extended schedule); -To be completed (no cost time extension)