# Enabling 10 mol/kg swing capacity in post-combustion $CO_2$ capture processes

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**Stephen J. DeWitt, Rohan Awati, Jongwoo Park, Eli Carter, Hector Rubiera Landa**

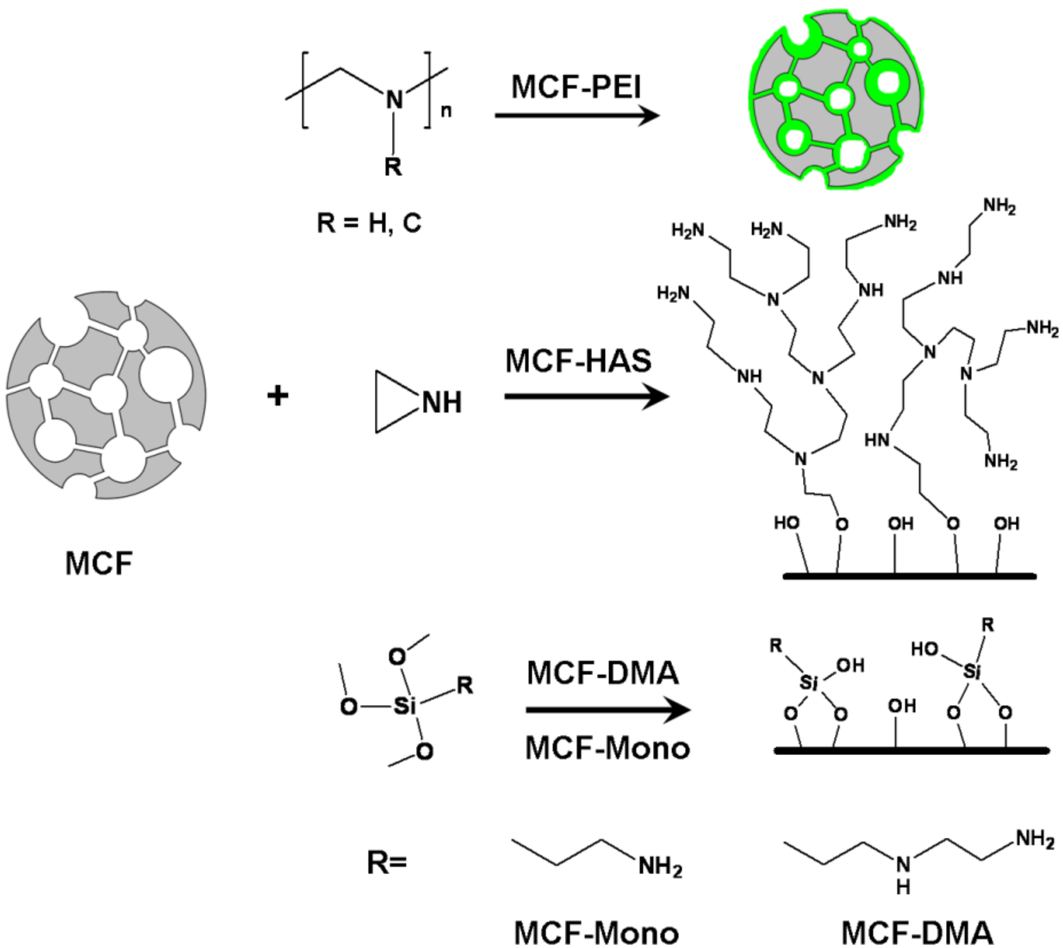
Georgia Institute of Technology
School of Chemical & Biomolecular Engineering
Atlanta, GA 30332

BM Sanderson, BC O'Neill, C Tebaldi, *Geophysical Research Letters* 2017
RP Lively, MJ Realff. *AIChE J.* 2016

inmondo tech Georgia Tech School of Chemical & Biomolecular Engineering

# Adsorption (and membranes) are materials-enabled separations






SH Pang, CW Jones et al., *J. Am. Chem. Soc.*, 2017, 139, 3627-3630

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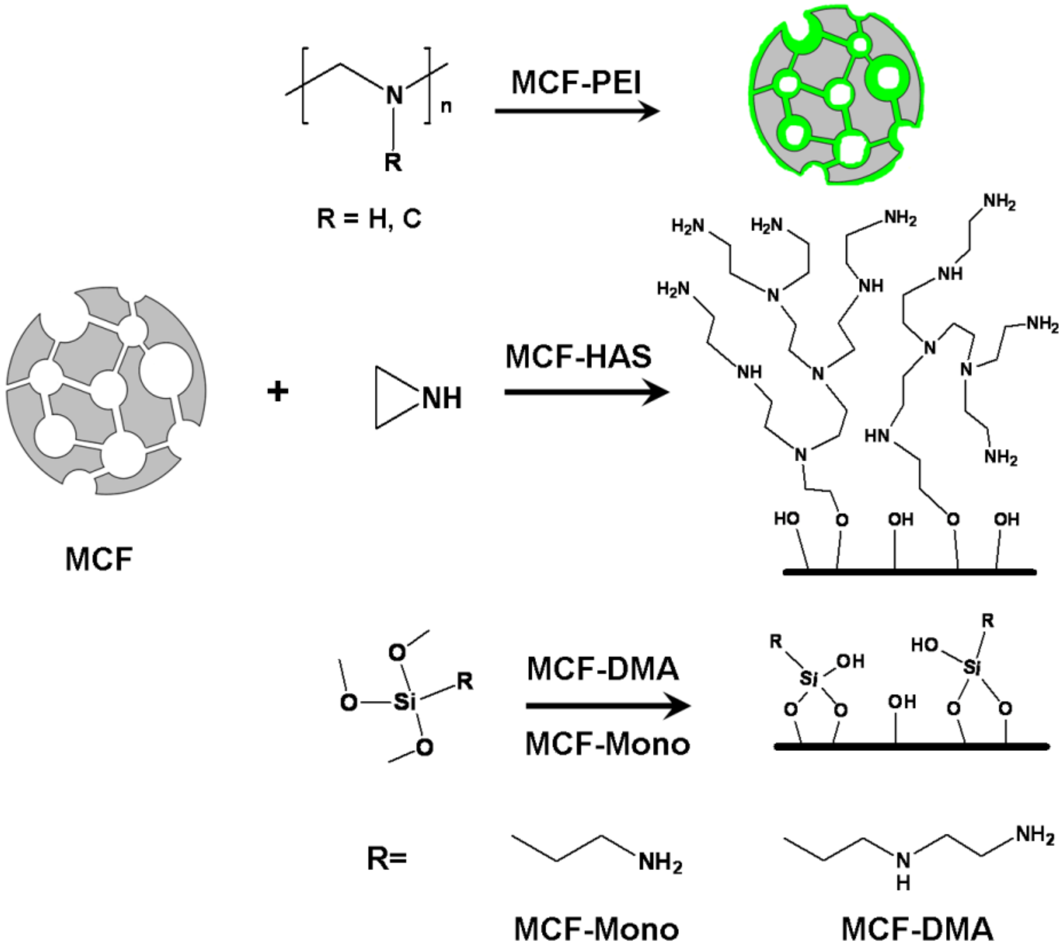


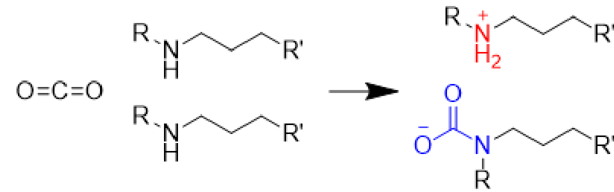


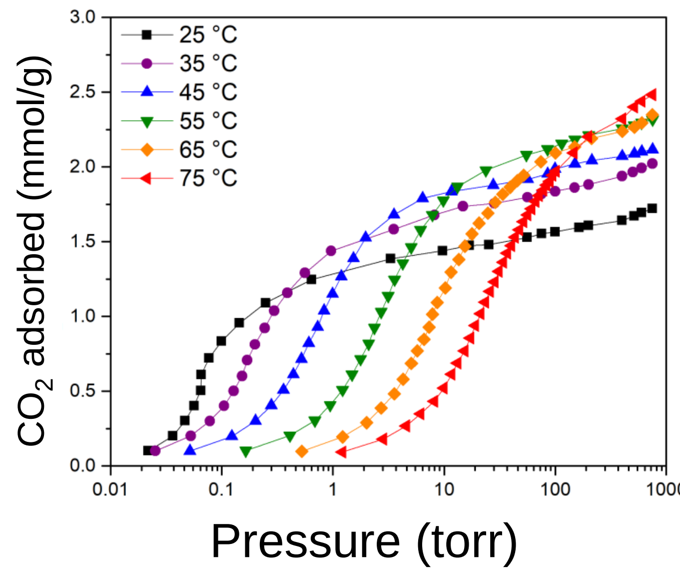


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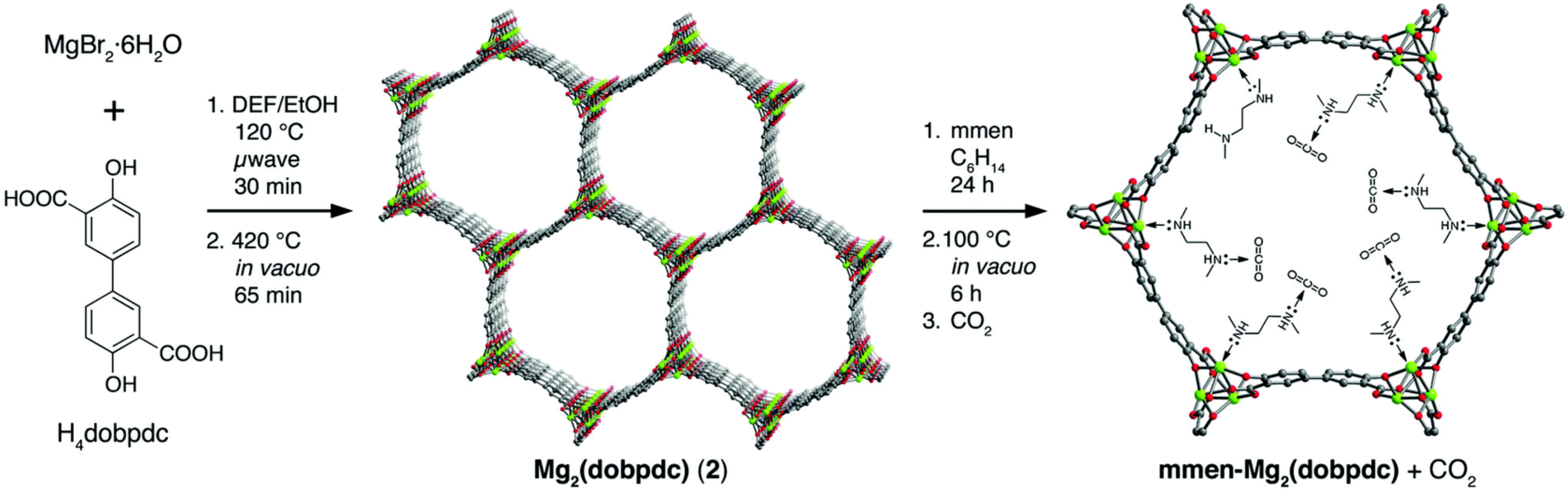
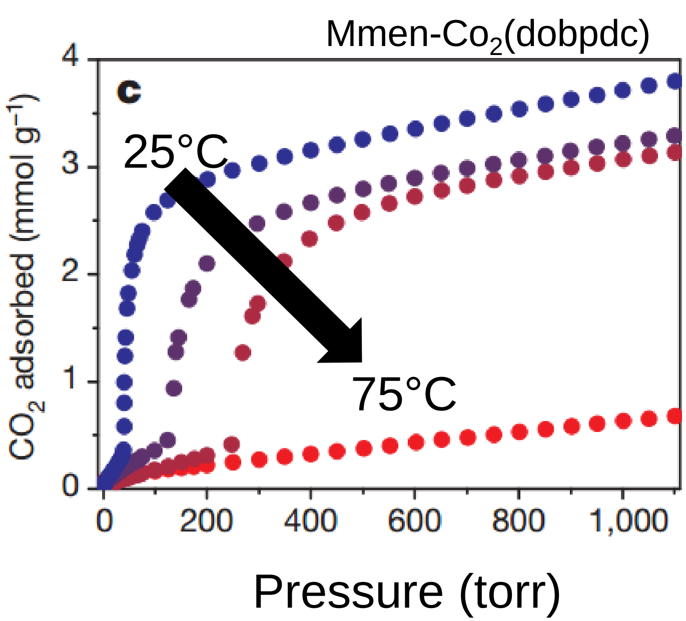
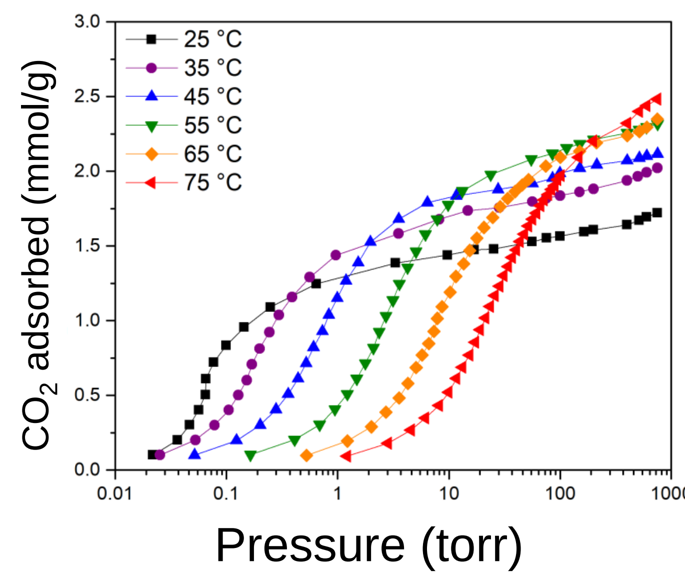
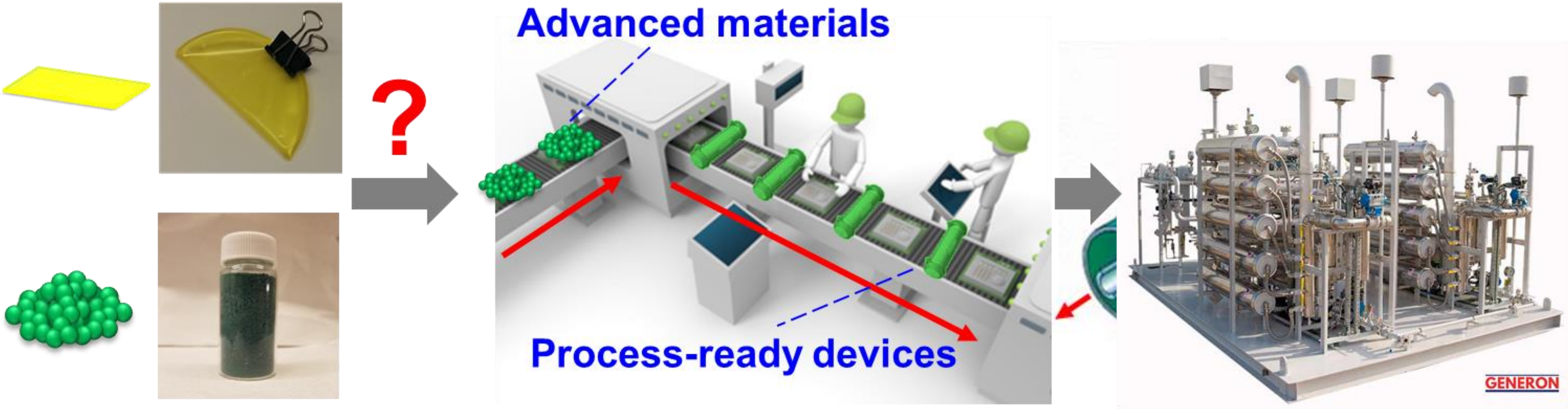



TM McDonald, JR Long et al., *Nature*, 2015, 519, 303-308
SH Pang, CW Jones et al., *J. Am. Chem. Soc.*, 2017, 139, 3627-3630

# Connecting materials to engineering solutions—fibers lead the way






WJ Koros, RP Lively. *AIChE J.* 2012, 58(9)

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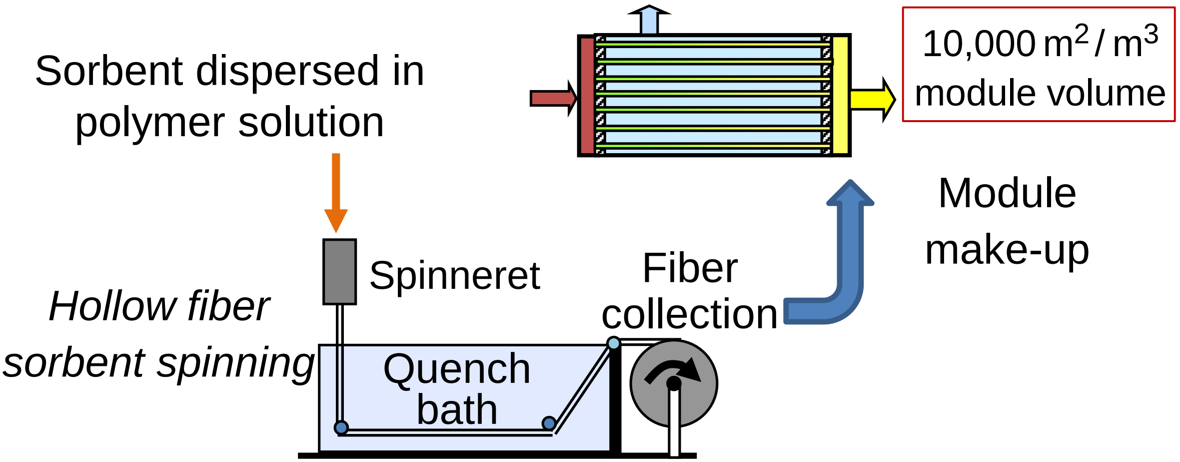


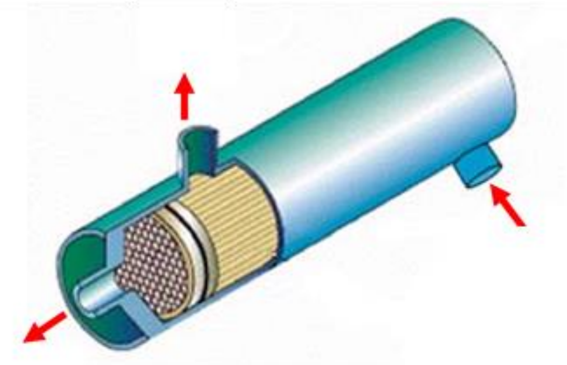

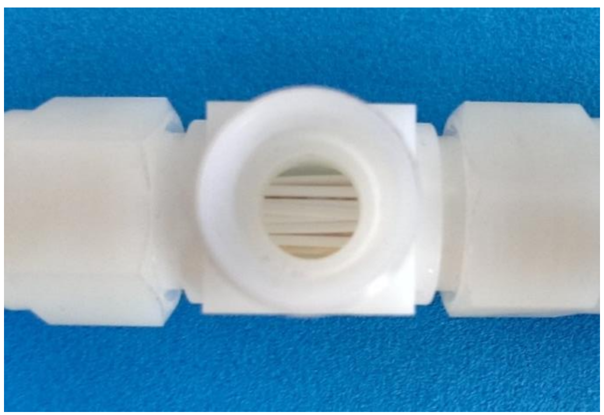

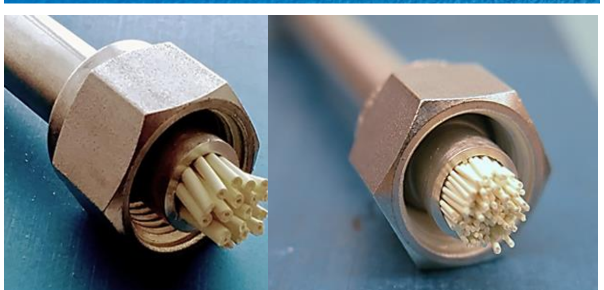

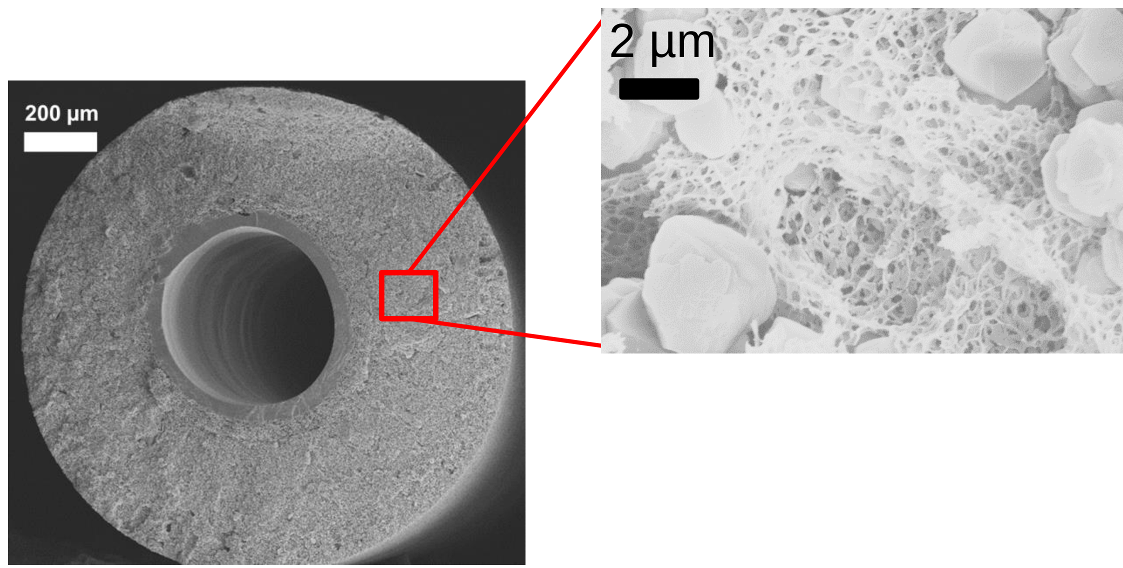


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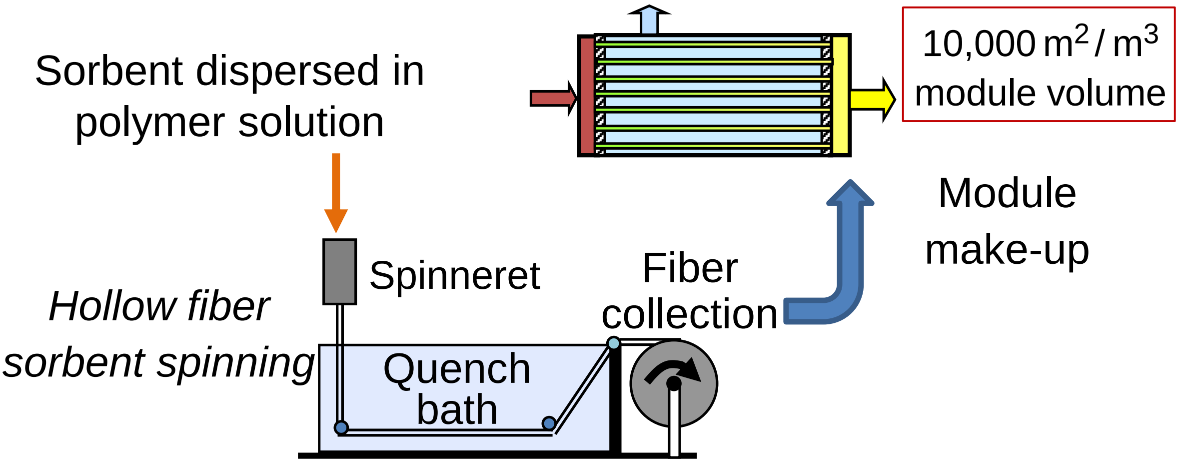


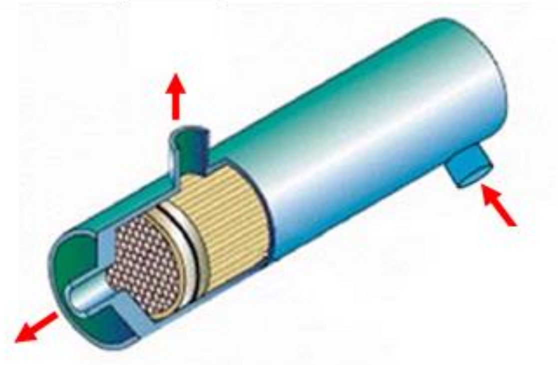

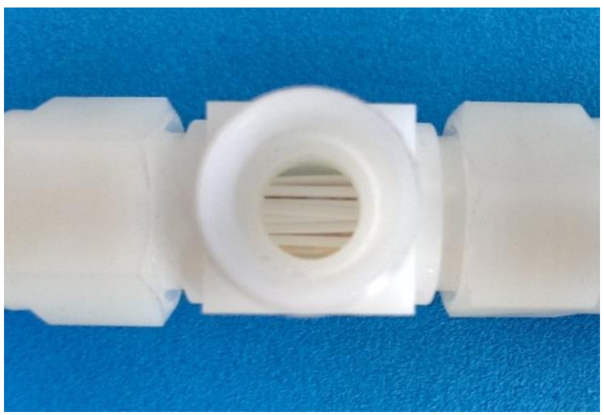

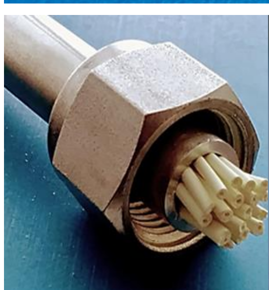

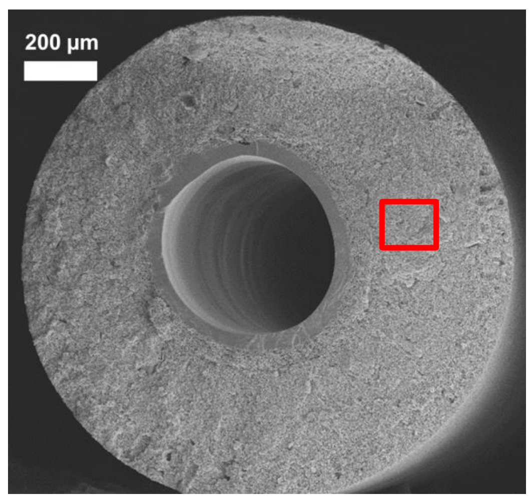


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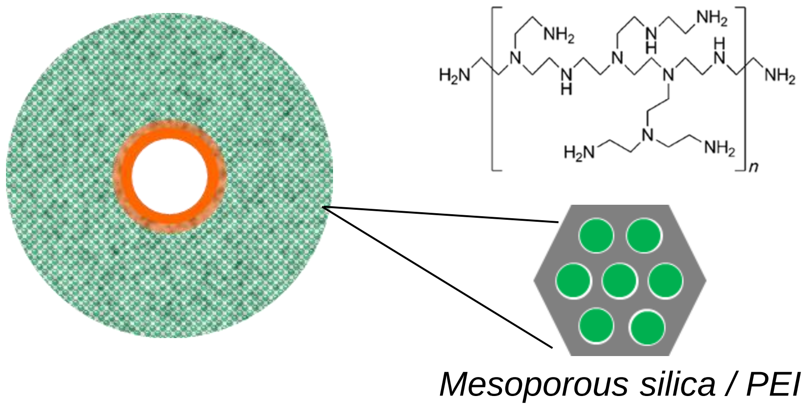
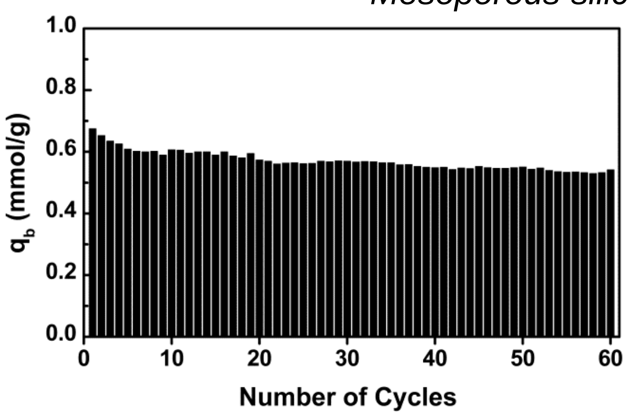
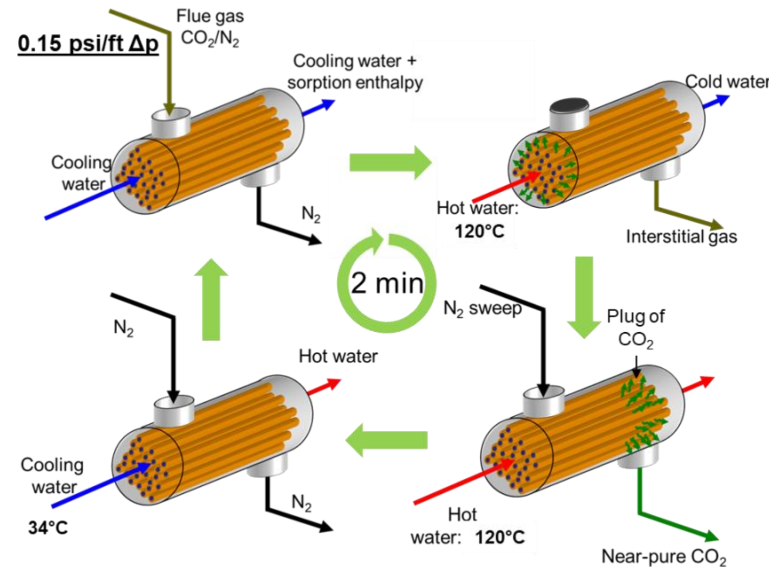
# Rapid thermal swing adsorption—amines/hollow fiber sorbents

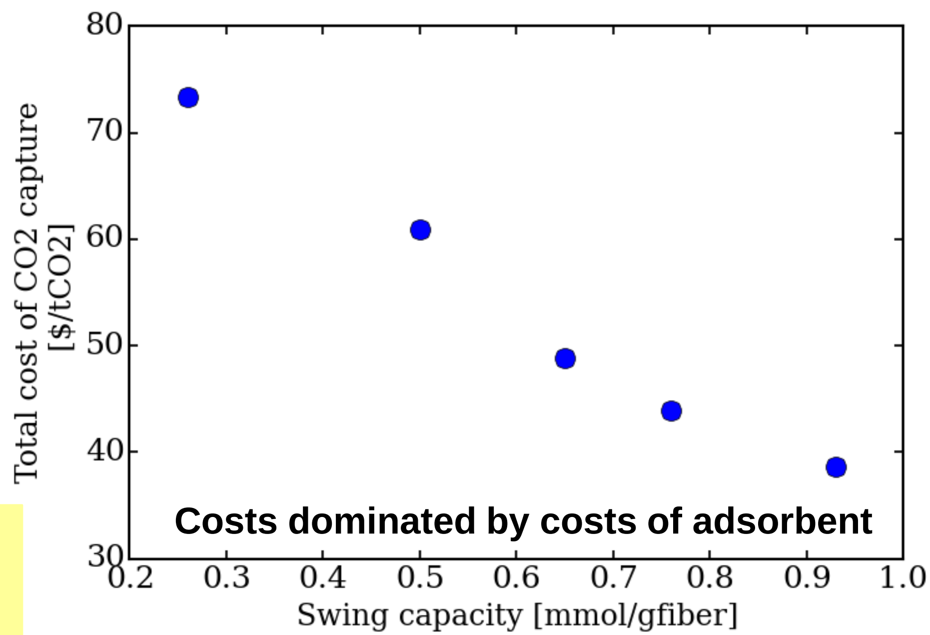



Swing capacity and cycle time are key for driving down capital costs of adsorption-based $CO_2$ capture systems!

*Key question: Can we increase swing capacity by 10x and reduce cycle time by 5x to dramatically drive down adsorbent costs?*




Y Fan, CW Jones et al., *Int. J. Greenhouse Gas Control* 2014, 21, 61-71

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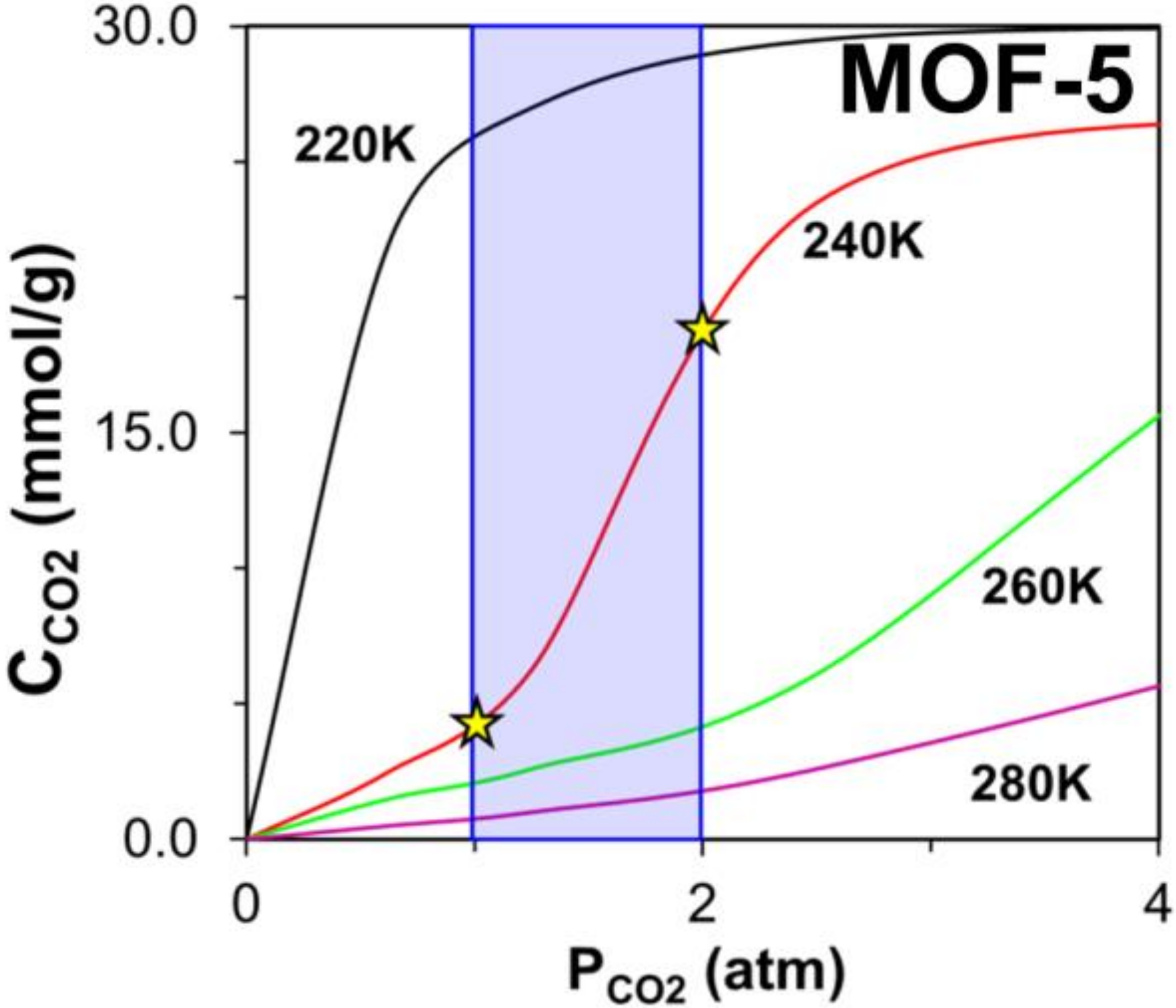
# Rapidly cycled pressure swing adsorption using MOFs

*Cycle times of ~20 seconds are common for industrial RCPSA (>5x faster than RTSA)*




JM Simmons, T Yildirim et al., *Energ. Env. Sci.*, 2011, 4(6), 2177-2185

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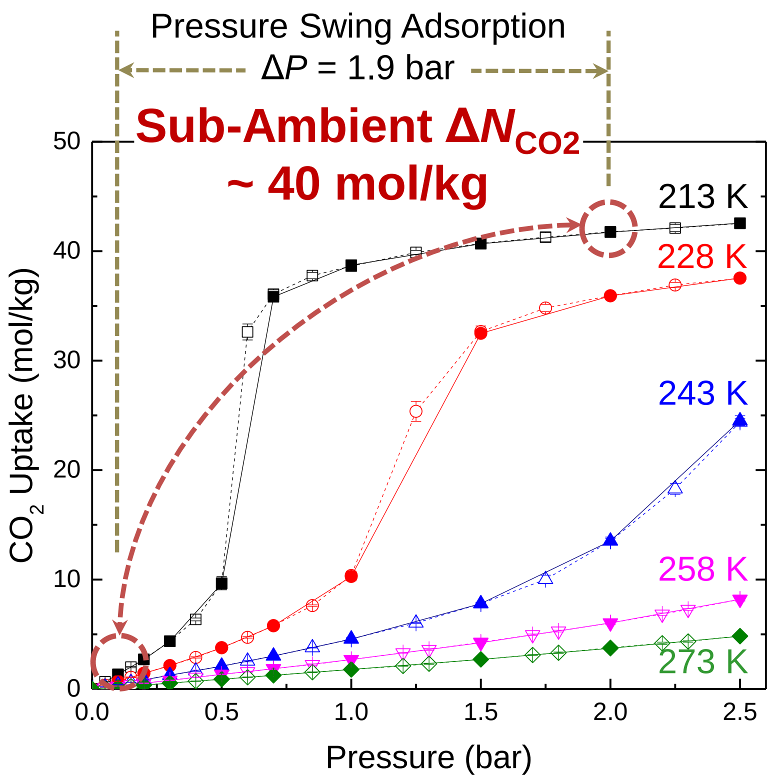


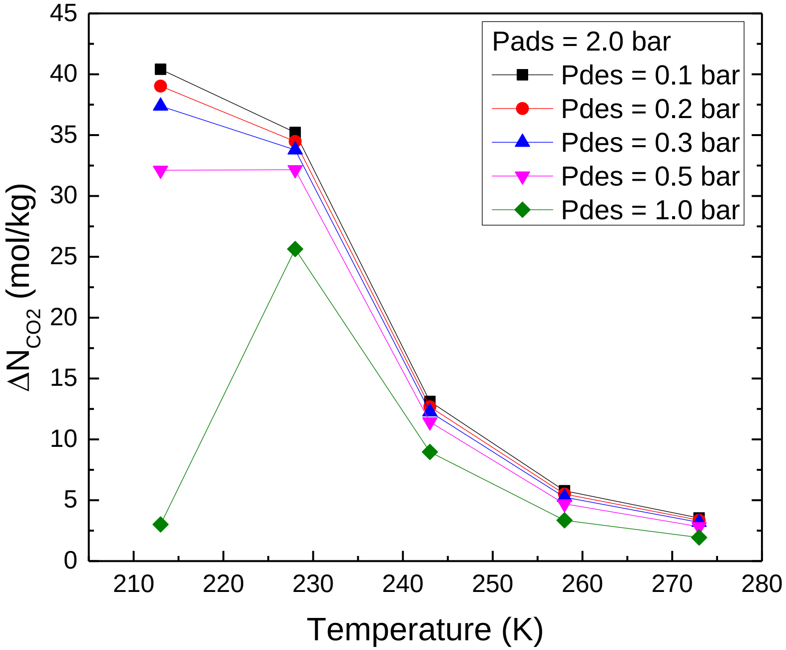


J Park, RP Lively, DS Sholl, *J. Mater. Chem. A.* 2017, 5, 12258-12265

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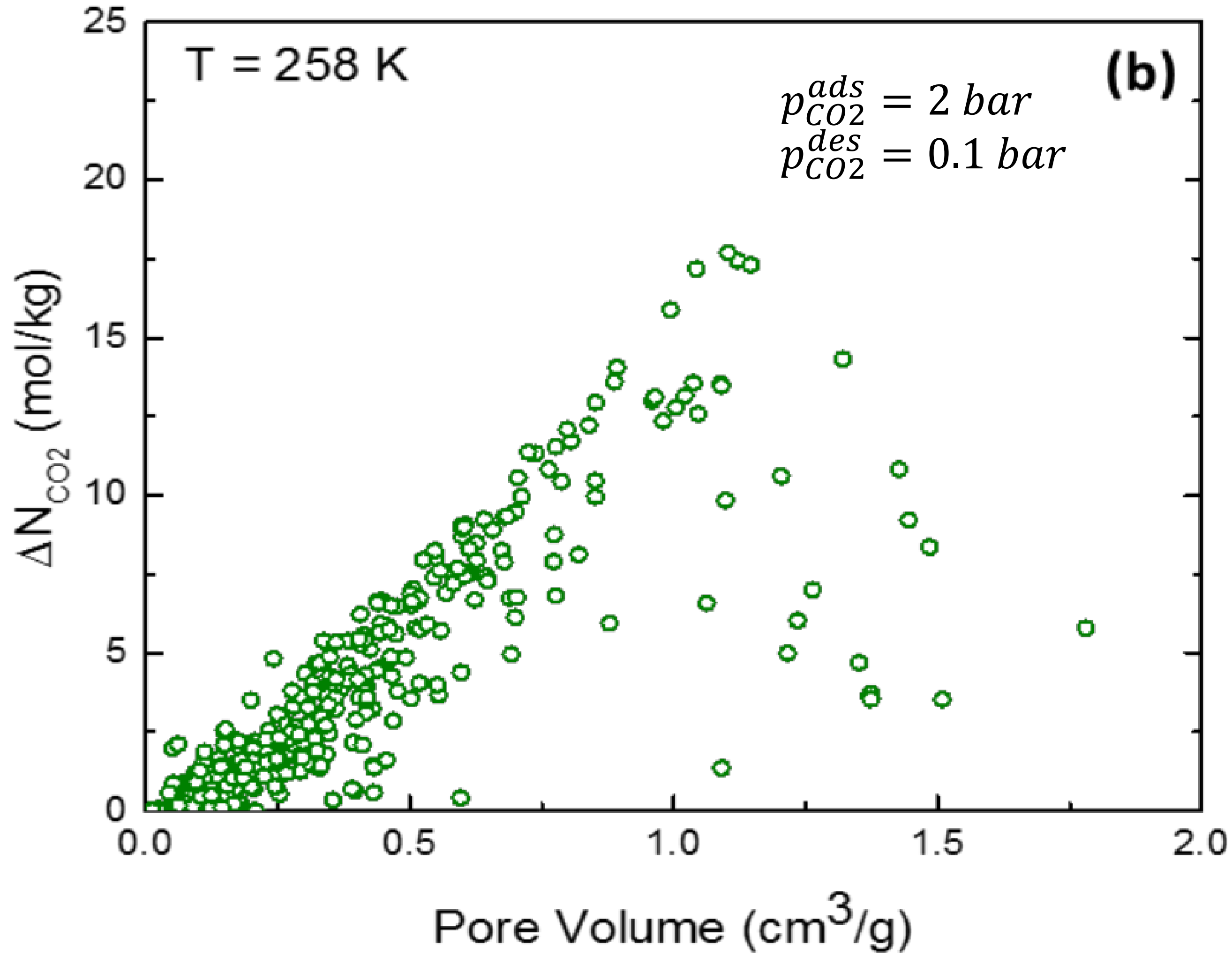


J Park, RP Lively, DS Sholl, *J. Mater. Chem. A.* 2017, 5, 12258-12265

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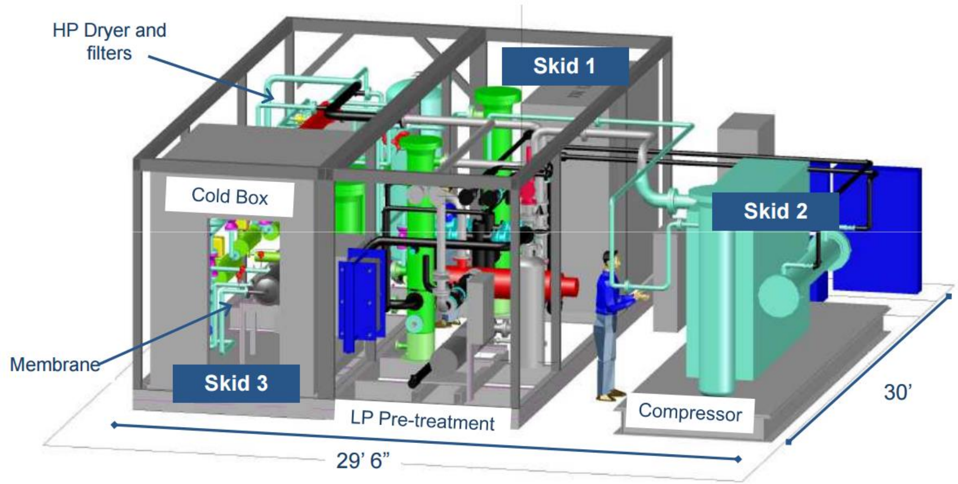
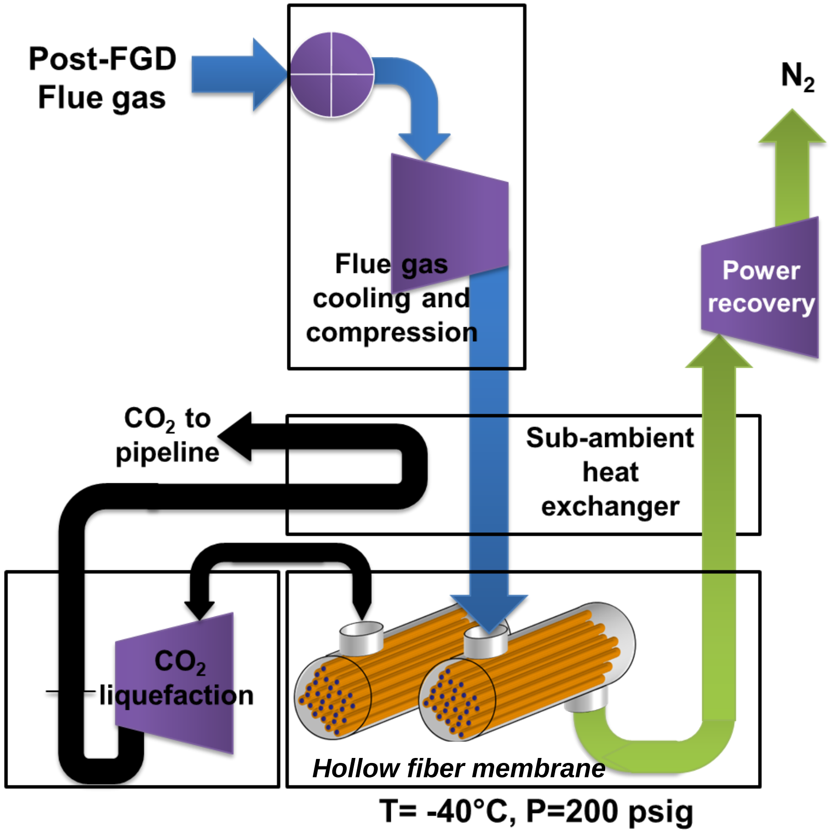
# Enabling 10 mol/kg swing capacities via flue gas pretreatment

## *Air Liquide Sub-Ambient Membrane System*




D Hasse, S Kulkarni et al., *Energy Procedia*, 2013, 37, 993-1003

# Enabling 10 mol/kg swing capacities via flue gas pretreatment

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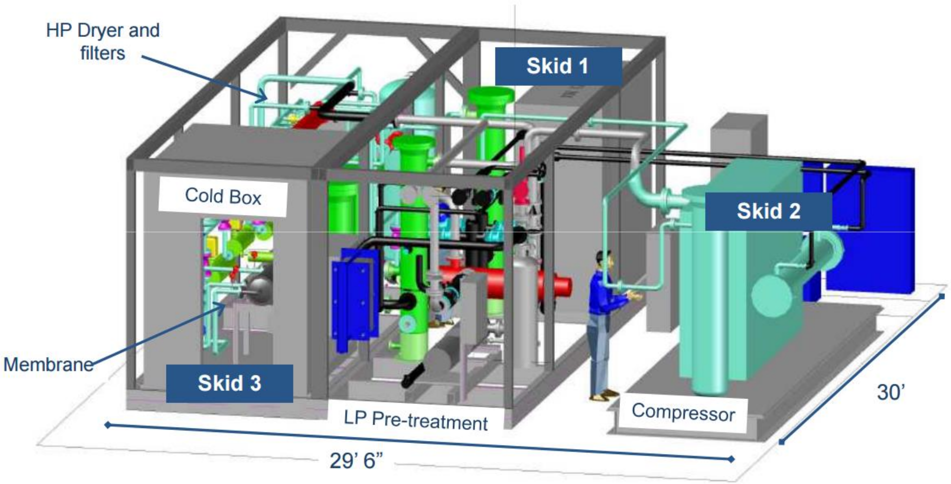


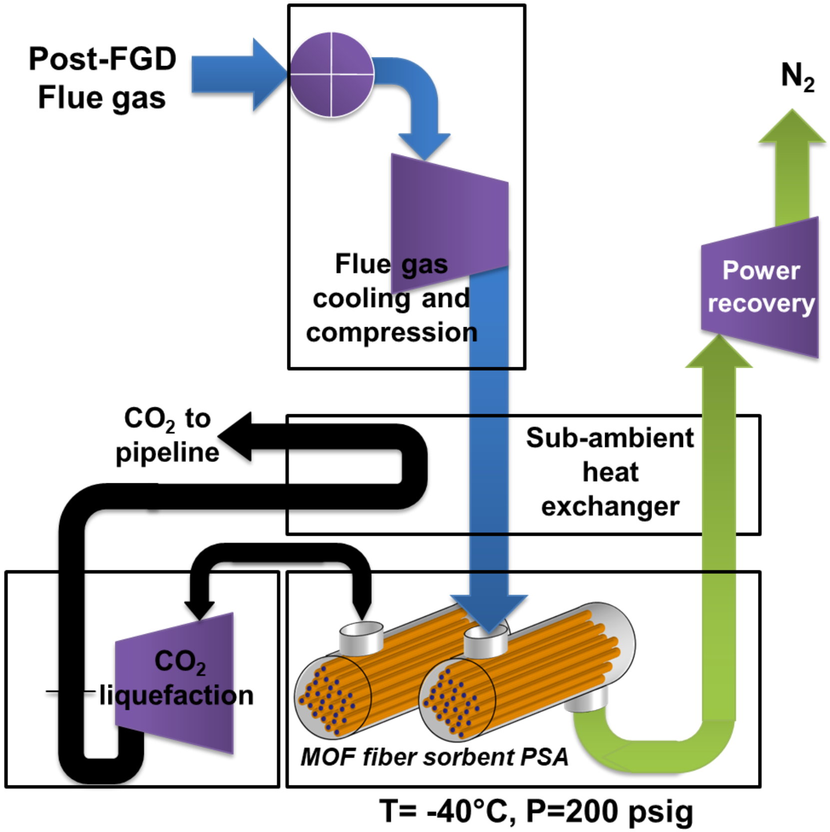


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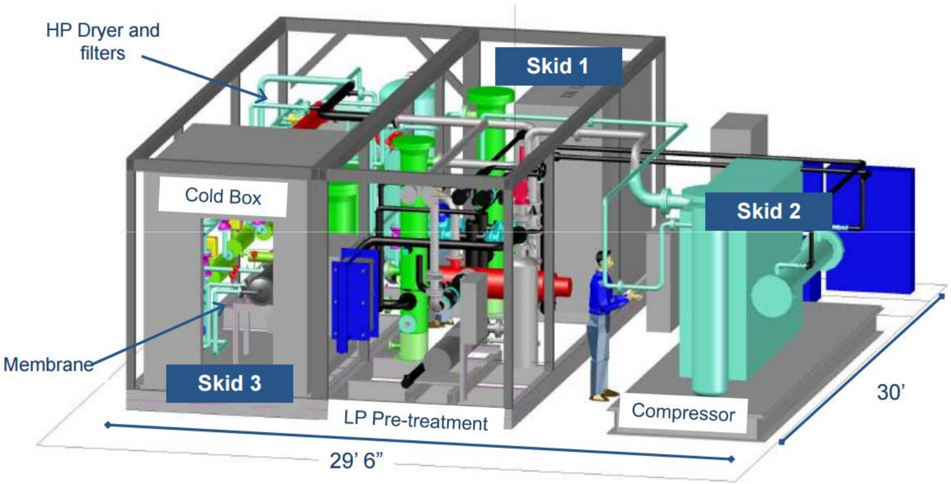
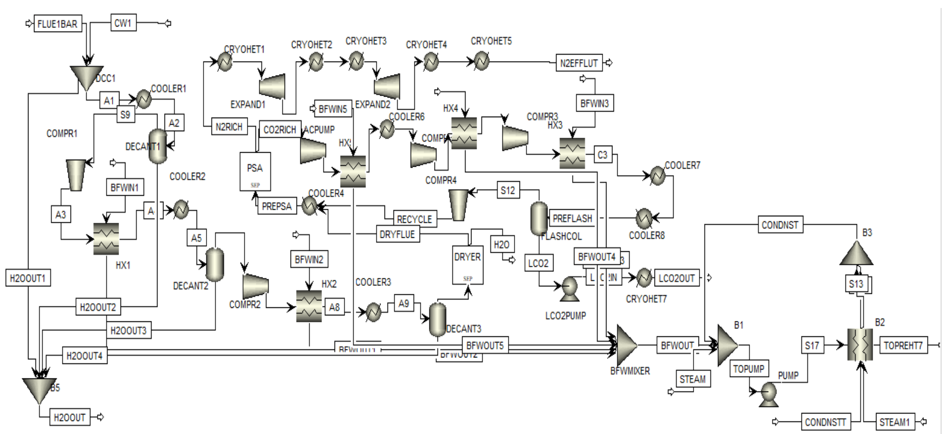
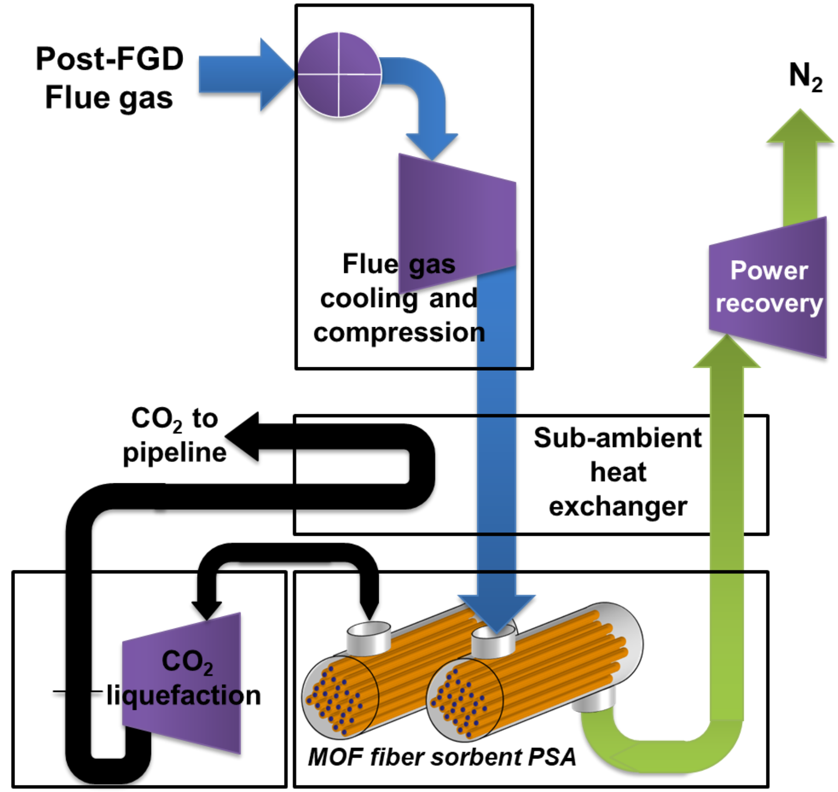



## *Sub-Ambient Adsorption System*





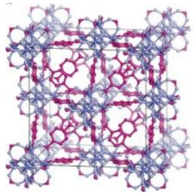

T= -40°C, P=200 psig

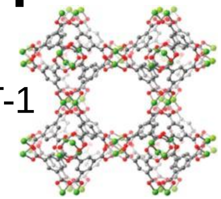
**Key parameters: swing capacity & selectivity**

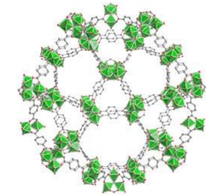
- DOE guideline: 90% $CO_2$ removal from flue gas
- Total heat integration with no external cold (i.e., refrigerant) or hot (i.e., steam) utility
- Costs between \$35-\$45/tonne $CO_2$
- Parasitic loads of 18-30%

D Hasse, S Kulkarni et al., *Energy Procedia*, 2013, 37, 993-1003

# Enabling 10 mol/kg swing capacities: Potential MOF candidates

UiO-66

[1]

HKUST-1

[2]

MIL-101(Cr)

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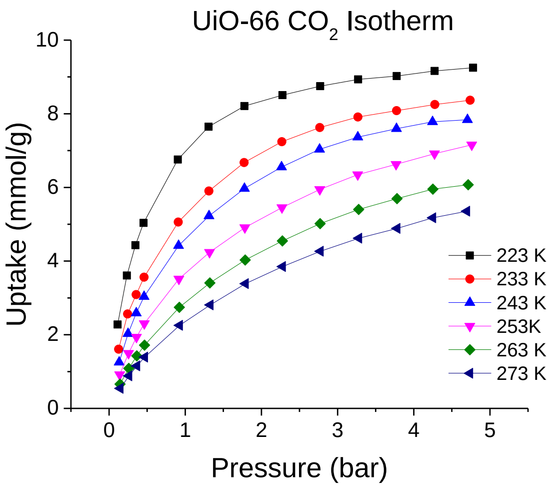
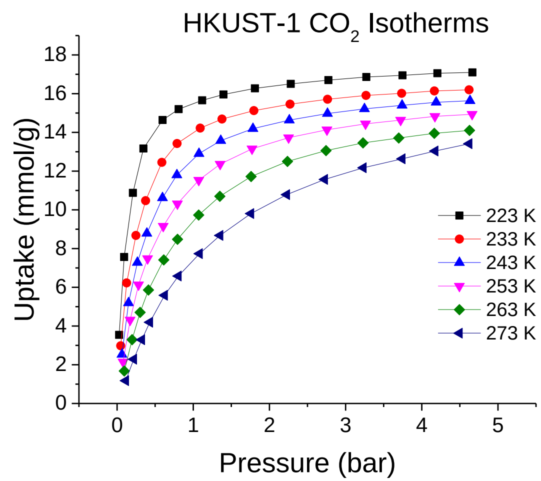
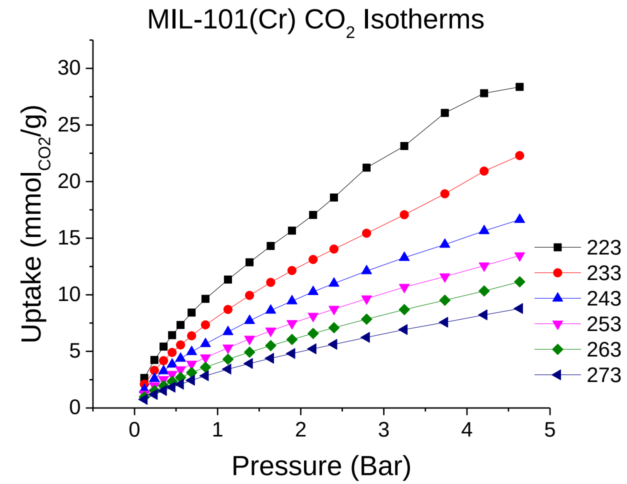
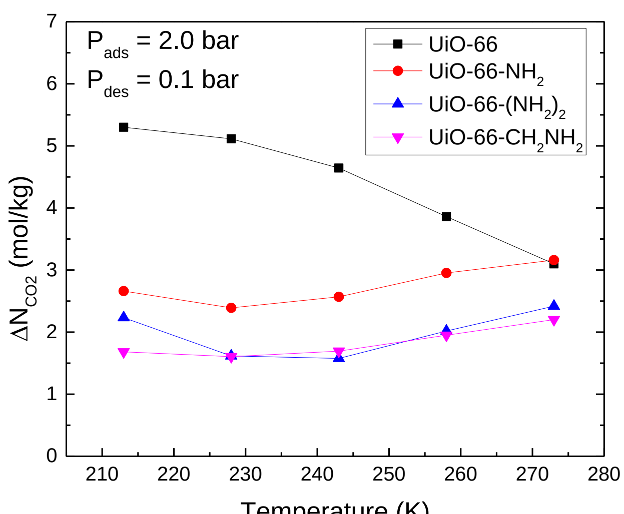
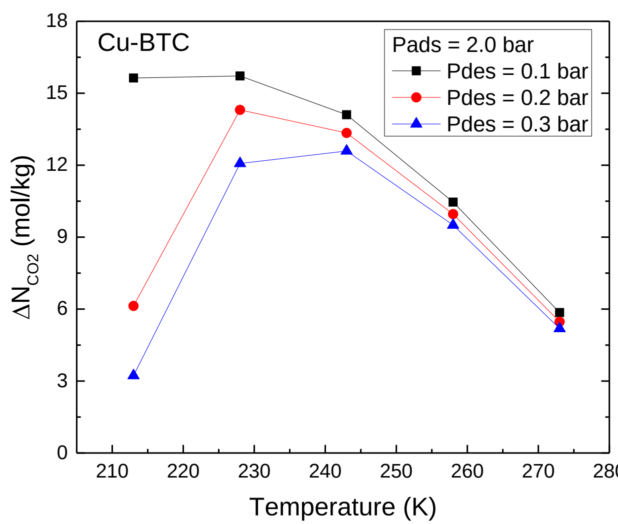
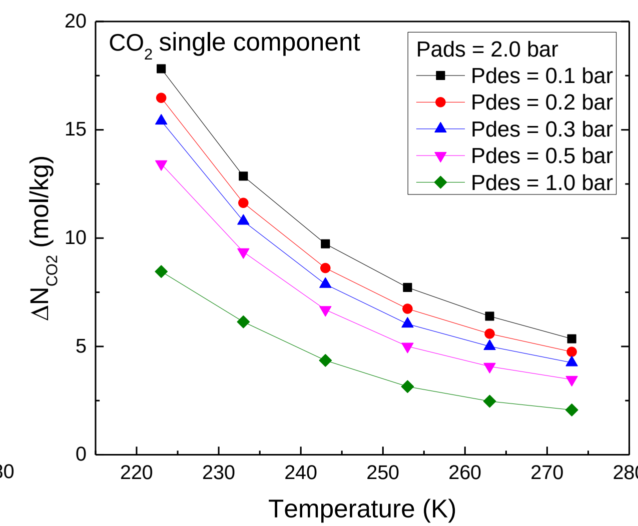


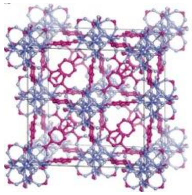




[1] MJ Cliffe, AL Goodwin et al., *Nature Comm*, 2014, 5
[2] A Zukal, J Jagiello et al., *Catal. Today* 2015, 243, 69-75
[3] L Hamon, GD Weireld et al., *J. Am. Chem. Soc.* 2009, 131, 8775-8777

# Enabling 10 mol/kg swing capacities: Potential MOF candidates

UiO-66



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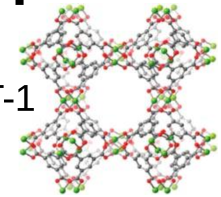
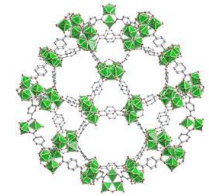


[2]

MIL-101(Cr)



[3]

***High stability***
***Low cost / high scalability***
***Low swing capacity***

***Low stability***
***Low cost / high scalability***
***High swing capacity***

***Good stability***
***Moderate cost***
***High swing capacity***

[1] MJ Cliffe, AL Goodwin et al., *Nature Comm*, 2014, 5
[2] A Zukal, J Jagiello et al., *Catal. Today* 2015, 243, 69-75
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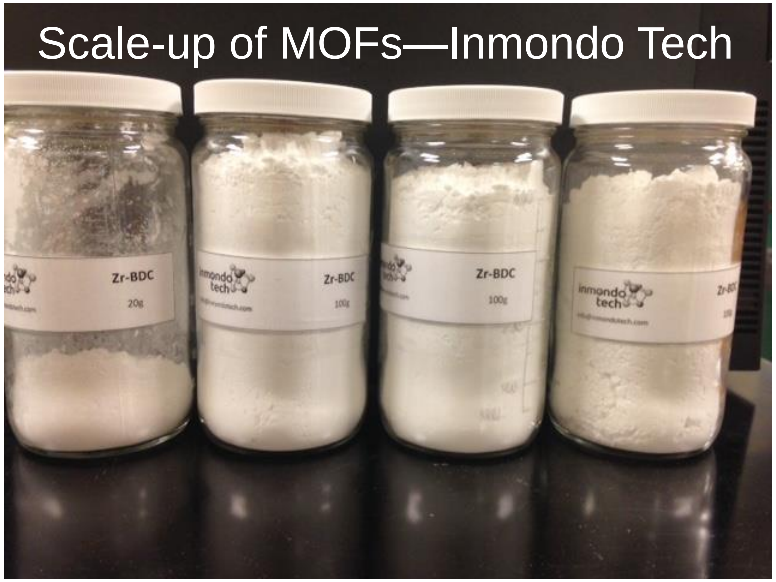
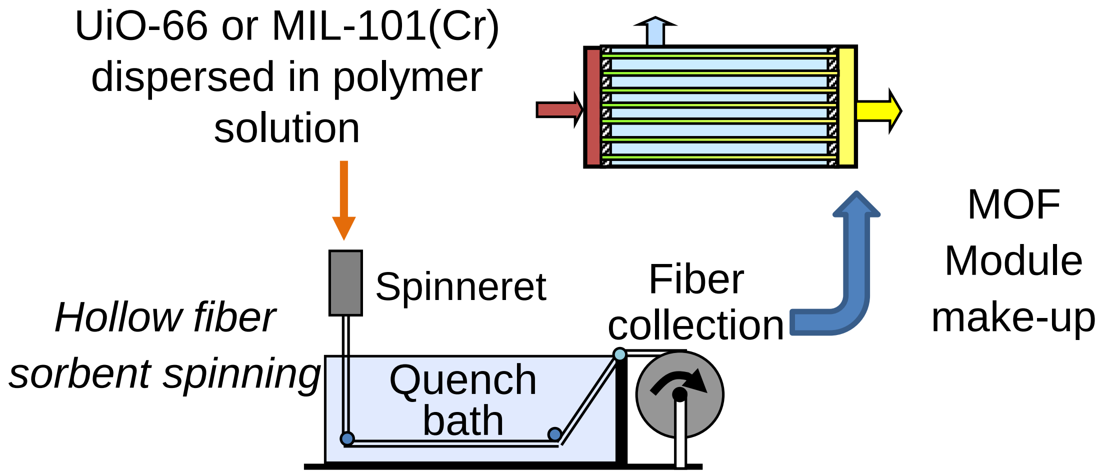
# Complexities of developing engineering solutions for post-combustion $CO_2$ capture (next 4 slides)

| | |
|---|---|
| *Scaling-up MOF contactors*<br>• *Synthesis*<br>• *Stability*<br>• *Etc.* | *Transport Limitations*<br>• *Heat effects*<br>• *Pressure drop*<br>• *Etc.* |
| *Contaminants*<br>• *Acid gases*<br>• *Water*<br>• *Etc.* | *Systems Engineering*<br>• *Optimized cycles*<br>• *Process Economics*<br>• *Etc.* |

# Complexities: Scaling up MOF fiber sorbent contactors



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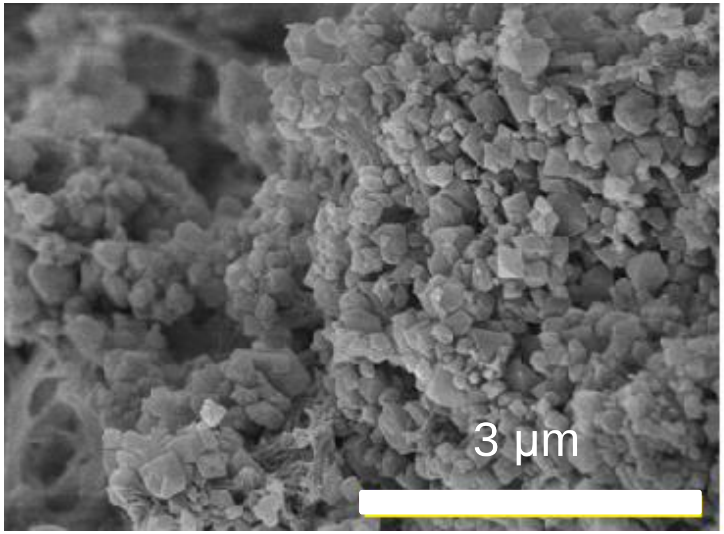


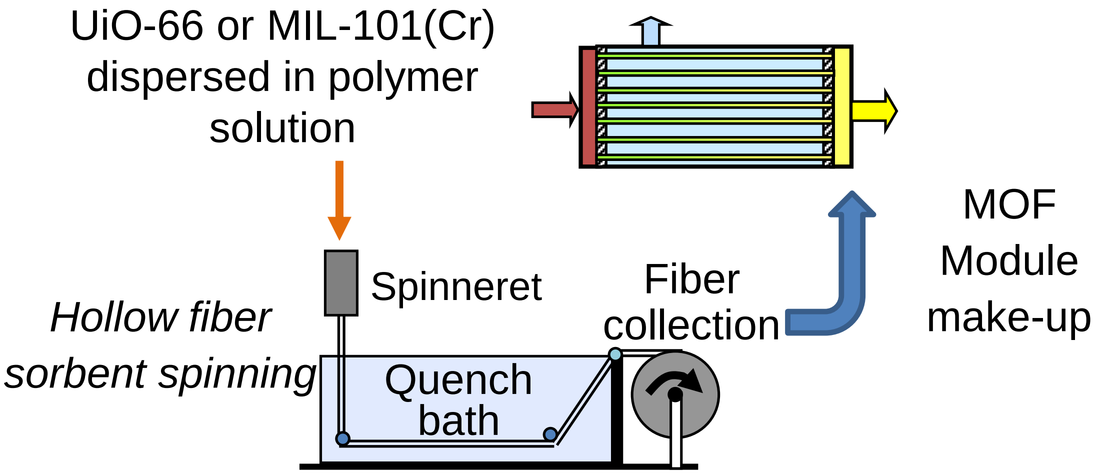


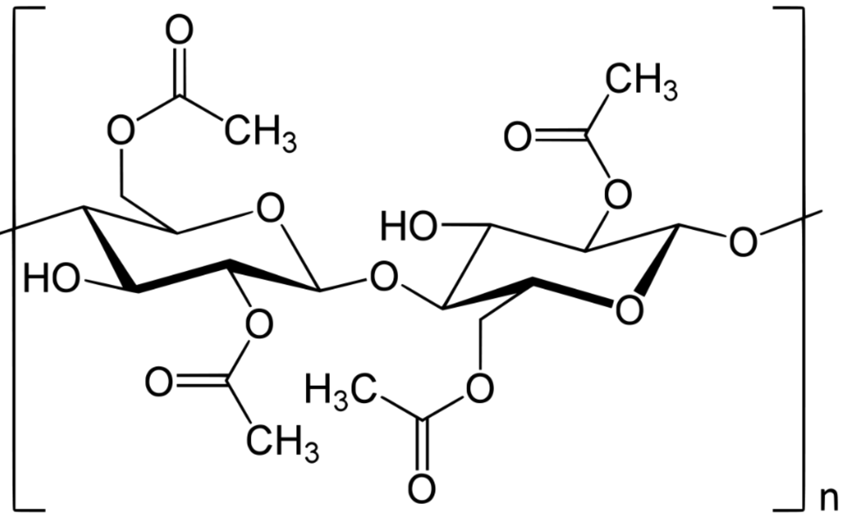


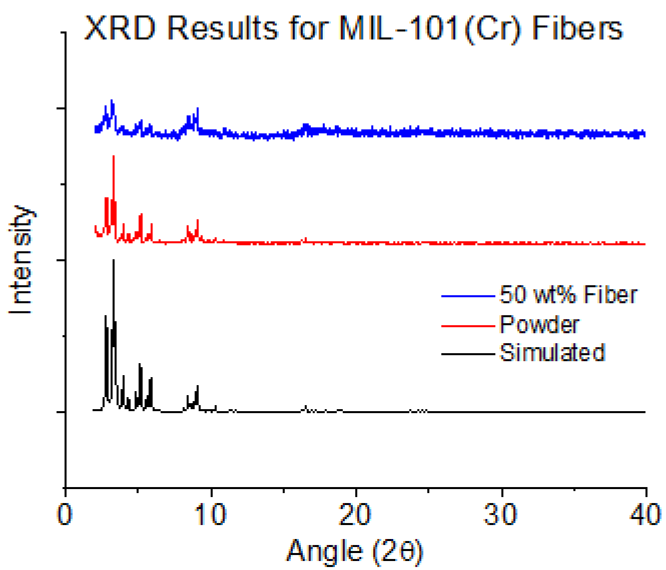


Unpublished data

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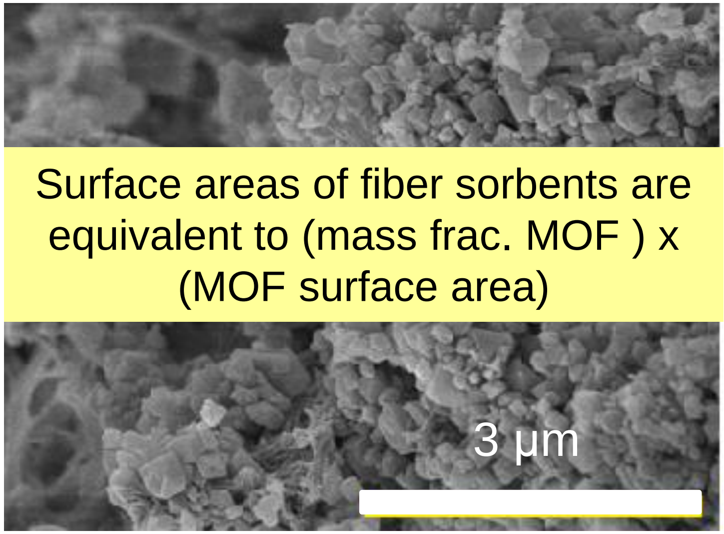


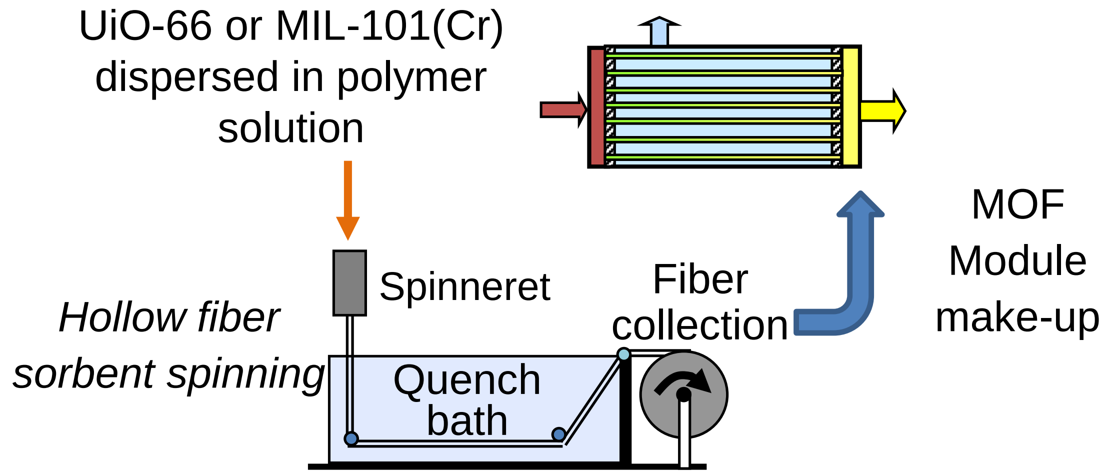


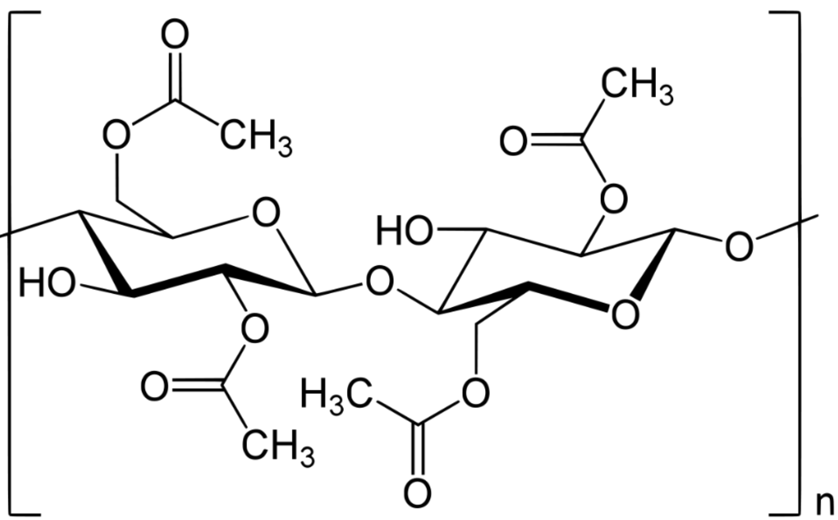


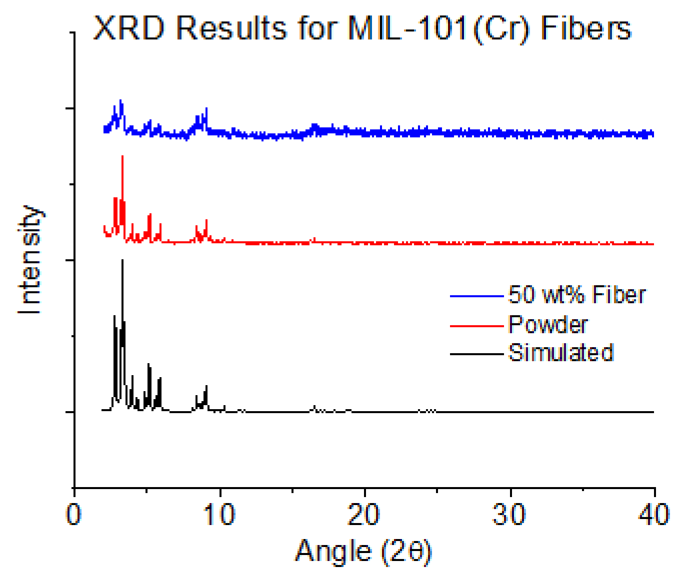


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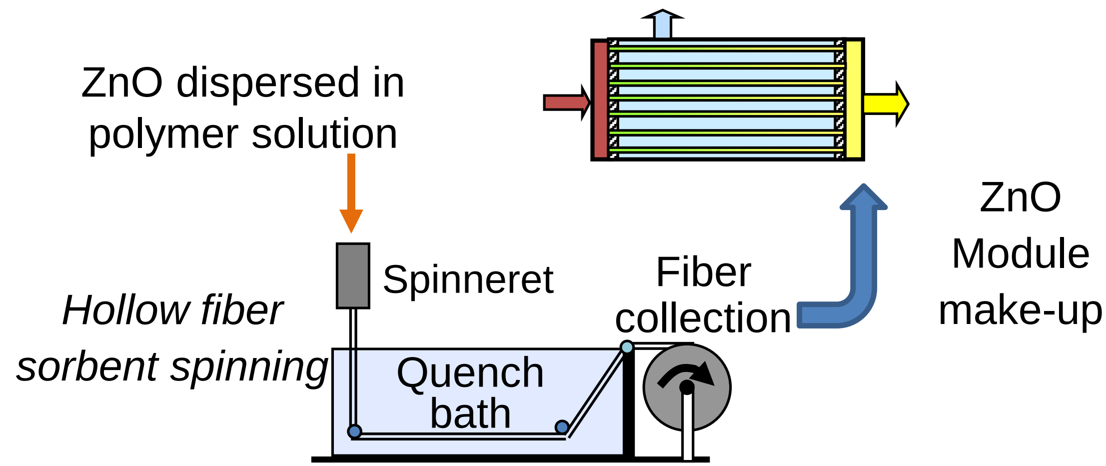


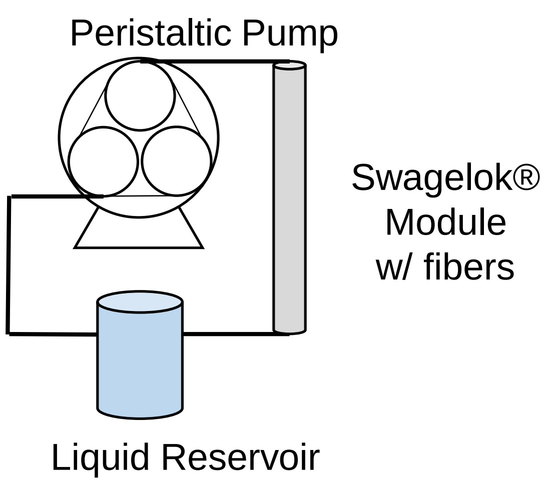


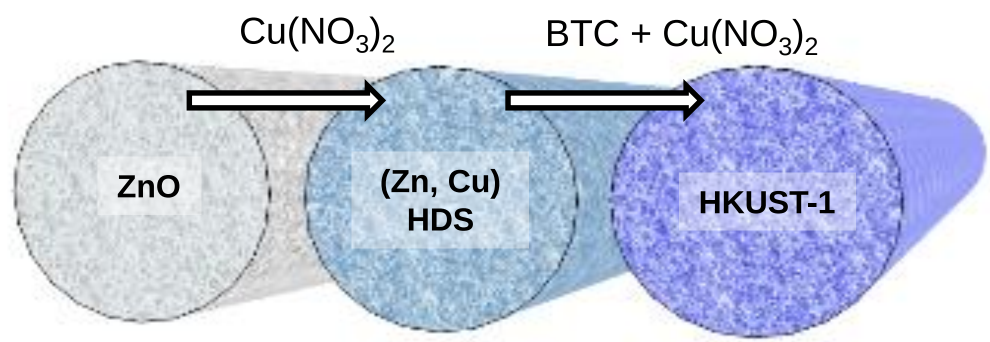


BR Pimentel, RP Lively et al., *Ind. Eng. Chem. Res.* **2017**, 56(17), 5070-5077

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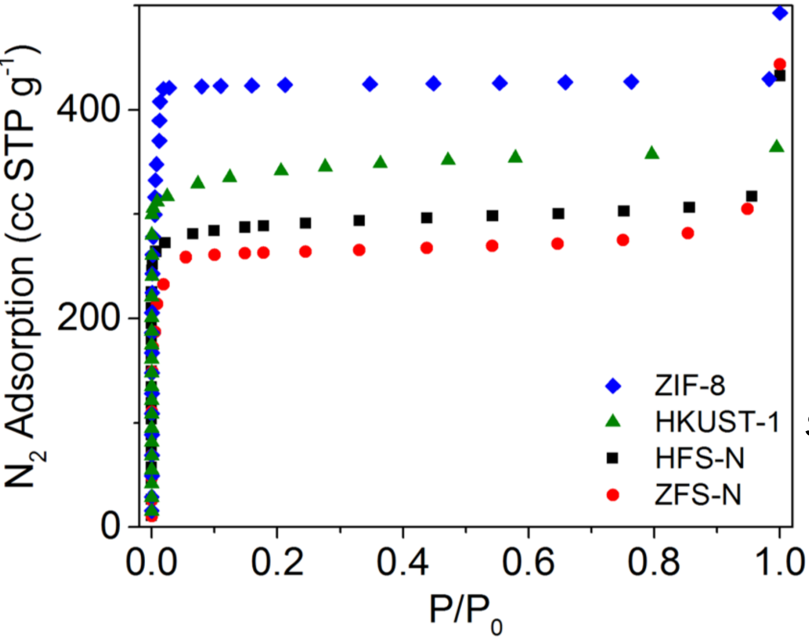
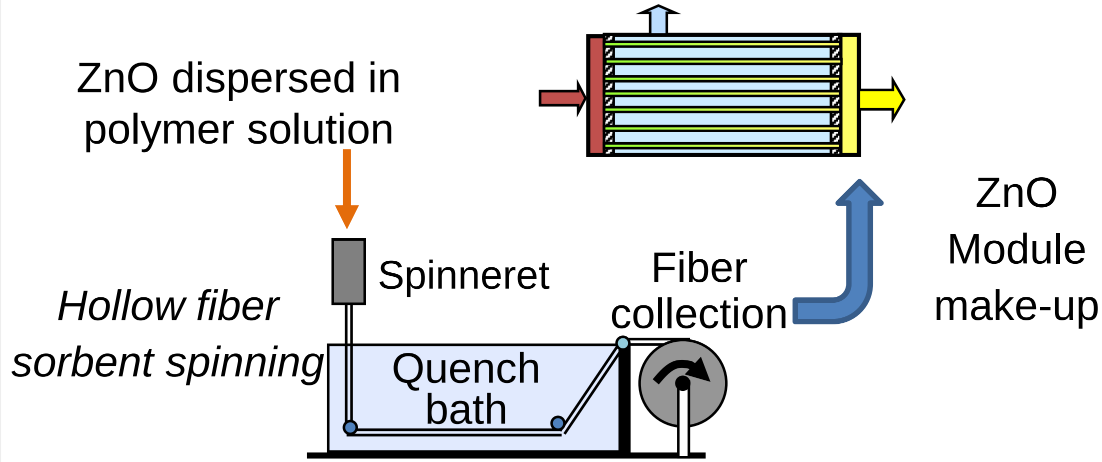
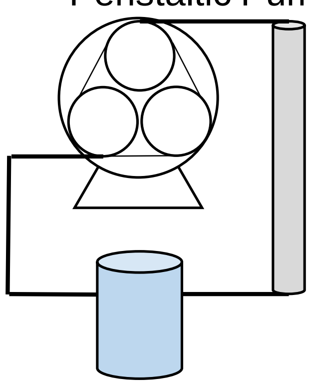
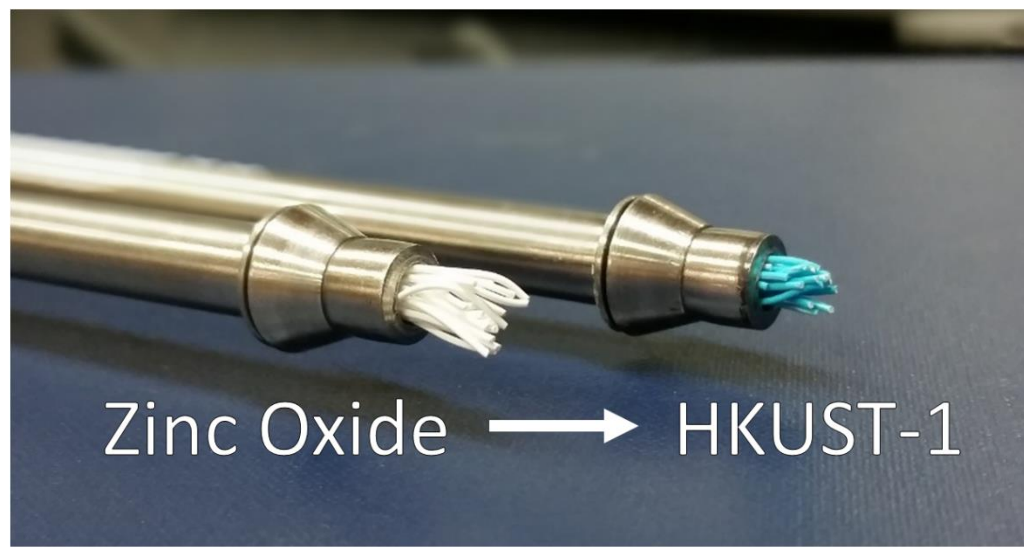


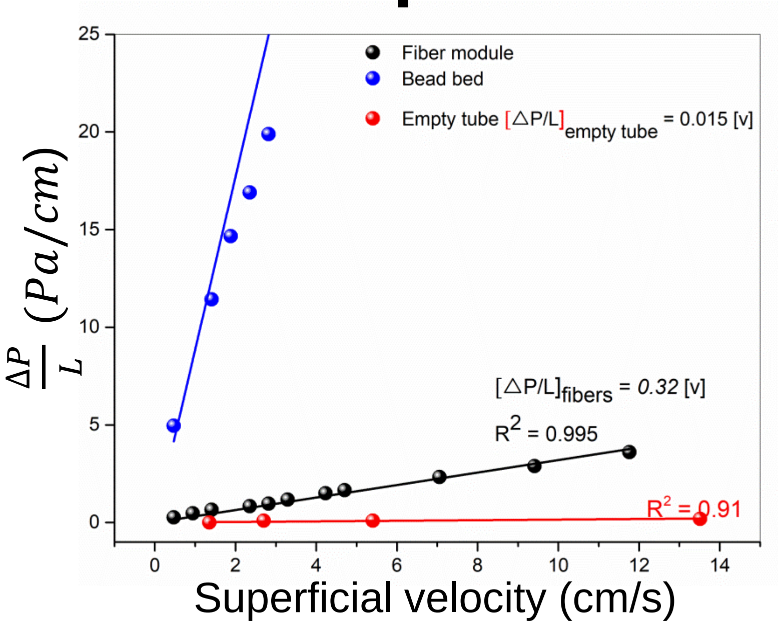




Angle (2θ)

BR Pimentel, RP Lively et al., *Ind. Eng. Chem. Res.* **2017**, 56(17), 5070-5077

# Complexities: Transport Limitations

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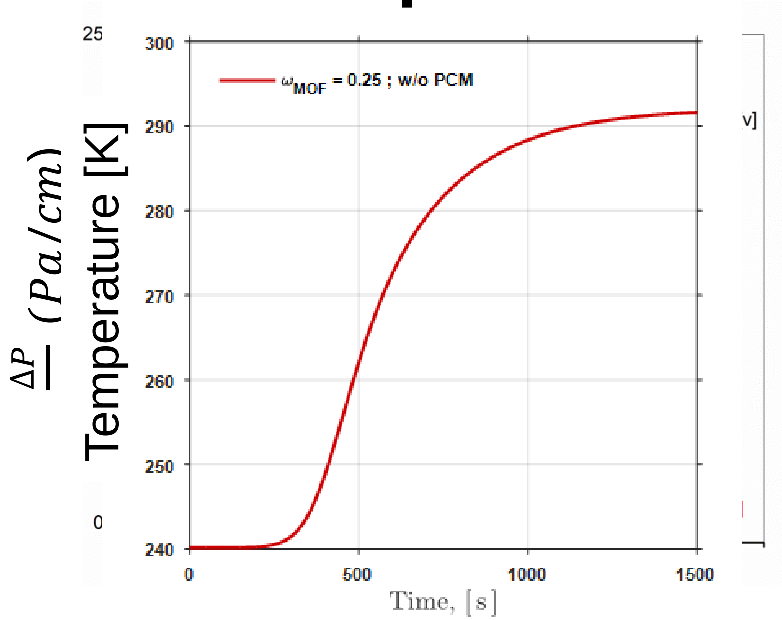
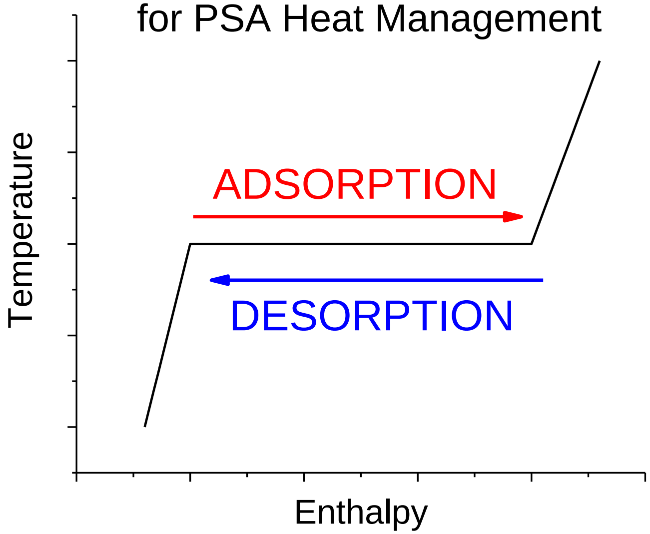
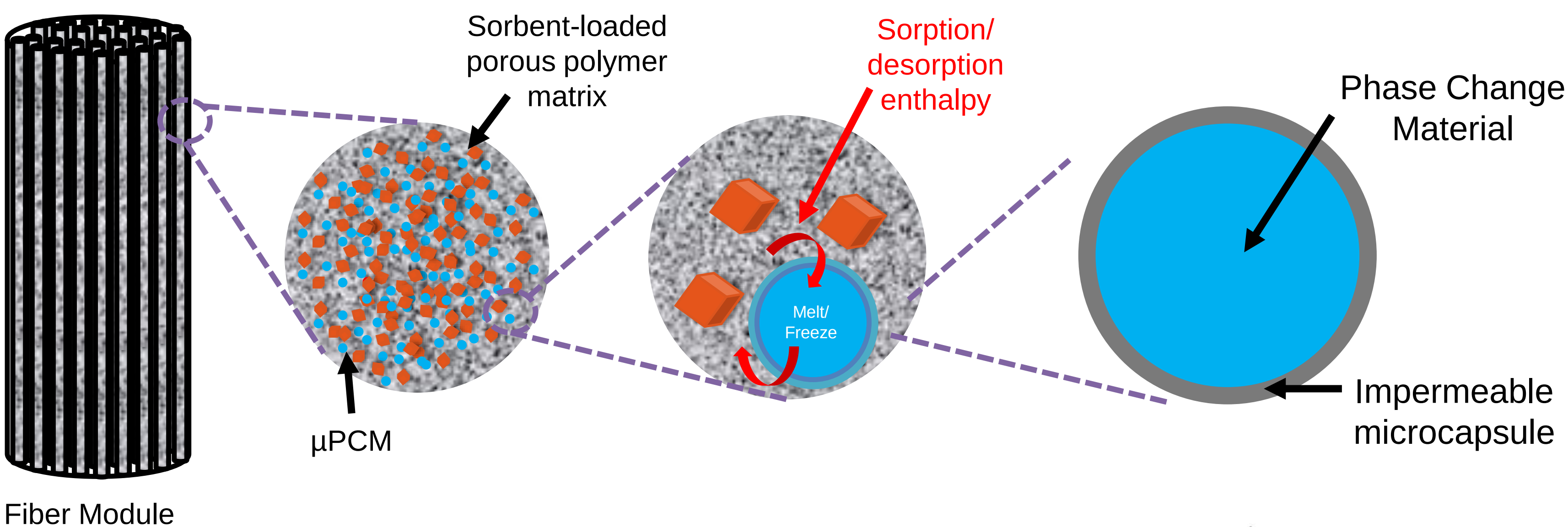
# Complexities: Transport Limitations

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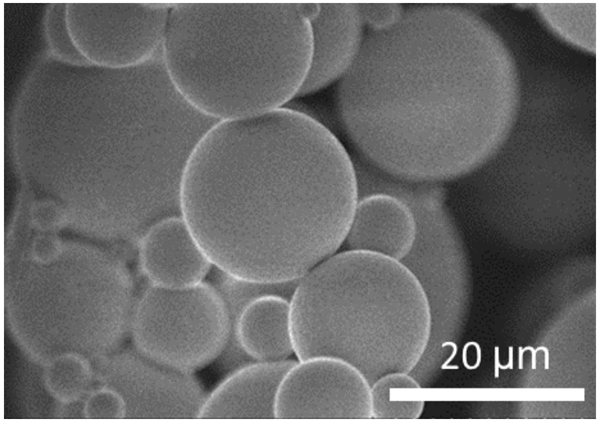


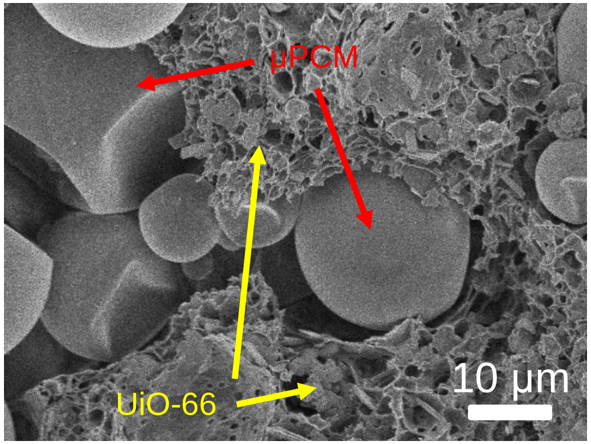


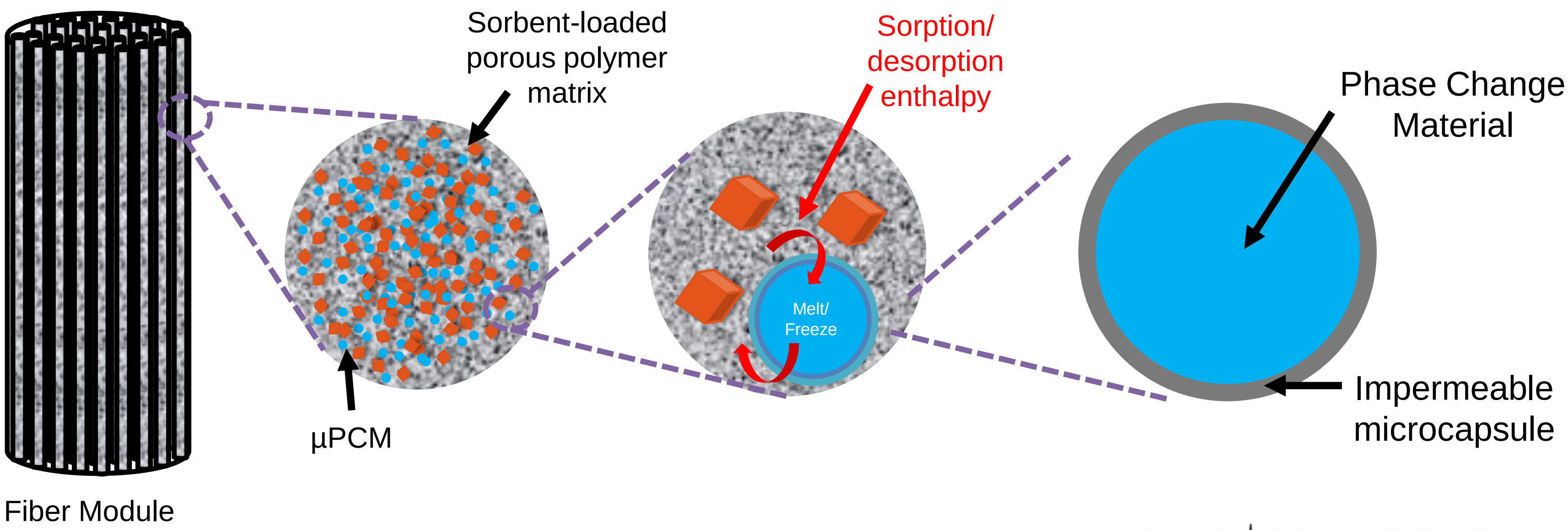


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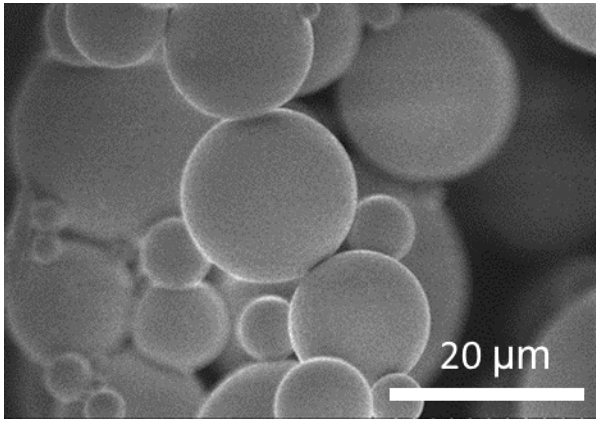


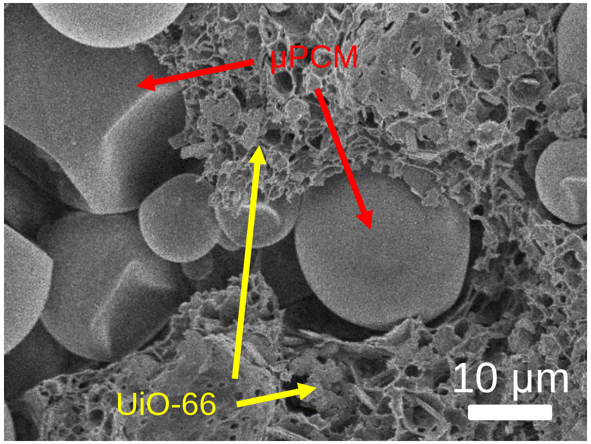


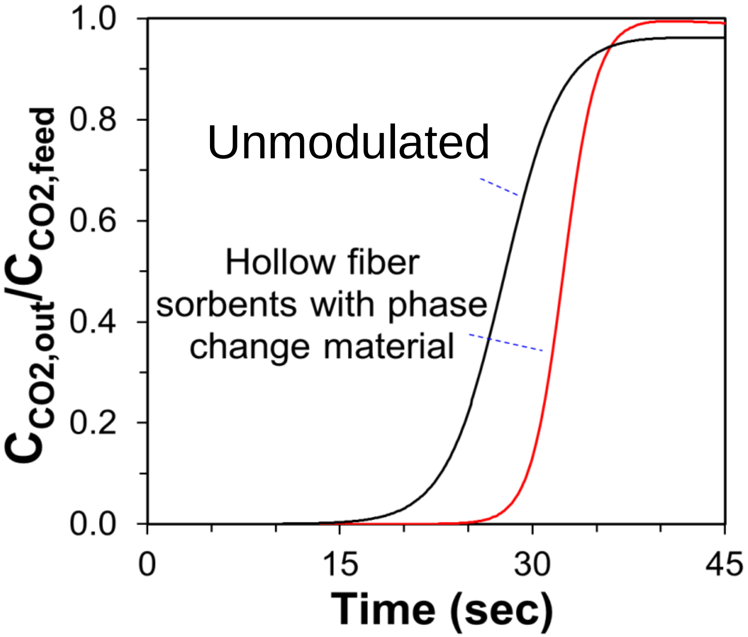


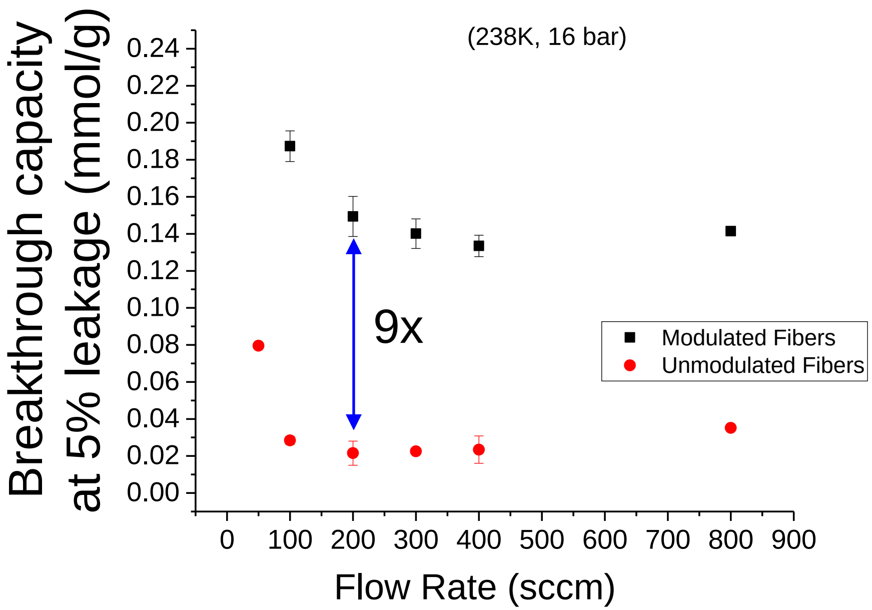


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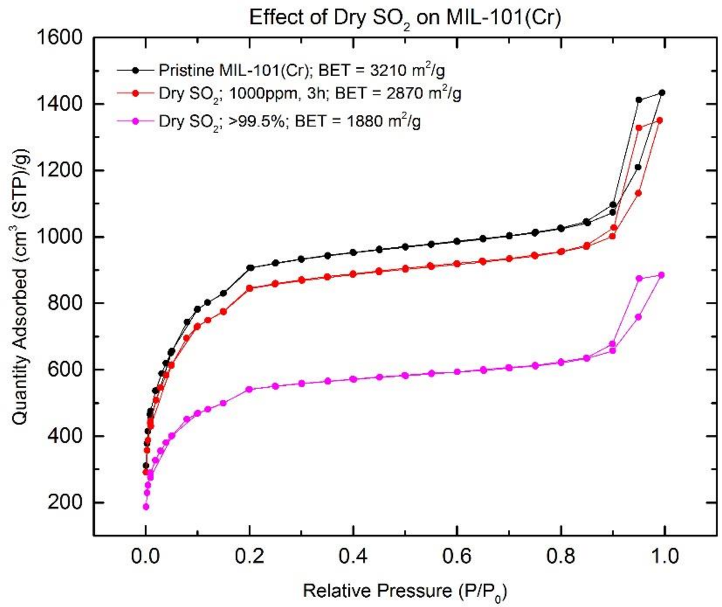
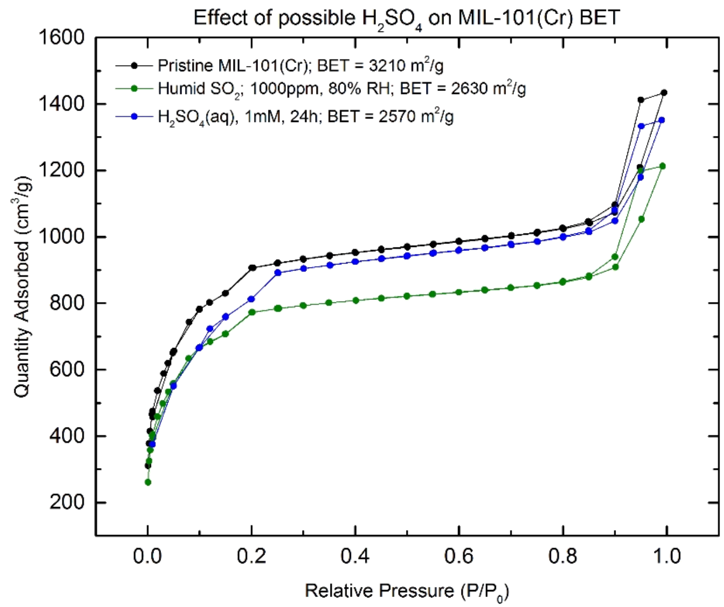
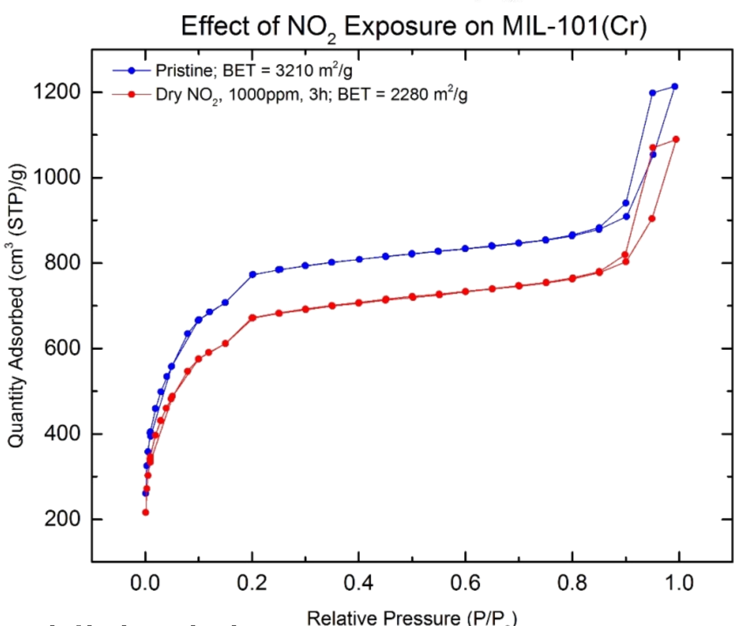
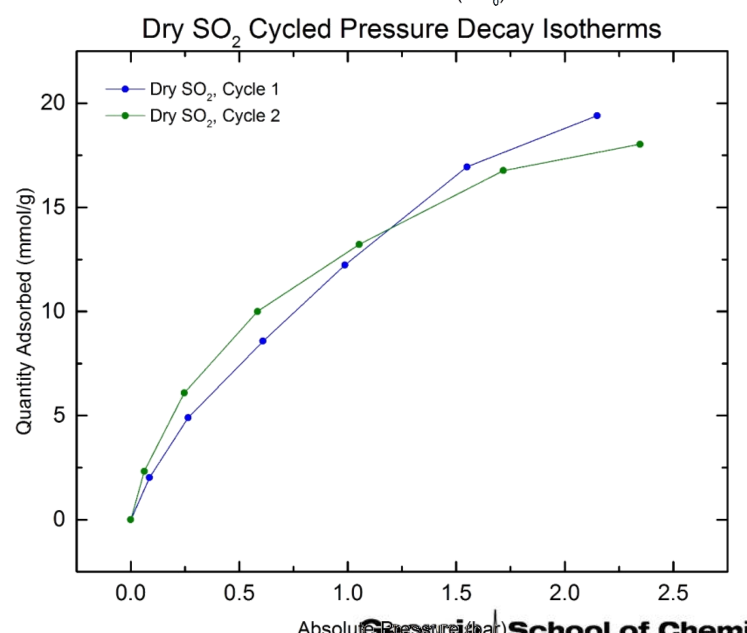
# Complexities: Contaminants and Stability

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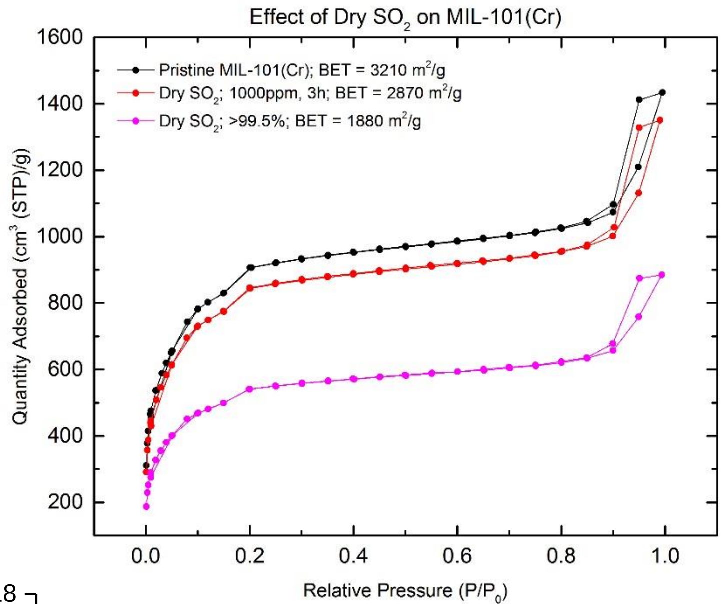


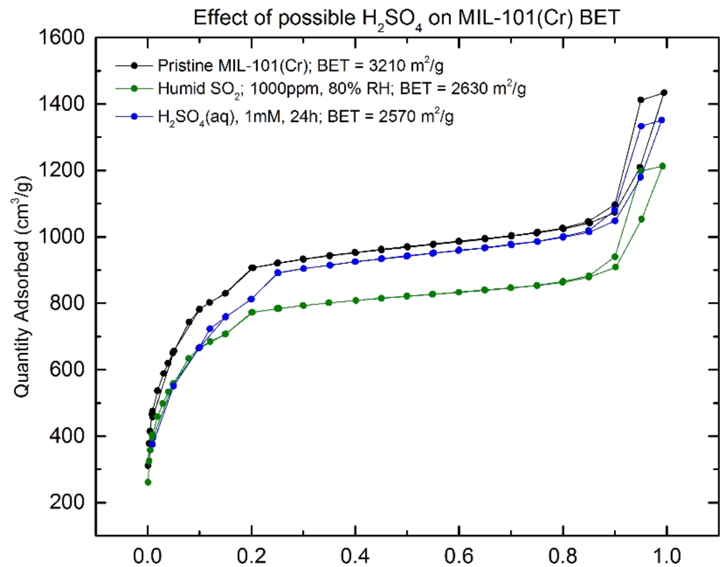


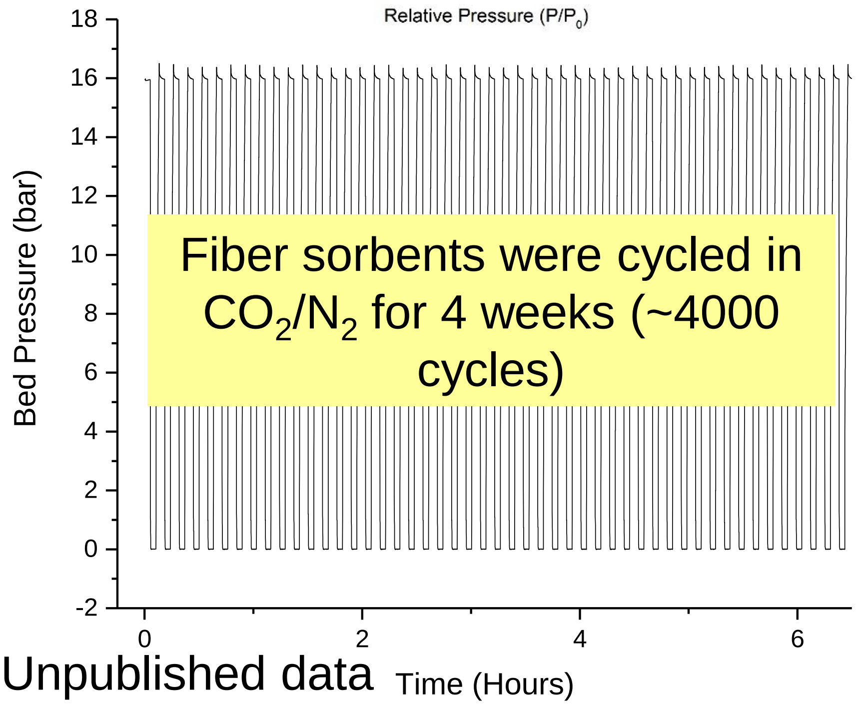


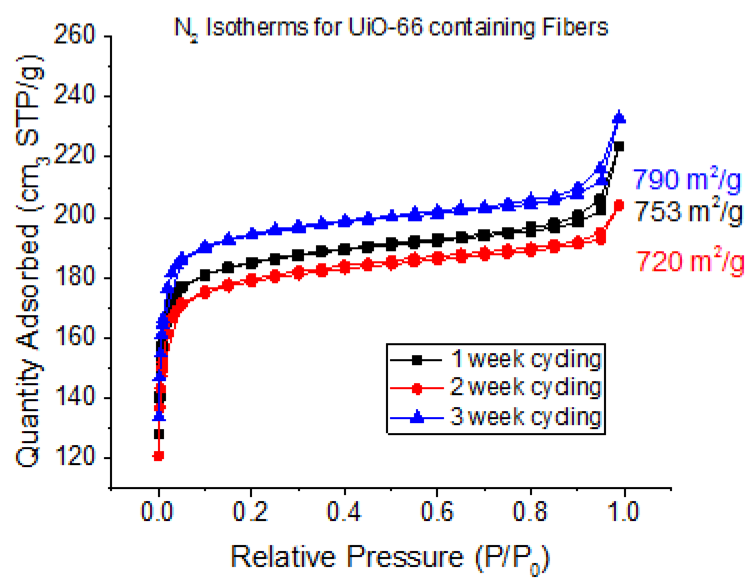


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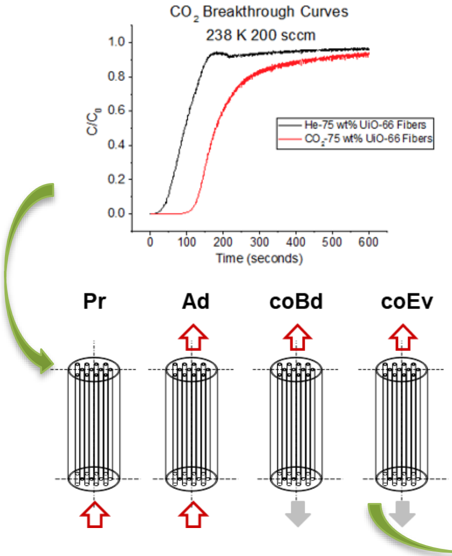
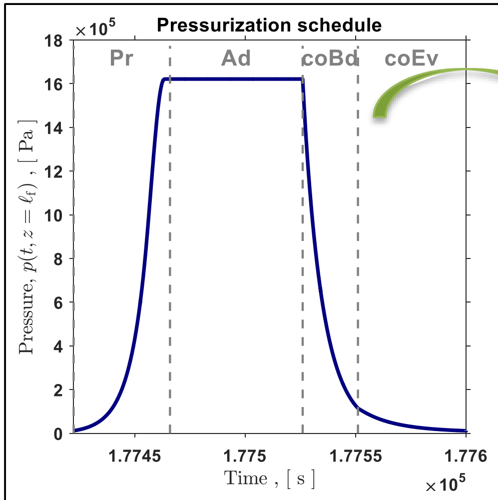
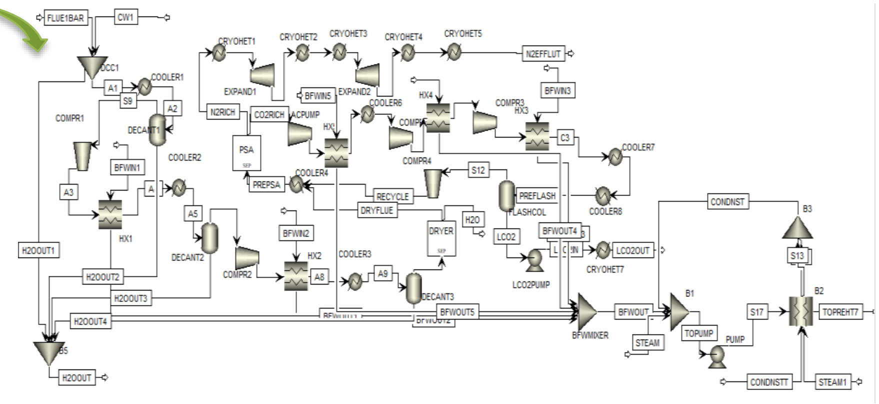
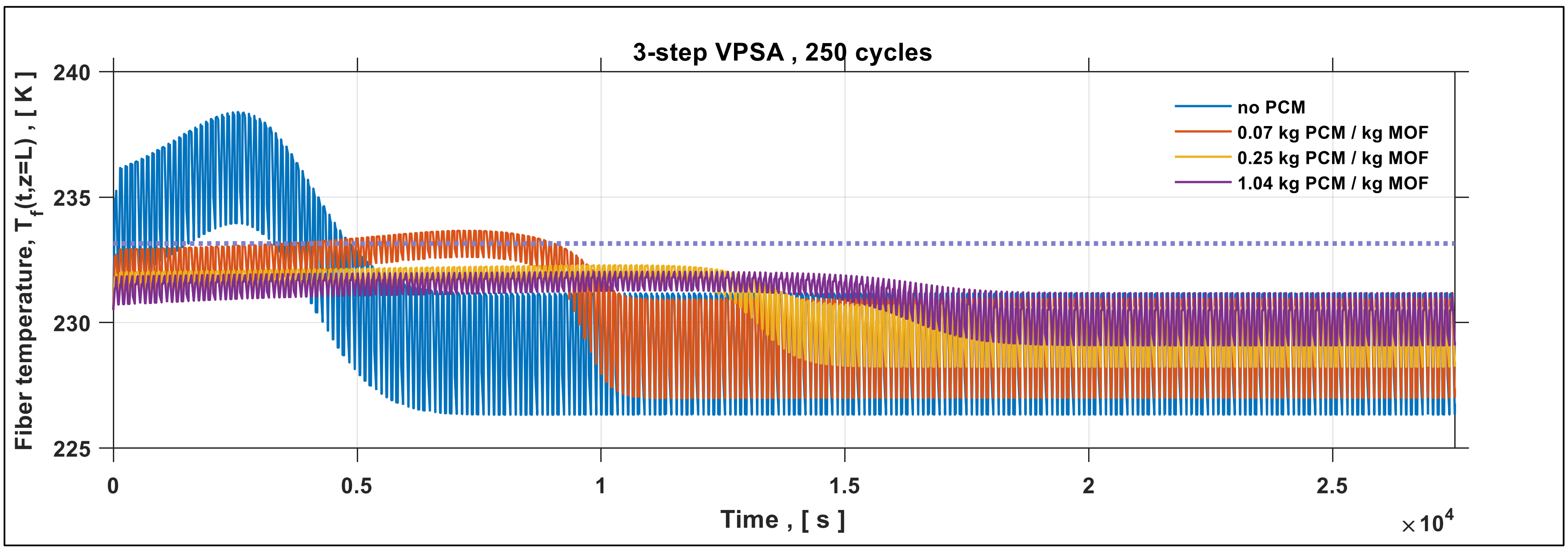
# Complexities: Cycle optimization and systems engineering



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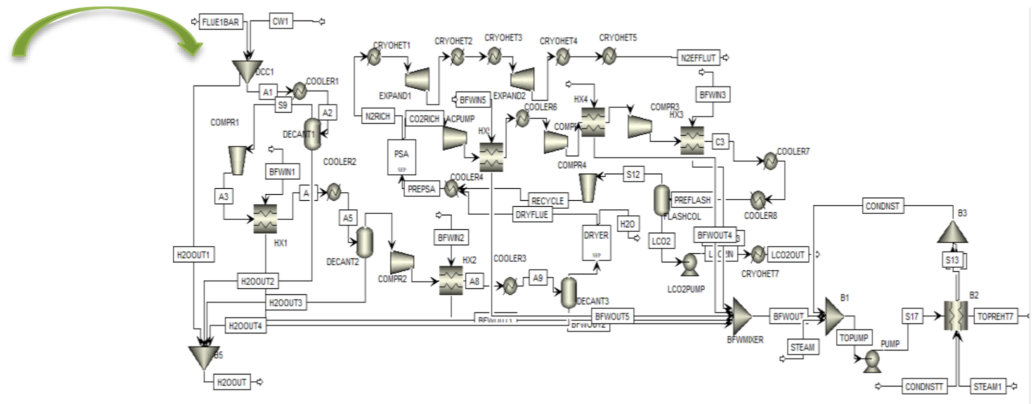
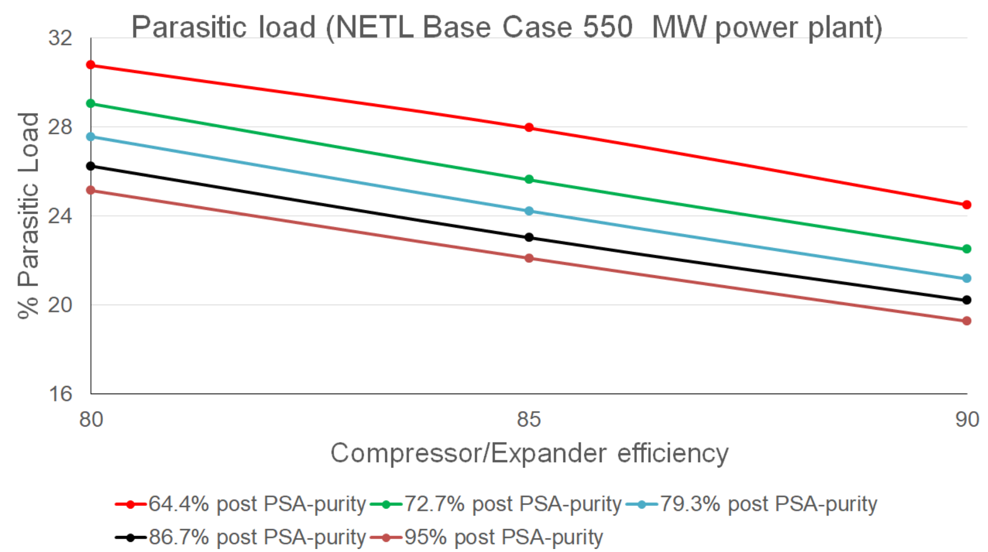


| 5 years equipment lifespan | |
|---|---|
| Parasitic load | $/tonne $CO_2$ |
| 100 MW (18%) | 37 |
| 137.4 MW (25%) | 41 |
| 165 MW (30%) | 44 |

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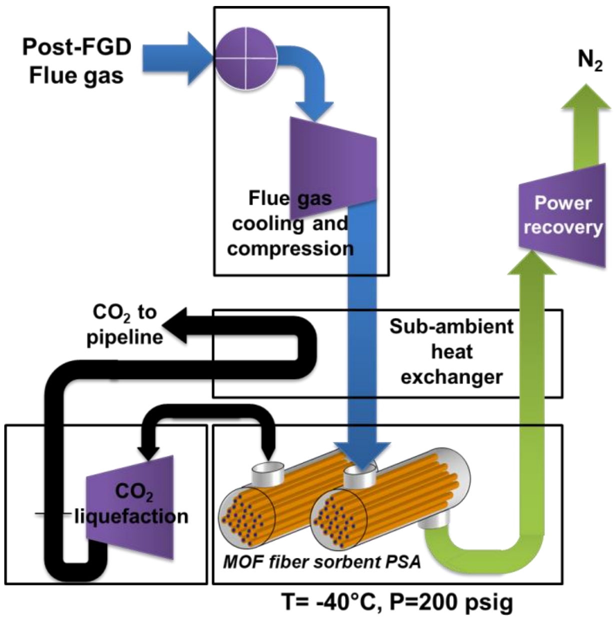
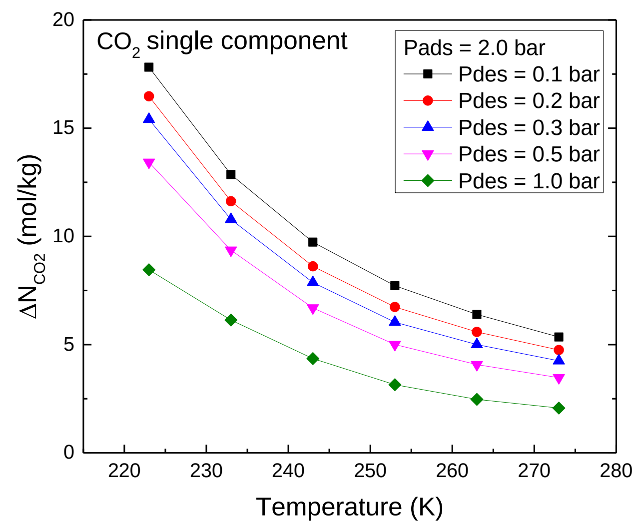
# Conclusions and perspectives

*Key question: Can we increase swing capacity by 10x and reduce cycle time by 5x to dramatically drive down adsorbent costs?*

- Combining RCPSA cycles with appropriate metal-organic frameworks in sub-ambient conditions results in highly productive adsorption systems (i.e., tonne $CO_2$/tonne adsorbent-day)




- Significant "real world" complexities exist, but hollow fiber sorbent platform provides solutions to many of these (scalability, transport limitations, etc.)

- Costs in the range of **$35-$45/tonne $CO_2$** may be achievable using these materials in this process concept, but significant work remains

# Process Scope—Key Topics, BP3 (Jan 18-Dec 18)

Eight major activity areas for BP2:

Task 15.0: Process flowsheet refinement **—Ongoing, 80% complete**

Task 16.0: Generate >250 g/quarter of UiO-66 and spin fibers **—Ongoing, 80% complete**

Task 17.0: Construct/test RCPSA system for dirty gas testing**—Ongoing, 50% complete**

Task 18.0: Model Validation for fiber module **—Complete**

Task 19.0: Monolithic Fiber sorbent stability in dirty gases **—Ongoing, 25% complete**

Task 20.0: Composite (PCM containing) fiber testing in sub-ambient PSA**—Complete**

Task 21.0: Sub-ambient Technical Feasibility Study **—Ongoing, 50% complete**

Task 22.0: Large module testing in sub-ambient PSA **—Task Initiated this quarter**

# Collaborators and funding




**Collaborators**
- Yoshiaki Kawajiri (GT)
- Ryan Lively (GT)
- Matthew Realff (GT)
- David Sholl (GT)

- Eli Carter

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