The Mars Air Refinery

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ASU LightWorks Arizona State University
ASU Arizona State University
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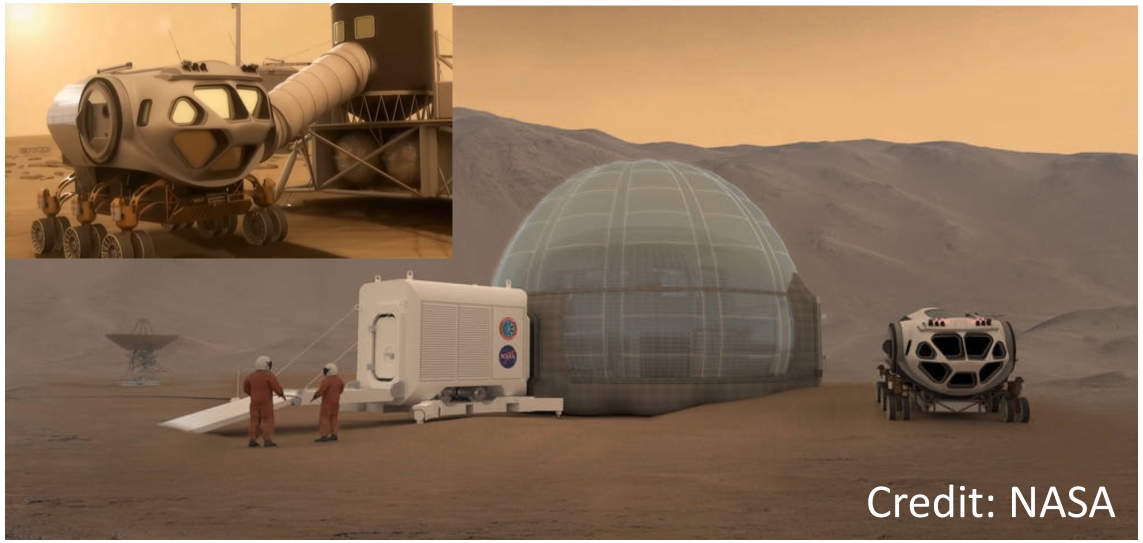
Mission Mars: In-Situ Resource Utilization

- **Stationary oxygen needs**
  - Habitat
  - Ascent vehicle oxidizer

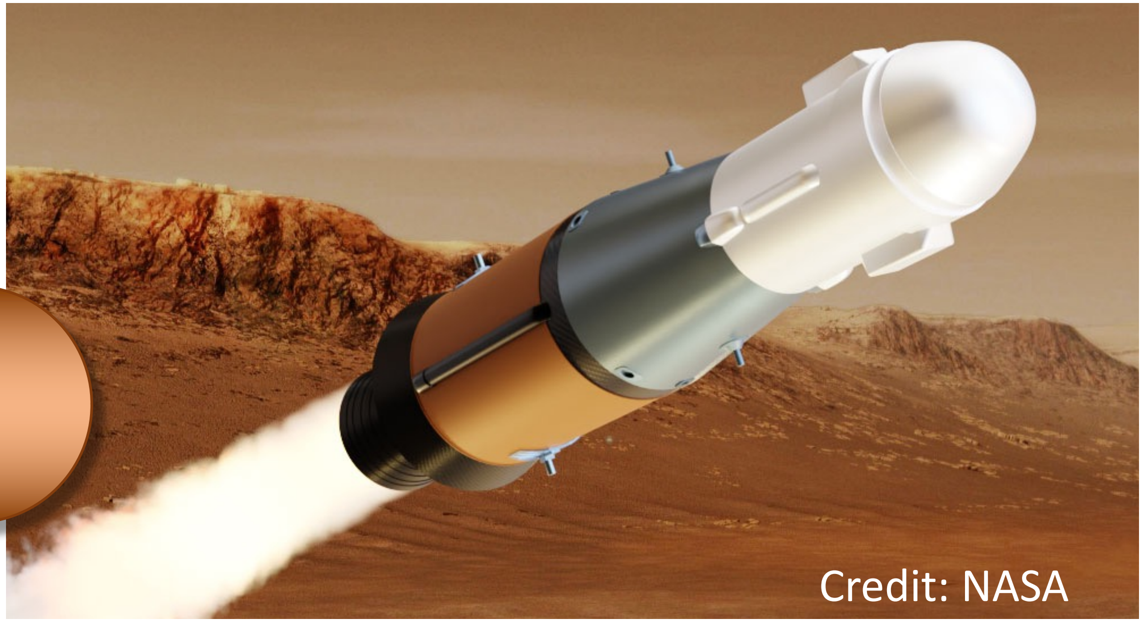
- **Portable needs**
  - Rovers

- **Energy?**

We will need oxygen
(and we cannot bring it from Earth)



Credit: NASA



Credit: NASA

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Prior Work and State of the Art

- **Mars atmosphere composition**

CO_2	95%	604 Pa
N_2	2.6%	16.5 Pa
Ar	1.9%	12.1 Pa
O_2	**0.16%**	**1 Pa**
CO	0.06%	0.38 Pa

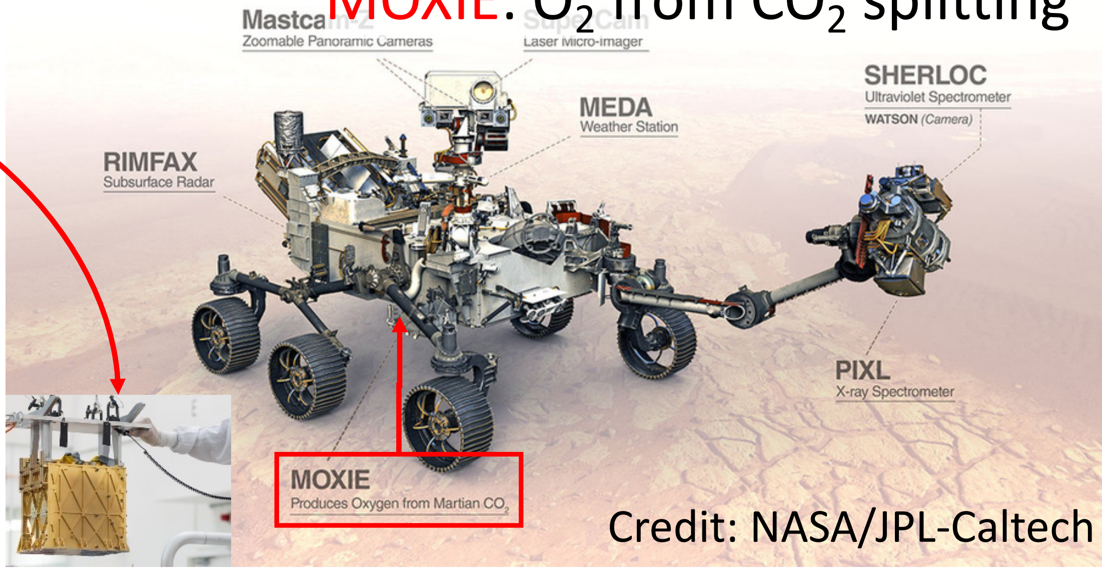
hν

- **Earth**

CO_2	0.041%	40 Pa

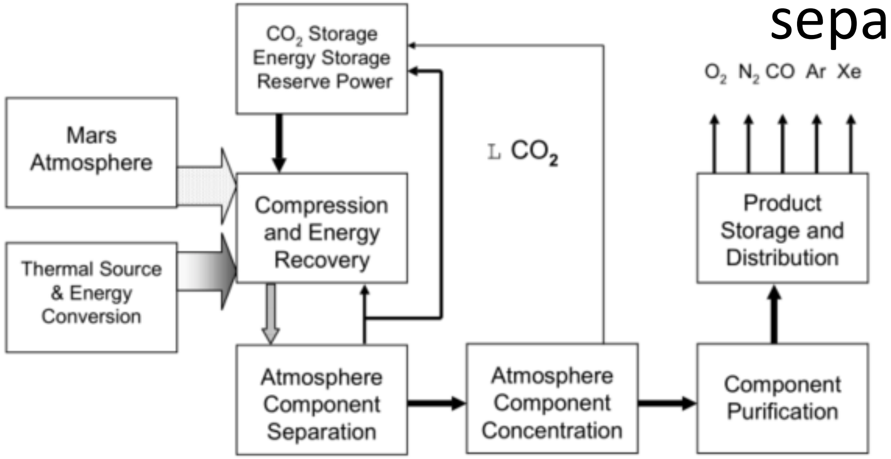
Is there room for improvement?

MOXIE: O_2 from CO_2 splitting



Credit: NASA/JPL-Caltech

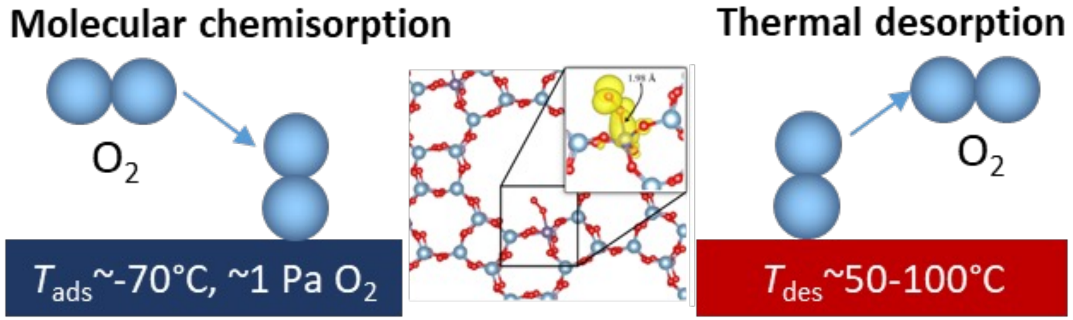
MARRS: O_2, N_2, CO, Ar, Xe, via cryogenic separation



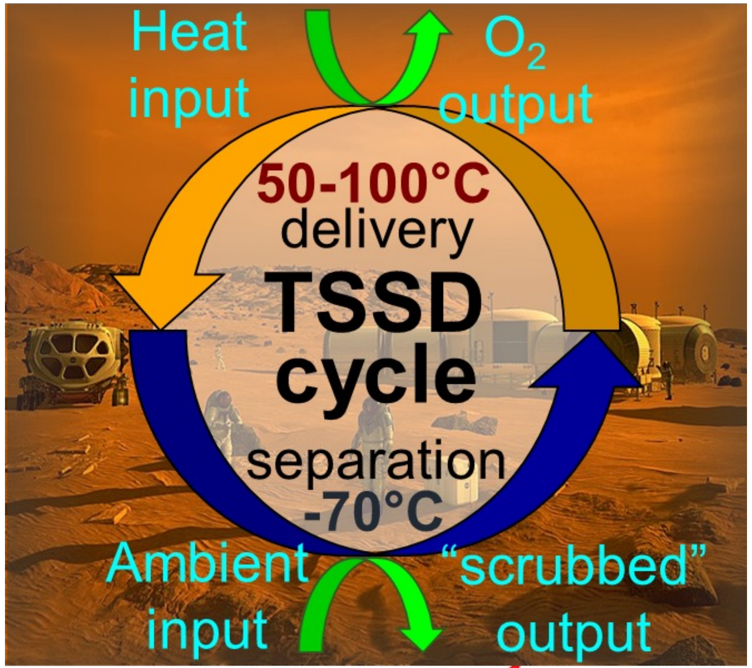
Credit: MARRS final report

Thermal Swing Oxygen Extraction

- Theoretical extraction work: 11.2 kJ/mol O_2
  (CO_2 splitting theoretical work is 572 kJ/mol O_2, practical ~9 MJ_{th}/mol O_2)
- Chemisorption at ambient temperature
- Thermal desorption at mildly elevated temperature



O_2-selective, high surface area adsorbent



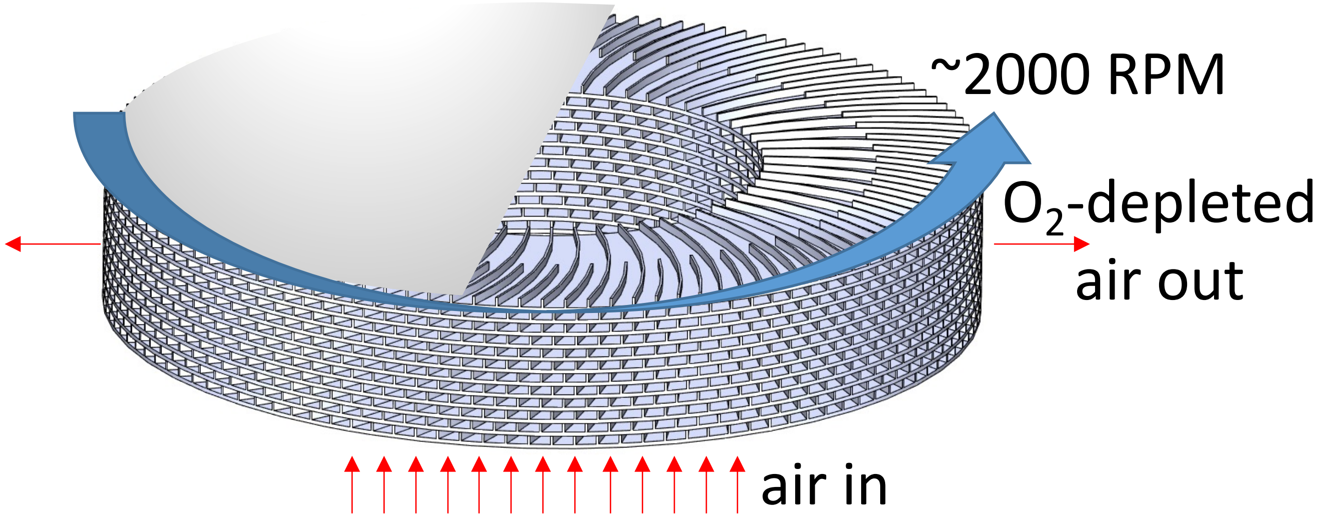
NASA Innovative Advanced Concepts

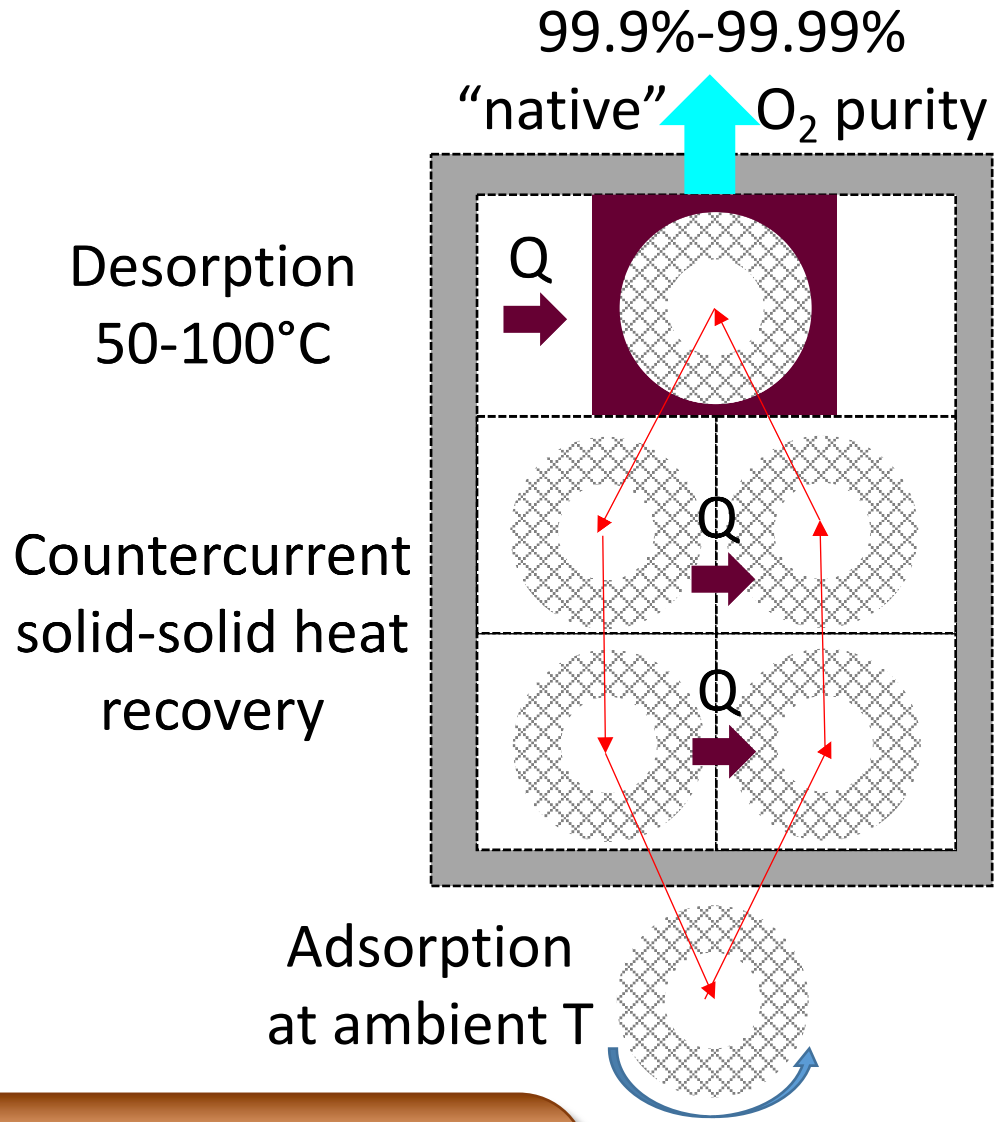
Thank you NIAC Phase 1!

- Builds on existing sorption separation and pumping
- Avoids most heat-to-electricity conversion
- Materials: Substituted zeolites and mesoporous oxides

Key challenges: Sorbents and real heat/power demand

Extractor Conceptual Design

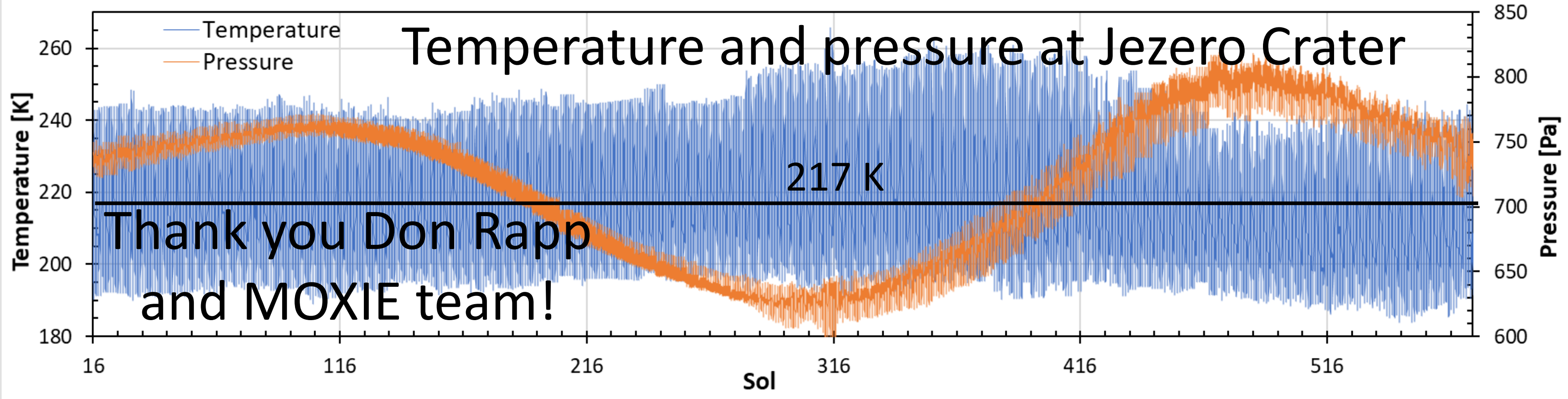


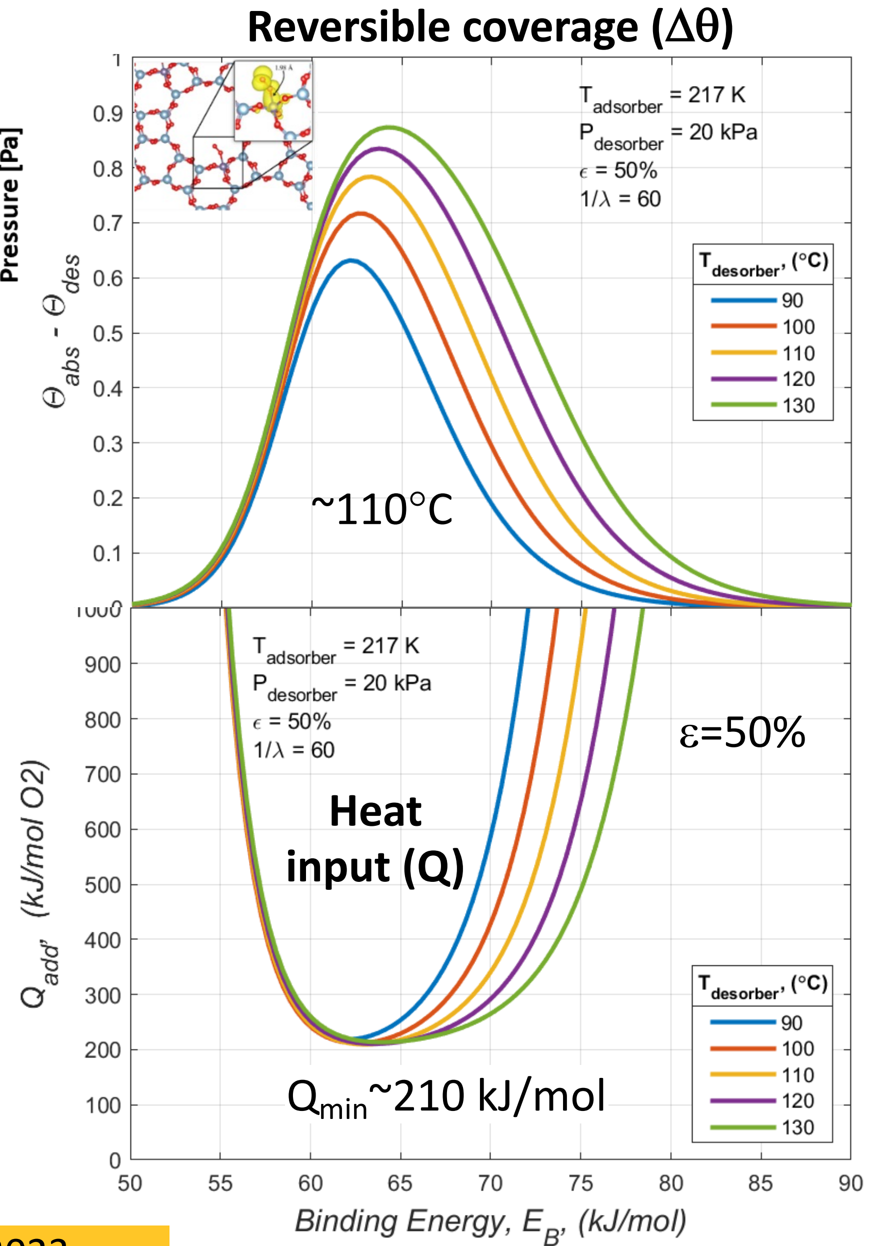


- **Rotating disc stack**
  - Dimensions and RPM similar to DVDs
  - Ribs add surface area and gas collisions
  - Centrifugal acceleration ~2700 m/s^2
    - Ejects dust particles
  - Pressure drop 1-10 Pa (2-20 $kJ_e/mol\ O_2$)
  - m ~ 2 kg/person

Minimizing mechanical work and filtering

Baseline Heat Demand for O_2 Extraction





- **Parameters**
  - Adsorption: 217 K
  - 1/60 active atoms (that is 1/10 of $AlPO_4$ unit formulas)
  - 50% solid-solid heat recovery (ε)
  - Desorption/delivery to 20 kPa

  - 210 kJ/mol ~ 75 W_{th}/person (at 1 kg O_2/person/day)

Heat input well below 572 kJ/mol

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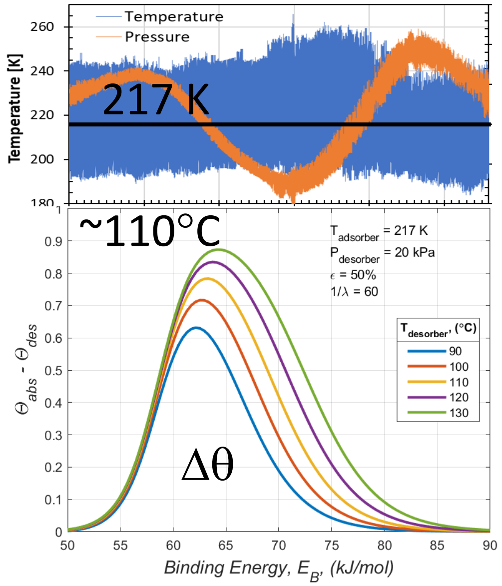
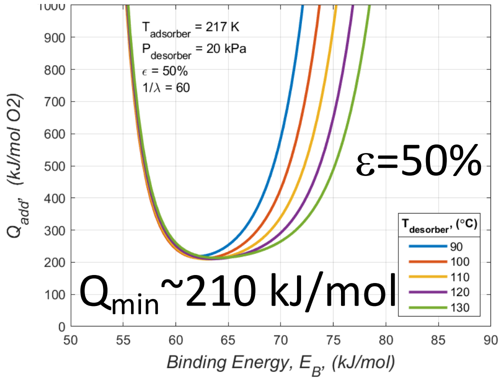
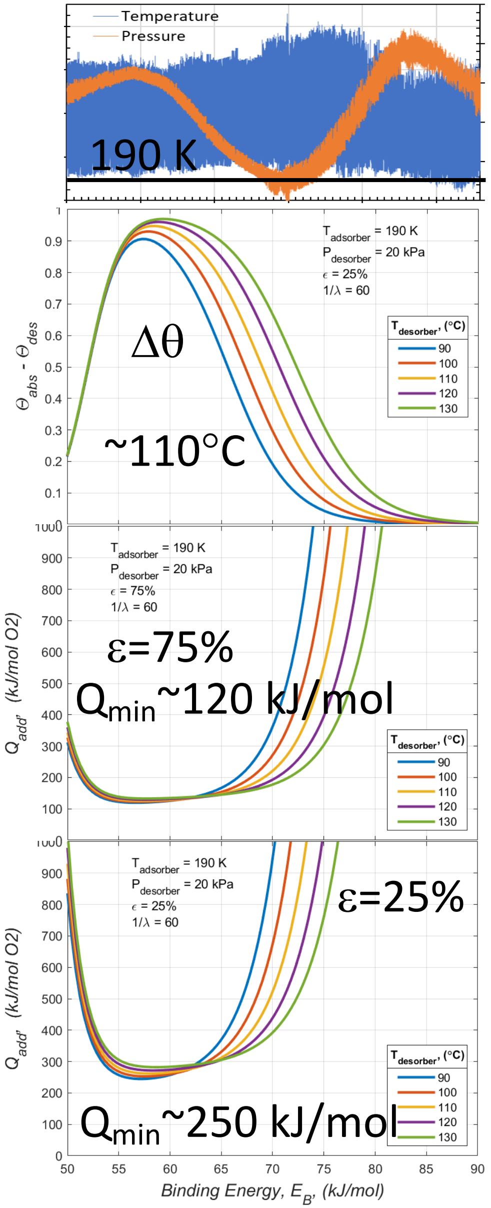
Extraction Heat Input Sensitivity

Baseline, 20 kPa

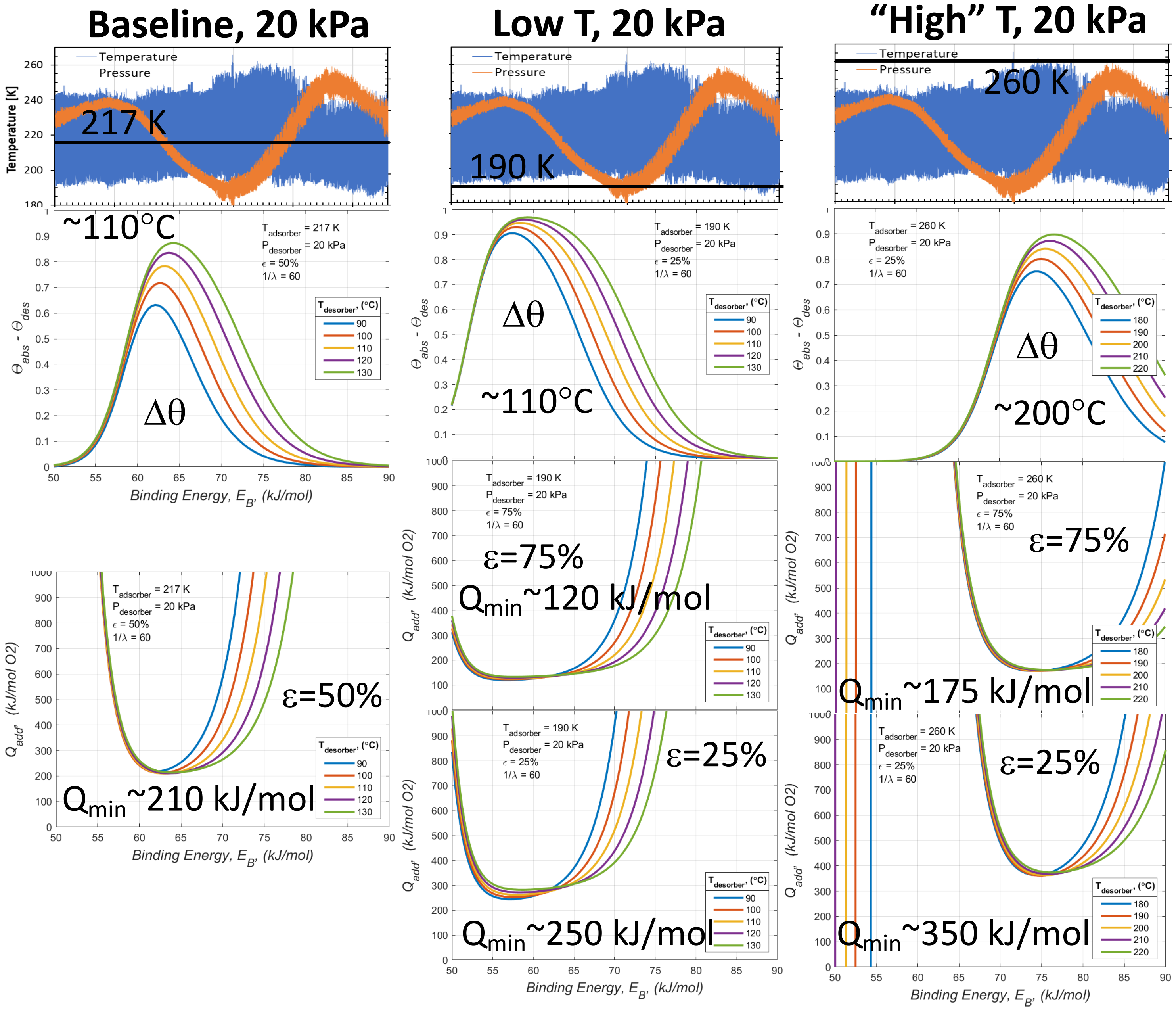




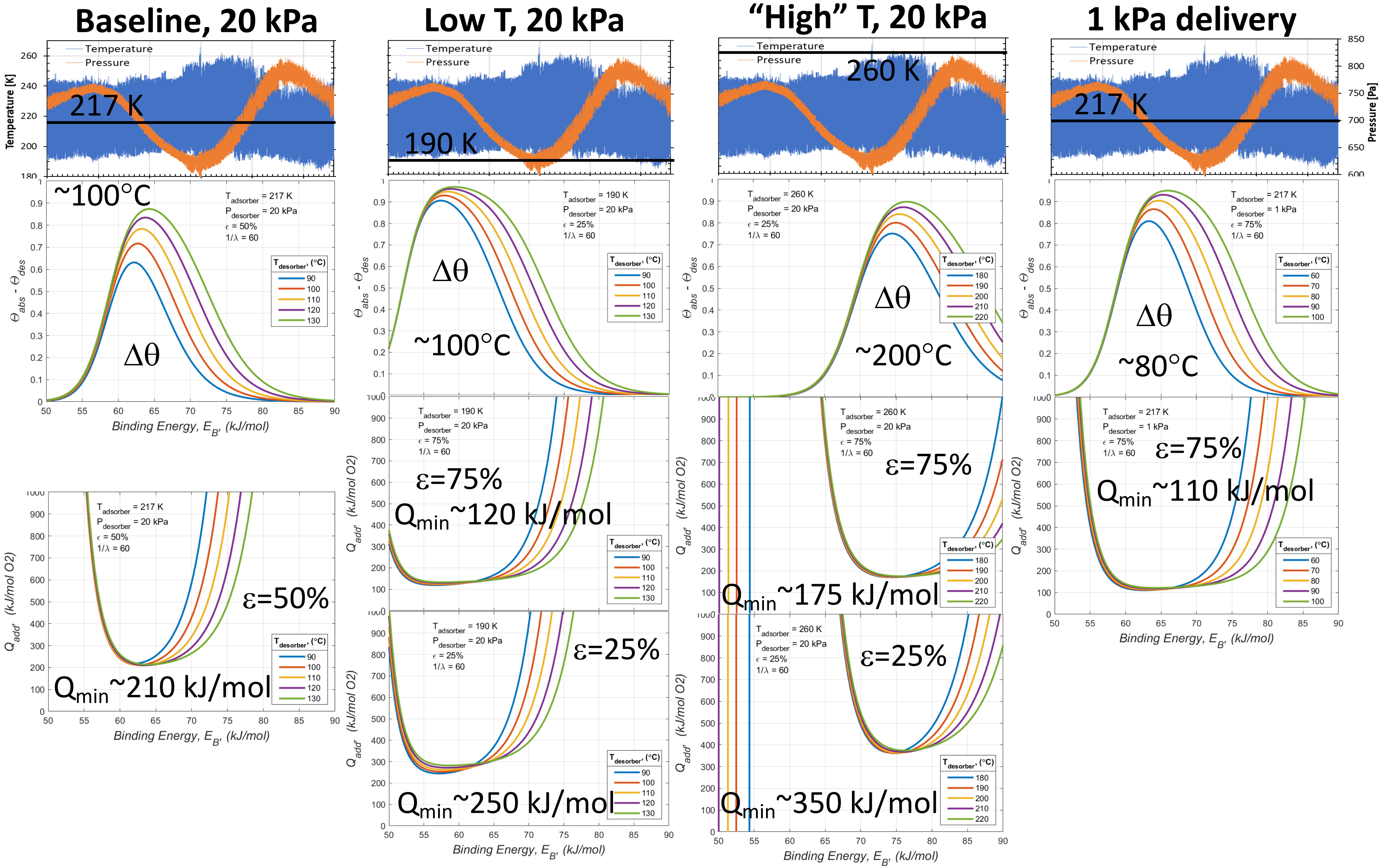
Low T, 20 kPa



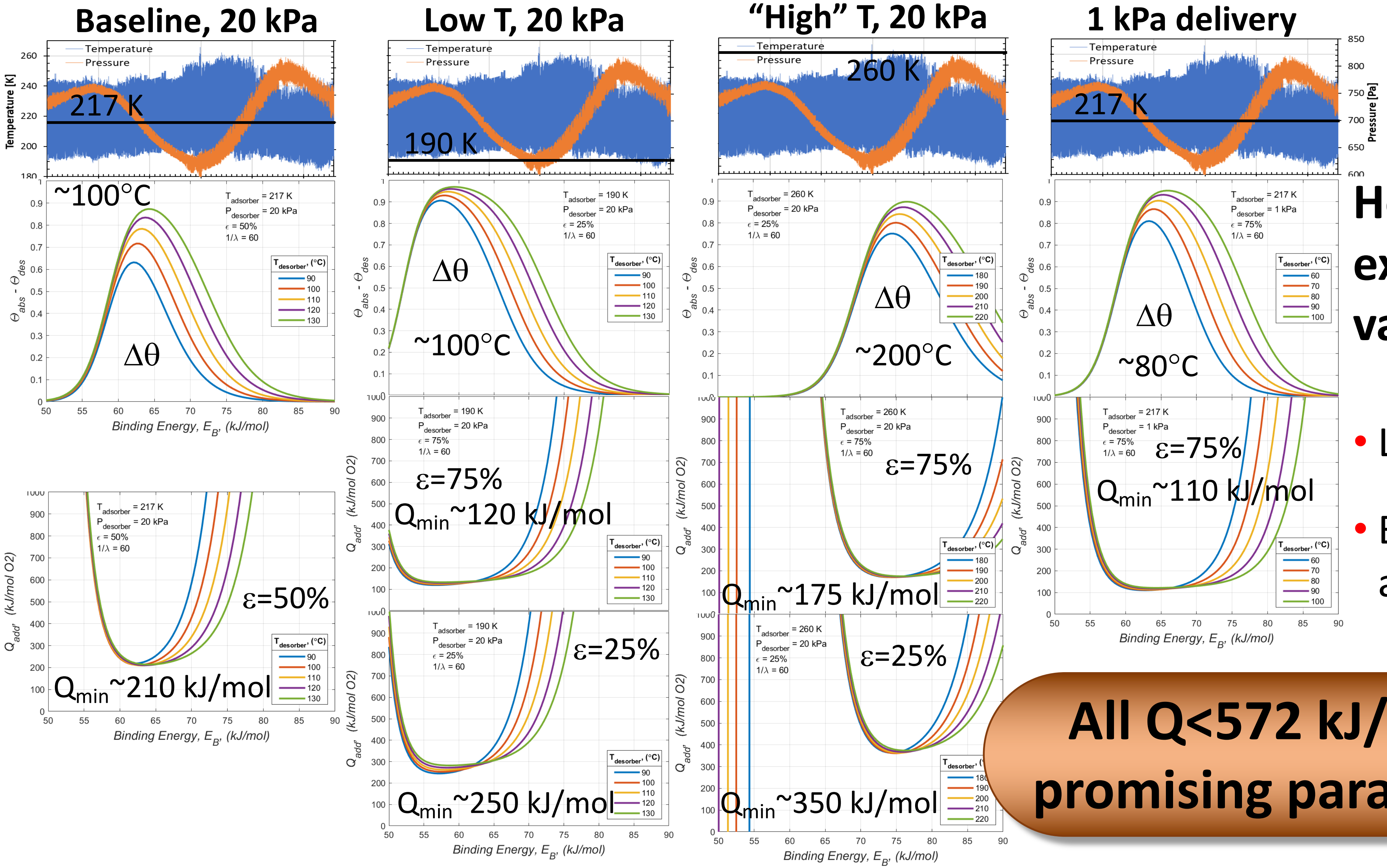
Extraction Heat Input Sensitivity



Extraction Heat Input Sensitivity



Extraction Heat Input Sensitivity

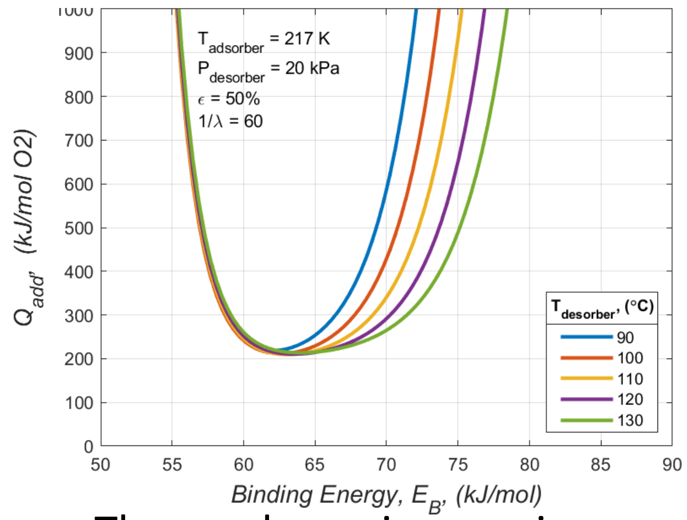


Heat recovery: exceptionally valuable

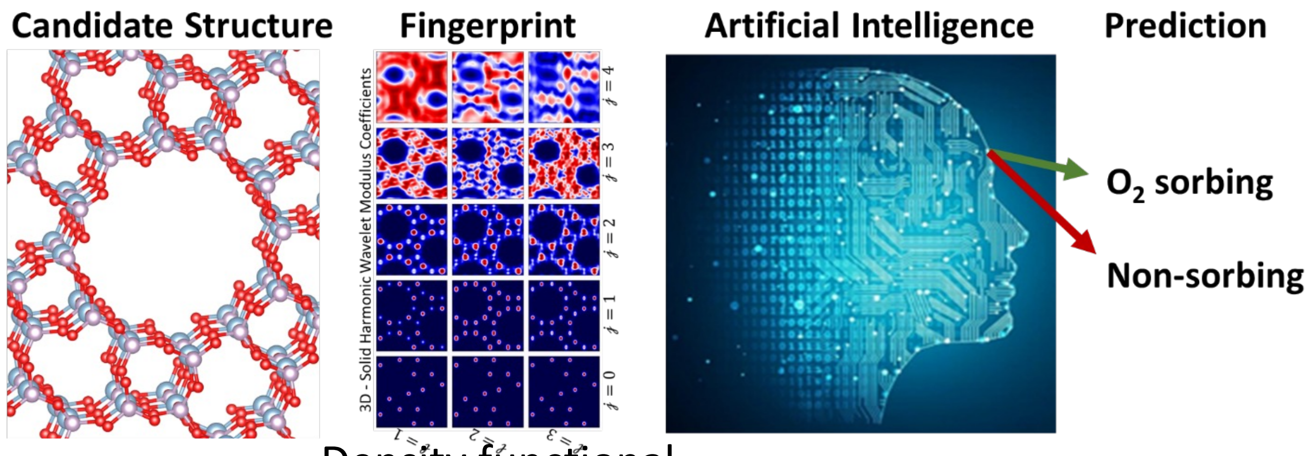
- Lowers Q_{min}
- Broadens materials and operating space

All Q<572 kJ/mol. Broad promising parameter space

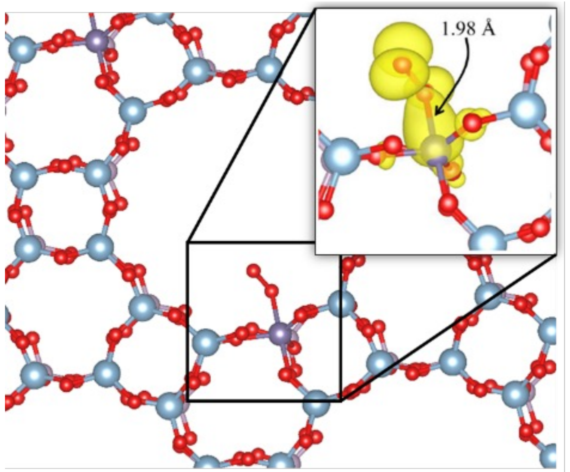
Sorbent Materials: Theory



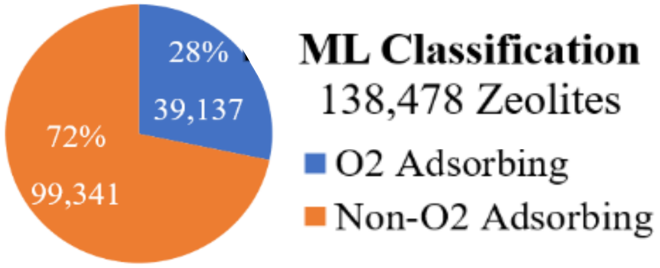
Thermodynamic mapping

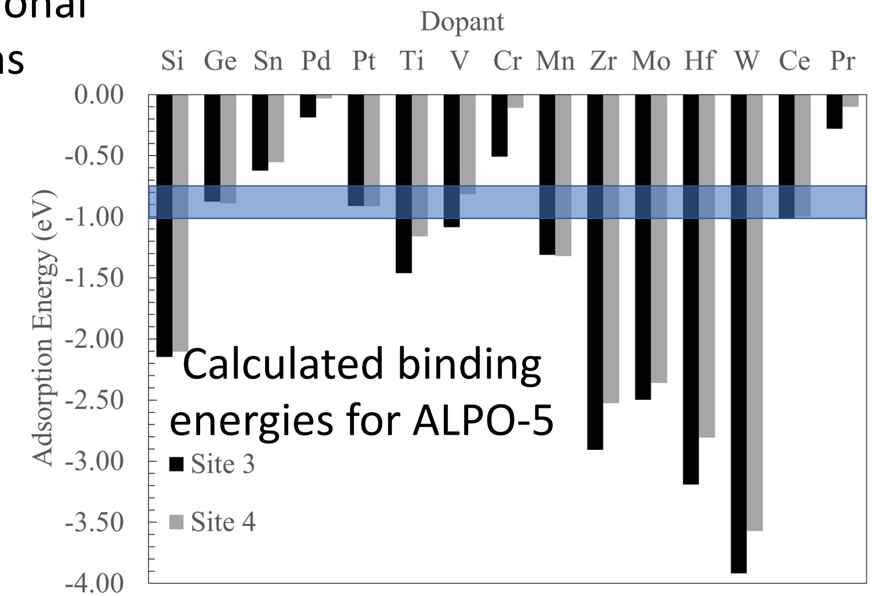


Density functional calculations



Electronic structure





Calculated binding energies for ALPO-5

Many promising sorbent candidates

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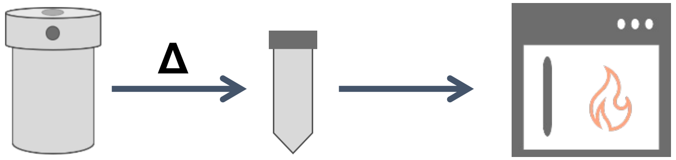
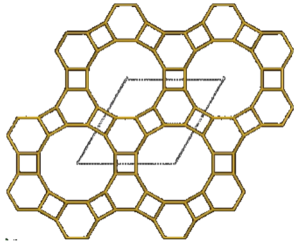
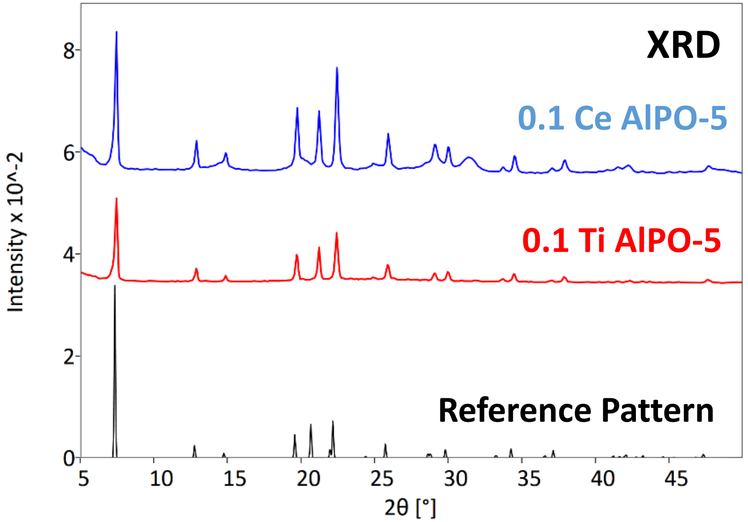
Sorbent Synthesis and Characterization

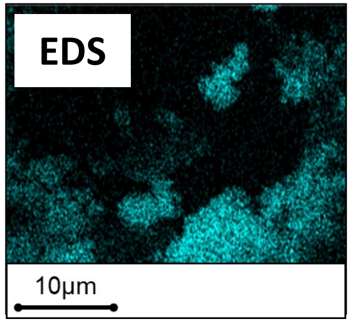
Substituted Zeolites: Hydrothermal Synthesis

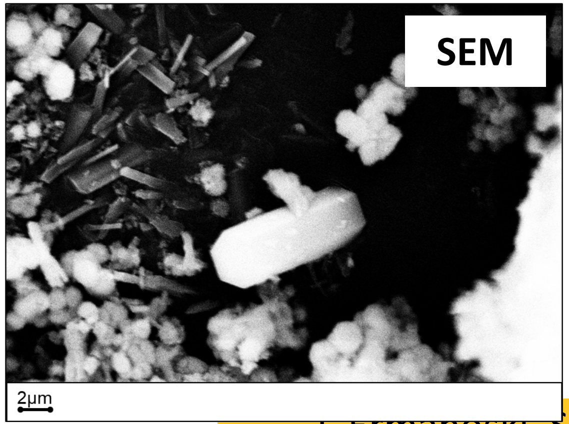




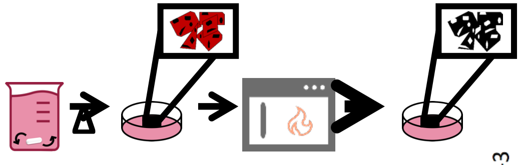


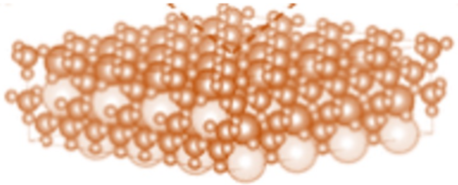
2% Ce atoms

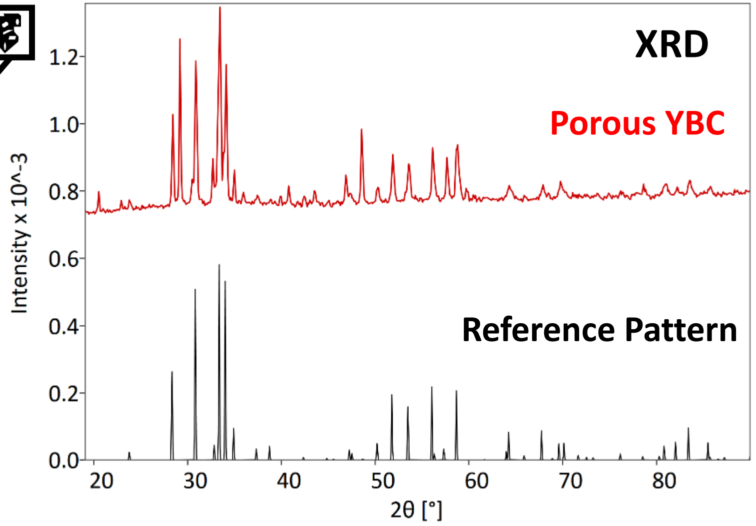


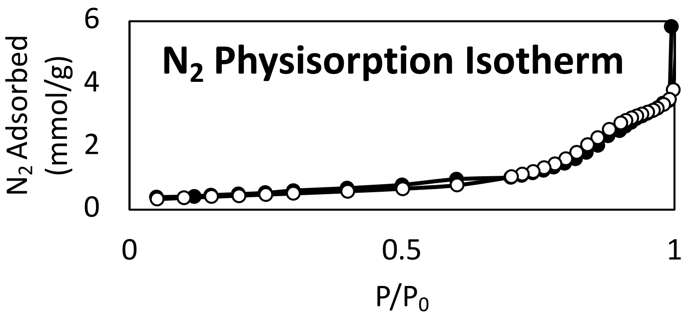


Porous $YBaCo_4O_{7+\delta}$: Sol Gel





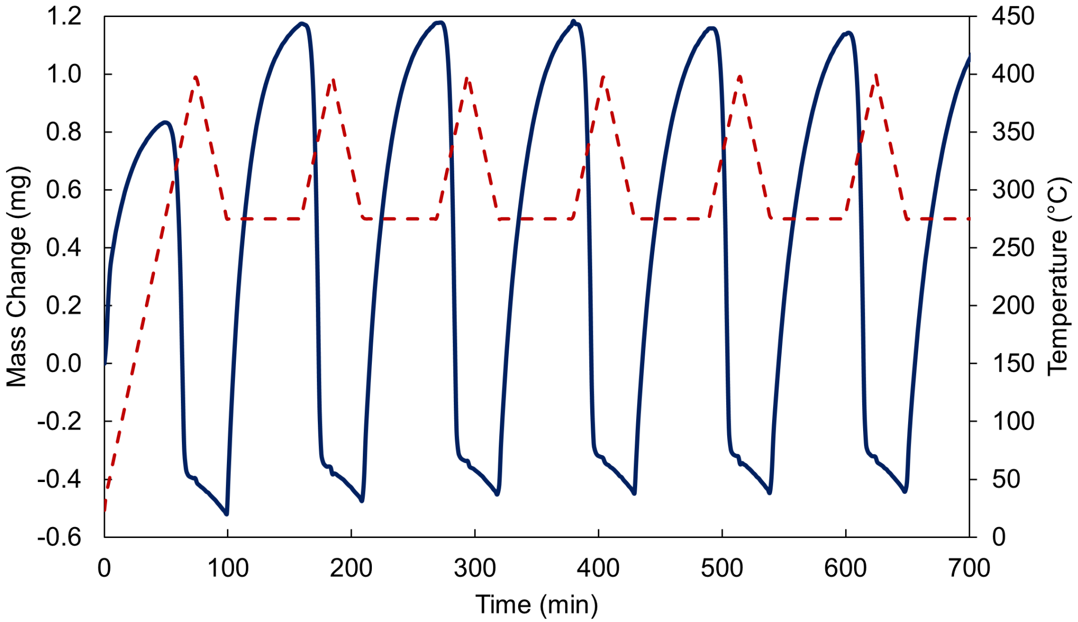




	Pore Treatment	Nonporous YBC
S_{BET} (m^2/g)	37.4	2.42
V_{Pore} (cm^3/g)	0.118	0.018

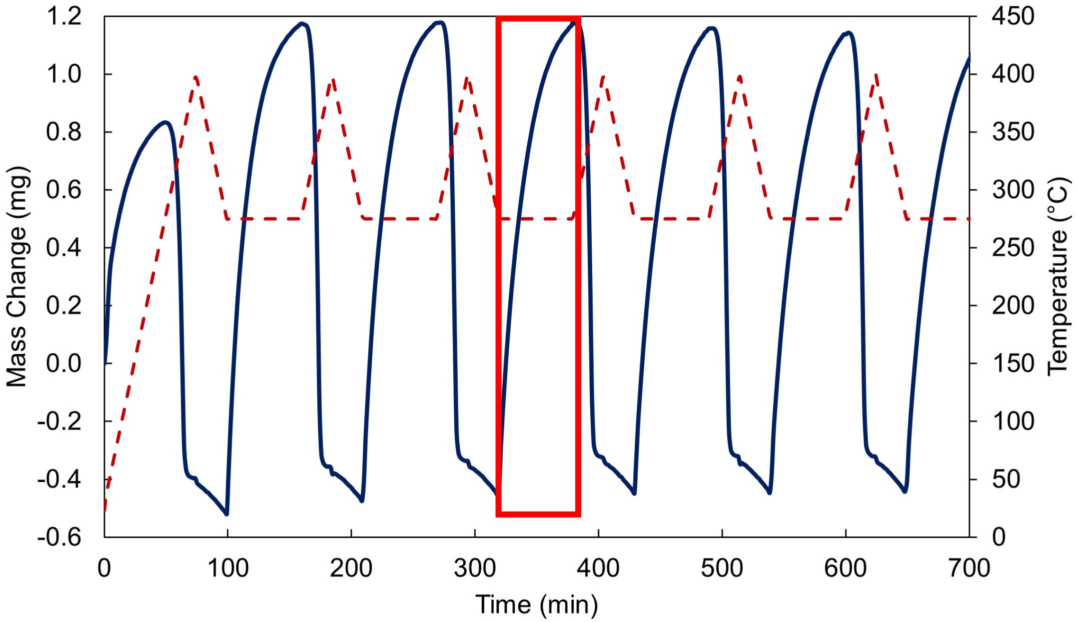
Most challenges, some successes

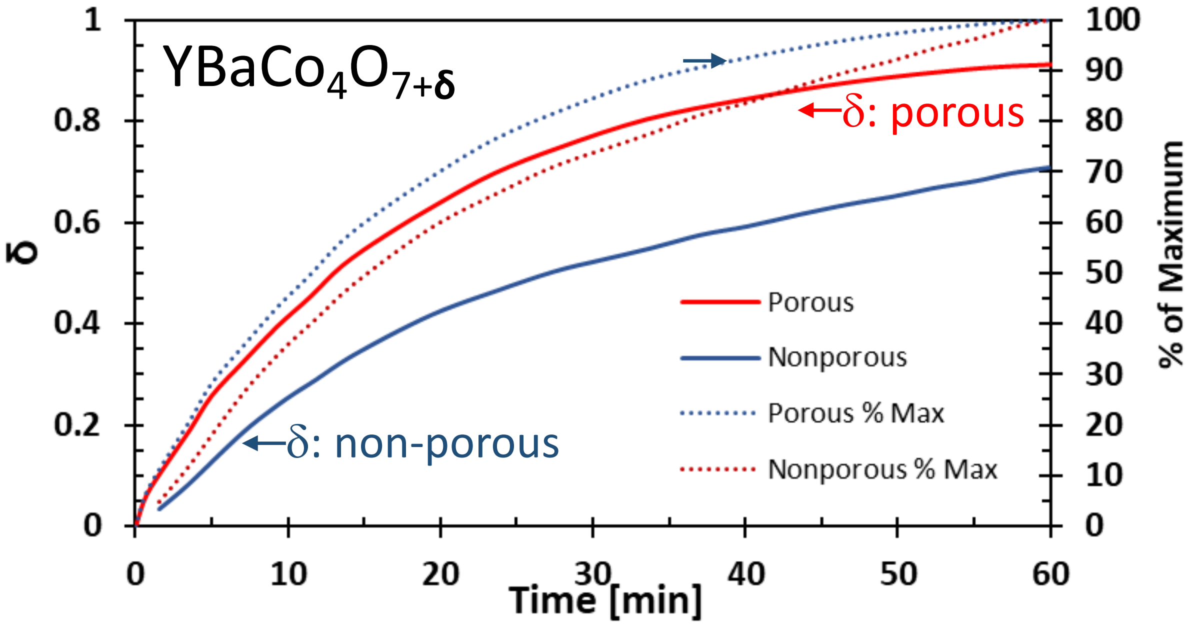
YBC: Experimental O_2 Capacity, Kinetics



- **Porous YBC TGA cycling experiment**
  - Activation/desorption at 400°C in N_2
  - Adsorption at 275°C in 20 kPa O_2

YBC: Experimental O_2 Capacity, Kinetics





	k [1/min]
Porous YBC	0.097388
YBC	0.044212

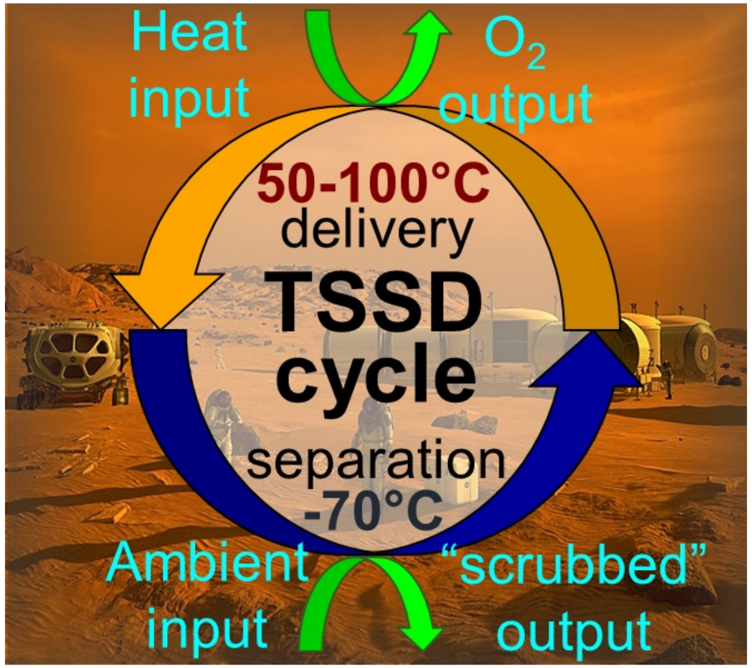
- **Porous YBC TGA cycling experiment**
  - Activation/desorption at 400°C in N_2
  - Adsorption at 275°C in 20 kPa O_2
  - Reversible oxygen capacity δ ~ 0.89
  - Active atom fraction λ ~ 1/29
  - Porosity improves kinetics

Proof of concept. Optimization and improvement needed

Summarizing O_2 Extraction

Potential and benefits

- Low energy consumption, almost all heat
- Mild operating temperature
- Heat recovery highly beneficial: Q_{min}, E_b, and T-range
- Rapid start/stop, continuous or intermittent operation
- Robust and durable, not subject to C-fouling
- Lightweight and portable?



Immediate challenge

- Synthesizing suitable sorbents

Longer-term

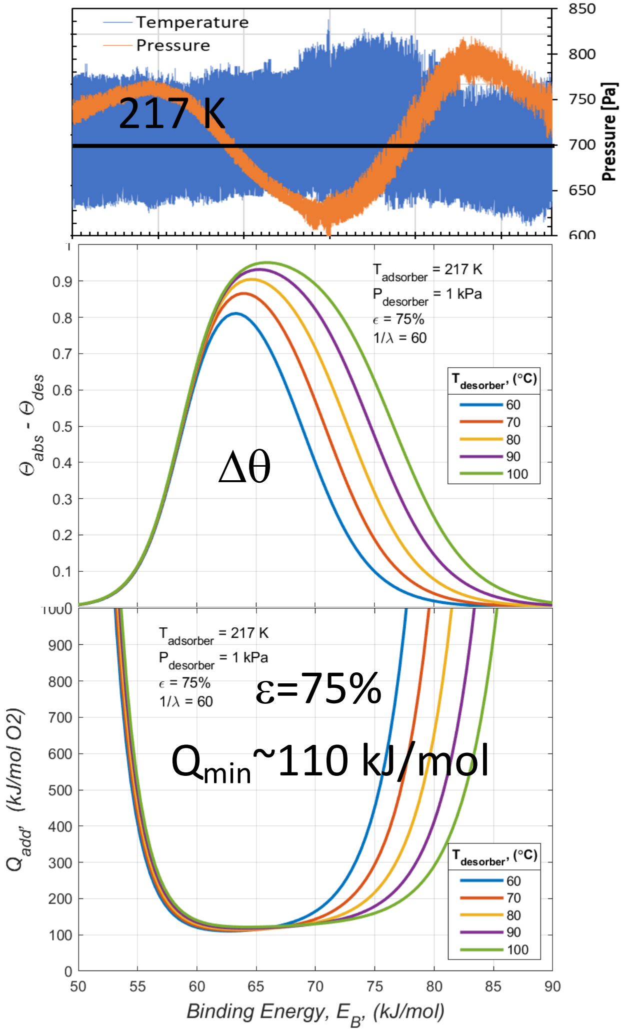
- ~~Polishing step(s)?~~
- Detailed mechanical design

Concept proven, much work remains

The Mars Air Refinery

Inputs

1 kPa delivery



- **Mars atmosphere**

• CO_2	95%
• N_2	2.6%
• Ar	1.9%
• **O_2**	**0.16%**
• CO	0.06%

O_2 + 2CO_2 extraction heat input

$Q_{min,\ O2}$ ~ 110 kJ/mol

$Q_{min,\ 2CO}$ ~ 300 kJ/mol ?

$Q_{min,\ tot}$ ~ 410 kJ/mol

Arizona State University

The Mars Air Refinery

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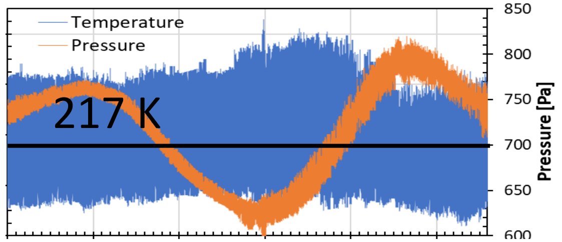

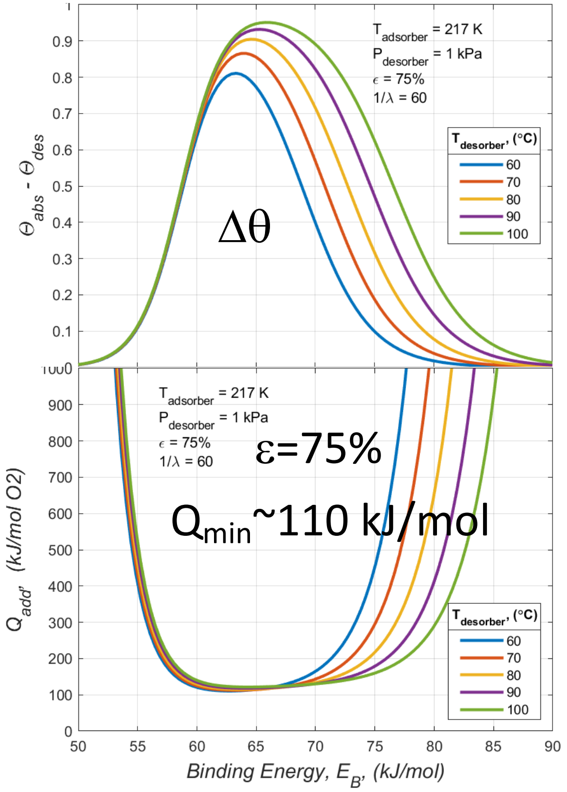

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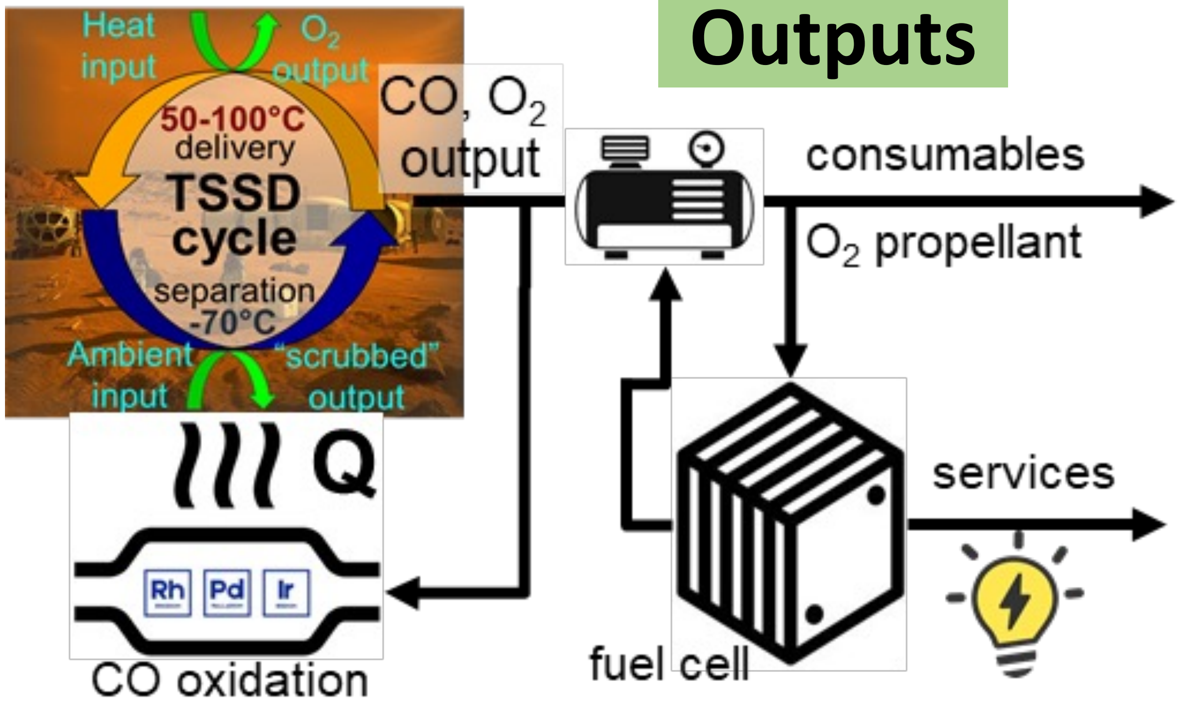

O_2 + 2CO → 2CO_2

572 kJ/mol O_2

Net: ~ 1.4 kWh_{th}/kg O_2

O_2 and CO from the Mars atmosphere can be EROI>1. A local energy source and more?

Arizona State University

I. Ermanoski, Space Resources Roundtable, 8 June 2023

The Mars Air Refinery

A portable O_2 source and genset?

I. Ermanoski, Space Resources Roundtable, 8 June 2023

Arizona State University

Thank You!

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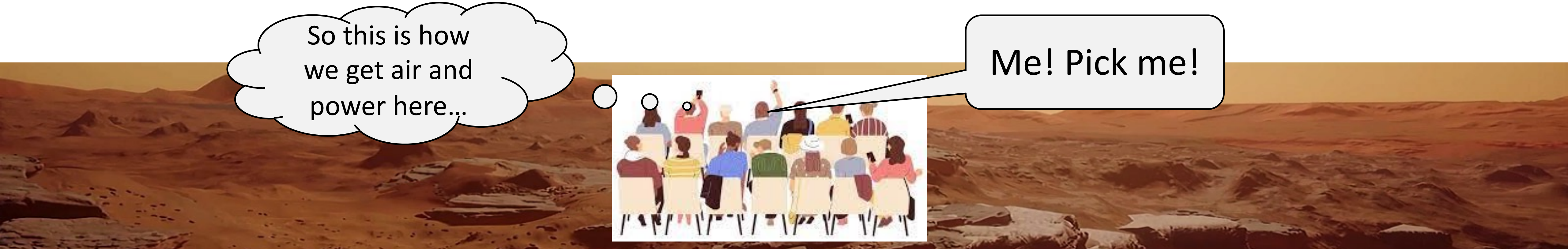
Questions and thoughts?



NASA

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NIAC NASA Innovative Advanced Concepts