TFAWS Passive Thermal Paper Session

Development of Concentric Vapor Chambers for Heating and Cooling of Advanced Sorption Systems

Elizabeth Seber*, Michael Ellis
Advanced Cooling Technologies

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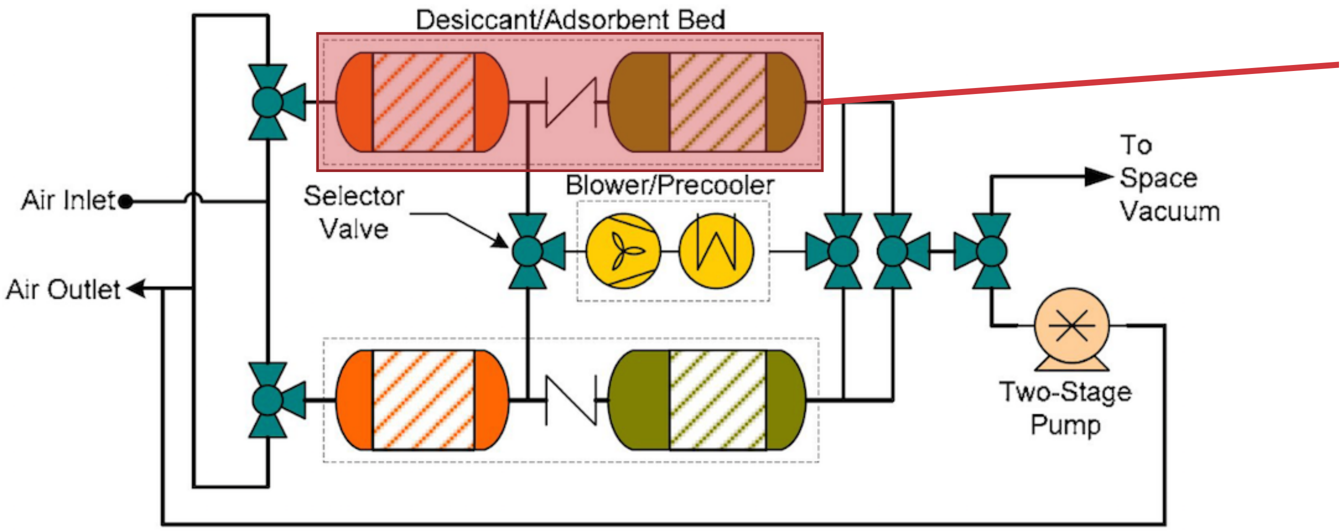
Agenda

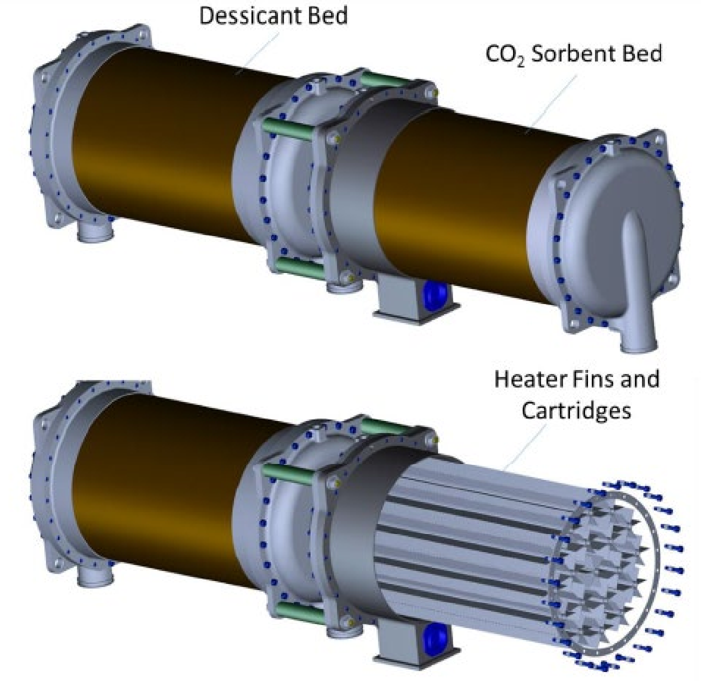
- Introduction
- State-of-the-Art
- Thermal Modeling Design Study
  - Vapor Chamber Geometries
  - Modeling Methodology
- Modeling Results
- Conclusion and Future Work

Introduction – Sorption Systems

- The **Carbon Dioxide Removal Assembly (CDRA)** on the International Space Station (ISS) uses a sorbent material to capture and release CO_2, typically as a waste product.
- The next generation of this system, the **Air-Cooled Temperature Swing Adsorption Compression System (AC-TSAC),** uses two zeolite beds in alternating operation to adsorb, then release pressurized, highly pure CO_2 that can be used in onboard processes.



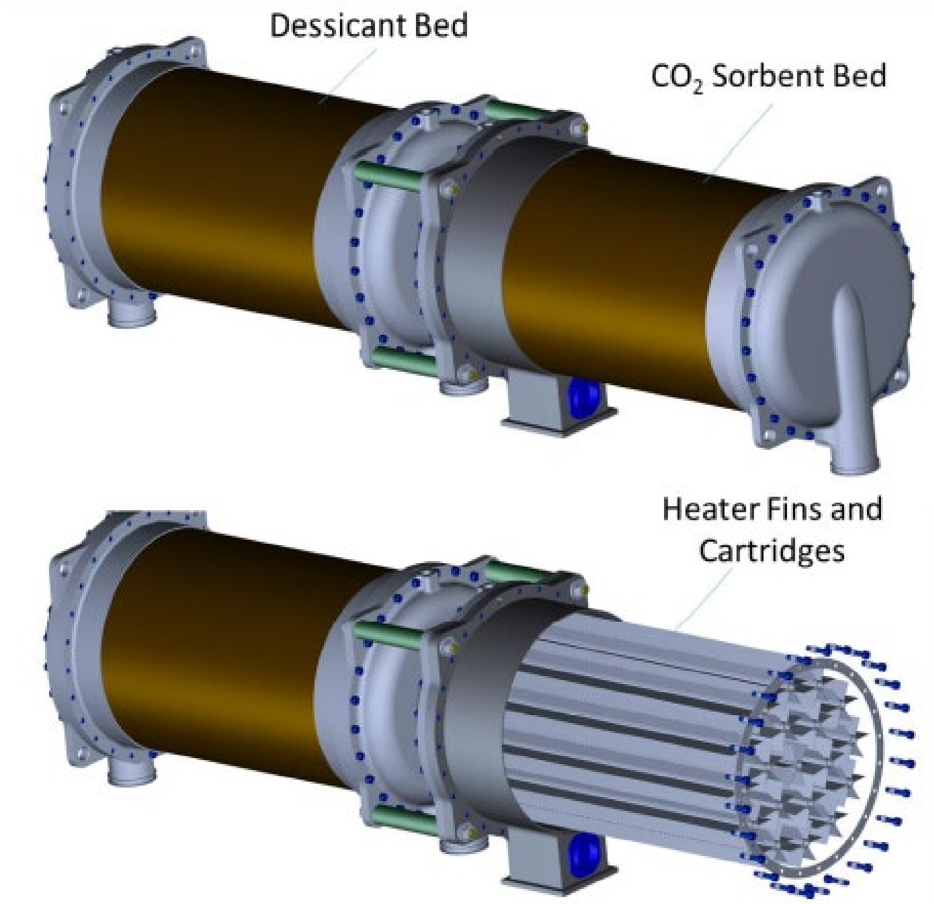
Carbon Dioxide Removal Assembly



Four-Bed Molecular Sieve (4-BMSX)

Introduction – Sorption Systems

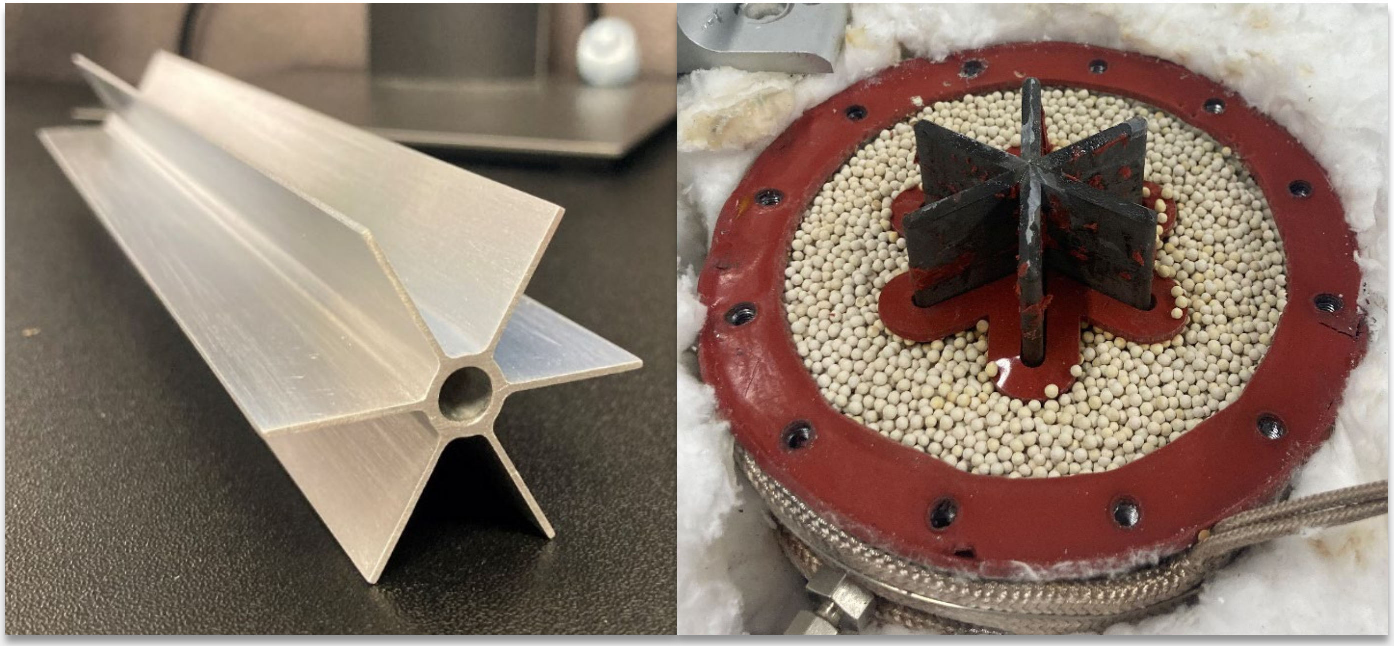
- The temperature swing cycle of each AC-TSAC bed contains four phases:
  - **Adsorption:** Dry cabin air is blown through the bed at ~20°C and CO_2 is adsorbed
  - **Compression:** The bed is sealed off and heated to ~200 °C to cause the zeolite to release the CO_2
  - **Production:** A CO_2 outlet valve is opened, and the high-purity CO_2 leaves the system
  - **Cooling:** Zeolite is cooled down to room temperature (20 °C) to reset the zeolite for more CO_2 adsorption



Four-Bed Molecular Sieve (4-BMSX)

State-of-the-Art Thermal Management System

- Zeolite's low thermal conductivity (0.6 to 4 W/m•K) necessitates a robust thermal management system
- Design efforts to optimize the thermal performance have been investigated in the past
  - Alternate Zeolite Bed Shapes (Rectangular vs. Cylindrical)
  - Alternate heater shapes, locations, and distributions
  - Sorbent Material

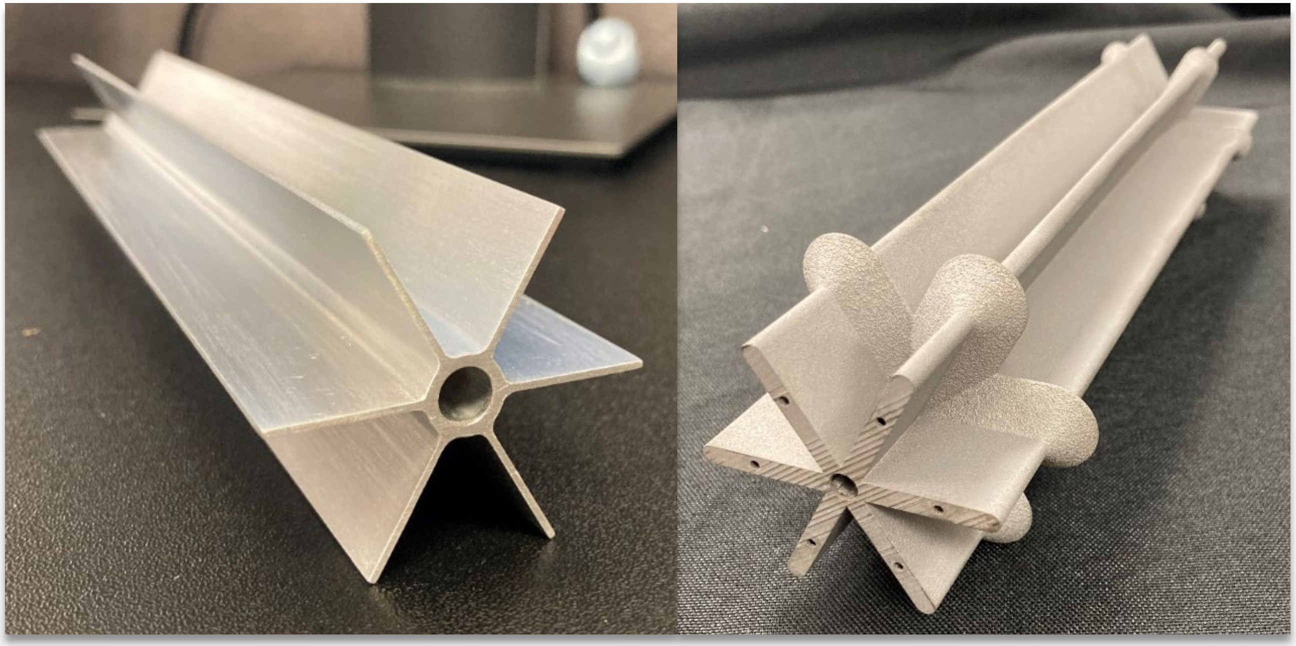


Left: NASA's SOTA Heater with Axial Fin Structures

Right: Subscale Test Bed with Zeolite Beads

State-of-the-Art Thermal Management System

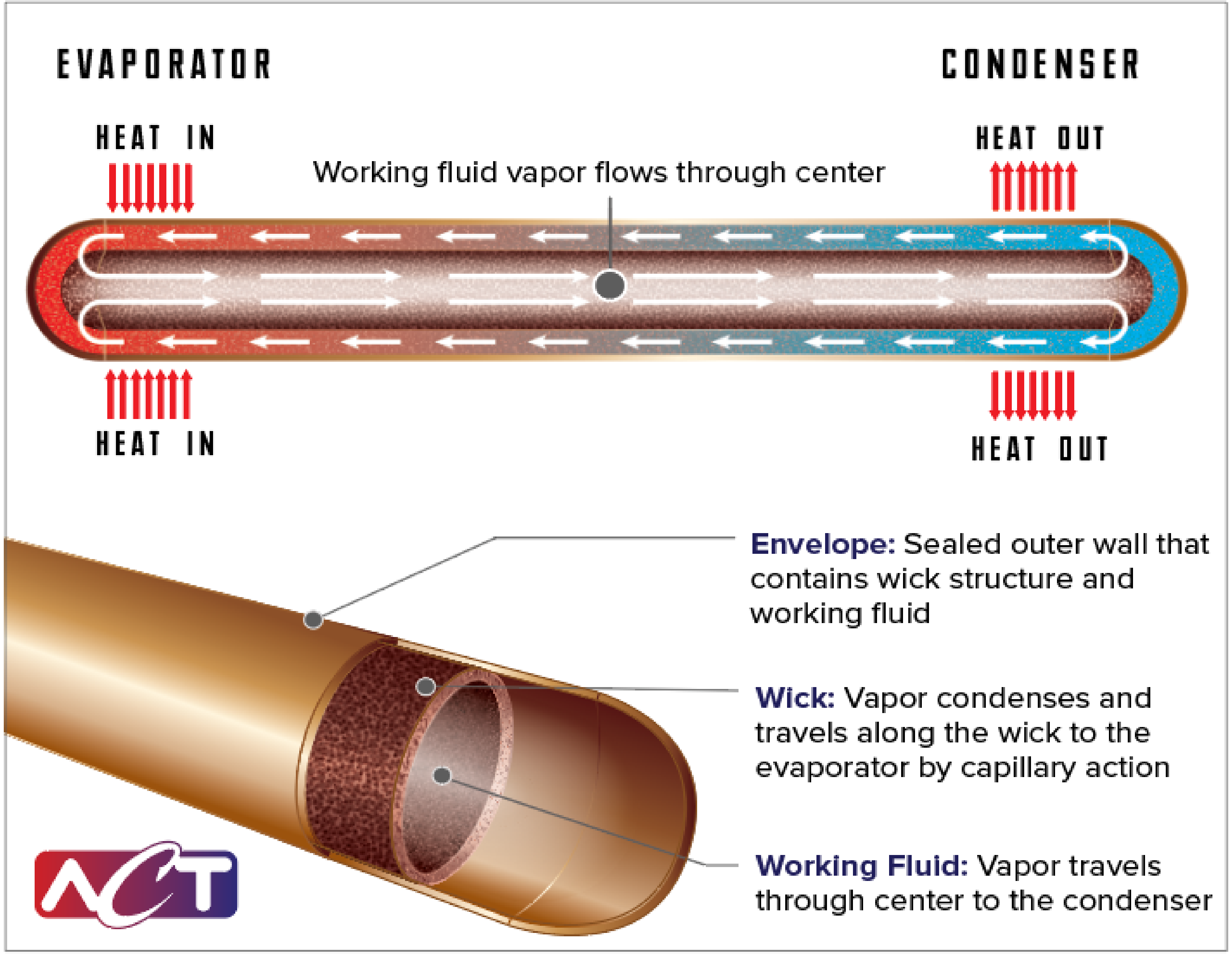
- Vapor Chambers (VC) are an attractive thermal solution:
  - Improve the conductivity throughout the bed
  - Allow heaters to be located exterior to the zeolite bed for easier replacement
  - Sorbent agnostic
  - Compatible with additive manufacturing lattice zeolite structures
  - Cooling mode improves cycle time



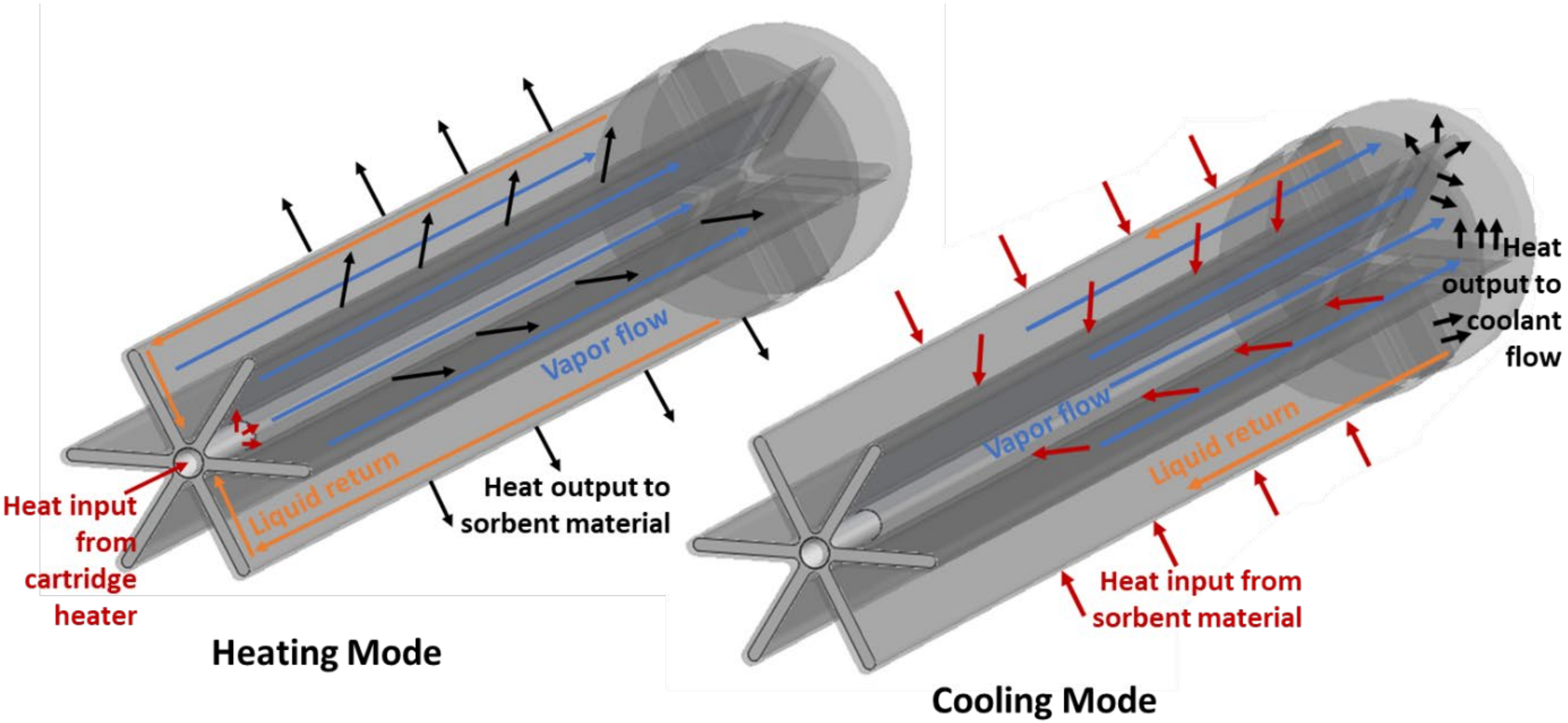
Left: NASA's SOTA Heater with Axial Fin Structures

Right: Phase I Novel Vapor Chamber (ICES-2023-131)

Heat Pipe or Vapor Chamber?



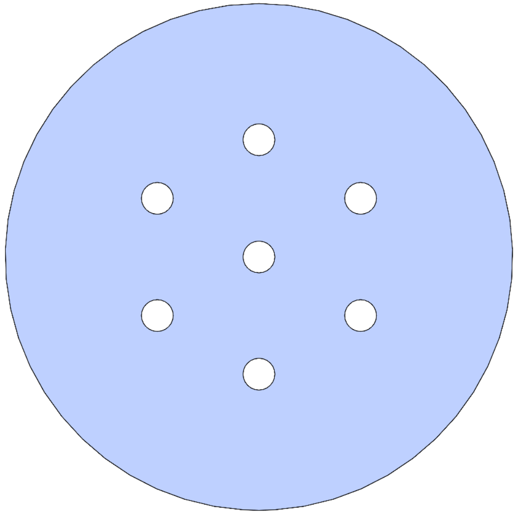
Vapor Chamber Operation



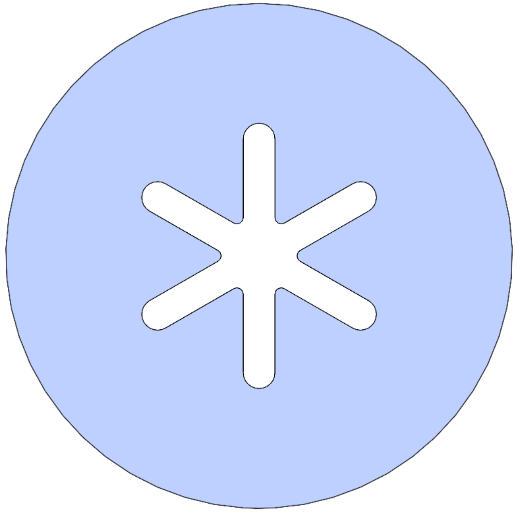
Thermal Modeling Design Study

- Building from Phase I efforts, four geometries are explored here using a conduction FEA analysis.
- A unit cell of these geometries was created, where the geometries were not optimized for their shapes, but rather were constrained with the following:
  - The subscale zeolite bed has a 4 in. diameter and a 12 in. depth.
  - Vapor Chambers could not extend more than 1.05 in. from the center of the bed
  - Maximum thickness/diameter held to 0.25 in.

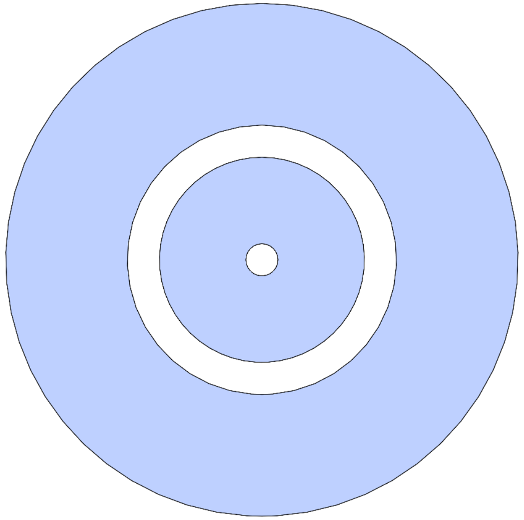
Cross-Sections of Models Tested



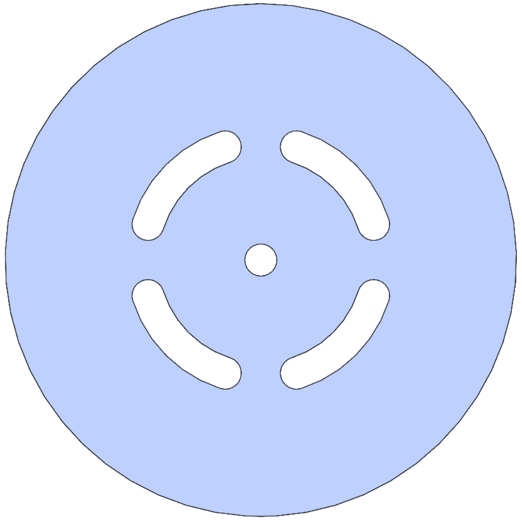
Seven Heat Pipes



Star-Shaped Vapor Chamber

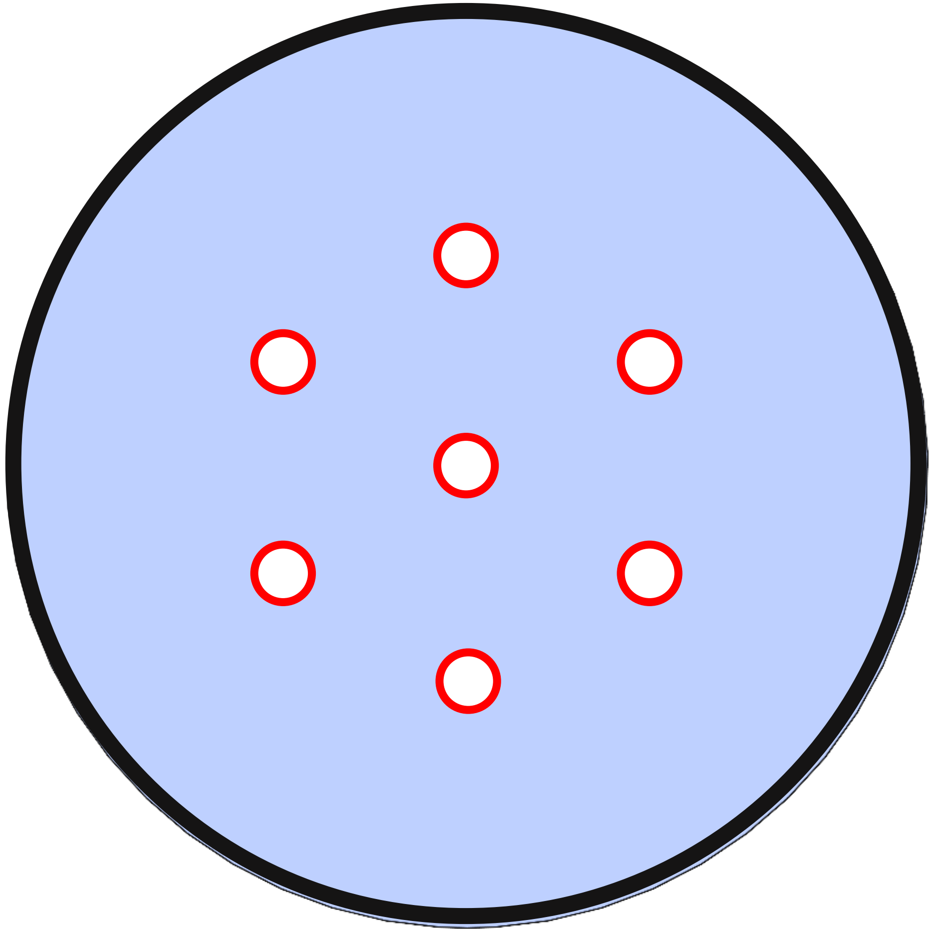


Annular Vapor Chamber



Four Arc-Shaped Vapor Chambers

Vapor Chamber Geometry	Cross-Sectional Area of VC [in^2]	Cross-Sectional Area of Zeolite [in^2]	Perimeter of VC [in]
No Vapor Chambers	-	12.57	-
Seven Heat Pipes	0.35	12.22	5.5
Star-Shaped Vapor Chamber	1.39	11.18	10.45
Annular Vapor Chamber	1.5	11.06	12.41
Four-Arc Vapor Chambers	1.14	11.43	10.25



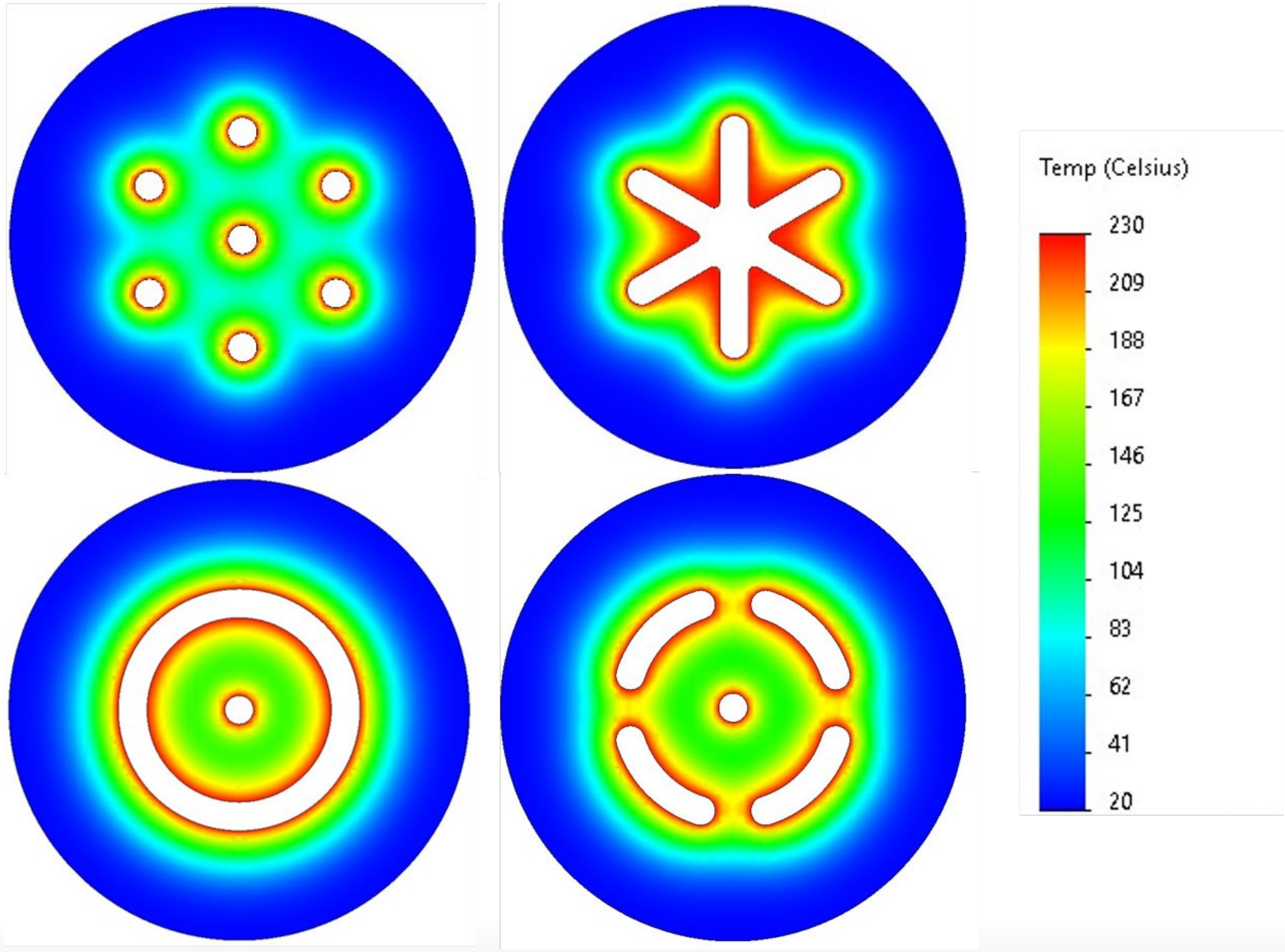
Convection Coefficient (10,000 W/m²·K)

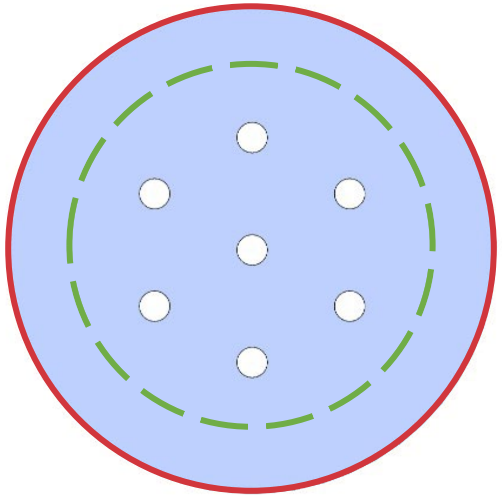
Adiabatic

Zeolite Material Properties
Initial Temperature: 20 °C

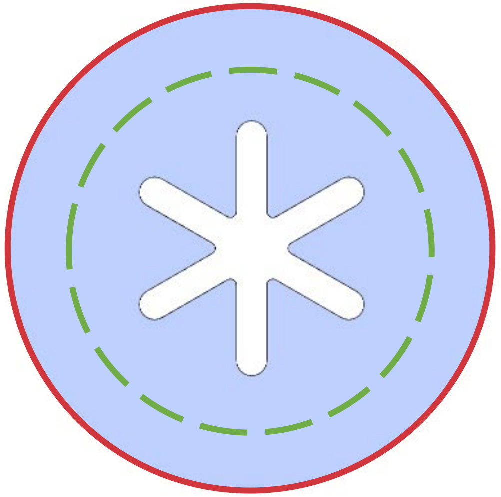
- Zeolite Properties:
  - Initial Temperature: 20 °C
  - Porosity: 0.35
  - Thermal Conductivity: 0.13 W/m•K
- Transient Duration of 600 s, Time Step of 1 s
- 2D Simplification
- Convection Coefficient reflects the heat load and the conductivity of the VCs

Temperature Gradient of Sorbent at t = 600 s

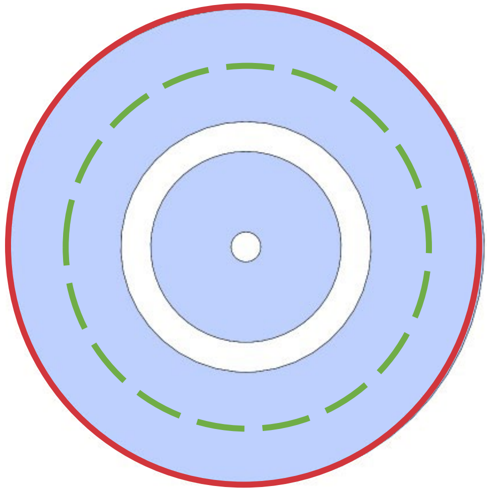




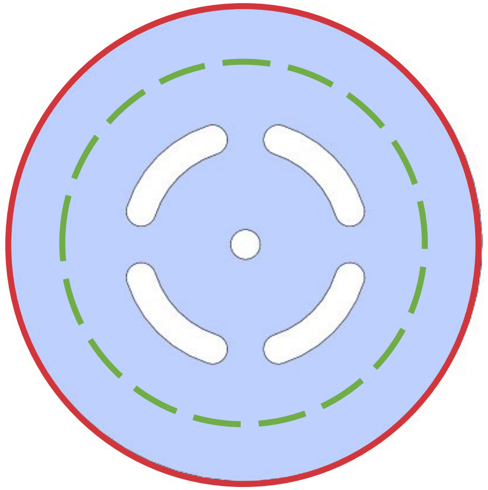
Seven Heat Pipes



Star-Shaped Vapor Chamber

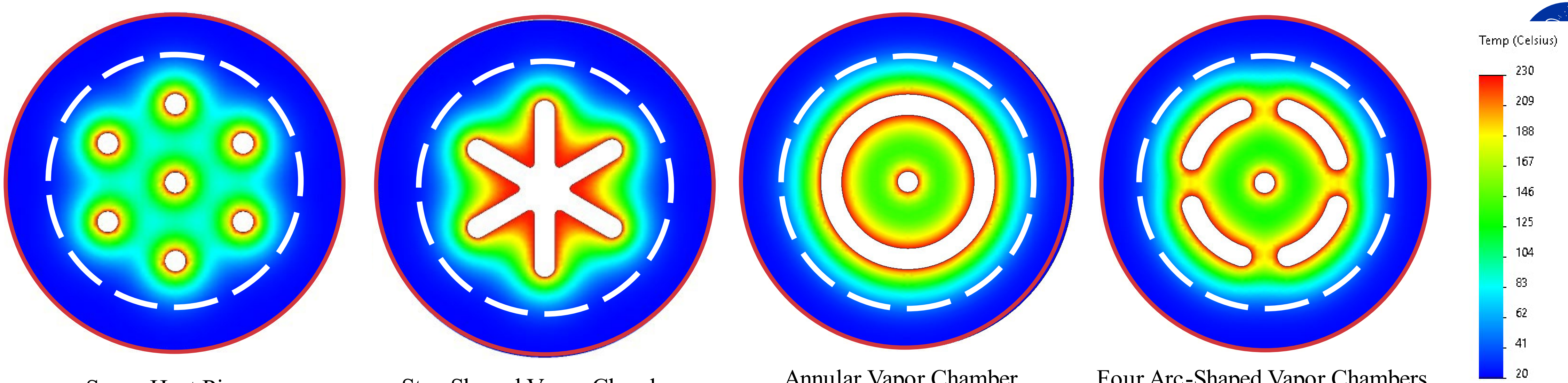


Annular Vapor Chamber



Four Arc-Shaped Vapor Chambers

	Seven Heat Pipes	Star-Shaped Vapor Chamber	Annular Vapor Chamber	4-Arc Vapor Chamber
Full Bed Area (4 in. Diameter)				
Maximum Temperature [°C]	227	227	227	227
Minimum Temperature [°C]	20.1	20.1	21.2	20.6
Average Temperature [°C]	61.986	69.43	84.65	84.44
Standard Deviation [°C]	51.27	66.68	68.73	68.51
3 in. Diameter				
Maximum Temperature [°C]	227	227	227	227
Minimum Temperature [°C]	25.6	26.1	49.9	39.3
Average Temperature [°C]	94.75	114.34	141.31	137.7
Standard Deviation [°C]	49.52	67.93	54.35	55.32



Seven Heat Pipes | Star-Shaped Vapor Chamber | Annular Vapor Chamber | Four Arc-Shaped Vapor Chambers

	Seven Heat Pipes	Star-Shaped Vapor Chamber	Annular Vapor Chamber	4-Arc Vapor Chamber
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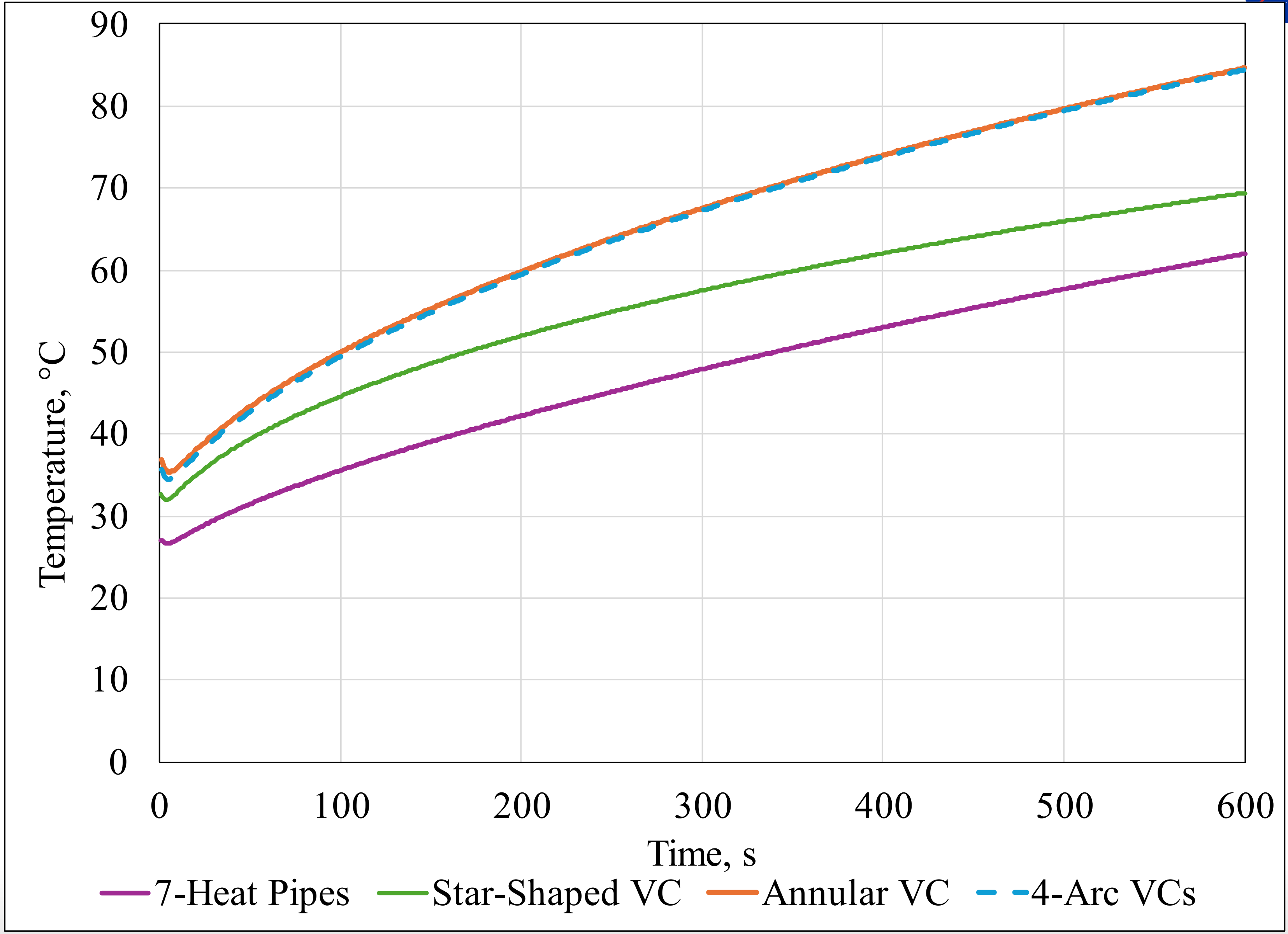
Time vs. Average Sorbent Temperature for Each Vapor Chamber Model

- 7HP Model had the lowest average temperature
- AVC and 4-AVC Performed nearly identically



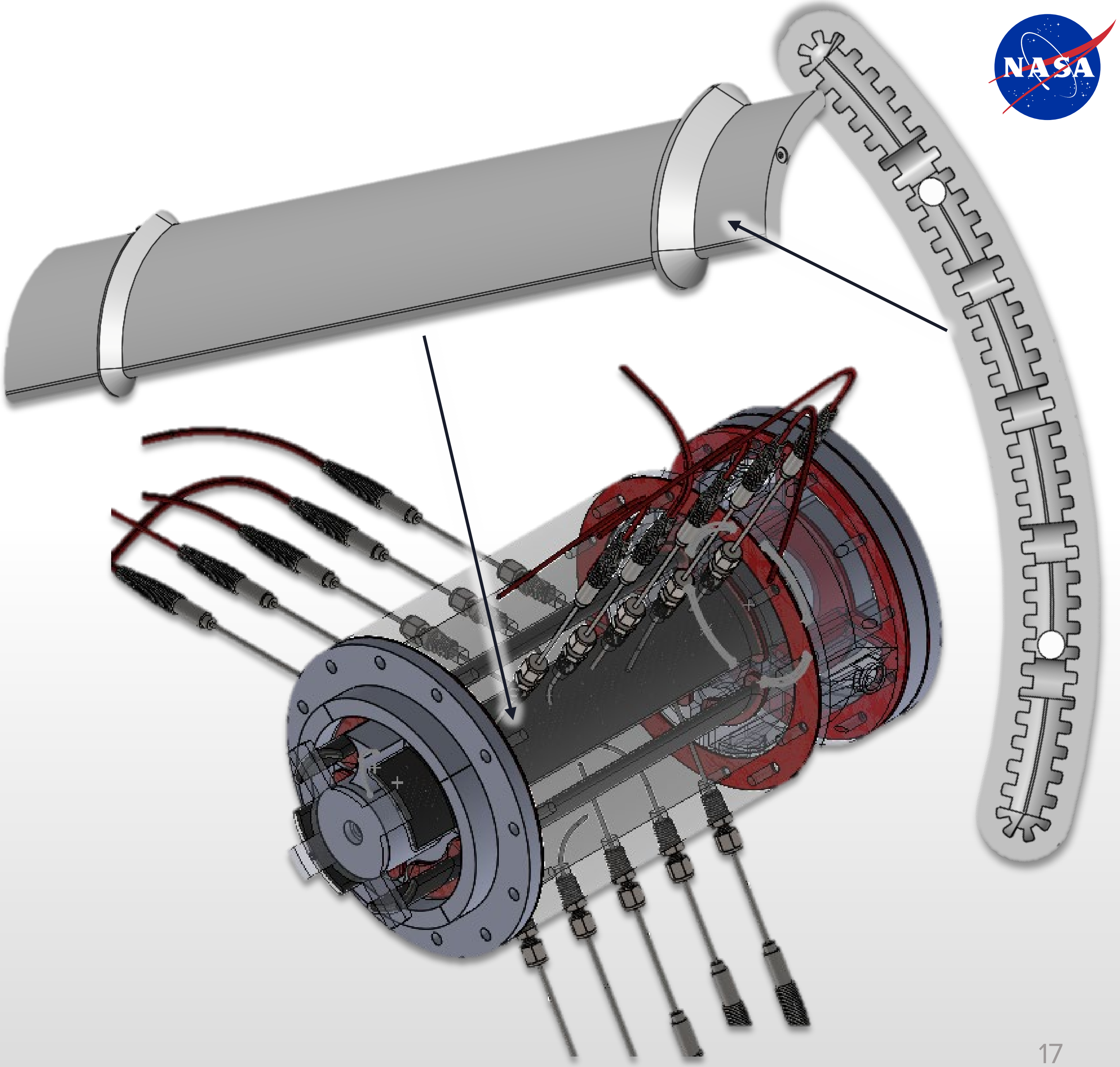
Conclusion

- Seven Heat Pipe Array had the lowest overall size, and lowest temperature deviation, indicating higher temperature uniformity.
  - Had the lowest average temperature and would require more time to heat the entire bed to 200 °C
  - Adding more HP may be a solution, but introduces manufacturing complexity
- The Star-Shaped Vapor Chamber had the second lowest overall size, as well as the second lowest temperature and temperature deviation.
  - Sharp temperature gradient between fins
  - Requires more mass for structural supports
- The Annular Vapor Chamber and 4-Arc Vapor Chamber perform similarly.
  - Both models showed the highest average temperature and comparably lower temperature deviation
  - The 4-AVC does so with 24% less cross-sectional area.
  - Sectioning of the annular vapor chamber into arc segments allowed for the same high conductivity in the bed while reducing the size and weight of the vapor chambers.

Future Work

Completed
- 7HP Testing Data
- 4-AVC Subscale Model

Up Next
- 4-AVC Testing Data
- Scaling up the design for a Full-Scale Model
  - Optimizing spacing and size of the vapor chamber
  - Optimizing Wick Structure
- Fabrication and Testing of the Full-Scale Model



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Further Questions:

Elizabeth K. Seber
elizabeth.seber@1-act.com
(717) 205-0696

Michael C. Ellis
mike.ellis@1-act.com

Advanced Cooling Technologies, Inc.
www.1-act.com (717) 205-6061

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