Four Bed Molecular Sieve – Exploration (4BMS-X) Heater Design and Analysis

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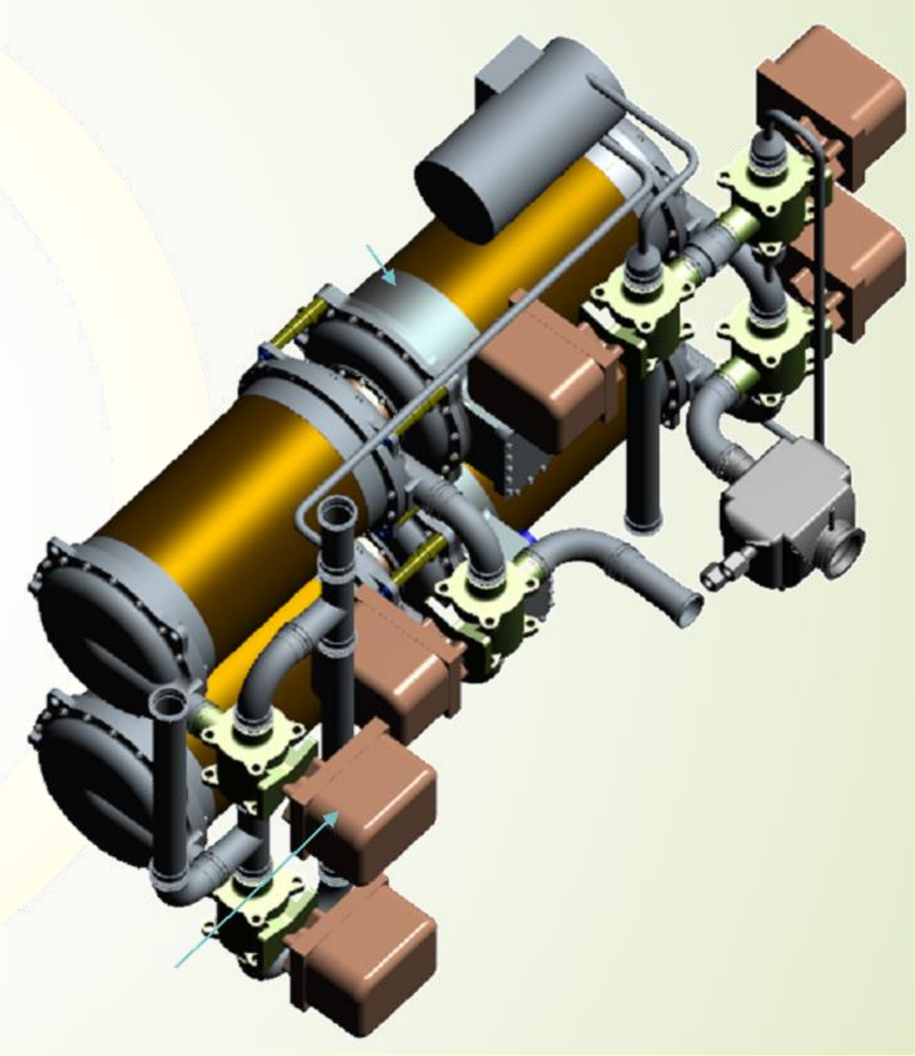
Introduction

- A CO_2 removal technology development roadmap for exploration has been formulated to advance both existing and new technologies to an on-orbit evaluation via an ISS flight demonstration early in the next decade.

- As part of the development process, the 4BMS-X (Four Bed Molecular Sieve for Exploration) will introduce a number of potential improvements over existing ISS CDRA (Carbon Dioxide Removal Assembly) technology including cylindrical sorbent beds and an improved heater core.

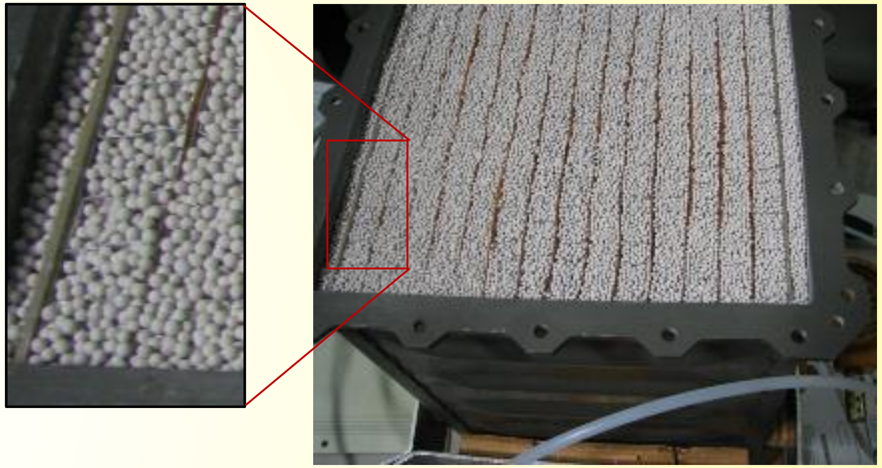
- The design and analysis of an optimized heater core for the 4BMS-X CO_2 sorbent beds is presented.



4BMS-X Concept

Adsorption Physics

- Adsorption is the adhesion of molecules of gas, liquid, or dissolved solids to a surface.
- This process creates a film of the adsorbate (the molecules or atoms being accumulated) on the surface of the adsorbent. It differs from absorption, in which a fluid permeates or is dissolved by a liquid or solid.
- In the 4BMS-X a sorbent (Zeolite 13X) is used to capture molecules of CO_2. The trapped CO_2 can be removed or "desorbed" through the application of heat and partial vacuum.
- Many CO_2 sorbents also have a strong affinity for water vapor, which must be removed upstream of the CO_2 sorbent bed.

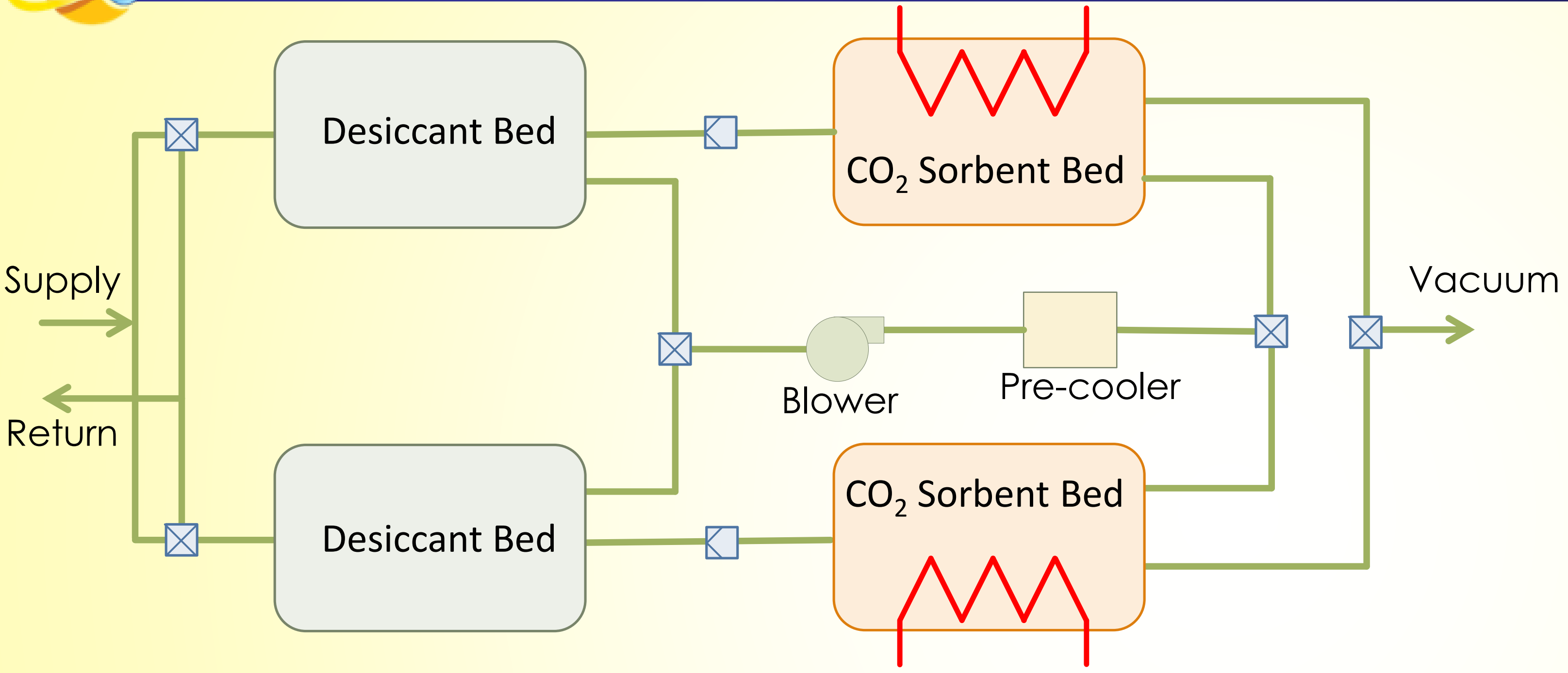


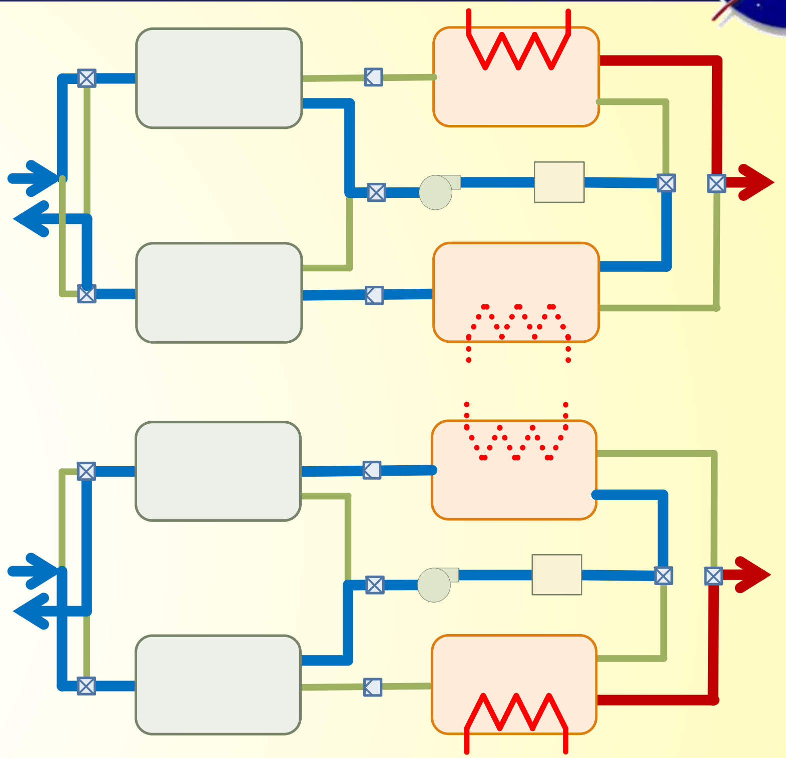
ISS Carbon Dioxide Removal Assembly (CDRA) CO_2 Sorbent Bed

4BMS-X Heater Core Design Requirements/Goals

- The primary heater sizing and design requirements established for this study are half cycle time, target temperature and the desire to minimize thermal gradients and flow channeling.
- The desired half cycle time is 80 minutes with an initial ramp time of 60 minutes.
- The desired target temperature is 200 °C which represents an average bed temperature.
  - In the baseline 4BMS-X design the sorbent bed is driven to higher temperature than is necessary to desorb CO2 from zeolite 13X (baseline sorbent) as the sensible energy of the effluent gas is also used to help desorb water vapor from the downstream desiccant bed.
- Minimizing thermal gradients in the sorbent bed will increase efficiency as well as potentially mitigate pellet dust formation resulting from thermal expansion.
  - A specific thermal gradient is not defined but a lower temperature limit of 150 °C in the bed is desired to facilitate CO_2 desorption and an upper limit within +10°C of the target temperature is desired to mitigate dust formation.
- Channeling is not quantified in this effort but qualitative assessments on heater fin geometry and surface area that could exacerbate channeling are made.

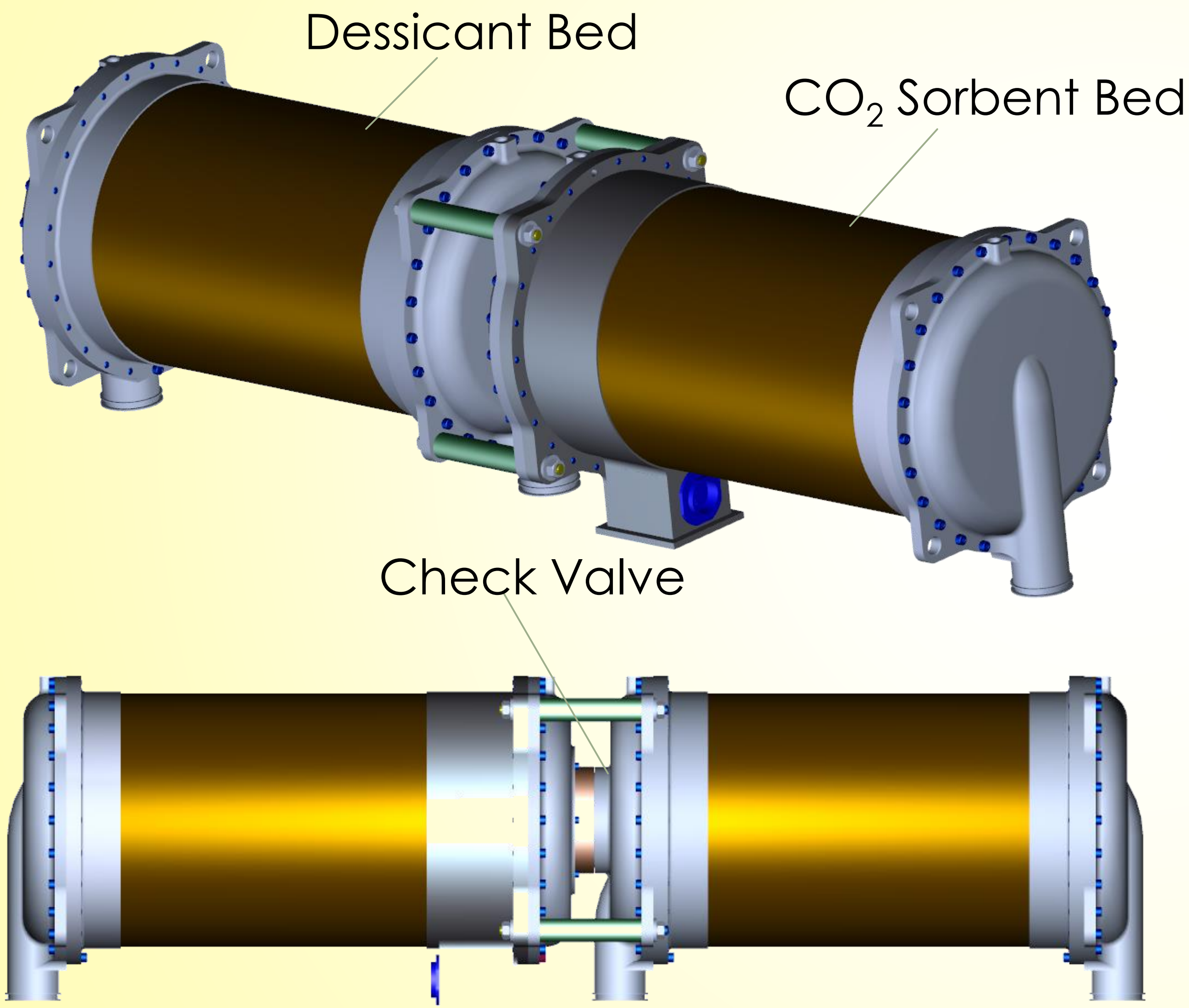
4BMS-X Process Technology





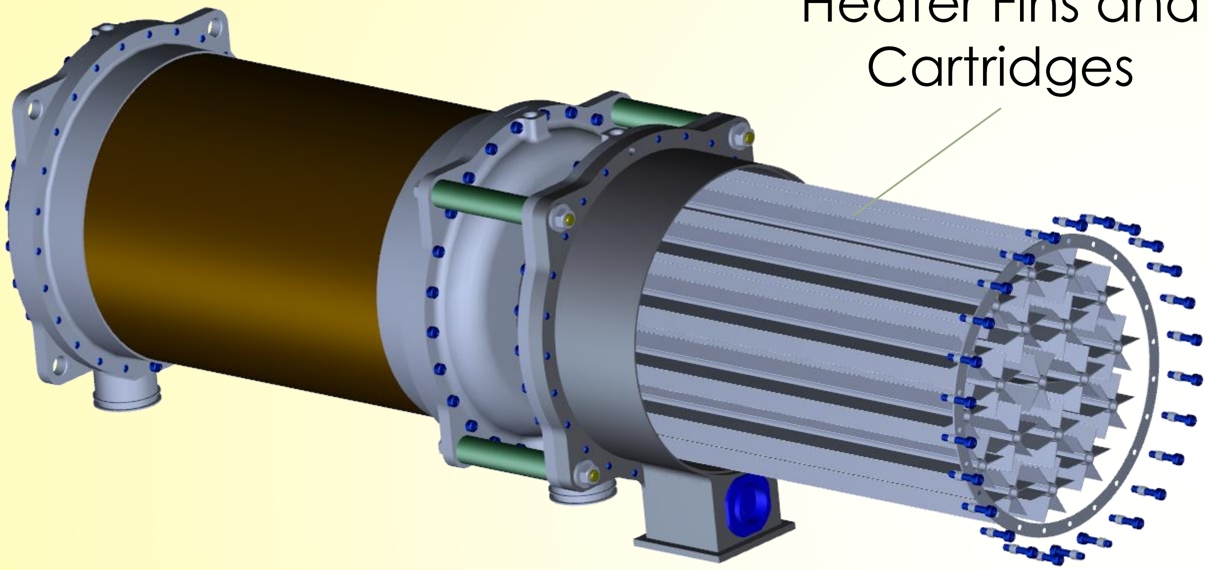
- The 4BMS-X contains two pelletized adsorbent beds to remove CO_2 respired by the crew. Each CO2 adsorbent bed is paired with an upstream desiccant bed to condition the inlet air (i.e. remove water vapor) prior to entry into the adsorbent bed.
- While one adsorbent bed is actively capturing CO_2 at near ambient pressure, the other is regenerated through applied heat and partial vacuum desorption.

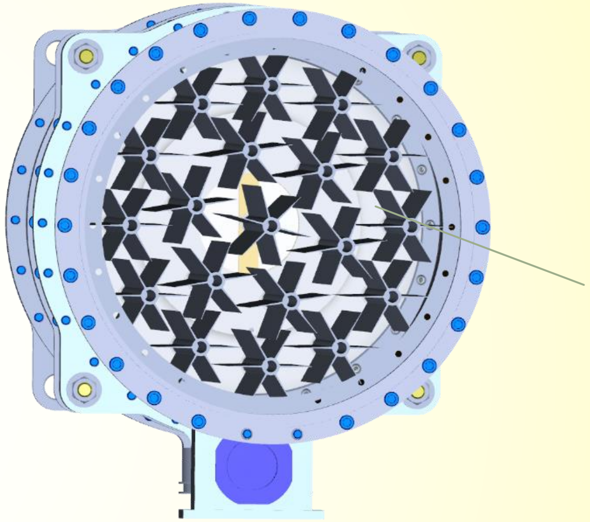
4BMS-X Conceptual Design



- The 4BMS-X beds are cylindrically shaped following industrial practice for fixed beds to insure the sorbents are fully compacted and to minimize heat transfer to the surroundings.
- Each cylindrical housing is constructed from Aluminum 6061 and is comprised of two end caps, mating flanges and a barrel section to contain the sorbent material.
- The two cylindrical beds are mated together through a common flow path containing a check valve between the beds.
- Each bed is insulated with a ¾ inch layer of Pyropel LD6 thermal insulation.
- The inside diameter and length of the CO2 sorbent bed are 8" and 12" respectively.

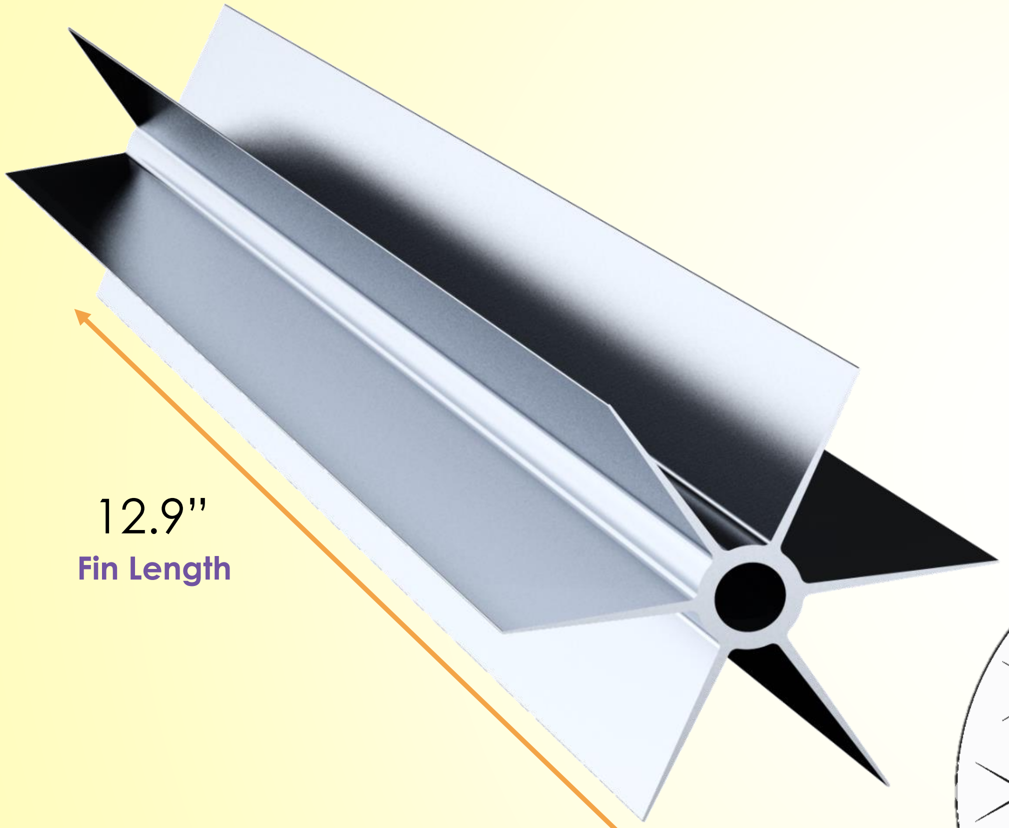
4BMS-X Conceptual Design utilizing Star Shaped Heater Fins

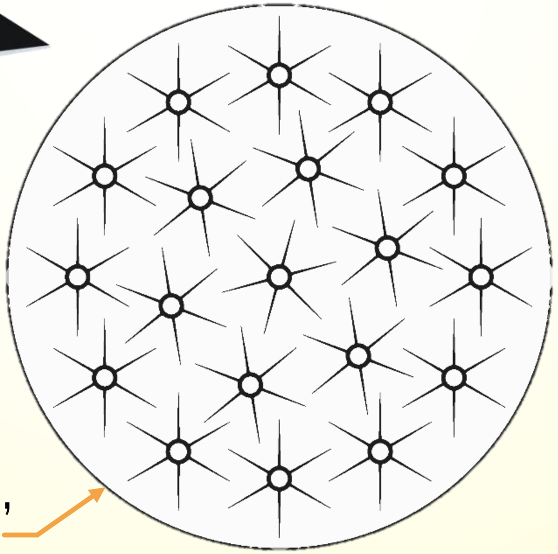


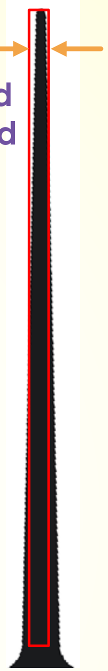


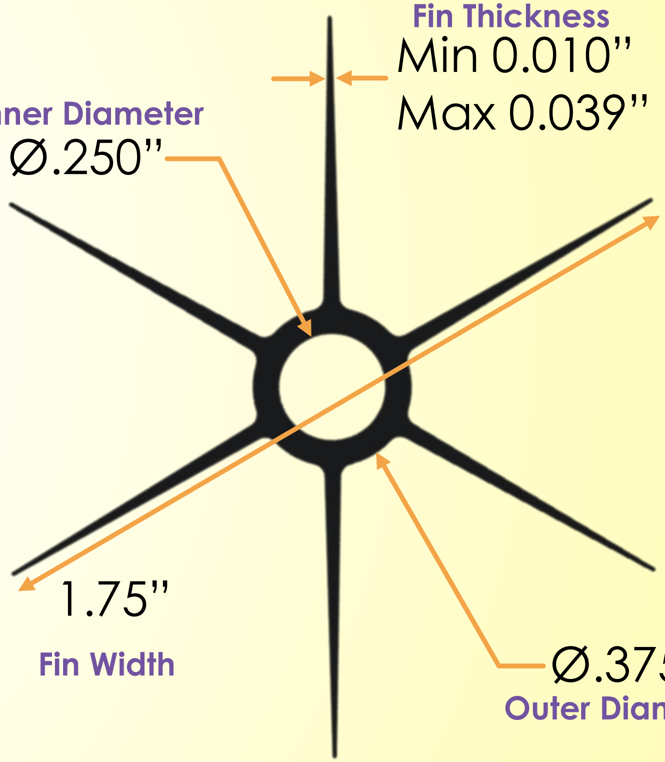
- The CO_2 sorbent bed container is removed to expose the heater core and associated fins. Each fin assembly has a 0.25" penetration in the base to accommodate a cartridge heater (not shown).
- Each fin assembly with embedded cartridge heater is mounted (cantilever) into an end plate inside one of the sorbent bed end caps.

4BMS-X Heater Fin Design

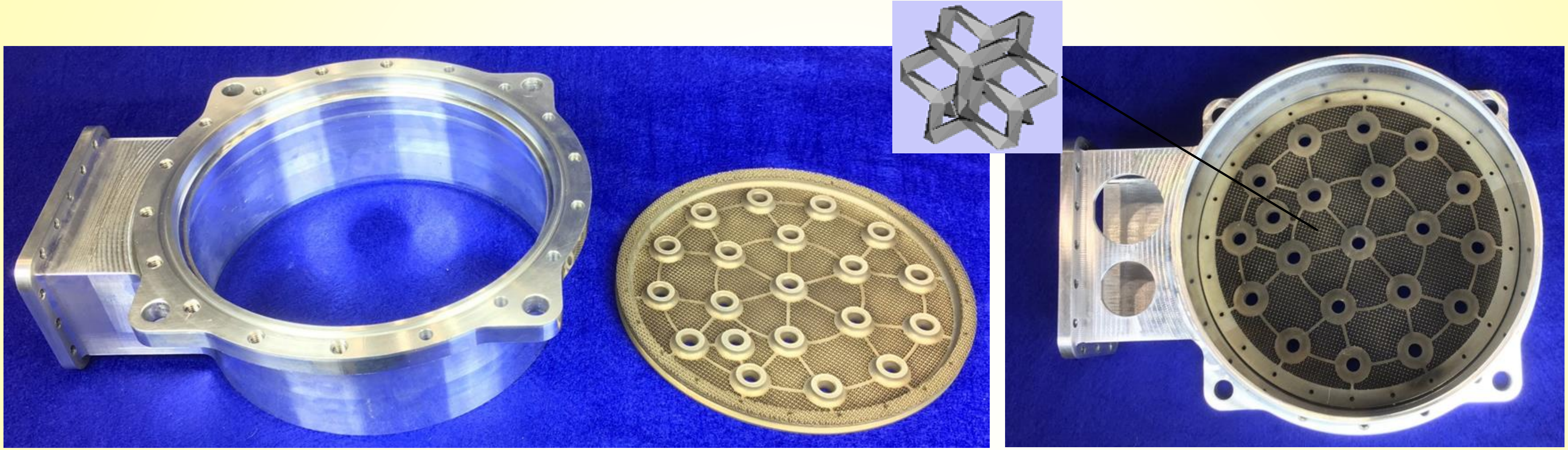






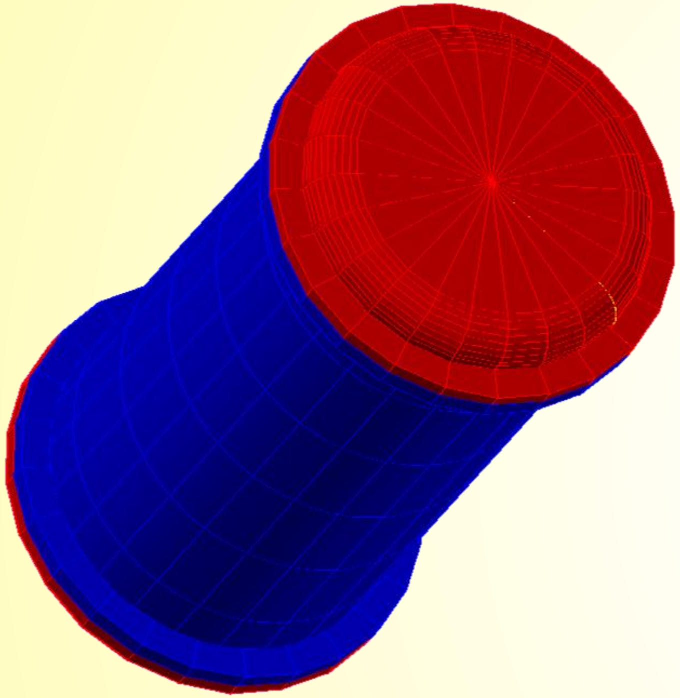


4BMS-X Heater End Plate

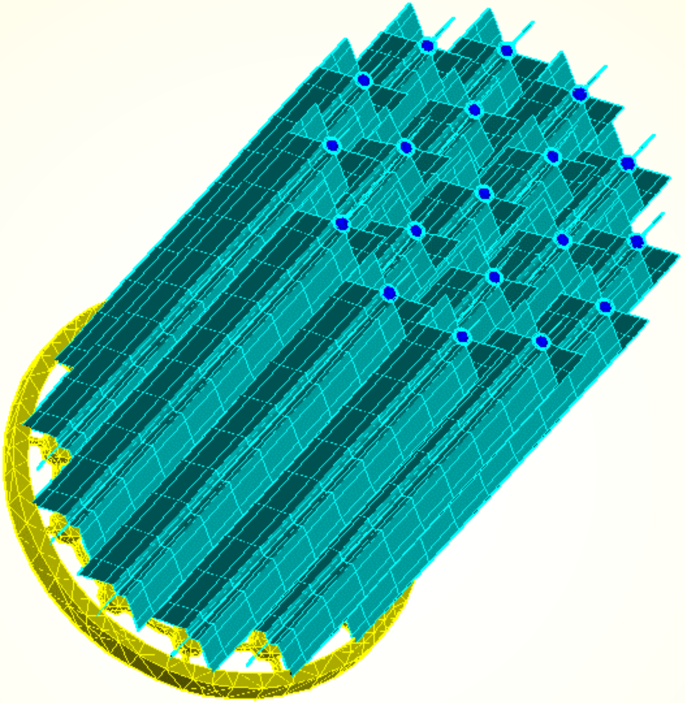


- The end plate is produced through an additive manufacturing process with a lattice filled spacing between cartridge heater mounting holes.
- The lattice provides structural strength while minimizing thermal conductivity (due to the void space inside the lattice).
- The end plate mounts on a flange inside one of the 4BMS-X sorbent bed end caps as shown.

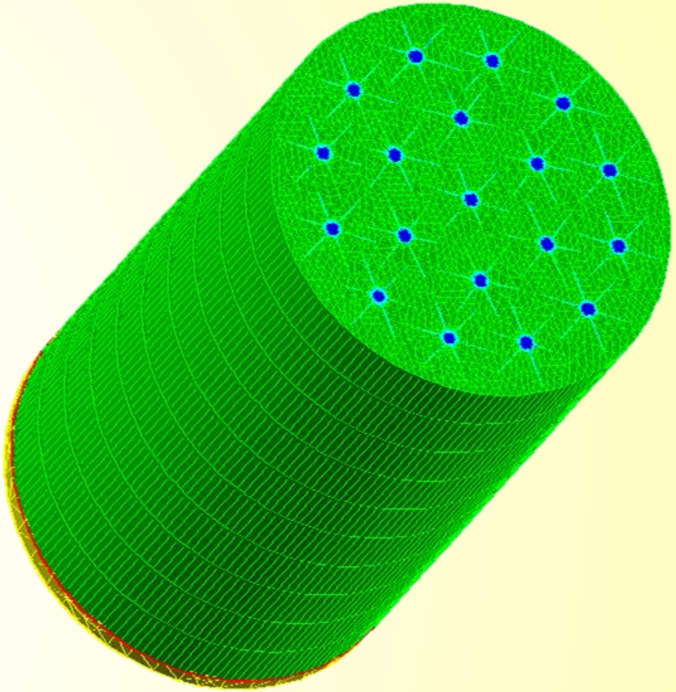
4BMS-X Sorbent Bed Thermal Model



External Container



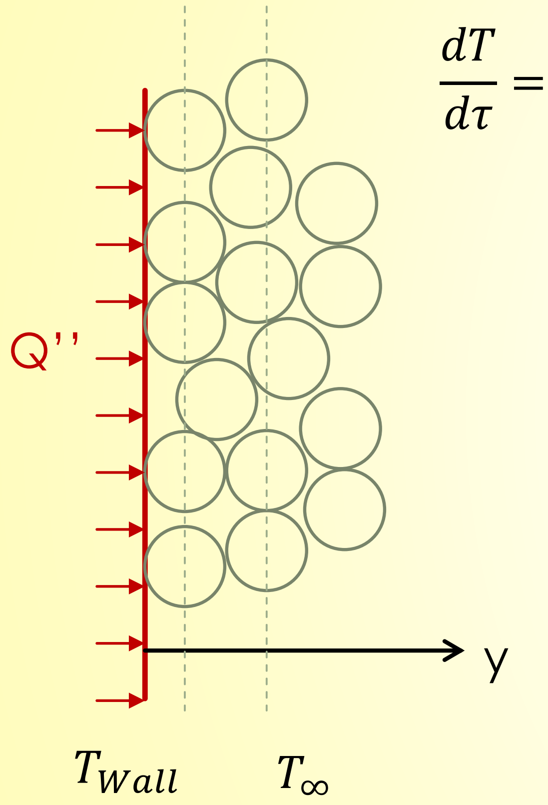
Heater Core and Mounting Plate



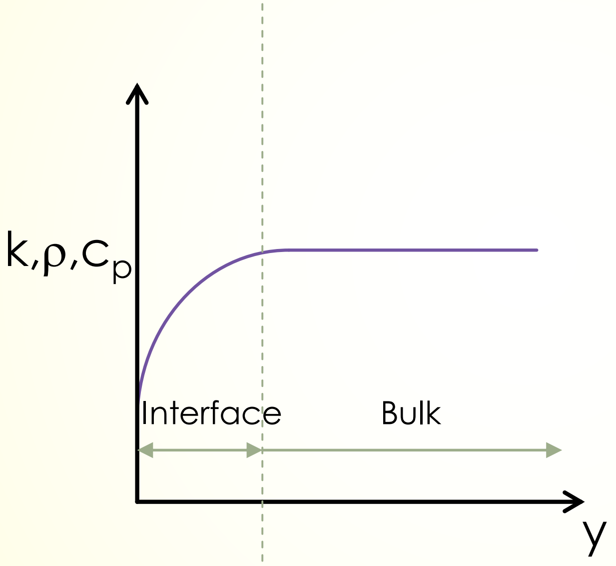
With Sorbent Material

- The Thermal Desktop© 4BMS-X 3D thermal model contains over 50,000 nodes with execution times on the order of 5 minutes for a 60 minute transient simulation.
- The sorbent volume (green) is discretized into finite element wedges and fits inside the external container model with a thermal contact coupling between the sorbent and container. Likewise, the heater assembly fits within the sorbent model with a contact coupling between the fins and the sorbent.

2D/3D Packed Bed Modeling Approach



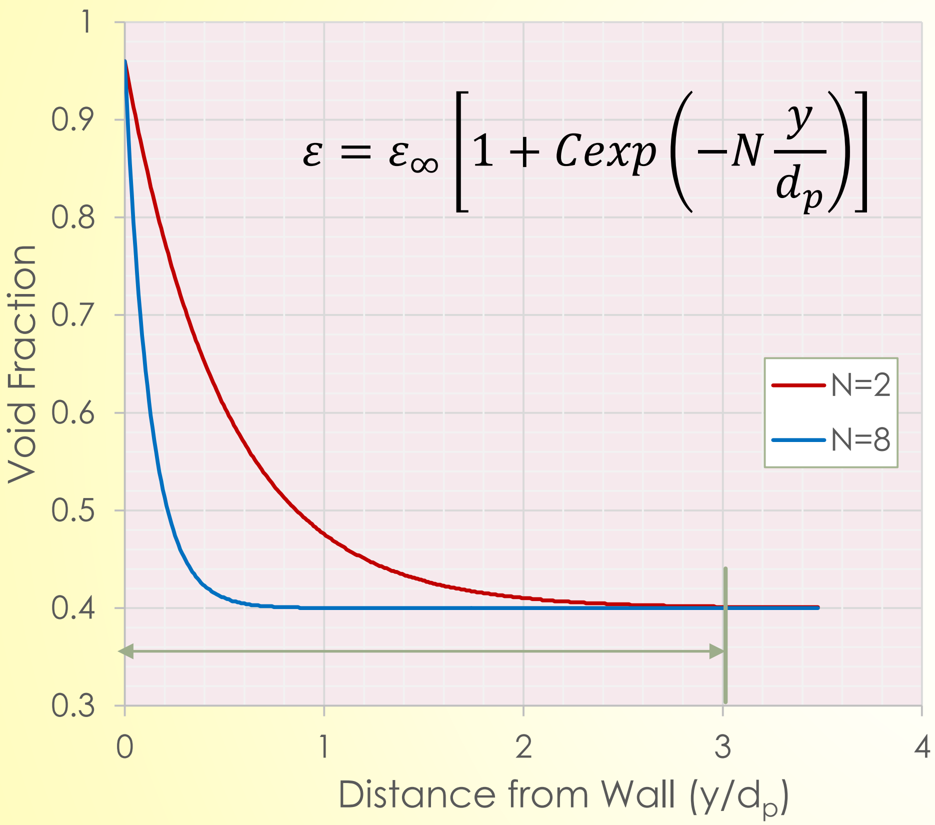
$$\frac{dT}{d\tau} = \alpha \nabla^2 T \quad \text{where} \quad \alpha = \frac{k}{\rho c_p}$$



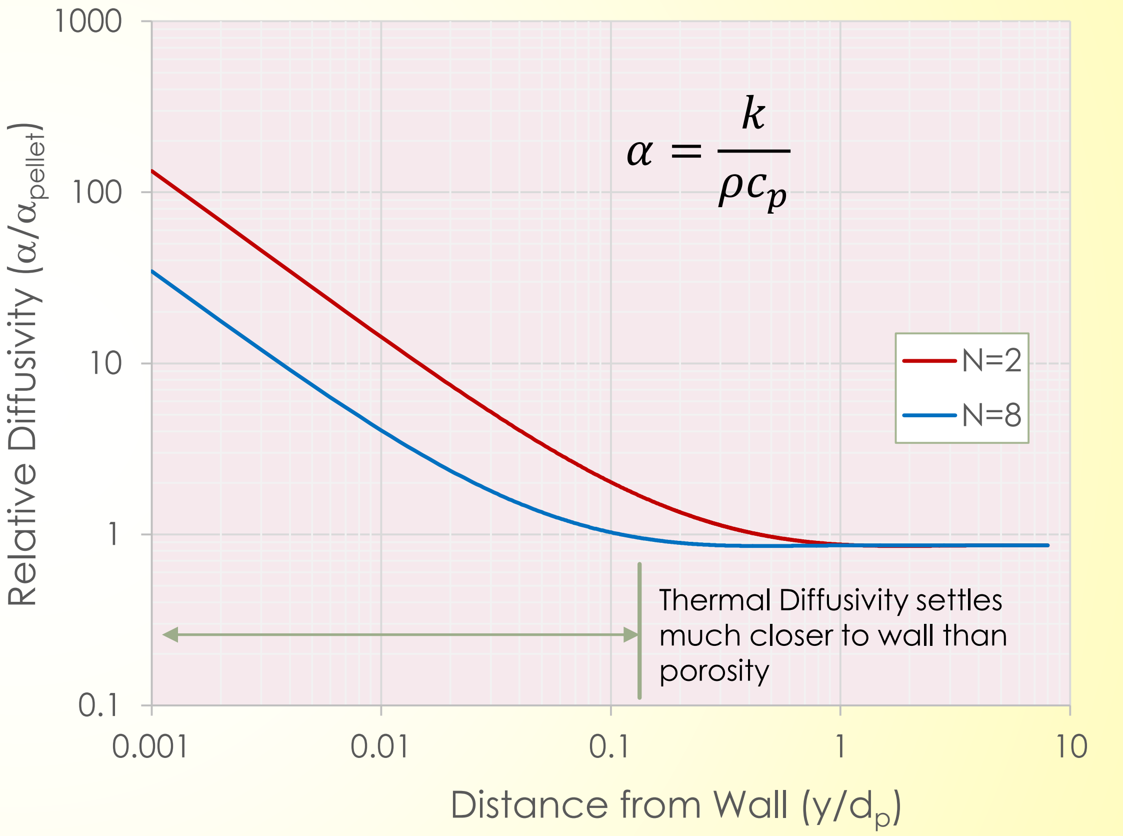
- During vacuum/thermal desorption of CO2 sorbent beds, the transient thermal response is dependent on the thermal diffusivity of the bed.
  - Radiation more significant with increasing temperature.
- A modeling approach is proposed where a thin interface region (of high diffusivity) near the wall is modeled as a thermal resistance with bulk properties used deeper in the bed.
- Thin interface region doesn't participate in energy storage (thermal diffusivity gas >> solid) but the thermal coupling is modeled via boundary condition or thermal contact.
- Thermal mass of any heater mounting structure also very significant.

Porosity Assumptions at Packed Bed Wall

Void Fraction versus Relative Distance from Wall



Thermal Diffusivity versus Relative Distance from Wall



*Nield and Bejan, 1992; N=2,…8

Thermal Interface Coupling

$$Q'' = -k\frac{dT}{dx}$$

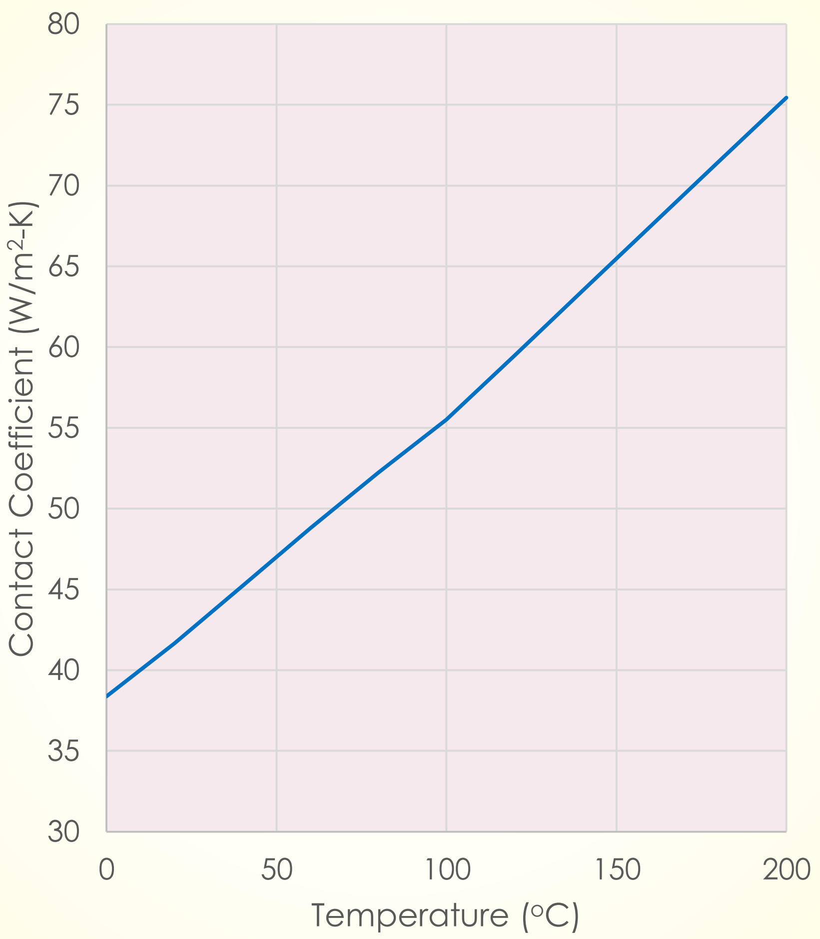
$$Q''\frac{dx}{k} = -dT$$

$$Q''\int_0^L \frac{dx}{k} = -\int_{T_{Wall}}^{T_\infty} dT$$

$$Q''\int_0^L \frac{dx}{k} = (T_{Wall} - T_\infty)$$

$$Q'' = \left(\int_0^L \frac{dx}{k}\right)^{-1} (T_{Wall} - T_\infty)$$

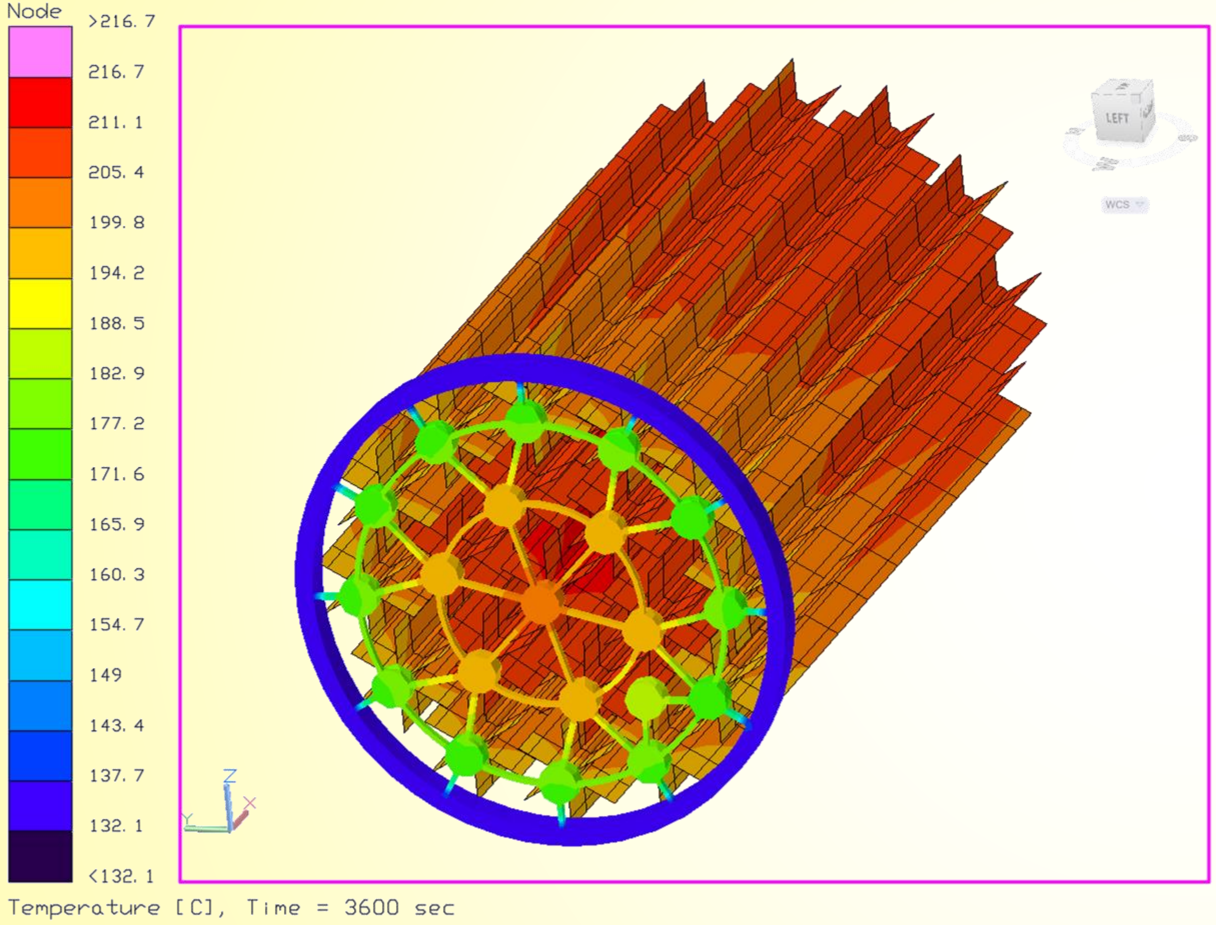
$$Q'' = h(T_{Wall} - T_\infty)$$



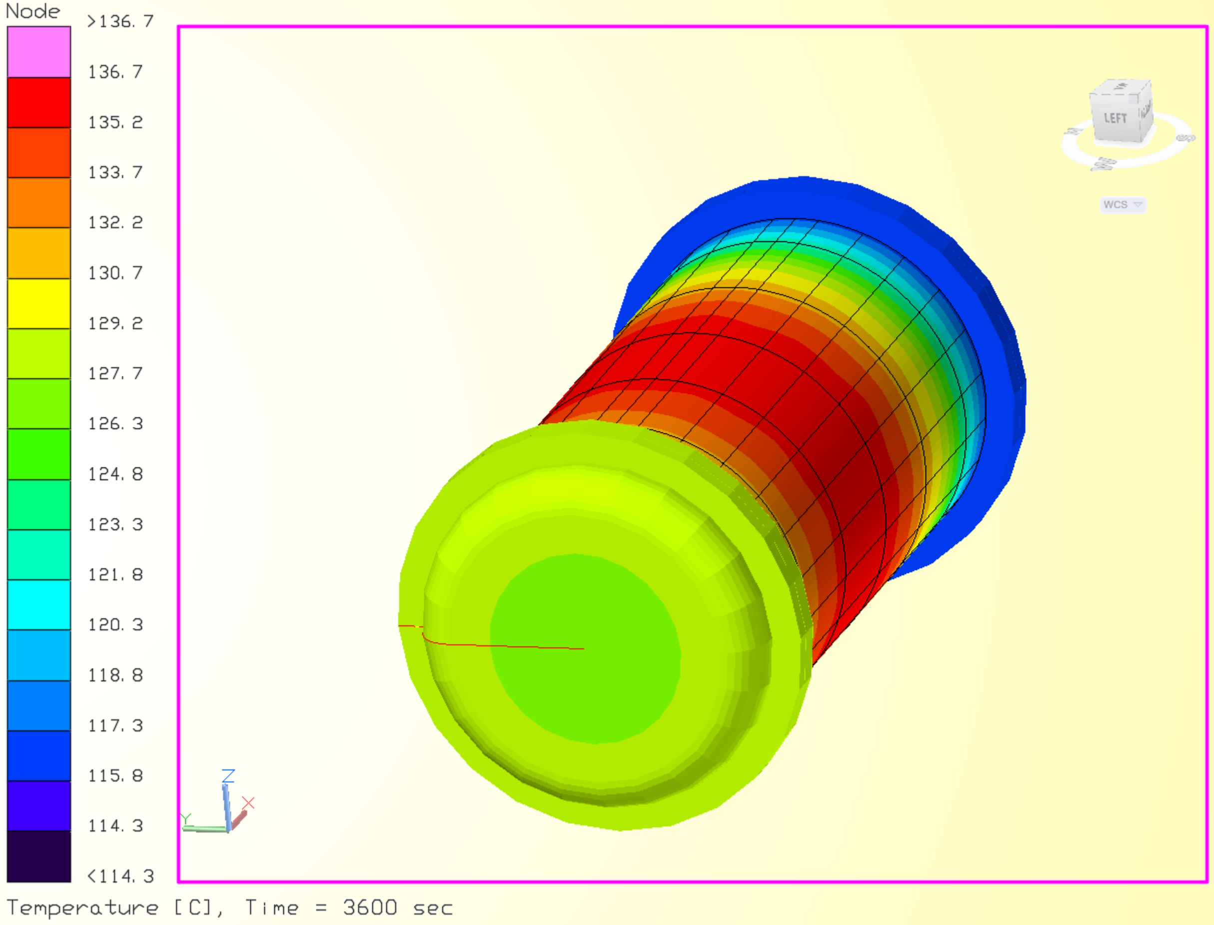
$$h = \left(\int_0^L \frac{dx}{k}\right)^{-1} \qquad k_{eff} = L\left(\int_0^L \frac{dx}{k}\right)^{-1}$$

- Fourier 1D heat conduction equation is integrated to determine equivalent "h" that is dependent upon depth of the interface layer.
- Coupling is shown versus depth of the interface layer.

4BMS-X Predicted Temperature Profile

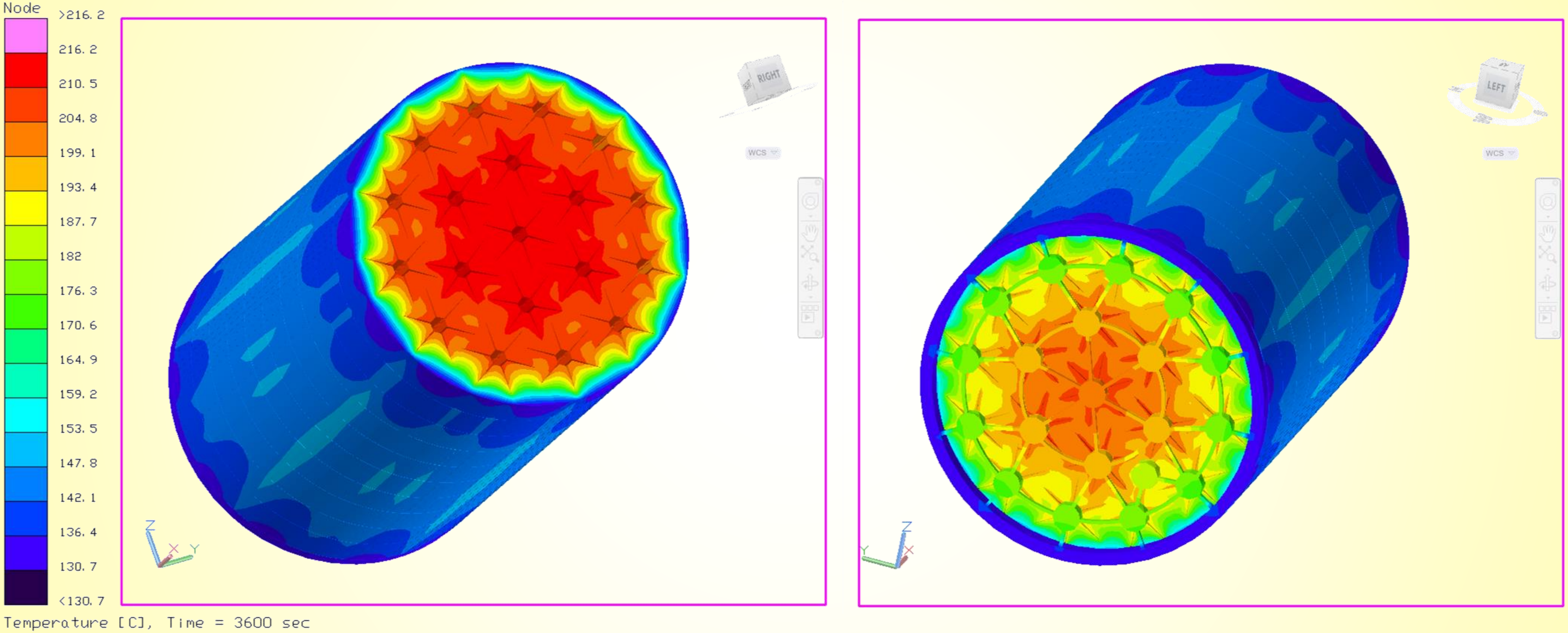


Inside- Heater Core and Mounting Plate

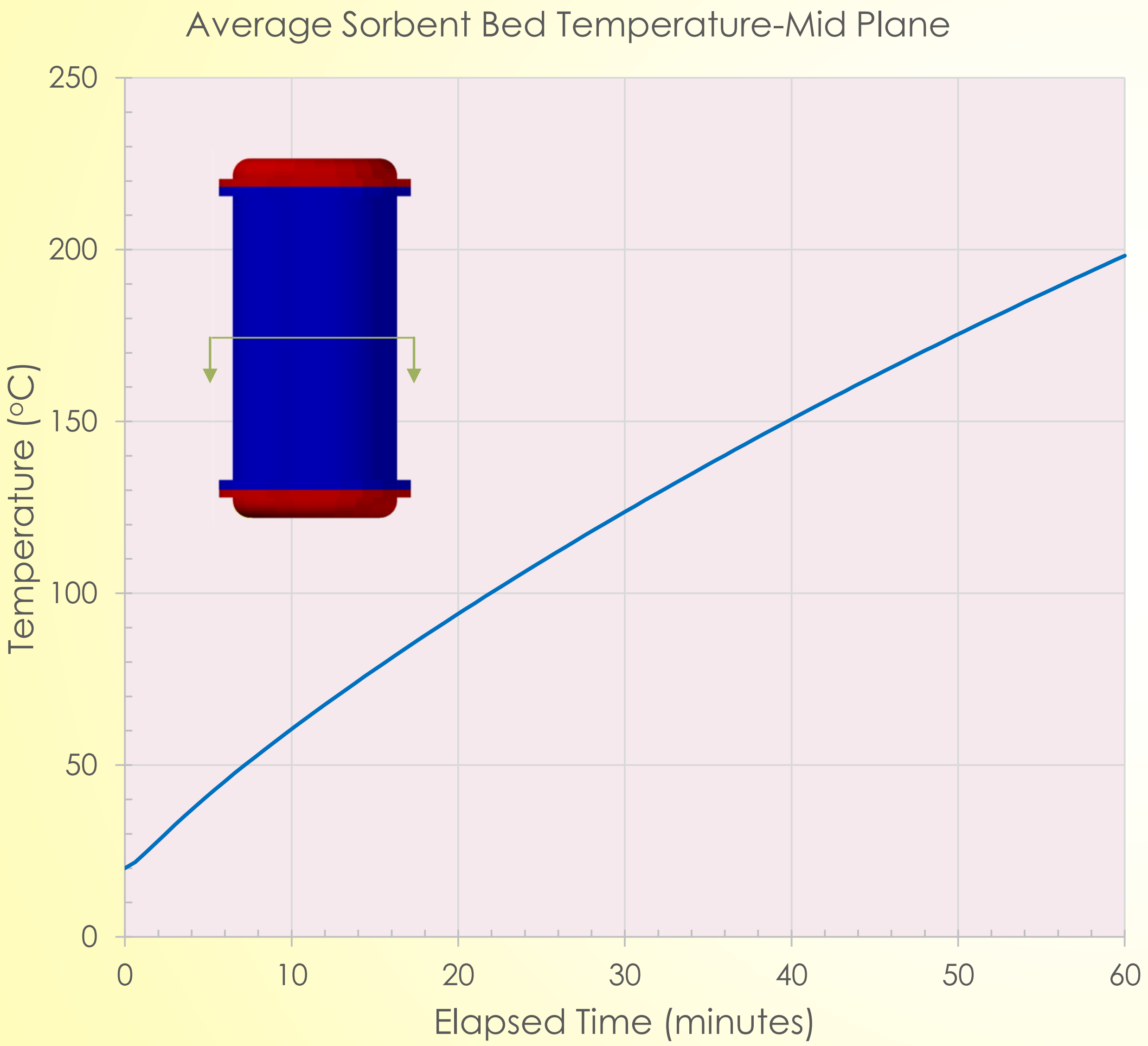


Outside- Container

Sorbent Bed Temperature Profiles

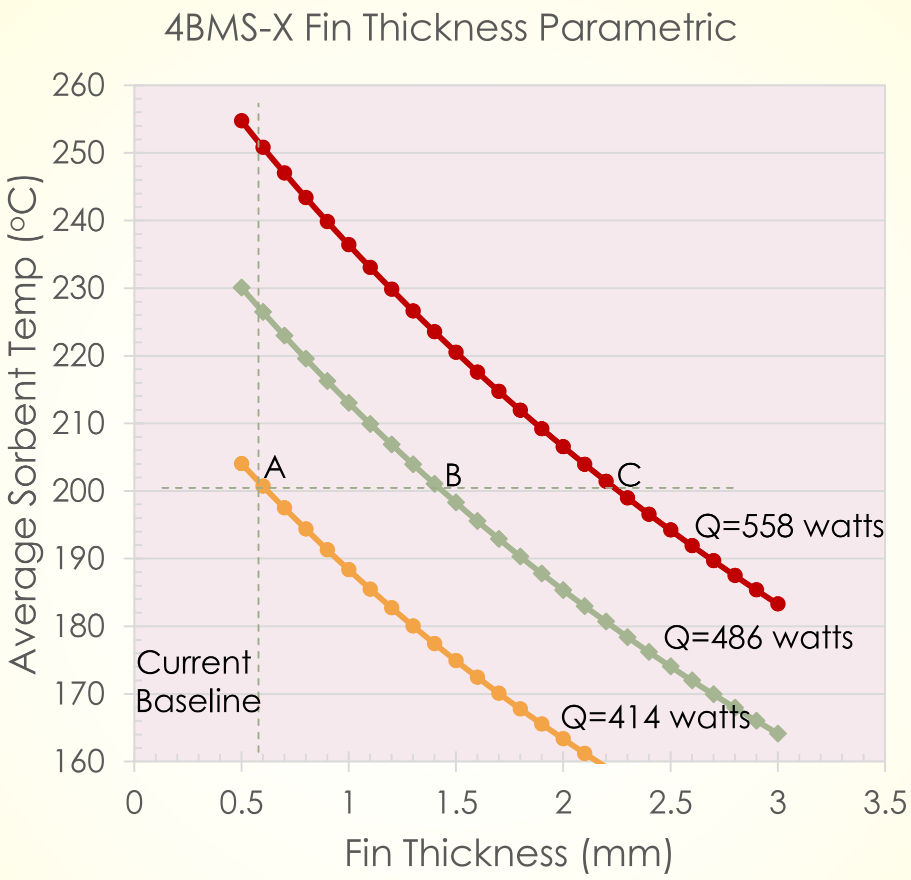


4BMS-X Sorbent Bed Transient Profile



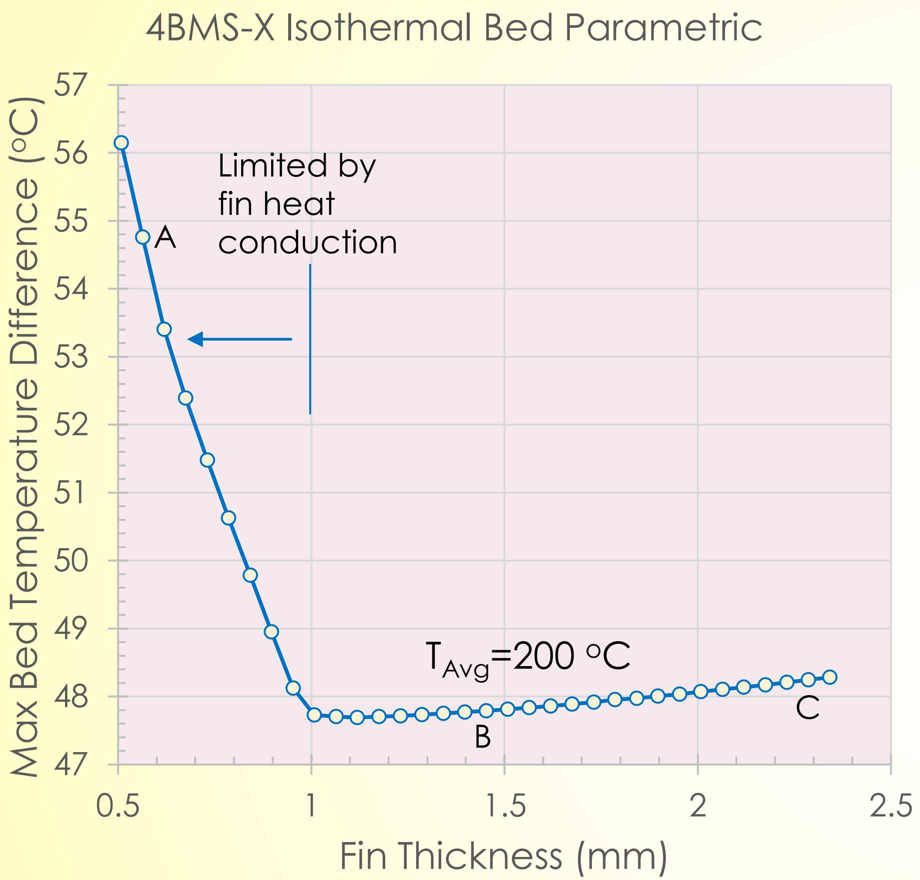
- The predicted transient profile for the cross section of a 4BMS-X sorbent bed is shown.
- The average temperature of the cross section reaches a target value of 200°C in 60 minutes.

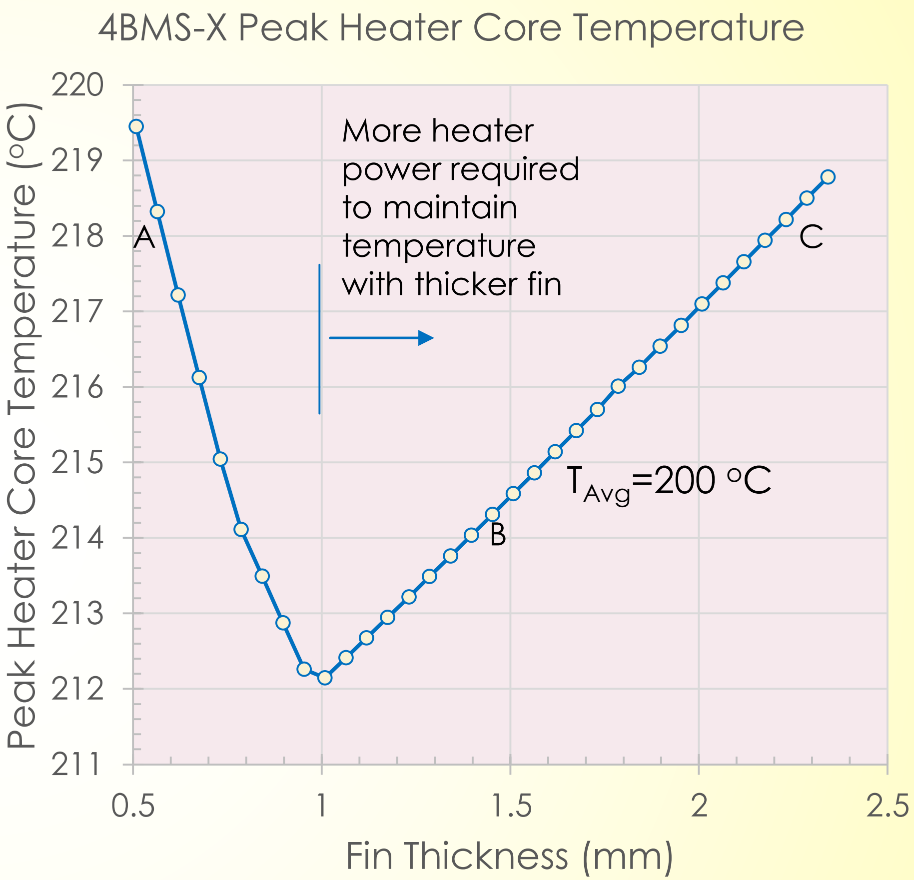
Parametric Results: Average Bed Temperature vs Fin Thickness



- Transient results at 60 minutes. Current (average) fin thickness is 0.02445 inches (or 0.62 mm).
- Increasing fin thickness lowers the average sorbent temperature at constant heater power due to better heat distribution and increased thermal mass of the fin.

Parametric Results: Average Bed Temperature vs Fin Thickness





- Heater sized to achieve target bed temperature (i.e. heater dissipation increases with fin thickness).
- Limited by fin heat conduction below the inflection point. Increased thermal mass of the fin above the inflection point requires more heater power to maintain temperature.

Summary and Future Plans

- A design and heater optimization study for 4BMS-X CO_2 sorbent beds in a proposed exploration system architecture has been completed.
- An analytical approach to predict the contact conductance between sorbent materials and solid surfaces based on empirical void fractions was developed.
- Two dimensional models of the baseline concept with roughly equidistant cartridge heaters/fins show thermal gradients confined mostly to the edges of the circular container with a roughly isothermal center section.
- Parametric studies with the two dimensional models show an optimum fin thickness with respect to gradient and heater power. Future designs may benefit from this optimization.
- Three dimensional thermal models of the baseline concept identified axial thermal gradients caused by heat loss through a conductive heater mounting plate.
- Additive manufacturing of the end plate to produce custom geometries may be used to further reduce the thermal gradient.
- Thermal model correlation to test data will be the highest priority for future work.

Acknowledgements

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