



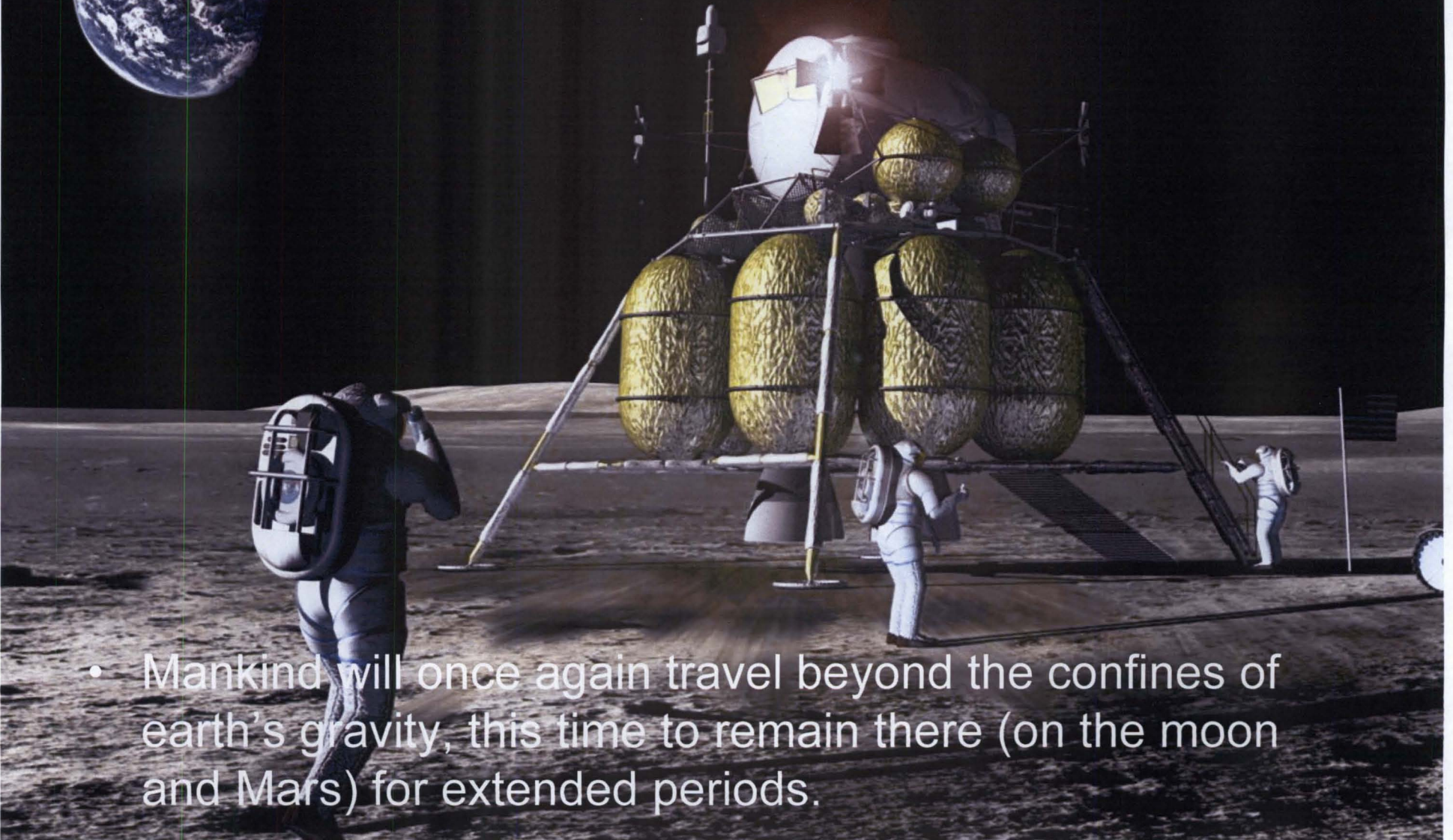
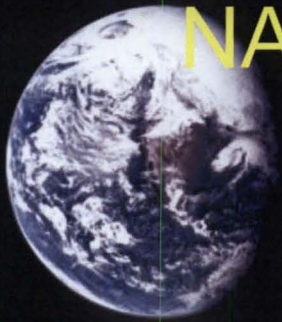
COMSOL Conference 2007

New Methods for the Adsorption of Carbon Dioxide and Water Vapor from Manned Spacecraft Atmospheres: Applications and Modeling



Jim Knox and David Howard
NASA Marshall Space Flight Center

NASA's Vision for Space Exploration



- Mankind will once again travel beyond the confines of earth's gravity, this time to remain there (on the moon and Mars) for extended periods.

NASA's Vision for Space Exploration

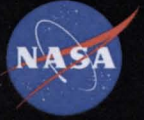


- These missions will place unprecedented demands on launch systems.
- We must not only blast out of earth's gravity well as during the Apollo moon missions, but also launch the supplies needed to sustain a larger crew over much longer periods.

NASA's Vision for Space Exploration

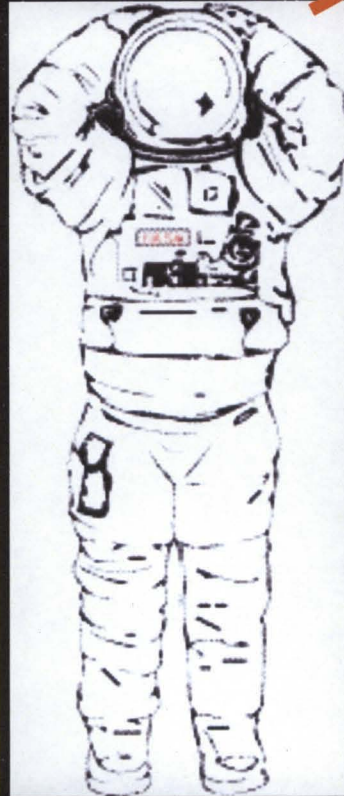
- All spacecraft systems must be minimized with respect to mass, power, and volume.
- Emphasis is also placed on system robustness to minimize replacement parts and ensure crew safety where a quick return to earth is not possible.

Human Metabolic Requirements for Life Support



Needs

- Oxygen = 0.84 kg (1.84 lb)
- Food Solids = 0.62 kg (1.36 lb)
- Water in Food = 1.15 kg (2.54 lb)
- Food Prep Water = 0.76 kg (1.67 lb)
- Drink = 1.62 kg (3.56 lb)
- Metabolized Water = 0.35 kg (0.76 lb)
- Hand/Face Wash Water = 4.09 kg (9.00 lb)
- Shower Water = 2.73 kg (6.00 lb)
- Urinal Flush = 0.49 kg (1.09 lb)
- Clothes Wash Water = 12.50 kg (27.50 lb)
- Dish Wash Water = 5.45 kg (12.00 lb)
- Total = 30.60 kg (67.32 lb)



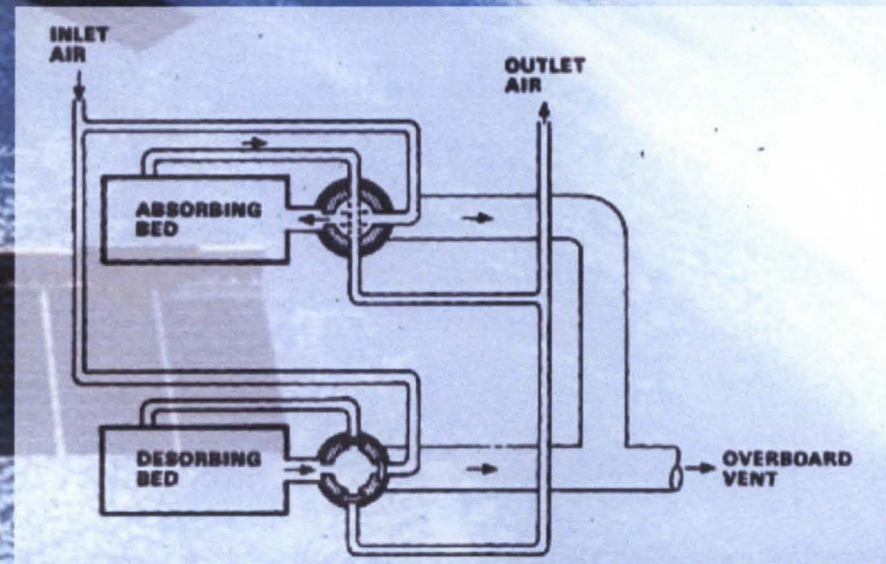
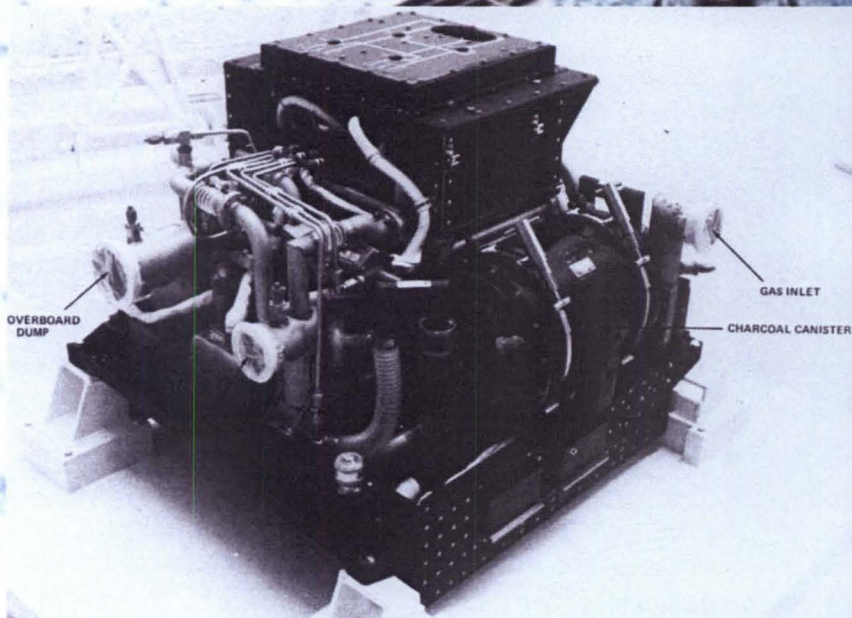
Effluents

- Carbon Dioxide = 1.00 kg (2.20 lb)
- Respiration & Perspiration Water = 2.28 kg (5.02 lb)
- Food Preparation, Latent Water = 0.036 kg (0.08 lb)
- Urine = 1.50 kg (3.31 lb)
- Urine Flush Water = 0.50 kg (1.09 lb)
- Feces Water = 0.091 kg (0.20 lb)
- Sweat Solids = 0.018 kg (0.04 lb)
- Urine Solids = 0.059 kg (0.13 lb)
- Feces Solids = 0.032 kg (0.07 lb)
- Hygiene Water = 12.58 kg (27.68 lb)
- Clothes Wash Water
Liquid = 11.90 kg (26.17 lb)
Latent = 0.60 kg (1.33 lb)
Total = 30.60 kg (67.32 lb)

Note: These values are based on an average metabolic rate of 136.7 W/person (11,200 BTU/person/day) and a respiration quotient of 0.87. The values will be higher when activity levels are greater and for larger than average people. The respiration quotient is the molar ratio of CO₂ generated to O₂ consumed.

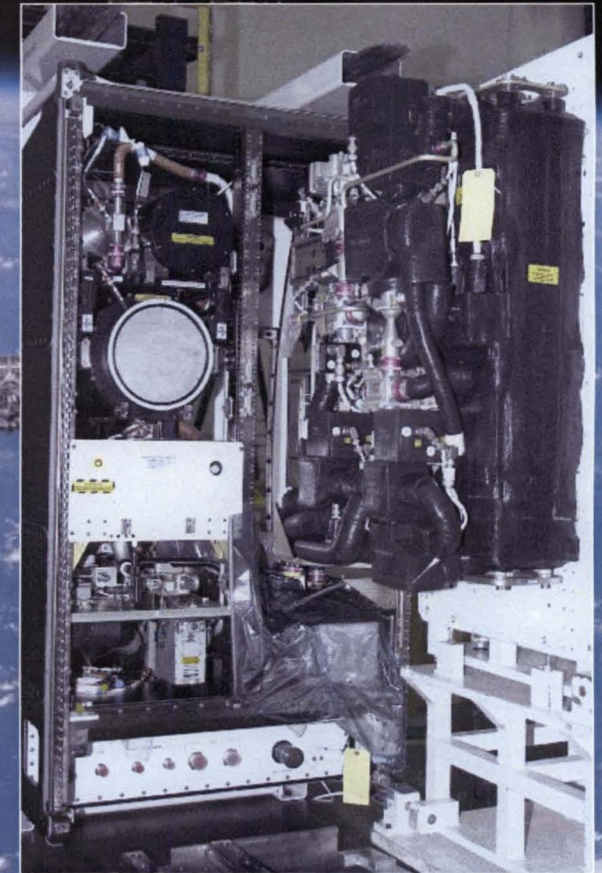
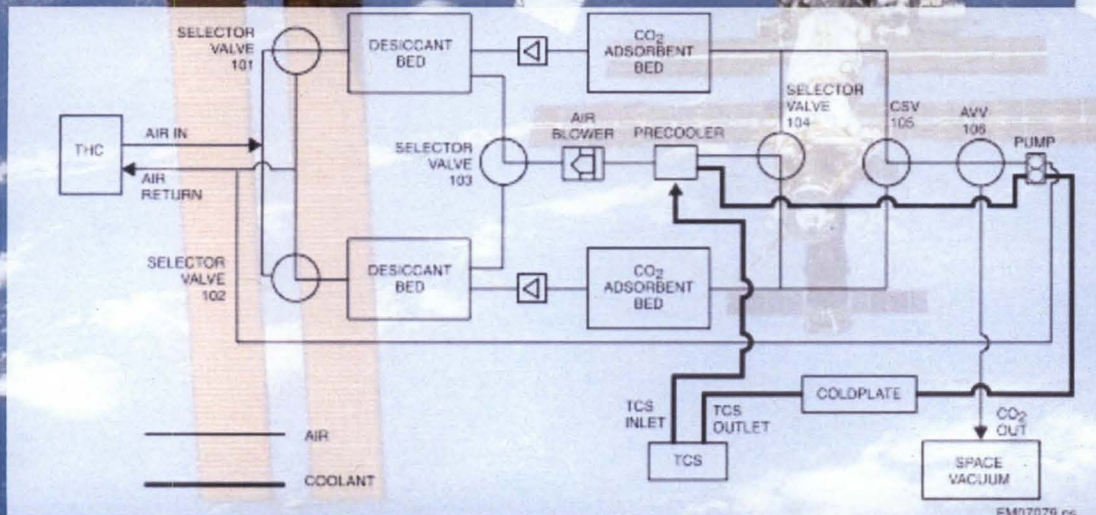
Historical Spacecraft Carbon Dioxide and Humidity Removal Systems

- Skylab was the United States first space station, with three manned missions totaling 171 days in the early 1970's.
- Molecular Sieves 13X and 5A were successfully used for CO₂ and H₂O removal on Skylab for 171 days without hardware anomaly.
- 70% of metabolic water and 100% of metabolic CO₂ for 3 crew was removed via a regenerable vacuum swing adsorption process.
- Three 2BMS units would provide sufficient removal for 6 non-exercising crew.

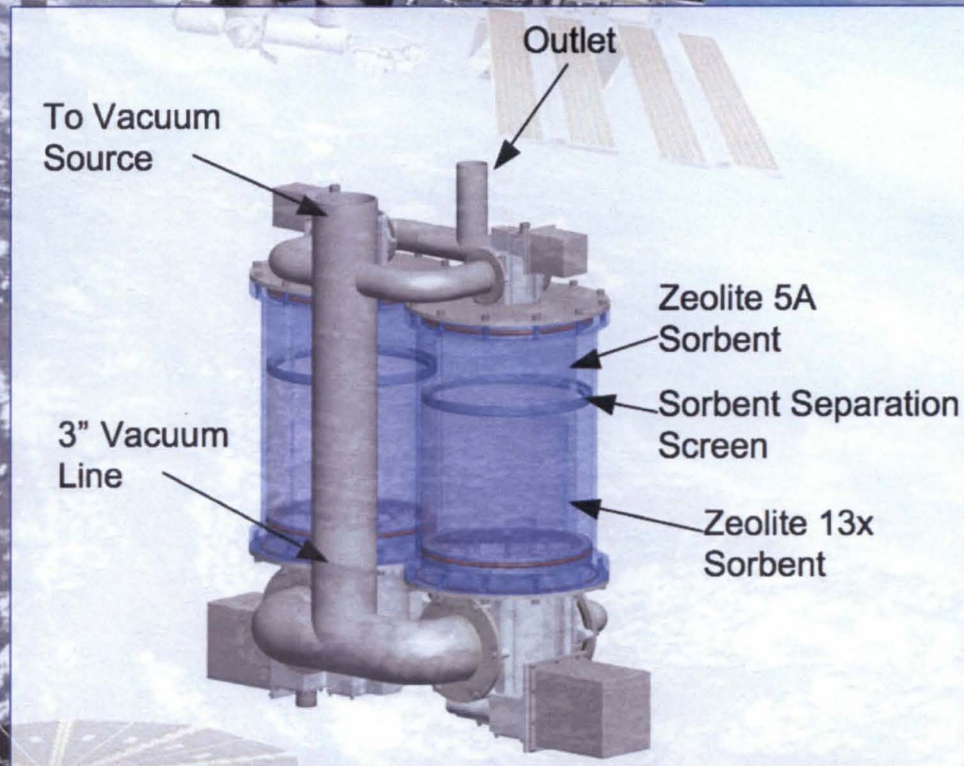
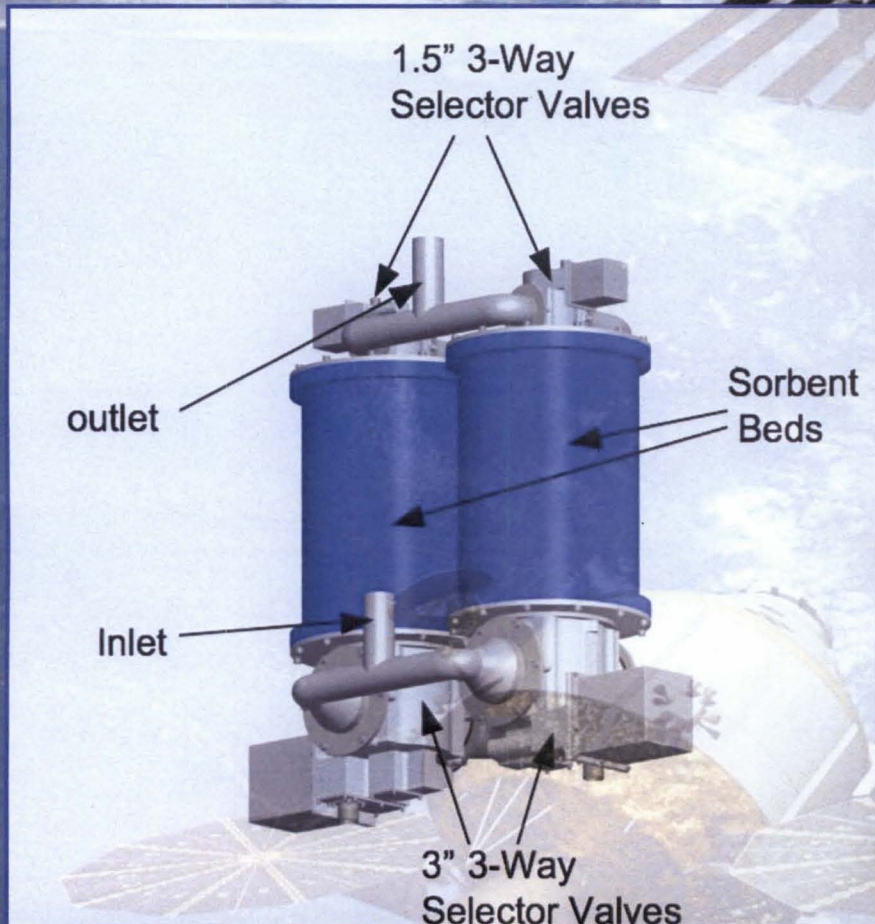


Current Spacecraft Carbon Dioxide and Humidity Removal Systems

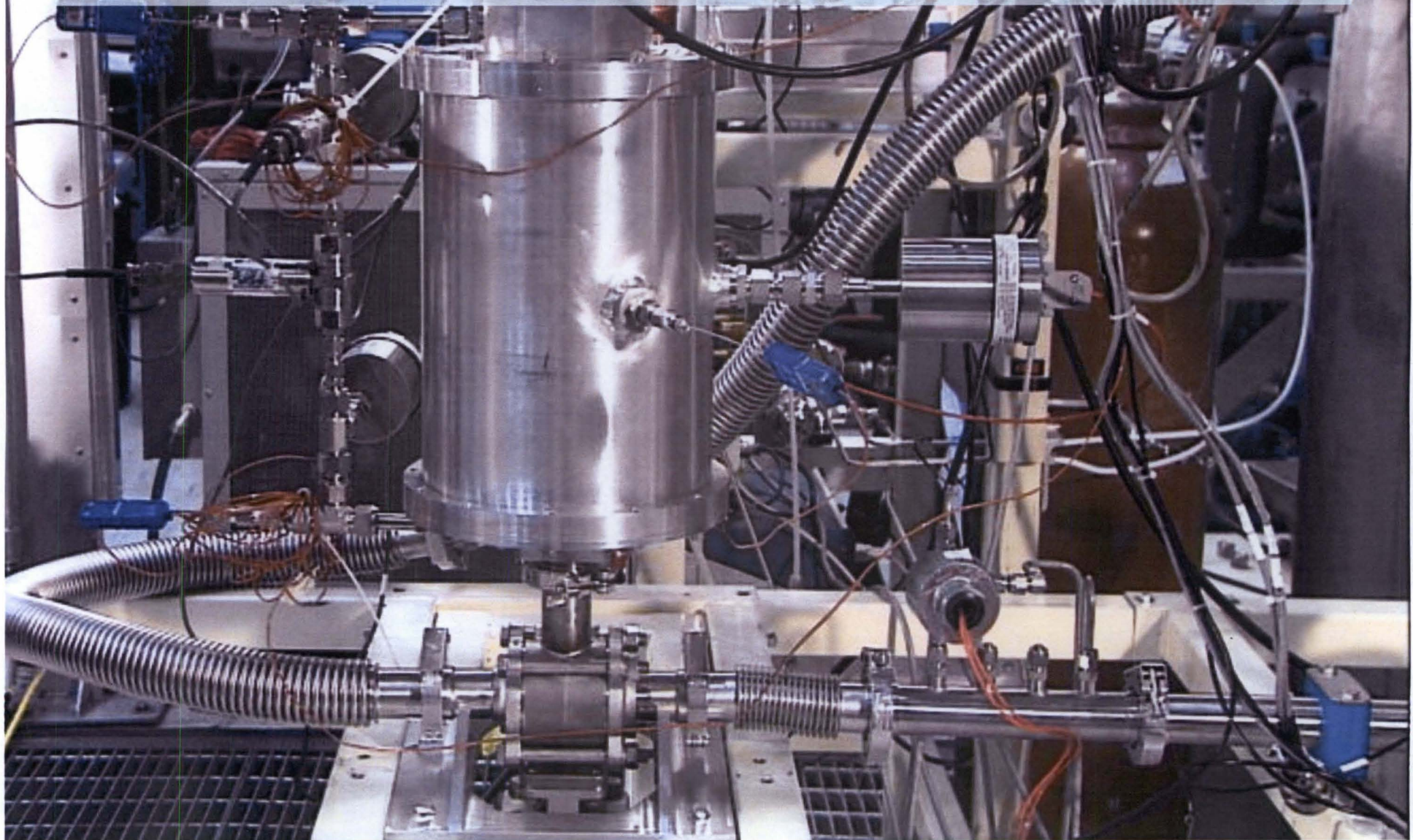
- The International Space Station uses a 4 Bed Molecular Sieve to remove CO₂ from the ISS.
- Anomalies due to a flaw in the containment design have highlighted the need for a more robust sorbent configuration.
- The 4BMS design returns water to the cabin and can either vent CO₂ or store it in an accumulator for subsequent reduction reaction and water recovery



Prototypic CO₂/H₂O Removal System for Orion Under Test at MSFC



Sorbent Based Atmosphere Revitalization - Assembled Hardware

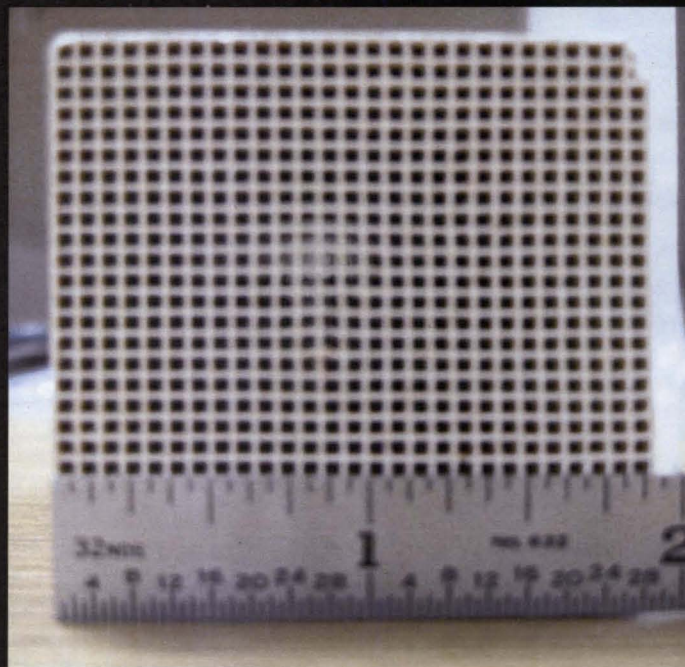
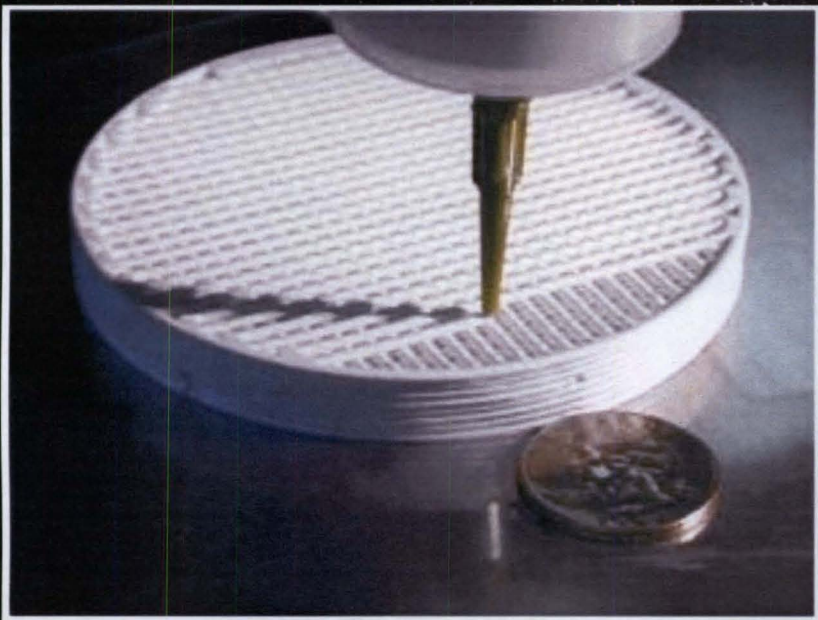




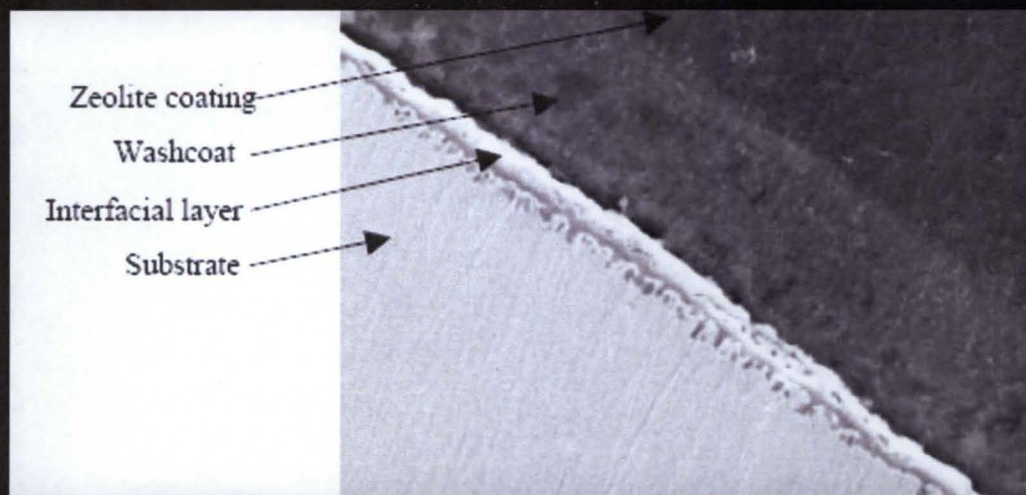
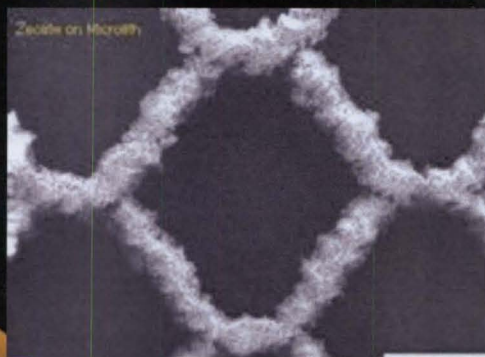
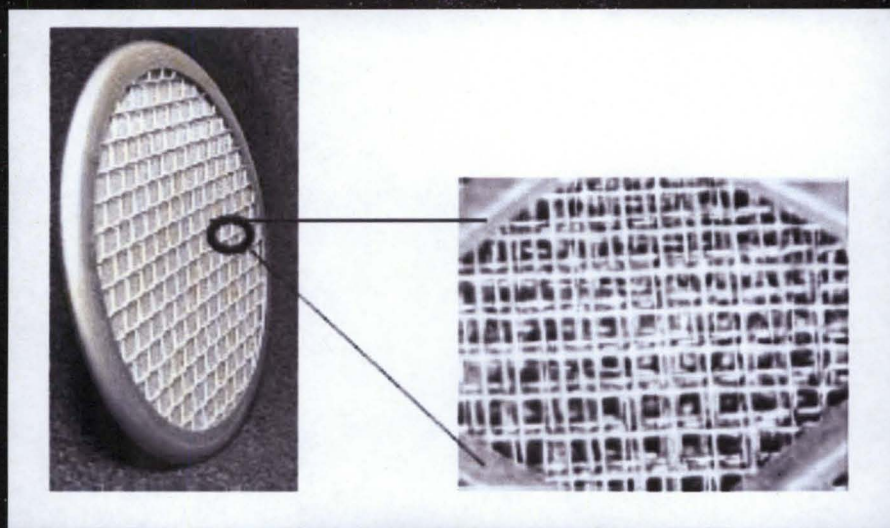
Lunar Lander, Lunar Outpost, and Engineered Structured Sorbents (ESS)

- Emerging engineered structured sorbent technologies will not be mature enough for use on Orion
- For follow-on programs, ESS has potential to increase the robustness of future life support systems
- Robustness is critical for long-term missions with no resupply, such as a mission to Mars
- ESS may also reduce resource requirements (power, weight, volume)

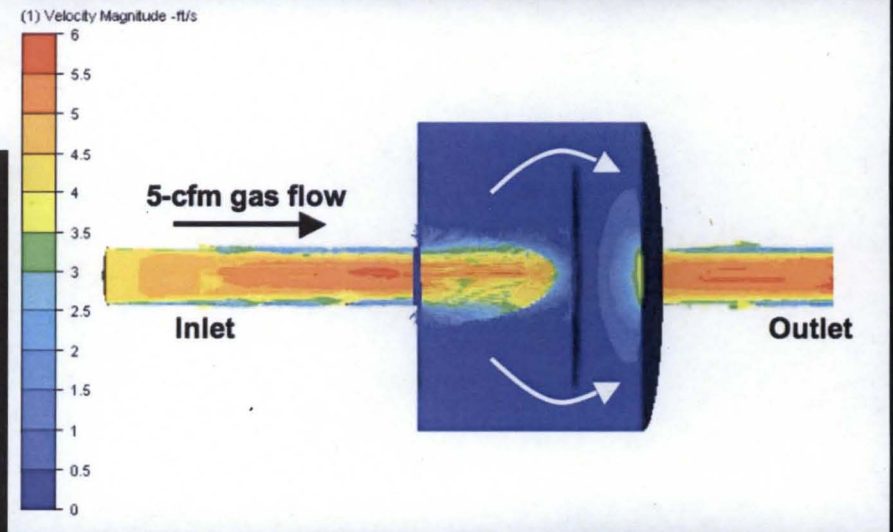
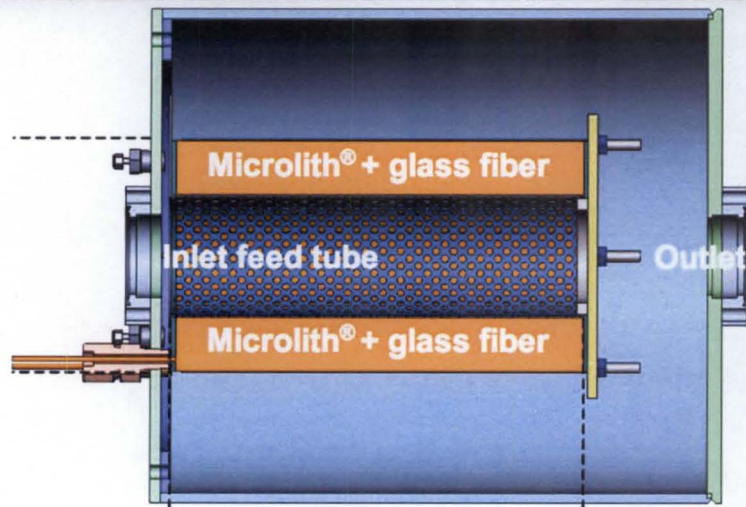
Monolithic Structured Sorbent Technologies



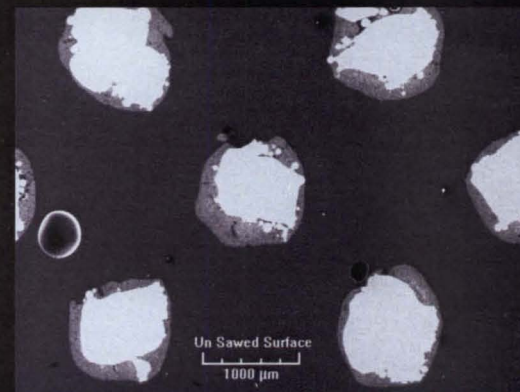
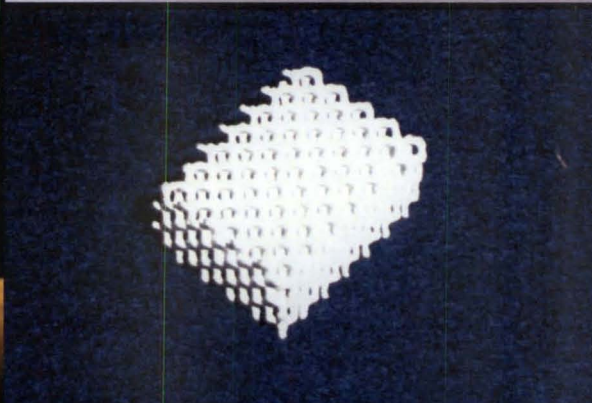
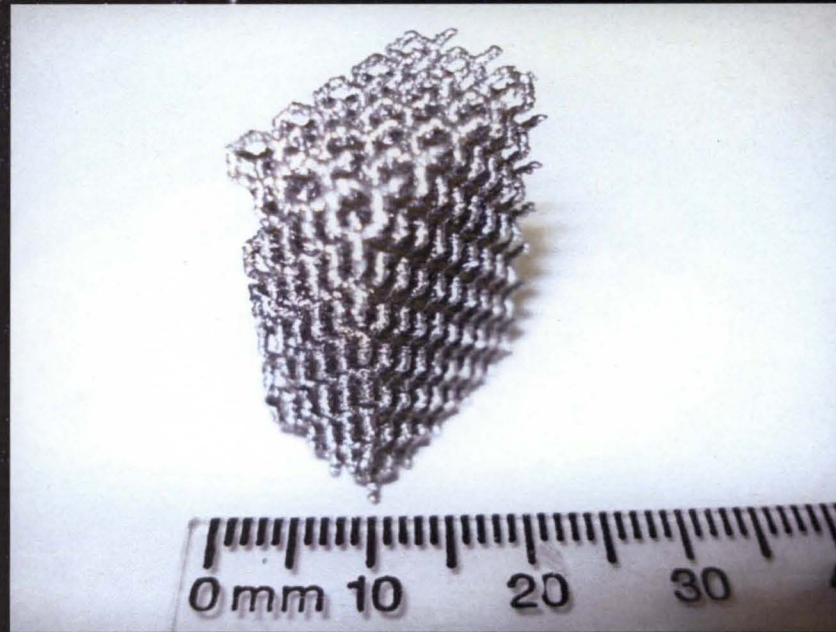
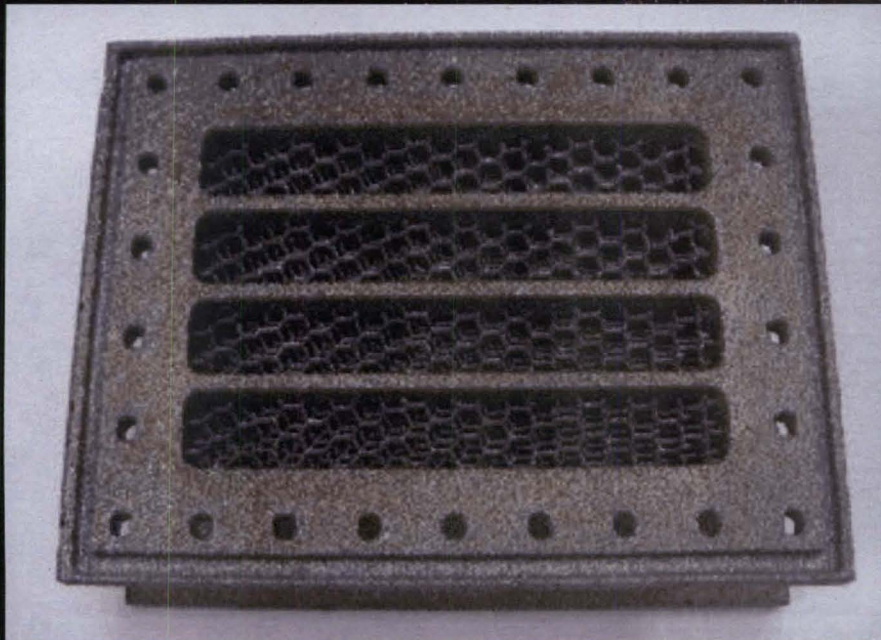
Precision Combustion Metal Microlith[®]



Precision Combustion Metallic Microlith[®]



Electron Beam Melting Metallic Structured Sorbent

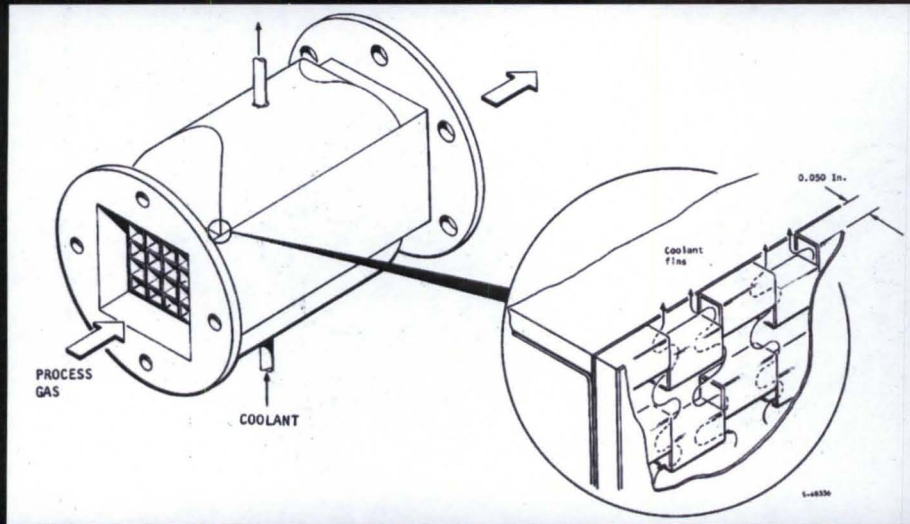




Determination of Regenerative Heating Efficiency Improvements via Simulation

- Metallic Structured Sorbents provide an efficient heat transport path
- Heat of adsorption is a negative influence on sorption removal processes
- Heating during adsorption reduces sorbent capacity - impedes adsorption
- Cooling during desorption increases sorbent capacity - impedes desorption
- Overall effect is a reduction in working capacity
- But, hardware costs (mass and volume) are associated with regenerative heating - *is it worth it?*
- To find out, build COMSOL models of packed bed adsorption process ...

Empirical Determination of LDF Coefficient via Simulation of Isothermal Testing



$$\frac{\partial C_i}{\partial t} = D_1 \frac{\partial^2 C_i}{\partial x^2} - \frac{\partial u C_i}{\partial x} - \frac{1 - \epsilon}{\epsilon} \frac{\partial \bar{q}_i}{\partial t}$$

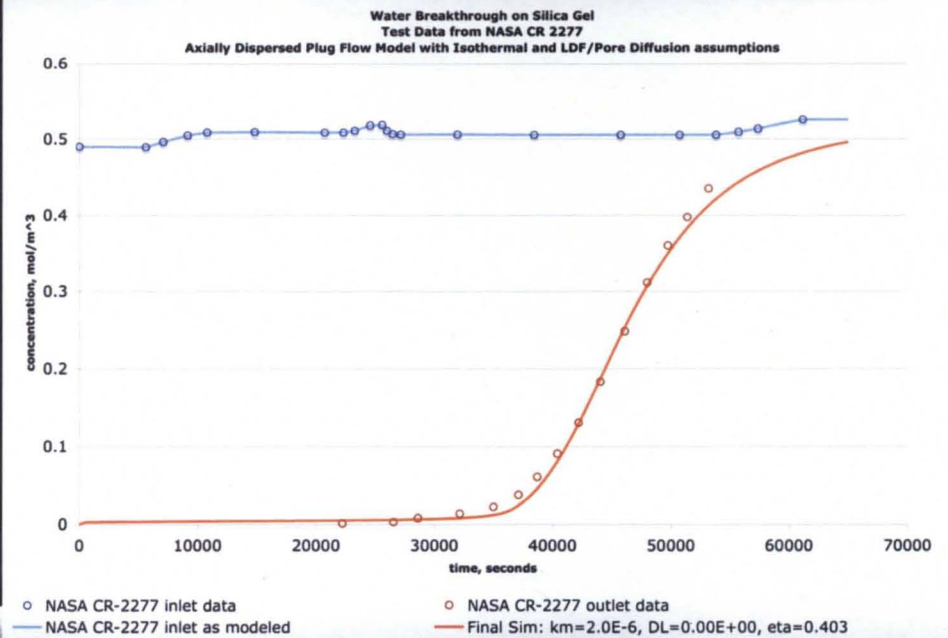
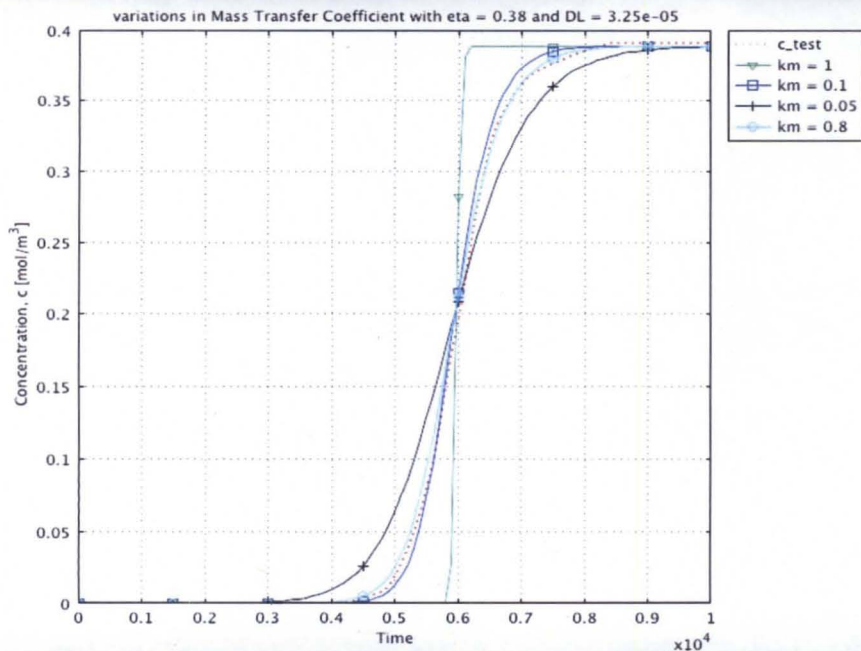
$$\text{at } t < 0, C_i = C_{i,0} \text{ for } 0 \leq x \leq L$$

$$\text{at } t < 0, \bar{q}_i = \bar{q}_{i,0} \text{ for } 0 \leq x \leq L$$

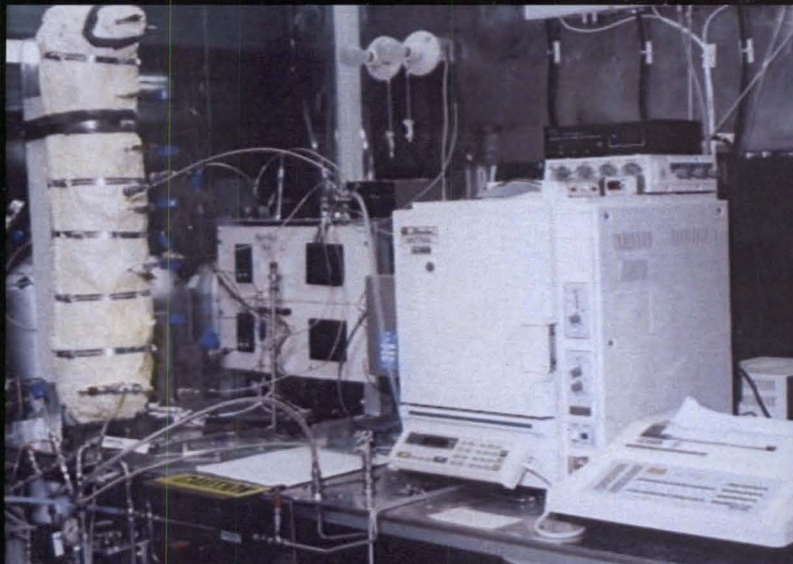
$$\text{at } t \geq 0, C_i = C_{i,0} \text{ for } x = 0$$

$$\text{at } t \geq 0, \partial C_i / \partial x = 0 \text{ for } x = L$$

$$\partial \bar{q}_i / \partial t = k_{ef} a_s (q_i^* - \bar{q}_i)$$



Empirical Determination of Heat Transfer Coefficient via Simulation of Thermal Characterization Testing



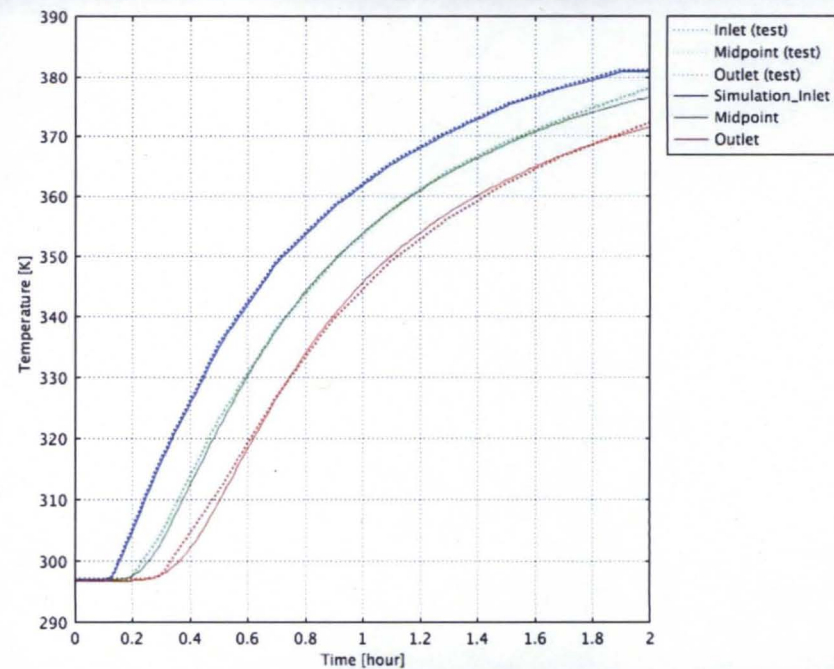
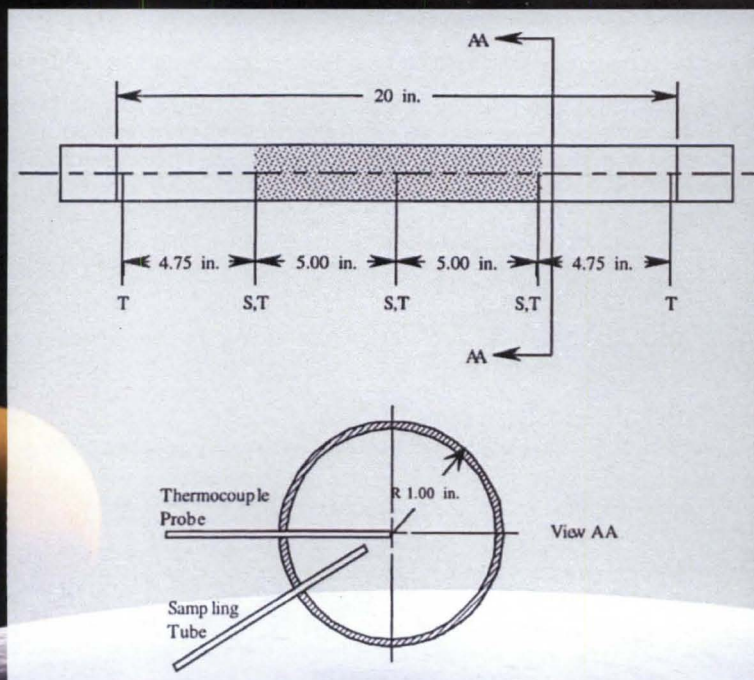
$$\rho_g c_{Pg} \frac{\partial T_g}{\partial t} = k_f \frac{\partial^2 T_g}{\partial x^2} - u \rho_g c_{Pg} \frac{\partial T_g}{\partial x} + \frac{1 - \epsilon}{\epsilon} h_s a_s (T_s - T_g) - \frac{4h_w}{\epsilon d} (T_g - T_w)$$

Boundary and initial conditions:

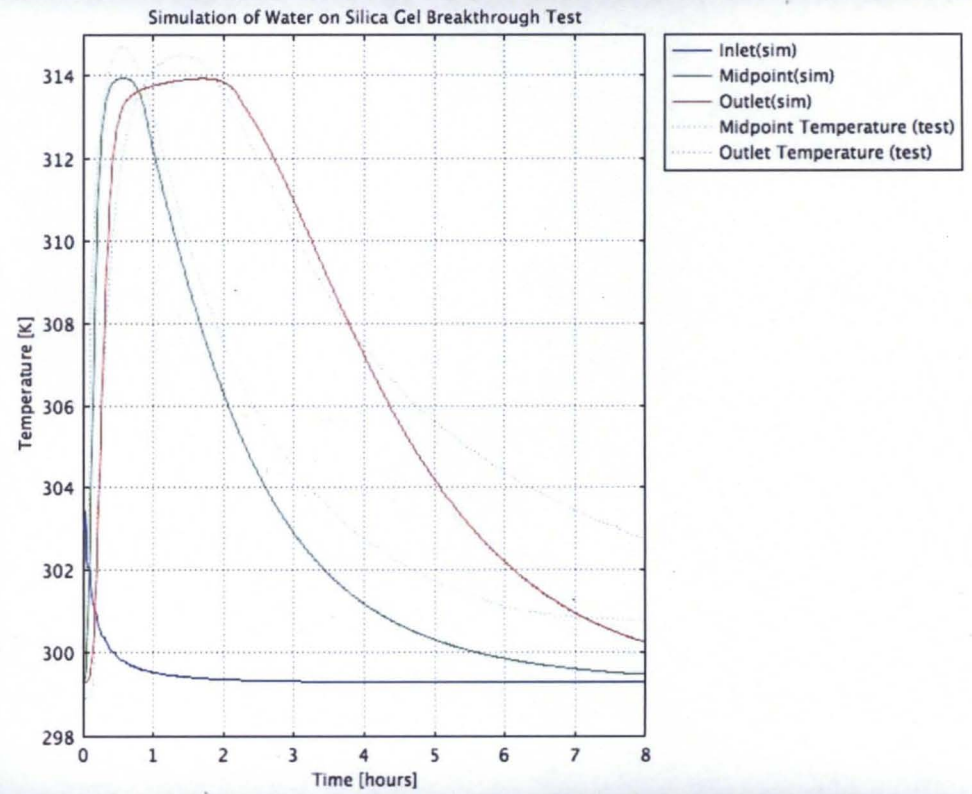
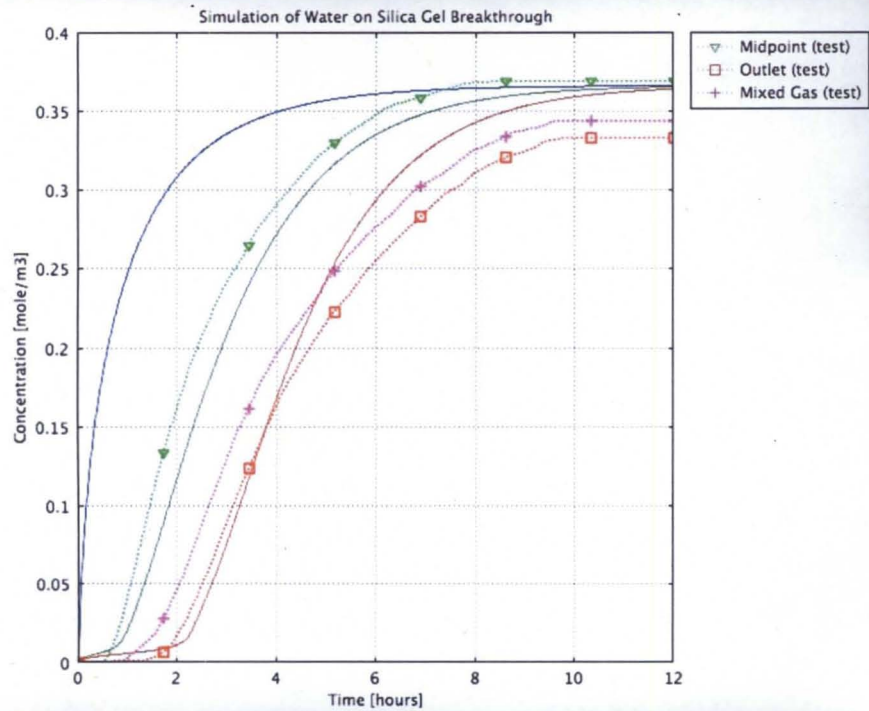
$$\text{at } t < 0, T_g = T_{g,0} \text{ for } 0 \leq x \leq L$$

$$\text{at } t \geq 0, T_g = T_i \text{ for } x = 0$$

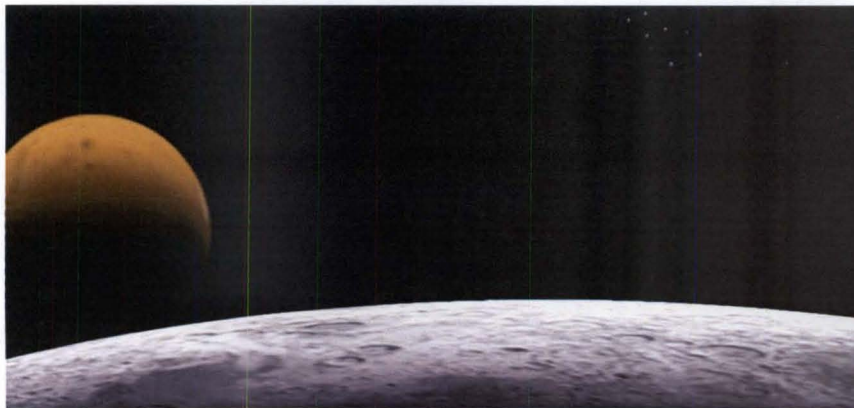
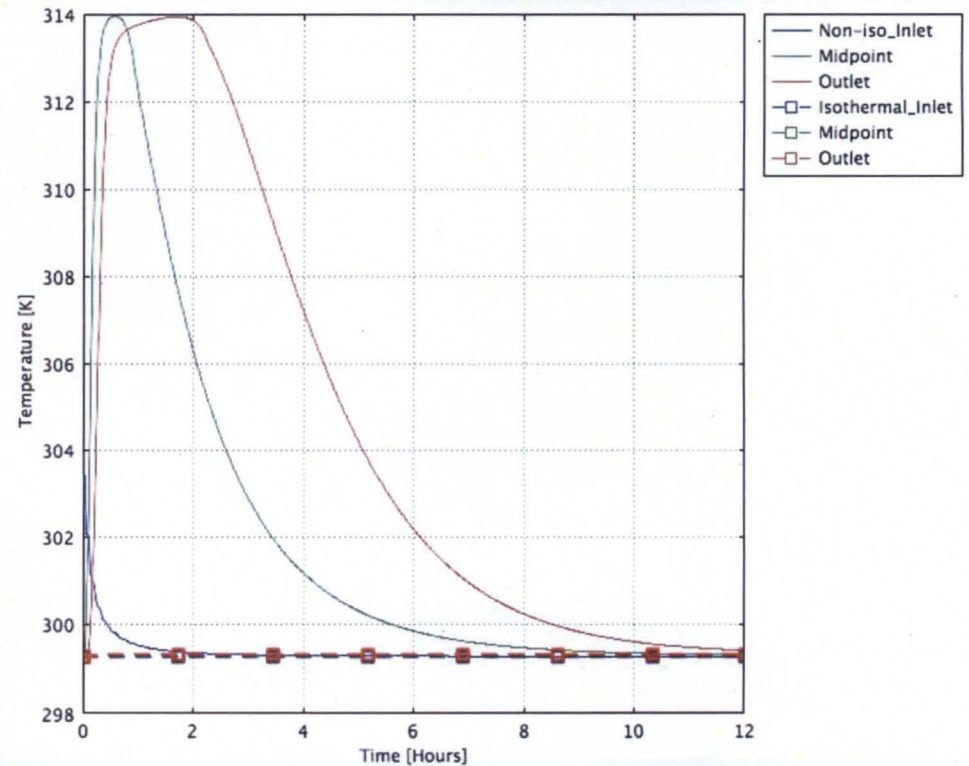
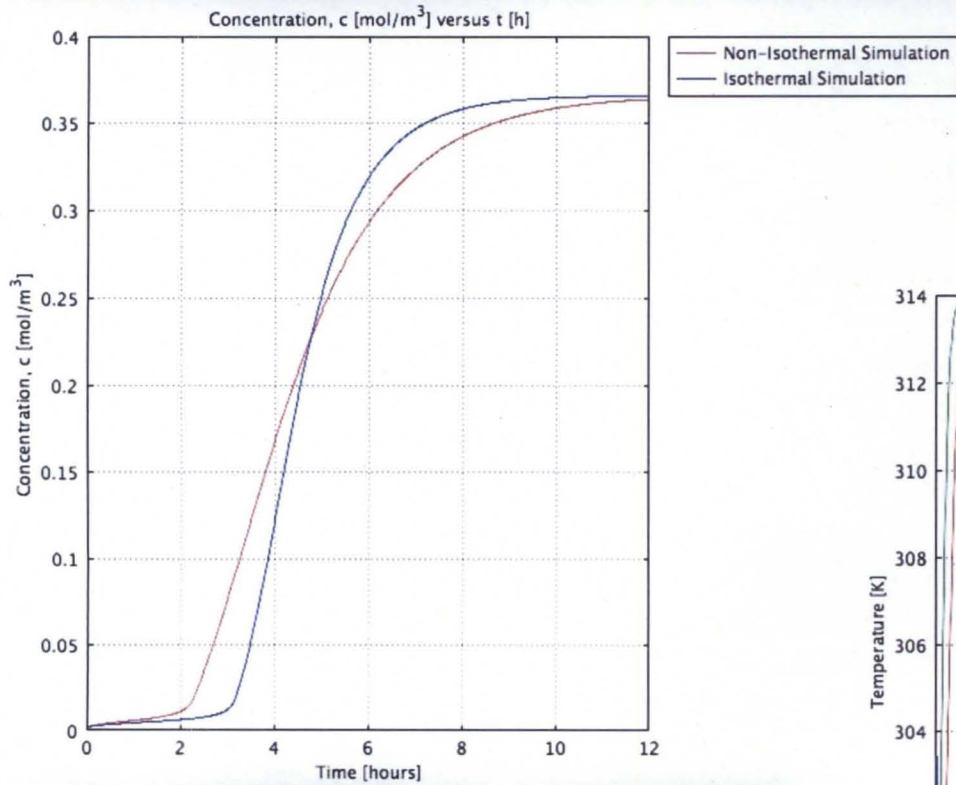
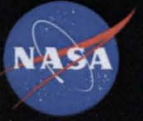
$$\text{at } t \geq 0, \partial T_g / \partial x = 0 \text{ for } x = L$$



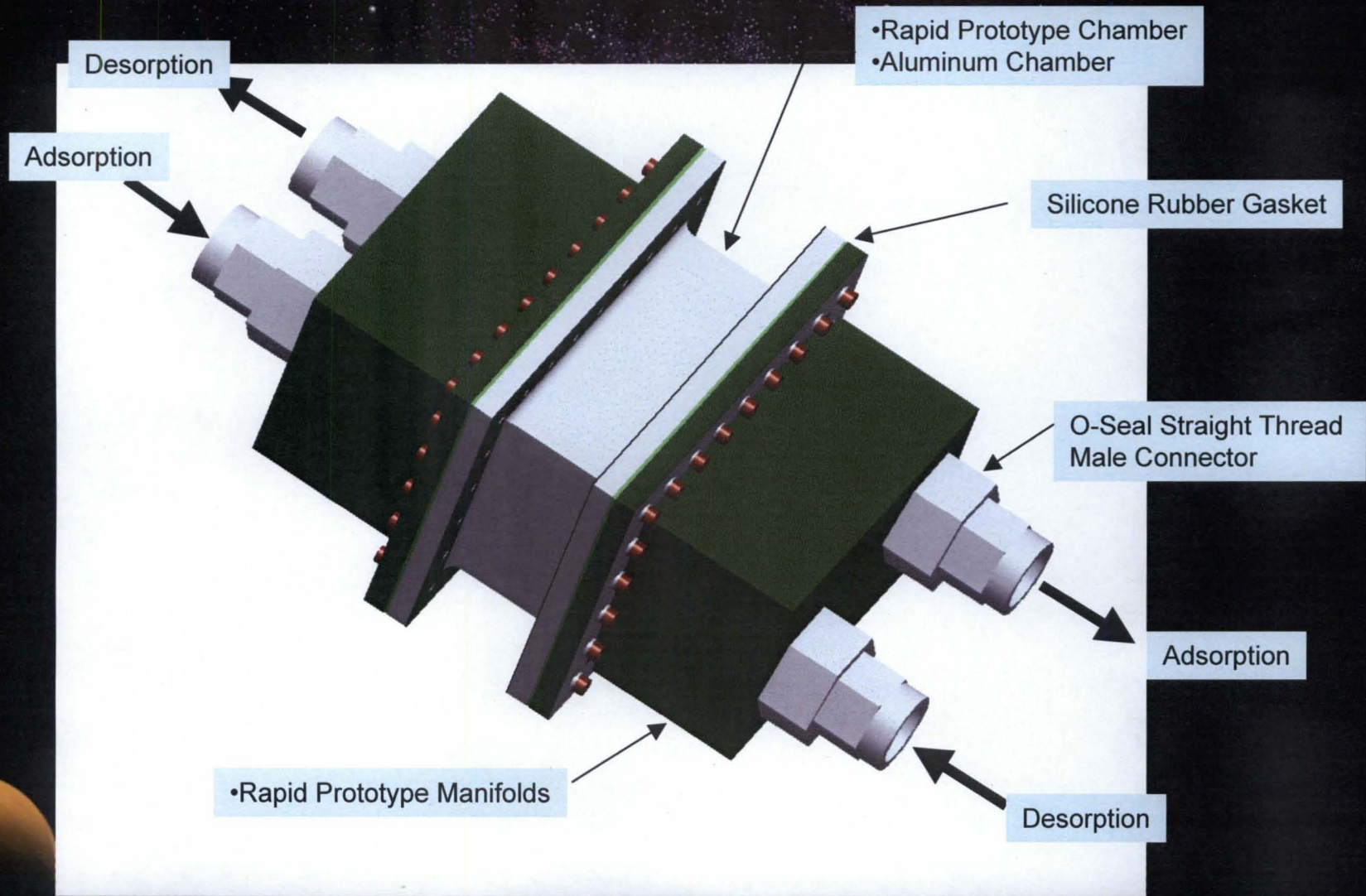
Simulation of Water Adsorption on Silica Gel including Heat of Adsorption Effects



Simulation of Theoretical Efficiency Improvement via Regenerative Heating

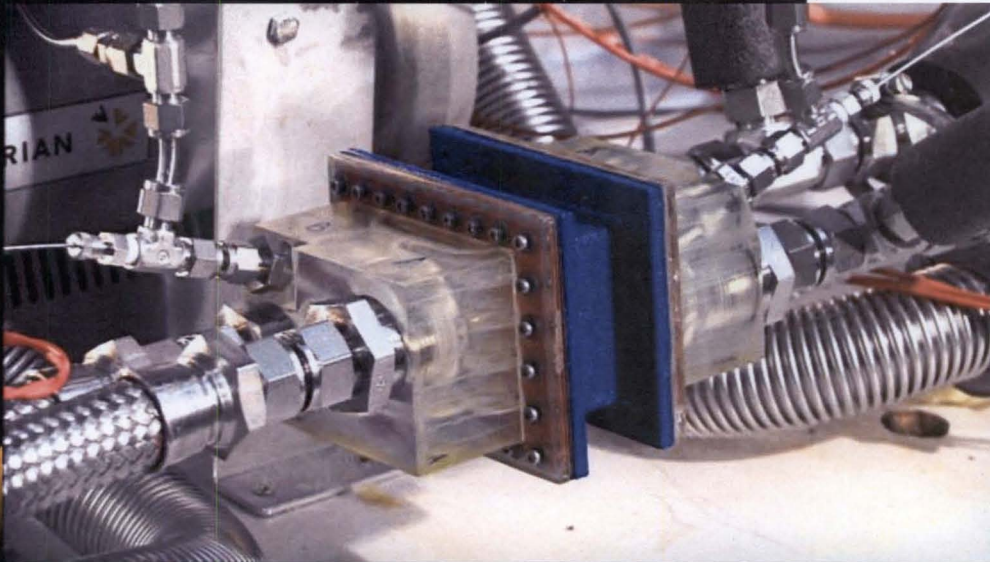
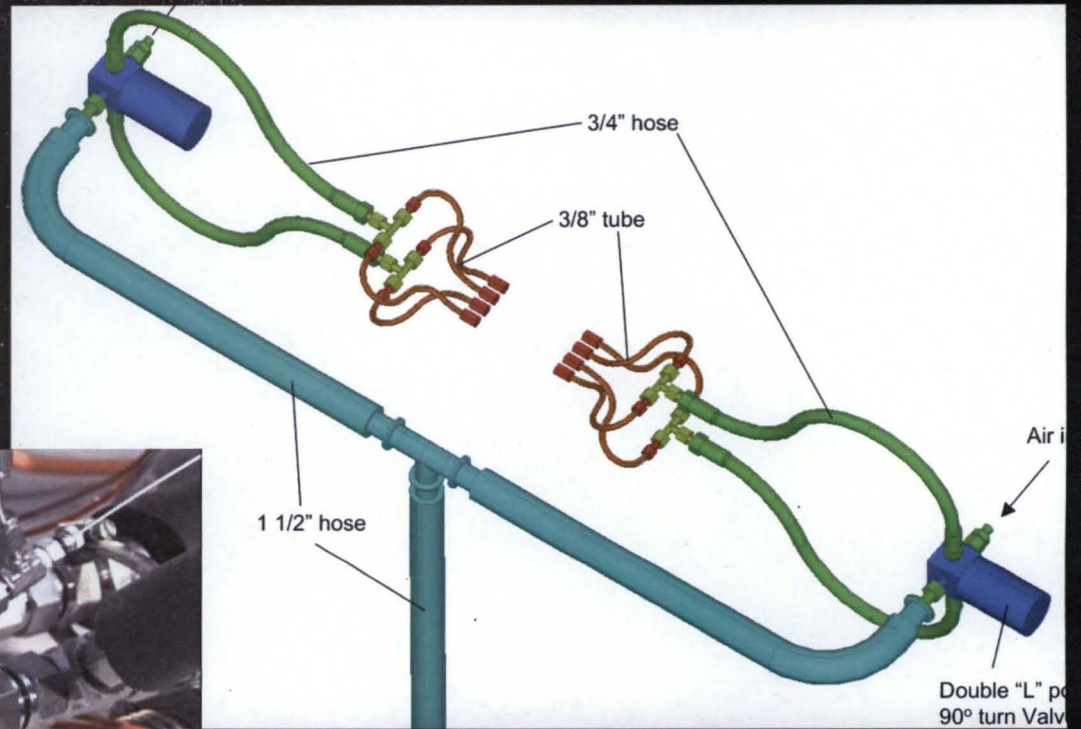


Regenerative Heating of Physical Adsorbents

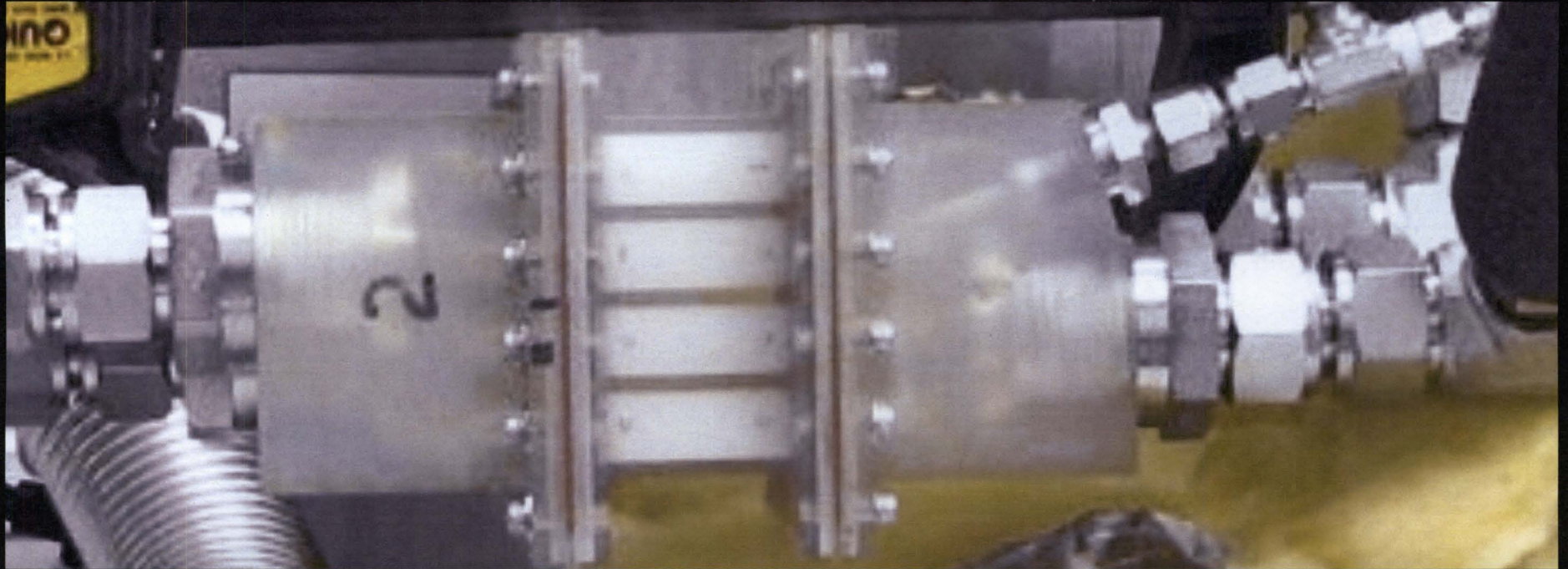




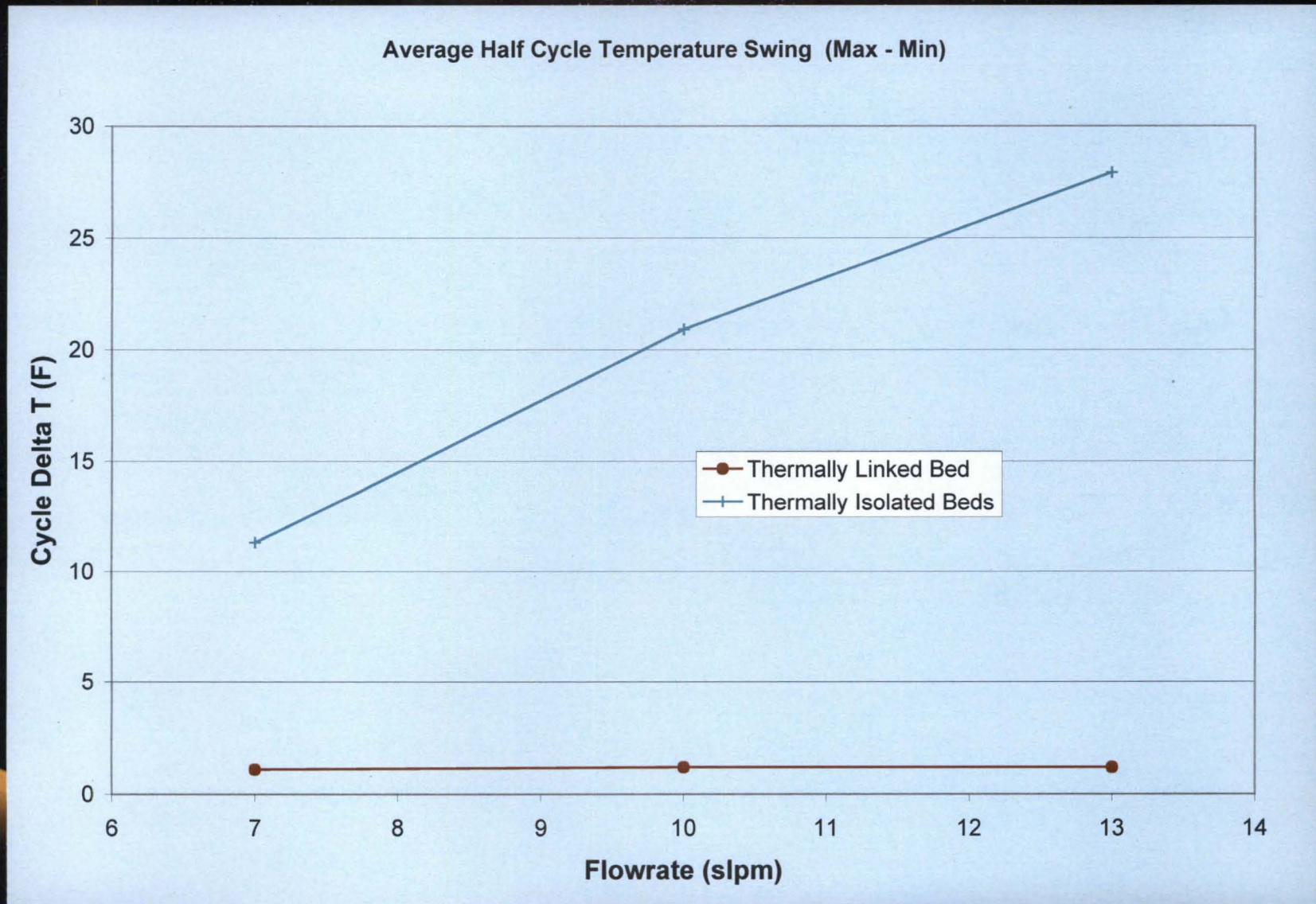
Subscale Adsorbent Bed Testing



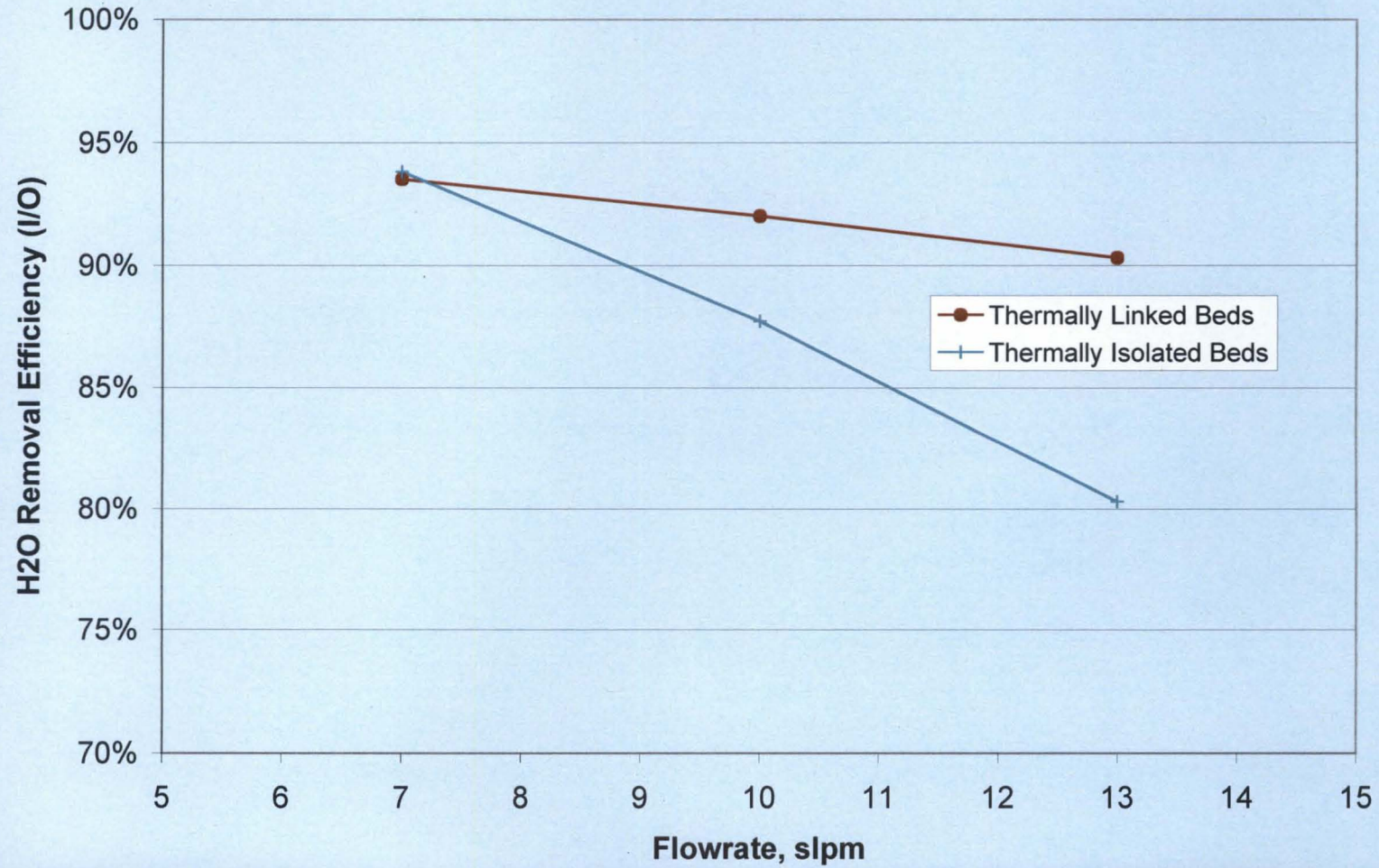
Regenerative Heating of Physical Adsorbents: *(Thermal Isolation Testing Shown)*



Subscale VSA Test Results

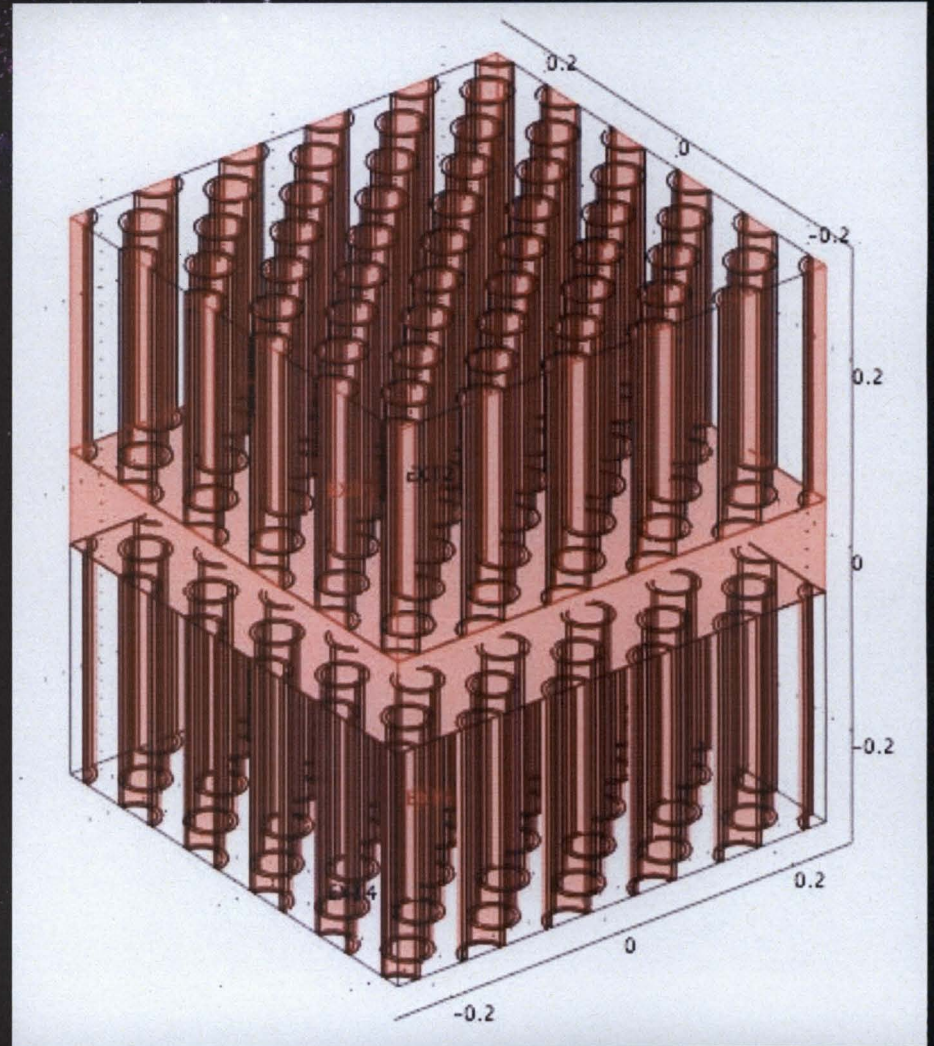
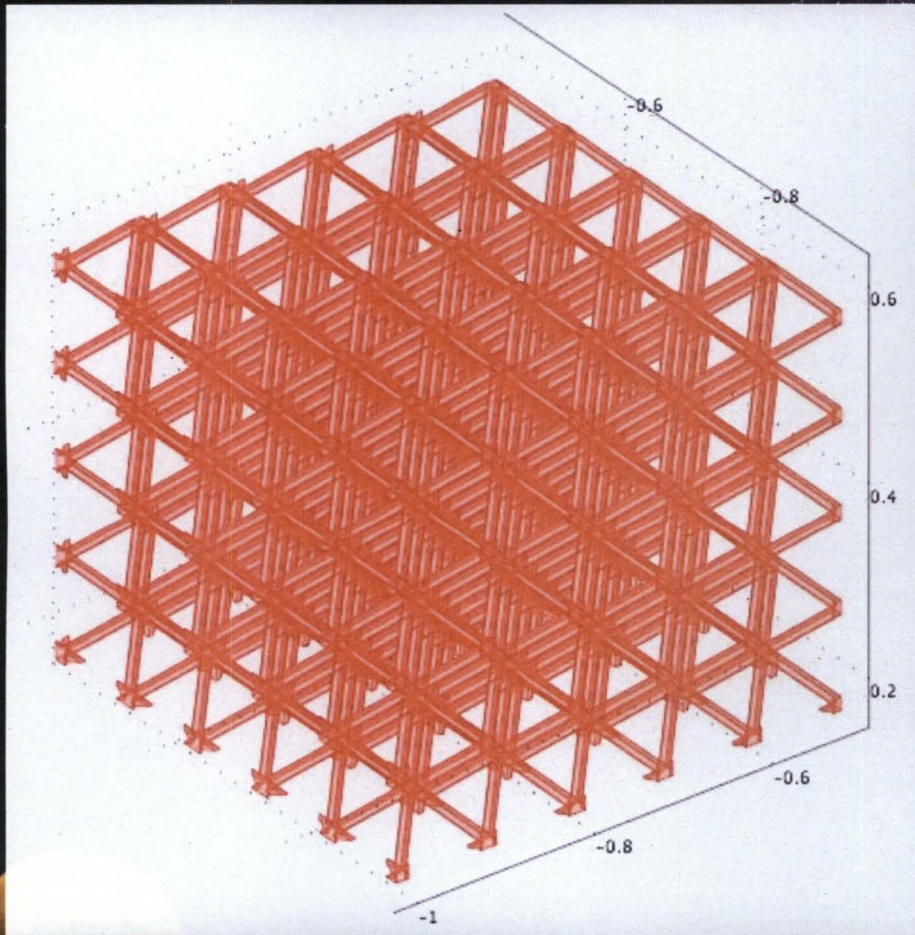


Subscale VSA Test Results



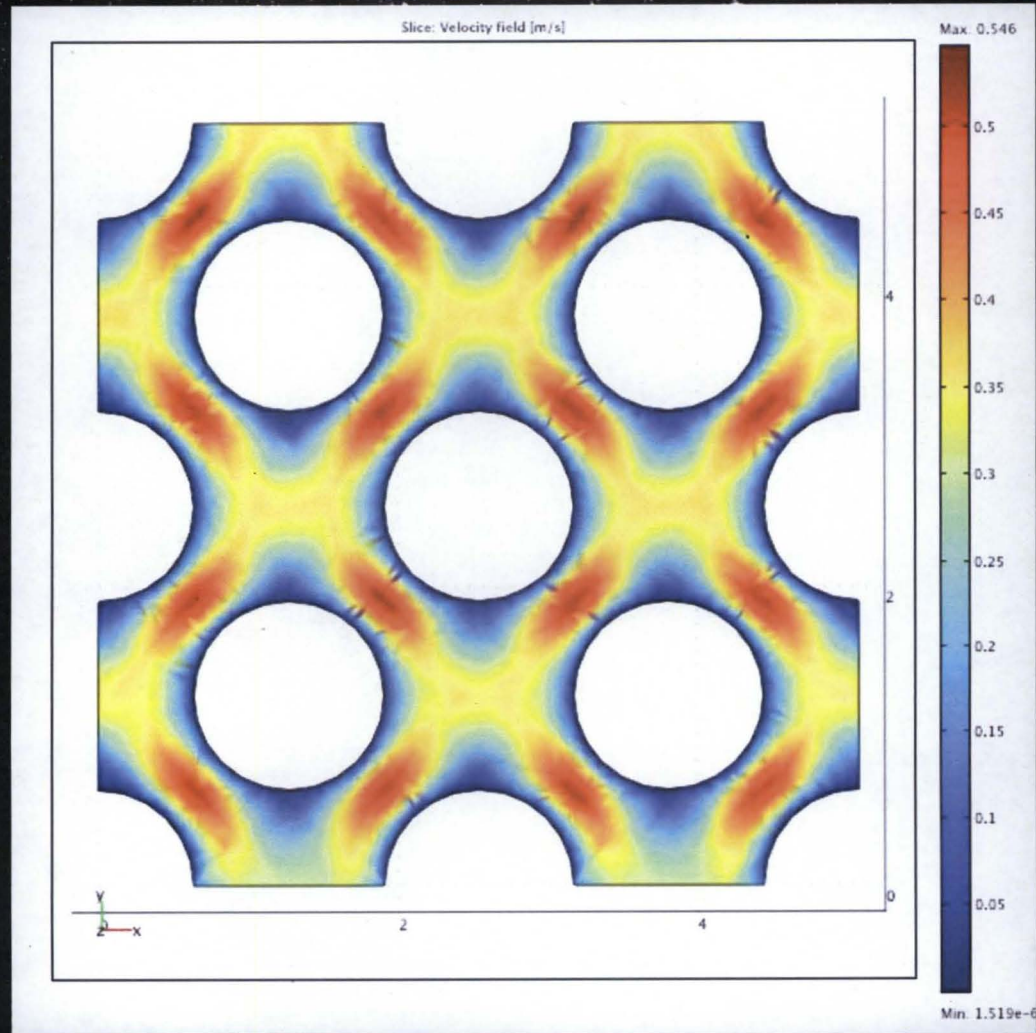


Fluid Flow Through Structured Sorbent Lattice



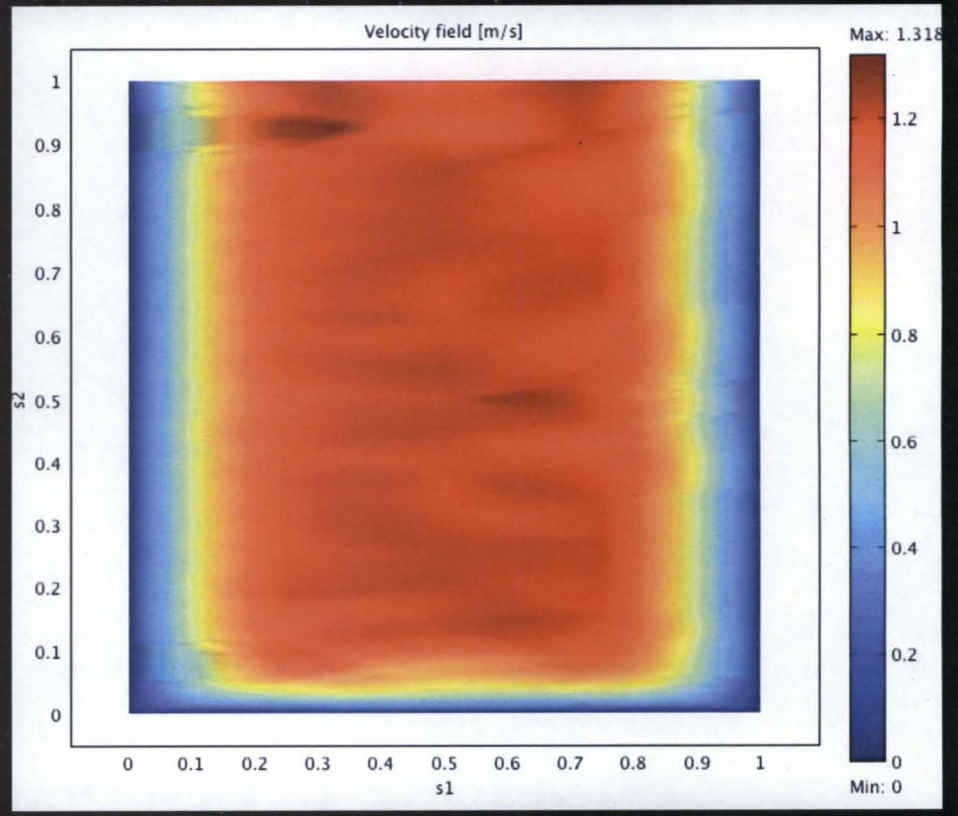
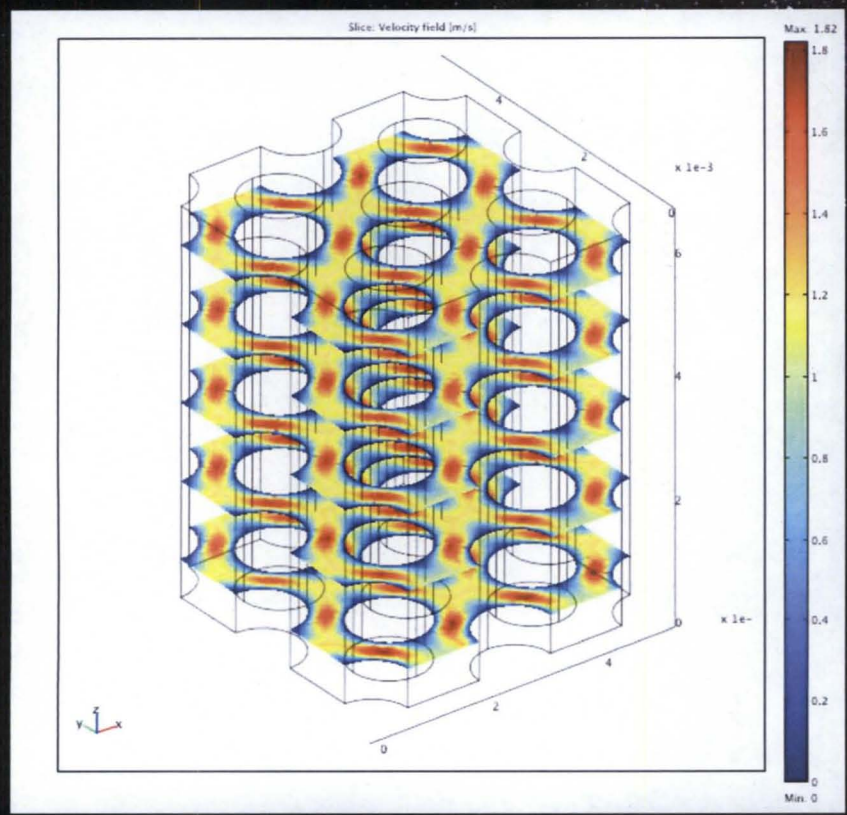


Fluid Flow Through 2-D Structured Sorbent Lattice





Fluid Flow Through 3-D Structured Sorbent Lattice





Continuing Work

- Develop multiphysics simulation of existing subscale tests with EBM and reticulated aluminum foam test articles
- Optimize process parameters (cycle time, flow rate, etc.) for existing test articles via simulation
- Optimize design of lattice and structure design (wall thickness, lattice geometry, diameter, and spacing, etc.) via simulation
- Fabrication and test of optimized regenerative heating design in subscale and full-scale configurations
- Continue comparative testing of alternate Engineered Structured Sorbent approaches with using packed bed performance as baseline

