# Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage

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May 14th

Hydrogen Storage Engineering
CENTER OF EXCELLENCE

ST 046



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Microproducts Breakthrough Institute

# Overview

## Timeline

- Feb 1st 2009 start
- June 30st, 2014 finish
- 72% Complete

## Budget

- Total project funding
  - DOE - $2,023,935
  - Contractor - $521,685
- DOE Funding for FY09/13 - $1,570,000
- OSU DOE Spending - $1,468,589

## Barriers

- Barriers addressed
  - **A**) System Weight and Volume
  - **E**) Charging and Discharging Rates
  - **H**) Balance of Plant

## Partners

- **HSECoE Partners** - SNRL, PNNL, LANL, NREL, JPL, United Technologies, GM, Ford, BASF, Lincoln Composite, HSM, UQTR
- **Center Lead** - SNRL

# Relevance -Objectives

- **Objective** – Use enhanced heat and mass transfer available from arrayed microchannel processing technology to …
  - 1) Reduce the size and weight of storage,
  - 2) Improve charging and discharging rate of storage
  - 3) Reduce size and weight and increase performance of thermal balance of plant components.
- **Barriers Addressed**
  - Reduce system size and weight (Barrier A)
  - Charging and Discharging rates (Barrier E)
  - Balance of Plant (Barrier H)

# Relevance – Arrayed Microchannel Processing Technology and Hydrogen Storage

- Significant reduction in size and weight are possible when a process is limited by diffusion
  - **Reduces storage size and weight related to heat and mass transfer**
  - **Reduces size of balance of plant thermal components**
- High degree of control over process
  - **Optimizes storage for weight minimization**
- Number up rather then scale up
  - **Maintain optimum performance attained in single cell**
- Complexity can be added without increasing cost
  - **Integrate hydrogen distribution in cooling surfaces**
- Low thermal mass and high heat and mass fluxes will allow rapid start-up and response to transients
- Attractive high volume, low cost manufacturing options exist.

# Approach - Programmatic

- Phase 1: System Requirements & Novel Concepts
  - OSU focused on simulation and experimental investigations to identify and prioritize opportunities for applying microscale heat and mass transfer enhancement techniques.
  - Working with other team members, OSU identified the highest value applications and conducted experimental investigations and modeling to collect data necessary to support the Go/No-Go decision to proceed to Phase 2.
- Phase 2: Novel Concepts Modeling, Design, and Evaluation
  - For each high-priority application, OSU is developing predictive models, design and evaluating components, fabricate proof-of-principle test articles, conduct proof-of-principle tests, and using the results to validate the predictive models.
  - With other team members, OSU will select one or more high-priority components for prototype demonstration.
- Phase 3: Subsystem Prototype Construction, Testing, and Evaluation
  - For each high-priority component, OSU will design, optimize, and fabricate the component.

# Approach – Technical Approach to Phase Two Scope of Work

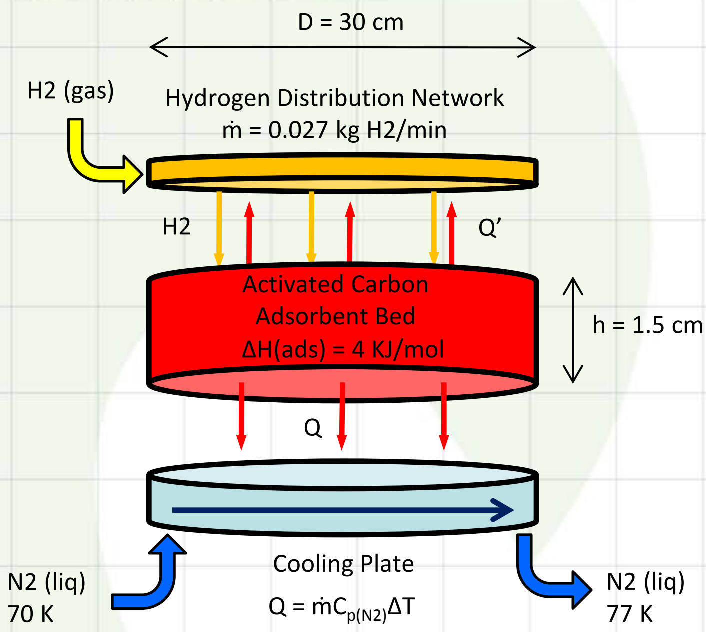
- For each high priority application we use microchannel technology to reduce barriers to heat and mass transfer and to facilitate integration with other storage system components (i.e. adsorption media)
- Optimize the performance of a single unit cell or module and then "Number Up" to attain desired performance
  - Develop appropriate simulation tools
  - Validated simulation tools by experimental investigations
  - Use simulation to  optimize a unit cell
- Validate microlamination as a path to "numbering up" by low cost high volume manufacturing

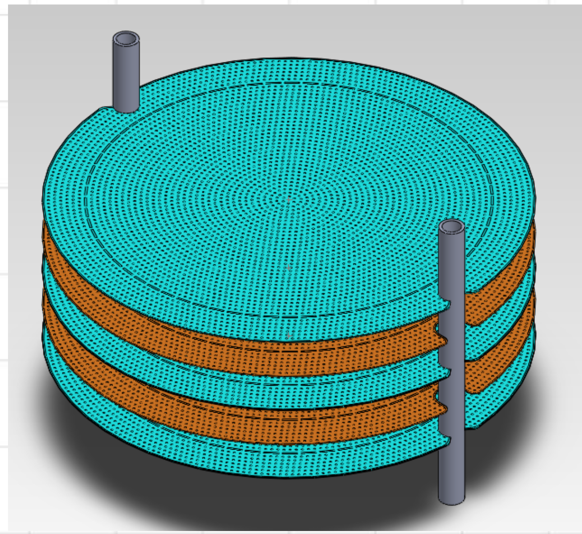
# Technical Accomplishments

- **Technical Progress Relative to 2012/2013 Milestones -** Completed feasibility studies and experimental investigations on the two highest value applications:
  - Modular Adsorption Tank Insert (MATI)
  - Microchannel Combustor-Recuperator for Hydrogen Conditioning in Adsorption System
- **Technical Progress relative to Objectives**:

1) Reduce the size and weight of storage and Improve charging and discharging rate of storage – **MATI**
   - Developed a revised design that reduces cost and weight through the use of micro pyramidal truss networks (MPTN)
   - Completed experimental investigations of single puck charging and validated model
   - Completed qualification of aluminum as a material of construction
   - Completed modeling of charge and discharge cycle
   - Completed separate effects experimental investigations of microchannel cooling plate heat transfer and pressure drop.
2) Reduce size and weight and increase performance of thermal balance of plant components – **Microchannel Combustor-Recuperator-for Hydrogen Conditioning**
   - Successfully completed design and modeling of a 1 $kW_t$ microchannel combustor for heating hydrogen during cold starts followed by a successful experimental demonstration.

# Barriers A and E - Modular Adsorption Tank Insert (MATI) Design Concept and Status



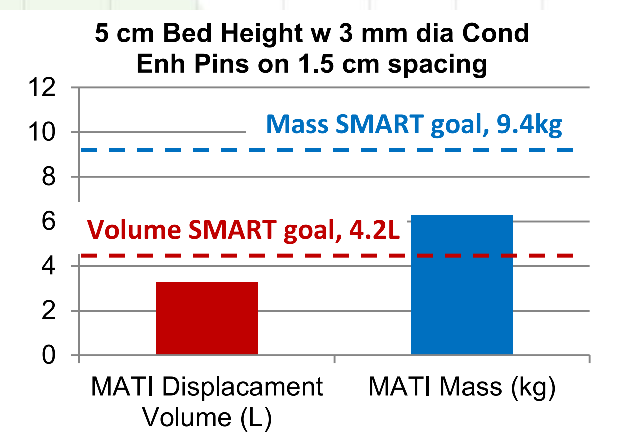



MATI Concept: can be enclosed to contain media

## Why?

1) **Separate cooling function from adsorption allowing a wider range of cooling strategies**
2) **Facilitates use of fuel cell waste heat for storage discharge**
3) **Optimized for use of densified media**
    - **Low void fraction (<5%)**
    - **Insensitive to mechanical failure of the media**

- Heat of adsorption removed by $LN_2$ and $H_2$
- Axial distribution of $H_2$ to adsorption bed




## Development Plan

*Phase 1*

– S.S. with combined cooling and $H_2$ distribution plates

*Phase 2*

– S.S. with separate cooling and $H_2$ distribution plates

*Phase 3*

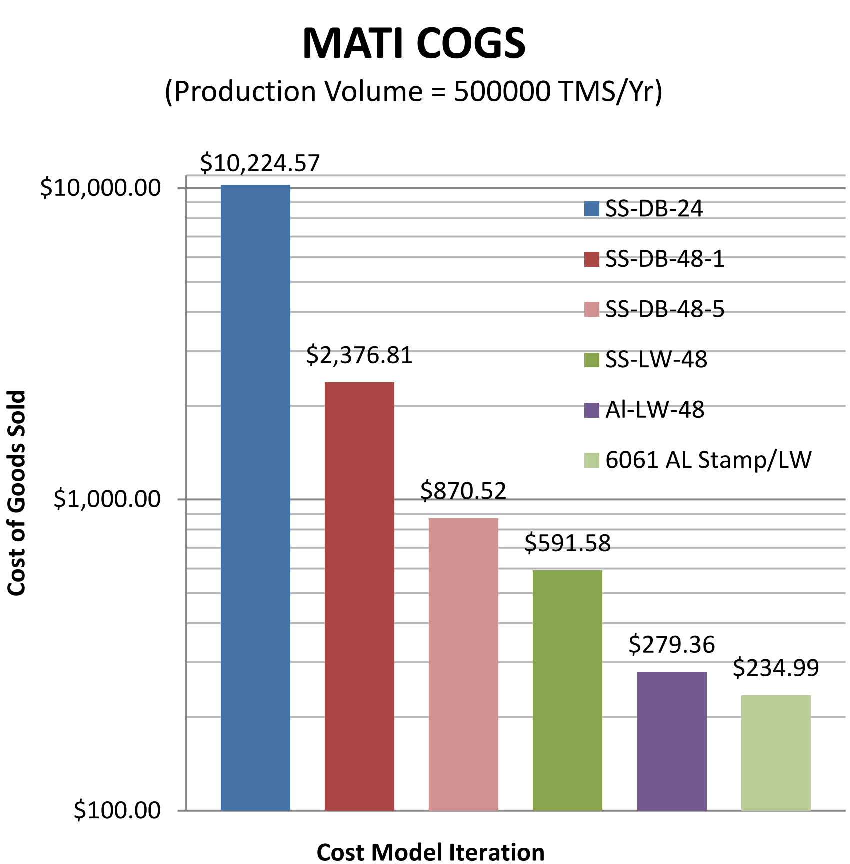
– Al with separate cooling and $H_2$ plates and enhanced media conductivity

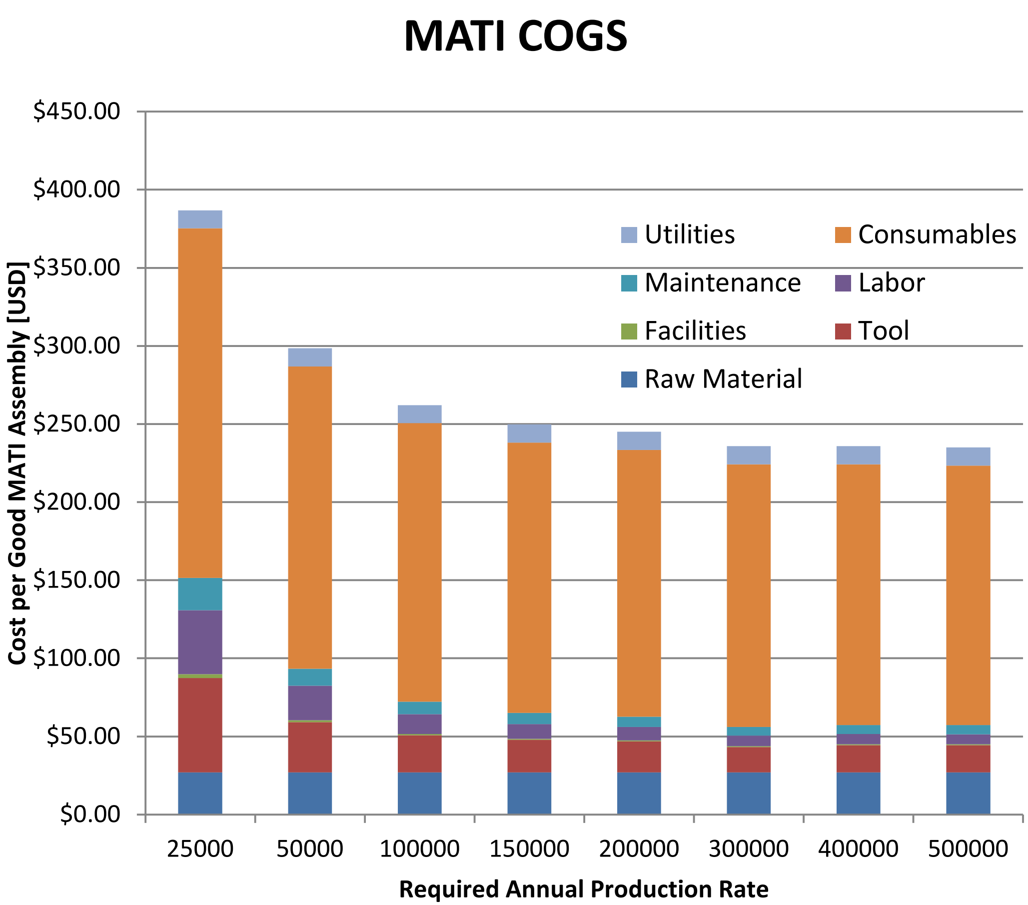
## Status

- Completed assembly of cryogenic test apparatus
- Completed fabrication and test of phase 1 single and multi module test articles
- Completed fabrication and test of phase 2 SS and Al test articles
- Qualified aluminum as a material for microlamination
- Initiated development of densified media conduction enhancement

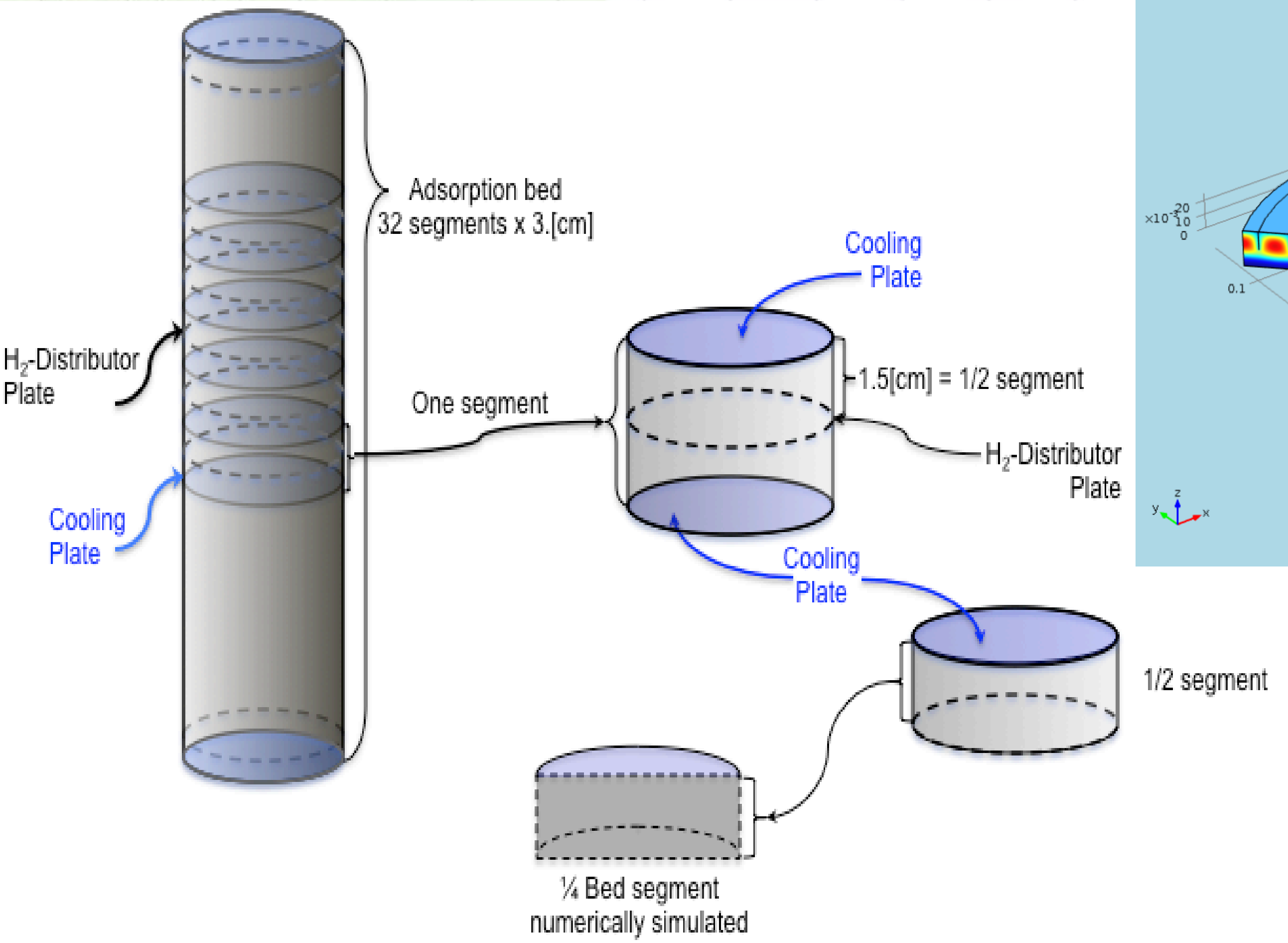
# Barriers A and E - MATI Cost Estimate

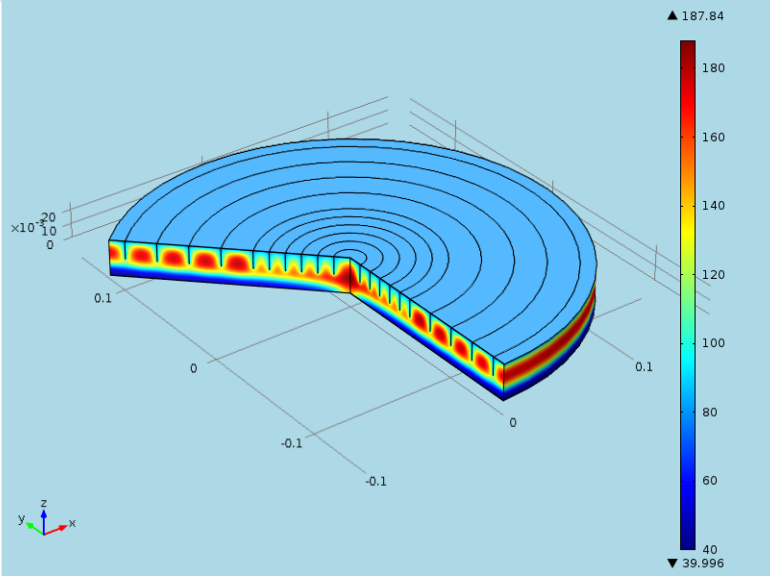
- Process-based cost models used to estimate Cost-of-Goods-Sold (COGS)
- Use of stamping significantly increases raw material utilization
- Opportunities to reduce consumables by increasing stamping tool life



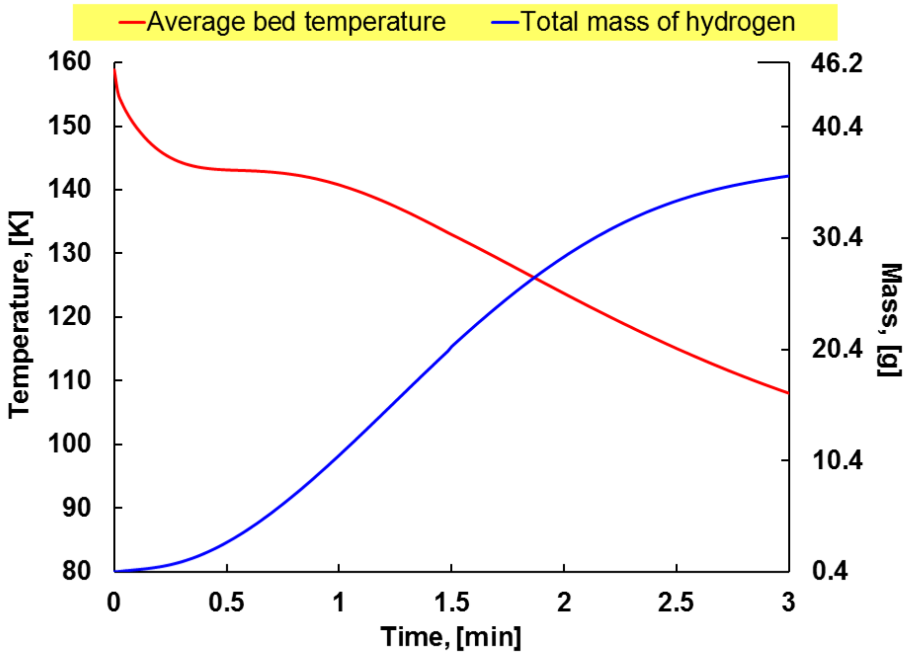



# Barriers A and E - Impact of bed conduction and MATI on charging and discharging cycle



# Barriers A and E - Impact of bed conduction and MATI on charging and discharging cycle




| Bed Property | 1/2 Bed Segment | Whole Bed |
|---|---|---|
| MOF-5 density | 320 [kg/m$^3$] | 320 [kg/m$^3$] |
| Initial bed temperature | 160 [K] | 160 [K] |
| Final bed pressure | 100 [bar] | 100 [bar] |
| Filling time | 3 min | 3 min |
| Additional cooling time | 5 min | 5 min |
| Total $H_2$ mass after 8 min | 43.5 [g] | 5568 [g] |
| Total $H_2$ mass at 80 [K] and 100 [bar] | 46.2 [g] | 5914 [g] |

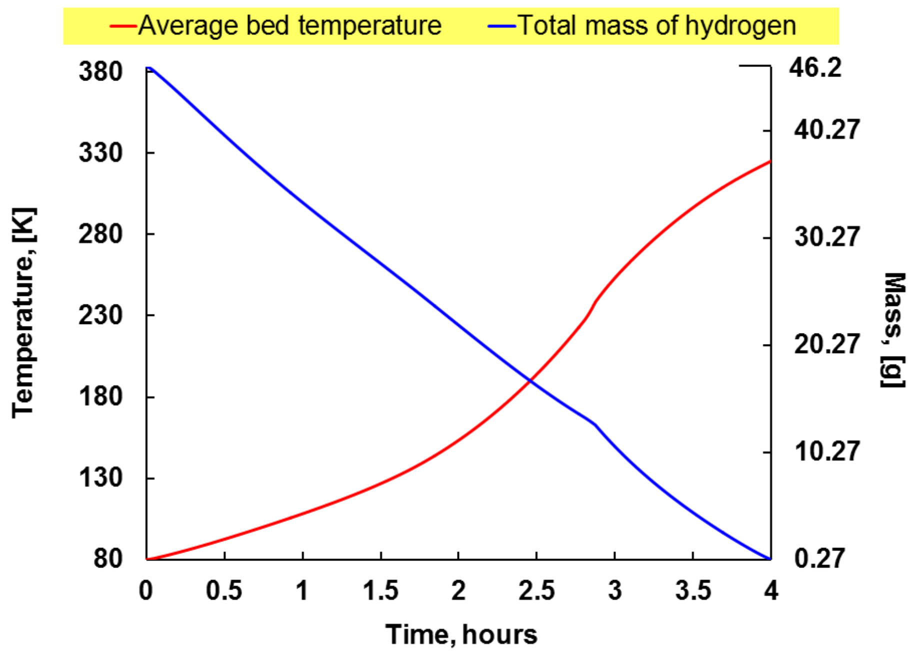
***Bed charging simulation results: ½ of a unit cell, no heat conduction enhancement used;***

***Charging is modeled by increasing the pressure at the side of the distribution plate during 3 min from 1 to 100 bar.***

***Conclusions:***

***-Without heat conduction enhancement it will take 8 minutes to fill the bed.***
***-heat conduction enhancement is needed in order to reach target mass of hydrogen stored (cm long pin-fins spaced 1 cm apart)***

# Barriers A and E - Impact of bed conduction and MATI on charging and discharging cycle

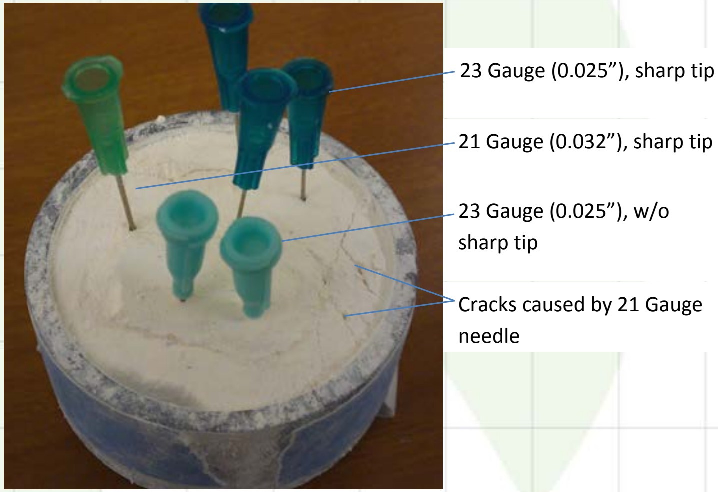



| Bed property | ½ Bed Segment | Whole Bed |
|---|---|---|
| MOF-5 density | 320 [kg/m³] | 320 [kg/m³] |
| Initial bed temperature | 80 [K] | 80 [K] |
| Initial bed pressure | 100 [bar] | 100 [bar] |
| Final bed pressure | 5 [bar] | 5 [bar] |
| Discharging time | 4 hours | 4 hours |
| Hydrogen outflow rate | 0.0032 [g/s] | 0.41 [g/s] |
| Total initial mass of $H_2$ | 46.2 [g] | 5914 [g] |
| Total final mass of $H_2$ | 0.27 [g] | 34.6 [g] |

Discharging is first driven by increasing the temperature of $H_2$ in the heat exchanger plate. When maximum temperature is reached, target hydrogen mass outflow is maintained by appropriate pressure drop.

**Conclusion: heat conduction enhancement is not needed to maintain the desired discharging performance during 4 hours.**

# Barriers A and E - Conduction Enhancement Study



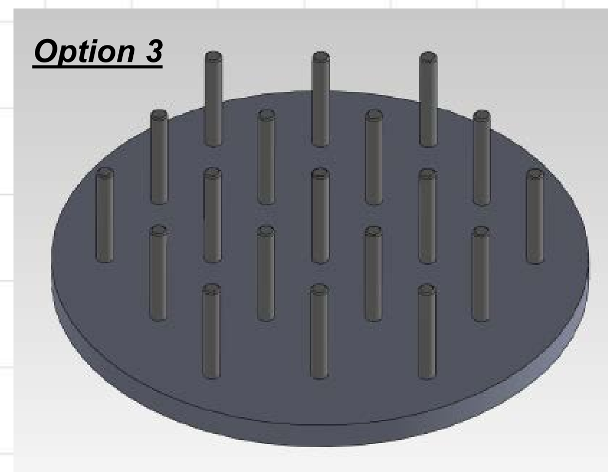

***Current Status:***

- ***Conducted needle insertion tests for MOF5 bed using 21 and 23 gauge needles***
- ***Cracks were mainly caused by the 21 Gauge needles indicating size limitation***
- ***Although the shape of needle tip was not critical, pushing solid pins of the same sizes will see significant challenges because of displacement stress***
- ***Shorter needle and/or insertion depth will likely succeed***
- ***The 23 Gauge needles seem to work well at the tested distance (12–19mm), it becomes a concern as the population increases or spacing decreases***

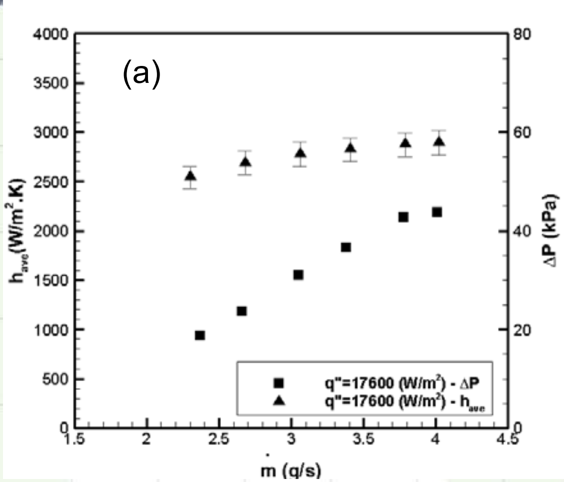
***Going Forward…***

- ***Option 1 (high risk but easy to make) --- Pushing solid pins into the MOF5 bed (Diameter=0.15-0.25mm; Length=10mm; Spacing=10mm)***
- ***Option 2 (medium risk but easy to make) --- Pushing hollow pins into the MOF5 bed (Diameter<0.65mm; Length=10mm; Spacing=10mm)***
- ***Option 3 (lower risk but hard to make) --- Forming the MOF5 bed around solid pins for higher conduction enhancement (Diameter=0.8-1.6mm; Length=10mm; Spacing=10mm)***

***The plan is likely to be investigate Option 1 first, then Option 2 and Option 3***

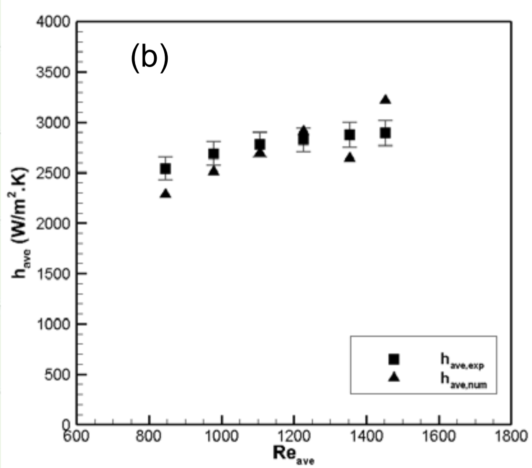


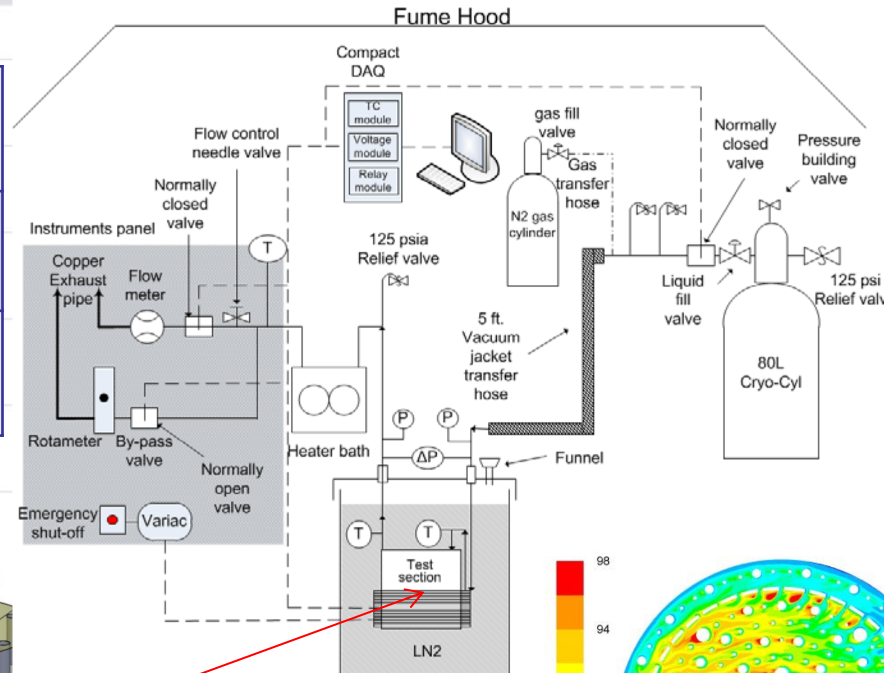
# Barriers A and E - MATI Separate Effects Heat Transfer Testing (Single Phase)

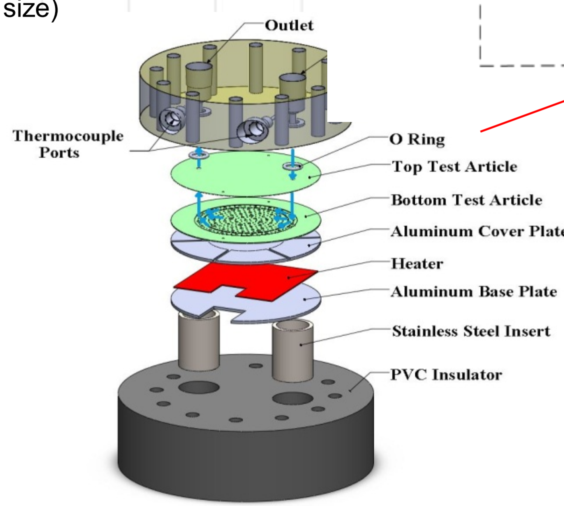


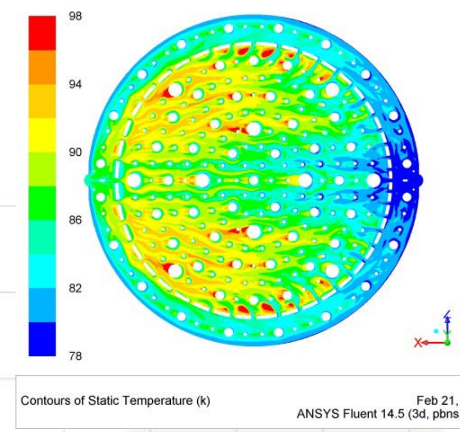

| Mean Average Error (MAE) at q"=17600 (W/m²) | |
|---|---|
| $h_{num}$ vs. $h_{exp}$ | 7.1% |
| $\Delta P_{num}$ vs. $\Delta P_{exp}$ | 13.7% |

(a)Pressure drop and heat transfer coefficient variation with mass flow rate including max error bars of measurements (ΔP error bars smaller than symbol size)
(b) Comparison of experiments and CFD results



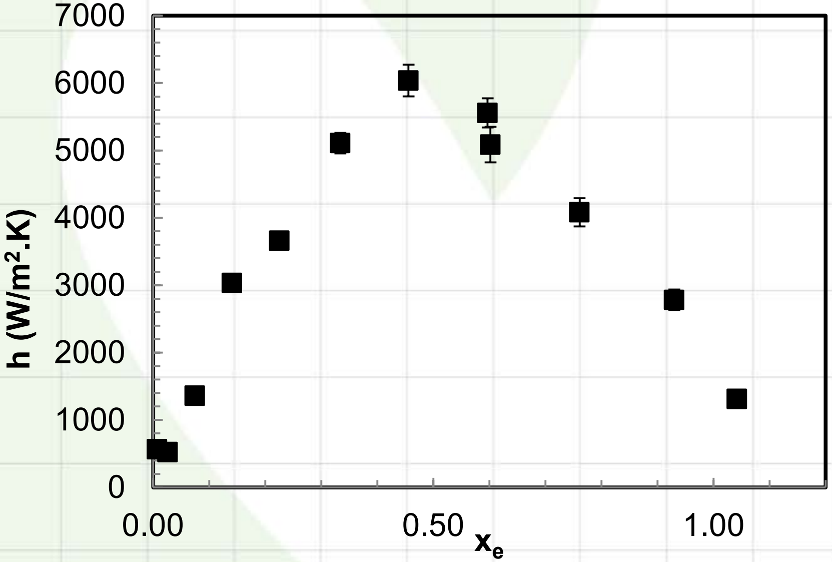



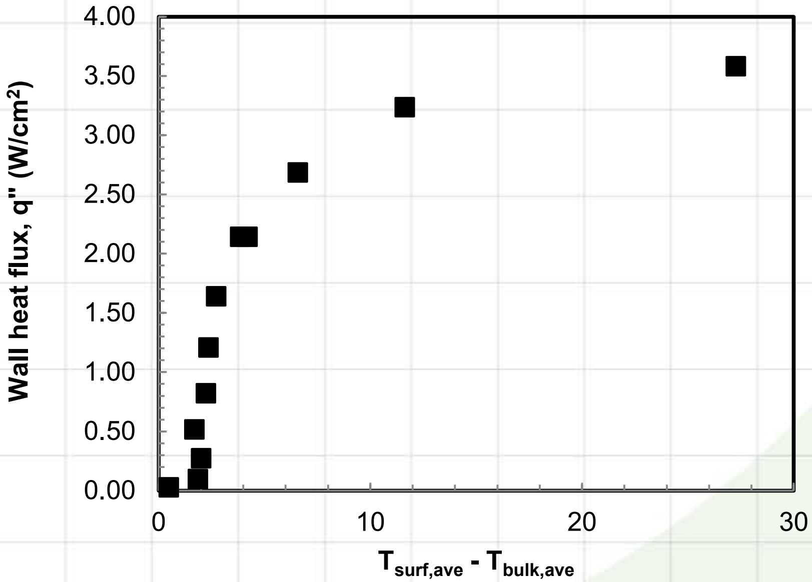

Contours wall temperature for a mass flow rate of 3 g/s and an applied heat flux to the bottom wall of 17600 W/m². The flow is from right to left.

# Barriers A and E - MATI Separate Effects Heat Transfer Testing (Preliminary Phase Change)

- It is likely that the available LN2 supply in the forecourt will be in a saturated state.
- A larger amount of heat per unit LN2 mass flow rate can be removed via phase-change, hence reducing the amount of LN2 used.



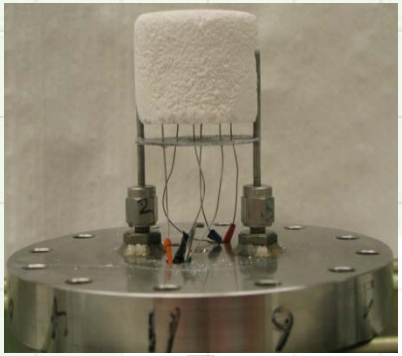

Corresponding heat transfer coefficient plot versus flow quality for a mass flow rate of ~ 0.36 g/s; inlet temperature is near saturation.



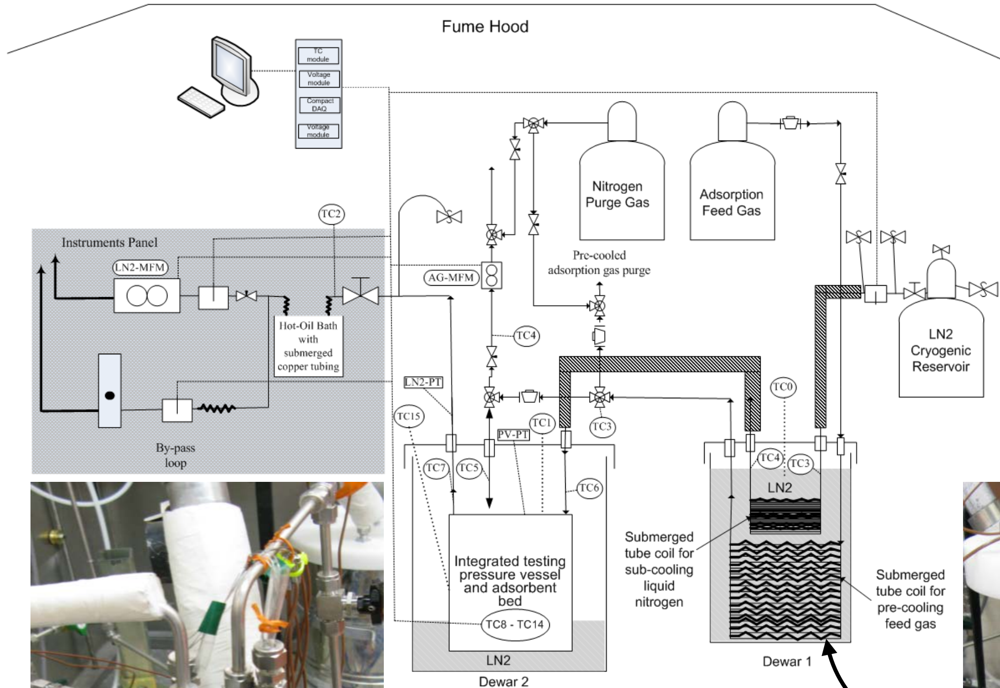

Preliminary boiling curve for a mass flow rate of ~ 0.36 g/s; inlet temperature is near saturation.

# Barriers A and E – MATI Integrated Adsorbent Test Bed

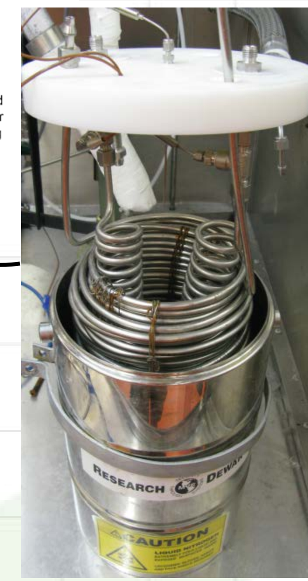
**MOF-5 Bed , thermocouples, single MATI cooling plate**



Fully assembled integrated pressure vessel



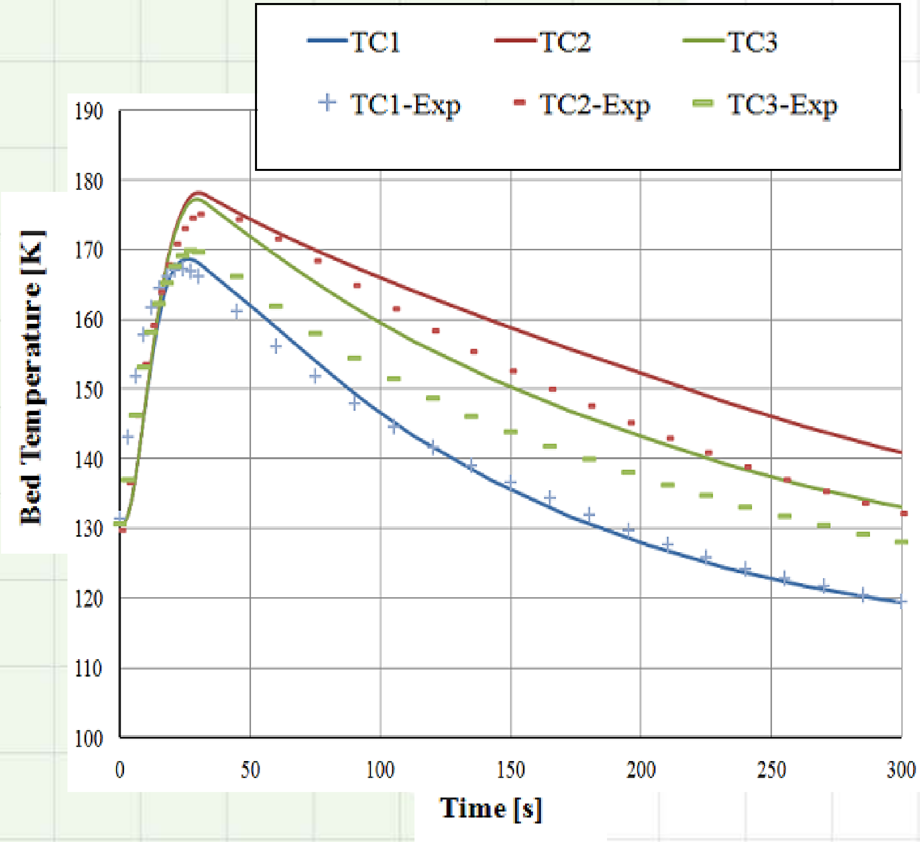

Integrated pressure vessel installed in experiment al test loop

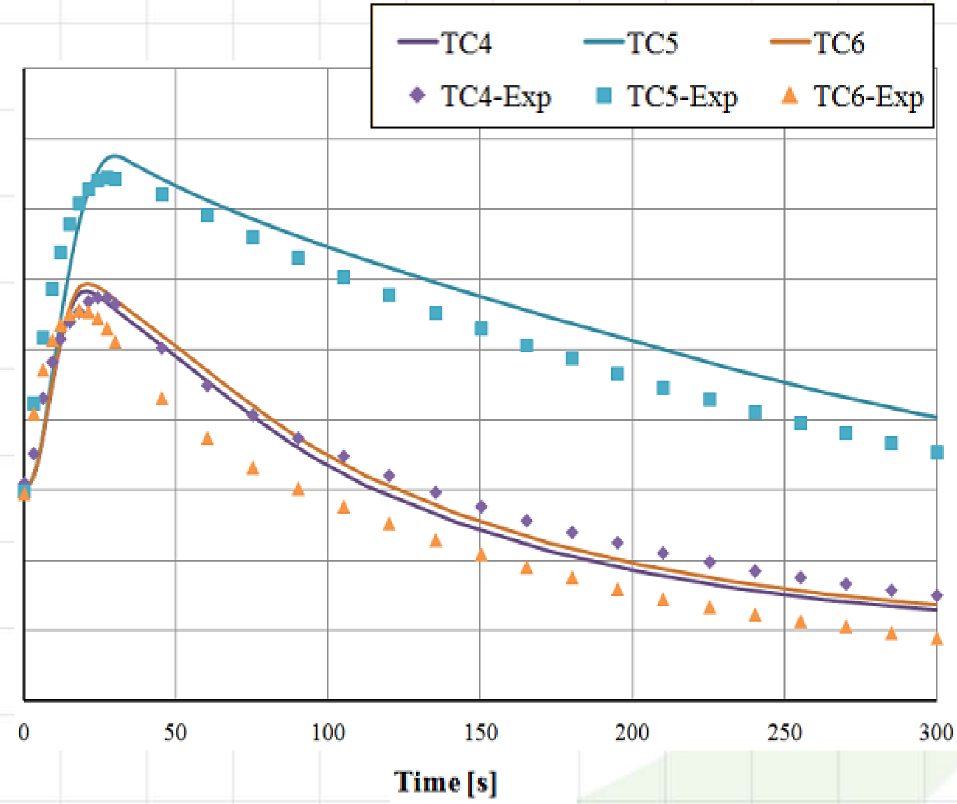


$LN_2$ sub-cooling and $H_2$ pre-cooling heat exchangers

# Barriers A and E – MATI Integrated Adsorption Bed Testing

***LN2 Cooled adsorption on MOF-5; Experimental and Modeling results***

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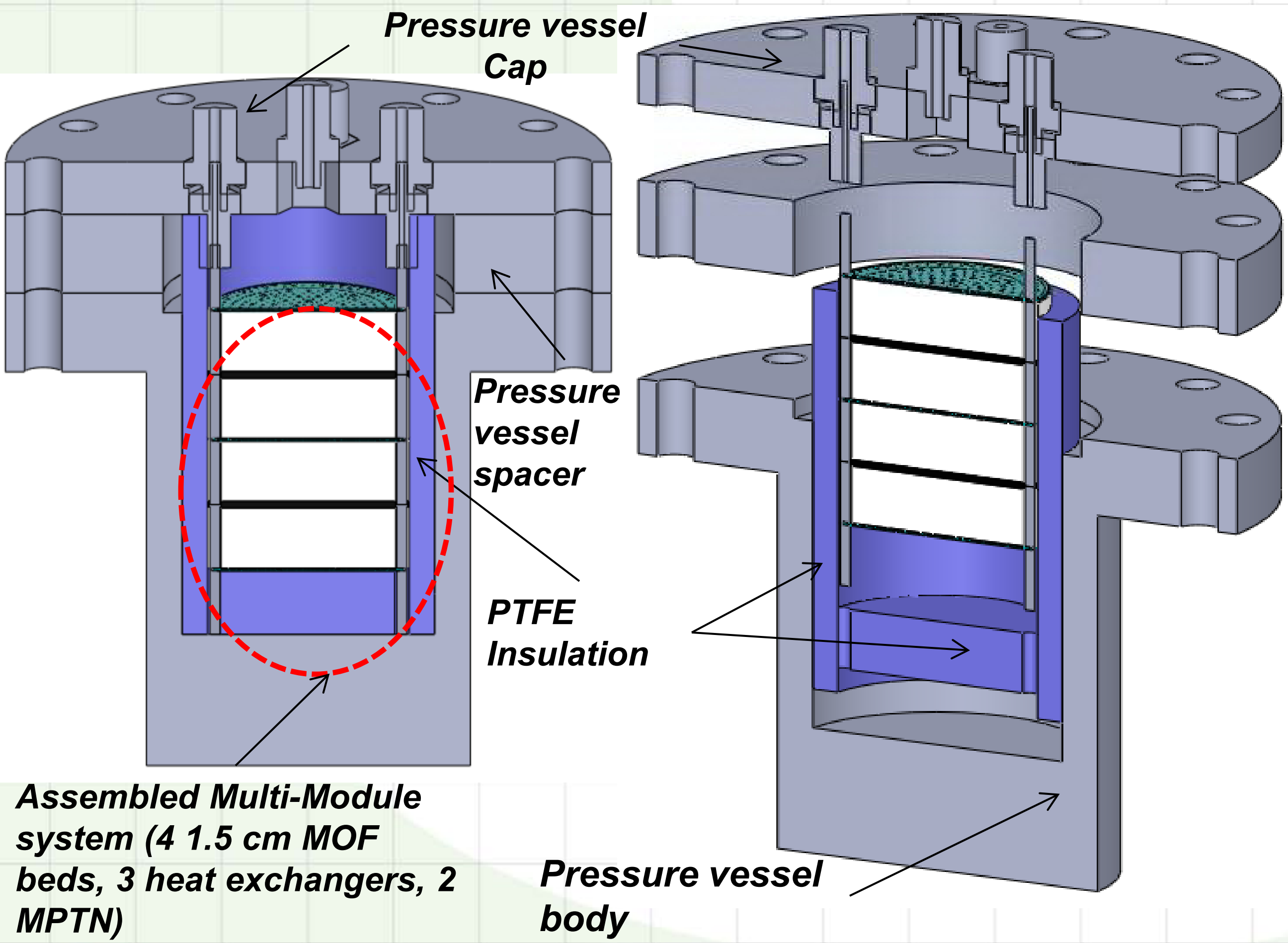
# Barriers A and E – MATI Multi-module Adsorption Bed Testing – System Design -Retrofitting

## *Multi-module adsorption system*



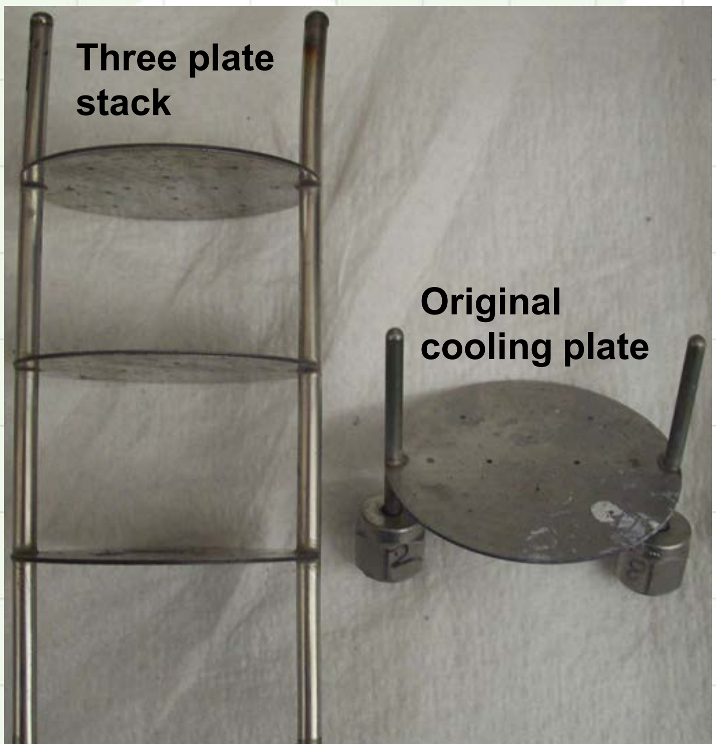

- Retrofitting experimental cryogenic adsorption system to accommodate a multi-modular stack;
- Stack consists of three cooling plates, four 1.5 cm compressed, MOF-5 beds, two sets of MPTN hydrogen distribution layers

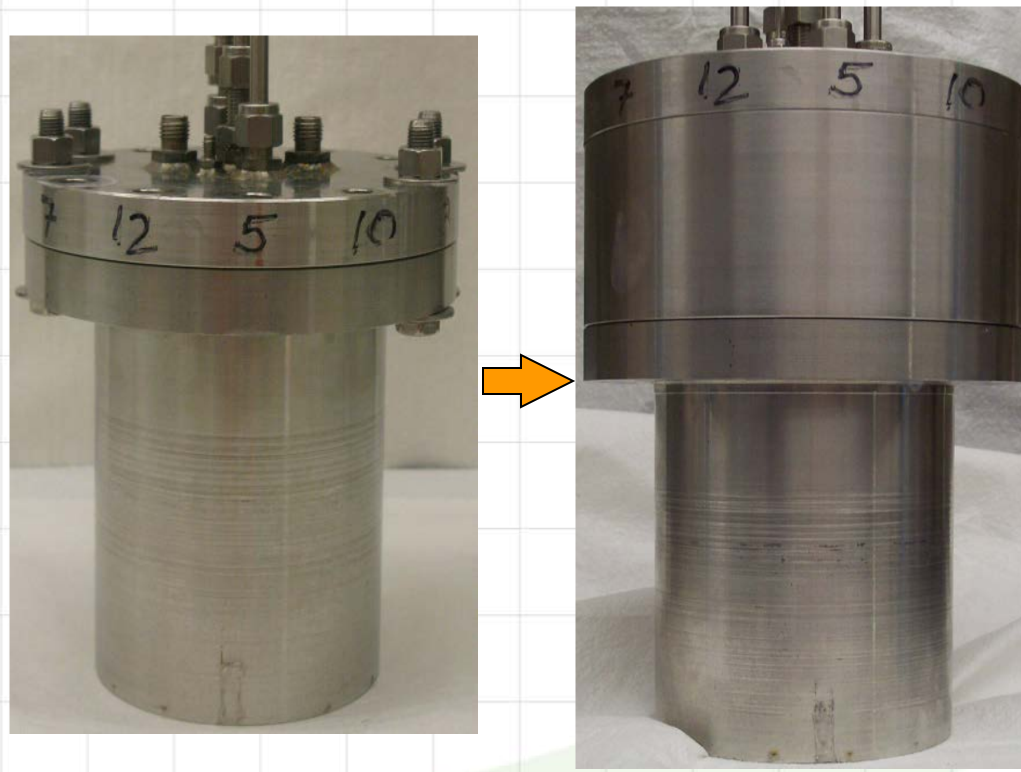
# Barriers A and E – MATI Multi-module Adsorption Bed Testing – System Design -Retrofitting

## *Status of Retrofitting: In progress*

Three cooling plate stack has been fabricated and excess header length has been welded and leak tested

Spacer has been fabricated to accommodate the increased height of the multi-module system



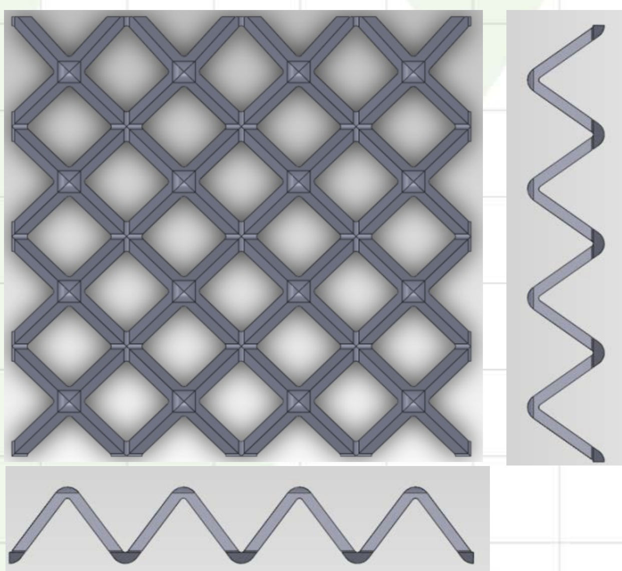



# Barriers A and E – MATI Multi-module Adsorption Bed Testing – System Design -Retrofitting

***Status of Retrofitting: In progress***

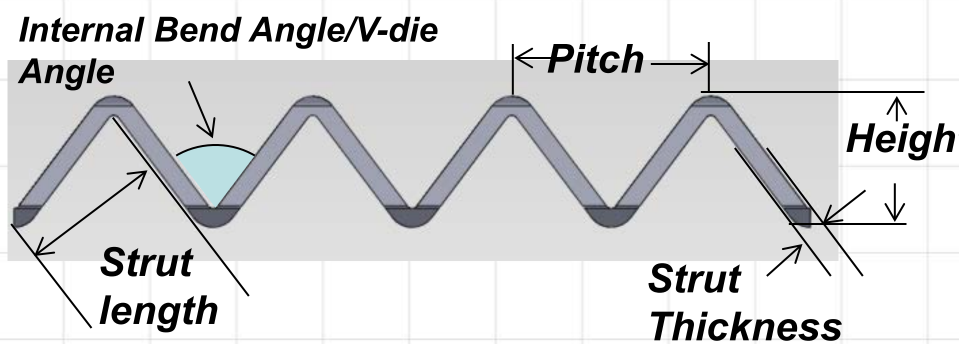
Activation of MOF-5 compressed beds

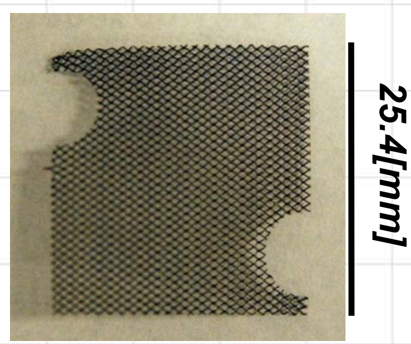
Pressing and fabrication of MPTN hydrogen distribution layers

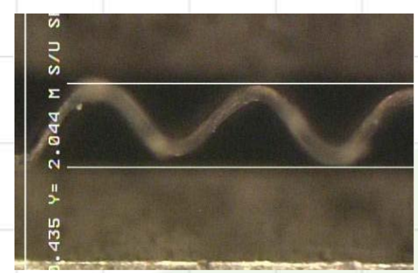


Top and side views of idealized PTN

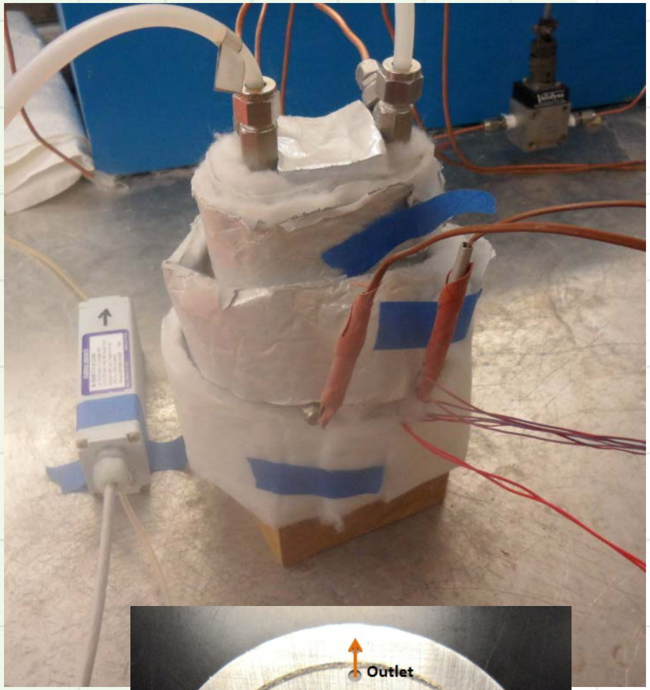
***Structural trusses***

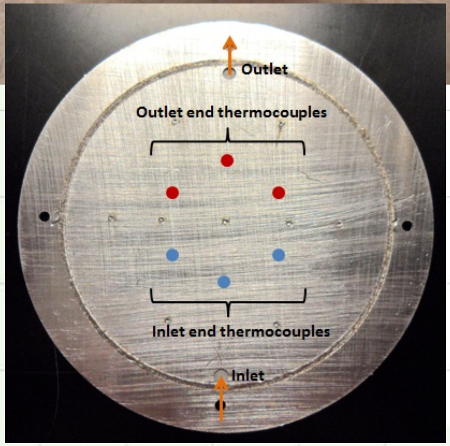


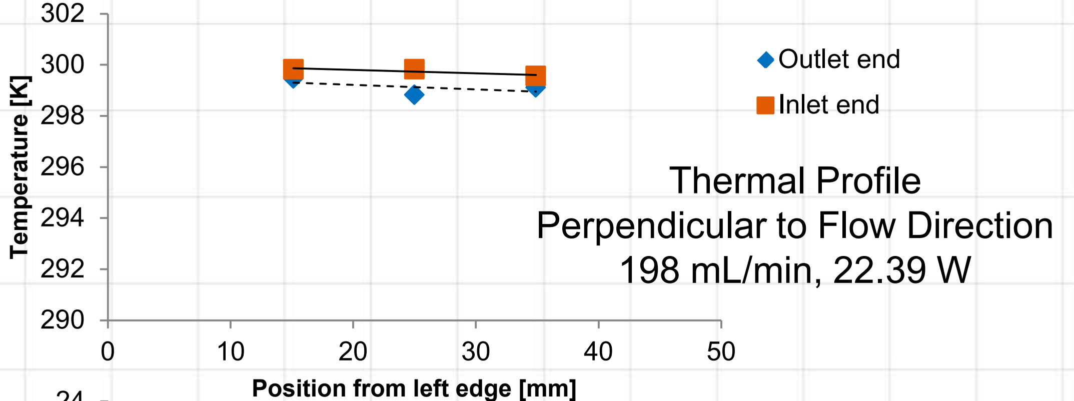



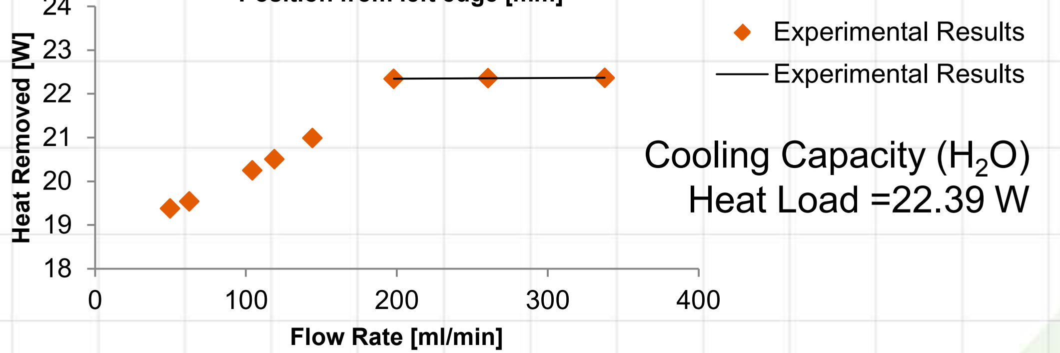



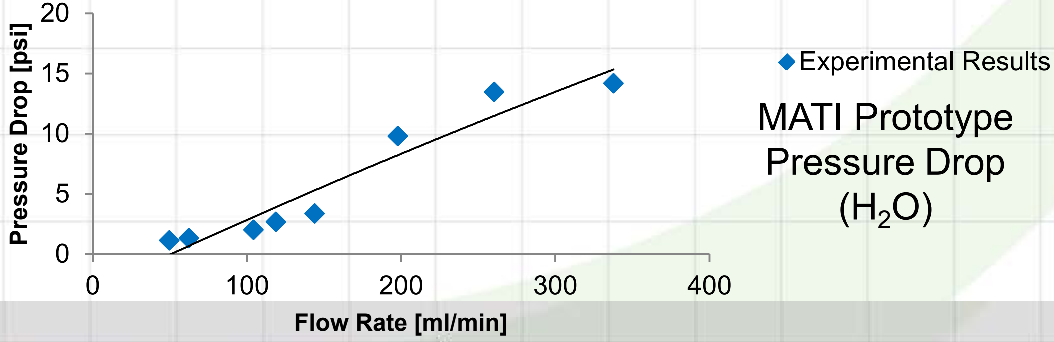
# Barriers A and E -
# 6061 Al MATI Cooling Plate





# Barriers A and E – MATI Smart Goals and Conclusions

## Smart Goals:

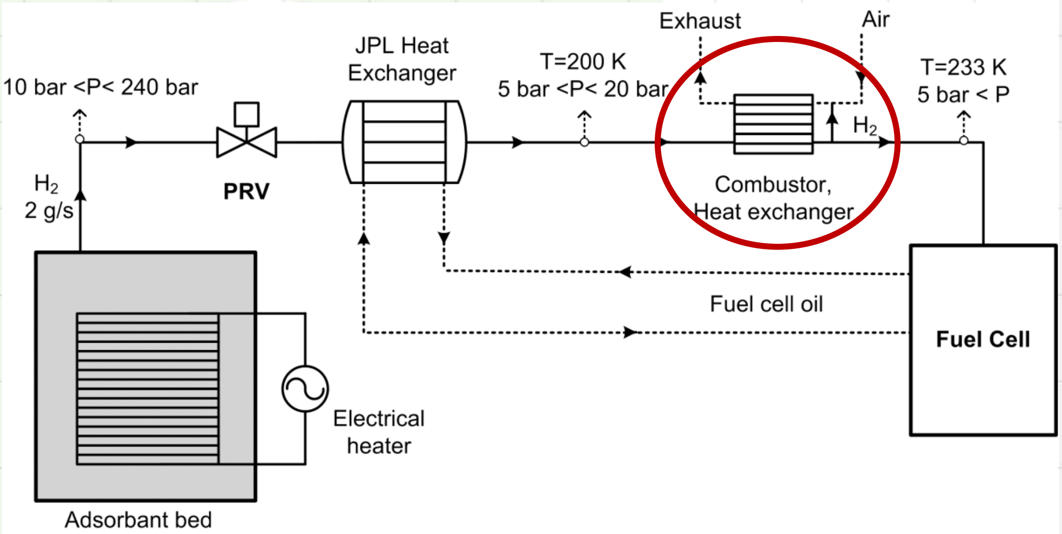
- Report on ability to develop and demonstrate a Modular Adsorption Tank Insert designed for a system consisting of 100% densified media and capable of allowing less than 3 min. refueling time and H2 release rate of 0.02 g H2/(sec. kW) with a mass less than 9.4 kg and a volume less than 4.2 liters.

## Conclusions

- Experimental results have validated our MATI charge and discharge models
- Simulation using validated models that predict that the MATI concept can meet the performance documented in the MATI smart goals
- Based on patterning and bonding testing, aluminum is a realistic material of construction for both the MATI and the microcombustor.
- It appears that some degree of puck conduction enhancement will be required.

# Barrier H - Application

- To heat the $H_2$ stream from 200K to acceptable fuel cell operating temperature (T>233K) when fuel cell coolant and ambient temperatures are as low as 233K.

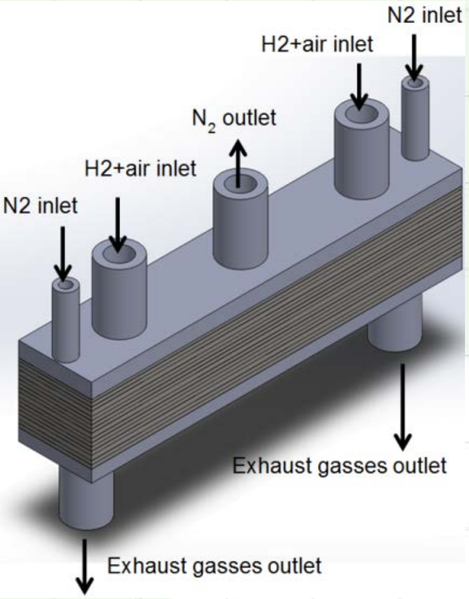


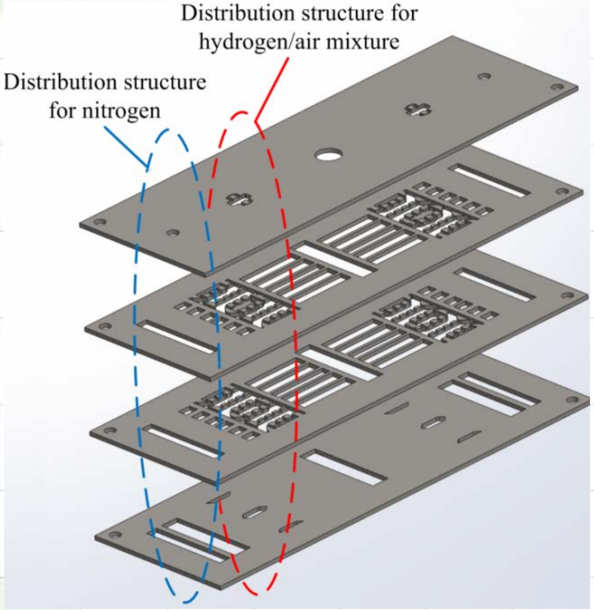

| | |
|---|---|
| Pressure range | Inlet pressure of 5 to 20 bar; outlet pressure greater than or equal to 5 bar |
| Temperature range | Inlet temperature of ~200 K |
| Target Heating | Increase temperature to a minimum of 233 K |
| Fluid flow rate | Maximum 2 g/s |

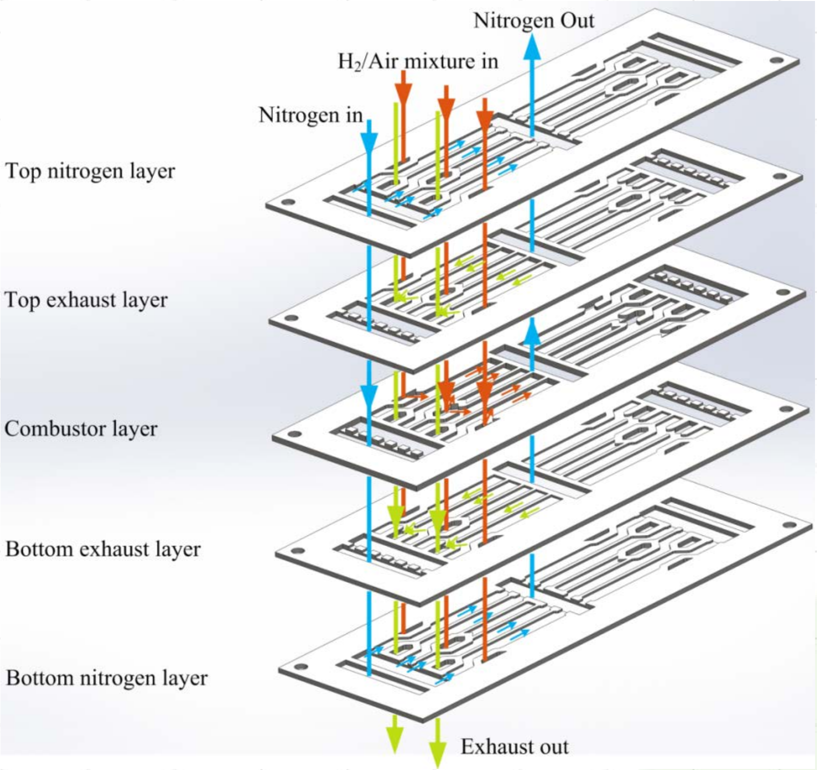
**SMART goal:**

*Develop and demonstrate a **1** kW catalytic combustor heat exchanger having > **85%** efficiency having a dry mass less than **0.9** kg and volume less than **0.65** liters*

# Barrier H- Microcombustor Multiple Unit Cell Design

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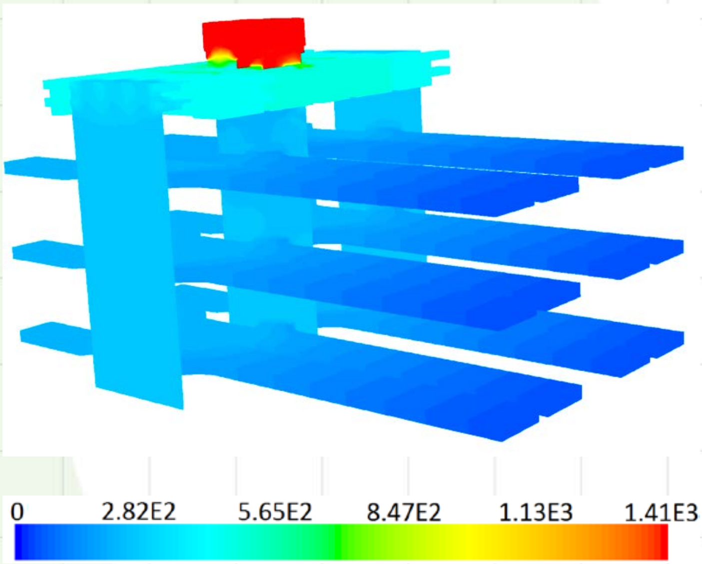
# Barrier H - Multiple Unit Cell Flow Distribution Simulations

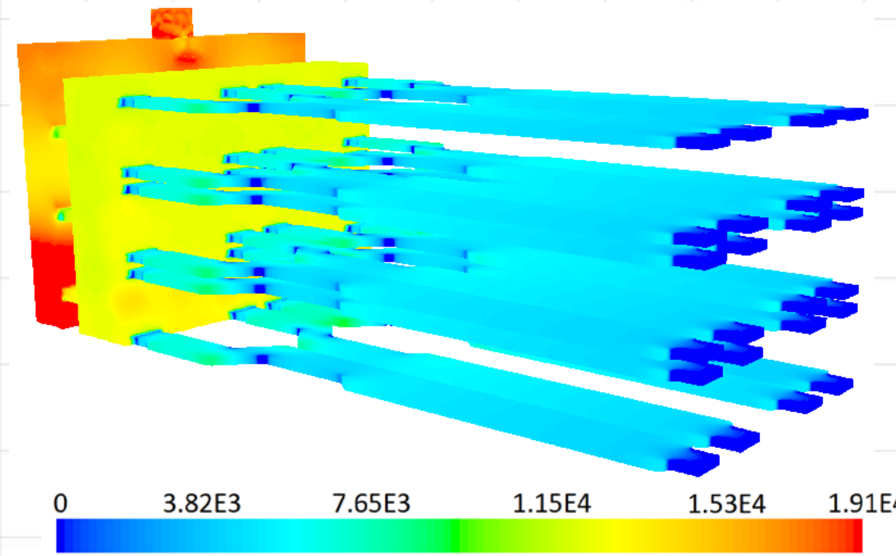
## Air/fuel inlet




Average velocity magnitude in combustor layers

| Channel velocity (m/s) | | | | |
|---|---|---|---|---|
| **Layer 1** | 2.61 | 2.59 | 2.57 | 2.6 |
| **Layer 2** | 2.57 | 2.51 | 2.51 | 2.57 |
| **Layer 3** | 2.56 | 2.53 | 2.53 | 2.55 |

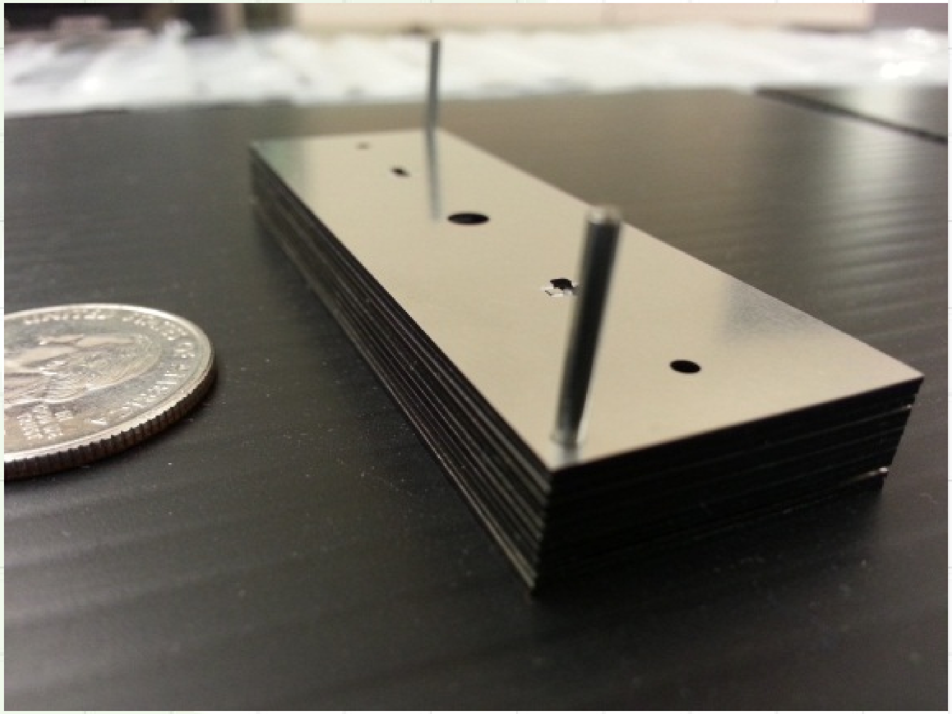
## Nitrogen inlet



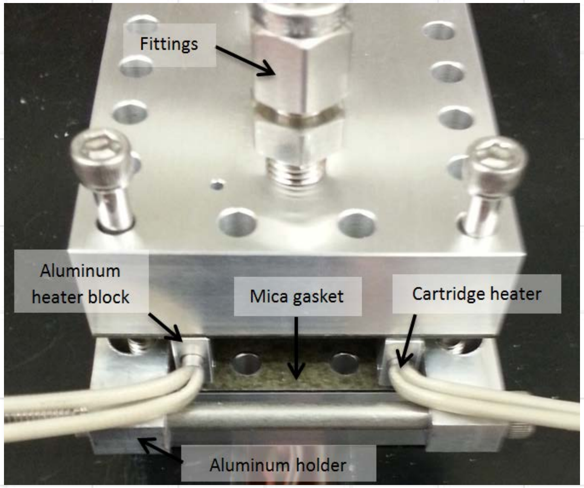

Average velocity magnitude in nitrogen layers

| | Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | Layer 6 |
|---|---|---|---|---|---|---|
| **Velocity (m/s)** | 37.2 | 37.4 | 37.6 | 37.4 | 37.2 | 37.1 |
| | 37.1 | 37.4 | 37.8 | 39.4 | 37.4 | 37.2 |
| | 37.1 | 37.5 | 37.3 | 37.2 | 39.2 | 37.1 |
| | 37.2 | 37.5 | 37.6 | 37.1 | 37.3 | 37.3 |

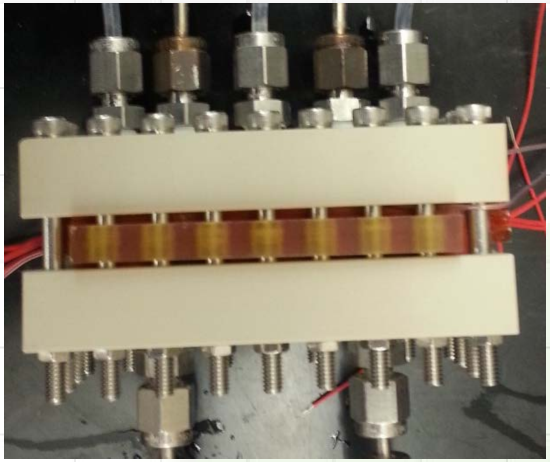
# Barrier H- Microcombustor Experimental Validation



A 16 unit cell device




Activation process setup



Experimental setup for the test conditions.

# Barrier H – Microcombustor Experimental Results

**The current results are for ambient temperature nitrogen as the heat transfer fluid and the first generation design.**

| Test case | Residence time (ms) | Hydrogen conversion (%) | Device Efficiency (%) | Device efficiency without heat loss (%) |
|---|---|---|---|---|
| 1 | 11.2 | 89.3 | 83.1 | 89.3 |
| 2 | 33 | 92 | 75 | 92 |
| 3 | 66 | 97 | 65 | 97 |

- Efficiency and conversion are strong functions of the body temperature of the device as well as the hydrogen/air mixture residence time.
- Based on the experimental results, 16 unit cell device can transfer 81.6 W to nitrogen flow with an efficiency of 83.1%. Therefore for a 1kW device 200 unit cell is required that produces 1020 W. The total size of such a system is 0.151 liters including the headers. The weight of the device will be 879.6 g if made from stainless steel and 296.9 g if made from Aluminum.

| | Power | Size | Weight | Efficiency |
|---|---|---|---|---|
| **SMART goal** | 1020 W | 0.65 liters | 900 grams | 85 |
| **Experimental data** | 1000 W ✓ | 0.151 liters ✓ | 880 grams ✓ | 84 ***Improvements ongoing*** |

# Barrier H – Microcombustor Smart Goals and Conclusions

- Smart Goal – Report on ability to develop and demonstrate a 1 kW catalytic combustor to augment partial H2 preconditioning by an exiting FC radiator with >85% efficiency having a mass less than .6 kg and volume less than .65 liters
- Conclusion – The current test article has achieved performance consistent with our smart goals using aluminum as the material of construction.

# Proposed FY 2014 Future Work

- Reduce Size and Weight of Storage and Improve Charge and Discharge Rates – **Modular Adsorption Tank Insert Development**
  - Complete experimental demonstration of the multi-cell test article in the current test apparatus
  - Demonstrate ability to enhance conductivity of the MOF-5 puck.
  - Complete design, assembly and initial testing of Phase 3 technology demonstration and test facility
- Reduce size and weight and increase performance of thermal balance of plant components - **Microchannel Combustor-Recuperator-Oil Heat Exchanger**
  - Complete demonstration of a 3 $kW_t$ microchannel combustor/heat exchanger

# Collaboration

- Oregon State University is a member of the Hydrogen Storage Engineering Center of Excellence (HSECoE) collaborating with five federal laboratories, one university and six companies
- Development of the Modular Adsorption Tank Insert heat exchanger is a collaboration with Savannah River National Laboratory (SNRL), Ford Motor Company, University of Michigan, Pacific Northwest National Laboratory and Universite' du Quebec a Trois-Rivieres.
- Development of system design for MATI is a collaboration with Savannah River National Laboratory, Ford Motor Company, Pacific Northwest National Laboratory and University of Michigan.
- Development of enhanced puck conductivity. Is a collaboration with Ford Motor Company and University of Michigan
- Development of the Microchannel Combustor-Recuperator-Hydrogen-HX is a collaboration with JPL and Savannah River National Laboratory

# Project Summary

- **Relevance**: Microchannel technology can reduce size, weight and charging time of hydrogen storage.
- **Approach**: For MATI and Microchannel Combustor-Recuperator-Oil-HX
  - Use MECS techniques to enhance the performance of heat and mass transfer devices.
  - Optimize a single unit cell
  - Use microlamination to “Number Up” .
- **Technical Accomplishments**:
  - Developed a revised MATI design that reduces cost and weight through the use of stamped MPTN.
  - Completed experimental investigations and model validation of single puck MATI
  - Completed modeling of charge and discharge cycles.
  - Initiated demonstration of enhance conductivity in “Hockey Puck”
  - Completed qualification of aluminum as a material of construction
  - Completed experimental investigation and model validation of microchannel cooling plate heat transfer and pressure drop
  - Completed design and testing of a 1 kWt Microchannel Combustor-HX unit for hydrogen heating during cold starts. Results confirm performance and demonstrate ability to meet SMART goals.
- **Collaboration**: Member of HSECoE team.
- **Proposed Future Research**:
  - Complete demonstration of multi-cell MATI test article,
  - Complete demonstration of puck conduction enhancement
  - Complete design, assembly and initial testing for Phase 3 2 liter prototype
  - Complete demonstration of a 1-3 $kW_t$ combustor for hydrogen conditioning

# Supplemental Slides

# HSECoE Center Organization

## *Hydrogen Storage Engineering Center of Excellence*

**D. Anton, SRNL**
**T. Motyka, SRNL**

### *Materials Operating Requirements*

D. Herling, PNNL

- Materials Centers of Excellence Collaboration – SRNL, LANL, NREL
- Reactivity – UTRC
- Adsorption Properties – UQTR
- Metal Hydride Properties – SRNL
- Chemical Hydride Properties - LANL

### *Transport Phenomena*

B. Hardy, SRNL

- Bulk Materials Handling – PNNL
- Mass Transport – SRNL
- *Thermal Transport – SRNL,OSU*
- Media Structure - GM

### *Enabling Technologies*

J. Reiter, JPL

- Thermal Insulation – JPL
- Hydrogen Purity – UTRC
- Sensors – LANL
- Materials Compatibility – PNNL
- Pressure Vessels – PNNL
- *Thermal Devices - OSU*

### *Performance Analysis*

M. Thornton

- Vehicle Requirements– NREL
- Tank-to-Wheels Analysis – NREL
- Forecourt Requirements - UTRC
- Manufacturing & Cost Analysis - PNNL

### *Integrated Power Plant/ Storage System Modeling*

D. Mosher, UTRC

- Off-Board Rechargeable - UTRC
- On-Board Rechargeable – GM
- Power Plant – Ford

### *Subscale Prototype Construction, Testing & Evaluation*

T. Semelsberger, LANL

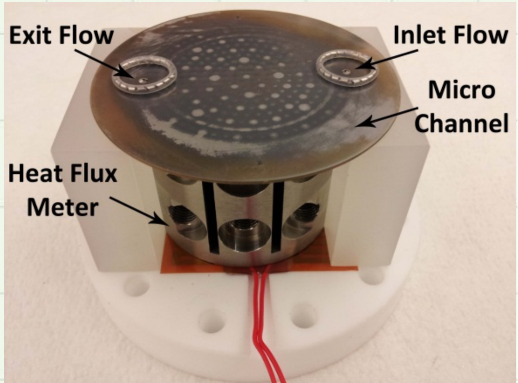
- Risk Assessment & Mitigation – UTRC
- System Design Concepts and Integration - LANL
- Design Optimization & Subscale Systems – LANL, SRNL, UQTR
- Fabricate Subscale Systems Components – SRNL, LANL
- Assemble & Evaluate subscale Systems – LANL, JPL, UQTR

### *Technology Area*

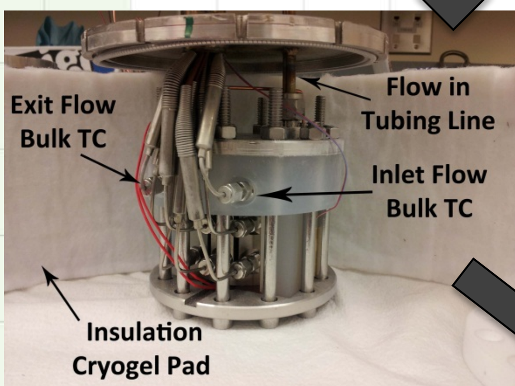
Technology Area Lead

- Technology Team – TT Lead
- Technology Team – TT Lead
- Technology Team – TT Lead

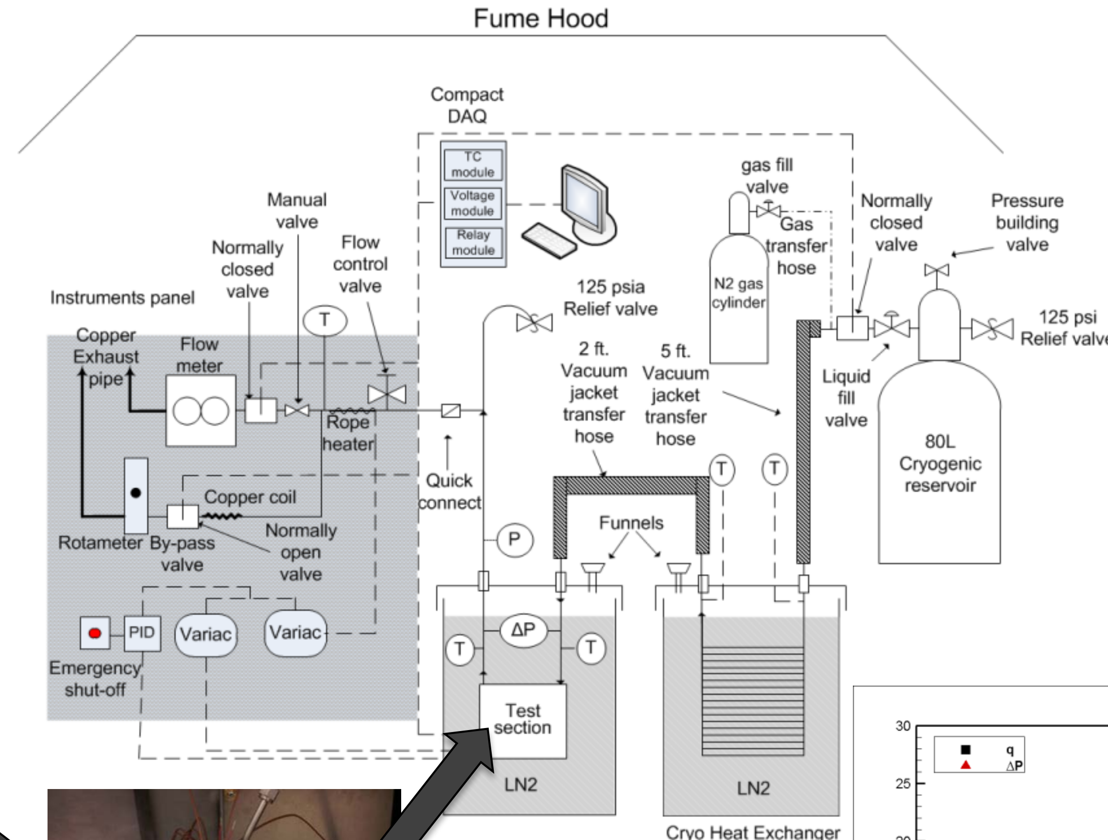
# Barriers A and E – MATI Separate Effects Heat Transfer Testing

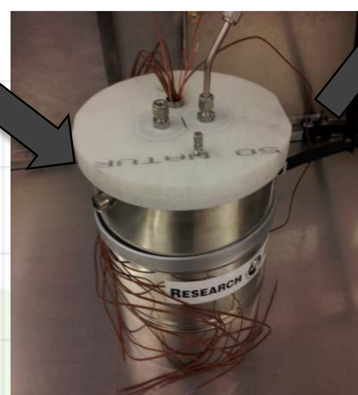



Partially assembled view of the test section

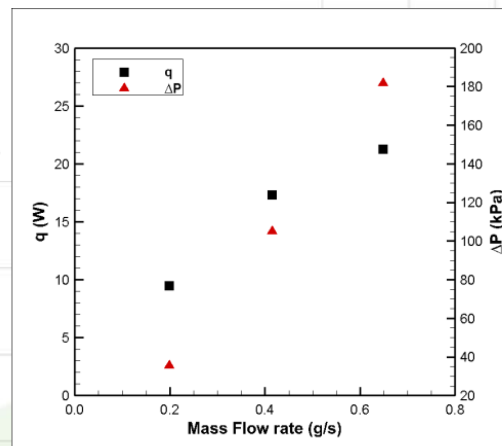



Assembled view of the test section



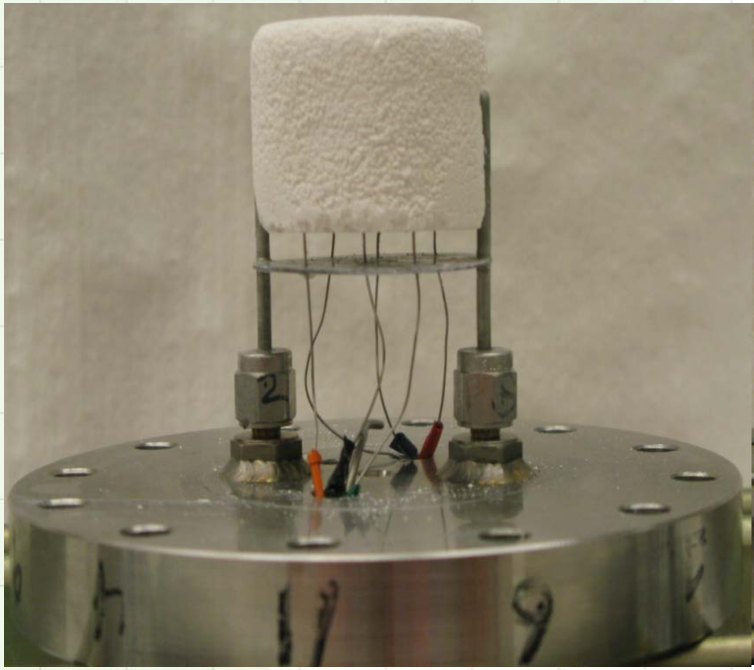



Test section dewar

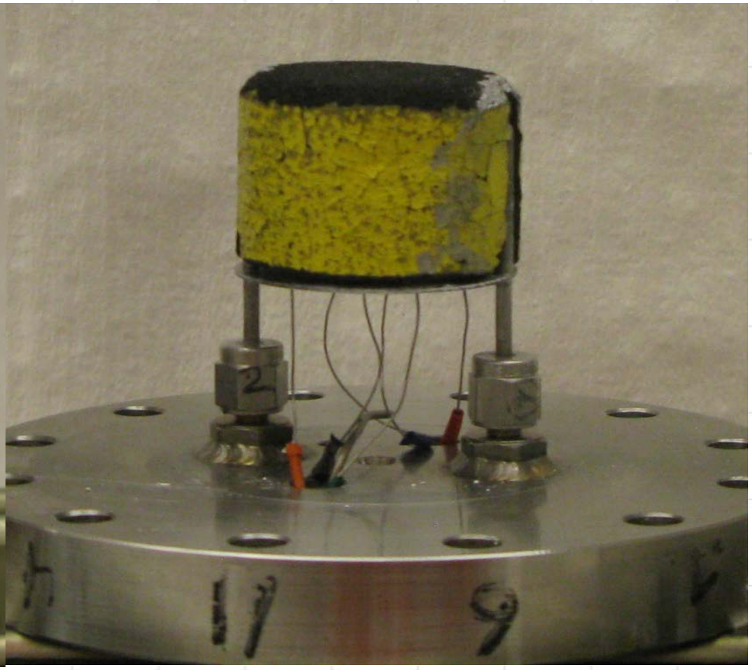



Preliminary heat transfer test with $N_2$ gas

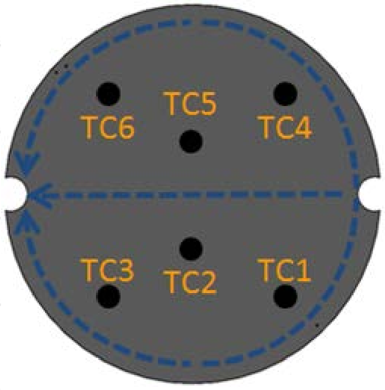
# Barriers A and E – Placement of Adsorbent Beds

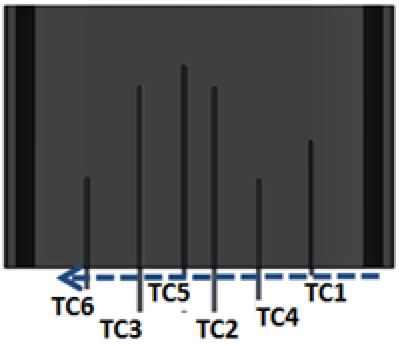


*MOF-5 suspended over single MATI cooling plate by thermocouples after completing $N_2$ and $H_2$ adsorption experiments.*



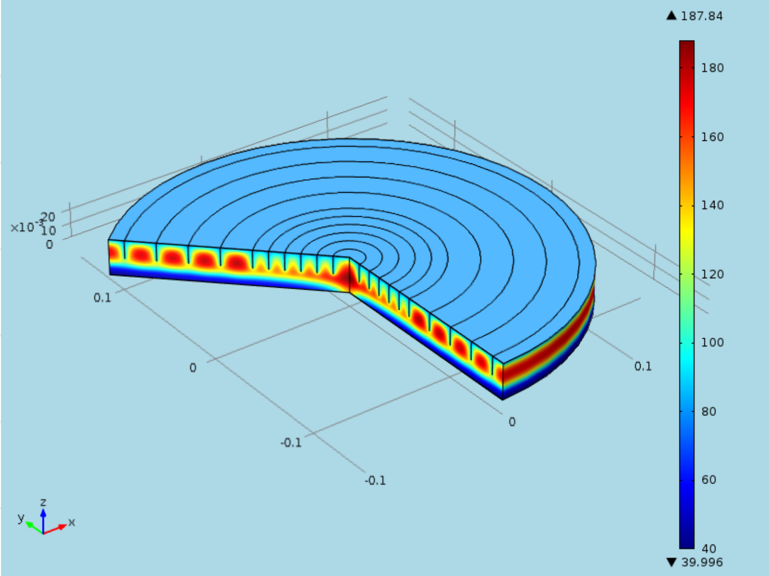
*Activated carbon sample on surface of single MATI cooling plate after completing $N_2$ and $H_2$ adsorption experiments.*



# Barriers A and E - Impact of bed conduction and MATI on charging and discharging cycle

*Hydrogen enter/leave the bed through a distribution plate. During charging, the bed is cooled by liquid nitrogen flowing through the heat exchanger. During discharging, the bed is heated by hot hydrogen flowing through the heat exchanger.*



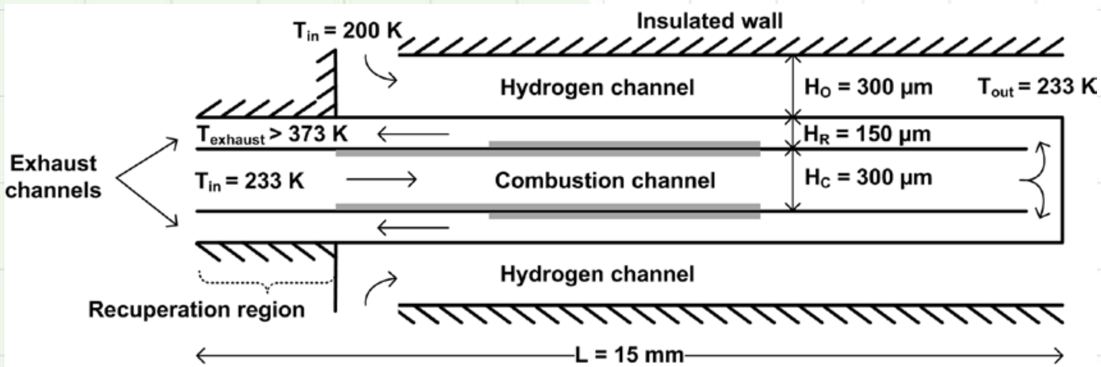

***Momentum conservation** is modeled with Navier-Stokes equations in the distribution and heat exchanger plates. Adsorption bed is modeled as porous media with Brinkman equations.*

***Mass conservation** is implemented through continuity equation.*

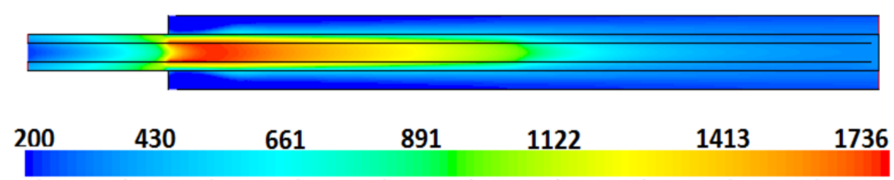
***Energy balance** in the bed distinguishes adsorbent material, adsorbed and free space hydrogen.*

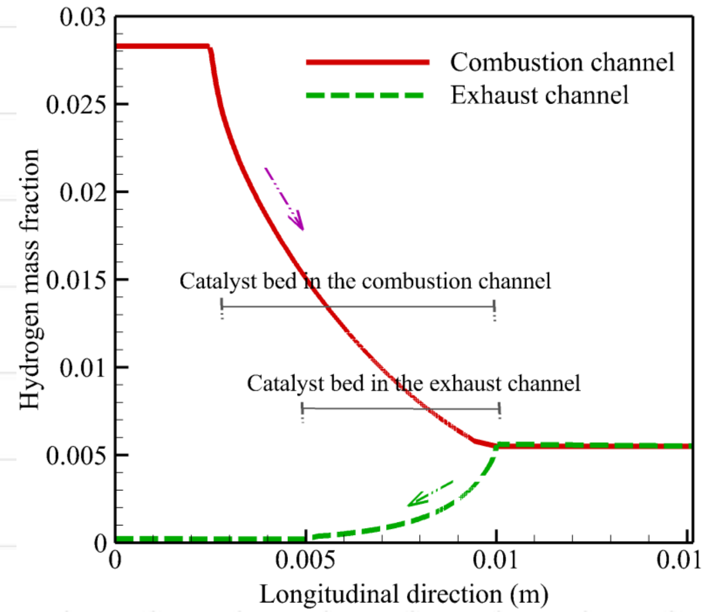
***Adsorption/desorption kinetics** is computed with Dubinin-Astakhov model and it's effects are accounted for in all three balances.*

# Barrier H – Microcombustor 2D Simulations




**Temperature contours (K)**




Hydrogen mass fraction along the length of the channel

## Working Fluid: Hydrogen

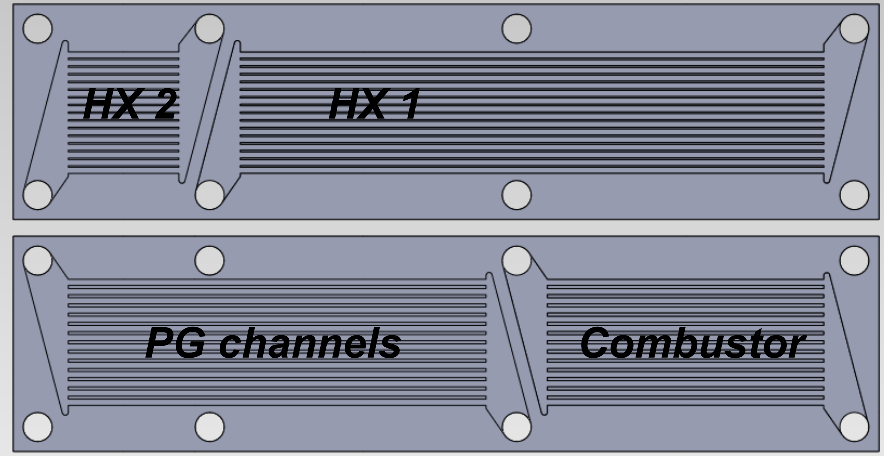
| $\dot{m}_{H_2}$ (g/s) | $P_{H_2}$ (bar) | $T_{out,H_2}$ (K) | $H_2$ conversion (%) | $\eta$ (%) | $\Delta P$ (Pa) |
|---|---|---|---|---|---|
| **2** | 5 | 235.7 | 99.8 | 93.3 | 5736.3 |
| | 20 | 236.1 | 99.5 | 92.9 | 5833.9 |
| **0.5** | 5 | 237.7 | 99.8 | 92.4 | 991.6 |
| | 20 | 243.8 | 99.4 | 92.1 | 1014.4 |

## For *L*ab *E*xperiments- Surrogate Working Fluid: Nitrogen

| $\dot{m}_{N_2}$ (g/s) | $P_{N_2}$ (bar) | $T_{out,N_2}$ (K) | $H_2$ conversion (%) | $\eta$ (%) | $\Delta P$ (Pa) |
|---|---|---|---|---|---|
| **26.1** | 5 | 233.6 | 99.9 | 93.1 | 5133.7 |
| **6.57** | 5 | 233.3 | 99.8 | 92.4 | 711.8 |

# Integrated Combustor-HXs

- *Length: 280 mm*
- *Width: 70 mm*
- *Height: 40 mm*
- *Volume: 540 cm^3 (material)*
- *Weight with SS: 4.25 kg*
- *Weight with Al: 1.46 kg*




***Channel Dimensions***
- *Depth = 0.4 mm*
- *Width = 2.0 mm*
- *16 channels/shim*
- *66 shims in total*

***Heat Duties***
- *HX1 = 5.4 kW*
- *HX2 = 4.5 kW*
- *Combustor = 1.7 kW*

***Pressure Drops***
- *HX1_PG = 1.7 psi*
- *HX2_PG = 0.6 psi*