Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage

Kevin Drost
Oregon State University
May 11th 2011

Hydrogen Storage Engineering
CENTER OF EXCELLENCE

ST 046

This presentation does not contain any proprietary, confidential, or otherwise restricted information

ONAMI
OREGON NANOSCIENCE AND MICROTECHNOLOGIES INSTITUTE

Microproducts Breakthrough Institute

Overview

Timeline

- Feb 1st 2009 start
- Jun 30th, 2014 finish
- 28% Complete

Budget

- Total project funding
  - DOE - $2,398,935
  - Contractor - $600,345
- Funding for FY10 - $350,000
- Funding for FY 11 - $400,000

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, TRC, 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 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**
  - **Reduces charging time**
- 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
- In the temperature range of interest, attractive high volume manufacturing options exist.

Approach - Programmatic

- **Phase 1: System Requirements & Novel Concepts**
  - OSU will focus 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 will identify the highest value applications and conduct 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 will develop predictive models, design and evaluate components, fabricate proof-of-principle test articles, conduct proof-of-principle tests, and use 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 – Phase One Technical Approach

- For each high priority component use microchannel technology to reduce barriers to heat and mass transfer.
- Optimize the performance of a single unit cell (i.e. an individual microchannel) and then “Number Up”
  - Develop appropriate simulation tools
  - Validated simulation tools by experimental investigations
  - Use simulation to optimize a unit cell
- Explore microlamination as a path to “numbering up” by low cost high volume manufacturing

Technical Accomplishments

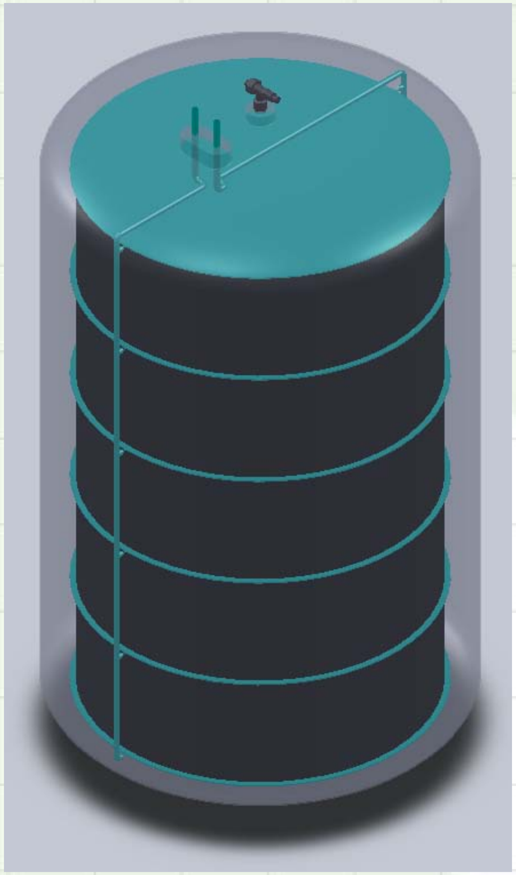
- **Technical Progress Relative to 2010/2011 Milestones -** Completed identification of highest value applications:
  - 1) **Modular Adsorption Tank Insert**
  - 2) **Microchannel Combustor-Recuperator-Oil HX Concept**
- **Technical Progress relative to Objectives**:

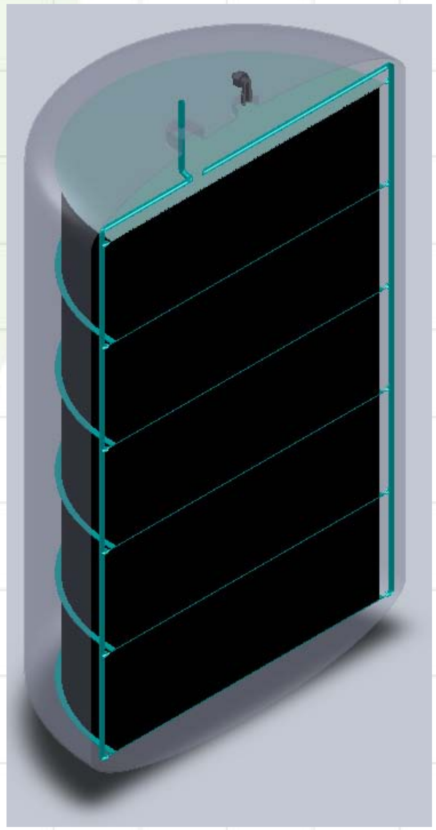
1) Reduce the size and weight of storage – **Modular Adsorption Tank Insert Feasibility Study**

2) Improve charging and discharging rate of storage – **Modular Adsorption Tank Insert Feasibility Study**

3) Reduce size and weight and increase performance of thermal balance of plant components – **Microchannel Combustor-Recuperator-Oil HX Development**

Barriers A and E - Multi-functional Modular Adsorption Tank Insert (MATI)





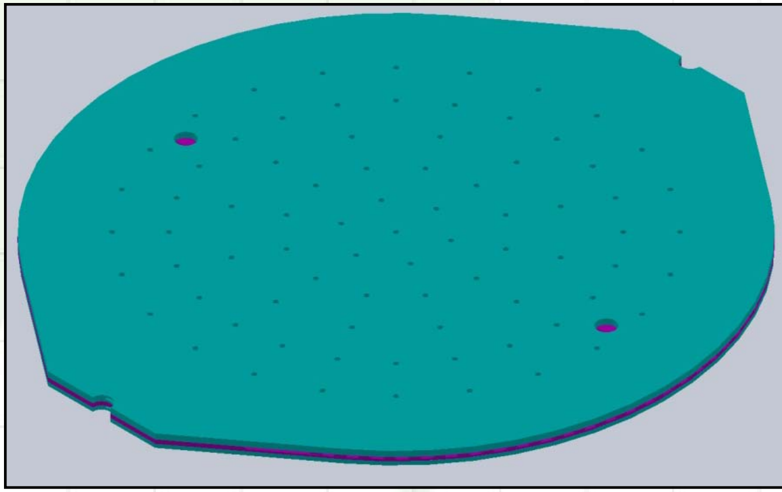
Why ?

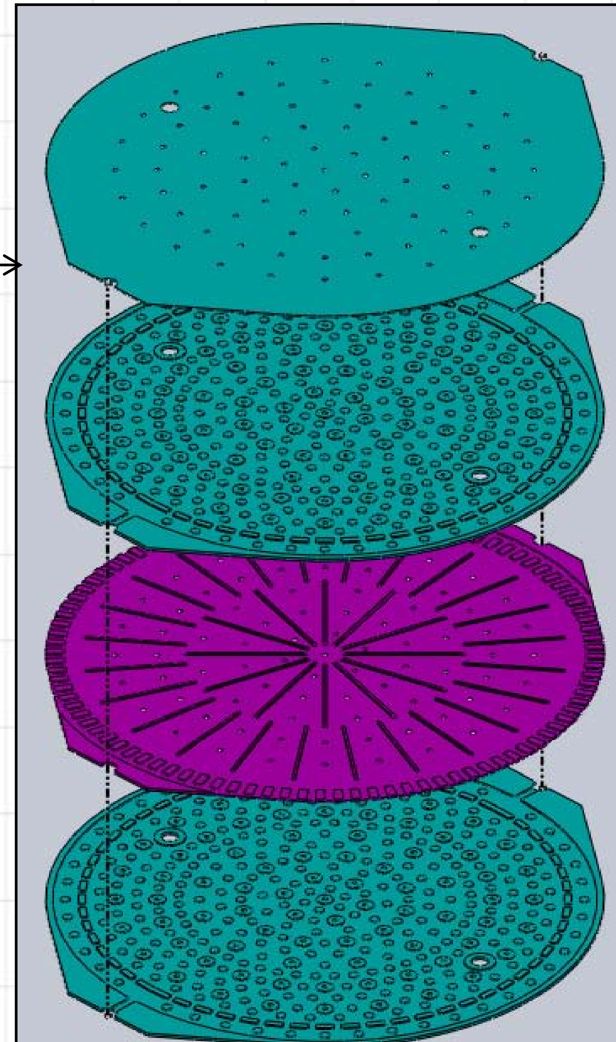
- *May allow densification without use of binder*
- *Integrated Thermal Management (heating and cooling)*
- *Integrated Hydrogen Distribution*
- *The module is not the primary pressure bearing surface*

Feasibility Study

- *Technical Feasibility*
- *Manufacturability*
- *Cost*

Barriers A and E - MATI Integrated Cooling, Heating and H_2 Distribution plates

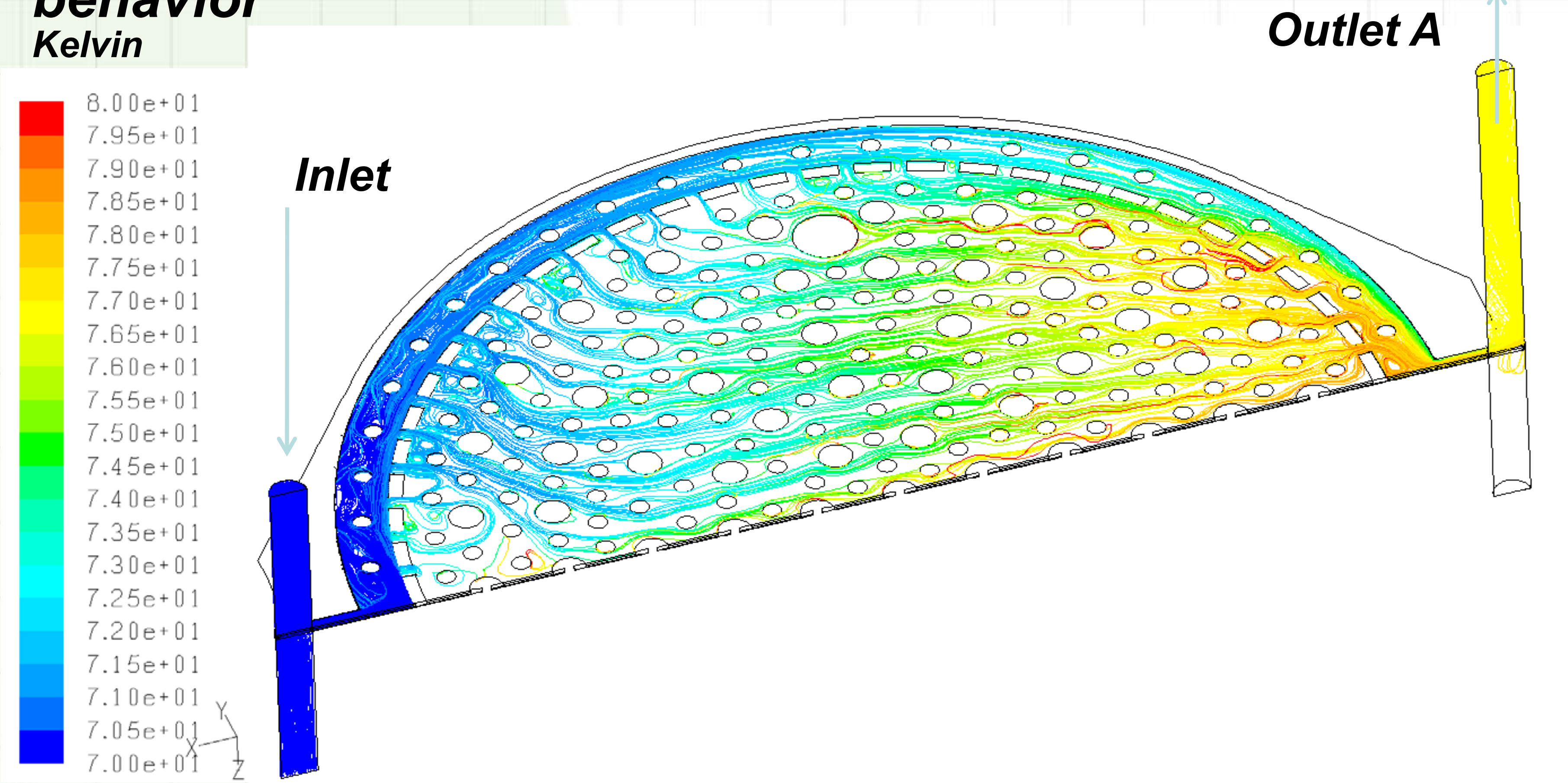




1 mm deep channels 500 µm thick fins

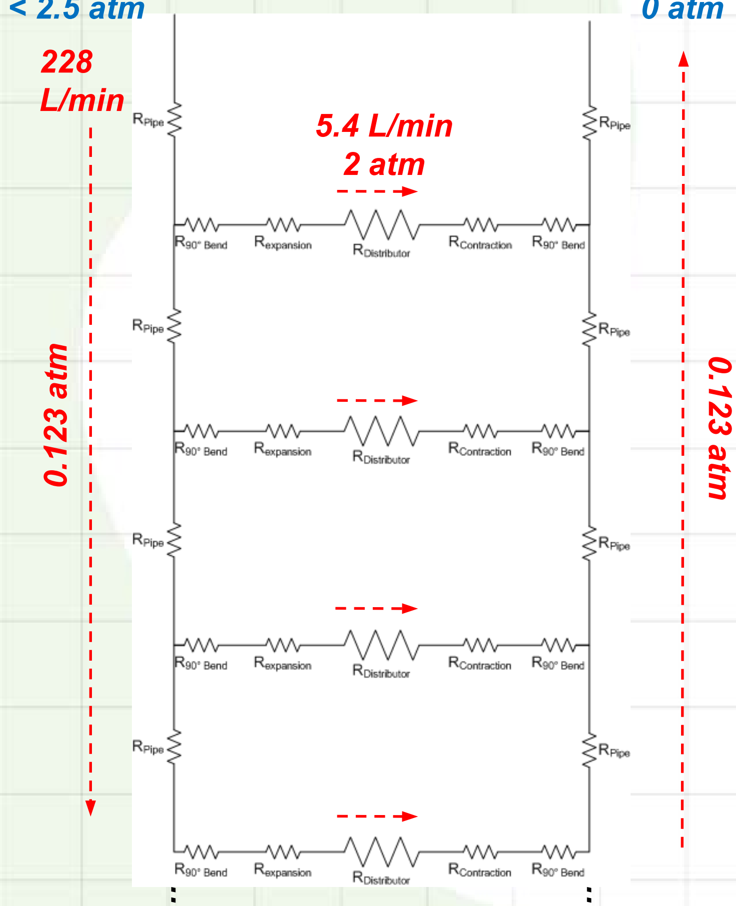
Barriers A and E - MATI LN2 Flow Through the Cooling Plate

Streamlines colored by temperature indicate flow behavior

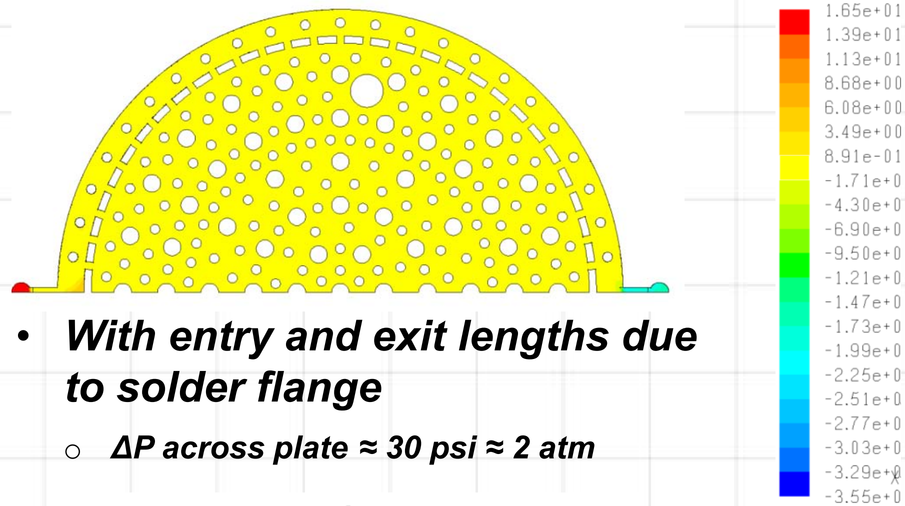


Barriers A and E - MATI Pressure Drop

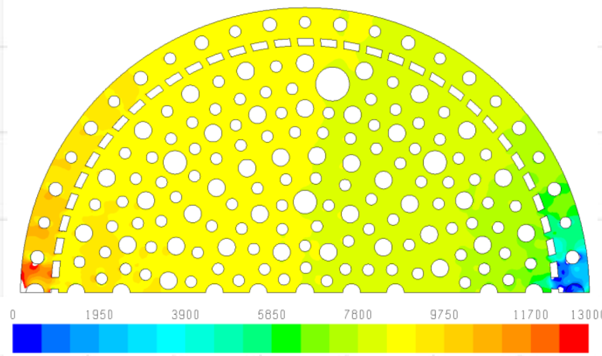
Distributor network (4 stack)



ΔP across header = 0.123 atm/header

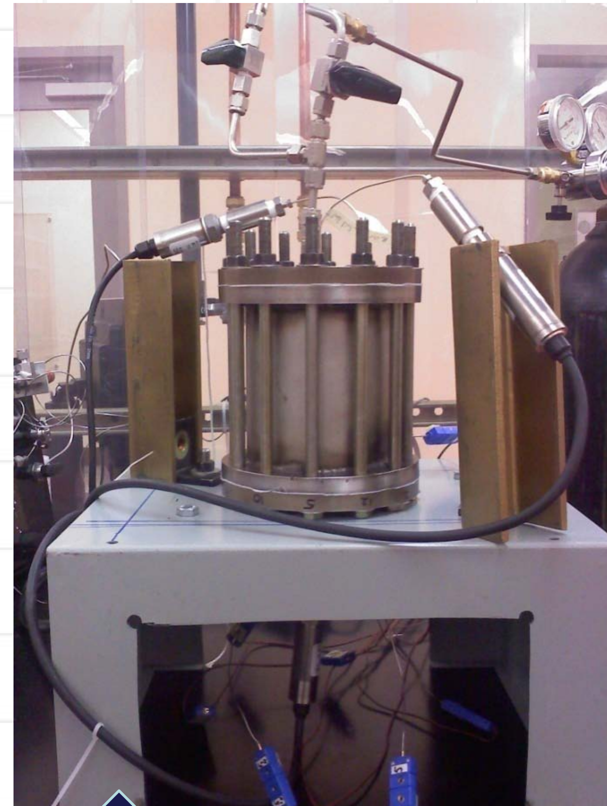


- ***With entry and exit lengths due to solder flange***
  - ***ΔP across plate ≈ 30 psi ≈ 2 atm***

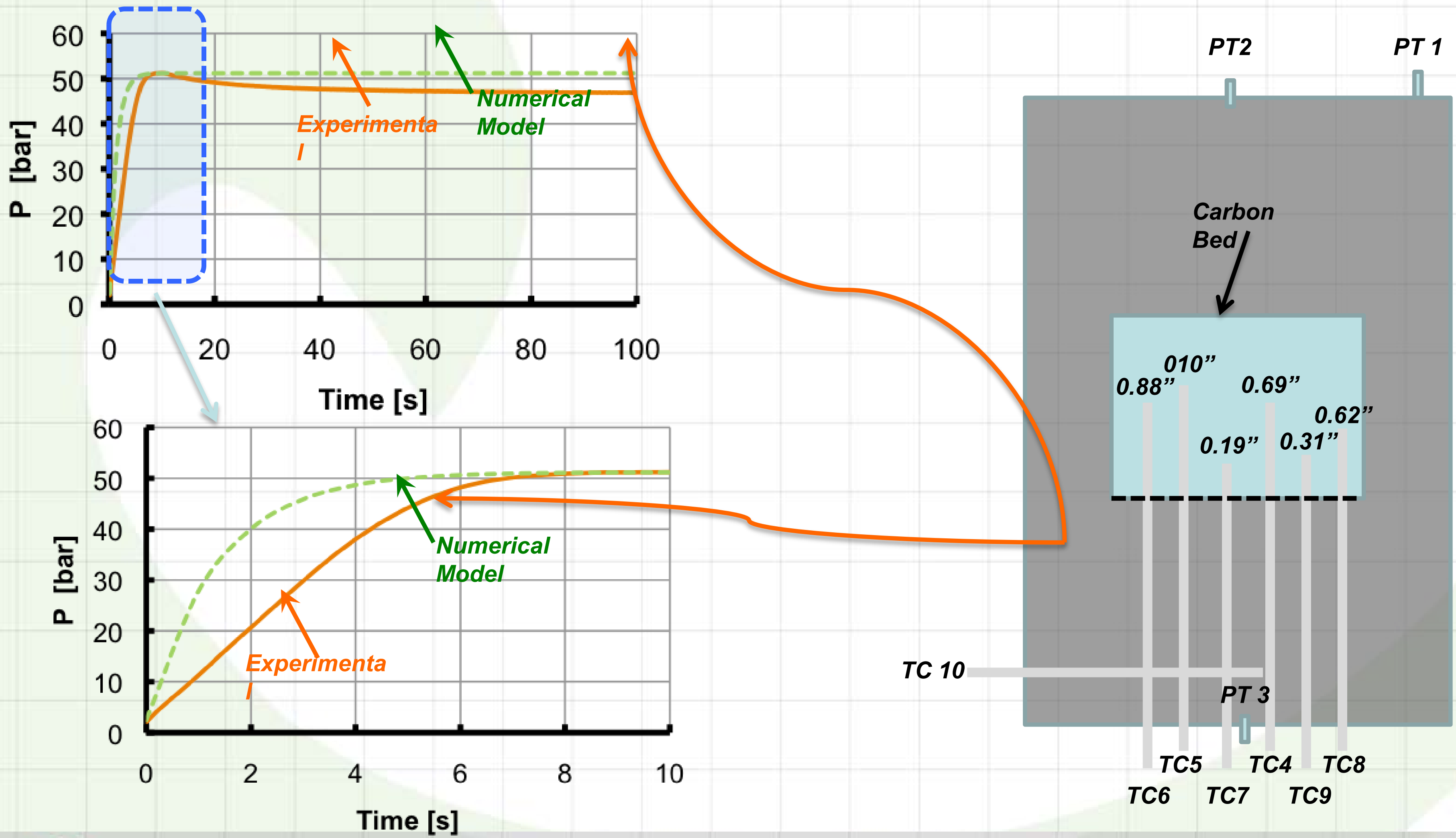


- ***Possible to greatly reduce by eliminating entry and exit lengths***
  - ***ΔP across plate =15.6 kPa = 0.154 atm***

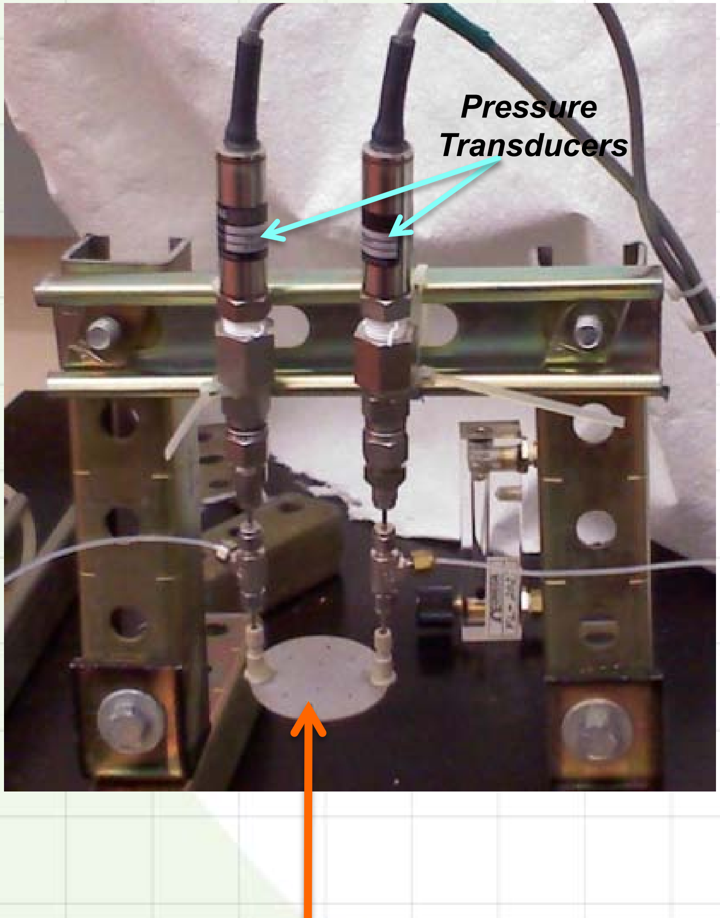
Barriers A and E - MATI Experimental Validation



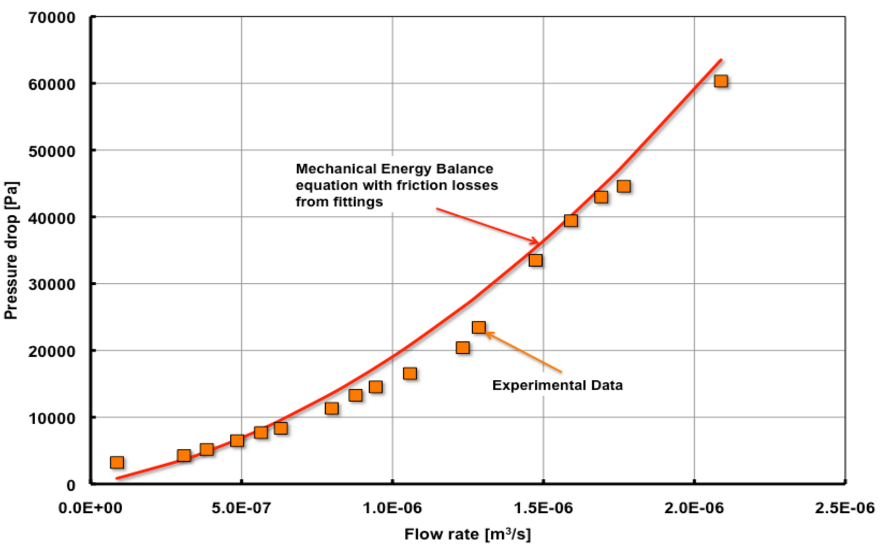
Barriers A and E - MATI Experimental Results with Carbon Bed Adsorption - Pressure

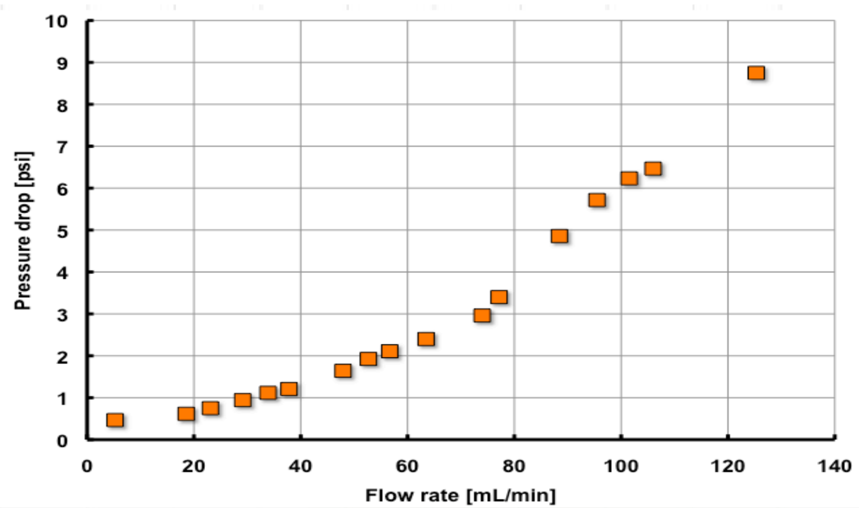


Barriers A and E - Pressure Drop Through an MATI Cooling Plate & Connectors

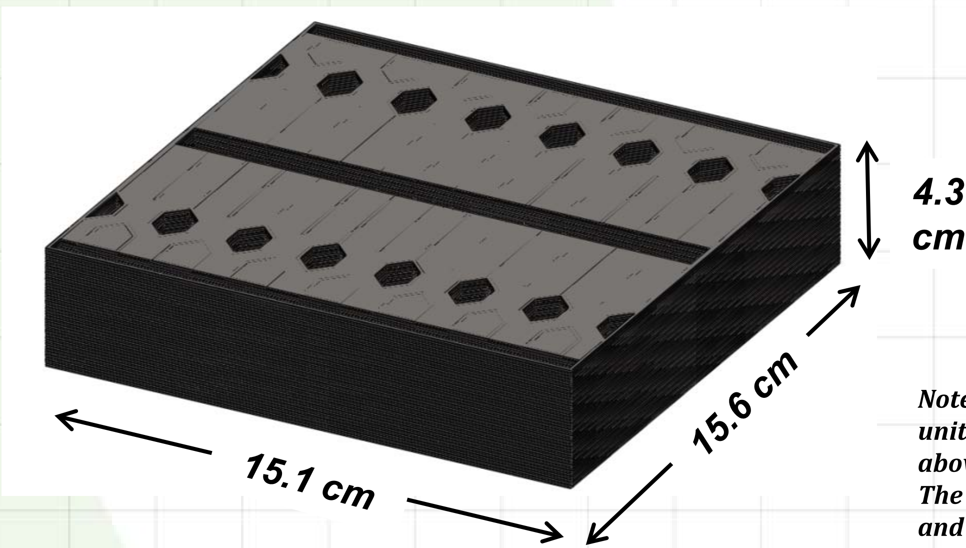


MAS Cooling Plate & H_2 Distributor





Barrier H - Microchannel Combustor-Recuperator-Oil-HX Concept



	12 kW OSU	30 kW OSU	30 kW Sandia
Width (cm)	15.1	22.2	32.0
Length (cm)	15.6	21.1	38.1
Height (cm)	4.3	7.9	29.7
Volume (L)	1.0	3.7	36.2
316 SS Weight (kg)	3.8	11.7	Unknown
3003-O Al Weight[2] (kg)	1.3	4.0	Unknown

Notes: 1. Estimates are based on detailed numerical simulations of a unit cell. The estimates include components shown in the schematic above. Not included inlet and exit ducting, insulation, pump and blower. The Sandia design included the inlet and exit ducting. However, the size and weight estimates should not change dramatically with inclusion of inlet and exit ducting.
2. The Aluminum combustor size is a potential estimate and represents a low-risk extension of the SS combustor. Further work is needed in testing and fabrication side to ensure its performance and manufacturability.

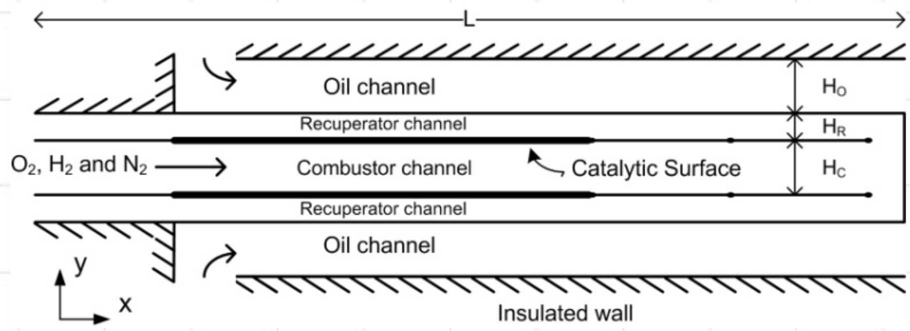
12 k W Microchannel Combustor-Recuperator-Oil-HX With an estimated cost of $120 to $200 at a production rate of 500,000 units per year

Barrier H - Numerical simulations of Microchannel Combustor-Recuperator-Oil-HX Concept

- ***The range of geometrical and fluidic values in the parametric study***

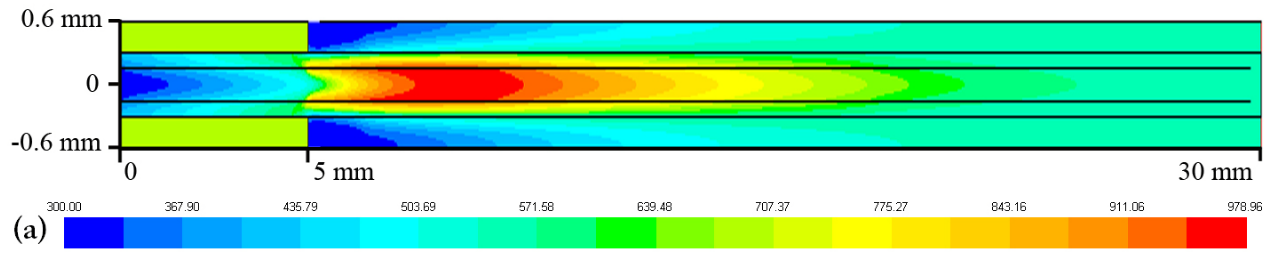
Parameter	Value
L (mm)	17-45
H_C (μm)	300
H_O (μm)	300
Oil inlet velocity (m/s)	0.01-0.02
Gas mixture inlet velocity (m/s)	4
Equivalence ratio (f)	0.1-1
Catalyst length (mm)	5-25
Oil inlet temperature (K)	300-450

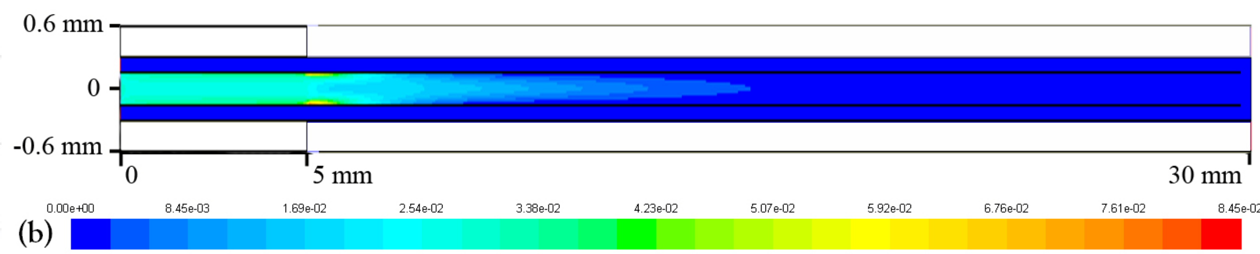
Schematic view of the modeled geometry



- ***Sample temperature (a) and H_2 mass fraction (b) contours. Conditions are shown in the below table.***

Catalyst length (mm)	15
L (mm)	30
Oil inlet velocity (m/s)	0.01
Gas mixture inlet velocity (m/s)	4
Equivalence ratio (f)	1
Oil inlet temperature (K)	300

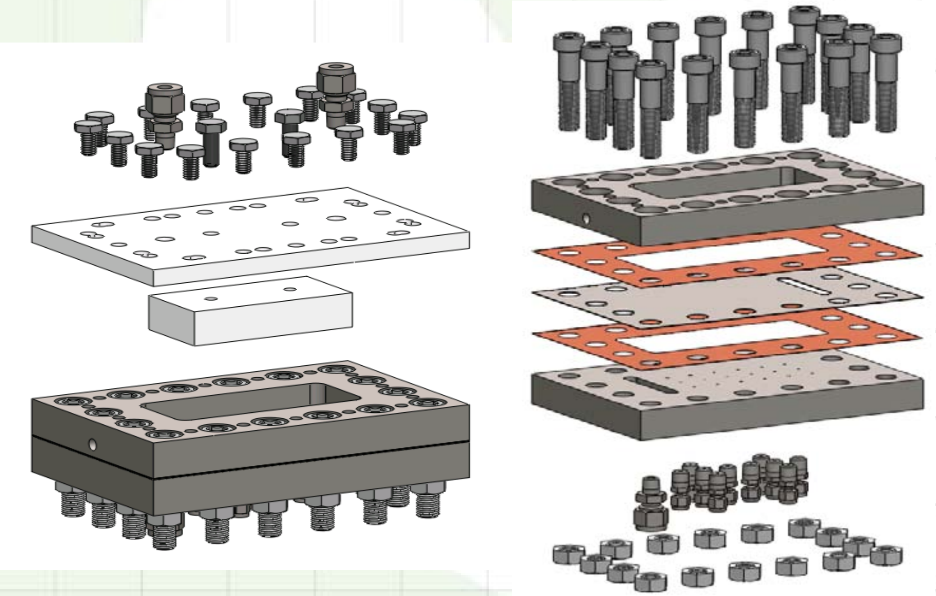




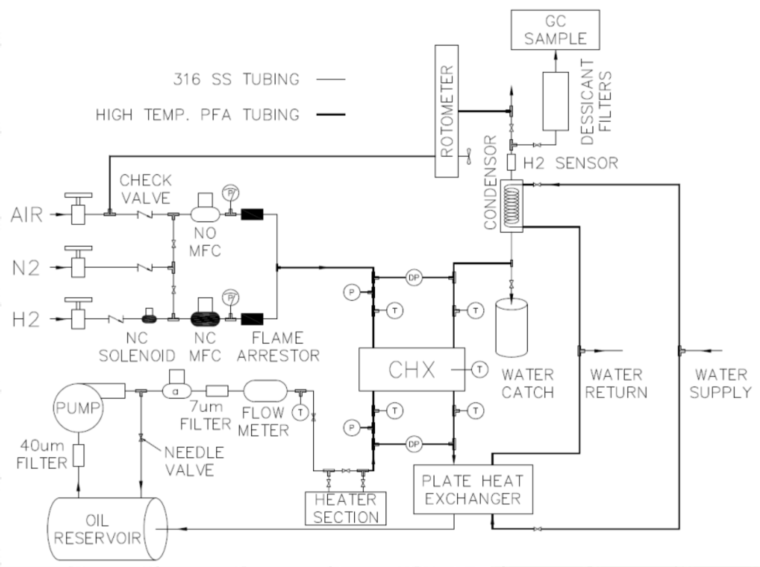
Barrier H - Microchannel Combustor-Recuperator-Oil-HX Experimental Facility

- A unit cell ***consisting of a combustor channel, a recuperator channel, and an oil channel will be tested***
- Facility fully ready for combustion experiments
- First gen. test section ready for combustion experiments

Assembled Experimental Facility

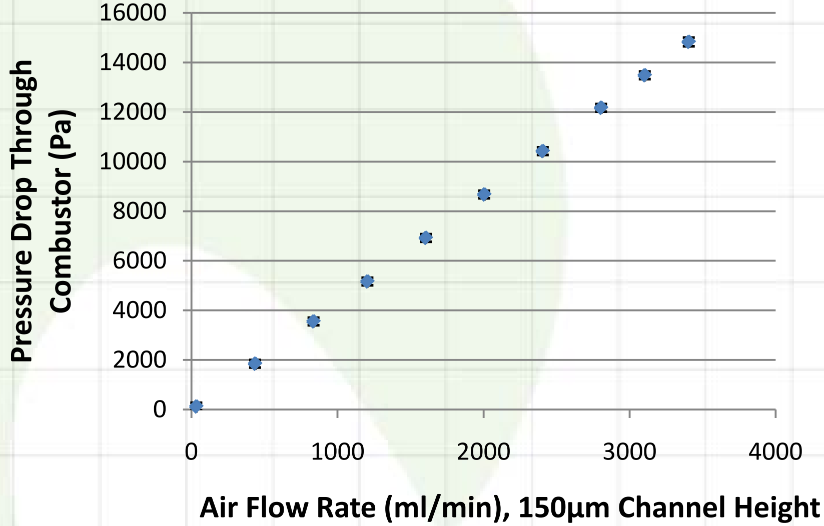


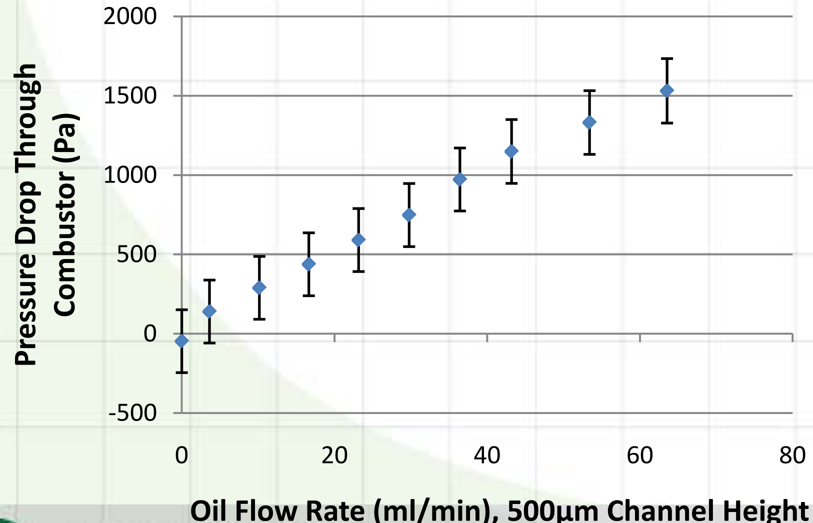
Exploded View of Combustor

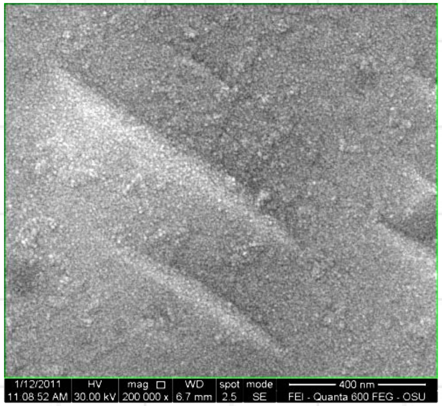


Experimental Facility Schematic

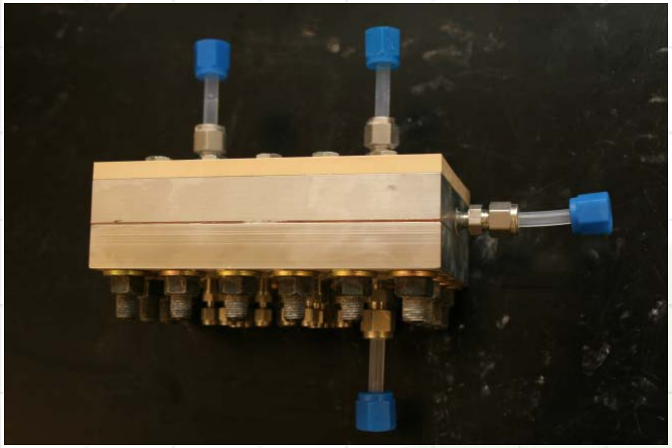
Barrier H - Microchannel Combustor-Recuperator-Oil-HX Preliminary Experiments







SEM image of Pd catalyst deposited on shim



Assembled combustor

Proposed FY 2011 Future Work

- Reduce Size and Weight of Storage and Improve Charge and Discharge Rates – **Modular Adsorption Tank Insert Development**
  - Complete experimental validation of tank insert simulation and unit cell performance
  - Optimize tank insert design to reduce weight, volume and cost
  - Complete design of Phase 2 technology demonstration
- Reduce size and weight and increase performance of thermal balance of plant components - **Microchannel Combustor-Recuperator-Oil Heat Exchanger**
  - Experimentally validate simulation results
  - Demonstrate rapid start-up and transient performance of device
  - Complete design of Phase 2 technology demonstration

Collaboration

- Oregon State University is a member (a prime contractor) of the Hydrogen Storage Engineering Center of Excellence (HSECoE) with five federal laboratories, one university and six companies
- Development of the Modular Adsorption Tank Insert is a collaboration with Savannah River National Laboratory (SNRL), Ford Motor Company and L'Université du Québec à Trois-Rivières.
- Development of the Microchannel Combustor-Recuperator-Oil-HX is a collaboration with General Motors.

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**:
  - Completed identification of the highest value applications of microchannel-based technology (2009/2010 DOE milestone)
  - Completed design of MATI , developed a fabrication plan and initiated testing of a tank insert unit cell
  - Completed component design and initiated testing of Microchannel Combustor-Recuperator-Oil-HX unit cell. Results suggest a large reduction in size and weight with a reasonable production cost.
- **Collaboration**: Member of HSECoE team.
- **Proposed Future Research**:
  - MATI - Complete cost estimate, design optimization and unit cell testing and initiate development of technology demonstration
  - Microchannel Combustor – Complete unit cell testing and initiate the development of the technology demonstration

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

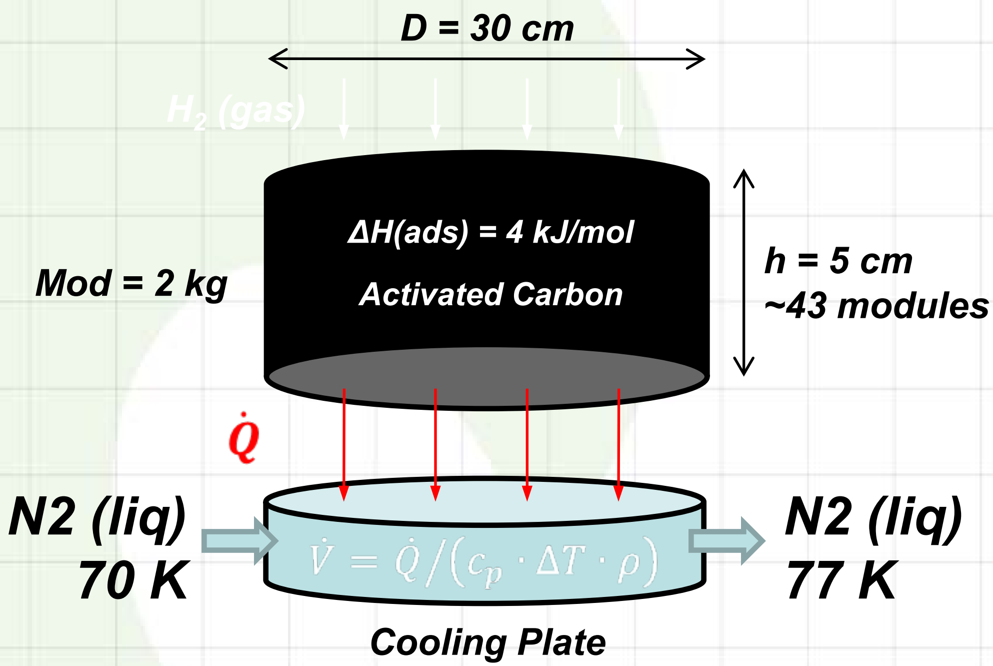
- Risk Assessment & Mitigation – UTRC
- System Design Concepts and Integration - LANL
- Design Optimization & Subscale Systems – LANL, SRNL, UQTR
- Fabricate Subscale Systems Components – SRNL, LANL
- Assemble & Evaluate subscale Systems – LANL, JPL, UQTR

Technology Area

Technology Area Lead

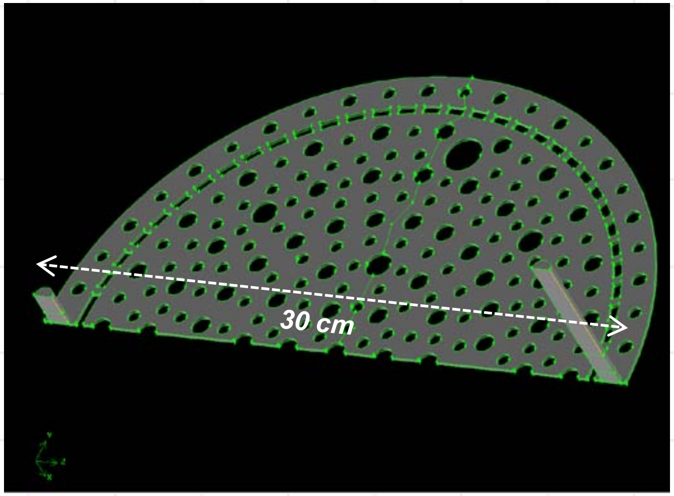
- Technology Team – TT Lead
- Technology Team – TT Lead
- Technology Team – TT Lead

Supplemental Slides - Barriers A and E - MATI LN2 Flow Requirements



Bed Diameter of 30 cm	Two Cooling Plates		
Bed Height (cm)	Heat Flux (W/cm2)	N2 Flow Rate (L/min)	Avg Velocity (m/s)
12.70	95.26	6.91	1.47
10.00	75.00	5.44	1.15
7.60	57.00	4.13	0.88
5.00	37.50	2.72	0.58
2.50	18.75	1.36	0.29

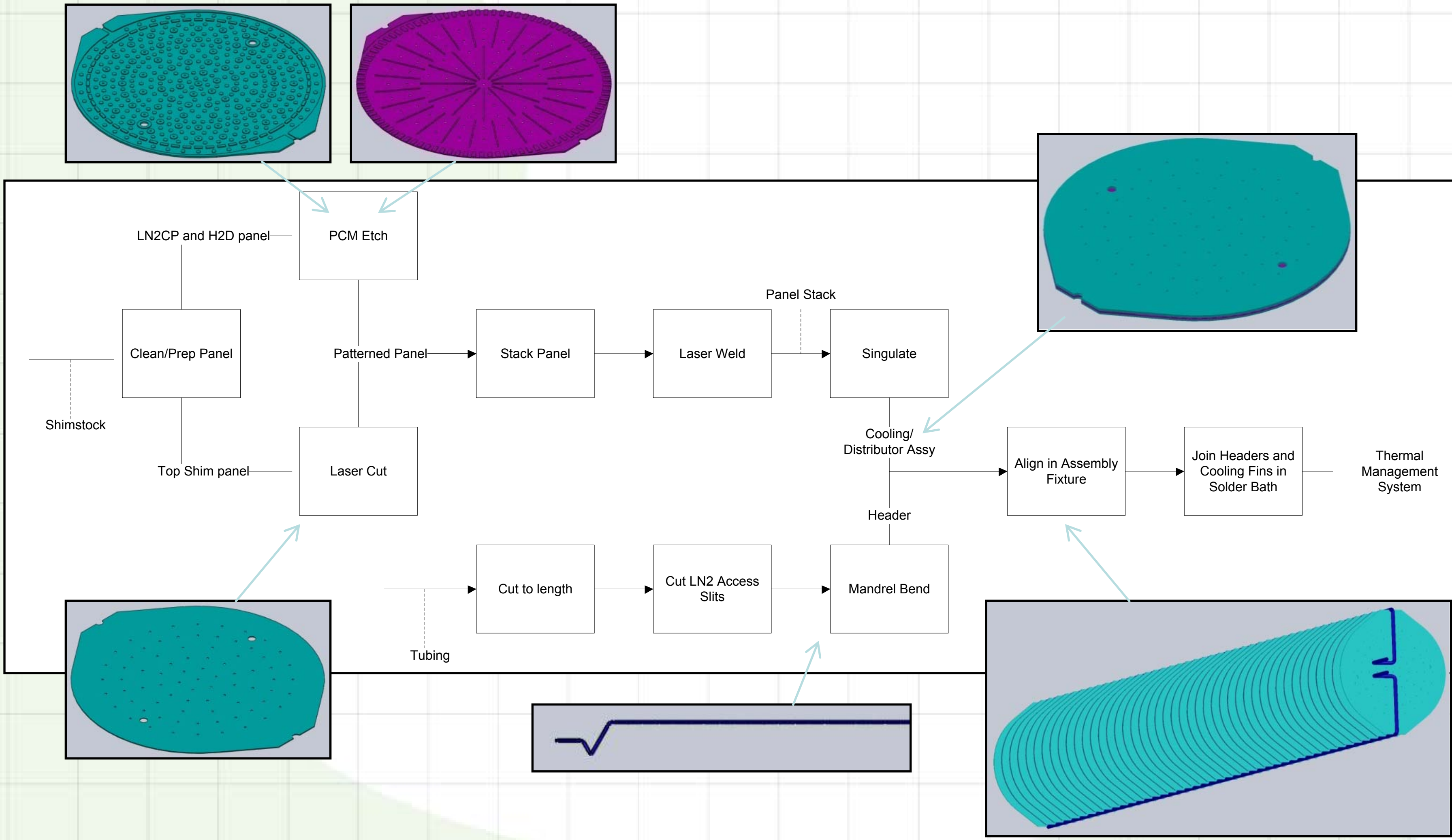
Current cooling plate design (half model)



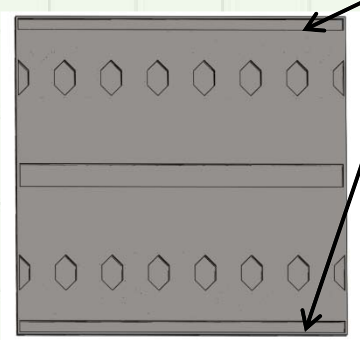
***Assumptions** (Activated carbon)*
- *Carbon density = 0.56 g/cc*
- *250 s H_2 charge time*
- *Assume all of adsorbent reacts*

***Important Parameters** (1 kW cooling plate)*
- *Inlet Area*
- *Pillar area*
- *Channel depth = 1 mm*
- *Pressure drop*
- *Temp distribution i.e. temp < 77 K*

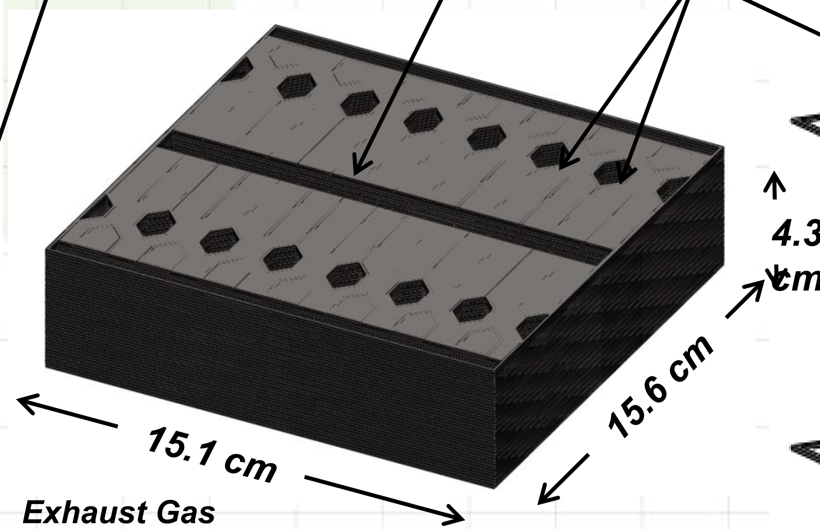
Supplemental Slides - Barriers A and E – MATI Manufacturing Plan

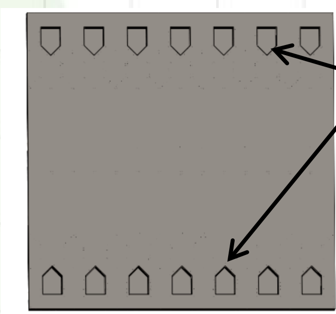


Supplemental Slides - Barrier E - Numbering up of Unit Cells to form a Full Scale Device

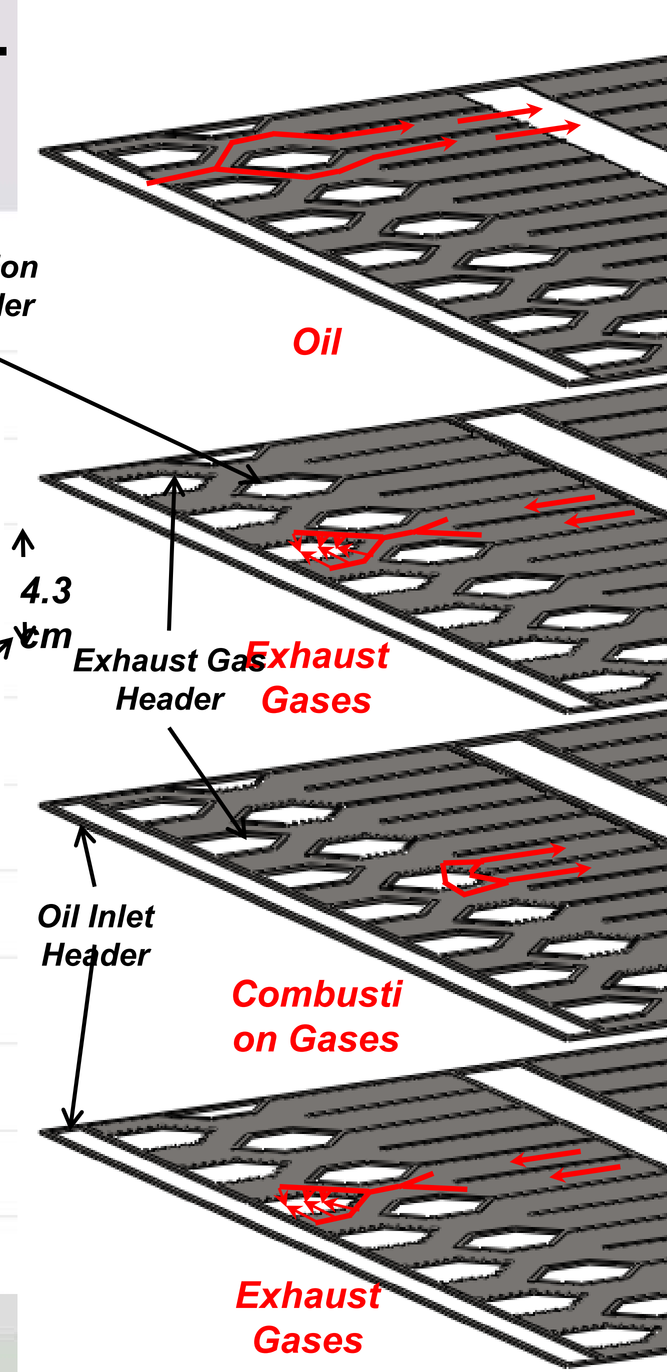


Top View



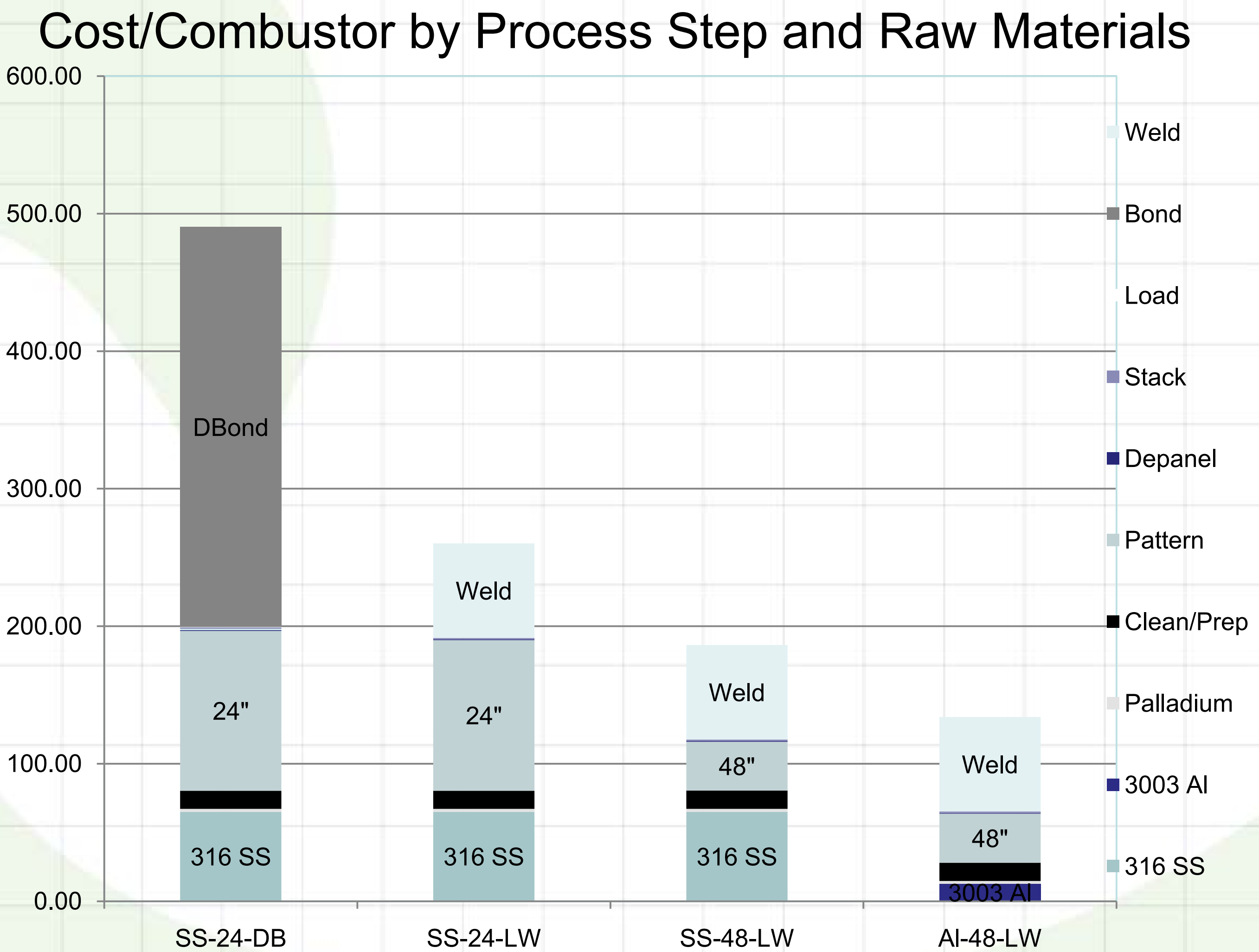


Bottom View



Exploded View of a Set of Channels

Barrier E - Estimated Cost of Microchannel Combustor-Recuperator-Oil-HX at Production Volumes of 500,000 units/year



ONAMI
OREGON NANOSCIENCE AND MICROTECHNOLOGIES INSTITUTE

MICROPRODUCTS BREAKTHROUGH INSTITUTE