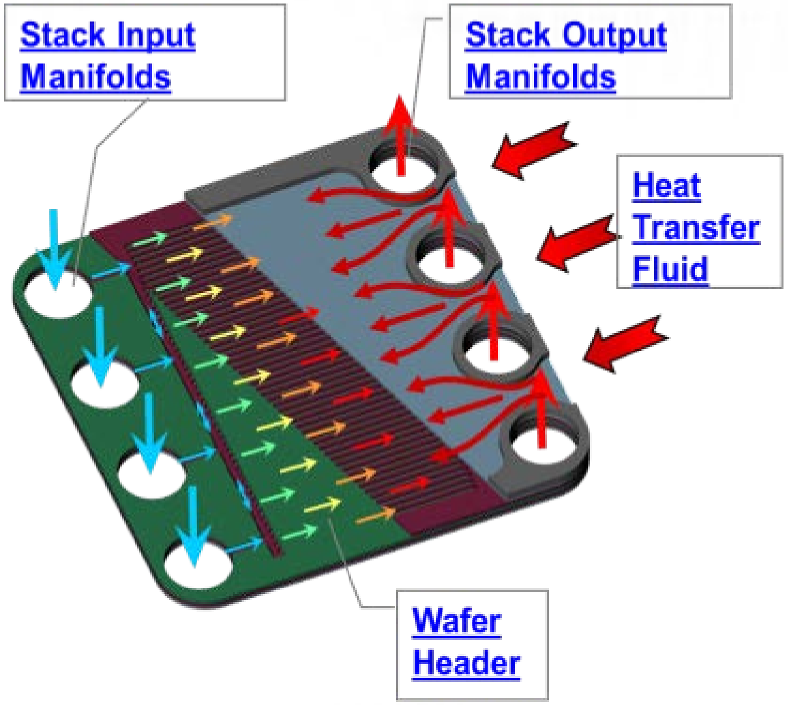
Ceramic, Microchannel Heat Exchangers for Supercritical Carbon Dioxide Power Cycles

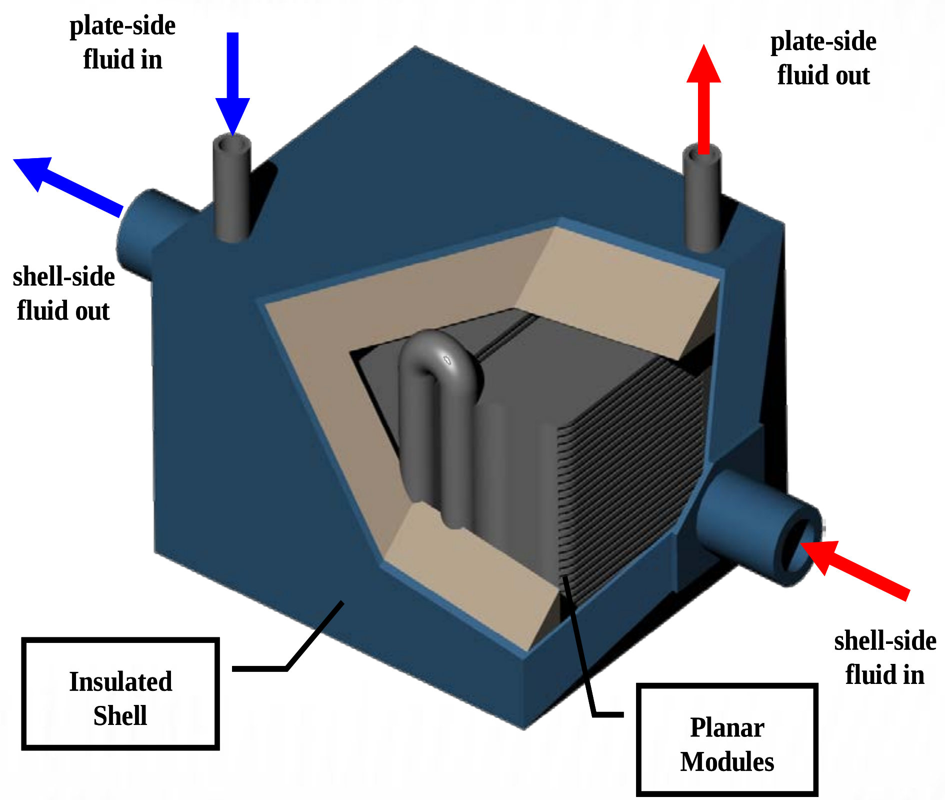


C. Lewinsohn and J. Fellows - Ceramatec, Inc.

N. Sullivan, R.J. Kee, and R. Braun – The Colorado School of Mines

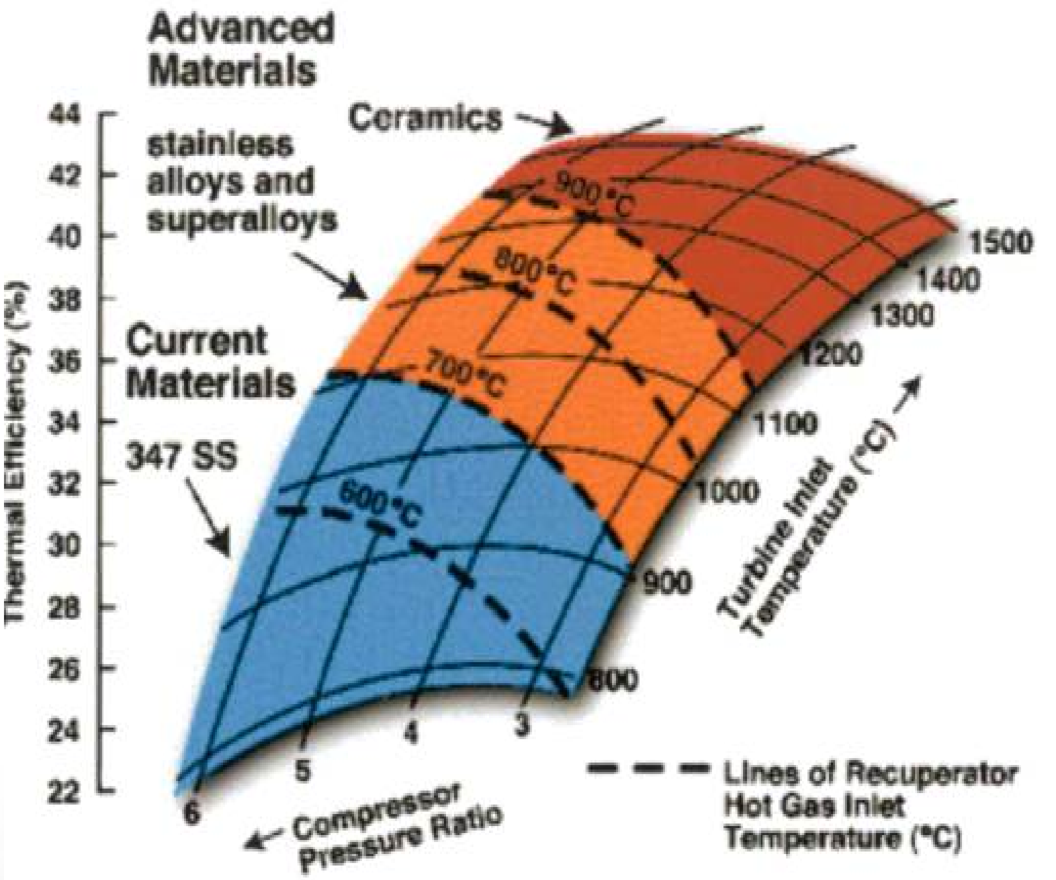
Introduction & Overview

- Benefits
- Design
- Fabrication
- Testing
- Summary

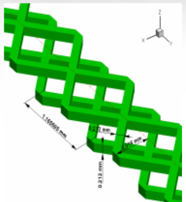


Benefits of Ceramic Heat Exchangers

- Allow higher operating temperatures.
  - Higher efficiency
  - Reduced emissions
- Corrosion resistant
- Low cost

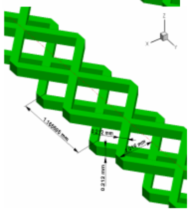


Compact Heat Exchanger Benefits



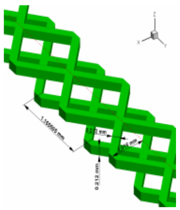
Diamond Channels

- ➢50% Overlap



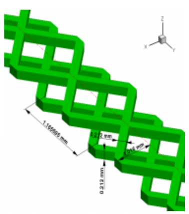
Hexagonal Channels

- ➢50% Overlap



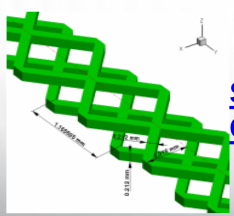
Hexagonal Channels

- ➢100% Overlap



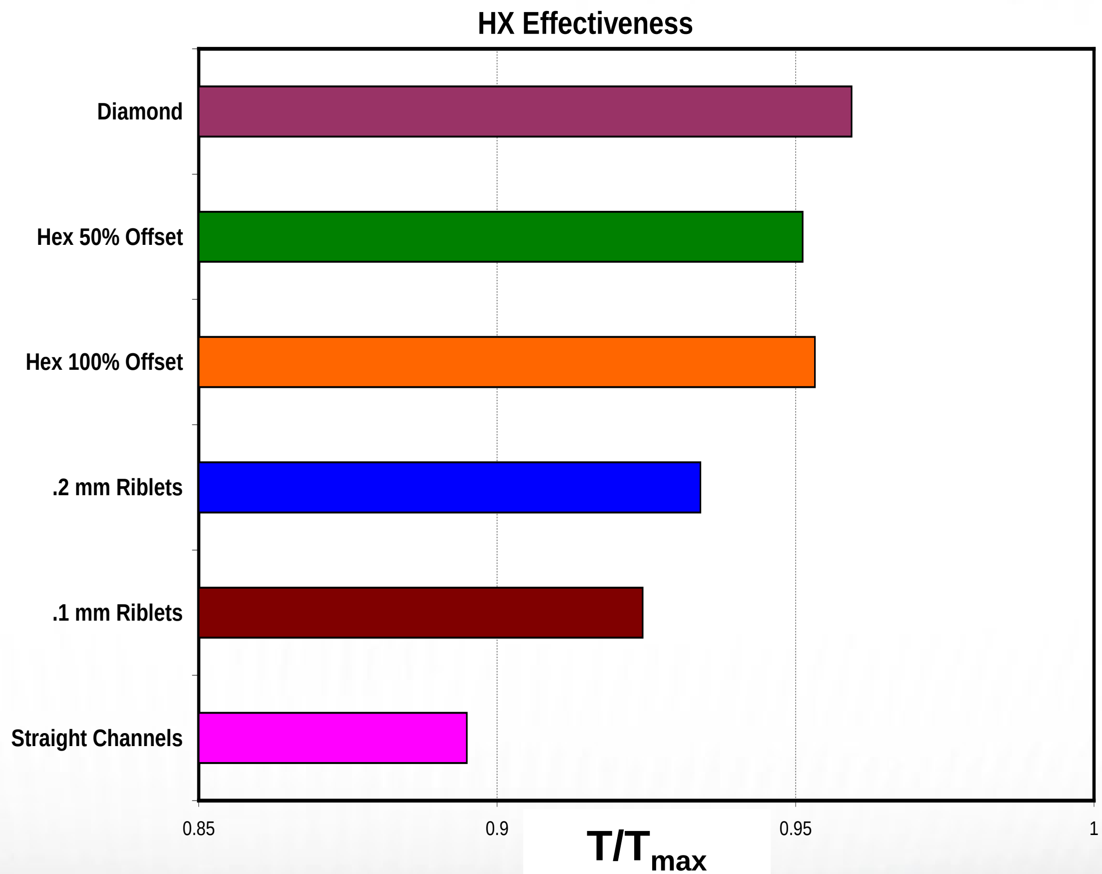
Channels w/ Riblets

- ➢0.1 mm
- ➢0.2 mm



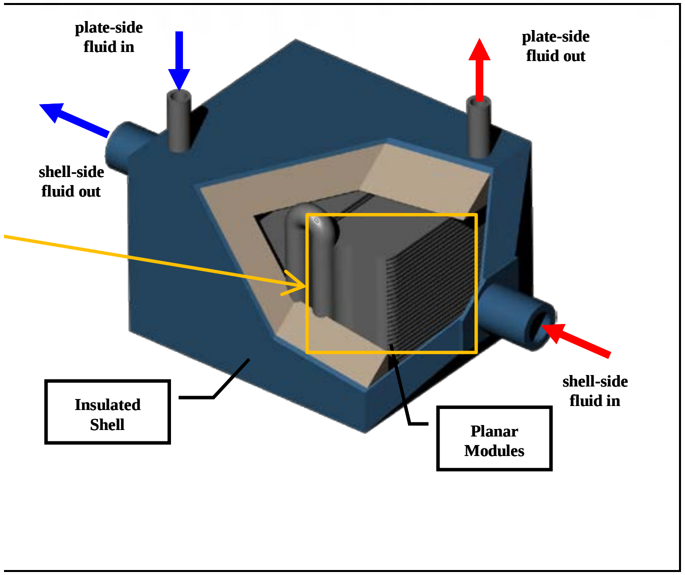
Straight Channels

Higher surface/volume ratio and small transport distances provide higher effectiveness than conventional designs.

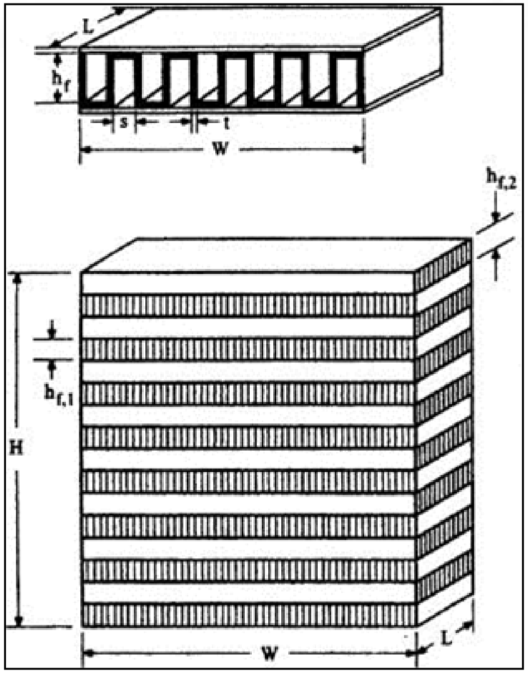


Scaling Microchannel Designs

Plate-Shell Design



Block Design

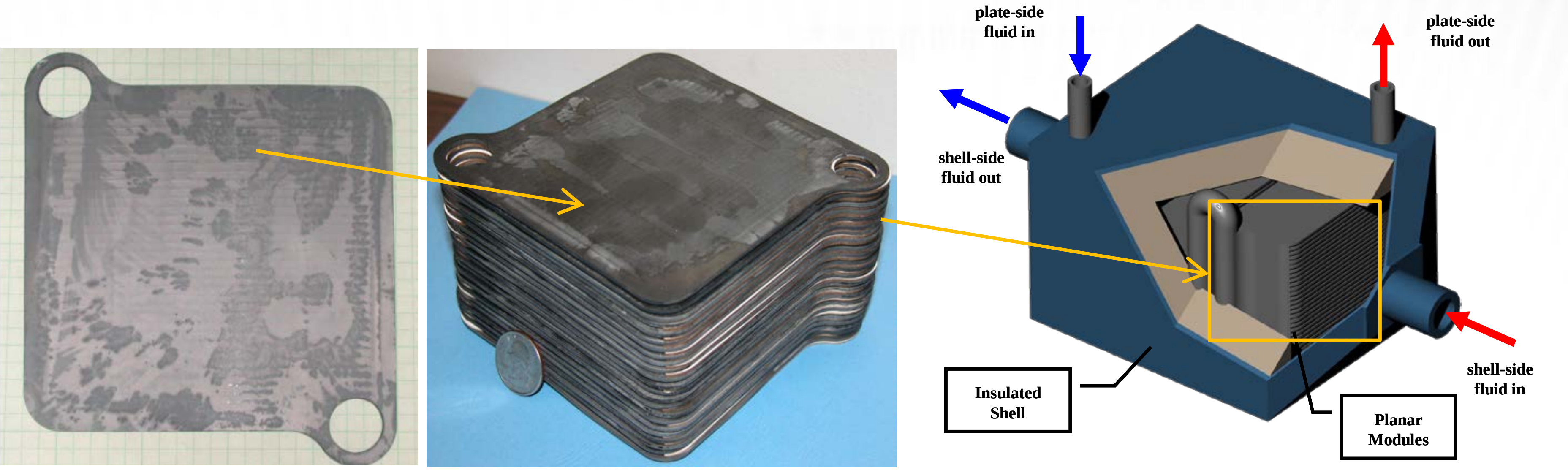


PCHE, FPHE, etc.

- Design options:
  - Plate-shell: microchannel plate/macrochannel shell
  - “Block” design

Ceramatec Approach

Plate-Shell Design



- Individual plates as repeat units in modular stacks reduce net cost:
  - Downstream yield of full component
  - Simpler layup
  - Simpler binder removal
  - Simpler manifolds

Laminated Object Manufacturing

1 Powder processing

2 Slip preparation

3 Tape fabrication

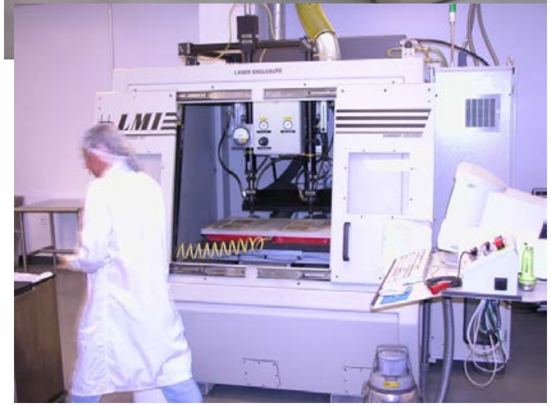
1 - Control surface area for slip properties and sintering.

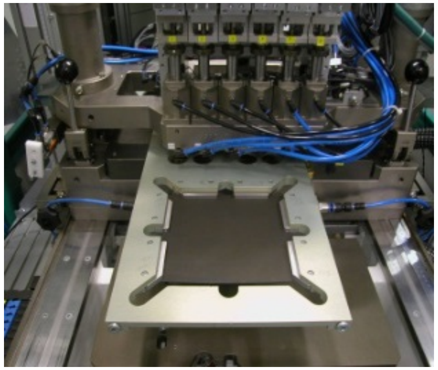
2 - Disperse materials for uniform tape properties (featuring and lamination), defect elimination and controlled sintering shrinkage.

3 - Dry tape uniformly for uniform thickness, minimal drying stress, without defects.

Laminated Object Manufacturing

4 Tape featuring





5 Tape lamination

4 – Optimise power and speed to minimise heat affected zone, maximize throughput, and obtain accurate channel dimensions.

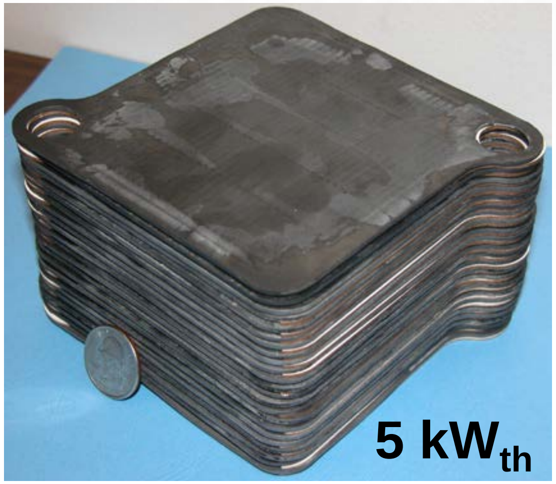
4 – Laser cut or punch depending on layer thickness and channel dimensions.

5 – Complete lamination for structural integrity without deforming internal features.

Laminated Object Manufacturing

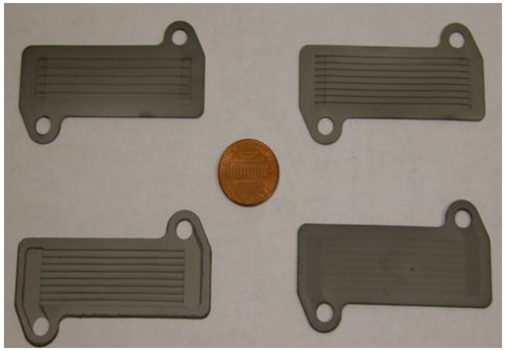
6 **Sintering**

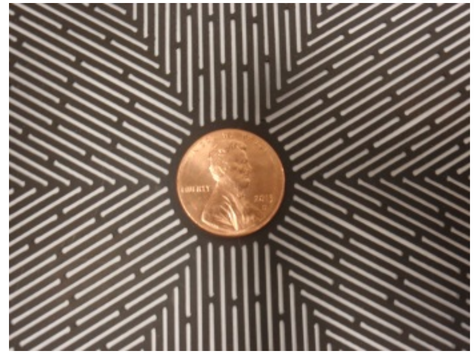
7 **Stack Assembly**

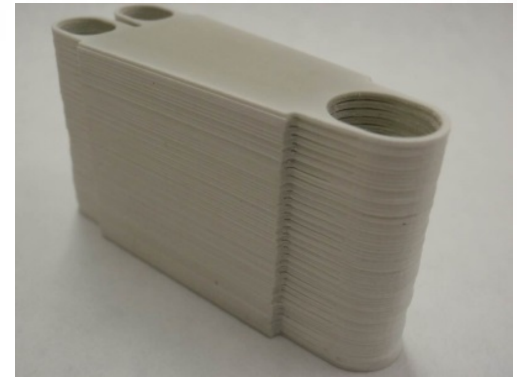


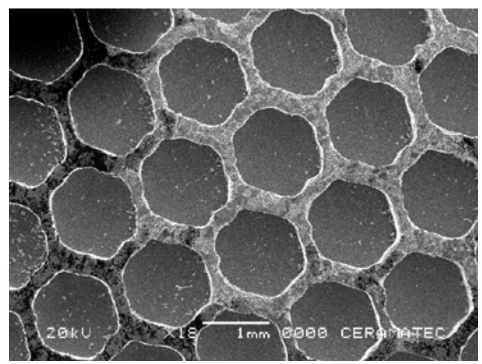
6 – Controlled thermal cycle/environment for binder burnout and densification to make leak tight components while maintaining flatness without creating defects.
6 – Complex designs require co-sintering dissimilar materials and porous and dense layers in the same component.
7 – Requires robust ceramic-ceramic joining.

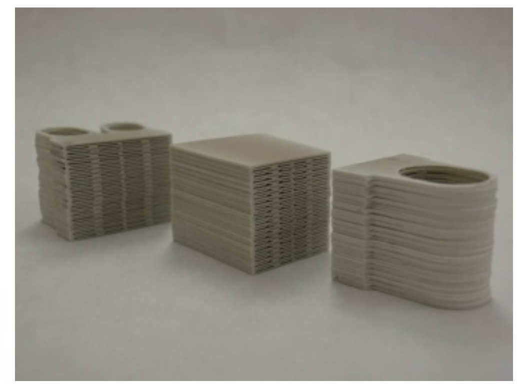
Microchannel Heat Exchanger Design Flexibility

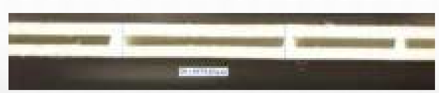












Microchannel Heat Exchangers Performance Metrics

Performance Metric	Value
Thermal Duty	1 MW (heat)
Hydraulic Diameter - Feed	636μ
Hydraulic Diameter - Exhaust	1684μ
Temperature Span (Inlet to Inlet)	450C to 950C
Volume	1.0 m^3
Log Mean Delta Temperature	25C
Overall Heat Transfer Coefficient	145 W/m^2C
Area Density (modular stack)	310 m^2/m^3

Calculated values

- Scaleable from kW to MW
- Estimated ceramic heat exchanger cost: \$100-200 kW_{th}
- Reference case: gas separation modules: 100 \$/kW (independently verified by 3rd party for DOE).

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Microchannel Size Selection

Effectiveness

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- Once again, channel width does not have a significant effect
- Effectiveness is better with lower Re
- Also lower with larger channel height
- Considering the plot of pressure drop, one might conclude that Re = 600, height = 0.6 mm provides optimal results
  - Effectiveness > 80%
  - Delta P < 20 kPa
- Re = 400 might also work, but this brings about some concern over total heat transfer and total mass flow rate

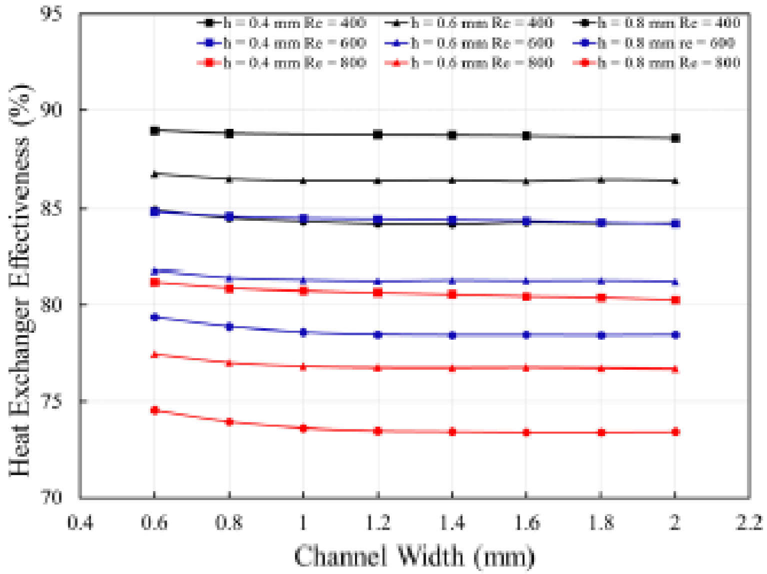

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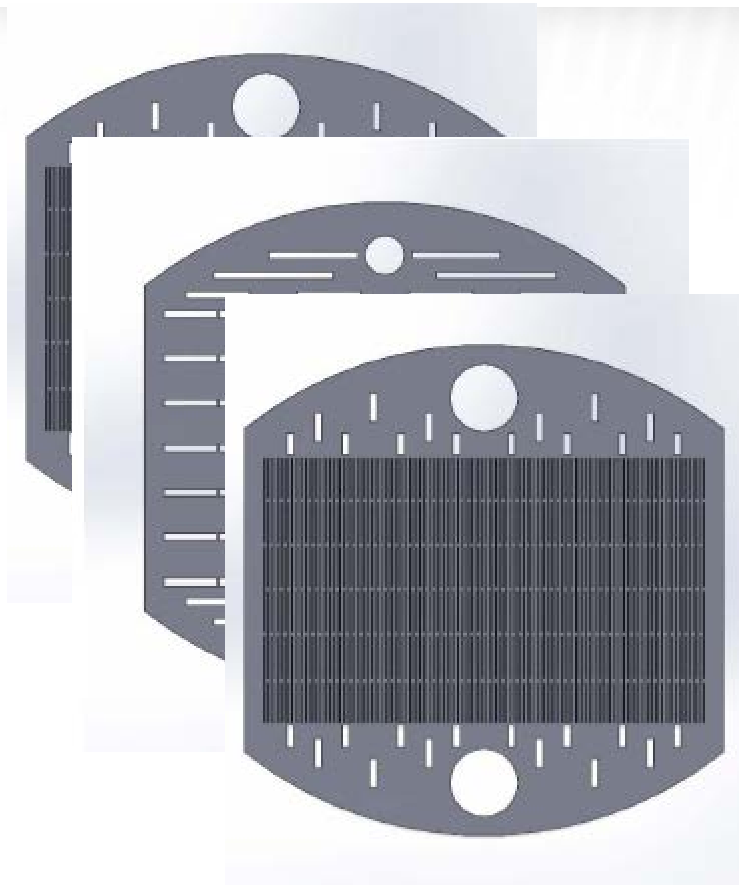
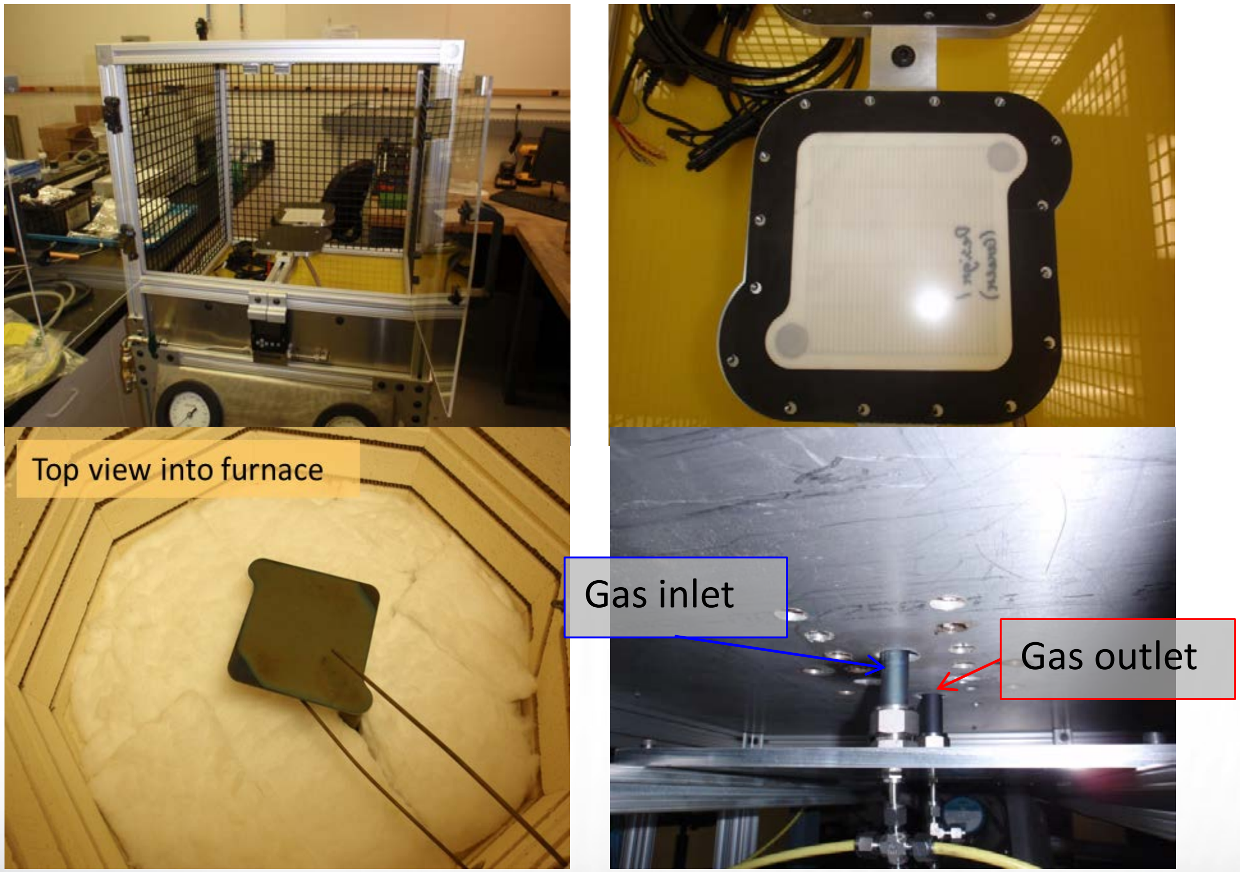
Plate Design



- Plate Shell design
- Flow distribution to channels
- Flow distribution across plates

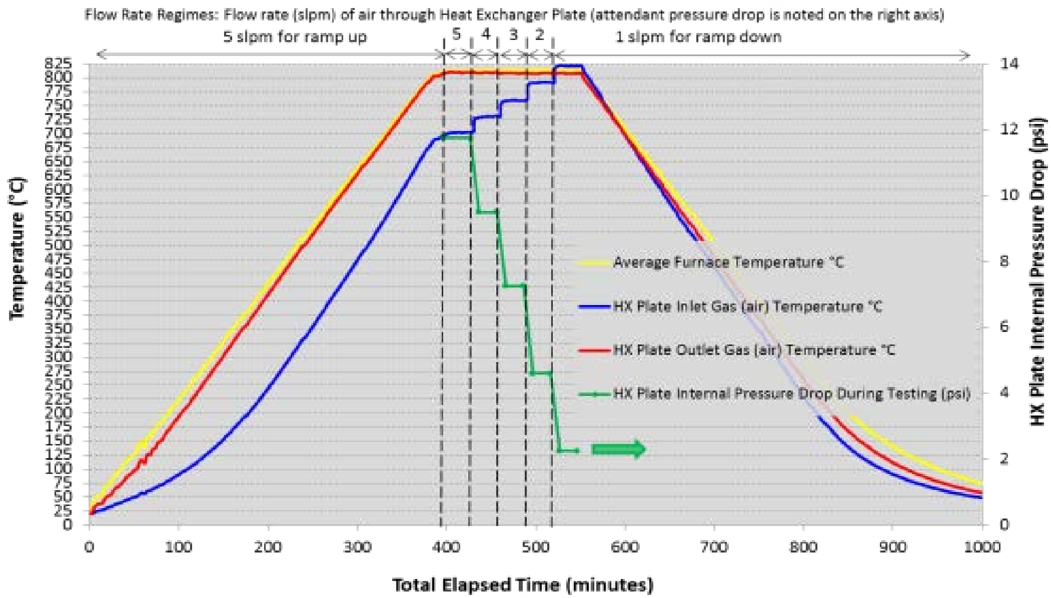
Plate Fabrication and Testing

Individual Plates



Microchannel Heat Exchanger Test Results

Individual Plates



Preliminary results:

- High pressure drop
- Approach temperature > 100C for >5 slpm
- Plate to be cross sectioned and characterised
- Additional plates to be tested

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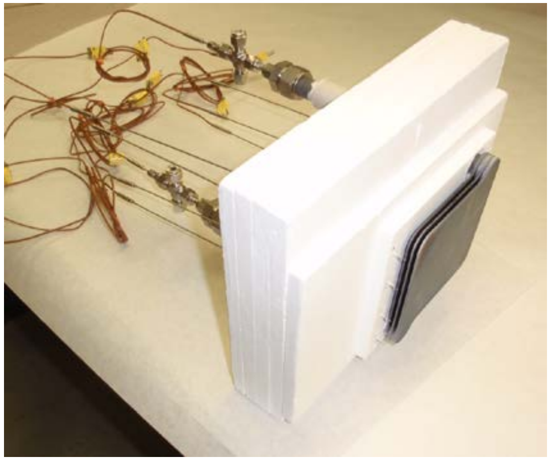
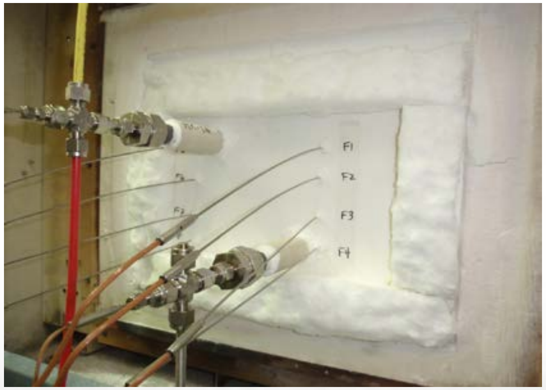
Microchannel Heat Exchanger Test Apparatus

3-10 plate stacks





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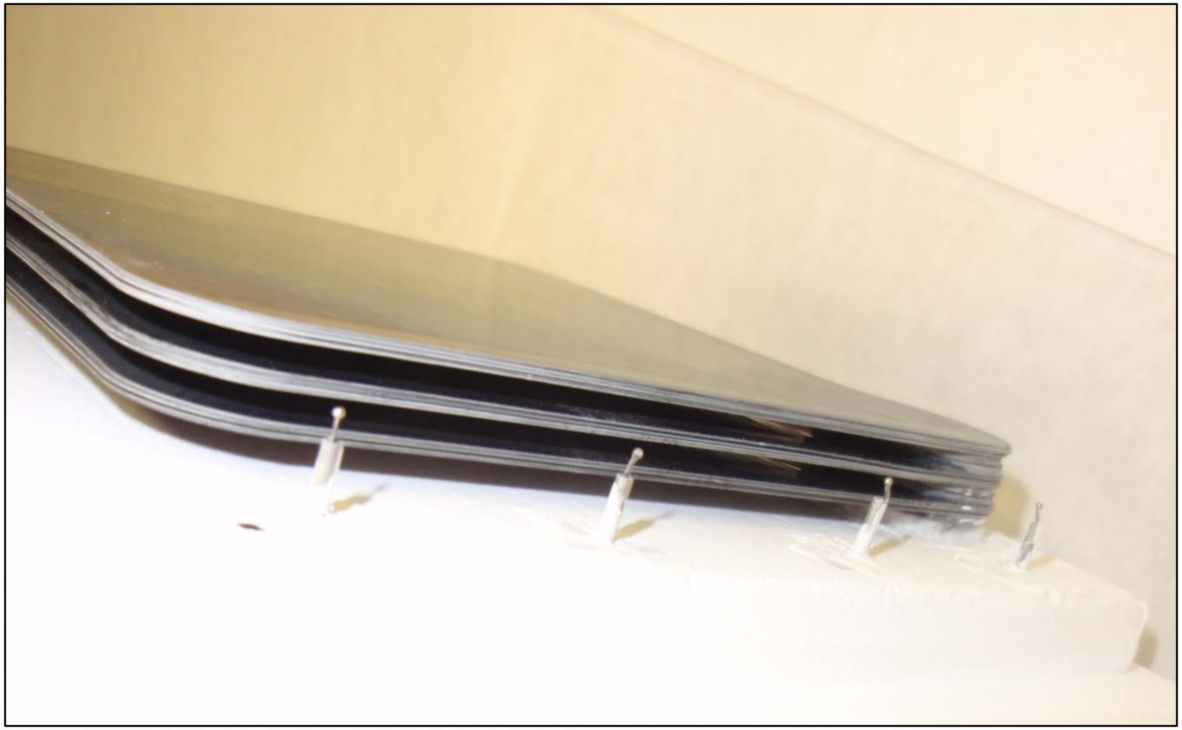
Microchannel Heat Exchanger Test Apparatus

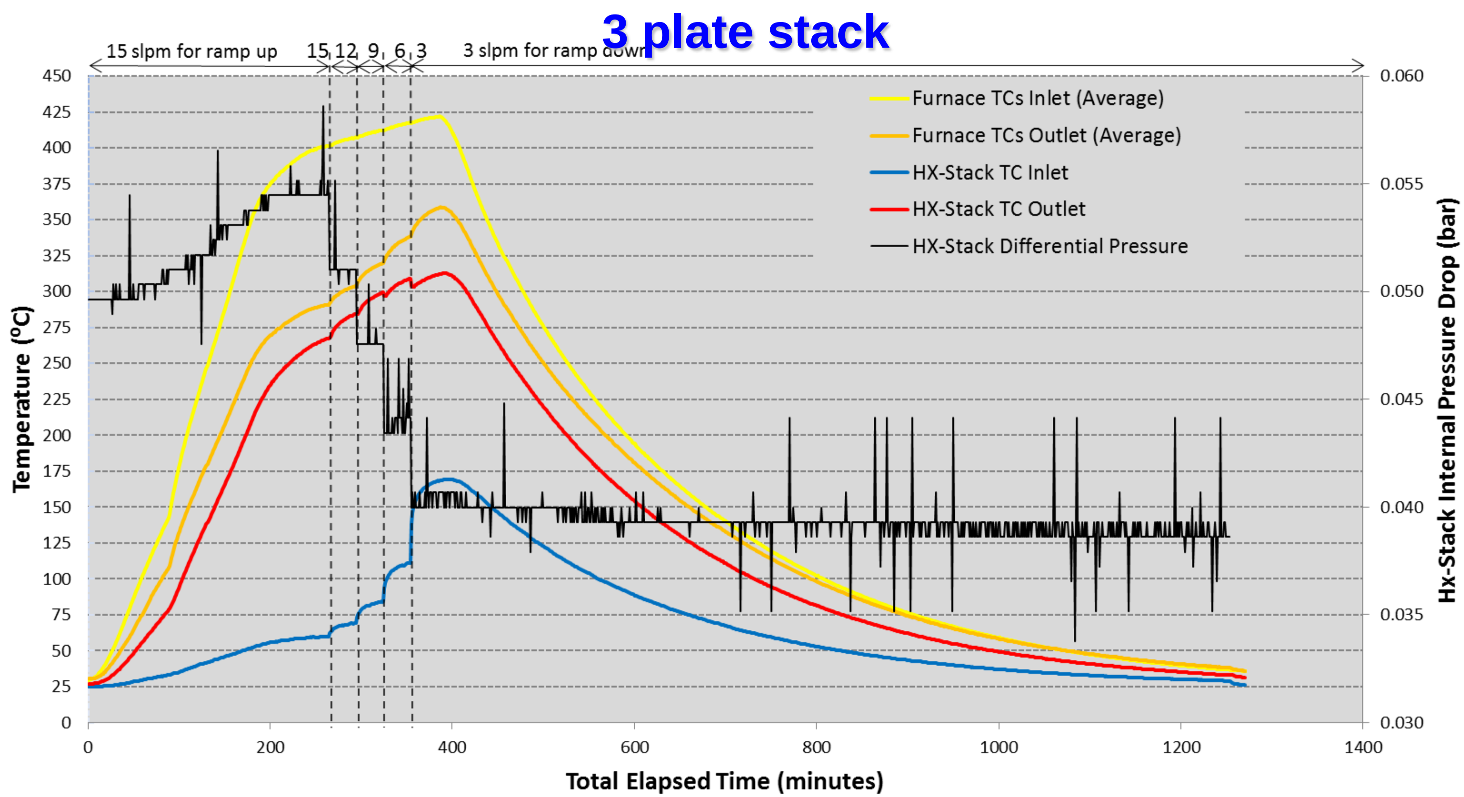
3-10 plate stacks



Measurements

Plate Temp in
Plate Temp Out
Channel Temp in
Channel Temp Out
Channel Pressure In
Channel Pressure Out

Microchannel Heat Exchanger Test Results



Preliminary results indicate good performance:
low approach temperature – 60C
Reasonable pressure drop – 3900 kPa

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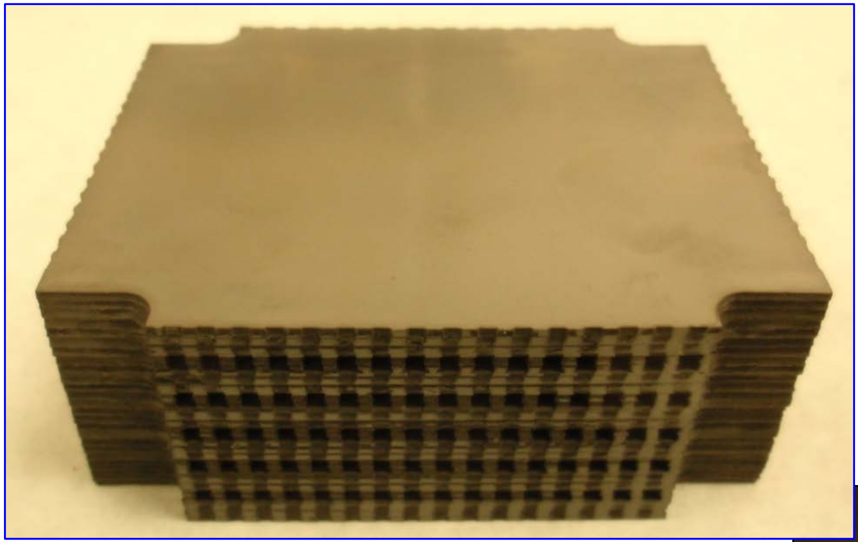
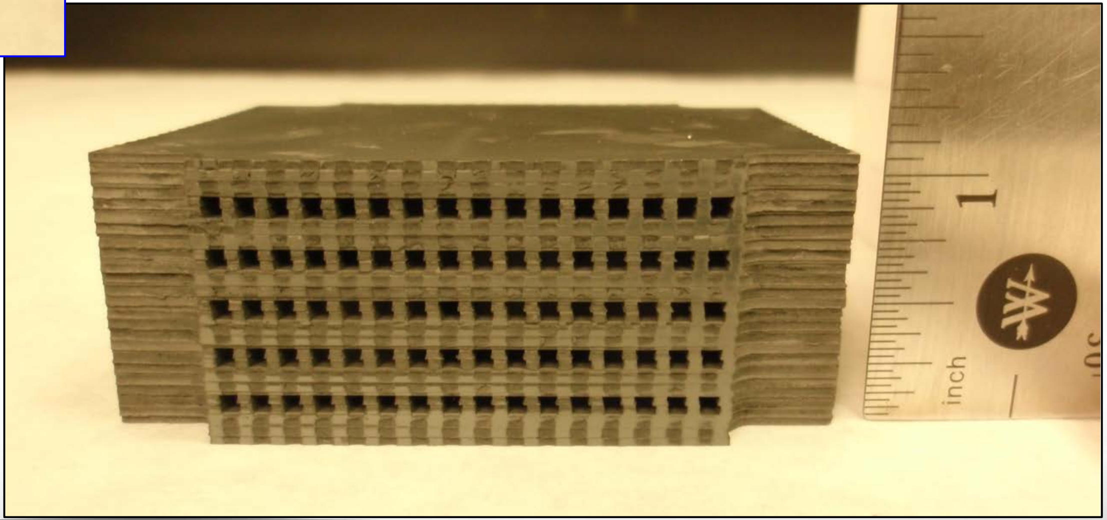
Status: UTRC Crosscutting Technology Award



Block Design

20-30 individual tape layers.
Featured, laminated, and sintered as one unit.
Successfully fabricated on second attempt.
R&D cost.



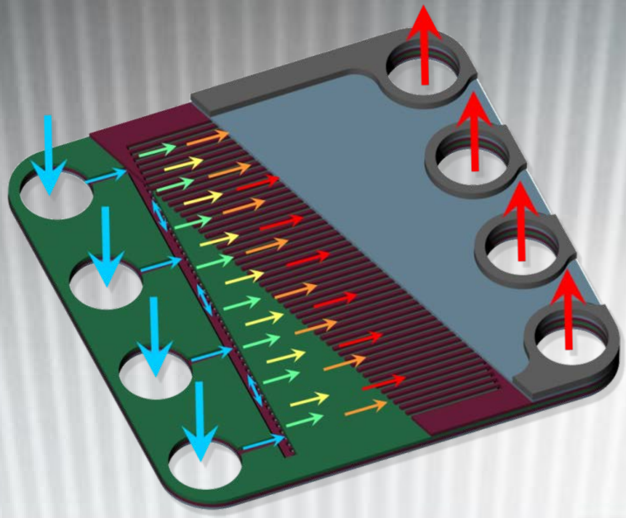
Future Work

Support mitigation of key technical risks, especially lifetime:

- Continue study and validation of design tradeoffs between design for manufacturing and performance.
- Materials testing: Oregon State U., U. Wisconsin.
- Assembly of 5-10 kW stacks and n * 1000 h testing.
- Verify reliability of integration with balance of plant, especially hot gas manifolds.
- Verification of viable manufacturing costs for robust and scalable processes.

Summary

- Ceramic microchannel heat exchangers offer improved efficiency for high temperature processes and potentially lower costs for fabrication of compact heat exchangers.
- Results obtained by Ceramatec and UTRC during Crosscutting Technology research show promising results and identify remaining challenges.
- A plan to mitigate risks and commercialize products, supported by CoorsTek, has been developed.



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Thank you. Questions?

Acknowledgement: DOE Office of Fossil Energy, Office of Crosscutting Technology, DE-FE-0024077.

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SiC Heat Exchanger: Economics

Basis

- Production
  - 26 kWe μ-turbine cycle
  - "Optimized Design"
  - 10,000 units/year
- Cost Model - CKGP / Ceramatec
  - Extension / Modifications
  - Capitalization (new plant)
  - Process Capacity
- Fixed / Variable Costs
  - Labor (DL & IL)
    - Efficiency / Rates
  - Materials
    - SiC (435 Tonne/yr)
    - Consumables

Item	Description	Amount
Direct Labor	Labor for value added fabrication processes (80 man years)	$2,093,077
Indirect Labor	Labor for management and QC in fabrication (68 man years)	$4,127,548
Benefits	For both direct and indirect labor (30% of labor)	$1,866,188
Overhead	Facilities, maintenance and utilities (20% of labor)	$1,617,363
Sub-total	Labor related variable costs	$9,704,176
Direct Materials	Material expenses directly used in product (SiC powder)	$5,216,013
Consumables	Materials used to produce product (mylar, solvents etc)	$3,662,557
Heat exchanger package	Finishing, packaging, insulating heat exchanger ($500 each)	$5,000,000
Sub-total	Materials related fixed costs	$13,878,570
Capital Depreciation	10 year straight-line (equipment, facilities)	$10,879,826
Sub-total	Annual expenses	$34,462,572
Management	Corporate G&A (20% of expenses)	$6,892,514
Sub-total	Cost of production	41,355,086
Profit	15% of production costs	$6,203,263
Total	Revenue	**$47,558,349**
Number of Units	10,000 per year	
Price per Unit	Total/Number of Units (26 kWe Micro-turbine)	**$4,755.83**
Price per kWe	26 kW electric micro-turbine cycle	**$183**
Price per kWh	107 kW heat recuperation	**$44**

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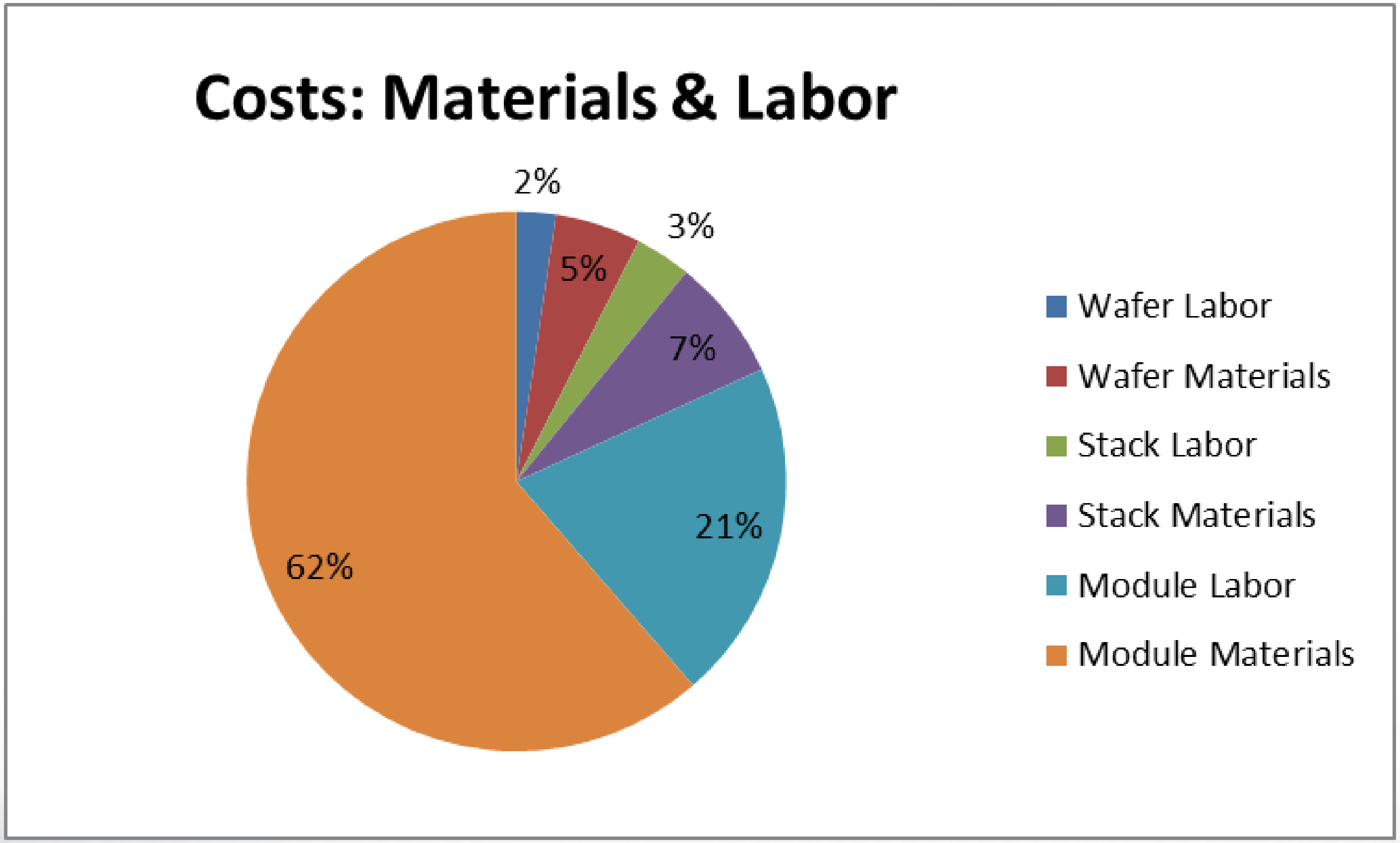
Cost Breakdown

1-200 kW_{th}/unit

1,000 units/yr



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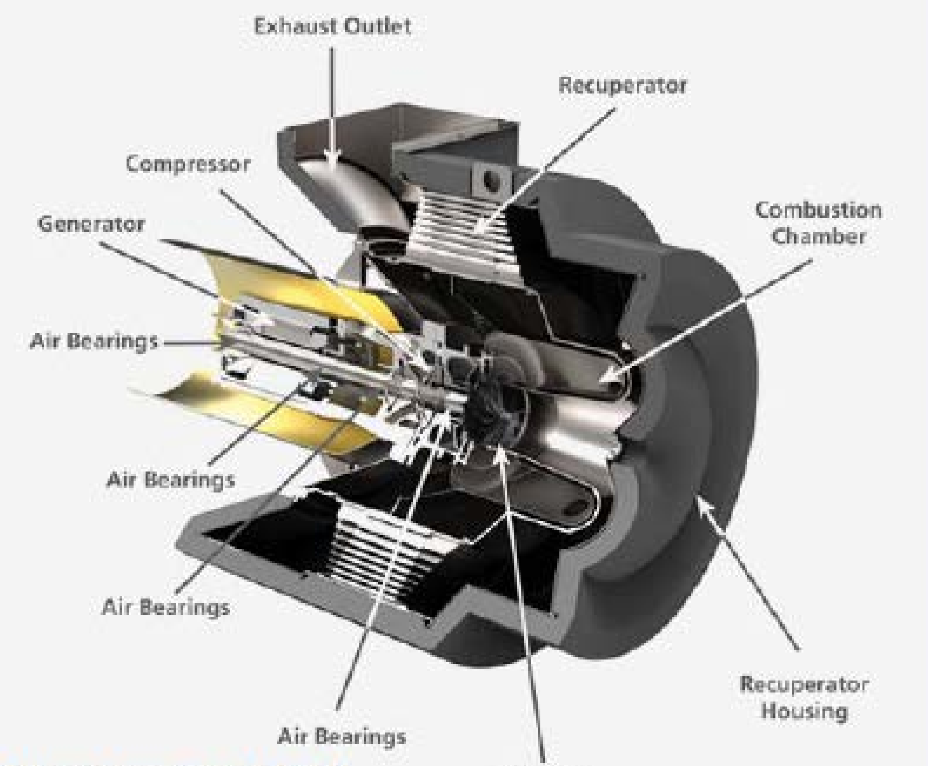
Application: microturbines

- Recuperator Inlet Temp:
  - Metal – 600C
  - Ceramic – 800C
- Turbine inlet temperature:
  - Metal – 900C
  - Ceramic – 1100C
- Efficiency
  - Non-recuperated: 20%
  - Metal, Recuperated: 50%
  - Ceramic, Recuperated: 60%
- Fuel savings:
  - $
  - kg
  - emissions



Cutaway graphic of a C200 Capstone Micro Turbine

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System Modeling & Design
Colorado School of Mines

Summary of recuperator design requirements derived from system modeling effort

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Turbine Model and Net Power (kW)	C30	C65	C200
Pressure Drop (kPa)	10	7.5	7.5
Air Side Mass Flow Rate (kg/s)	0.2991	0.498	1.348
Exhaust Side Mass Flow Rate (kg/s)	0.3051	0.5027	1.36
Air Inlet (SP 2) Temp (C)	149.4	168.1	190.6
Air Outlet (SP 3) Temp (C)	589.4	571.6	594.7
Exhaust Inlet (SP 5) Temp (C)	694.4	690.6	666.7
Exhaust Outlet (SP 6)Temp (C)	275.3	309.3	280.7
Recuperator Heat Transfer (kW)	140.9	215.2	585.8
Recuperator Effectiveness	0.799	0.7632	0.8427

Microchannel Size

Single Micro-Channel Fluent Study

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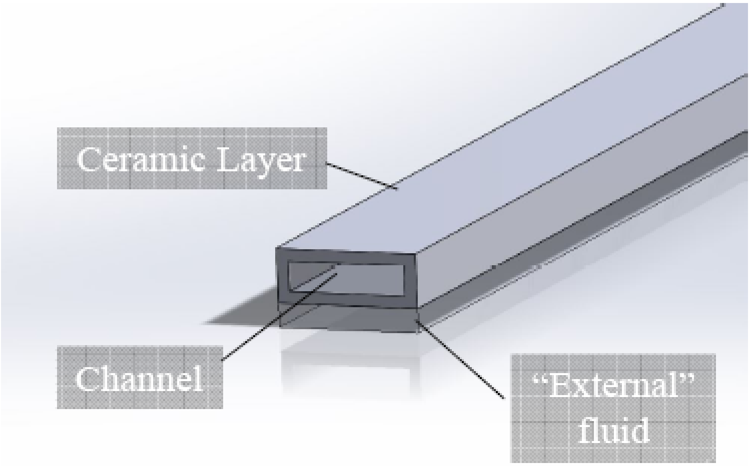
- Investigating effects of varying channel dimensions of a single channel on pressure drop, effectiveness ,etc.
- Channel width 0.6-2 mm
- Channel height 0.4 – 0.8 mm
- Rib width 0.4 mm
- “External” fluid gap height 0.4 – 1 mm
- Length of 150 mm (full length)
- Boundary conditions
  - Channel mass flowrate set based on Re – 400, 600, 800
  - External mass flowrate set proportional to channel flow rate, based on proportion from EES system model (difference due to fuel addition)
  - T_ch_in = 463 K, T_ext_in = 939 K (from EES 200 kW turbine system model)
  - P_out = 0 Pa gauge



SolidWorks drawing representing the single channel geometry.

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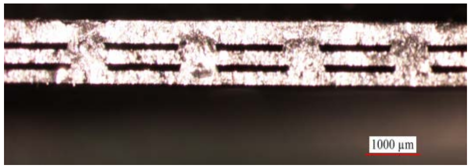
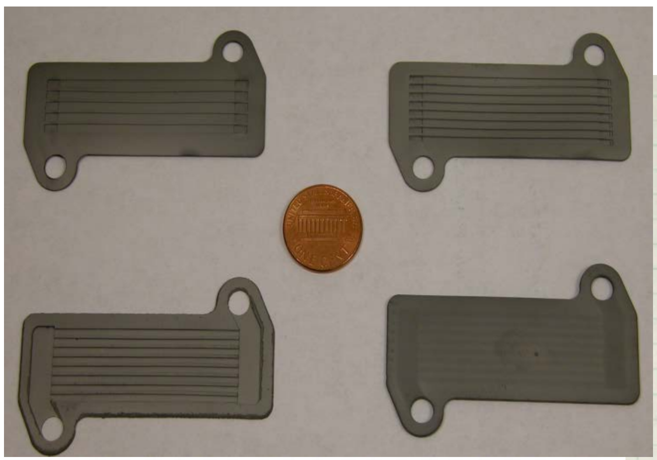
Component Scale-up



Scale-up

Numbering-up

Modular Stack



Test Coupon

Full-Size Wafer

Compact vs Conventional Design

Reliability

$$P_f = 1 - \exp\left(-\frac{1}{\sigma_0{}^m} \right) \iiint_V \sigma(x,y,z)^m dV$$

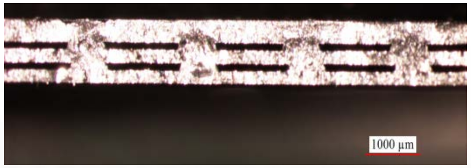
Where:

$\sigma(x,y,z) = \sigma(P) + \sigma(\Delta T)$

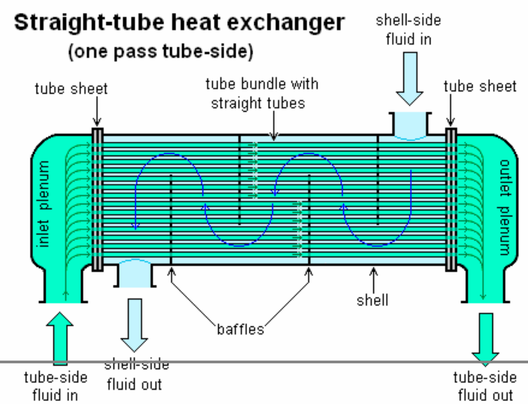
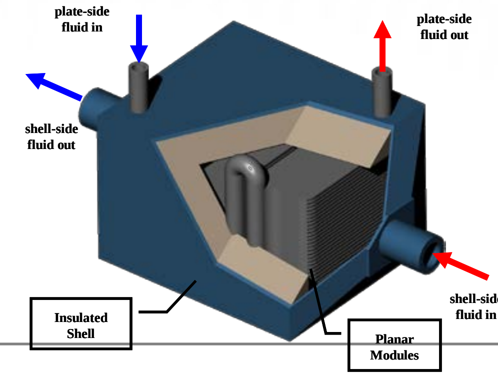
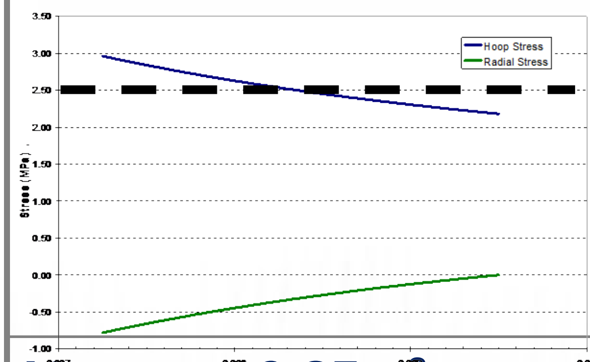
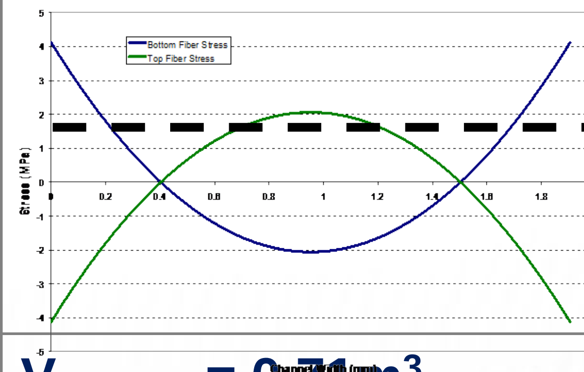
σ_0 = Weibull Material Scale Parameter

m = Weibull Modulus

Stress



Metrics

Tubular Designs	Planar Designs
	
	
$V_{ceramic}$ = 9.85m^3	$V_{ceramic}$ = 0.71m^3
σ_{hoop} = 2.5 MPa	$\sigma_{tensile}$ = 1.6 MPa
S.F. = 1.008	S.F. = 2.12

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Microchannel Heat Exchanger Fabrication

- Pressure Laminated Integrated Structure Manufacturing (PLIS)

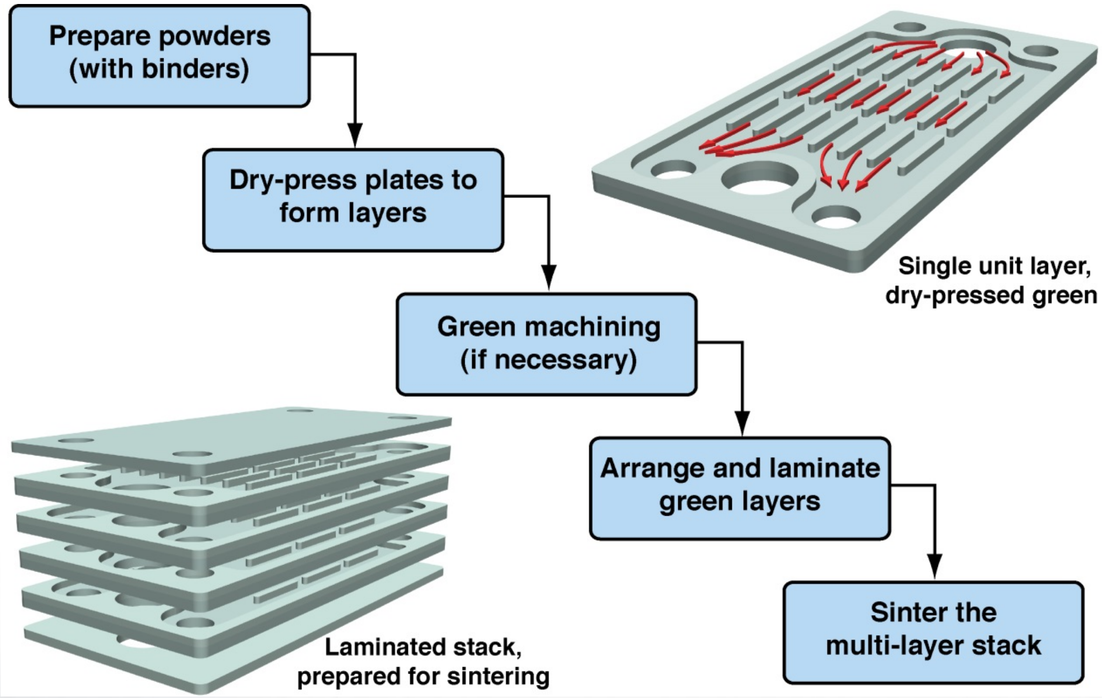

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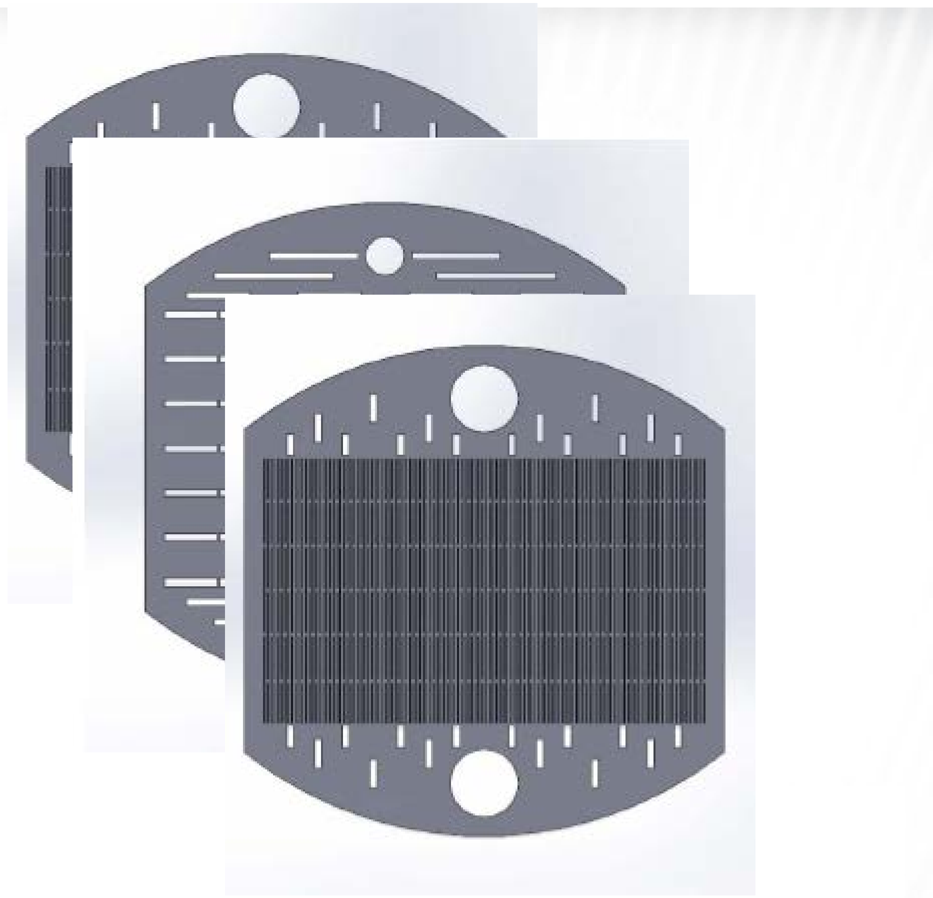
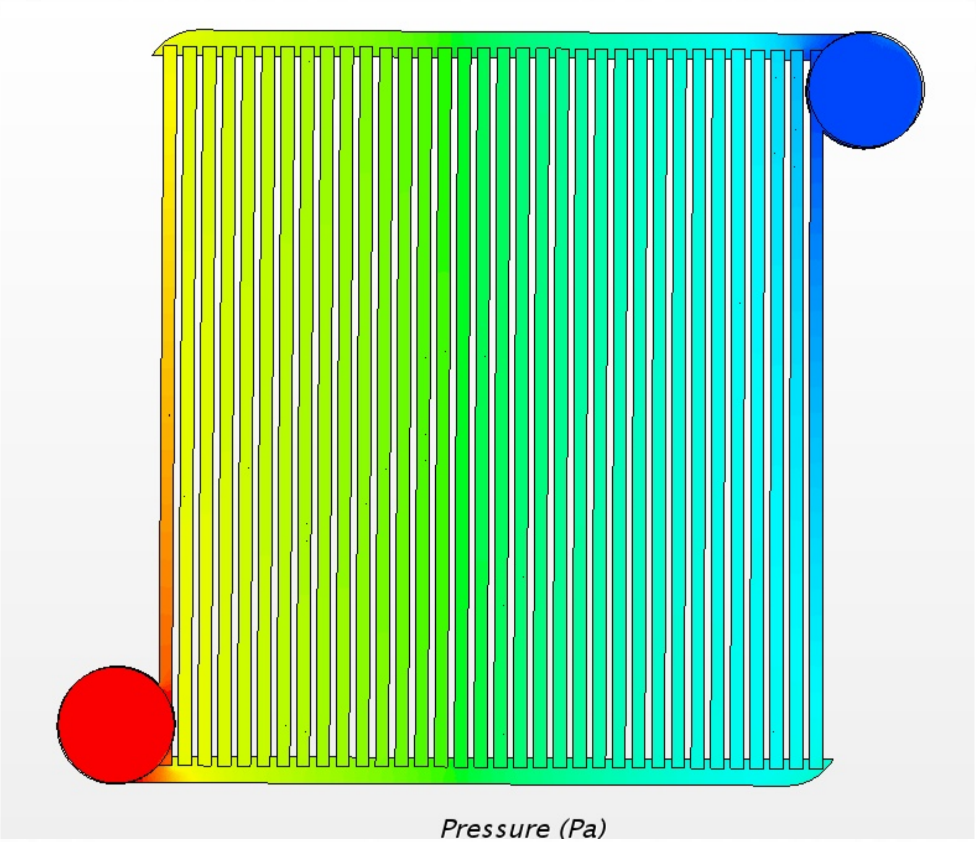
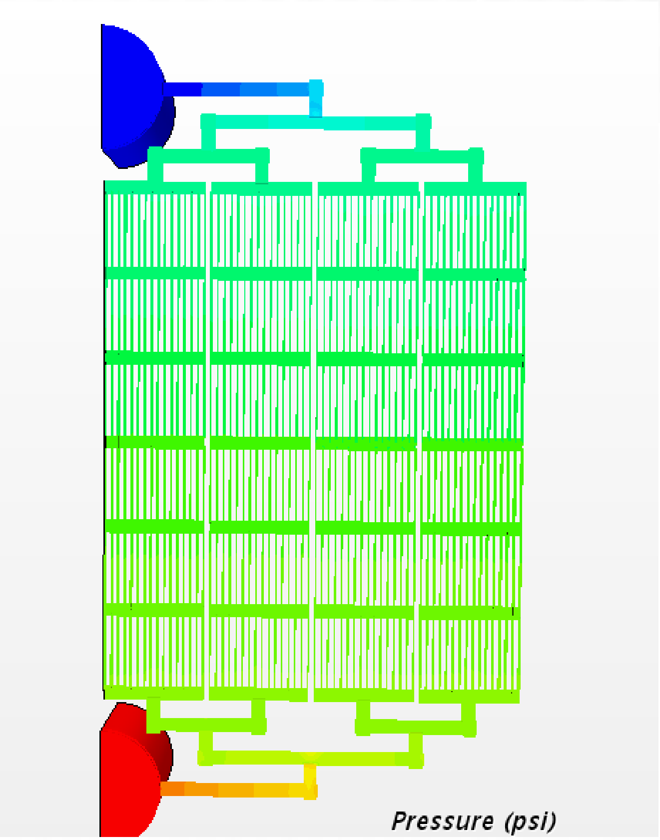
Plate Design



- Plate Shell design
- Flow distribution to channels
- Flow distribution across plates

Plate Design

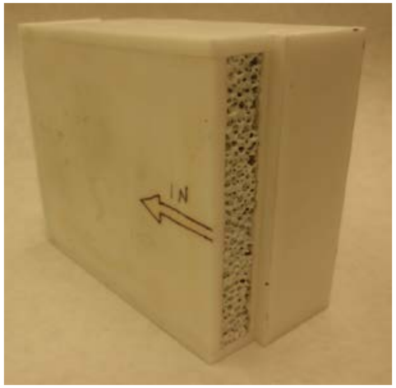


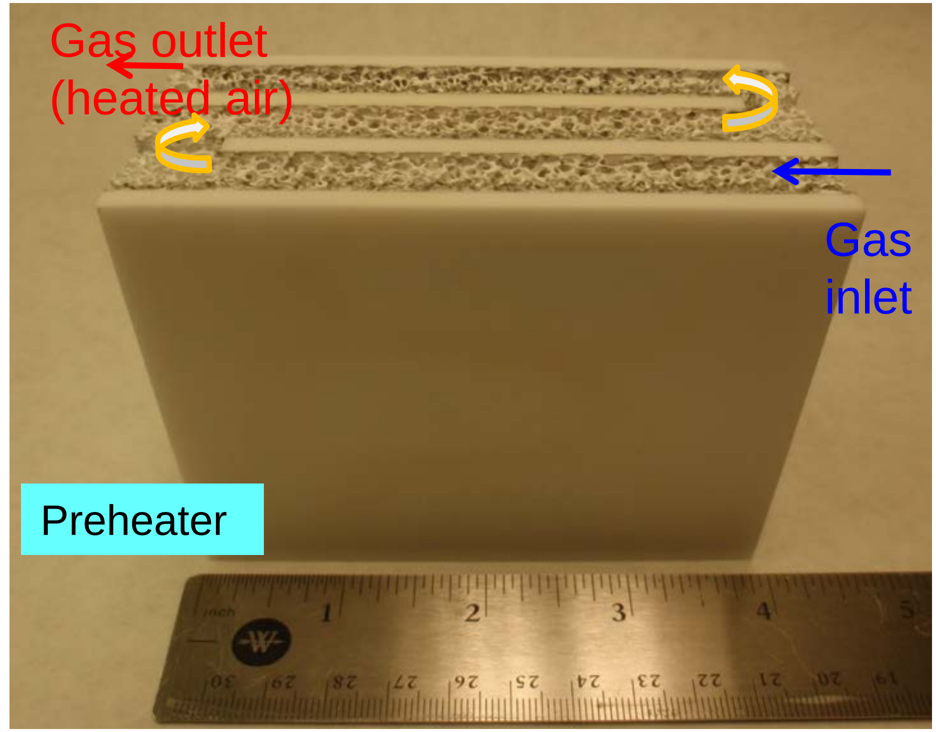


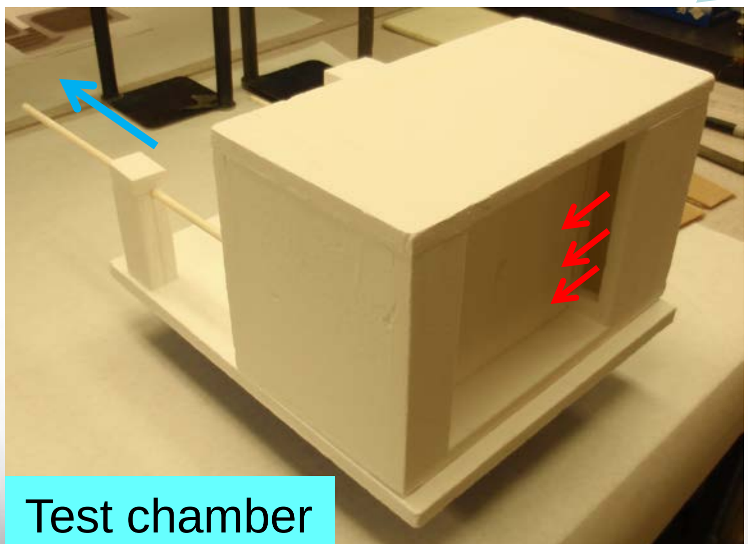
- Revision to manifold to improve flow distribution
- Final revision in process.

Microchannel Heat Exchanger Test Apparatus

3-10 plate stacks







Preheater and Test chamber are placed inside furnace

CERAMATEC
TOMORROW'S CERAMIC SYSTEMS
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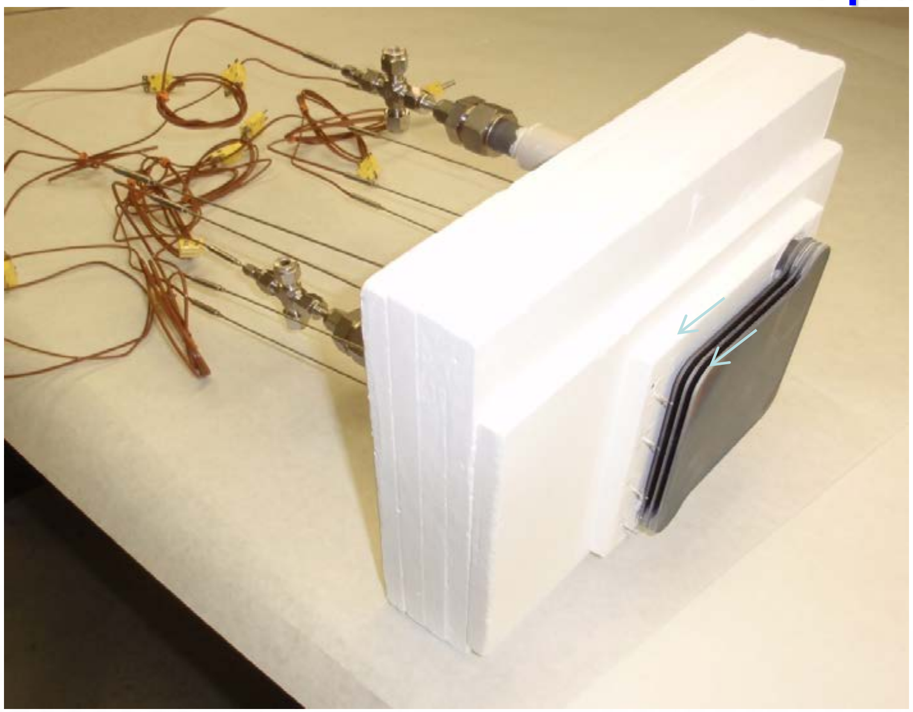
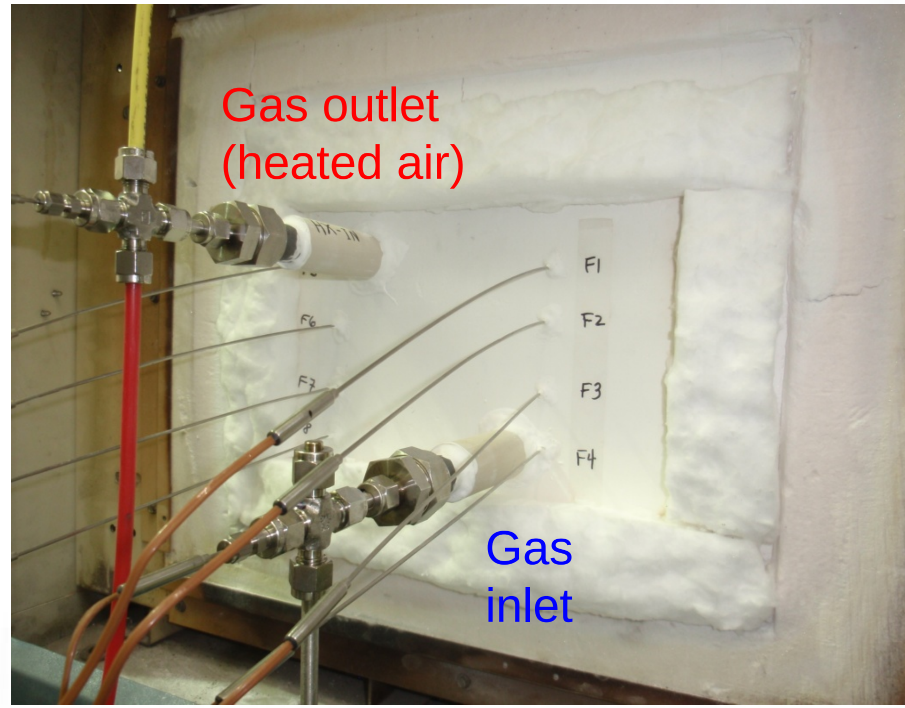
Microchannel Heat Exchanger Test Apparatus

3-10 plate stacks





Heat exchanger stack inserted into test chamber to make flow duct for plate-side gas.
Microchannel gas flows into and out of manifolds.