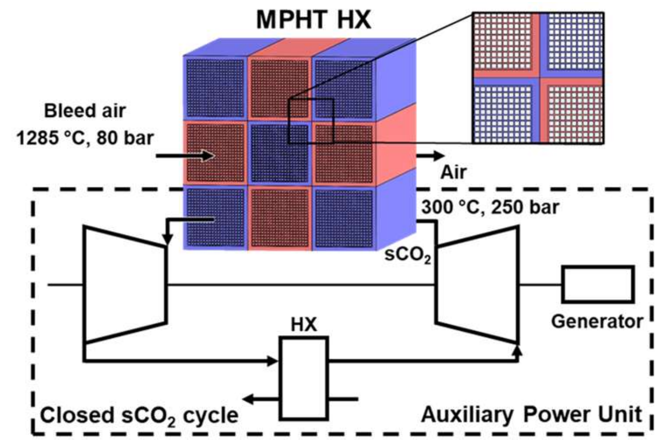
Multiscale Porous High-Temperature Heat Exchanger Using Ceramic Co-Extrusion

Evelyn N. Wang, MIT

We are developing a novel high performance, compact and durable ceramic heat exchanger design with a multi-scale porous configuration by scalable co-extrusion fabrication for aerospace applications.



Brief Project Overview

Fed. funding:	$1.7M
Length	36 mo.

Team member	Location	Role in project
MIT	Cambridge, MA	Design, modeling and characterization
Purdue University	West Lafayette, IN	Fabrication and mechanical characterization
General Electric	Niskayuna, NY	High temperature demonstration and commercialization

Context/history of the project

- MIT: Multi-scale porous heat exchanger design with compact headers
- Purdue: Ceramic co-extrusion fabrication to enable the design
- GE: High-temperature demonstration and commercialization of heat exchangers

- Goal: Design, fabricate and characterize a high-performance multiscale ceramic HX with scalable co-extrusion method

Brief Project Overview

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MIT

- PI: Evelyn Wang
- Postdoc: Xiangyu Li
- Graduate Student: Chad Wilson


Evelyn N. Wang


Xiangyu Li


Chad Wilson

Purdue

- co-I: Rodney Trice, Jeffrey Youngblood
- Graduate Student: Rodrigo Orta Guerra, Olivia Brandt


Rodney Trice


Jeffrey Youngblood

GE

- co-I: Gregory Natsui
- Eyitayo Owoeye


Gregory Natsui


Eyitayo Owoeye


Rodrigo
Orta Guerra


Olivia Brandt

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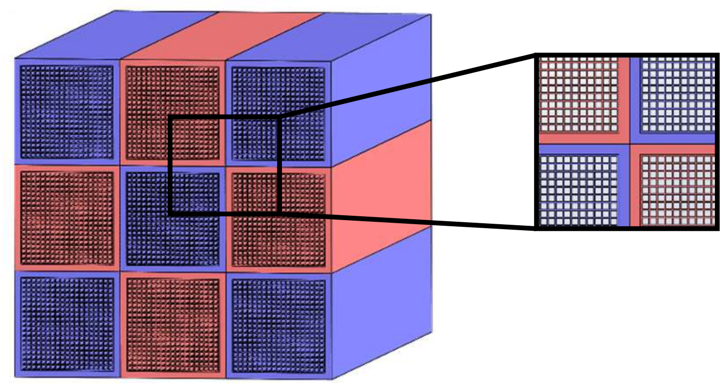
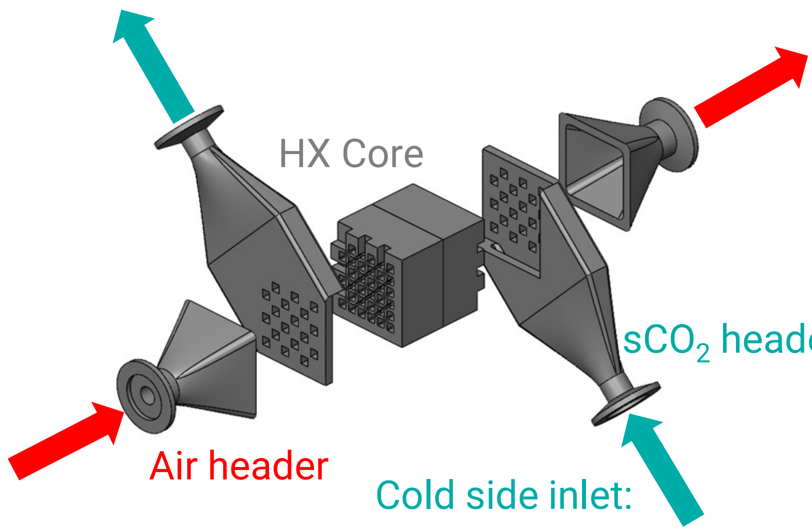
Heat Exchanger (HX) Design Details

- Multiscale porous counterflow design
  - Enhanced performance
  - Low pressure drop



- Ceramic co-extrusion fabrication
  - Scalable and low cost
  - High temperature and pressure

- Compact header integration with HX core



Hot side inlet:
– Air, 1285°C, 80 bar
– Flow rate: 0.083 kg/s

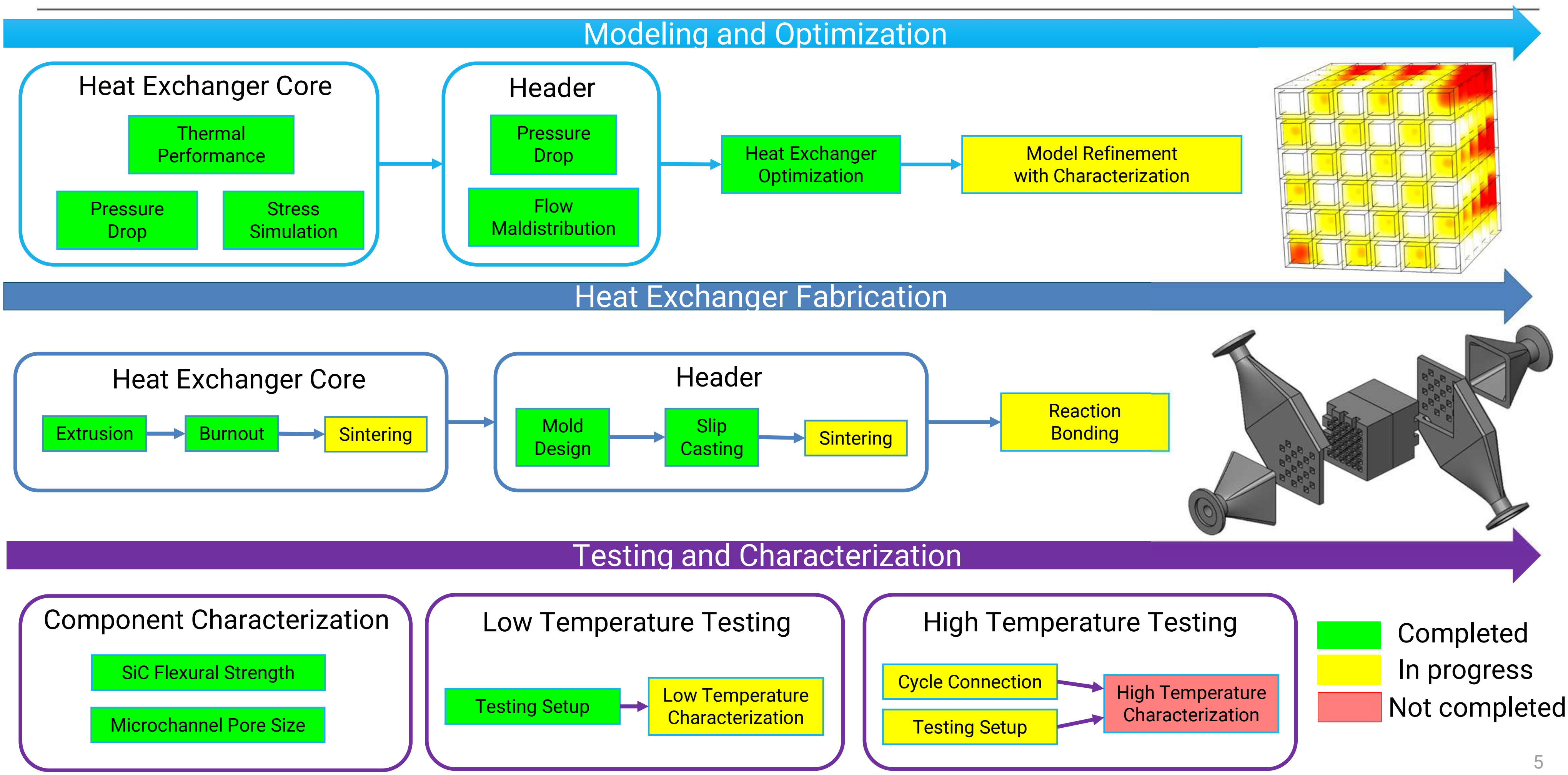
Cold side inlet:
– sCO_2, 300°C, 250 bar
– Flow rate: 0.083 kg/s

Heat Exchanger Design Details

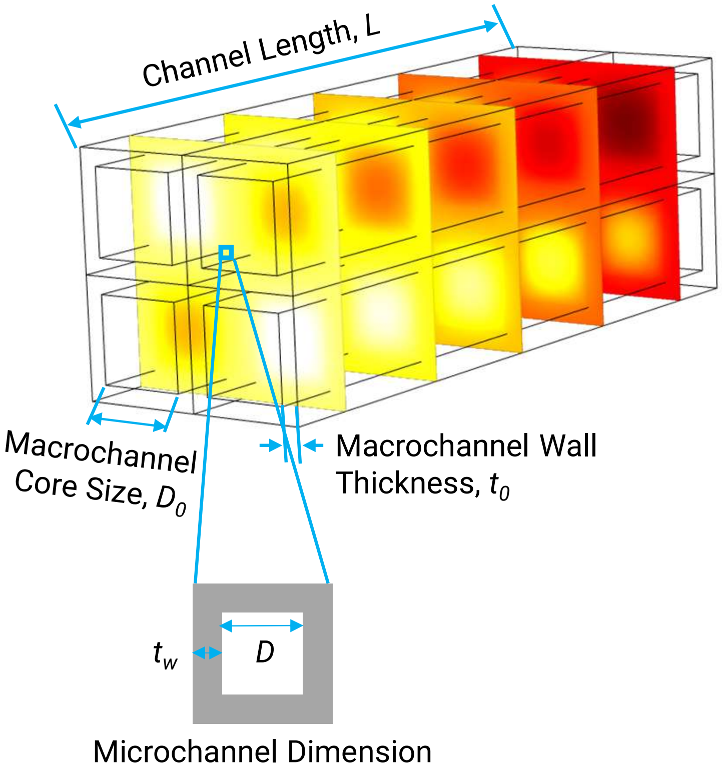
Metric Name	Category B Target	MPHT HX Core Performance
Targeted application(s)	Aviation	
Hot-side pressure drop, $(\Delta P/P_{inlet})_{,hot}$	≤ 4%	≤ 4%
Cold-side pressure drop, $(\Delta P/P_{inlet})_{,cold}$	≤ 4%	≤ 4%
Heat exchanger effectiveness	≥ 50%	> 50%
Heat exchanger thermal capacity	≥ 50 kW_{th}	50 kW_{th}
Heat exchanger mass-based power density	kW_{th}/kg	> 100 kW_{th}/kg
Heat exchanger volume-based power density	kW_{th}/m^3	> 7×10^5 kW_{th}/m^3
Heat exchanger material(s)		SiC

- Detailed multiscale model of the heat exchanger core
- A HX core predicted with > 50% effectiveness and > 700 MW_{th}/m^3, > 100 kW_{th}/kg power density

Progress Against Tasks – Timetable



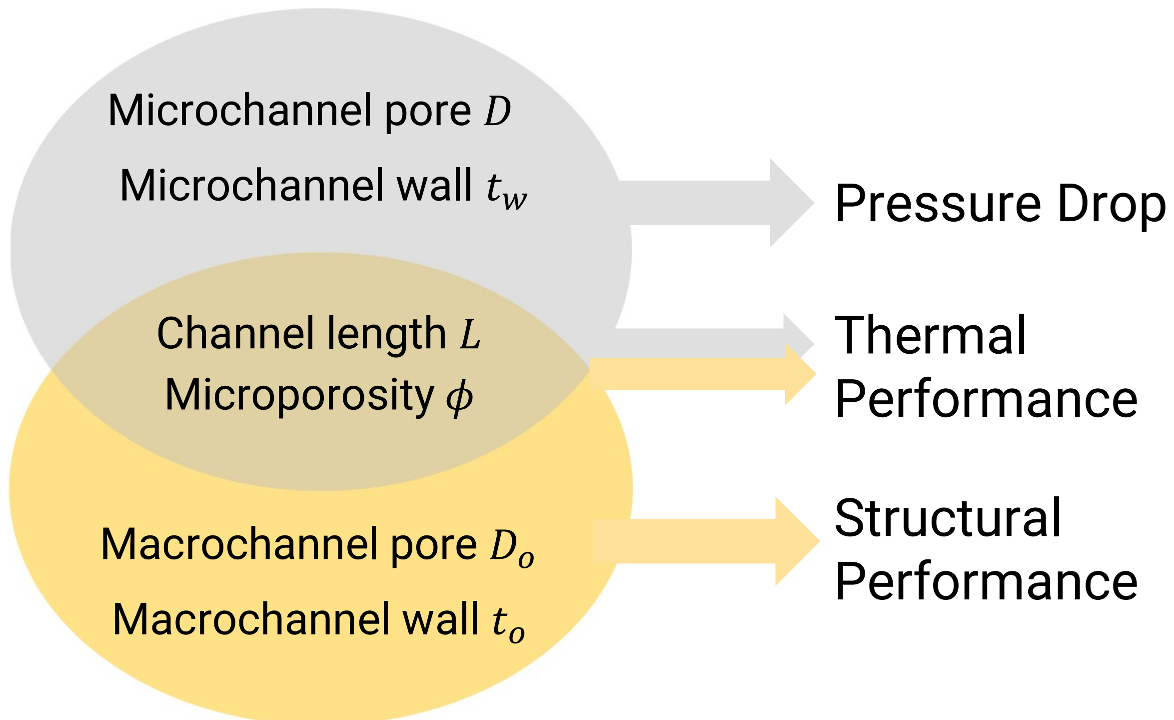
Model Overview of the Heat Exchanger Core



Microporosity $\phi = \left(\frac{D}{D+2t_w}\right)^2$

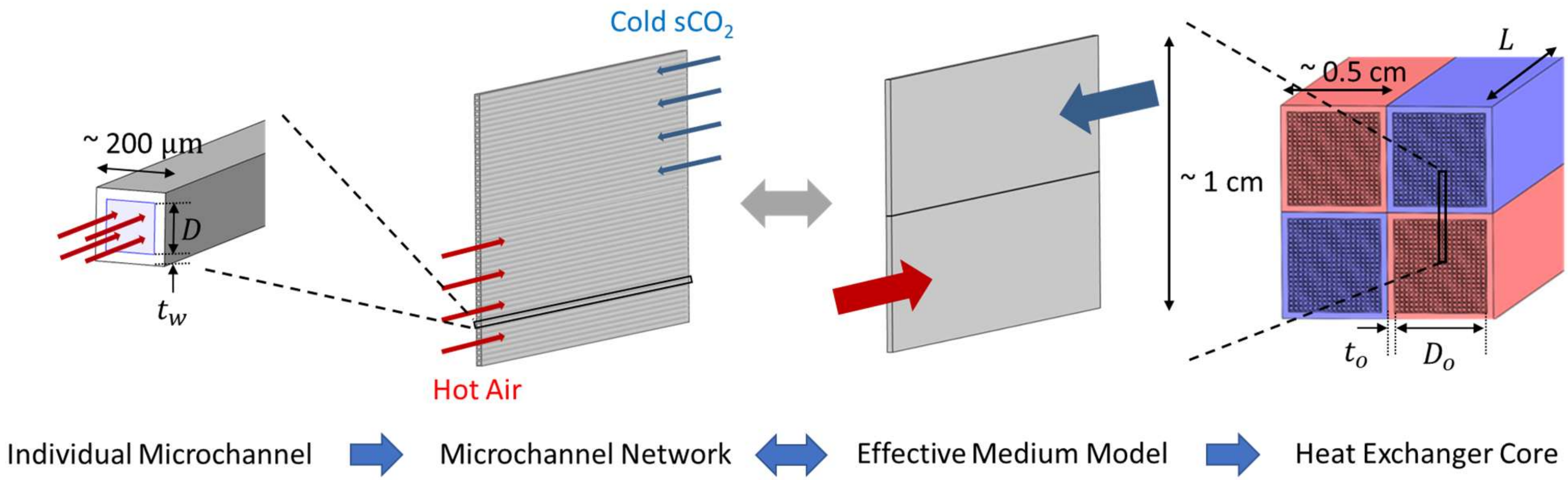
Design Parameters

Performance Metrics



Thermal-Fluidic Modeling

- COMSOL Hierarchical Thermal-Fluidic Simulation
  - Fluidic simulation in individual microchannels for pressure drop
  - Effective thermal conductivity for microchannel network
  - Optimizing HX core for thermal performance



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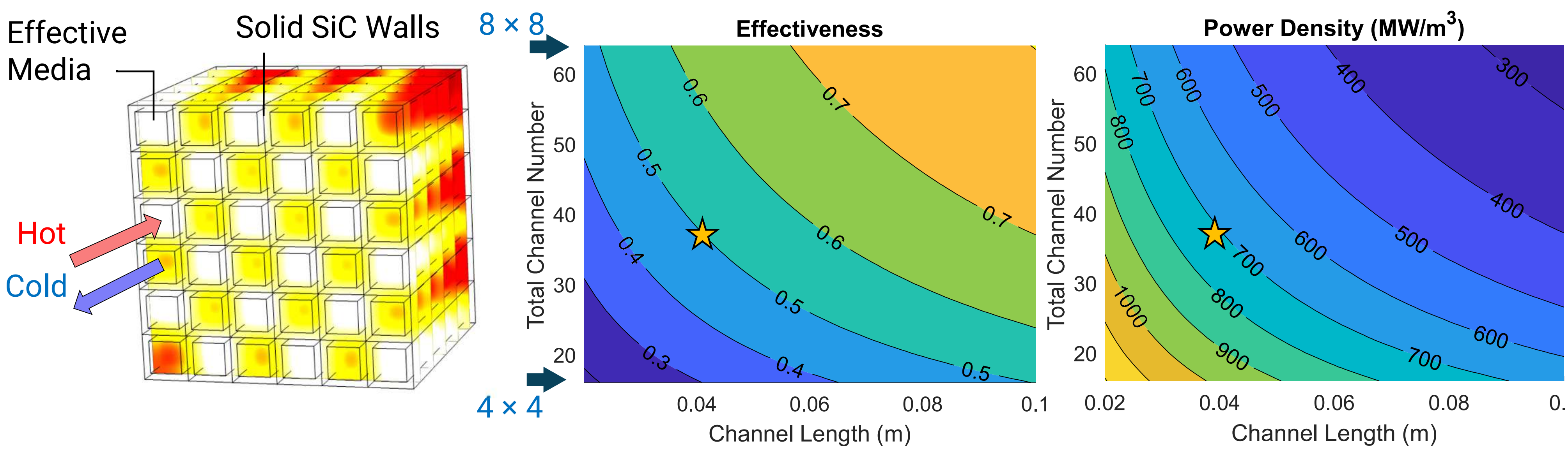
HX Prototype Optimization

- 0.083 kg/s mass flow rates

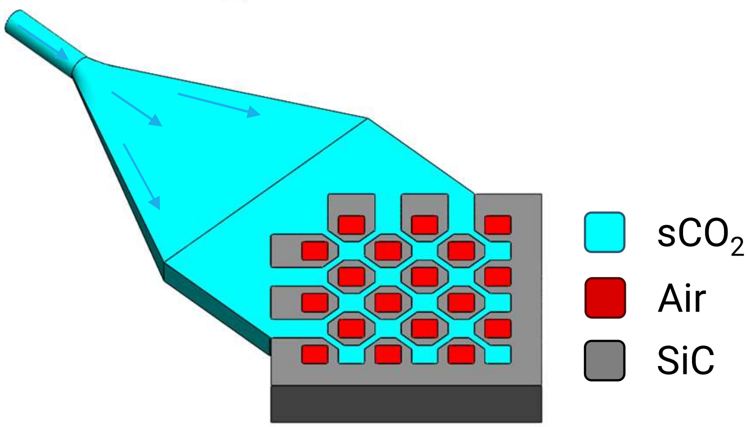
Geometry Parameters	Current Design
Microporosity, ϕ	0.34
Microchannel Size, D	105 µm
Channel Length, L	4 cm
Macrochannel Size, D_o	5 mm
Macrochannel Wall, t_o	1 mm

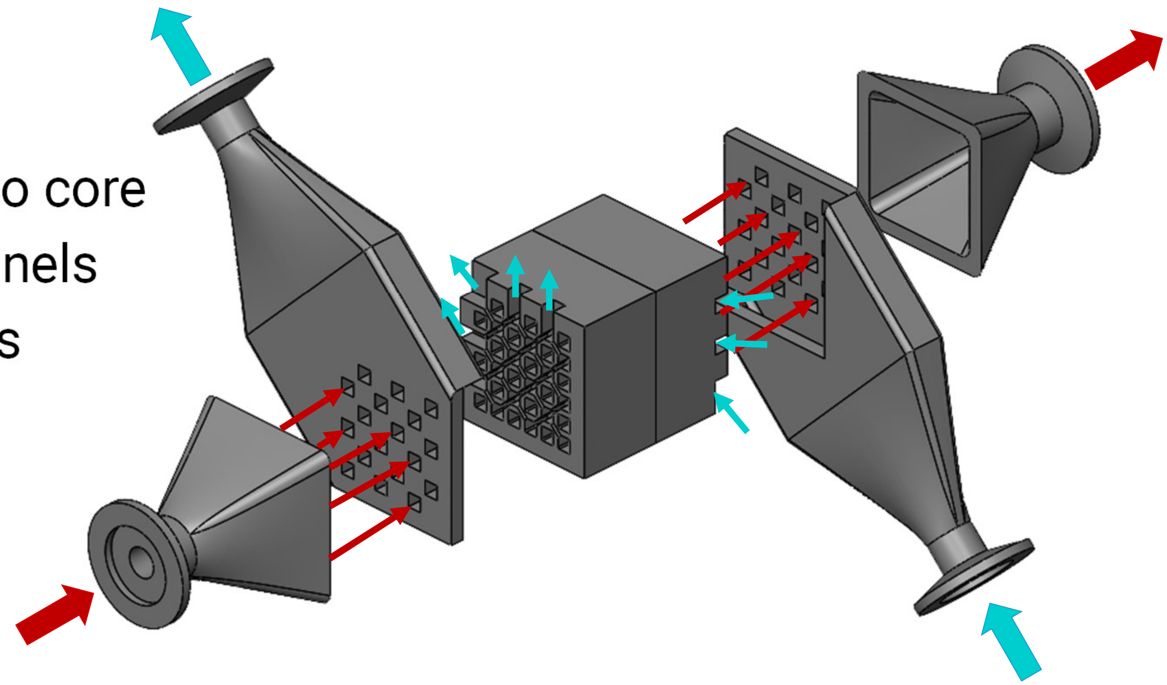
- HX Core Performance
  - Heat Capacity, 51 kW_{th}
  - Pressure Drop, $\Delta P/P$ < 2%
  - Effectiveness, $\varepsilon > 50\%$
  - Volume Power Density, 700 MW/m^3
  - Weight Power Density, 230 kW/kg



Header Design

- Goal: Low pressure drop without sacrificing manufacturability
- Solutions:
  - Mill part of header directly into core
  - Air inlet in line with core channels
  - sCO_2 inlet turns 90˚ in headers

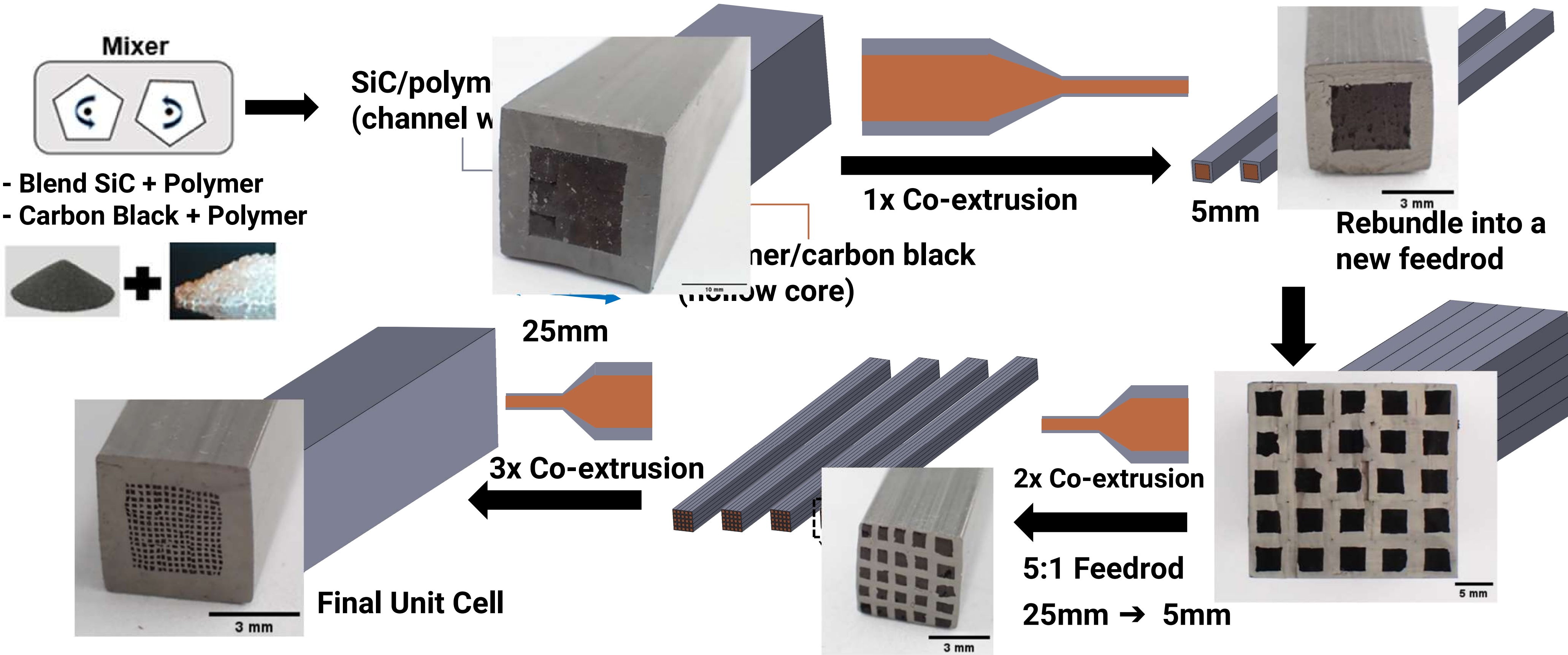




- Total pressure drop: $\Delta P / P$ < 4%
- Flow maldistribution: 1.4 g/s

* Model refinement ongoing with experimental characterization

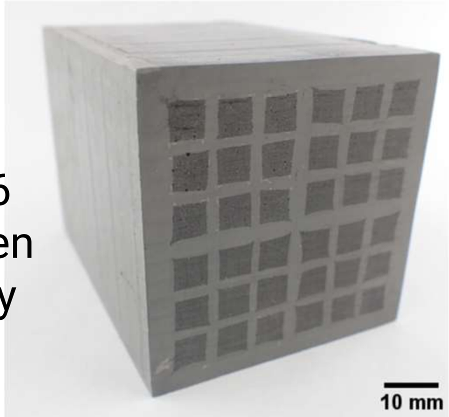
Co-Extrusion of Microchannels - Manufacturing Process Overview



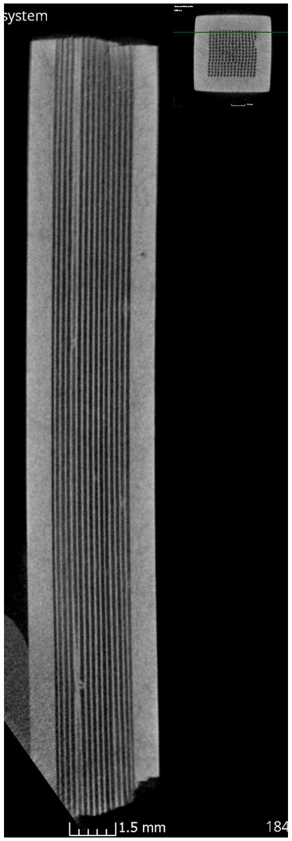
Scale Up of Heat Exchanger and Microchannel Openness

- Finalized 6 by 6 heat exchanger design
  - Each unit cell has 625 square microchannels, approx. 100 µm x 100 µm (22,500 channels)

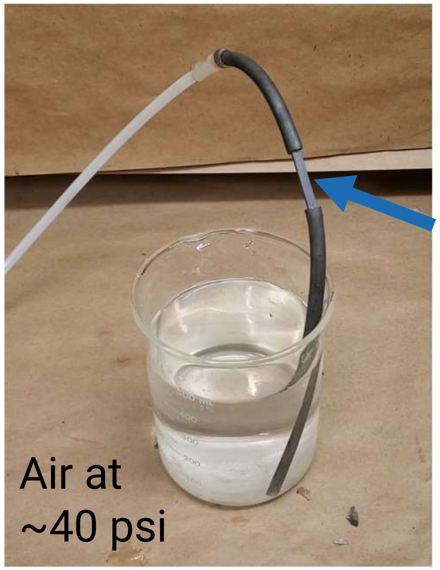
6 x 6 Green Body



- Microchannels are open and continuous after sintering



microCT of unit cell after sintering (courtesy APL/JHU)



Air at ~40 psi

25 mm long sintered SiC unit cell

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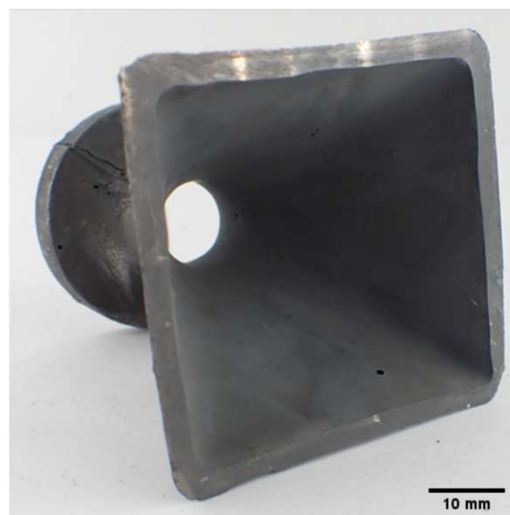
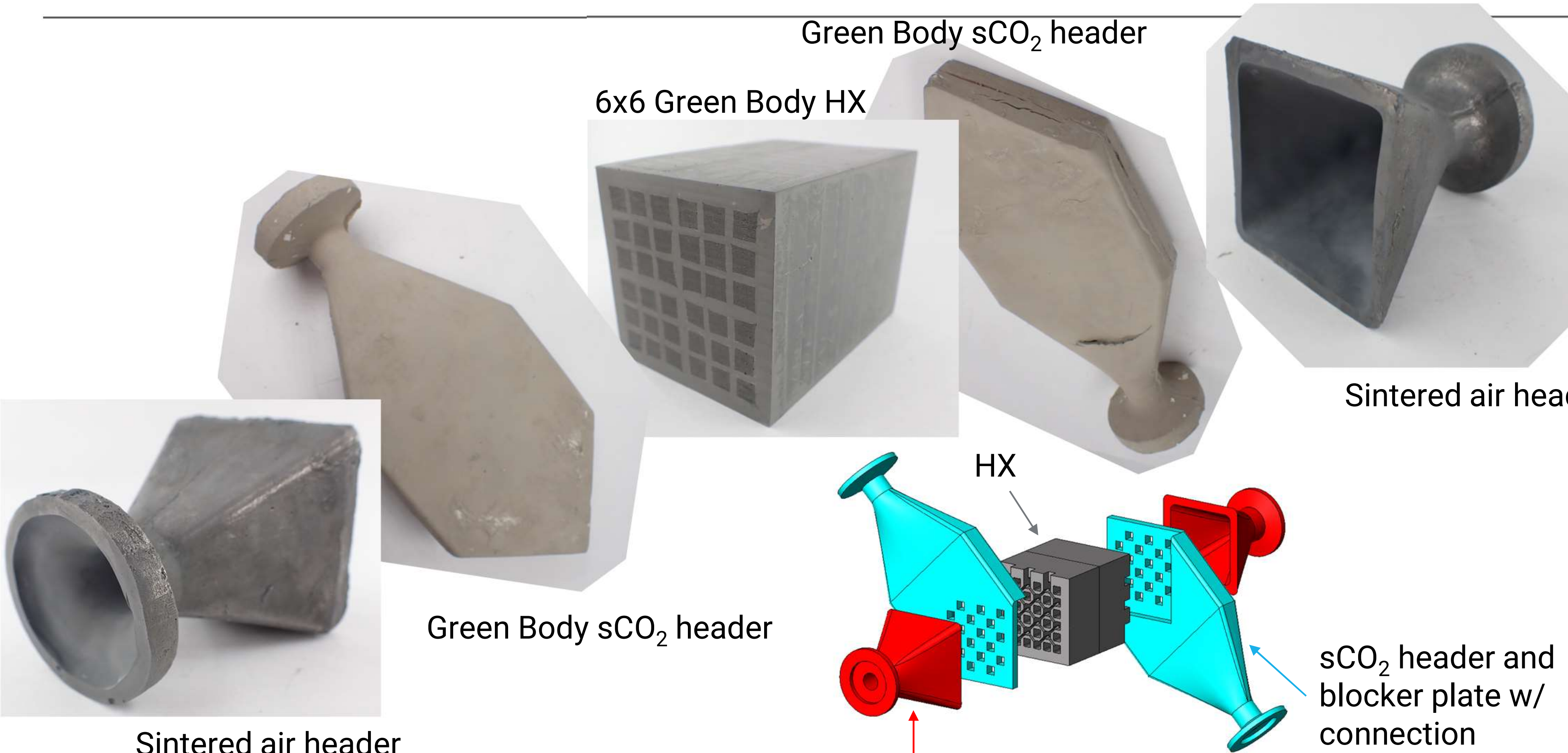
Slip Casting of SiC for Header Fabrication

- Fabrication of air and sCO_2 headers through SiC slip casting
- Successful sintering of air header with 96% RD
- Parts complete and ready for bonding

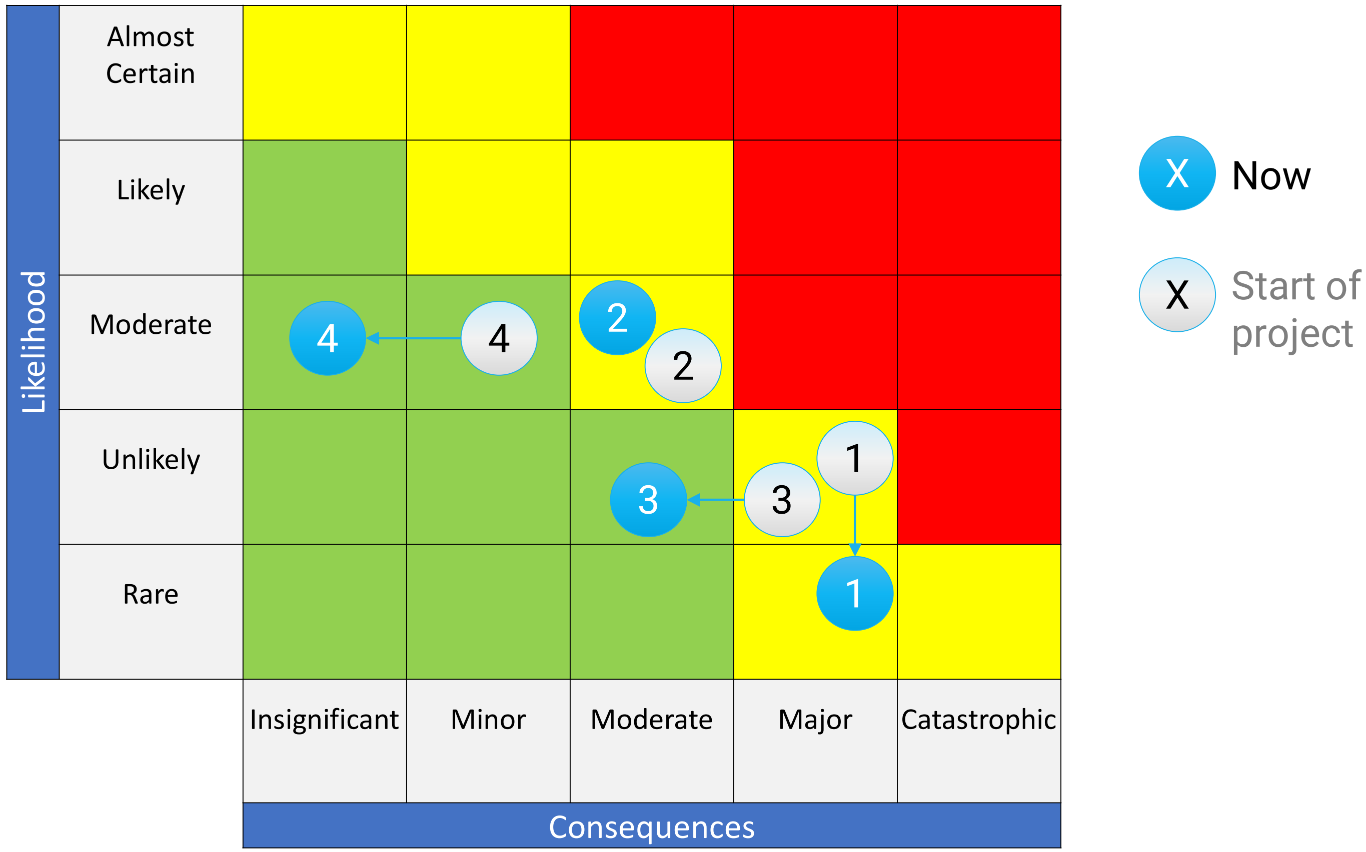


Fabrication of Heat Exchanger and Headers Progress



Risk Update

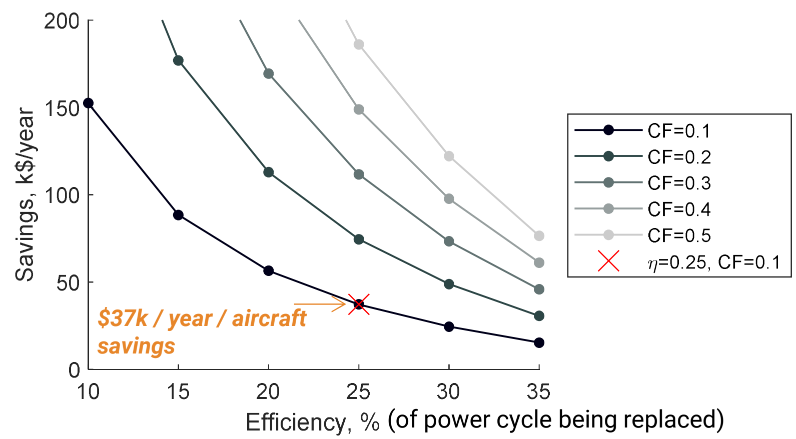
Risk	#
Unsuccessful co-extrusion of SiC	1
Weak joint between SiC components	2
Poor durability of the heat exchanger	3
Not ideal for aircraft APUs	4



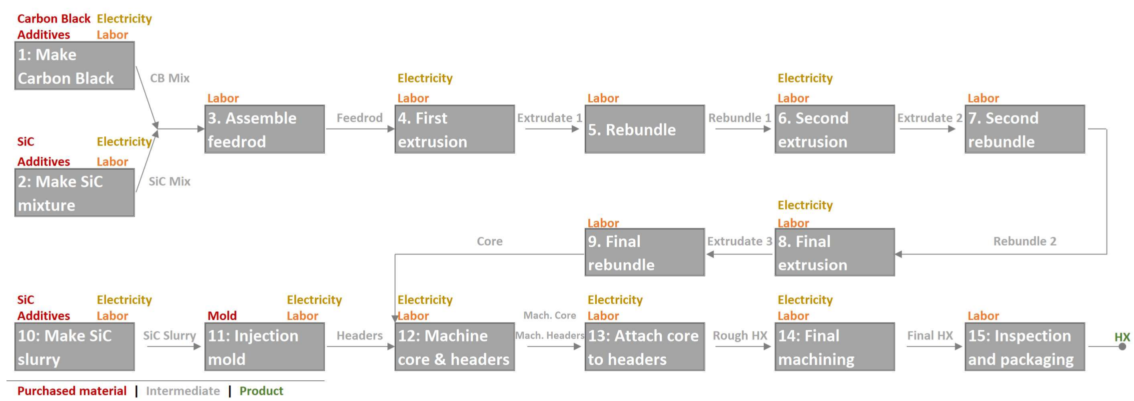
Technology-to-Market Updates

- Notable accomplishments
  - System level value proposition
  - Initial market surveys
  - Initial monetization plan
  - IP study complete, HX core design has been filed as a disclosure
  - Characterized first markets
  - Drop-in value propositions
  - Costing model
- Key assumptions driving economic viability
  - Willingness to adopt
  - Targeting low-risk first markets

Value proposition of a new power cycle in aircraft APU



Cost model process diagram



Potential Partnerships

- Needs at this time
  - Industrial co-extrusion entity
  - **Applications**
    - **Immediate (drop-in): may not leverage full capabilities – but – <u>ideal first market</u>**
    - Long term (advanced system): yield greater value stories – but – <u>not ideal near term</u>
  - Identify a follow-on program which utilizes our technology in a system.

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Q & A

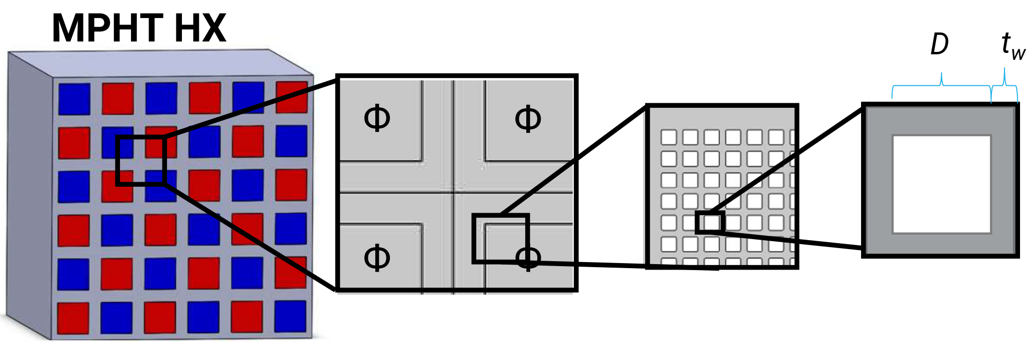
https://arpa-e.energy.gov

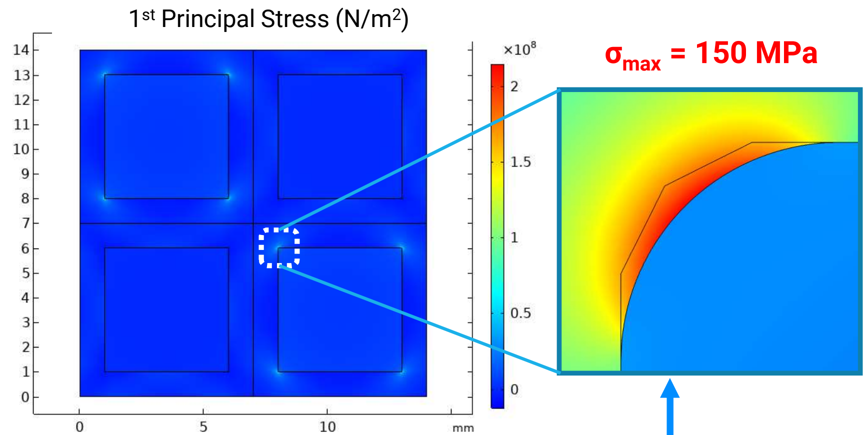
Structural Performance of HX Core

- Microscale geometry adjustment

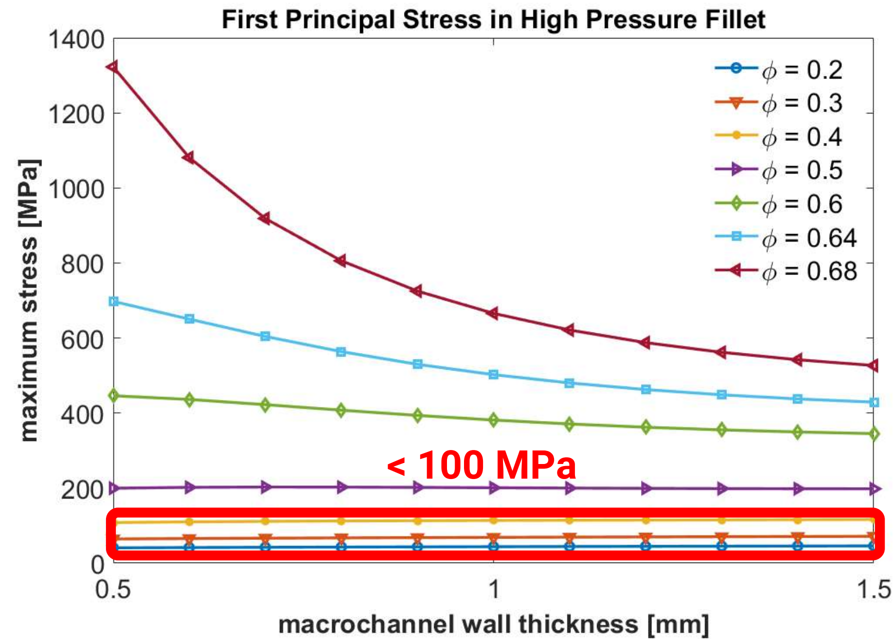
Current: D = 105 μm, t_w = 38 μm

$\Phi_{original}$ = 50% → $\boldsymbol{\Phi_{actual}}$ **= 34%**

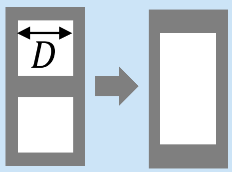
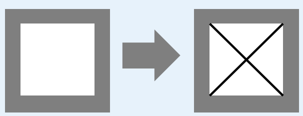
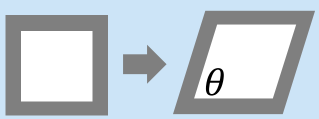




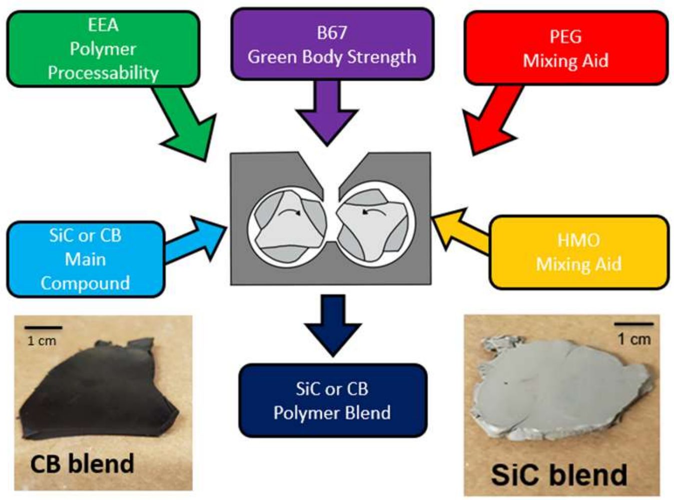
$$E_{porous} = (1-\phi)\frac{1-\phi}{0.684}E_{SiC}$$



Summary – Imperfect Square Channels

Microchannel Imperfection	Percentage/ Likelihood	Effect on pressure drop	Effect on power density	Effect on mechanical strength
Merged channels 	< 5%	Minor reduction	Minor reduction	No significant impact
Blocked channels 	< 5%	Minor increase	Minor reduction	Minor enhancement
Rhombus channels 	< 5%, 60°-90°	Minor increase	Minor enhancement	No significant impact

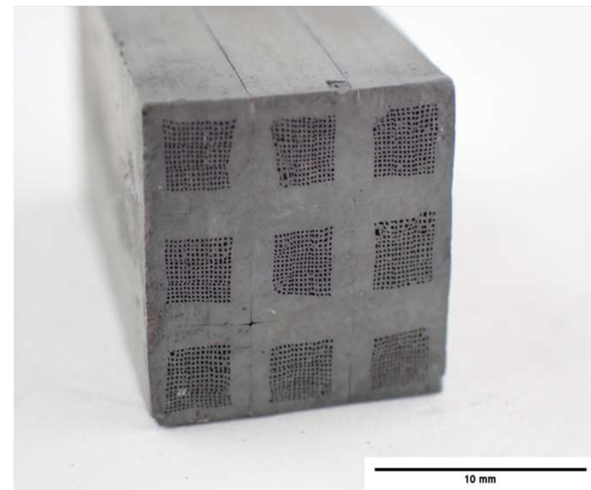
Silicon Carbide 3 by 3 Heat Exchanger Fabrication



Vol% SiC or Carbon Black	Torque (N-m)	Temp (°C)
54 vol% SiC*	16.5	149
40 vol% CB	17.1	147

* SiC plus sintering aids (Al_2O_3 + Y_2O_3)

Green body 3 x 3 prototype



Sintered 3 x 3 prototype

- Torque matching of blends for co-extrusion
- Removal of polymer without distortion
- Sintering of SiC to 90% Relative Density