Low Cost Ceramic-Matrix Composites for Harsh Environment Heat Exchanger Applications

Contract Number: DE-EE0008318
UTRC/Oak Ridge National Lab/MR&D
Sept. 2018 – Aug. 2020

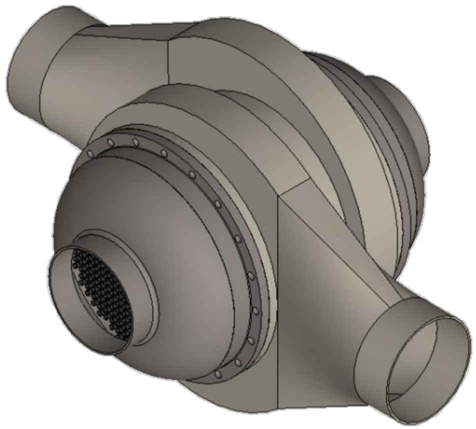
Brian St. Rock/Rajiv Ranjan, United Technologies Research Center

U.S. DOE Advanced Manufacturing Office Peer Review Meeting
Washington, D.C.
June 11-12, 2019

Project Overview

Glass Ceramix Matrix Composite (GCMC) in new HX topology

Concept



Timeline & Budget

Award issued Sept 2018
Budget Period 1 = Sept 2018 to Aug 2019
Budget Period 2 = Sept 2019 to Aug 2020

	Budget Period 1	Budget Period 2	Total Planned Funding
DOE Funded	$0.493M	$0.843M	$1.336M
Project Cost Share	$0.124M	$0.210M	$0.334M

Barriers/Risks

Reliable /repeatable fabrication of HX-relevant features

Bonding and joint design and scalable assembly

Leak-free seal coating

Partners

UTRC (Prime)

- Heat exchanger (HX) design & testing
- Materials technology
- Bonding process

MR&D

- CMC mechanical modeling
- Fabrication plan support

ORNL

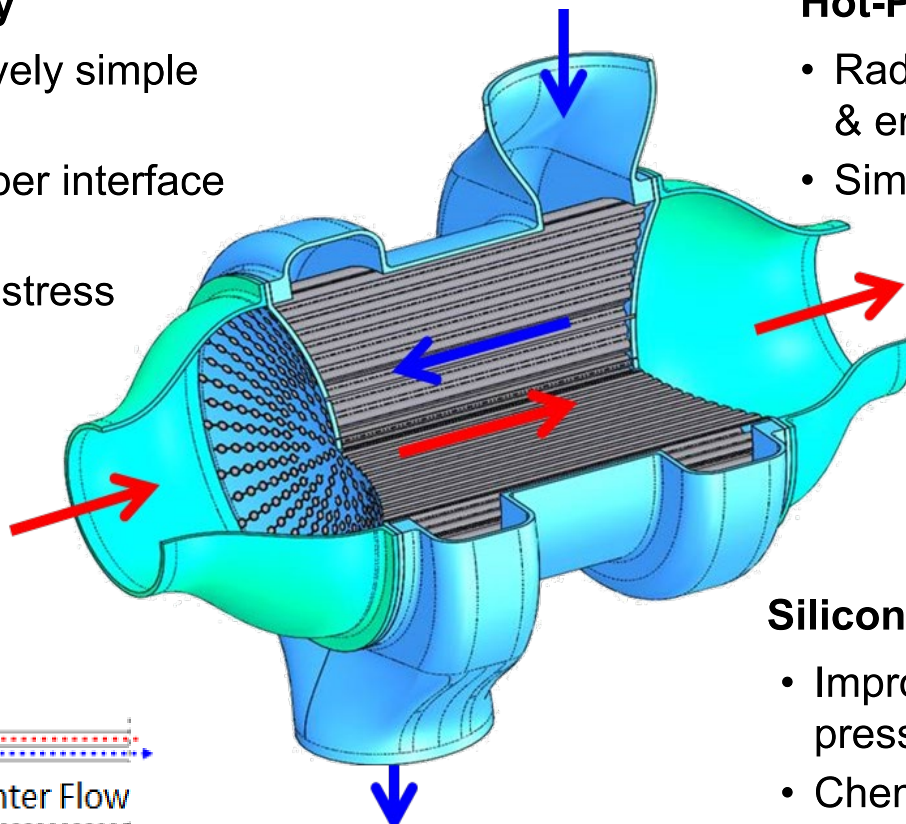
- CVD seal coating
- Materials characterization

Technical Innovation

Unique GCMC material system in producible HX configuration

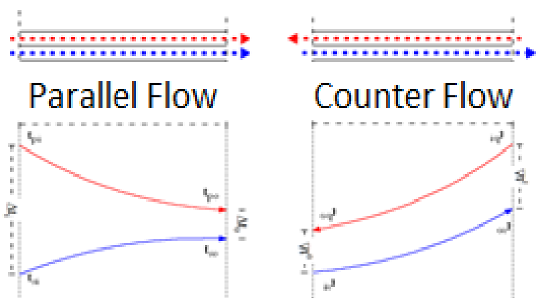
GCMC HX Assembly

- Assembly of relatively simple CMC components
- In-situ growth of fiber interface coating (low cost)
- Low CTE reduces stress



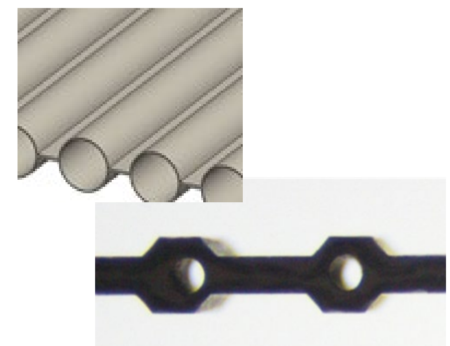
Cylindrical Counterflow HX

- Improved thermal performance & reduced stress



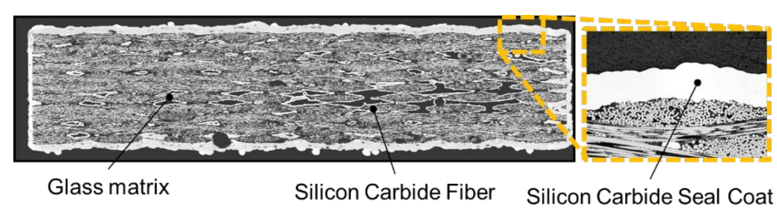
Hot-Pressed Tube Sheets

- Radial sheets reduce stress & enable core penetration
- Simplifies fabrication



Silicon Carbide Seal Coating

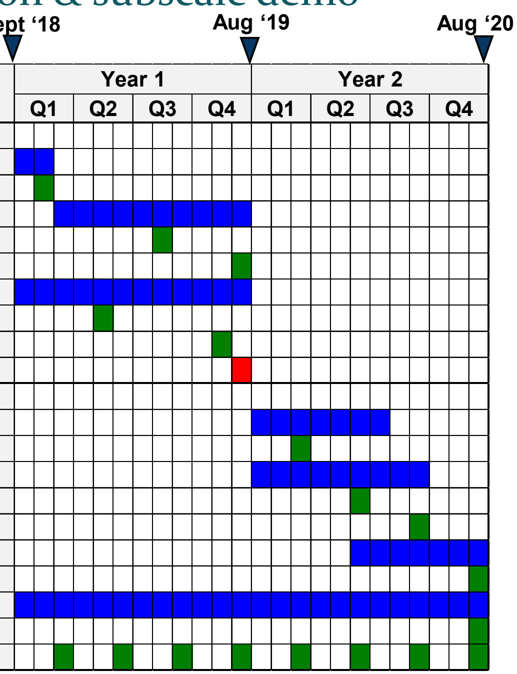
- Improves air retention under pressure
- Chemically-inert surfaces



Technical Approach

- Leverage prior DoD materials investment
- Technical Focus Areas (driven by key risks):
  - Design for manufacturing
  - Focus on manufacturing maturity
  - Joint and coating development
- Phased Approach
  - Phase 1: Coupon-scale demonstration
  - Phase 2: Component integration & subscale demo

	Task Descriptions	Owner
	BP-1: Coupon-Level Studies	
1	**HX Design & Requirements**	
	Design Specs & Requirements Allocation	UTRC
2	**CMC Manufacturing Studies**	
	Application-Specific Property Database	UTRC
	Processing Specifications for Joining	UTRC
3	**CVI Processing Studies**	
	Reactor Facility Complete	ORNL
	Coupon-Level Downselection	ORNL
	Go/No-Go: Acceptable Material Limits	UTRC/DOE
	BP-2: Subscale-Level Characterization	
4	**HX Prototype Fabrication**	
	HX Component Fabrication	UTRC
5	**CVD Processing & Characterization**	
	Subscale Leak Testing Complete	UTRC
	Single-Layer HX Prototype Complete	ORNL
6	**Single Layer HX Testing**	
	Single Layer HX Test Complete	UTRC
7	**Program Management**	
	TRL/MRL Review	UTRC
	Quarterly Reporting	UTRC



SPONSOR: U.S. DEPARTMENT OF ENERGY — Energy Efficiency & Renewable Energy

Program Management — United Technologies Research Center
PM: Mr. Brian St. Rock

HX Design & Analysis — United Technologies Research Center
PI: Dr. Rajiv Ranjan
- Thermodynamic HX Sizing & Performance
- HX Testing

CMC Fabrication Dev. — United Technologies Research Center
PI: Dr. John Holowczak
- CMC Manufacturing & Assembly
- Material Characterization Testing

Composite Design & Analysis — MR&D Materials Research & Design
PI: Mr. John Podhiny
- Micromechanics & Reliability Modeling
- Materials & Manufacturing Plan Support

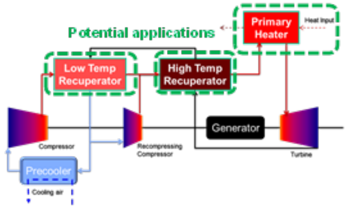
Multifunctional Coating — Oak Ridge National Laboratory
PI: Dr. Allen Haynes
- Silicon Carbide Seal Coat Development
- Coating Characterization

Likehood \ Impact	Trivial	Significant	Major	Catastrophic
Very Likely				
Likely			CMC alone (no CVD seal coat) has excessive leak rate	
Quite Possible	Initial HX design not manufacturable requiring new design	Tube to header interface leak path	Header pressure requirement not met	
Possible	CMC tube sheet warpage due to residual stresses	Tube sheet approach process difficult to scale	Excessive tube sheet leakage w/CVD seal coat	Approach selected for tube to header bonding does not work at full scale
Not Like	Inadequate CMC thermal conductivity	CG Nicalon® supply disruption requiring switch to alternate	CMC tube sheet fails to meet 1 ksi pressure requirement	Rig pressure control fails over-pressurizing full scale HX

Results and Accomplishments

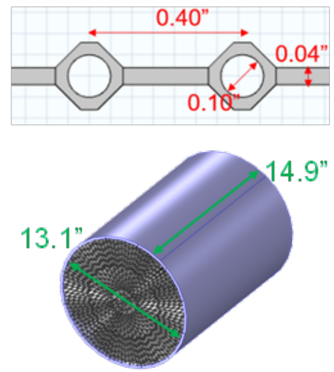
Task 1: HX Design & Requirements

Recuperated SCO2 Brayton cycle



	Hot Side	Cold Side
Inlet temp	1300-1600 F	240.8 F
Inlet pressure	1145 psi	1987 psi
Flow rate	3.2 kg/s	2.3 kg/s
Pressure drop	0.82 psi	2.32 psi
Heat transfer rate	1 MW	

HX core design

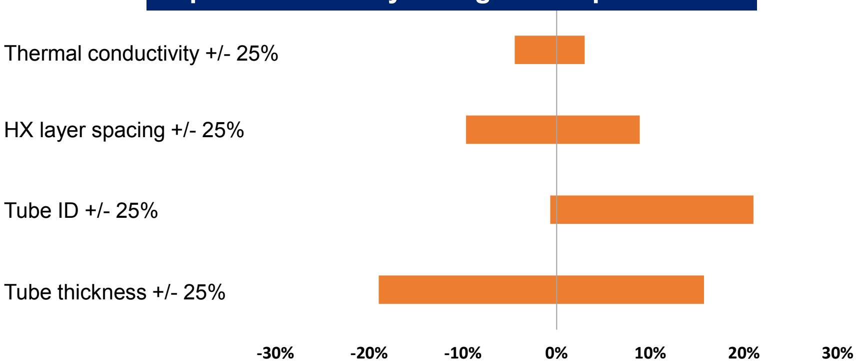


1MW HX sizing	
Counterflow Core Design	Full scale HX core dimension (inch)
Core Diameter	13.1"
Core Length	14.9"
Number of tubes	1410

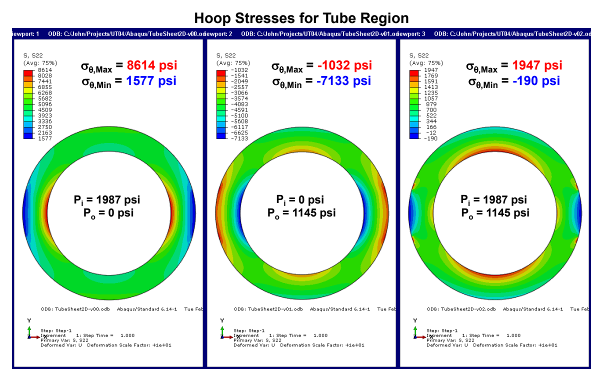
Volumetric HT rate = 34 kW/L

HX parameter sensitivity study

Impact on Q/vol by change in HX parameters



Preliminary FEA analysis

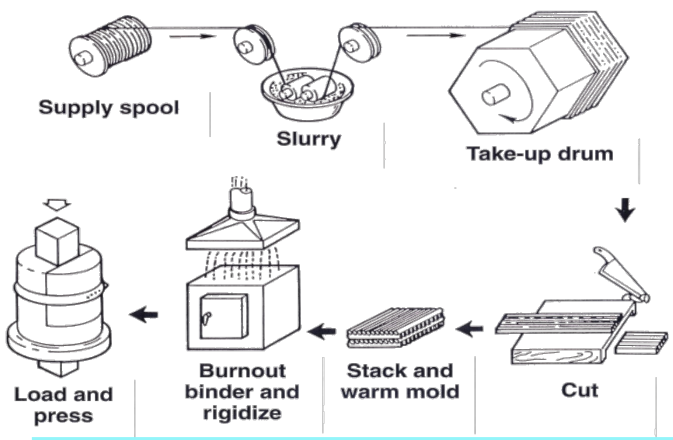


Guides the risk reduction path

Results and Accomplishments

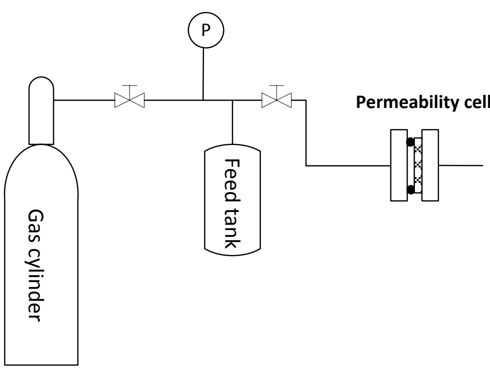
Task 2: CMC Manufacturing Studies

CMC fabrication process (hot pressing)



UT-16 CMC coupons

Permeability studies

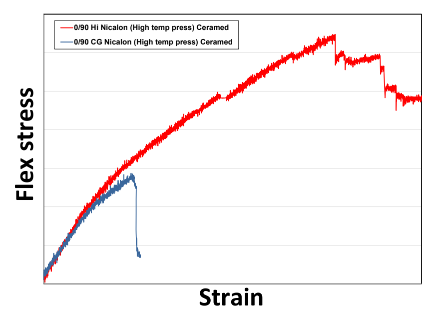


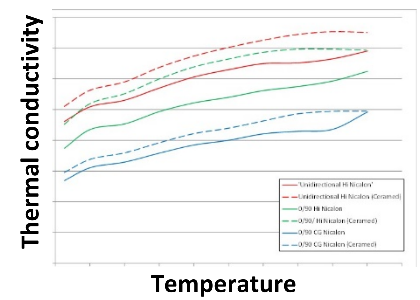
Permeability cell

Samples (Inconel, UT-16)

Initial tests show ultra-low permeability

CMC mechanical properties



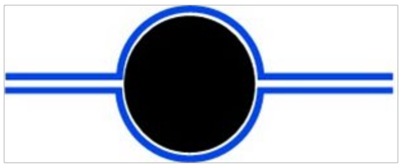


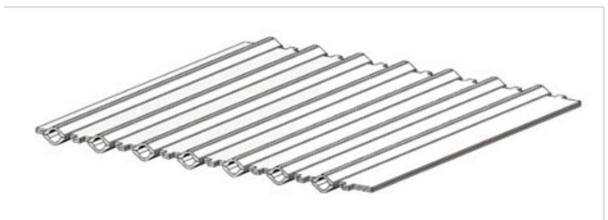
UT-16 characterization shows desired mechanical properties

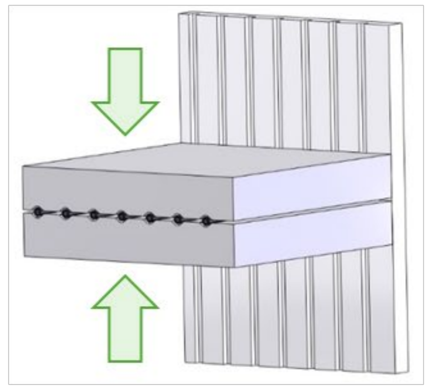
Results and Accomplishments

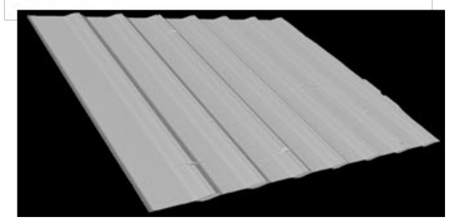
Task 2: CMC Manufacturing Studies (contd.)

Tube sheet fabrication (tooling, fabrication trials)



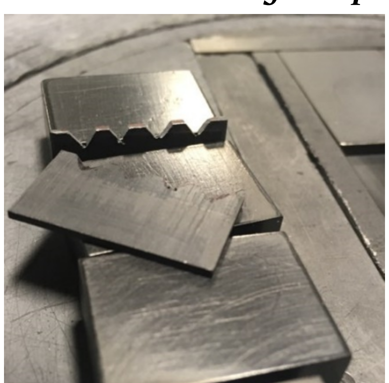




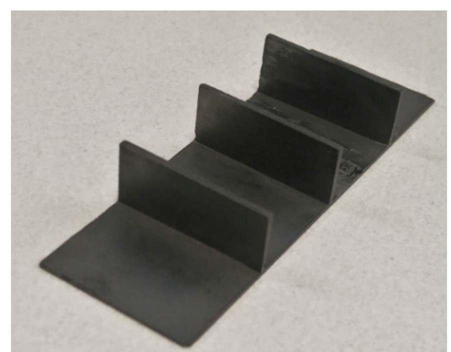


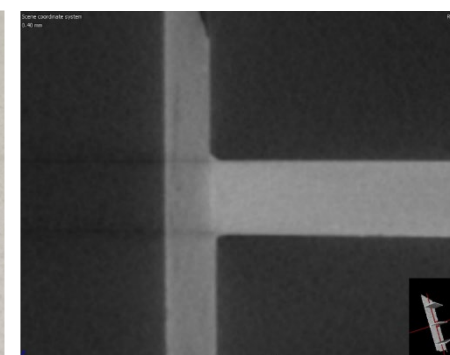
Sub-component joining trials

Tooling and process for T-joint trials



Optical and CT imagea of T-joint





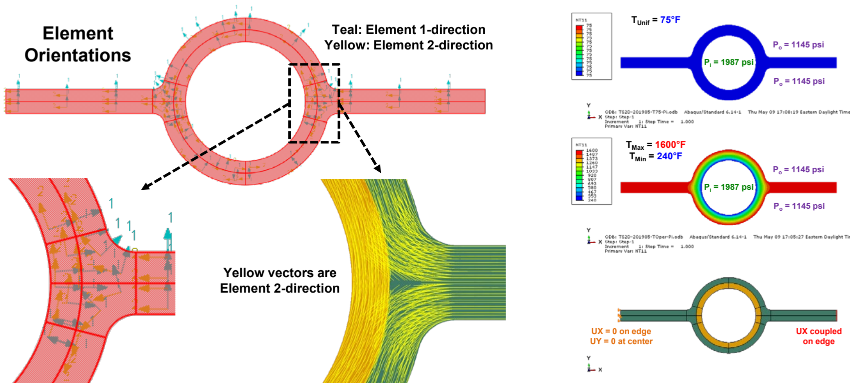
Continued joining trials for sub-component integration

Results and Accomplishments

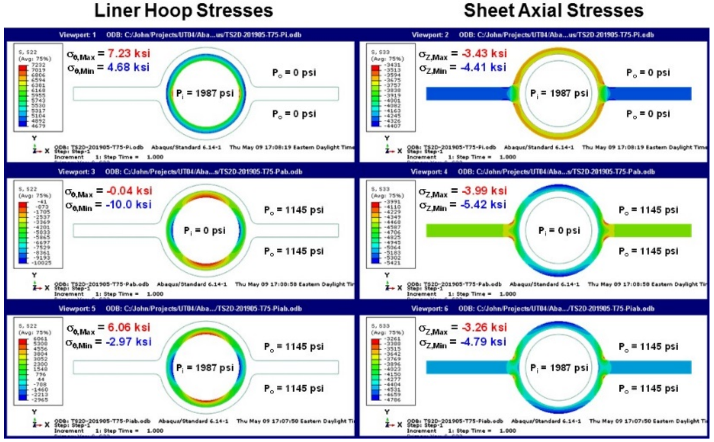
Micromechanical CMC Modeling & CVI coating

FEA stress analysis:

FEA study setup: Element orientation & Boundary conditions



FEA results for hoop and axial stress

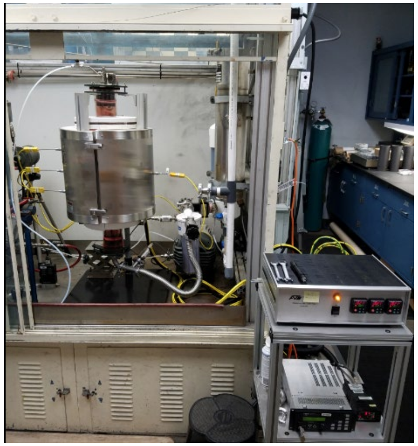


FEA study guiding the CMC fabrication strategy

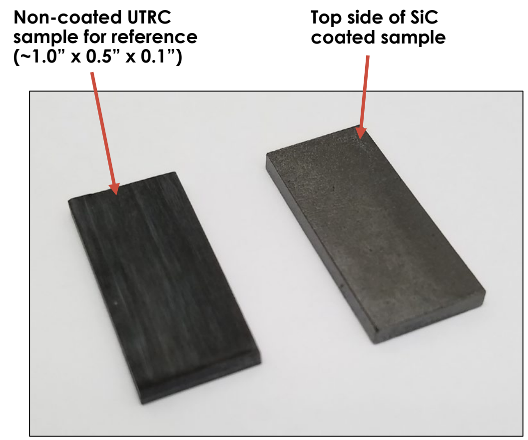
SiC CVI coating:

Two reactors setup complete at Oak Ridge National Lab

- CVD reactor for smaller coupons
- CVI reactors for larger samples
- Coating trials underway



CVI reactor setup at ORNL



SiC coating of CMC coupons

CVI study underway to optimizing coating

Summary

Major Accomplishments:

- Preliminary (full, sub-scale) HX design completed
- HX parametric study & optimization
- FEA analysis shows risk-reduction path
- Completion of DoE for coupon fabrication (reliability, reproducibility)
- Initial permeability study shows low leakage risk
- Tube sheet manufacturing & Joining study underway
- CVI coating demonstrated; DOE study underway

Key Next Steps:

- CVD coating tube sheets
- Tube-sheet to header joining
- Micro-mechanical CMC modeling

Questions?

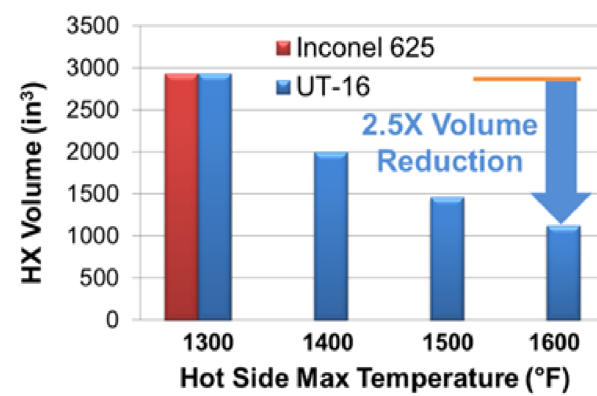
Thank You

Project Objectives

Project/Technology Objectives

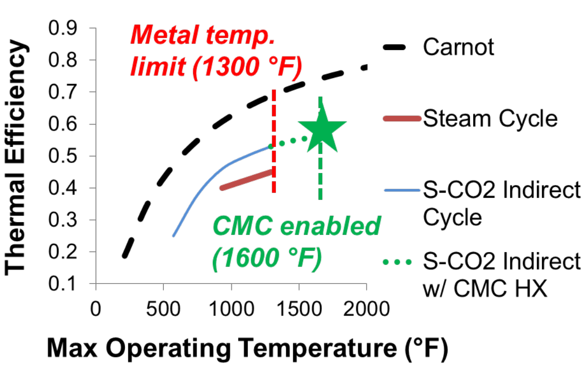
Metric	Go/No-Go Criteria	Program Success Criteria	Comments
Max Operating Temp	1500 °F	1600 °F	300°F higher than continuous use Inco
Hot-to-Cold Pressure Differential	900 psi	1000 psi	Industrial recuperator applications
Volumetric Heat Transfer	33 kW/L	26.7 kW/L	20% improvement over Inco baseline
Gravimetric Heat Transfer	19 kW/kg	13.6 kW/kg	20% improvement over Inco baseline
Cold-to-Hot Leakage Rate	0.5%	0.1%	Coldside flow loss has negligible effect
Cold-to-Ambient Leakage Rate	0.1%	0.0 g/s	No fluid leakage to environment
Thermal Cycling	N/A	20 cycles	Establish basic evidence of cyclic perf

Reduces:
Weight = 86%
Volume = 60%
Low Cost
Improved Durability

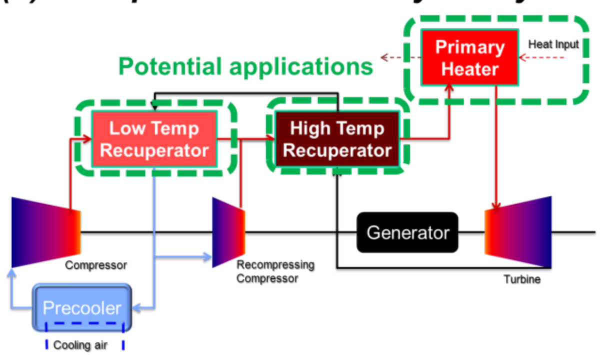


DOE Value Proposition

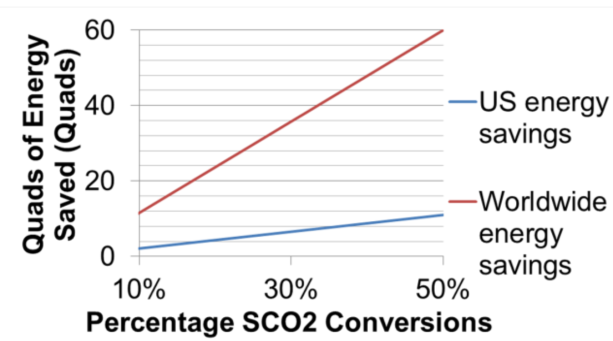
(a) Cycle Thermal Efficiency



(b) Recuperated SCO2 Brayton Cycle



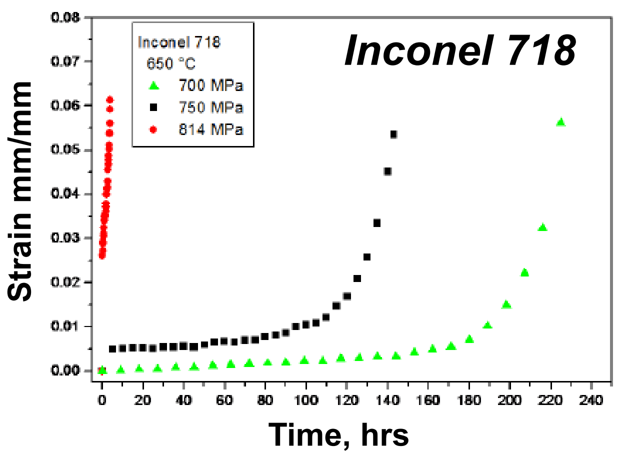
(c) Projected Energy Savings



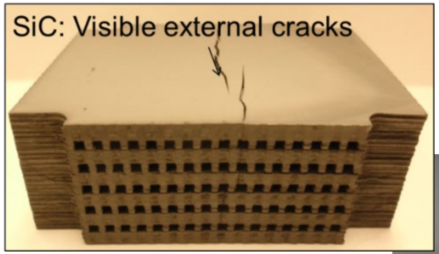
Technical Innovation

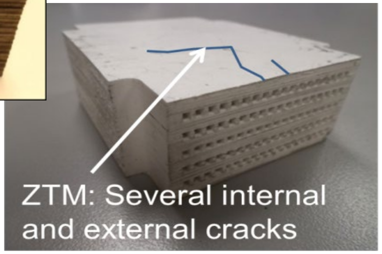
Current material options are costly and have limited strength and durability

Property	Inconel	Ceramics	CMC SOA
High temperature	<1200 F	<2000 F	1600-2500 F
Thermal expansion	~ 16 ppm/ºC	2-10 ppm/ºC	2-4 ppm/ºC
Density	1X	0.4X	0.4X
Manufacturability	Excellent	Poor	Good
High pressure	< 2000 psi	< 1000 psi	< 2000 psi
Chemical Resistance	Moderate	High	Moderate
Thermal Cycling	Moderate	Good	Excellent
Air Retention	Excellent	Varies	Moderate
Strength	Low strength at high temp	Poor strength, brittle fracture	High strength at high temp.
Cost	Moderate	High	High



Ceramic HX Prototypes





Transition (beyond DOE assistance)

Support transition by achieving cost targets

Raw Material	Mass per HX, kg	Cost per kg	Cost per HEX
CG Nicalon®	4.1	$2,090	$8,569
LAS Glass	7.9	$165	$1,304
Unit Assembly			$9,873
CVD Sealcoat			$5,000
		Total	$24,745

"Objective" Target Current Estimate	$25,000 (25 $/kW)	Cost estimate (Table 2)
"Threshold" Limit Max Allowed	$100,000 (100 $/kW)	DOE STEP Program*

* "Technology Development of Modular, Low-Cost, High-Temperature Recuperators for Supercritical CO2 Power Cycles", DE-FE0026273 Kick-off Meeting, Nov 12, 2015

Technology Transition Council

Engage high temp materials suppliers and end-users in benefitting industries

Organization	Industry/Sector	Point-of-Contact
Coorstek-Vista	US CMC Manufacturer	Frank Anderson, R&D VP
3M/Ceradyne	US CMC Manufacturer	Ken Hanley, Director - Advanced Materials
Tetra Engineering	Power Generation	Dave Moelling, Chief Engineer
Climate, Controls & Security	Industrial Refrigeration	Craig Walker, Director CCS Programs
Pratt & Whitney	Commercial Aerospace	Paul D'Orlando, Director - Advanced Technology
UTC Aerospace Systems	Commercial Aerospace	Brent Staubach, Director – Advanced Cycles