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

Contract Number
UTRC/Oak Ridge National Lab/MR&D
July 2018 – June 2020

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U.S. DOE Advanced Manufacturing Office Program Review Meeting
Washington, D.C.
July 17-19, 2018

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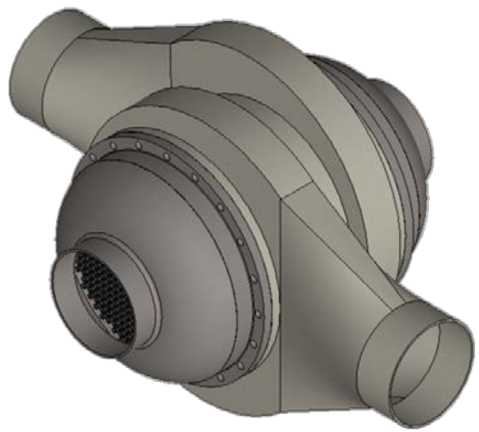
Project Overview

Glass Ceramix Matrix Composite (GCMC) in new HX topology

Concept



Timeline & Budget

Award issued July 2018 (expected)
Budget Period 1 = July 2018 to June 2019
Budget Period 2 = July 2019 to June 2020

	Budget Period 1	Budget Period 2	Total Planned Funding
DOE Funded	$0.493M	$0.123M	$1.336M
Project Cost Share	$0.843M	$0.211M	$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

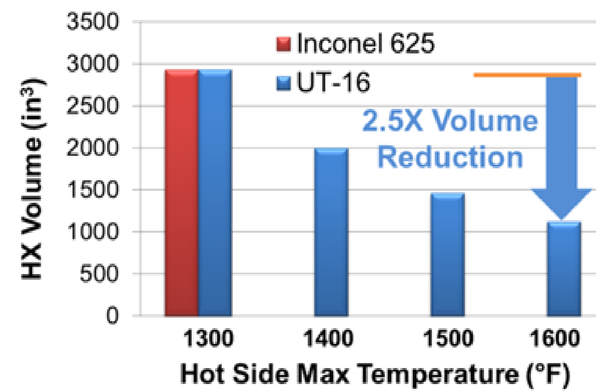
Project Objectives

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

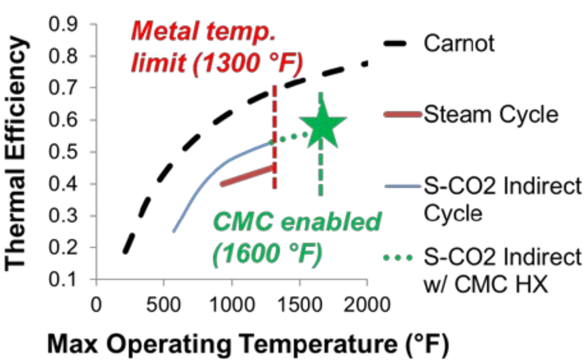
Reduces:
Weight = 86%
Volume = 60%

Low Cost
Improved Durability

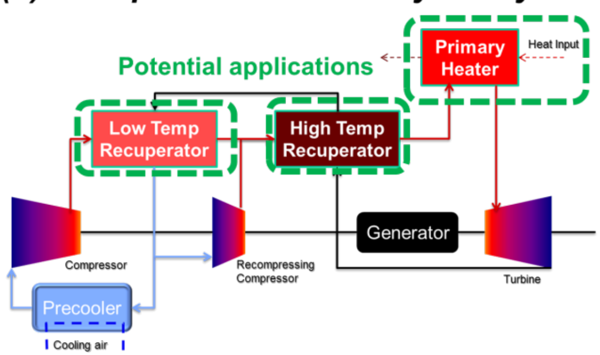


DOE Value Proposition

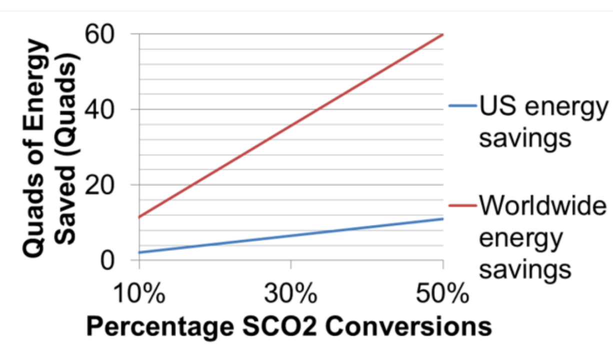
(a) Cycle Thermal Efficiency



(b) Recuperated SCO2 Brayton Cycle



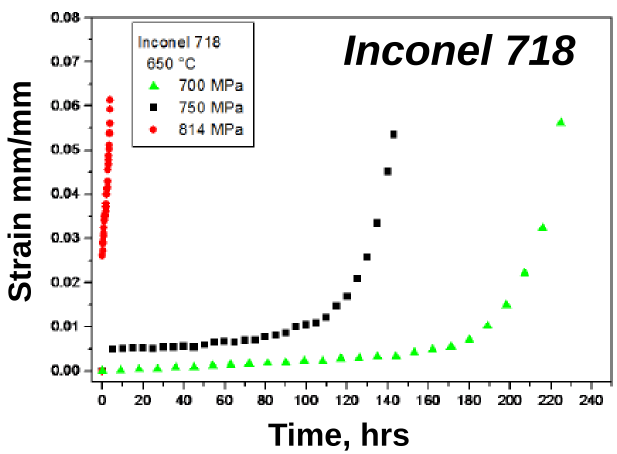
(c) Projected Energy Savings

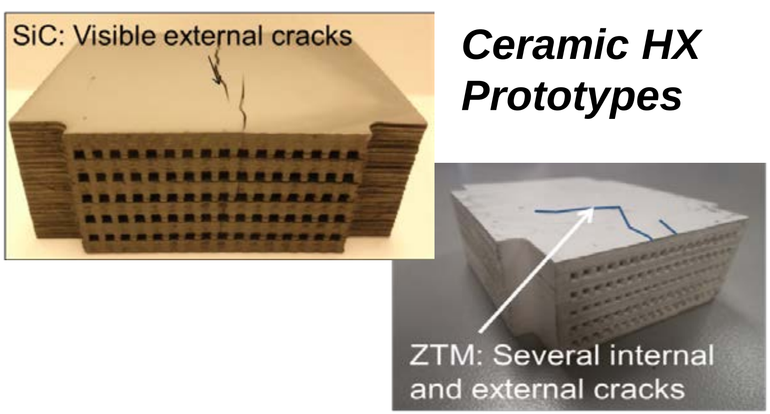


Technical Innovation

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





Technical Innovation

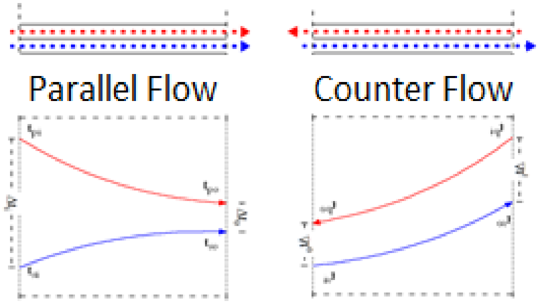
Unique GCMC material system in producible HX configuration

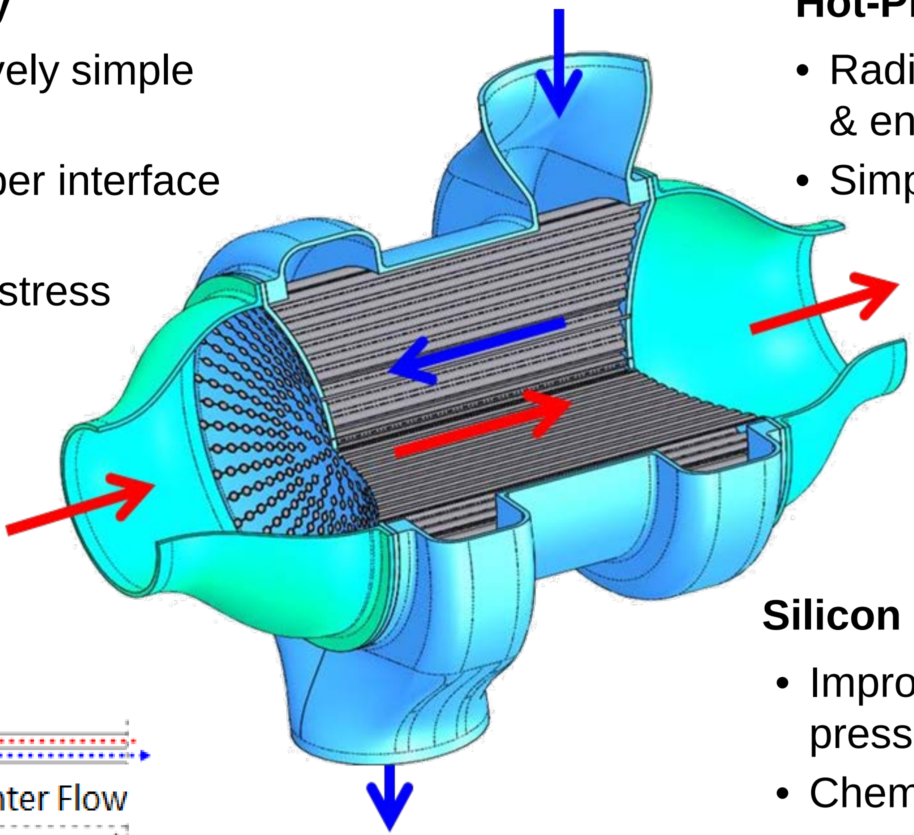
GCMC HX Assembly

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

Cylindrical Counterflow HX

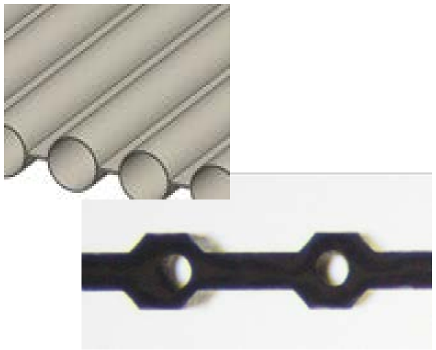
- Improved thermal performance & reduced stress





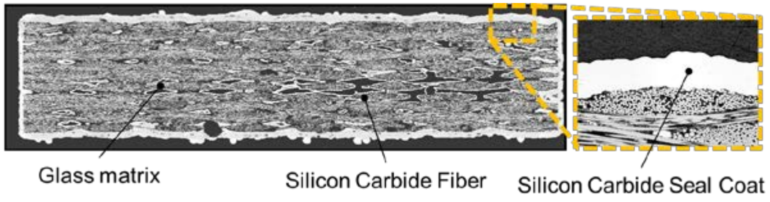
Hot-Pressed Tube Sheets

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



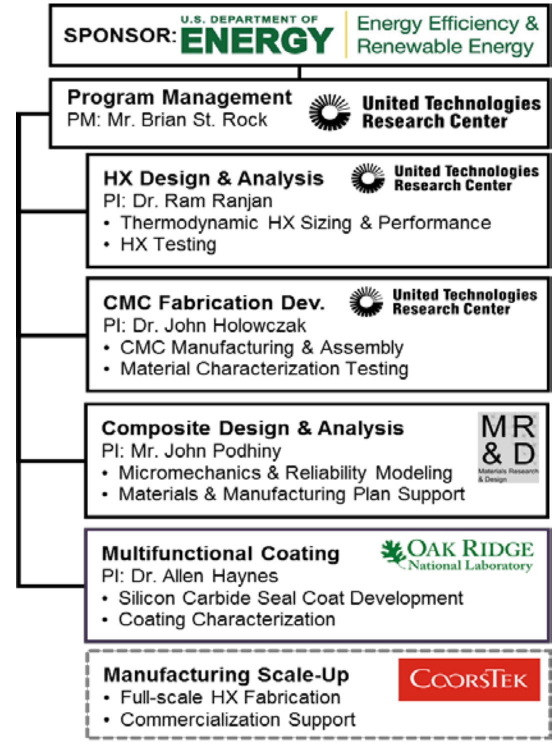
Silicon Carbide Seal Coating

- Improves air retention under pressure
- Chemically-inert surfaces

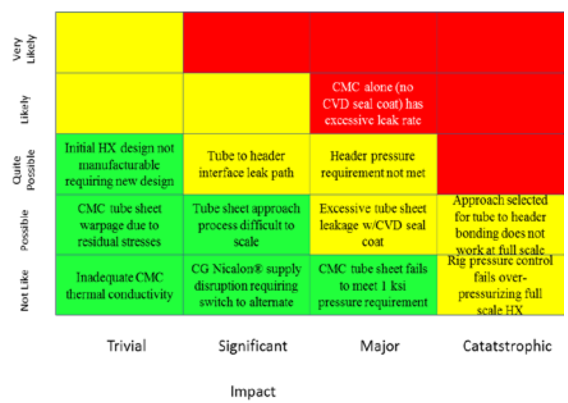


Technical Approach

- 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	Year 1				Year 2			
			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
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								



Technical Approach

Milestone Summary Table							
Task #	**Task Title**	**Milestone Type**	**Milestone Number**	**Milestone Description**	**Milestone Verification Process *(What, How, Who, Where)***	**Ant. Month**	**Ant Qtr**
1	HX Design & Requirements	Milestone	1.1	Design Specs & Requirements Allocation	HX design parameters (# tubes, geometry), KPC's, and allocated requirements for HX subcomponents [UTRC & MR&D]	2	1
3	CVI Processing Studies	Milestone	3.1	Reactor Facility Complete	CVD fabrication equipment modified for SiC precursor and commissioned to enable ONRL to begin coating UTRC fabricated tube sheet CMCs [ORNL]	5	2
2	CMC Manufacturing Studies	Milestone	2.1	Application-Specific Property Database	Coupon-level testing completed to augment existing database with HX-critical properties [UTRC & MR&D]	8	3
3	CVI Processing Studies	Milestone	3.2	Coupon-Level Downselection	Identify >3 sets of seal coating processes capable of meeting gas permeability req'mnts from M1.1, [ORNL]	11	4
2	CMC Manufacturing Studies	Milestone	2.2	Processing Specifications for Joining	After completing trials on at least two types of CMC to CMC bonding techniquesSelect lowest cost header-to-tube bonding approach capable of meeting req's from M1.1 [UTRC]	12	4
2	Coupon-Level Studies	Go/No-Go	2.3	Material System Limits Defined	Assessment of adequate performance (strength, heat transfer, interlaminar properties) of the CMC system. Detailed specifications for this milestone are listed in Table 1. [UTRC]	12	4
4	HX Prototype Fabrication	Milestone	4.1	HX Component Fabrication	Functional HX component hardware (headers, tubes) fabricated based on Task 2 downselections [UTRC]	15	5
5	CVD Processing & Characterization	Milestone	5.1	Subscale Leak Testing Complete	Meet/exceed leakage levels defined in M1.1 based on high pressure tests on tube bundles [UTRC & ORNL]	18	6
5	CVD Processing & Characterization	Milestone	5.2	Single-Layer HX Prototype Complete	Leak-free, functional single-layer HX prototype assembly successfully fabricated [UTRC/ORNL]	21	7
6	Single Layer HX Testing	Milestone	6.1	Single Layer HX Test Complete	TRL-4 test program complete (leak, performance, and burst) complete for single-layer HX prototype [UTRC]	24	8
7	Program Management	Milestone	10.1	TRL/MRL Reviews	Successfully complete TRL4/MRL4 review per UTC PPE Process (Section [UTRC]	24	8

Results and Accomplishments

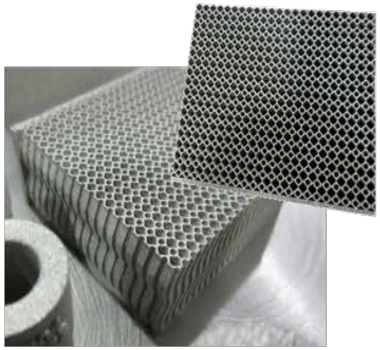
Preproposal Activity

Fabrication risk reduction activity

Misc Disks, Cones and Platefin HX Prototypes

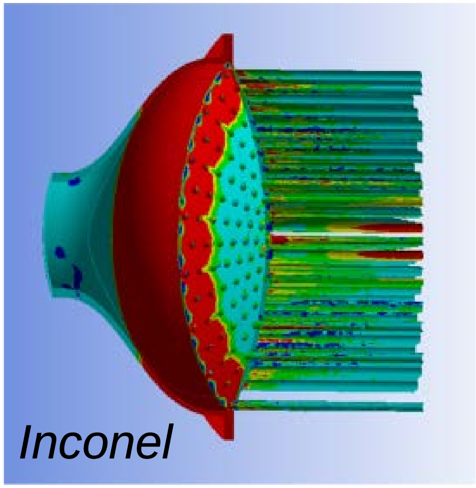
High Temp/Press Compressor Shroud

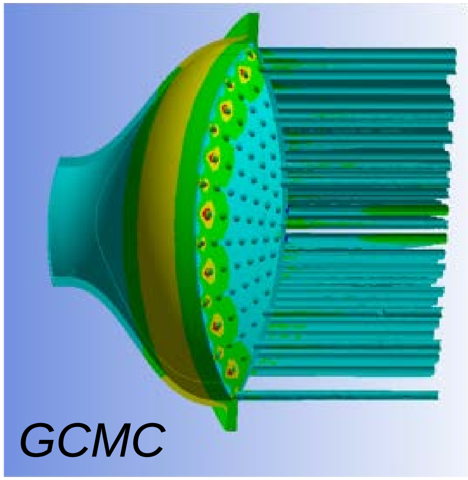
Fintube Prototypes for Proposed GCMC HX (TRL3 Demo)



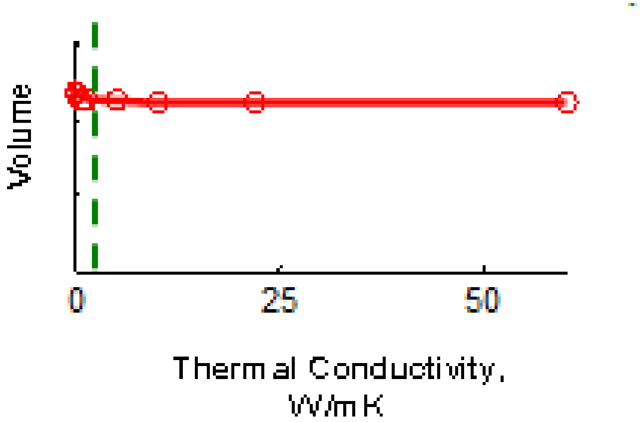
Additively-Manufactured Inconel CTHX

10X lower stress compared to Inconel





Thermal conductivity study



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

Questions?