Low Cost Ceramic Matrix Composites for Harsh Environment Heat Exchanger Applications

Contract Number: DE-EE0008318

RTRC / Materials Research & Design / Oak Ridge National Laboratory

Sept. 2018 – Aug. 2020

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Washington, D.C.
June 2-3, 2020

Overview

Glass-Ceramic Matrix Composite having complex heat exchanger geometry

AMO MYPP Connection:

- Emerging Research Exploration
  - Advanced Materials
    - Novel Materials for Use in Harsh Service
- Specifically, heat exchanger (HX) applications for high temperatures, high pressures and/or corrosive environments.

Barriers and Challenges:

- CMC fabrication of thin walled and small diameter heat exchanger tubing.
- Coincident fabrication of headers, bond integrity and tube sheet transition quality.
- Low leakage rates.

Timeline, Budget and Costs:

- Start date: September 2018
- End date: August 2020 (extension in process)

	DOE Share	Cost Share	Total
Overall Budget	$1.061M	$0.334M	$1.395M
Costs as of 3/31/20	$0.668M	$0.210M	$0.878M

Cost share: 23.9%. All of budget has been approved.
Does not include $0.275M of FFRDC (ORNL)

Project Team and Roles:

- RTRC (Prime)
  - Heat exchanger design & testing
  - GCMC technology & fabrication
- MR&D
  - Modeling of composites and structures
- ORNL
  - CVI seal coating and characterization

Project Objectives

Problem / Background

- Heat exchangers (HXs) are integral to a variety of applications including manufacturing and industrial processing, waste heat recovery, land-based / aerospace power generation and aircraft advanced thermal management.
- The operation temperature of the HX, with its thin walled structures and high differential pressures, often can be the limiting element in a system.
- Increasing the temperature capability of the HX can lead to significant increases in efficiency for existing systems and in other cases can make the difference between whether a novel system is advantageous or not.
- Glass-Ceramic Matrix Composites (GCMCs) have the high temperature benefits of CMCs and can be fabricated faster and at a lower cost than conventional CMCs.

Objective:

- This project seeks to advance the design and manufacturing methods of GCMC material in its application to high temperature, high pressure HXs with targets of ≥1600 °F (875 °C) hot inlet temperature and ≥1000 psi (70 bar) pressure differential.

AMO Mission and Goals:

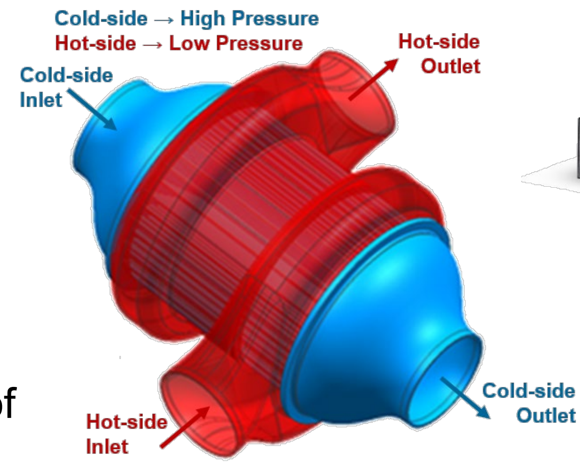
- The various HX applications mentioned above are associated with the goal of reducing life cycle energy impact of manufactured goods. This project is closely aligned with the "Materials for Harsh Service Conditions" Technology Area. In addition, the capability of fabricating GCMC material into complex and fine scaled geometries beyond HXs can support broader AMO goals and plans.

Technical Innovation

GCMC material is more durable at high temperatures than HX superalloys

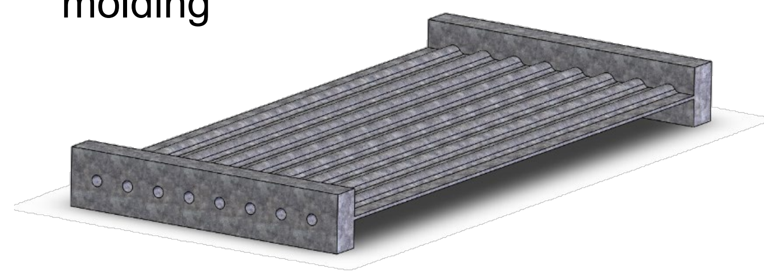
Conventional Approach:

- High temperature HXs composed of nickel based superalloys.
- Practical temperature limitations of 1200 to 1350 °F
- Thermal fatigue durability issues



Hot-Pressed Tube Sheets:

- Single layer HX to examine fiber architectures & processing
- Design amenable to compression molding

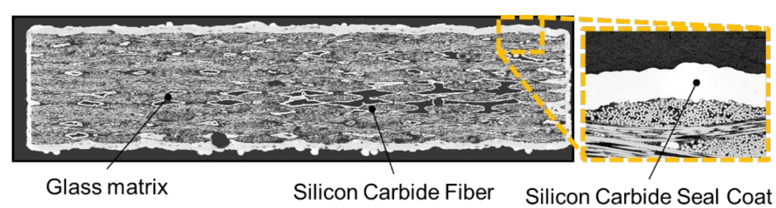


GCMC HX Concept:

- High temperature capability of ceramics (1600 to 2200 °F)
- Flaw tolerance of CMCs
- Faster, lower cost matrix formation with glass molding than normal CMCs
- Low CTE reduces stress
- High fatigue resistance

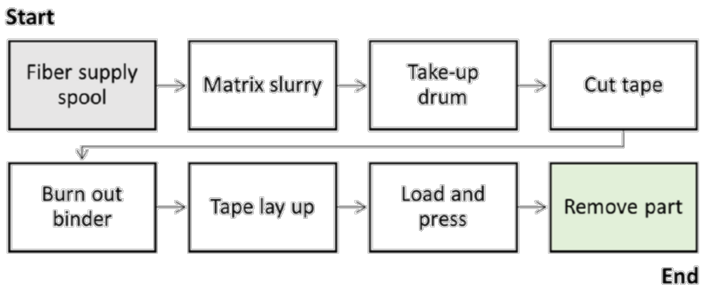
SiC Seal Coating:

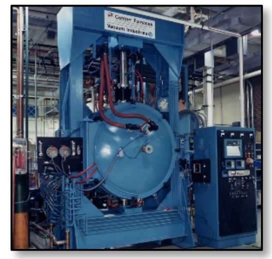
- Chemically-inert surfaces
- Further reduces leakage rate

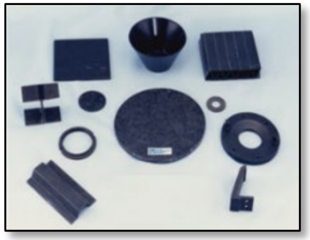


Technical Approach

- Leverage many years of prior GCMC material development at RTRC.

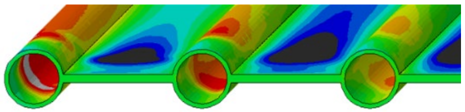






GCMC components (RTRC)

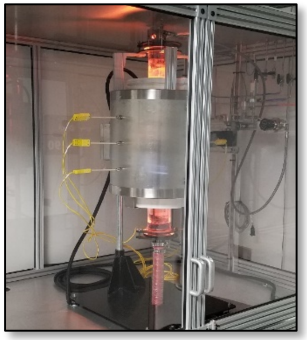
- Apply expertise at MR&D in CMC analysis and tools.
- Utilize ORNL capability in CVD/CVI coating deposition/infiltration.



Composites & structures modeling (MR&D)

- Technical focus areas
  - Novel fiber architecture design for tube sheets (RTRC, MR&D)
  - Compression molding processing (RTRC)
  - CVI coating development and application (ORNL)
  - HX concept stress analysis (MR&D)
  - Tube sheet HX testing (RTRC)

- Key risks
  - Defects due to thin wall structure
  - Header joining and process consistency
  - Leakage



CVI reactor (ORNL)

Results and Accomplishments

Milestones	Status
Milestone 1.1 Design Specs & Requirements: sCO_2 application specific requirements, HX core sizing, HX parameter sensitivity study. Reported at 2019 Peer Review. (RTRC & MR&D)	Achieved
Milestone 2.1 Application Specific Property Database: fabricate GCMC flat panels, cut and test mechanical coupons, achieve target strengths, analyze elastic and thermal properties and provide to MR&D. Partially reported at 2019 Peer Review. (RTRC & MR&D)	Achieved
Milestone 2.2 Processing Specifications for Joining: two methods of bonding evaluated, one down-selected. Partially reported at 2019 Peer Review. (RTRC)	Achieved
Milestone 3.1 Reactor Facility Complete: CVI equipment modified for SiC precursors. Reported at 2019 Peer Review. (ORNL)	Achieved
Milestone 3.2 CVI Coupon Level Down-selection: establish seal coating processing conditions. (ORNL)	Achieved
Go / No-Go Milestone 2.3 Material System Limits Defined: adequate performance of CMC system including operating temperature, strength, volumetric & gravimetric heat transfer, leakage rate. (RTRC)	Achieved
Milestone 4.1 HX Component Fabrication: fabricate headered tube sheets. Multiple tube sheets have been fabricated which appear defect-free and will be verified with testing once site is reopened. (RTRC)	In Progress
Milestone 5.1 Subscale Leak Testing: meet leakage level goal on tube sheets. (RTRC & ORNL)	Waiting M4.1 Completion
Milestone 5.2 Single Layer HX Prototype: fabricate leak-free header tube sheet. (RTRC & ORNL)	In Progress
Milestone 6.1 Single Layer HX Testing: develop testing system, complete testing at 1600 °F inlet temperature and 1000 psi pressure differential for heat transfer, evaluate pressure capability and leakage rates. (RTRC)	In Progress

COVID-19 has closed the RTRC site starting March 23, 2020.

A partial reopening is anticipated for May 26, 2020.

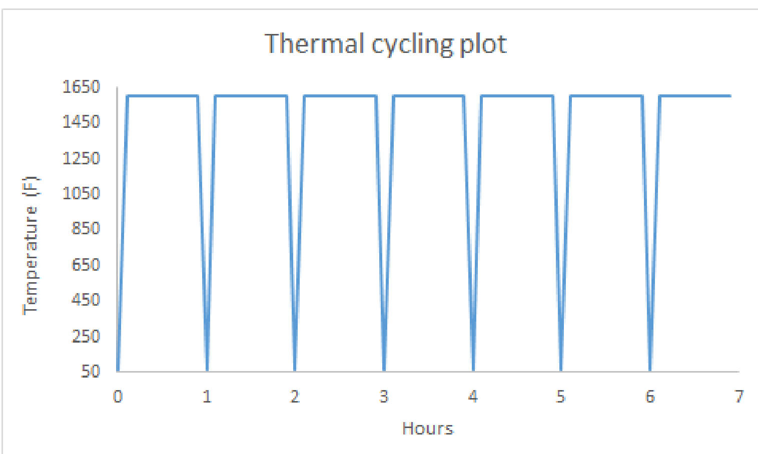
Results and Accomplishments

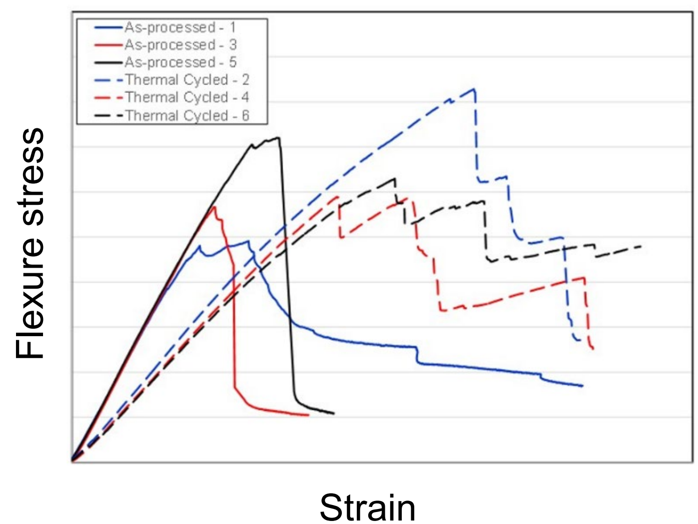
Task 2: CMC Manufacturing Studies

Mechanical Strength

- Thermal cycling: 100 cycles to 1600 °F each of 1 hr. duration
- No strength reduction
- Increase in strain to failure

UT-16 CMC Coupons





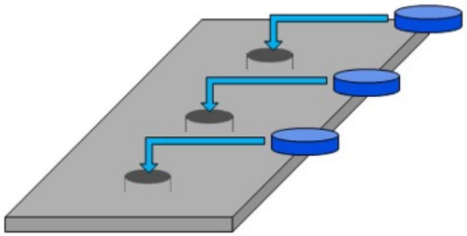
Results and Accomplishments

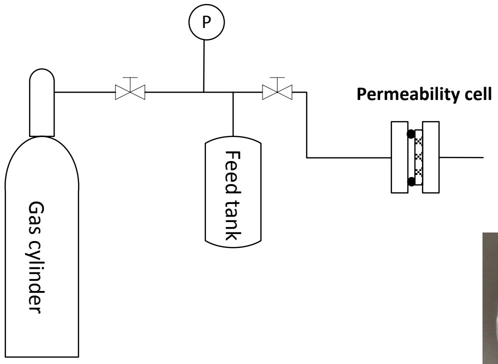
Task 2: CMC Manufacturing Studies

Leakage

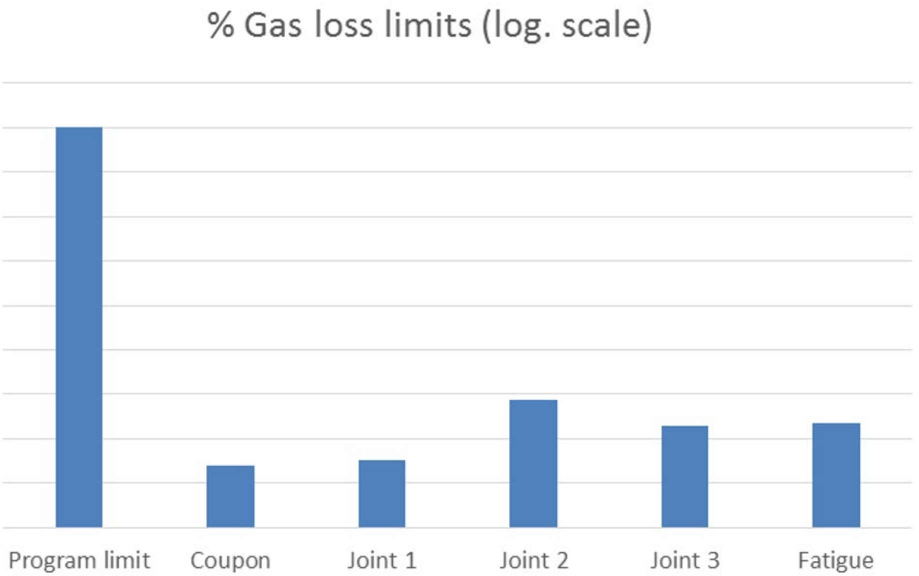
- Material has low porosity < 0.5%
- Button joint fabrication to test leakage
- Thermal cycling: 100 cycles to 1600 °F each of 1 hr. duration
- Leakage rate of $<10^{-6}\%$ is well below goal

Button Joint Specimens





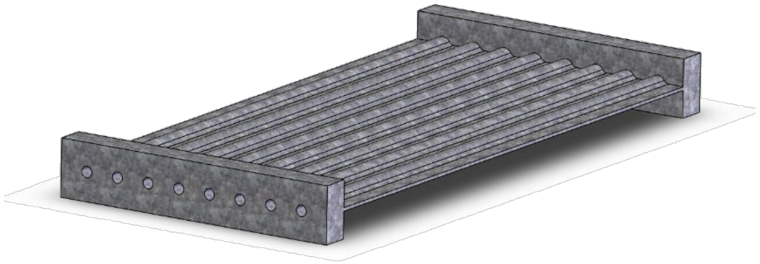

Permeability cell

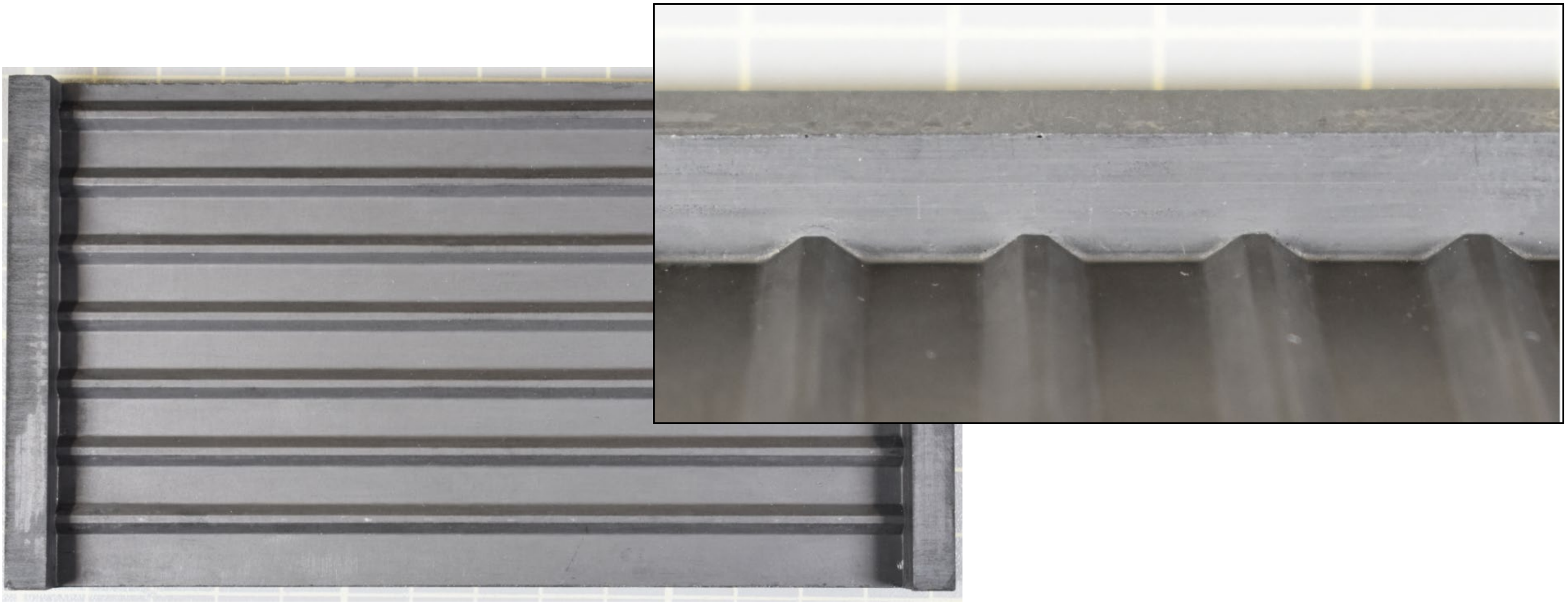


Results and Accomplishments

Task 4: HX Prototype Fabrication

- Numerous (>10) proprietary variations of fiber architectures and manufacturing process methods developed both for tube sheet and header sections.
- Refinements made to obtain desired reinforcement, eliminate defects and obtain more consistent fiber placement.





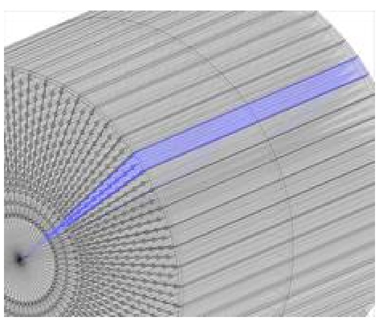
Results and Accomplishments

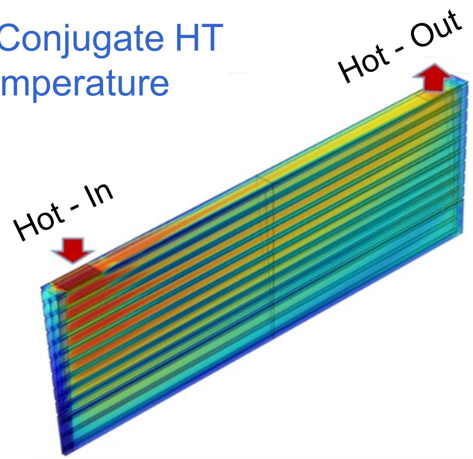
Tasks 2 and 4: HX Thermo-Structural Analysis

Task 2

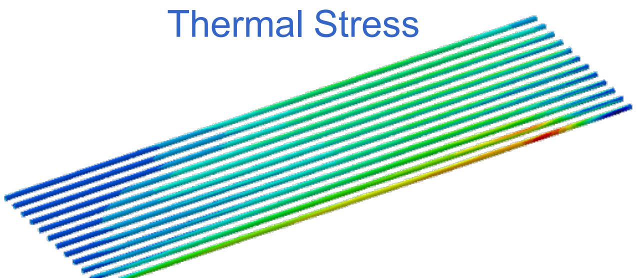
- Completion of 2D tube sheet analysis
- Development of 3D thermal stress simulation
  - Stresses from pressure well below proportional limit strength
  - Thermal stresses also < 50% of strength

CFD Conjugate HT Temperature





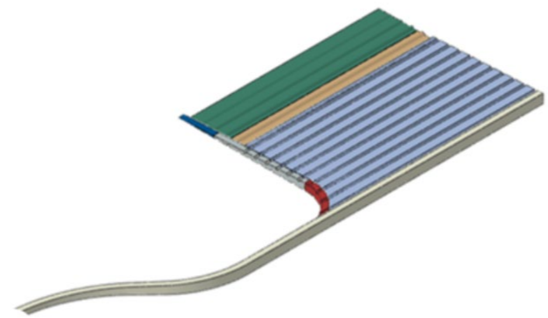
Thermal Stress



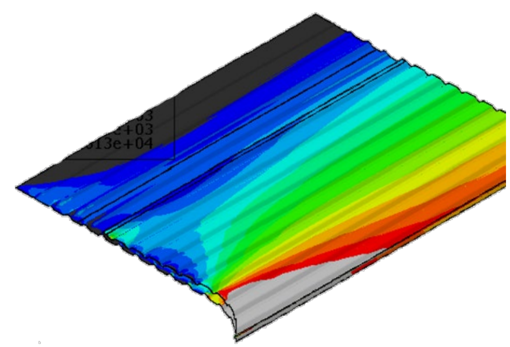
Task 4

- Examination of tube sheet stresses caused by high pressure header deflection (full scale HX) and the impact of different designs.

Symmetric - Half Model



Stress from Pressure Loading

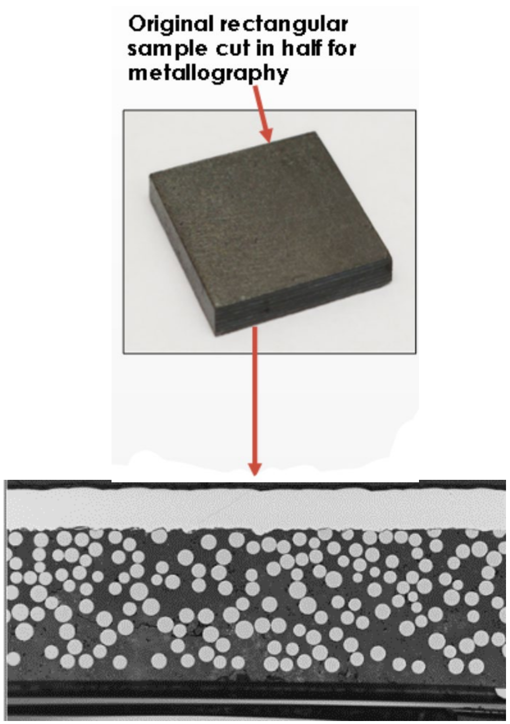


Results and Accomplishments

Tasks 3 and 5: CVI Processing and Characterization

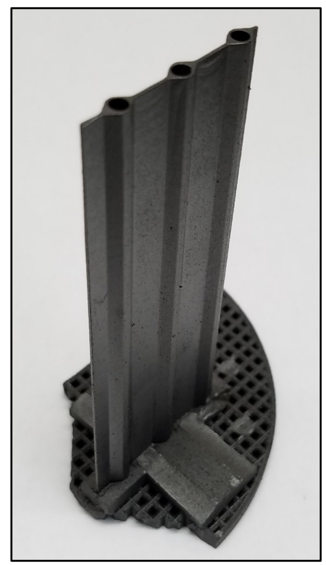
Task 3: Coupon Level

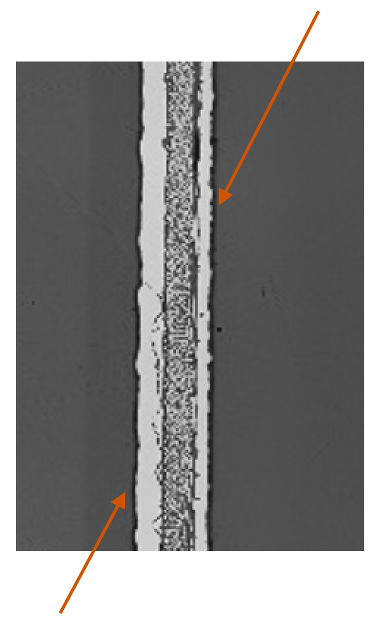
- Processing parameters established for SiC coating using thick coupons
- Coating was well adhered and showed no separation



Task 5: Tube Sheets

- 1.5”, 3” and 5” tube sheets coated
- Characterization of 3” tube shows well adhered coating with minor tapering



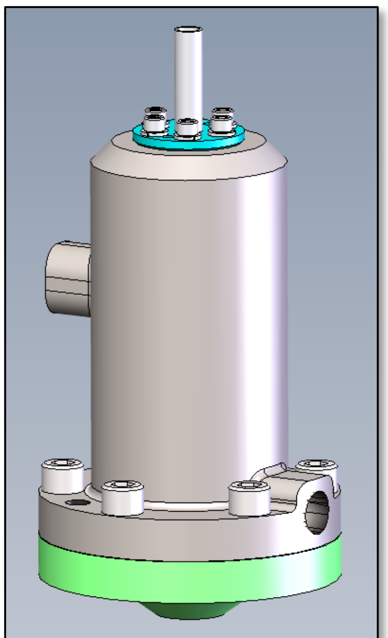


Results and Accomplishments

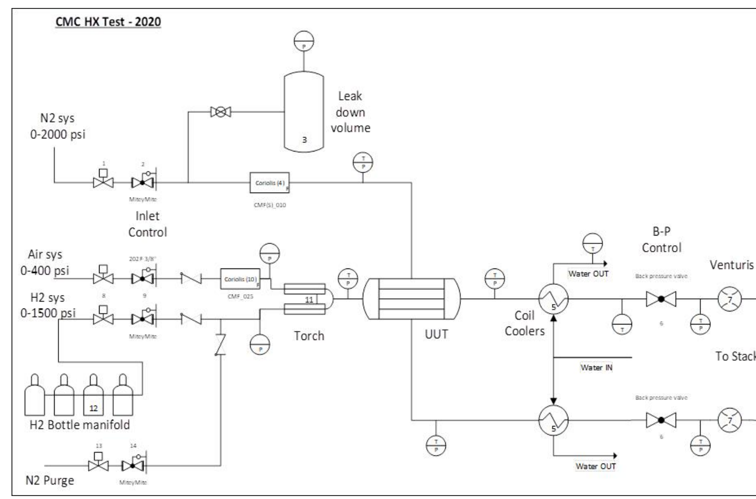
Tasks 6: Single Layer HX Testing

- Housing for headered tube sheet designed to withstand pressures, guide the flow in a thin layer and handle thermal expansion mismatch between CMC test article and metallic housing.
- Test system in RTRC's Jet Burner Test Stand facility configured for 1600 °F hot inlet temperature and 1000 psi pressure differential.

Test Article Housing



Test System Layout



Conclusions

Transitions:

- Communications and discussions are being held with Collins Aerospace, a business unit of Raytheon Technologies Corporation (the merged entity of United Technologies Corporation and Raytheon Company on 4/3/20). These discussions are taking place with both the group developing heat exchangers as well as the Materials and Process Engineering group which supports them.
- The technology space and advancements also is being discussed with the Pratt and Whitney business unit of Raytheon Technologies.
- Technology readiness level of 3-4 is anticipated by project end.
- IP has been generated to support the product business cases within Raytheon Technologies.
- A related effort under ARPA-E has started recently and additional advancement ideas have been conceived for a future AMO opportunities.

Next Steps:

- Complete characterization of latest generation headered tube sheets once RTRC site reopens.
- Perform additional FEA related to manufacturing processing.
- Coat full headered tube sheets with SiC layer.
- Test HX at 1600 °F (875 °C) hot inlet and 1000 psi (70 bar) pressure differential.
- Final review and reporting.

Acknowledgements

DOE AMO:

- Stephen Sikirica, Technology Manager
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- William Higginson

ORNL:

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