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Enhancing CMC Temperature Performance in High-Hydrogen Environments Using Field Assisted Sintering Technology

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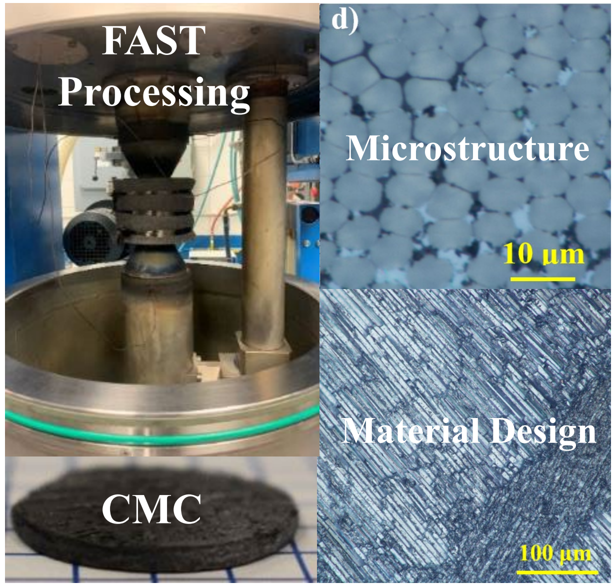

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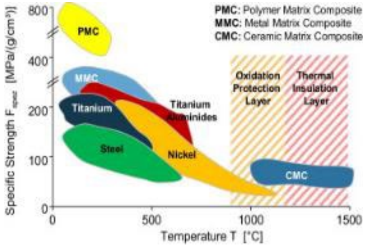
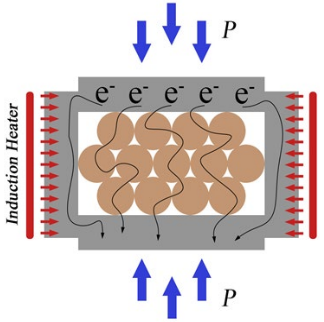
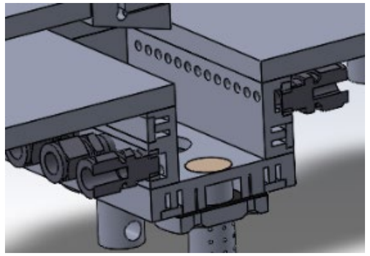
This presentation covers the project management and technical task details for our work on developing novel CMC manufacturing processes to enable high hydrogen operation



Background, motivation, and technical advancement being pursued



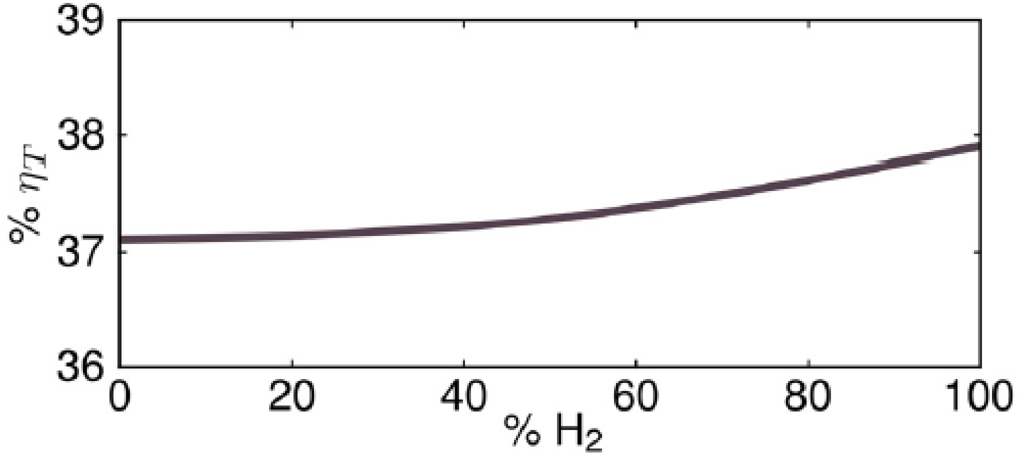
Developments of baseline CMC formulations using Field Assisted Sintering Technology (FAST)

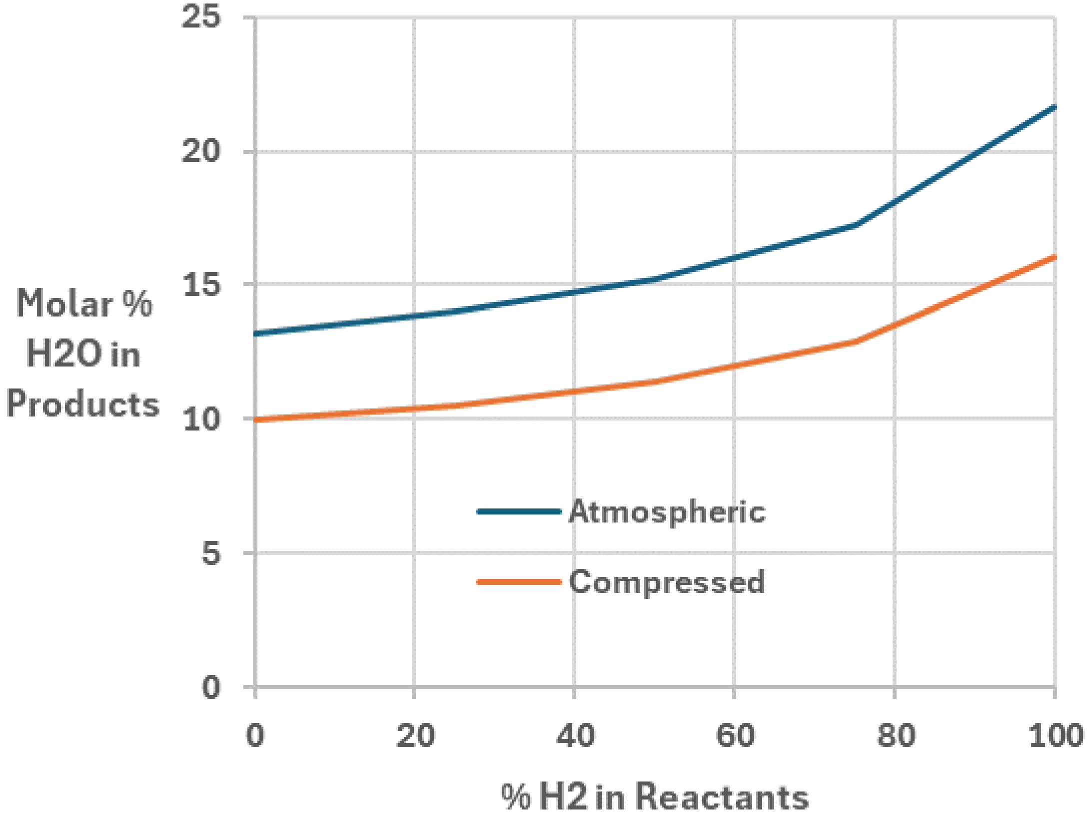


Developments in a realistic combustion exposure test facility

Increasing the blend of hydrogen in natural gas can result in 1 point increase in gas turbine cycle efficiency for the same firing temperature, due to the higher water vapor content

Thermal efficiency at constant turbine inlet temperature





Douglas, C. M., Shaw, S. L., Martz, T. D., Steele, R. C., Noble, D. R., Emerson, B. L., & Lieuwen, T. C. (2022). Pollutant Emissions Reporting and Performance Considerations for Hydrogen–Hydrocarbon Fuels in Gas Turbines. *Journal of Engineering for Gas Turbines and Power*, *144*(9), 091003.

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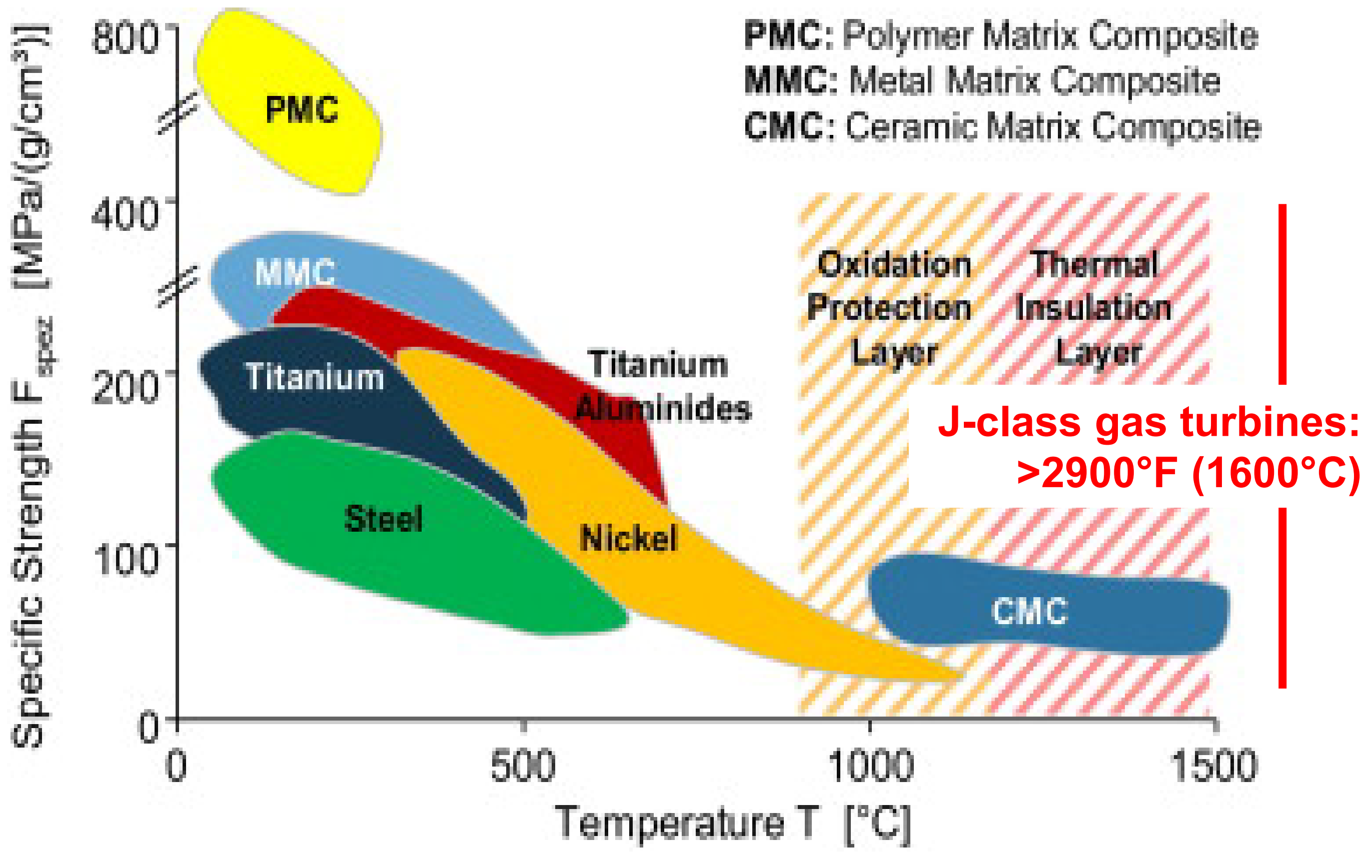
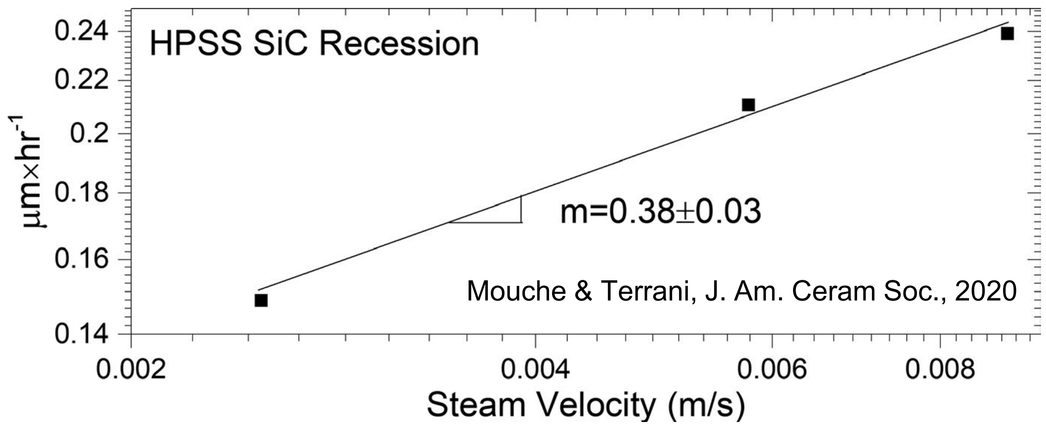
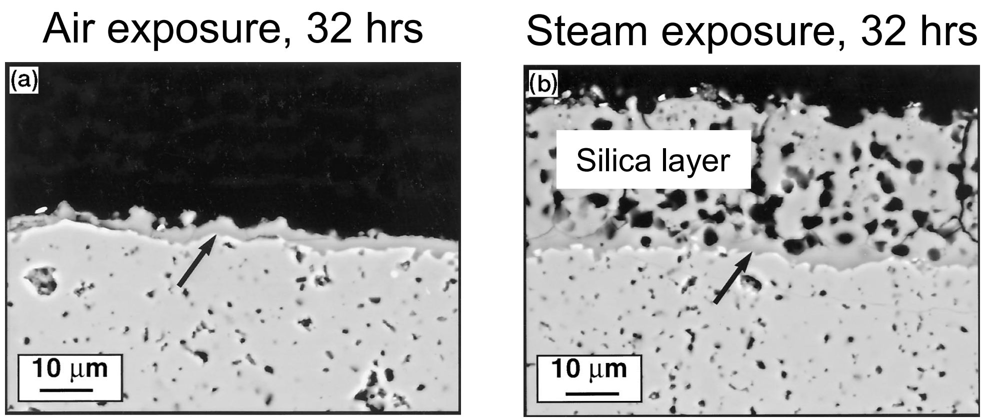
By enabling even higher temperatures, ceramic matrix composite (CMC) parts could generate another 4 pt increase in efficiency, but are highly susceptible to water vapor degradation



Klocke, et al., CIRP Annals, 2014

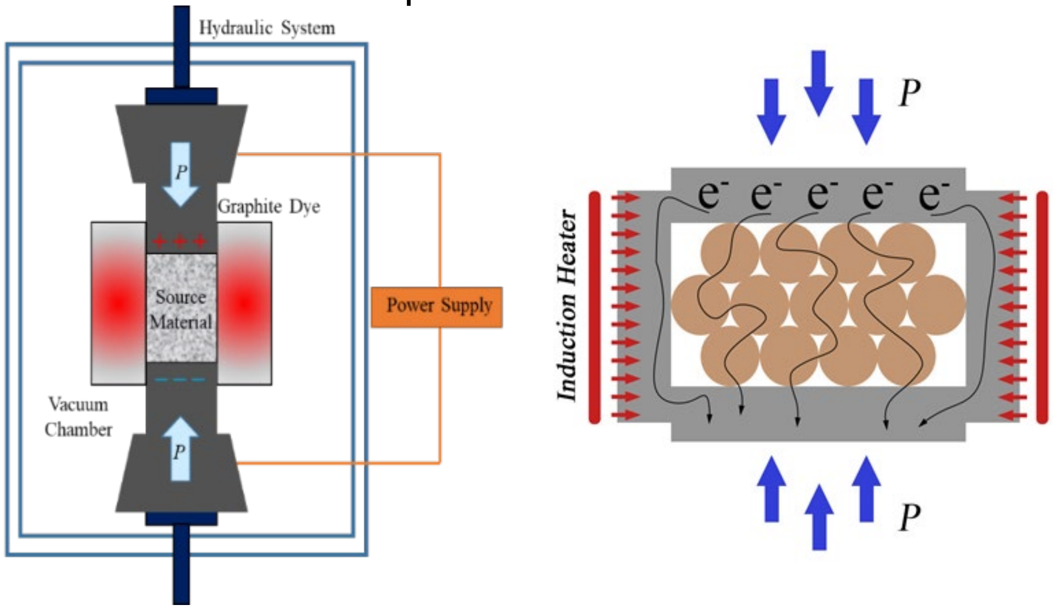




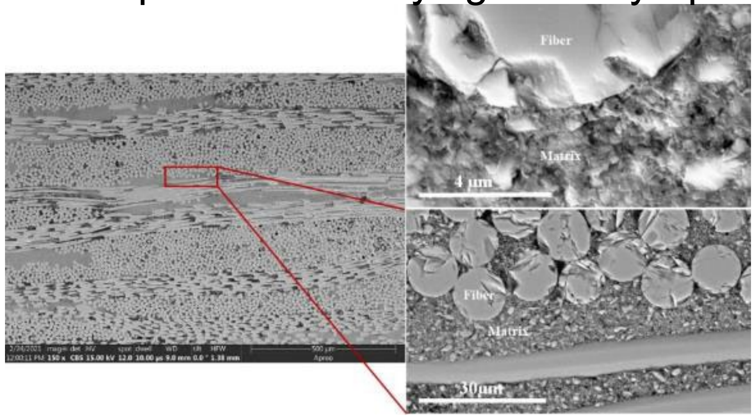
More, et al., J. Am. Ceram Soc., 2000

The advancement here is development of CMCs with higher oxidation resistance and integrated environmental barrier coatings using Field Assisted Sintering Technology (FAST)

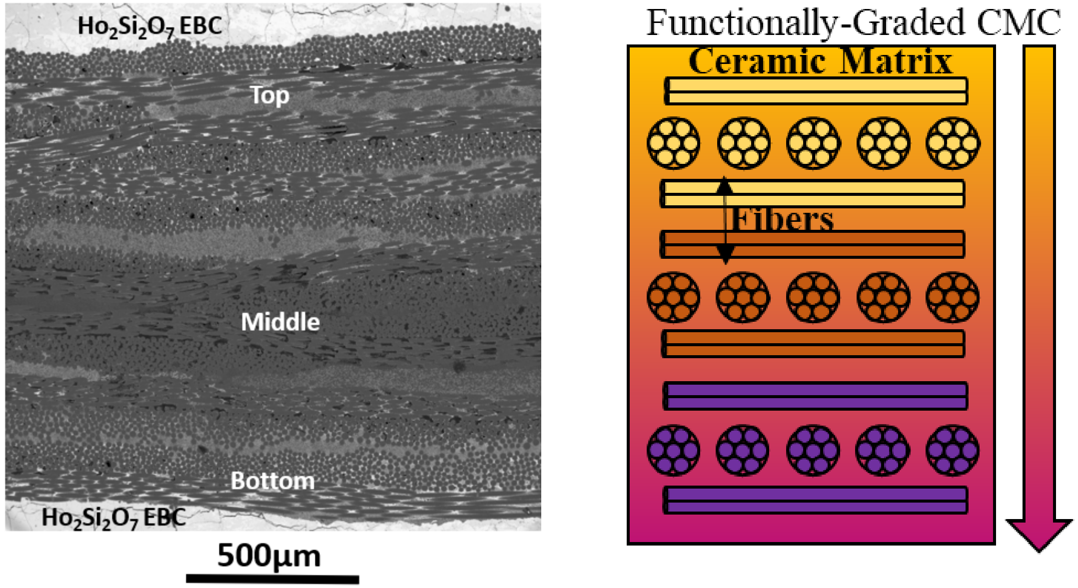
FAST process schematic



SiC/SiC composite with varying fiber lay-up orientation



Direct incorporation of rare-earth EBCs into CMC



Benefits of FAST:

- Near theoretical density (~100%)
- Short sintering times
- Can retain sub-grained structure
- Compositional graded structures
- Solid state joining of dissimilar materials (metal and ceramics)
- Compatible with metals, ceramics, polymers, and composites

The full task list for the project is shown; we will be discussing Tasks 2 and 3 today

- **Task 1: Project Management and Planning**
  - 1.1: Project management plan
  - 1.2: Technology maturation plan
  - 1.3: Environmental justice questionnaire
  - 1.4: Revitalization of job creation questionnaire

- **Task 2: CMC Development with Field Assisted Sintering Technology (FAST)**
  - 2.1: Fabricate baseline CMC formulations
  - 2.2: Fabricate improved CMC compositions and build methods

- **Task 3: Experimental Facility Development and Build**
  - 3.1: Design and build new exposure test facility
  - 3.2: Startup and shakedown exposure test facility

- **Task 4: Experimental Testing of CMC Samples**
  - 4.1: Perform exposure tests at different operating conditions and fuel compositions
  - 4.2: Perform exposure tests in high water vapor environments

- **Task 5: Post-Test Analysis of CMC Samples**
  - 5.1: Perform microstructural inspection and failure analysis
  - 5.2: Perform mechanical property testing

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Task 2.1 – Baseline CMC Silicon Carbide (SiC) Cloth Development

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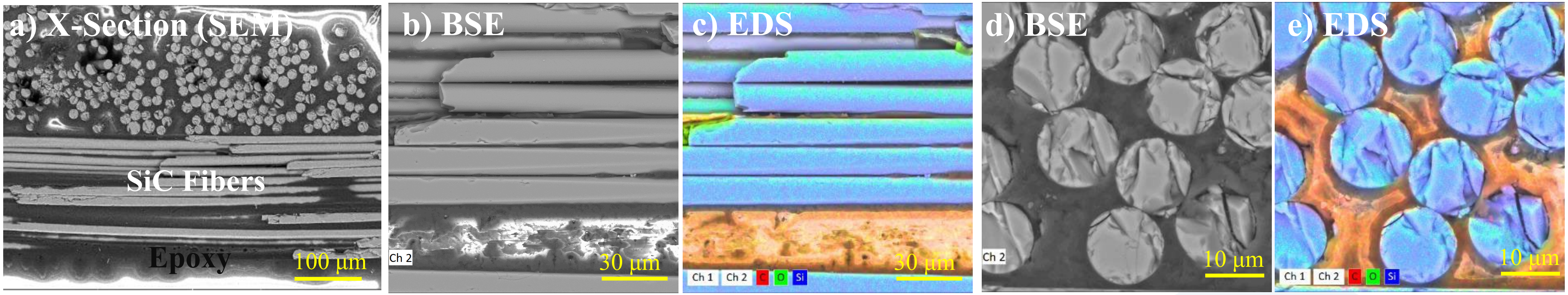
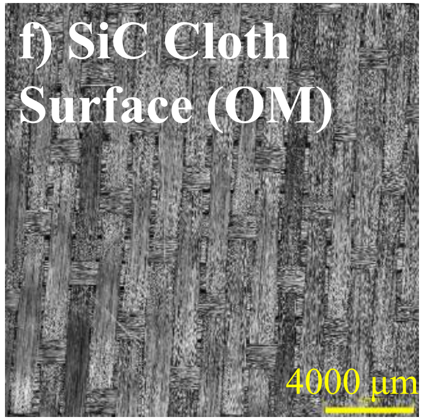
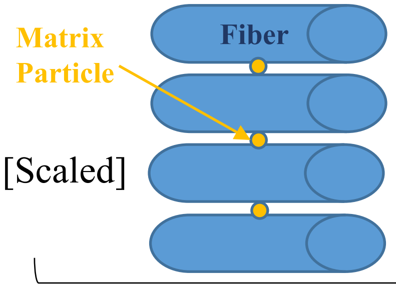
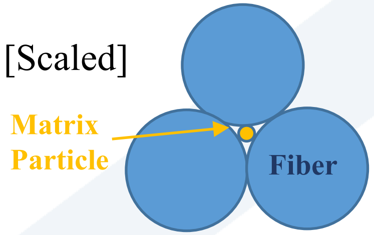






Parallel Fiber X-Section

Avg ± 1σ: 12.0 ± 1.1 µm
Min-Max: 11.1-13.9 µm
Mean Fiber Gap Size: 2.4 µm



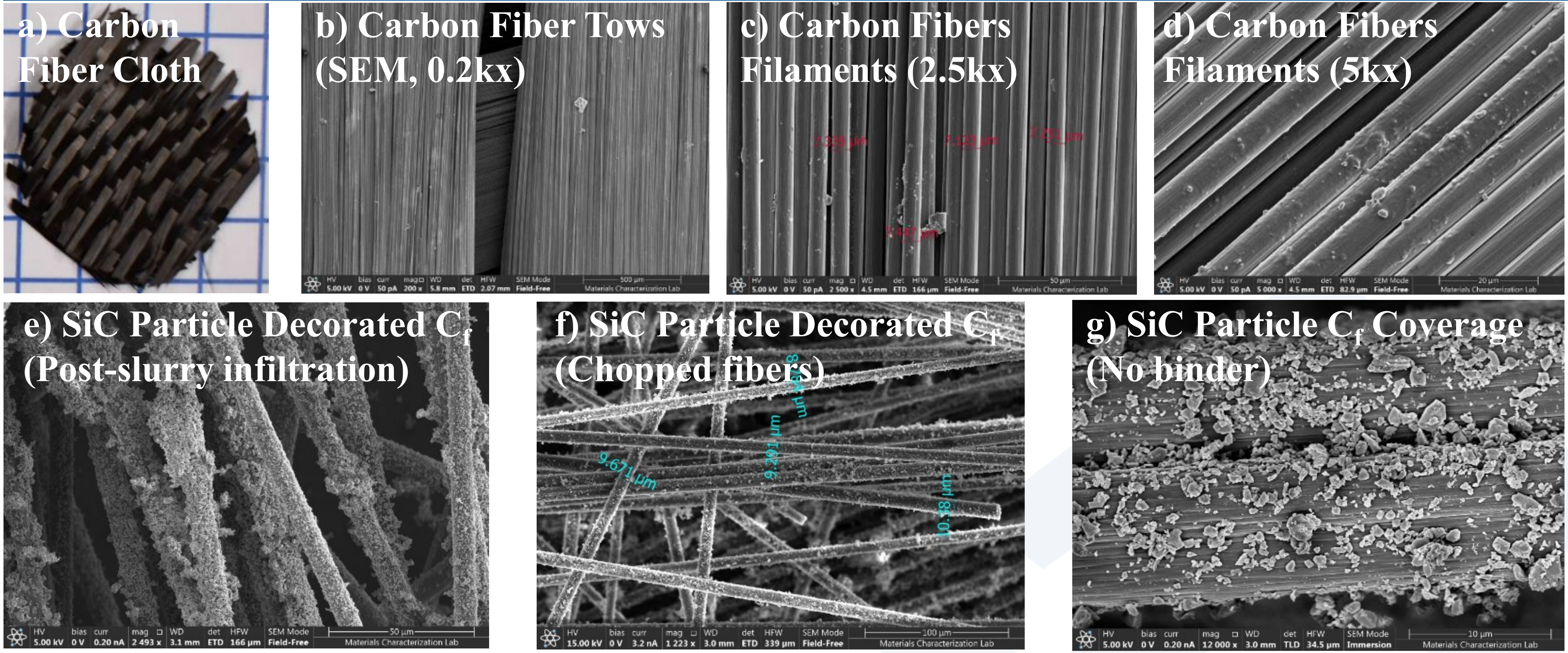
Perpendicular Fiber X-Section

Avg ± 1σ: 14.4 ± 0.5 µm
Min-Max: 13.4-15.0 µm
Tetrahedral Site Pore Size: 1.8 µm

Target < 2µm SiC Particle Sizes for Max Infiltration/Density

- Characterization of woven SiC Nicalon™ cloth (1mm tow, 22 epi) for baseline CMC-EBC FAST processing provided direct insights into fiber architecture and matrix particle size requirements for pore/interstitial infiltration
- Insights have been applied to powder processing and green body developments → **Targeting max densities**

Task 2.1 – Baseline CMC Carbon Fiber (C_f) Analog Cloth Development



- Analog carbon fiber cloth/chopped fibers (similar weave, tows, filaments) for efficient CMC testing has been developed with custom cut shapes using tape lamination/solvent-debinding methods and organic binder coatings
- As-received SiC particles on chopped fibers demonstrate promising coverage → **Fiber/matrix developments**

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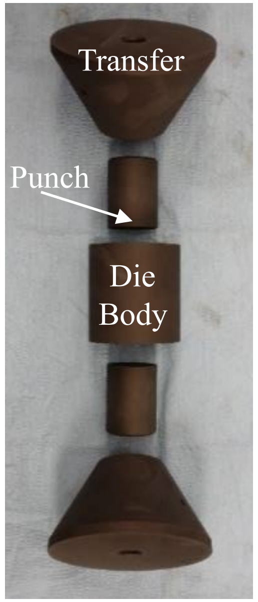
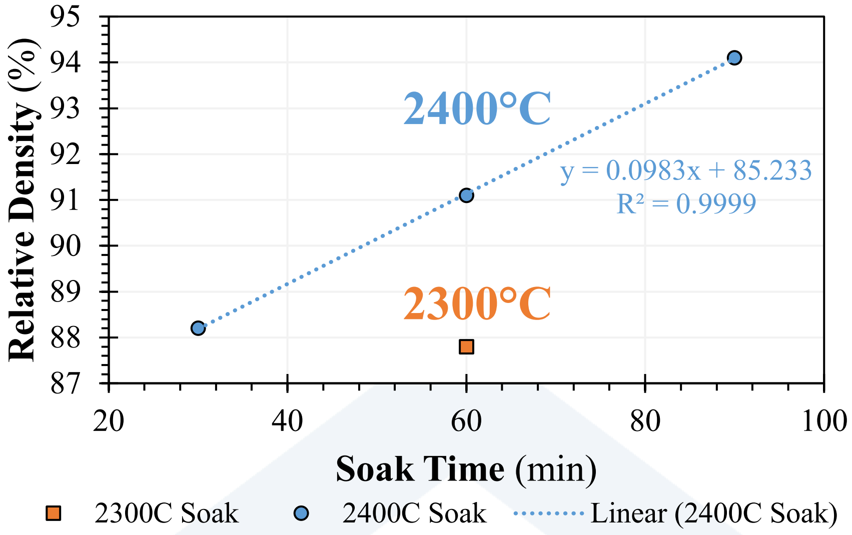
Task 2.1 – Baseline FAST Processing of SiC Matrix

#	SiC Sintering Conditions	Rationale	Soak Temperature (°C)	Soak Time (min)	Density (g/cc)	Relative Density (%)
1	2300°C/60min @ 30-55 MPa	Typical for previous carbides	2300	60	2.819 ± 0.00031	87.8%
3	2400°C/30min @ 30-55 MPa	Effect of Time	2400	30	2.8328 ± 0.00554	88.2%
2	2400°C/60min @ 30-55 MPa	Effect of Time/Temp.	2400	60	2.926 ± 0.00392	91.1%
4	2400°C/90min @ 30-55 MPa	Effect of Time	2400	90	3.021 ± 0.00158	94.1%

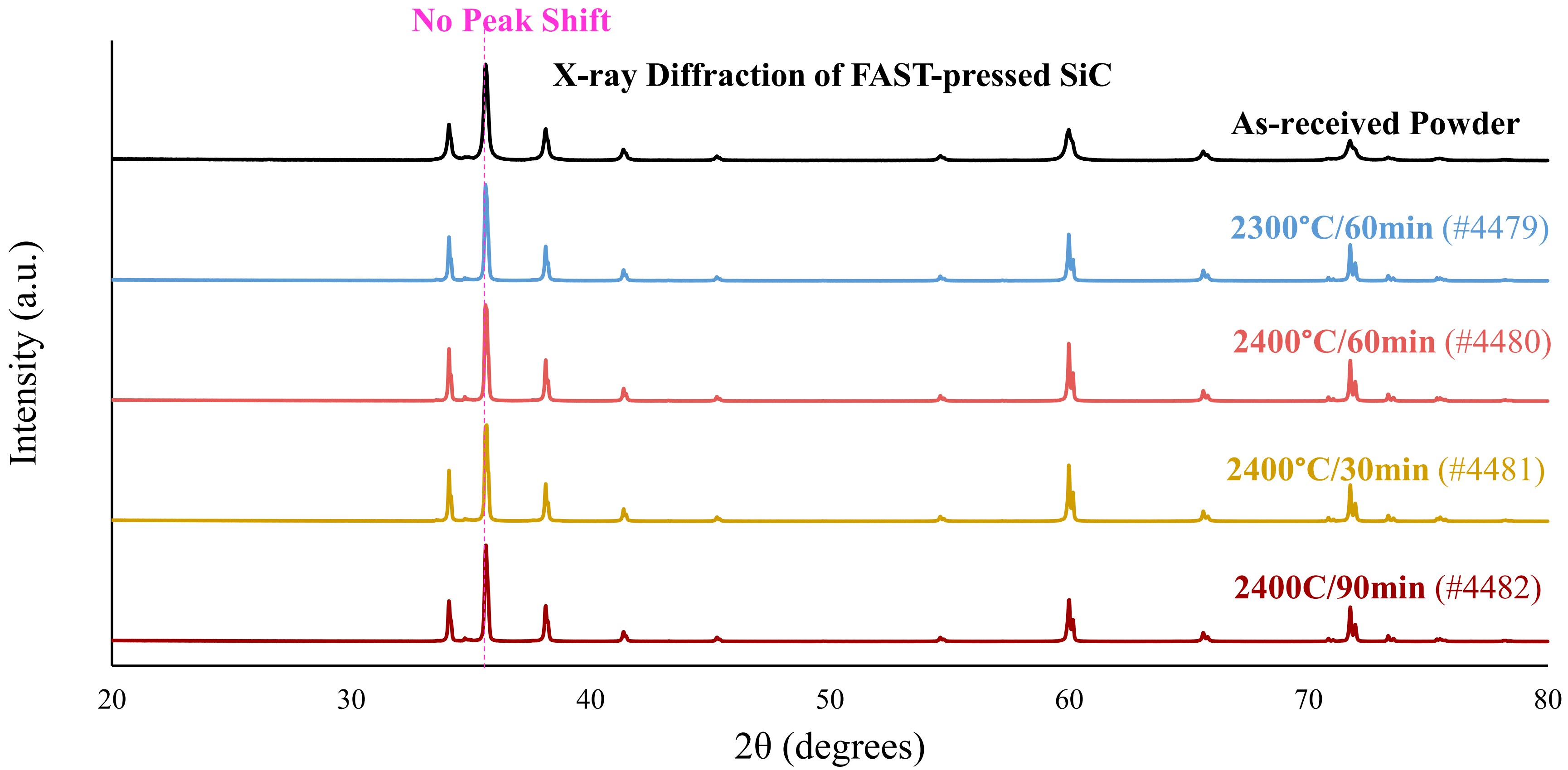




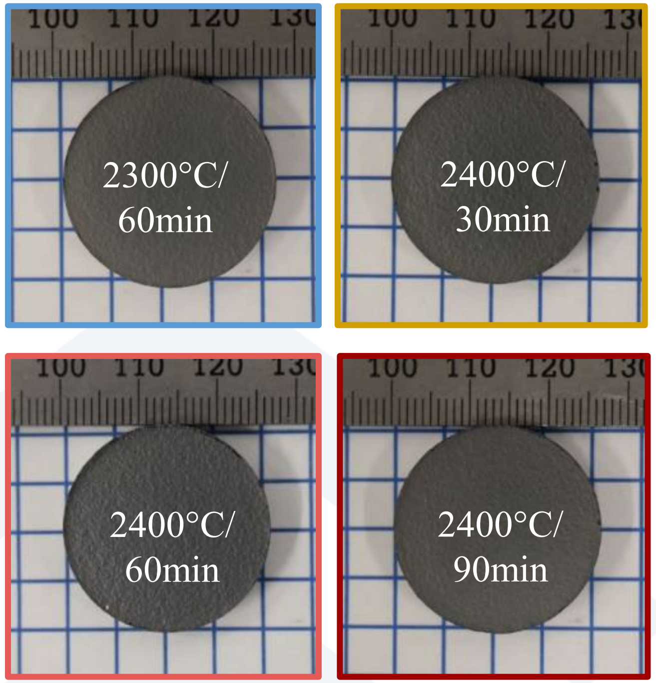
#	Temp. (°C)	Time (min)	Density (%)	Thickness (in)			Outer Diameter (in)		
				Min - Max	Midrange ± Tolerance	Avg ± 1 Stdev	Min - Max	Midrange ± Tolerance	Avg ± 1 Stdev
1	2300	60	87.8	0.219 - 0.224	0.222 ± 0.0024	0.222 ± 0.0018	1.019 - 1.022	1.021 ± 0.0016	1.021 ± 0.0012
2	2400	30	88.2	0.218 - 0.222	0.220 ± 0.0024	0.221 ± 0.0020	1.026 - 1.029	1.028 ± 0.0016	1.027 ± 0.0011
3	2400	60	91.1	0.208 - 0.214	0.211 ± 0.0030	0.212 ± 0.0022	1.024 - 1.025	1.025 ± 0.0006	1.025 ± 0.0003
4	2400	90	94.1	0.207 - 0.215	0.211 ± 0.0037	0.211 ± 0.0030	1.024 - 1.027	1.026 ± 0.0012	1.026 ± 0.0009
Average	-	-	-	**0.213 - 0.219**	**0.216 ± 0.0029**	**0.216 ± 0.0022**	**1.023 - 1.026**	**1.025 ± 0.0012**	**1.024 ± 0.0009**

- Preliminary FAST processing of SiC powder matrix across various soak conditions provided baseline insights
- **New critical SiC densification, pressed dimensions, tolerances, & carbide layer thicknesses were obtained**

Task 2.1 - Characterization of Baseline FAST Processed SiC Matrix



FAST-pressed SiC 1" OD Test Coupons



- Characterization of SiC crystallinity via XRD demonstrates high apparent reproducibility between baseline test coupons
- Preliminary NDE insights of pre-combustion SiC test coupons were obtained → **Available for first burn tests**

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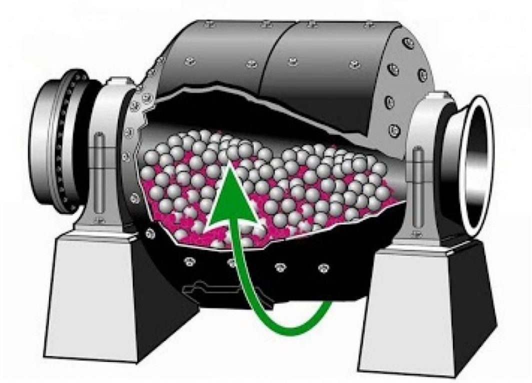
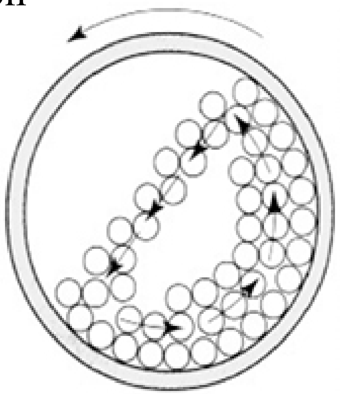
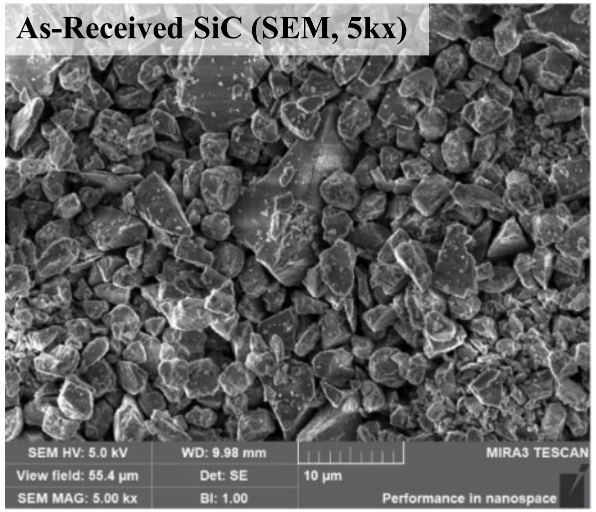
Task 2.1 – Baseline Powder Processing of SiC Matrix

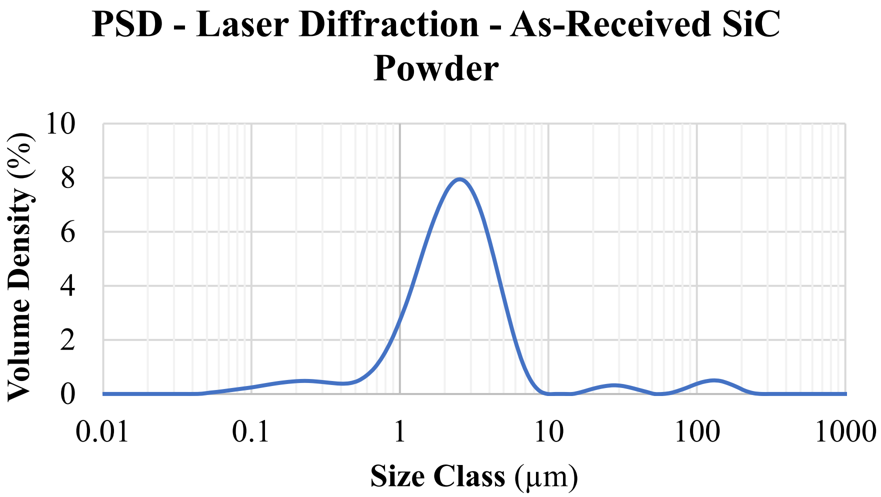
Mechanical Ball Milling:
- Tailor particle size/distribution
- Homogeneous mixing





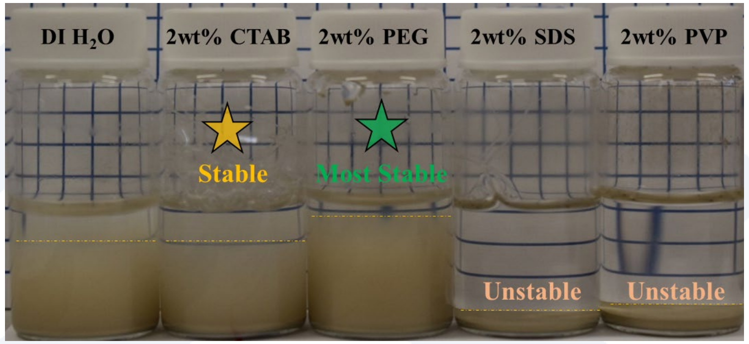
- Ball-to-powder ratio (BPR)
- Speed (RPM)
- Wet or dry milling





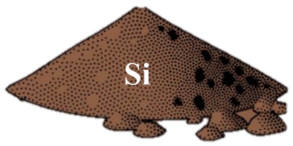
*Step #	Dry Milling (hr)	Wet Milling (hr)	Dv [3,2] (μm)	Dv (25) (μm)	Dv (50) (μm)	Dv (75) (μm)
1	0	-	1.32	1.23	2.10	3.21
2	24	-	0.98	0.98	1.89	2.99
3	Post-milled	24	0.90	0.87	1.67	2.76

*10mm YSZ, 200 RPM, 9:1 BPR, 500ml HDPE Bottles, 100g SiC, Reagent Alcohol (100g)

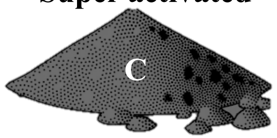


- Initial baseline powder processing of SiC powder for CMC matrix was developed using ball milling to reduce particle size
- SiC slurry dispersions were found to be most stabilized/deagglomerated using polyethylene glycol (PEG)
- Applying PEG to SiC was found to be an **effective dispersant/binder for robust infiltration & green bodies**

Task 2.1 – Baseline Powder Processing of Reactive SiC via Elemental Si/C Precursors

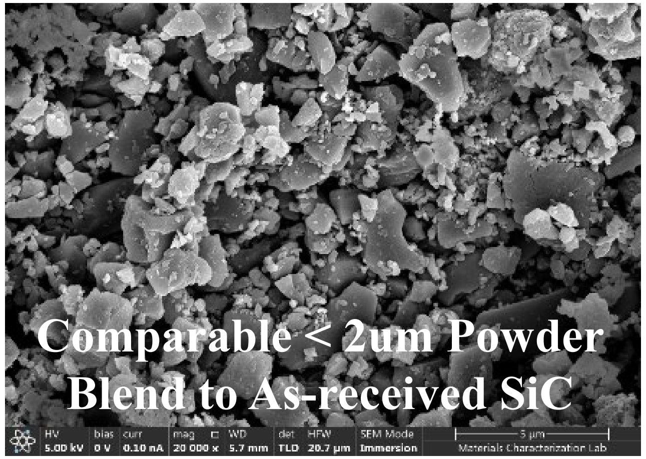


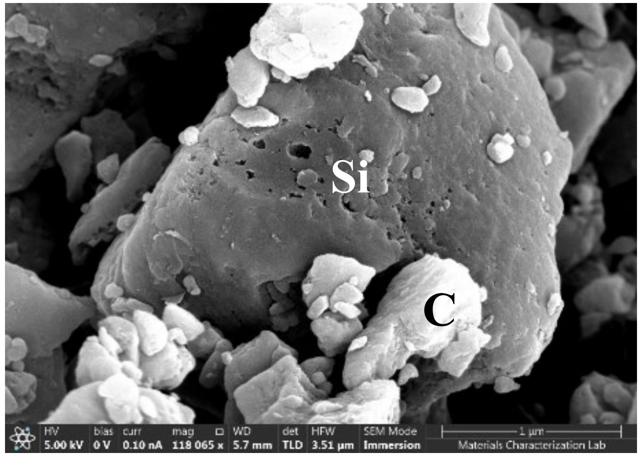
+
Super activated

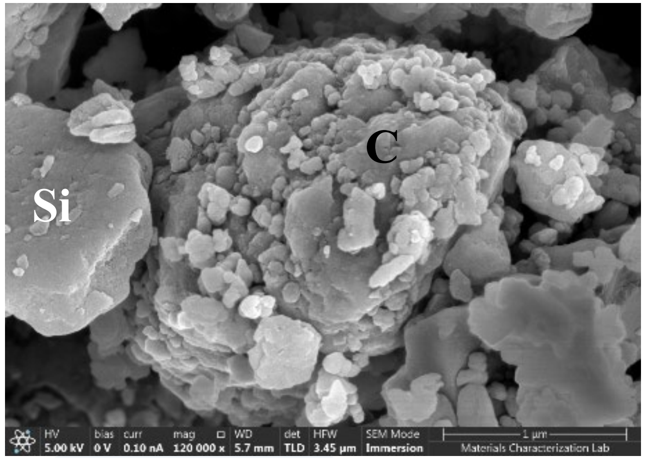


Nanopowder Precursors

Si/C Blend

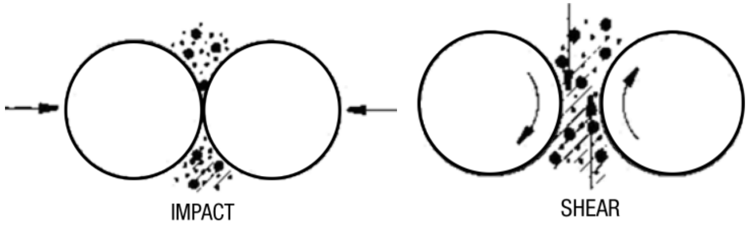






Mechanical Activation for Reactive SiC

Milling Action



Increased interfacial area and reactivity

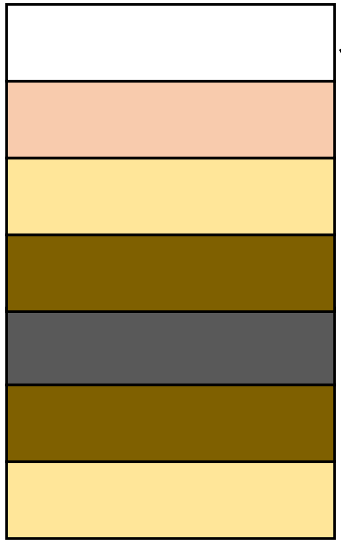
#	Name	Initial Values	4x Scaled Values
1	**Sample Name**	Reactive SiC Blend #1	Reactive SiC Blend #2
2	**Blend Composition**	1:1 Si/C (at%) 30/70 Si/C (wt%)	1:1 Si/C (at%) 30/70 Si/C (wt%)
3	**Bottle Size (ml)**	125	500
4	**10mm YSZ Mass (g)**	275	1100
5	**Carbon NPs Mass (g)**	3.5	14
6	**Silicon NPs Mass (g)**	1.5	6
7	**Batch Mass (g)**	5	20

- Baseline powder processing of new reactive SiC via elemental nanopowder blends were developed via ball milling
- **Substantial potential for in-situ CMC molten infiltration and densification through reactive FAST**

Task 2.1 – Baseline CMC-EBC Green Body Processing

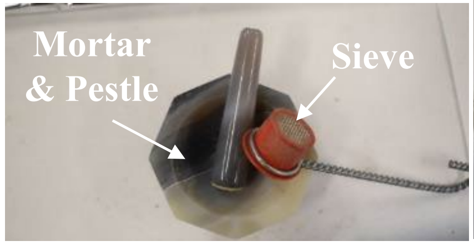
SiC_m (Matrix)	**SiC_f/C_f** (Fiber Cloths)	**Si** (Bond Coat)	**Mullite/RE-Silicate** (EBC)	**$[Si/C]_m$** (Reactive Matrix)

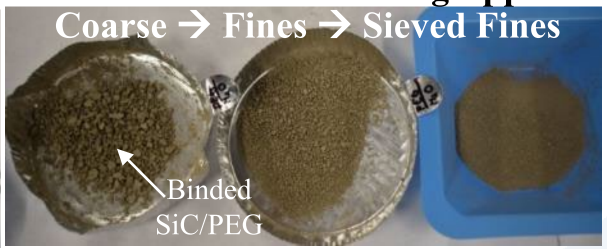
Green CMC

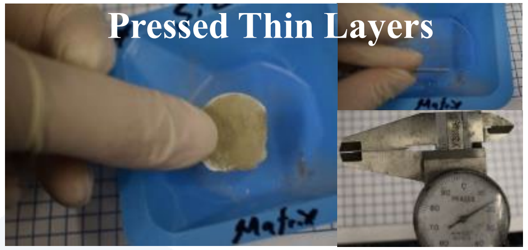


Miniaturized
(press, debind sinter)

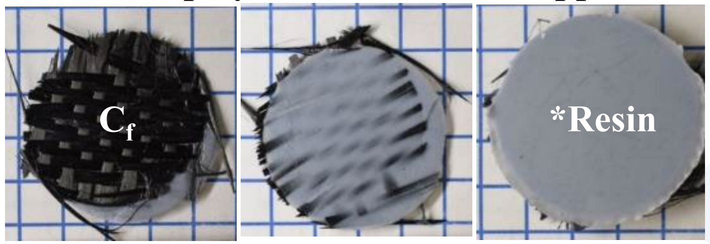
Conventional Cold-Pressing Approach



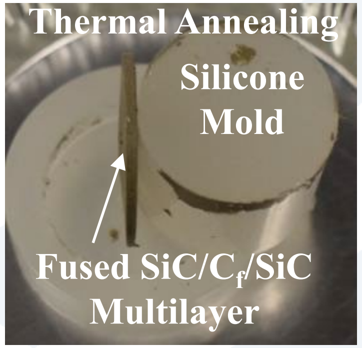




Vat Photopolymerization – AM Approach



*Resin to be applied will be SiC/SiOC-preceramic for PIP

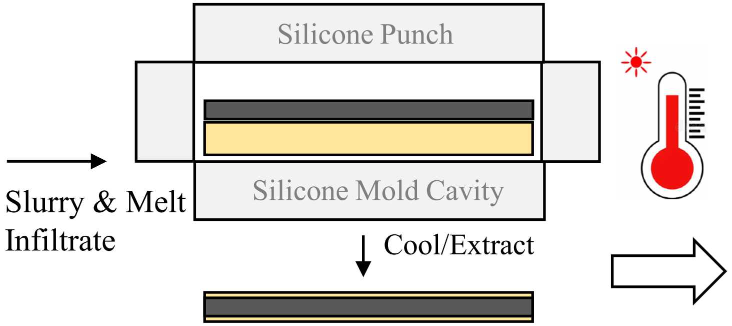


1" OD Green Body Thin Layer	Mass (g)	Thickness (μm)
Current (Measured)	0.1926	279
Max Target (Estimate)	0.0690	100
Min Target (Estimate)	0.0345	50

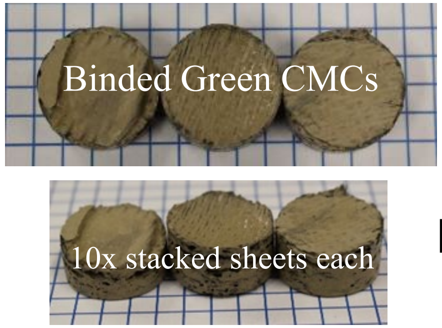
- Baseline CMC-EBC green body processing is currently being explored across various methods, such as conventional cold-pressing of thin layers, vat photopolymerization, and direct graphite die cavity fillings for FAST
- Thus far, binding, pulverizing, sieving, thin layer cold-pressing, stacked-layer pressing, thermal annealing, and debinding appears to yield the most tailorable/uniform green CMC-EBC architectures → **Still more to develop**

Task 2.1 – Baseline FAST CMC Processing Lifecycle

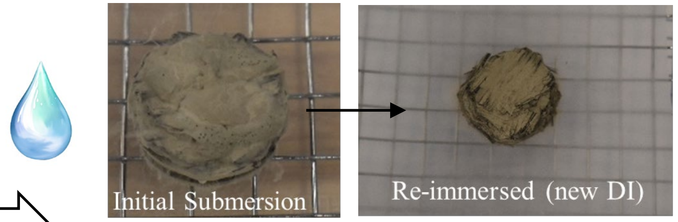
Green CMC Assembly



Stacked Green CMCs



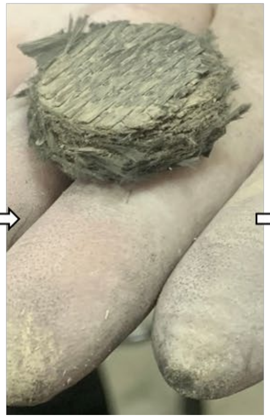
Aqueous Debinding



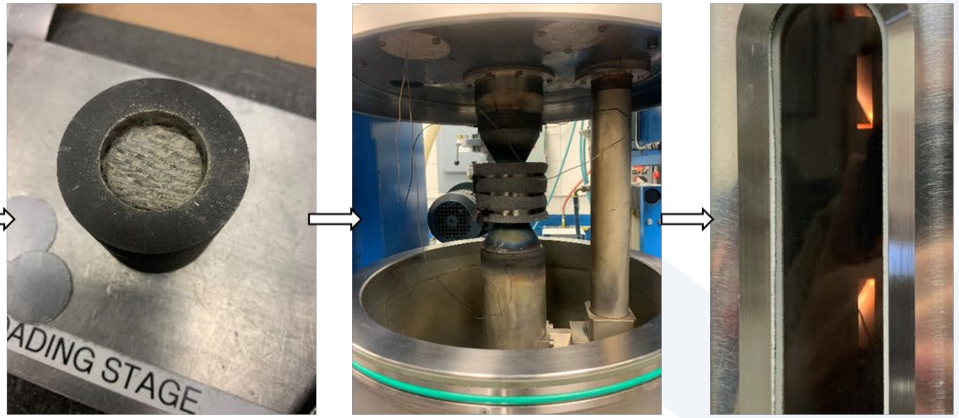
Dissolve out PEG binder before FAST Processing

Trimming of Debinded CMC

Before Sintering

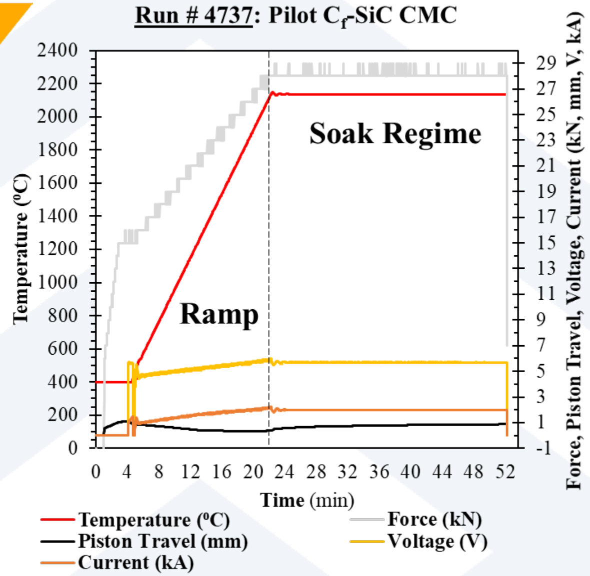


Loaded in Die



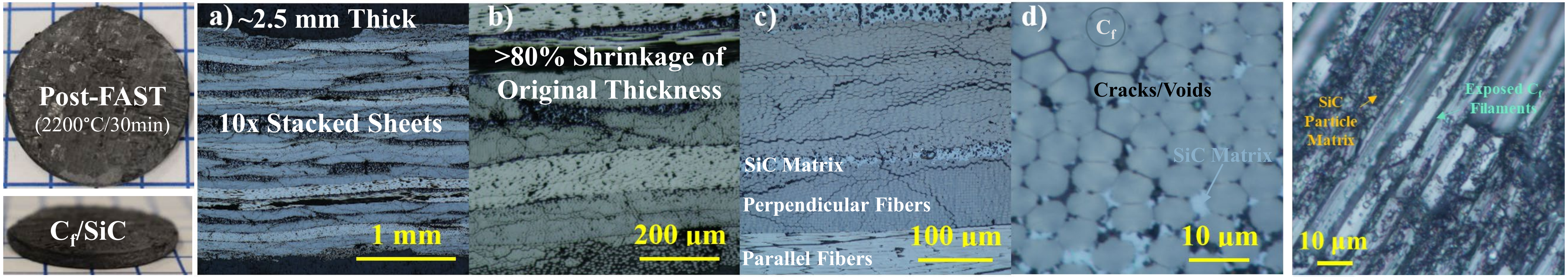
Loaded in Assembly

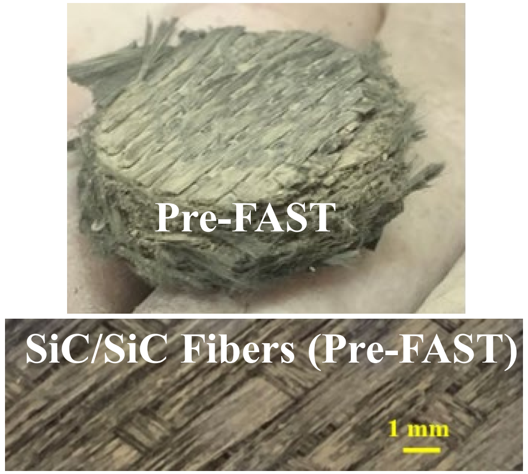
FAST Sintering

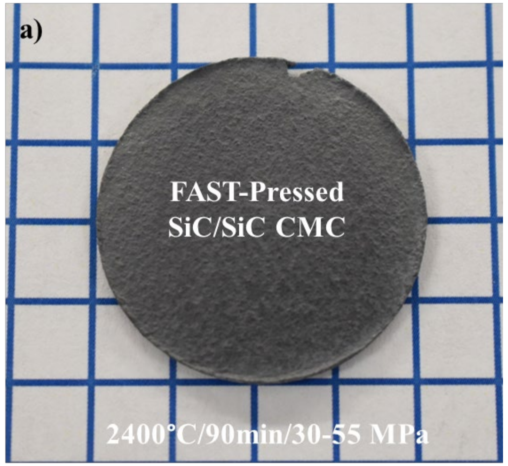


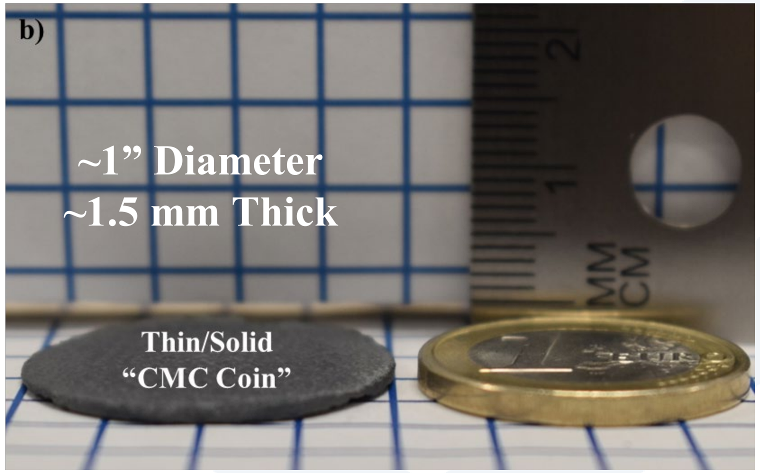
- Slurry/melt infiltration of SiC-PEG mixture into fiber cloth sheets are stacked/fused into green CMCs with silicone molds
- The green CMCs are aqueously debinded, dried, & loaded into the graphite FAST die assembly for sintering → **Scalable Process**

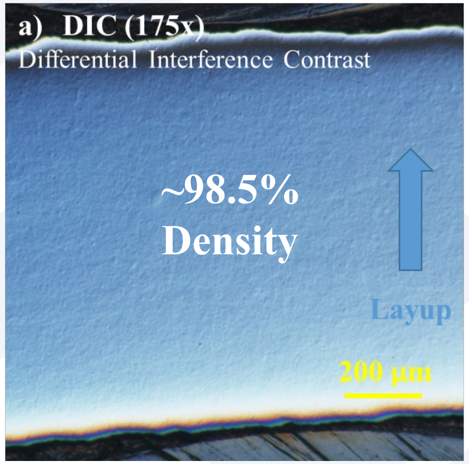
Task 2.1 – Baseline FAST CMC Processing Results











- **C_f/SiC** – Fairly low sinterability between carbon fiber & SiC particles, useful analog for processing developments
- **SiC_f/SiC** - High sinterability observed in porous fabric, balancing between max density & fiber/matrix interfaces is critical

→ Optimize FAST parameters for sufficient activated diffusion to densify with minimal composite changes

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Task 2: Next Steps

1.
- **Optimize SiC/SiC FAST sintering conditions**
- Compare between matrix, chopped fibers, & fabric sheets

2.
- **Prototype CMC-EBC candidate development with initial testing**
- Compare between different coatings, interface grading, & doping

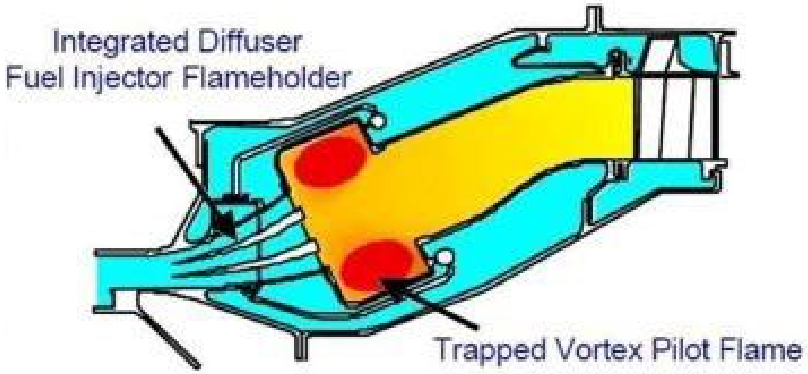
3.
- **Improved CMCs with layering, slurry, reactive, & PIP methods**
- Baseline testing/characterization using best EBC integration method

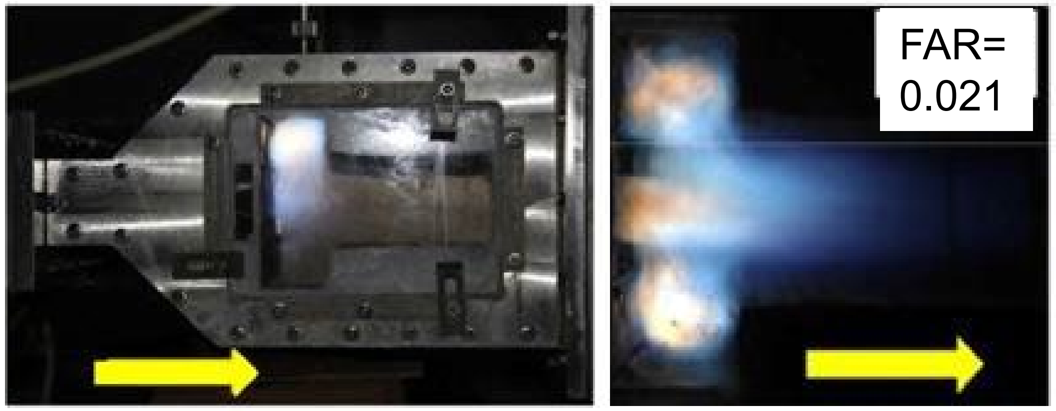
Task 3.1: Specific design goals were identified for the test facility that led to selection of a trapped vortex combustor design

Design goals:

- Fuel flexible – 100% H2 to 100% natural gas
- Highly instrumented – be able to measure temperatures, heat flux (total and radiative), and H2O concentration
- Ability to place samples in two different flow regimes (low and high velocities) to change H2O residence time above the samples
- Long term stable combustion for long duration test times without combustion dynamics issues

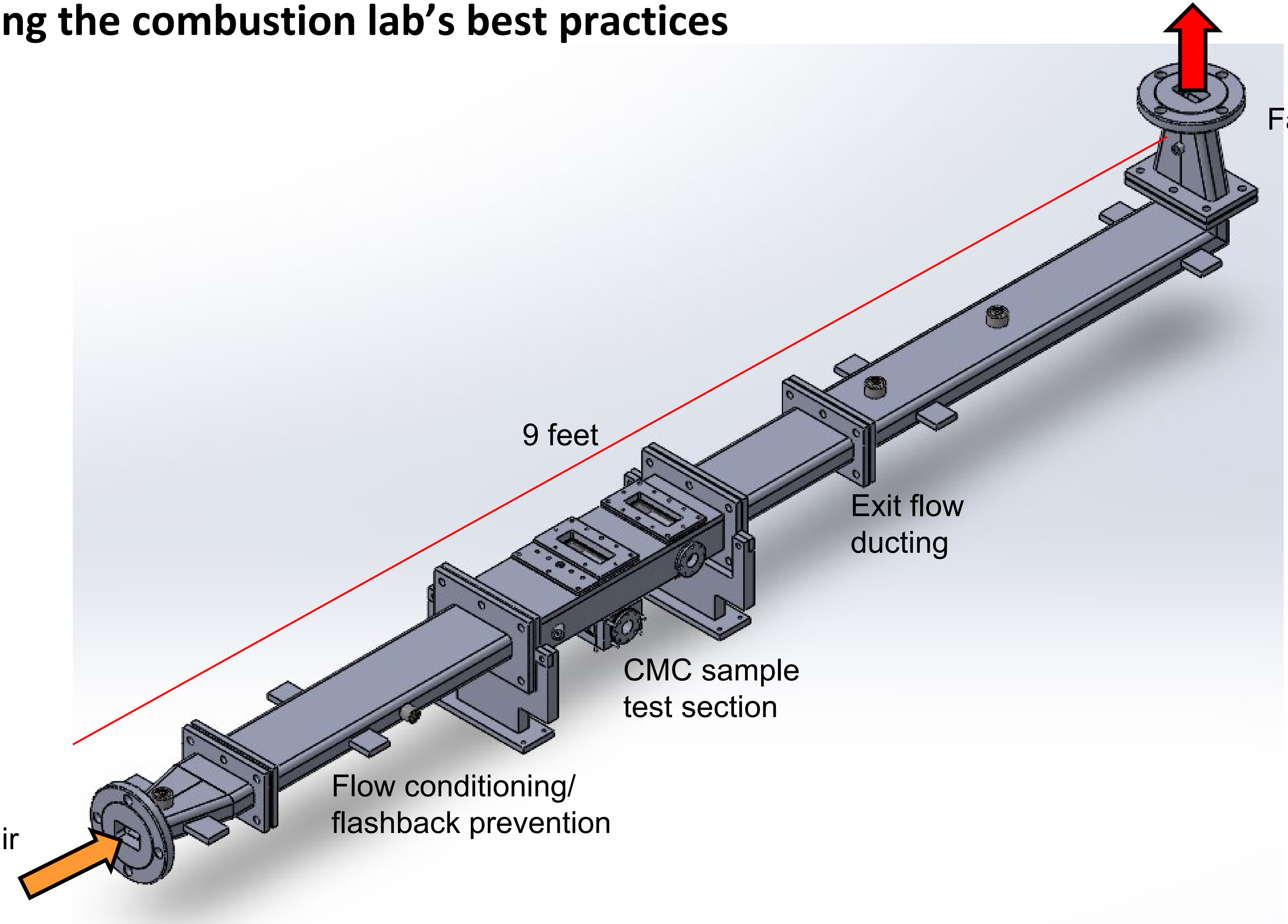
Trapped vortex combustor design





Zhao, Gutmark, de Goey, 2018, Progress in Aerospace Sciences

Task 3.1: Airflow conditioning, test section, and interface to PSU infrastructure have all been designed using the combustion lab's best practices



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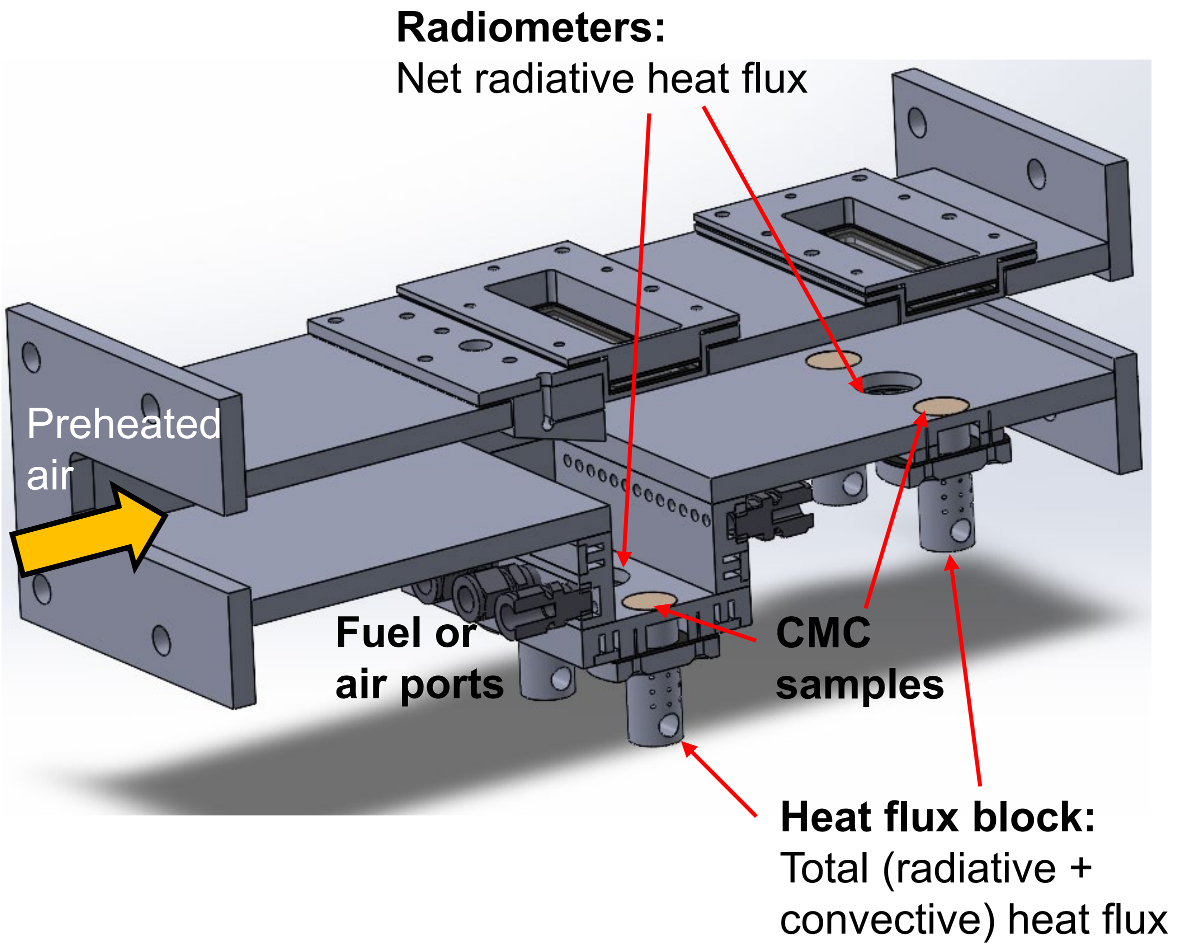
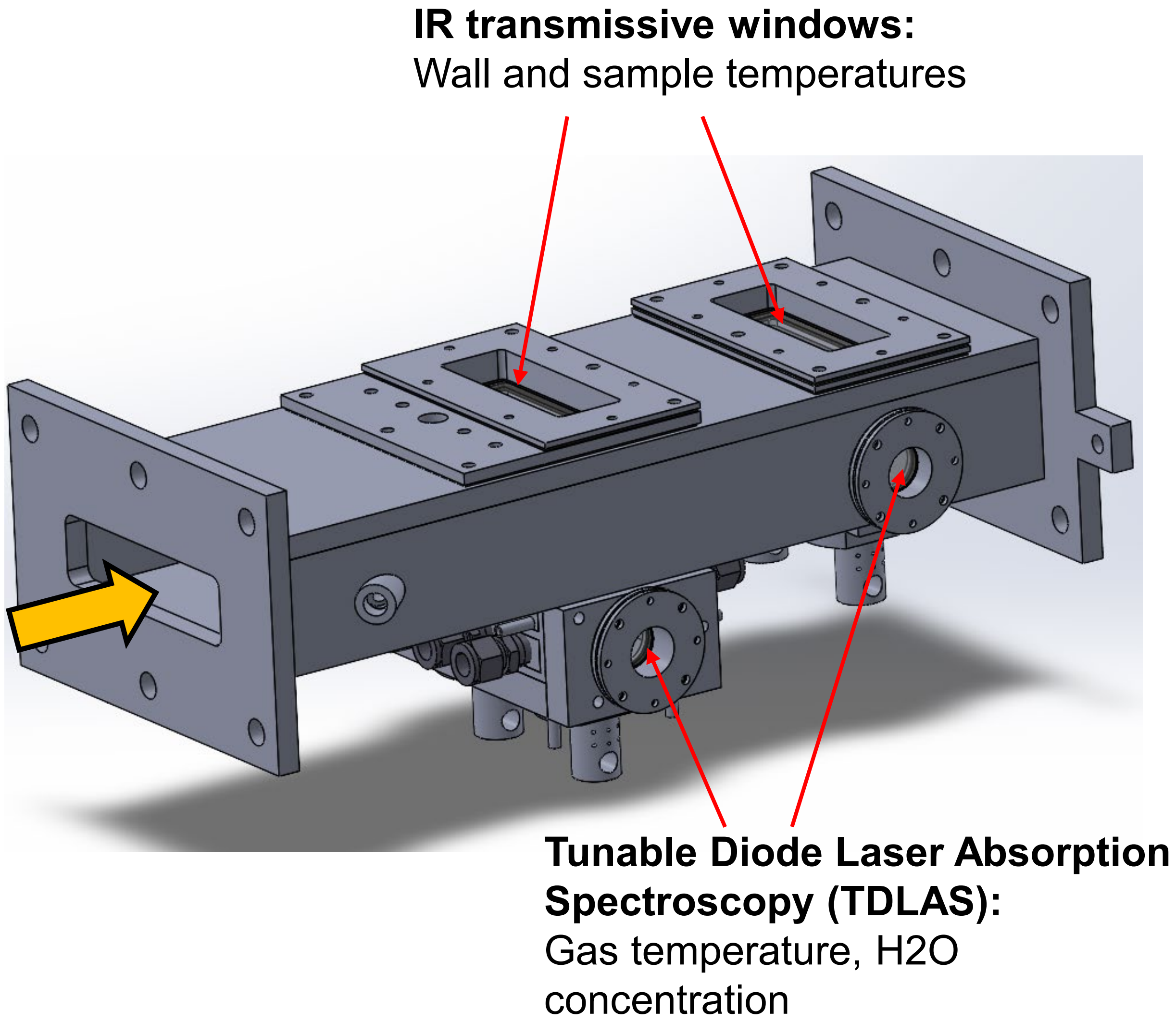
Task 3.1: The test section was designed to hold 1” diameter coupons in two important regions, and have a high degree of instrumentation for sample temperature and gas composition





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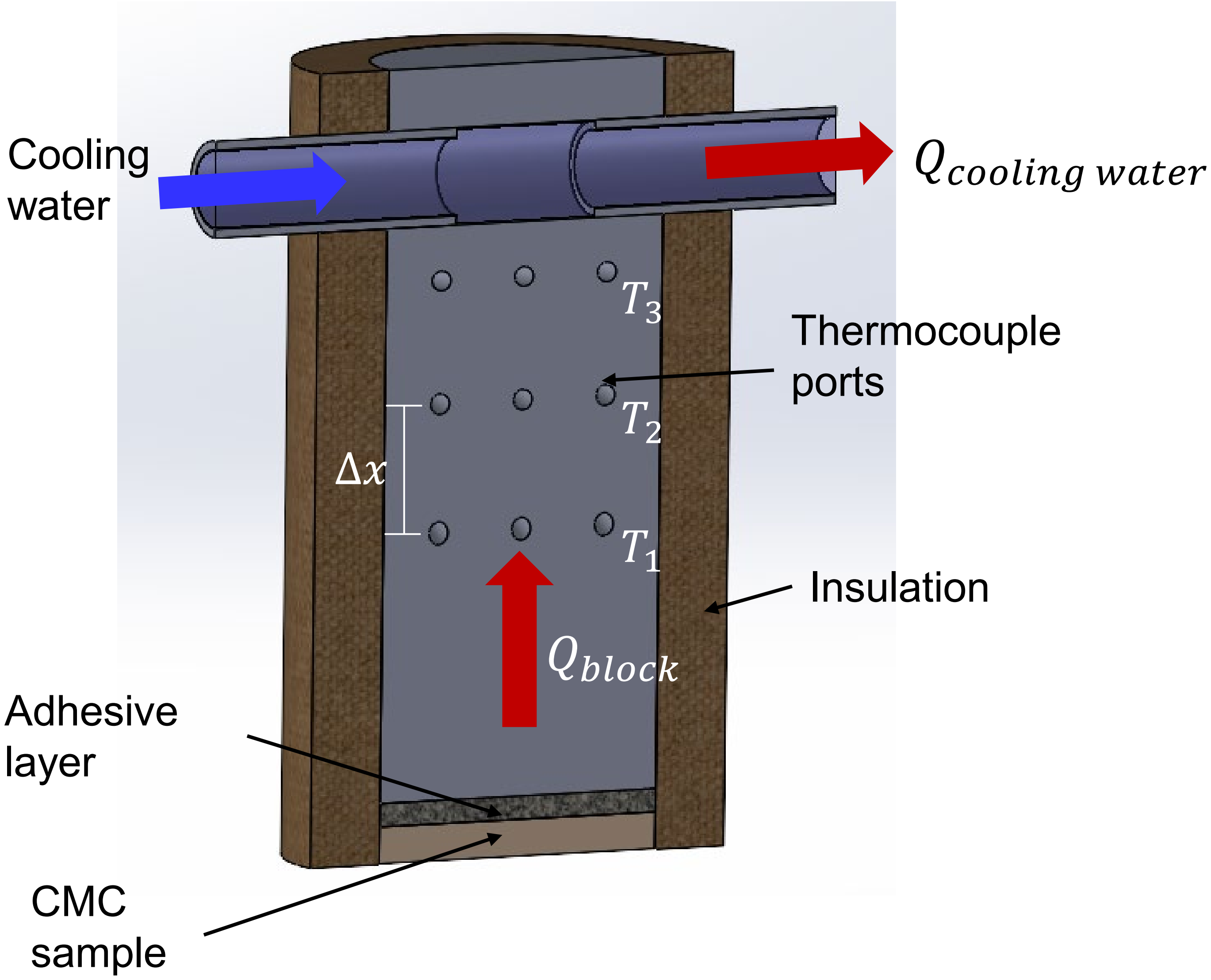
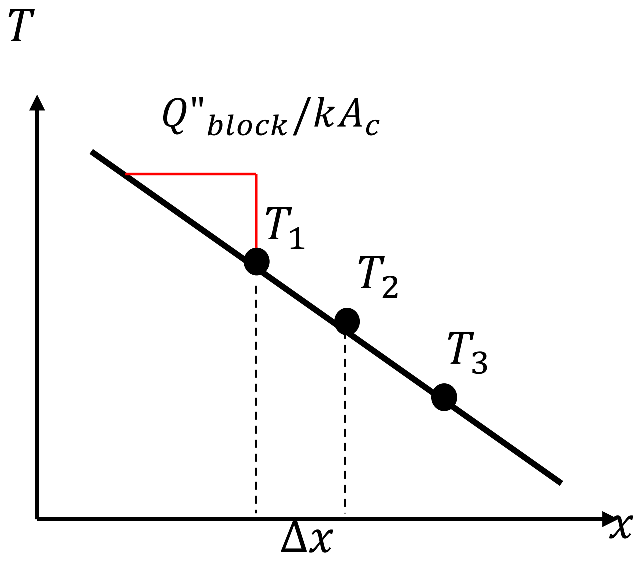
Task 3.1: The heat flux block will be used to mount the CMC samples and measure the steady state total heat flux in the test facility.



$$Q_{cooling\ water} = \dot{m}_{H_2O} C_{p_{H_2O}} (T_{out} - T_{in})$$

$$Q_{block} = -kA_c \frac{T_i - T_j}{\Delta x}$$



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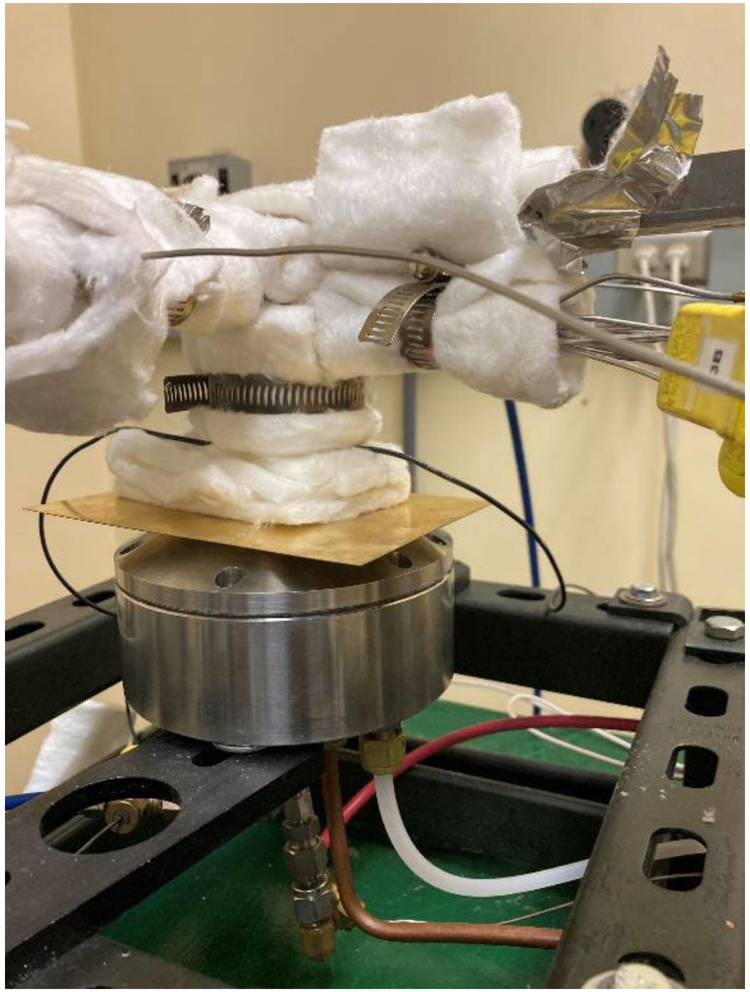
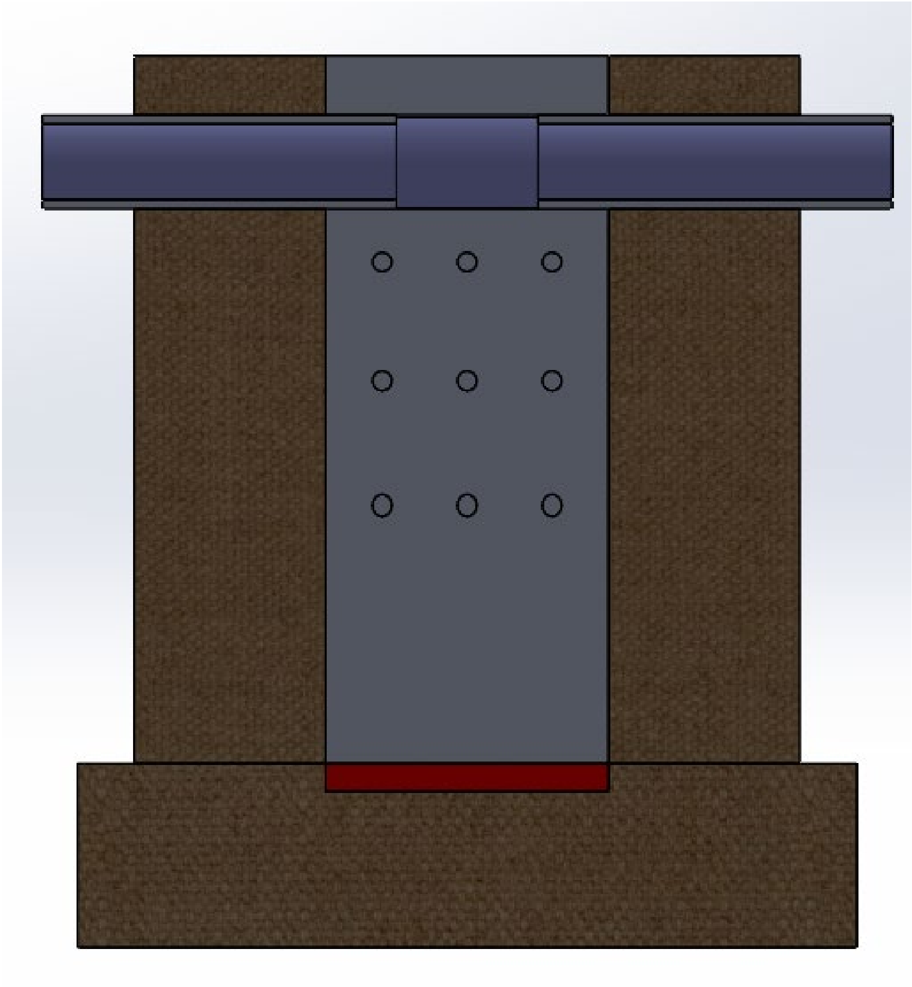
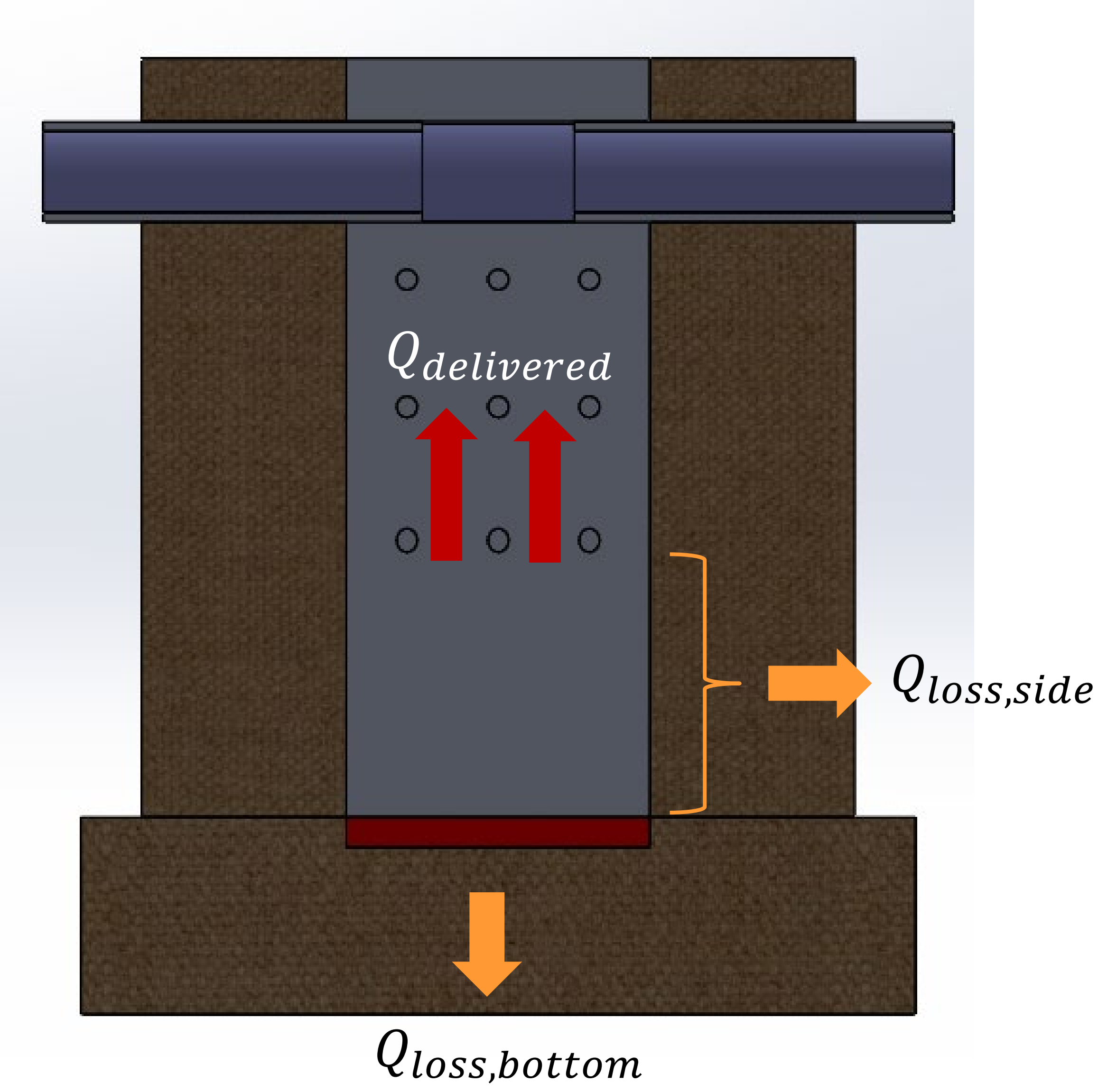
Task 3.1: To validate the heat flux block measurements, tests were taken by using an element heater connected to a power supply to create a known heat flux.





Task 3.1: Heat loss through insulation was estimated using thermal resistance circuits.



$$Q_{supplied} = Voltage * current$$

$$R_{total,side} = \frac{ln\left(\frac{r_2}{r_1}\right)}{2\pi Lk} + \frac{1}{hA_s} \longrightarrow Q_{loss,side} = \frac{T_{ave} - T_\infty}{R_{total,side}}$$

$$R_{total,bottom} = \frac{L}{kA_{c,block}} \longrightarrow Q_{loss,bottom} = \frac{T_{heater} - T_\infty}{R_{total,bottom}}$$

$$Q_{delivered} = Q_{supplied} - Q_{loss,bottom} - Q_{loss,side}$$

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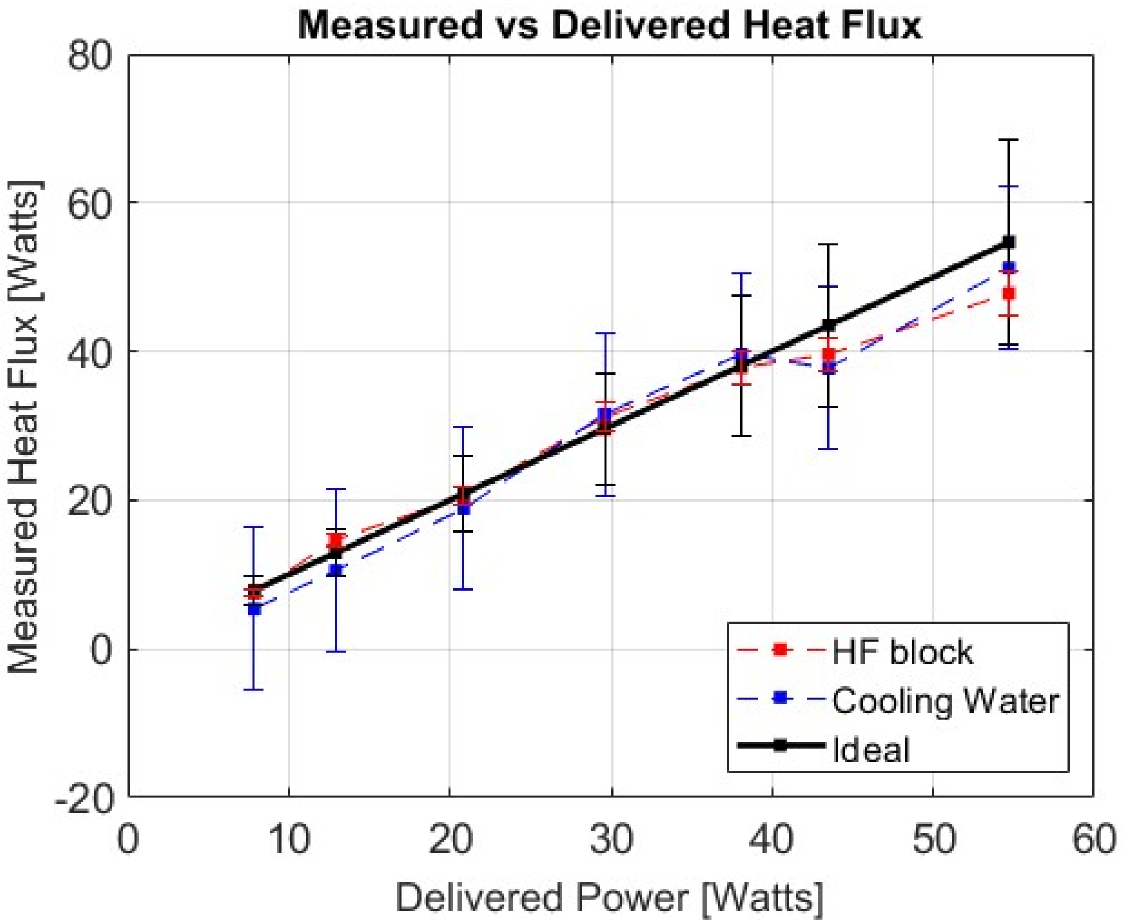
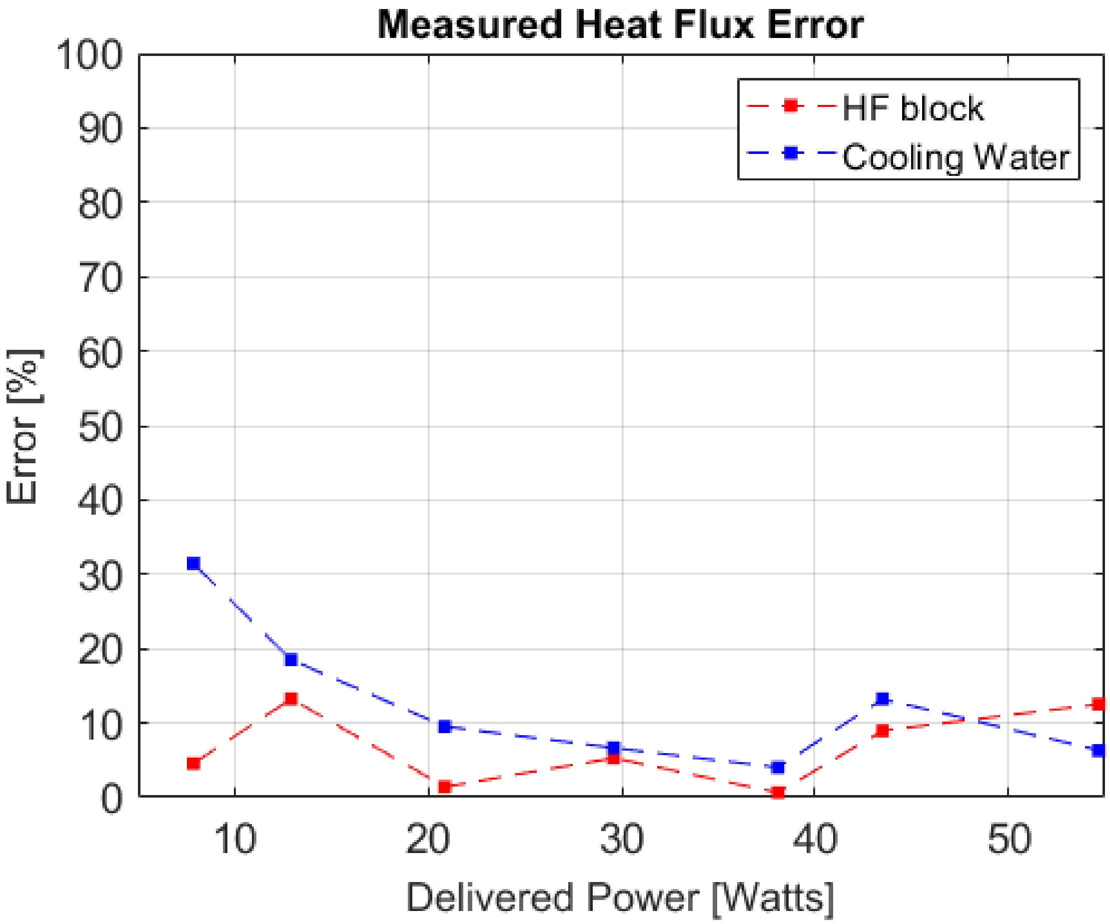
Task 3.1: The block temperature measurements and cooling flow calculations agreed well with delivered heat flux indicating accuracy of the block measurement technique.





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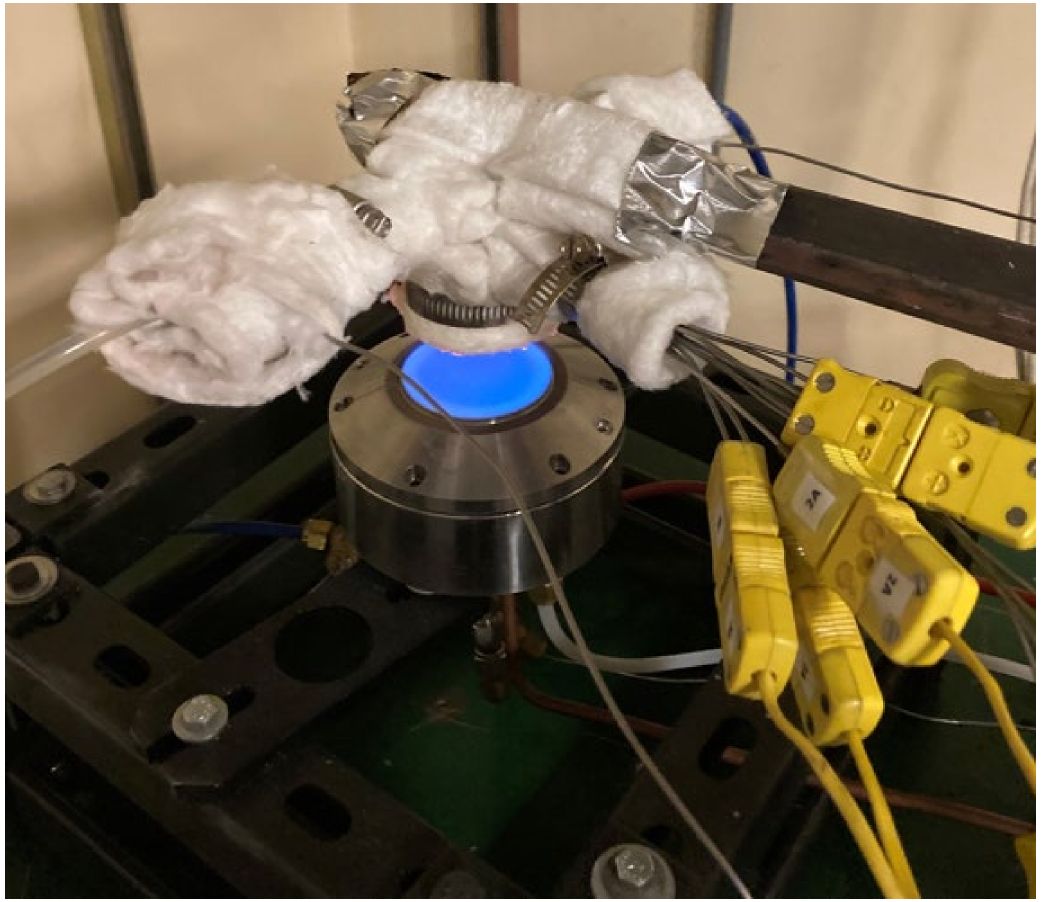
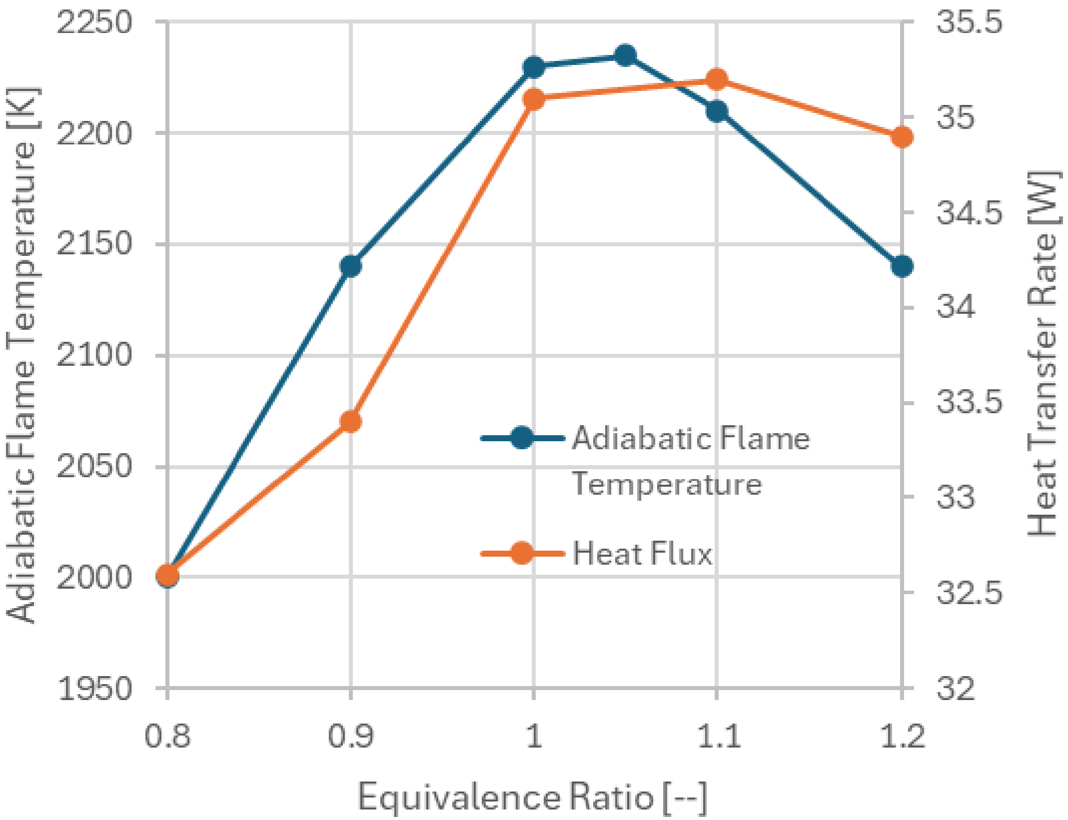
Task 3.1: The heat flux block was tested over a natural gas flame to test the method in combustion, and indicated that heat flux was correlated to adiabatic flame temperature





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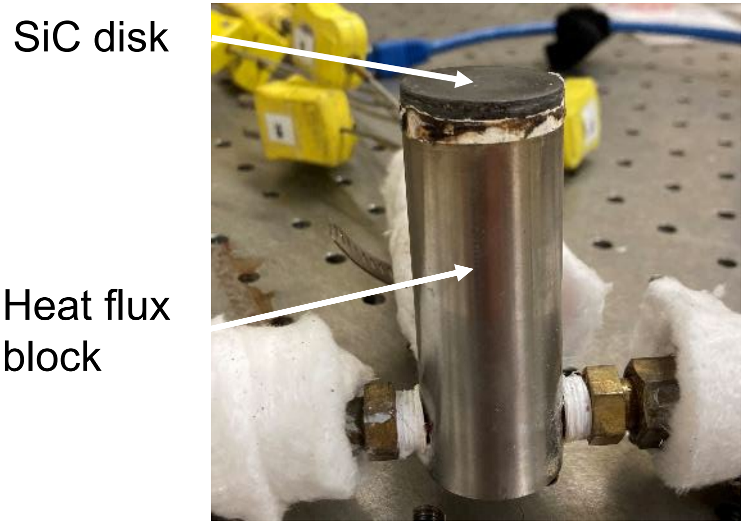
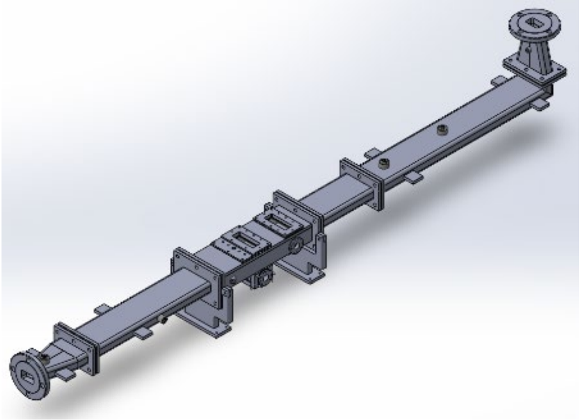
Task 3.1: Next steps include validation of heat flux block with SiC sample disks, and assembly of test rig once parts are received

Trial SiC disks are being tested for adhesive attachment and validation of the total heat flux block



The testing facility is currently being manufactured, and shakedown testing will be conducted in the coming months.



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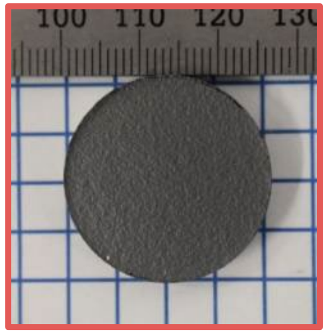
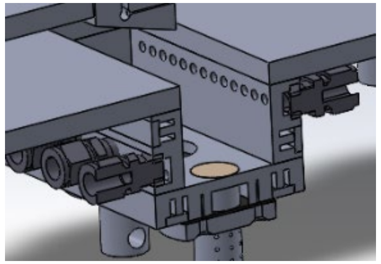
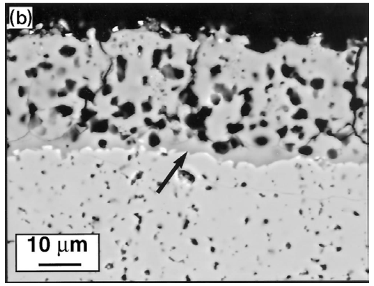
In conclusion, we are developing the CMC manufacturing processes and fabricating the exposure testing facility with a goal to be testing CMC samples by summer 2024



We are establishing SiC matrix processing parameters and have established fiber layup/matrix infiltration processes



A highly instrumented combustion exposure test facility has been designed and will be online this summer



Future testing will establish degradation rates and microstructural changes in untreated SiC/SiC, and efficacy of integrated EBC coatings

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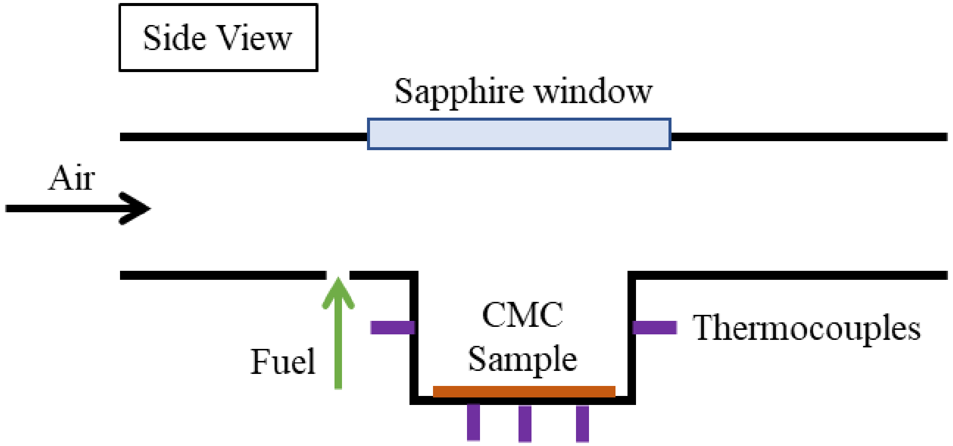
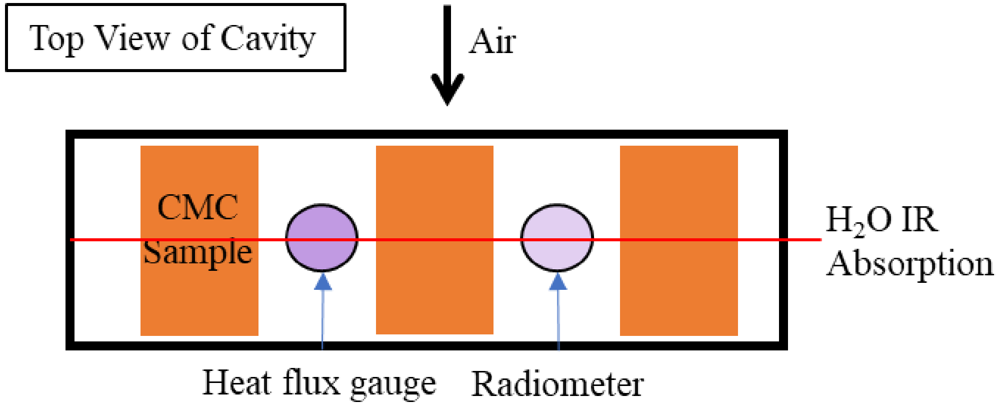
Appendix

We expect gas temperatures between 1800 – 2200 K and H_2O concentrations up to 30% in the combustion products. Experimental design will incorporate several GT-relevant flow features

- Task 4: Expose CMC samples to relevant environment
  - 4.1: Exposure at various relevant operating conditions
    - Evaluate different fuel compositions (hydrogen/natural gas blends), fuel air ratios, exposure times; measure concentration and thermal conditions for all cases
  - 4.2: Exposure to high water vapor conditions
    - Repeat selected cases from 4.1 but with additional water vapor added to reactants (steam dilution)





Variable	Fuel composition H_2/NG	Equivalence ratio	Preheat temperature	Added H_2O concentration
Levels	0/100 – 100/0	0.3 – 1	25 – 250 °C	0 – 5%

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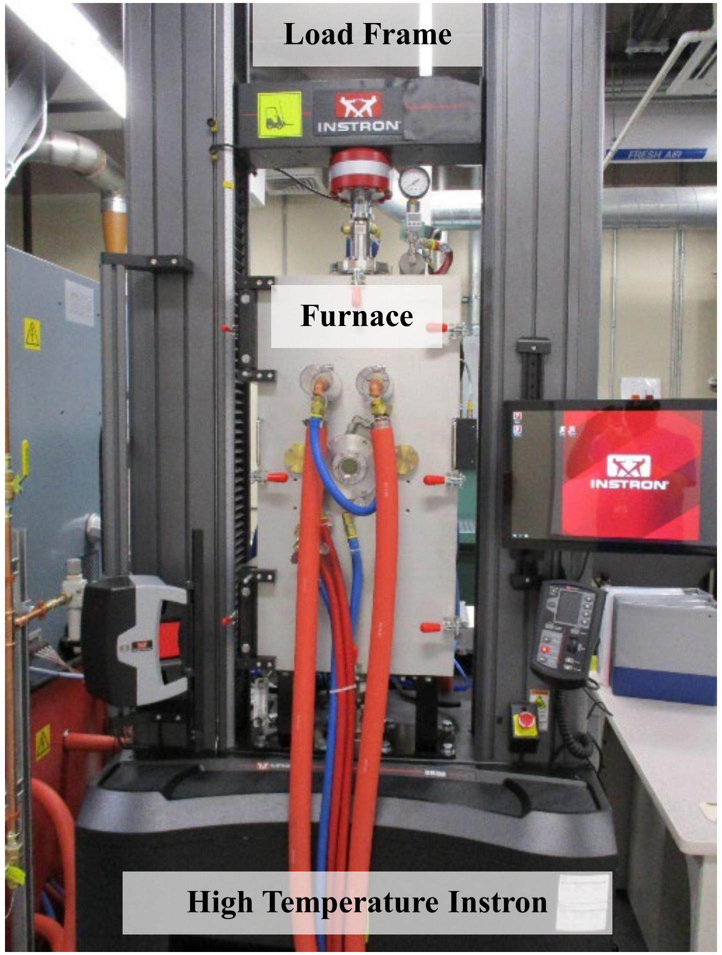
The significant measurement capabilities at Penn State's Materials Characterization Lab and at ARL-Penn State will be used to analyze the CMC samples

- Task 5: Perform post-exposure analysis of CMC samples
  - 5.1: Microstructural inspection and failure analysis
    - SEM, EDS, X-ray CT to analyze density, homogeneity, EBC bond
  - 5.2: Mechanical property testing
    - Shear, flexural, hardness, in-plane tensile strength characterization after exposure

Scanning electron microscope

Energy dispersive spectroscopy

High temperature Instron Tensile Tester (2500°C)



Task 2.0. Develop new CMC compositions using FAST build method
Subtask 2.1 Perform Baseline CMC fabrications

Progress Summary:

1. ✓ **Procured majority of raw CMC FAST materials (i.e. powders, graphite dies, fiber cloths, etc.) and enrolled participating personnel** [1-8/23]
   - Includes SiC powder, EBC powders, SiC fiber cloth, binders, carbon fiber cloth/chopped fiber analog, Si/C nanoparticles, and 1"OD graphite dies
2. ✓ **Performed baseline characterization of raw components (i.e. powders, fiber cloths) before processing** [8-10/23]
   - XRD, SEM-EDS, OM, planimetric measurements, Laser PSD, and effect of milling conditions/surfactants
3. ✓ **Performed baseline SiC matrix FAST processing, optimization, and characterization** [9-10/23]
   - Evaluated effects of sintering soak temperature & time on density, dimensions/tolerances, and crystallinity (XRD)
4. ✓ **Investigated viable & scalable fiber cloth processing methods for FAST CMCs** [9-10/23]
   - Compared/evaluated cloth processing between taped lamination (single/dual) & infiltrated organic binder matrices (esp. PEG)
5. ✓ **Explored various slurry infiltration methods for producing FAST CMC green bodies** [10/23]
   - Investigated conventional gravity infiltration and centrifugal-accelerated infiltration of slurries into fiber preforms
6. ✓ **Evaluated cold-pressing methods for producing FAST CMC green bodies** [10/23-2/24]
   - Investigated effect of pressure, binder content, binder type (esp. stearic acid vs. PEG), fiber treatment, trimming, & layup

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Task 2.0. Develop new CMC compositions using FAST build method
Subtask 2.1 Perform Baseline CMC fabrications

Progress Summary:

7. ✓ **Explored Vat photopolymerization as an AM technique for PIP-based FAST CMCs** [10/23-3/24]
   - Evaluated viability of direct resin printing on fibers; developed preliminary SiC-based precursor/photoinitiator prints
8. ✓ **Explored reactive Si/C nanopowder processing for in-situ SiC formation via FAST in CMCs** [11-12/23]
   - Developed ball milling process from small to large-scale nanopowder blends and evaluated post-milled particle morphology/crystallinity
9. ✓ **Improved cold-pressed green CMCs with miniaturization & mold-assisted fusing for robust stacking** [12/23]
   - Developed thin layers with pressing of sieved fines & thermal fusing of fiber/matrix layer stacks with silicone molds
10. ✓ **Optimized slurry composition for ideal particle infiltration/retention, green body robustness/machinability, and scalable processing** [1-2/24]
    - Investigated effects of solvent type, solvent concentration, binder content, particle loadings, viscosity, & duration
11. ✓ **Optimized solvent debinding processes for preparing binderless green CMCs before subsequent FAST processing** [1-2/24]
    - Investigated effects of green body diffusion barriers/containment, submersion duration, & debinding cycles
12. ✓ **Performed initial baseline FAST CMC fabrication from cumulative developments (i.e. slurry infiltrating, cutting, stacking, debinding)** [3/24]
    - Obtained post-fired shrinkages, average layer thicknesses, dimensions, and preliminary CMC microstructural insights (surface/X-section)

Task 5.0. Perform Post-Test Analysis of CMC Samples
Overview of Microstructural & Mechanical Analysis (subtasks 5.1-5.2)

Planning Overview:

Feedback to all experimental processes

Down-select best EBC integration via FAST

Down-select best CMC fabrication via FAST

1. Pilot Baseline CMC Combustion → **2. CMC-EBC Integration Screening** → **3. Improved CMC Fabrication with Selected EBC Method** → **4. Optimized CMC-EBC Candidates with Controls**

Per Combustion Trial Subset

A) Microstructural & Failure Analysis → **B) Mechanical Property Testing** → **C) Feedback to Processes**

Project team leads

- PI: Prof. Steve Lynch
  - Associate Professor, Mechanical Engineering, Penn State
  - Expertise in cooling and durability for gas turbine hot section components
- Co-PI: Prof. Jackie O'Connor
  - Professor, Mechanical Engineering, Penn State
  - Expertise in combustion and renewable fuels
- Co-PI: Dr. Doug Wolfe
  - Associate Vice President for Research, and Prof of Mat'l Science & Engineering and Engr Sci & Mechanics, Penn State
  - Expertise in high temperature materials and coatings including development, processing, and evaluation
- Industry partner: EPRI
  - Technical contact: Bobby Noble, Program Manager: Gas Turbine Life Cycle Management (P216) and Gas Turbine Advanced Components & Technologies (217)

Project milestones were updated with a revision of the PMP in July due to personnel delays but Milestones 1, 2, and 4 are completed

Task/ Subtask	Milestone Title & Description	Original Completion	Revised Completion	Actual Completion	Comments
1.1	M1: Deliver PMP to NETL	1/31/2023	--	01/03/2023	Revision provided 7/2023
1.2	M2: Deliver TMP to NETL	3/31/2023	--	04/13/2023	
2.1	M3: Fabrication of baseline CMC formulation complete	9/30/2023	3/30/2024	4/30/2024	
3.1	M4: Experimental facility detail design review	6/30/2023	12/30/2023	10/4/2023	Review completed with EPRI
3.1	M5: Experimental facility fabrication complete	9/30/2023	3/30/2024		Delayed due to procurement of materials
3.2	M6: Standard operating procedures and operability map for experimental facility	12/31/2023	6/30/2024		
4.1	M7: Testing results for baseline CMC in experimental facility	3/31/2024	8/30/2024		
5.1	M8: Detailed characterization for baseline CMC complete	6/30/2024	9/30/2024		
2.2	M9: Fabrication of improved CMC formulation	6/30/2024	8/30/2024		
4.1	M10: Testing results for improved formulation CMC	9/30/2024	11/30/2024		
5.1	M11: Detailed characterization for improved formulation CMC complete	12/31/2024	12/31/2024		

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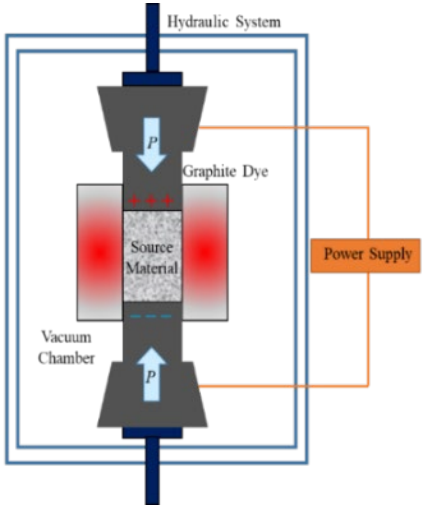
The full project schedule is shown below with some shift of task completions due to the aforementioned delays

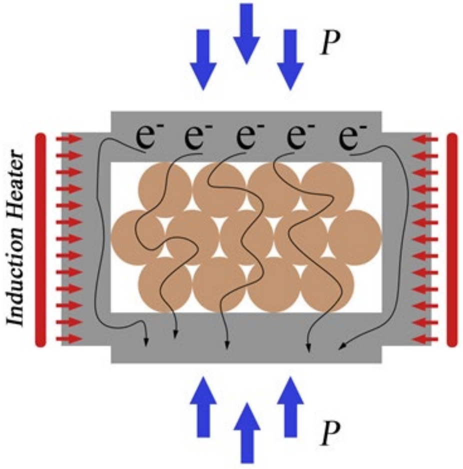
	2023				2024			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Task 1 - Project Management and Planning								
1.1 -- Update PMP, facilitate meetings, deliver required reports	M1							
1.2 -- Develop and update Technology Maturation Plan	M2							
Task 2 – CMC Development with Field Assisted Sintering Technology								
2.1 -- Baseline fabrication					M3			
2.2 – Improved build							M9	
Task 3 – Experimental Facility Development and Build								
3.1 -- Experimental design and fabrication			M4		M5			
3.2 -- Experimental shakedown						M6		
Task 4 – Experimental Testing of CMC Samples								
4.1 – Test CMCs over fuel and compositional variations							M7	M10
4.2 – Increase water vapor content								
Task 5 – Post-Test Analysis of CMC samples								
5.1 -- Microstructural inspection and failure analysis							M8	
5.2 – Mechanical property testing								M11

There are significant manufacturing and cost challenges with CMC materials; one recent development is the use of Field Assisted Sintering Technology (FAST)

Challenges:
- Scalable manufacturing of net-shape, continuous fiber structures via CVD, infiltration, and pyrolysis-based techniques
- High internal surface area for oxidation and sensitivity to embrittlement

Approaches/Solutions:
- *FAST processing* – Rapid/enhanced consolidation, joining, adhesion, and minimal thermal degradation of CMCs
- *EBC coatings* – Deposit environmental barrier coatings for protection

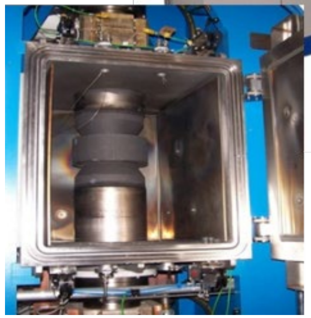




Benefits of FAST:
- Near theoretical density (~100%)
- Short sintering times
- Can retain sub-grained structure
- Compositional graded structures
- Solid state joining of dissimilar materials (metal and ceramics)
- Compatible with metals, ceramics, polymers, and composites

1) R&D Unit
Max load: **25 Ton;**
Max Dia. = **80 mm**

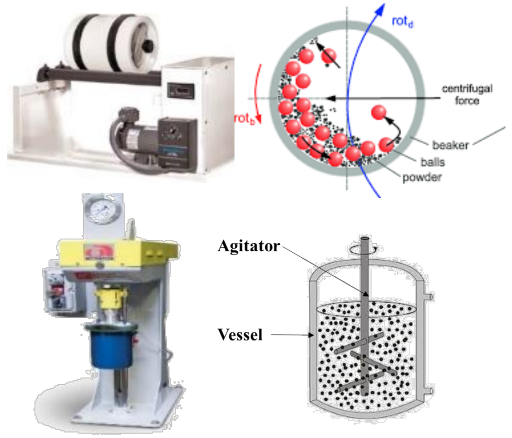
2) Prototype R&D
Max load: **250 Ton;**
Max Dia. = **300 mm**



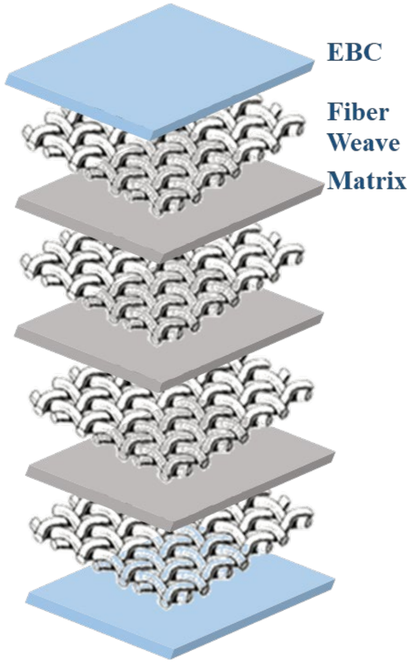
We will develop a baseline CMC against which to evaluate improved formulations including integrated EBC

- Task 2: Develop new CMC compositions using FAST method
  - 2.1: Perform baseline CMC fabrication
    - Procure SiC cloths and powders, infiltrate cloths with slurry, determine FAST processing parameters, evaluate pre-exposure microstructure and properties
  - 2.2: Fabricate improved CMC compositions and build methods
    - Improve cloth formulation (fiber coatings), slurry formulation (add YbDS, YbMS), and integrated EBC coatings, revisions to FAST processing parameters, evaluate pre-exposure microstructure and properties

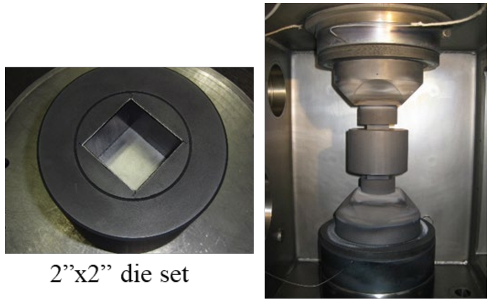
Powder Processing and Slurry Preparation



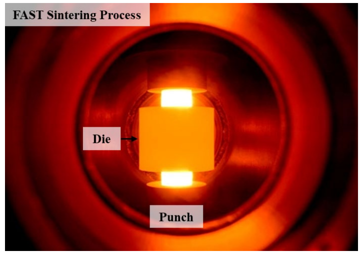
CMC Preform Construction



FAST Die Preparation



FAST Processing



Initial design of the test facility has begun in collaboration with Bobby Noble at EPRI. Facility is designed to vary H_2 concentration and gas temperature for a range of material samples

- Task 3: Design, build, and shakedown a hydrogen combustion test facility for CMC samples
  - 3.1: Design and build facility
    - Mechanical & thermal design for long term operation; novel instrumentation for diagnostics of flame/products composition and thermal environment; capability to increase water vapor content
  - 3.2: Shakedown of facility
    - Evaluate safe and stable operating ranges, temperatures, achievable water vapor levels

Exhaust drop

This is being moved…

Out-of-picture: I have a complete flow and fuel-blending system ready to go in this room

Test section will rest above this table, which will have all the optics/ diagnostics.

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Task success criteria review

- **Task 2 – CMC Development with Field Assisted Sintering Technology (FAST):** this task will be deemed successful if the project team can fabricate SiC/SiC CMCs with integrated EBC coating using the FAST process.

- **Task 3 – Experimental Facility Development and Build:** this task will be deemed successful if the experimental facility can operate with up to 100% hydrogen at repeatable conditions.

- **Task 4 – Experimental Testing of CMC Samples:** this task will be deemed successful if the project team can expose the CMC samples to a range of hydrogen blend levels and measure the accompanying combustion gas conditions.

- **Task 5 – Post-Test Analysis of CMC Samples:** this task will be deemed successful if the project team is able to observe quantitative differences in microstructural effects and degradation of uncoated and EBC coated SiC/SiC composites after several run cycles.

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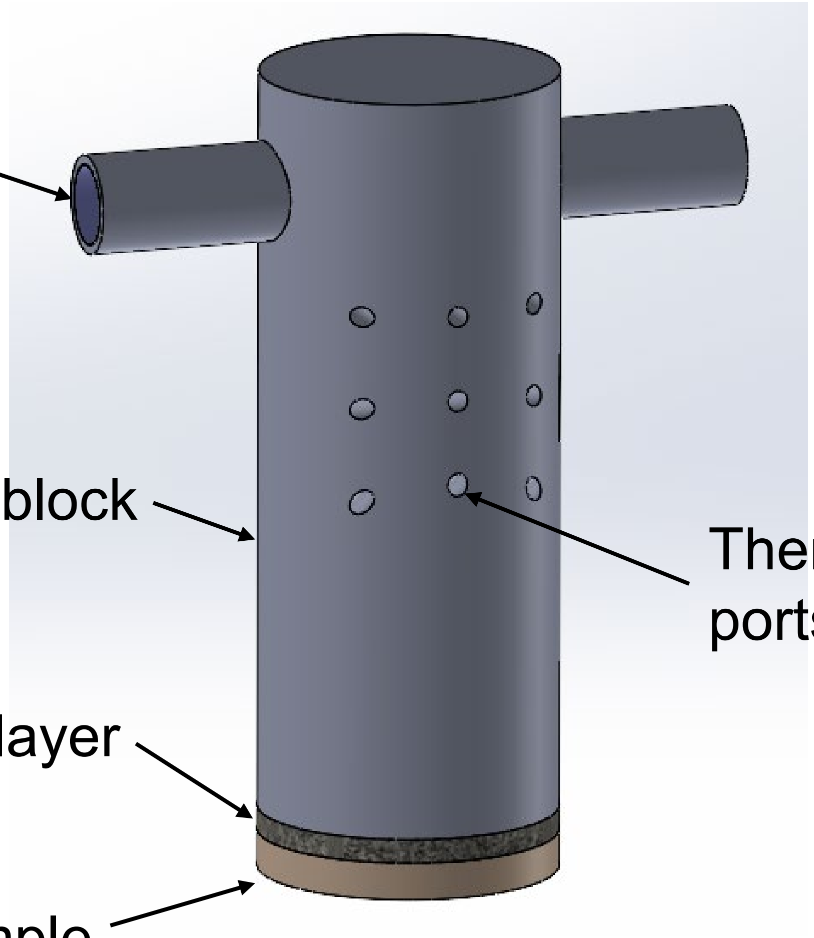
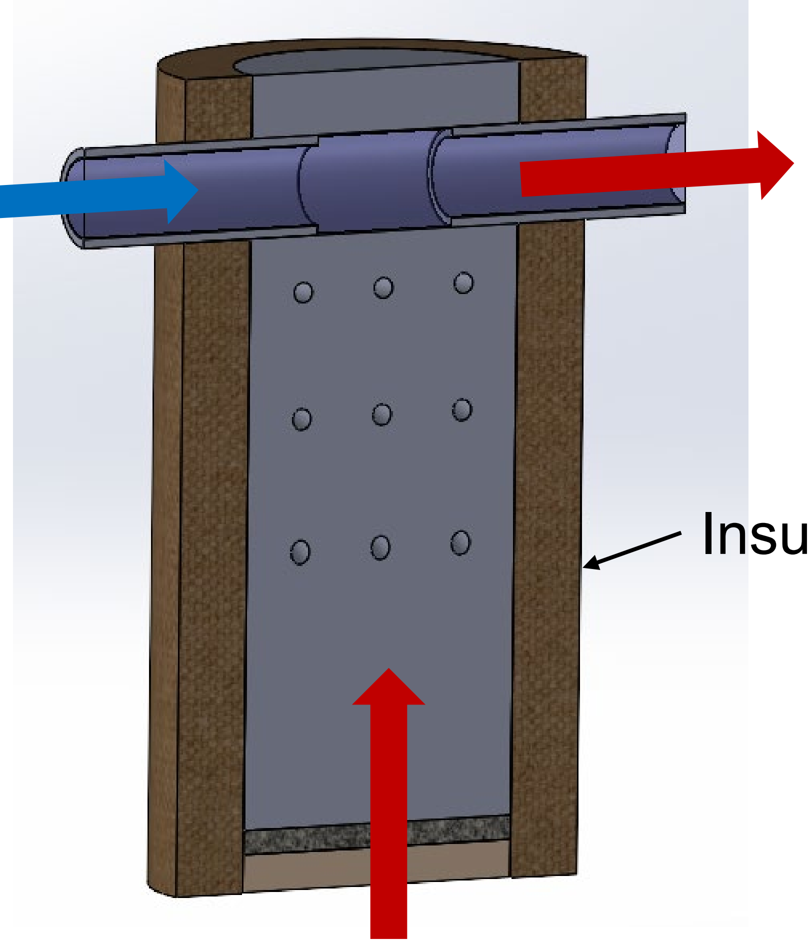
We are tracking success criteria that will be evaluated for each major task

Task/ Subtask	Milestone Title & Description	Status	Comments
2	**CMC Development with Field Assisted Sintering Technology (FAST):** this task will be deemed successful if the project team can fabricate SiC/SiC CMCs with integrated EBC coating using the FAST process.	In progress	
3	**Experimental Facility Development and Build:** this task will be deemed successful if the experimental facility can operate with up to 100% hydrogen at repeatable conditions.	In progress	
4	**Experimental Testing of CMC Samples:** this task will be deemed successful if the project team can expose the CMC samples to a range of hydrogen blend levels and measure the accompanying combustion gas conditions.		
5	**Post-Test Analysis of CMC Samples:** this task will be deemed successful if the project team is able to observe quantitative differences in microstructural effects and degradation of uncoated and EBC coated SiC/SiC composites after several run cycles.		

Task 3.1: The heat flux block is the method that will be used to mount the CMC samples and measure the steady state total heat flux through the samples in the test facility.





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