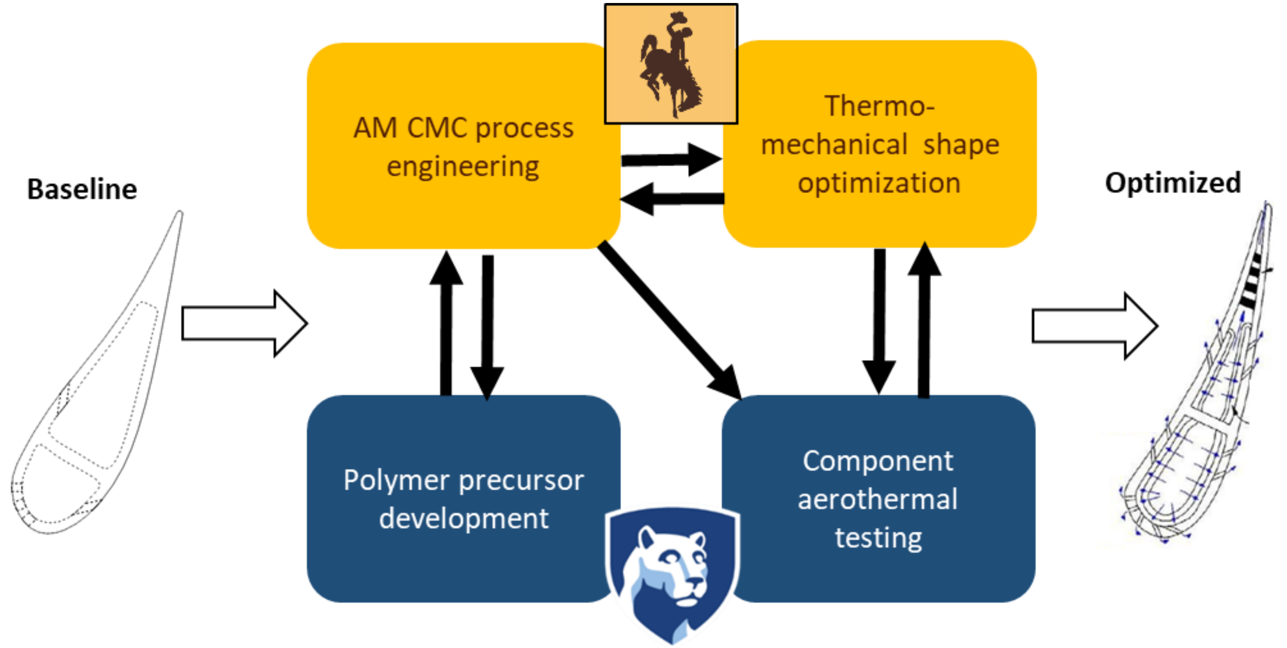
Development of Additive Manufacturing for Ceramic Matrix Composite Vanes



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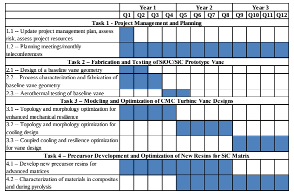
Project: DE-FE0031758

This review covers the motivation, project plan, and Year 1 progress on our UTSR-supported project

Motivation: enable superalloy-like cooling features in CMC-like materials to enable higher temperature operation

Approach: push polymer-derived ceramics development through additive manufacturing engineering, polymer science, part design, and performance verification

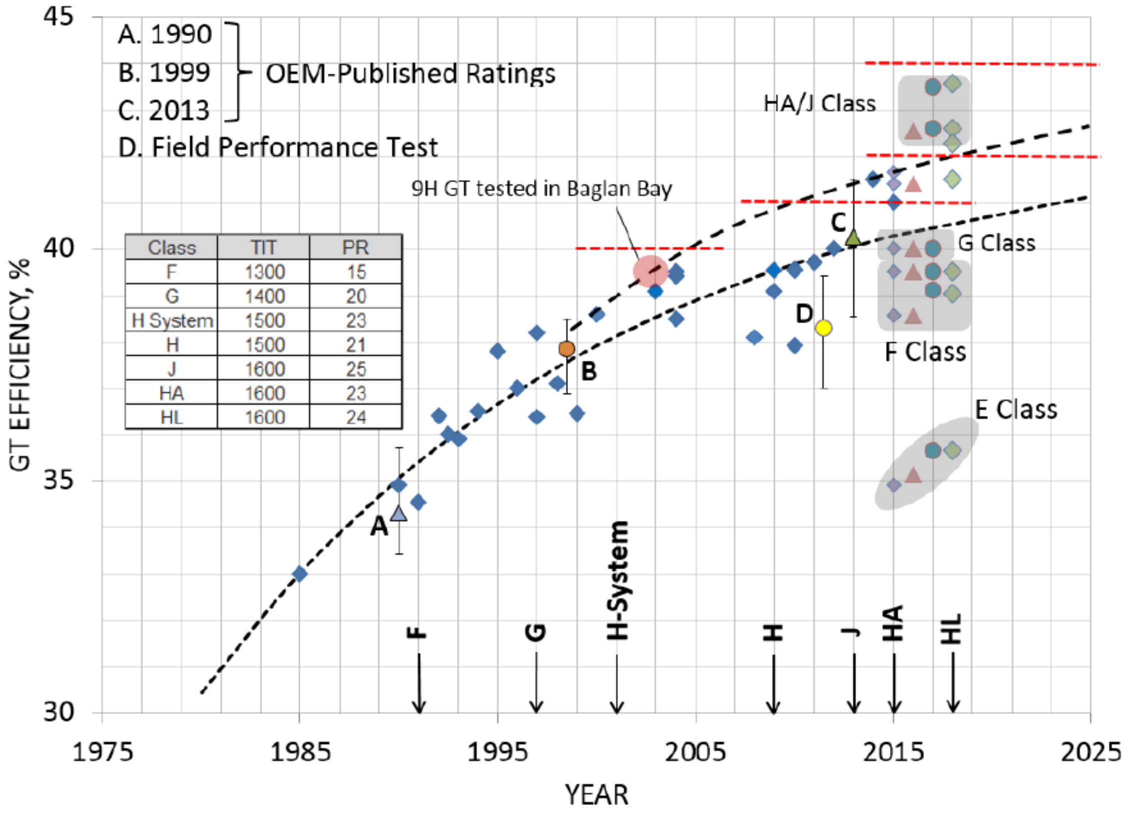


	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Task 1 - Project Management and Planning												
1.1 -- Update project management plan, assess risk, assess project resources												
1.2 -- Planning meetings/monthly teleconferences												
Task 2 – Fabrication and Testing of SiOC/SiC Prototype Vane												
2.1 -- Design of a baseline vane geometry												
2.2 – Process characterization and fabrication of baseline vane geometry												
2.3 -- Aerothermal testing of baseline vane												
Task 3 – Modeling and Optimization of CMC Turbine Vane Designs												
3.1 -- Topology and morphology optimization for enhanced mechanical resilience												
3.2 -- Topology and morphology optimization for cooling design												
3.3 -- Coupled cooling and resilience optimization for vane design												
Task 4 – Precursor Development and Optimization of New Resins for SiC Matrix												
4.1 – Develop new precursor resins for advanced matrices												
4.2 – Characterization of materials in composites and during pyrolysis												

Project plan: execute simultaneous materials/design/process engineering to regularly produce vane test articles

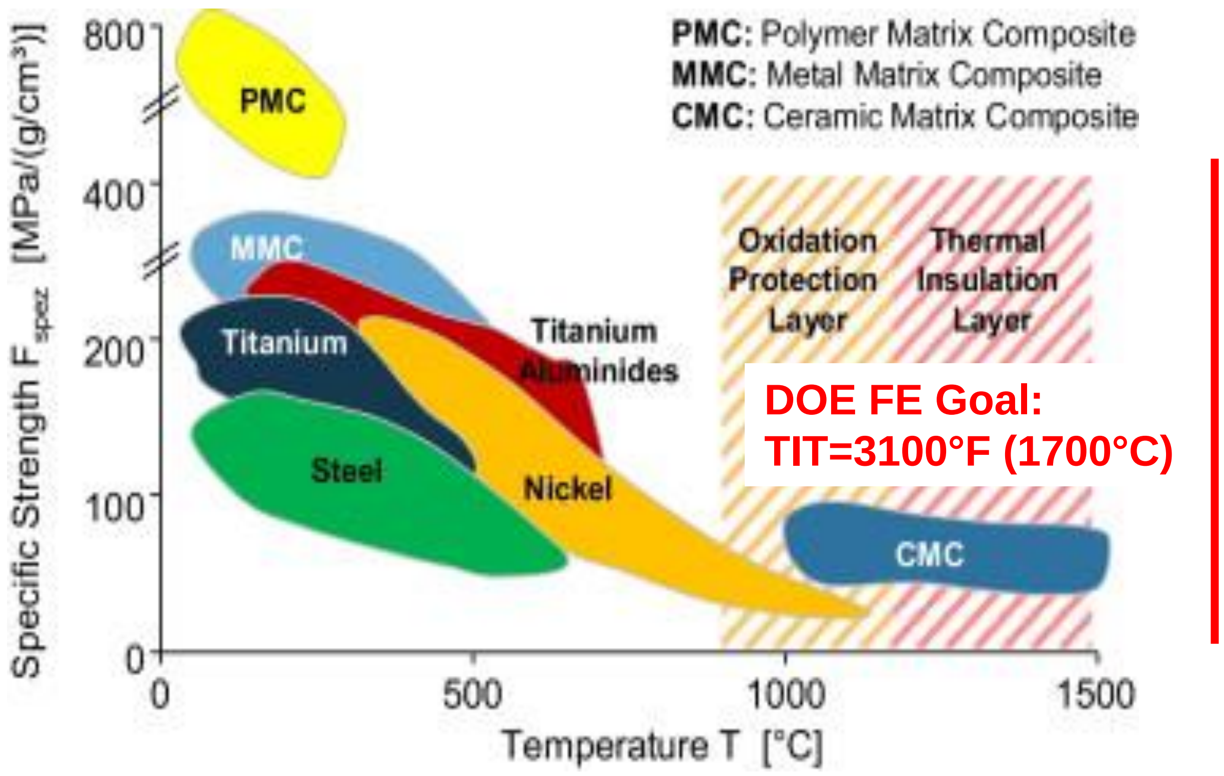
Current progress

To achieve DOE firing temperature targets and push higher thermodynamic efficiency, even advanced CMC materials will require some cooling



Class	TIT	PR
F	1300	15
G	1400	20
H System	1500	23
H	1500	21
J	1600	25
HA	1600	23
HL	1600	24

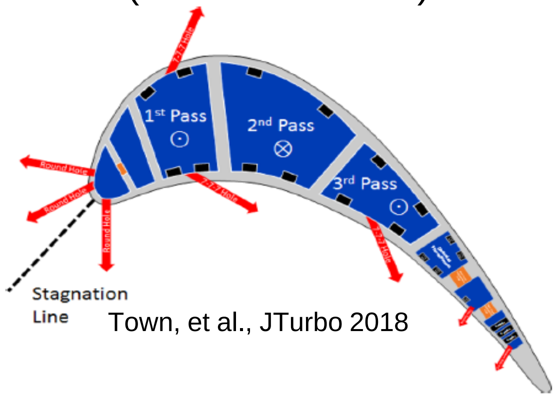
National Academies of Sciences, Engineering, and Medicine 2020. *Advanced Technologies for Gas Turbines*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25630.



Klocke, et al., CIRP Annals, 2014

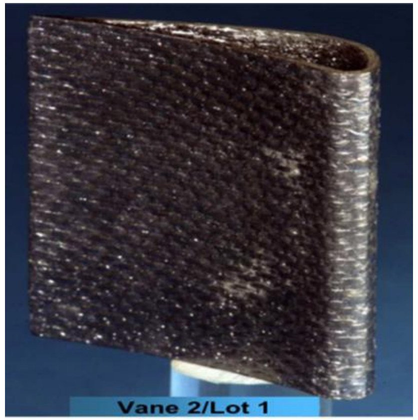
Highly effective internal cooling technologies used in superalloy cast parts are difficult to implement in conventional CMC’s

DOE NETL Advanced Cooled Blade
(PSU START Lab)



Town, et al., JTurbo 2018

Melt-infiltrated woven CMC



https://technology.nasa.gov/patent/LEW-TOPS-25

Example superalloy
internal/external cooling

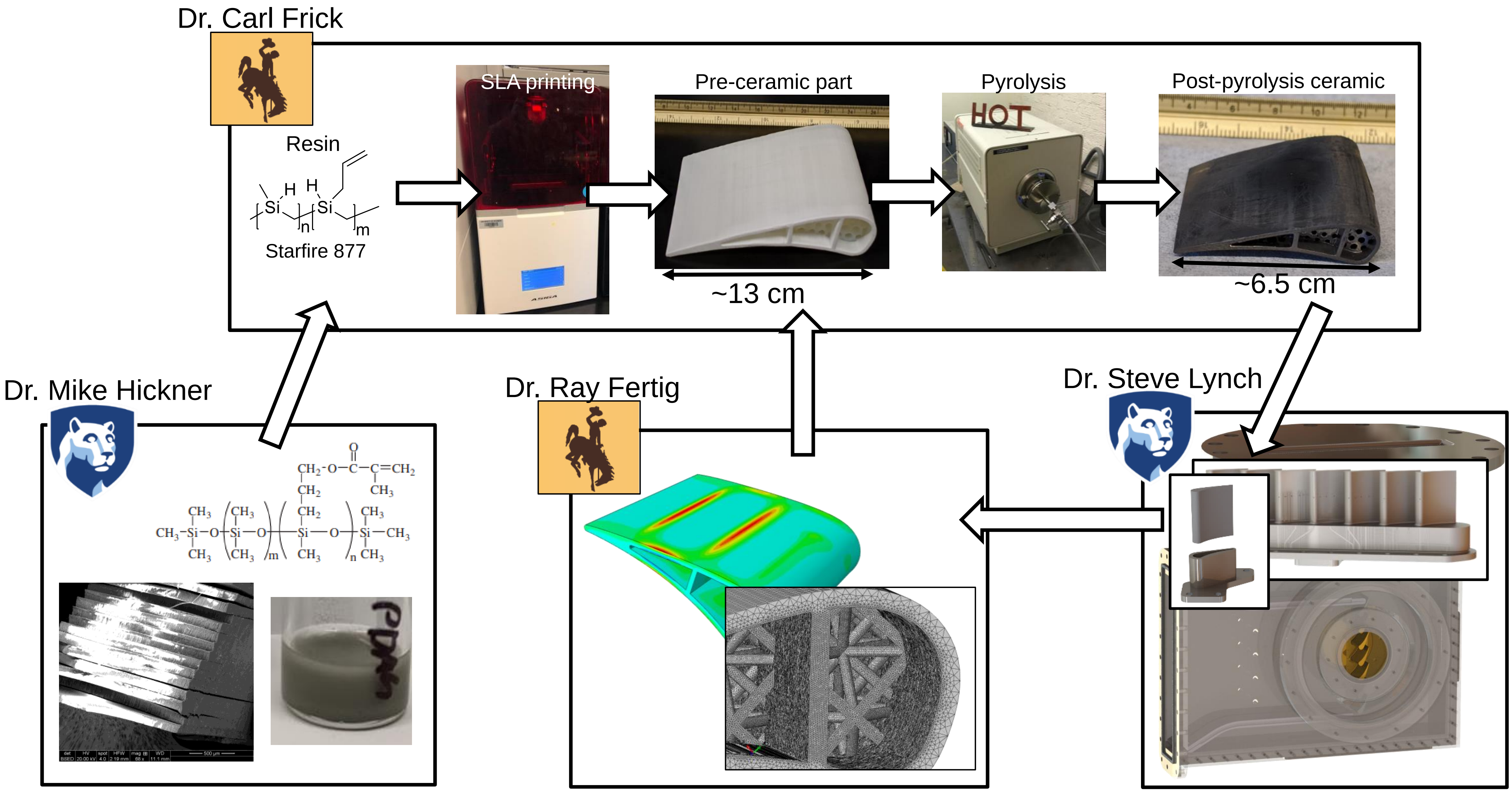
https://mdx.plm.automation.siemens.com

Binder-jet CMC with pass-through cooling

https://ntrs.nasa.gov/search.jsp?R=20160010285 2019-02-28T01:25:33+00:00Z

Project goal: enable complex cooling features in CMC-like materials for realistic shapes and confirm cooling benefit

Our approach is to develop novel chemistries and manufacturing processes, coupled with design optimization, to create internally cooled CMC vanes that can be tested



The project has five technical tasks that address process engineering, material development, modeling, and validation of cooling technologies

Task 1: Project management

Success criteria: Project Coordinator delivers all required reports to NETL

Task 2: Design, fabrication, and testing of SiOC/SiC baseline vane

Success criteria: project team is able to obtain surface temperatures on baseline SiOC/SiC internally cooled vane test articles tested in the transonic cascade at Penn State

Task 3: Modeling and optimization of CMC turbine vane designs

Success criteria: mechanical and thermal stresses reduced by 10%; increase overall cooling effectiveness by 0.05 relative to baseline

Task 4: Development of new SiC precursor chemistries

Success criteria: demonstrate that new precursors have equivalent or better material properties than SiC formed through traditional methods

Task 5: Integrate SiC precursor chemistry into AM process

Success criteria: project team is able to deliver a baseline vane part for transonic cascade testing using new SiC/SiC chemistry

Task 6: Fabricate and test optimized vane with SiC/SiC chemistry

Success criteria: project team obtains surface temperatures on optimized AM vane and shows overall cooling effectiveness increase relative to baseline

The project schedule is designed to produce improved airfoil cooling geometries and chemistries at regular intervals throughout

2019 Q3 | Q4 | 2020 Q1 | Q2 | Q3 | Q4 | 2021 Q1 | Q2 | Q3 | Q4 | 2022 Q1 | Q2 | Q3

	Year 1				Year 2				Year 3			
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Task 1 - Project Management and Planning												
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3.1 -- Topology and morphology optimization for enhanced mechanical resilience	■	■	■	■								
3.2 -- Topology and morphology optimization for cooling design					■	■	■	■				
3.3 -- Coupled cooling and resilience optimization for vane design									■	■	■	■
Task 4 – Precursor Development and Optimization of New Resins for SiC Matrix												
4.1 – Develop new precursor resins for advanced matrices	■	■	■	■	■	■	■	■				
4.2 – Characterization of materials in composites and during pyrolysis					■	■	■	■	■	■	■	■

The project schedule is designed to produce improved airfoil cooling geometries and chemistries at regular intervals throughout

2019 2020 2021 2022

Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3

	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Task 5 – Integrate SiC Precursor Chemistry into AM Process												
5.1 -- Engineering of AM process for SiC precursor												
5.2 – Fabrication of baseline test vane using SiC matrix												
5.3 -- Aerothermal testing of baseline vane with SiC/SiC												
Task 6 – Fabricate and Test Optimized Vane with SiC/SiC Chemistry												
6.1 -- Fabricate thermomechanically optimized vane												
6.2 -- Perform aerothermal testing of optimized vane												

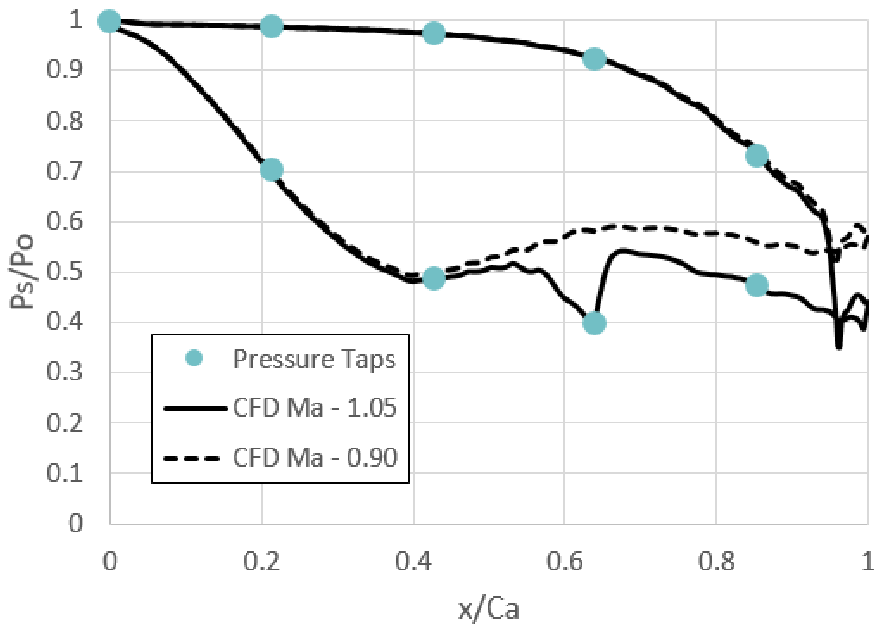
The project has several milestones that will be tracked for progress, with annual updates to the airfoil test articles

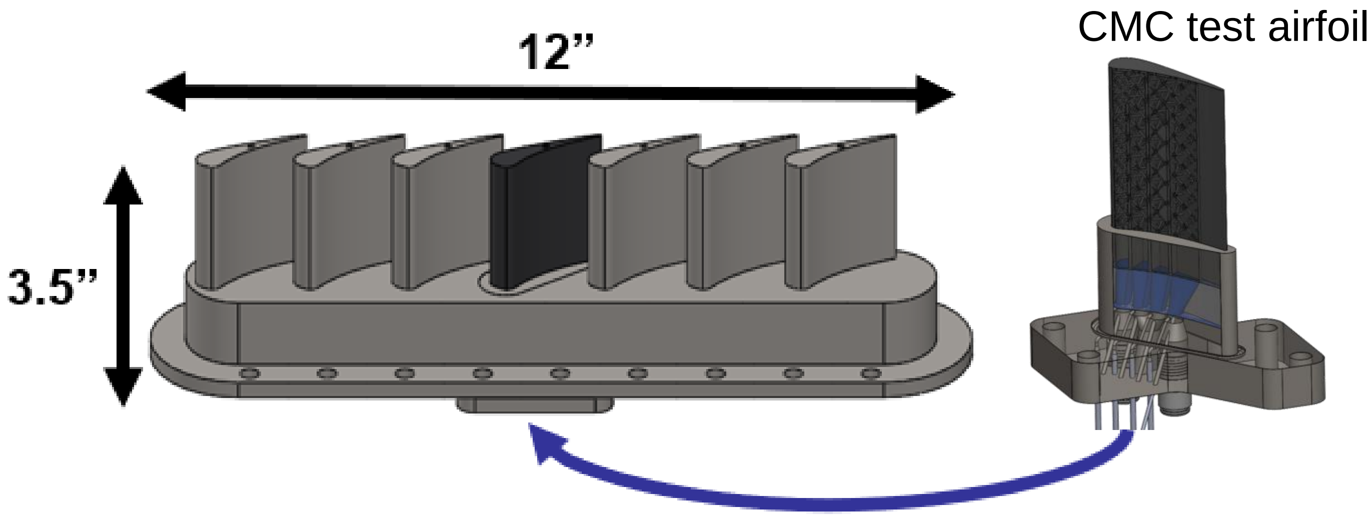
Task/ Subtask	Milestone Title & Description	Planned Completion	Actual Completion
2.1	M1: Baseline cooled vane design complete	Feb 2020	Feb 2020
2.2	M2: Fabrication of baseline cooled SiOC/SiC vane complete	Dec 2020	
3.1	M3: Topology optimization code for mechanical loading complete	Dec 2020	
4.1	M4: First generation SiC precursor chemistry delivered from PSU to UWYO	Dec 2020	
3.2	M5: Topology optimization code for thermal stress/cooling complete	Aug 2021	
4.2	M6: Detailed property characterization for SiC precursor complete	Aug 2021	
5.2	M7: Fabrication of baseline cooled vane with new chemistry complete	Aug 2021	
5.3	M8: Comparison of SiOC/SiC to SiC/SiC vane temperatures	Nov 2021	
6.2	M9: Comparison of baseline SiC/SiC vane temperature to optimized design	Aug 2022	

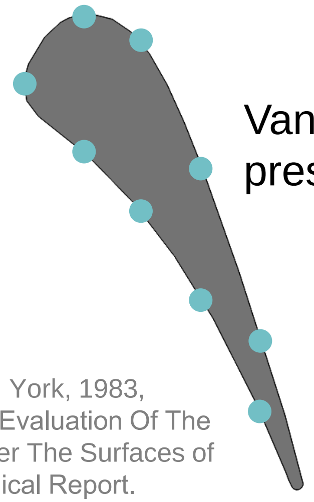
Shifted due to COVID

Color key: process engineering, material development, modeling, validation of cooling technologies

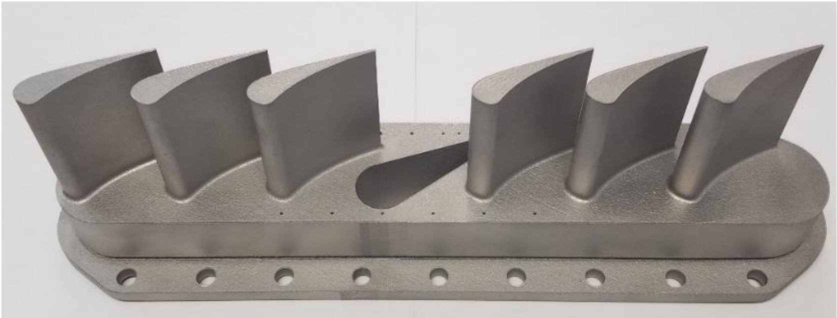
Task 2.1: The test article will be a NASA C3X vane geometry; the adjacent vane hardware design and fabrication was completed including capability to test a cooled CMC airfoil

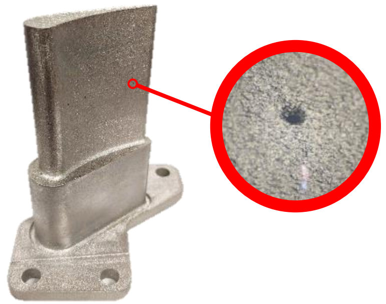






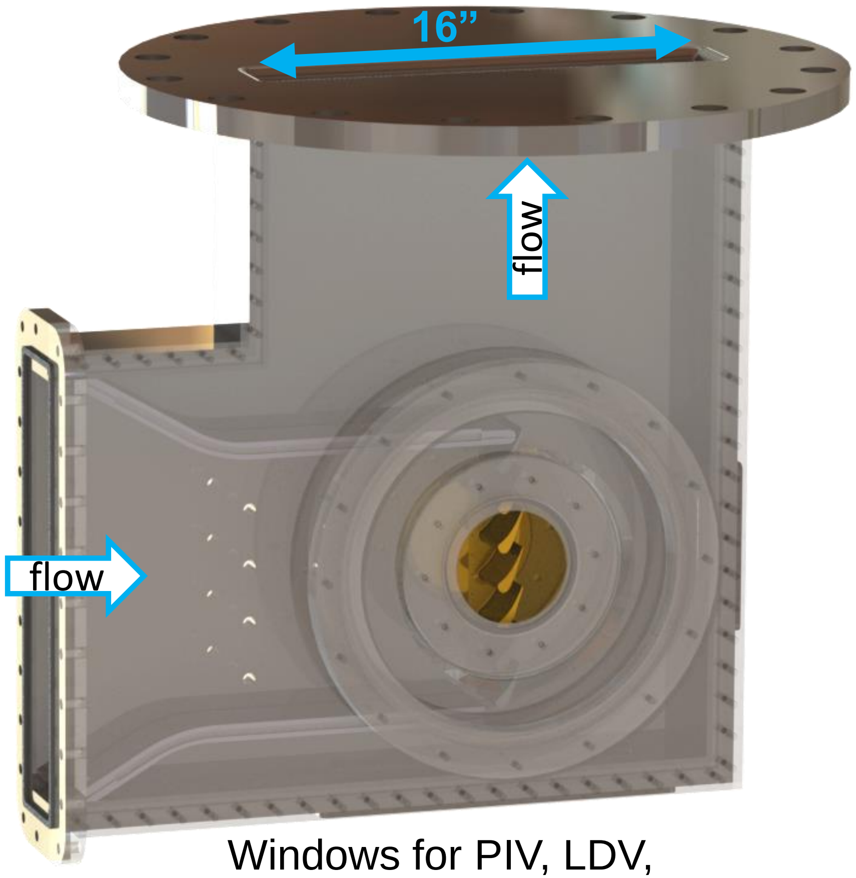
Vane static pressures



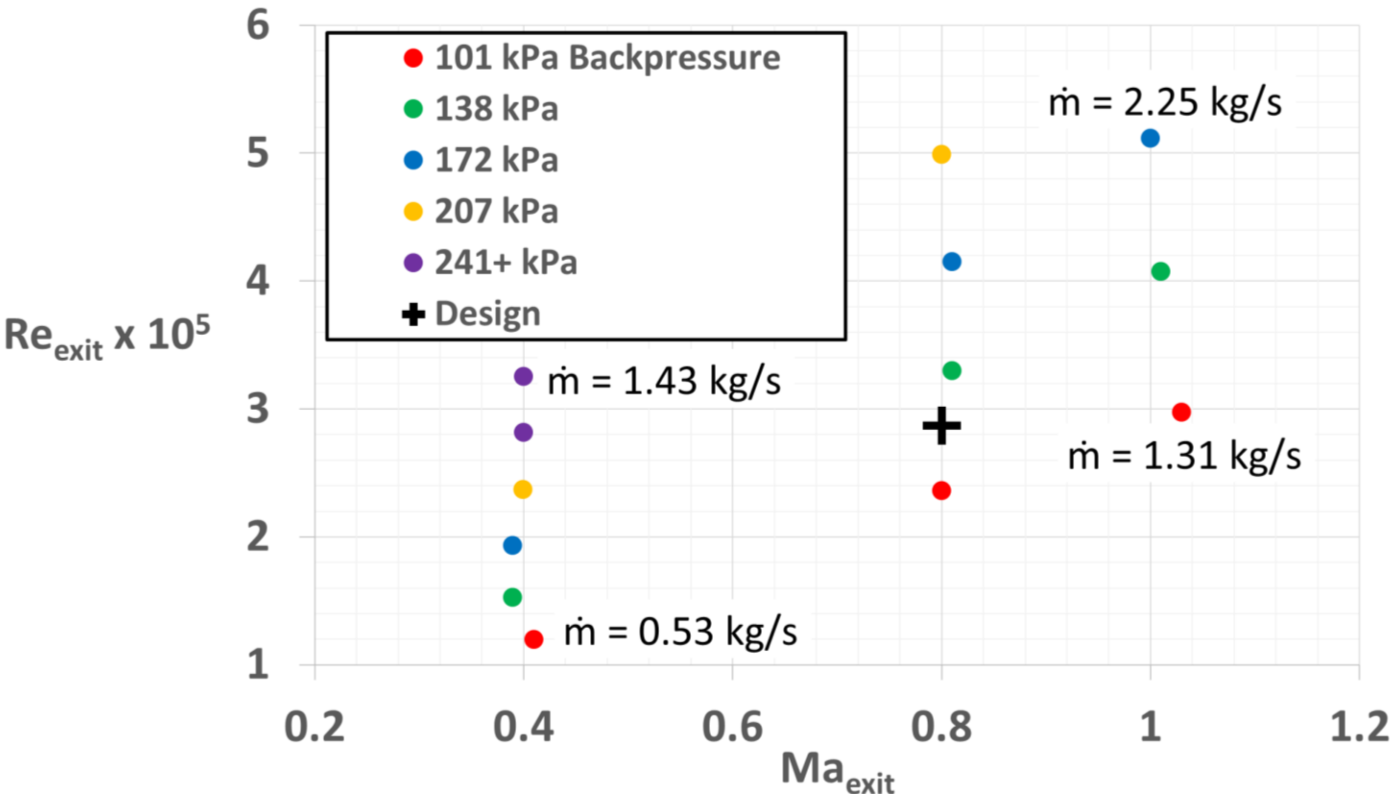


Hylton, Mihelc, Turner, Nealy, York, 1983, “Analytical And Experimental Evaluation Of The Heat Transfer Distribution Over The Surfaces of Turbine Vanes”, NASA Technical Report.

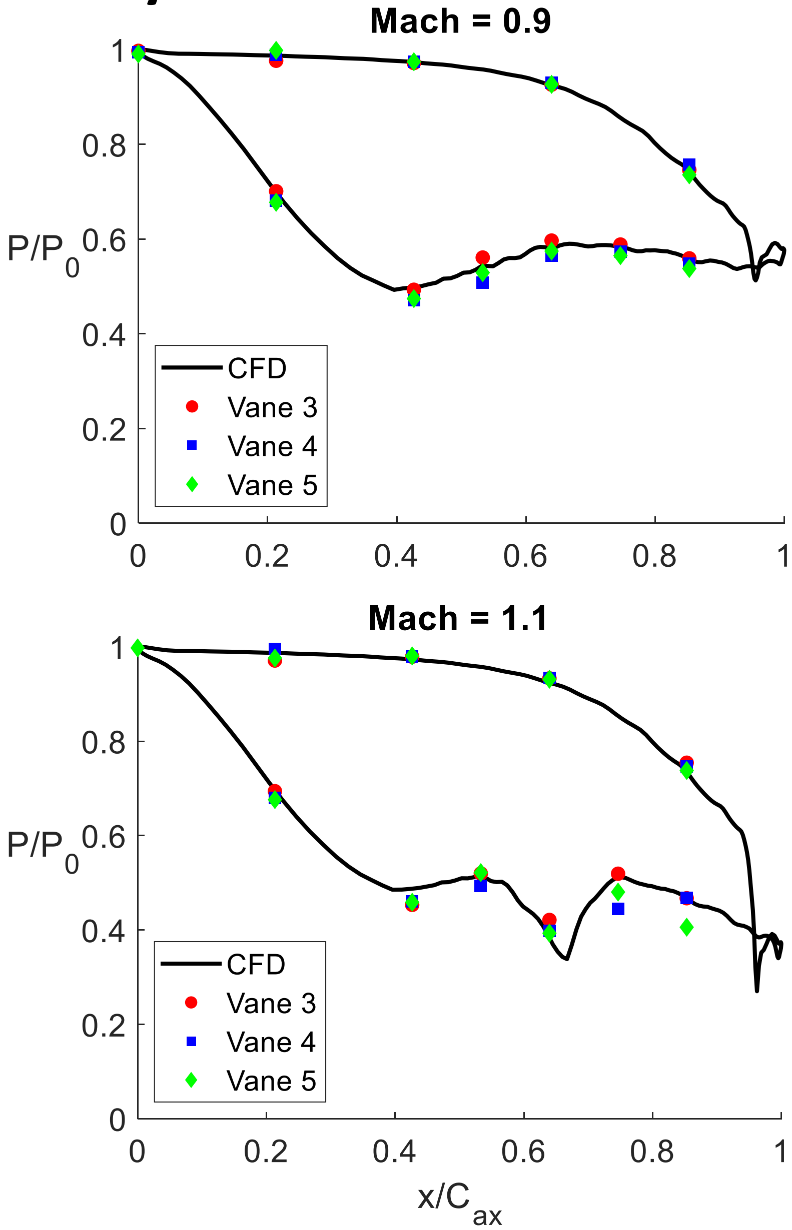
Task 2.1: The vane assembly will be tested in a new high speed cascade facility at Penn State capable of relevant Mach and Reynolds numbers, as well as cooled air capability

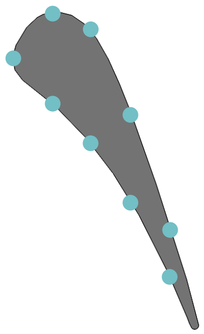


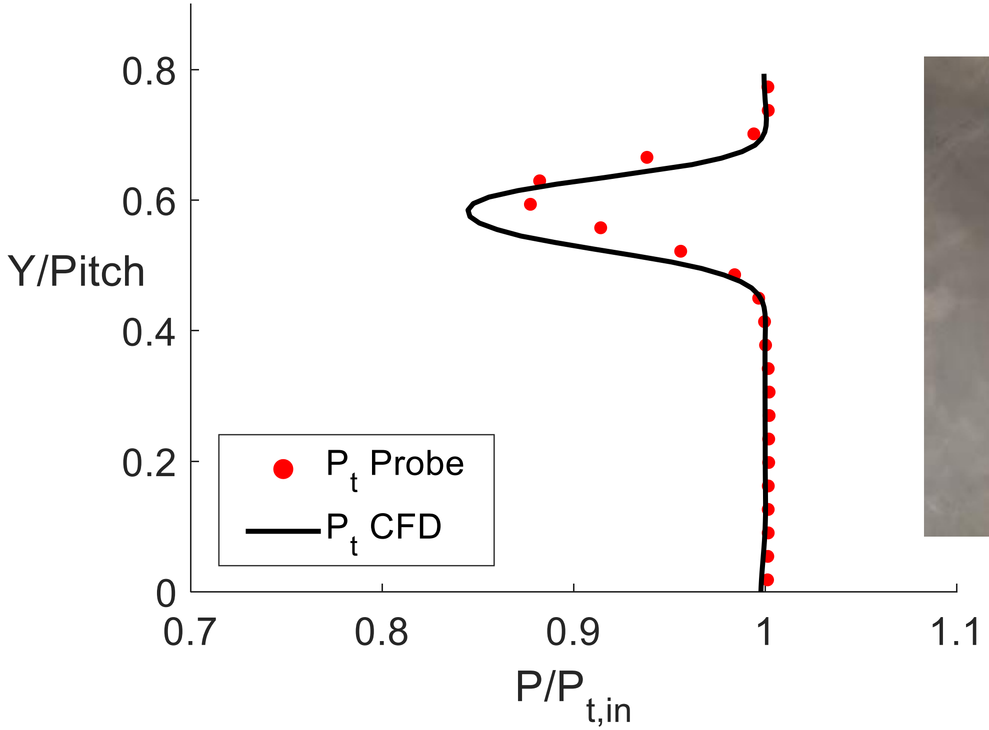
Windows for PIV, LDV, and IR measurements



Task 2.1: Aerodynamic measurements have been taken to benchmark the cascade and vane assembly without CMCs

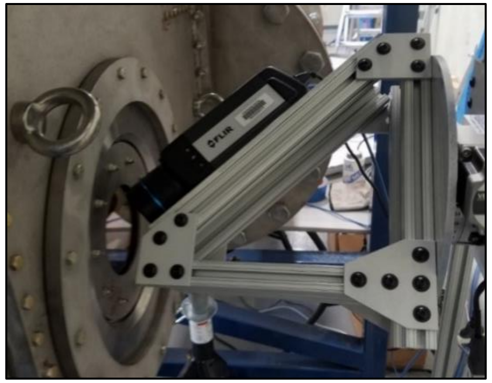




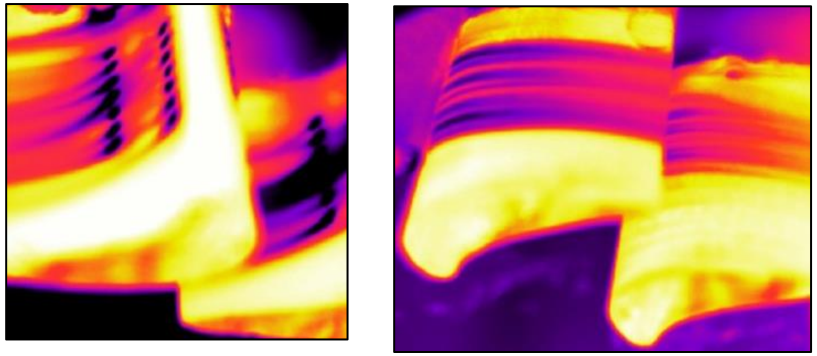


Task 2.1: We are developing infrared temperature sensing procedures as well as total pressure measurement procedures to characterize the CMC airfoil performance

Infrared camera in facility



Example images (not CMC vanes)

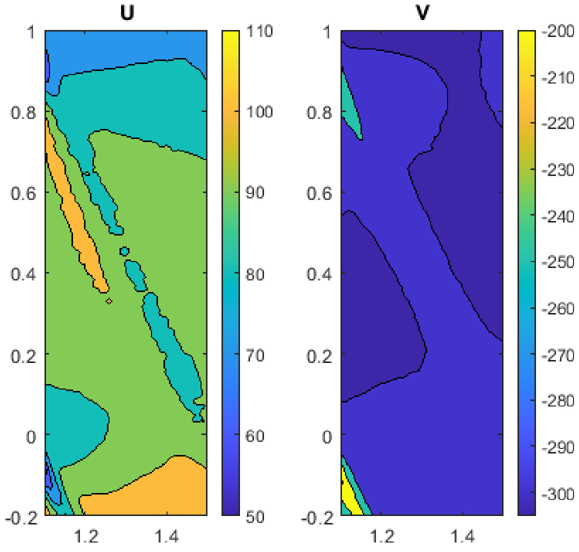


Momentum Equation

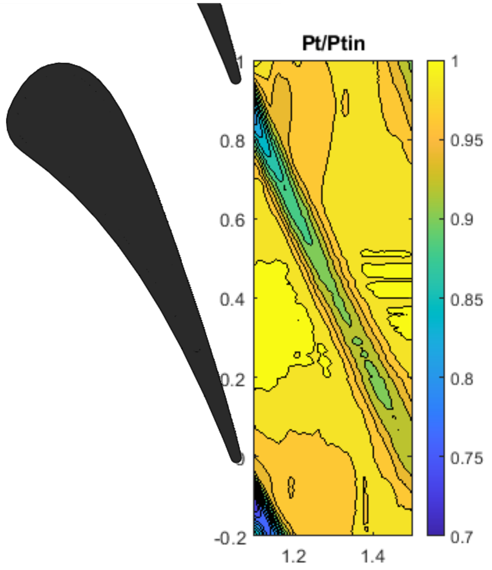
From measured velocity fields (PIV)

$$-\frac{\partial \bar{p}}{\partial x_i} = \rho \boxed{\bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j}} + \rho \boxed{\frac{\partial \overline{u_i' u_j'}}{\partial x_j}} - \mu \boxed{\frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j}}$$

Measured velocity fields

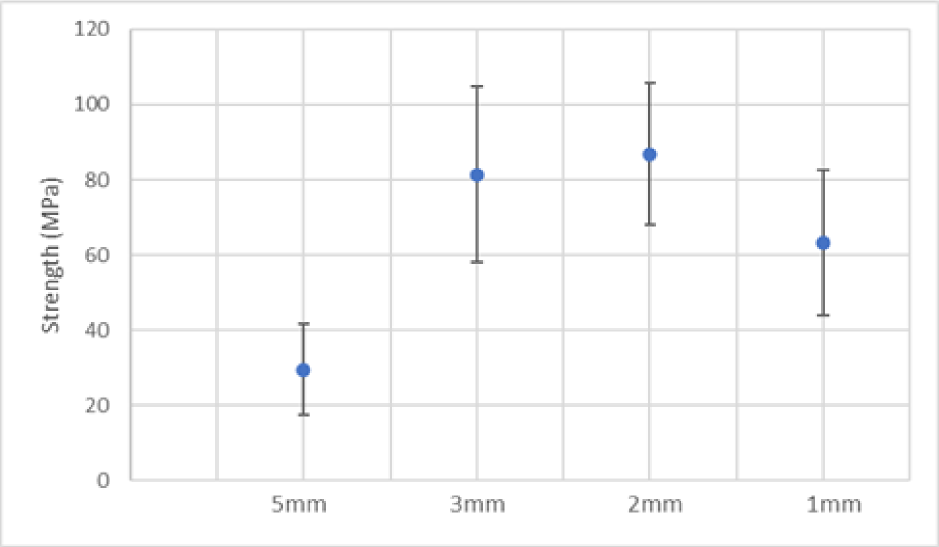


Total pressure field



Task 2.2: Parametric studies are being conducted on the original pre-ceramic resin formulation ("EA Resin") to attempt to optimize ceramic yield and reduce shrinkage

Strength vs wall thickness



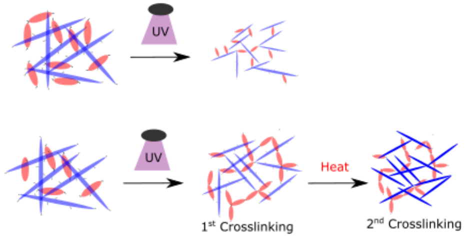
PEGDA/VMS ratio variation

EA Resin	Wt%
PEGDA	49.5
VMS	49.5
Photo-Initiator	0.3
Free Radical Scavenger	0.7

Self-crosslinking with thermal post-cure

Type II

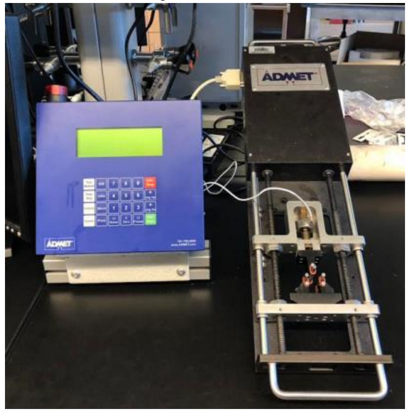
Type III



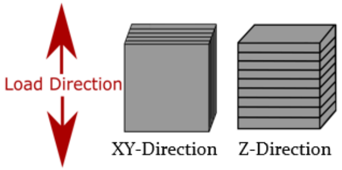
Task 2.2: The impact of layer thickness and orientation on strength is being tested for both the pre-ceramic polymer and the pyrolyzed material

MTS Servo-Hydraulic Load-frame

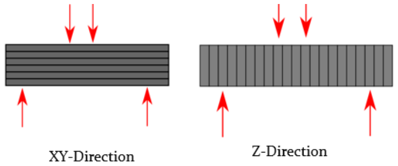
ADMET Micro four point bend



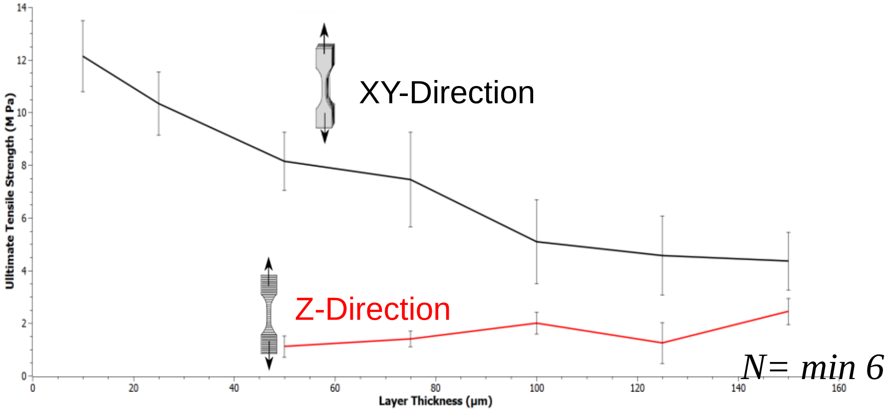
Pre-ceramic polymer characterization

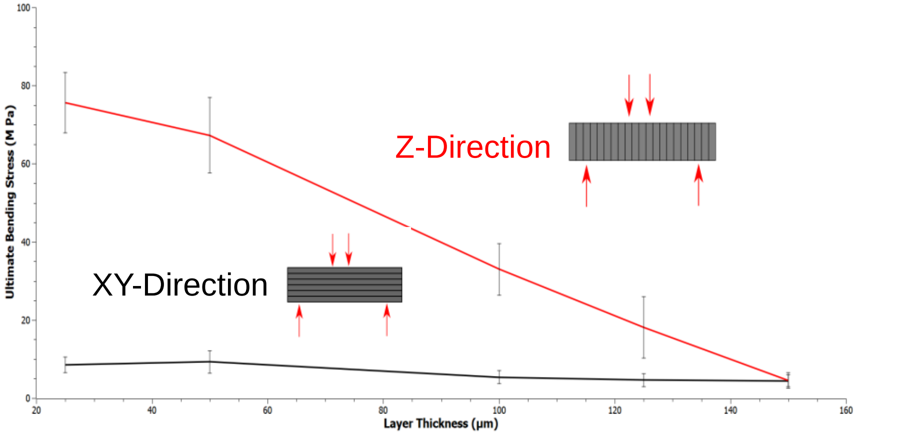


Ceramic characterization



Strength testing, indicating anisotropic properties that vary with layer thickness

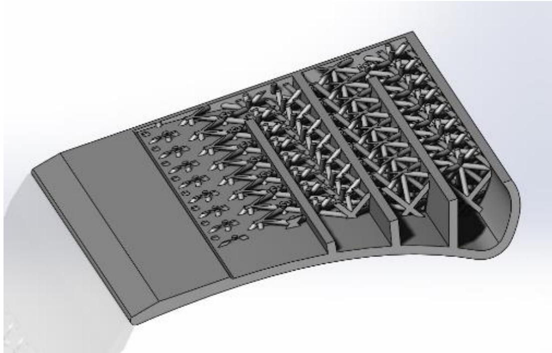




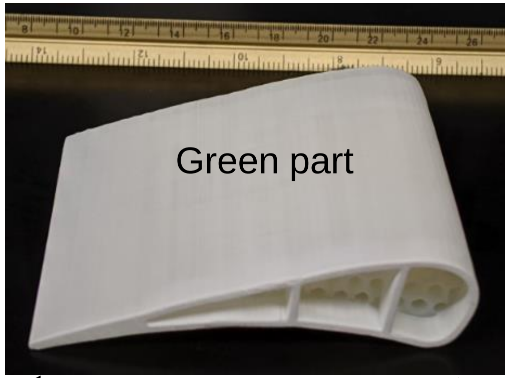
N= min 12

Task 2.2: We have investigated structure design for best resolution and limited cracking, with some constraints on achievable post-pyrolysis size due to high shrinkage

Octet lattice design



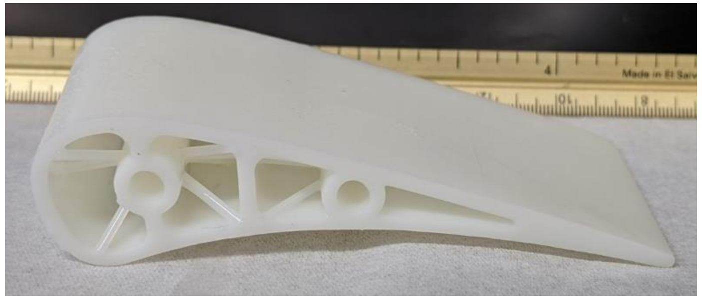
Honeycomb design

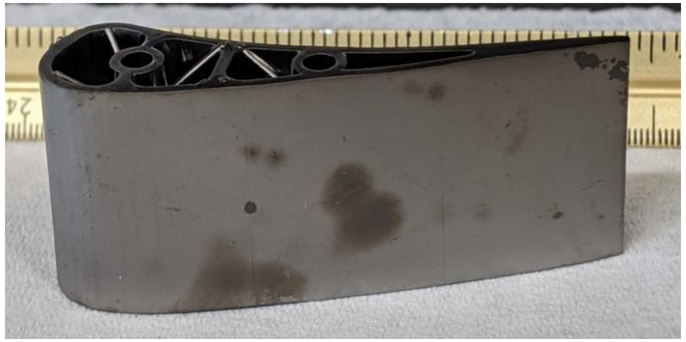


~13 cm

~6.5 cm

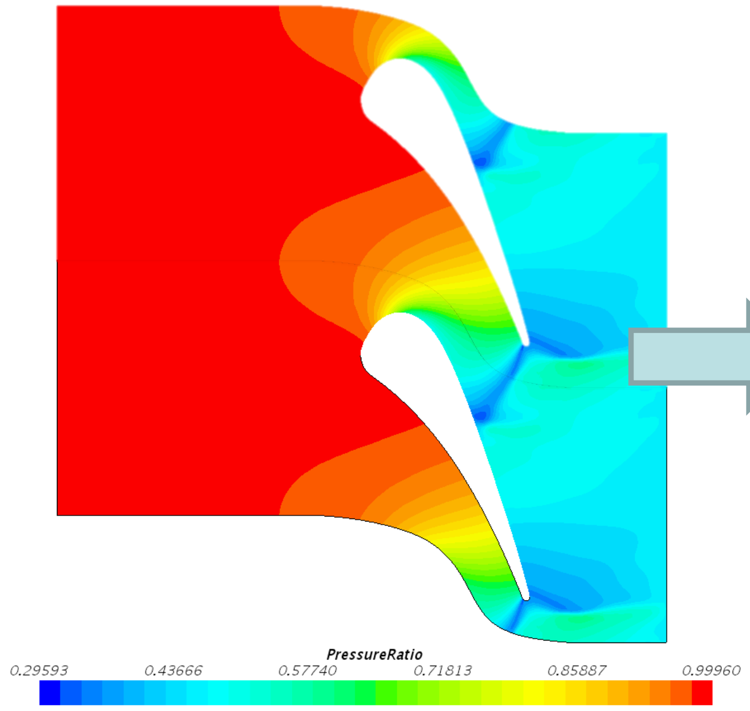
CMC sandwich design



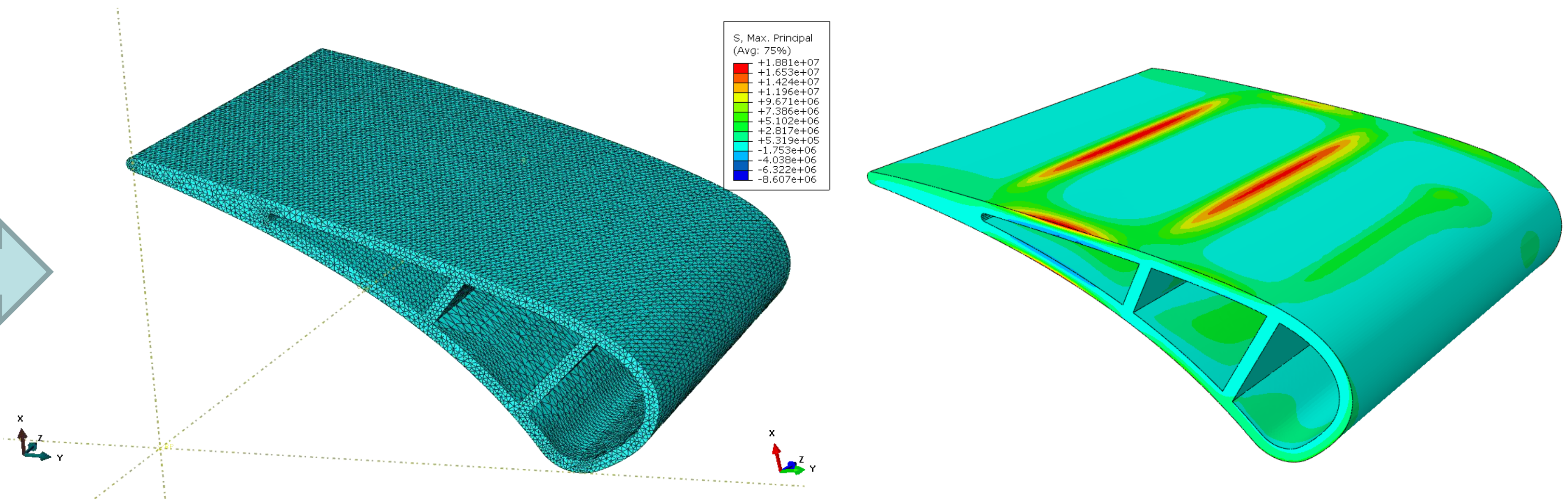


Task 3.1: Estimates of internal coolant forces and external aerodynamic forces were applied to FEA models of the airfoil, using early mechanical properties that need to be refined

External pressure from CFD

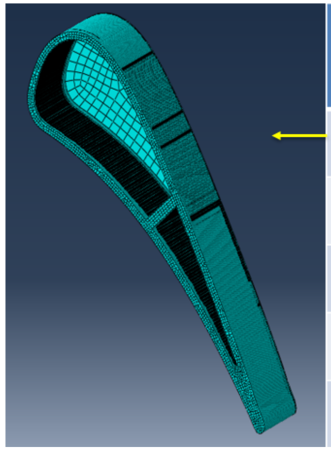


FEA modeling showing stress concentration areas

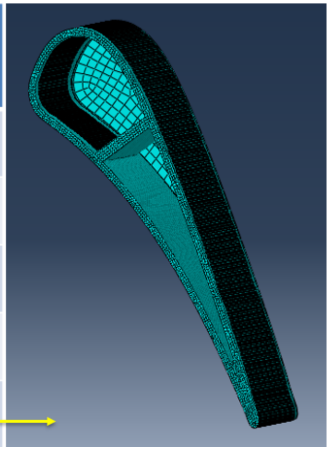


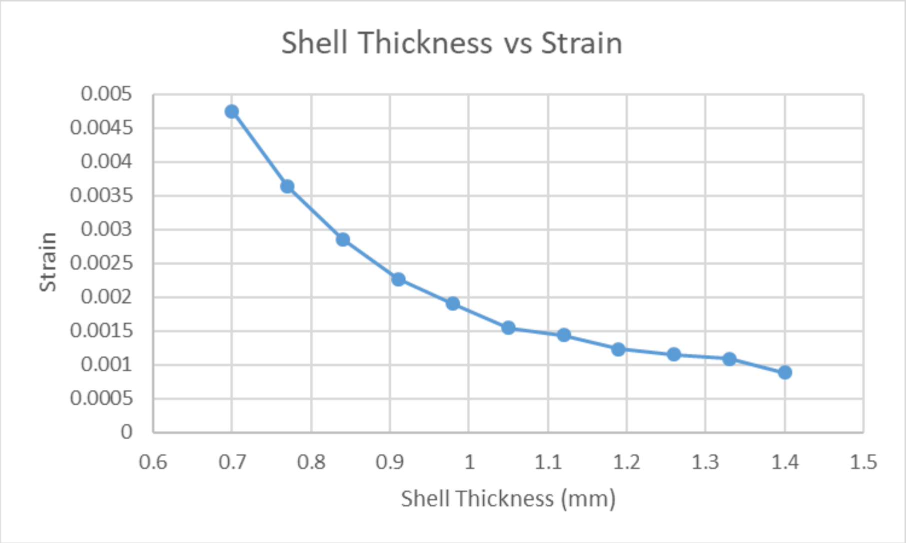
Modulus	52.8 GPa	± 1.87 GPa
Failure Stress (4pt Bend)	54.15 MPa	± 5.51 MPa
Displacement at Failure	145 μm	± 19 μm
Failure Strain (FS/Modulus)	0.0103	

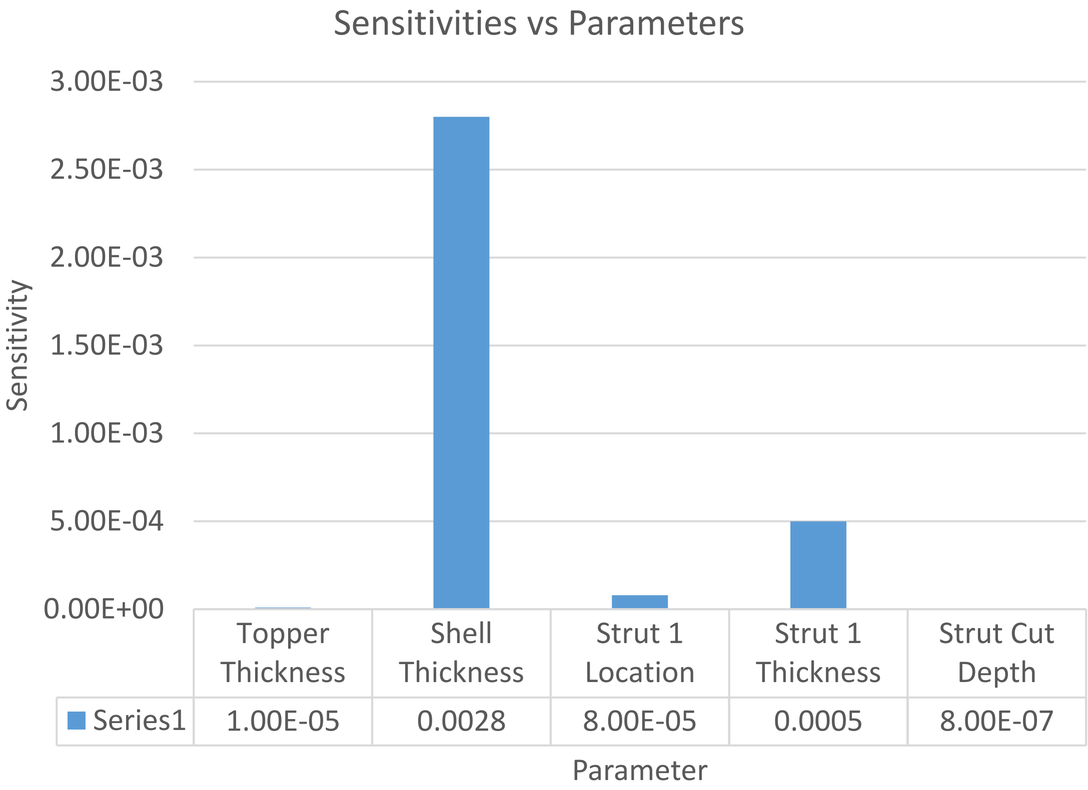
Task 3.1: Parametric studies are being conducted on the vane internal structure to guide design choices and determine sensitivities



Shell Thickness	Strut Location	Maximum Strain
0.7	20	0.003983
0.8	17.5	0.003211
0.9	16.5	0.002788
1.0	15.5	00.00243
1.1	12	0.002133







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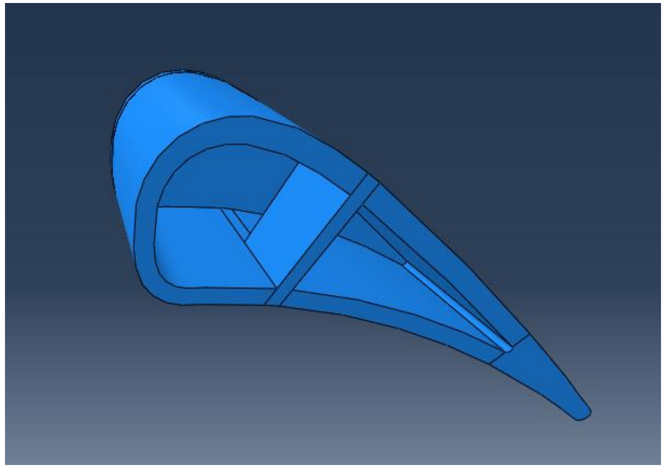
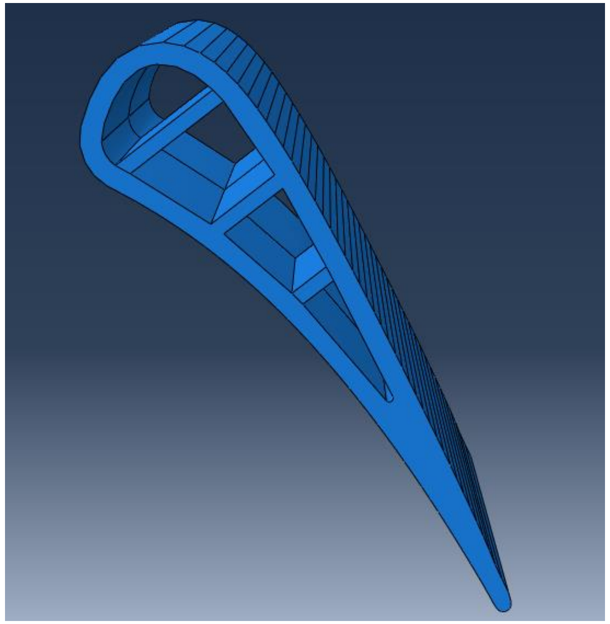
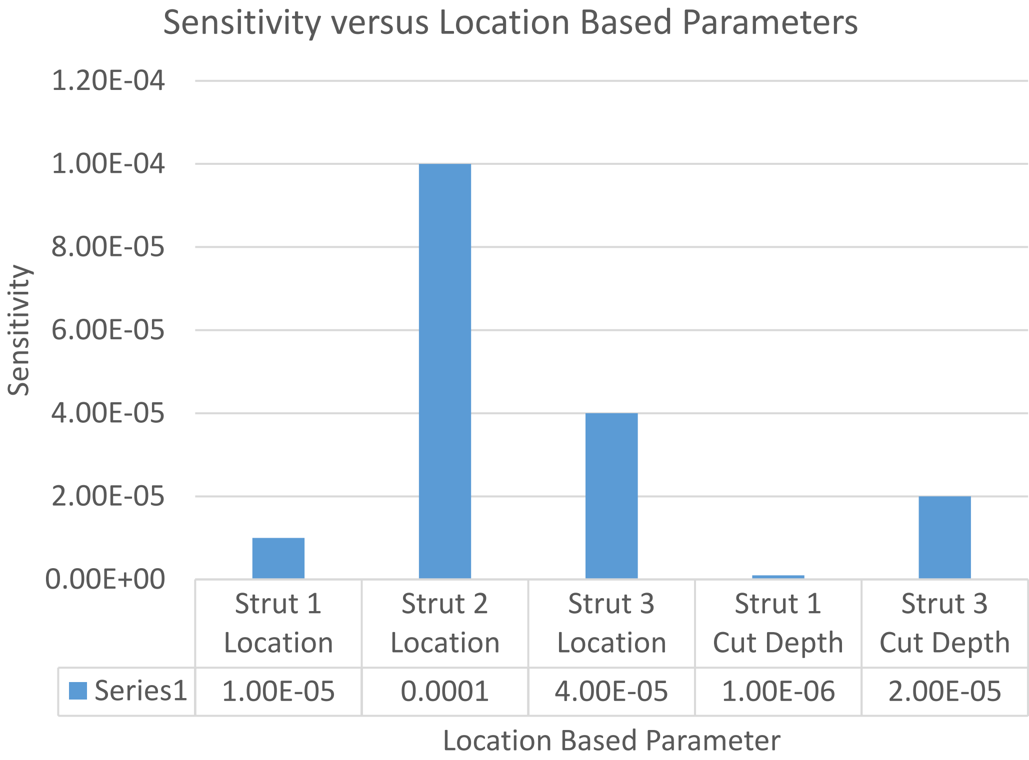
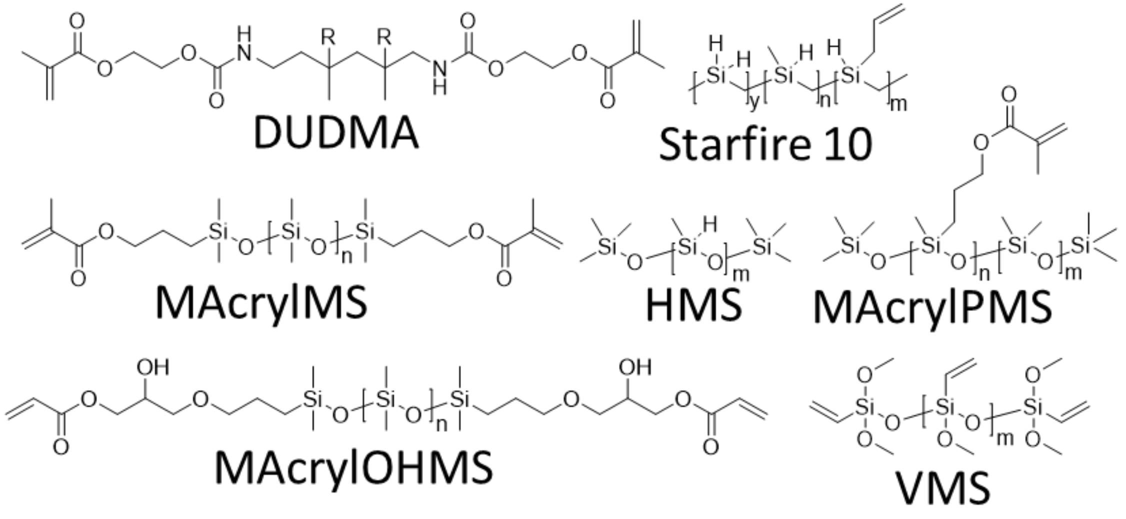


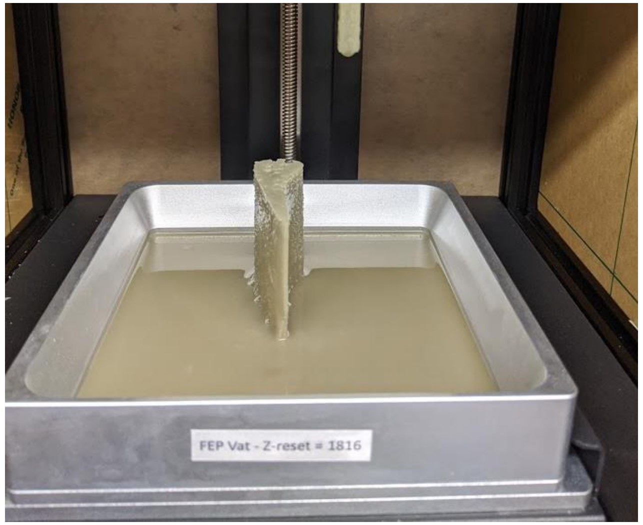




Task 4.1: Several new resin formulations were developed using acrylate siloxanes (SiOC) to attempt to increase ceramic yield and decrease shrinkage

Resin 10	wt%	**Resin 16**	wt%	**Resin 28**	wt%
VMS	38.6	VMS	35.71	Starfire 10	50
MAcrylPMS	40	HMS	35.71	DUDMA	25
AcrylOHMS	20	AcrylOHMS	27.45	PPGGDMA	25
PhTrimPO	1	PhTrimPO	0.26	PhTrimPO	0.3
TMTBOHB	0.3	TiCp2Cl2	0.04	TMTBOHB	0.7
Sic whiskers	0.1	SiC Whisker	0.82	TiCp2Cl2	0.195
Average shrinkage	***26.1***	***Average shrinkage***	***25.2***	***Average shrinkage***	***23.2***
Ceramic yield	***39.7***	***Ceramic yield***	**48.4**	***Ceramic yield***	***48.3***

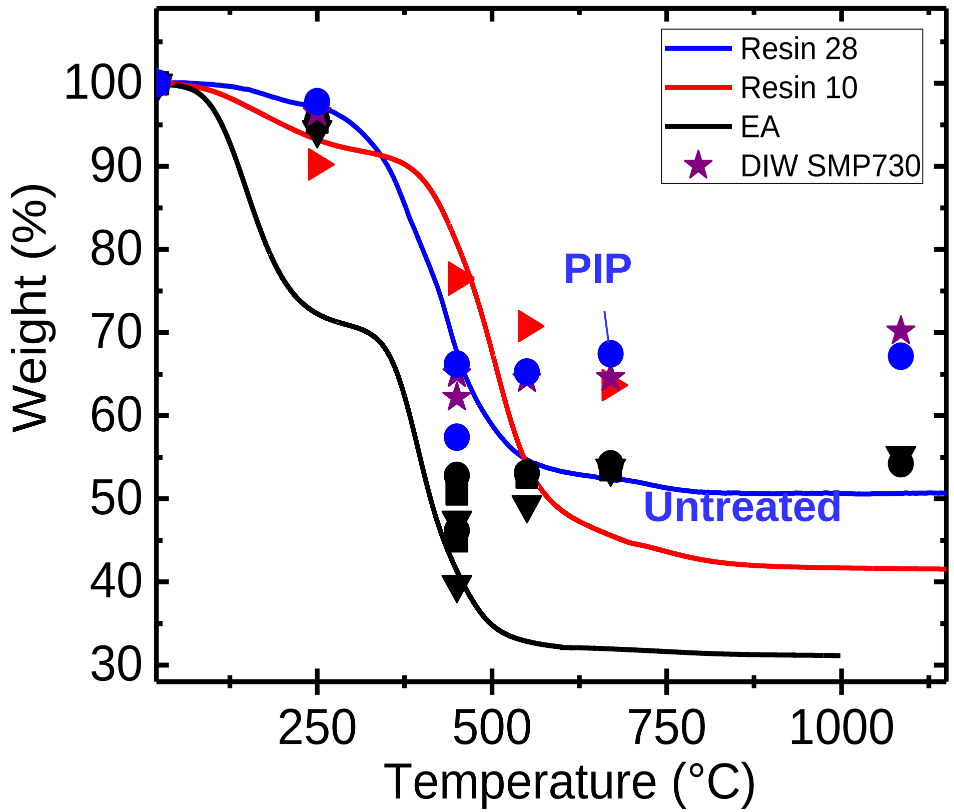




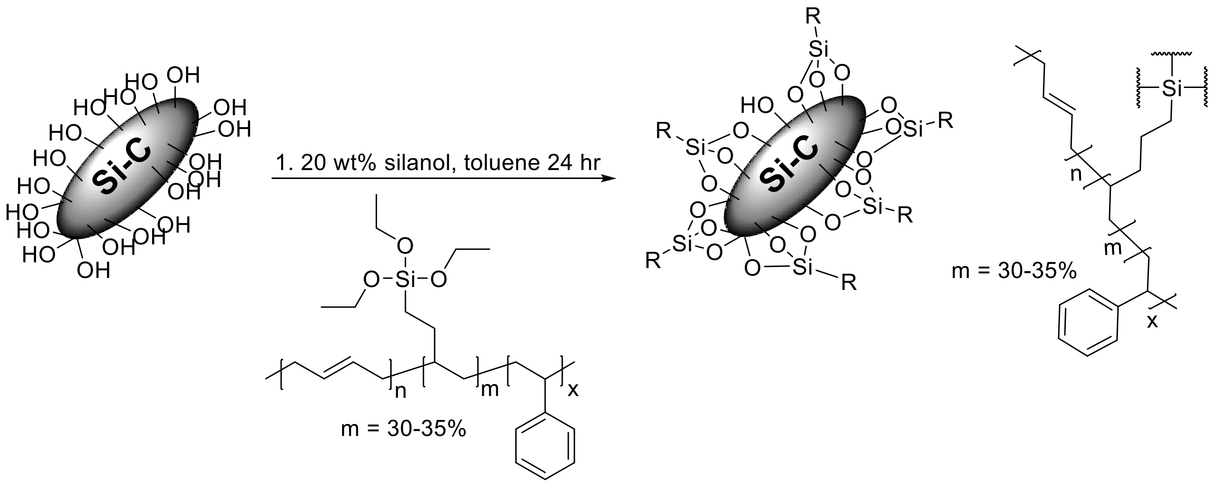
Task 4.1: Extra processing steps are being investigated to increase ceramic yield, including thermal annealing (secondary cross-linking) and polymer infiltration processing (PIP)

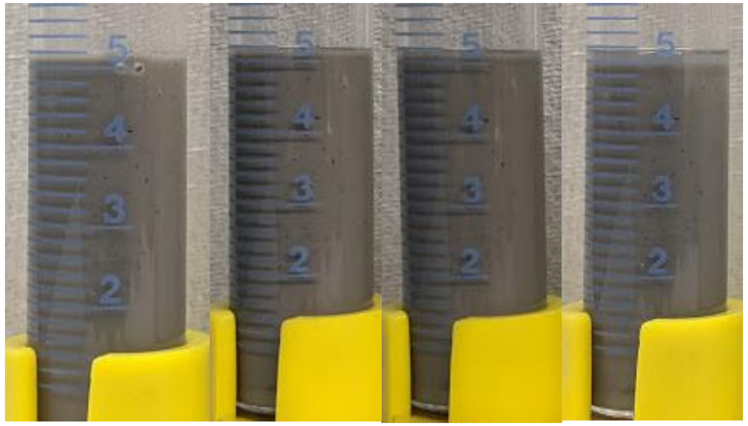
Moai 130: Heated curing chamber

Thermogravimetric analysis with PIP



Task 4.1: Decorated SiC nanoparticles can remain indefinitely suspended in resin but impact optical density; much higher particle loading is being investigated in polysilazanes (SiN)



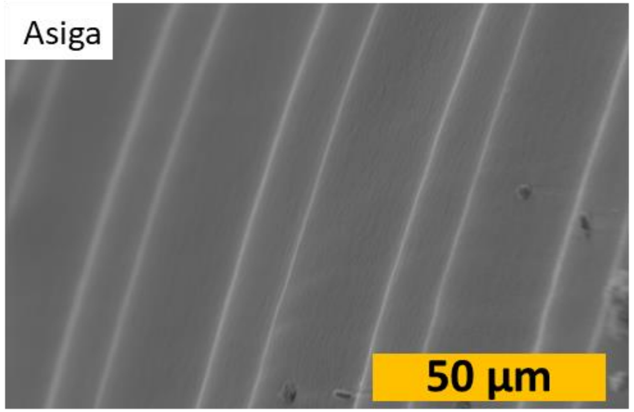


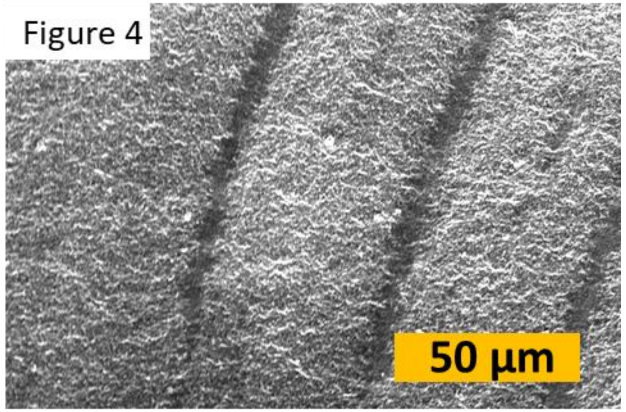
0 min 60 min 100 min 24 hr

Resin 10	wt%	Resin 28	wt%	EA Resin	wt%	Durazane Resin	wt%
VMS	38.6	Starfire SMP-10	50	Gelest VMM-010	49.5	Merck durazane 1800	65.0
MAcrylPMS	40	DUDMA	24.5			DUDMA	21.7
AcrylOHMS	20	PPGDMA	24.5	PEGDA	49.5		
PhTrimPO	1	PhTrimPO	0.3	PhTrimPO	0.3	PhTrimPO	0.3
TMTBOHB	0.3	TMTBOHB	0.7	TMTBOHB	0.7	TMTBOHB	0.8
SiC whiskers	0.1					20nm Si_3N_4 particles	4.3
Average shrinkage	**30.3 (±4.7)**	**Average shrinkage**	**25.6 (±1.8)**	**Average shrinkage**	**33.6 (±4.2)**	**Average shrinkage**	**34.8**
Ceramic yield	**40.9 (±1.1)**	**Ceramic yield**	**51.4 (±2.6)**	**Ceramic yield**	**34.6 (±4.9)**	**Ceramic yield**	**49.3**
Ceramic composition	Not measured	Ceramic composition	$Si_1N_{0.07}C_{1.5}O_{1.2}$	Ceramic composition	$Si_1C_{6.5}O_{1.1}$	Ceramic composition	Awaiting results

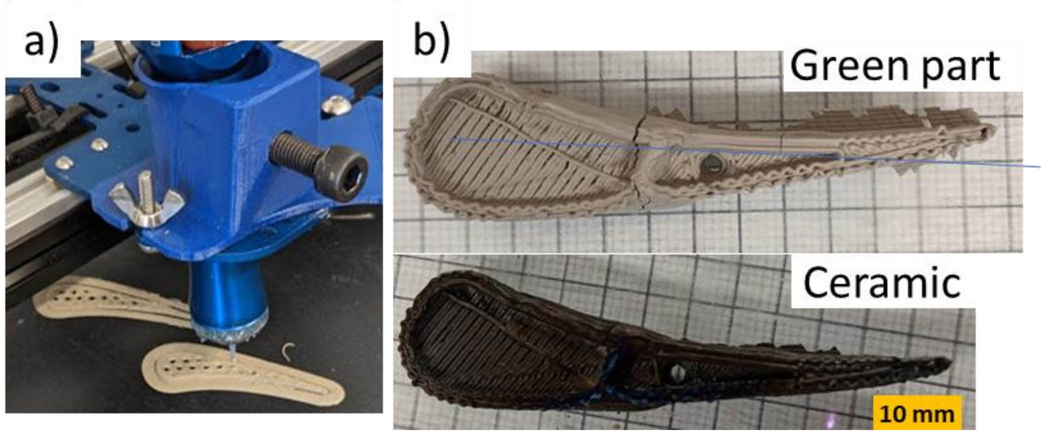
Task 4.1: Investigations are also being conducted on alternate manufacturing methods, including Direct Ink Writing with extremely low shrinkage but reduced resolution

Continuous Liquid Phase





Direct Ink Writing



Resin 54	wt%
SiC (micron)	72.0
SMP-877	22.5
$TiCp_2Cl_2$	0.04
chloroform	5.4

Average shrinkage	5%
Ceramic yield	98.2%

Our tasks over the next year will be to test an initial airfoil design, develop the topology optimization tools and PDC chemistries, and produce a revised design by next year end

Task 2 (PSU):

- Incorporate cooled airfoil and measure surface temperature (IR) and aero performance (PIV)
- Co-develop new cooling designs with UWYO

Task 2 (UWYO):

- Produce first test airfoil part
- Characterize material properties
- Co-develop new cooling designs with PSU

Task 3 (UWYO):

- Refine structural topology optimization code for internal supports
- Start developing thermal topology optimization tool

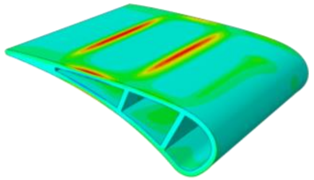
Task 4 (PSU):

- Continue to investigate methods for high particle/whisker loading and long term suspension
- Explore interlayer linking processes (thermal post-processing?) to improve part strength

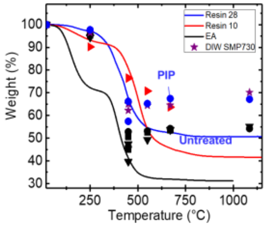
Color key: process engineering, material development, modeling, validation of cooling technologies

In conclusion, we have capability to print and test articles but have more work on increasing ceramic yield and particle loading, as well as design of optimal shapes

Test prints show good control of internal features with proper support



Novel design tools for shape optimization are being built



High ceramic yield and particle loading are being systematically investigated

High speed cascade test facility is benchmarked and ready for tests

Questions?

Appendix

We expect financial and schedule risks will be easily manageable with outlined research plan

Perceived Risk	Risk Rating (Low, Med, High)			Mitigation/Response Strategy
	Probability	Impact	Overall	
Financial Risks:				
High cost for polymer precursor materials (Task 2, 4, 5, 6)	Low	Med	Low	Fewer extra test parts will be produced and materials will be conserved.
Cost of vane test hardware is high (Tasks 2.3, 5.3, 6.2)	Low	Low	Low	Fewer extra test parts will be produced, or will be sourced through lower-cost vendors.
Schedule Risks:				
Unable to schedule time in transonic testing facility (Tasks 2.3, 5.3, 6.2)	Low	Low	Low	There is plenty of buffer in schedule to account for conflicts with other facility users
Shape optimization tool development takes longer than planned (Task 3.1-3.3)	Low	Low	Low	Existing structural optimizers can be used as a backup, or a design can be developed manually and model can be validated with that design.
Novel SiC precursor material development takes longer than planned (Task 4.1)	Med	Low	Low	Intermediate precursor recipes can be provided early to build expertise.

There are some technical risks for this low-TRL project but high payoff if the technology is successful

Perceived Risk	Risk Rating (Low, Med, High)			Mitigation/Response Strategy
	Probability	Impact	Overall	
Technical Risks:				
Unable to fabricate cooled SiOC CMC vane with large internal cavity (Task 2.2)	Low	Med	Med	UWYO has fabricated turbine-like test parts previously, but if thin walls are an issue, can resort to thicker walls. If film cooling is a problem, can be removed from design without impact to technical goals.
Unable to integrate new SiC material into SLA process (Task 5.1)	Low	Med	Med	3D printable variants of the SiC precursor formula would be investigated although may not have the same desired material capabilities of SiC.
Unable to fabricate optimized vane shape using SiC/SiC (Task 6.1)	Med	Low	Low	This risk is avoided early by creating intermediate test prints as novel designs are developed, so that final design fits within manufacturing constraints.
Management, Planning, and Oversight Risks:				
None				Organizational team is collaborative and all PI's have management experience.
ES&H Risks:				
None				Co-PI's have expertise and facilities to handle volatile chemicals and hot furnace objects.
External Factor Risks:				
None identified				