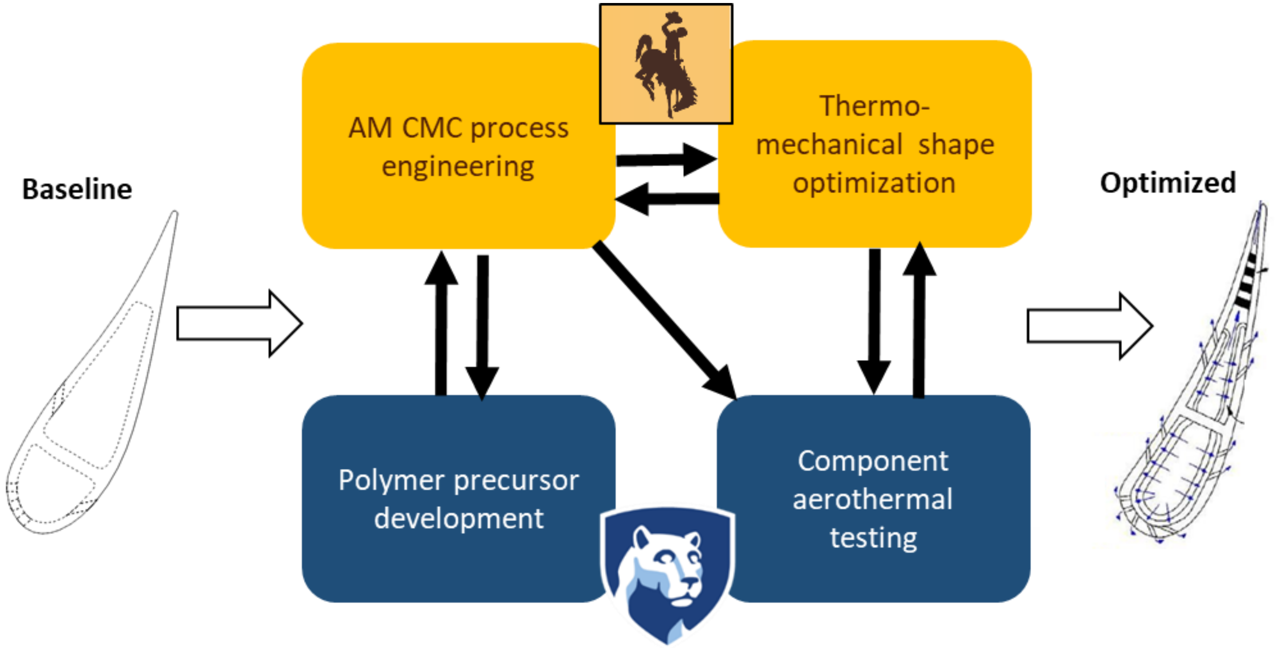
Development of Additive Manufacturing for Ceramic Matrix Composite Vanes



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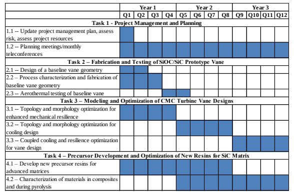
Project: DE-FE0031758

This review covers the motivation, project plan, and Year 2 progress on our UTSR-supported project

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

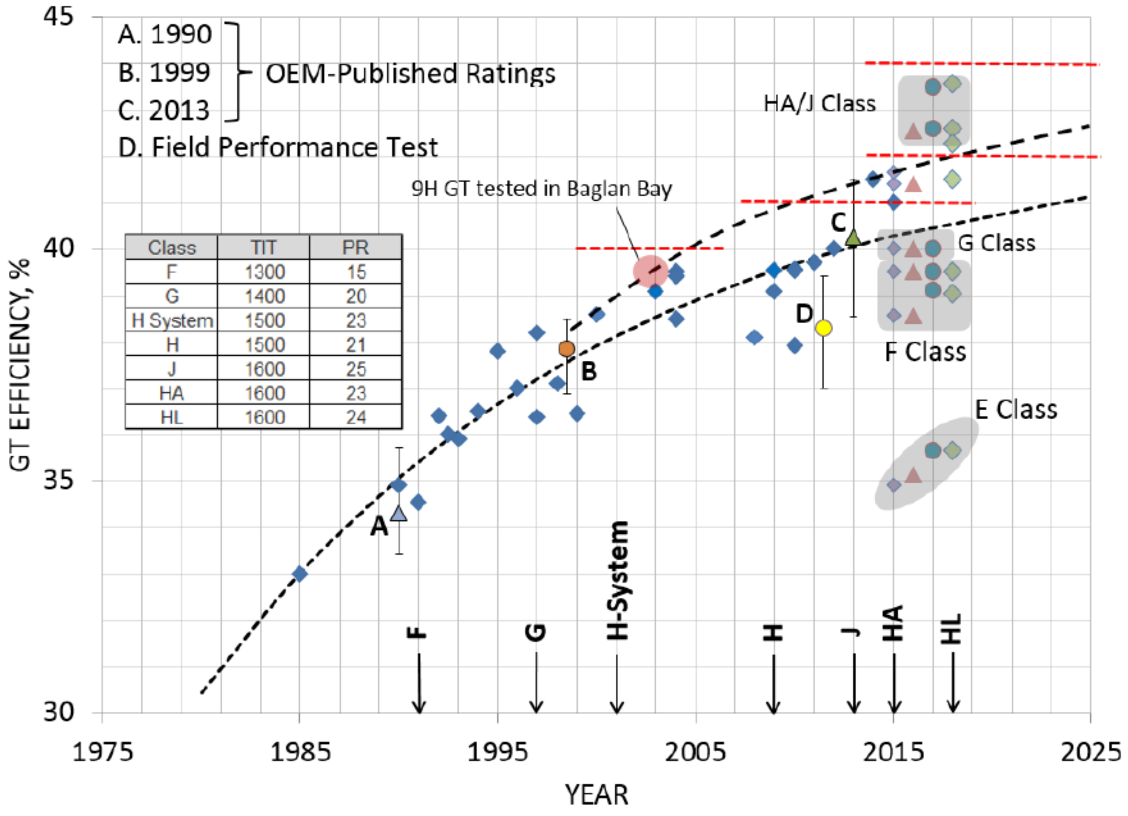
Approach: push polymer-derived ceramics development through additive manufacturing engineering, polymer science, part design, and performance verification



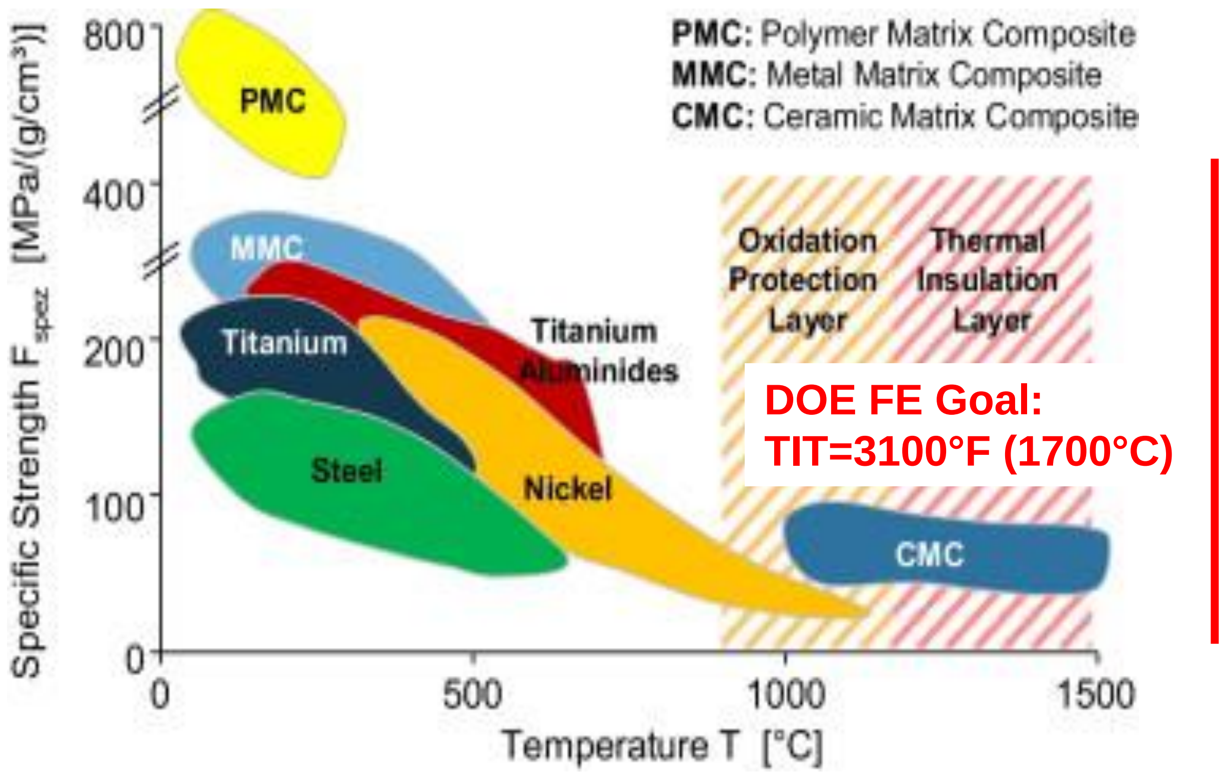
Project plan: execute simultaneous materials/design/process engineering to regularly produce vane test articles

Current progress

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



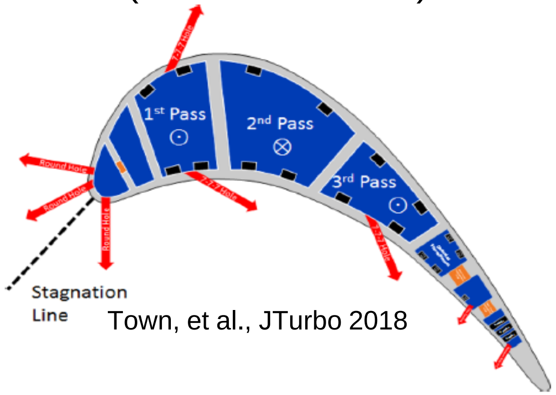
National Academies of Sciences, Engineering, and Medicine 2020. *Advanced Technologies for Gas Turbines*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25630.



Klocke, et al., CIRP Annals, 2014

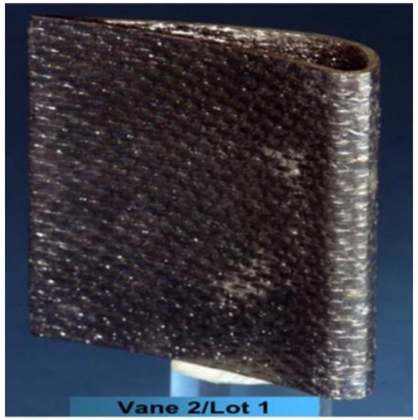
Highly effective cooling technologies used in superalloy cast parts are difficult to implement in conventional CMC’s

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

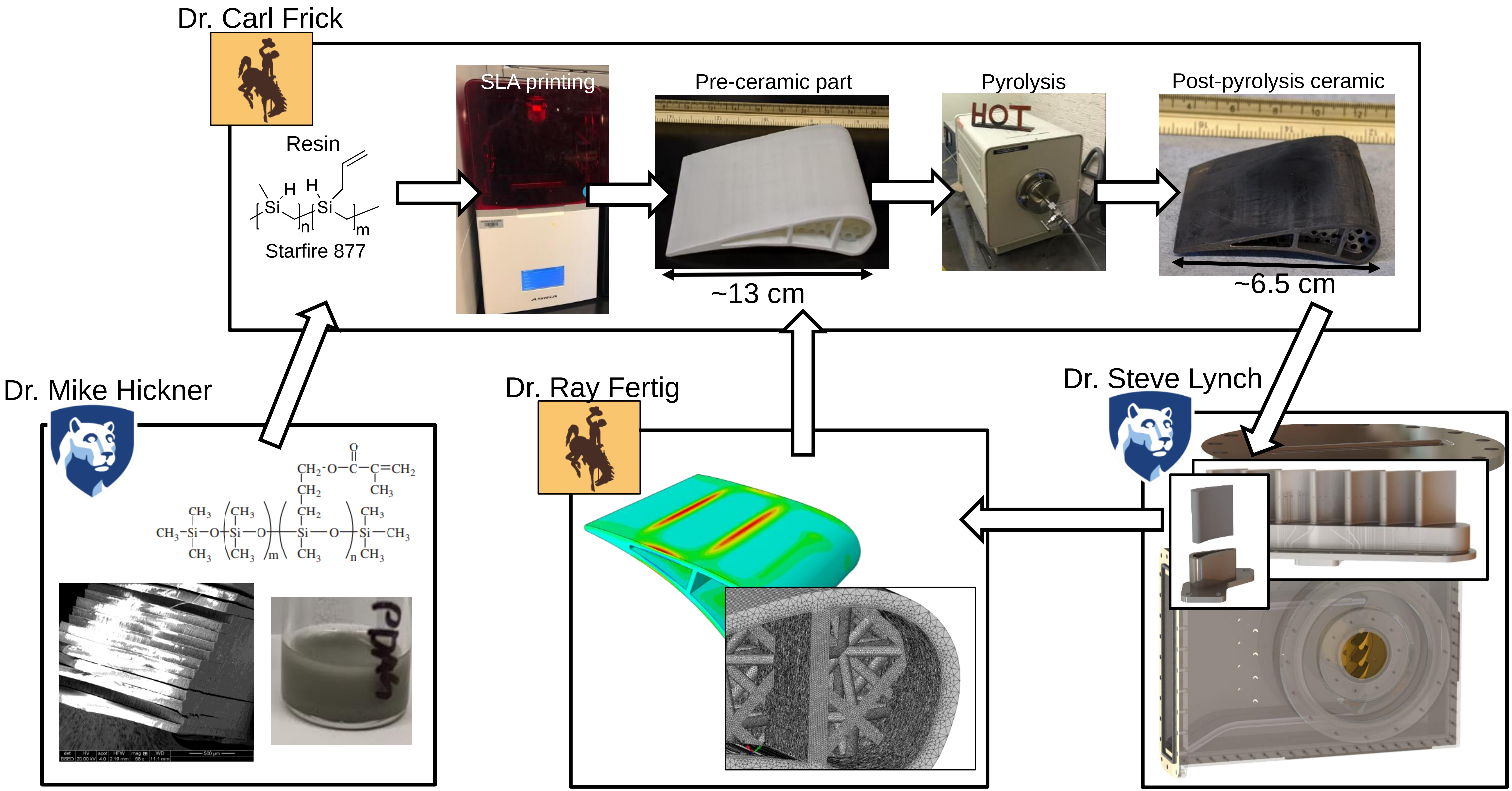
https://mdx.plm.automation.siemens.com

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 ceramic 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 ceramic turbine vane designs

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

Task 4: Development of new precursor chemistries

Success criteria: demonstrate that new precursors have equivalent or better material properties than baseline formulation

Task 5: Integrate new precursor chemistries into AM process

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

Task 6: Fabricate and test optimized vanes with new chemistries

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

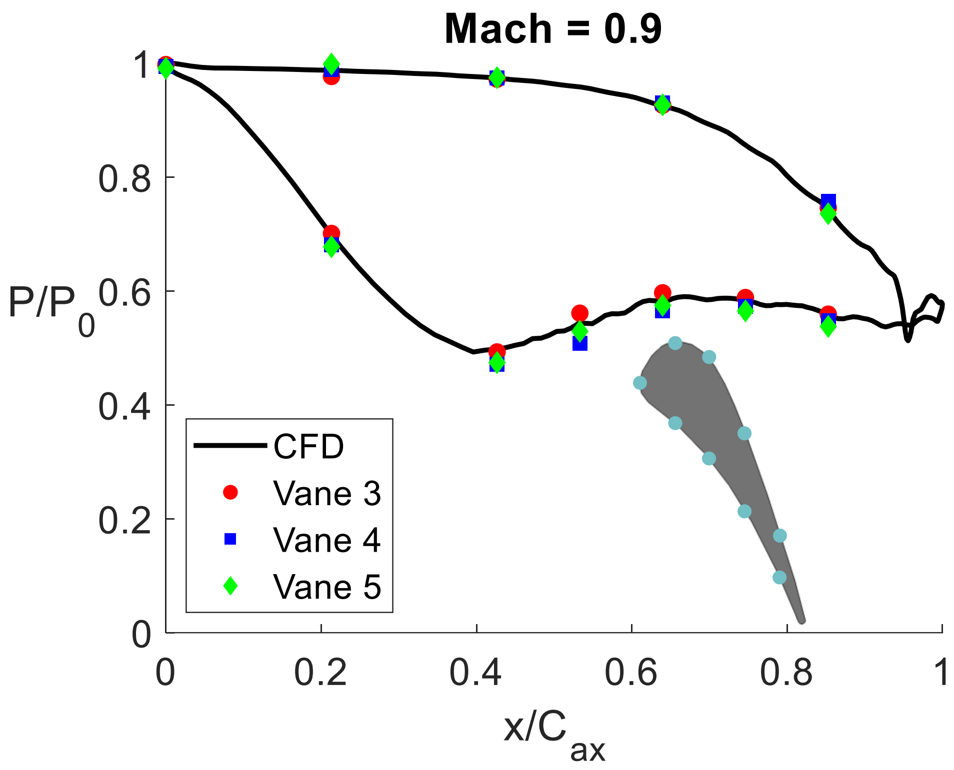
The project has several milestones that are being tracked for progress

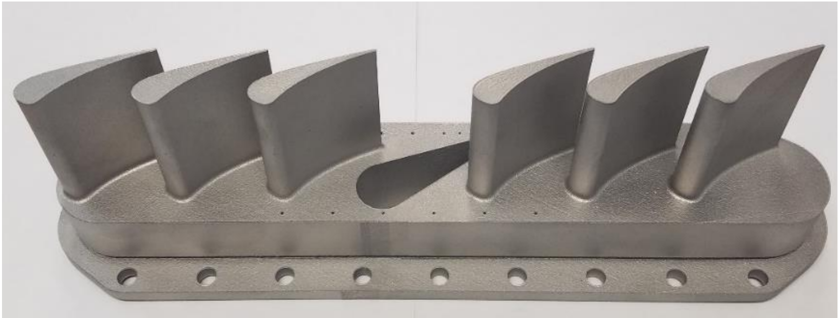
Task/ Subtask	Milestone Title & Description	Planned Completion	Actual Completion
2.1	M1: Baseline cooled vane design complete	Feb 2020	Feb 2020
2.2	M2: Fabrication of baseline cooled SiOC/SiC vane complete	Dec 2020	Dec 2020
3.1	M3: Topology optimization code for mechanical loading complete	Dec 2020	Dec 2020
4.1	M4: First generation SiC precursor chemistry delivered from PSU to UWYO	Dec 2020	Dec 2020
3.2	M5: Topology optimization code for thermal stress/cooling complete	Aug 2021	Oct 2021
4.2	M6: Detailed property characterization for SiC precursor complete	Aug 2021	Oct 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	

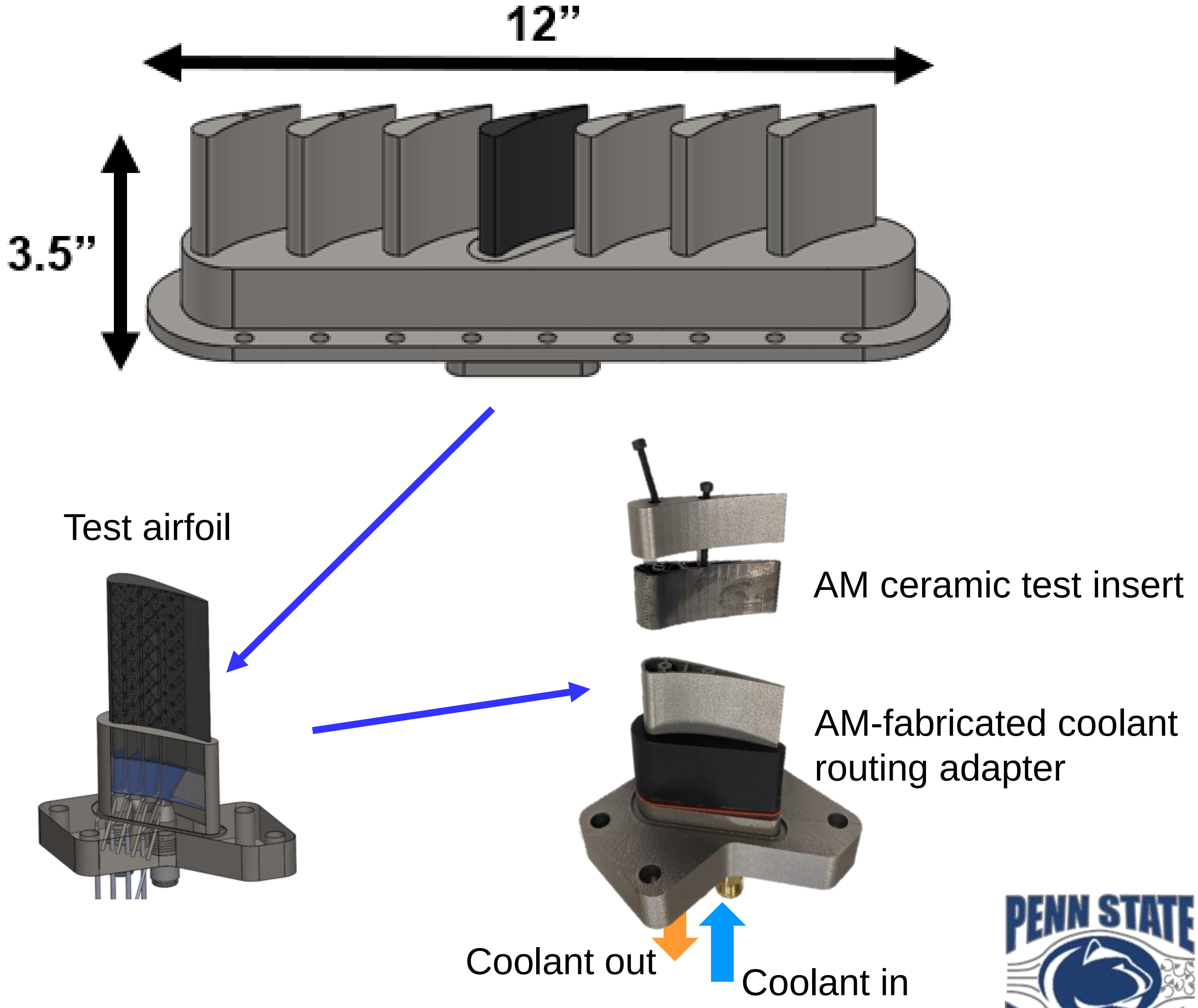
Shifted due to COVID

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

Task 2.1: A NASA C3X vane at 1X scale has been benchmarked in PSU's high speed cascade; a flexible design using AM allows for insertion of various cooled AM ceramic designs

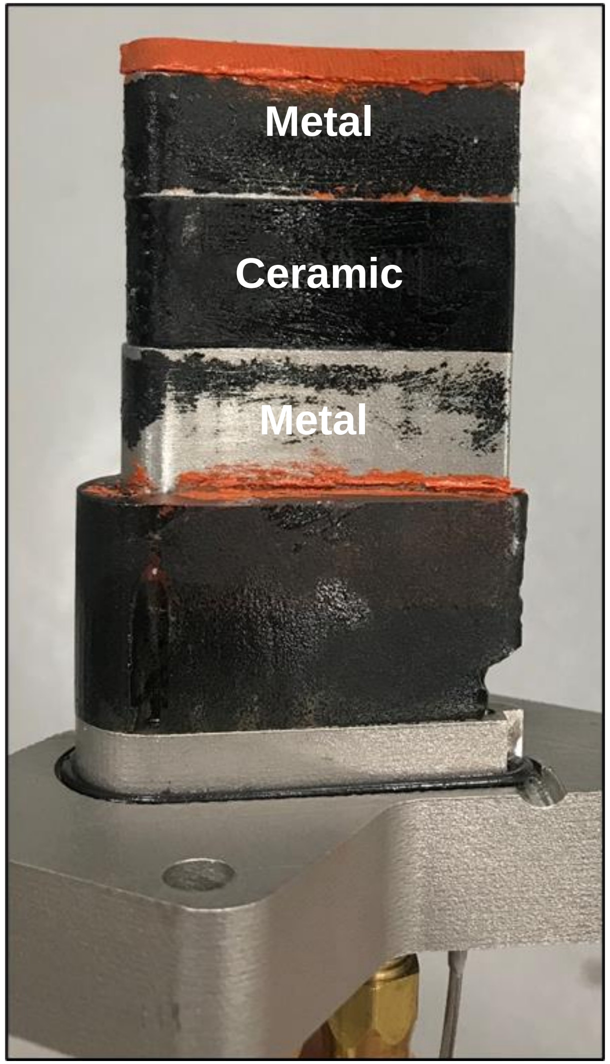






Task 2.1: Baseline ceramic airfoil designs have been constructed but we are having some difficulty with assembly due to slight distortion and stress concentrations in ceramic parts

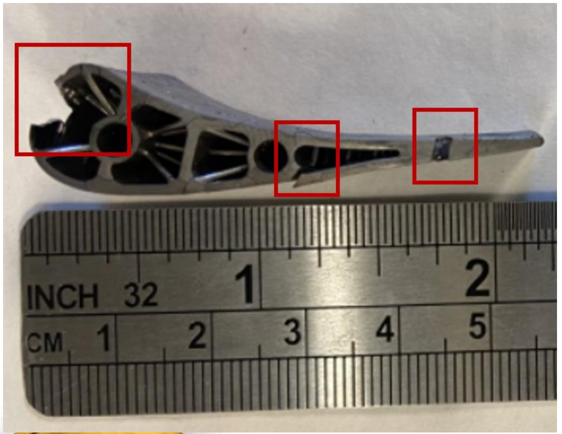
Baseline cooled airfoil design in SiOC



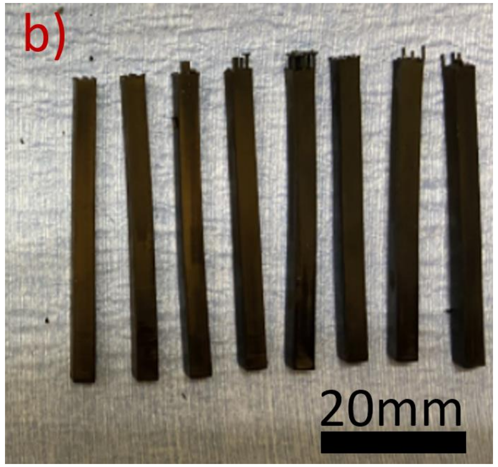
Leading edge cracking issues

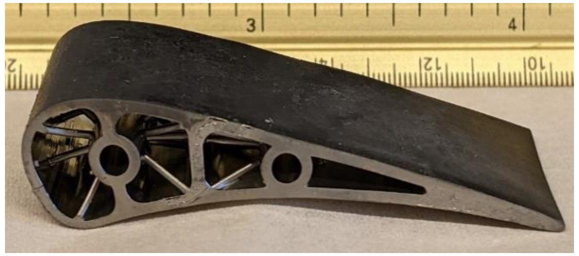
Task 2.2: Initial poor yield (<30%) with the original resin (Wyoming EA) was investigated and a new formulation was developed with significantly more success in the size range of interest

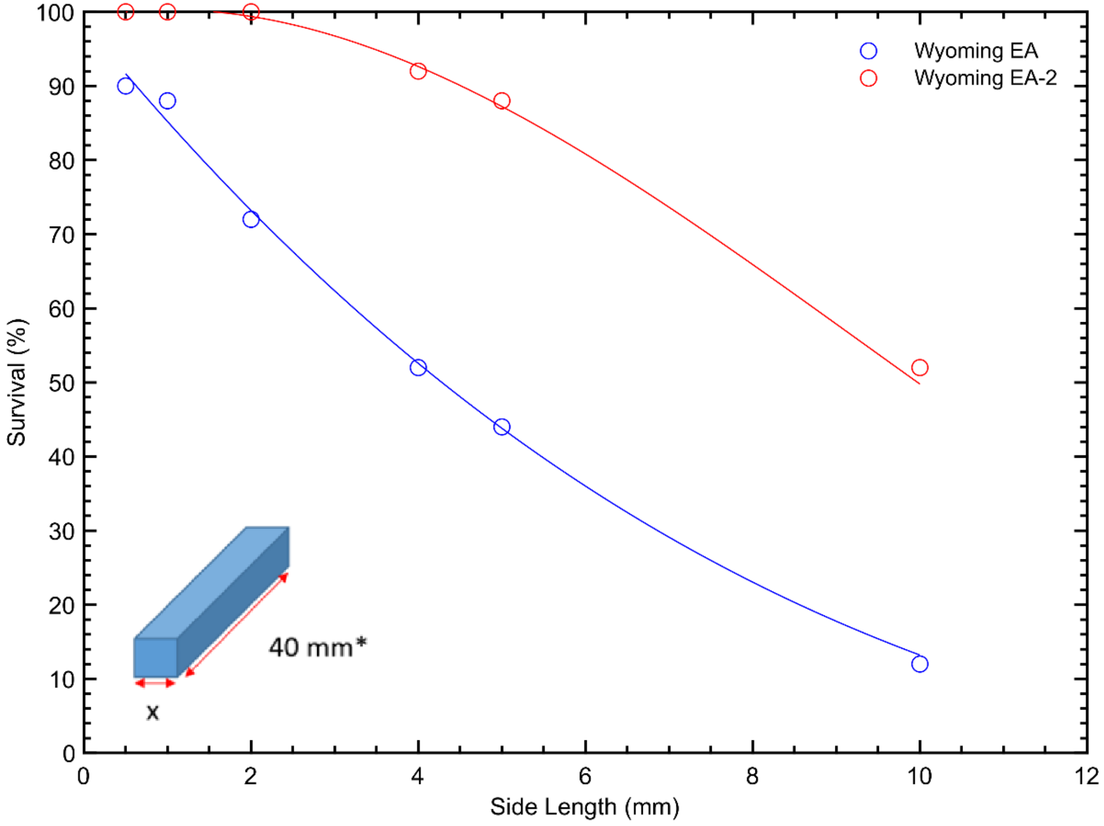
Prior formulation:
1:1 wt% VMS:PEGDA



New formulation:
3:2 wt% VMS:PEGDA







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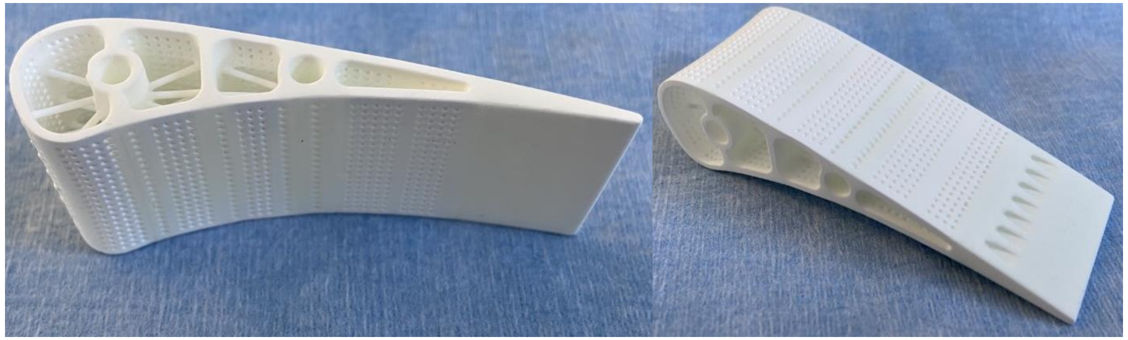
PENN STATE

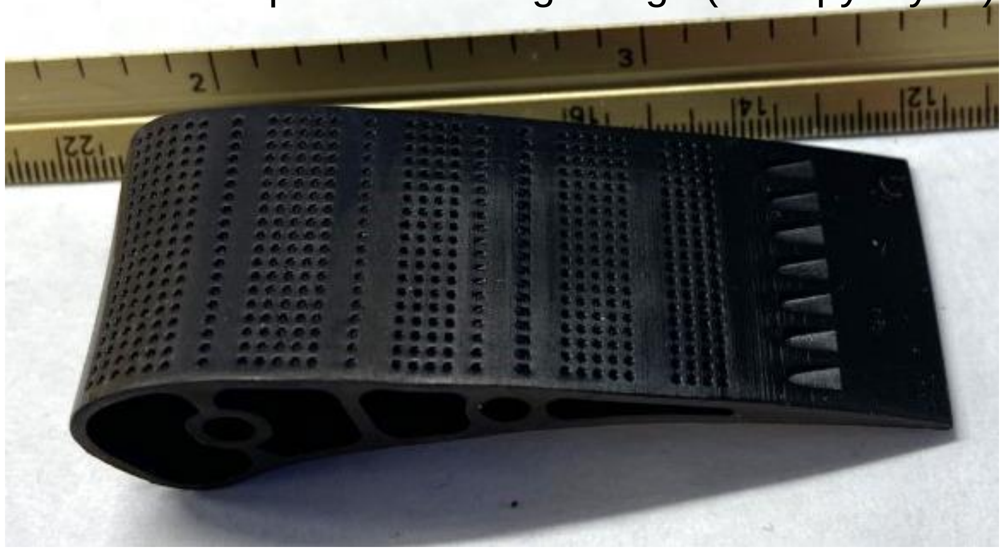
Task 2.2: Advanced cooling designs including shaped hole film cooling and transpiration cooling have been printed and have survived pyrolysis, but need to be tested

Good repeatability and survivability

Advanced transpiration cooling design (green bodies prior to pyrolysis)



Advanced transpiration cooling design (after pyrolysis)



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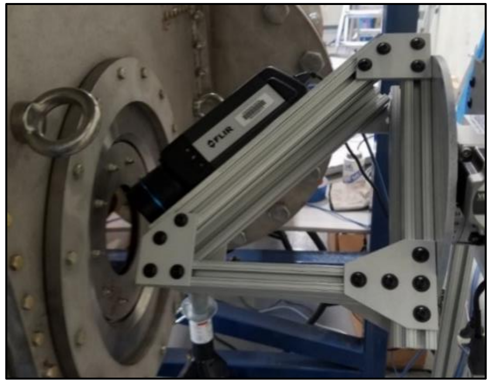
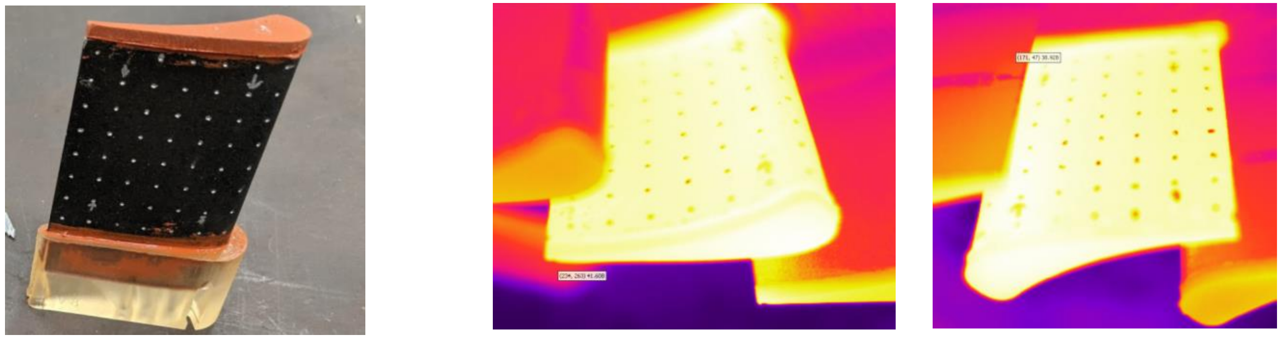
Task 2.1: We have developed in-situ infrared image spatial/temperature calibration for cooling performance, as well as novel total pressure measurement for aerodynamic performance

Infrared camera in facility



Calibration vane with spatial markers visible in IR

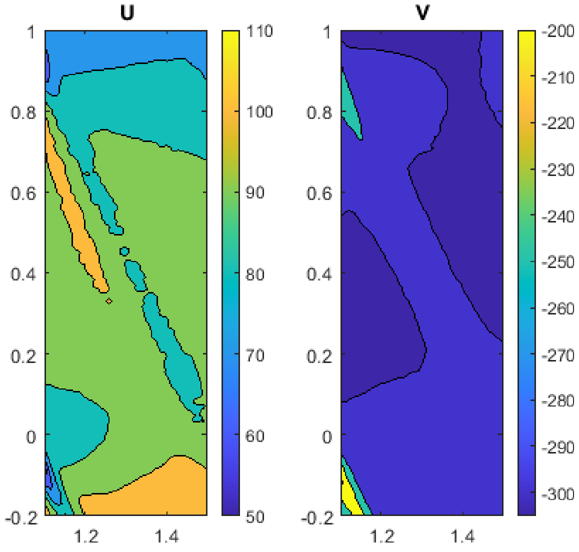


Momentum Equation

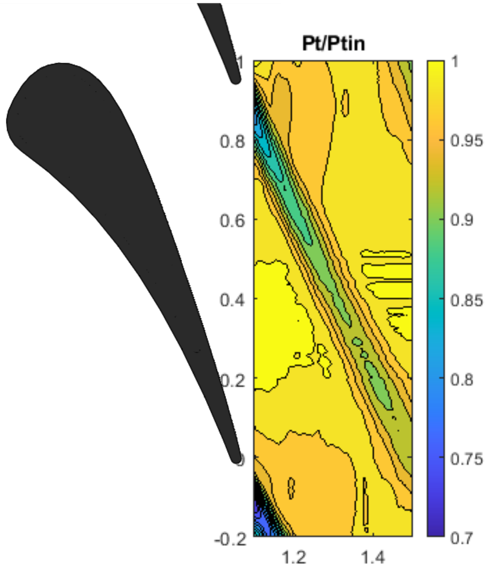
From measured velocity fields (PIV)

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

Measured velocity fields

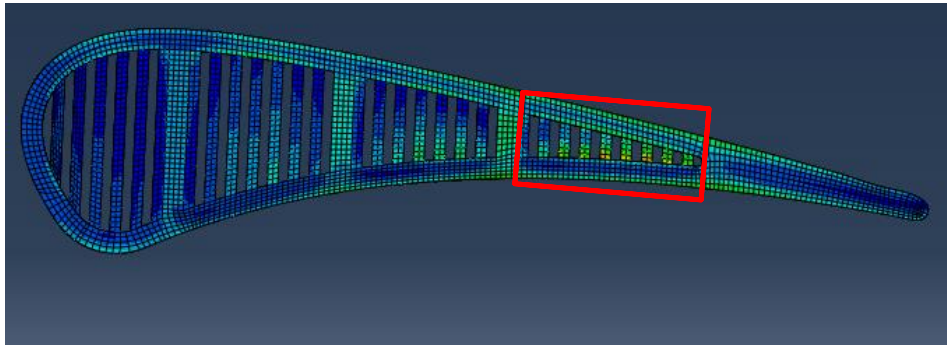


Total pressure field

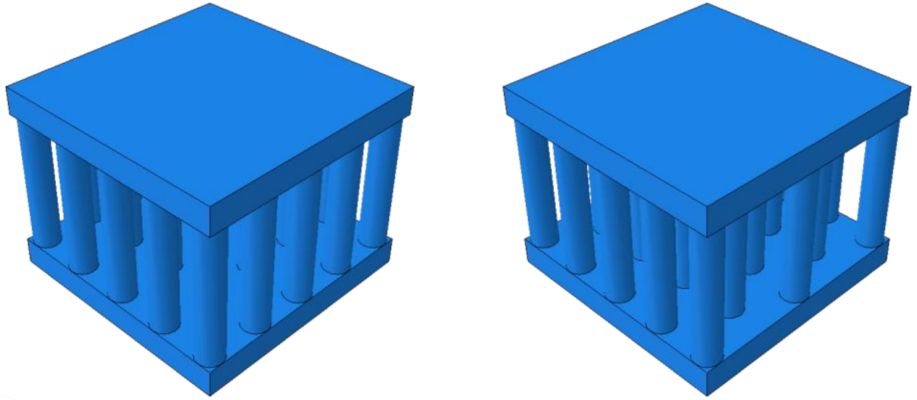


Task 3.2: Thermo-mechanical optimization of internal cooling and support structures is underway

Airfoil model with internal struts

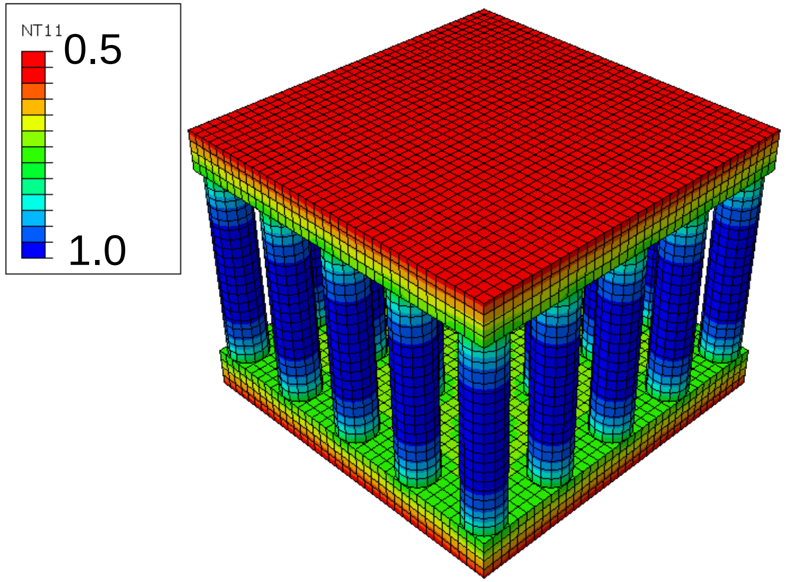


In-line versus staggered strut design



Cooling effectiveness of internal strut

$$\phi = \frac{T_\infty - T}{T_\infty - T_c}$$



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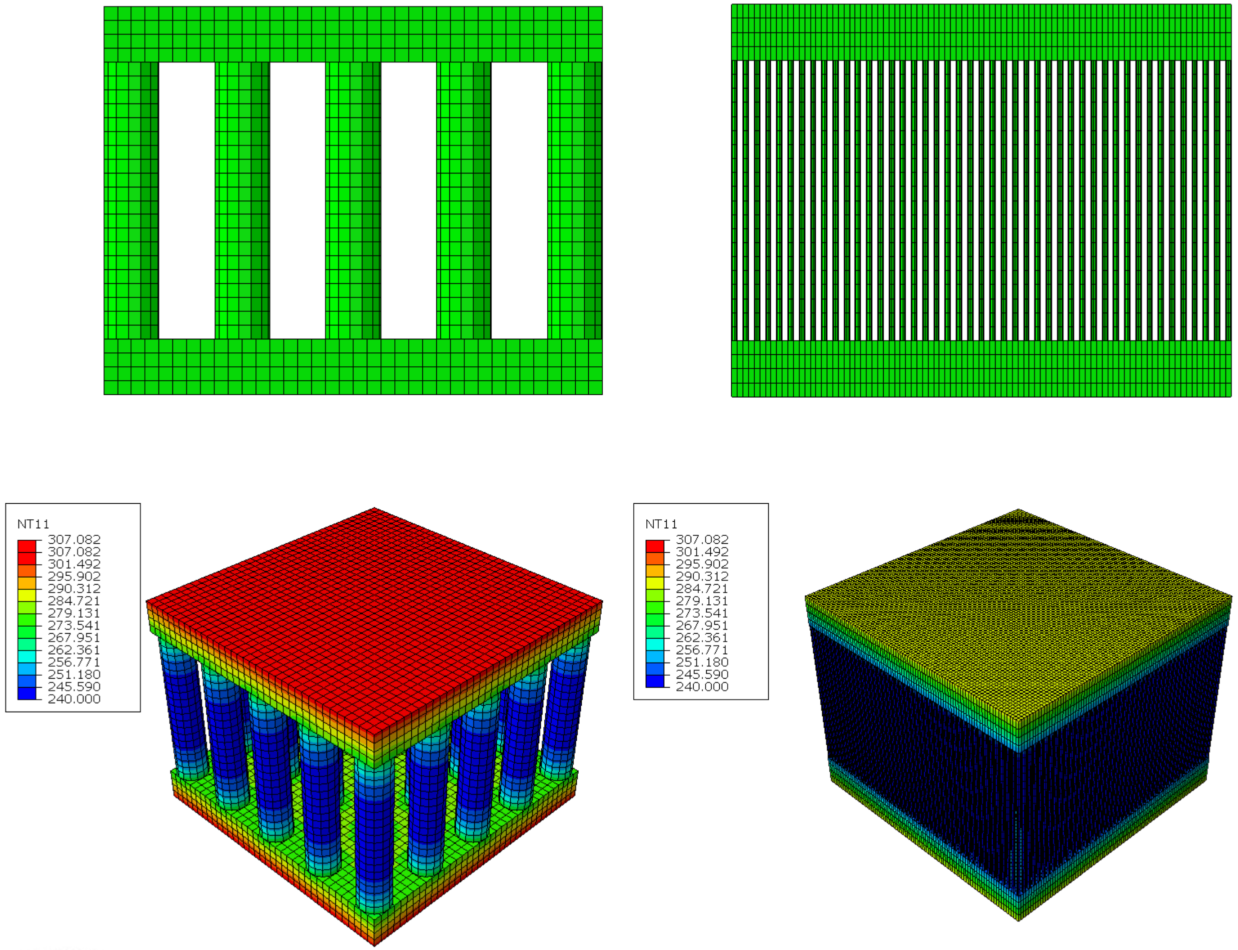
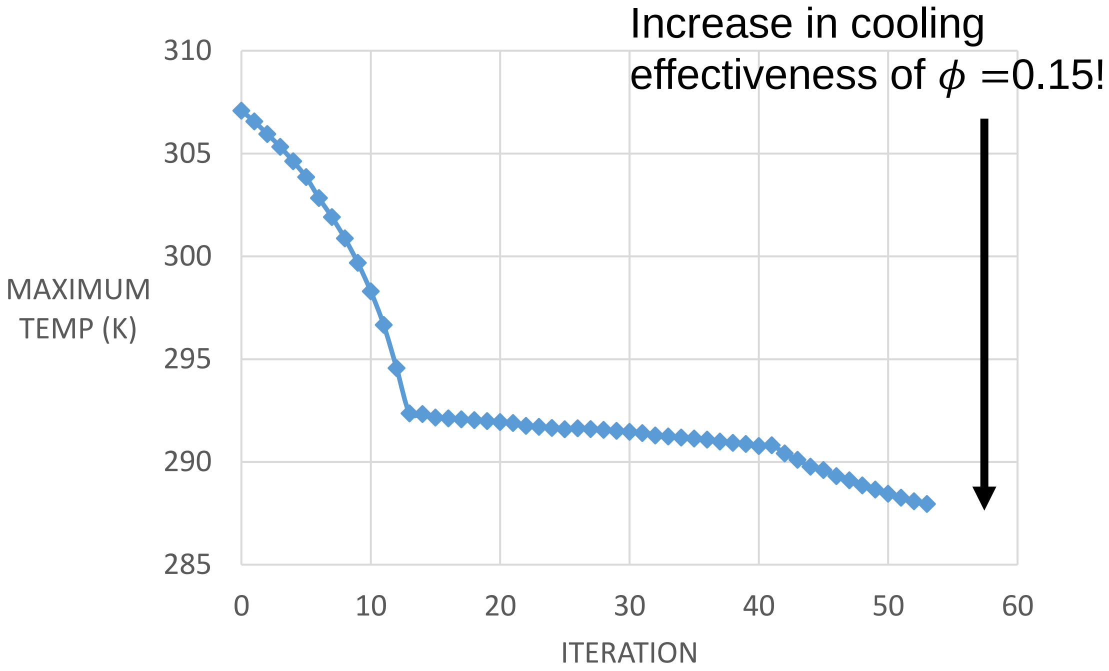
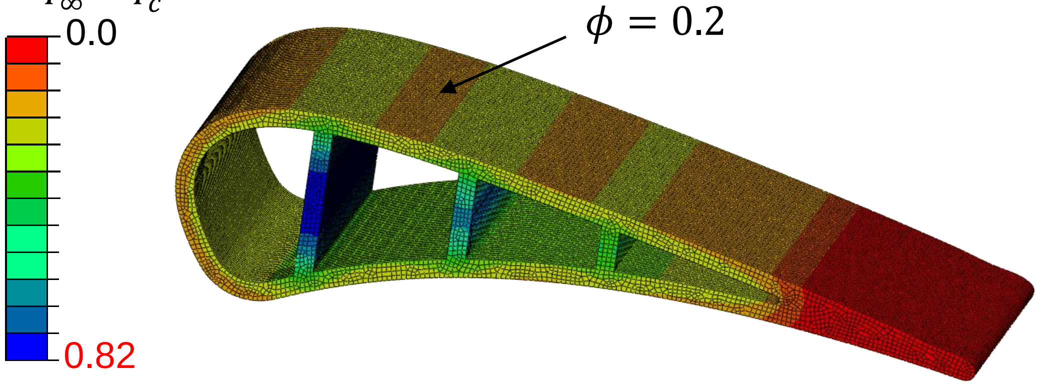
Task 3.2: Parametric studies of internal strut designs reduce maximum surface temperature but need more design constraints, such as maximum allowable internal pressure drop

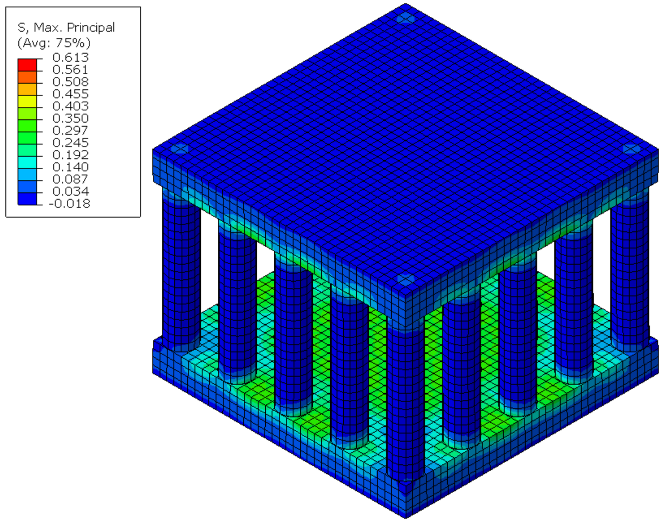




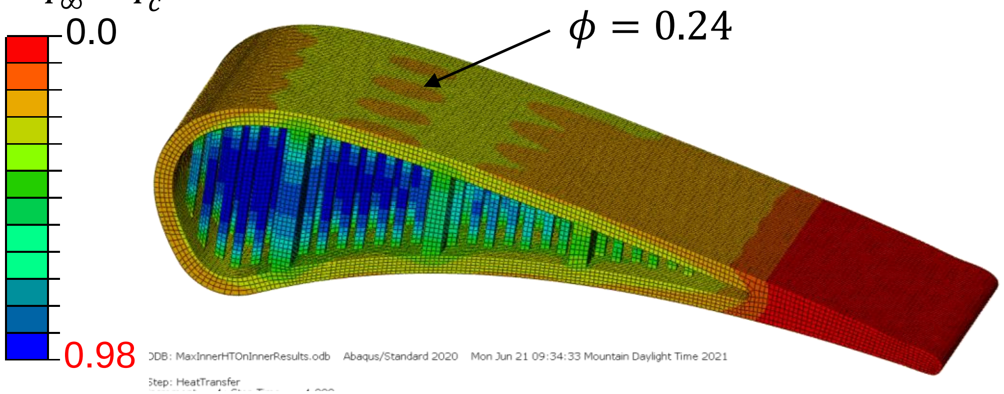
Task 3.2: Non-optimized internal strut design could increase the cooling effectiveness (decrease surface temperature) but leads to local stresses that we will optimize against

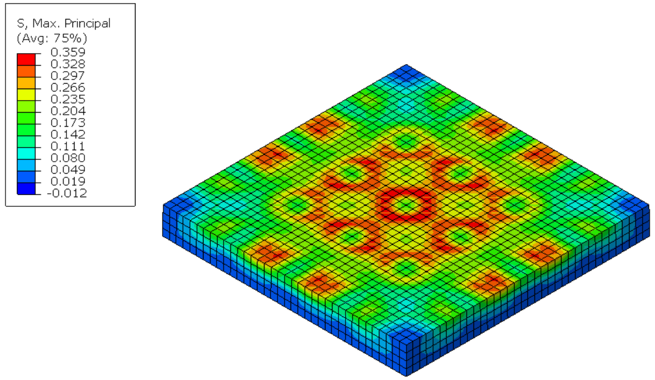
$$\phi = \frac{T_\infty - T}{T_\infty - T_c}$$





$$\phi = \frac{T_\infty - T}{T_\infty - T_c}$$



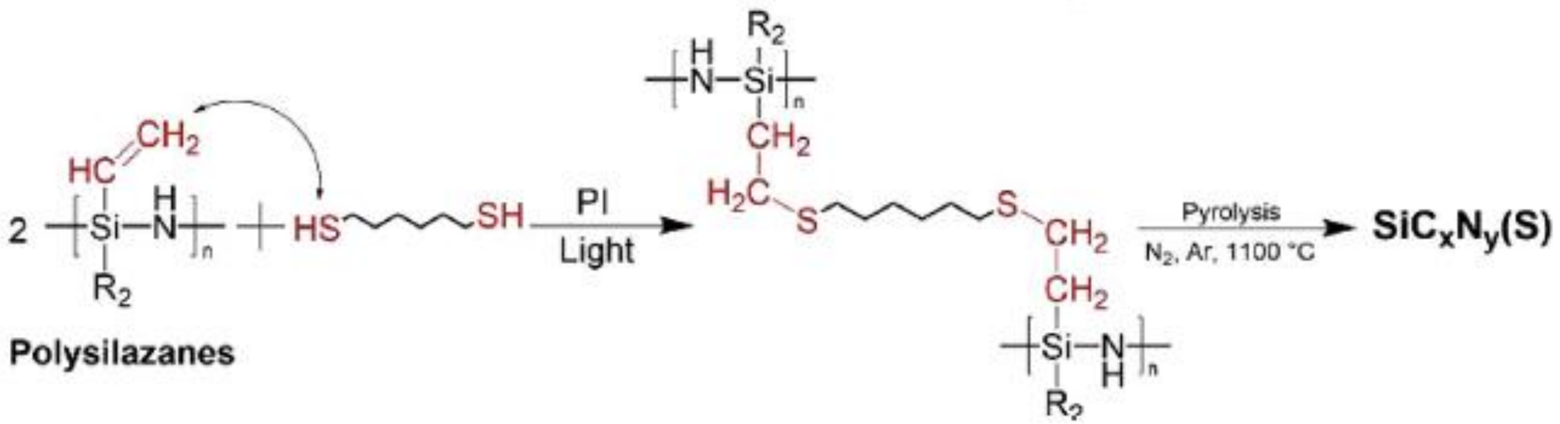


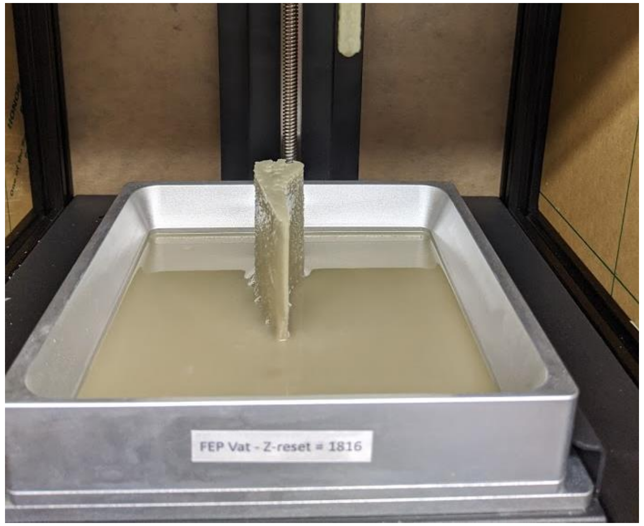
Task 4.1: Several new resin formulations were developed using Durazane (polysilazane) to increase ceramic yield and decrease shrinkage

Resin name	Durazane (wt %)	RMS resin (wt %)	Hexanedithiol (wt %)
DZ RMS	70	30	
DZ hxdt	91		9

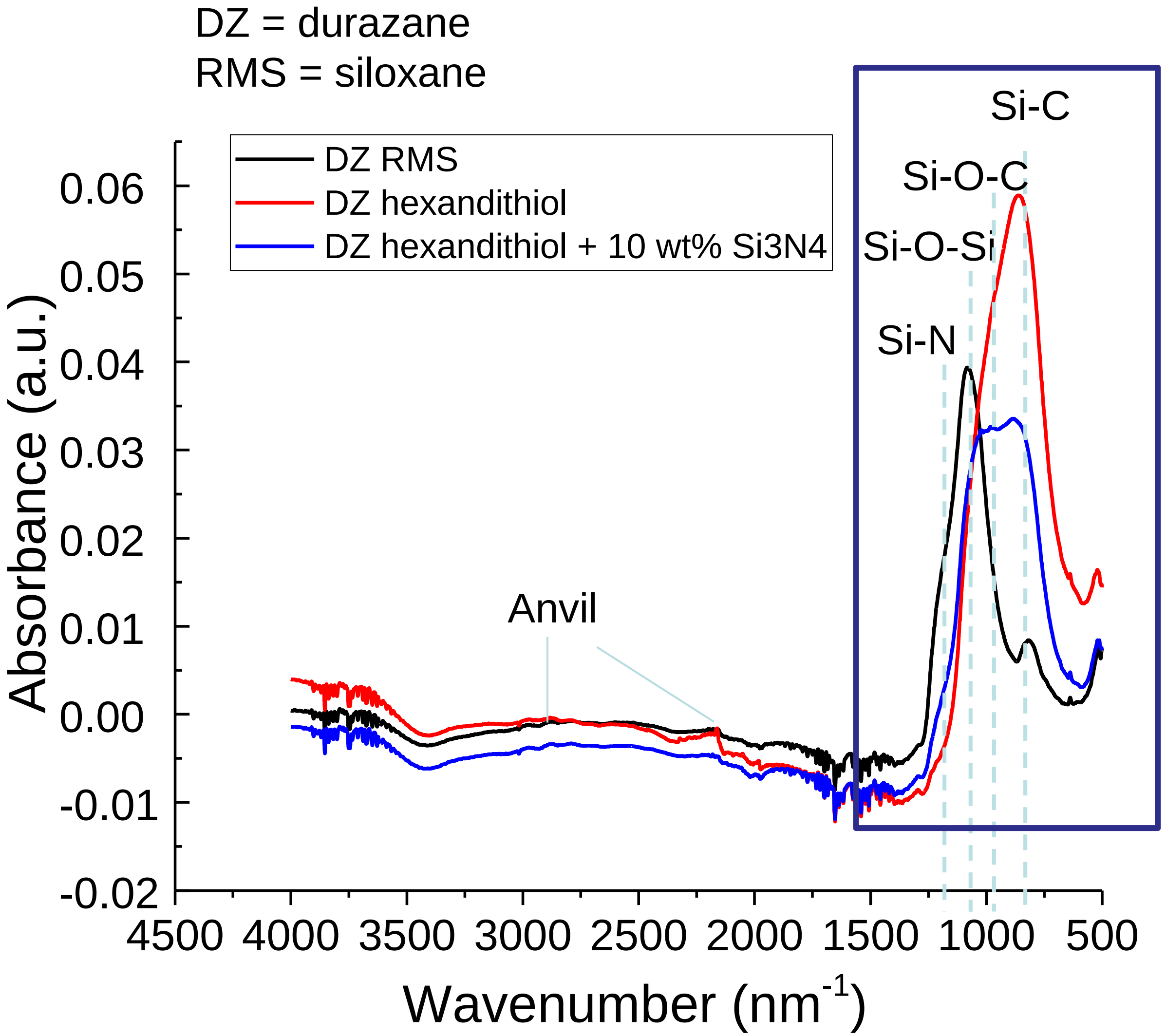
Best base resin

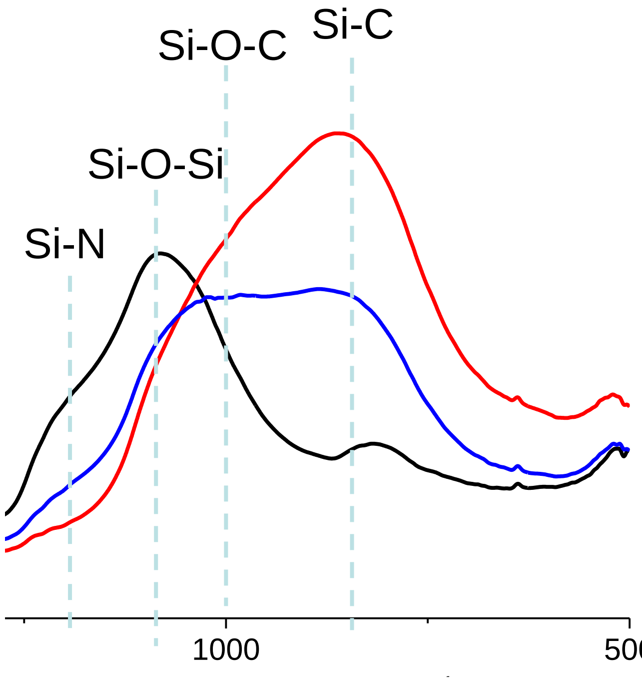
Click reaction for crosslinking Durazane with hexanedithiol provides best materials to date (**~15% shrinkage, vs >35%**)





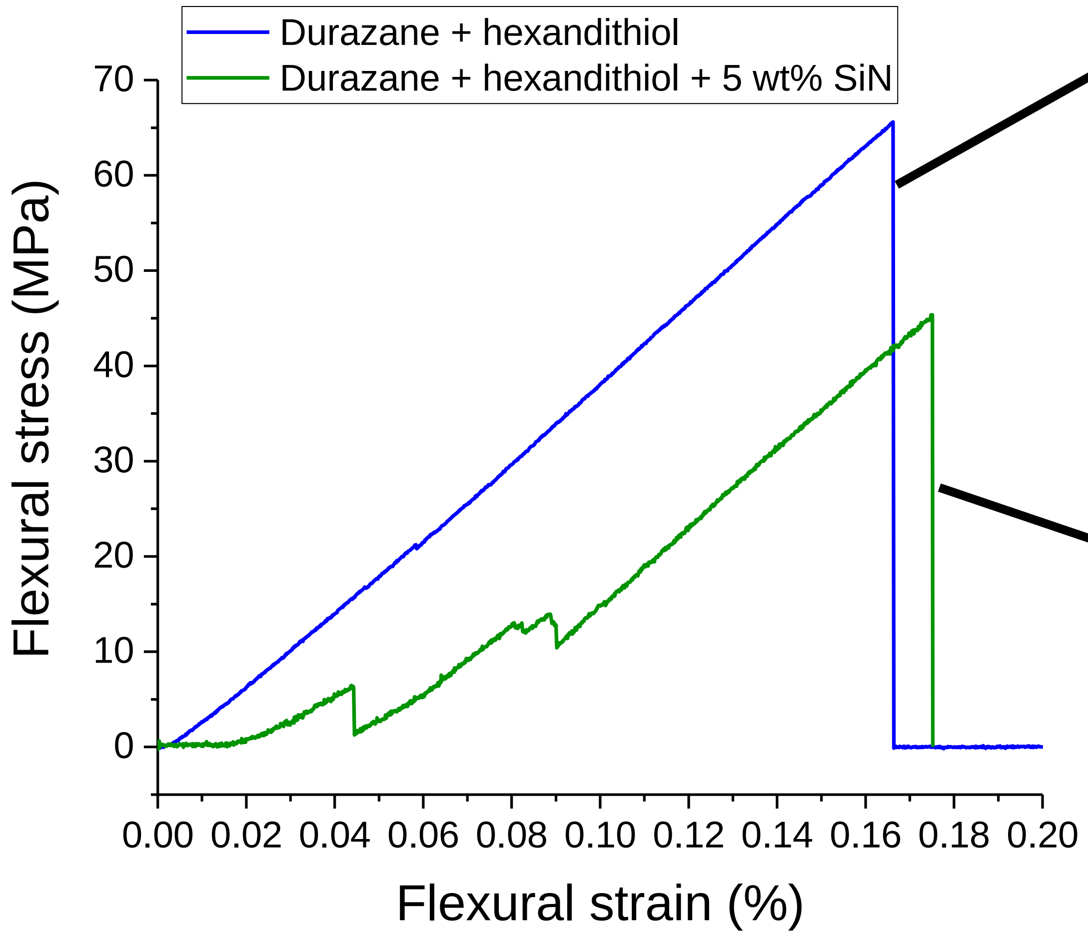
Task 4.1: We are investigating ceramic chemistry using FTIR for different resin compositions and processing conditions.





- Durazane with RMS => Majority SiO_2 (not desirable)
- Durazane with hexanedithiol click reaction => SiC and SiOC; better overall composition.
  - Improvement perhaps due to click reactions creating a higher crosslink density compared to other crosslinkers.
- Need to further investigate effect of post-processing and particles.

Task 4.2: We are working to obtain and improve mechanical properties in Durazane/ Hexanedithiol ceramics and composites.



Resin composition (without particles):
Durazane = 3 g
Hexandithiol = 0.3 g
Photoinitiator = 0.028 g

Shrinkage = 12%
Flexural modulus = 36258 (± 34) MPa
Failure stress = 66 MPa

Resin composition (with particles):
Durazane = 2.6 g
Hexandithiol = 0.26 g
Si3N4 particles = 0.15g
Photoinitiator = 0.028 g

Shrinkage = 15%
Failure stress = 46 MPa

To date, several students on the project have received graduate degrees and we have disseminated work through the ASME Turbo Expo conference and invited seminars

- Publications to date:
  - Rusted & Lynch, “Determining Total Pressure Fields from Velocimetry Measurements in a Transonic Turbine Flowfield”, ASME Paper GT2021-59388
- Students graduated to date:
  - PSU: Yifan Deng (PhD), Alex Rusted (MS)
  - UWYO: Jackson Rambough (MS)
- Other outreach:
  - PSU
    - Invited presentation (virtual) for New Mexico State University Graduate Seminar
    - American Institute for Aeronautics & Astronautics: “Frontiers in Gas Turbine Technology” seminar
  - UWYO
    - Interaction with NETL on other additives for PDCs

Our tasks over the next year will be to test baseline and advanced cooled airfoils, finalize the topology optimization tools and PDC chemistries, and produce improved designs

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):

- Incorporate new resins and refine manufacturing processes for resolution and material properties
- Co-develop new cooling designs with PSU

Task 3 (UWYO):

- Refine thermo-structural topology optimization tool
- Provide optimal design features for best thermo-mechanical strength

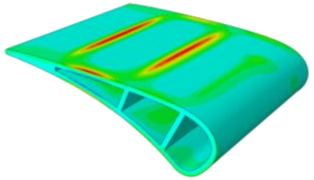
Task 4 (PSU):

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

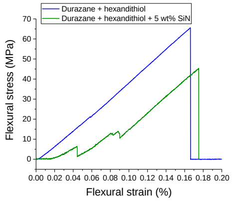
Color key: process engineering, material development, modeling, validation of cooling technologies

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

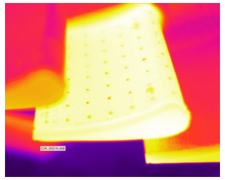
We can make complicated cooling geometries using PDC but are working on robust attachment/sealing in the aerothermal test rig



Thermomechanical shape optimization is helping guide cooling design choices



Various resin formulations have been constructed with improvement in shrinkage but need to be characterized further



Advanced instrumentation in a high speed cascade environment will help characterize performance of PDC airfoils

Questions?

Appendix

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			
	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					■	■	■	■	■	■	■	■

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			
	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												

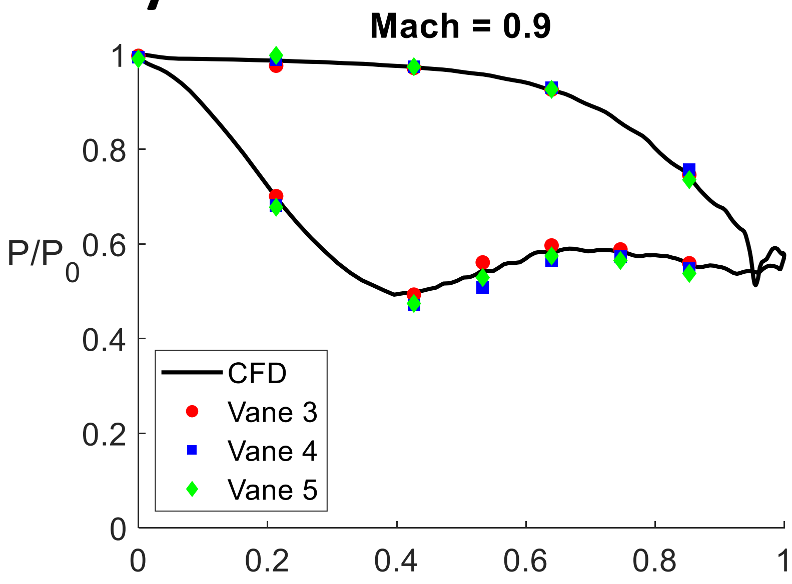
We expect financial and schedule risks will be easily manageable with outlined research plan

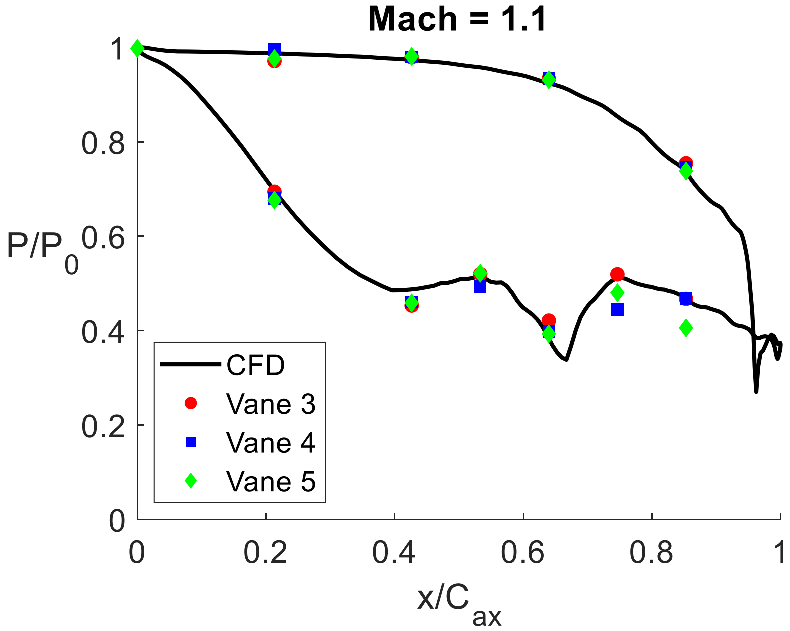
Perceived Risk	Risk Rating			Mitigation/Response Strategy
	Probability	Impact	Overall	
	(Low, Med, High)			
Financial Risks:				
High cost for polymer precursor materials (Task 2, 4, 5, 6)	Low	Med	Low	Fewer extra test parts will be produced and materials will be conserved.
Cost of vane test hardware 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.

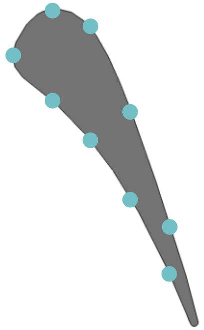
There are some technical risks for this low-TRL project but high payoff if the technology is successful

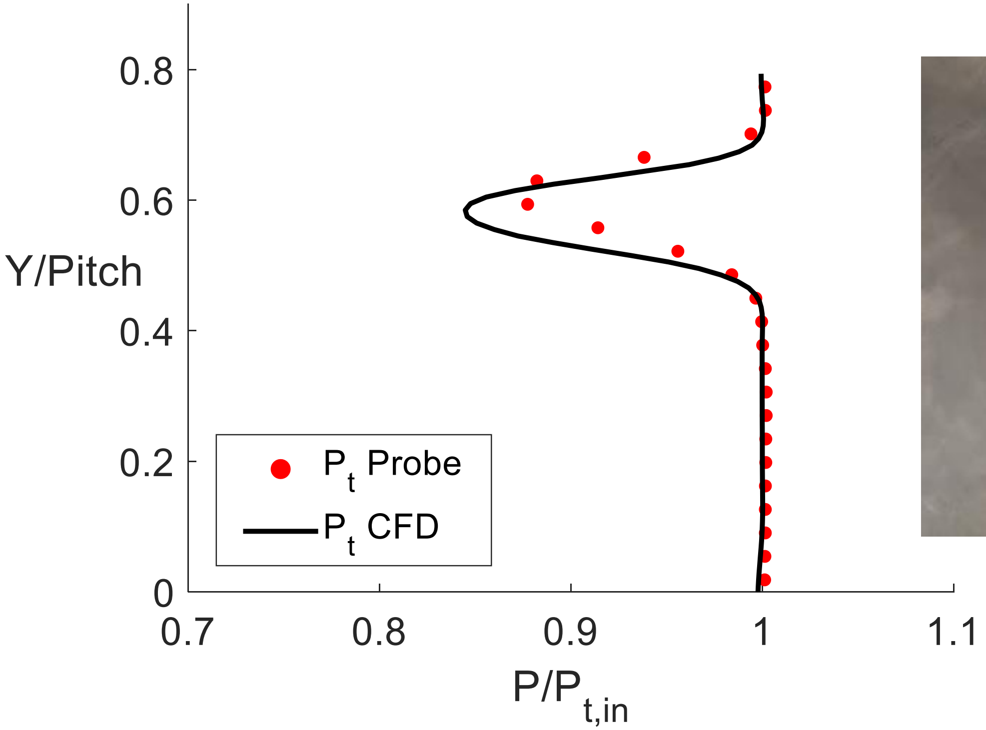
Perceived Risk	Risk Rating (Low, Med, High)			Mitigation/Response Strategy
	Probability	Impact	Overall	
Technical Risks:				
Unable to fabricate cooled SiOC CMC vane with large internal cavity (Task 2.2)	Low	Med	Med	UWYO has fabricated turbine-like test parts previously, but if thin walls are an issue, 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				

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

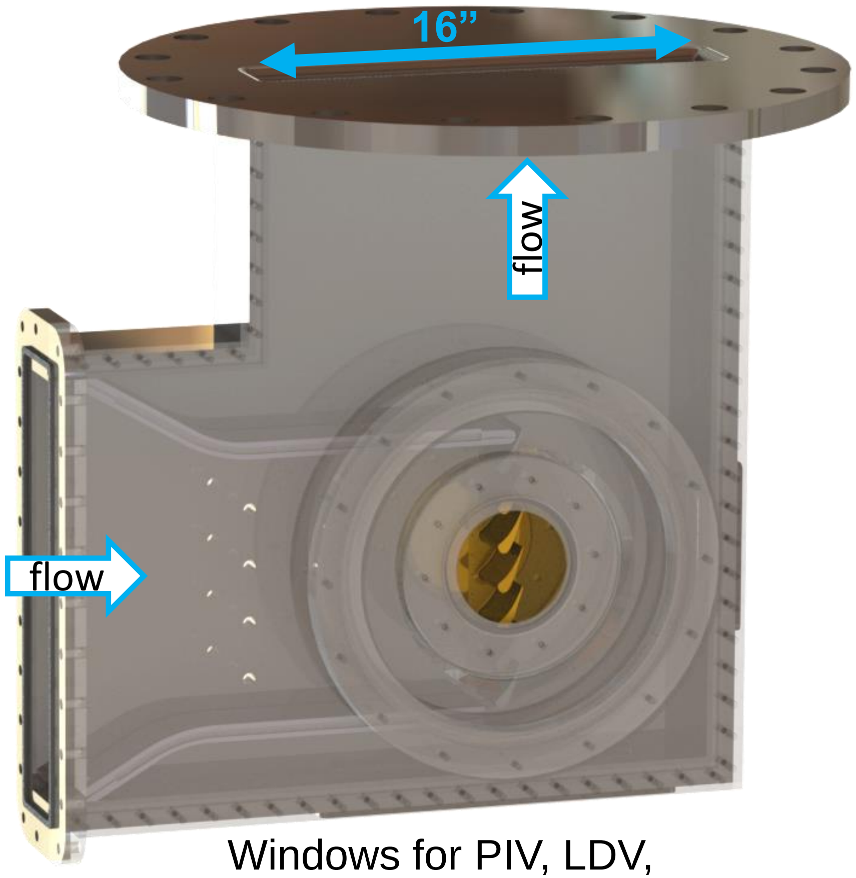








Task 2.1: The vane assembly will be tested in a new high speed cascade facility at Penn State capable of relevant Mach and Reynolds numbers, as well as cooled air capability



Windows for PIV, LDV, and IR measurements