Project 056 Turbine Cooling through Additive Manufacturing

The Pennsylvania State University

Project Lead Investigator

Karen A. Thole
Distinguished Professor
Department of Mechanical Engineering
The Pennsylvania State University
136 Reber Building
University Park, PA 16802-4400
Phone: (814) 865-2519
E-mail: kat18@psu.edu

University Participants

The Pennsylvania State University

- PIs: Dr. Karen Thole, Dr. Stephen Lynch
- FAA Award Number: 13-C-AJFE-PSU-054
- Period of Performance: February 5, 2020 to February 4, 2021
- Tasks:
    1. Manufacture and test existing FAA CLEEN (Continuous Lower Energy, Emissions, and Noise) II blade designs.
    2. Design new double-wall cooling technologies.
    3. Manufacture and test new double-wall cooling designs for linear cascade (2021–22).
    4. Manufacture and test optimal double-wall cooling designs for the Steady Thermal Aero Research Turbine (START) Lab turbine (2022–2023).

Project Funding Level

The FAA has provided $800,000 of funding to date with $400,000 available to The Pennsylvania State University (Penn State) START. The other $400,000 is processing through Penn State's financial system and will be available soon to the team. In-kind cost share of $1,500,000 has been provided to Penn State from Pratt & Whitney to cover the entire program.

Investigation Team

Name	Affiliation	Role	Tasks Responsible For
Distinguished Professor Karen A. Thole	Penn State	PI	Management, reporting, oversight of all technical tasks
Associate Professor Stephen Lynch	Penn State	Co-PI	Management, reporting, oversight of Tasks 1–3
Assistant Research Professor Reid Berdanier	Penn State	Staff Scientist	Task 1, 4
Associate Research Professor Michael Barringer	Penn State	Staff Scientist	Task 1, 4
Scott Fishbone	Penn State	Project Manager	Task 1, 4
Jeremiah Bunch	Penn State	Laboratory Technician	Task 1, 4
Justin Wolff	Penn State	Graduate student	Tasks 1–4

Project Overview

Gains in cooling performance of cooled turbine airfoils have a direct impact on the efficiency and durability (lifetime) of turbine engines and therefore are the subject of much development. Today, many cooling designs for turbine airfoils use complex micro-channels placed within the wall of the airfoil to extract heat, which is otherwise known as double-wall cooling. The geometric complexities (and thus effectiveness) of the micro-channels, however, are limited by the current design space available using conventional investment casting and core tooling methods to manufacture relatively small intricate internal cooling features. This project will investigate potential thermal performance and aerodynamic efficiency improvements made possible by exploring the expanded cooling design space opportunities by directly fabricating complex cooling geometries using three-dimensional laser powder bed fusion (L-PBF), a common type of metal-based additive manufacturing (AM) method. L-PBF AM has begun to see many uses in the gas turbine industry, particularly because of the new design space enabled by this new fabrication method. However, the ability to manufacture high-efficiency intricate complex double-wall cooling airfoils design concepts is unknown. This research would generate some of the first thermal performance data at engine-relevant conditions comparing traditional cast airfoils to advanced L-PBF AM manufactured airfoils. Understanding the potential of new innovative geometric heat transfer cooling design features coupled with unique airfoil cooling configurations will serve as an important guide to future investments in advanced manufacturing and cooling design technologies.

Task 1 – Manufacture and Test Existing FAA CLEEN II Blade Designs

The Pennsylvania State University

Objectives

The objective of this task is to measure the as-manufactured shape of FAA CLEEN II turbine blade airfoils using x-ray computed tomography and use that information to fabricate additively manufactured (AM) copies for direct comparison in the rotating turbine facility at Penn State. The outcomes of this effort will be: 1) to provide a direct back-to-back comparison of cast versus additively manufactured airfoils; 2) learn the unknown challenges with creating double-wall designs via AM and how to translate them to cast parts for commercialization; and 3) work through the design, fabrication, and testing of additive blades that will spin at engine-relevant conditions.

Research Approach

Training

The initial portion of the project involved familiarizing the graduate student on the project with software such as Avizo (for computerized tomography (CT) scan analysis) and StarCCM (for cooling feature design). CT scan analysis training was performed with existing data on a previously published public microchannel coupon [1], which would be similar to the technology being deployed in this project. The training included the generation of a surface from raw CT data in Avizo, exporting said surface to SolidWorks (CAD program) to measure the CT surface and remodel it as a solid body, and comparing the solid body and CT surface via a nominal-actual comparison in Avizo.

Figure 1 shows the segmentation editor in Avizo, which was used to select the raw CT data that was rendered into a 3D surface. The CT surface was then exported into SolidWorks; its dimensions were analyzed and measured, and the solid body in Figure 2 was modeled.

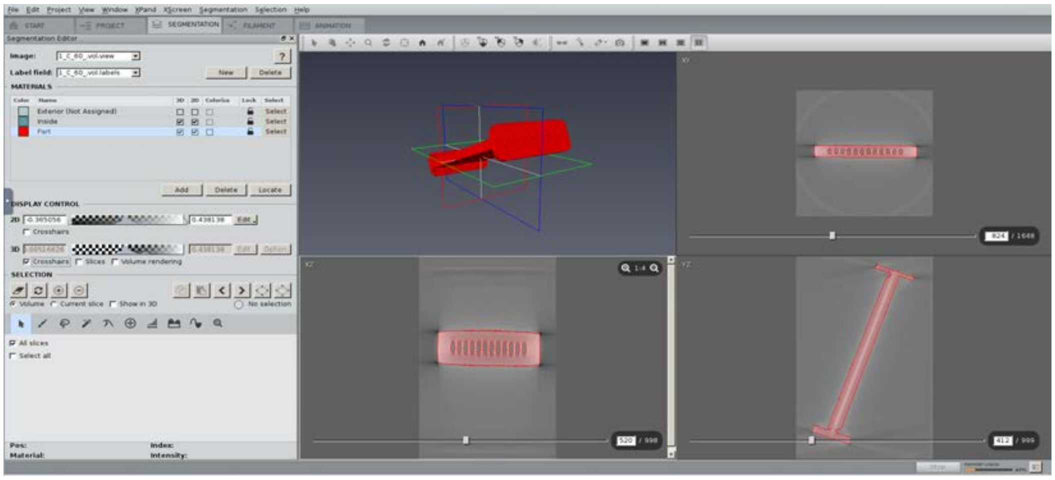

Figure 1. Segmentation editor views for the 1_C_60 public coupon.

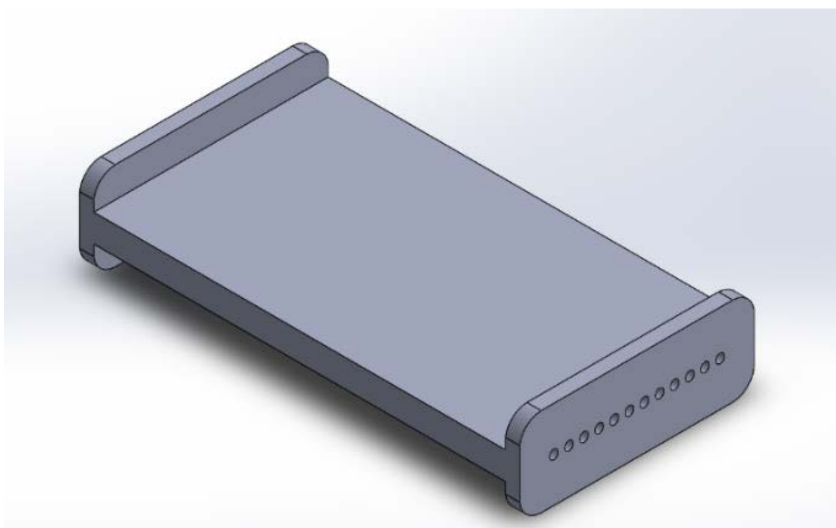

Figure 2. Solid body of the 1_C_60 public microchannel coupon in SolidWorks.

The nominal-actual comparison process is shown through Figures 3–5. The first step to a nominal-actual comparison starts with the registration or alignment of the two surfaces to be compared. Avizo has two ways of registering surfaces; one way is to attach an align surfaces operation to both surfaces and another is to add landmark pairs between the two surfaces. The align surfaces operation is used for an automatic registration of two surfaces, where Avizo utilizes its built-in computing code to align the centers, principal axes, and surfaces of the two bodies. Landmark pairs on the other hand are pairs of points that the user specifies to register the surfaces to one another. The landmark registration was used for the nominal-actual comparisons for the FAA CLEEN II blades but for the 1_C_60 public coupon, the align surfaces operation was used.

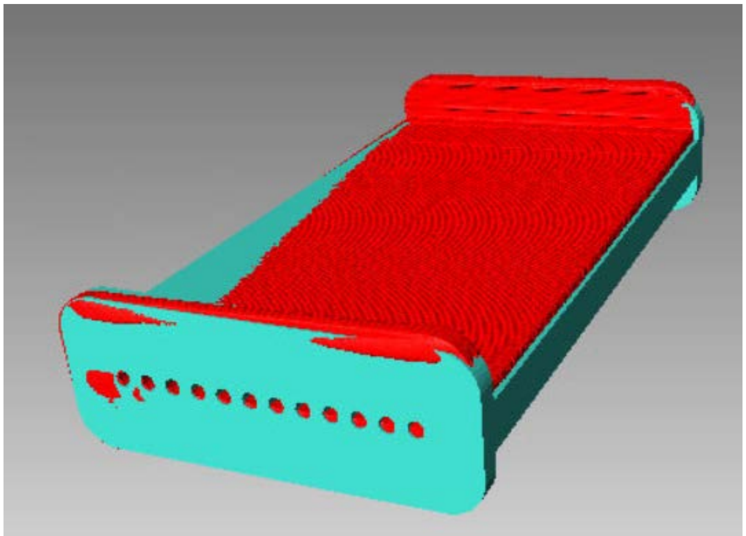

Figure 3. Registration/alignment of the 1_C_60 public coupon's CT surface and solid body model.

After registration, or alignment, of the surfaces, Figure 4 shows the steps used in Avizo to produce the image in Figure 5, and also shows the histogram produced from the surface distance calculations. The surface distance computation is the key step in completing the nominal-actual comparison; it is defined as the distance from the vertex of one surface to the closest point on another surface. Figure 5 shows the surface distance computation values mapped onto the 1_C_60 public coupon, where the colormap legend expresses the surface distance values in mm.

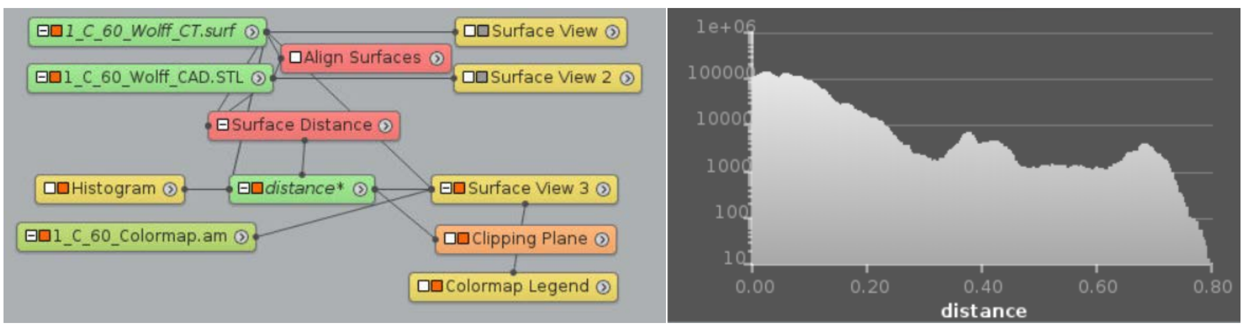

Figure 4. Steps performed in Avizo for a nominal-actual comparison, and the computed histogram of surface distance.

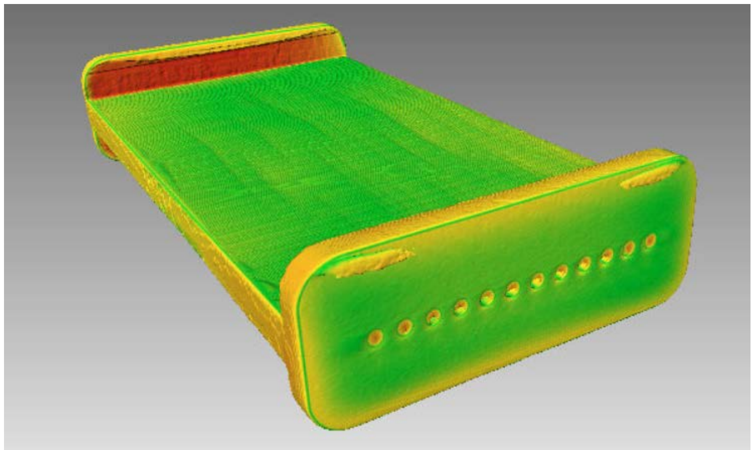

Figure 5. Nominal-actual comparison surface view with associated colormap legend.

After each of the steps explained above are completed, a nominal-actual comparison has been performed. Key information can be collected from the histogram of the surface distance calculations such as mean surface distance, range, and standard deviation. The same nominal-actual comparison process has been conducted on the FAA CLEEN II blades to determine which blades are appropriate to additively manufacture.

Measurement of FAA CLEEN II Blades

Substantial progress has been made in comparing the six desired FAA CLEEN II blades in order to decide which blade to fabricate using additive manufacturing techniques. Two different types of CT scans were obtained for each of six blades; one set of scans from a Pratt & Whitney vendor, and another set using on-campus facilities in the Center for Quantitative Imaging (CQI). The scan settings were changed for the two types, enabling either better determination of the solid wall boundary, or high resolution of small-scale cooling features. The learning from both types of scans will be compared, and scan settings have been documented for future use as the project progresses.

Several comparison techniques were employed for the blades: nominal-actual comparisons (CAD versus CT and CT versus CT) in Avizo, the overlap of blade cross-sectional slices, and plotting the overall cooling effectiveness (calculated from the infrared (IR) data). The CAD design intent was provided by Pratt & Whitney.

The process of nominal-actual comparisons in Avizo involves creating surfaces from raw CT data, registering the two surfaces that are to be compared, and computing a histogram that includes information such as mean surface distance, range, and standard deviation. The registration step was performed by aligning each surface based on points placed along the fir-tree (the airfoil root geometry). After the surfaces were aligned, the surface distance, which is the distance from the vertex of one surface to the closest point on another surface, was calculated. Then, the histogram was computed using the surface distance results to obtain the following: the mean surface distance (the average distance between the two triangulated surface), the range, and the standard deviation.

The nominal-actual comparisons that were calculated first involved comparison of the design intent of the blade (CAD model) compared to the six scanned airfoils. From this analysis, one airfoil (designated BA06) had an average surface deviation from CAD that was in the middle of the range among the six blades. Then, that airfoil was used as the “actual” in the nominal-actual comparisons to other airfoils. The surface distance determination from the nominal-actual comparison were mapped onto the blade surface to produce a qualitative image indicating distortion, whereas the quantitative results were summarized in a table.

Additional qualitative images that proved useful in the comparison of the blades were constructed as well. To qualitatively understand the variations between the CAD model and the CT surfaces, and between CT blade surface BA06 and the rest of the CT surfaces, cross-sectional slice images were compared at 10%, 50%, and 90% of blade height. The height is defined as the distance from just above the blade platform, to the tip of the blade.

Lastly, previously obtained infrared data on the blade surfaces from recent tests in the START turbine facility was post-processed to produce overall cooling effectiveness. This data has been reduced and is being compared to the CT data to understand any correlations between blade geometry deviation and overall cooling effectiveness.

The above data package is being discussed with Pratt & Whitney in order to make a final determination of the airfoils for which structural analysis will be performed and design drawings generated.

Mechanical Analysis and Manufacturing
Pratt & Whitney was engaged as a subcontractor on the Task 1 effort, in order to provide mechanical analysis, generation of manufacturing drawings for the additively manufactured airfoils, and assistance with securing an additive manufacturing vendor. The subcontract was established on 9/28/2020, and a kickoff meeting was held on 10/2/2020. Pratt & Whitney engineers have started to perform some structural analyses of the existing FAA CLEEN II airfoil at the conditions of the START turbine rig and will update their models once a representative CT scan is selected. Pratt & Whitney has also helped to engage additive manufacturing vendors and the process of setting up non-disclosure agreements (NDAs) is underway.

References
[1] Wildgoose, A., Thole, K. A., Sanders, P. A., and Wang, L., 2020, "Impact of Additive Manufacturing on Internal Cooling Channels with Varying Diameters and Build Directions," *Proceedings of ASME Turbo Expo*, London, UK.

Task 2 – Design New Double-Wall Cooling Technologies
The Pennsylvania State University

Objective(s)
The objective of this task is to develop novel double-wall cooling designs that feature microchannel concepts being explored in literature and which are possible to achieve via AM. The designs will be generated with advice from Pratt & Whitney so that the concepts can be translated to the FAA CLEEN II airfoil later in this project, as well as leveraged for commercialization. The designs will be packaged into cascade test articles that will be measured in the high-speed linear cascade at Penn State using infrared thermography in Year 2 of the project. Best designs will be identified for re-integration into the FAA CLEEN II airfoil shape and run in the START turbine to confirm operational benefit.

Research Approach
Training
StarCCM training was performed by the graduate student, as it will be used for design work later in this task. A tutorial for StarCCM was performed using a NASA C3X public first vane. A mesh was created, and boundary and initial conditions were set, to run a 2D analysis. Figures 6–8 show the mesh, Mach number, and temperature results.

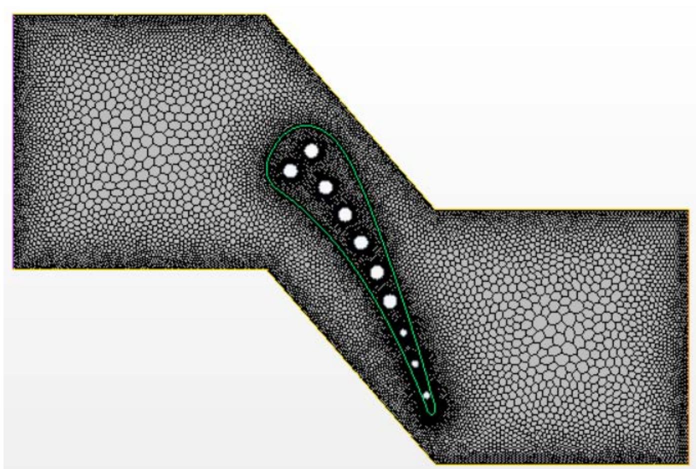

Figure 6. Mesh generated in StarCCM for the NASA C3X first vane.

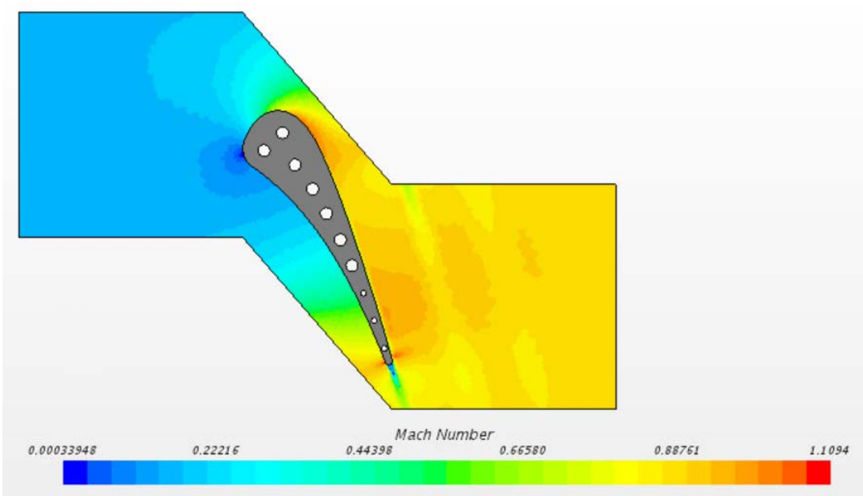

Figure 7. The predicted Mach number profile of the NASA C3X vane.

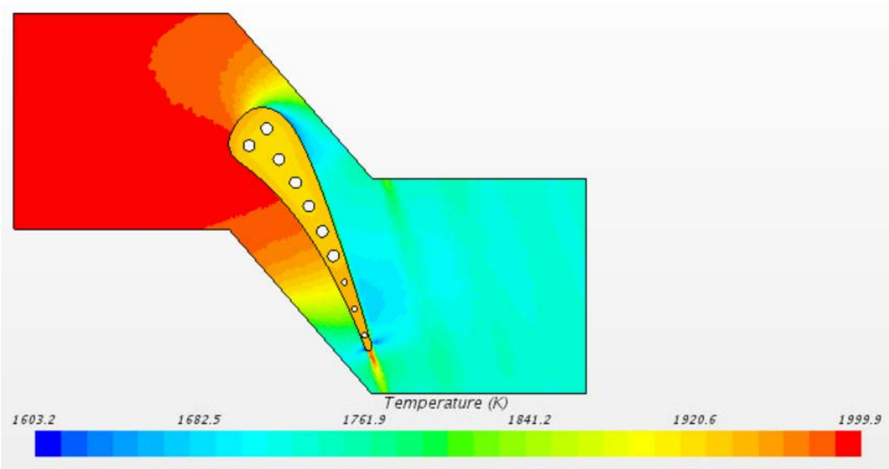

Figure 8. The predicted temperature profile of the NASA C3X vane.

An additively manufactured microchannel cooling design in [2] was also modeled in StarCCM to learn about internal cooling feature modeling. The triangle pin fin design from that study was modeled in SolidWorks and set up in StarCCM for a 2D analysis. More work on understanding the accuracy of the modeling is pending.

Milestones

Milestone	Due Date	Estimated Date of Completion	Actual Completion Date	Status
Workplan	3/4/20	3/4/20	3/5/20	Completed
COE Meeting 1	4/1/20	4/1/20		Cancelled
COE Meeting 2	10/1/20	10/1/20	10/28-10/29/20	Completed
Annual Report	2/4/21	2/4/21		
Project Closeout	2/4/21	2/4/21		

Major Accomplishments
The major activities are: 1) execution of the Pratt & Whitney subaward and a kickoff meeting to start design work; 2) completion of CT scans of existing FAA CLEEN II airfoils; 3) identification of the critical criteria (geometric match to design intent, cooling flow behavior relative to design intent, variation relative to other airfoils, etc.) to determine most appropriate airfoil design to additively manufacture. All of these activities will help us to execute Task 1, and the learning from these tasks will be leveraged throughout the rest of the project.

Publications
Nothing to report yet.

Outreach Efforts
Presented research findings to Pratt & Whitney (cost share partner) at bi-annual Center of Excellence review meeting on 11/30/2020.

Awards
Nothing to report yet.

Student Involvement
Justin Wolff (currently a first year Masters student) has been responsible for analyzing CT scan data of the FAA CLEEN II blades and compiling a review package to be discussed with Pratt & Whitney. Justin has learned the analysis tools and his next role will be designing novel double-wall cooling strategies that will be implemented by him into high-speed linear cascade hardware.

Plans for Next Period
The most appropriate airfoil to model as an AM fabricated part will be decided in the near term and the design will be relayed to Pratt & Whitney. Structural analysis of the airfoil will be conducted to ensure that the airfoil will be safe to operate in the Penn State rig, and the design finalized. Once the design is complete, an AM vendor will be selected and a purchase order will be issued. The necessary post-processing steps will also be identified (blade machining operations, inspections, flow characterization, instrumentation, etc.) prior to installation in the rig.

The airfoils will be tested in the START turbine in the 2nd quarter of 2021 using the IR thermography capability recently developed, and the results will be compared to the original FAA CLEEN II cast airfoils.

The preliminary and detailed design of novel microchannel designs will begin shortly. The designs will use an appropriate airfoil geometry decided in conjunction with Pratt and Whitney, and the initial database for microchannel designs will be taken from public literature or patents. Test articles will be fabricated for the linear cascade at Penn State toward the middle of Year 2 and tested by the end of Year 2.

The current project plan is indicated below in the Gantt chart. Due to some delays attributed to COVID and shutdown of the facility in mid 2020, the design and fabrication of the AM blades for Task 1 is delayed and would be expected to be completed in 2021 Q1.

Table 1. Project Schedule

Calendar Year	2020			2021				2022				2023
Project Year	Year 1				Year 2				Year 3			
	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
Task 1: Manufacture and test existing FAA CLEEN II blade designs	■	■	■	■								
1.1: Quote and purchase AM blades	■											
1.2: Fabricate AM blades		■										
1.3: Machining and heat treatment			■									
1.4: Installation, shakedown, and testing of blades in START Rig			■	■								
Task 2: Design new double-wall cooling technologies	■	■	■	■	■							
2.1: Evaluation of existing IP and concepts	■											
2.2: Conceptual designs		■										
2.3: Preliminary and detailed designs			■	■	■							
Task 3: Manufacture and test new double-wall cooling designs for linear cascade					■	■	■	■				
3.1: Purchase and fabricate AM airfoils					■	■						
3.2: Inspect and compare to design intent						■						
3.3: Instrumentation and flow checks							■					
3.4: Data collection at design conditions							■	■				
Task 4: Manufacture and test optimal double-wall cooling designs for START turbine								■	■	■	■	■
4.1: Design blades for START turbine								■	■			
4.2: Quote and purchase AM blades									■			
4.3: Fabricate AM blades										■		
4.4: Machining and heat treatment											■	
4.5: Installation, shakedown, and testing of blades in START Rig											■	■