Progress Summary for FAA ASCENT #56: Turbine Cooling Through Additive Manufacturing

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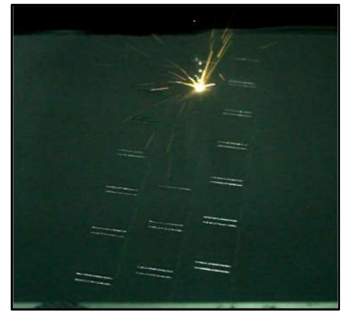
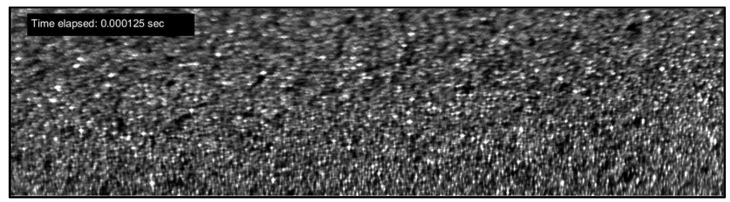




[Bidare et al. 2018]

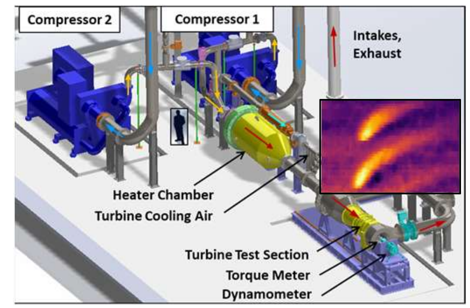
The overall goal is to study advanced double-wall cooling features and apply our learning to relate defects to blade durability

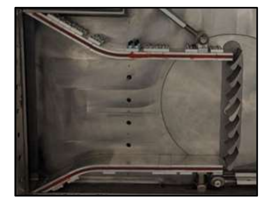
Task 1: Manufacture FAA CLEEN II TECH blade design using AM, and test in START Lab to obtain benchmark data for cast versus additive blades.

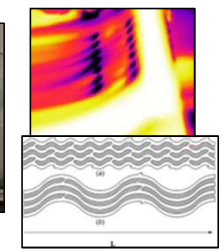
Task 2: Design and manufacture novel double wall cooling concepts in a section of the CLEEN II TECH blade to evaluate feasibility.

Task 3: Test novel double wall cooling concepts in PSU's high speed linear cascade to downselect best cooling geometries.

Task 4: Use wealth of data from the CLEEN II TECH testing and the AM blades to relate specific manufacturing defects to cooling debits (blade life).





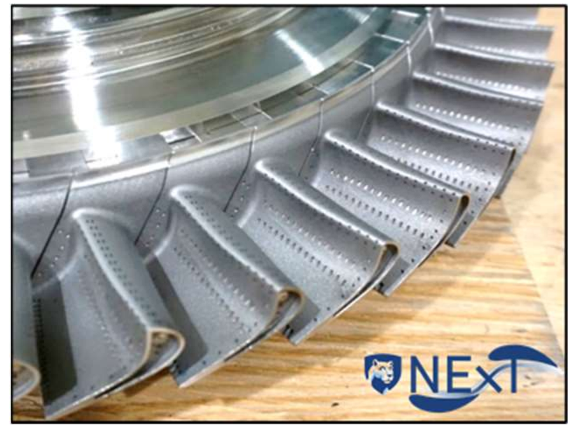


Important Outcomes:

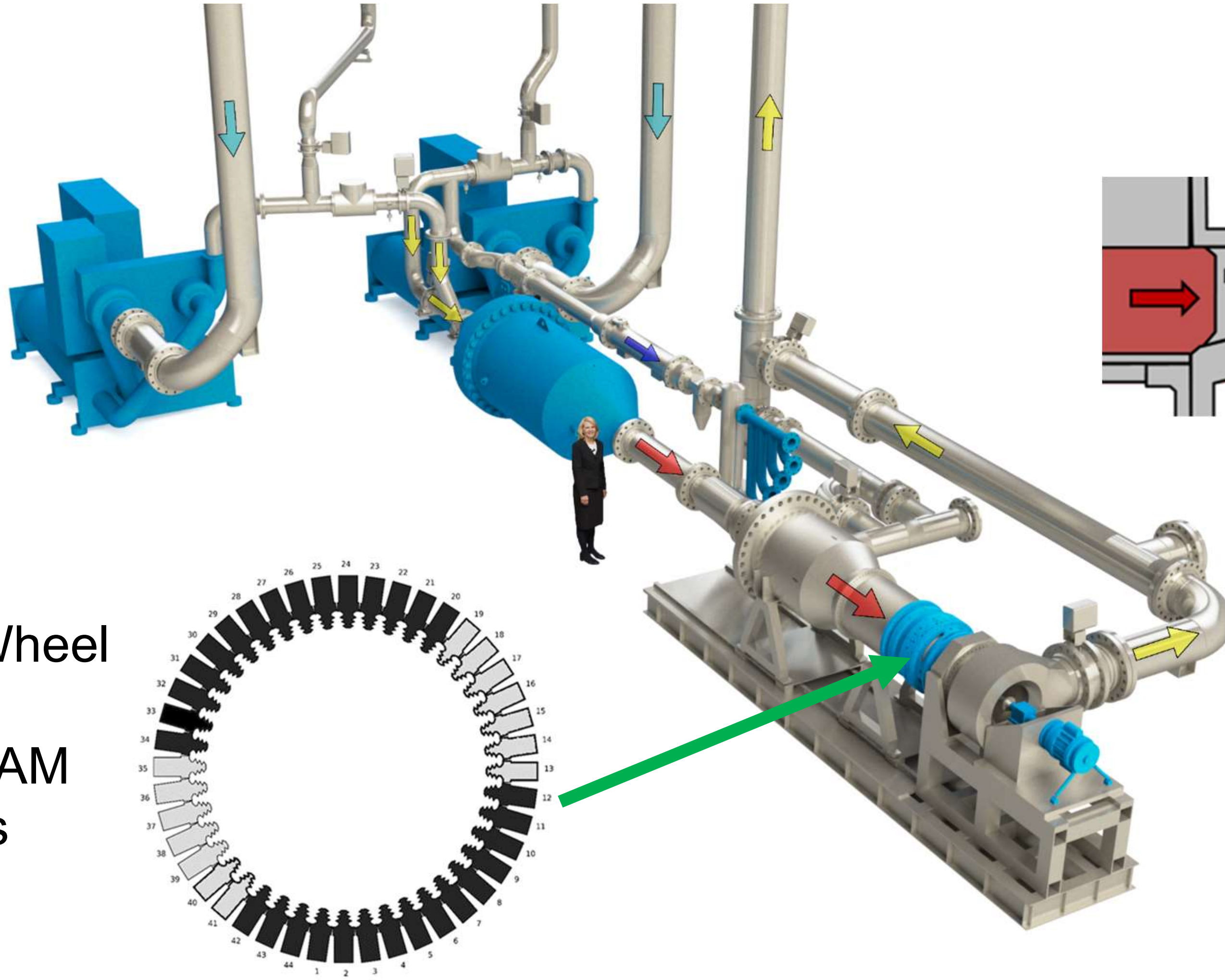
1. Comparison of cast vs AM blades at turbine-relevant conditions
2. Design of advanced double-wall cooling in collaboration with Pratt & Whitney

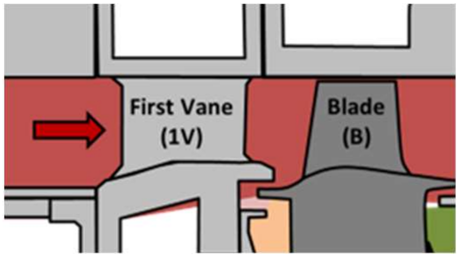
Additively manufactured turbine components enables rapid prototyping and accelerated timelines relative to traditional casting

Turbine Blade Manufacturing Process	Casting	Additive
Tooling 	16 weeks	-
Cores 	12 weeks	-
Wax Patterns 	12 weeks	-
Casting / Printing 	20 weeks	16 weeks
Machining 	10 weeks	10 weeks
Completed Component 	70 weeks	26 weeks



The existing test turbine in START is a single stage





Rainbow Wheel
of
Cast and AM
Blades

Spatial measurements in START are presented non-dimensionally so they can be directly related to engine blade temperatures

Requirements: Matched Re, Ma, and Biot

$$\phi = \frac{T_{MGP} - T_s}{T_{MGP} - T_c}$$

START Conditions:

T_{mgp}	450° F
T_c	70 ° F

IR Blade Surface Measurements: T_s

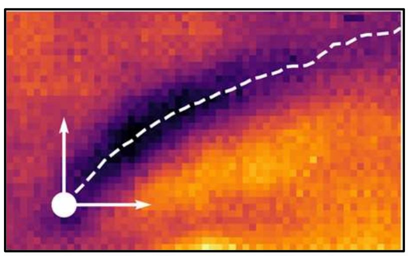
→ ϕ →

Engine Conditions:

T_{mgp}	XXX° F
T_c	XX ° F

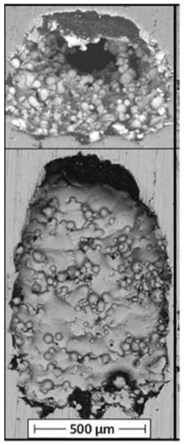
Engine Blade Surface Temperatures: T_s

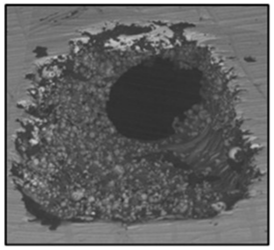
Feature to Entire Blade

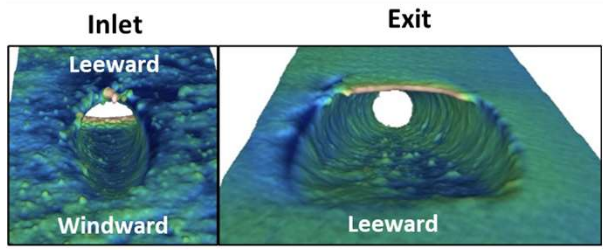


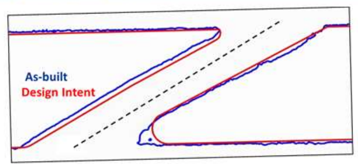
Film-cooling holes and small features continue to be challenging to print at small scales, but AM technology has been advancing

2017 **2019** **2021** **2022**

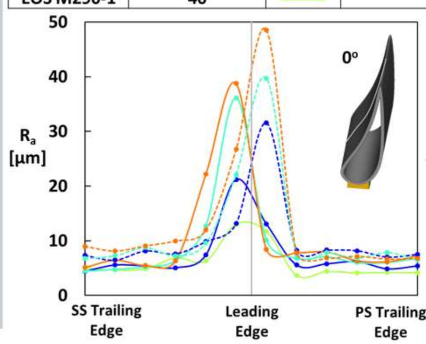


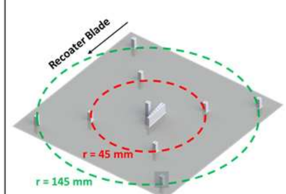


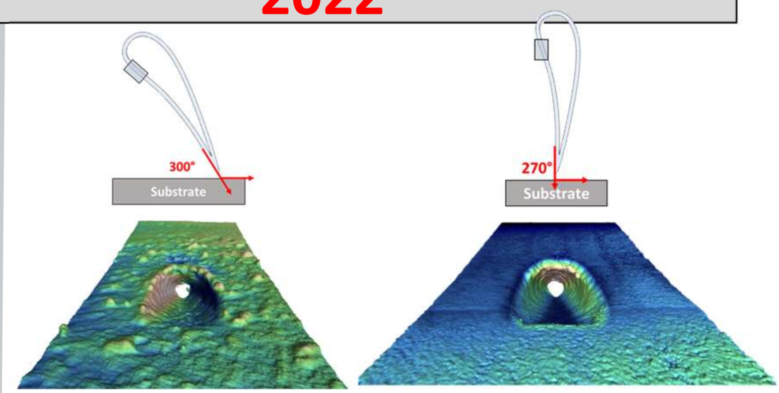




AM Machine	Layer Thickness [µm]	Build Radius [mm]		
		75	112.5	187.5
EOS M400-1	40	—	—	—
EOS M400-1	80	- - -	- - -	- - -
EOS M290-1	40	—		

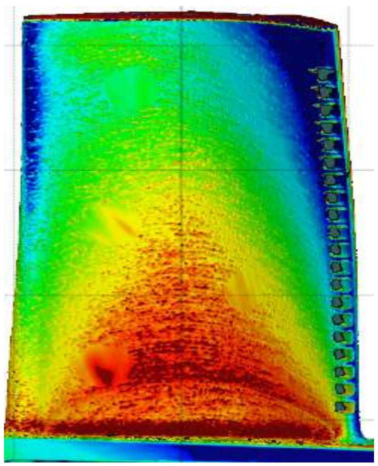




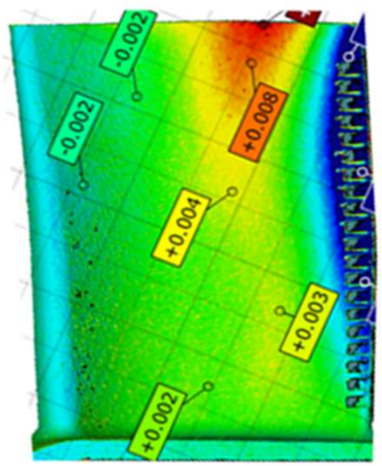


In practice, trial prints are still a requirement to assess build direction, processing parameters, feature choices, etc

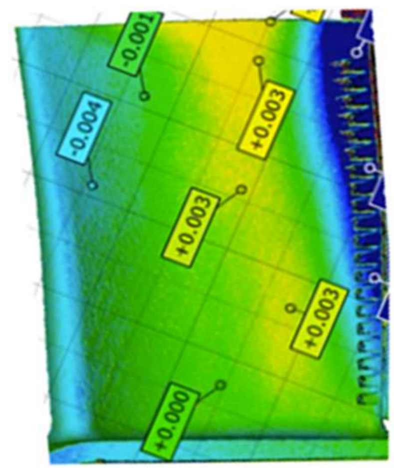
Trial #1

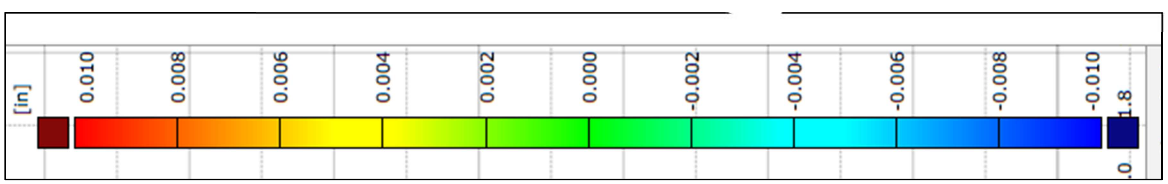


Trial #2

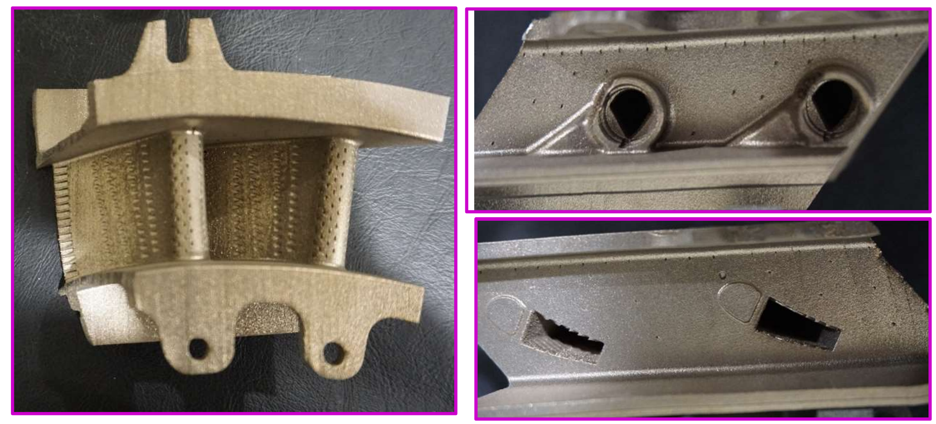


Trial #3

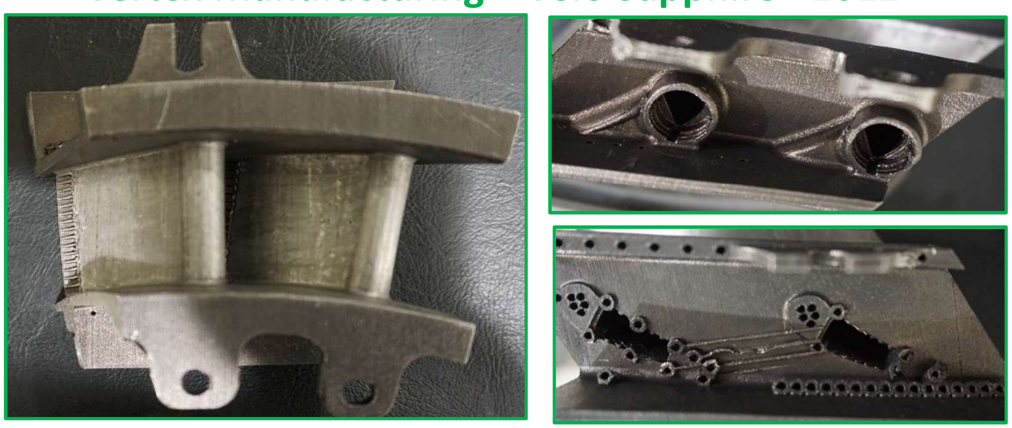




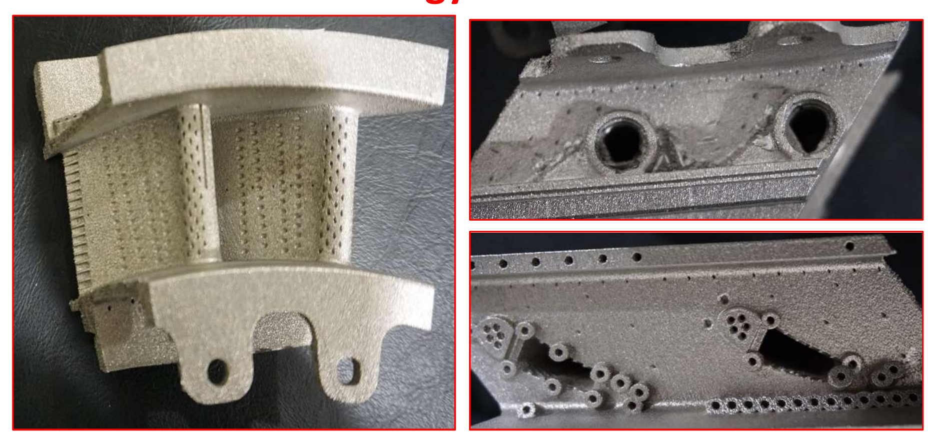
The NExT vane was printed at four locations to learn how vendor, partner, and machine influence part quality



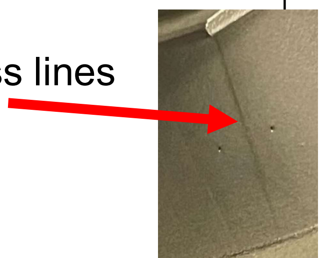
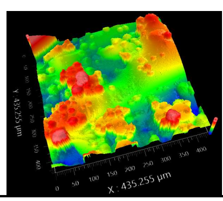
Vertex Manufacturing – Velo Sapphire - 2022



Siemens Energy – EOS - 2022

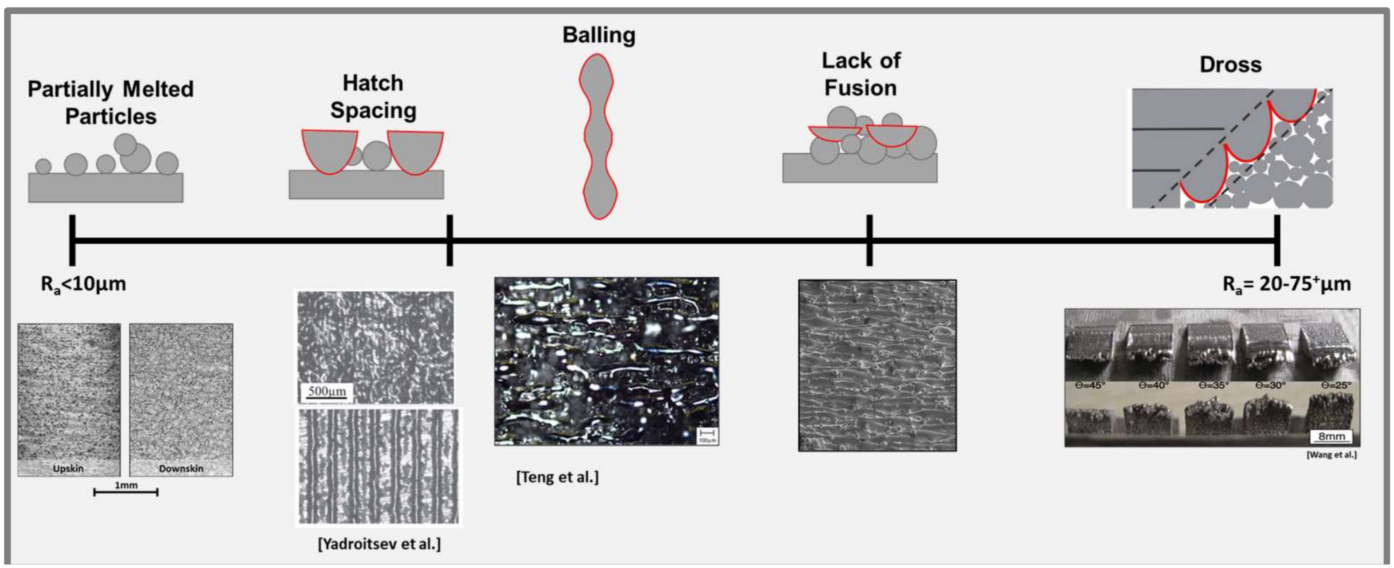


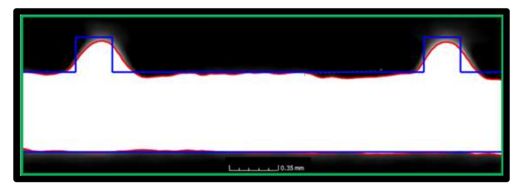
FAA ASCENT 56 allowed Penn State and Pratt and Whitney to learn about what differences AM creates versus casting on a turbine blade

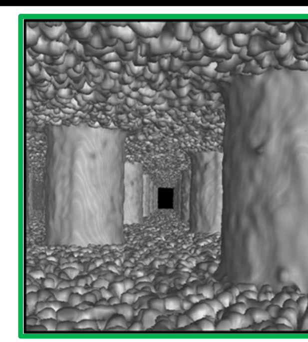
Airfoil Feature	Variations Experienced	Explanation of Variance	Best Practice Moving Forward
Aerodynamic shape and witness lines 	Up to 0.020”	Support structures will pull or push due to heat sinks. Interior features cause witness lines.	Vendors who understand how to design supports are key to a good shape.
Interior passage walls	Communication	Walls are often thinner than AM can print	Trial cut ups, flow testing, or CT scans needed to ensure all walls are printed
Interior roughness 	High roughness >200 Ra (deviation from a mean height in microinches)	Incorrect orientation; build parameters (layer thickness); machine issues	Trials and experienced vendors with in-house parameters are good. Some vendors have consistently lower roughness levels.

The program taught the team and partners about AM issues

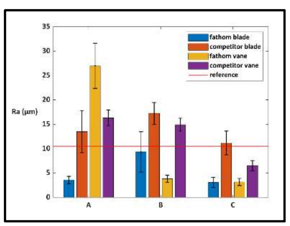
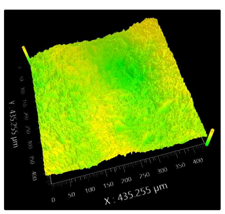
AM Issue	Variations Experienced	Explanation of Variance	Best Practice Moving Forward
Globules	Balls of metal	Down skin small features do not melt before gravity takes over	Try to limit down skin interior features by print direction,
Rib shape	Not symmetric / not matching cast	Each side of the rib can be different and ribs can be wavy	Trials needed and design for additive
Pin shape	Not symmetric / not matching cast	Not circular per design	Trial with CT scan evaluations to update design





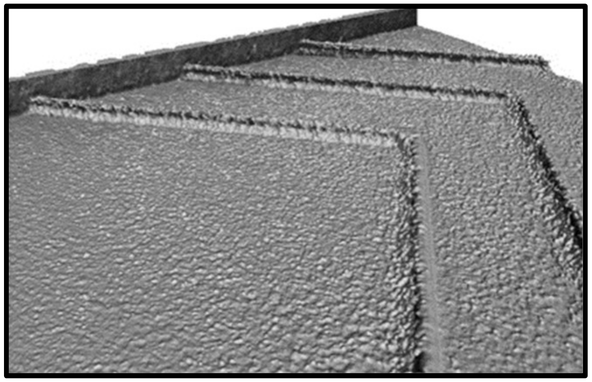


Some features must be machined due to today's AM limitations

Airfoil Feature	Variations Experienced	Explanation of Variance	Best Practice Moving Forward
Dove Tails / Fir Trees 	Unable to meet tolerance	These features have tolerances less than 0.001" which additive cannot yet match	Need the AM vendor to overstock the part so a machining vendor can finish it.
Cooling holes 	Hole collapsing	Holes are either too small or collapse due to print orientation.	Use EDM on the majority of holes. TE slots and larger tip holes have printed well.
Exterior Roughness  	High roughness (>200 RA)	Incorrect build orientation, printing parameters (layer thickness) or machine issues	Trials and experienced vendors with in-house parameters help. Some vendors have consistently less roughness than others and some have better smoothing methods.

Penn State, Pratt and Whitney, and Vertex were able to produce a blade that met key inspection data

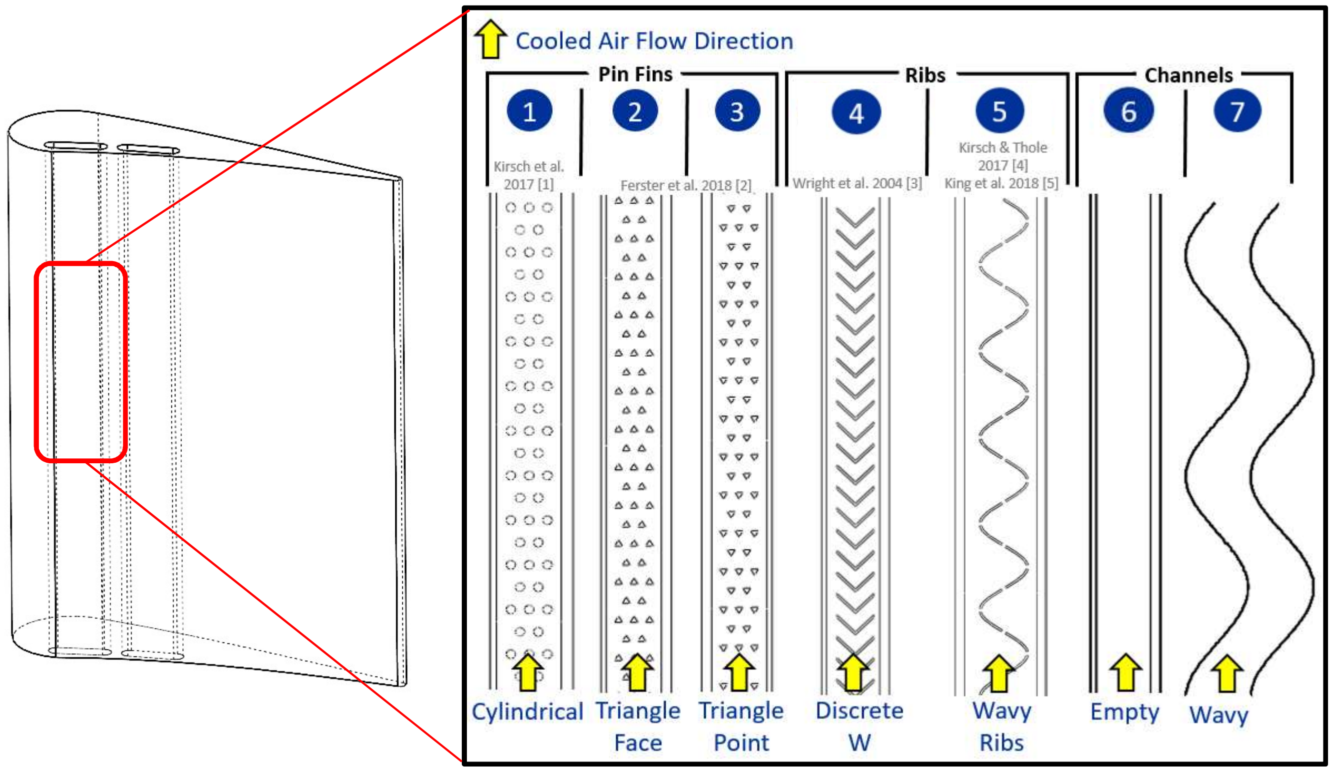
Airfoil Feature	Inspection Method	Comments
Aerodynamic Shape	Blue Light Scan/ CMM	Aerodynamic shape was well within tolerance and better than cast blades
Interior Features	Destructive Testing with Blue Light Scan	Interior ribs (trip strips) printed well even at scale
Overall Flow	Bench Top Test	Overall blade was within 15% of the cast blade
Exterior Roughness	Vertex data	Less than 120 RA on the aerodynamic surface

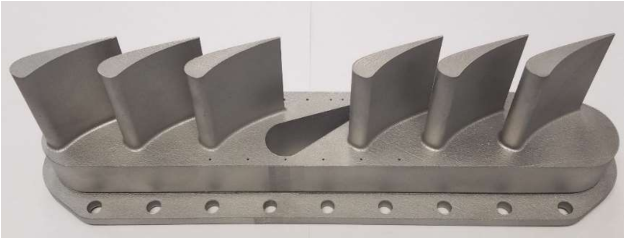


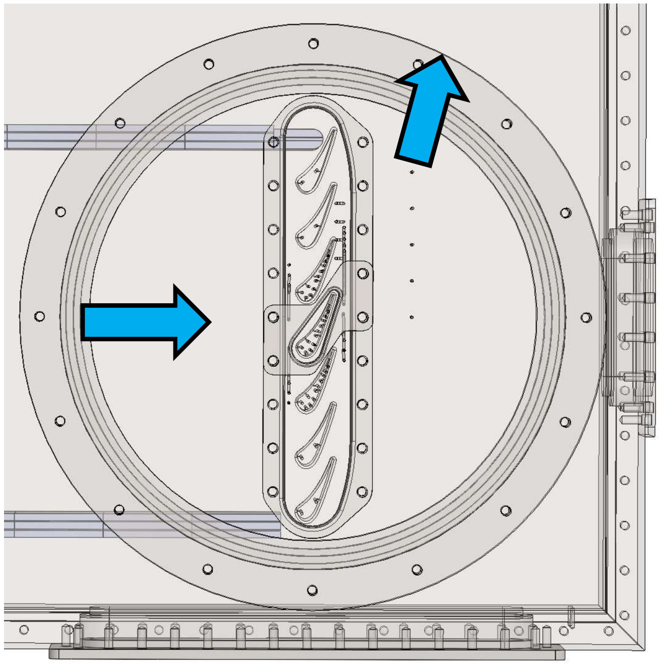
The learning from this program has allowed Penn State and Pratt and Whitney to go after new programs using AM

Program	How Ascent 56 Impacts	Program Benefit
NASA HyTEC (PW is Prime)	Pratt and Whitney is manufacturing turbine blades at the same vendor as Ascent 56 because of their performance. They will be using inspection, printing parameter, and design lessons learned.	The NASA HyTEC program will allow Pratt and Whitney to advance their new blade geometry to a higher TRL that would not have been possible without AM and the Ascent 56 program.
NExT	Lessons learned about inspection and printing parameters allowed START to make informed decisions to successfully print AM vanes and blades.	AM allowed the program to go much faster than casting. START has been waiting for cast blades for over three years while AM took one year.
NASA ULI	Penn State will use its experience in AM to print a new set of blades using Ascent 56 lessons learned.	Cast blades for this project would have been too expensive and not within the program timeline.

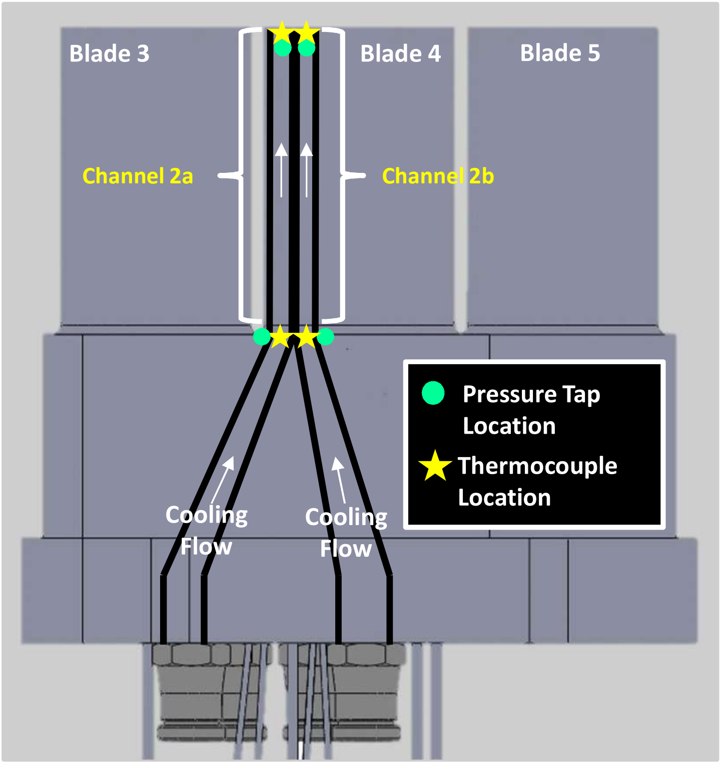
Novel cooling features were packaged into microchannels in a section of the FAA TECH blade, for testing in a high speed cascade

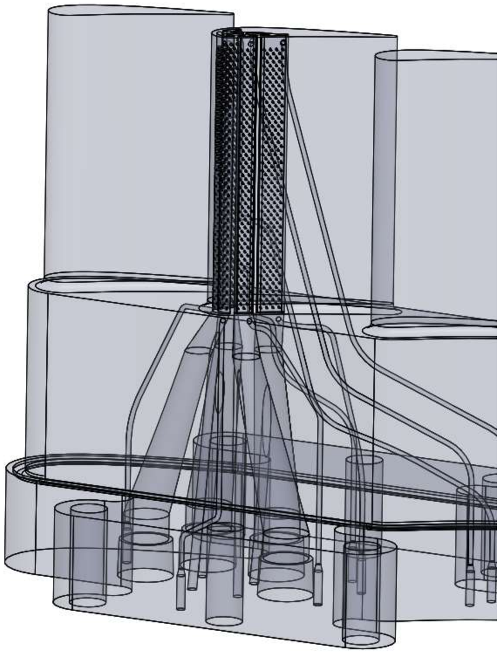






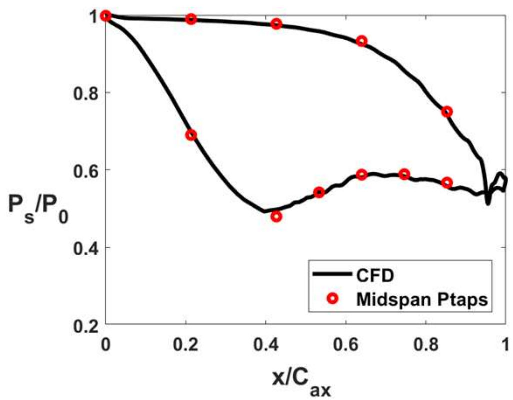
The AM-fabricated test blades contain cooling feeds and internal instrumentation that would otherwise be impossible to create



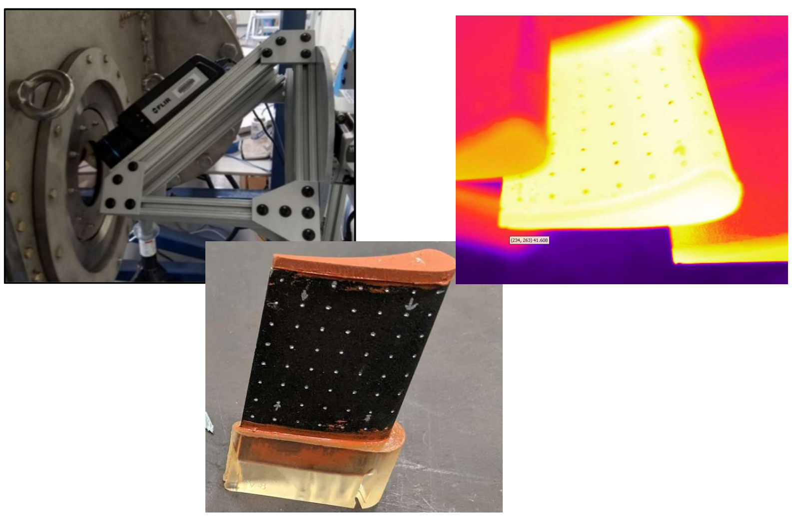


High speed cascade benchmarking has been completed and novel data reduction techniques have been developed

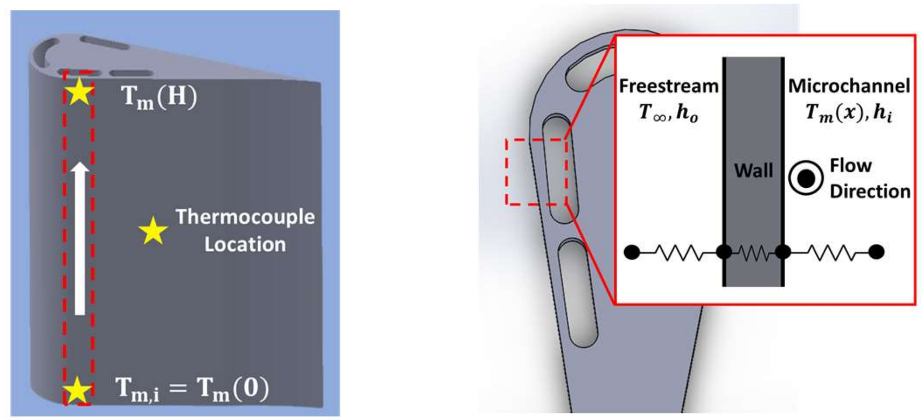
Example of airfoil static pressure



Example IR thermography of surface including spatial calibration



Method to obtain convection coefficients in-situ



<u>Overall</u> convection coefficient:

$$\bar{U} = -\frac{\dot{m}c_p}{A_s}\ln\left[\frac{(T_\infty - T_m(H))}{(T_\infty - T_{m,i})}\right]$$

Heat flux through wall:

$$q(x) = h_o[T_\infty - T_s(x)] \approx \bar{U}[T_\infty - T_m(x)]$$

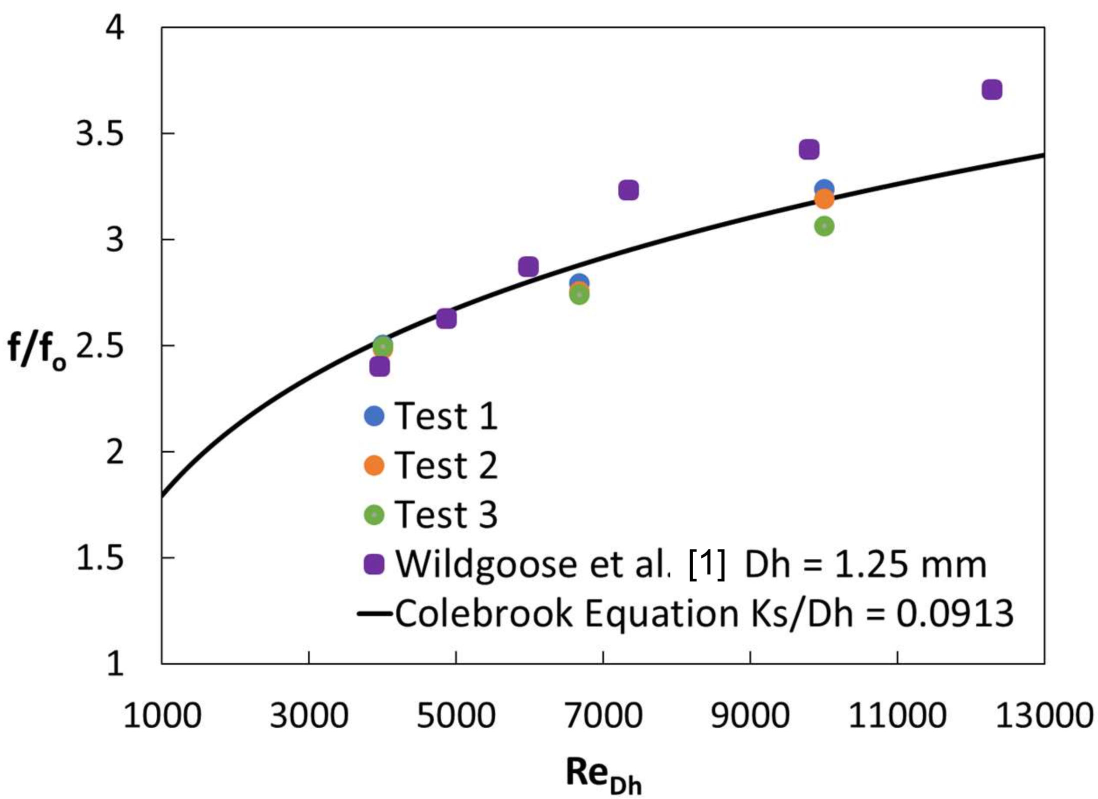
External convection (hot gas path):

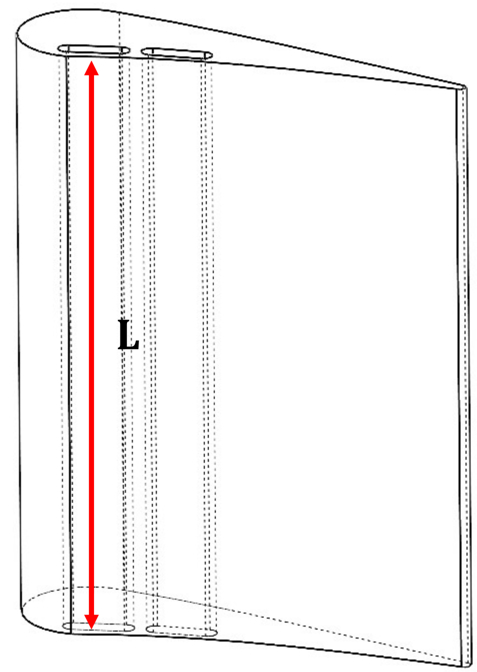
$$h_o = \bar{U}\frac{[T_\infty - T_m(x)]}{[T_\infty - T_s(x)]}$$

Internal convection (inside microchannel):

$$h_i = \frac{1}{\left(\frac{1}{\bar{U}} - \frac{1}{h_o}\right)}$$

The friction factor for the baseline microchannel shows excellent repeatability and compares well to prior data on AM microchannels

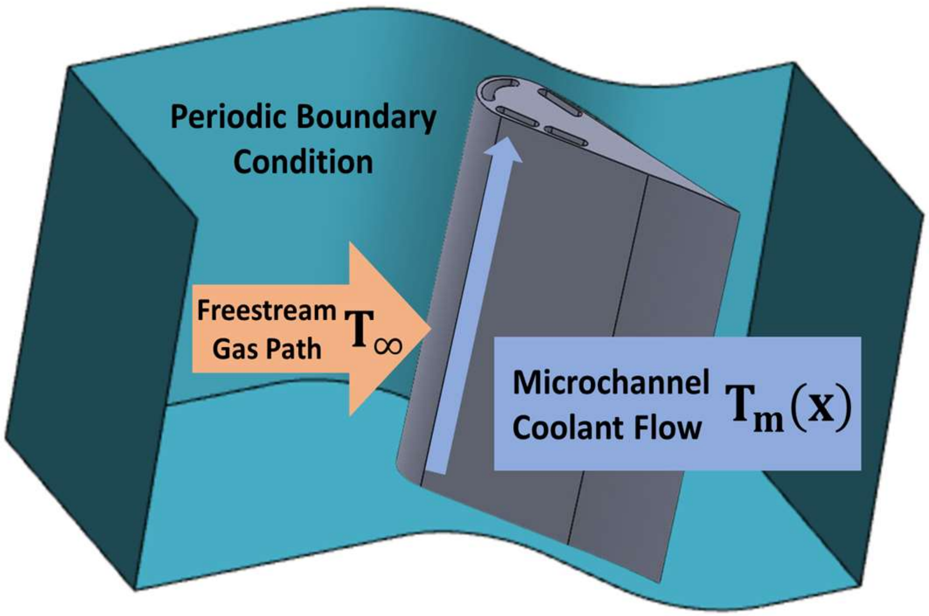


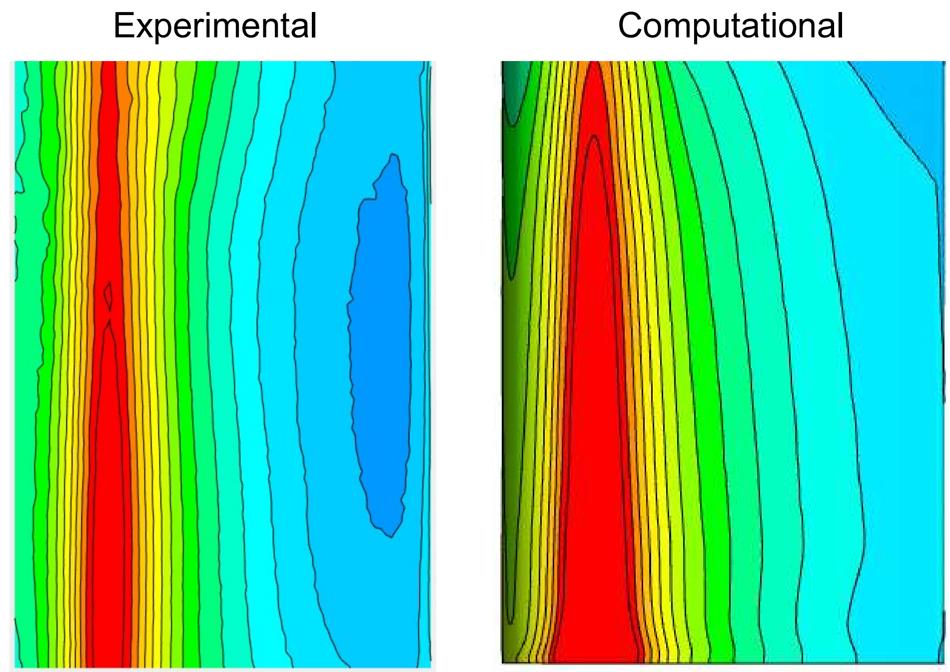


$$f = \frac{\Delta p}{0.5\rho U_m^2}\frac{D_h}{L}$$

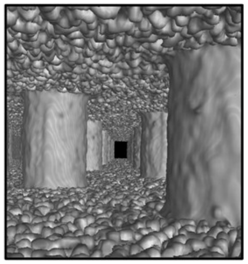
[1] Wildgoose, Thole, Sanders, and Wang, J. Turbomach 2021

Computational predictions of the external metal temperature with the baseline microchannel compare reasonably to experiments

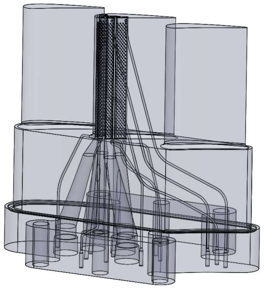




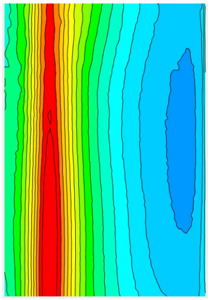
This program has already had significant impact in development of advanced manufacturing for improved turbine efficiency



We have acquired a lot of learning through this program about applying AM to turbine airfoils to advance the state of the art



Novel high performance cooling designs have been fabricated through AM and will be analyzed using CT scanning



Analysis of novel cooling designs will provide information about cooling performance enhancement potential

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