DOE Projects: Cooled Blades and NExT

Nov 2021 UTSR Update

Department of Mechanical Engineering

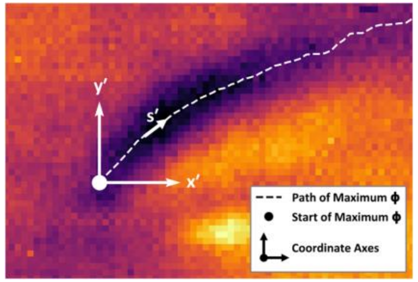
Research Staff

Michael Barringer	Assoc. Res. Prof
Reid Berdanier	Asst. Res. Prof
Jeremiah Bunch	Eng. Technician
Scott Fishbone	Project Manager
Joel Wagner	Res Scientist
Karen A. Thole	Professor

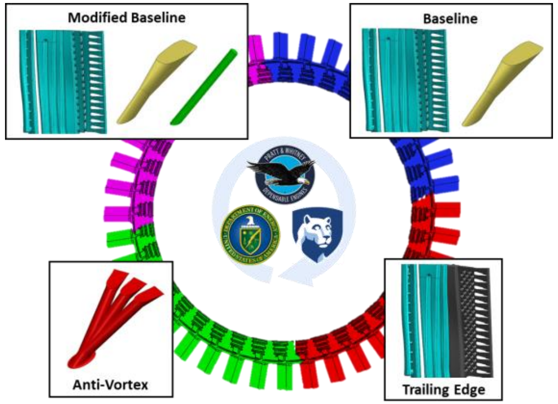
Graduate Students

Eric Deshong	Emma Veley
Nicholas Gailey	Brandon Fallon
Maria Rozman	Justin Wolff
Thomas Corbett	Pete Wilkins
Alexander Wildgoose	Cynthia Letting
Kelsey McCormack	Chad Schaeffer

This update provides a summary of recent START 2021 progress made towards supporting two important DOE-NETL funded programs



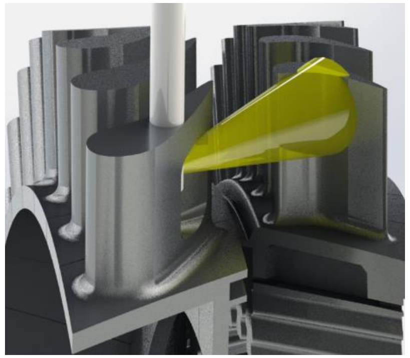
Instrumentation Updates



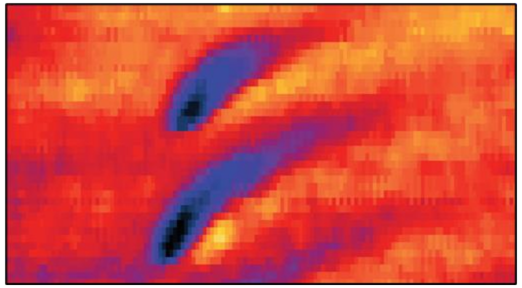
Cooled Blades Project

NExT Project

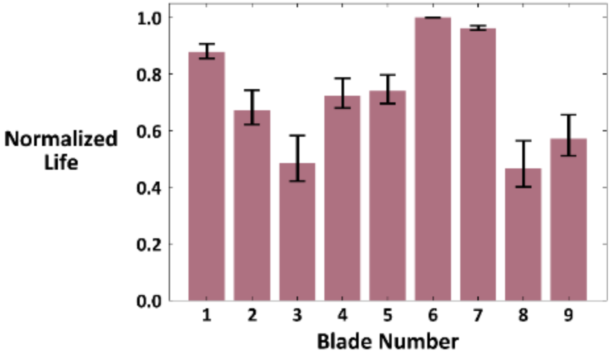
Infrared (IR) temperature measurements of the blade surface were collected and analyzed to assess part-to-part variability



Thermal imaging capabilities



Blade-to-blade and hole-to-hole cooling inconsistency

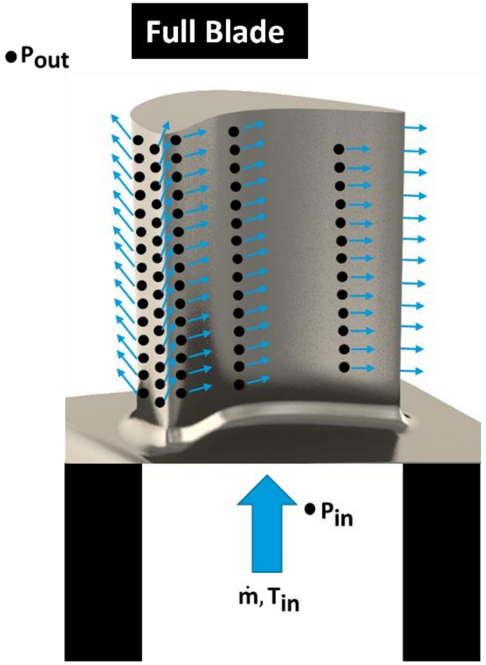


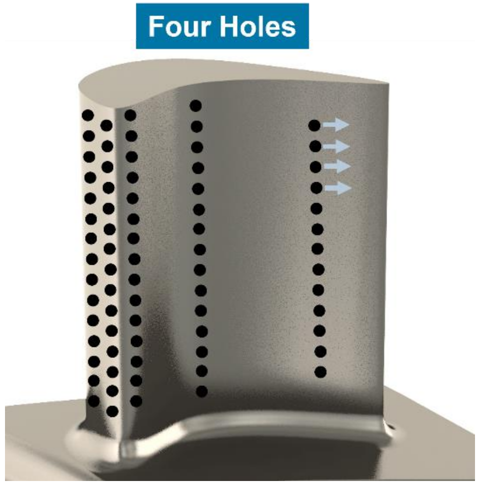
Blade life variability resulting from cooling inconsistencies

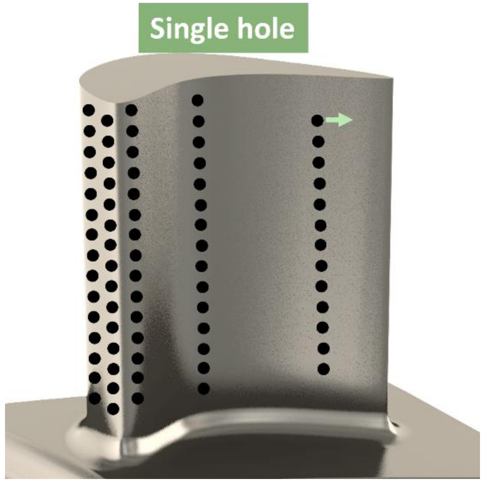
Flow parameters between nine blades tested at the nominal pressure ratio varied by ±15% for the full blade and nearly 50% through a single hole

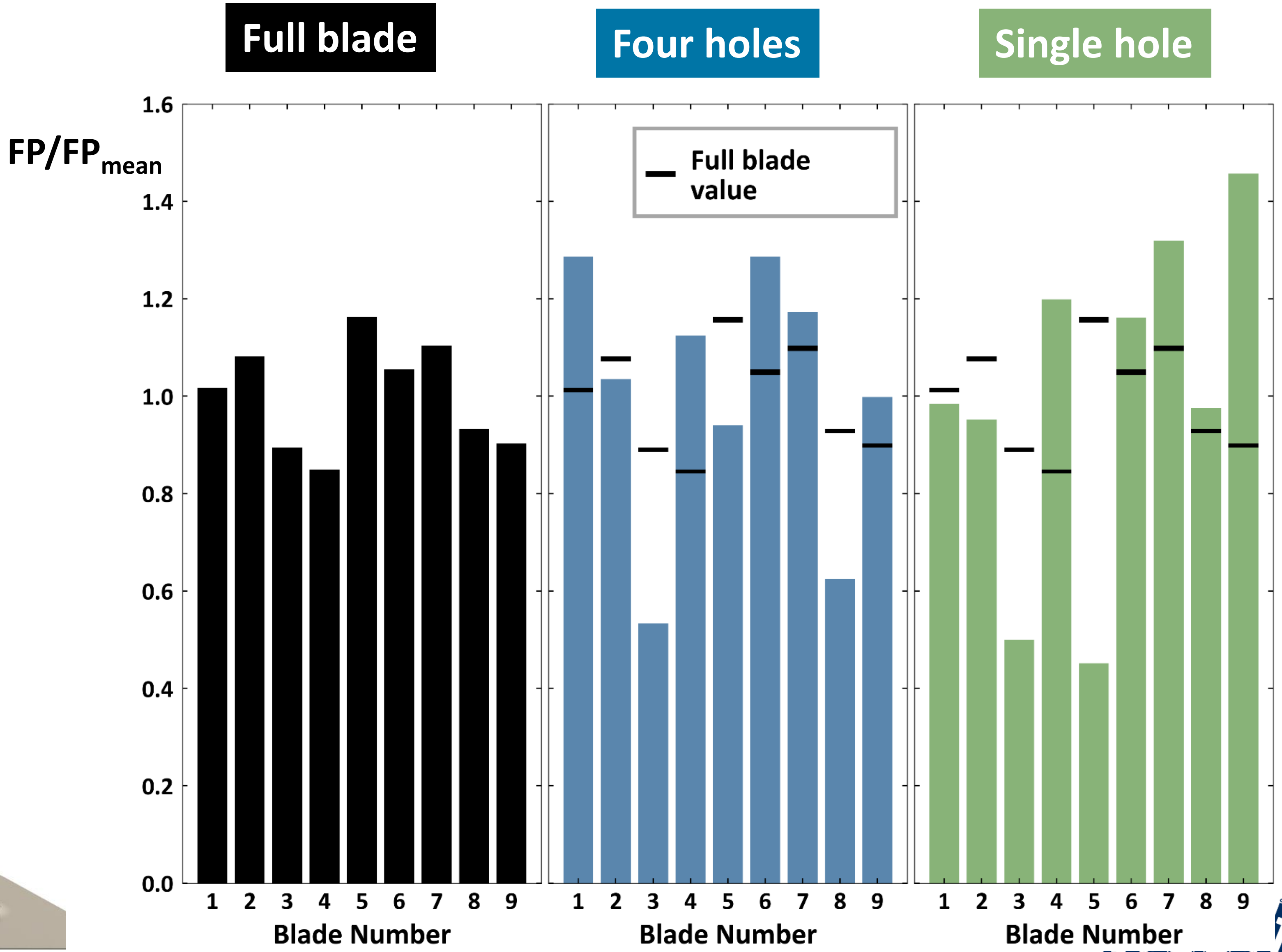
$$PR = \frac{P_{in}}{P_{out}}$$

$$FP = \frac{\dot{m}\sqrt{T_{in}}}{P_{out}}$$

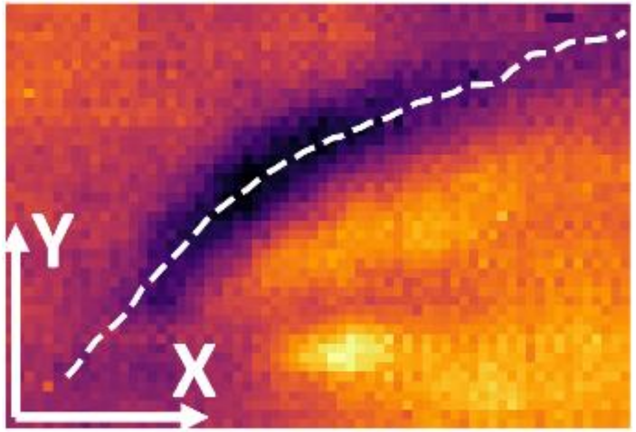




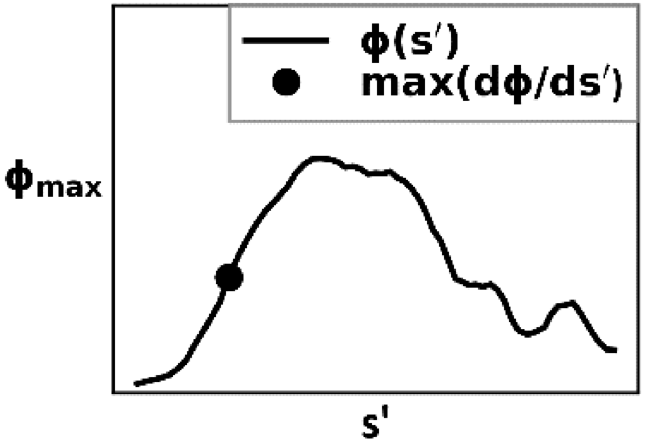




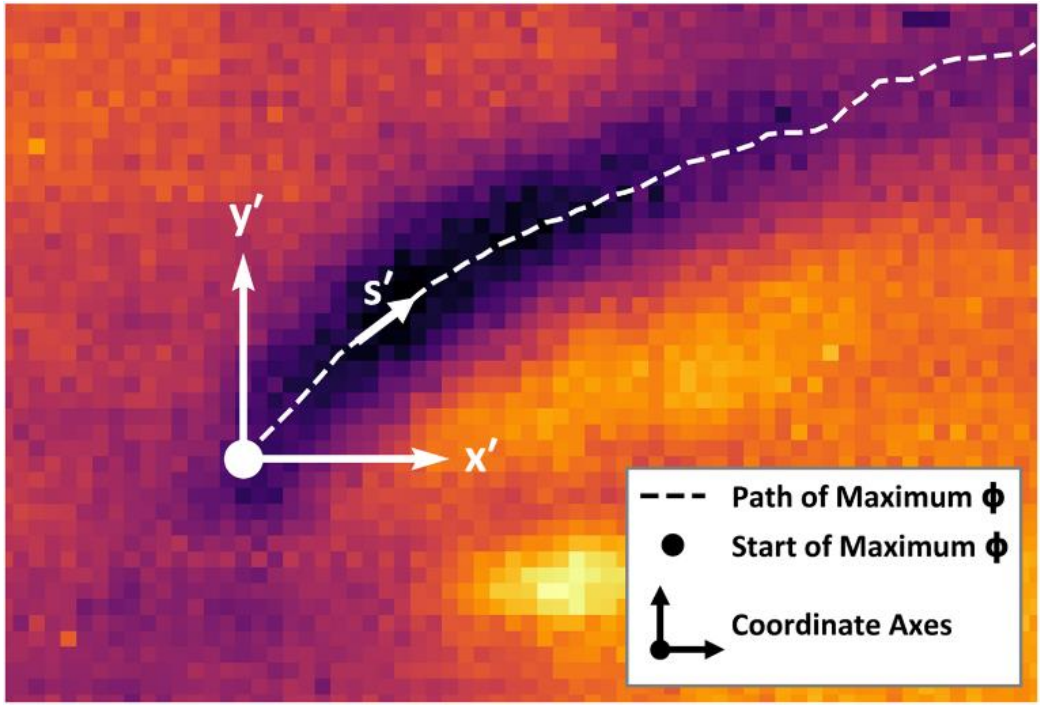
To establish the coordinate system (s' = 0) the maximum slope was used; several methods were compared resulting in nominally the same approximate location



Determine path of maximum effectiveness

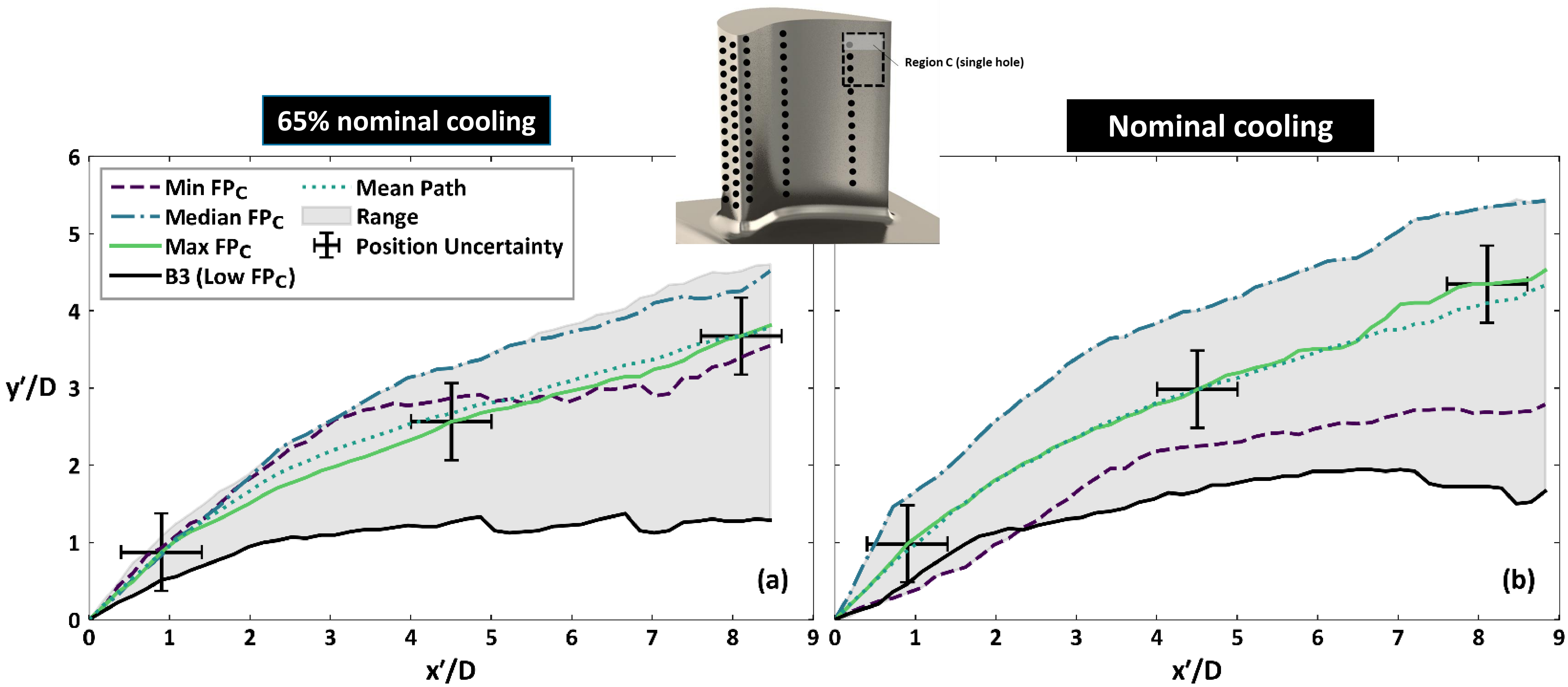


Find location of maximum slope $d\phi/ds'$

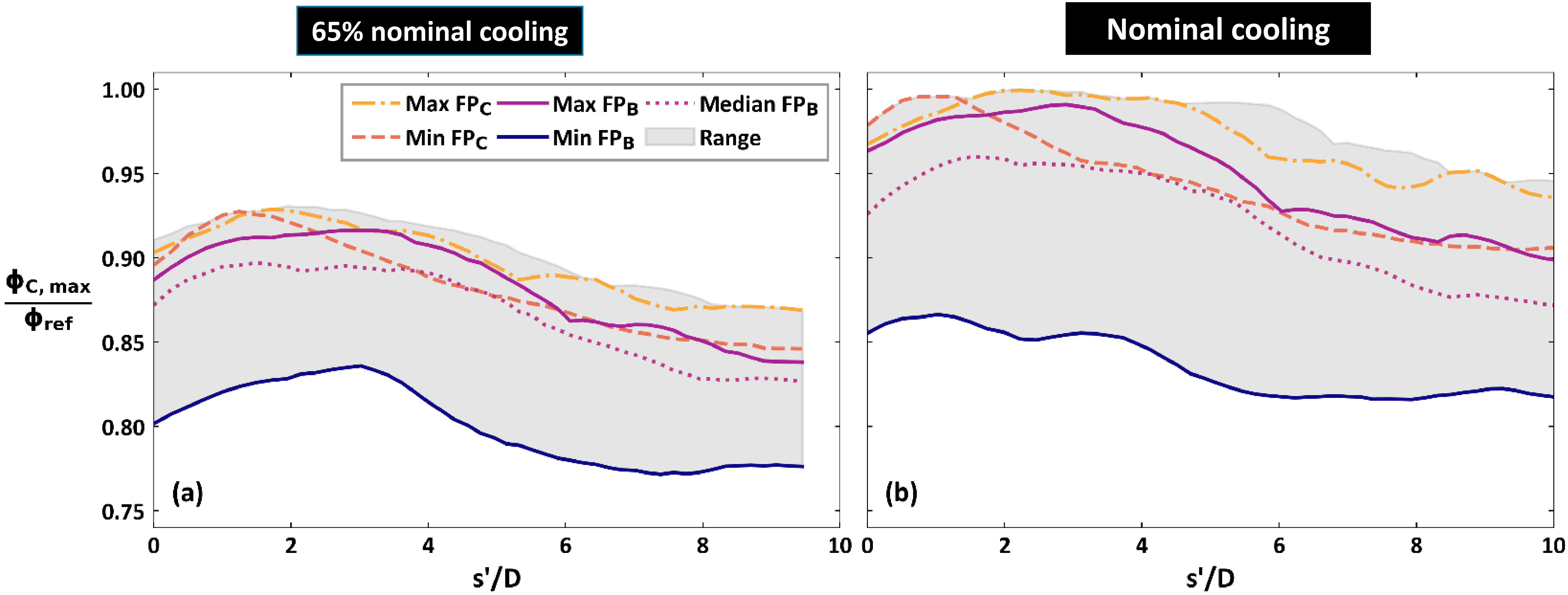


Use location of maximum slope as origin of (x', y') coordinates

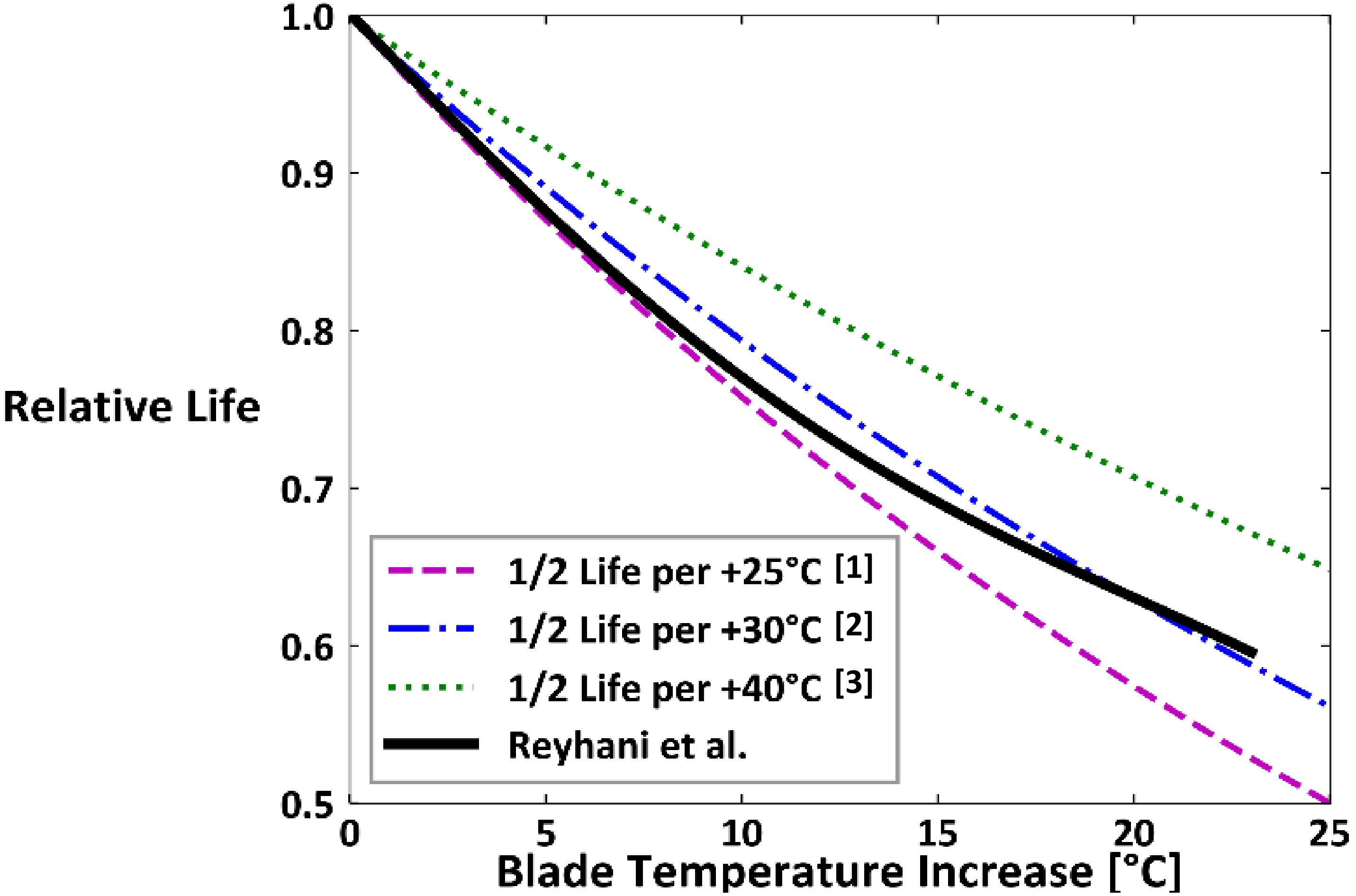
Film cooling trajectories showed a wider variability at nominal cooling compared with 65% cooling



Maximum effectiveness varied between blades by about 10% at 65% cooling flow rate and nearly 15% at the nominal cooling



Blade life is a strong function of surface temperature, and part-to-part variations in temperature can lead to variations in part life



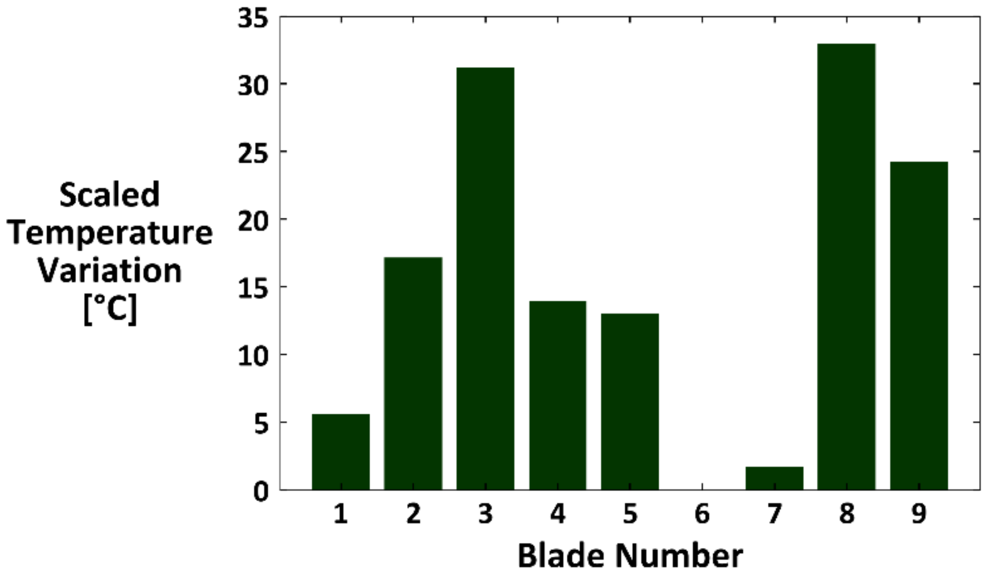
1. [Bogard and Thole] 2. [Bunker et al.] 3. [Han and Wright]

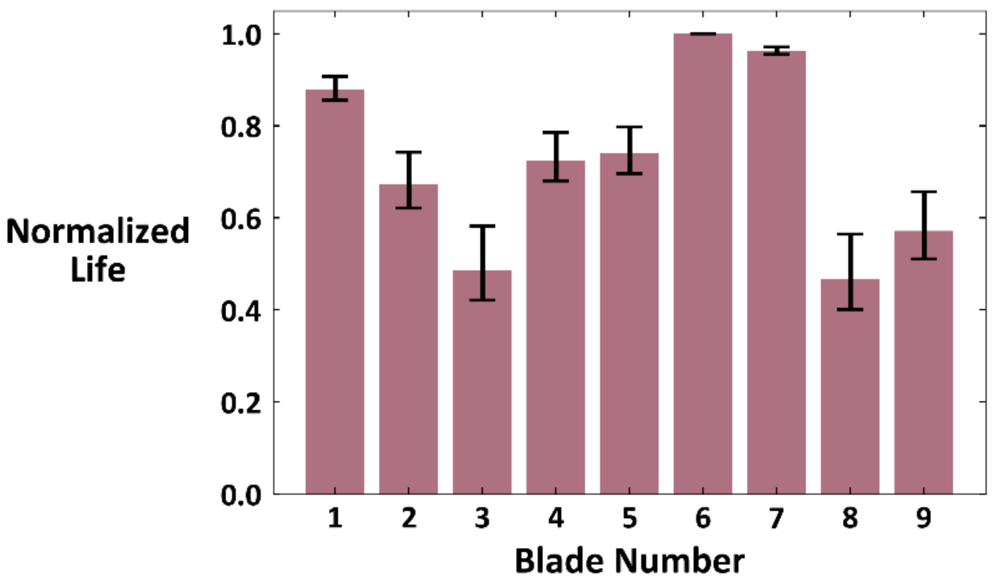
Variations in normalized effectiveness were scaled to engine conditions to show the expected variations in temperature and life

Design values for engine conditions, NASA E³ [Halila et al.]

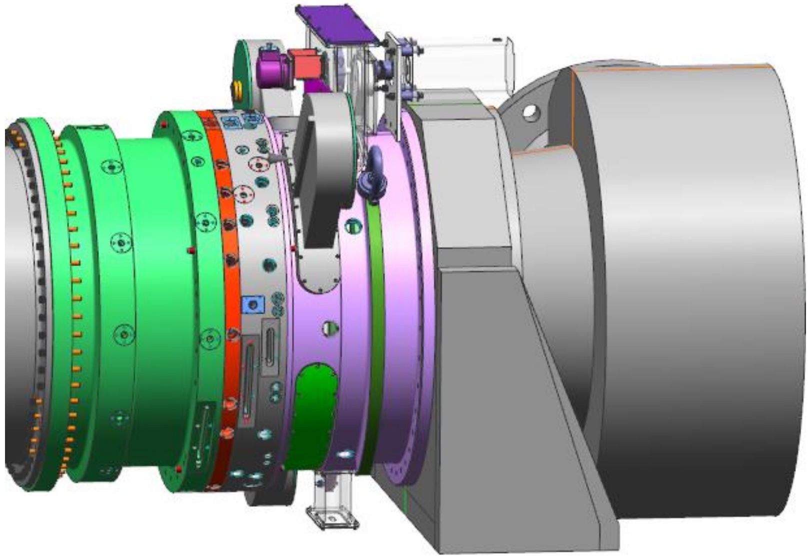
Specification	Design Value
Blade Inlet Temperature, T_∞	1396°C (2545°F)
Cooling Air Temperature, T_c	628°C (1162°F)
Blade Overall Effectiveness, ϕ	0.48

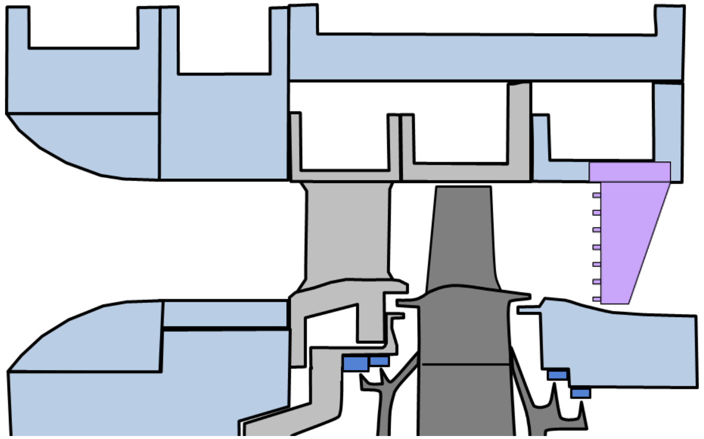
Variations in ϕ/ϕ_{ref}

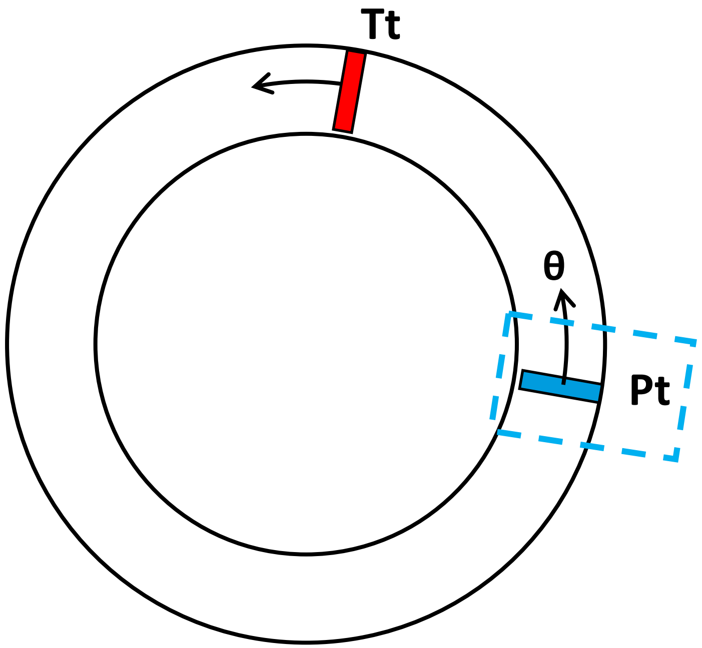


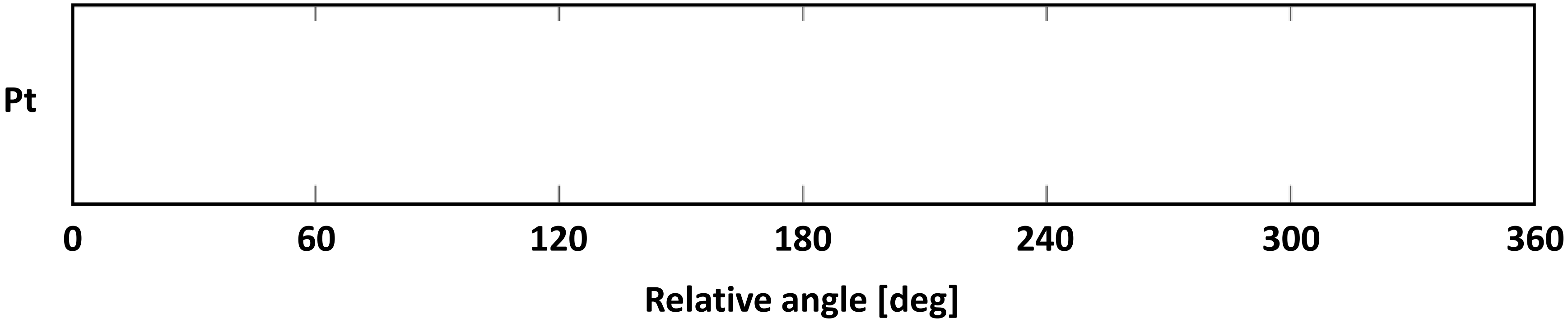


A custom traversing mechanism has been commissioned to enable stage exit measurements from multi-element Pt and Tt rakes around the full circumference



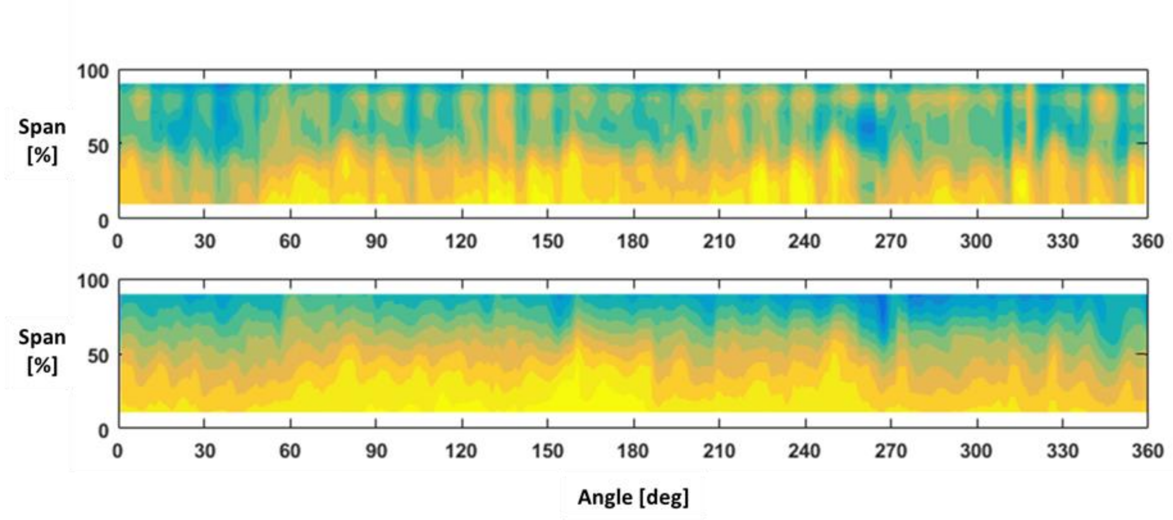


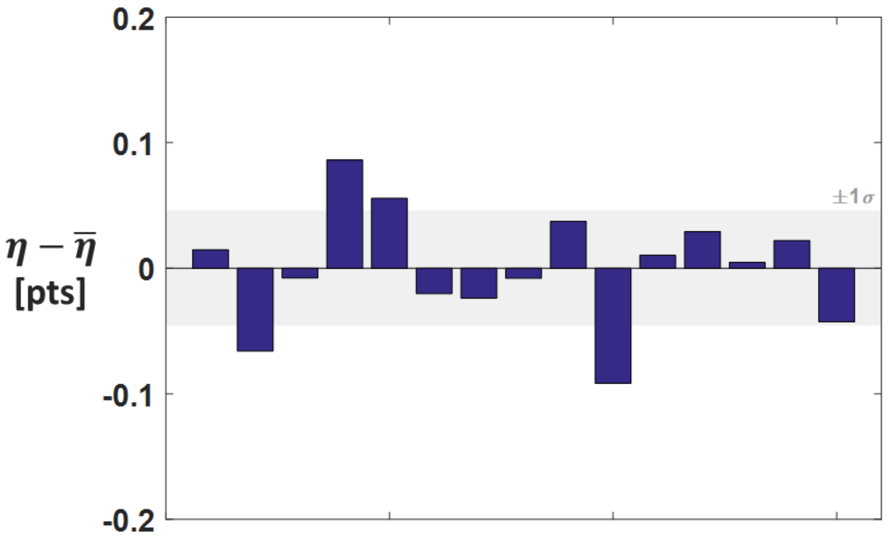




DeShong et al., 2021, “Evaluating the Influence of Rotor-Casing Eccentricity on Turbine Efficiency Including Time-Resolved Flow Field Measurements,” GT2021-59112

Unique traversing rakes for efficiency measurements have been introduced with demonstrated capabilities for calculated aerodynamic efficiency repeatability





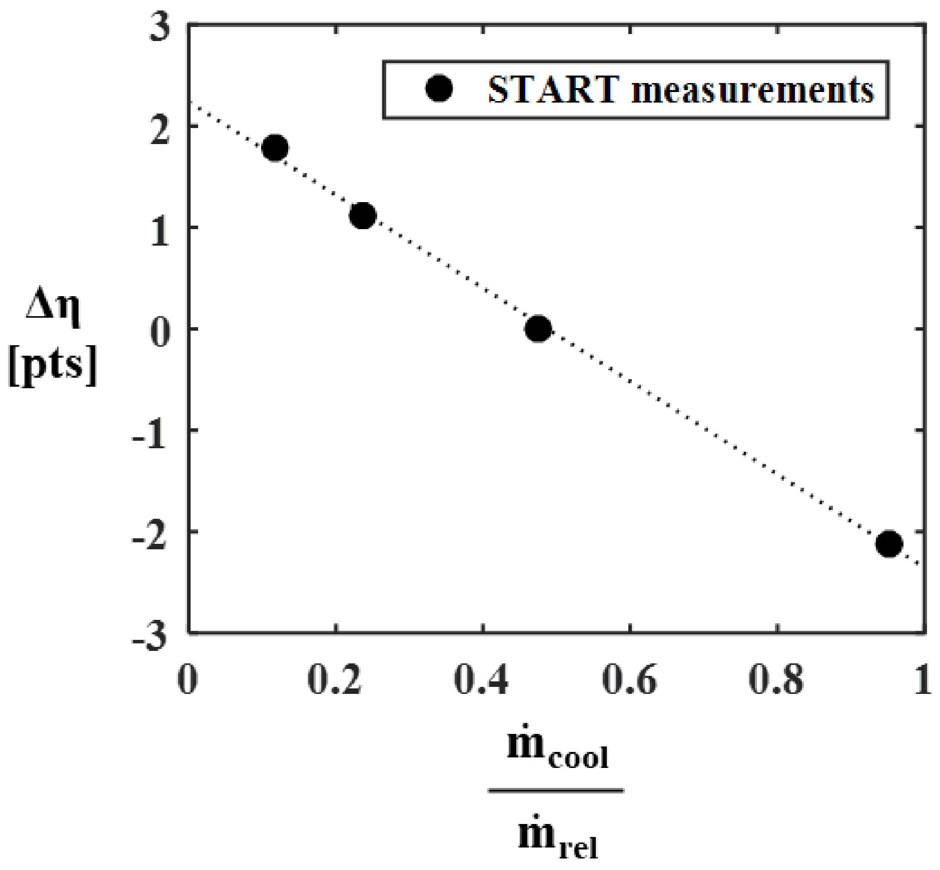
360-degree traversing capability at the turbine stage exit provides unprecedented spatial resolution for integrated efficiency calculations

Efficiency measurement campaigns using this equipment have shown test-to-test repeatability better than 0.1 points

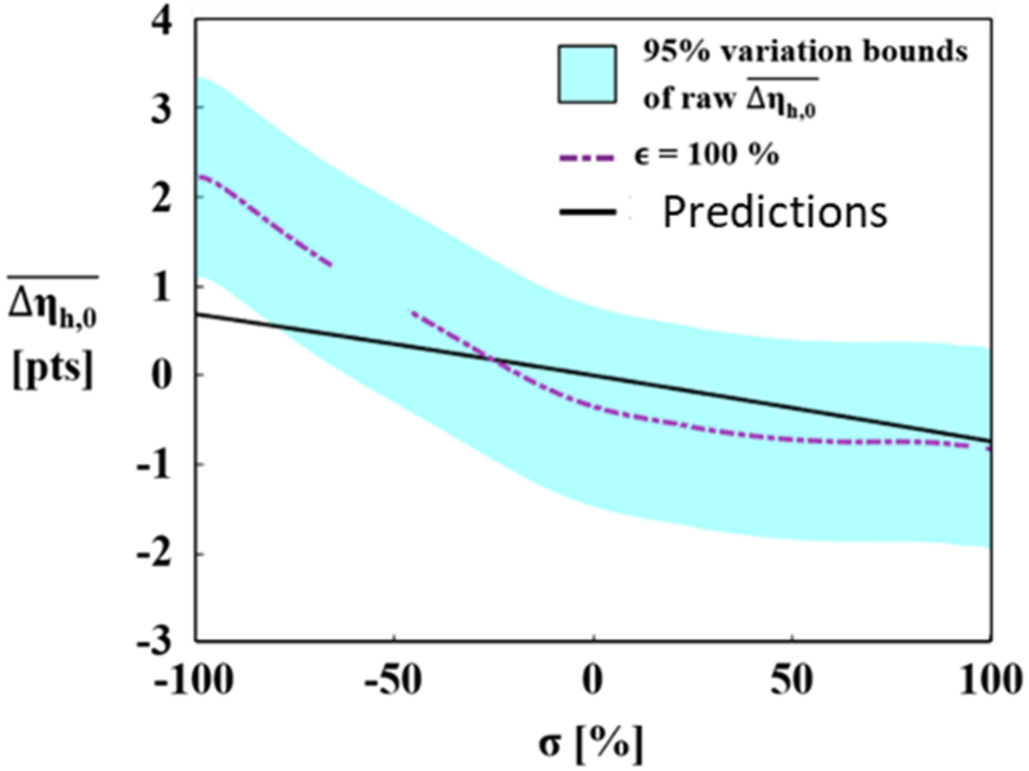
DeShong et al., 2021, "Evaluating the Influence of Rotor-Casing Eccentricity on Turbine Efficiency Including Time-Resolved Flow Field Measurements," GT2021-59112

Cumulative results from START show that the greatest opportunity for increasing efficiency comes from reducing TOBI flow and tip clearance

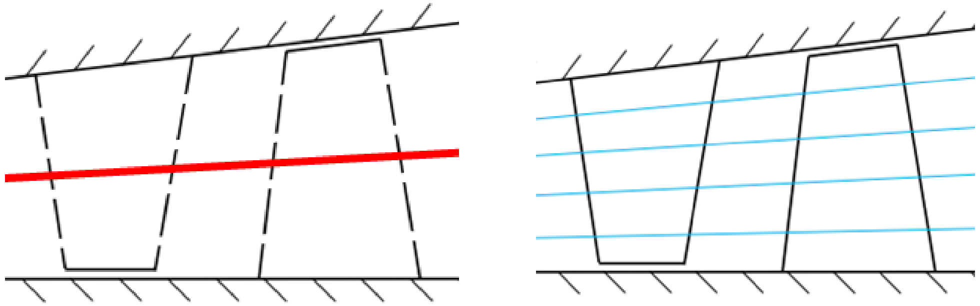
Cooling Flow Impacts



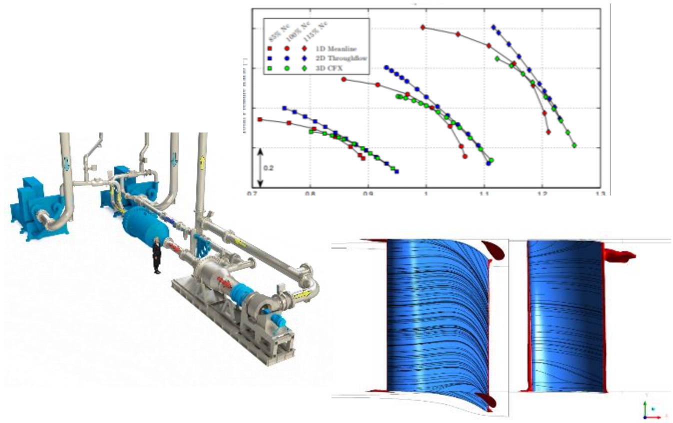
Tip Gap Impacts



START is building new predictive capabilities through the NExT umbrella to further improve test program planning and physics-based understanding



1D and 2D software tools are being utilized to create NExT models and understand performance sensitivities

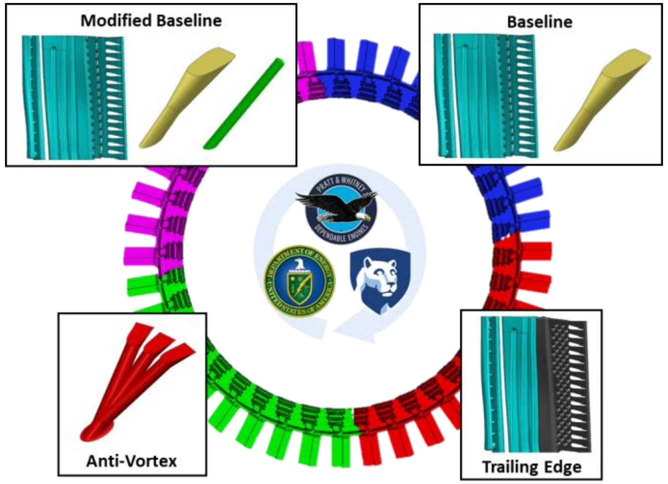


Lower-order results will be compared with pre-test CFD predictions and START rig experimental data

Both the NExT and Cooled Blade projects are in manufacturing with hardware arriving in the coming months

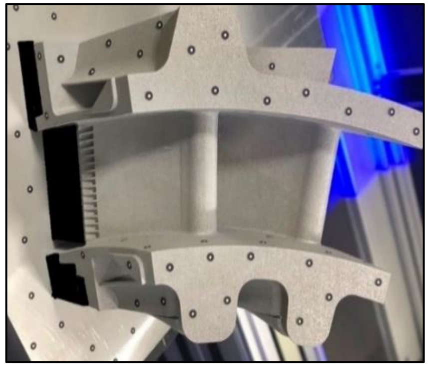
DOE Cooled Blades

The blades are being cast and prepared for machining. Arrival to Penn State is estimated in Q4 2021



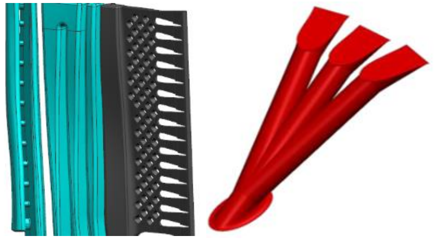
National Experimental Turbine (NExT)

All parts are in manufacturing, with casting and additive blade and vane trials complete. AM and stationary hardware arrival is in Q1 2022.

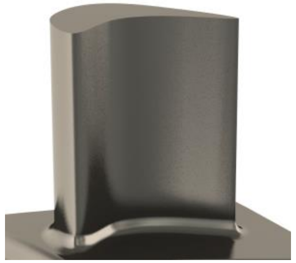


START has been evaluating internal and external blade cooling technologies under sponsorship from DOE-NETL

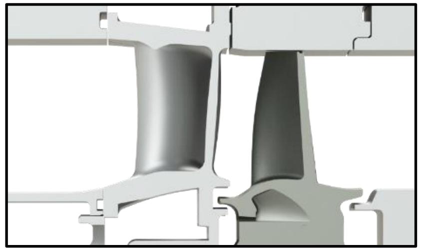
NETL Cooling Features

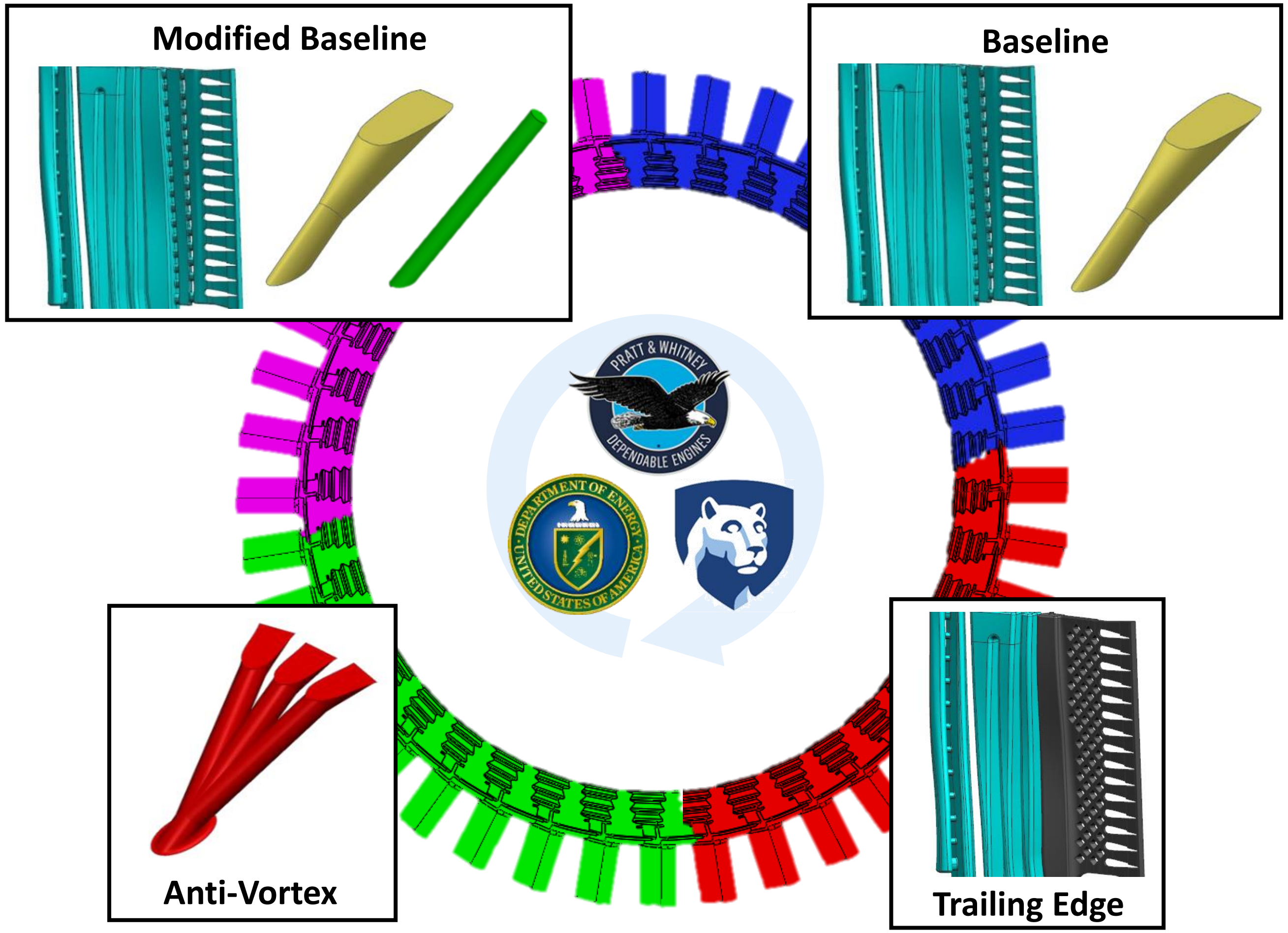


PW Blade Geometry



PSU START Rig



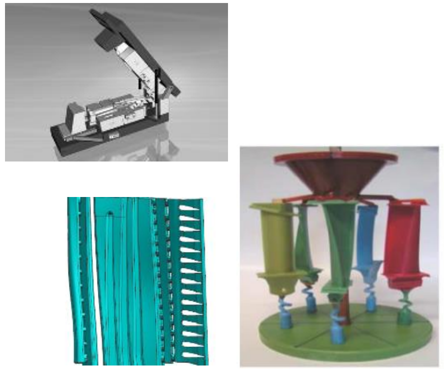


To help ensure the program’s success, Penn State provided a subaward to Pratt and Whitney for technical support during the blade manufacturing process

Scott Fishbone and Michael Barringer

Carl Verner and Kendall Konrath

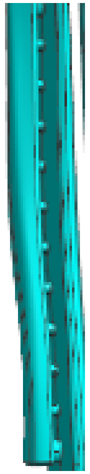
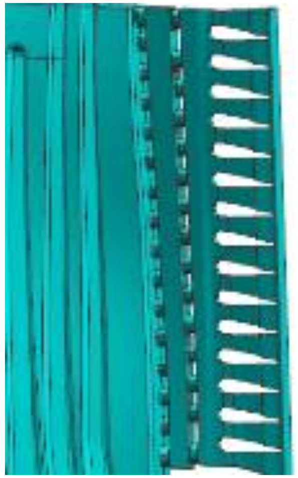
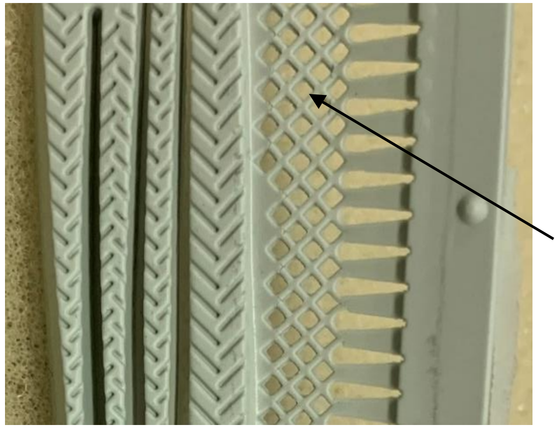
Tooling/Cores/Wax Patterns



Casting

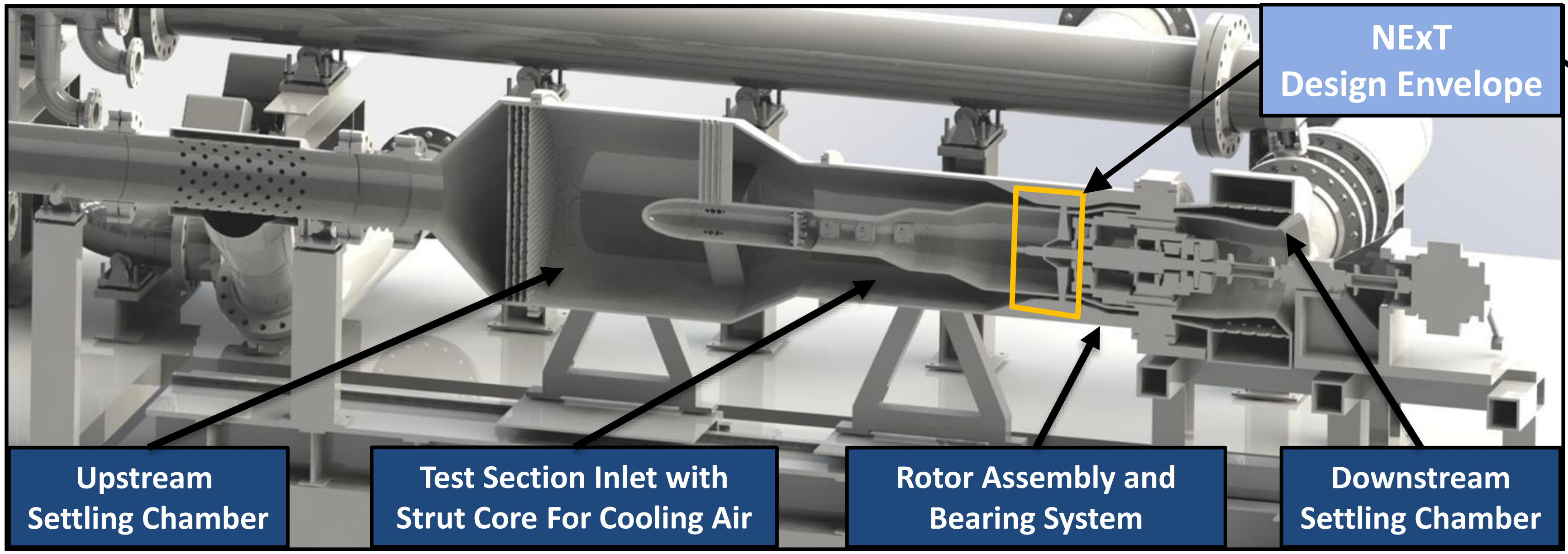
Machining

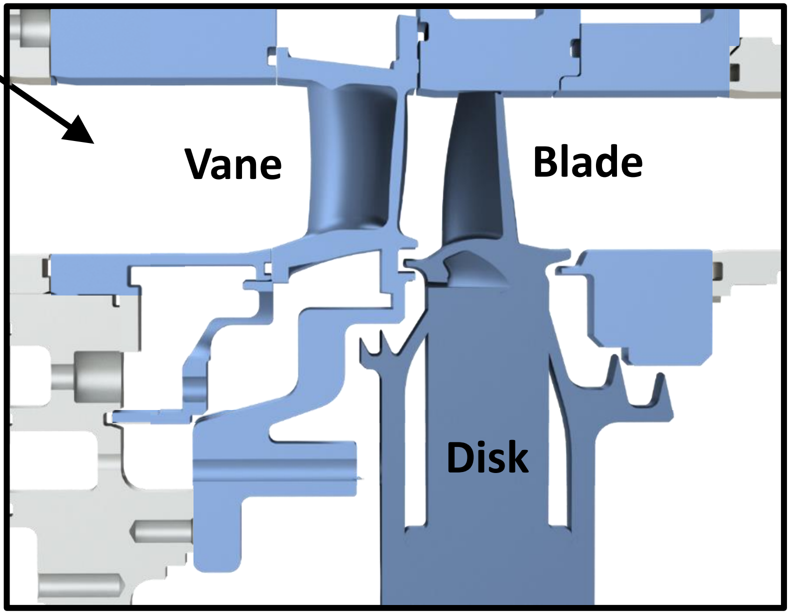
Ceramic core manufacturing has advanced in 2021 with many successful batches for the baseline design, while the pedestal design has proved more challenging

	Leading Edge	Baseline Design (V1) Center and Trailing Edge	Diamond Pedestal Design (V2) Center and Trailing Edge
Design			
Actual			

High Quantity of Fractures in This Zone Upon Batch Completion
25-55% Yield

National Experimental Turbine (NExT) Project
AM and Schedule Update





NExT

NATIONAL ENERGY TECHNOLOGY LABORATORY

PRATT & WHITNEY — DEPENDABLE ENGINES

Solar Turbines — A Caterpillar Company

AGILIS — Revolutionary Insight

Honeywell AEROSPACE

SIEMENS — Ingenuity for life

The current NExT project status has hardware delivery to START beginning at the end of 2021, with testing beginning in early 2022

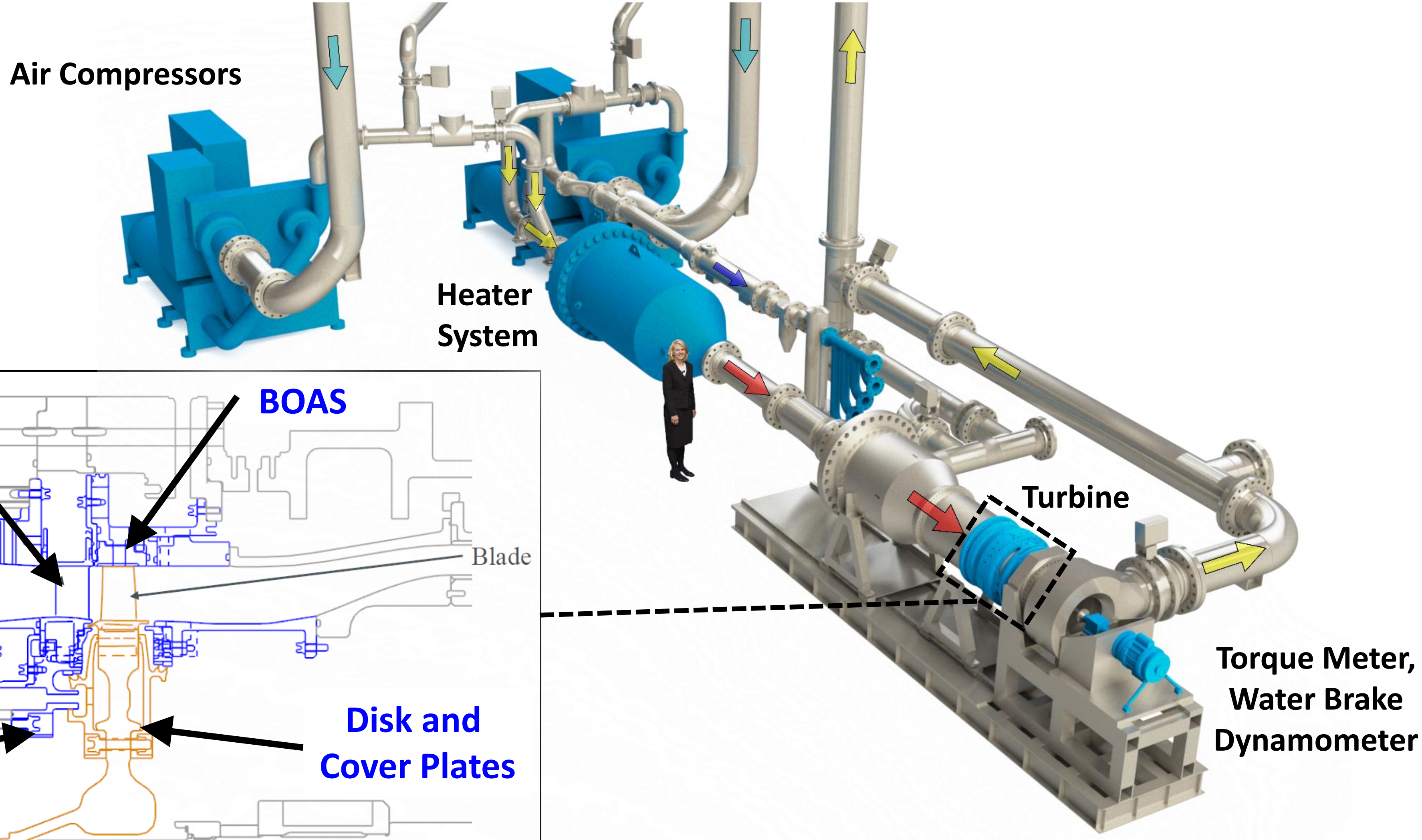
2019	• RFI: Solicit Input from Partners on NExT Geometry and Requirements Perform Turbine Design Vendor Bidding and Selection • Kick-Off: Agilis Kick-off to Begin Conceptual Design, September 2019 • CDR: Conceptual Design Review, December 2019
2020	• PDR: Preliminary Design Review, April 2020 • DDR: Detailed Design Review, November 2020 • DDR Follow-up: Individual Team Members, December 2020
2021	• Final Detailed Design • Production Definition • Manufacturing • Delivery of NExT Hardware Begins
2022	• Delivery of NExT Hardware Completed • Testing of Additively Manufactured Blades and Vanes • Testing of Cast Blades and Vanes

Complete

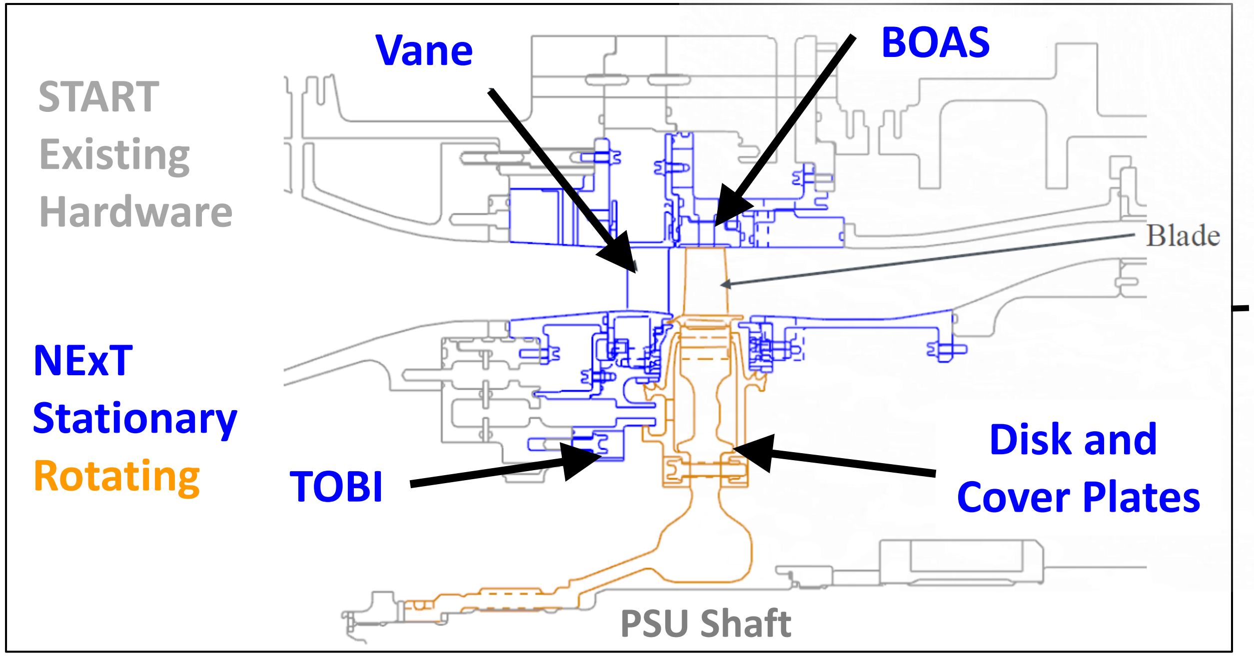
In Progress

Upcoming Tasks

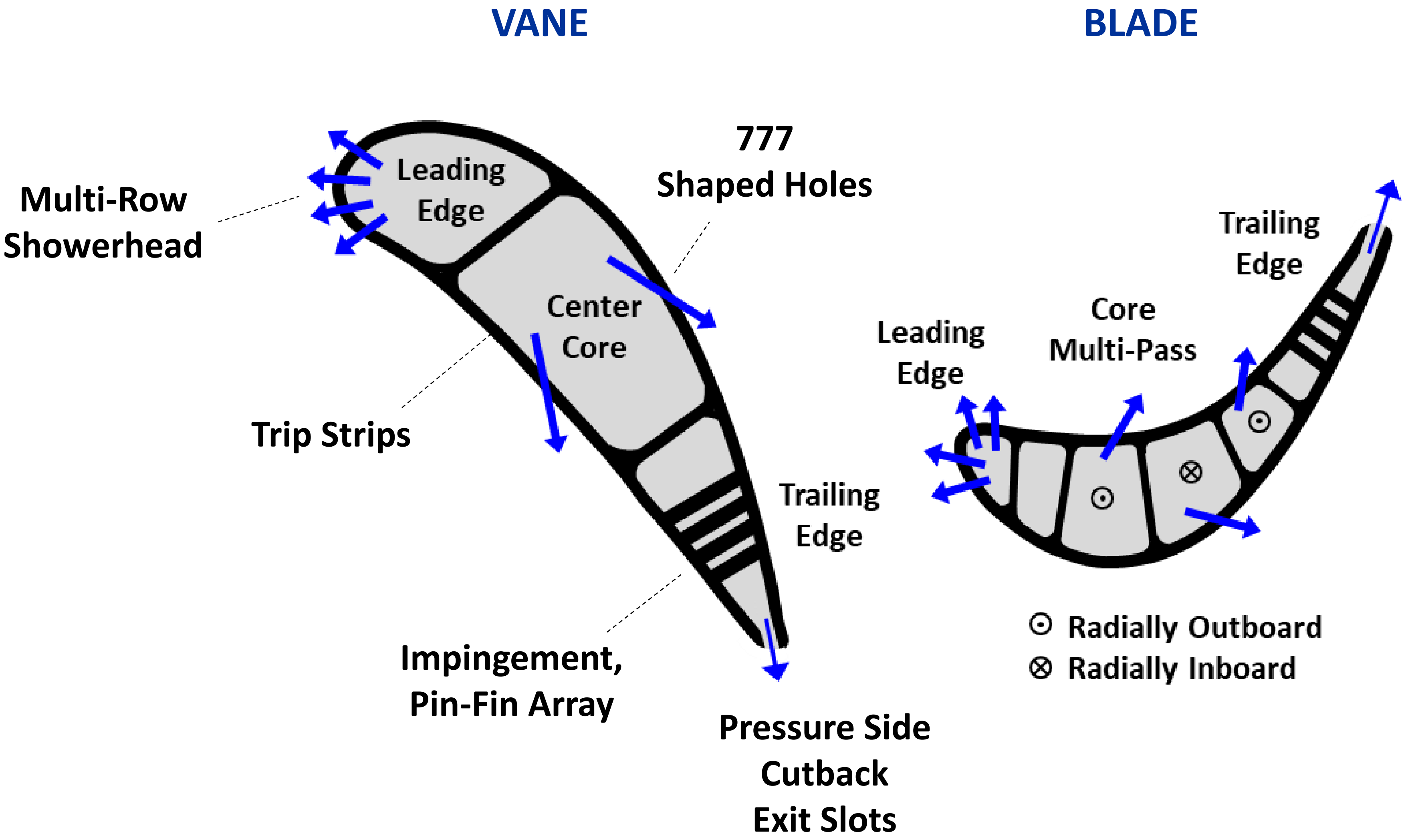
Recall the START turbine test section for NExT includes new vanes, blades, TOBI air pre-swirl, disk and cover plates, blade outer air seal, and aft rim seal



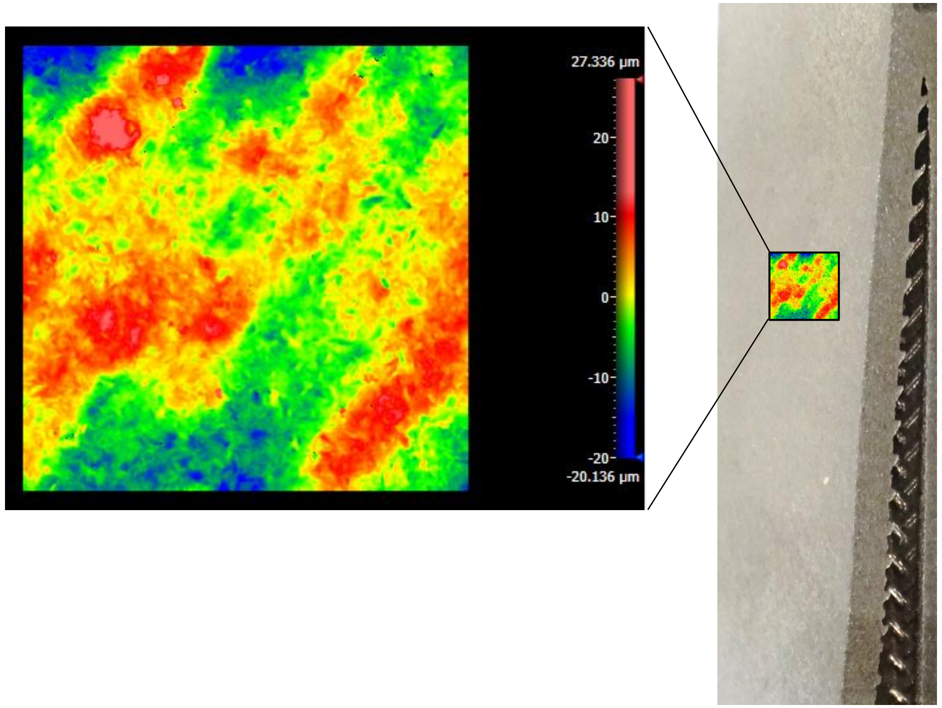
NExT Cross-Section

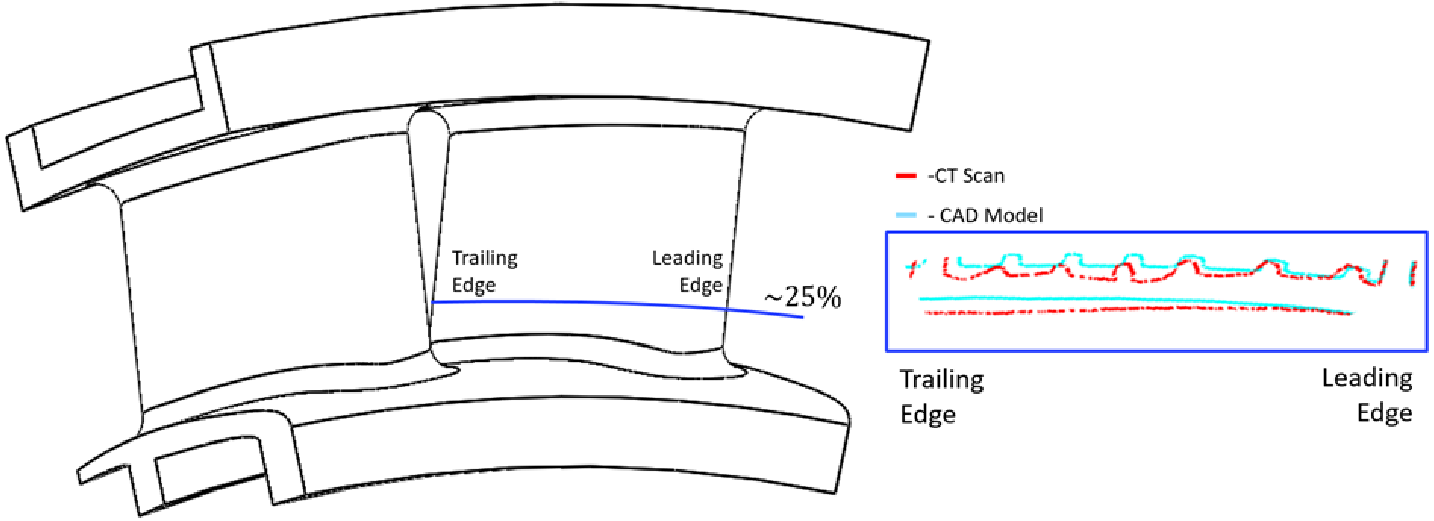


The cooling architecture for NExT is representative of modern high-pressure turbines including dedicated cooling for the leading edge, core, and trailing edge



Initial assessments of AM trial parts show high quality internal features, and characterizations are underway to quantify roughness and overall geometry



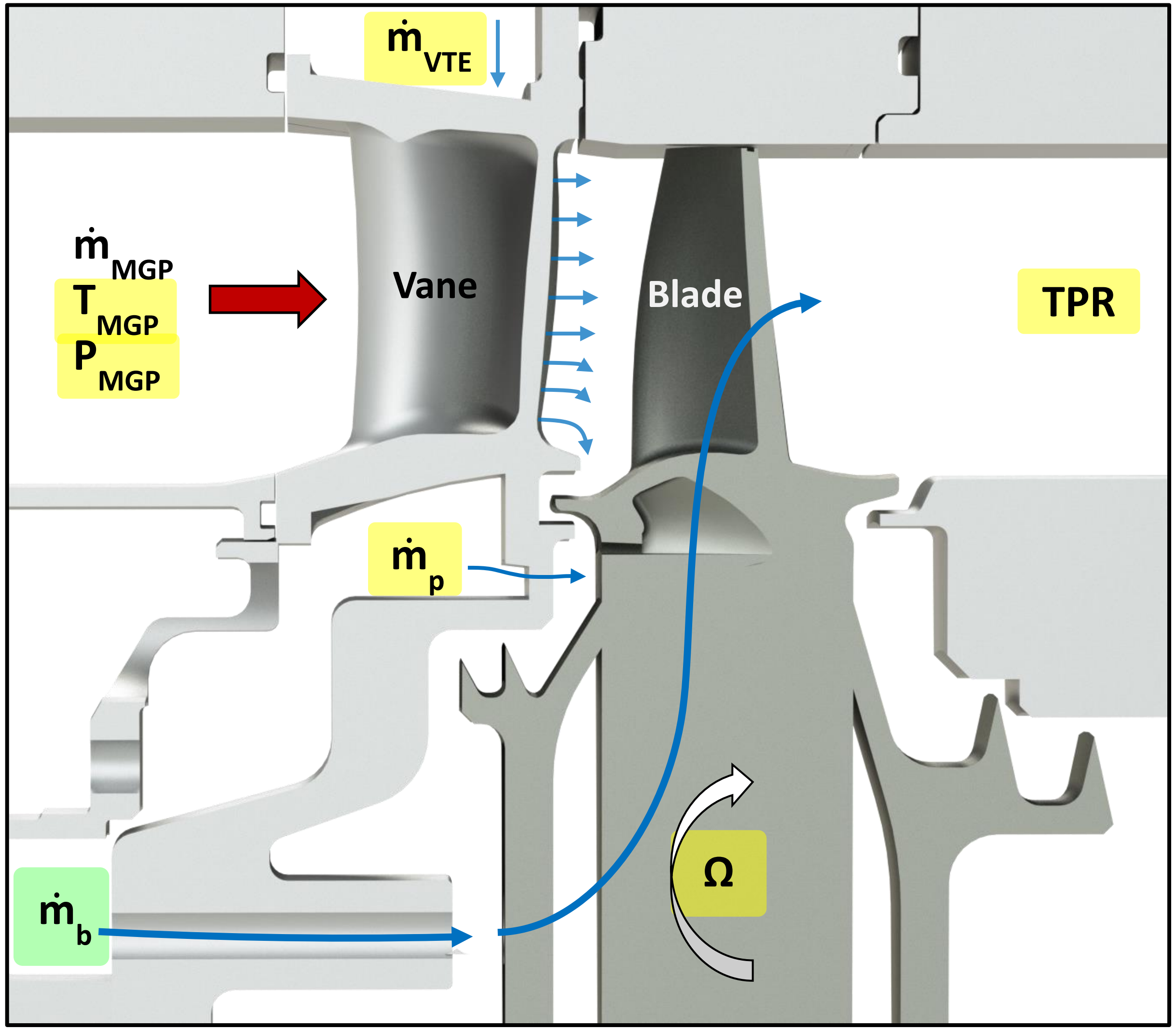


Airfoil	Interior Roughness (µin)	Exterior Roughness (µin)
Vane	Ra ≈ 640	Ra ≈ 280
Blade	Ra ≈ 520	Ra ≈ 400

***Typical AM: Ra ≈ 400 µin**

Stimpson, C. K., Snyder, J. C., Thole, K. A., and Mongillo, D., “Scaling Roughness Effects on Pressure Loss and Heat Transfer of Additively Manufactured Channels,” J. Turbomach, vol 139(2), pp. 021003, 2016.

A preliminary test matrix has been drafted to assess the influence of different turbine operating parameters on blade cooling performance

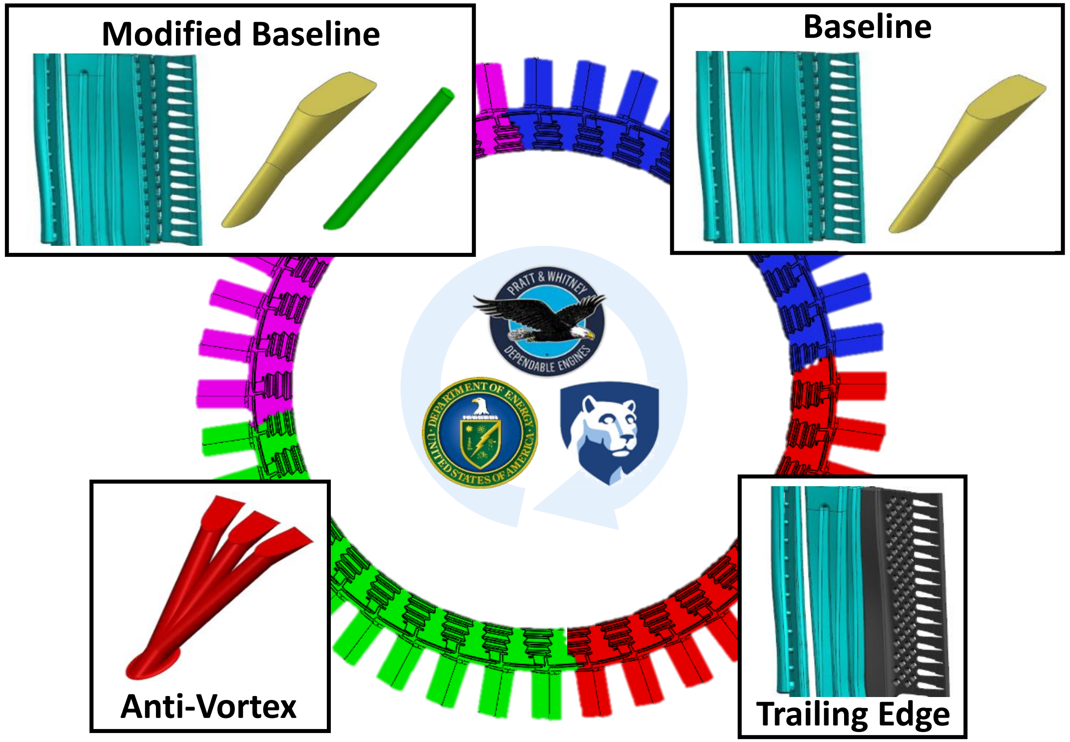


- Sweep blade flow rate, $\dot{m}_b$
- Nominal operating conditions
- Vary speed parameter, Re_Φ (Ω, T_{MGP})
- Vary Inlet Re (P_{MGP})
- Vary Total Pressure Ratio (TPR)
- Vary Other Cooling Flows ($\dot{m}_p$, $\dot{m}_{VTE}$)

A NExT Computational Advisory Board has been formed with membership from all partners to lead the CFD analysis and coordinate with experimental test plans

CAB Coordinator:
Prof. Rob Kunz
(PSU)

The team is excited with the progress of the program and sincerely appreciates the support from DOE-NETL



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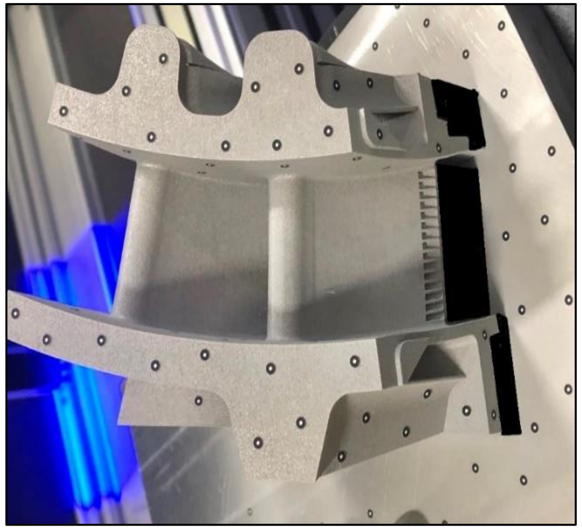

NExT