GO BEYOND

Pratt & Whitney – FAA CLEEN II Consortium
May 8, 2019
Cleveland, OH

A UNITED TECHNOLOGIES COMPANY

Pratt & Whitney's CLEEN II Technologies

Today's Agenda

- Overview of UTC and Pratt & Whitney
- Summary of P&W's CLEEN II Efforts
- Overview of P&W's CLEEN II Compressor Technologies
- Overview of P&W's CLEEN II Turbine Technologies
- Overall mission performance and fleet impacts (initial estimates)
- Geared Turbofan™ entry into service and applicability of CLEEN II technology to future products

PRATT & WHITNEY DEPENDABLE ENGINES

GO BEYOND

United Technologies

Note: 2018 Net Sales Shown

Collins Aerospace
A United Technologies Company

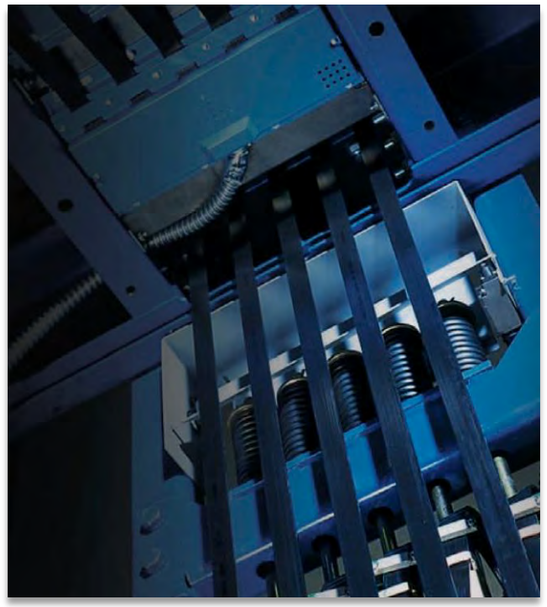
Net Sales $16.6B

PRATT & WHITNEY
DEPENDABLE ENGINES

Net Sales $19.4B

Otis
A United Technologies Company

Net Sales $12.9B



Carrier

Net Sales $18.9B

UTC is 240,000 Employees Strong, Four Major Business Units, $66.5B Sales

GTF ENGINE FAMILY

FOR LARGE COMMERCIAL AIRCRAFT

AND REGIONAL JETS

17,000 – 33,000
Pounds Thrust Class

16% Improvement in fuel efficiency

50% Reduction in regulated NOx emissions

75% Reduction in noise footprint

GTF Technology Provides Major Benefits

Legacy

Boeing 757

Airbus A320

Boeing 767

Airbus A330

Boeing 777

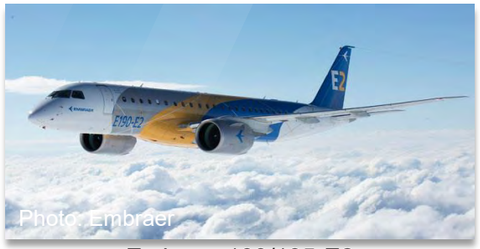
Airbus A380

GTF

Airbus A320neo

Mitsubishi MRJ

Airbus A220



Embraer 190/195-E2

Irkut MC-21

Embraer 175-E2

P&W Powers Commercial Legacy Fleets and the Exclusive Geared Turbofan Fleets

Pratt & Whitney ADVANCED Manufacturing

Investment in facilities for productivity

Investment in automated manufacturing

Investment in inspection technology for quality

State of the Art Technology to Produce Advanced Aerospace Products

Sustainability goals at Pratt & Whitney

Strive to be the best aerospace engine company FOR the world

FOR OUR PRODUCTS

Emissions
Reduce the environmental impacts of our products
Work with our customers to reduce in-service impacts

Sustainable Products
Design, manufacture and service products to minimize impacts
Use Ecodesign to drive product innovation

FOR OUR SITES

Zero Waste
All by-products 100% recycled
Increase efficiency and reduce “non-product” output

Carbon Neutral
Use only sustainable energy sources
Lower our footprint to avoid future impacts and costs

FOR OUR PEOPLE

Influence
Be a force for positive change
Support and engage employees and communities in building a better future

Owning Our Future

Pratt & Whitney's CLEEN II Technologies

Today's Agenda

Overview of UTC and Pratt & Whitney

Summary of P&W's CLEEN II Efforts

Overview of P&W's CLEEN II Compressor Technologies

Overview of P&W's CLEEN II Turbine Technologies

Overall mission performance and fleet impacts (initial estimates)

Geared Turbofan™ entry into service and applicability of CLEEN II technology to future products

PRATT & WHITNEY
DEPENDABLE ENGINES

GO BEYOND

Pratt & Whitney's CLEEN II Technologies

GO BEYOND

Improved propulsive efficiency enabled by Geared Turbofan™ architecture

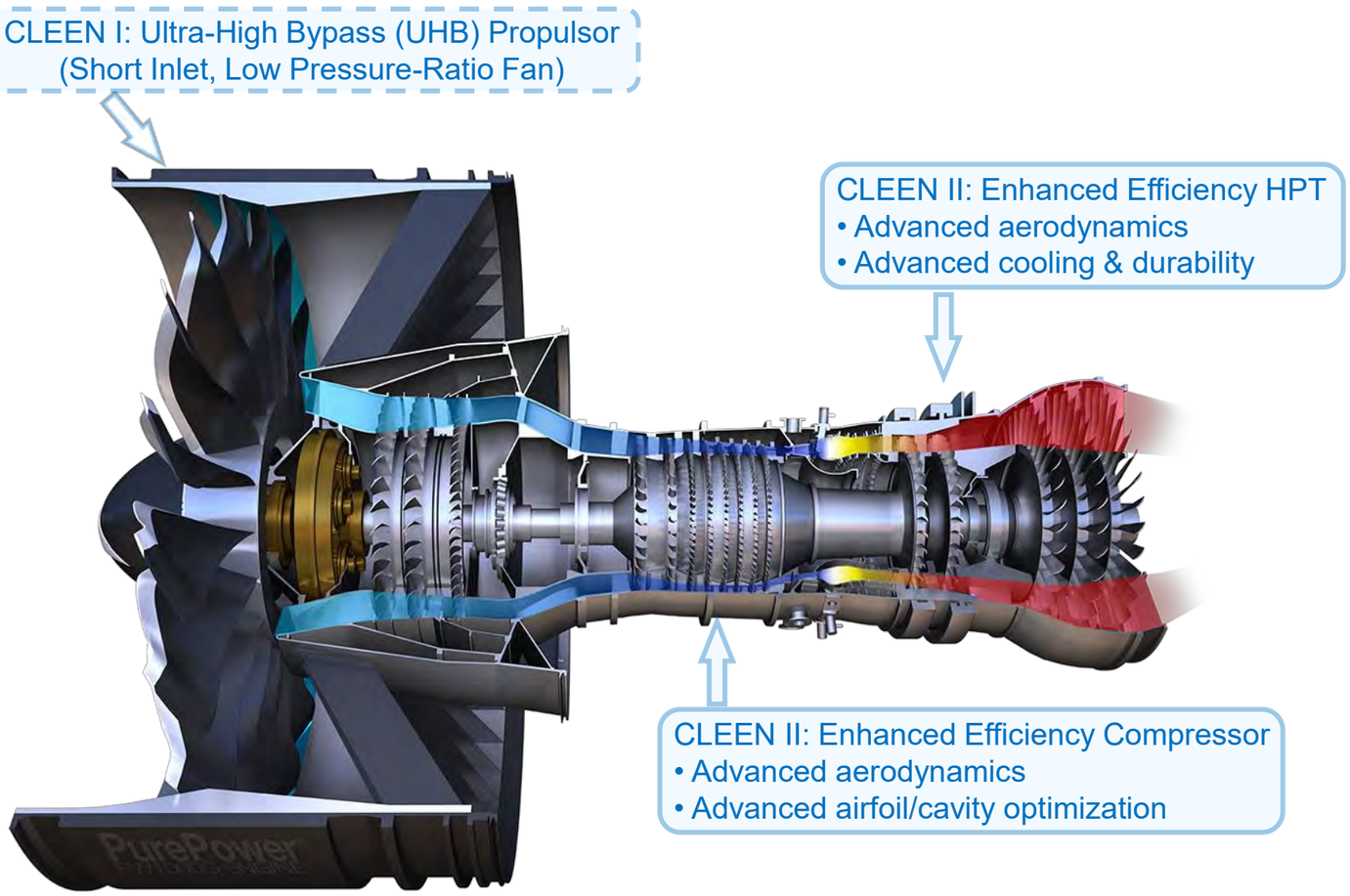
CLEEN II builds upon CLEEN I for overall GTF engine architecture efficiency benefits

Compressor Section – advanced aerodynamics and cavity/airfoil optimization

Turbine Section – advanced aerodynamics and reduced cooling requirements and chargeable flow losses

CLEEN II compressor and turbine technologies together improve the thermodynamic efficiency of the GTF architecture.

Leads to a 1.6-2.0% total fuel burn reduction



Pratt & Whitney's CLEEN II Technologies

GO BEYOND

CLEEN II Progress To-Date

HPC rig scope completed in 2017

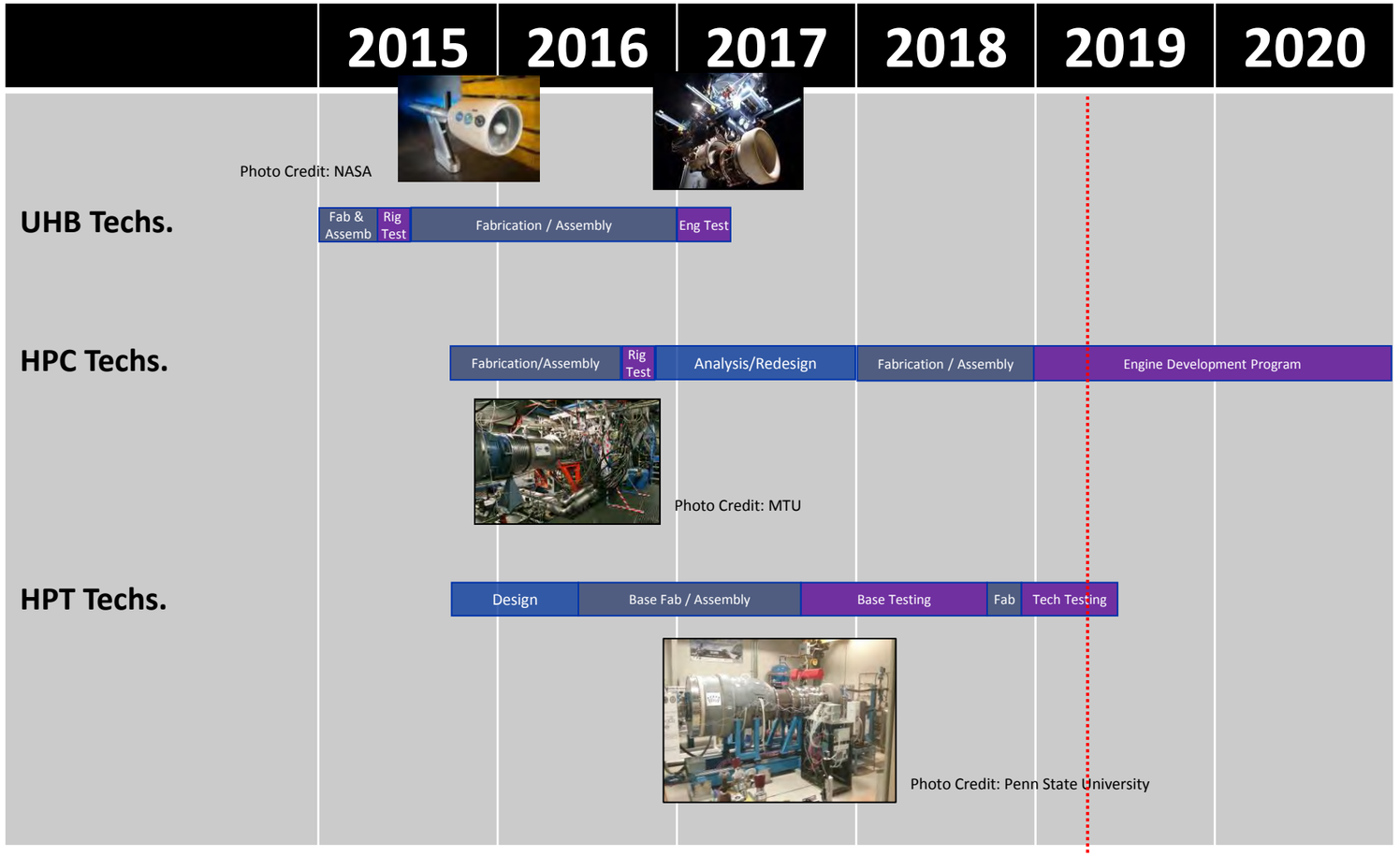
Engine demonstration program in full swing for HPC Technologies

PSU HPT START facility upgrade completed

HPT testing running a little behind to plan

Technology hardware fabrication in-process

HPT Cascade testing completed



Pratt & Whitney's CLEEN II Technologies

Today's Agenda

Overview of UTC and Pratt & Whitney

Summary of P&W's CLEEN II Efforts

Overview of P&W's CLEEN II Compressor Technologies

Overview of P&W's CLEEN II Turbine Technologies

Overall mission performance and fleet impacts (initial estimates)

Geared Turbofan™ entry into service and applicability of CLEEN II technology to future products

PRATT & WHITNEY DEPENDABLE ENGINES

GO BEYOND

Pratt & Whitney's CLEEN II Technologies

GO BEYOND

Compressor Aero Efficiency Technologies

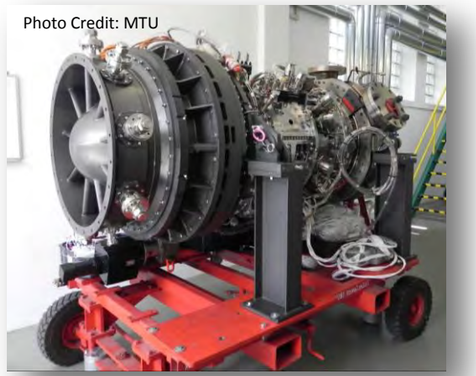
Benefits:

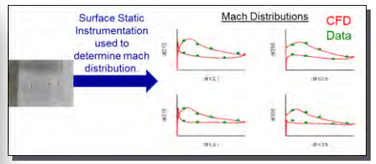
Improved thermal efficiency

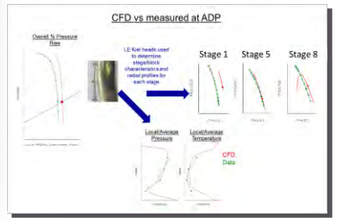
- ~ 0.8 – 1.0% fuel burn reduction

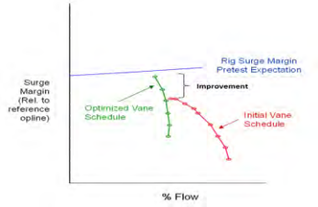
Risks/Mitigations

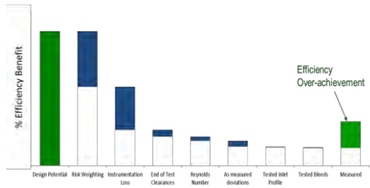
- No risks identified at this time











2016-17 Rig Test → Data Reduction → Module Benefits

Objectives:

Demonstrate improved high pressure compressor efficiency via advanced aerodynamic airfoil optimization

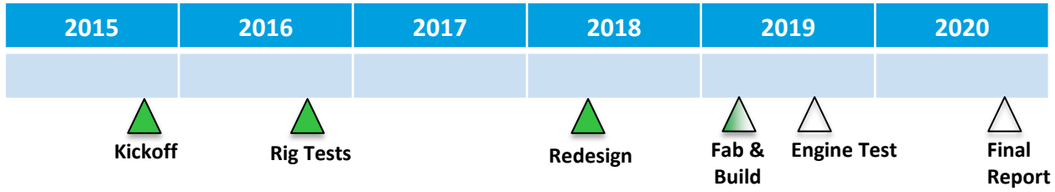
Work Statement:

Continue the TRL advancement of compressor aero-efficiency technologies via detailed design, fabrication, full-scale rig tests, and engine validation.

Prior Accomplishments:

- Redesign completed, component fabrication complete, test engine in final assembly

Schedule & Planned Milestones:



Pratt & Whitney's CLEEN II Technologies

GO BEYOND

HPC Technology Rig – What's next?

Same compressor aero design slated to go to ground test shortly to bring HPC technology to TRL 6 – "Subsystem demonstration in a relative environment"

Tools developed and knowledge gained will be utilized for flight test asset sometime in the future and eventual introduction into GTF product line

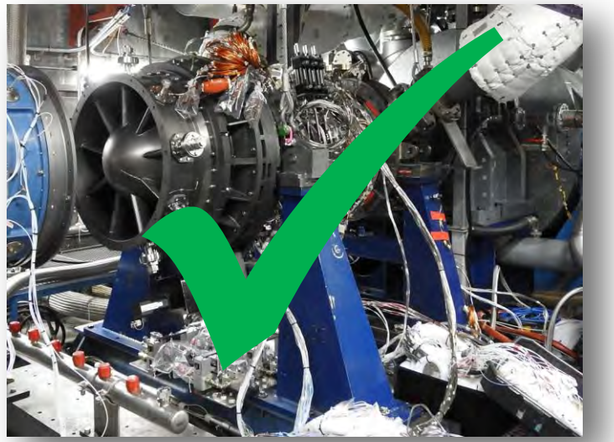


Photo Credit: MTU

Pratt & Whitney's CLEEN II Technologies

Today's Agenda

Overview of UTC and Pratt & Whitney

Summary of P&W's CLEEN II Efforts

Overview of P&W's CLEEN II Compressor Technologies

Overview of P&W's CLEEN II Turbine Technologies

Overall mission performance and fleet impacts (initial estimates)

Geared Turbofan™ entry into service and applicability of CLEEN II technology to future products

GO BEYOND

Pratt & Whitney's CLEEN II Technologies

GO BEYOND

Turbine Aero Efficiency and Durability Technologies

Benefits:

Improved thermal efficiency

- ~ 0.8 – 1.0% fuel burn reduction

Risks/Mitigations

Technology interaction prevents assessment of contribution of individual items

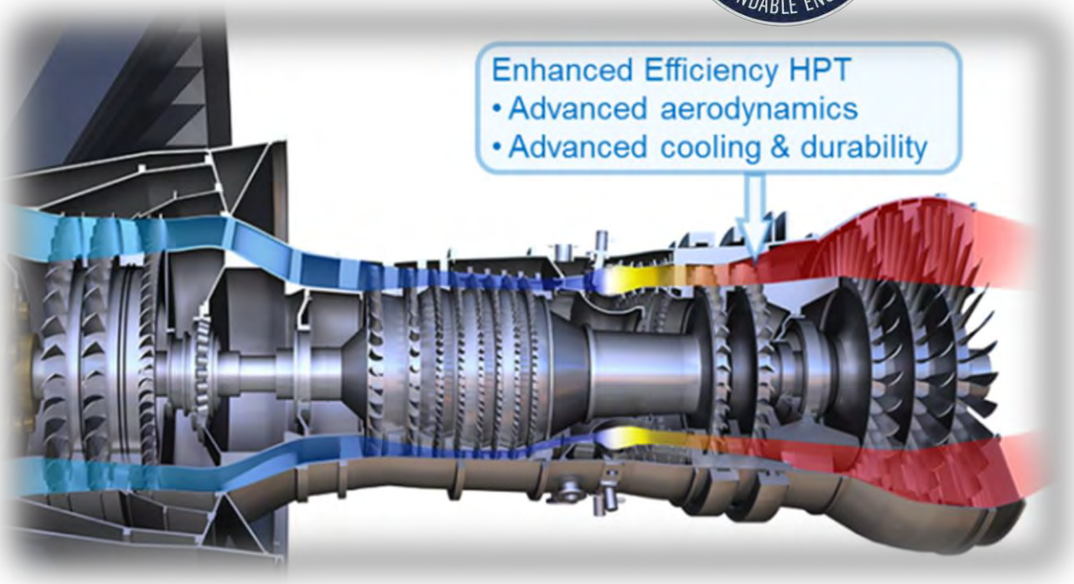
- Execute additional rig trials to isolate

Testing delayed due to linear build schedule

- Procure additional hardware to facilitate parallel build

New facility debugging

- Actively working to understand failure modes and backup facility hardware



Objectives: *Demonstrate improved high pressure turbine efficiency via advanced aerodynamic airfoil and durability optimization*

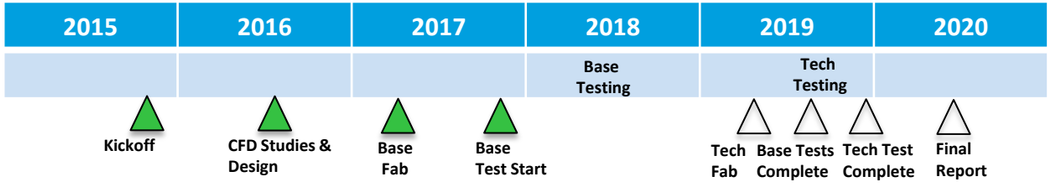
Work Statement:

Continue the TRL advancement of turbine aero-efficiency and durability technologies via CFD studies, detailed design, fabrication, and full-scale rig tests.

Prior Accomplishments:

- Completed cascade rig testing
- Completed START rig traverse assembly
- Kicked off baseline testing

Schedule & Planned Milestones:



Pratt & Whitney's CLEEN II Technologies

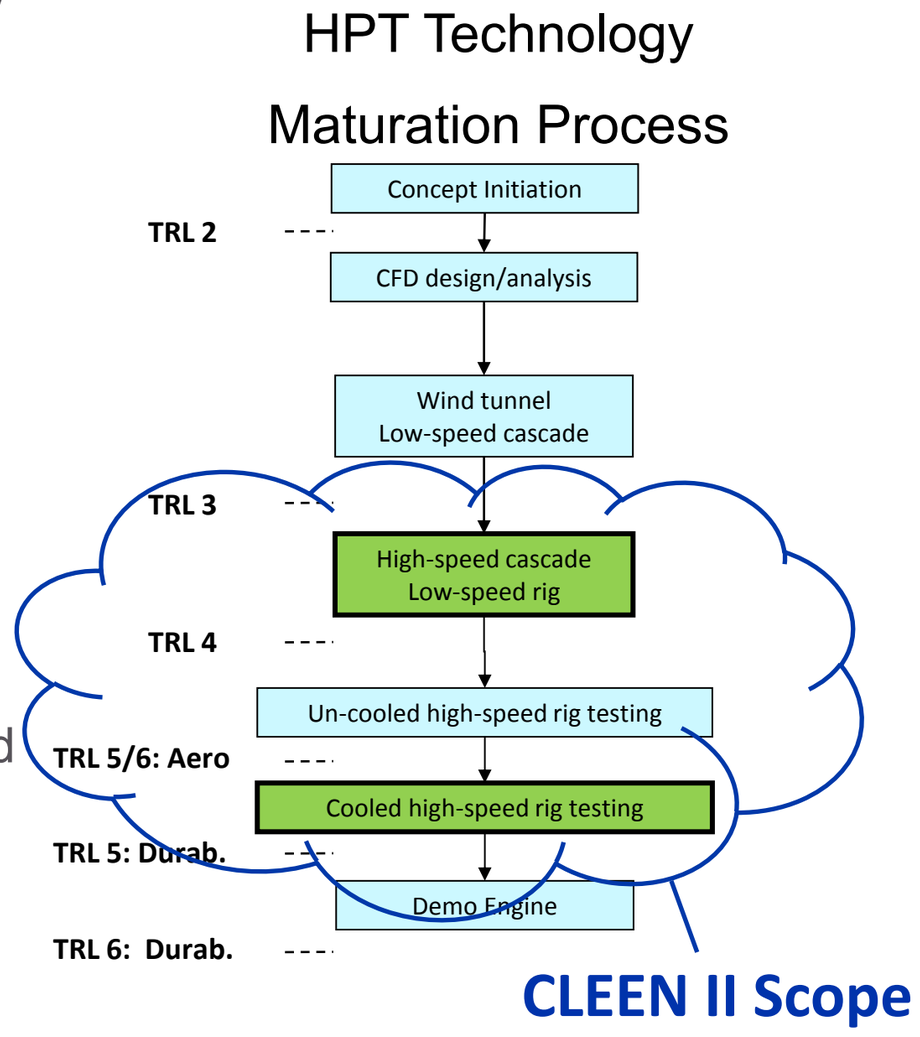
GO BEYOND

HPT Technology Maturation Strategy

Previous investment from P&W has brought HPT technologies through Technology Readiness Level (TRL) 3

- CFD design and analysis for conceptual design of the technologies
- Low speed wind tunnel testing for initial learning

Under FAA funding, bringing HPT technologies to TRL 5 for durability and TRL6 for aero technologies



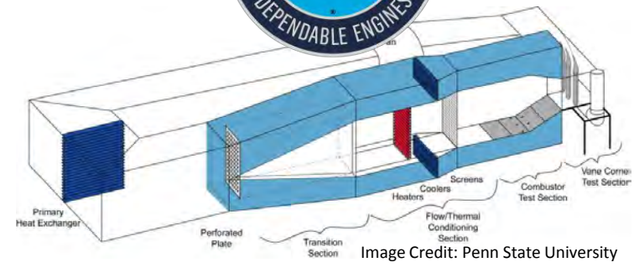


Image Credit: Penn State University

Image Credit: Penn State University

Image Credit: Penn State University

Pratt & Whitney's CLEEN II Technologies

GO BEYOND

HPT Technology Status - Schedule

Conceptual design work started prior to CLEEN II contract start

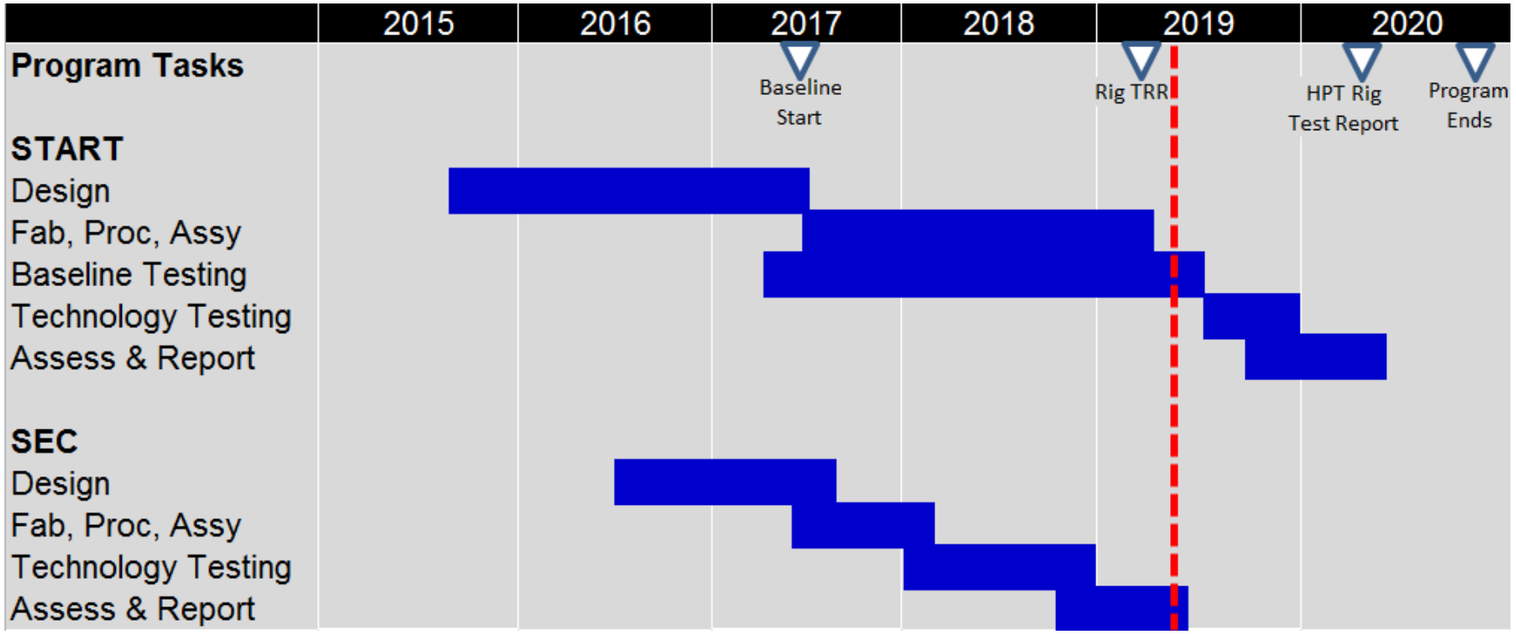
FAA has helped to further mature the HPT technologies beyond TRL 3

HPT scope holding schedule for full-scale hardware Aero/Thermal testing in 2019

Single Element Cascade testing completed

Baseline START testing in process

Hardware fabrication in process and working on final rig preparation for technology testing

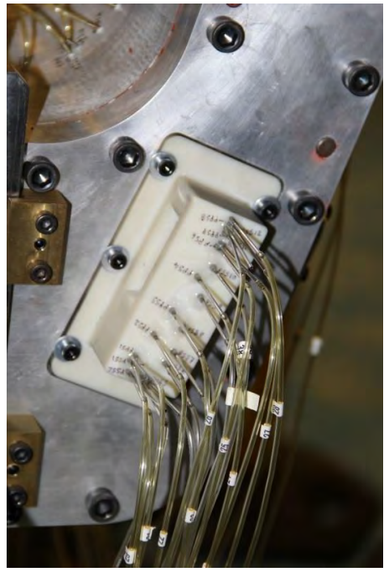


Pratt & Whitney's CLEEN II Technologies

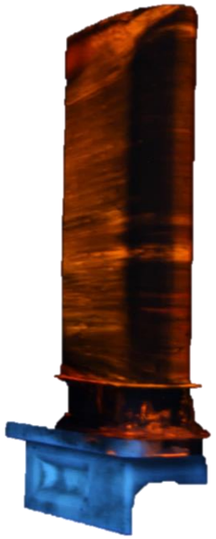
GO BEYOND

Single Element Cascade (SEC) - Objectives

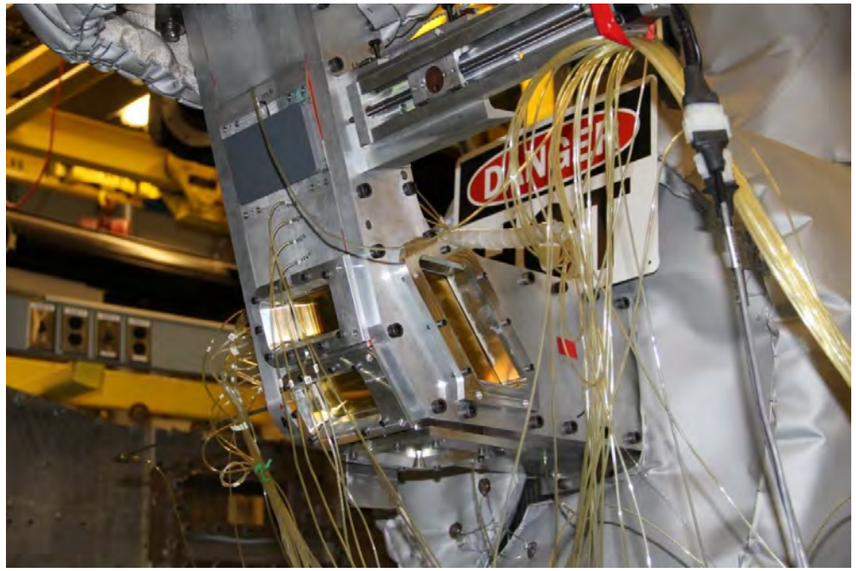
- Measure film cooling effectiveness and aerodynamic loss for a current state-of-the-art airfoil design
- Compare baseline and advanced cooling hole shapes at engine-representative operating conditions
- Enhance the understanding of performance losses due to advanced cooling configurations
- Generate benchmark-quality aero/thermal data to validate Pratt & Whitney's turbine cooling analytical modeling (CFD)



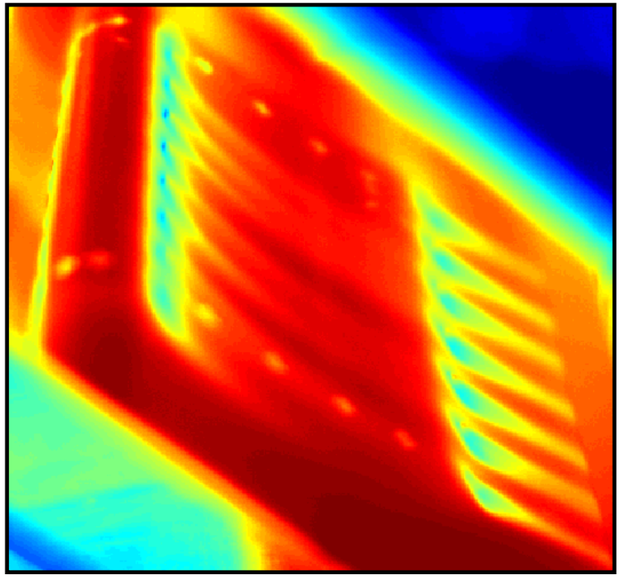
Single Element Cascade Rig Blade



Flow Visualization



Single Element Cascade Rig



Processed IR Image Data

Pratt & Whitney's CLEEN II Technologies

GO BEYOND

Single Element Cascade (SEC) - Execution

SEC facility and test article assembly was completed at United Technology's Research Center (UTRC) in March 2018

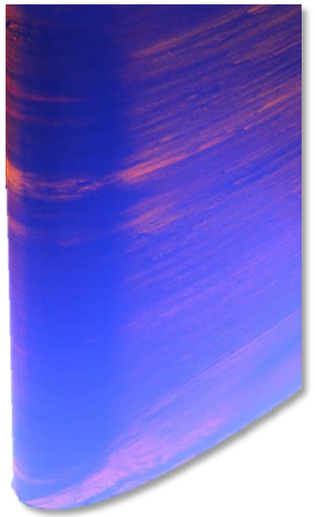
Uncooled and cooled testing for one airfoil geometry (CLEEN 2) with different cooling arrangements for the CLEEN II technologies

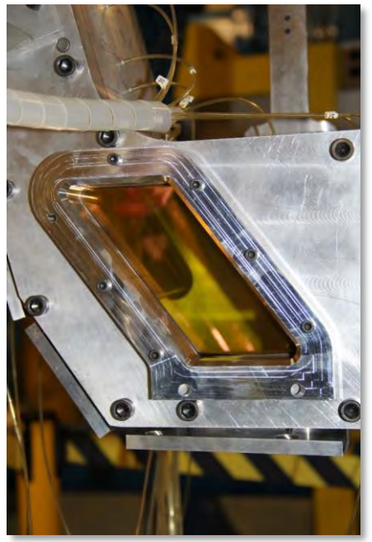
Testing commenced in April and was completed in June 2018

Additional testing completed in November 2018

Test report to be submitted in May 2019

Technologies proven-out by the SEC testing allows for future turbine components to reduce cooling air requirements; thus reducing the amount of losses in the engine





Pratt & Whitney's CLEEN II Technologies

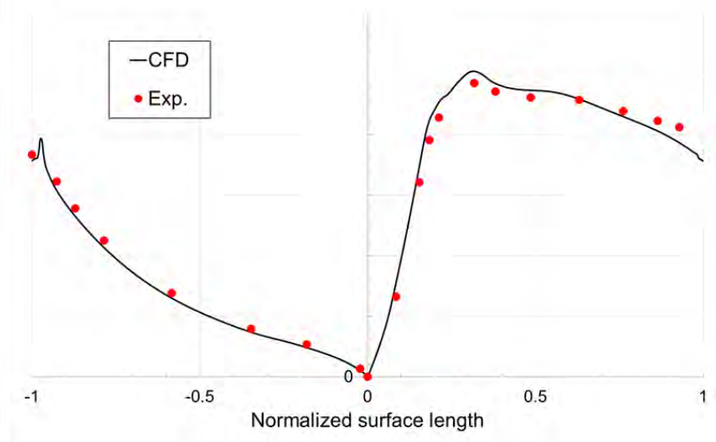
GO BEYOND

Single Element Cascade (SEC) - Results

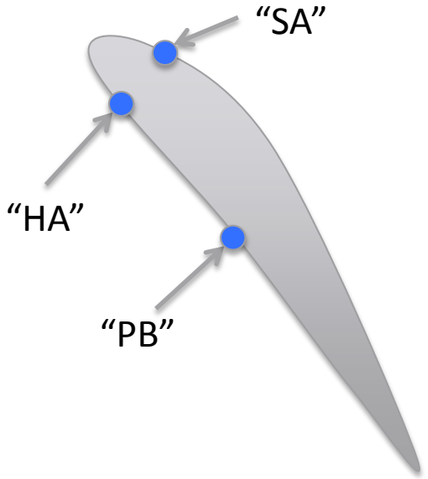
Cascade rig fully instrumented with pressure and temperature probes along with IR camera system

Good correlation of experimental data back to CFD pre-test predictions for surface pressure and Mach number distribution

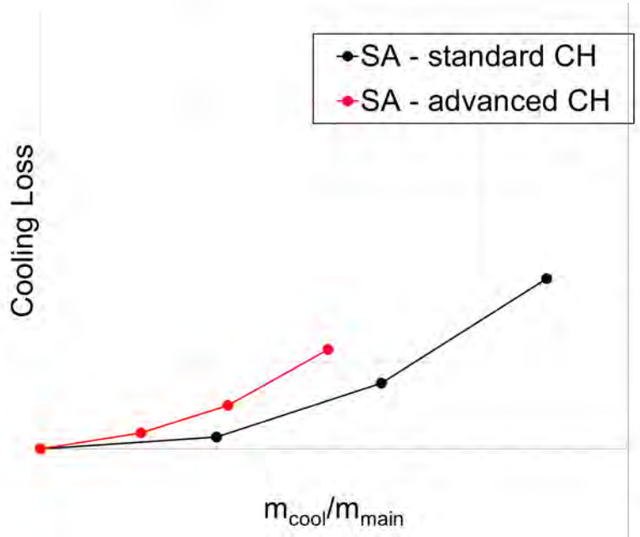
Cooling hole loss data obtained for various cooling hole shapes and blowing ratios on suction side, leading edge, and pressure side



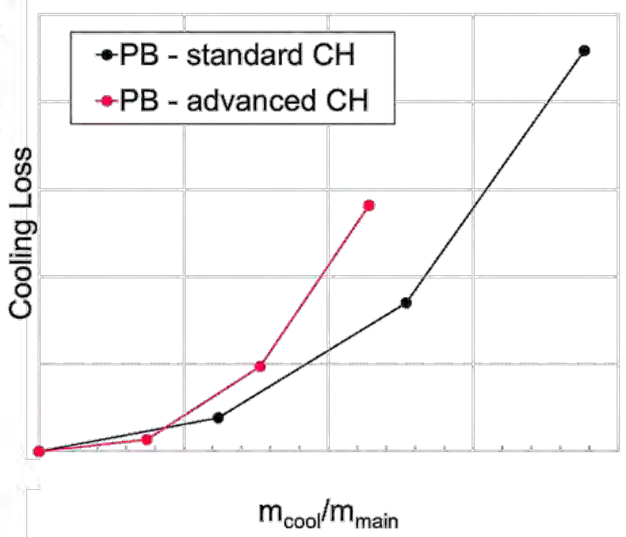
Cooling Hole (CH) Key



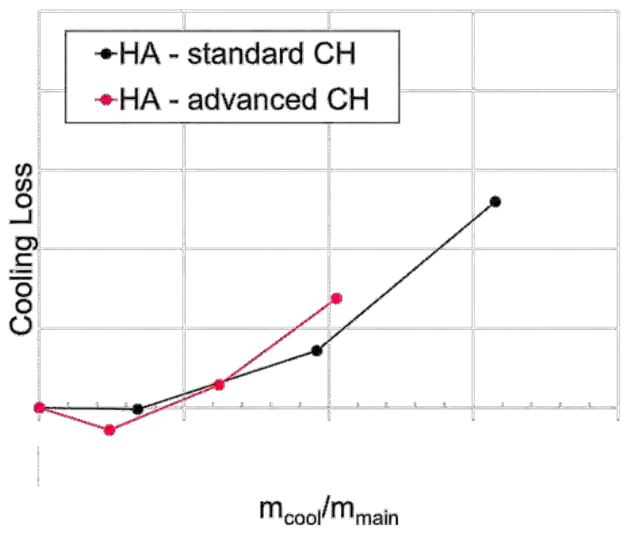
Suction Side Losses



Pressure Side Losses



Shower Head Losses



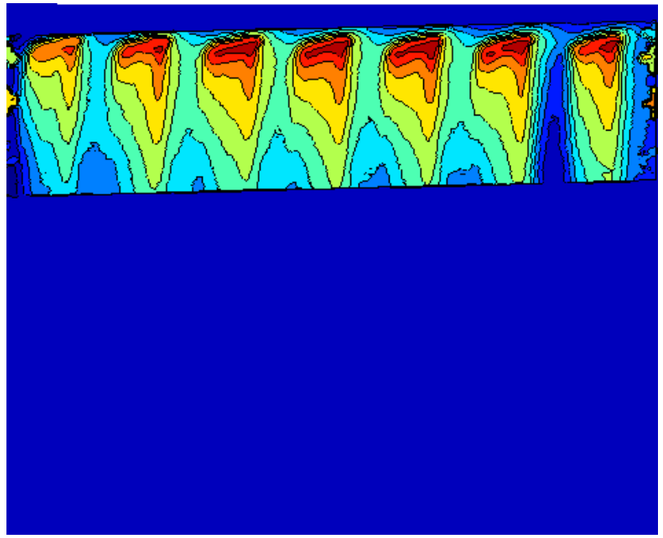
Pratt & Whitney's CLEEN II Technologies

GO BEYOND

Single Element Cascade (SEC) - Results

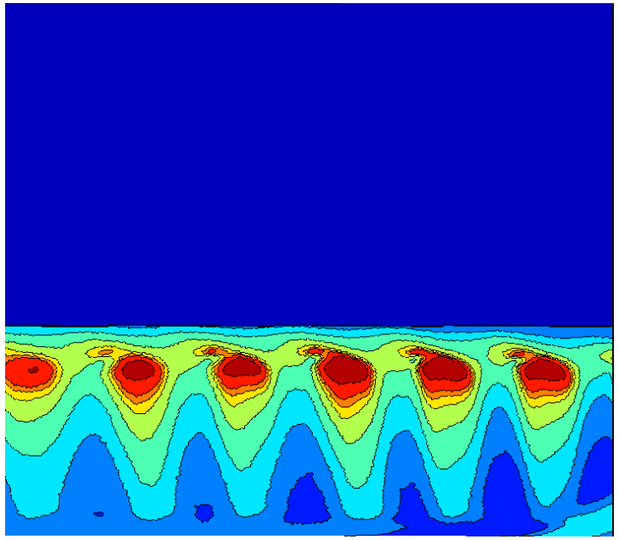
Suction Side Film Effectiveness

- Wider film-footprint potential enabler for fewer cooling holes for a given airfoil span
- Film distortion is pronounced for advanced holes at tested blowing rates



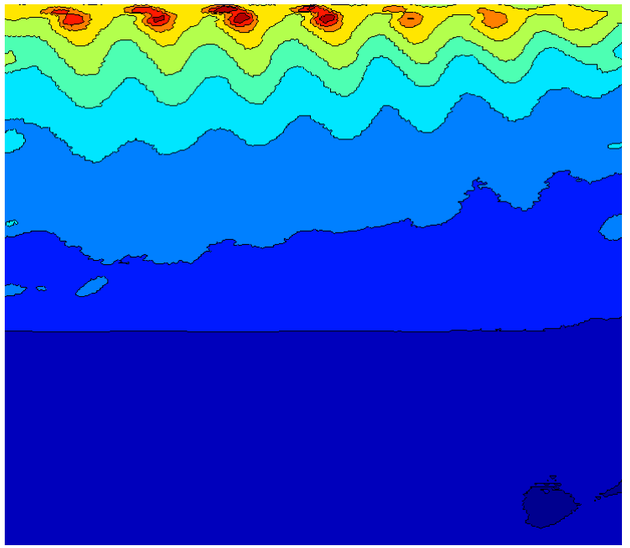
Pressure Side Film Effectiveness

- Slight benefit in film-core size for advanced hole compared to standard hole
- Suppressed double-lobed film distortion previously seen on the suction side advanced holes
- Both hole types show better film effectiveness at medium blowing rates



Shower Head Film Effectiveness

- Shaped showerhead holes provide uniform radial film distribution on the airfoil pressure side
- Differences in lateral film distribution between round & shaped showerhead holes is distinct at higher blow rates



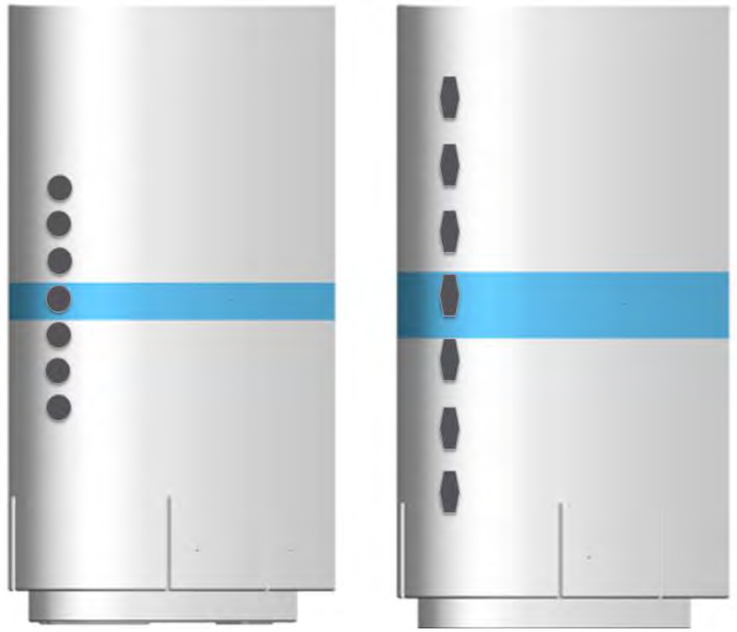
Pratt & Whitney's CLEEN II Technologies

GO BEYOND

Single Element Cascade (SEC) - Summary

- Testing was carried out at engine-relevant conditions (Re, Mach)
- Cascade tests were conducted to simultaneously measure cooling effectiveness and loss associated with film cooling using standard and advanced cooling hole shapes
- Advanced cooling hole shapes showed improved lateral film footprint albeit with some reduction in average film-effectiveness at the chosen coverage levels.
    - Benefits can be realized for advanced cooling holes when considering the overall airfoil surface to be cooled
- Selected cases from test matrix were either repeated or measurements were taken at different spanwise locations to show repeatability of loss measurements
- Test results offer unprecedented and invaluable insight to potential film performance improvement.

Film Coverage



Pratt & Whitney's CLEEN II Technologies

GO BEYOND

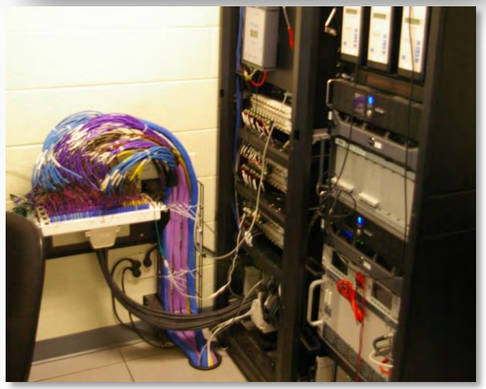
Penn State START Facility – Background

START = Steady Thermal Aero Research Turbine.

Test section is modeled after Pratt & Whitney's GTF high pressure turbine module

~$10M combined investment into the facility over the past 5 years

Pratt & Whitney Center of Excellence, World Class Facility



2013 → **2018**

All Photo and Image Credits: Penn State University
Trademarks used on this page are the property of their respective owners

Pratt & Whitney's CLEEN II Technologies

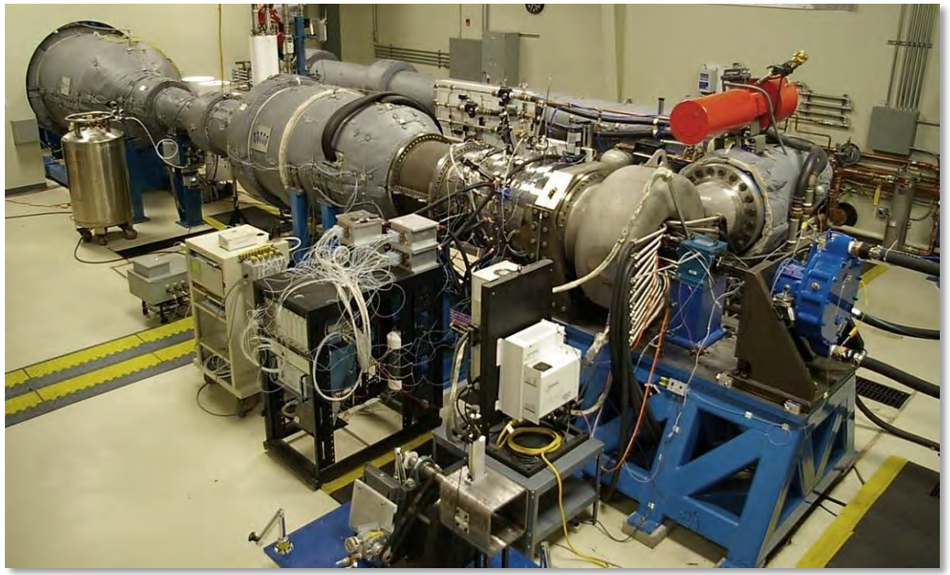
GO BEYOND

Penn State START Facility – Objectives

Validate predictions for novel aero/thermal component designs in order to correlate analytical tools for CLEEN II technologies

Compare baseline and advanced aero/thermal technologies at representative operating conditions

Build upon completed SEC testing; verifies full-span 3-dimensional aero



All Photo and Image Credits: Penn State University

Pratt & Whitney's CLEEN II Technologies

GO BEYOND

Penn State START Facility – Execution

Procurement and assembly of "Phase II" START rig facility completed

START facility shakedown completed Cavity Aero testing completed

Analytical aero/thermal pre-test predictions completed

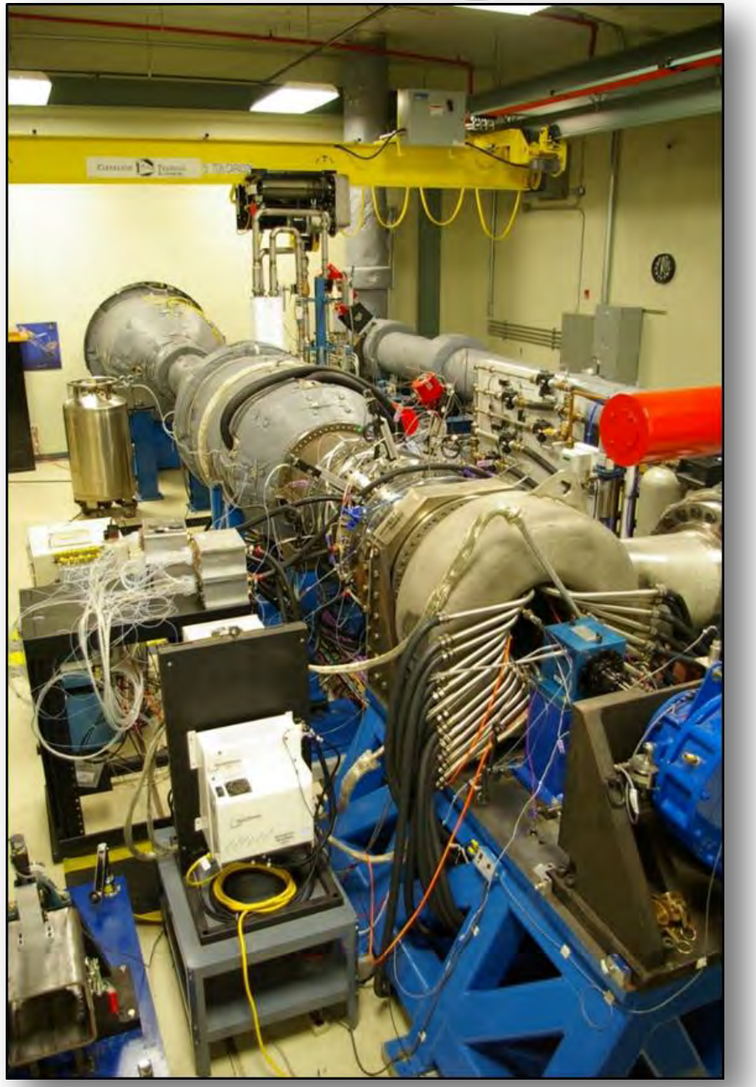
Testing of baseline GTF technology anticipated by mid-2019

CLEEN II advanced technology blade aero/thermal instrumentation fabrication being finalized

CLEEN II advanced technology blade fabrication in-process

Rig hardware for CLEEN II technology blade delivered

On schedule for 2019 test completion



All Photo and Image Credits: Penn State University

Pratt & Whitney's CLEEN II Technologies

GO BEYOND

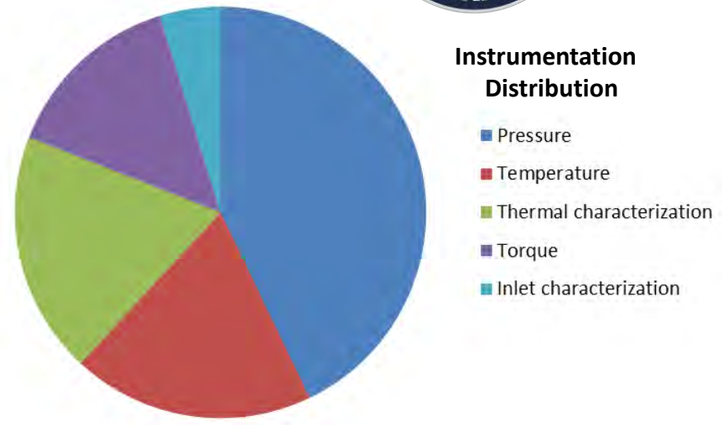
Penn State START Facility – Pretest Predictions

Analytical aero pre-test predictions completed, and are ready for experimental data comparison

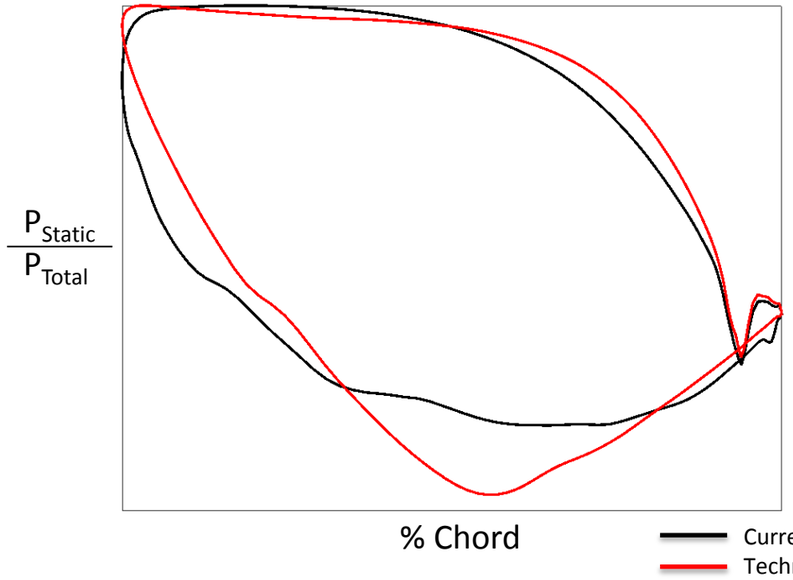
Main gas path CFD has been coupled with secondary flow cavity CFD model for test correlation

Instrumentation required for baseline testing has been installed into the START facility

Additional instrumentation specific to technology blade testing is in-process



CFD Prediction for Pressure Distribution



Pratt & Whitney's CLEEN II Technologies

Today's Agenda

Overview of UTC and Pratt & Whitney

Summary of P&W's CLEEN II Efforts

Overview of P&W's CLEEN II Compressor Technologies

Overview of P&W's CLEEN II Turbine Technologies

Overall mission performance and fleet impacts (initial estimates)

Geared Turbofan™ entry into service and applicability of CLEEN II technology to future products

PRATT & WHITNEY DEPENDABLE ENGINES

GO BEYOND

Pratt & Whitney's CLEEN II Technologies

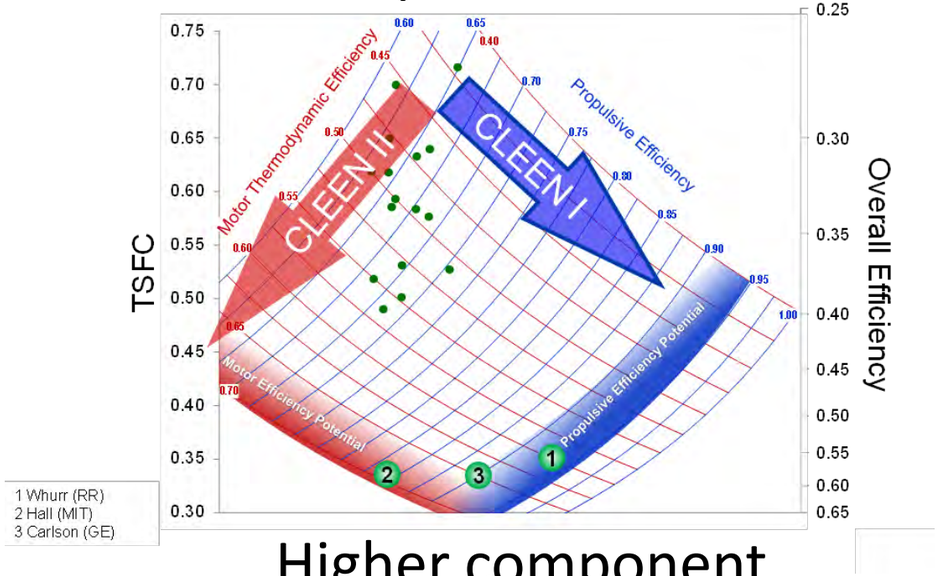
GO BEYOND

System Level Impact

CLEEN I increased the propulsive efficiency of the GTF engine with fan technologies

CLEEN II technologies continue to push towards more thermodynamically efficient turbofan engines.

Component Level



Higher component efficiency

Engine / Airframe Level

1.6-2.0% Fuel Burn Reduction

Fleet Level

34-43K gallons of fuel saved per year per plane

A320NEO, 2.0 hour flights, 3,100 annual flight hours

Pratt & Whitney's CLEEN II Technologies

GO BEYOND

80+ Customers/8000+ Engine Orders

Including Firm Orders and Options

CLEEN II HPC and HPT technologies to be infused into GTF fleet.

Pratt & Whitney's CLEEN II Technologies

GO BEYOND

Program Summary

High Pressure Compressor scope was completed in 2017, ongoing integration of learning into ground test and flight test assets

High Pressure Turbine (HPT) Single Element Cascade (SEC) testing complete, final test report underway

START Test Readiness Review (TRR) complete, technology blade testing to commence later this year

Industrial phase of CLEEN II technology HPT hardware for START rig continues on-schedule

Queueing-up system level benefits analysis for 2019 and 2020

Plans are in place for introduction of technologies matured under CLEEN II efforts into Pratt & Whitney's product offerings

GO BEYOND