Pratt & Whitney

A United Technologies Company

P&W CLEEN TECHNOLOGY DEMONSTRATOR
CLEEN II: HIGH PERFORMANCE CORE

CLEEN TECHNOLOGY DEMONSTRATORS

Topics for Discussion

Program Overview

HPC Technology Overview

HPT Technology Overview

Discussion

E195-E2 Flight

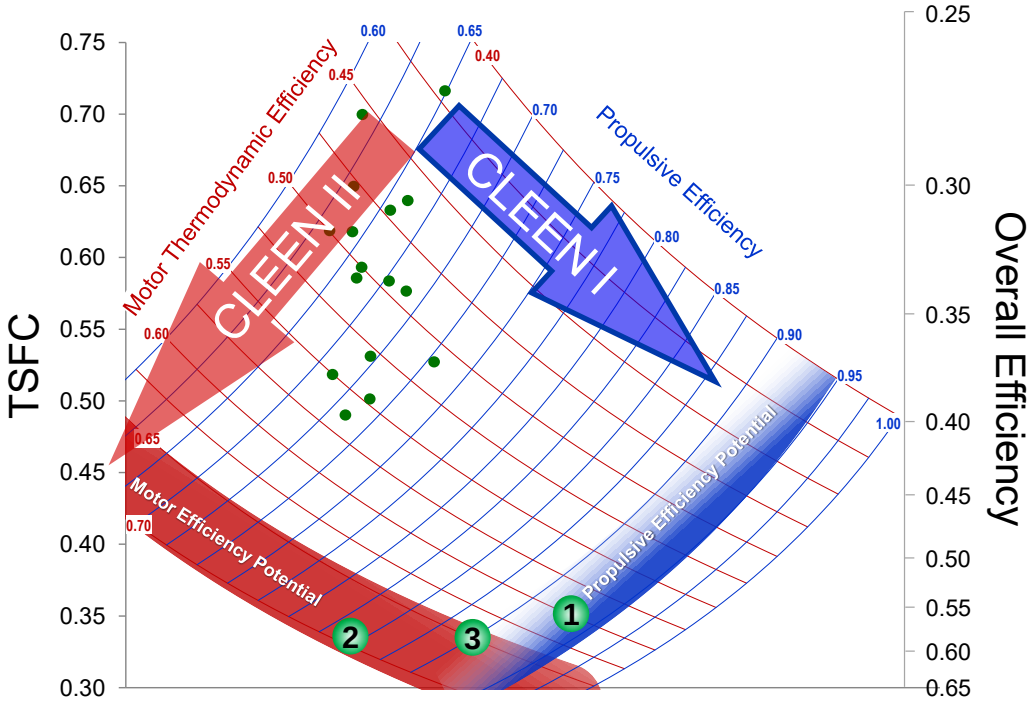
Photo credit: Embraer

CLEEN TECHNOLOGY DEMONSTRATORS

Entering A New Era of Engine Architecture

Improved propulsive efficiency enabled by PurePower® Geared Turbofan™ architecture

CLEEN I and II efforts enhance performance of GTF system

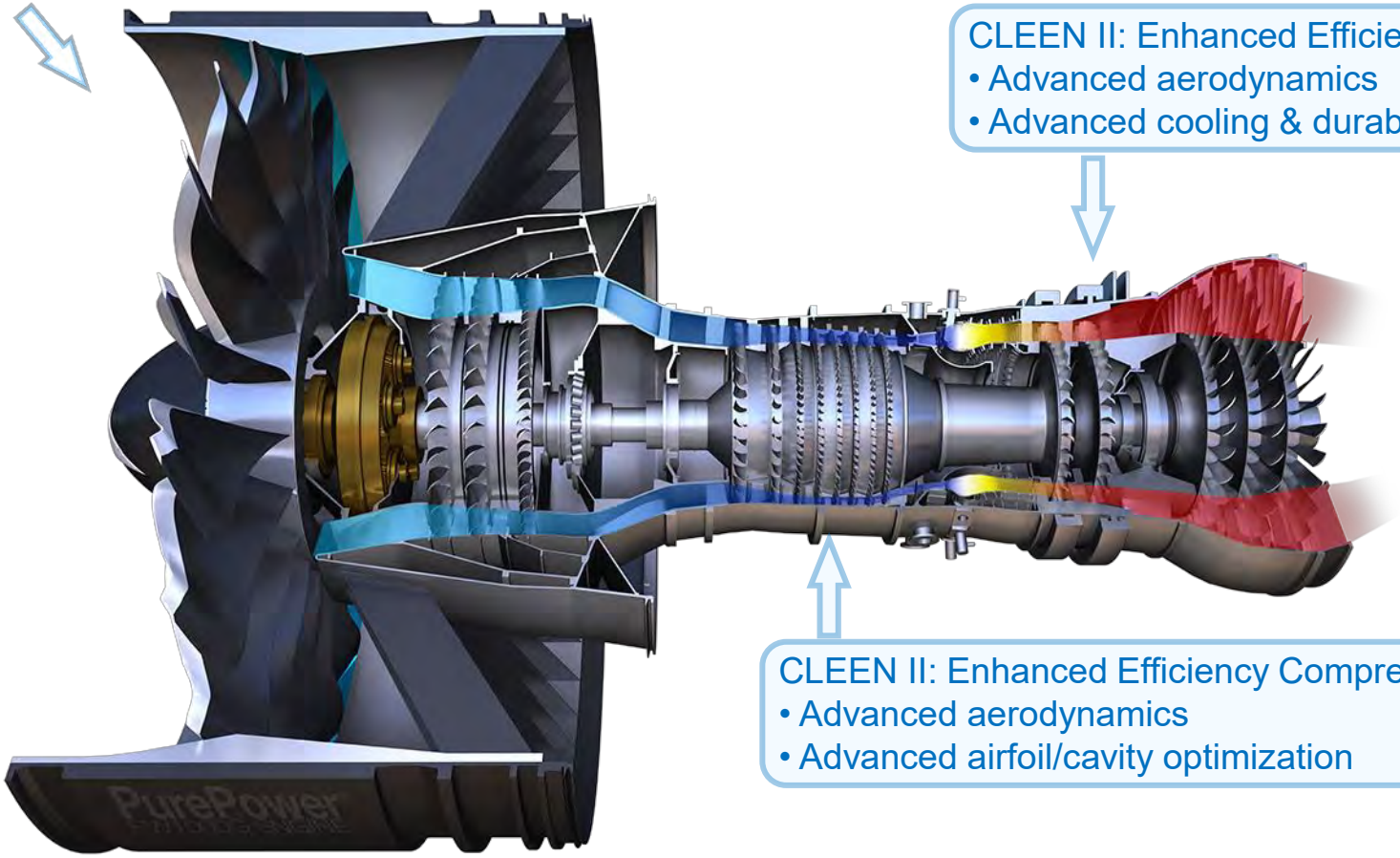


1 Whurr (RR)
2 Hall (MIT)
3 Carlson (GE)

CLEEN TECHNOLOGY DEMONSTRATORS

Core and Propulsor Technologies under Evaluation

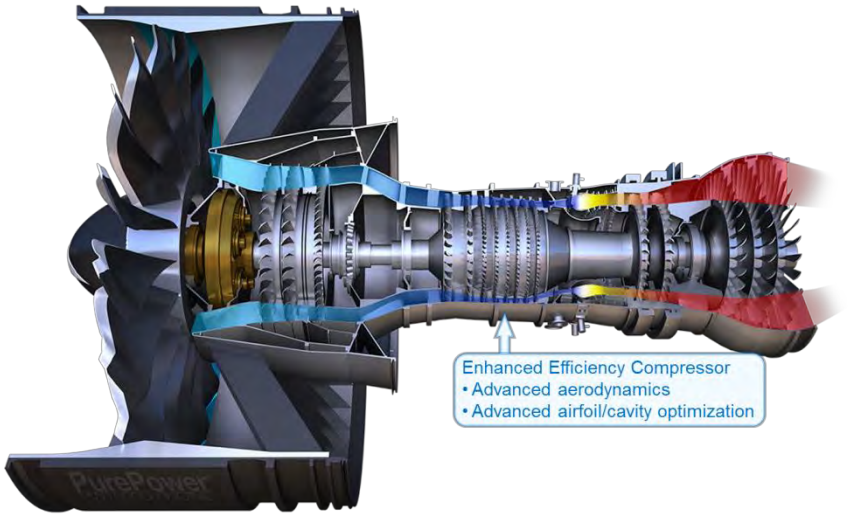
CLEEN I: Ultra-High Bypass (UHB) Propulsor
(Short Inlet, Low Pressure-Ratio Fan)



CLEEN II: Enhanced Efficiency HPT
- Advanced aerodynamics
- Advanced cooling & durability

CLEEN II: Enhanced Efficiency Compressor
- Advanced aerodynamics
- Advanced airfoil/cavity optimization

Compressor Aero-Efficiency Techs.



Benefits:

- Improved thermal efficiency
  - ~ 0.8 – 1.0% fuel burn reduction

Risks/Mitigations

- Achievement of performance and operability targets
  - Utilize multi-stage rigs for early validation
  - Execute redesign, if needed, and utilize lower-level rigs for progressive validation before engine demo

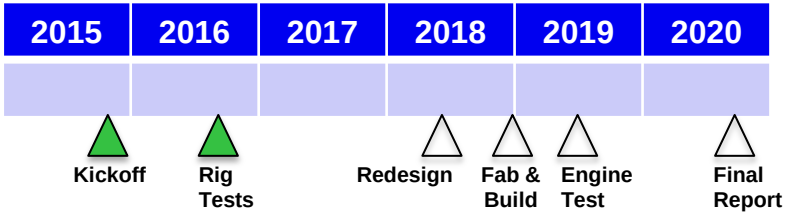
Objectives: *Demonstrate improved high pressure compressor efficiency via advanced aerodynamic airfoil optimization*

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

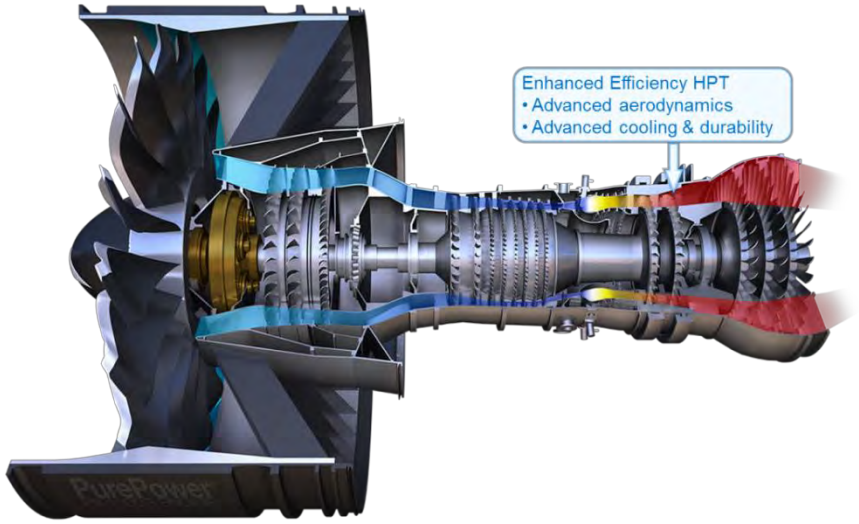
Prior Accomplishments:

- Completed post test technical review

Schedule & Planned Milestones:



Turbine Aero-Efficiency & Durability



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

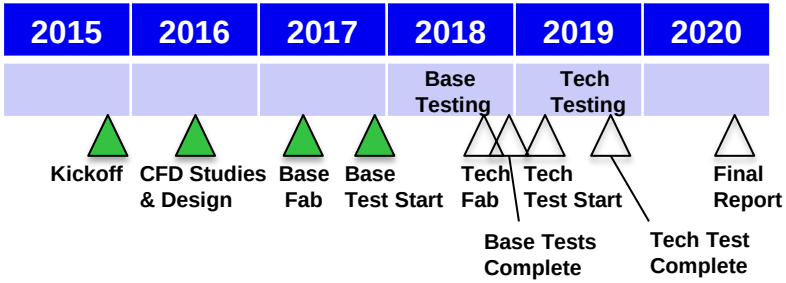
Objectives: *Demonstrate improved high pressure turbine efficiency via advanced aerodynamic airfoil and durability optimization*

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 component fabrication
- Completed START rig instrumentation & calibration
- baseline testing underway

Schedule & Planned Milestones:



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What if the FAA CLEEN program didn't exist?

Missed opportunity to develop fuel-burn reduction technologies that would mature in time for insertion into future product upgrades and new engine offerings...

Missed opportunity to reduce emissions in candidate product upgrades and future new aircraft fleet...

Reduced competitiveness in the global marketplace relative to foreign aerospace technology development activities, which may lead to a business disadvantage...

...FAA CLEEN funding has been critical to developing new technologies for future aircraft engines.

CLEEN TECHNOLOGY DEMONSTRATORS

Program Schedule

	2015	2016	2017	2018	2019	2020
UHB Techs.	Fab & Assemb / Rig Test	Fabrication / Assembly	Eng Test			
HPC Techs.		Fabrication/Assembly / Rig Test	Analysis/Redesign	Fabrication / Assembly	Engine Development Program	
HPT Techs.		Design	Base Fab / Assembly	Base Testing	Fab / Tech Testing	

Photo Credit: NASA

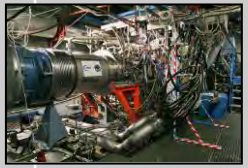


Photo Credit: MTU

Photo Credit: Penn State University

CLEEN TECHNOLOGY DEMONSTRATORS

Program Overview – Summary Status

Key technology demonstrators running or completed test

HPC rig post test evaluation completed

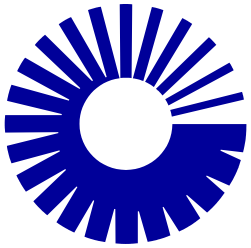
- Post test hardware acceptable
- Engine demo in planning phase

PSU HPT START facility upgrade shakedown completed

- Baseline turbine test in process
- Technology hardware casting in process

HPT Cascade Testing proceeding

- Rig assembly complete
- Baseline geometry testing in process
- Technology geometry test articles in production



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CLEEN II High Pressure Compressor Technologies

Compressor Rig

CLEEN TECHNOLOGY DEMONSTRATORS

HPC Technology

Maturation Strategy

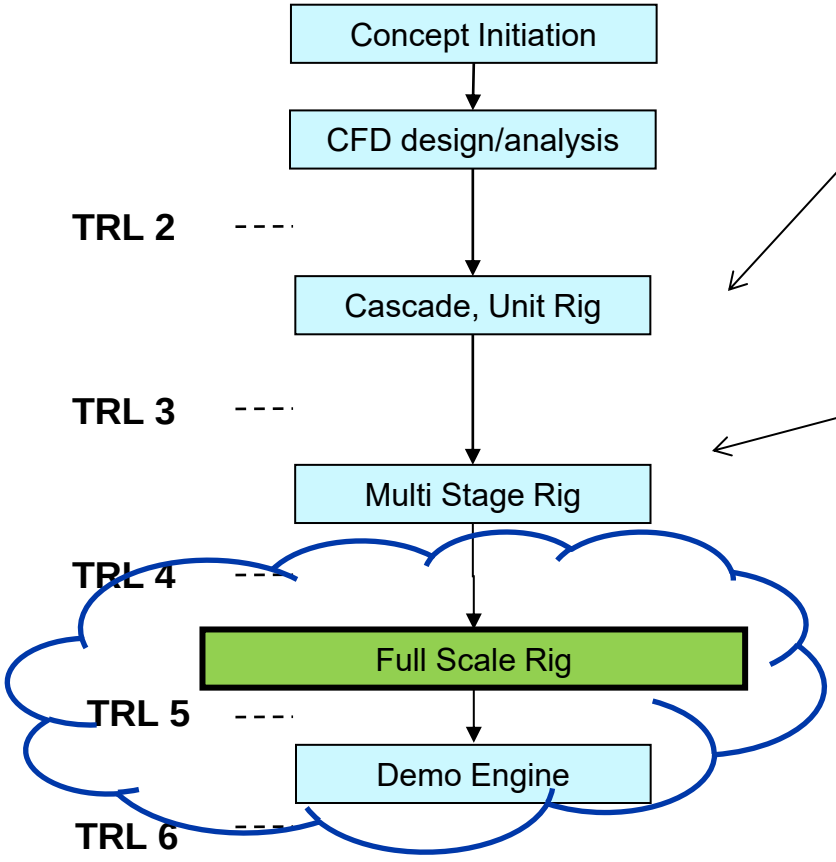


Photo Credit NRC Canada

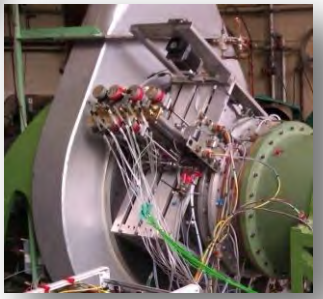
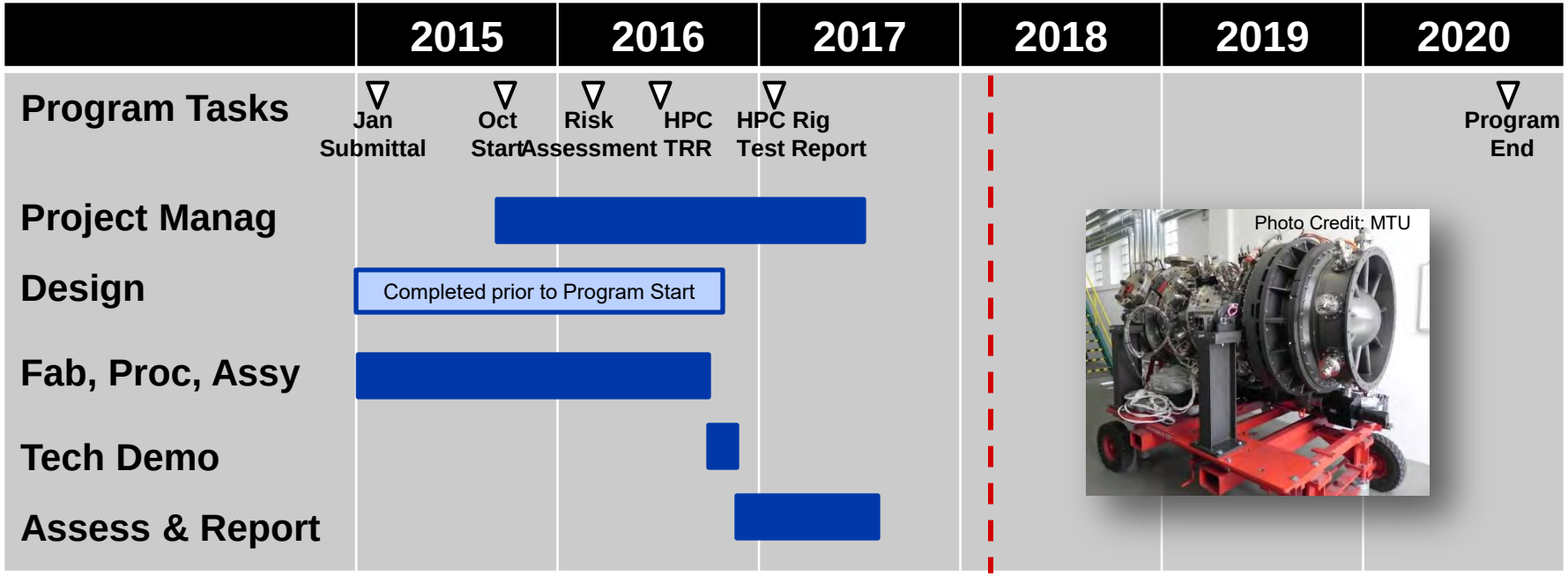


Photo Credit: MTU

HIGH PERFORMANCE CORE

HPC Technology - Schedule

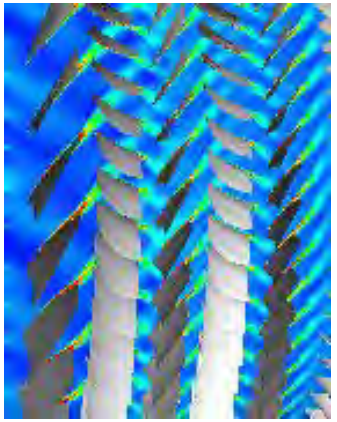
HPC Scope under CLEEN II completed mid 2017



HIGH PERFORMANCE CORE

HPC Technology – Key Attributes

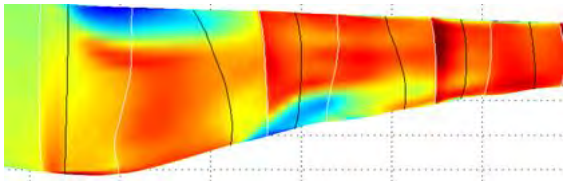
Engine representative hardware



Multi-stage optimization over range of operating conditions

Aerodynamic & operability

Broad range of engine sensitivities



Comprehensive instrumentation set

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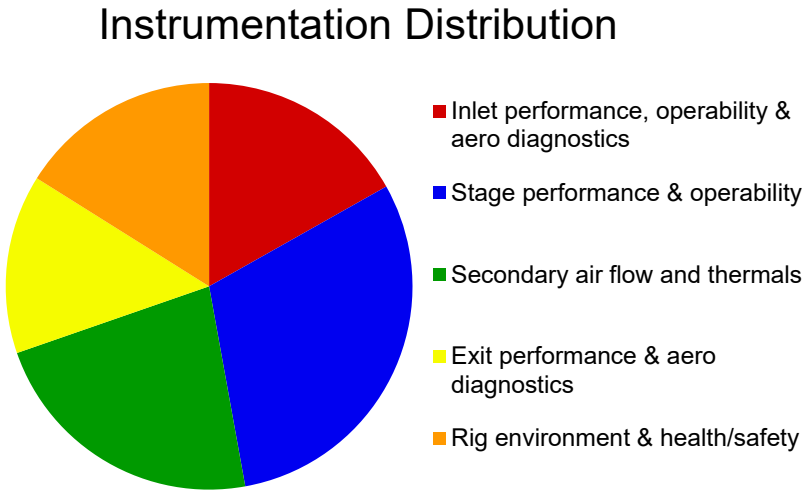
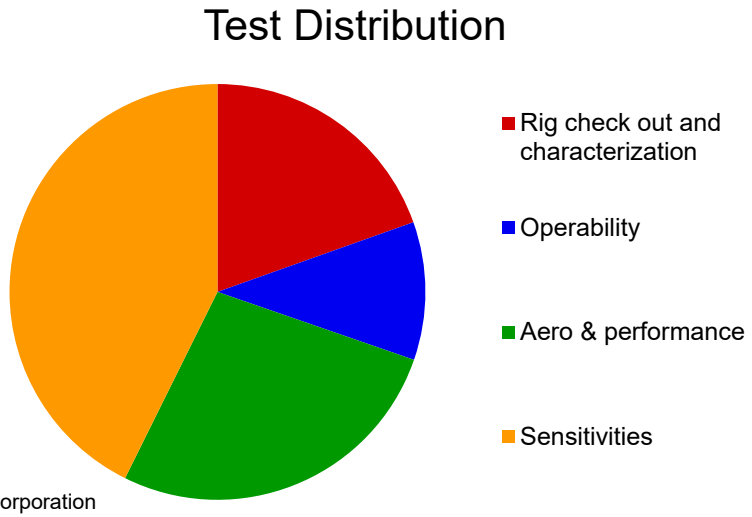
HPC Technology– Test and Instrumentation

Extensive instrumentation suite for compressor characterization and technology optimization



Testing focused on technology maturation and compressor optimization



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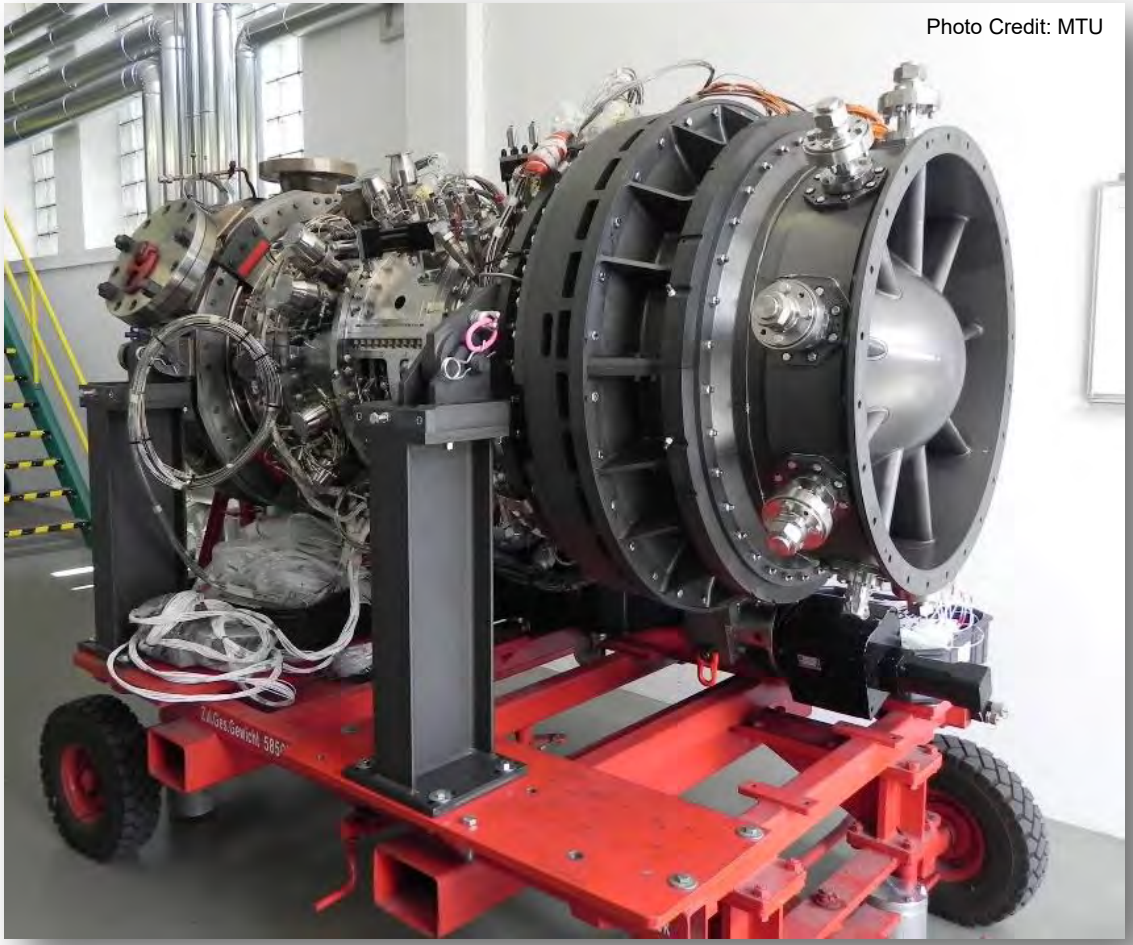
HPC Technology– Rig Assembly

Rig was transferred to test cell on July 21, 2016

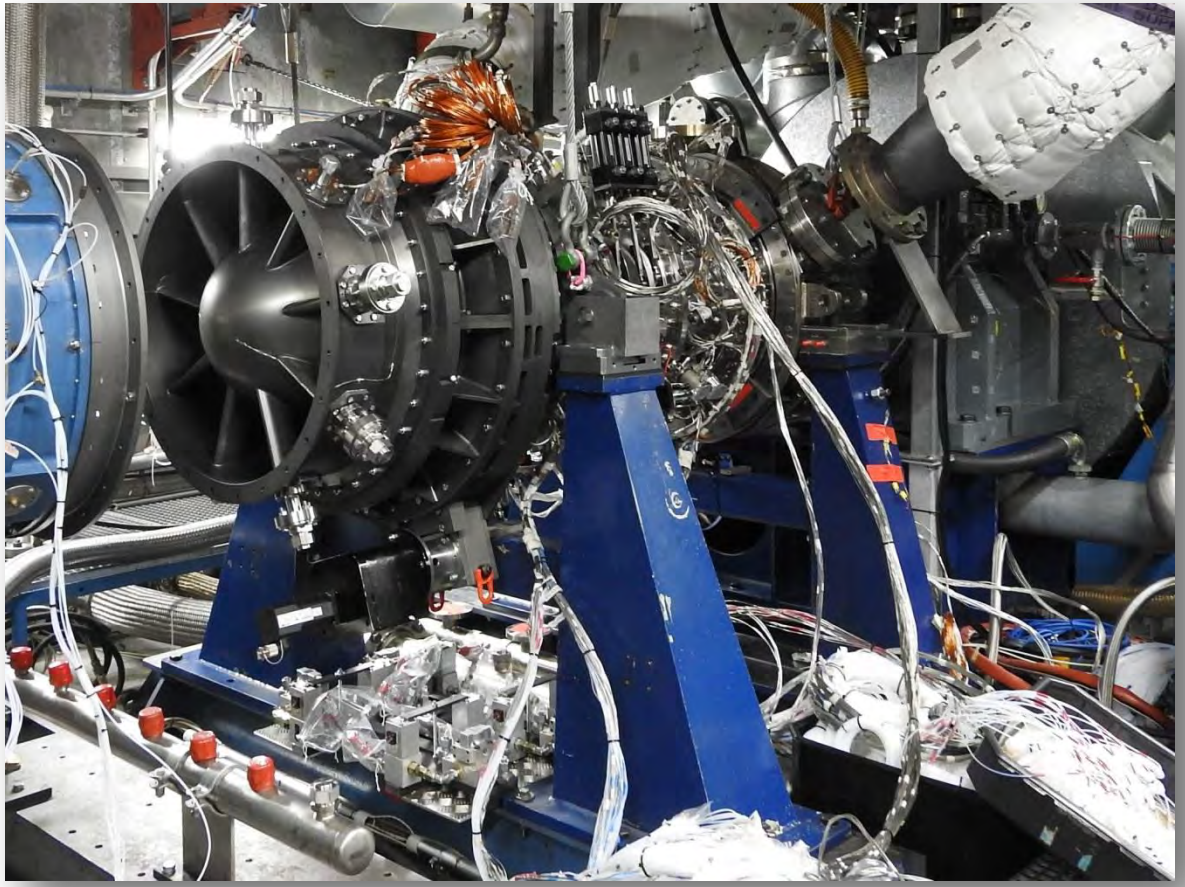


HIGH-PERFORMANCE CORE

HPC Technology – Rig Installation

Rig installed in test cell and functional check August 23, 2016

Photo Credit: MTU



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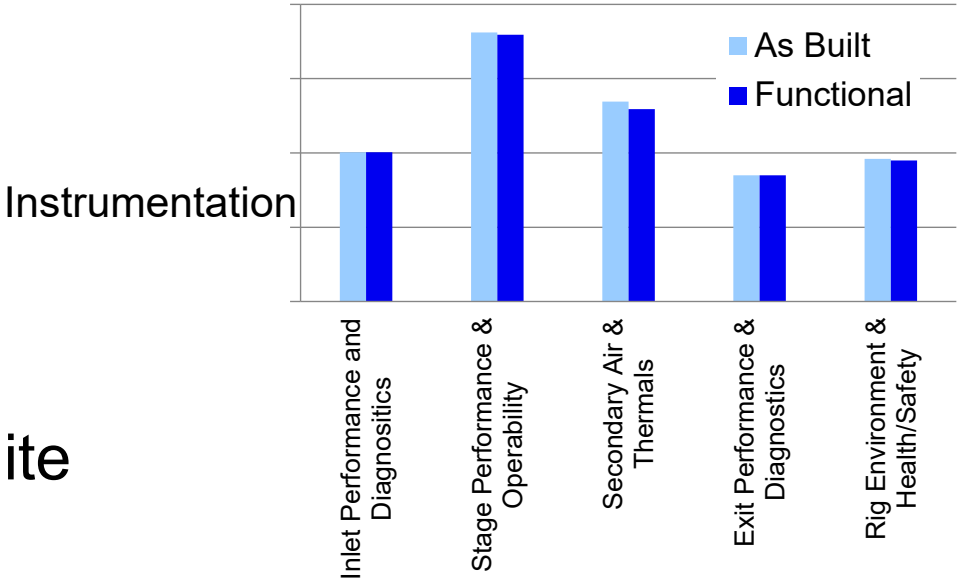
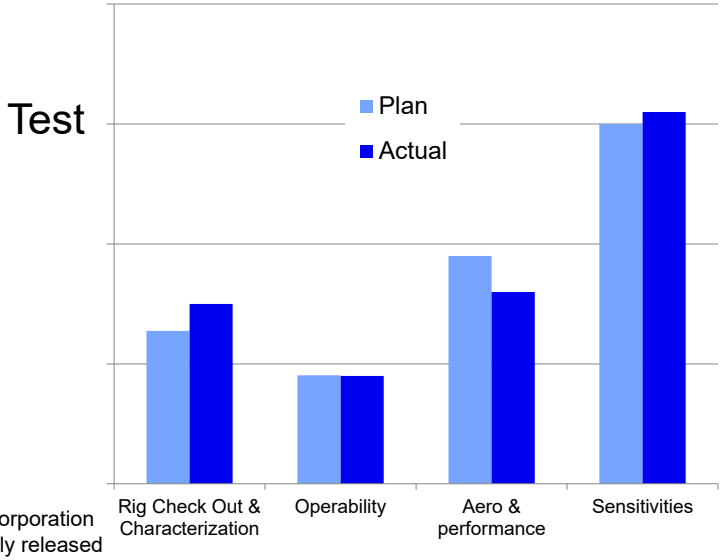
HPC Technology – Test and Instrumentation

Over 100 hours of testing conducted

Robust instrumentation suite (> 99% survivability)

Adapted to minor adjustments to test plan to react to rig learning





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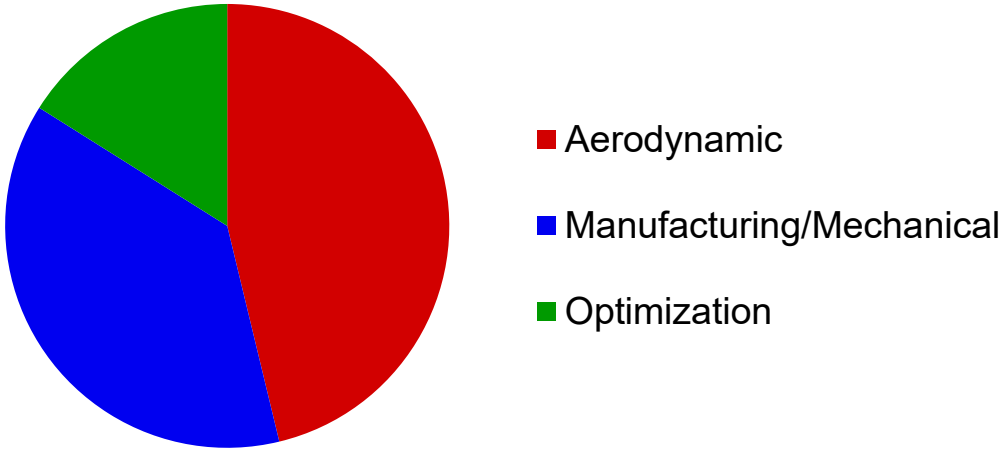
HPC Technology – Testing Completed Oct 28th, 2016

Technology projections achieved, detailed assessment in process

Performance benefits from both technology maturation and compressor optimization

- Aero technologies
- Manufacturing technologies
- Mechanical design technologies

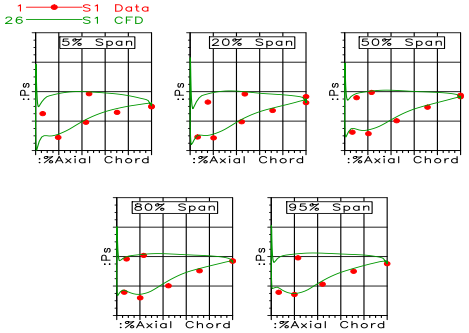


HIGH-PERFORMANCE CORE

HPC Technology – Data Analysis

Completed data assessment and test reporting

- Compressor mapping & characterization (reference - for illustration only)



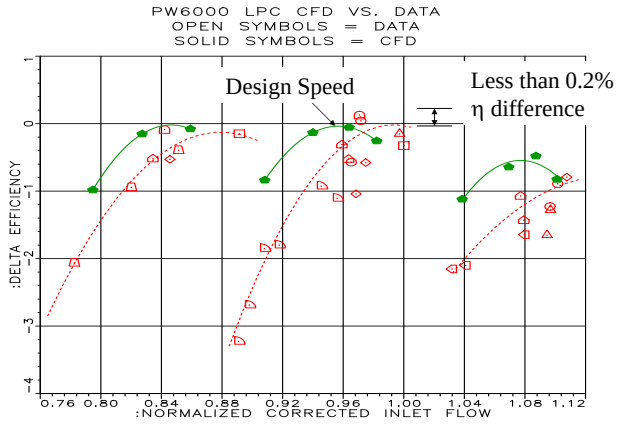

Proceedings of ASME TURBO EXPO 2004:
Power for Land, Sea, and Air
June 14-17, 2004, Vienna, Austria

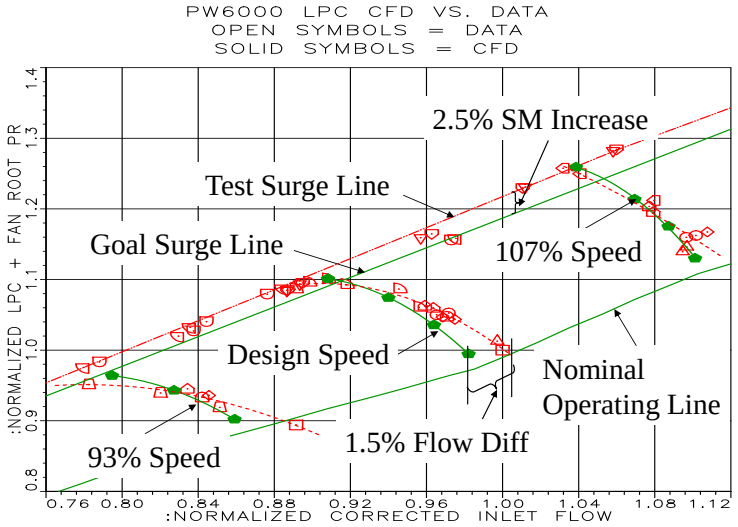
GT2004-54263

APPLICATION OF MULTISTAGE CFD ANALYSIS TO LOW PRESSURE COMPRESSOR DESIGN

Lisa Brilliant
Pratt and Whitney

Stanley Balamucki
Pratt and Whitney





Clearance and surge behavior

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HPC Technology – Data Assessment & Next Steps

Data assessment completed

Improved GTF HPC achieved

Extensive instrumentation enables detailed HPC understanding

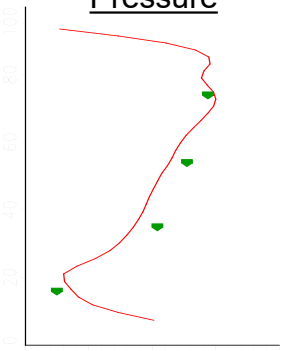
Comprehensive sensitivities study completed

Results comparable to CFD predictions

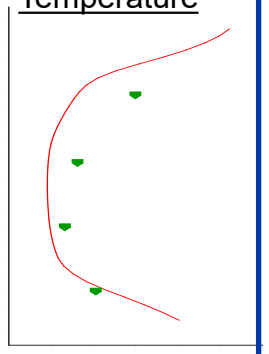
Demo engine planning in process

Leading Edge Kielhead Data

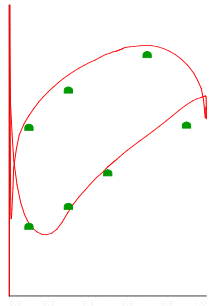
Local/Average Pressure



Local/Average Temperature

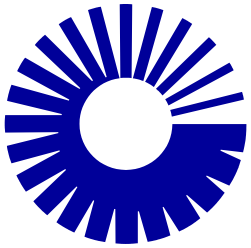


Airfoil Surface Static Pressure



CFD

Data



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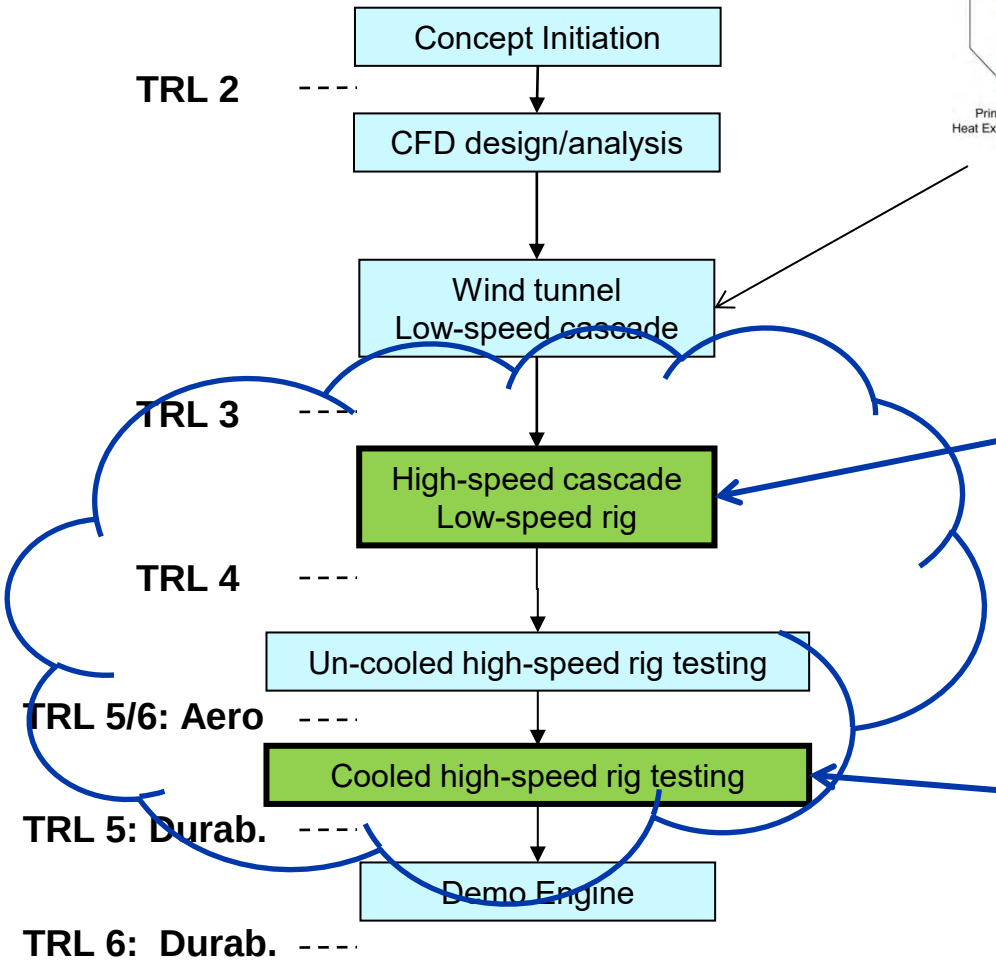
HPT Technology Status

Maturation Strategy



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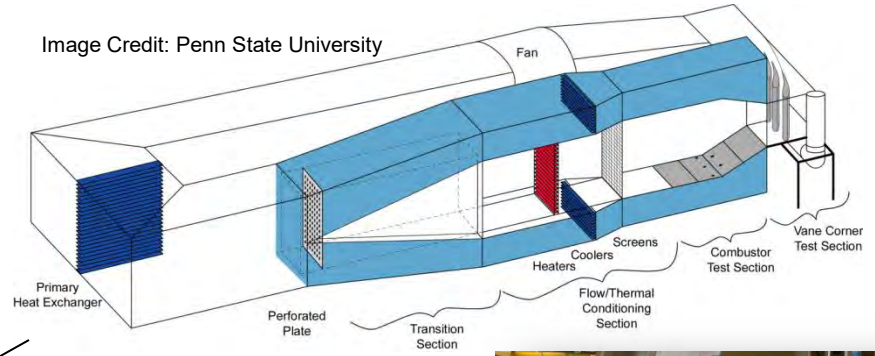

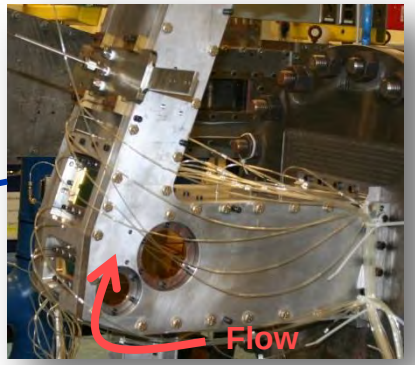

Image Credit: Penn State University

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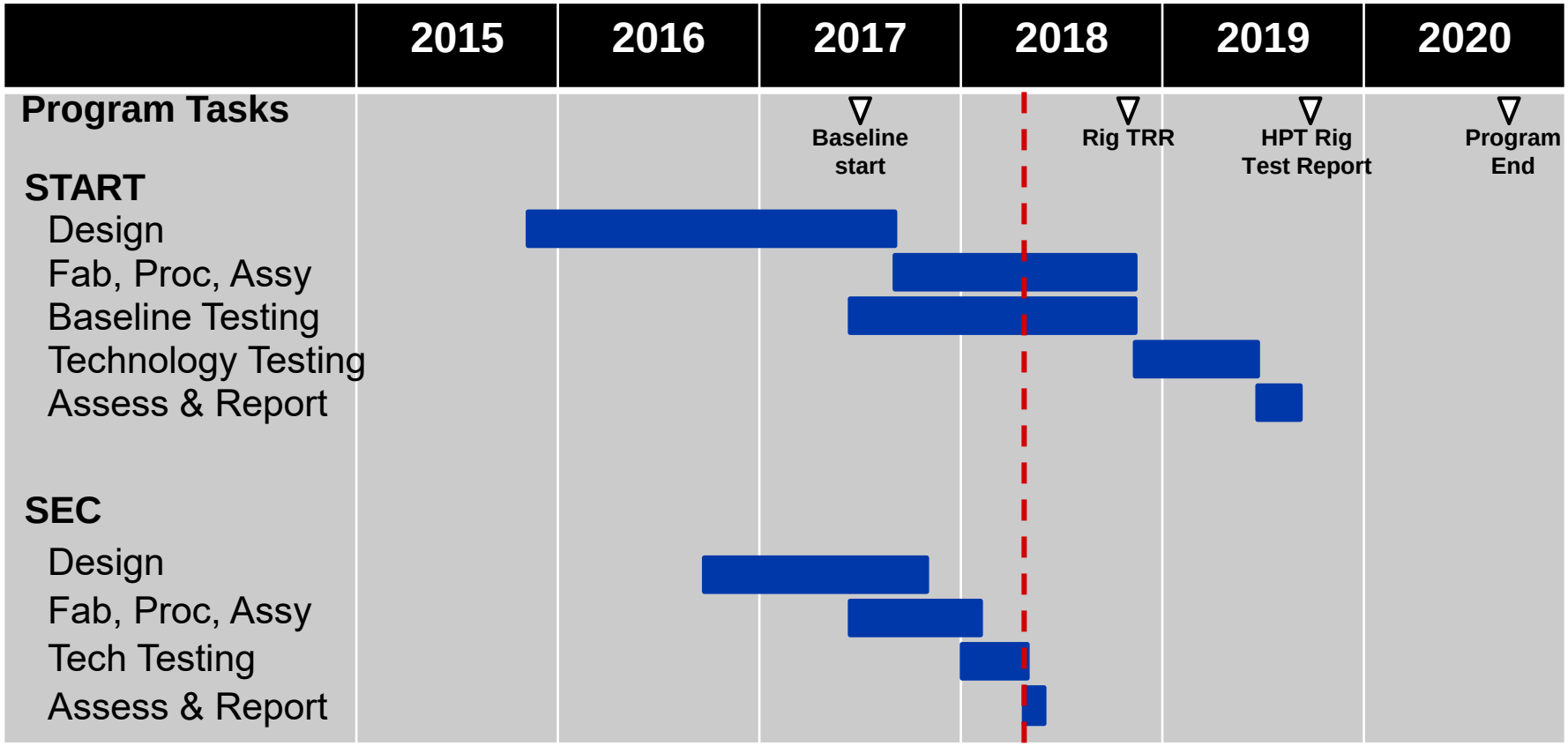
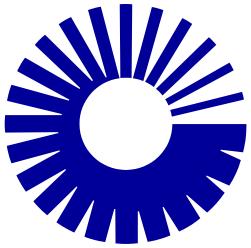
HPT Technology Status - Schedule

HPT scope underway, Industrial and Baseline Testing Phases





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CLEEN II High Pressure Turbine Technologies

START Rig

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START test objectives

- Use rig data for validation of aero design and durability pretest predictions
- Use flowfield and thermal measurements to validate performance improvement
    - Understand cooling losses and loss modeling details
    - Verify full-span 3D aero
    - Correlate rig/engine maps for cooled turbine aero and durability
    - Validate thermal predictions & demonstrate improved cooling capability

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HPT Technology – Near Term Milestones Status

PSU START rig

- ✓ Baseline cavity testing complete
- ❑ Integrate the exit traverse system into the PSU START rig
- ❑ Complete PSU START rig baseline Aero testing

Complete Single Element Cascade (SEC)

- ✓ Rig fabrication and assembly complete
- ✓ Baseline Aero testing complete
- ❑ Thermal technology airfoil testing in-process

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History of the START rig facility

START = Steady Thermal Aero Research Turbine.

~$10M invested into the facility over the past 5 years

Pratt and Whitney Center of Excellence, World Class Facility

All Photo and Image Credits: Penn State University

2013

2018

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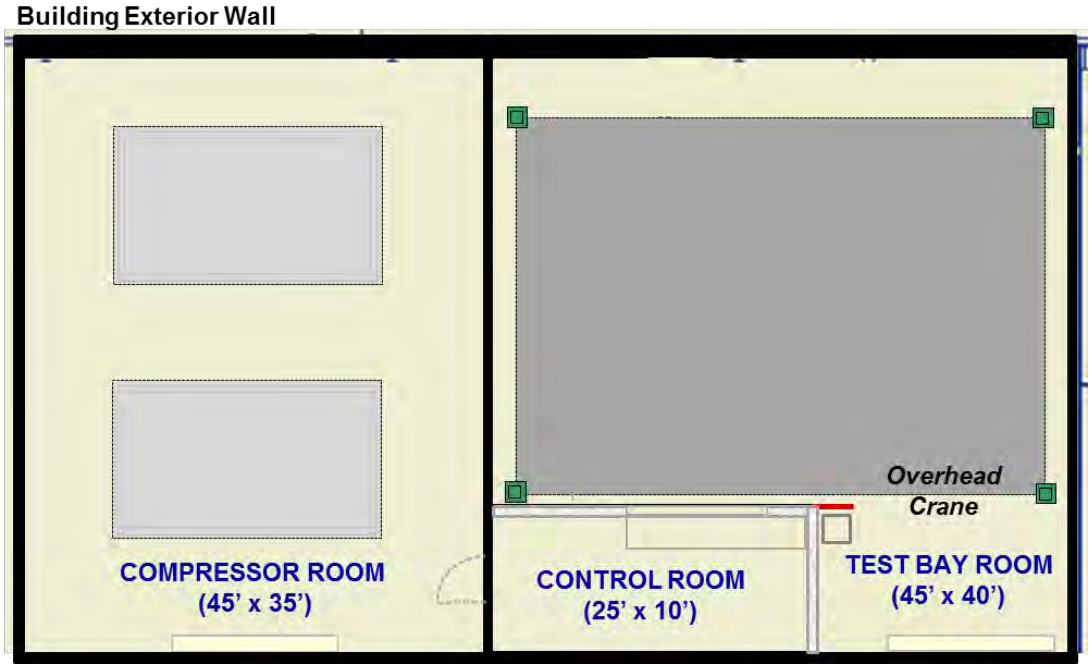
PSU START Facility

February 2012: Ground broken on the PSU START facility



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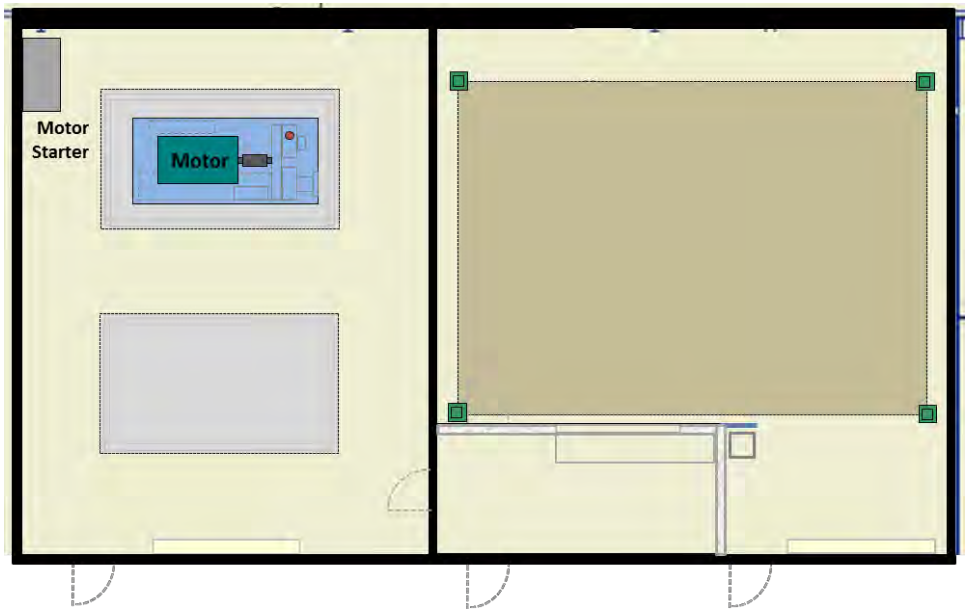
PSU START Facility

May 2012: First of two planned compressor units installed



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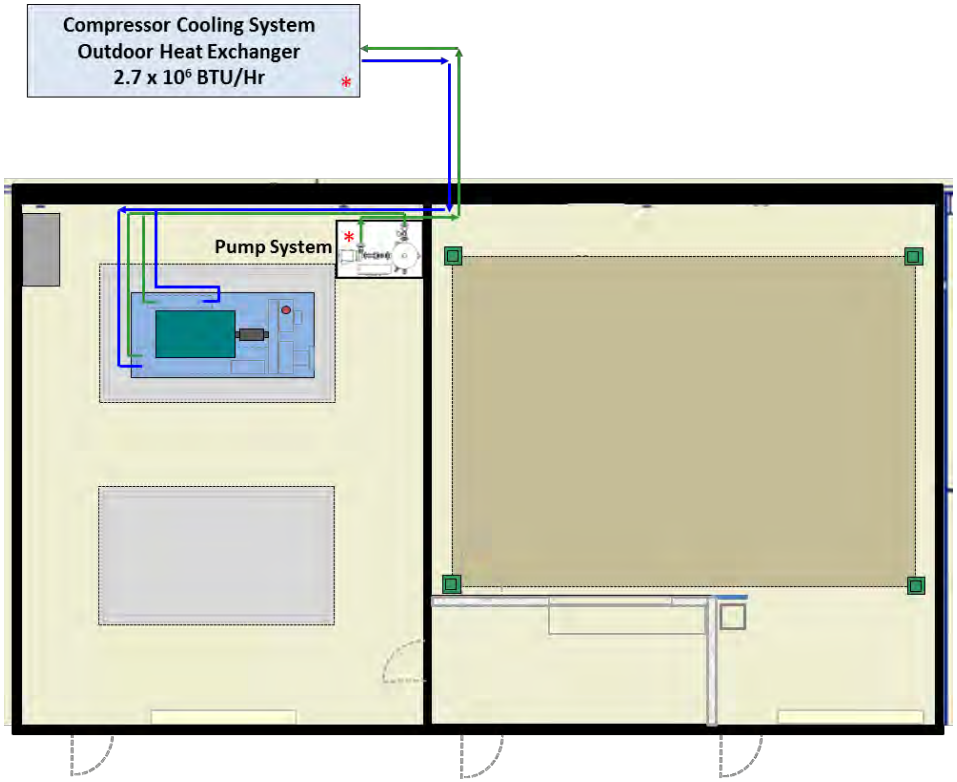
PSU START Facility

March 2013: Cooling system for the compressor installed



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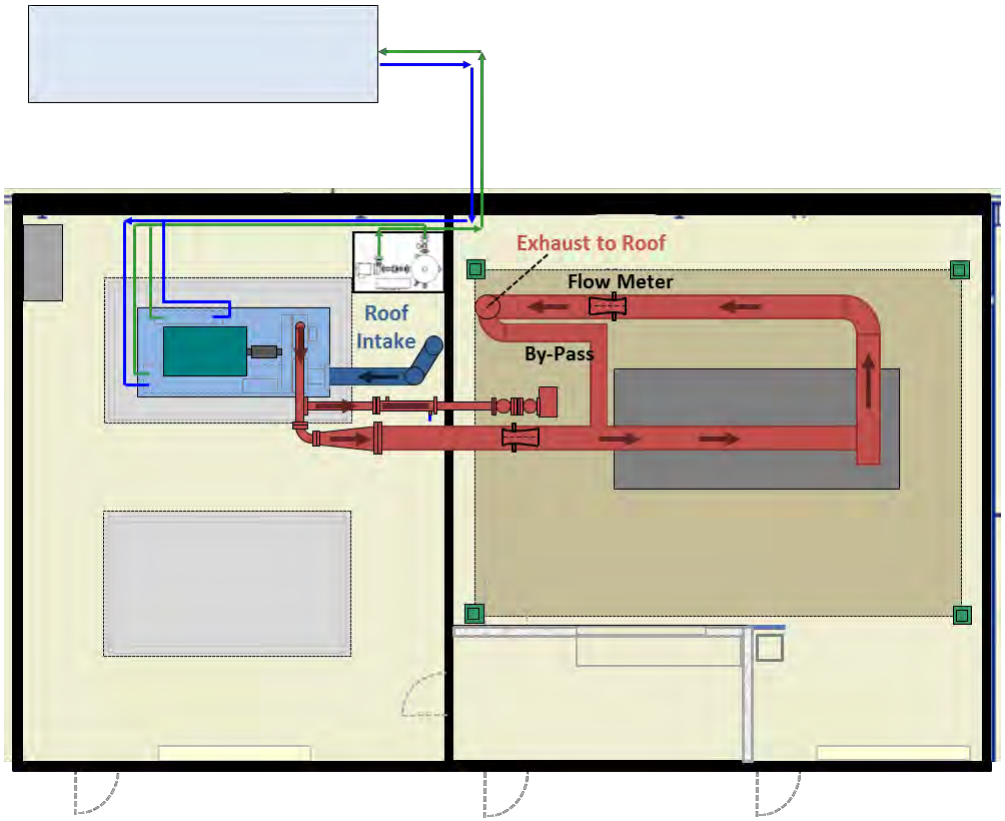
PSU START Facility

January-June 2014: Facility air piping completed



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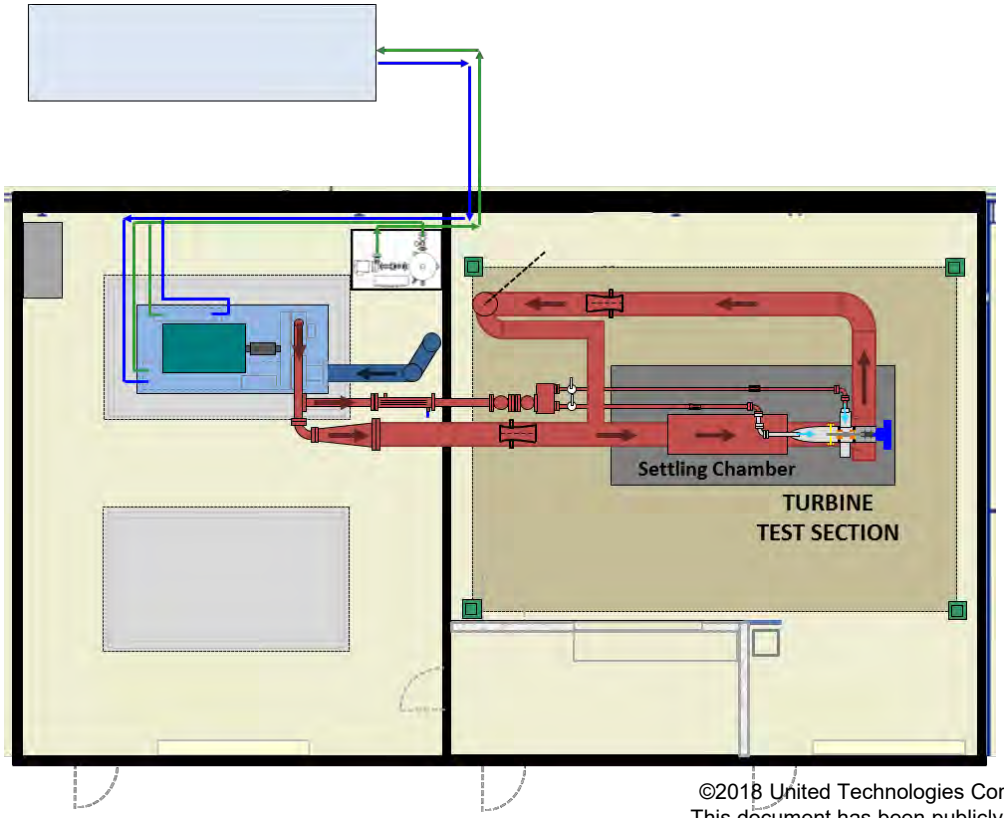
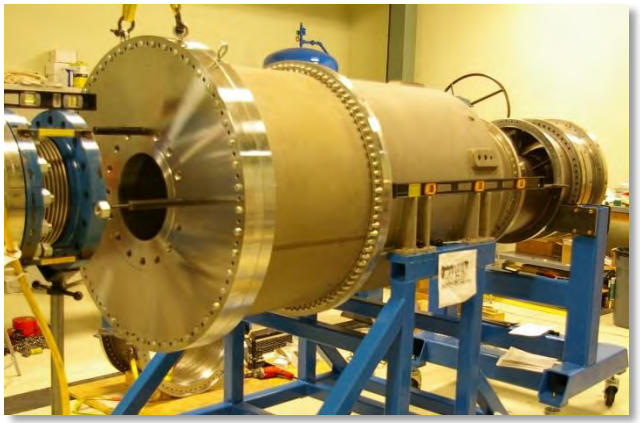
PSU START Facility

August 2014: Installation of turbine test section and start of facility utilization





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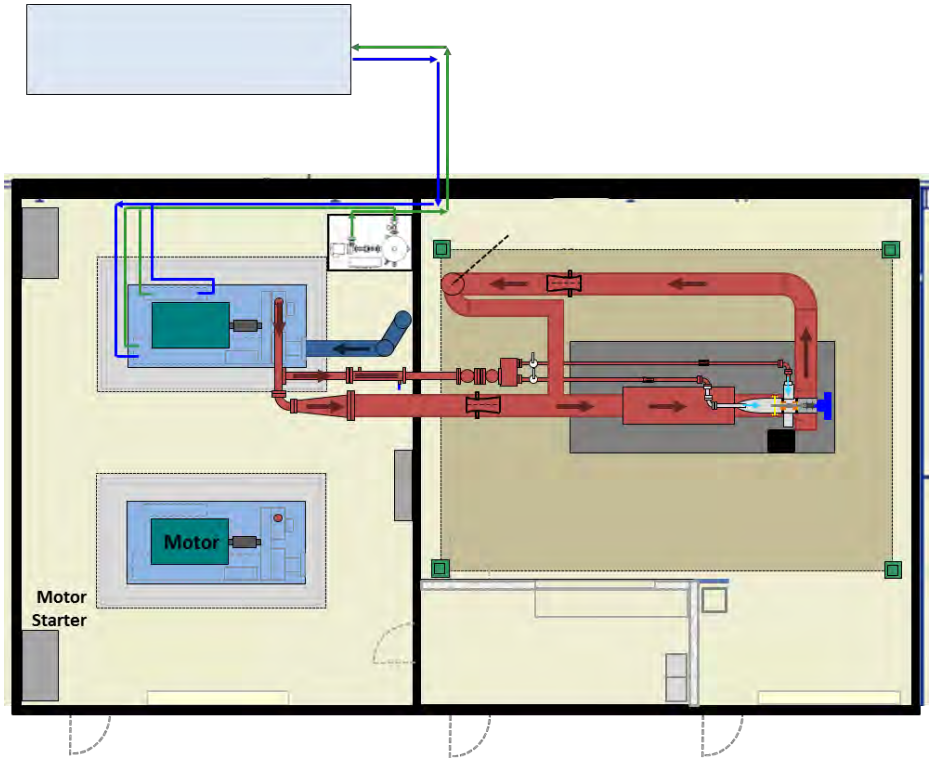
PSU START Facility

October-November 2014:
Installation of second air compressor



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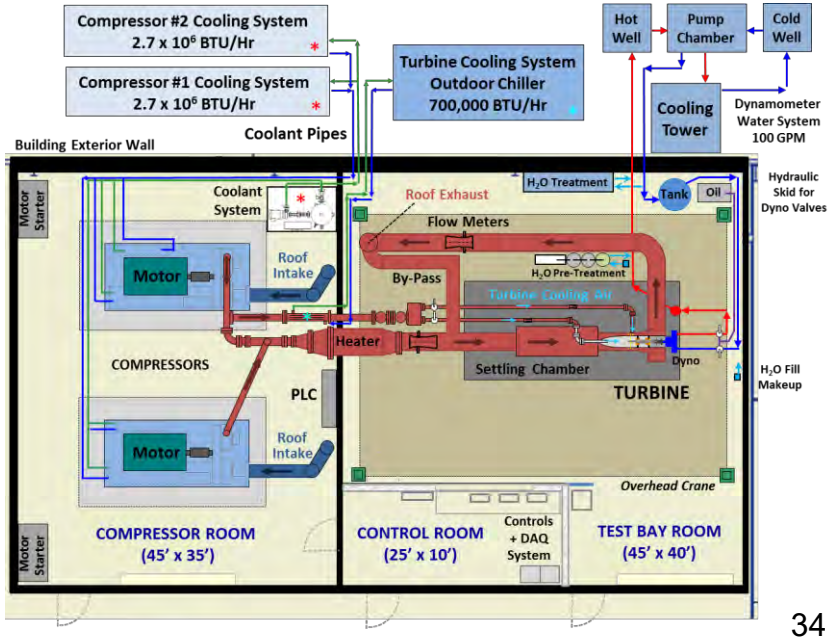
PSU START Facility

Under CLEEN II...

- ✓ Plumbing of second compressor
- ✓ Doubling of compressor cooling capacity
- ✓ Natural gas heating chamber added for hot flow path testing
- ✓ Water brake dynamometer installation, with cooling system
- ✓ Installation of shaft torque meter
- ✓ Turbine cooling air chillers installed and plumbed
- ✓ Control room completed with Data Acquisition System
- ✓ Half height test section to full span test section
- ✓ Additional Instrumentation

All Photo and Image Credits: Penn State University

(Above) Dyno H2O wells being installed, 2016
(Left) Natural Gas Heating Chamber



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HPT Technology Status – High Speed Rig Testing

Facility upgrade complete – full span, multi-stage, cooling capable

Increased capability, enhanced instrumentation & controls

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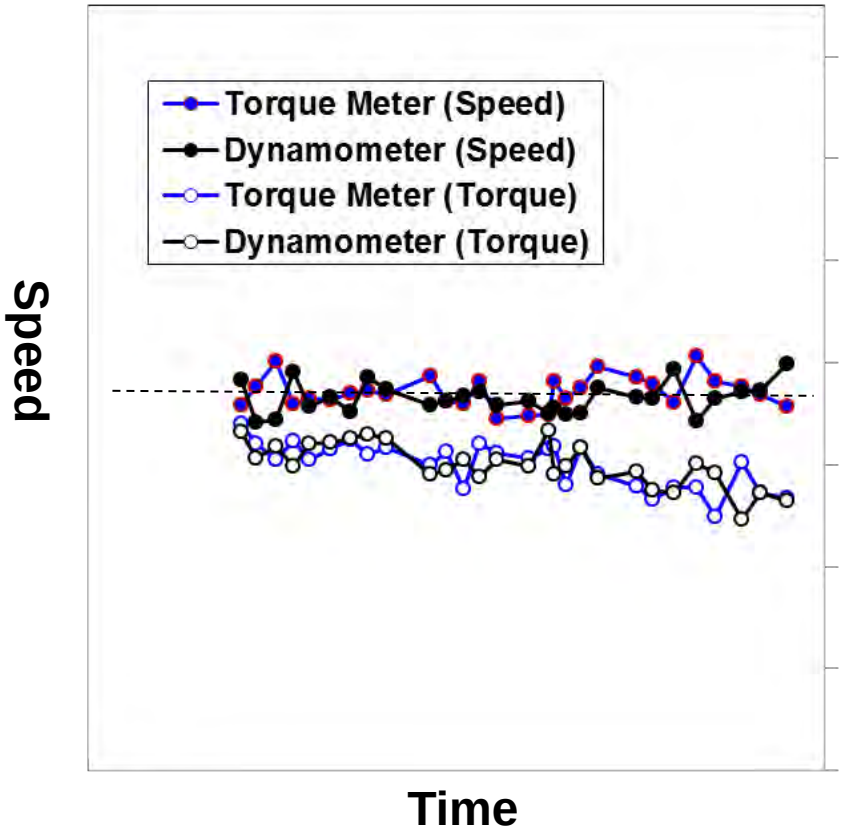
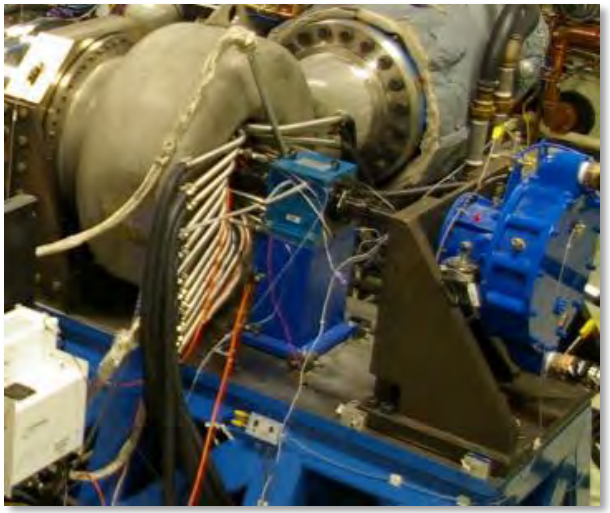
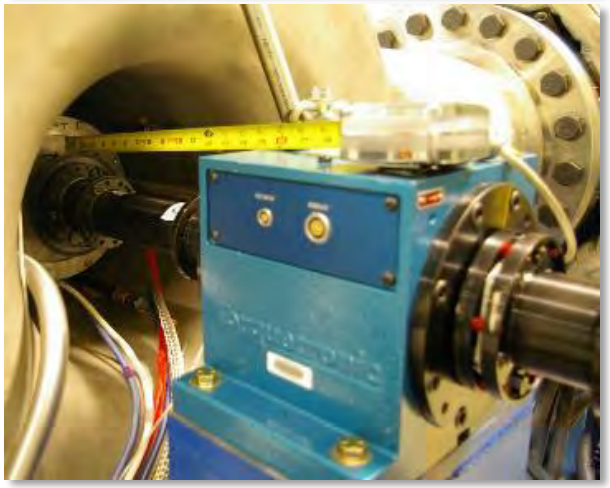
Torque meter & dyno installation

Calibration complete



Torque





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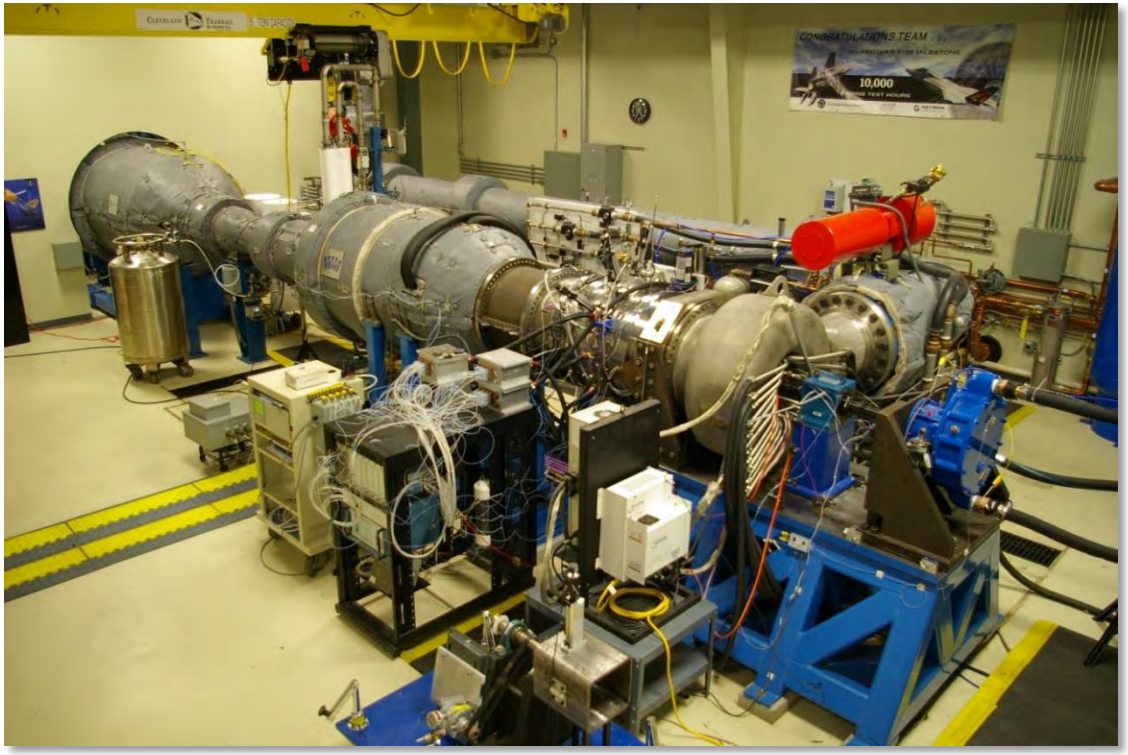
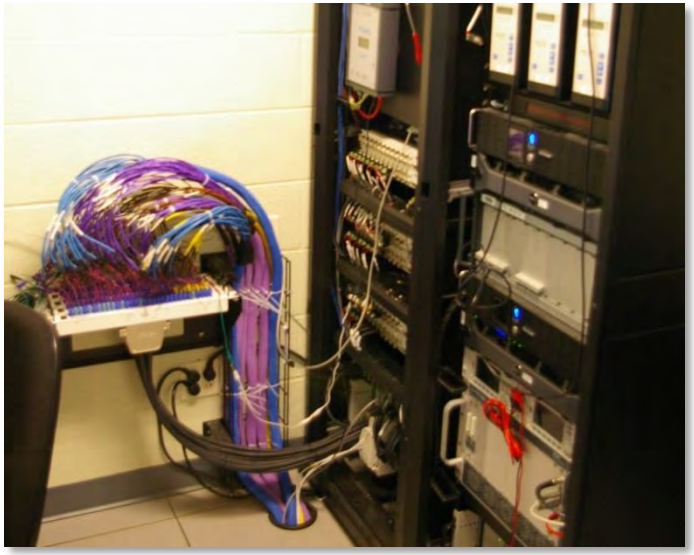
HPT Technology – High Speed Rig Testing

Rig instrumented and calibrated

Rig shakedown complete

Baseline turbine testing in-process





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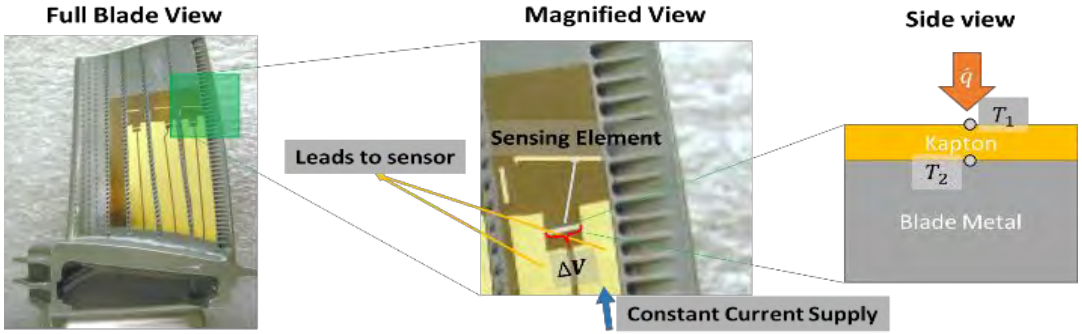
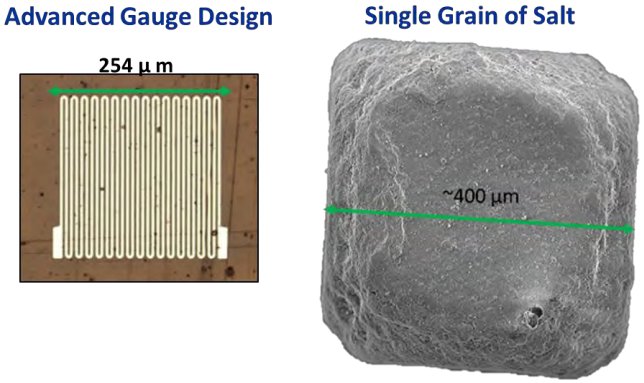
START Rotating Heat flux System

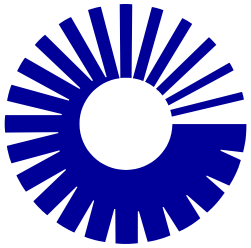
System design & bench testing in-process

Utilizes Individual blade heat flux sensors developed at PSU's Advanced nanofabrication technology to create next-generation gage design



Anthony et al. 2011





Pratt & Whitney

A United Technologies Company

CLEEN II High Pressure Turbine Technologies

Single Element Cascade Rig

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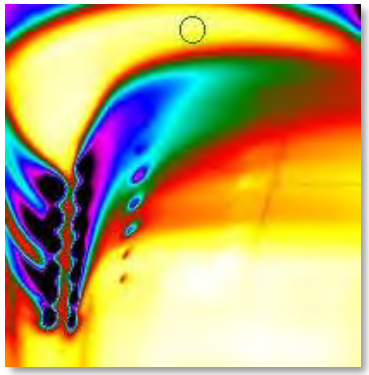
SEC Test Objectives

Measure film cooling effectiveness and aerodynamic loss on high-lift airfoil sections comparing Nominal and advanced Cooling-hole shapes at relevant operating conditions

Generate high-quality aero/thermal data to validate analytical models

Enhance understanding of performance losses due to film-cooling

Example of Raw IR Image Data



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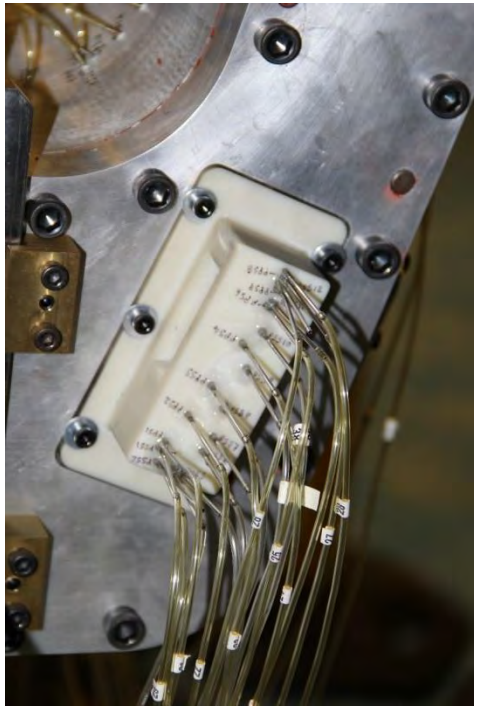
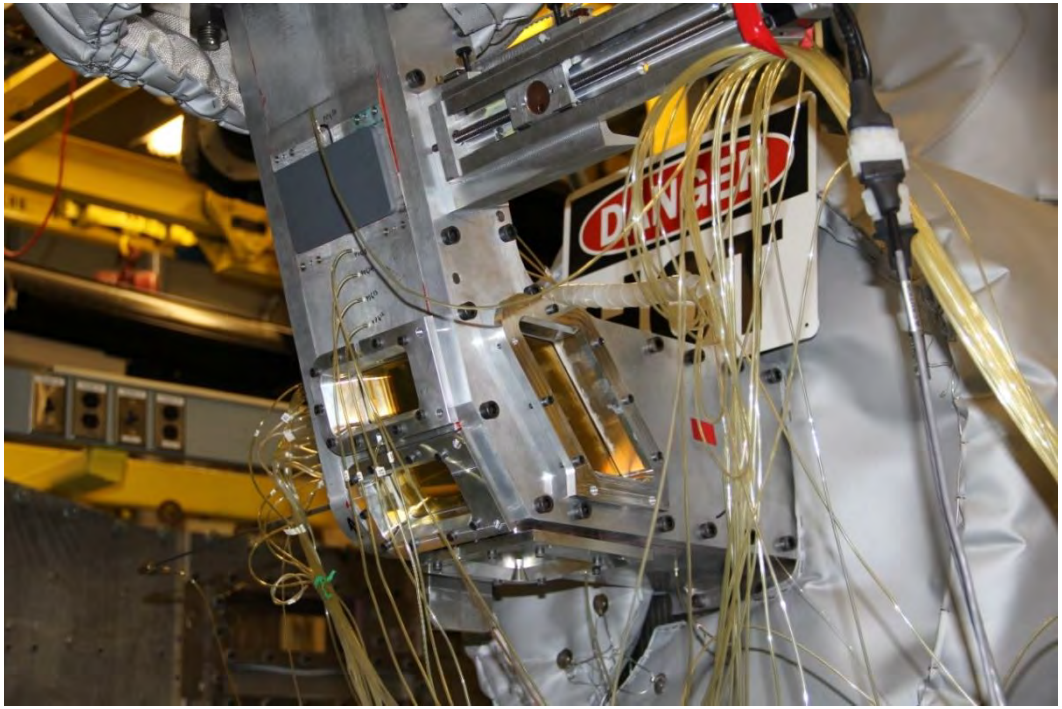
Single Element Cascade (SEC) Overview

High-speed Film-cooling Test at UTRC's Cascade facility

Aero-Durability cascade facility to bridge gap between fundamental flat-plate experiments and rig/engine tests





Single Element Cascade assembly

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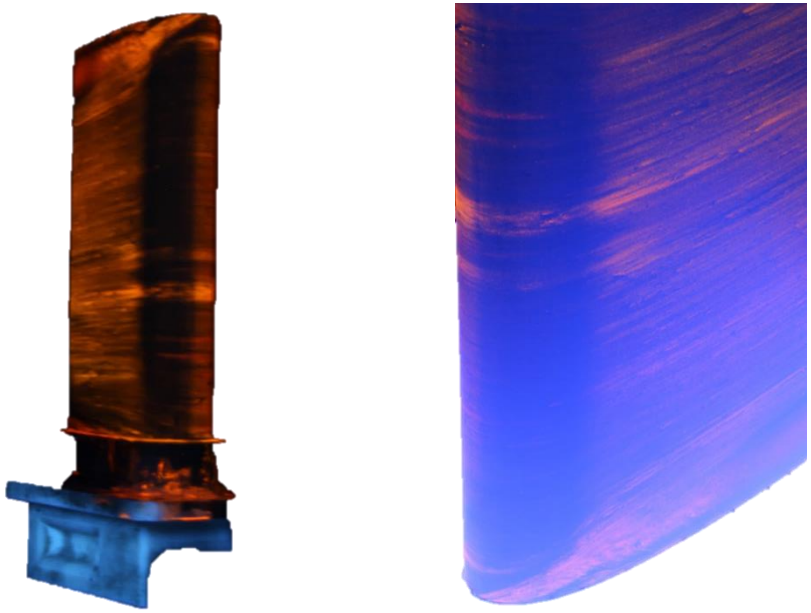
HPT Technology Status – Cascade Testing

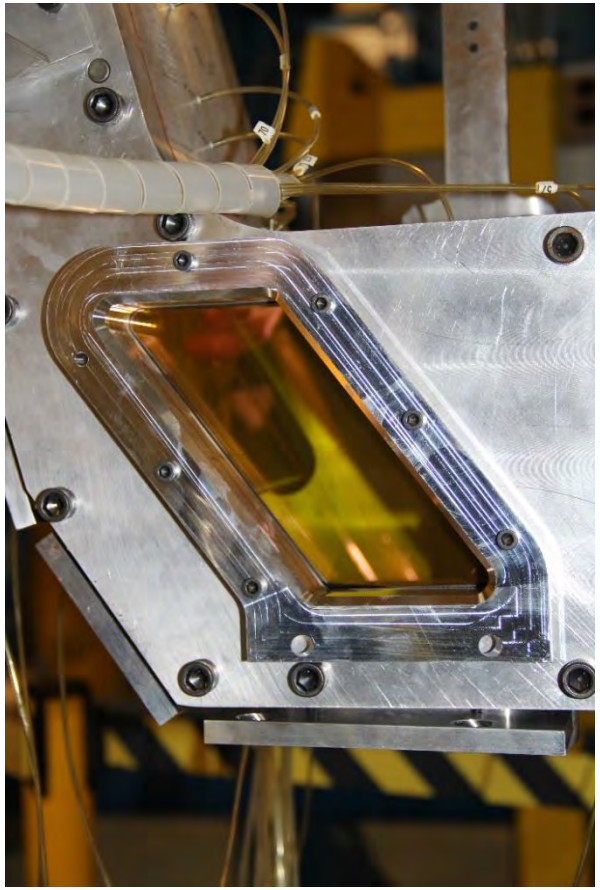
Cascade rig special test equipment Guidewalls, airfoil, & IR window fab complete

Rig assembly complete

Uncooled Aero Baseline Testing complete



Flow visualization



SEC IR windows

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HPT Technology – Summary & Next Steps

START rig fully instrumented and calibrated for cavity flow testing and aero cavity testing complete

Single element cascade rig fabrication and uncooled aero testing complete

FAA technology blade fabrication in-process

START aero & thermal testing equipment fabrication in-process

PSU START rig

- Integrate the exit traverse system into the PSU START rig
- Complete PSU START rig baseline Aero testing

Single Element Cascade (SEC)

- Complete Thermal technology airfoil testing

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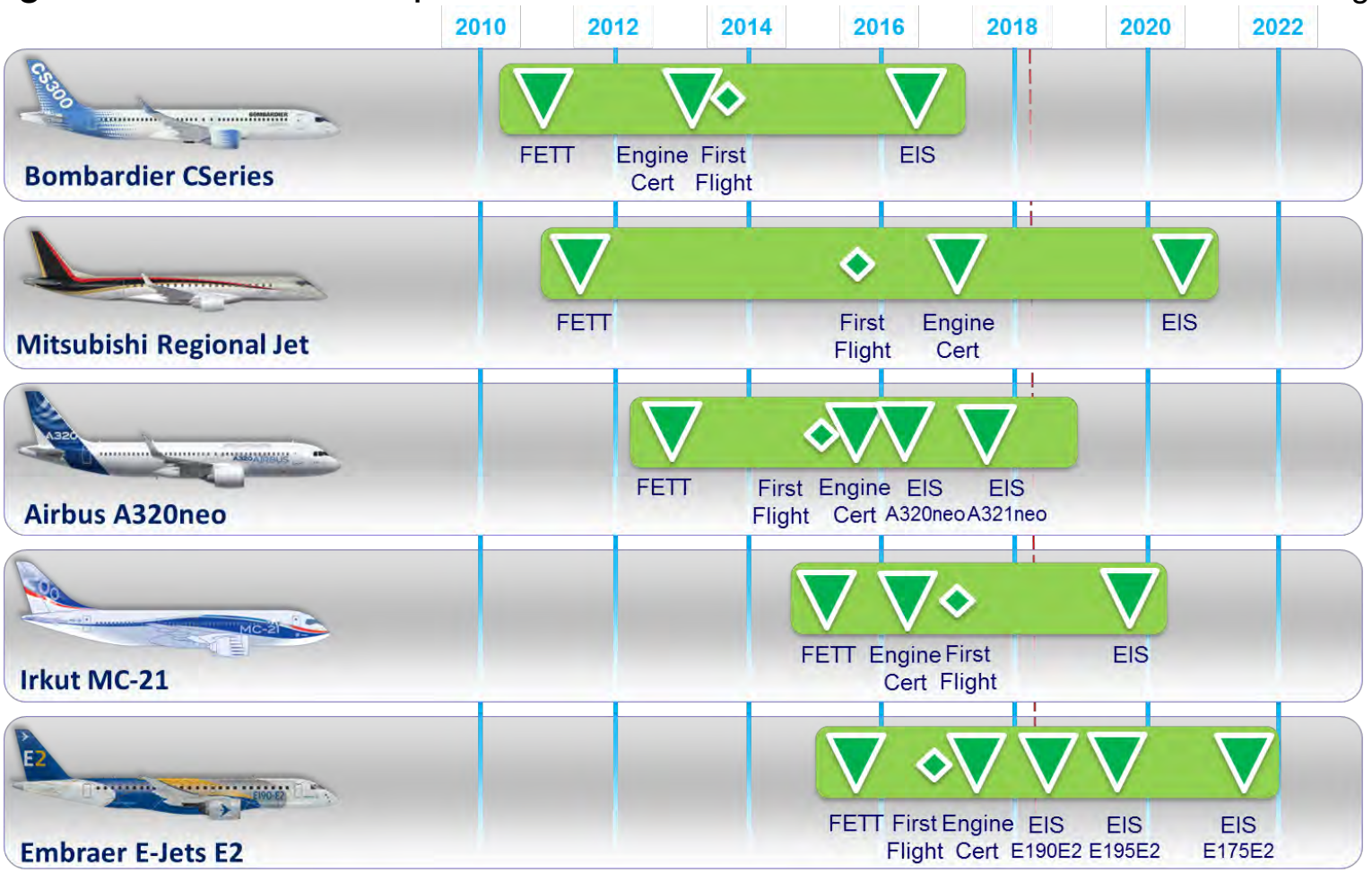
UHB Technologies
HPC Technologies
HPT Technologies



CLEEN TECHNOLOGY DEMONSTRATORS

Summary

P&W CLEEN programs progressing to plan

Technology delivering improved GTF performance

HPT technology facility upgrades completed

HPT technology testing underway

HPC technology rig performance assessment complete

THANK YOU