National Aeronautics and Space Administration

United Technologies Research Center

Fundamental Aeronautics Program

Subsonic Rotary Wing Project

Progress towards the Aerodynamic Testing of the High Efficiency Centrifugal Compressor

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2012 Technical Conference
March 13-15, 2012

Outline

- **Project Objectives/Background**
- Aerodynamic Design Summary
- Experimental Plan and Instrumentation
- Hardware Fabrication & Integration with NASA Rig
- Research Test Plan/Next Steps

Motivation

Advance the SOA of Centrifugal Compressors for Rotorcraft Applications

- Objectives
  1. Identify key technical barriers to advancing SOA of small centrifugal compressors
  2. Delineation of measurements that will provide insight into flow physics of technical barriers
  3. Design, fabricate, install, and test a SOA compressor
  4. Acquisition of high-quality measurements to clarify flow physics of technical barriers

HECC Team Members

Project Team

- Program Management
  - United Technologies Research Center
- NASA Glenn Researchers
  - NASA
- Design Review Team
  - ARL
  - AATD (Aviation Applied Technology Directorate)
  - NAVAIR
- Test Article Mechanical Design
  - Agilis Engineering
- Aero-Design Team
  - United Technologies Research Center
  - Agilis Engineering
  - ADS – AeroDynamic Solutions LLC
- Experimental Test Program
  - United Technologies Research Center
  - NASA

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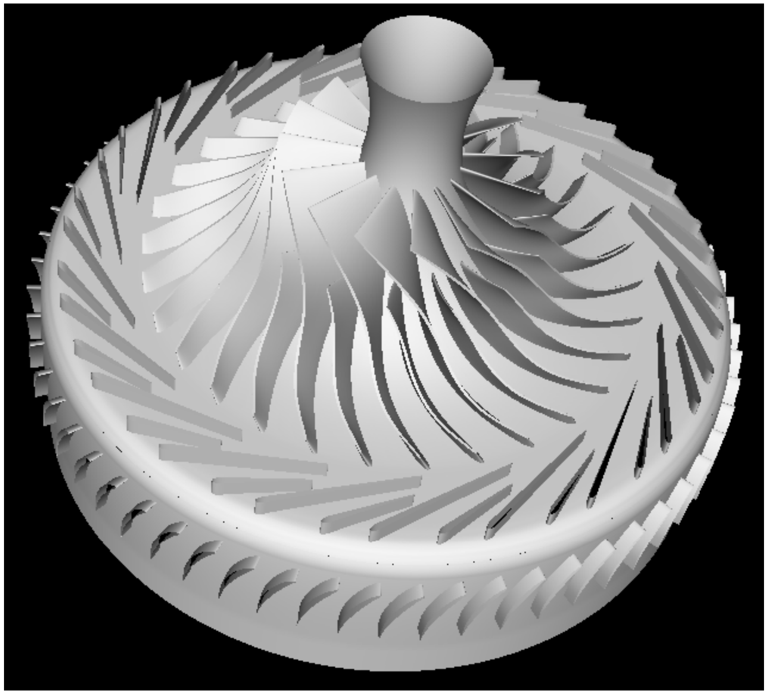
Test Article Summary

- Impeller: 15 blade/splitter pairs, spanwise varying backsweep, lean, elliptical leading and trailing edges
- Diffuser: 20 vane/splitter pairs, with splitters offset to maximize pressure recovery
- EGVs: 60 cascade-style airfoils
- Impeller blade shaping and flowpath developed through optimization



Aerodynamic Design Strategy

Starting point: NASA CC3 established as reference compressor

- CC3 is well characterized "public" compressor that scales to a rotorcraft relevant system
- Reference compressor critical to identifying performance enhancements
- Maintaining CC3 rotational speed and impeller exit diameter to minimize rig changes
- Used CFD to carry out several sensitivity studies in order to establish the change in impeller performance due to changes in geometry (impeller lean, bow, leading and trailing edge shapes, etc.)

Design choices were based on deltas to CC3 CFD results

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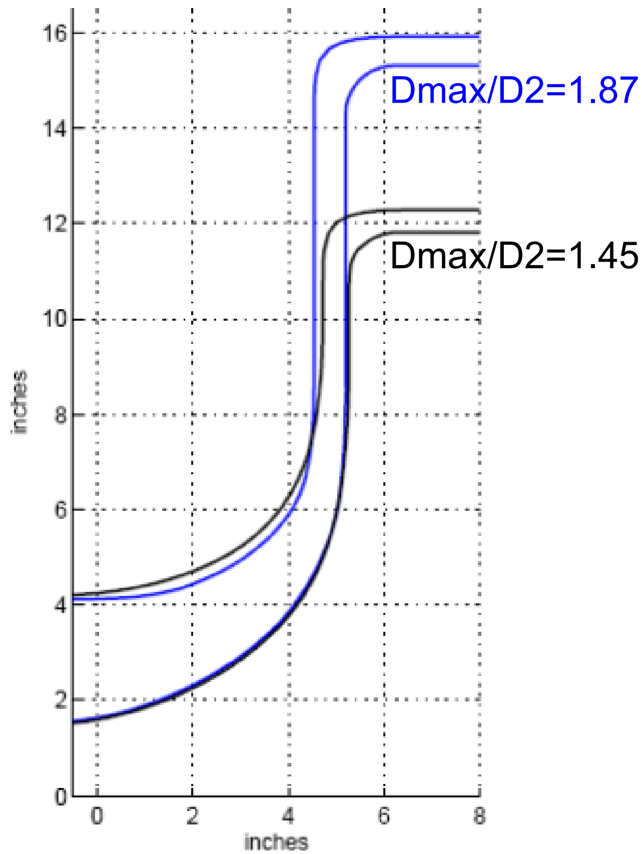
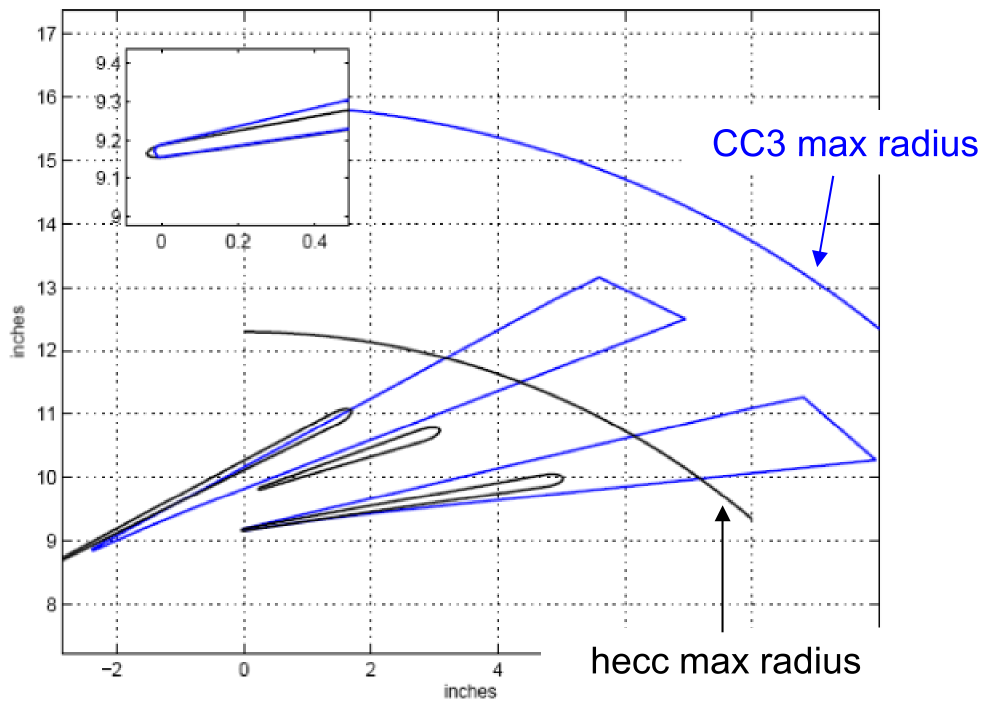
Diffuser Design

Significant reduction in maximum radius limits amount of diffusion achievable



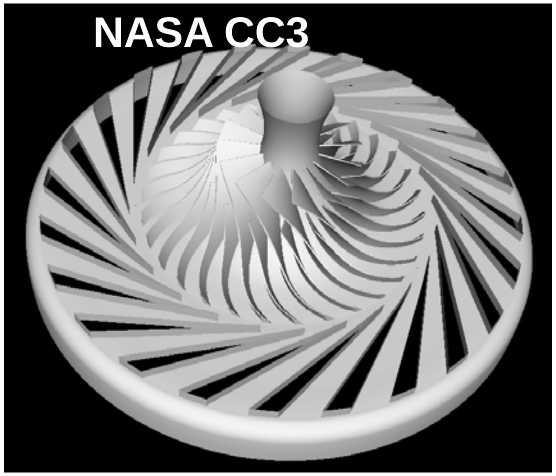
Black = CC3+ iteration 2, blue = CC3

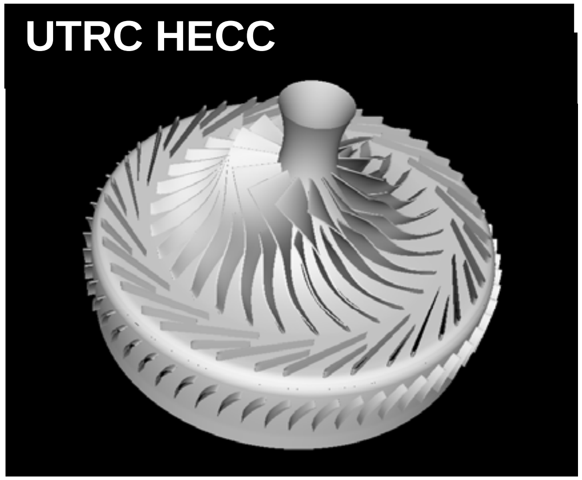


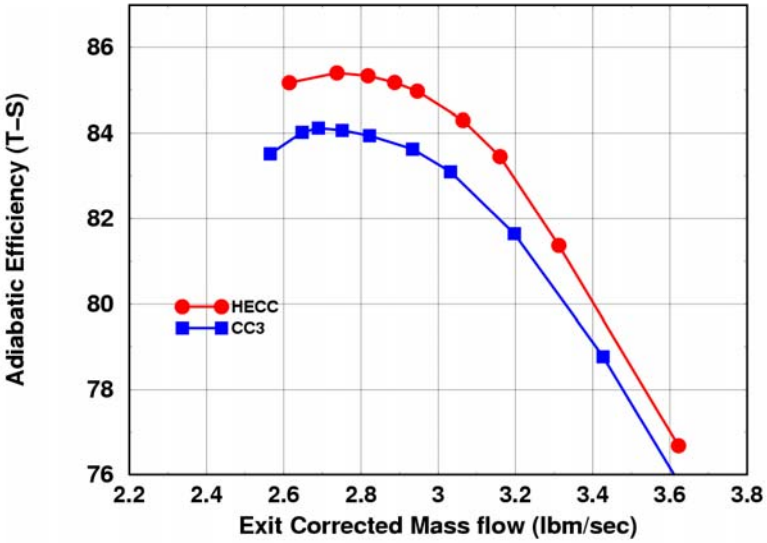
Careful tailoring of geometry required to maximize pressure recovery;
Shifted splitter gives "free" +0.3% efficiency

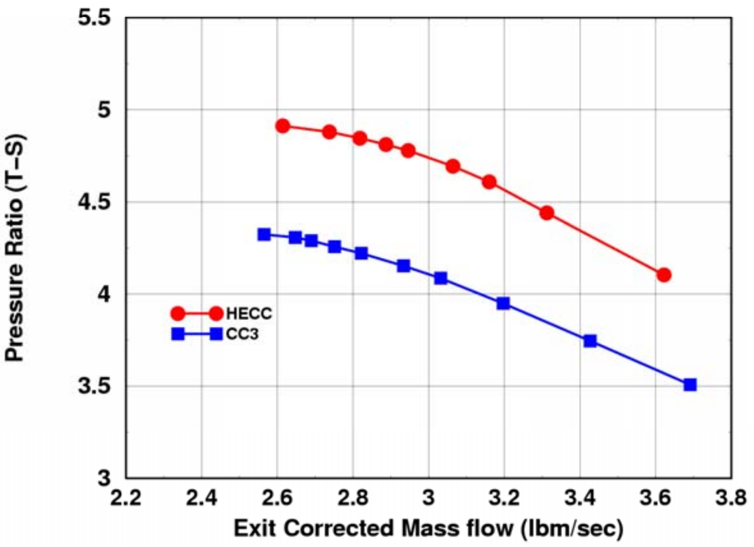
Pre-test Prediction: Stage Performance Results

Higher PR, +2% efficiency over CC3, 23% max diameter reduction









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Pre-test Prediction: Stage Performance Results

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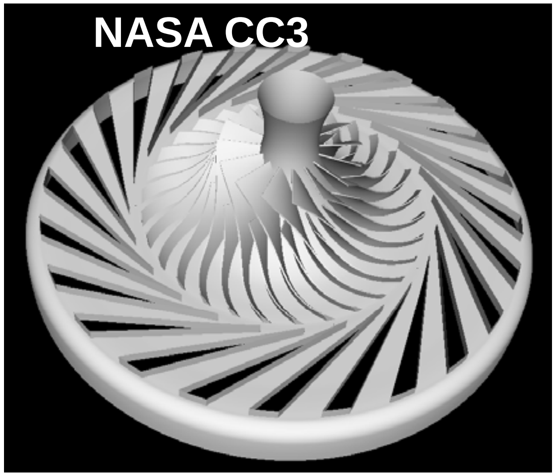

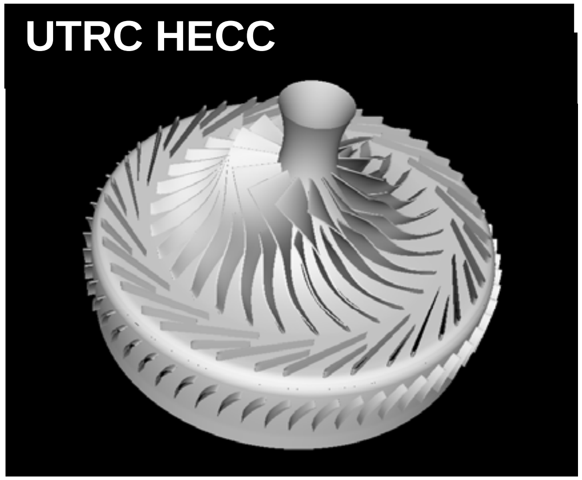

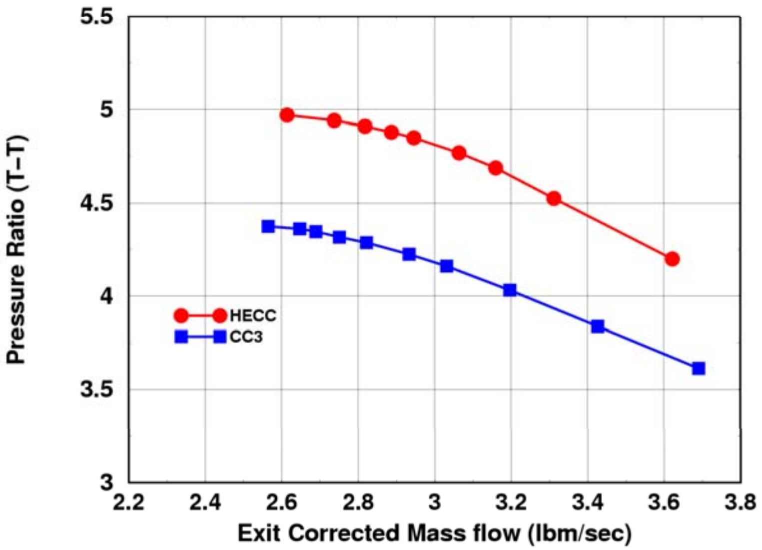

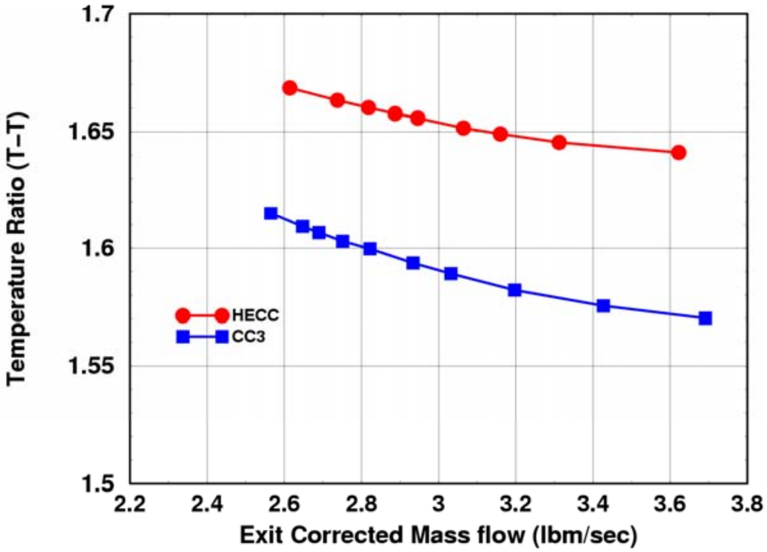

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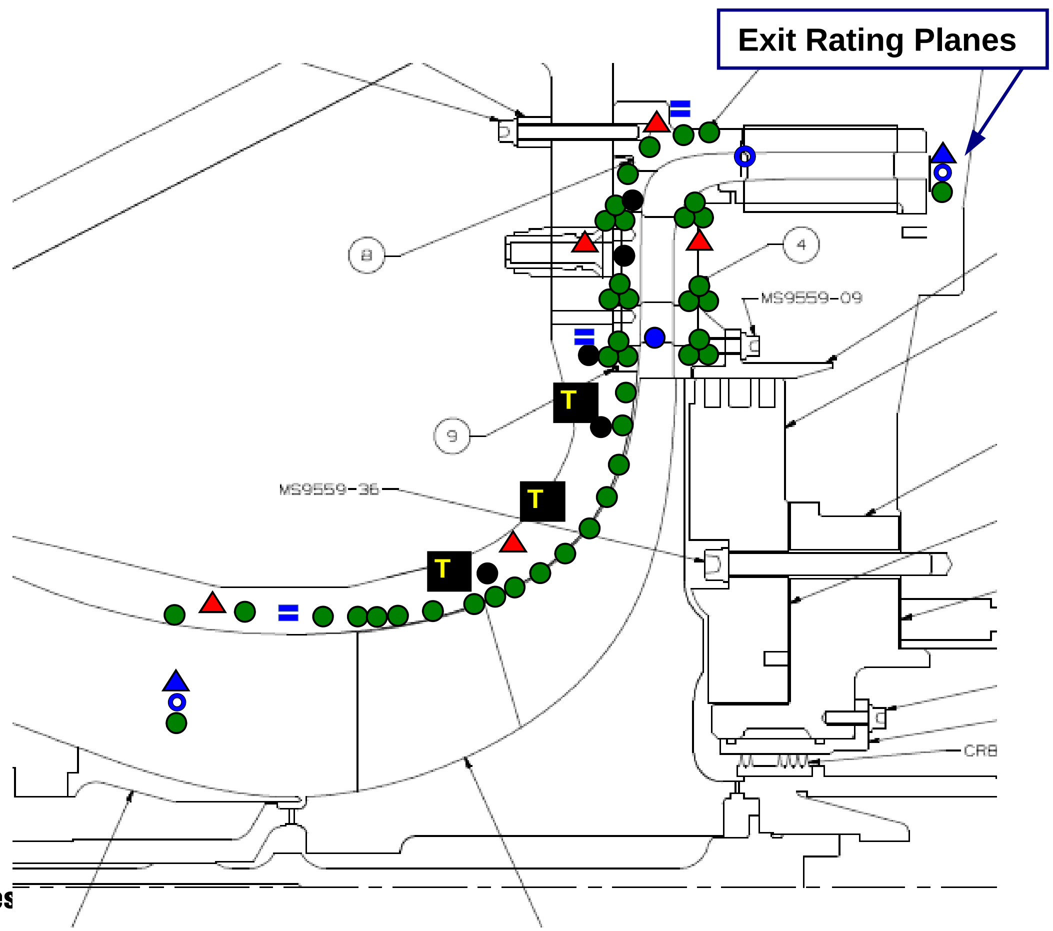
Measurements to Address Technical Barriers

Question	Instrumentation to address question
What is the loss in performance associated with large tip clearances?	Tip capacitance probes
What is the loss in performance associated with exit (backplate) bleed?	Variable backplate bleed capability already present in rig
HCF: What is the relationship between the unsteady pressure fields created by the impeller at blade passing frequency (BPF) interacting with the diffuser vanes?	Unsteady pressure measurements on the impeller shroud and in the diffuser area
Does the split diffuser achieve the design goal of balanced pressure recovery and mass flow split?	Unsteady pressure measurements in the diffuser splitter region
How does the impeller stall originate, and then progress into rotating stall?	Unsteady pressure measurements upstream of the impeller, in the vaneless space distributed around the circumference, in the diffuser throat, and at the diffuser exit

Experimental Plan: Instrumentation Layout

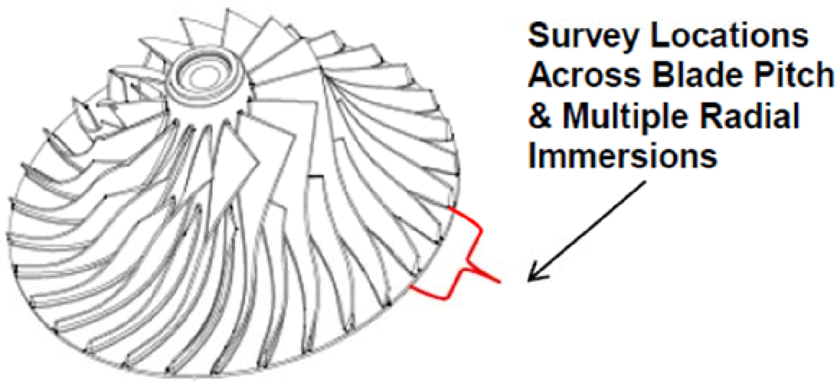
- To confirm key performance improvements
- To address technical barriers
- To provide validation data for the design community

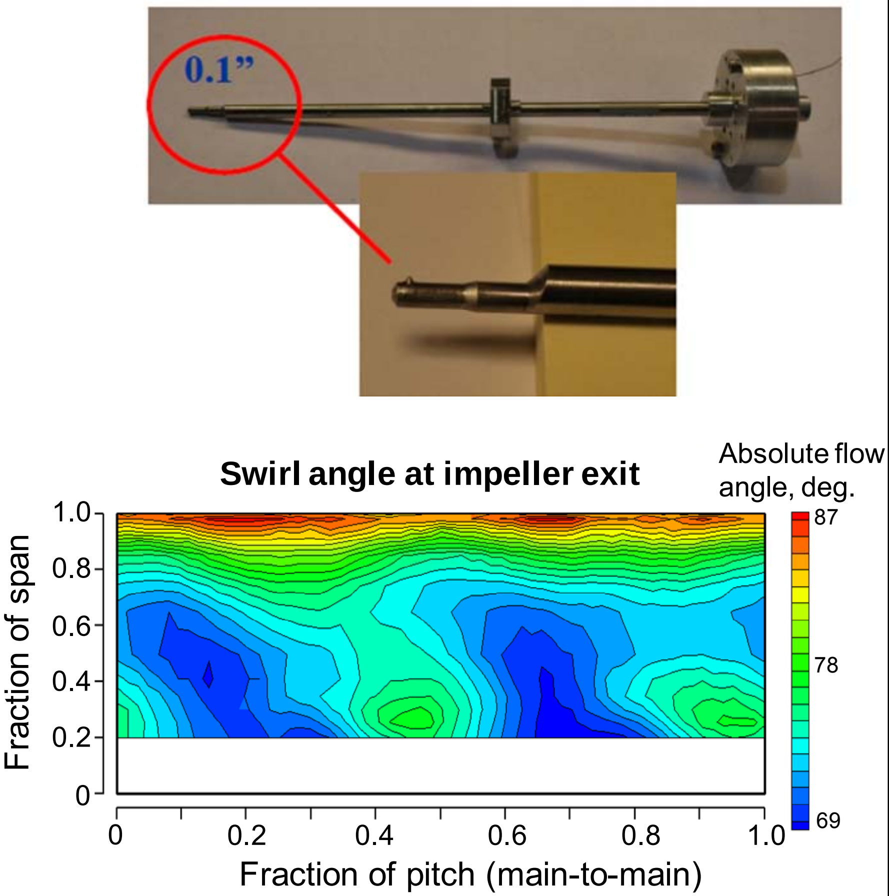


- Static Pressures (215)
- Total Pressures
- Kielhead Total Pressures
- Static Pressure Cluster
- Kulite Pressures (20)
- Total Air Temperatures
- Static Air Temperatures
- Metal Temperatures
- Probe Traverse
- Tip Clearance Probe

Advanced Measurement Technique

Probe developed at NASA Glenn will allow detailed mapping of the impeller exit swirl angle





(From E. Braunscheidel & J. Lepicovsky)

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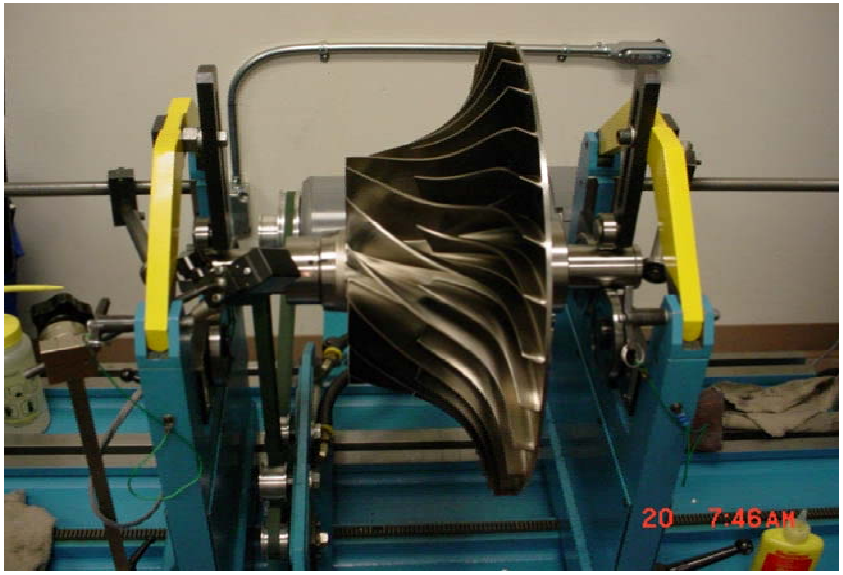
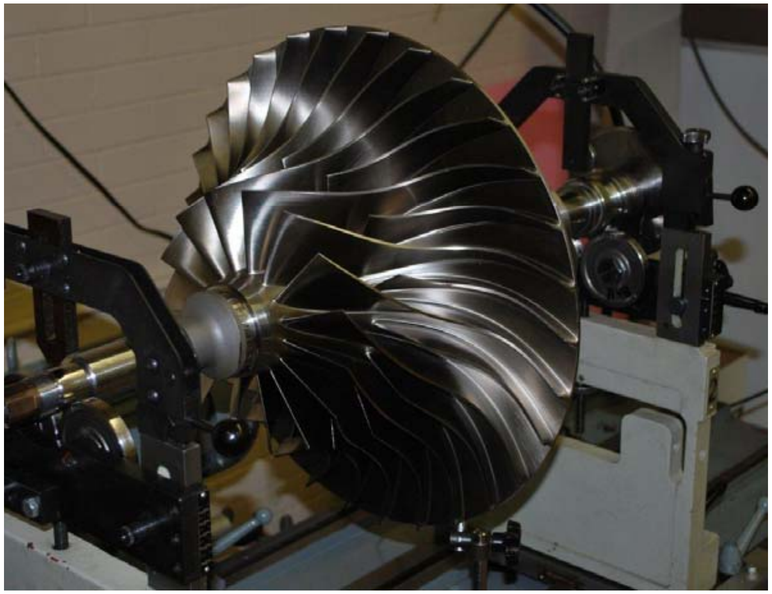
Impeller Fabrication





Challenges

- Initially the impeller blade tip had 0.003 inches of total-indicator runout (TIR)
- The impeller clearance is 0.012 inches
- This runout amounted to 25% variation in clearance
- Team expressed a desire to bring the TIR to 0.001 inches
- This proved to be very challenging, but was finally achieved after regrinding the curvic couplings, and the impeller outer diameter
- Impeller was then re-balanced within drawing specifications.

Differences in Blade Profiles

- HECC impeller has rounded trialing edges instead of the constant radius trailing edges of CC3
- HECC impeller has a backsweep of 32-42 degrees that changes with span, compared to 50 degrees of backsweep for CC3.
- The blade angle distribution from the inlet to the exit is also different between the two impellers.

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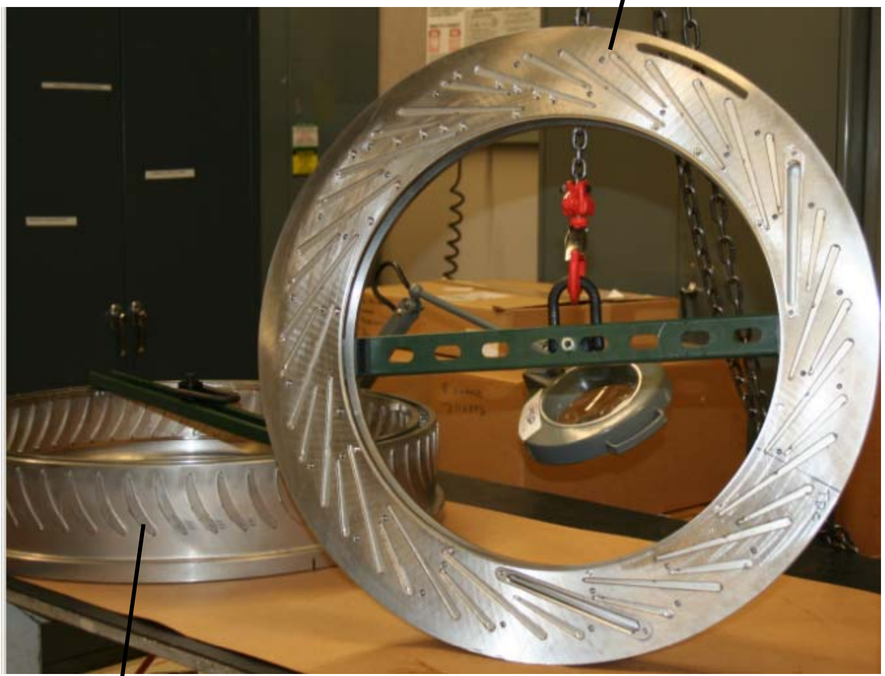
Diffuser Fabrication

Brazing used to assemble the diffuser blades with the hub and the shroud.

Diffuser, EGV, and Shroud Assembly

Diffuser sub-assembly

Shroud

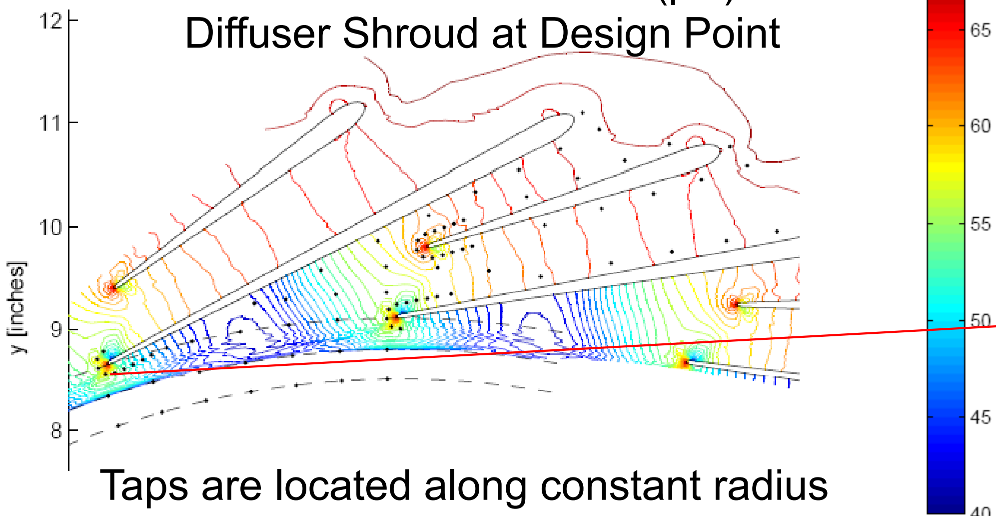


EGV sub-assembly

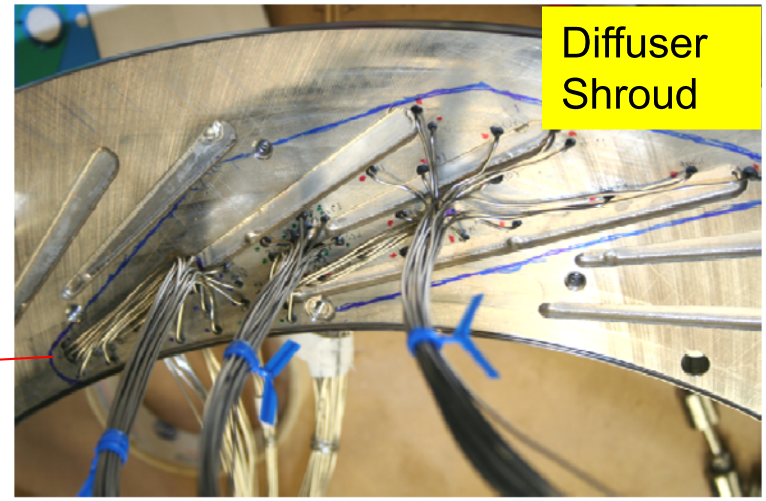
A special fixture was fabricated to assemble diffuser, EGV and shroud

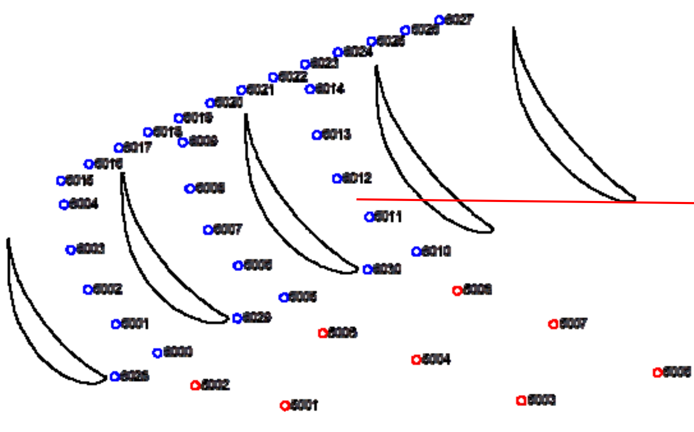
Diffuser and EGV Instrumentation

Static Pressure Contours (psi) on Diffuser Shroud at Design Point

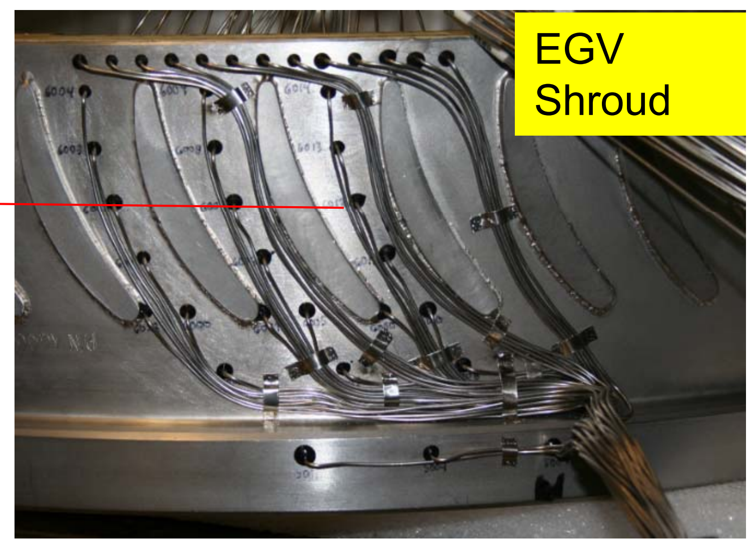


Taps are located along constant radius arcs for ~1D diffusion

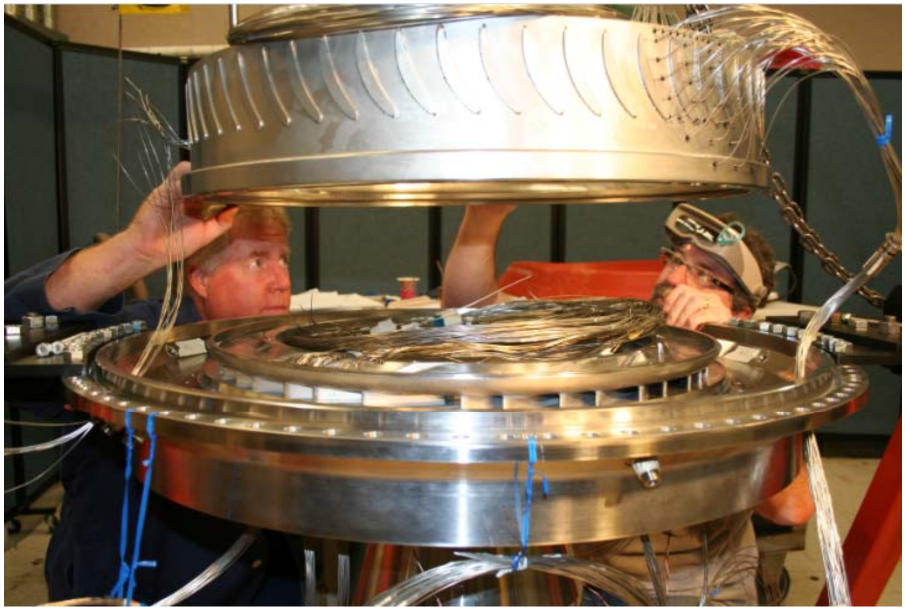




EGV Shroud Endwall Statics Location and Numbering Scheme



Diffuser, EGV & Shroud Assembly

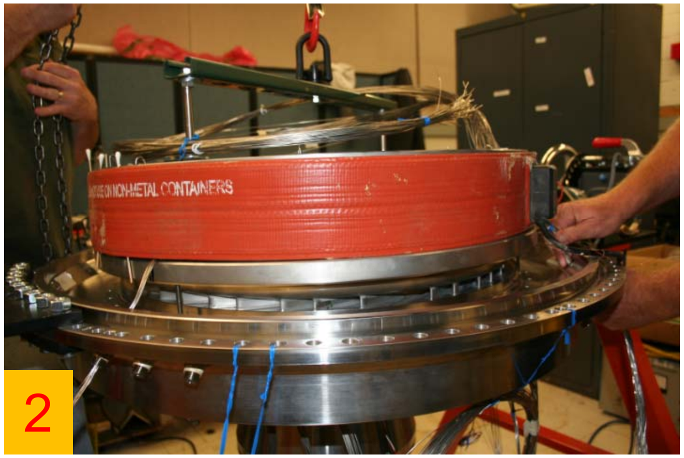


While the diffuser sub-assembly is lowered down onto the shroud the instrumentation tubing bundles are carefully pulled through the provisions in the shroud.

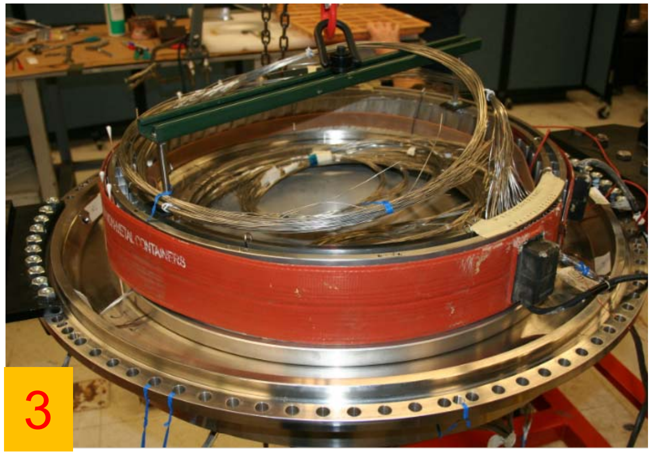
Once the diffuser sub-assembly is properly located on the shroud, the EGV sub-assembly is lowered down on to the diffuser and shroud. Again care is needed to pull the instrumentation tubing bundles through the provisions on the shroud.

Diffuser, EGV & Shroud Assembly

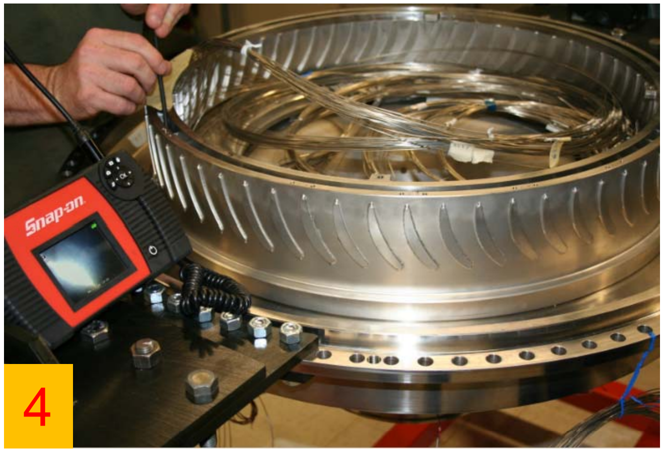
The diffuser is heated using the heating belts



The diffuser is lowered on to the EGV and shroud after the required surface temperature is reached



After the stationary parts are assembled, the heat is turned off …



and the mating surfaces are checked for a tight fit with a boroscope

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Tight fit between diffuser & EGV designed to maintain the flowpath seal

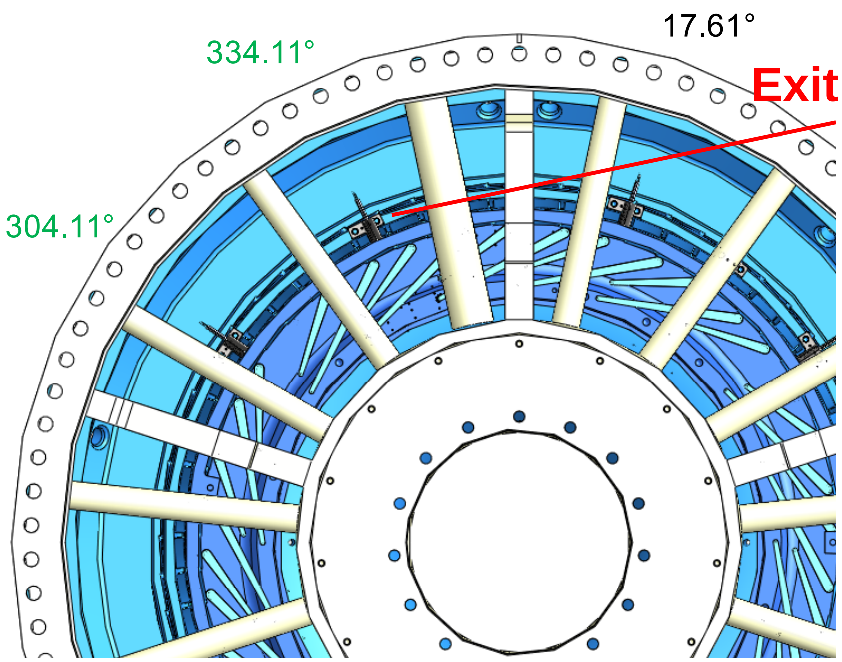
Diffuser, EGV & Shroud Assembly

Diffuser and EGV bolts were tightened while the assembly fixture was still in the horizontal position.

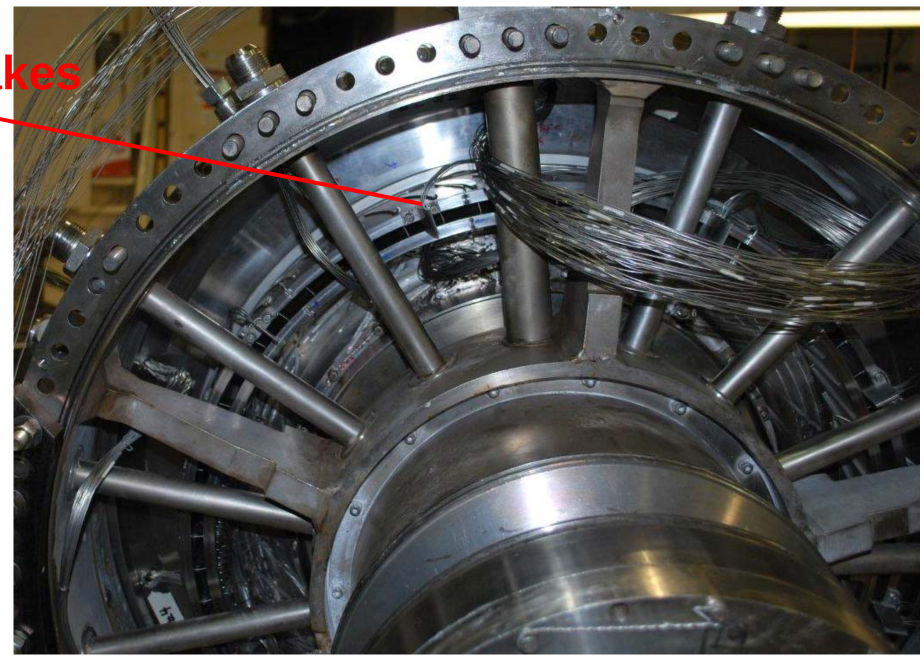
Final inspection of the assembly of the stationary parts .

HECC Integration with the NASA Glenn Rig

Assembly of the Stationary Parts to the Rig Hardware



CAD Model

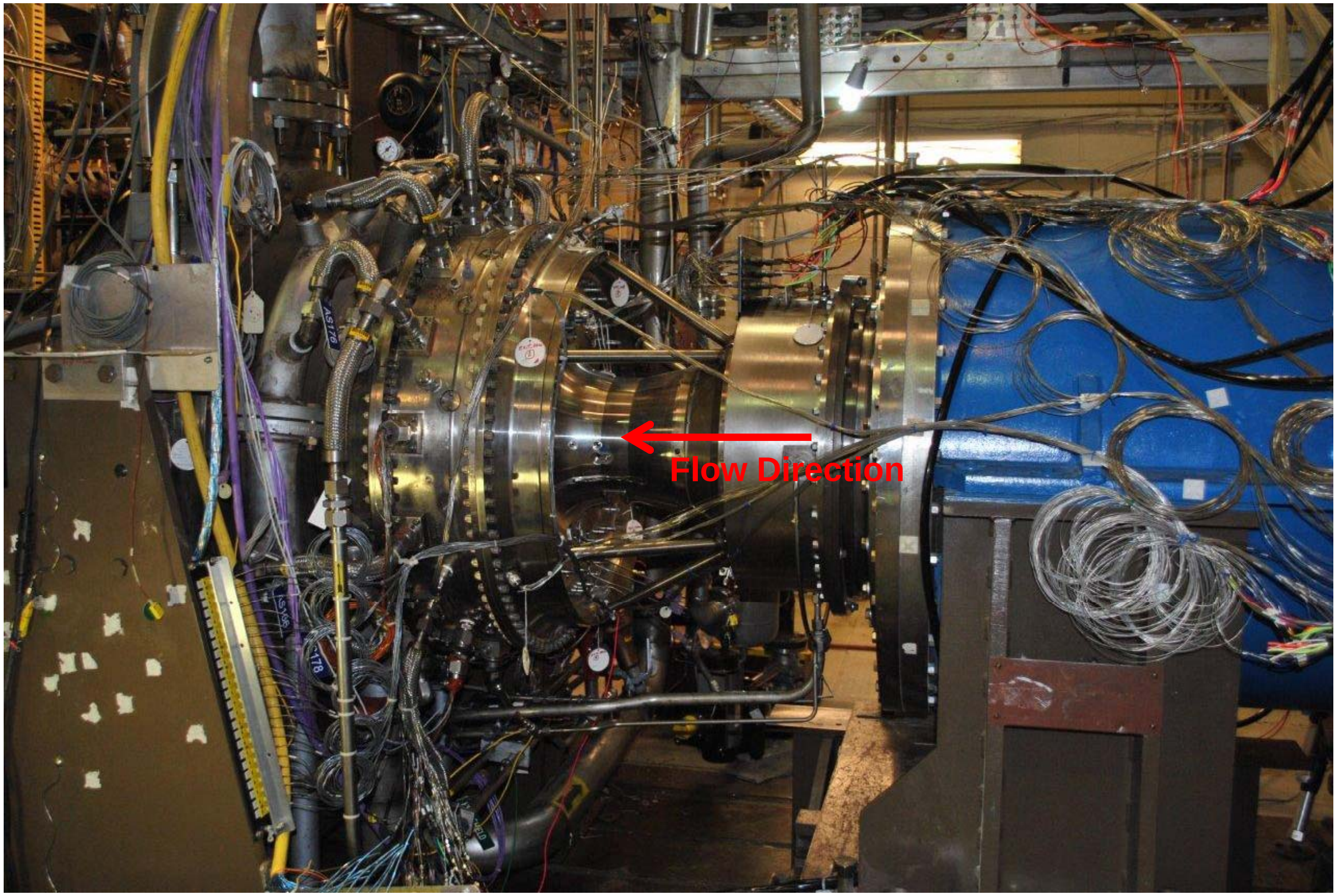


During Assembly with the Rig

(View Aft Looking Front)

HECC Integration with the NASA Glenn Rig

Test Article fully assembled and installed in NASA test facility   2/24/2012



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Research Test Plan

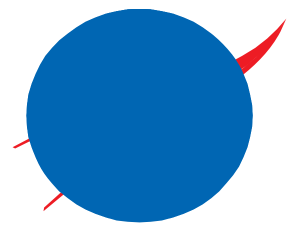
- Structural /Mechanical testing *March 2012*
  - Establish Impeller deflections vs. operating condition
  - Verify shroud/diffuser thermal transients are within design limits
  - Qualify the compressor for operation to maximum rig speed limit

- Pre-Test CFD *March 2012*
  - Complete the impeller tip clearance sensitivity assessment to establish the effect on the overall stage performance.
  - Complete the unsteady analysis to establish the impeller-diffuser interaction, and for comparison with the experimental data.

Research Test Plan

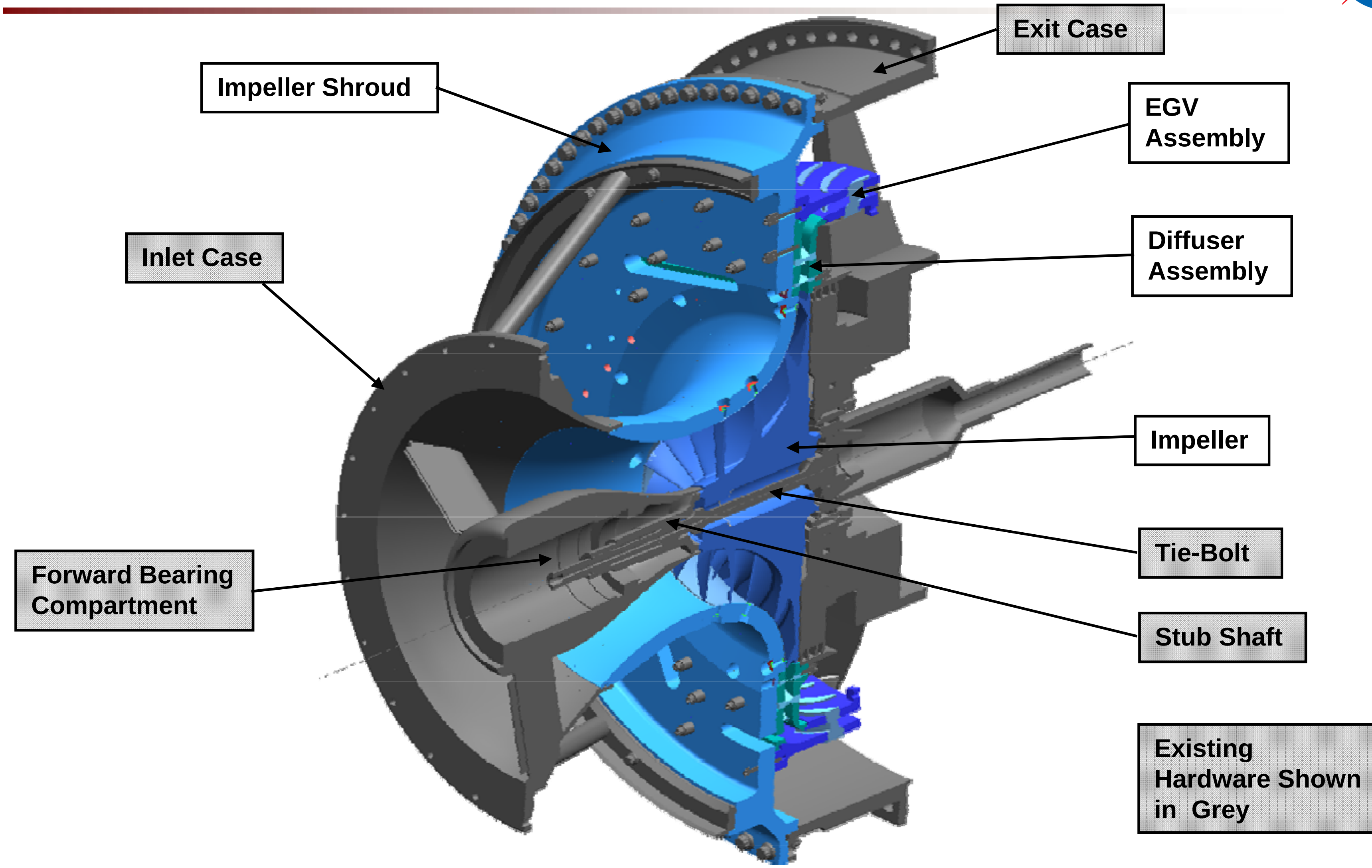
- Validation of Overall Compressor Performance *Apr-Jun 2012*
  - Compressor mapping from 70 to 105% speed
  - Determine operating range at design tip clearance
  - Operability and performance tip clearance sensitivities
  - Unsteady shroud pressures for high cycle fatigue/structural analysis tools
  - Comparison between Pre-test CFD and experimental data

- Validation of Component Level Performance/Interactions *Oct-Nov, 2012*
  - Dynamic pressure probe at impeller exit p_0, swirl Angle
  - Diffuser Vanes with leading edge instrumentation (p_0 and T_0)
  - Probe access at diffuser vane exit
  - Comparison between Pre-test CFD and experimental data
  - EGV vanes with leading edge p_0



Extra Slides

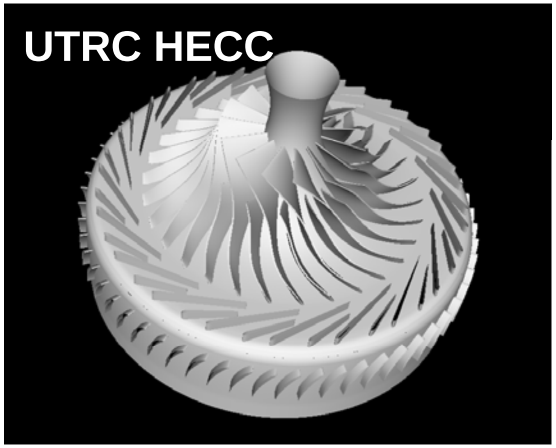
Rig Overview



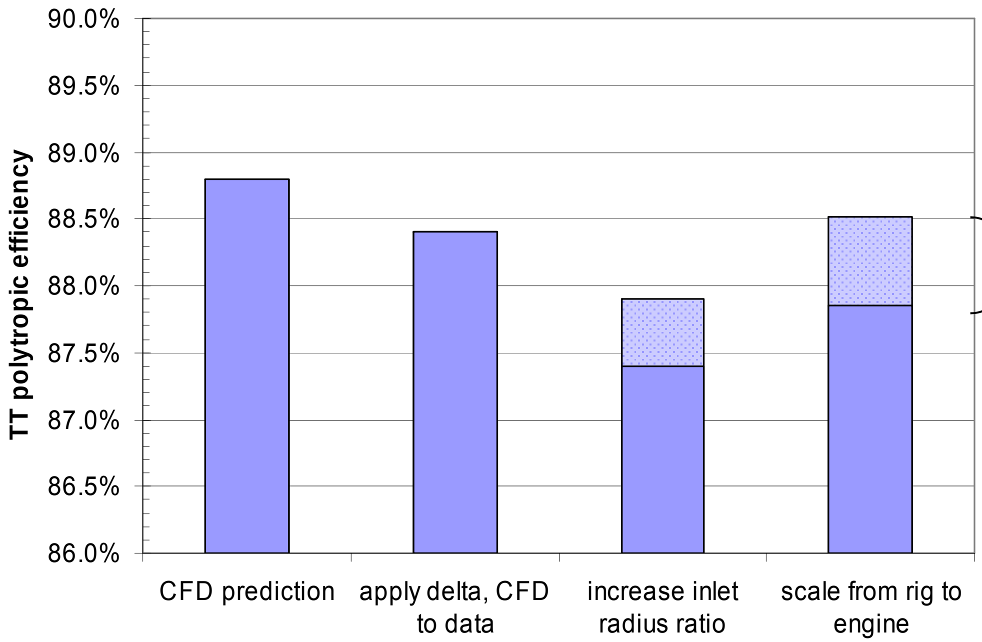
HECC test article geometry integrates with existing CE-18 hardware

Estimates at Rotorcraft Scale

UTRC HECC is expected to meet efficiency target, stall margin uncertain



Metric	UTRC HECC Rig	
	target	CFD predicted
Stage Pr	4.0 - 5.0	4.85
Exit Corrected Flow (lbm/s)	2.6 - 3.1	2.98
Work Factor (DH_0/U_2^2)	0.58 - 0.7	0.68
Poly Eff TT	≥ 88%	88.8%
T3 (^oF)	350-410	399
Dmax/Dtip	1.45	1.45
Stability Margin	13%	~12%
M_{exit}	0.15	0.15
α_{exit}	15^o	14^o



Engine scale polytropic efficiency is estimated as 87.9 - 88.5%

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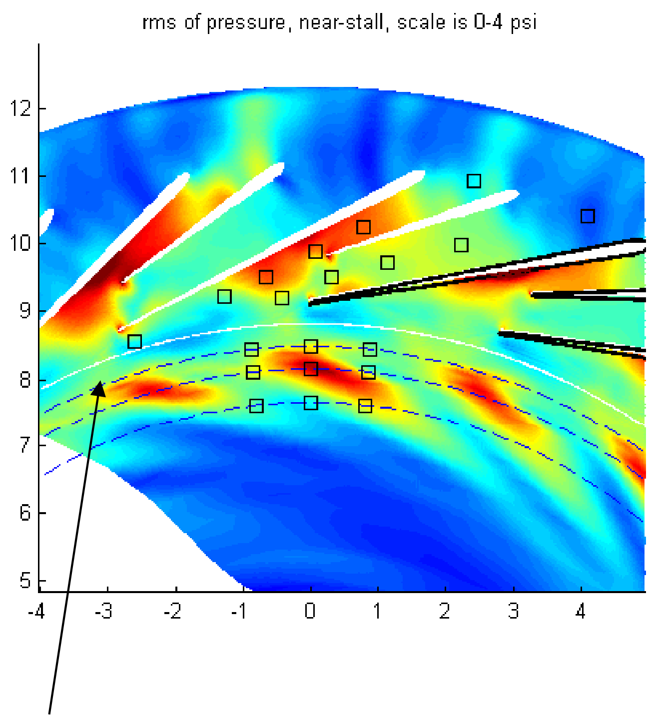
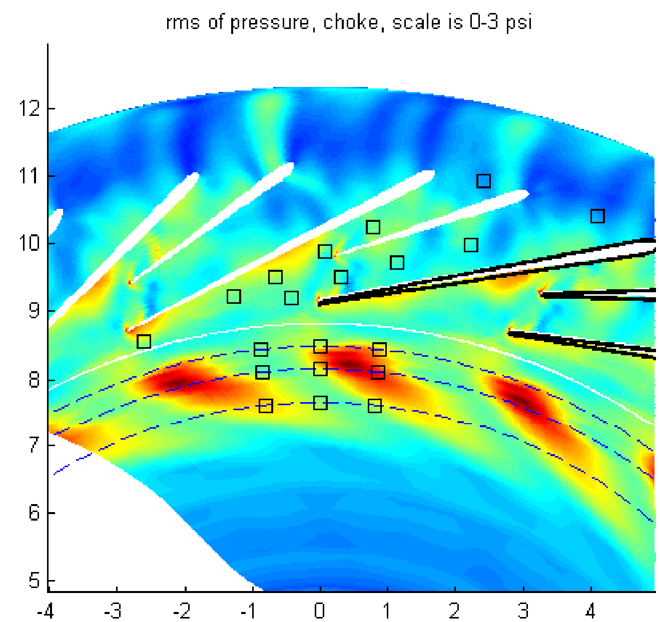
Unsteady Pressure Measurements for BPF and Stall

- Impeller shroud: 9 kulites at (90, 96, 100%) impeller TE radius, in (0,1/3,2/3) pitch increments
- Diffuser shroud: in both passages to capture traveling waves and possible “pumping” pressure field
- Rotating stall: 10 sensors at r/R2=1.05, evenly spaced around wheel + 1 inlet, + diffuser throat and exit locations





Impeller TE radius

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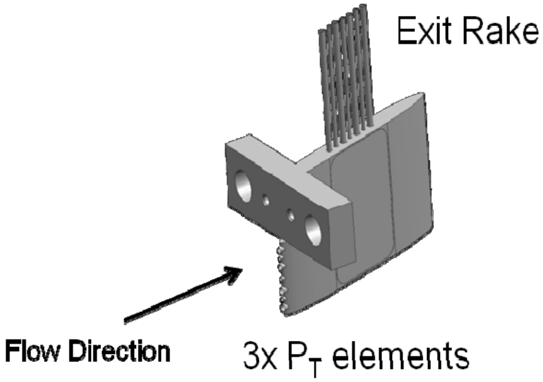
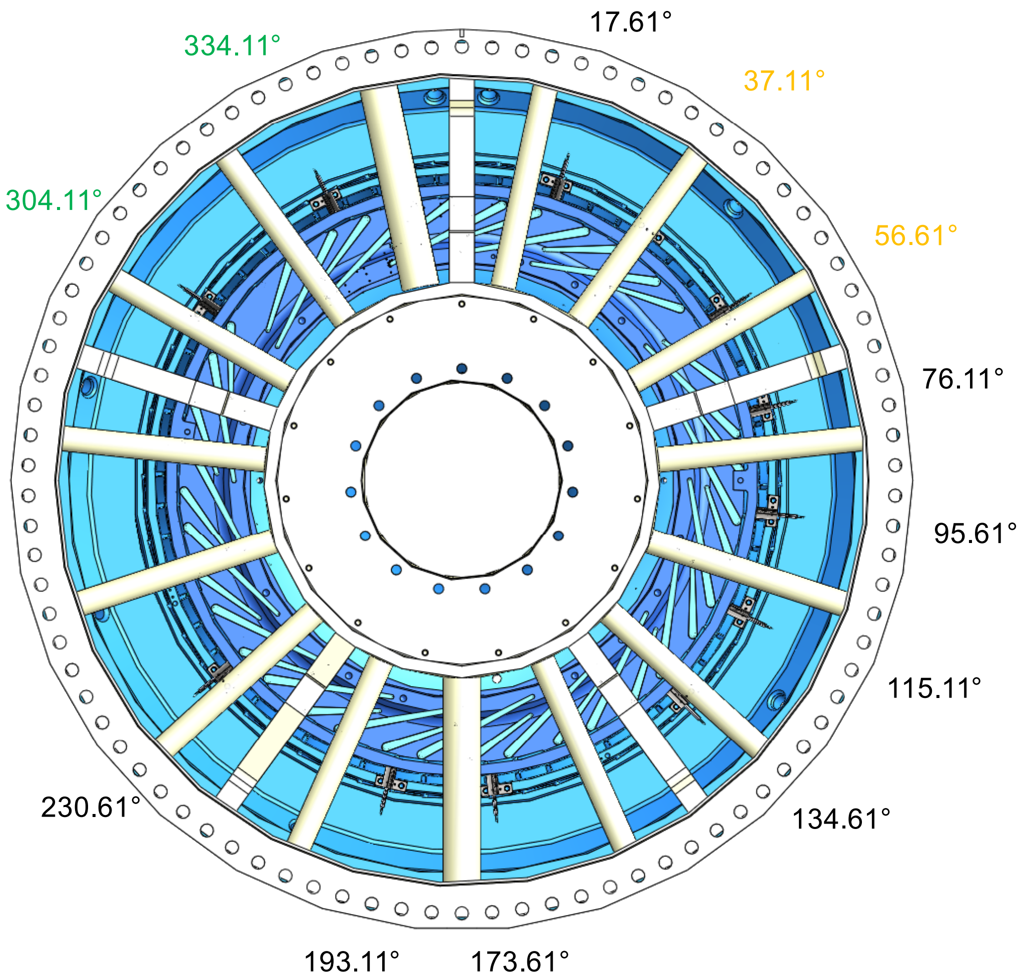
Instrumentation – EGV Exit Rakes



3x P_T elements
2x T_T elements



(View Aft Looking Front)

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