



# Turbomachinery Overview

Dr. James D. Heidmann

Turbomachinery & Heat Transfer Branch

Turbomachinery Peer Review

NASA Glenn Research Center

June 26-27, 2012



# Agenda

<b>start time</b>	<b>DAY 1 - June 26th</b>	
8:00 AM	Welcome/Introductions/Agenda	<b>D.R. Reddy</b>
8:30 AM	Turbomachinery Overview	<b>J. Heidmann</b>
9:30 AM	RTA Fan Testing & Analysis	<b>S. Prahst</b>
10:00 AM	Break	
10:15 AM	Multistage Transonic Compressor Test Capability	<b>J. Fabian</b>
10:45 AM	Multistage Turbomachinery Analysis	<b>S. Kulkarni</b>
11:15 AM	High Fidelity Fan/Compressor CFD	<b>C. Hah</b>
11:45 AM	Boxed Lunch at OAI	
12:30 PM	Compressor Icing Modeling & Altitude Testing	<b>D. Rigby</b>
1:30 PM	High Efficiency Centrifugal Compressor Stage Experiment	<b>E. Braunscheidel</b>
2:00 AM	Axi-Centrifugal Compressor Analysis Capability	<b>S. Kulkarni</b>
2:30 PM	Break	
2:45 PM	NASA Wind Tunnel Fan Aerodynamic Testing	<b>B. Fite</b>
3:15 PM	Transonic Cascade Heat Transfer & Film Cooling Capability	<b>P. Giel/A. McVetta</b>
3:45 PM	Fundamental Film Cooling Experiments	<b>P. Poinatte</b>
4:15 PM	High-Fidelity Turbine Heat Transfer Modeling	<b>V. Shyam/A. Ameri</b>
5:00 PM	Conclude Day 1	
	<b>DAY 2 - June 27th</b>	
8:00 AM	Day 2 Welcome, Agenda	<b>J. Heidmann</b>
8:15 AM	Incidence-Tolerant Turbine Blade Experiments	<b>J. Welch/A. McVetta</b>
9:00 AM	Transition Prediction for VSPT	<b>A. Ameri</b>
9:45 AM	Break	
10:00 AM	Single Spool Turbine Facility Capability	<b>P. Giel</b>
10:30 AM	LPT workshop & DBD Plasma Actuator Development	<b>D. Ashpis</b>
11:15 AM	Boxed Lunch at OAI	
12:15 PM	Panel Convene	<b>Panel</b>
4:00 PM	Panel Comments	<b>Panel Chair</b>
4:45 PM	Summary	<b>J. Heidmann</b>
5:00 PM	Conclude Day 2	



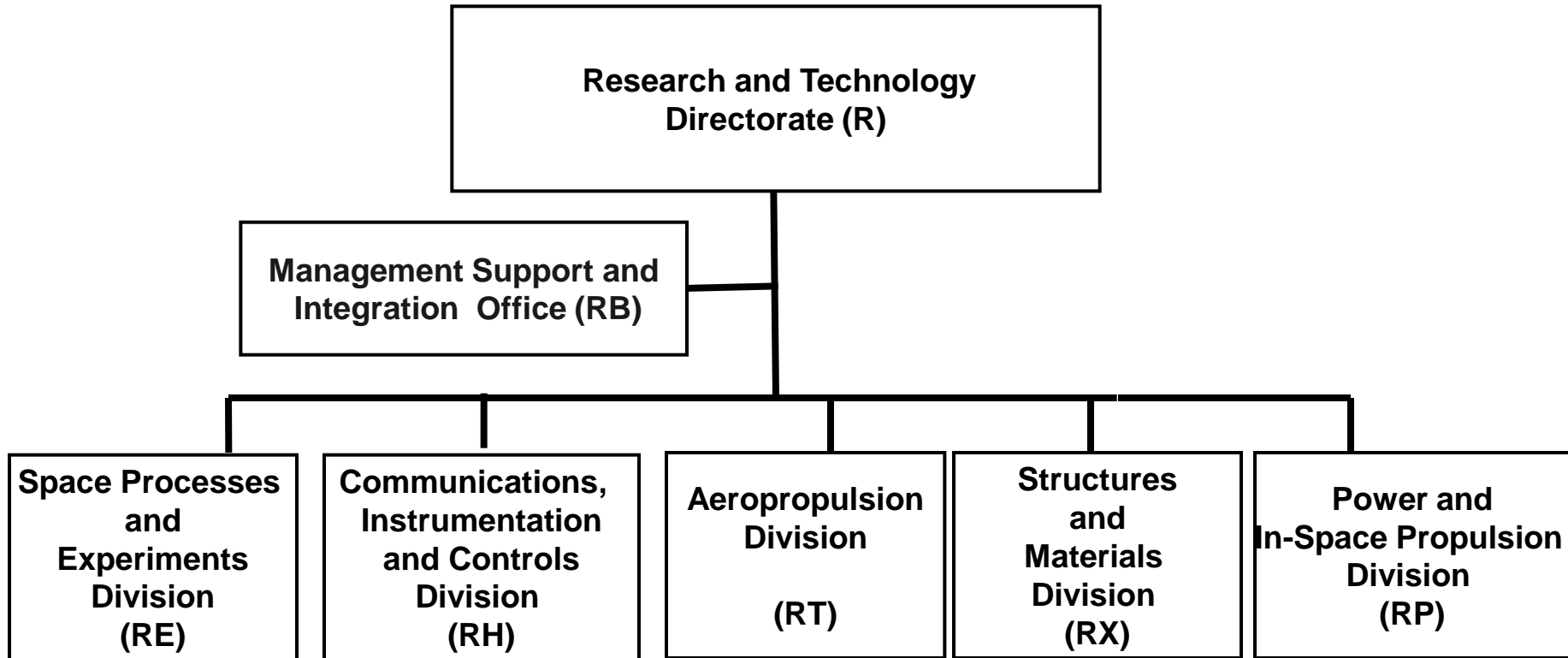
# Peer Review Objectives

The peer review is not intended to be a program review. The purpose of the review is to assess the technical excellence of GRC's Turbomachinery research. The panel will assess the following:

- Quality and innovativeness of research
- Adequacy of research staff to meet current and future needs
- State of experimental capabilities
- Strength and weaknesses of different research areas, including competitive strength of GRC with respect to rest of the country
- Preparedness of GRC to meet future national need in turbomachinery for aeropropulsion systems
- Suggestions for improvement

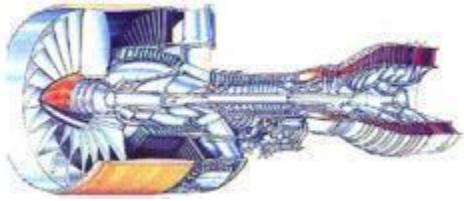
# Research and Technology Directorate (Code R)

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# Aeropropulsion Division

## Aeronautics



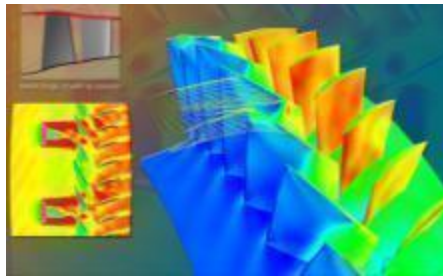
**Turbomachinery**  
**Inlets**  
**Combustors**  
**Icing**  
**Heat Transfer**

**Nozzles**  
**MDAO**  
**Propulsion Systems**  
**Acoustics**  
**Advanced Concept**

## Access to Space



**Engine Tests**



**Components**



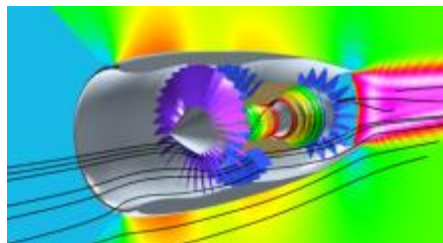
**Icing Physics**



**Low-Noise Jets**



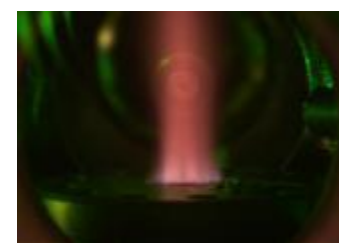
**Advanced Propulsors**



**System Simulations**



**Alternative Fuels**



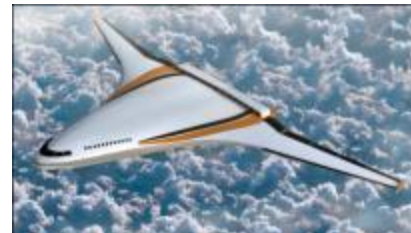
**Combustion Diagnostics**



**Low-Boom Inlets**



**Combined Cycle Propulsion**



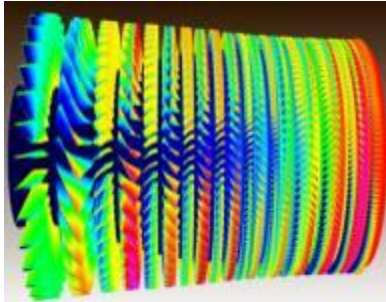
**Advanced Concepts**



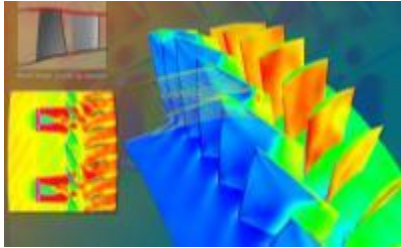
**Flight Tests**

# Turbomachinery & Heat Transfer Branch

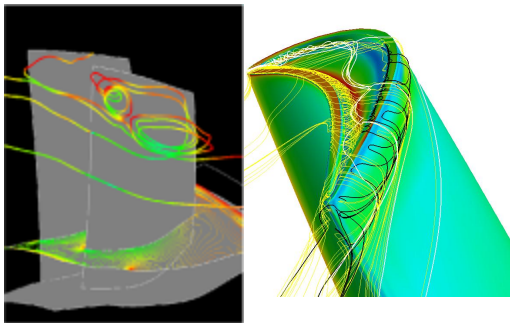
## Overview



### • Turbomachinery Flow Physics



### • Advanced Concept Simulations



### • High-Fidelity Simulations

### Advanced Turbomachinery Models:

- Steady & Unsteady RANS
- Large Eddy Simulation

### Advanced Turbomachinery Concepts:

- High stage loading
- Flow control
- Turbine cooling concepts
- Tip leakage mitigation
- Low Reynolds number LPTs

### Turbomachinery Research Experiments

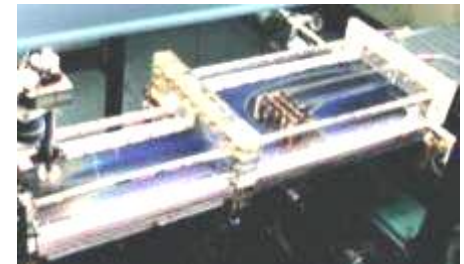
- High-speed rotating testing
- Fundamental benchmark studies
- Turbomachinery concept validation



High-Speed Turbomachinery Testing



Advanced Concept Validation



Fundamental Heat Transfer Studies

# Turbomachinery and Heat Transfer Personnel

[James D. Heidmann](#) (216) 433-3604 Chief, Turbomachinery and Heat Transfer Branch

[David E. Ashpis](#) (216) 433-8317 Low pressure turbine flow physics & flow control

[Donald C. Braun](#) (216) 433-5147 Dynamic data acquisition, digital signal processing & algorithmic programming

[Edward P. Braunscheidel](#) (216) 433-6298 Compressor aerodynamics experimentalist

[Mark L. Celestina](#) (216) 433-5938 CFD code development and analysis of fans, compressors, and turbines

[Shu-Cheng \(Simon\) S. Chen](#) (216) 433-3585 Turbine aerodynamic conceptual design

[Randall M. Chriss](#) (216) 433-6516 Highly-loaded compressor measurements and experimental techniques

[John C. Fabian](#) (216) 433-6023 Compressor & Turbine CFD modeling & steady and unsteady turbine blade row aero analysis

[Chunill Hah](#) (216) 433-6377 CFD code development steady/unsteady & analysis of fans, compressors and pumps

[Michael D. Hathaway](#) (216) 433-6250 SFW Technical Lead and compressor research

[Philip C. Jorgenson](#) (216) 433-5386 Engine icing analysis, computational fluid dynamics methods

[Sameer Kulkarni](#) (216) 433-6504 Compressor CFD

[Barbara L. Lucci](#) (216) 433-5902 Turbine external heat transfer experiments

[Ashlie B. McVetta](#) (216) 433-8037 Turbine experiments

[Philip E. Poinsette](#) (216) 433-5898 Turbine internal heat transfer exp., Turbine aerodynamics

[Vikram Shyam](#) (216) 433-3511 Turbine Aerodynamics and Heat Transfer CFD Development

[Joseph P. Veres](#) (216) 433-2436 Engine Icing Technical Lead and compressor conceptual design

[Gerard \(Jerry\) E. Welch](#) (216) 433-8003 SRW Technical Lead and turbomachinery aerodynamics

## Army

[Gary J. Skoch](#) (216) 433-3396 Small turbine engine technology development and component testing

[Douglas R. Thurman](#) (216) 433-6573 Turbine internal heat transfer experiments and small engine thermo cycle analysis

## Contractors

[Paul W. Giel](#) (216) 977-1340 Turbine computational and experimental heat transfer

[David L. Rigby](#) (216) 433-5965 Turbomachinery CFD development

[Sue P. Prahst](#) (216) 433-3746 Compressor experimentalist, data acquisition and reduction specialist

[Ali A. Ameri](#) (216) 433-8346 Computational modeling of turbine heat transfer

[Richard A. Mulac](#) (216) 433-5936 Compressor CFD developer, high performance computing

[Wai Ming To](#) (216) 433-5937 CFD developer, unsteady aero analysis of fan, compressor

[Tim Beach](#) (216) 433-5771 Turbomachinery grid generation and analysis

[Erlendur Steinthorsson](#) Turbomachinery CFD software development

# NASA Aeronautics Programs



## Fundamental Aeronautics Program

Conduct fundamental research that will produce innovative concepts, tools, and technologies to enable revolutionary changes for vehicles that fly in all speed regimes.

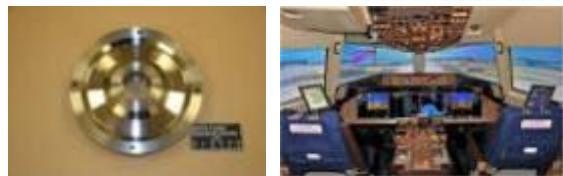
## Integrated Systems Research Program

Conduct research at an integrated system-level on promising concepts and technologies and explore/assess/demonstrate the benefits in a relevant environment



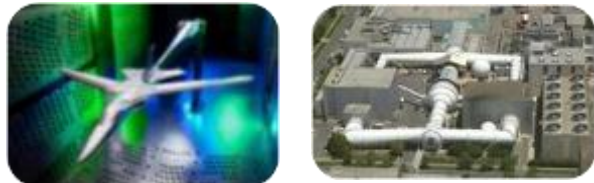
## Airspace Systems Program

Directly address the fundamental ATM research needs for NextGen by developing revolutionary concepts, capabilities, and technologies that will enable significant increases in the capacity, efficiency and flexibility of the NAS.



## Aviation Safety Program

Conduct cutting-edge research that will produce innovative concepts, tools, and technologies to improve the intrinsic safety attributes of current and future aircraft.



## Aeronautics Test Program

Preserve and promote the testing capabilities of one of the United States' largest, most versatile and comprehensive set of flight and ground-based research facilities.



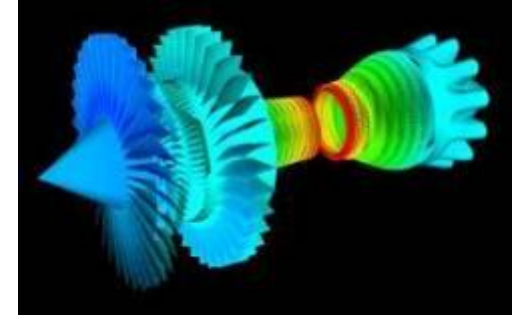


# Fundamental Aeronautics Program Overview



## Overarching goal:

To achieve technological capabilities necessary to overcome national challenges in air transportation including reduced noise, emissions, and fuel consumption, increased mobility through a faster means of transportation, and the ability to ascend/descend at very high speeds through atmospheres.



## *Subsonic Fixed Wing (SFW)*

Explore and develop tools, technologies, concepts, and knowledge for improved energy efficiency and environmental compatibility for sustained growth of commercial aviation

## *Subsonic Rotary Wing (SRW)*

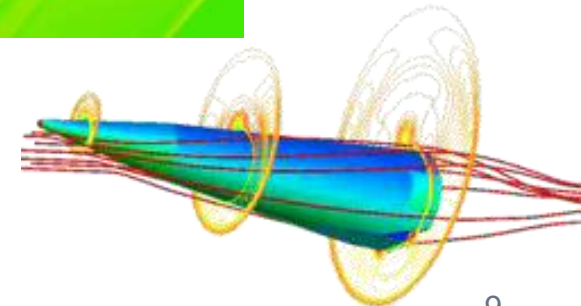
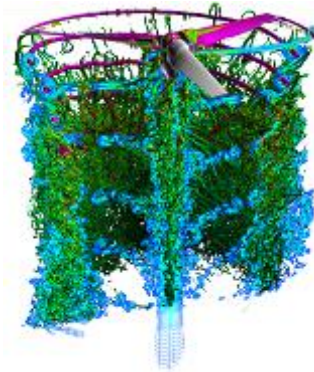
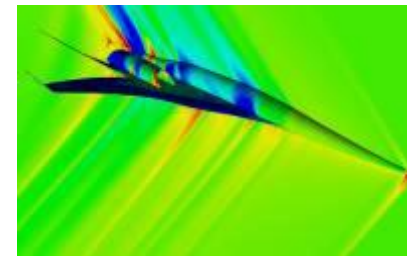
Develop tools, technologies and knowledge to enable radical changes in the transportation system through advanced rotary wing vehicle concepts and capabilities

## *Supersonics (SUP)*

Develop tools, technologies and knowledge to overcome the environmental & performance barriers to practical civil supersonic airliners.

## *Hypersonics (HYP)*

Develop tools, technologies and knowledge to enable hypersonic airbreathing vehicles and high-mass entry into planetary atmospheres.



# Integrated Systems Research Program Overview



## **Program Goal:**

Conduct research at an integrated system level on promising concepts and technologies and demonstrate the benefits in a relevant environment

### ***Environmentally Responsible Aviation (ERA) Project***

Explore and assess new vehicle concepts and enabling technologies through system-level experimentation to *simultaneously* reduce fuel burn, noise, and emissions



### ***Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) Project***

Contribute capabilities that reduce technical barriers related to the safety and operational challenges associated with enabling routine UAS access to the NAS



# Fundamental Aeronautics and Integrated Systems Research



2010

2015

2020

2025

2030

Generation: "N+1"

"N+2"

"N+3"

## Subsonics – FW & ERA

Energy Efficiency & Environment

- UHB Engines
- (Podded)



- Embedded Propulsion Systems

- Hybrid Propulsion Systems



## Supersonics

Affordable Supersonic flight Over land

- Small Jets Over Land
- Variable cycle engines

- Commercial Supersonic Jets Over Land

Increasing Payload



## Rotorcraft (Subsonics – RW)

- Variable Speed Engines/Transmissions

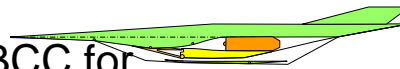
- Heavy Lift Vehicles
- City-to-City Transport

## Hypersonics

Access to Space

- X-51

- RBCC & TBCC for launch systems
- DoD Partnerships



- High mass flow CCE for Access to Space

# NASA Subsonic Transport System Level Metrics

.... technology for dramatically improving noise, emissions, & performance

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-71 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption <sup>‡</sup> (rel. to 2005 best in class)	-33%	-50%	-60%

\* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

\*\* ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ CO<sub>2</sub> emission benefits dependent on life-cycle CO<sub>2e</sub> per MJ for fuel and/or energy source used

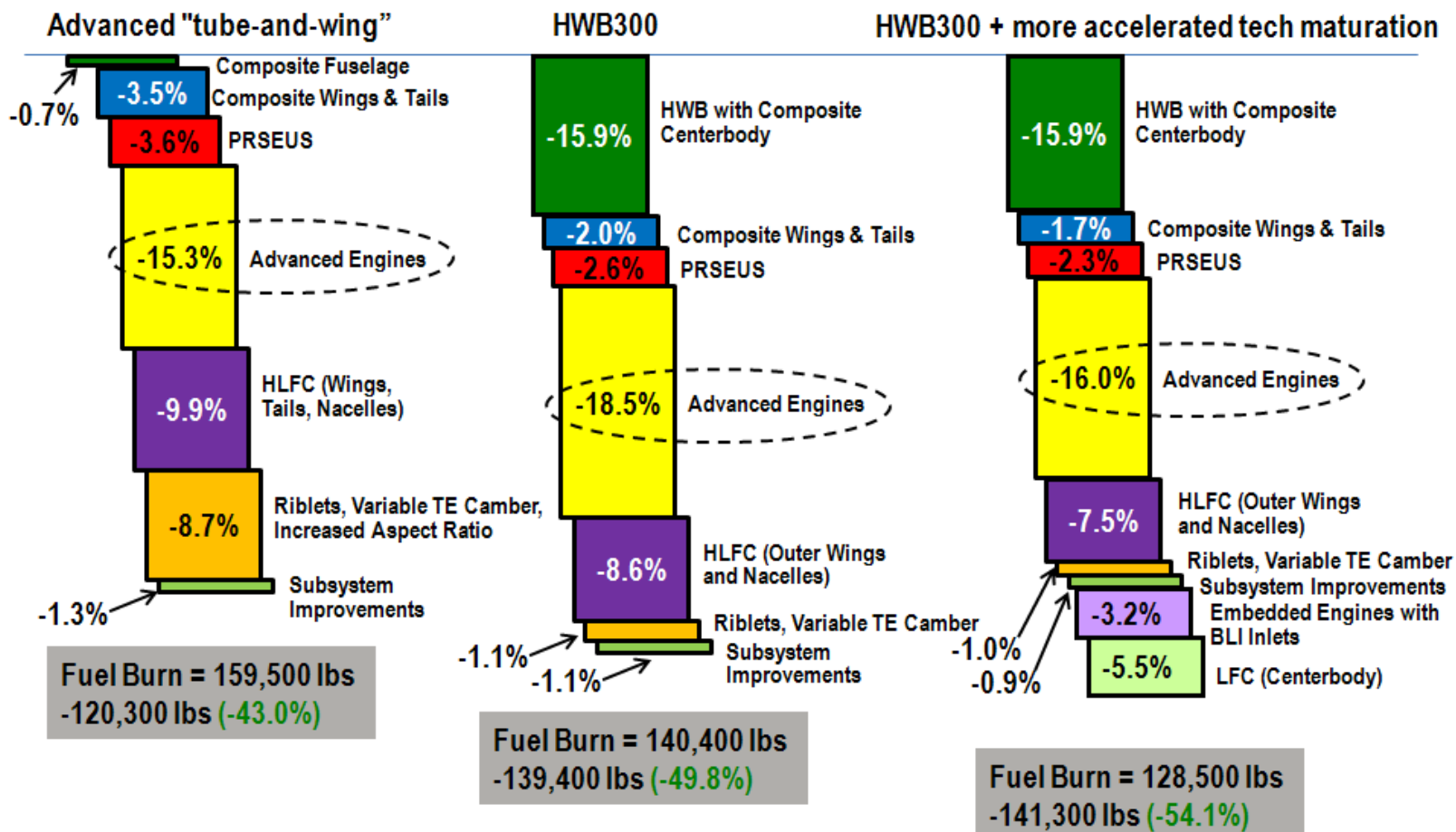
## **SFW Approach**

- **Conduct Discipline-based Foundational Research**
- **Investigate Advanced Multi-Discipline Based Concepts and Technologies**
- **Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes**
- **Enable Major Changes in Engine Cycle/Airframe Configurations**

# Projected Fuel Burn Savings using Advanced Aircraft Technologies including Advanced Engine Cycles

- Fuel Burn Technology Readiness in 2020
- Large Twin Aisle Replacement Aircraft in 2025+

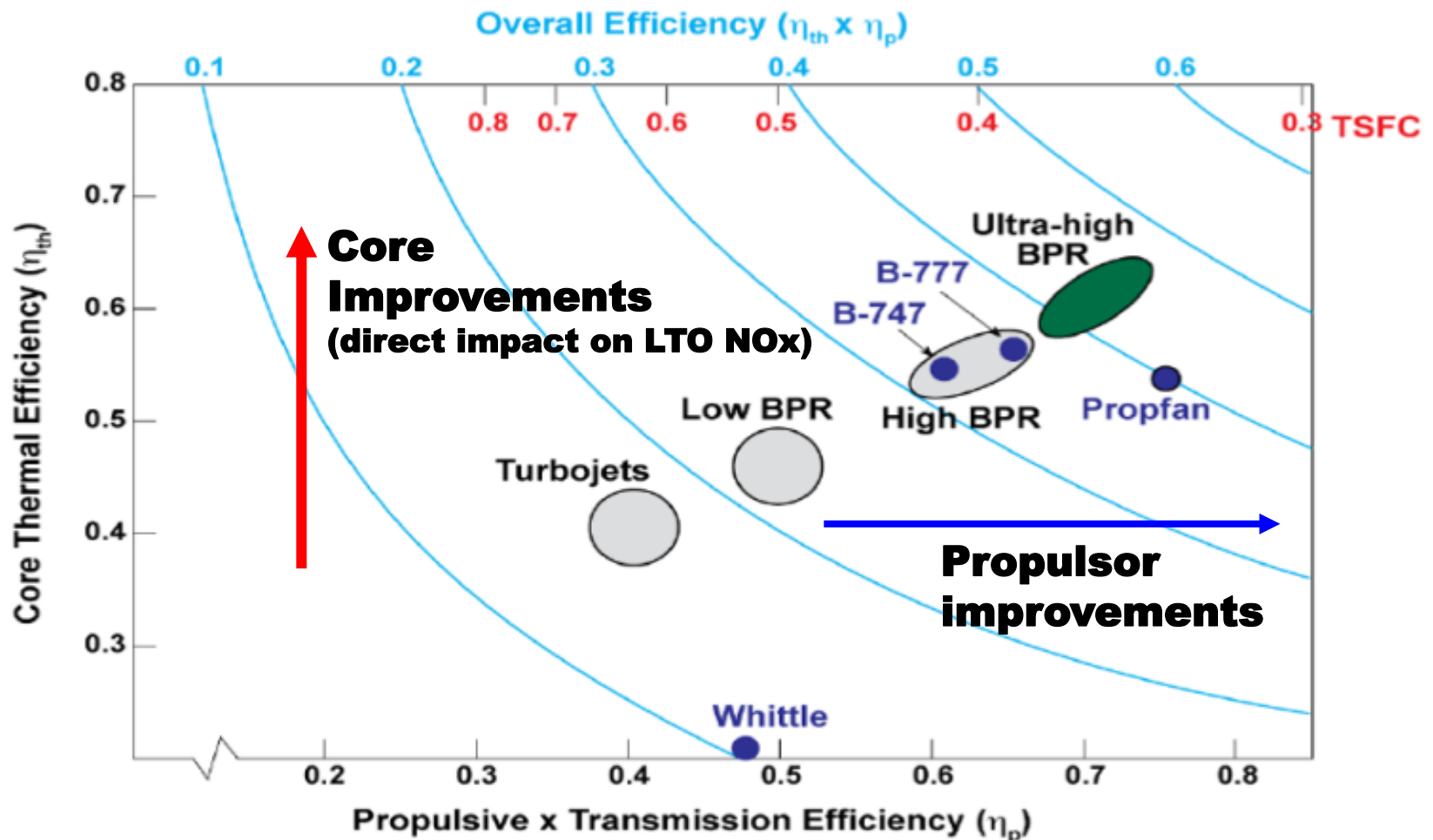
Technology Benefits Relative to Large Twin Aisle (Reference: 777-200LR "like" Vehicle)



Reference Fuel Burn = 279,800 lbs

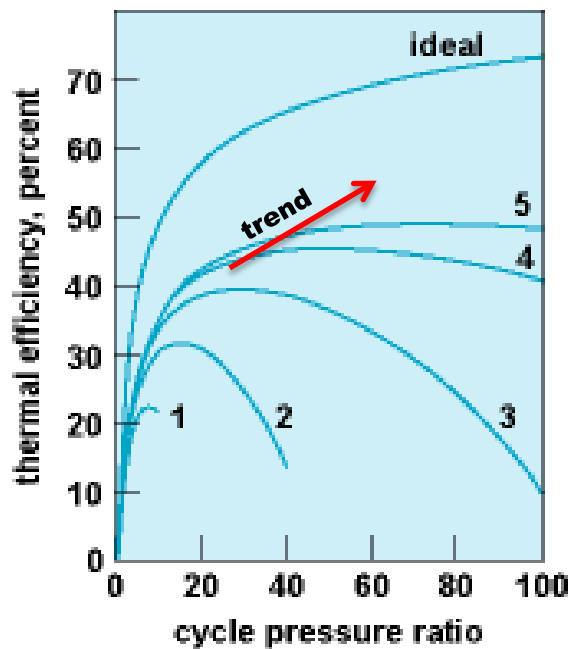
# Propulsion Technology Opportunity

Propulsion system improvements require advances in both propulsor and core technologies

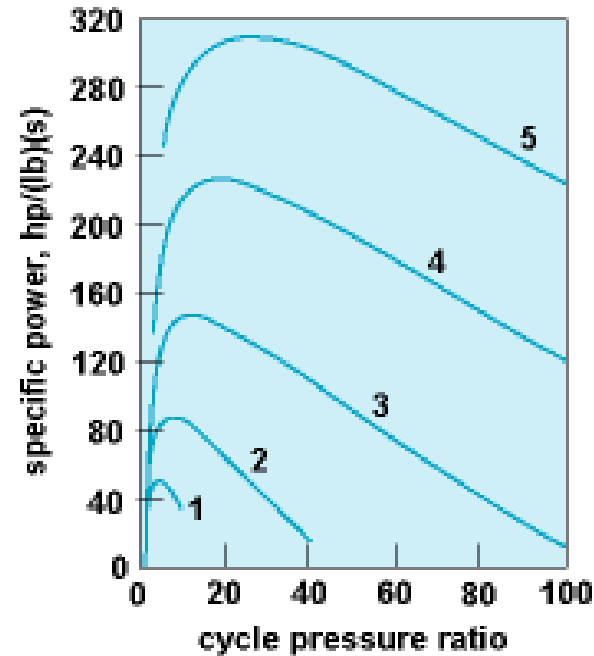


# Thermal Efficiency Trend with OPR and T4

- *Current technology level is OPR ~ 40*
- *N+3 goal is OPR ~ 60*



(a)



(b)

Turbine inlet temperature at standard day 59°F (15°C)

1 - 1000°F (537.8°C)    3 - 2000°F (1093.3°C)    5 - 3000°F (1648.9°C)

2 - 1500°F (815.5°C)    4 - 2500°F (1371.1°C)

# NASA Turbomachinery Technical Working Group

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Technologies identified and ranked by NASA-led technical working group (TWG) consisting of representatives from industry, university & government agencies. Set of white papers prepared by TWG:

- Inlet Flow Distortion Sensitivity and Stability
- Tip Leakage Flows in High Pressure Ratio Cores
- Combustor/Cooled Turbine Interaction
- Endwall Contouring
- Turbine Tip Flows
- Highly Loaded Low Pressure Turbines

Red items formed basis for NASA SFW NRA (2011)

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# NRA-Funded Turbomachinery Research

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## NASA Research Announcement Topic

# Understanding & Mitigating Tip Leakage & End Wall Losses in High Pressure Ratio Cores

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### 5 Contracts Awarded – Year 1 Reviews in September 2012:

#### **Pratt & Whitney, Penn State**

Understanding and Mitigating Tip Leakage and Endwall Losses in High Pressure Ratio Cores

#### **Honeywell, Notre Dame**

High Pressure Turbine Tip Clearance Data and High Fidelity Analyses

#### **Purdue, Rolls-Royce**

An Experimental Investigation of the Flow Physics Associated with End Wall Losses and Large Rotor Tip Clearances as Found in the Rear Stages of a High

#### **John Hopkins University**

High Resolution Measurements of the Effects of Tip Geometry on Flow Structure and Turbulence in the Tip Region of a Rotor Blade

#### **U.S. Naval Academy, Cleveland State**

Experimental and Computational Investigation of Unsteady Endwall and Tip Gap Flows in Gas Turbine Passages

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# Other Turbomachinery-Related NRAs

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- Embedded Inlet/Fan Propulsor – UTRC
    - Design, fabricate & test BLI inlet/fan in NASA 8x6 wind tunnel
  - D8 “Double Bubble” Aircraft – MIT/P&W/Aurora
    - Wind tunnel test w/ model BLI propulsor
      - Wright tunnel & 14X22 Langley tunnel
    - Small core sub-task
      - Investigating compressor rear stage challenge
        - High OPR in compact size – low exit corrected flow
        - Low Re, large clearance, manufacturing tolerances
      - Unconventional configurations
  - Matched Bi Conjugate Test – U. of Texas/GE Global
    - Open geometry and dataset
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# Embedded Inlet-Fan Propulsor Research (NASA/UTRC/Va Tech)

## Goal:

- Determine the Feasibility, Potential of and Advance Technologies for Embedded HWB Propulsors

## Objectives:

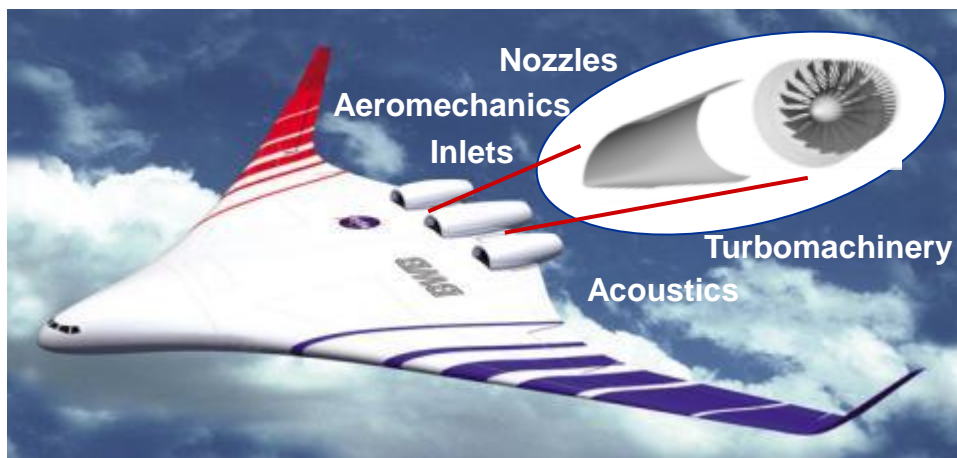
- Build on Knowledge From Prior NASA, MIT/Cambridge SAX-40, etc Efforts
- Identify Propulsion Trade Sensitivities and Exploit the Optimal Design Space
- Integrated Inlet-Fan Propulsor with  $< 2\%$  Loss in Fan Performance, Stability

## Technology Challenges:

- Boundary Layer Ingestion (BLI) / Distortion Mitigation
- Integrated Inlet-Fan CFD Tools Incorporating Flow Control
- Distortion Tolerant Fan Technologies (e.g. Tip Shroud, Non-Traditional Blade Loading Distribution, Asymmetric Casing Treatment, Spinner Mods, etc)
- Aeromechanic Modeling for BLI Distortion
- Acoustic Assessments

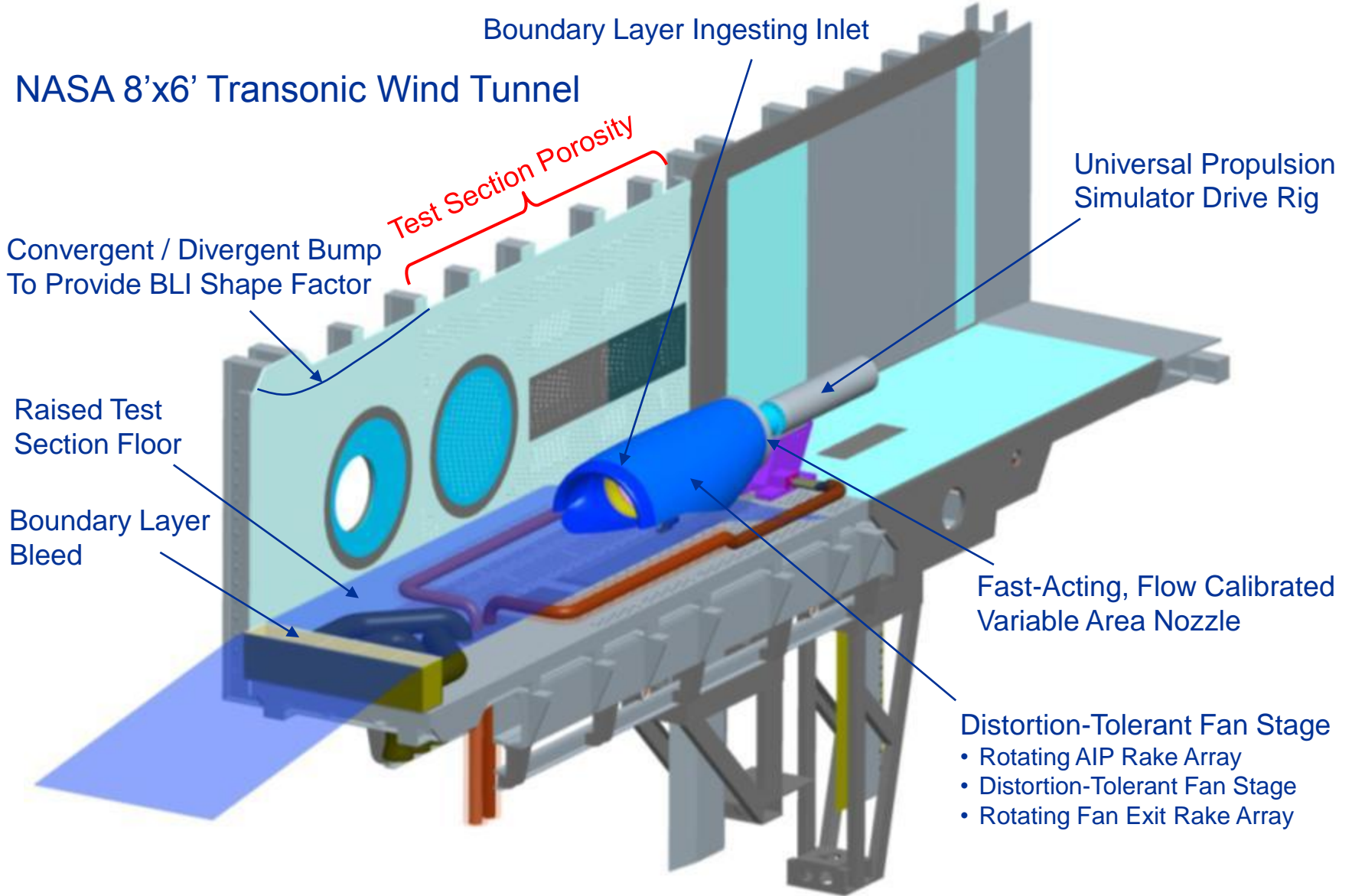
## Approach:

- Complementary SFW NRA / ERA Project Investments
- Early System Study to Guide Technology Development
- Holistic Multidisciplinary Technology Development
- Computational Analysis, Multi-Use Wind Tunnel Experiment (Cruise)





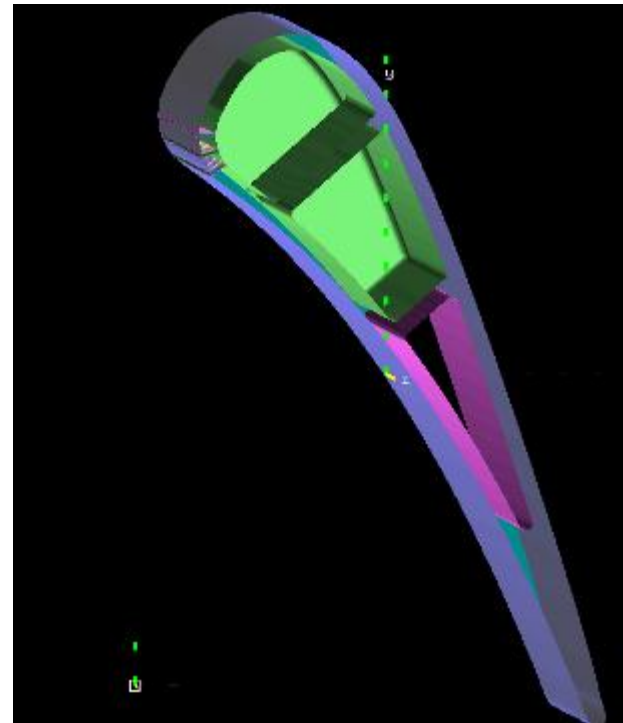
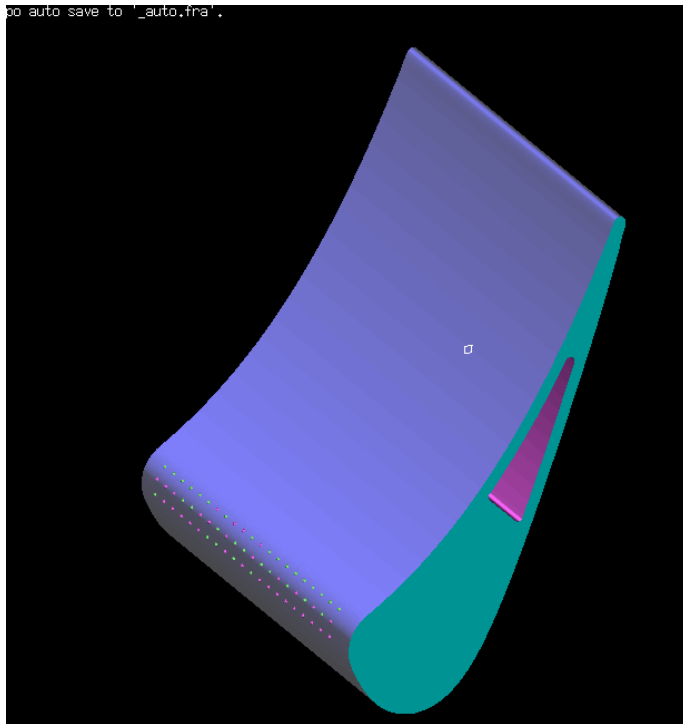
# Robust Design Experiment Layout



# U. of Texas (Bogard) Cooled Vane NRA

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Internally cooled blade with two independent cooling channels – matched Biot Number method – open dataset





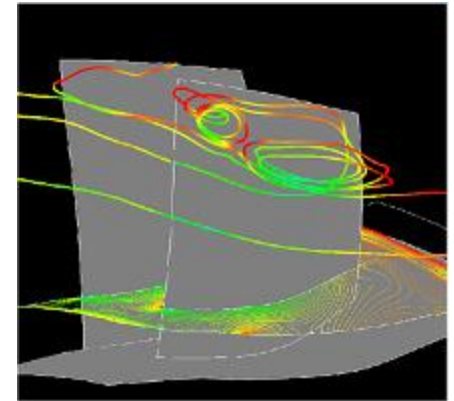
# NASA Turbomachinery Codes



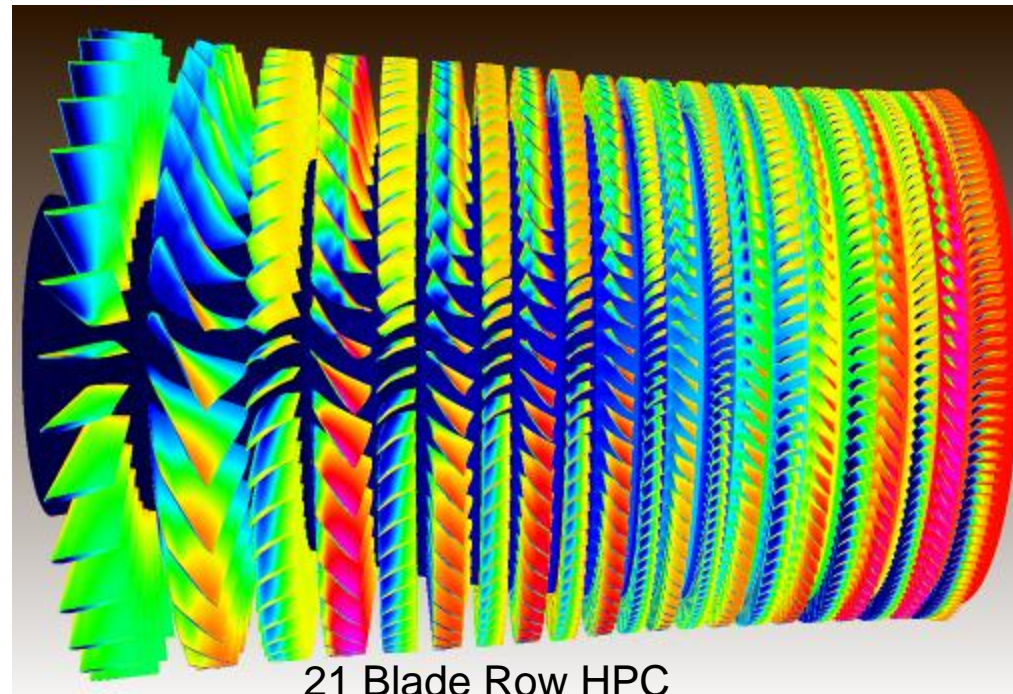
**APNASA:** Multi-stage compressor CFD code. Tip clearance and circumferential groove casing treatments can be modeled.

### APNASA Features:

- 4 Stage Runge-Kutta Explicit Navier-Stokes Solver
- Local Time Steps
- Implicit Residual Smoothing
- Implicit  $k-\epsilon$  Turbulence Model
- Models Multi-Stage Effects by Calculating Deterministic Stresses with Generalized Closure
- Domain Decomposition in Axial Direction
- Uses MPI Message Passing Interface
- Two levels of parallelism
- Radial and Tangential Multiblock with I-Grid
- Cooling and Leakages handled by Sources Terms and Endwall Model
- Real Gas (Linear Gamma) Model in 3D



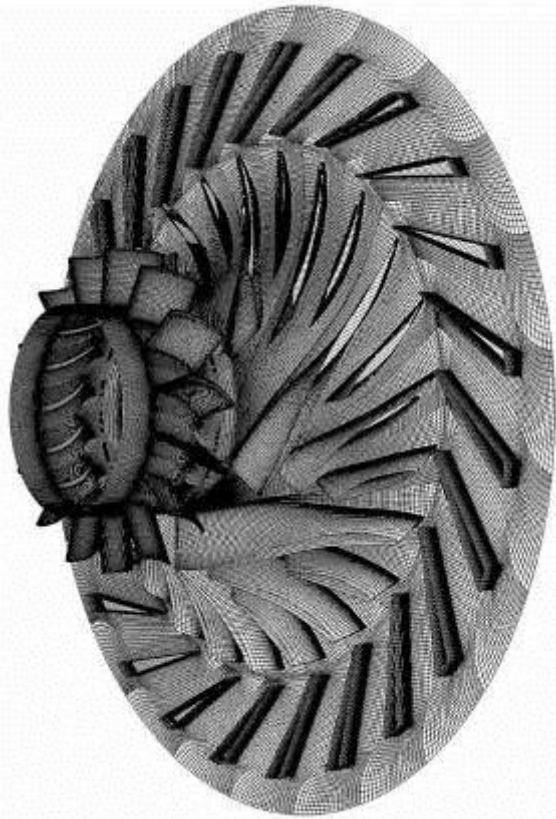
Flow Separation



21 Blade Row HPC

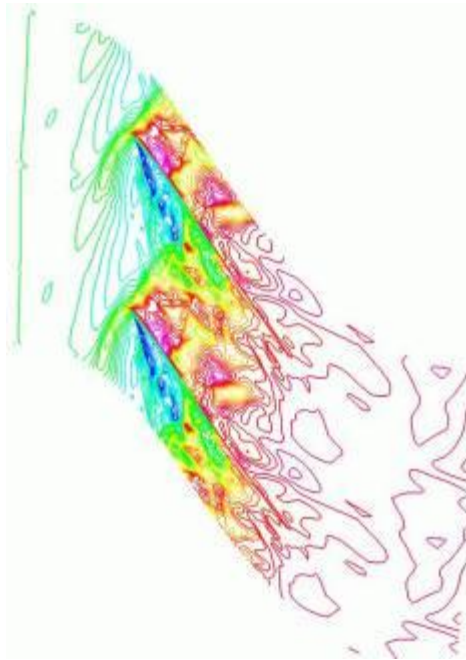


**H3D:** Pressure-based Navier-Stokes analysis code for all types of turbomachinery. Pressure based solver. Two-equation k-epsilon turbulence model RANS, Unsteady Reynolds Averaged Navier-Stokes (RANS) , and Large Eddy Simulation (LES) modes.

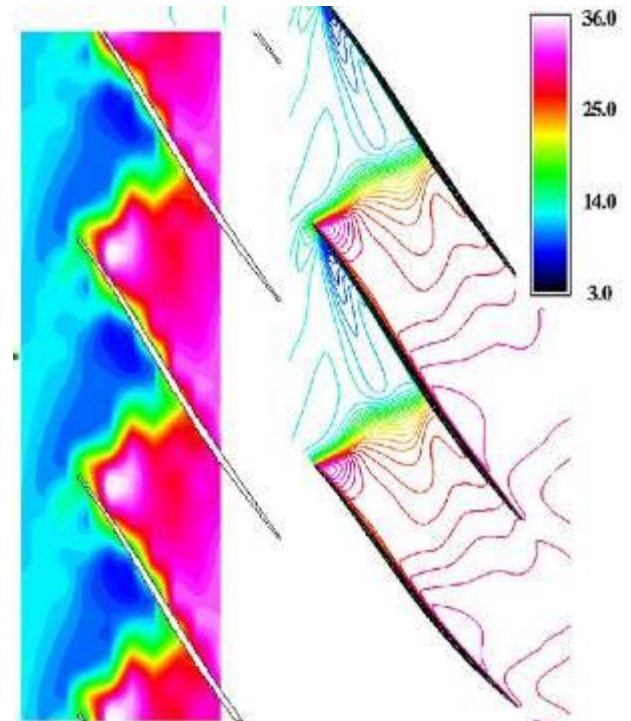


**Centrifugal Pump with Wedge Diffuser**

## Axial Compressor



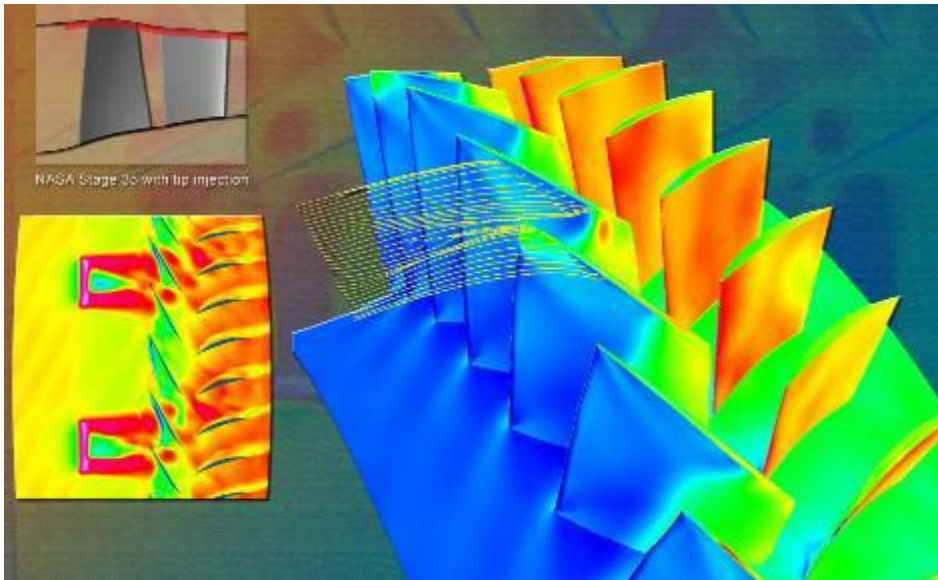
**LES**



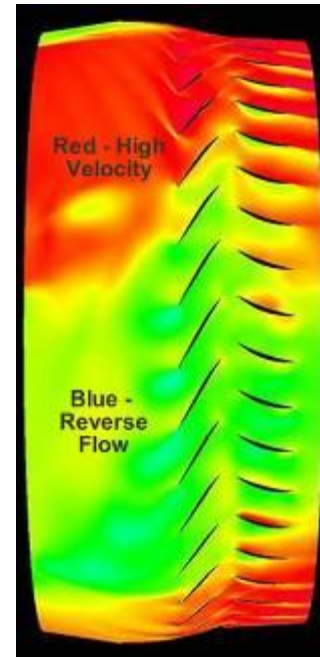
**Test Data**

**RANS**

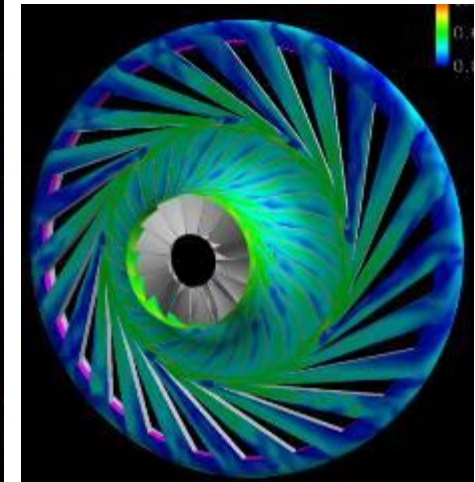
**TURBO:** Unsteady Navier-Stokes flow code for multi-stage axial and centrifugal turbomachinery.



**Axial Compressor with discrete flow injection to mitigate rotating stall**



**Full Annulus Simulation Of Axial Compressor with Rotating Stall Cell**



**Full Annulus Simulation of Centrifugal Compressor & Wedge Diffuser**

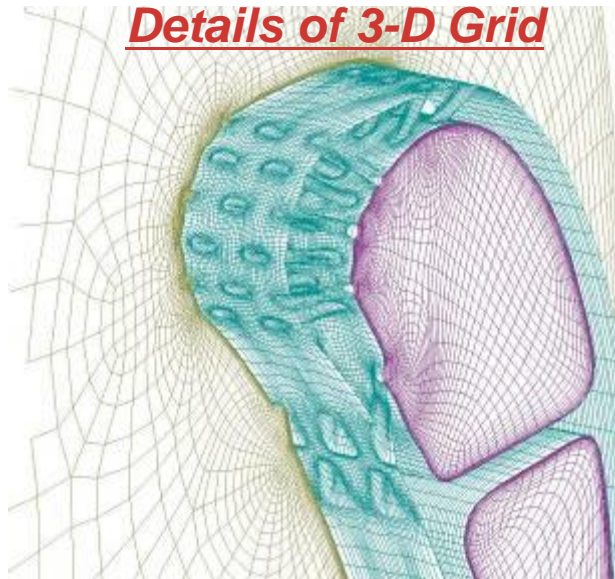


# NASA Glenn-HT Analysis Capabilities

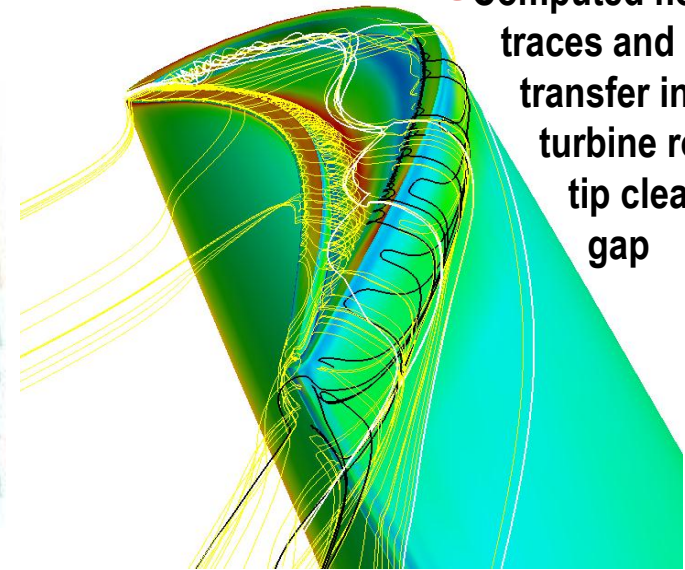
**Examples showing detailed predictions of internal and external flow and heat transfer**

Detailed grid for conjugate film cooling

## Details of 3-D Grid

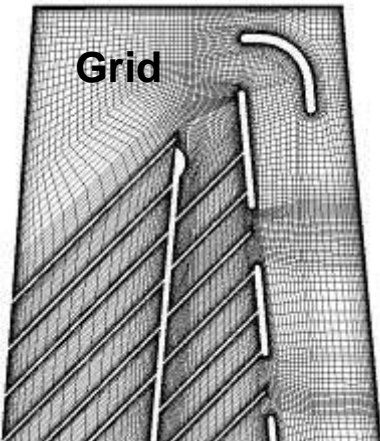


## Tip Gap Modeling

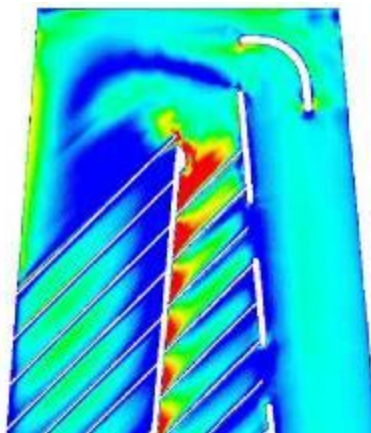


Computed flow traces and heat transfer in a turbine rotor tip clearance gap

## Internal Coolant Passage Modeling

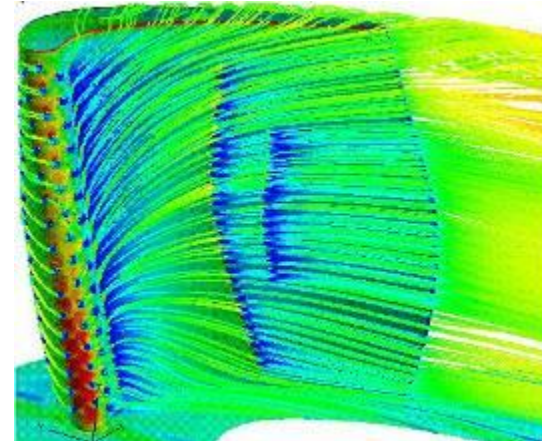


Grid



Glenn-HT computed heat transfer in internal passages

## Film Cooling Modeling



Whole blade film cooling analysis

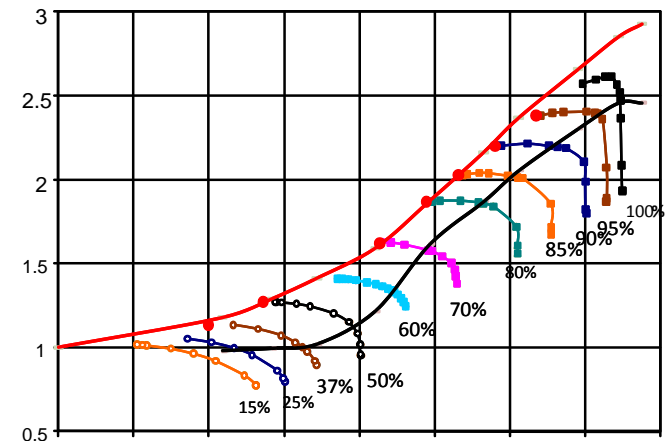


# Fan/Compressor Research



# RTA Fan Testing and Analysis

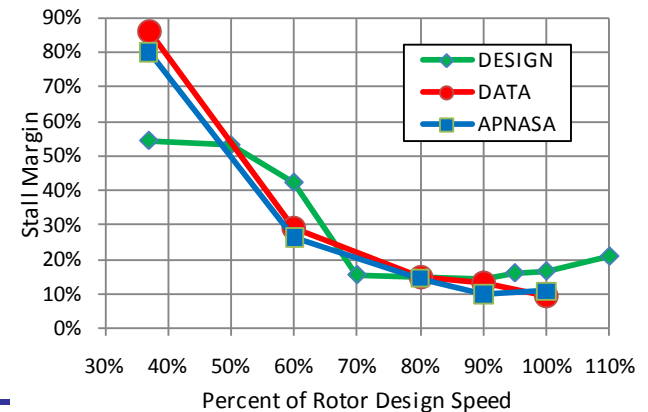
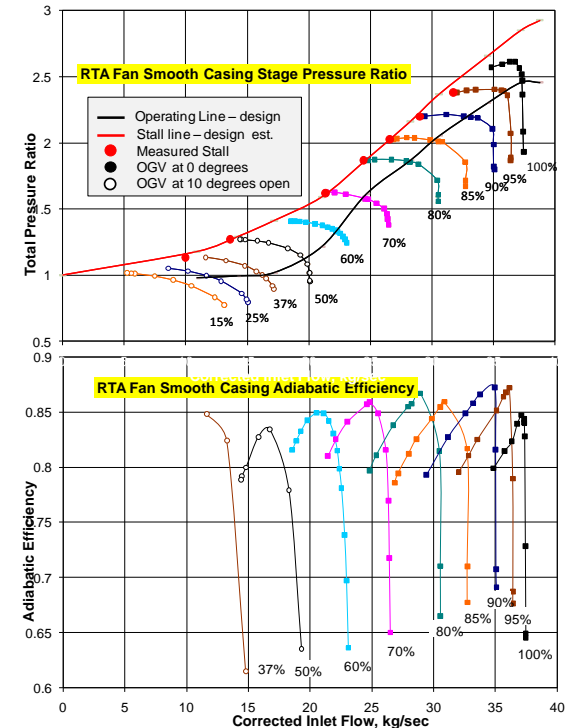
- **Problem:** Investigate a Mach 4 variable cycle turbofan/ramjet engine for access to space. Assess SOA design & analysis tools.
- **Objective:** Characterize a TBCC engine fan stage performance and stability limits over a wide operating range including inlet/engine interactions.
- **Approach:** Aerodynamic and aeromechanical testing in the NASA high speed compressor facility over a wide operating range and inlet distortion.
- **Results:** Testing was completed over a range of 15%-100% speeds with and without distortion. Completed APG milestone.
- **Significance:** Advancement has been made in propulsion design capability relevant to the NASA FAP Hypersonics Reusable Airbreathing Launch Vehicle mission.



# RTA Fan Testing and Analysis

## Completed Experimental and Computational Assessment of Advanced Fan Stage Operating over Wide Range of Speed and Bypass Ratios

- Aerodynamic fan stage performance characteristics acquired from 15% to 100% of design rotor speed.
- Stall margin predicted within 5.75% over entire operating range
- The successful fan test was done in partnership with GE Aviation. Peter Wood (GE) stated “the Mach 4+ fan demo test at NASA GRC was extremely successful, and technology learned from it will benefit all future GE commercial and military turbine engine product lines”.



Fan Rotor Blisk



Outlet Guide Vane



# High OPR Core Compressor Task

## OBJECTIVE:

Test the first two stages of an advanced GE Core Compressor using state-of-the-art research instrumentation to investigate the loss mechanisms and interaction effects of embedded transonic highly-loaded compressor stages.



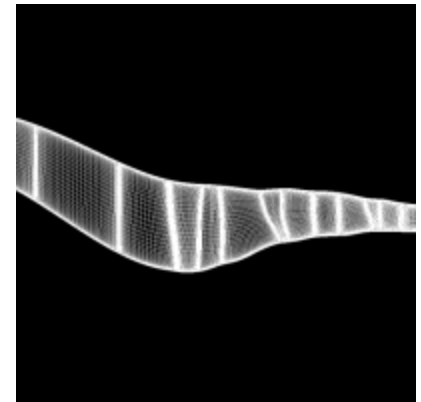
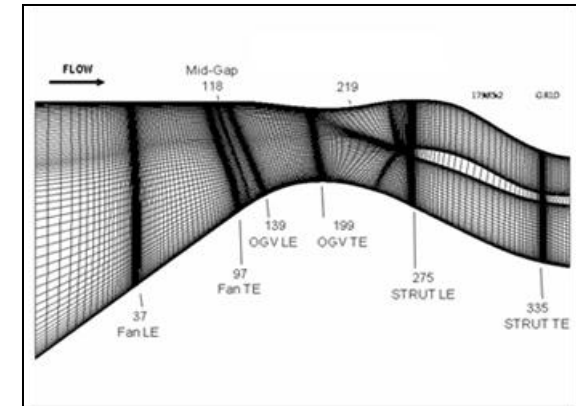
**ERB Test Cell W7**

- Cost-share arrangement with GE under ERA project of the ISRP program.
- Test single stage then 2-stage front block geometry in newly refurbished W7 test cell
- CFD will be used to assess both single stage and two stage geometries with inlet strut and IGV to determine location of interesting flow features.
- Unsteady instrumentation will be employed for comparison with unsteady CFD



# APNASA / TURBO Capability

- **Problem:** Develop & validate CFD tools for NASA to assess multistage turbomachinery performance toward reduced fuel burn
- **Objective:** Incorporate more 'real' geometry into average-passage and unsteady simulations to reduce reliance on modeling.
- **Approach:** Solve average-passage and/or unsteady equations for multistage turbomachines to understand flow physics and assess and improve current designs.
- **Results:**
  - RTA fan successfully simulated over wide range of speeds (APG milestone),
  - W7 2-stage helping determine interesting flow physics.
  - Purdue 3-stage helping characterize tip clearance losses.
- **Significance:** In-house developed code that is currently in use at several engine companies and is being distributed to universities (Purdue).

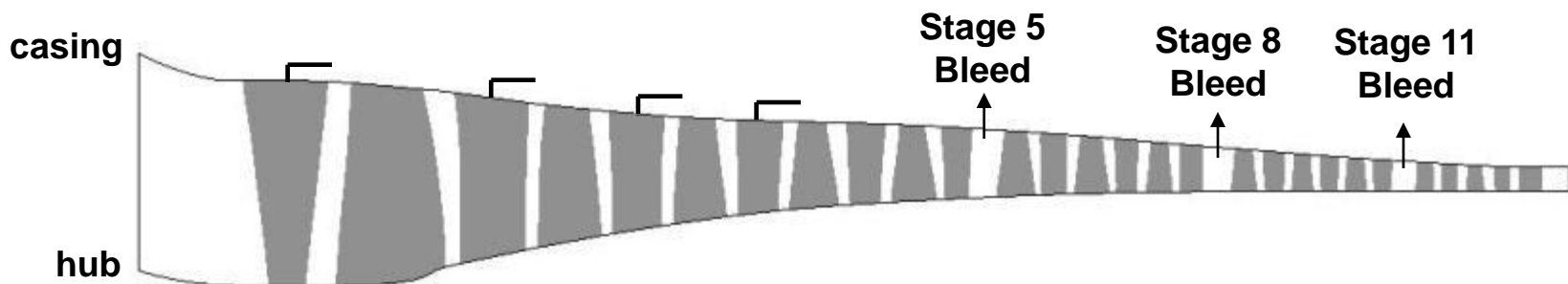






# Harmonized Compressor: Overview

- **Problem:** Compressor aero designers are often required to evaluate/adapt an existing design to an application different from its original intent, and require reliable and fast off-design compressor performance and operability estimates to support an assessment process.
- **Objective:** Rapidly generate estimates of off-design performance and operability of a 13-stage axial compressor (Harmonized Compressor).
- **Approach:** A stage stacking procedure is developed and applied, using stage performance characteristics populated with the APNASA CFD solver.
- **Results:** The stage stacking procedure with a novel mathematical closure for blockage, which correlated with flow coefficient and corrected speed, allowed for estimation of off-design performance, stalling speed, and a bleed schedule to expand the compressor's operating range. The estimates yielded total pressure ratio within 1.6% and adiabatic efficiency within 0.42 points of CFD simulations of the entire compressor at equivalent inlet corrected flows.

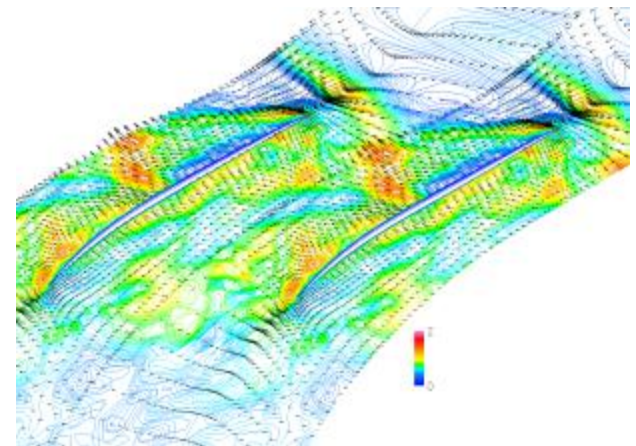
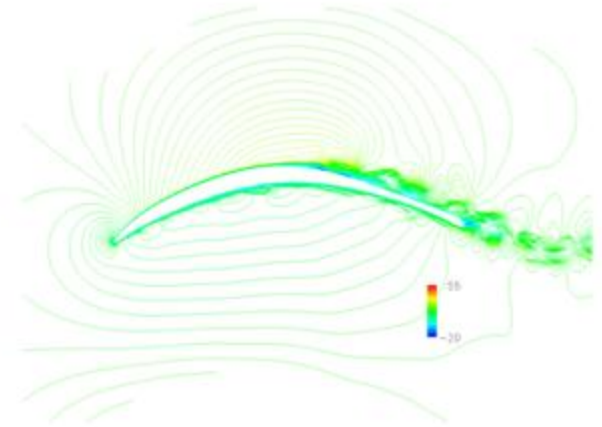


**Research team:** Sameer Kulkarni / RTT, Mark Celestina / RTT

# High Fidelity Fan/Compressor CFD

- **Problem:** Current generation of RANS-based CFD tools can not calculate flow field with flow separation and/or flow transition accurately.
- **Objective:** Development a fan/compressor simulation tool which can calculate flow field with flow separation and flow transition accurately.
- **Approach:** Develop a practical LES based code with near wall modeling.
- **Results:** Has been tested for transonic fan/compressor flows and flow transition in a cascade of compressor blades.
- **Significance:** Can be used for development of flow control devices and design optimization of fan with flow transition and Reynolds number effects

Instantaneous axial velocity contours, LES, Re. # 210,000



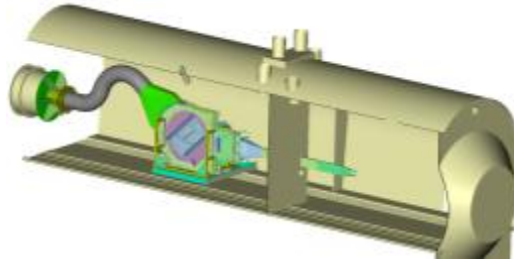
# Compressor Icing Modeling & Altitude Testing

## Objective:

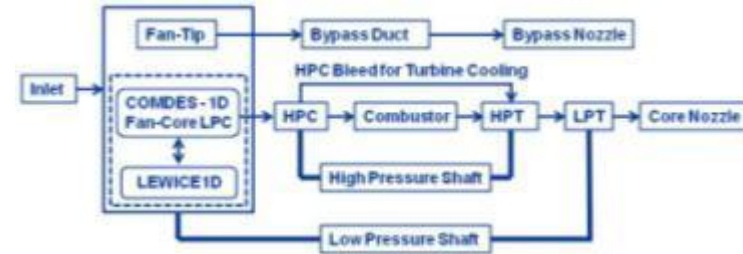
To develop key technologies needed to address the problem of aircraft engine icing due to high altitude ice-crystal ingestion. These key technologies include knowledge bases, both computational and experimental, analysis methods, and simulation tools.

## Approach:

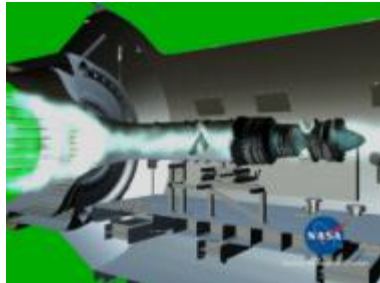
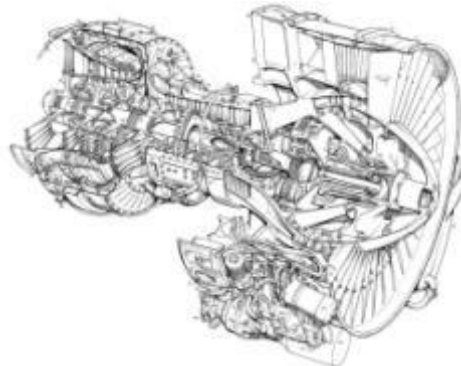
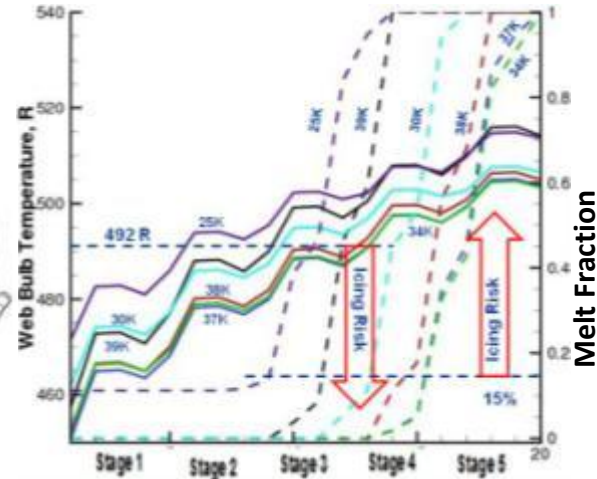
- Laboratory testing: of compressor vane under iced conditions (Collaboration with National Research Council of Canada)



- Computational Research: Application of modern numerical simulation codes to the investigation, understanding, and ultimately, the solutions to avoid engine icing.

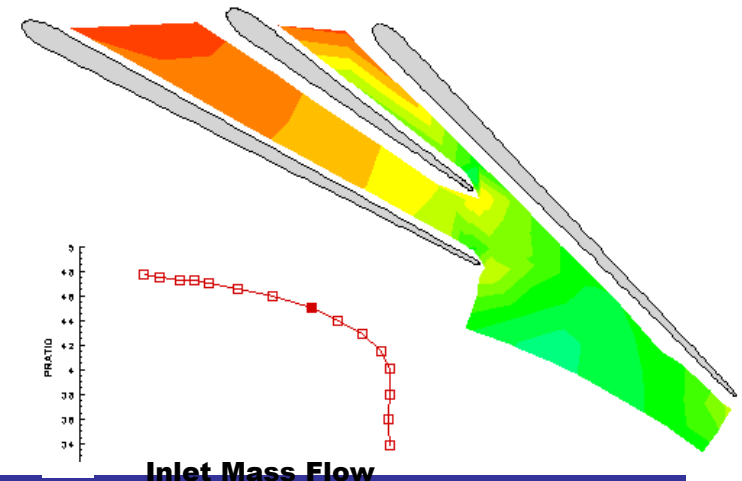
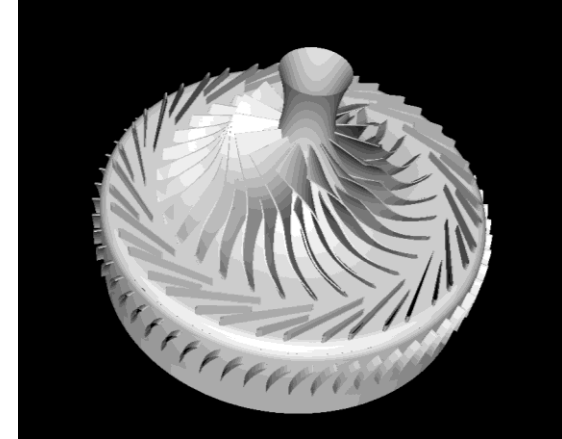


- Engine Testing: Propulsion System Laboratory (PSL) Direct connect full scale gas turbine engine ice ingestion tests at altitude conditions, with water spray bars to create ice crystals.



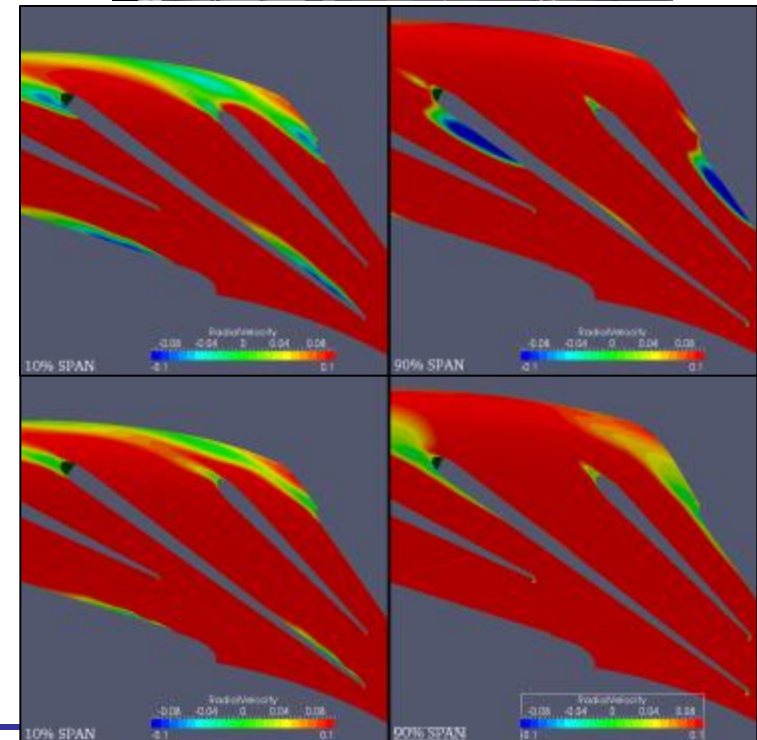
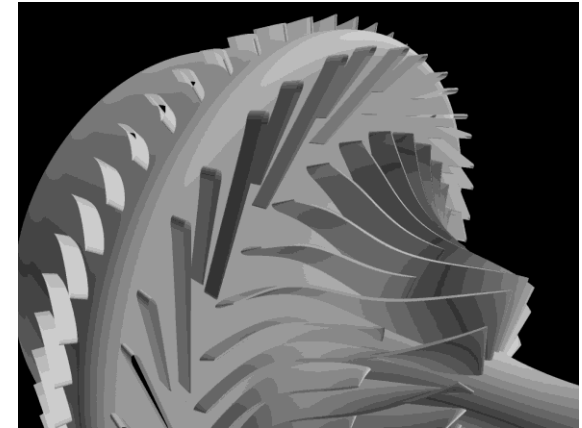
# High Efficiency Compact Centrifugal Compressor (HECC) Research-Experimental Effort

- **Problem:** Retain operability and SOA efficiency, while reducing exit corrected flows and increasing compactness.
- **Objective:** Develop centrifugal compressor (CF) component to address key aero challenges of high OPR CFs & obtain aero performance and flow field data sets for community.
- **Approach:**
  - Refurbish GRC CE-18 and re-baseline an existing centrifugal compressor (CC3)
  - Assess new high-response (5 BPF) p0-probe
  - Execute fabrication, installation, test, and evaluation of a SOA centrifugal compressor stage designed/instrumented by industry to meet NRA goal set.
- **Results:**
  - CE-18 re-certified & CC3 stage re-baselined.
  - HECC stage (NASA/UTRC NRA cost-share) currently under test & evaluation
- **Significance:** High resolution steady and high-response data obtained will enable assessment of success of 3-D design approach and constitute a industry-relevant dataset for advanced CFs.



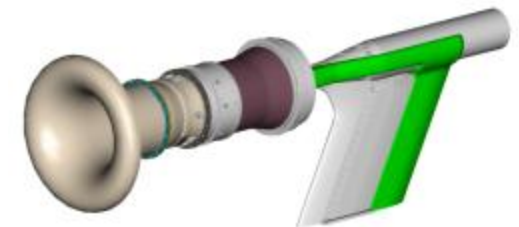
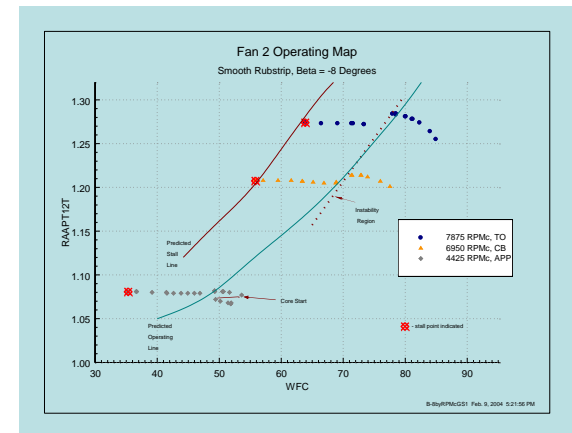
# Axi-Centrifugal Unsteady Simulation Analysis Capability

- **Problem:** Accurate CFD predictions are required for small, high OPR, axi-centrifugal core compressors for future engines
- **Objective:** Develop and demonstrate CFD analysis capability for axi-centrifugal geometries
- **Approach:** The TURBO solver with phase lag boundary conditions, modified for centrifugal geometries, is used with grids generated by TGS. ParaView is used for visualization and post-processing.
- **Results:** TURBO/TGS CC3 simulation was calibrated with existing test data. Design speed simulations of HECC are in progress, and a tip clearance sensitivity study is underway.
- **Significance:** Accurate computation of the complex flow in axi-centrifugal compressors further the understanding of aerodynamics in these low exit corrected flow machines.



# NASA Wind Tunnel Fan Aerodynamic Testing

- **Problem:** Define current challenges and evaluate concepts for quiet, high efficiency fan systems central to modern high bypass turbofan propulsion systems.
- **Objective:** Establish current SOA, identify challenges, advance quiet fan technology with high performance
- **Approach:** 22" scale model propulsion systems with nacelle, internal flow lines, core simulations, tested in the 9x15 LSWT.
- **Results:** Advanced measurement capabilities, low PR fan systems, improved stability tools, CFD computations, operability improvements
- **Significance:** Modern propulsors are very high performance; higher loading, pushing down PR (increasing BPR), present system integration challenges requiring evaluation to help industry advance SOA for quiet high efficiency fan systems





# Turbine Heat Transfer Research

# Transonic Cascade Heat Transfer & Film Cooling Measurement Capability

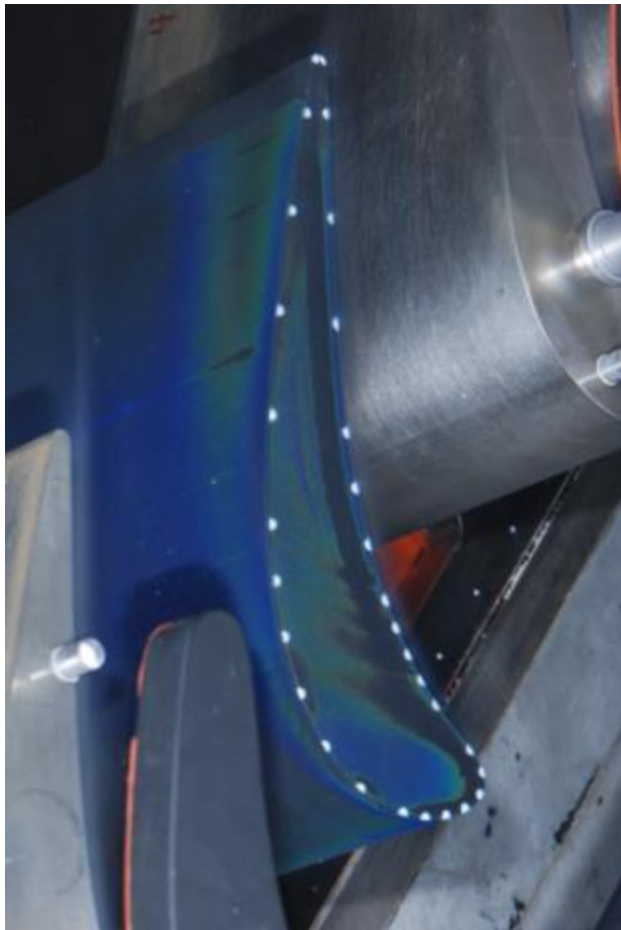
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- **Problem:** Detailed, reliable heat transfer data are needed for improved understanding and validation of advanced modeling.
- **Objective:** Acquire high quality, spatially resolved data under engine-realistic Reynolds numbers, Mach numbers, and turbulence intensities.
- **Approach:** Obtain data in NASA's large-scale, Transonic Turbine Blade Cascade (CW-22). Make the data, geometry, and boundary conditions openly available.
- **Results:** Acquired blade, endwall, and tip heat transfer and aerodynamic data with low uncertainty on realistic geometries.
- **Significance:** Data have been transmitted extensively and continue to be requested.



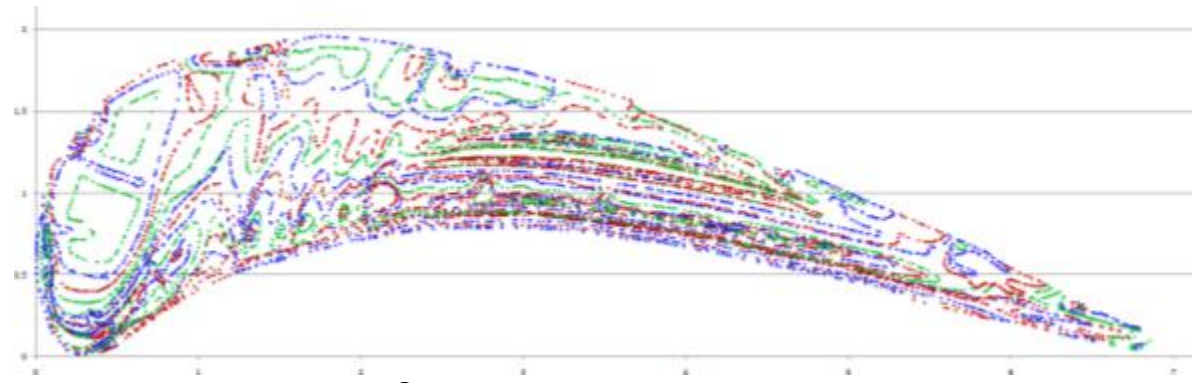


# Blade Tip Surface Heat Transfer Measurements (CW22)



**Sample E<sup>3</sup> Tip Surface liquid crystal photograph**

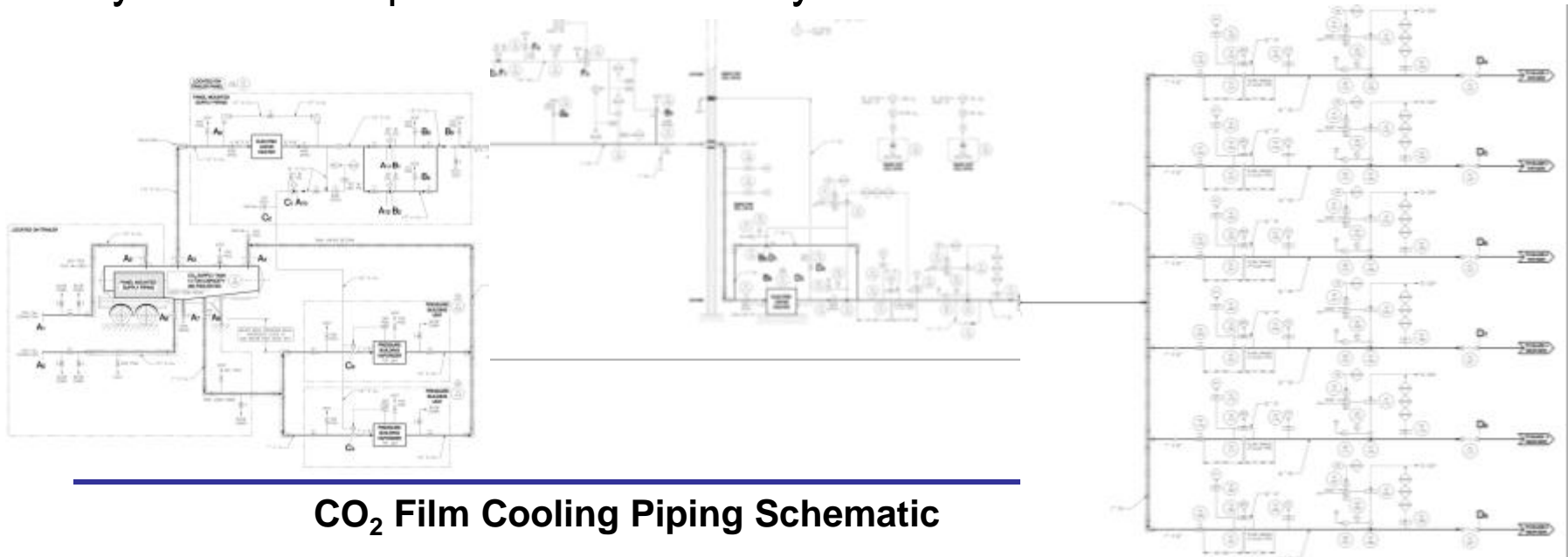
- differentially heated copper blade;
- covered with low conductivity bonded layer;
- painted with flat black paint, then sprayed with 115.8° F liquid crystals;
- heater power controlled to maintain isothermal copper substrate;
- power varied to move isotherms.



**Sample E<sup>3</sup> digitized liquid crystal data**

# CW-22/SW-6 Film Cooling Capability

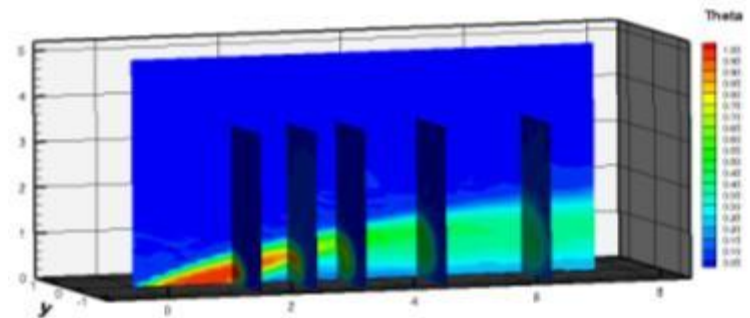
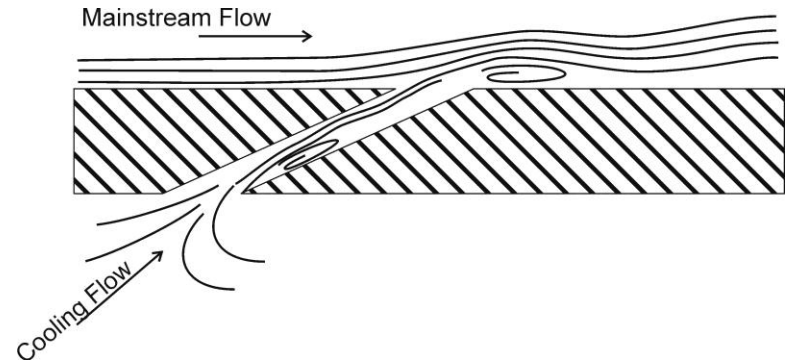
- Long-term interest in expanding facility capabilities to include film cooling.
- Use CO<sub>2</sub> to approximate engine coolant/primary density ratio.
- Cooled coolant for measurement of heat transfer coefficient.
- Six individually controlled coolant branches.
- Temperature control.
- Maximum 2 lb/s CO<sub>2</sub> mass flow capability.
- System to be operational in January 2013.



**CO<sub>2</sub> Film Cooling Piping Schematic**

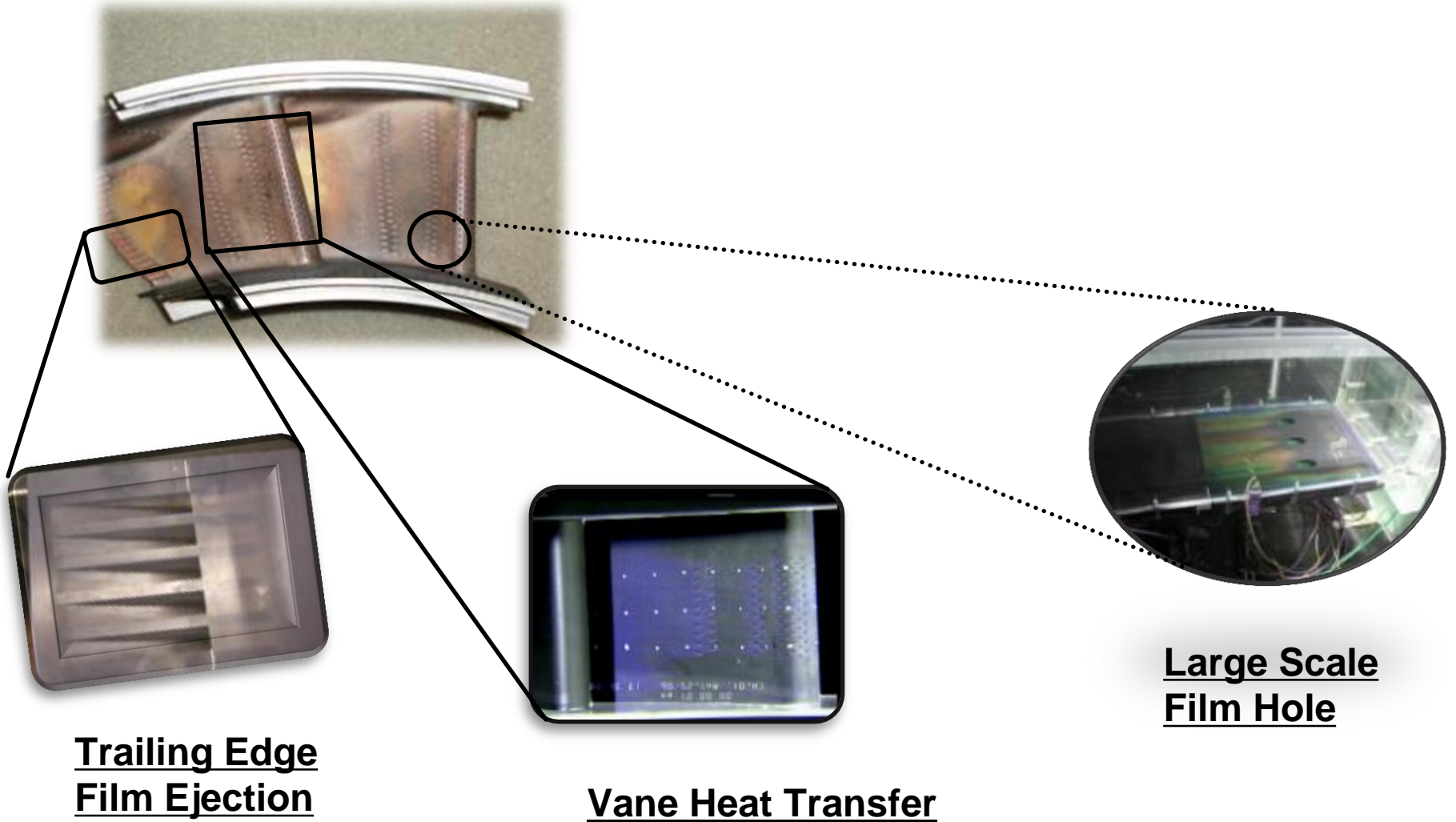
# Fundamental Film Cooling Experiments

- **Problem:** Reduce Specific Fuel Consumption by improving turbine cooling.
- **Objective:** Identify advanced configurations to reduce turbine blade cooling
  - Understand the flow physics to improve modeling efforts
- **Approach:** Perform detailed flow and temperature measurements on large scale turbine cooling hole configurations
  - Evaluate effectiveness of advanced configurations
- **Results:** Detailed data sets were obtained and evaluated against various computations.
- Several promising cooling concepts are being developed
- **Significance:** Potential improvements in film cooling understanding and turbine design.



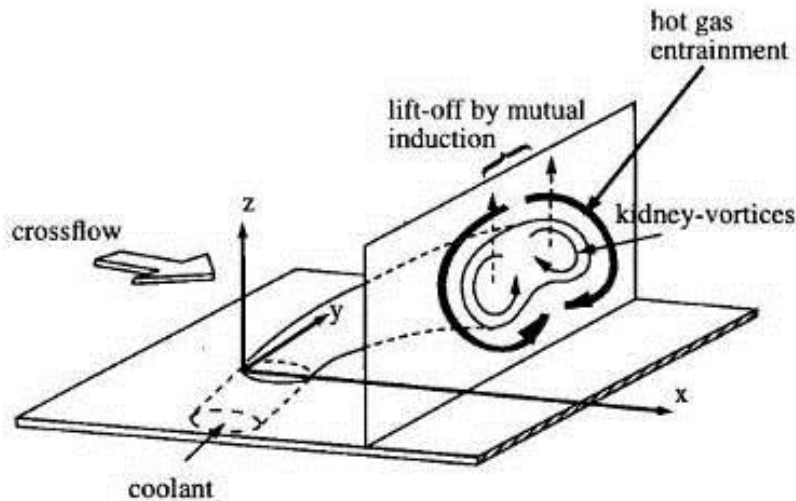
# Fundamental Film Cooling Experiments

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# Advanced Turbine Cooling Concepts

**Objective: Computationally and experimentally develop and demonstrate improved turbine film cooling concepts.**



**Jet lift-off**

At high blowing ratios, round film cooling holes become ineffective due to jet lift-off

**Improved cooling effectiveness can reduce cooling required for given turbine inlet temp.**

## **Approaches To Improve effectiveness:**

- Increase lateral spreading by enhancing mixing near surface
- Decrease effective blowing ratio by speeding up Mainstream
- Create vorticity adjacent to hole to promote spreading
- Pulse coolant jet in or adjacent to hole
- Add vorticity or counter-vorticity inside hole.
- Downstream actuation to control shedding
- Create negative vorticity

# Glenn-HT Multi-Blade Row Capability

## Objective:

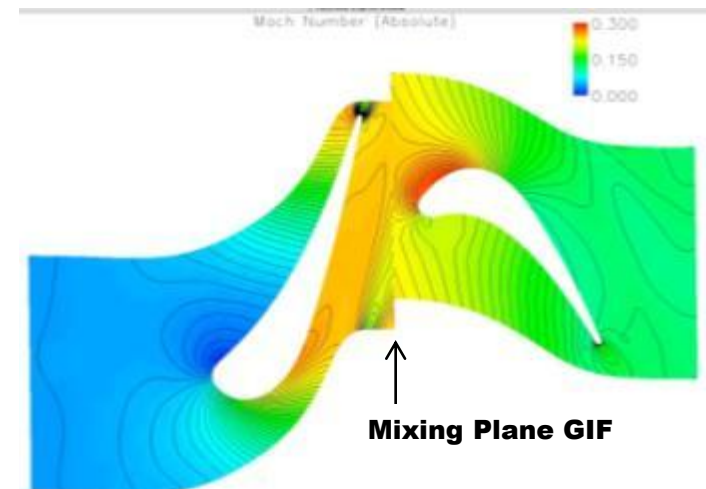
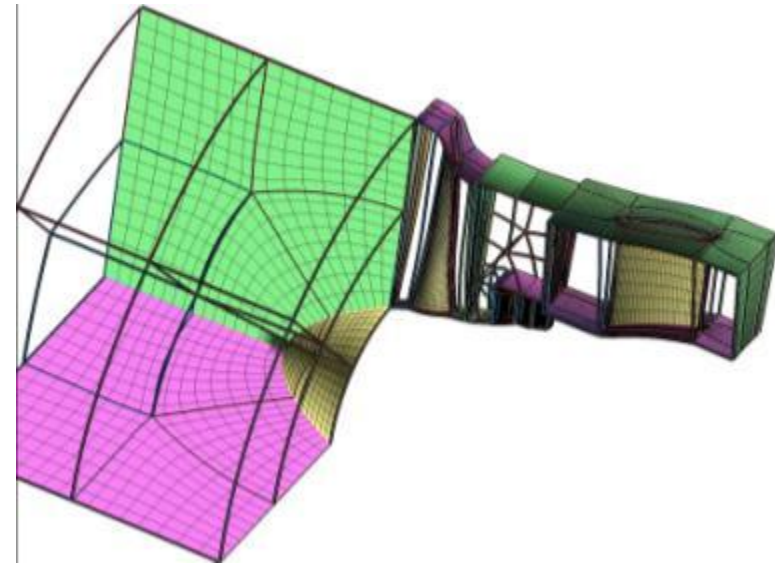
- Provide ability, in Glenn-HT, to perform Multi-Blade Row Simulations including fluid and solid regions

## Approach:

- Allow ability to perform time accurate and average simulation
- Implement multiple zones, each zone having its own set of properties.
- Implement General Interface (GIF) boundary conditions of various types to accommodate all required interface types.

## Status:

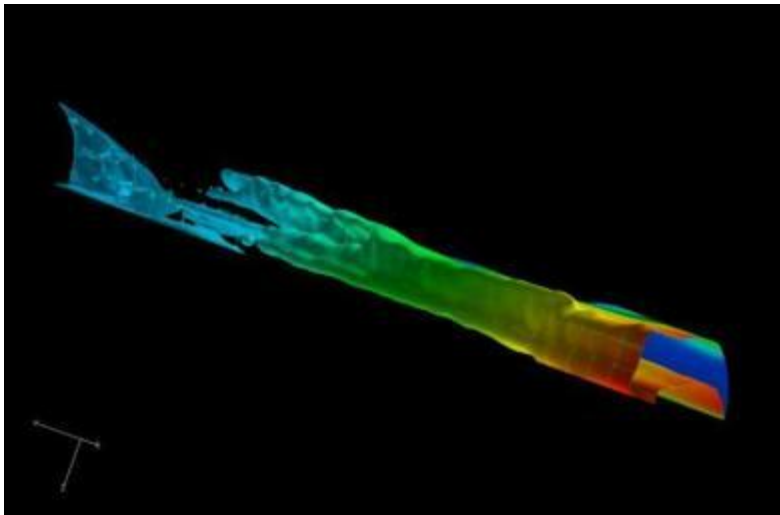
- Multi-zone capability implemented to allow separate fluid or solid properties in each zone. Each zone can have a different rotation rate.
- Required GIF types implemented including:
  - Interpolation, Conjugate, Periodic, Rotating-Sliding, Phase-Lag, and Mixing Plane
- Testing and production cases currently in progress



# Glenn-HT PRNS/LES for Heat Transfer

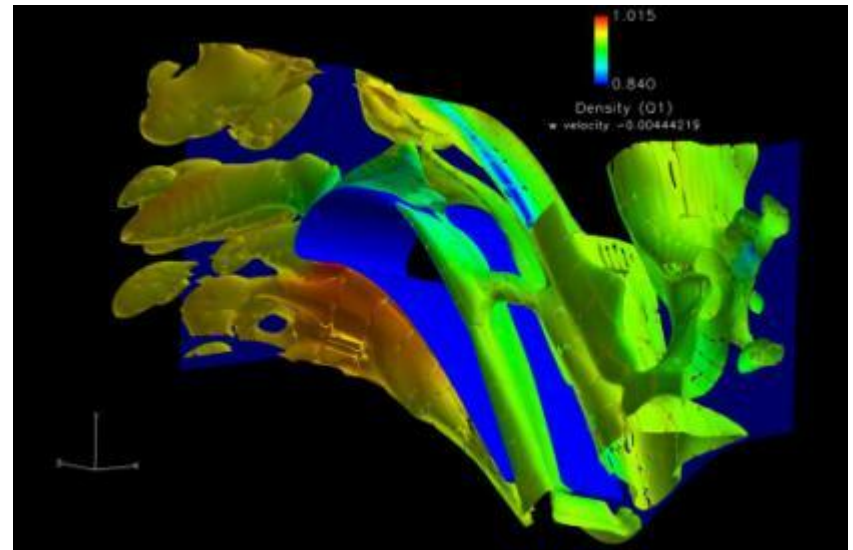
**Implement Partially Resolved Navier-Stokes simulation capability (PRNS) in Glenn-HT.**

**Moving toward full LES (Large Eddy Simulation) capability**



**Channel flow**

**Turbine blade passage**



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# Turbine Aero Research

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# Variable-Speed Power Turbine for Large Civil Tilt-Rotor

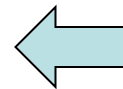


**NASA FAP/SRW Large Civil Tilt-Rotor Notional Vehicle**

Need for variable-speed power-turbine with range of operation  $54\% < N_{PT} < 100\%$

Research addresses key technical challenges:

- High efficiency at high stage work factor
- Wide ( $50^\circ$ ) incidence range requirement
- Low Reynolds number operation



Large Civil Tilt-Rotor	
TOGW	108k lb <sub>f</sub>
Payload	90 PAX
Engines	4 x 7500 SHP
Range	> 1,000 nm
Cruise speed	> 300 kn
Cruise altitude	28 – 30 kft

**Goal** – to enhance airport throughput capacity by utilizing VTOL capable rotary wing vehicles.

**Principal challenge** for LCTR – required variability in main-rotor speed:

- 650 ft/s at take-off
- 350 ft/s at Mn 0.5 cruise

# Incidence Tolerant Blade Tests

**Problem:** Investigate aerodynamic impact of large incidence angle and Reynolds number variation as needed for incidence-tolerant blade development.

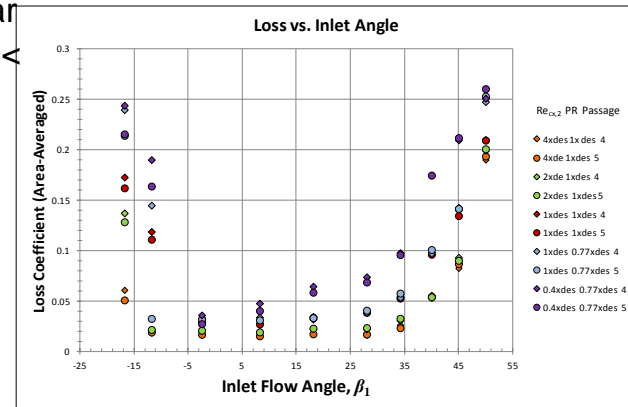
**Objective:** Address the key VSPT aerodynamic challenges by documenting the aerodynamic performance of incidence-tolerant (IT) blading for a variable-speed power-turbine (VSPT) application over a wide range of incidence angles and Reynolds numbers of relevance to the NASA LCTR (Large Civil Tilt Rotor) mission.

**Approach:** Obtain aero loss measurements on an LCTR-relevant blade in a linear transonic turbine blade cascade over an inlet angle range of  $-16.8^\circ < \beta_1 < +50.0^\circ$  and at five flow conditions which varied over a full order of magnitude in Reynolds number.

**Results:** Successful completion of the SRW VSPT first test entry milestone.

## Significance:

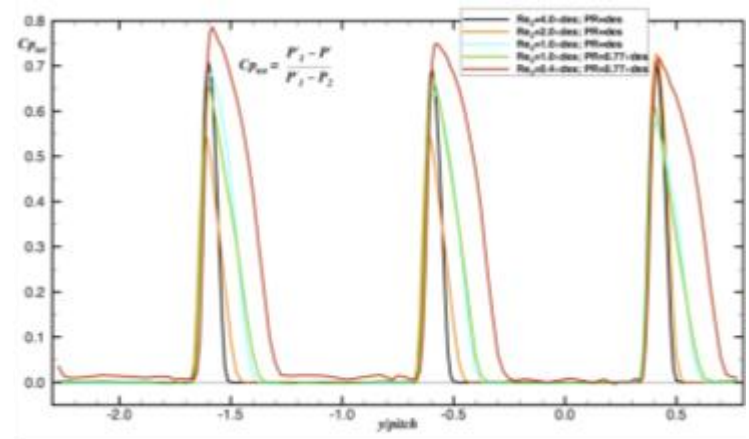
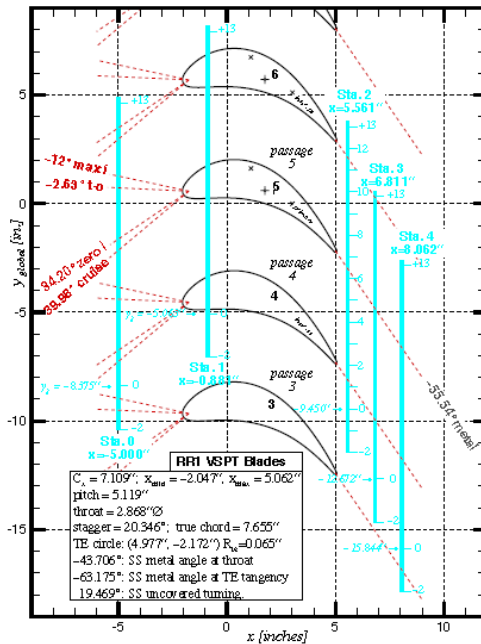
- Data/findings to be used to assess transition/turbulence models of RANS/URANS computational tools used for analysis of multistage turbines operating at low Reynolds numbers over a 50% shaft-speed range.
- Data/findings will inform engine company VSPT blade designs for advanced turboshaft engines of future rotary wing applications.
- Data set to be corroborated and expanded to lower Reynolds numbers through NASA Space Act Agreement with U. North Dakota.



# Variable-Speed Power Turbine Testing (CW22)

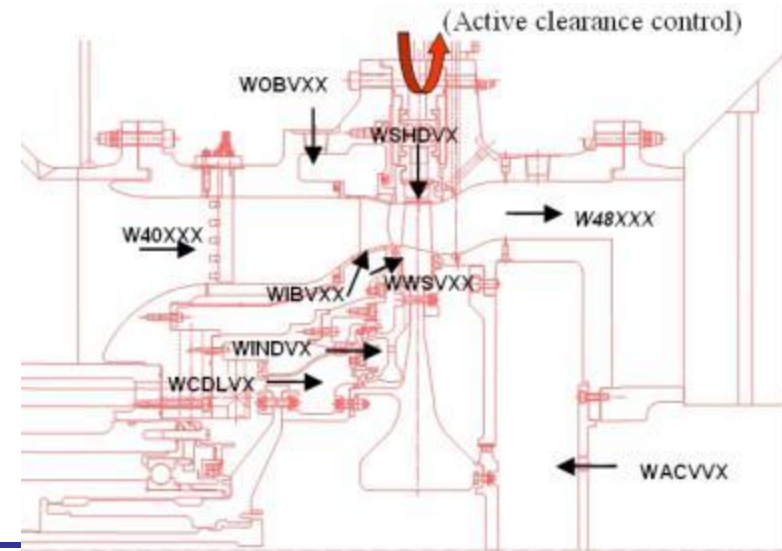
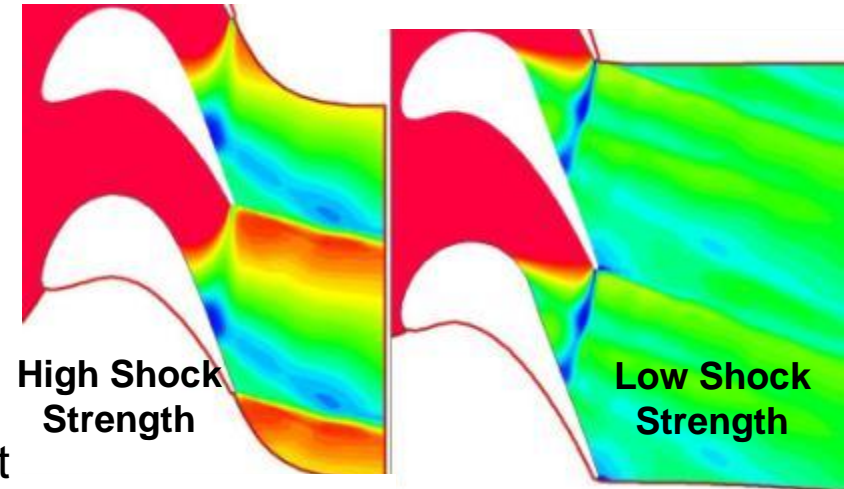
**Objective:** Examine aerodynamic effects of large incidence angle variations on a Variable-Speed Power Turbine relevant blade profile for a Large Civil Tilt Rotor.

**Status:** Aerodynamic 5-hole and 3-hole probes are being used to acquire downstream exit total pressure and flow angle data in conjunction with blade loading and endwall static pressure measurements.



# Single Spool Turbine Facility Capability

- **Problem:** Turbines contribute significantly to engine SFC, but fundamental understanding and validation capability lacking in a realistic, scaled, high-speed, cooled environment.
- **Objective:** Experimentally assess advanced turbine aerodynamic concepts and technologies.
- **Approach:** Develop a steady-state turbine test facility with full cooling/secondary flow simulation and research capabilities.
- **Results:** Re-hab of former warm core turbine facility in process.
- **Significance:** The SSTF will be only one of only two large-scale, high-speed, steady-state turbine test facilities in the U.S.



# NASA/GE Highly-Loaded Turbine Tests

- **Objective:** Aerodynamic testing of advanced, highly-loaded GE-UEET high-pressure and flow-controlled low-pressure turbine to provide detailed experimental data for CFD code validation.
- **Approach:** Major upgrade to turbine test (W-6) facility in progress to accommodate tests
- **Status:**
  - Synchronous machine delivered, installed, and tested.
  - Gearbox installed and driveline alignment completed.
  - Exhaust collector delivered, outlet enlarged, PSO required modifications, code stamped.
  - Spray cooler tank modified, inlet enlarged, pressure systems recertified.
  - Test article design modifications complete and fabrication underway.
  - Inlet, exhaust, secondary, and natural gas piping installation underway.
  - Research testing in 2013.



- **Synchronous machine will absorb test turbine power.**
- **Generator mode will put power back on the GRC electrical grid.**
- **Up to 12,400 hp (9.2 MWatts).**

# NASA-Industry LPT/PT Efficiency Improvement Workshop

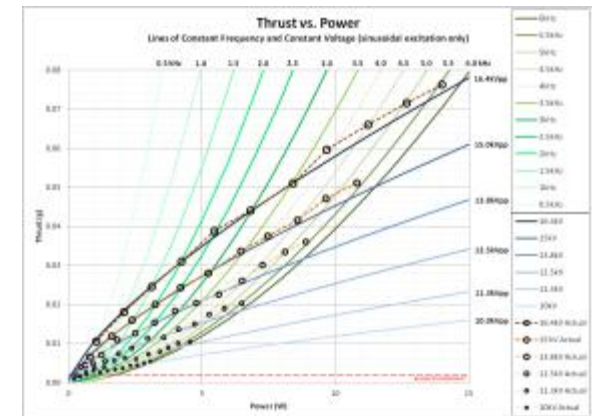
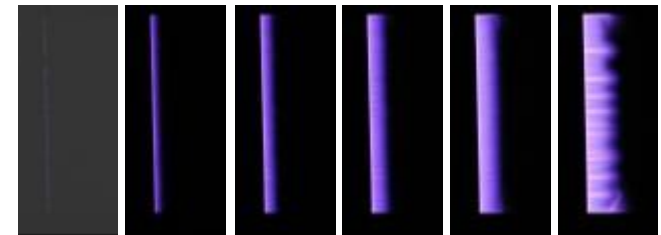
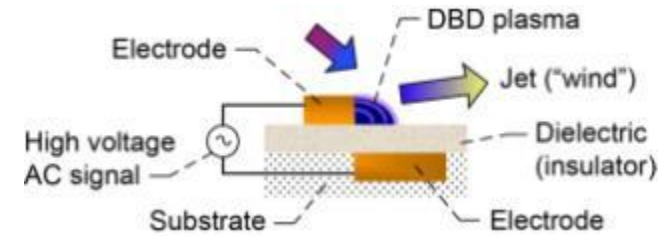
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- August 10-11, 2010, at NASA GRC
- Goal: Understand feasibility of additional efficiency improvements in high-lift LPTs
- Participants: PW, GE, Rolls-Royce, ITP, Honeywell, UTRC, GE-Global, AFRL, NASA, Army, NRC Canada, Academia
- Link: <http://evt.grc.nasa.gov/lpt-workshop/Presentations>
- Main recommendation strongly supported by industry was to focus on:
  - Full scale multistage rig experiments
  - 3 stages min., range of low Re, include cavities and purge flows
  - P&W EEE LPT design possible candidate
  - Challenge finding common geometry due to company differences
- POC: David Ashpis 216-433-8317 ashpis@nasa.gov



# DBD Plasma Actuators for Active Flow Control

- **Problem:** Improve efficiency and reduce fuel burn of gas turbines is limited by design and optimization constraints
- **Objective:** Develop active flow control technologies to improve turbomachinery aerodynamics, reduce losses and enable off-design operation
- **Approach:** Focus on Dielectric Barrier Discharge (DBD) plasma actuators. The momentum or pressure waves generated are used to affect the flow.
- **Results:** ♦ Successful demonstration of separation delay in simulated LPT wind tunnel flow (2003). ♦ Constructed a world-class laboratory for characterization of actuators. ♦ Analyzed required test conditions at room temperature to simulate actuator operation at flight conditions. ♦ Developed accurate methods for actuators electrical power measurements.
- **Significance:** Active flow control enables leap improvements in fuel burn via improved component aerodynamics. DBD plasma actuators have significant advantages and are suitable for high temperature operation.



# Turbomachinery Research Summary

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NASA Turbomachinery research plays an important role in the NASA Aeronautics projects toward goals of reduced fuel burn, increased mobility & improved safety

Range of research areas encompassing fan/compressor aerodynamics, turbine aerodynamics and turbine heat transfer

Mix of computational model development and application, experimental testing, and concept development

Research spread across TRL range from very fundamental to high-speed rig/engine testing

Research objectives met through combination of external (NRA, space act agreement, contracts) and in-house efforts – this review will focus on in-house

Looking to peer review panel for forthright assessment of research activities

Welcome and enjoy! If you should need anything over the next two days, feel free to call my cell: (216) 287-4425

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