IMPROVING ENGINE EFFICIENCY THROUGH CORE DEVELOPMENTS

Brief summary:
The NASA Environmentally Responsible Aviation (ERA) Project and Fundamental Aeronautics Projects are supporting compressor and turbine research with the goal of reducing aircraft engine fuel burn and greenhouse gas emissions. The primary goals of this work are to increase aircraft propulsion system fuel efficiency for a given mission by increasing the overall pressure ratio (OPR) of the engine while maintaining or improving aerodynamic efficiency of these components. An additional area of work involves reducing the amount of cooling air required to cool the turbine blades while increasing the turbine inlet temperature. This is complicated by the fact that the cooling air is becoming hotter due to the increases in OPR. Various methods are being investigated to achieve these goals, ranging from improved compressor three-dimensional blade designs to improved turbine cooling hole shapes and methods. Finally, a complementary effort in improving the accuracy, range, and speed of computational fluid mechanics (CFD) methods is proceeding to better capture the physical mechanisms underlying all these problems, for the purpose of improving understanding and future designs.

National Aeronautics and Space Administration

Improving Engine Efficiency Through Core Developments

Dr. James Heidmann
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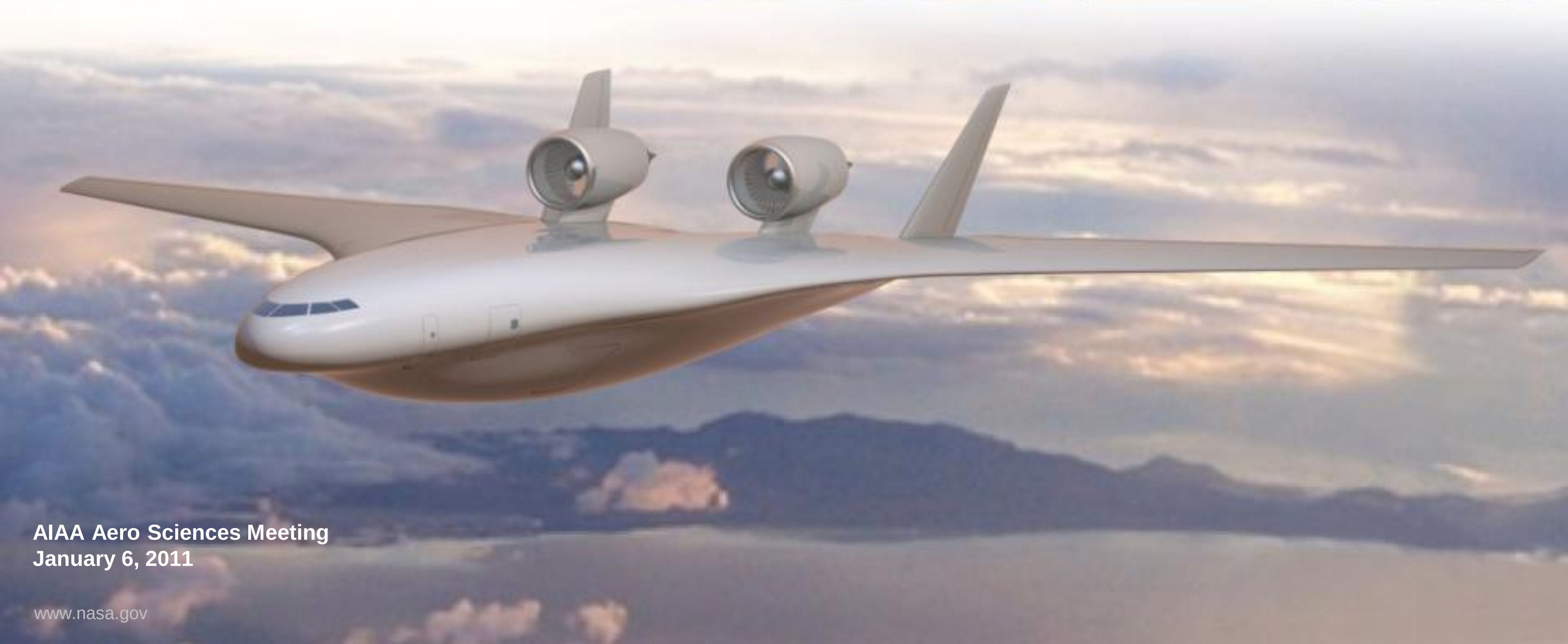
Environmentally Responsible Aviation
Integrated Systems Research Program



AIAA Aero Sciences Meeting
January 6, 2011

NASA's Subsonic Transport System Level Metrics

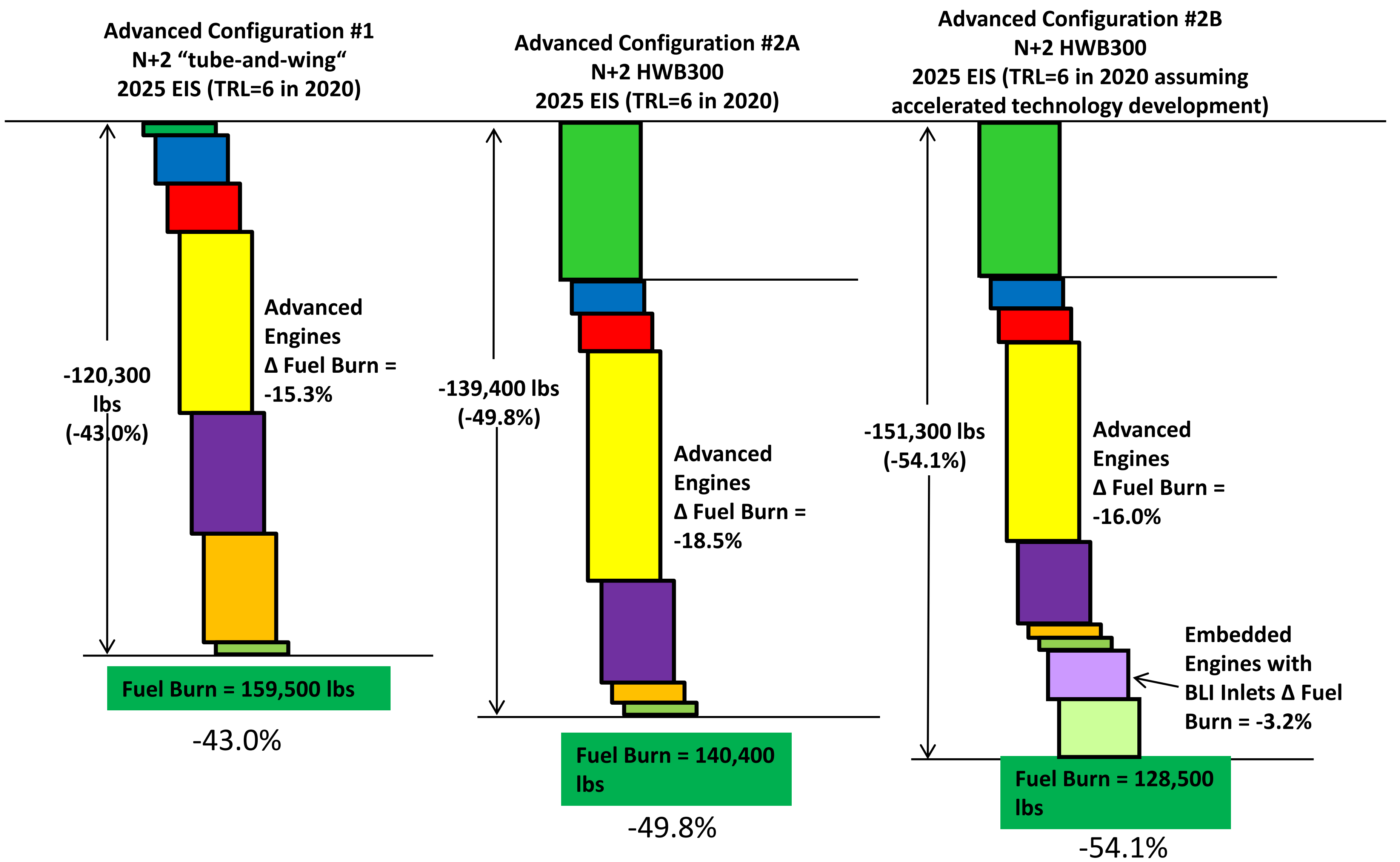
…. technology for dramatically improving noise, emissions, & performance

CORNERS OF THE TRADE SPACE	N+1 = 2015 Technology Benefits Relative To a Single Aisle Reference Configuration	N+2 = 2020 Technology Benefits Relative To a Large Twin Aisle Reference Configuration	N+3 = 2025 Technology Benefits
Noise (cum below Stage 4)	-32 dB	-42 dB	-71 dB
LTO NO_x Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%	**-50%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts

Goals are relative to reaching TRL 6 by the timeframe indicated
Engine core research primarily focused on fuel burn metric (SFC)
Core developments have positive and negative impacts on NOx

POTENTIAL REDUCTION IN FUEL CONSUMPTION

Advanced N+2 Configurations



Propulsion Technology Enablers

Fuel Burn - reduced SFC (increased BPR, OPR & turbine inlet temperature, potential embedding benefit)

$$\text{Aircraft Range} = \frac{\text{Velocity}}{\text{TSFC}} \left(\frac{\text{Lift}}{\text{Drag}}\right) \ln\left(1 + \frac{W_{fuel}}{W_{PL} + W_{O}}\right)$$

- Engine Fuel Consumption
- Aerodynamics
- Empty Weight

TSFC = Velocity / ($\eta_{overall}$)(fuel energy per unit mass)

$$\eta_{overall} = (\eta_{thermal})(\eta_{propulsive})(\eta_{transfer})(\eta_{combustion})$$

$$\eta_{th} = 1 - \left(\frac{p_2}{p_1}\right)^{\frac{1-\gamma}{\gamma}}$$

assuming constant component efficiencies

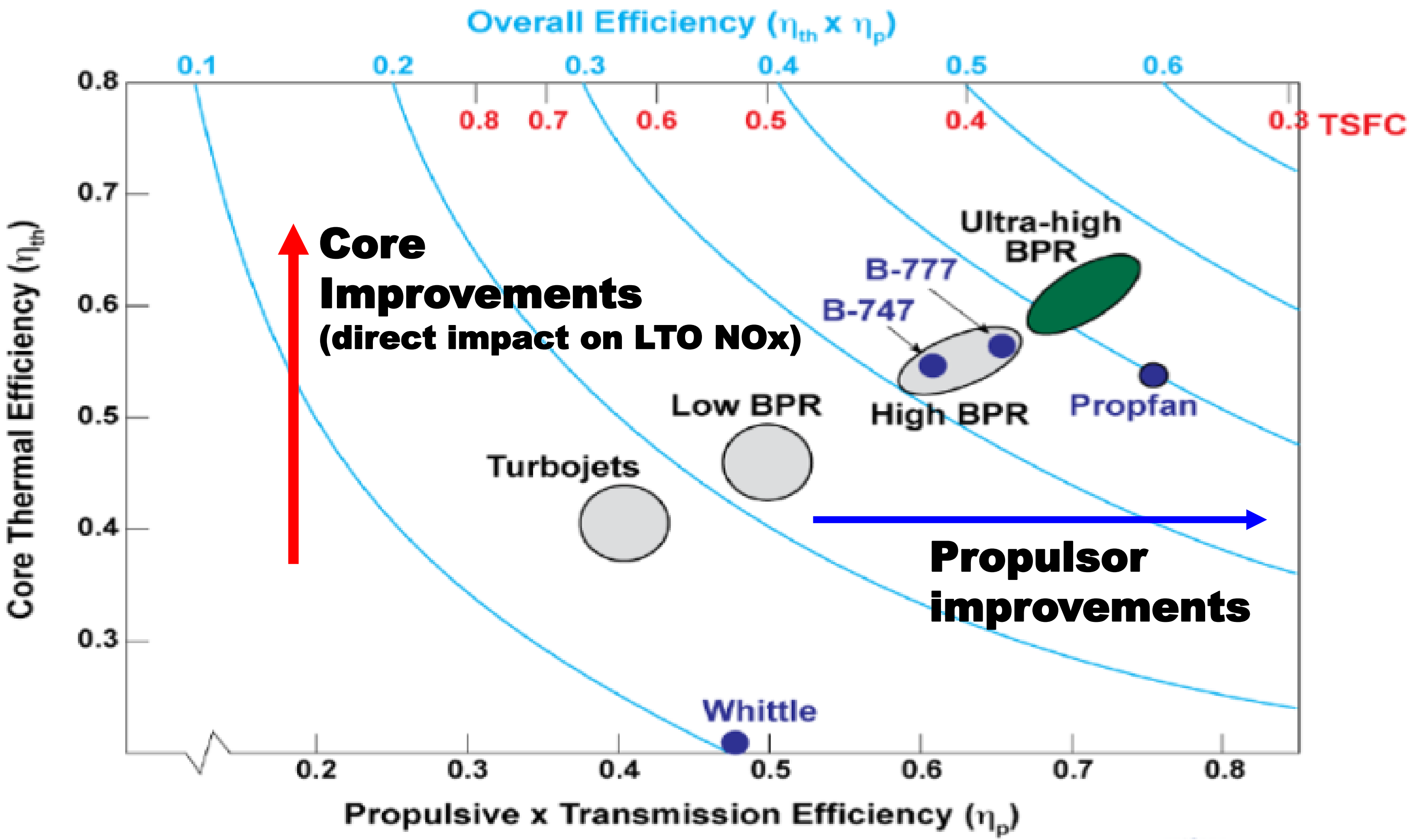
Core research impacts thermal efficiency through increased OPR

High power density cores enable higher propulsive efficiency cycles

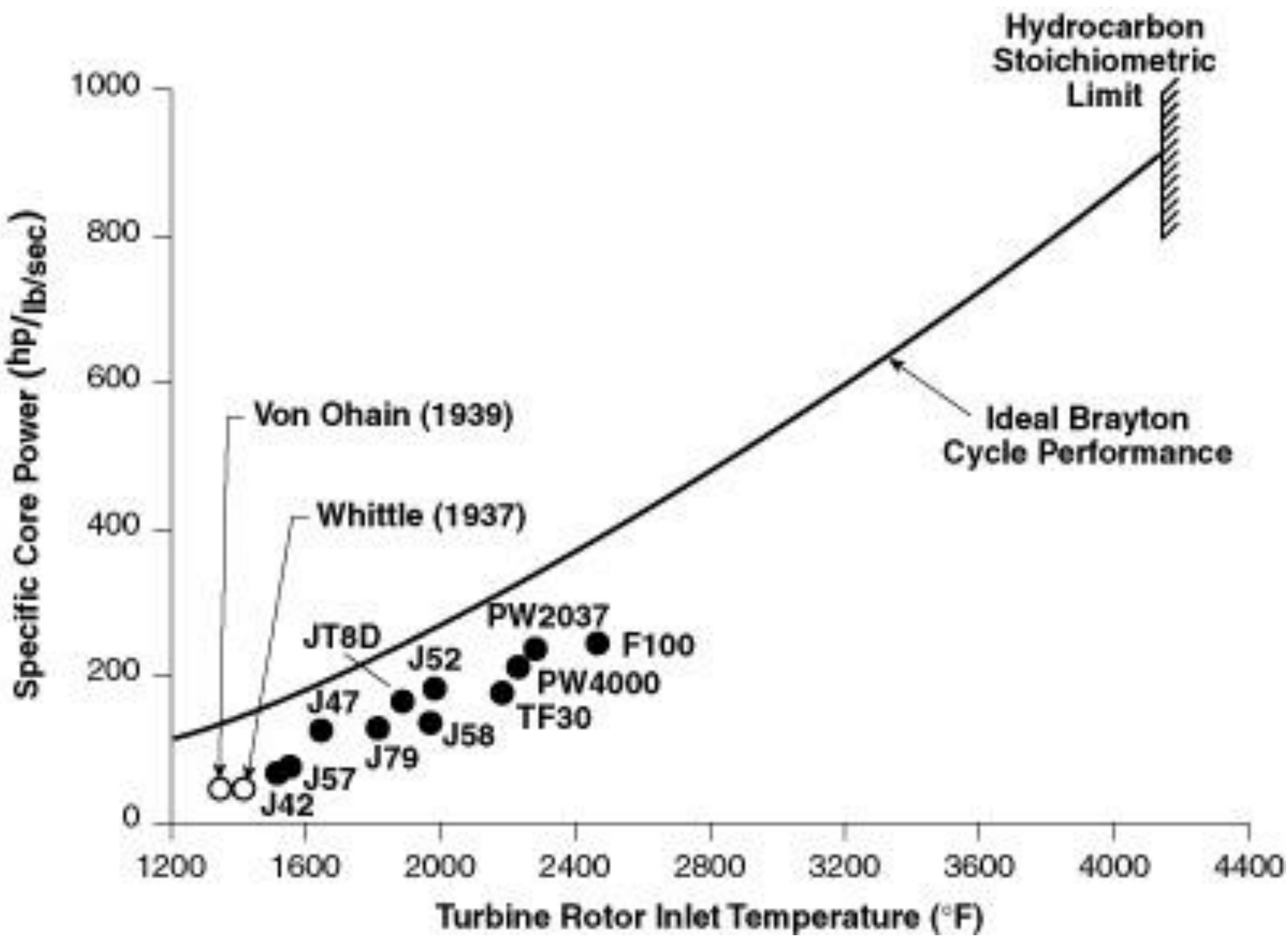
Low pressure turbine improvements impact transfer efficiency

Propulsion Technology Opportunity

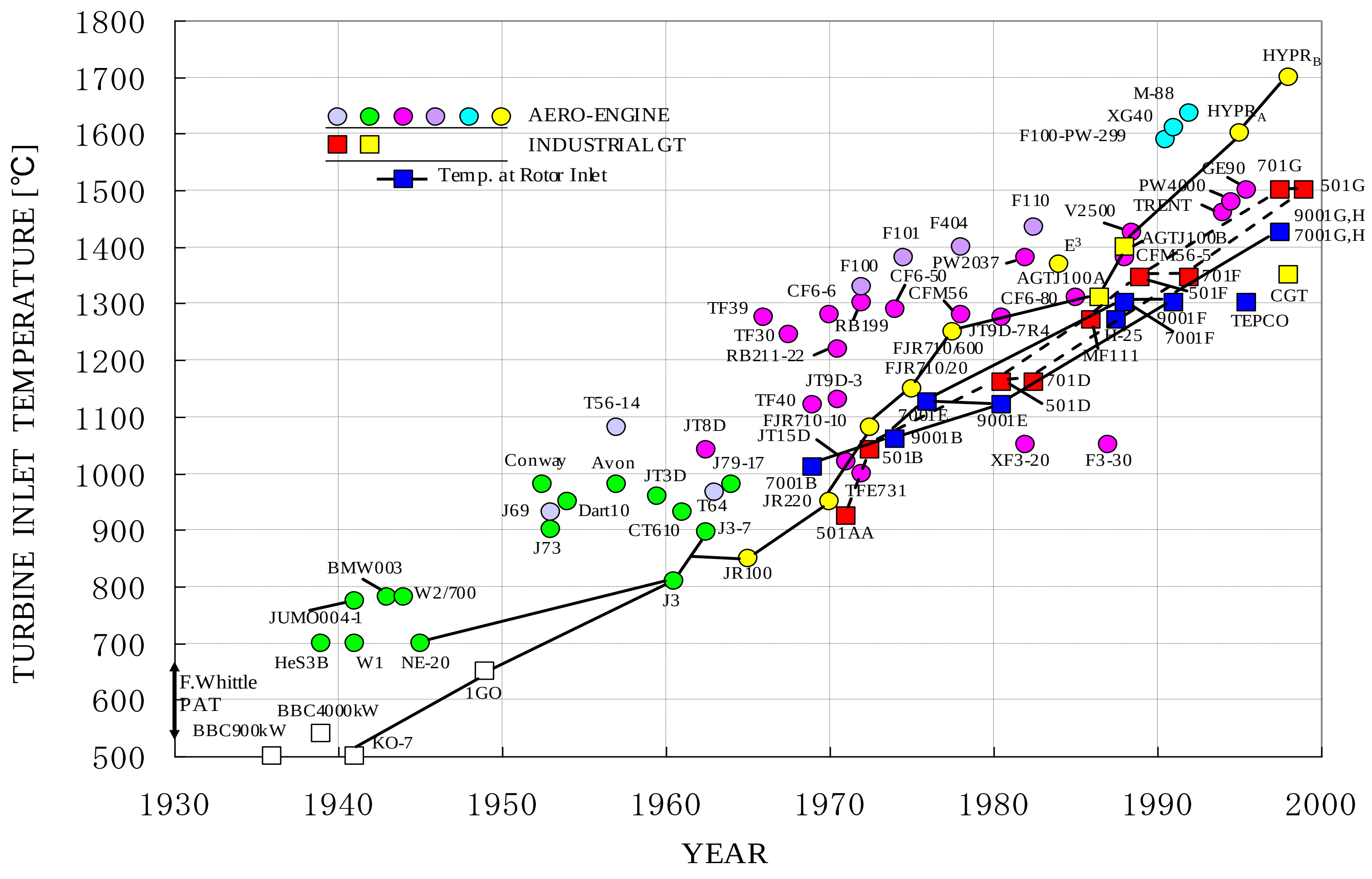
Propulsion system improvements require advances in both propulsor and core technologies



Cycle Performance Improves with Temperature

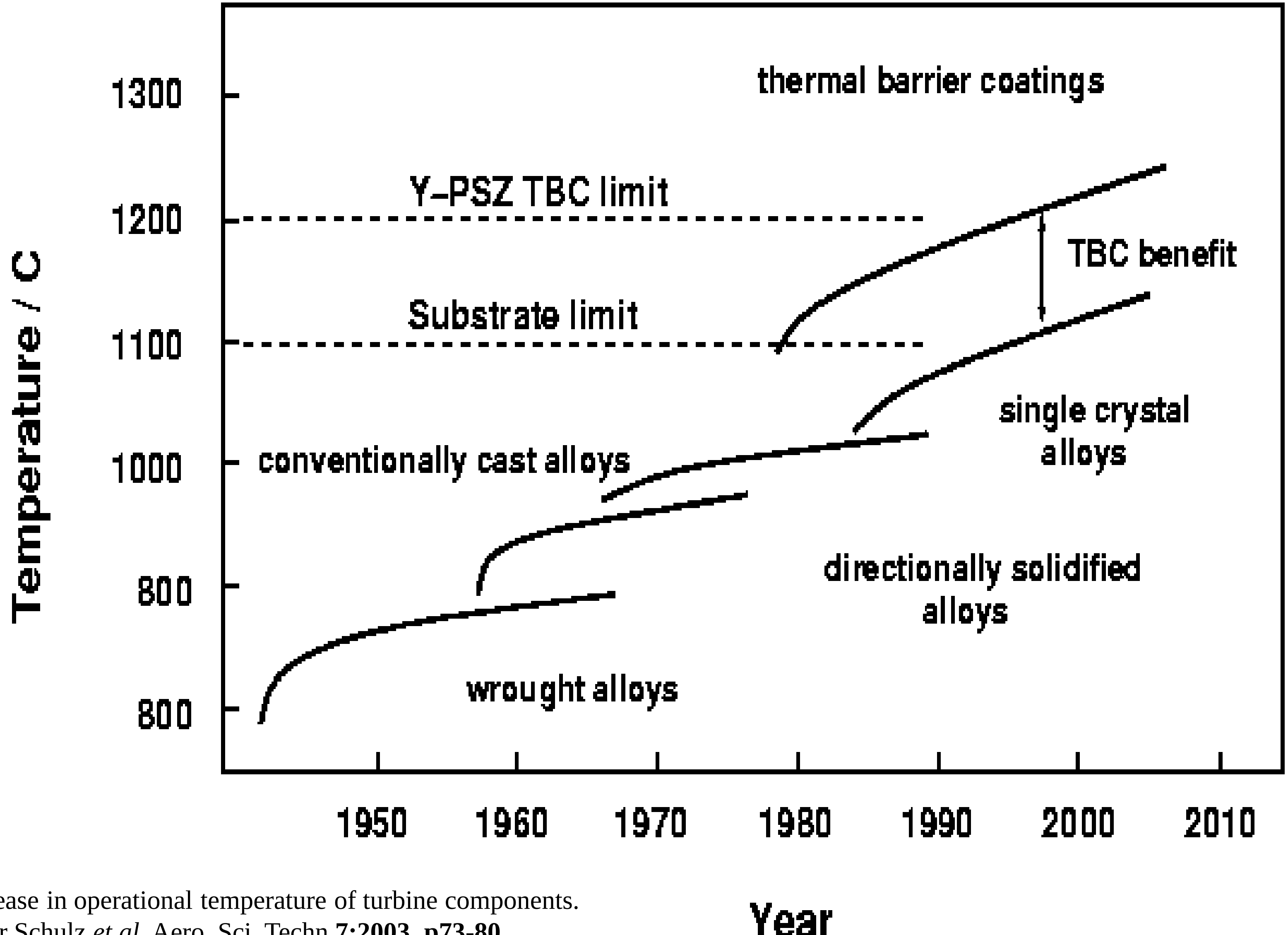


Engine Thermal Trends



From Dr. Toyoaki Yoshida, National Aerospace Laboratory, Japan

Turbine Materials Improvements



Increase in operational temperature of turbine components.
After Schulz *et al*, Aero. Sci. Techn.**7:2003, p73-80.**

Turbine Cooling Improvements

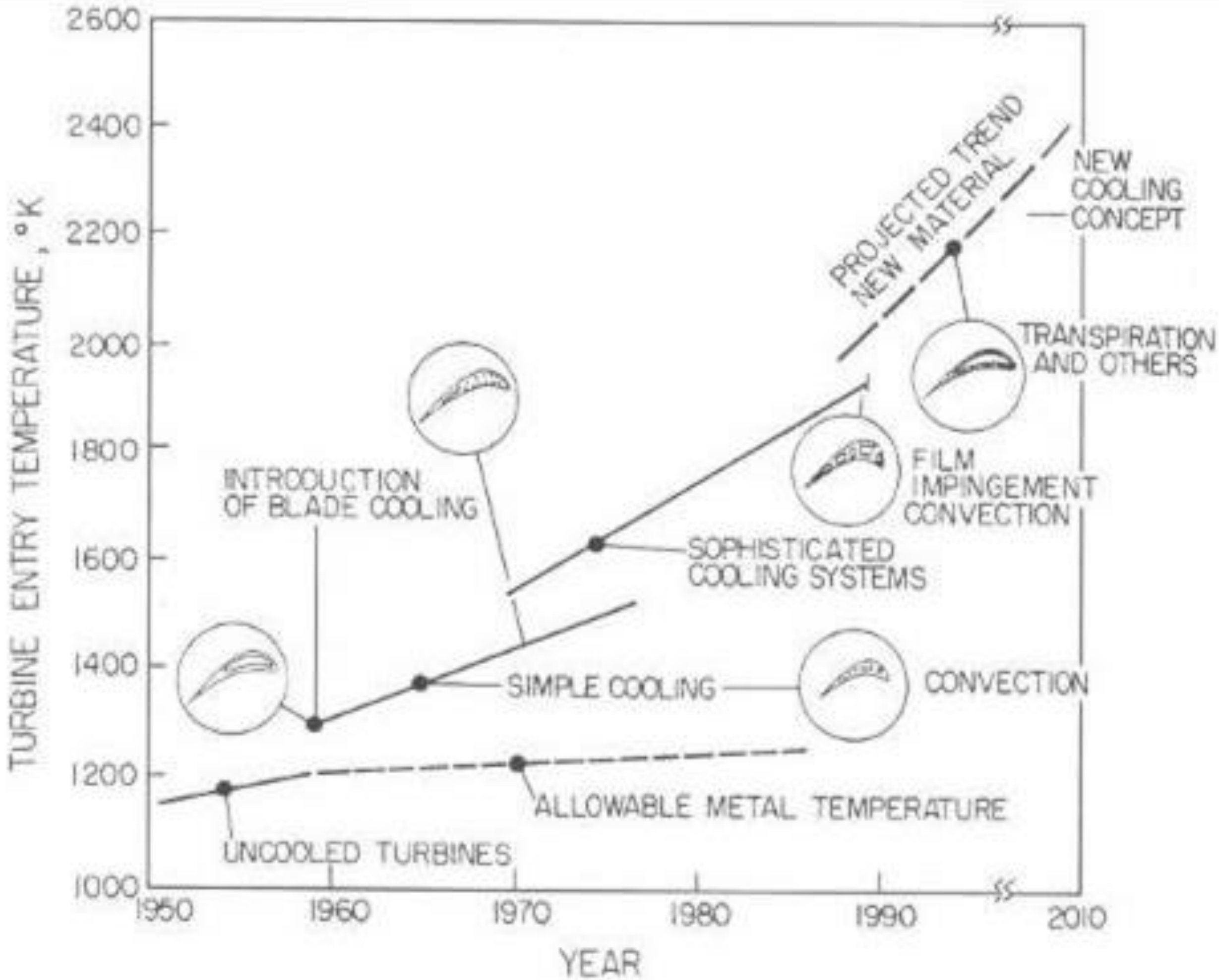
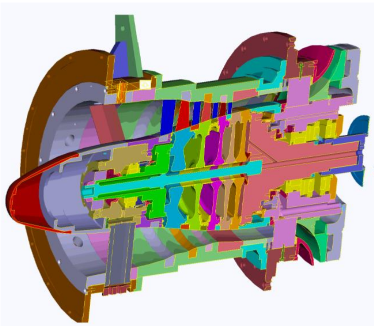


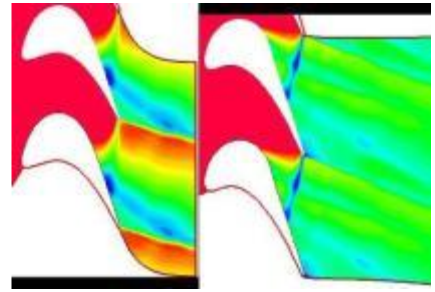
Figure 1.2: Variation of turbine entry temperature over recent years (Clifford, 1985; AGARD CP 390; collected in Lakshminarayana, 1996).

Turbomachinery Aero Design-Based Tech Enablers

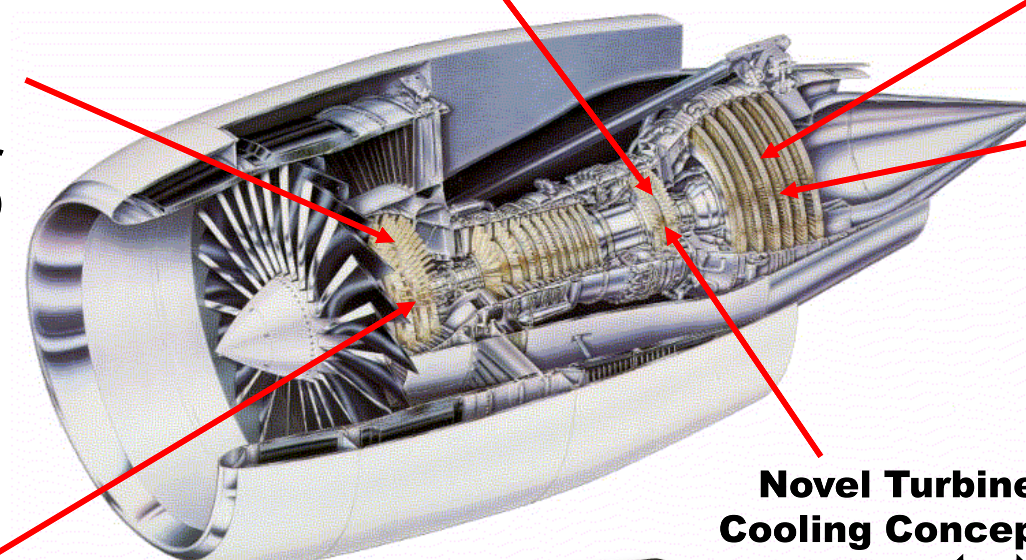


Highly-Loaded, Multistage Compressor (higher efficiency and OPR)

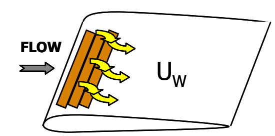
Low-Shock Design, High Efficiency, High Pressure Turbine

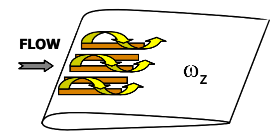


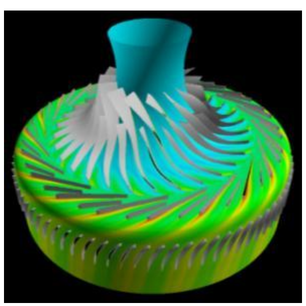
Aspiration Flow Controlled, Highly-Loaded, Low Pressure Turbine



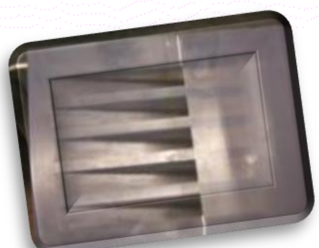
Low Pressure Turbine Plasma Flow Control







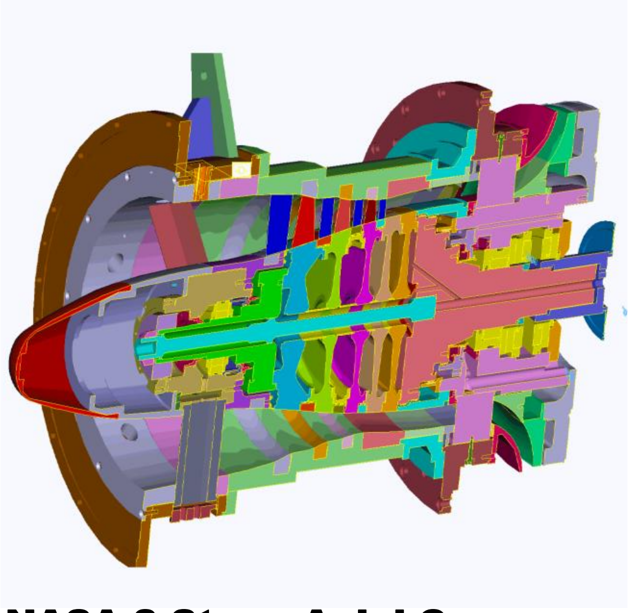
High-Efficiency Centrifugal Compressor (small high efficiency core)



Novel Turbine Cooling Concepts

Multi-Stage Axial Compressor (W7)

Objective: To produce benchmark quality validation test data on a state-of-the-art multi-stage axial compressor featuring swept axial rotors and stators. The test in ERB cell W7 will provide improved understanding of issues relative to optimal matching of highly loaded compressor blade rows to achieve high efficiency and surge margin.

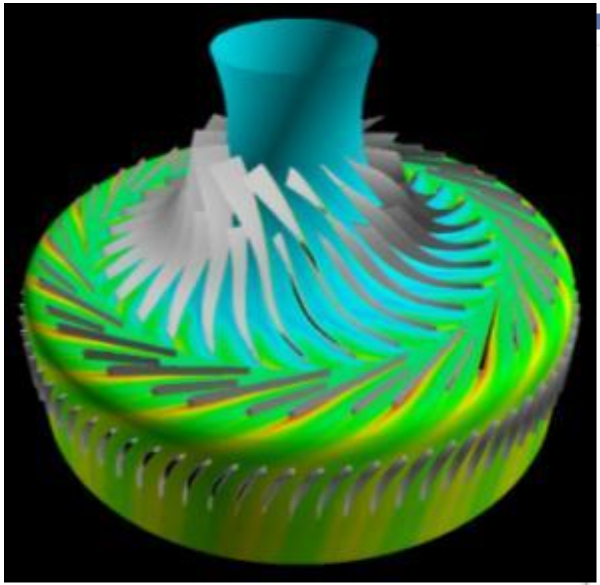


NASA 3-Stage Axial Compressor

ERB Test Cell W7

Approach:
Test a modern high OPR axial compressor representative of the front stages of a commercial engine high pressure compressor in partnership with General Electric. Test will enable improved high OPR designs for reduced engine SFC.

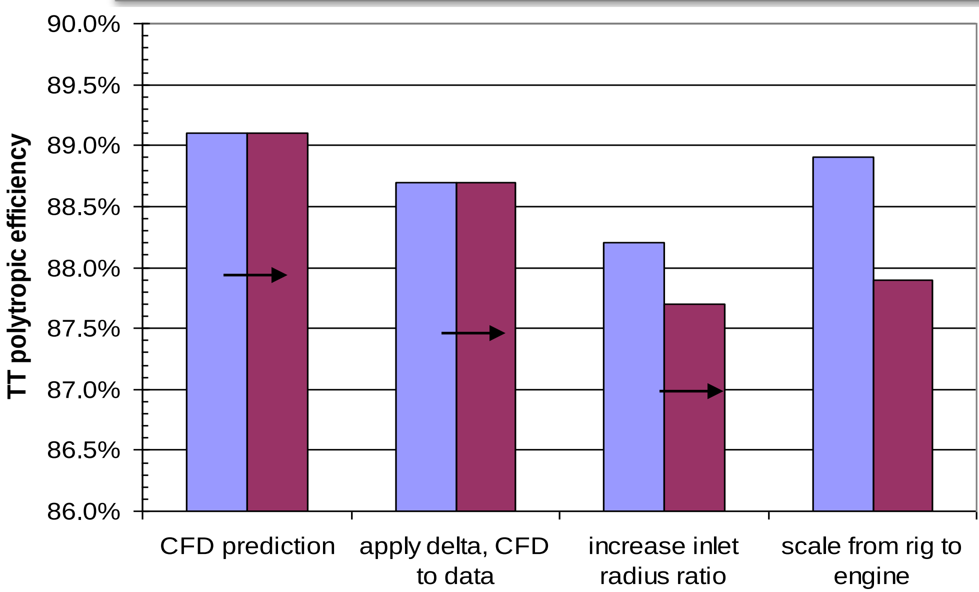
UTRC NRA – High Efficiency Centrifugal Compressor (HECC)



m = 10.1 lbm/s

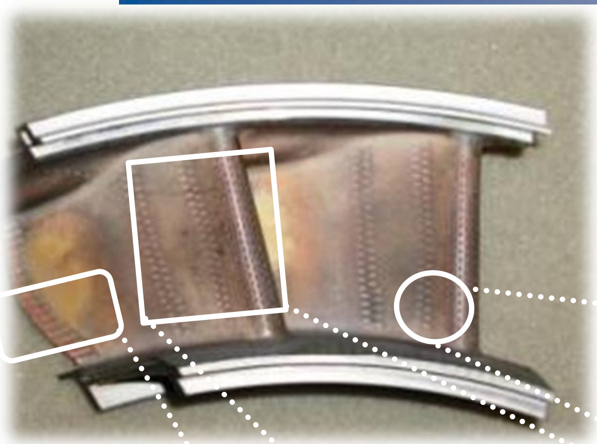
Metric	CC3+ Iteration 2	
	target	CFD predicted
Stage Pr	4.0 - 5.0	4.32
Inlet Corrected Flow (lbm/s)	10.0	10.1
Exit Corrected Flow (lbm/s)	2.6 - 3.1	2.95
Work Factor (DH_0/U_2^2)	0.58 - 0.7	0.69
Poly Eff TT	≥ 88%	89.1%
T3 (°F)	350-410	366
Dmax/Dtip	1.45	1.45
Stability Margin	13%	~13%
M_{exit}	0.15	0.15
α_{exit}	15°	14°

Opportunity for improved rotary wing vehicle engine performance as well as rear stages for high OPR fixed wing application



Engine scale polytropic efficiency is estimated as 87.9 - 88.9%

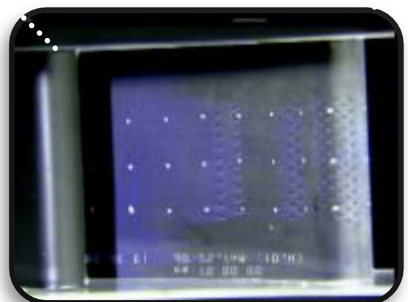
Turbine Film Cooling Experiments

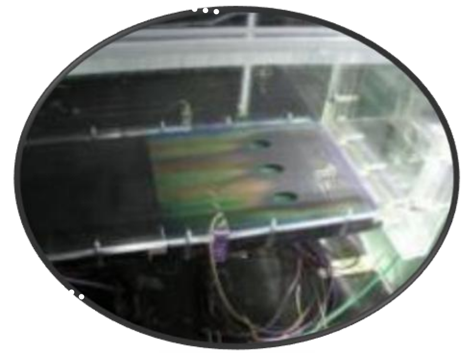


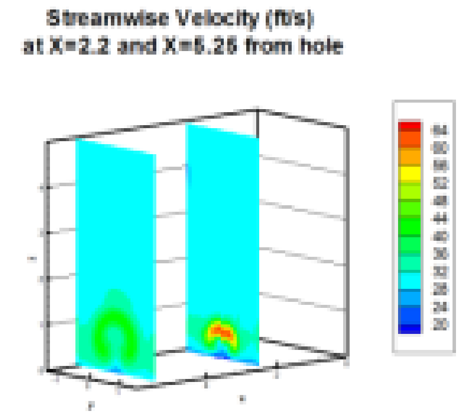
Objective: Fundamental study of heat transfer and flow field of film cooled turbine components

Rationale: Investigate surface and flow interactions between film cooling and core flow for various large scale turbine vane models

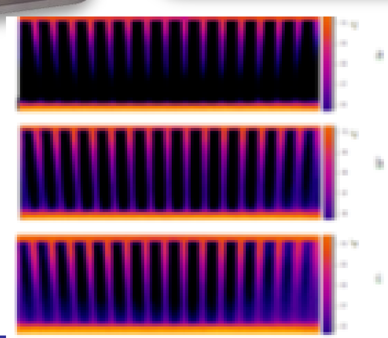
Approach: Obtain detailed flow field and heat transfer data and compare with CFD simulations







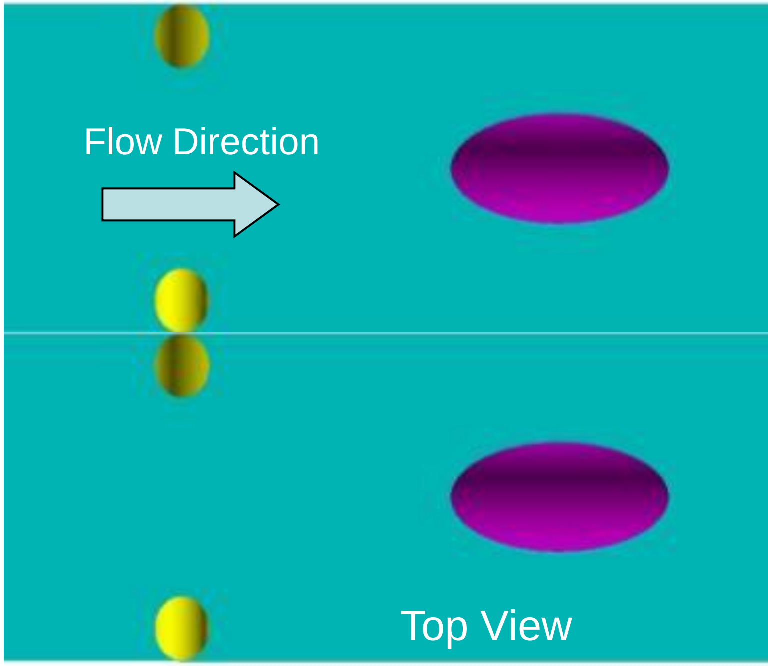
<u>Large Scale Film Hole</u>: Film cooling jet downstream of hole

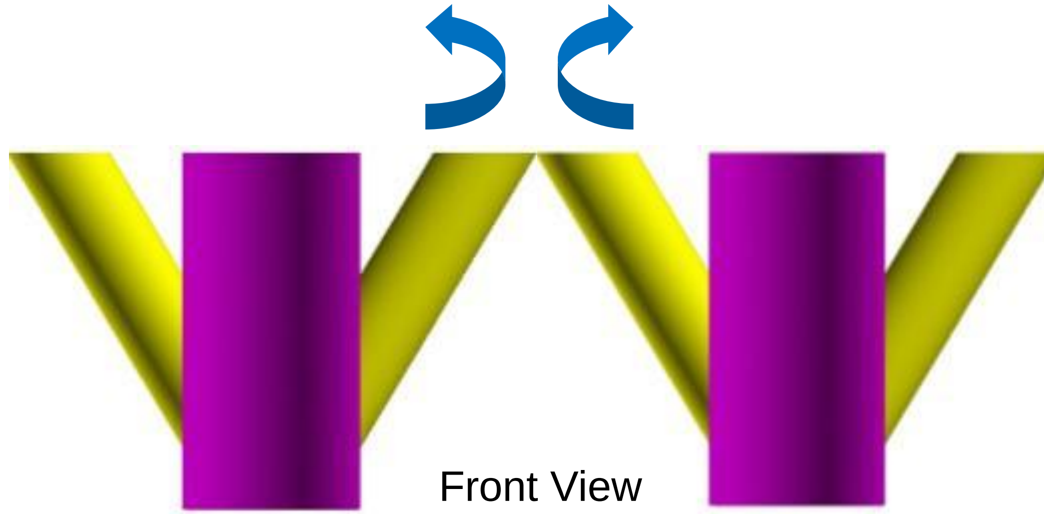


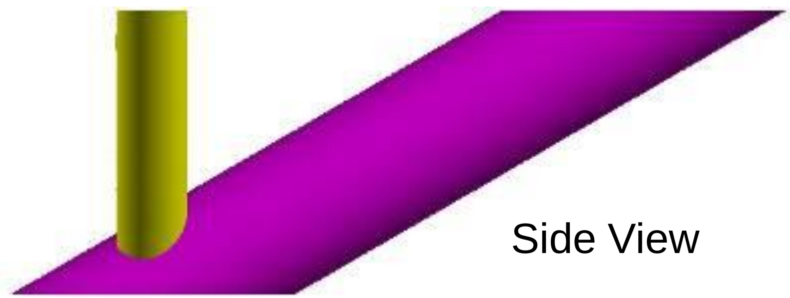
<u>Trailing Edge Film Ejection</u>: IR images

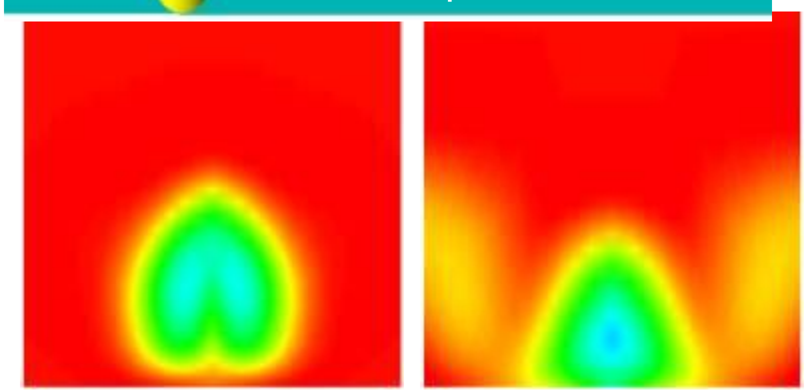
<u>Vane Heat Transfer:</u> Good agreement between GlennHT and experiment

Anti-Vortex Film Cooling Concept





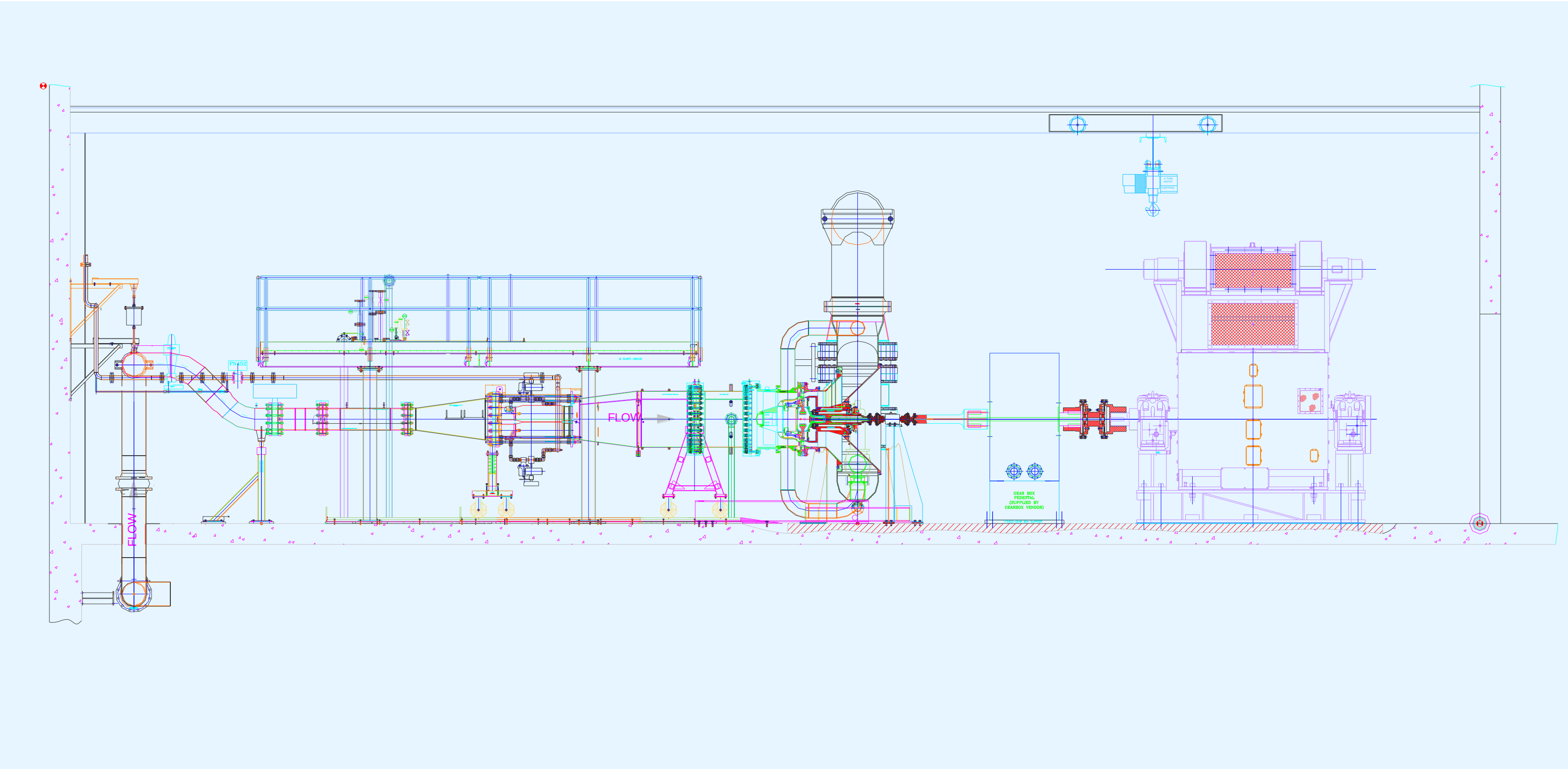




Comparison of round hole and “anti-vortex” turbine film cooling jet attachment

Auxiliary holes (yellow) produce counter-vorticity to promote jet attachment
Advantages: Inexpensive due to use of only round holes, hole inlet area unchanged

NASA/General Electric Highly-Loaded Turbine Tests

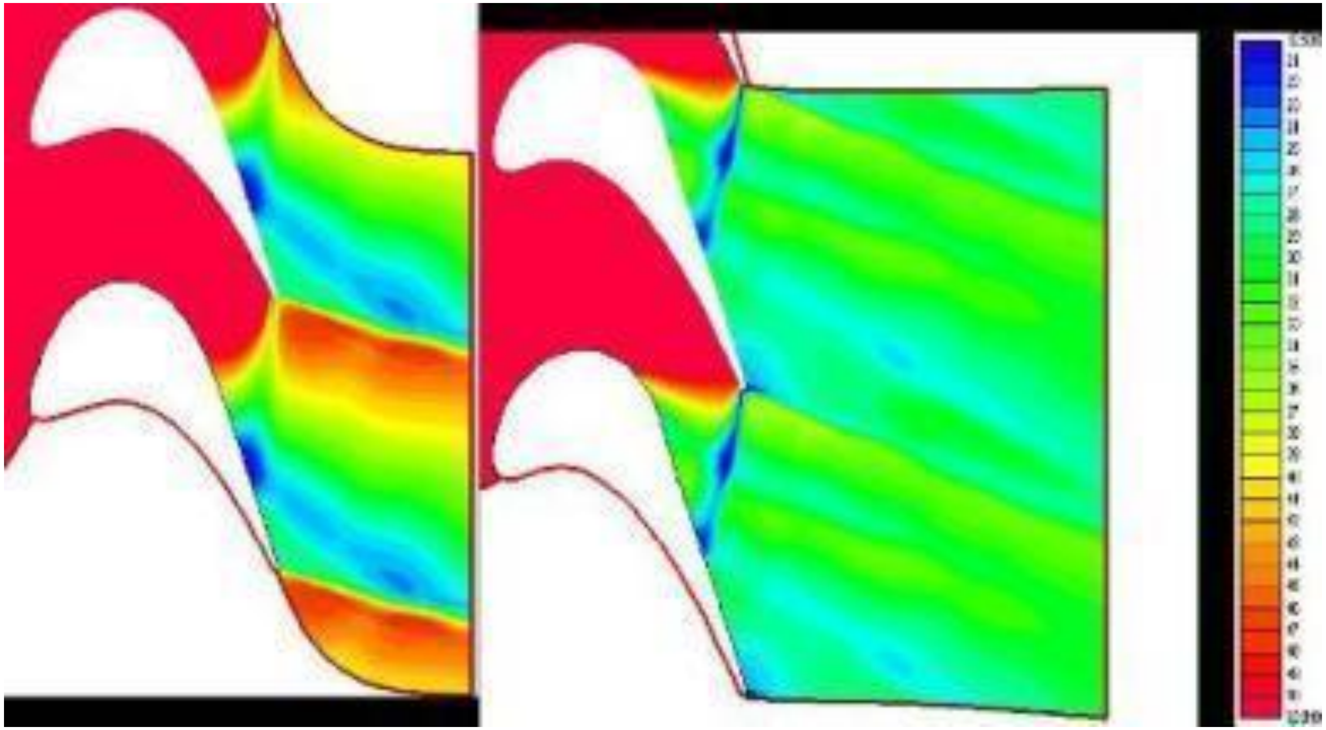


Turbine Testing in NASA Glenn Single Spool Turbine Facility (W6)

Unique High-Speed High Pressure Ratio Capability

NASA/General Electric Highly-Loaded Turbine Tests

Conventional HPT | **Reduced Shock Design**



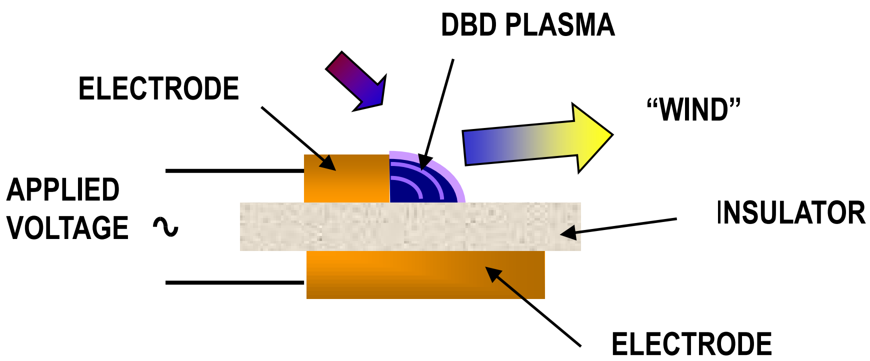
Pressure Ratio (PTR/PS) = 3.25
Stage Pressure Ratio = 5.5

HPT: Reduced Shock Design
LPT: Flow-Controlled Stator & Contoured Endwall

Enables efficient high overall pressure ratio turbine capability with reduced cooling flow and reduced SFC

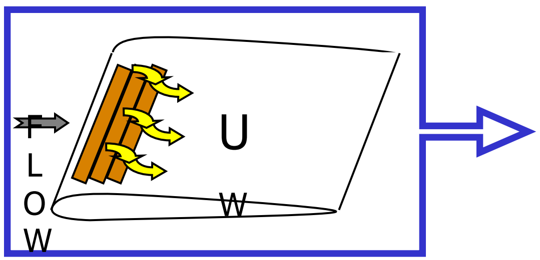
Dielectric Barrier Discharge Plasma Actuators

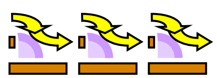
Low pressure turbine flow control – reduced weight and improved efficiency



<u>Advantages of GDP actuators:</u>

- Pure solid state device
- Simple, no moving parts
- Flexible operation, good for varying operating conditions
- Low power
- Heat resistance – w/ proper materials

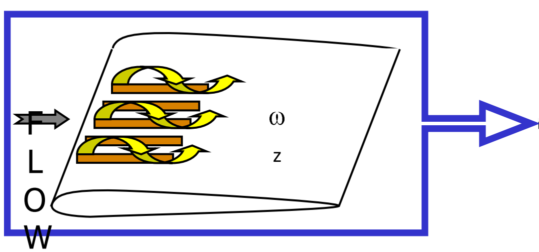




Electrode perpendicular to flow

Active Flow Control via

Oscillating wall jet

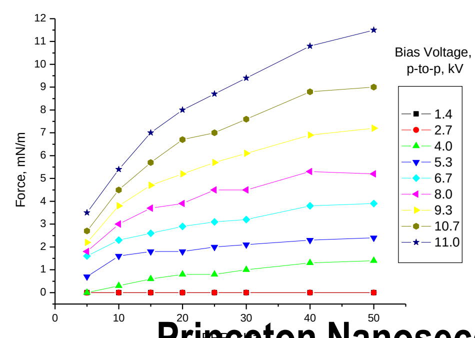


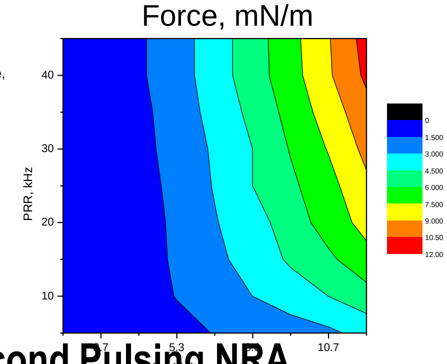
Electrode parallel to flow

Active Flow Control via

Streamwise vortices

Force Versus Pulse Repetition Rate & Bias

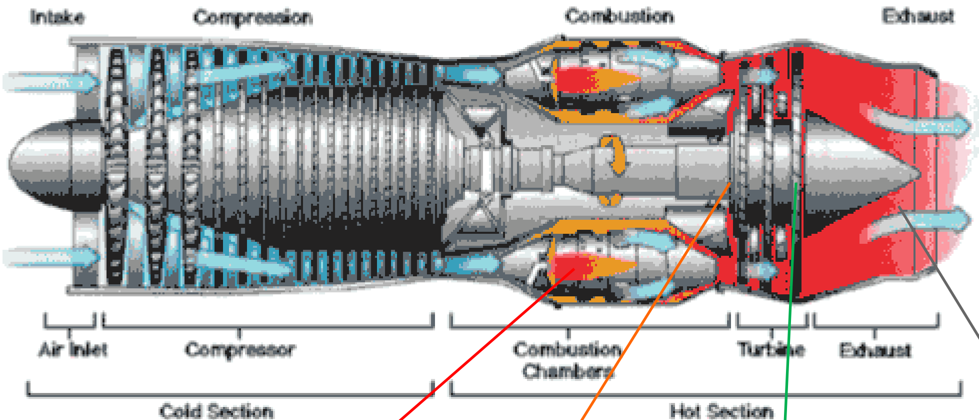




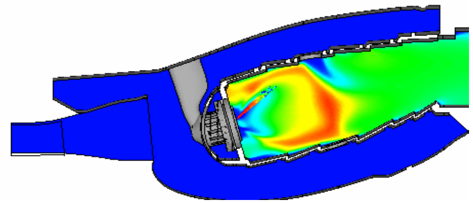
Princeton Nanosecond Pulsing NRA

Large force induced with voltage bias

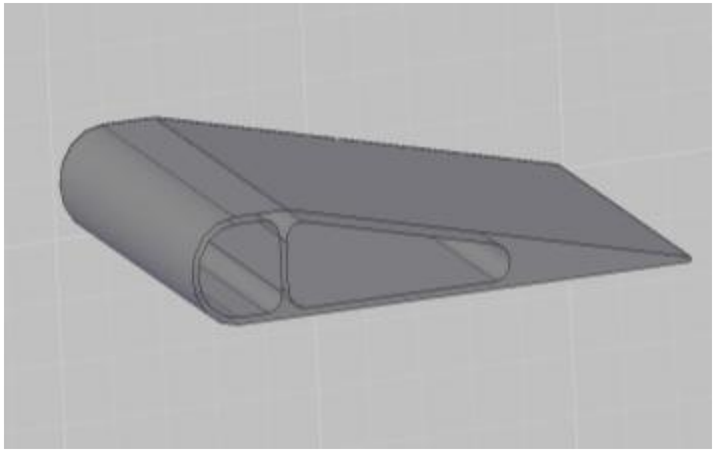
CMC Engine Components Reduce Cooling Air Requirements



	Combustor	High Pressure Turbine	Low Pressure Turbine	Exhaust Nozzle
Temperature	2200-2700°F	2400-2700°F	2200-2300°F	1500-1800°F
CMC System	SiC / SiC	SiC / SiC	SiC / SiC	Oxide / Oxide
Engine Benefit	• Reduced cooling • Reduced NOx • Pattern Factor	• Reduced cooling • Reduced SFC	• Reduced cooling • Strength / weight	• Light weight • Noise reduction • Higher use temp
Challenges	• Durability • Attachment & Integration	• Manufacturing • Durability • Attachment & Integration	• Manufacturing • Durability • Attachment & Integration	• Manufacturing • Durability

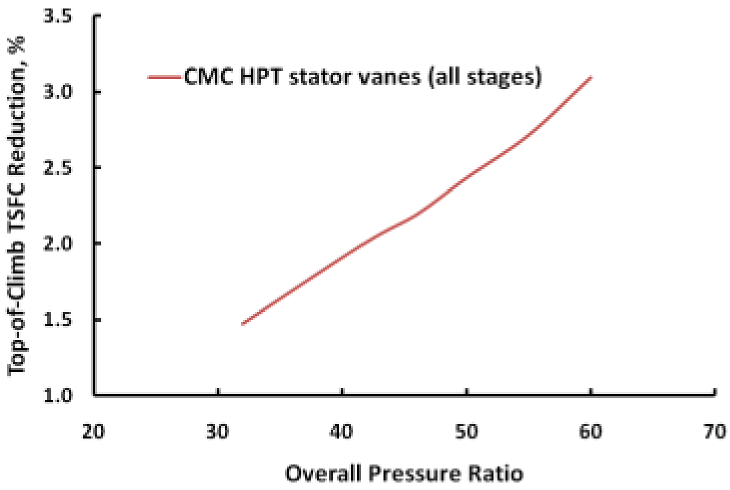


CMC Turbine Vane Reduces Fuel Burn



Prepreg lay-up assembly

- Hi-Nic type S fibers
- BN interface coatings
- Balanced ply lay-up
- 0/90^{o} tapes
- Fiber volume ~ 28%



CVI SiC with MI SiC

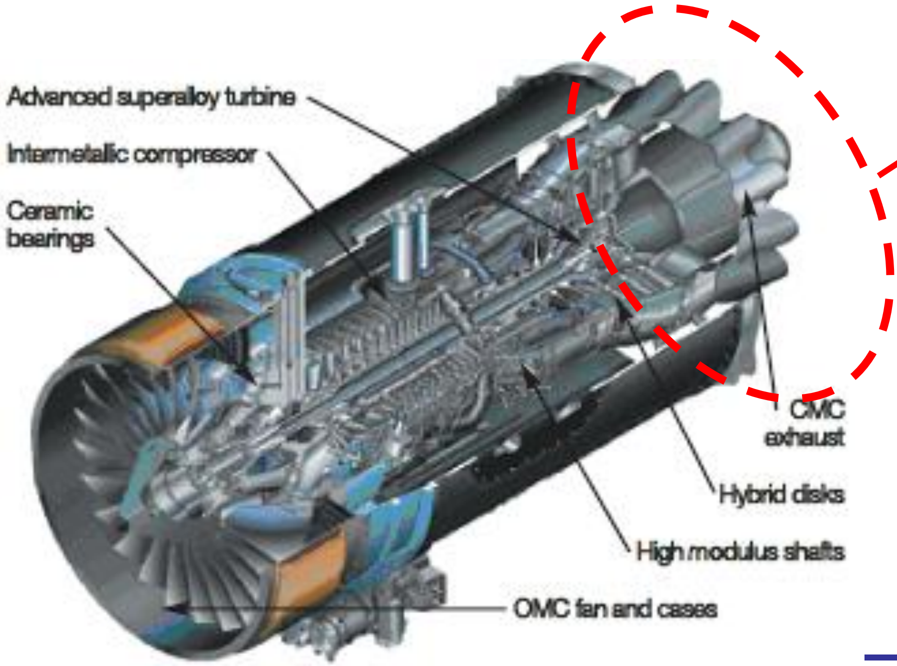
- Hi-Nic Type S fibers
- CVI BN fiber coatings
- 5 harness satin weave
- Fiber volume ~ 35%

Durability comparison of candidate CMC material systems planned for 2011

CMC Nozzle Reduces Weight, Increases Temperature Capability, Potential Noise Benefit

- NASA teaming with Rolls Royce/LibertyWorks on CMC exhaust mixer nozzle development
- Subscale aero-rig component testing (<12” dia.)
- Example of a similar article fabricated by ATK COIC shown.
- Structural benchmark testing at NASA GRC, with stress & failure model validation to follow.

18-inch dia. CMC Mixer Demonstration Article



CMC (Ceramic Matrix Composite)

- ATK COIC Oxide/Oxide CMC: AS-N610 (Aluminosilicate matrix, Nextel 610 fabric reinforcement)
- Composition: 51% fiber, 24% matrix, 25% open porosity

Core Engine Research Summary

Core turbomachinery research directly impacts fuel burn reduction goals of ERA and other NASA Aeronautics projects

Compressor research focused on increasing overall pressure ratio while maintaining or improving aerodynamic efficiency

Turbine research focused on increased loading, reduced cooling flows, and improved aerodynamic efficiency

High OPR axial compressor testing with General Electric

Centrifugal compressor testing with United Technologies Research Center

Highly-loaded HPT testing with General Electric

Fundamental testing of turbine cooling flows and low pressure turbine flow control with universities and Department of Energy

Computational fluid dynamic development and assessment across all components, including advanced turbulence models such as LES and DNS