TBCC Discipline Overview

The “National Aeronautics Research and Development Policy"[1] document, issued by the National Science and Technology Council in December 2006, stated that one (among several) of the guiding objectives of the federal aeronautics research and development endeavors shall be stable and long-term foundational research efforts. Nearly concurrently, the National Academies issued a more technically focused aeronautics blueprint, entitled: the “Decadal Survey of Civil Aeronautics - Foundations for the Future."[2] Taken together these documents outline the principles of an aeronautics maturation plan. Thus, in response to these overarching inputs (and others), the National Aeronautics and Space Administration (NASA) organized the Fundamental Aeronautics Program (FAP), a program within the NASA Aeronautics Research Mission Directorate (ARMD). The FAP initiated foundational research and technology development tasks to enable the capability of future vehicles that operate across a broad range of Mach numbers, inclusive of the subsonic, supersonic, and hypersonic flight regimes.

The FAP Hypersonics Project concentrates on two hypersonic missions: (1) Air-breathing Access to Space (AAS) and (2) the (Planetary Atmospheric) Entry, Decent, and Landing (EDL). The AAS mission focuses on Two-Stage-To-Orbit (TSTO) systems using “air-breathing” combined-cycle-engine propulsion; whereas, the EDL mission focuses on the challenges associated with delivering large payloads to (and from) Mars. So, the FAP Hypersonic Project investments are aligned to achieve mastery and intellectual stewardship of the core competencies in the hypersonic-flight regime, which ultimately will be required for practical systems with highly integrated aerodynamic / vehicle and propulsion / engine technologies. Within the FAP Hypersonics, the technology management is further divided into disciplines including one targeting Turbine-Based Combine-Cycle (TBCC) propulsion. Additionally, to obtain expertise and support from outside (including industry and academia) the hypersonic uses both NASA Research Announcements (NRA’s) and a jointly sponsored, Air Force Office of Scientific Research and NASA, National Hypersonic Science Center that are focused on propulsion research. Finally, these two disciplines use selected external partnership agreements with both governmental agencies and industrial entities.

The TBCC discipline is comprised of analytic and experimental tasks, and is structured into the following two research topic areas: (1) TBCC Integrated Flowpath Technologies, and (2) TBCC Component Technologies. These tasks will provide experimental data to support design and analysis tool development and validation that will enable advances in TBCC technology

National Aeronautics and Space Administration

TBCC Discipline Overview

Hypersonics Project

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2011 Technical Conference
March 15-17, 2011
Cleveland, OH

OUTLINE

- Benefits of TBCC Propulsion
- Technical Challenge
- TBCC Discipline Roadmap
- Technology Approach
- Combined Cycle Engine Large Scale Inlet Mode Transition Experiment (CCE LIMX) in NASA GRC 10X10 SWT
- Integrated Flowpath Computational Efforts
- High Mach Fan Rig Testing in NASA GRC W8 Compressor Facility
- Component Technology Computational Efforts
- High Mach Turbine Engine Development
- Summary and Concluding Remarks

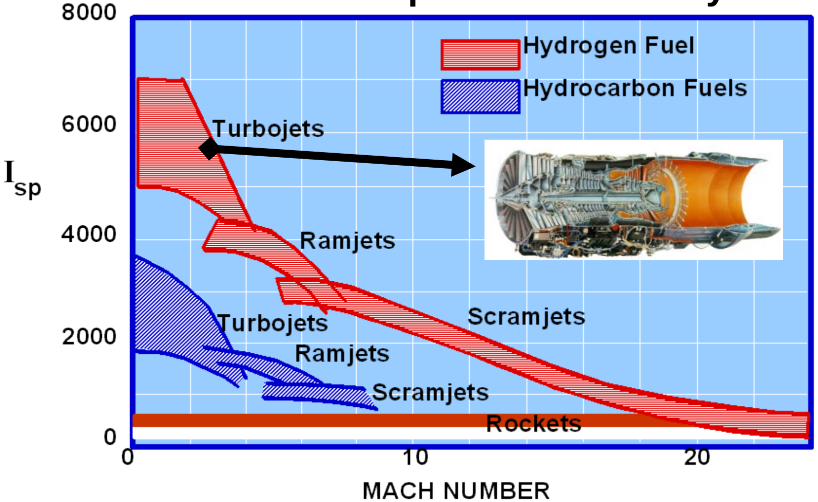
TBCC Propulsion Benefits : Efficiency, Safety, Reliability

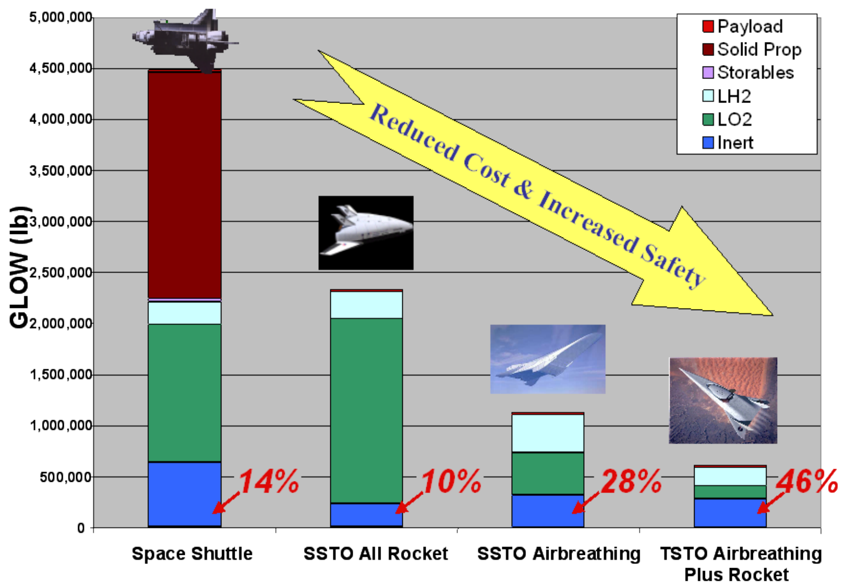
- **High structural mass fraction providing large margins**
  - ✓ **Design for life – Low Maintenance & High Durability**
  - ✓ **Design for safety**
  - ✓ **Re-usable> 1000 missions**

- **Horizontal takeoff and landing enhances launch, flight and ground operability**
  - ✓ **Benign ascent abort/engine out**
  - ✓ **Launch Pad not needed**
  - ✓ **Flexible Operations & Quick Turn Around Time (Aircraft Like Operations)**

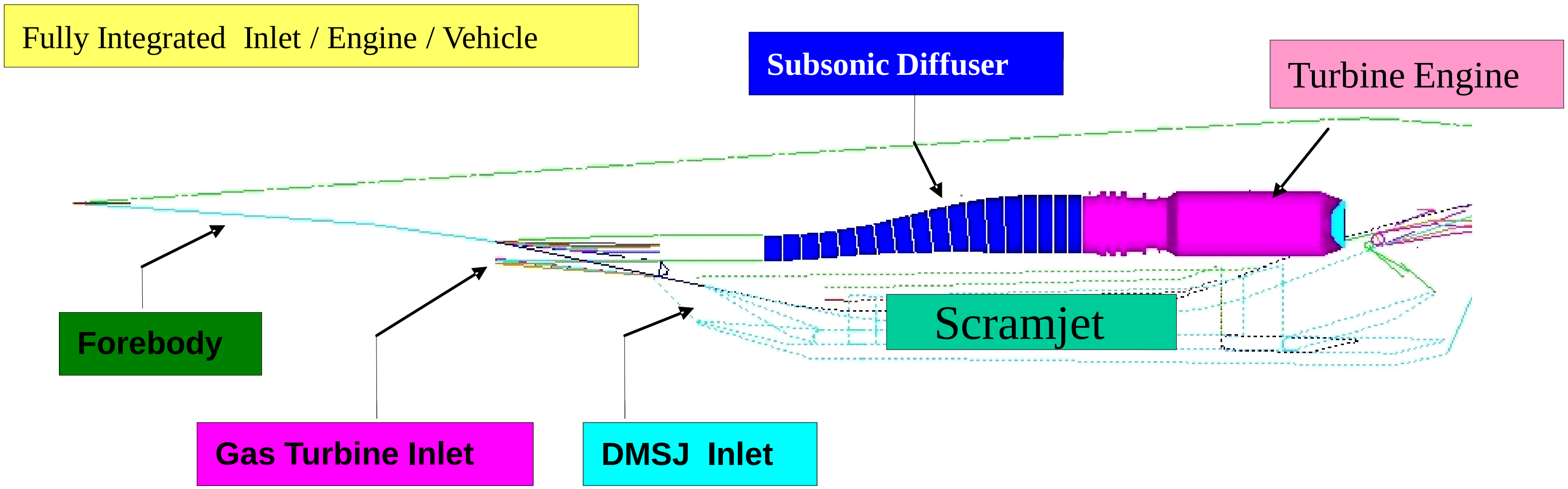
I_{SP} = Thrust/Pound per second of propellant (fuel) flow rate

Airbreathing Propulsion Significantly Increases Propulsion Efficiency



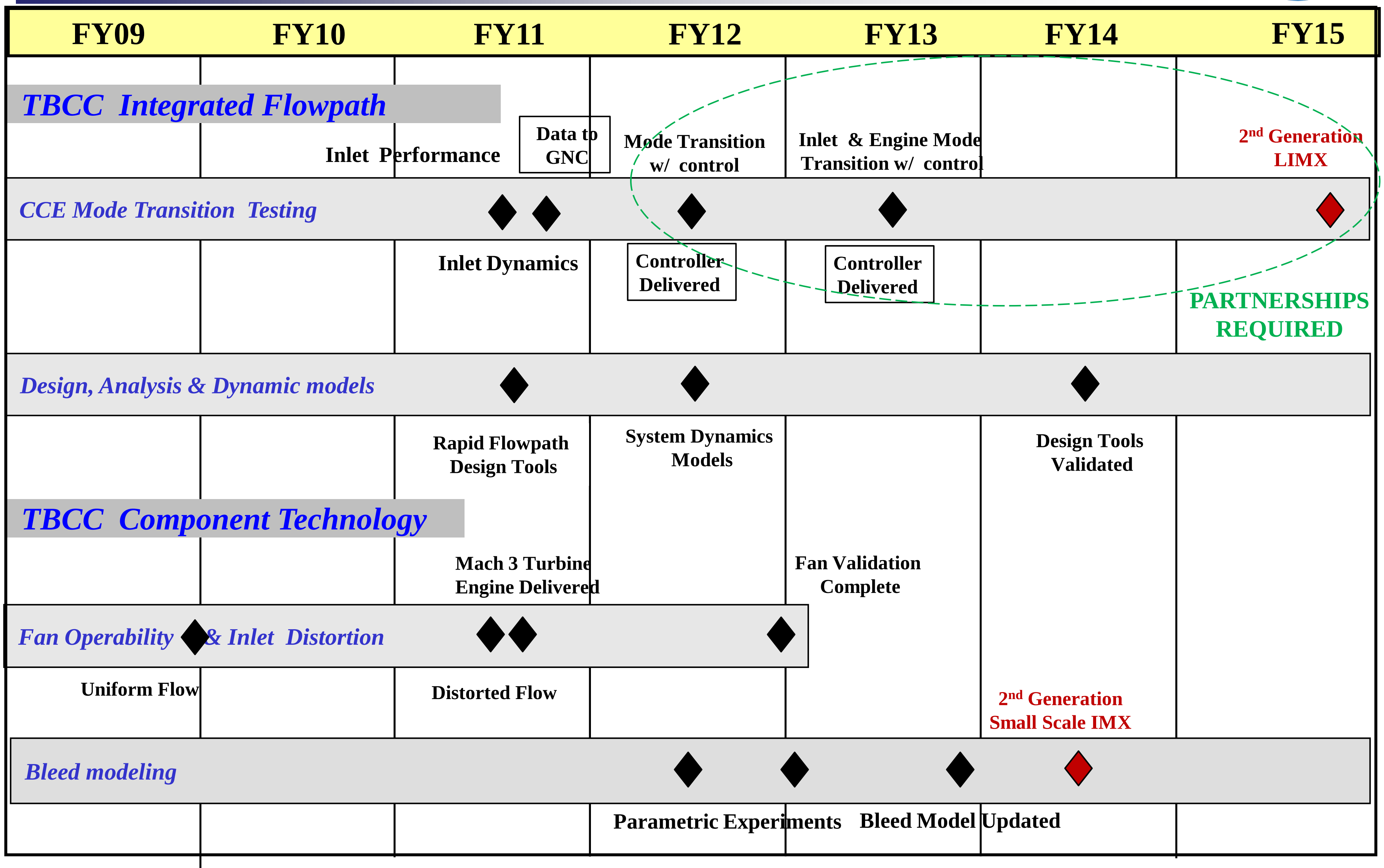


Technical Challenge: Develop Airbreathing Turbine Based Combined Cycle Propulsion for TSTO Vehicles



- **Develop Integrated TBCC Propulsion Technology – Inlet, High Mach Turbine Engine, Dual Mode Scramjet , Nozzle**
- **Establish a stable mode transition process while maintaining Propulsion System performance & operability**
- **Perform a stable controlled mode transition**
- **Avoid inlet and/or engine unstart**
- **Mitigate low/high speed inlet/engine interactions.**
- **Account for backpressure and cowl positioning effects.**
- **Develop, Validate, & Utilize design tools to optimize the configuration**

TBCC Discipline Roadmap



TBCC Technology Approach

Propulsion
M & S
GNC

Supporting Disciplines

Integrated Propulsion System Design & Analysis Tools

Validated Tools

MDAO

Partnerships & Collaboration

- **AFRL/Aerojet TBCC inlet tests**
- **DARPA/AFRL Facet / MoTr, et al**
- **RATTLRS - inlet /controls**
- **AFRL/ WI High Mach Turbine**

Ground Experiments

CCE LIMX Testing in the GRC 10x10 SWT (4 phases)

High Mach Fan Rig testing in GRC W8 Compressor Facility

Inlet Bleed Studies in GRC 15X15 cm & 1X1 ft SWT facility

Integrated Flowpath: Computational Efforts

CCE Low Speed Flowpath

CCE High Speed Flowpath & Isolator

Component Technologies: Computational Efforts

High Mach Turbine CFD Analysis

High Mach Turbine Integrated Inlet/ Fan Analysis

NRA's

Techland: Mode Transition Strategies for TBCC inlets

Boeing: Flowpath Integration for TBCC Propulsion Systems

Spiritech: TBCC Dynamic Simulation Model Development

Combined Cycle Engine Large Scale Inlet Mode Transition Testing NASA GRC 10X10 SWT

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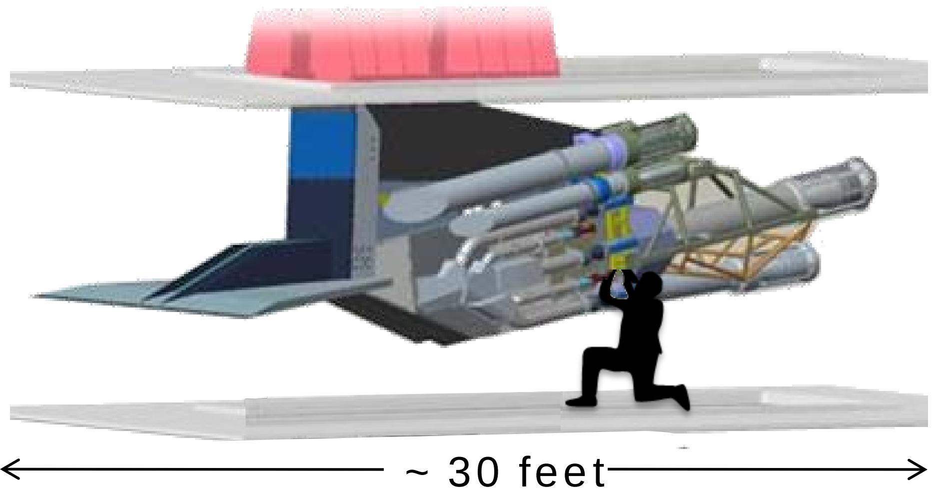
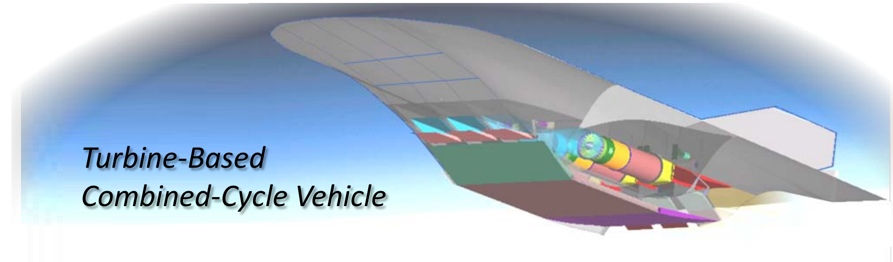
Integrated Flowpath Computational Efforts

CCE Inlet and Controls research in the GRC 10x10 SWT
Supported by both TBCC and GNC Disciplines





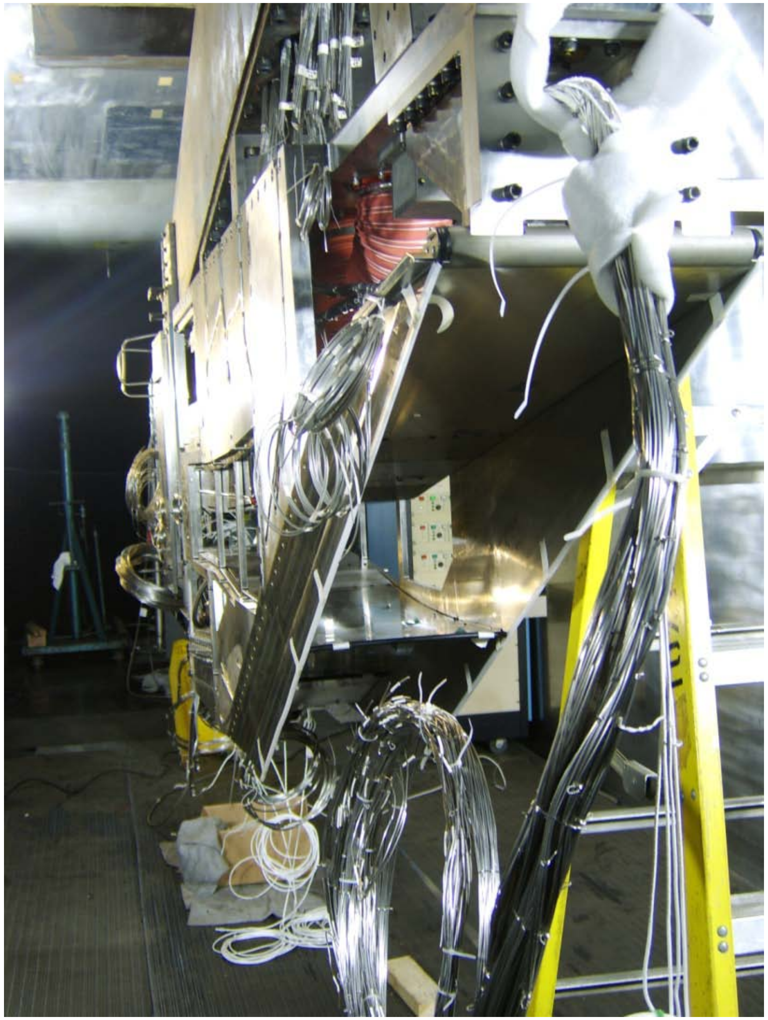
Testbed Features

- Variable Low Speed Cowl
- Variable High Speed cowl
- Variable Ramp
- Variable Compartmented Bleed (13)
- Low Speed Mass flow / Backpressure Device
- High Speed Mass flow / Backpressure Device
- Inlet Performance Instrumentation (~800)
- Engine Face: Flow Characteristics (AIP)

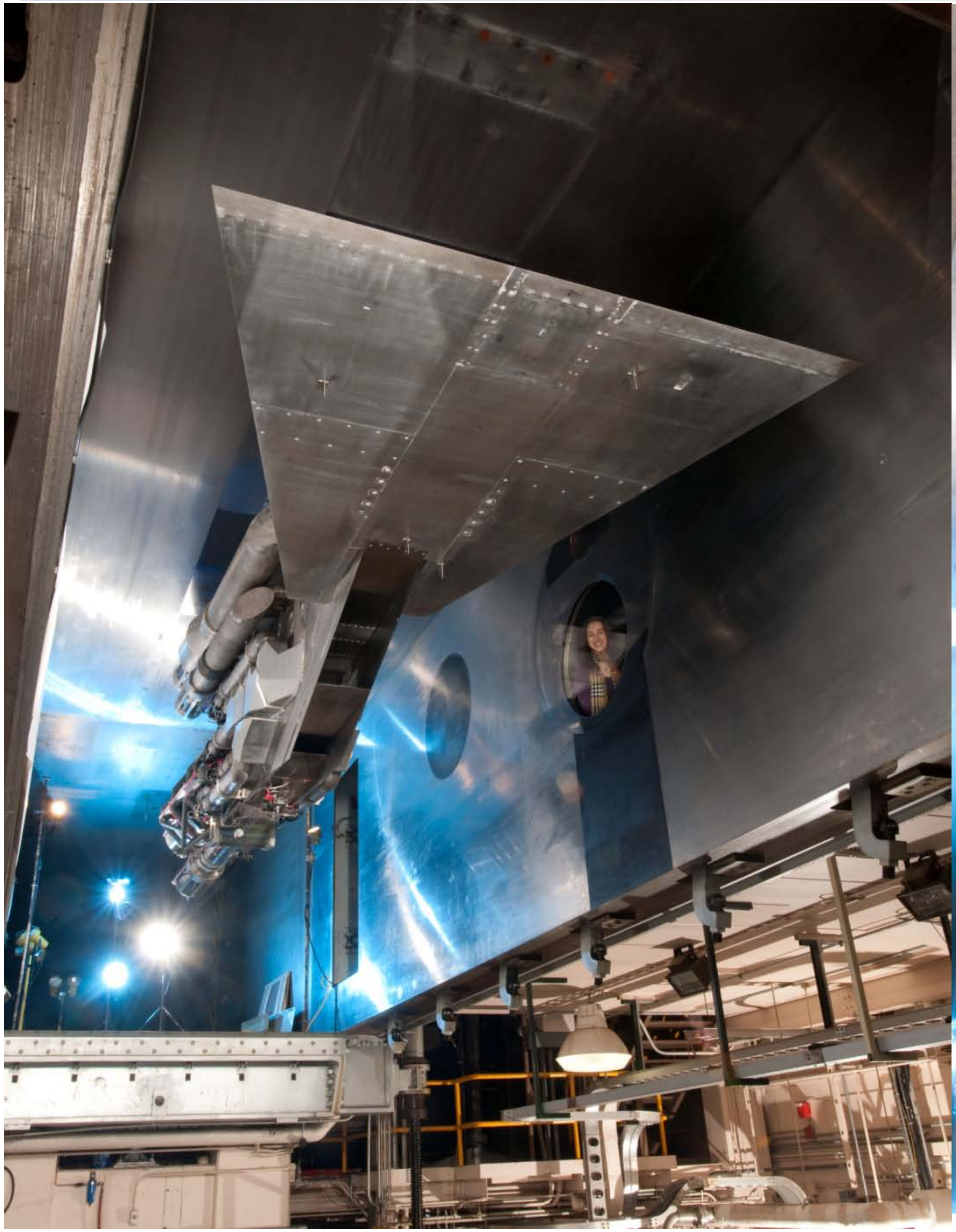
Test Approach - 4 Phases

1. Inlet performance and operability characterization, Mode Transition Sequencing
2. System Identification of inlet dynamics for controls
3. Demonstrate Control strategies for smooth & stable mode transition without inlet unstart
4. Add turbine engine/ nozzle for integrated system test with simulated Scramjet

CY10 - CCE LIMX Build-up and Installation



CCE LIMX Installed in NASA 10X10 SWT
(Phase I - Testing On-Going- Status next Presentation)

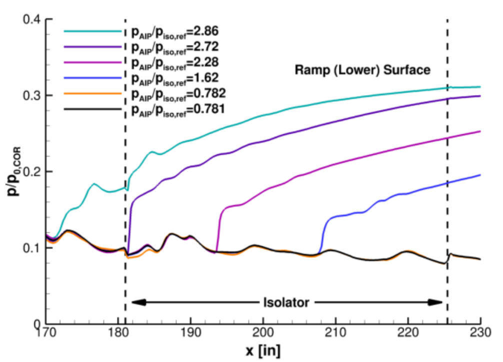


CCE LIMX CFD Effort

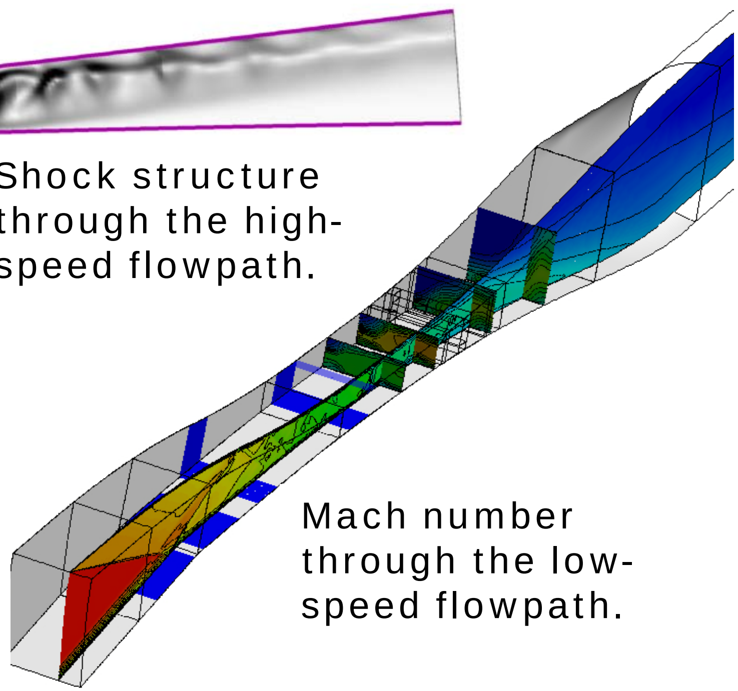
Objectives of Pre-Test LIMX CFD Analyses:

- Characterize the turbulent boundary layers and shock waves within the low and high-speed flowpaths under back-pressure.
- Evaluate performance of the low-speed flowpath as characterized by bleed and engine flow rates and total pressure recovery.
- Evaluate the total pressure distortion at the turbofan face.
- Evaluate the effectiveness of porous bleed and vortex generators.
- Explore sensitivities to variations in low-speed ramp angle and back-pressure for development of inlet controls.

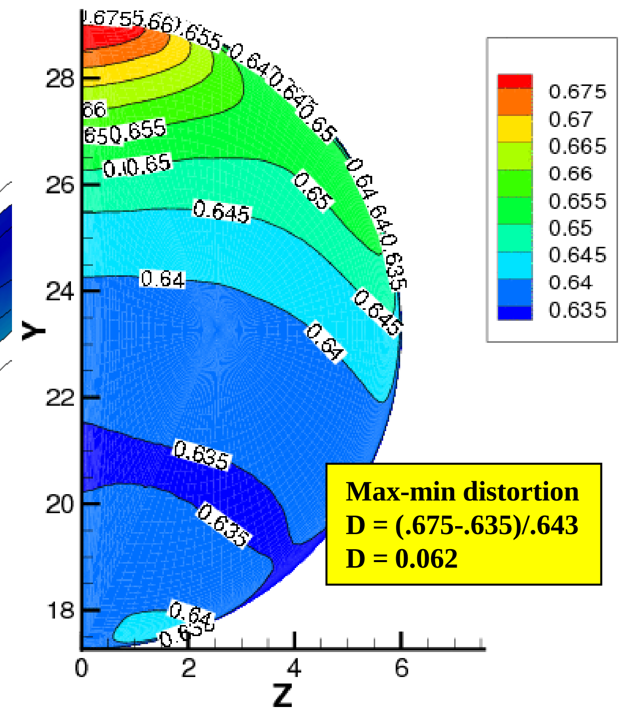
Shock structure through the high-speed flowpath.



Variation in static pressure with back-pressure in the high-speed flowpath.



Mach number through the low-speed flowpath.



Total pressures distortion at the engine face.

Bleed Modeling

Elements of Modeling:

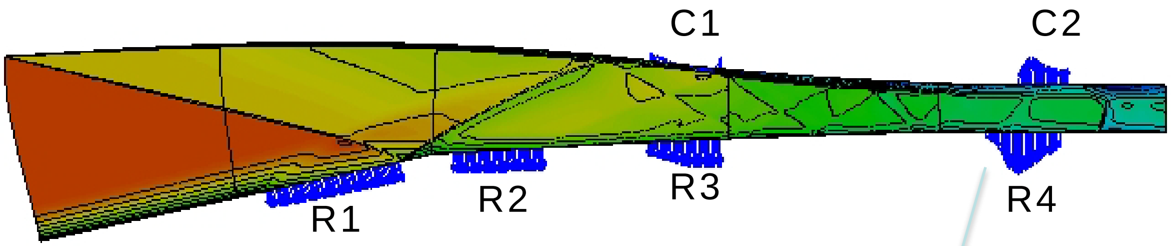
- The low-speed flowpath of the LIMX incorporates 13 separate porous bleed regions to minimize adverse effects of the shock / turbulent boundary layer interactions.
- Bleed rates may vary over the bleed region in response to shock waves within the flow field.
- Modeling evaluates bleed rates and bleed plenum pressures based on local flow conditions and plenum exit conditions (fixed-area, choked exits).

Computational Efforts:

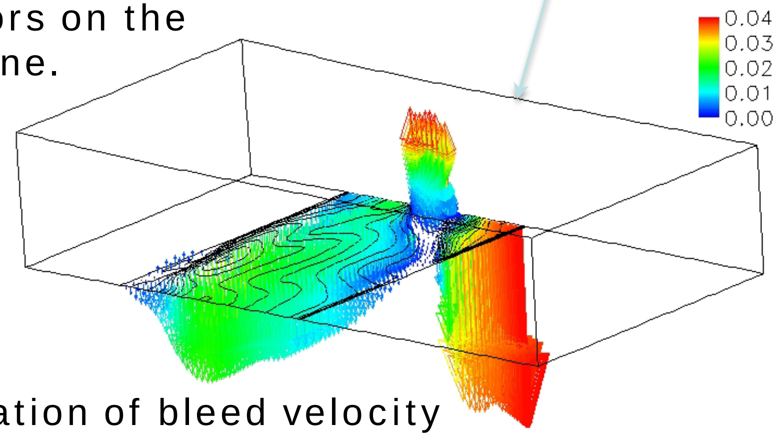
- Models incorporated into Wind-US and BCFD for LIMX simulations.
- Models incorporated into PEPSI-S PNS solver.

Experimental Efforts:

- Test of bleed holes in 15x15 cm supersonic wind tunnel facility in FY11.
- CCE LIMX testing in 10x10 ft facility in FY11.
- CCE IMX testing in 1x1 ft facility with variable bleed regions.



Mach number and bleed velocity vectors on the symmetry plane.



Variation of bleed velocity vectors in the R4 bleed region.

High Mach Fan Rig Testing
NASA W8 Compressor Facility

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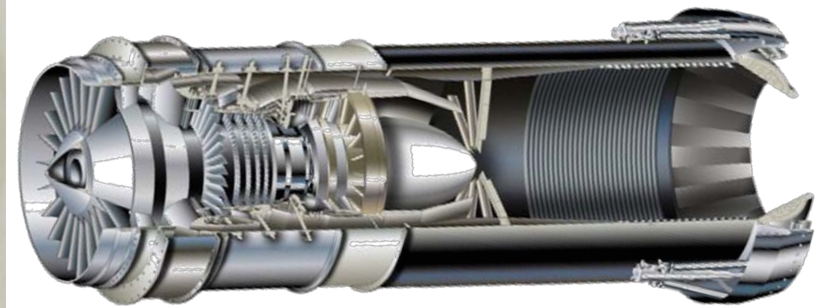
Component Technology Computational Efforts

TBCC Fan Stage Operability and Performance

Fan Rotor Blisk

Inlet Distortion Screens

RTA: GE 57 / NASA Mach 4 capable TBCC Engine

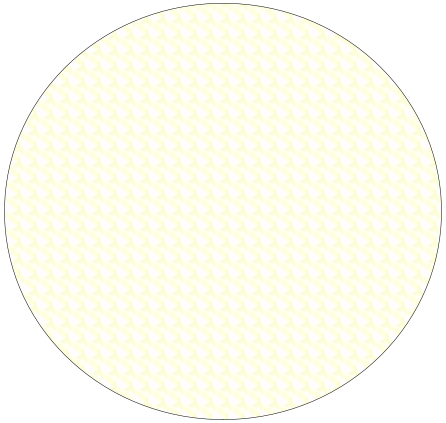


FAN STAGE = Rotor + OGV + Fan Frame Strut

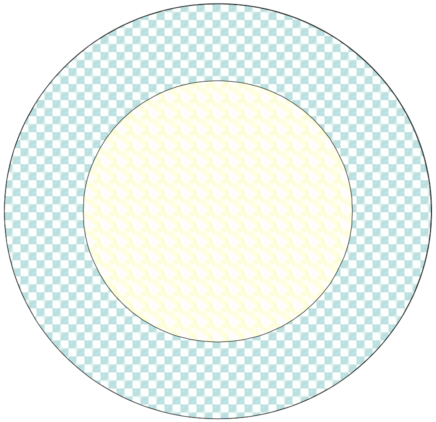
Approach:

- Perform sub-scale testing of a relevant Mach 4 turbine engine fan stage in the NASA W8 high speed compressor facility.
- Predict performance & operability prior to test using SOA analysis tools.
- Map fan stage performance and measure stall line stability boundary over wide range of engine operation and compare to pre-test predictions.
- Incorporate inlet distortions and quantify performance & operability
- Assess the capability of SOA tools to predict results with flow distortions
- Utilize test article to understand physics and improve models.

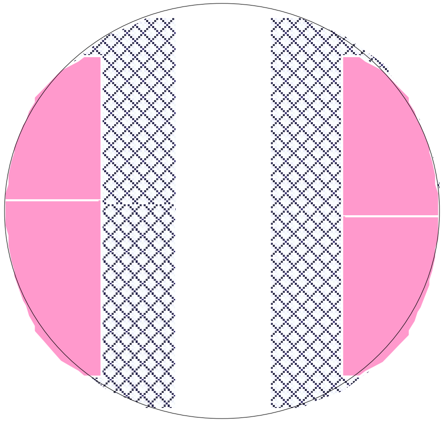
High Mach Fan Rig Test Distortion Screens



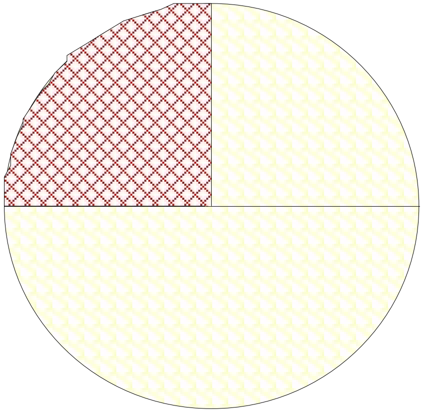
Uniform Flow



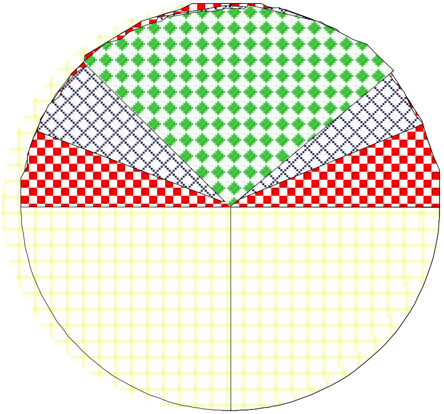
Distortion Screen #2
Circumferential



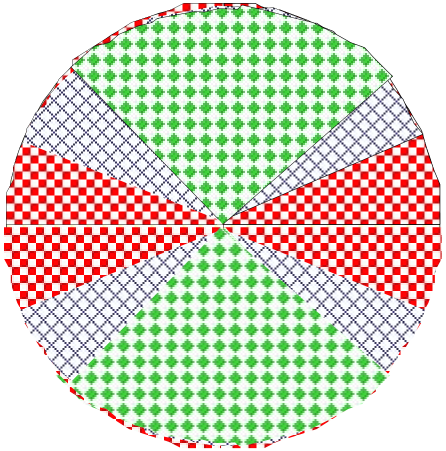
Distortion Screen #4
Based on CCE CFD #1



Distortion Screen #1
Sector



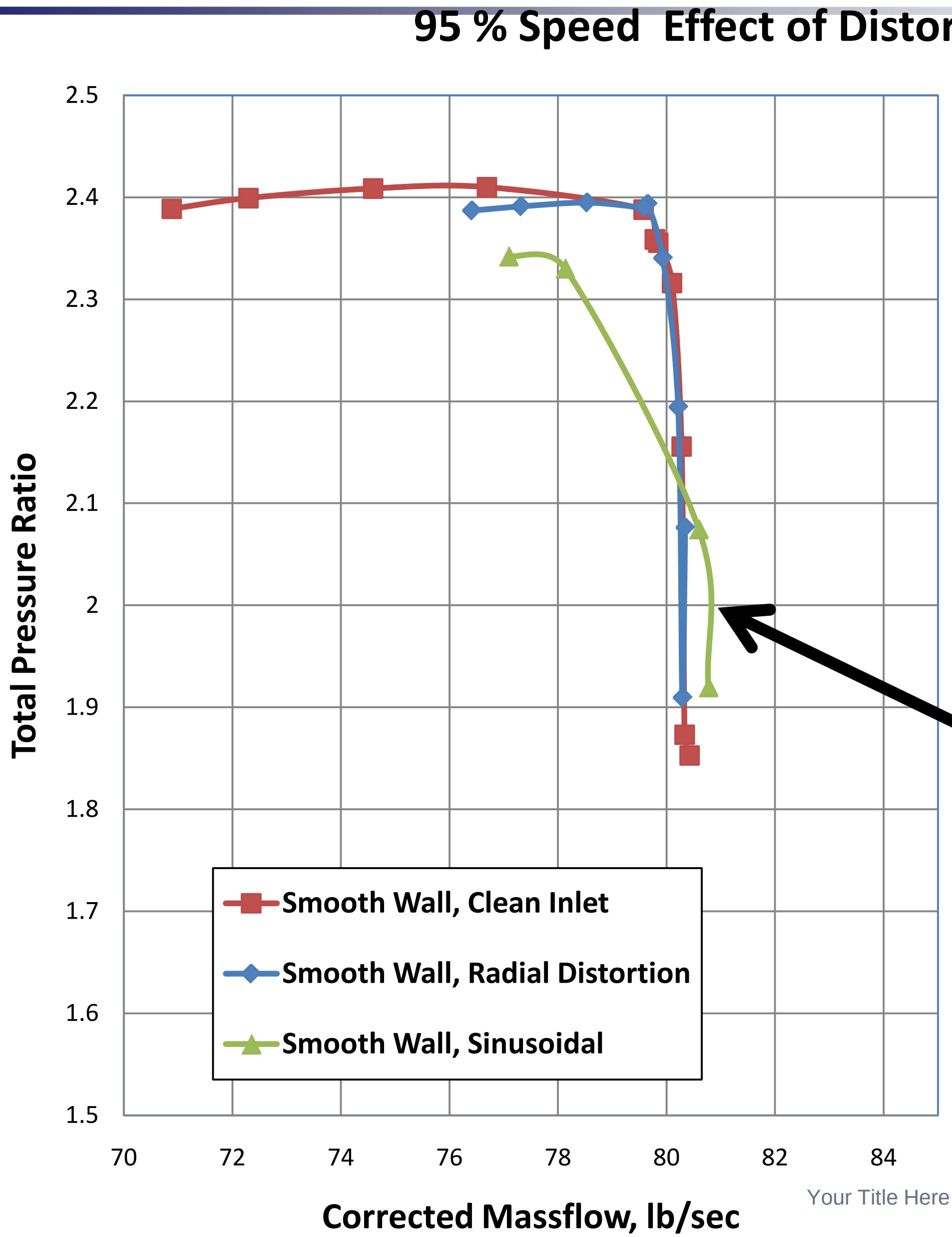
Distortion Screen #3
Sinusoidal

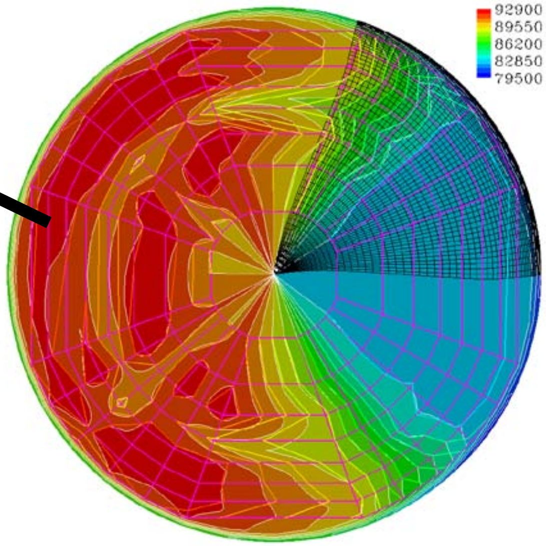


Distortion Screen #5
Based on CCE CFD #2

Example: IMPACT OF DISTORTION : 50% Reduction in Stall Margin

(due to 10% Total Pressure Deficit – High Mach Fan Rig Results to be Presented)





10% Deficit in Total Pressure

Computational Efforts - Flow Solvers (Complex 3-D RANS)

APNASA

- Average-Passage Equation System
- Multi-stage turbomachinery code
- Finite Volume Formulation (Central Differencing)
- Multiple exit flow paths capability
- Cylindrical Coordinate System (LHR)
- 4-stage Runge-Kutta with convergence accelerators
- k-ε turbulence model with wall damping fcn
- Real gas model
- Steady state analysis
- Boundary Conditions
  - Uniform Flow or Radial Profile
  - Total Conditions and flow angles specified at Inlet
  - Specified static pressure and/or massflow at Exit

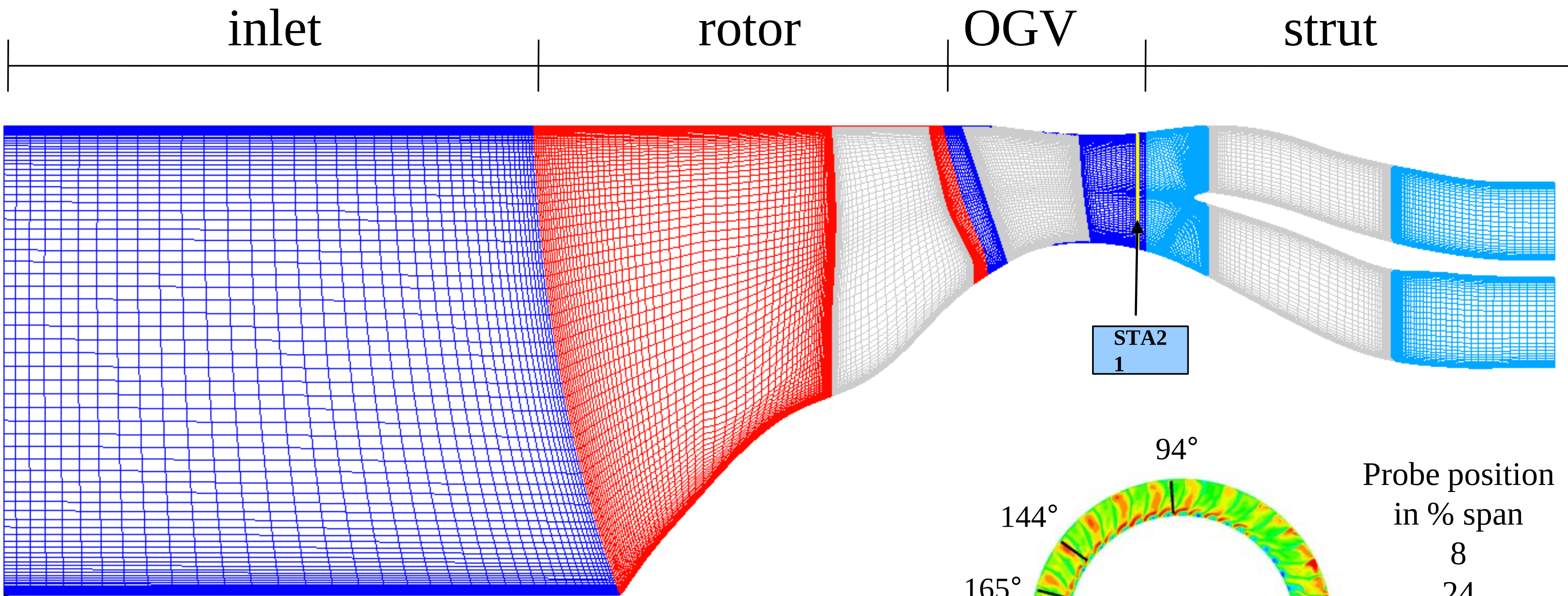
Uniform Flow or Radial Profile – Has been used as input for Unsteady Analysis - 1 day turn around

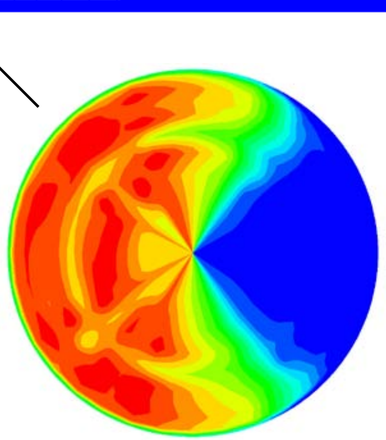
TURBO

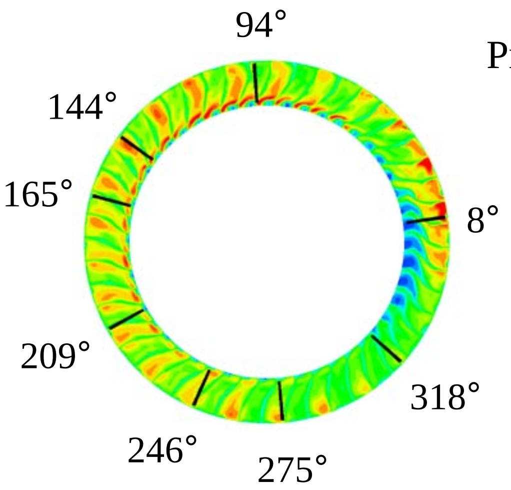
- MPI-Implemented multi-block parallel code
- Full annulus or phase-lag multi-stage turbomachinery code
- Finite volume discretization, flux splitting upwind scheme
- Multiple exit flow paths capability
- Cartesian Coordinate System
- Implicit iterative Newton algorithm
- 3-D unsteady Reynolds-averaged Navier-Stokes rotation frame formulation
- k-ε turbulence model with wall damping fcn
- Real gas model
- Flutter simulation capability
- Boundary Conditions
  - Uniform flow or with flow distortion
  - Total Conditions and flow angles specified at Inlet
  - Specified static pressure and/ or massflow at Exit

Flow Distortion & Unsteady – 1 week turn around

High Mach Fan Computational Results (example TURBO)







Probe position
in % span
8
24
39
53
67
81
94

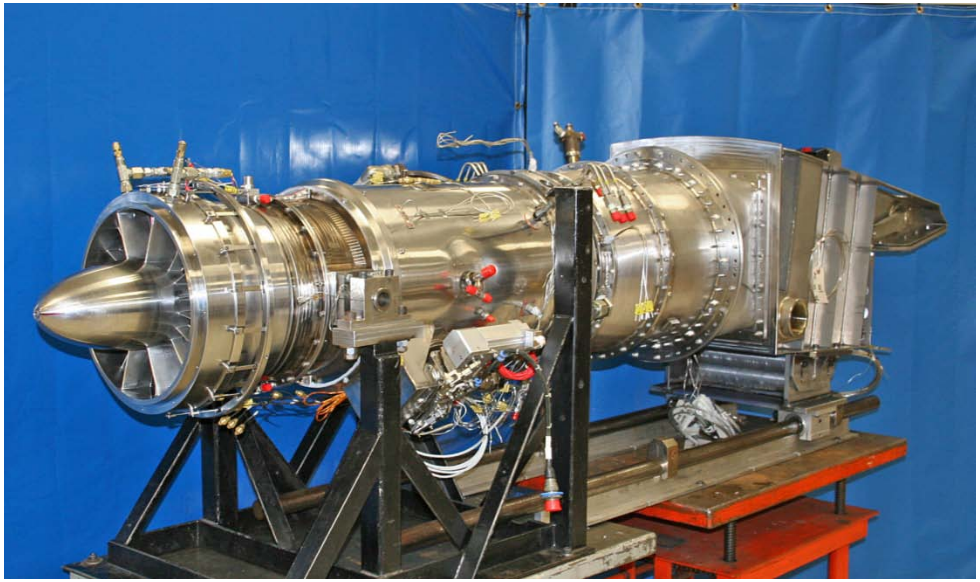
inlet : 5x39x81x51
rotor : 25x169x81x51, [71x81x51]
OGV : 48x133x81x51, [87x81x51]
strut : (6x156x41x201)x2, [61x41x201]

Ground Experiment

Williams International Modified WJ-38-15 High Mach Turbine Engine

Williams WJ38 Modifications For Mach 3 Operation & Wind Tunnel Integrated Inlet Test

- **Expanded operational envelope to accommodate**
  - ✓ SLS development tests
  - ✓ Mach 3 capable (Base engine M 0.9)
- **Increase T2 temperature capability (fan stage, housing, bearings, rub strips)**
  - ✓ New distortion tolerant fan stage, bypass duct, liners, high specific flow fan and IGV
  - ✓ All new hardware downstream of turbine (AB design from IR&D program)
- **SLS testing At WI**
  - ✓ Core engine test completed June 2010
  - ✓ Full AB, SERN Nozzle, High T abradable - April 2011
- **Engine Delivery 2nd / 3rd Quarter FY11**
- **CCE TBCC integrated inlet / engine Test FY 2013 (Partnership Required)**



Summary and Concluding Remarks Accomplishments Since FAP Atlanta

- Provided an overview of the major tasks in the TBCC Discipline
  - Combined Cycle Engine Large Scale Inlet Mode Transition Experiment (CCE LIMX)
  - High Mach Fan Rig Experiment
  - High Mach Turbine Engine Development
  - Integrated Flowpath Computational Efforts
  - Component Technology Computational Efforts

- Major Achievements Since Last FAP
  - CCE LIMX Model and Supporting Hardware Fabrication Completed
    - Very Complex Model with significant variable geometry
  - CCE LIMX Installed into the GRC 10X10 SWT
    - Researchers very particular on requirements and alignment
    - Numerous hardware, interface, and instrumentation issues were resolved in field
  - CCE Phase I Testing Commenced (10X10 is a Continuous Flow Facility)
  - High Mach Fan Rig Testing Completed with Varying Flow Distortion Distributions in the NASA GRC W-8 Facility
    - Flow Profile: Uniform, Radial, Sinusoidal, and Matching CCE LIMX CFD
  - High Mach Turbine Engine Core Test Completed

Summary and Concluding Remarks
Upcoming Activities & Potential Issues

- **FY11+ Key Deliverables and Milestones**
  - **Large Scale Inlet Steady State Testing Completed**
  - **Large Scale Inlet Dynamics Testing Completed**
  - **High Mach Turbine Engine Acceptance Test Complete & Engine Delivered to NASA**
  - **Integrated Flowpath Computational Efforts – Post CCE Testing Analysis**
  - **Component Technologies Computational Efforts – Comparison to W-8 Test Data**
  - **FY12 – Large Scale Inlet Controlled Mode Transition Testing (Partnership Required)**
  - **FY13 – Large Scale Inlet Controlled Mode Transition Testing with Turbine Engine (Partnership Required)**

- **Potential Issues/ Concerns**
  - **Complexity of CCE LIMX Model – Some Risk of Delays during Operation**
    - Significant variable geometry and continuous flow of 10X10 SWT enables much data to be obtained during each test (Phase I is on-going and proceeding well)
  - **Funding – Partnerships required to conduct some future activities**

ACRONYMS

- AFRL – Air Force Research Laboratory
- AIP – Aerodynamic Interface Plane
- CCE – Combined Cycle Engine
- CFD – Computational Fluid Mechanics
- DARPA – Defense Advanced Research Projects Agency
- DMSJ – Dual Mode ScramJet
- GE – General Electric, Inc.
- GNC – Guidance, Navigation, and Control (Discipline)
- IMX- Inlet Mode Transition Experiment (smaller scale in NASA GRC 1X1 SWT)
- LH2 – Liquid Hydrogen
- LIMX – Large Scale Inlet Mode Transition Experiment (in NASA GRC 10X10 SWT)
- LO2 – Liquid Oxygen
- OGV – Outlet Guide Vane
- M&S – Materials and Structures (Discipline)
- MDAO – Multi-Disciplinary Analysis and Optimization (Discipline)
- RATTLRS – Revolutionary Approach To Time critical Long Range Strike (missile concept)
- SOA – State Of the Art
- SSTO – Single Stage To Orbit
- SWT – Supersonic Wind Tunnel
- TBCC – Turbine Based Combined Cycle (Discipline)
- WI – Williams International, Inc.