State of the NASA Aeropropulsion Discipline Input from the Glenn Research Center

D. R. Reddy and George Schmidt
Propulsion Division
NASA Glenn Research Center

NESC Propulsion Technical Discipline Team (TDT) Face-to-Face Meeting
Marshall Space Flight Center
Huntsville, AL
April 6 – 7, 2017

GRC Propulsion Division Main Thrust Areas

Aeropropulsion

- Subsonic Aeropropulsion focused on improved fuel utilization, cleaner emissions, lower acoustic signatures and improved safety
- Supersonic Propulsion focused on affordable supersonic flight over land with reduced sonic boom signature
- Hypersonic propulsion – smooth and stable mode transition; efficient supersonic combustion
- FTE: 139
- WYE: 35

In-space Propulsion

- Chemical and Thermal Propulsion focused on MPCV/Orion development, Cryogenic Fluid Management (CFM), Lander and Green Prop technologies, Nuclear Thermal Propulsion and In-Situ Resource Utilization (ISRU)
- Electric Propulsion focused on flight implementation of high-power Hall and Ion technologies, technology development of condensible-propellant and microspray systems, and research of advanced plasma-based technologies
- FTE: 57
- WYE: 12

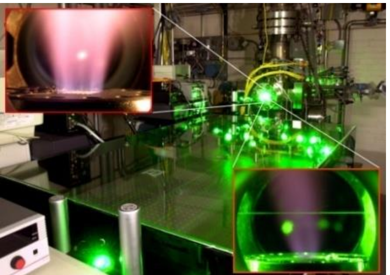
Cross-cutting Engineering Disciplines in Fluid and Thermal Systems

Physical Sciences and Biomedical Technologies

Air-Breathing Propulsion Technologies

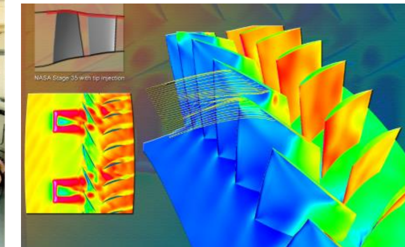
(~ 360 FTEs and 265 WYEs Supporting ARMD)

Fundamental Physics, Engine Components, Propulsion Systems, Future Concepts

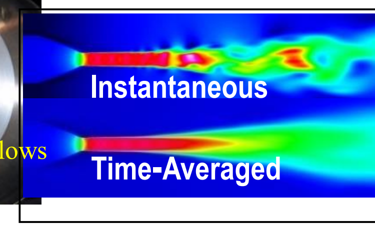

Combustion


Propulsion Acoustics


Icing



Turbomachinery and Heat Transfer

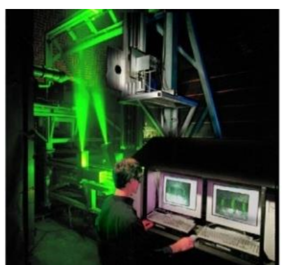
Systems Integration

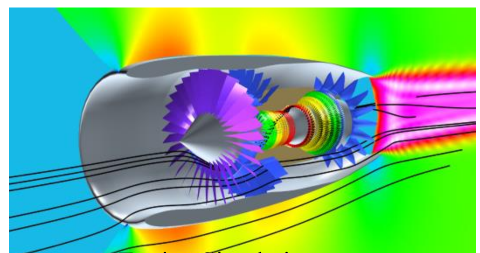



Inlet & Nozzle Flows

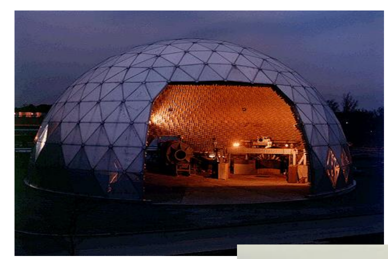
Instrumentation & Controls


Active Flow Control


Particle Image Velocimetry

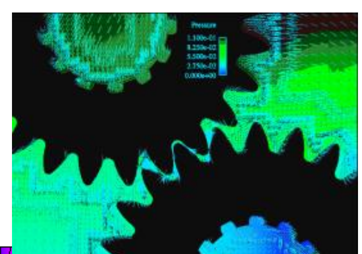
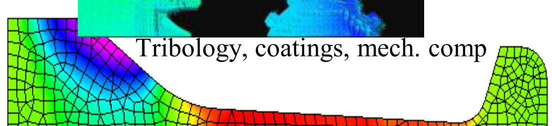

Engine Simulation

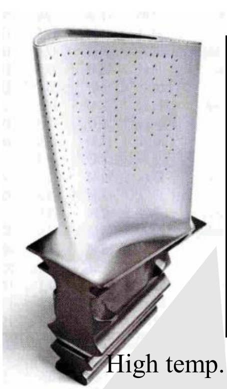
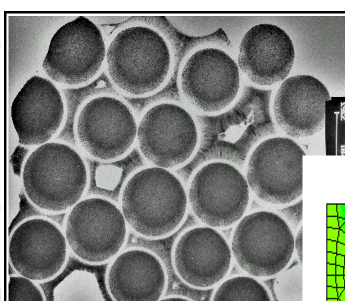
Test & Evaluation


AeroAcoustic Propulsion Laboratory (AAPL)


S3 Viking Aircraft for Icing and other Flight Research

Materials & Structures




Tribology, coatings, mech. comp

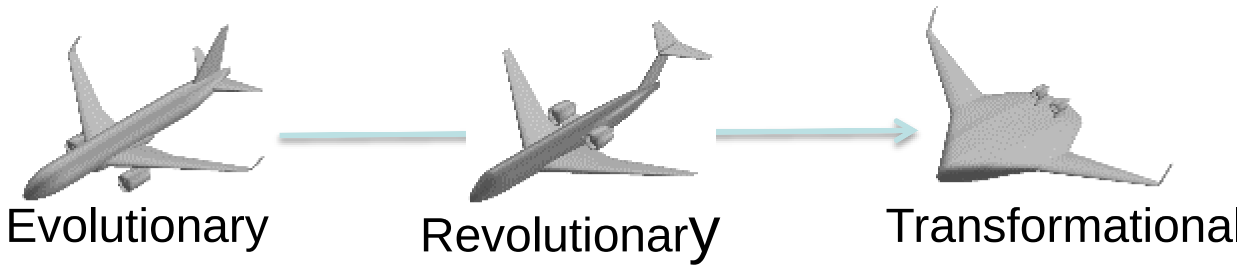


High temp. materials, composites, mechanics, life prediction, structural dynamics

NASA Subsonic Transport System-Level Metrics

…technologies for dramatically improving noise, emissions, & performance

(Energy Efficiency & Environmental compatibility)

TECHNOLOGY BENEFITS	TECHNOLOGY GENERATIONS (Technology Readiness Level = 5-6)		
	Near Term 2015-2025	**Mid Term** 2025-2035	**Far Term** beyond 2035
Noise (cum below Stage 4)	22 – 32 dB	32 – 42 dB	42 – 52 dB
LTO No_x Emissions (below CAEP 6)	70 – 75%	80%	>80%
Cruise No_x Emissions (rel. to 2005 best in class)	65 – 70%	80%	>80%
Aircraft Fuel/Energy Consumption (rel. to 2005 best in class)	40 – 50%	50 – 60%	60 – 80%



Targeted Supersonic Transport Capability Metrics

VEHICLE CAPABILITIES	VEHICLE GENERATION	
	MID-TERM 2025-2035	FAR-TERM BEYOND 2035
Operating Economics	Business aircraft economics	Airline economics
Cruise Speed	Mach 1.6 to 1.8	Mach 1.3 to 1.6 overland, higher over water
Range	4,000 n.mi.	4,000 to 5,500 n.mi.
Passengers	6 to 90	100 to 200
Sonic Boom Noise	70 to 75 PLdB	65 to 70 PLdB
Airport Noise	Airport noise: ICAO Ch. 14, with margin	Airport noise: 15 EPNdB below Ch. 14
Cruise NO_x Emissions	<10 grams per kg fuel+	<5 grams per kg fuel (plus reduced particulates and H2O vapor)

NASA Aeronautics/DoD: Leveraging hypersonic capabilities

Department of Defense

- Focus on operational mission (especially in near-term)
- In-house expertise aligned with mission need
- Enhancing test capabilities
- Significant investment (especially in demonstrators)

Develop new military capability

Share valuable data with NASA enables DOD Mission

Provide subject matter experts and key facilities

Developing future workforce

NASA

- Focus on fundamental research (long term emphasis with near term impact)
- Fully utilizes data from demos to advance/validate fundamental capabilities
- Performs independent studies to assess Technology Readiness for advanced civil & military applications
- Maintains unique facilities & skills with unique expertise to benefit broad aerospace community

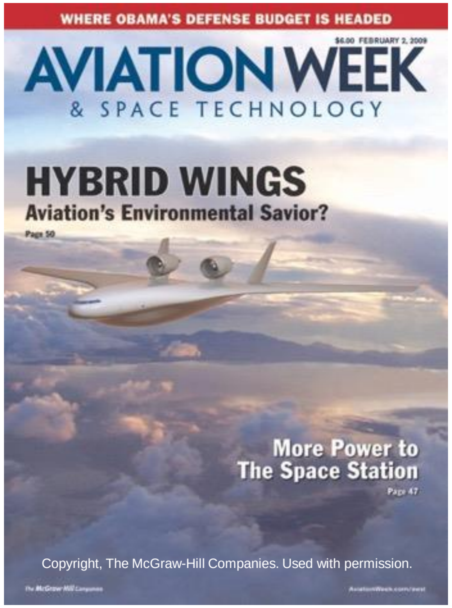
Fundamental research base for country & future missions

New Aviation Horizons - Supersonics

Low-boom flight demonstrator will pave the way for the development of a noise design standard for overland flight and new generations of supersonic civil aircraft.

Preliminary Design underway and proceeding on track with completion expected in Summer 2017. Further action pending Agency decisions.

New Aviation Horizons - Ultra-Efficient Subsonic Transport Demonstrators



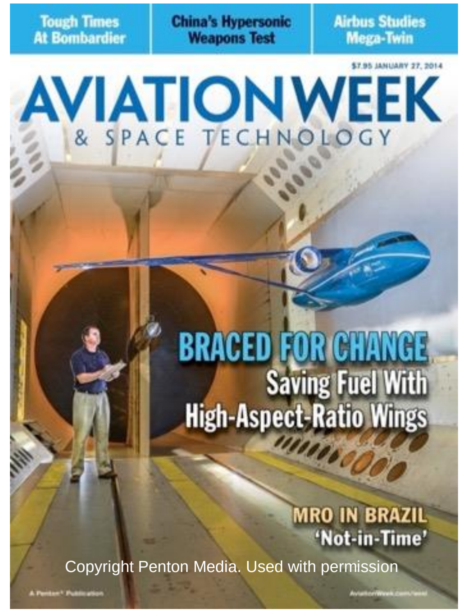
HWB Concept 1 (Tailless)

- Hybrid/blended wing body without a tail
  - Non-circular, flat-walled pressurized composite fuselage
- Upper aft fuselage mounted propulsion
- Propulsion noise shielding
- Unique cargo door for military/civil application

HWB Concept 2 (Tail w/OWN)

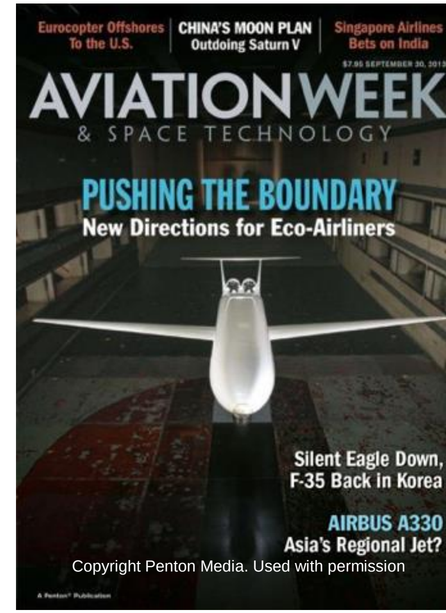
- Hybrid/blended wing body with conventional T-tail
  - Non-circular, oval pressurized composite fuselage
- Aft, Over-the-Wing Nacelles
- Fan noise shielding from wing
- Unique cargo door for military/civil application

Image Credit: Lockheed Martin



TTBW–Transonic Truss-Braced Wing

- Truss-braced, thin, very high aspect ratio wing with folding tips
- Conventional, circular pressurized fuselage
- Conventional T-tail
- Conventional under-wing propulsion system w/hybrid-electric variant



D8–Double Bubble

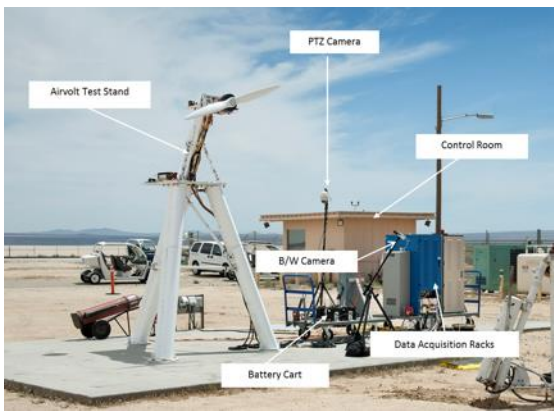
- Double bubble fuselage with unique Pi-Tail
  - Non-circular, pressurized composite fuselage
- Upper aft fuselage boundary layer ingesting (BLI) propulsion system
- Propulsion noise shielding
- Thin, flexible, high aspect ratio wing

X-57 approaching first flight

- X-57 “Maxwell”: general aviation-sized all-electric airplane
- Phased modifications make X-57 a “design/build/learn” for future larger X-plane
- Phase 1 first flight: March 2018

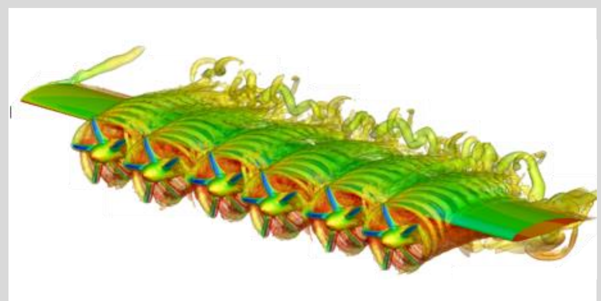
GROUND TESTING

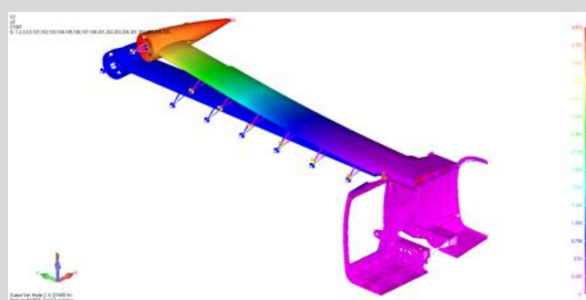
Critical ground testing to validate key technology systems and vehicle performance and control



NUMERICAL ANALYSIS

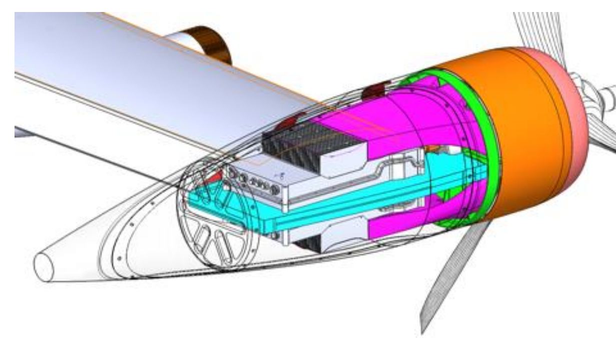
Computational Analysis to ensure Aerodynamic and Structural Performance





X-PLANE DESIGN

X-Plane Design Passes Critical Design Review



QueSST 8x6 Supersonic Wind Tunnel Test

Description

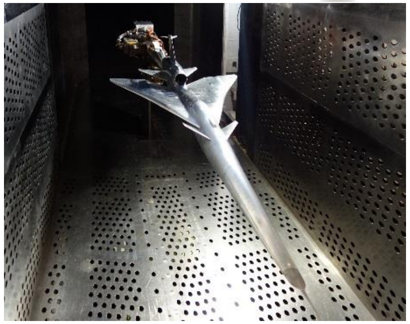
- NASA Commercial Supersonics Technology and New Aviation Horizons have partnered with Lockheed Martin to complete the preliminary design of a new demonstrator aircraft – an "X-Plane" – to demonstrate low-boom supersonic flight and validate NASA and industry's low-boom design tools.
- **The Quiet Supersonic demonstrator design is being tested in the NASA Glenn Research Center 8x6 Supersonic Wind Tunnel in two phases: Aerodynamic and Propulsion.**
- The Aerodynamic phase of the test will use a live force balance to collect differential stability data for the aircraft design with various control surface configurations and inlet flow-through nacelle **screens.**
- The Propulsion phase of the test will vary inlet geometry and mass flow plug position to collect inlet performance data.

Accomplishments

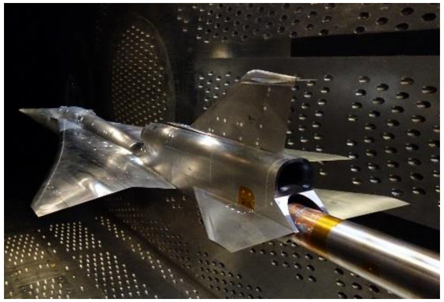
- Model built by Tri-Models and delivered to NASA GRC on 1/9/2017.
- **Model installed/check out complete on 2/24/2017.**
- First wind tunnel run on 2/24/2017.
- First supersonic run on 2/28/2017.
- Aerodynamic phase completed on 3/31/2017, with a total of 73 runs.

Significance

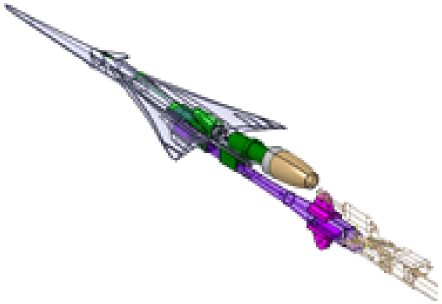
- **The data will be used to evaluate the preliminary design and establish data for the final design/build RFP.**
- **If the preliminary design phase is successful and approval/funding is received, a follow on project, based on a fully competitive process, will complete the design and fabrication of the X-Plane.**



QueSST Aerodynamic Model (front)



QueSST Aerodynamic Model (aft)



QueSST Propulsion Model (CAD)

Boundary Layer Ingesting Inlet/Distortion Tolerant Fan (BLI^{2}DTF) Completed Cruise Performance Testing in 8'x6' Tunnel Completed L2 Milestone: AATT.03.L2.BLI.61.013

PROBLEM: Boundary layer ingestion (BLI) can provide a significant propulsive efficiency improvement relative to clean-inflow systems. In order to realize the system level fuel burn benefit from BLI, the propulsion system must be capable of performing well in a highly-distorted flow environment.

OBJECTIVE: Obtain experimental measurements of performance and operability for an integrated boundary-layer-ingesting inlet (BLI^2) and distortion-tolerant fan (DTF) propulsor to validate pre-test predictions of 4.2% fuel burn benefit.

APPROACH

- Contracted with UTRC, Virginia Tech, and AEDC to conduct R&D required to advance the BLI^{2}DTF technology to TRL 4
- Designed an experiment to generate appropriate incoming boundary layer characteristics for an embedded propulsion system of a candidate hybrid wing body vehicle at cruise
- Used NASA's fan drive rig to power the BLI^{2}DTF propulsor and made detailed flowfield measurements at the inlet and upstream/downstream of the fan stage to determine performance and operability

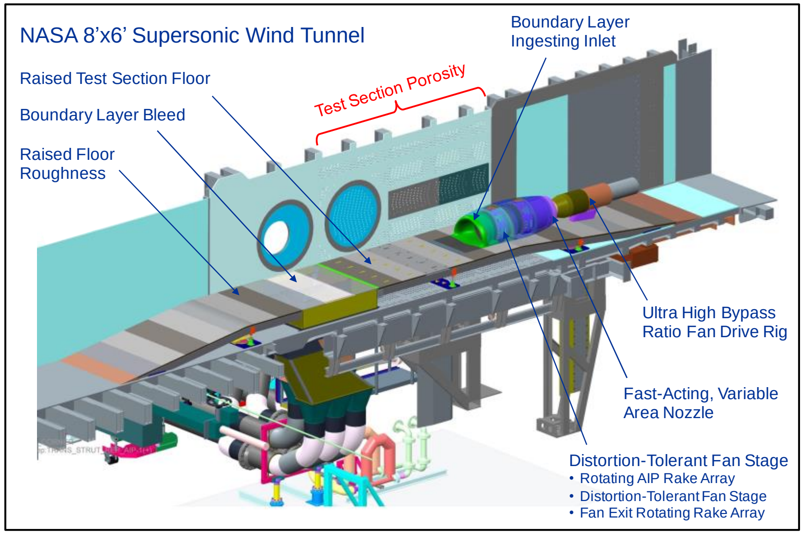
ACCOMPLISHMENTS

- Completed wind tunnel tests of the BLI^{2}DTF propulsor on Dec 9, 2016
- Successfully acquired high-quality data needed to validate BLI^{2}DTF performance
- Propulsor's operability and stability was well-behaved across the range of conditions tested
- Data analysis is underway with four papers being prepared for the AIAA Propulsion and Energy Forum in July, 2017

SIGNIFICANCE

- Advances the technology to improve fuel efficiency using BLI for a wide range of advanced air vehicle concepts.

BLI^{2}DTF Wind Tunnel Experiment



Combined Cycle Engine (CCE) Large Scale Inlet Mode Transition Experiment (LIMX) in the NASA GRC 10'X10' 3/29/2017

hypersonic technology project

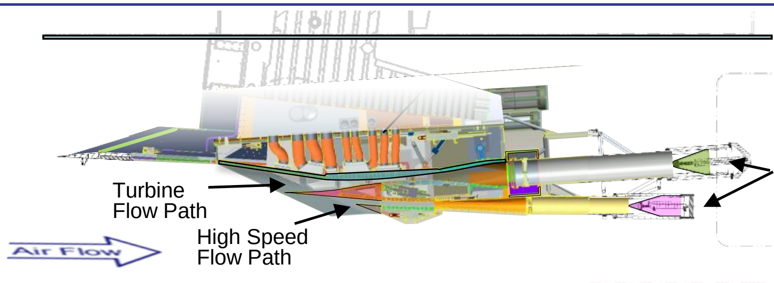
Objective: Obtain a unique Turbine-Based Combined-Cycle (TBCC) mode transition database and provide an assessment of SOA computational tools

Four Phase Test Approach

- ✓ **Phase 1 (Mar, 2011 – Jun, 2011)**
  - Inlet characterization at Mach 4.0 & 3.0 with "open loop" mode transition sequencing
- ✓ **Phase 2 (Aug, 2011 – May, 2012)**
  - System identification of inlet dynamics for linear control models
- ✓ **Phase 3: 3A (Apr, 2015 – Jun, 2015) & 3B (December, 2015 – January, 2016)**
  - Demonstrate closed loop inlet mode transition control at Mach 3.0
  - Characterize alternate inlet mode transition sequences at Mach 2.5 & 3.0
  - Demonstrate closed loop control at Mach 3.0, 2.5, and accelerating mode transition (M2.5 →3.0)
- ✓ **Phase 3C (September, 2016 – October, 2016)**
  - Phase 4 facility risk reduction and WJ38-15 turbine engine operations simulation
- **Phase 4 (FY18-FY22)**
  - Finish risk reduction checkout tests for WJ38-15 engine.
  - Demonstrate closed loop inlet mode transition with operating turbine engine (modified WJ-38-15 turbofan) at Mach 2.5 - 3.0
  - Feasibility of added propulsion elements (high speed DMRJ and integrated nozzle) are underway.

Phase 3C Configuration to simulate turbine engine

Turbine engine to be used in Phase 4



Phase 3C Test Results:

- Simulate start up and shutdown of the turbine engine
- Nominal mode transition (accelerating and decelerating) sequences while running a real-time engine simulation
- Turbine engine hazard procedure verification
- Controls investigation for safe engine operations
- Some higher Mach number tests curtailed due to facility issues with electric power quality

- **Results contributed to progress in reducing risks for complete TBCC propulsion system demonstration with combustion**

Phase 4 Schedule:

Phase 4 checkout: complete WJ-38 risk reduction testing.

Complete Ph.3c tests with engine controller hardware:	4/2018
Install WJ-38 engine for combustion testing:	9/2018
Phase 4a: Mode transition with WJ-38 engine	~ 2/2019
Phase 4b,c: Mode transition with DMRJ and full TBCC	TBD

Auxiliary activities

NASA Hypersonic Technology Project formalized. Excellent DoD/AFRL collaboration continues.

Contracts underway or complete with 7 contractors:

- Inlet support continues with TechLand Research
- Turbine engine tasks underway with Williams International including oil-mist bearing work and wind tunnel integration engineering
- DMRJ feasibility studies: Orbital/ATK, Aerojet/Rocketdyne, Innoveering
- Integrated Nozzle conceptual design complete: Spiritech
- Strongback design complete: Vantage Partners

Capability Assessment of 0D/1D Icing Risk Code

PROBLEM

Develop in-house tool to predict the engine response to ice particle ingestion to evaluate the risk of icing.

OBJECTIVE

Estimate the parameters that indicate the risk of accretion, as well as to estimate the degree of blockage and losses caused by accretion for the ALF502, LF11 engine test points. Identify enhancement needed in the code (Level 2 AATT project milestone).

APPROACH

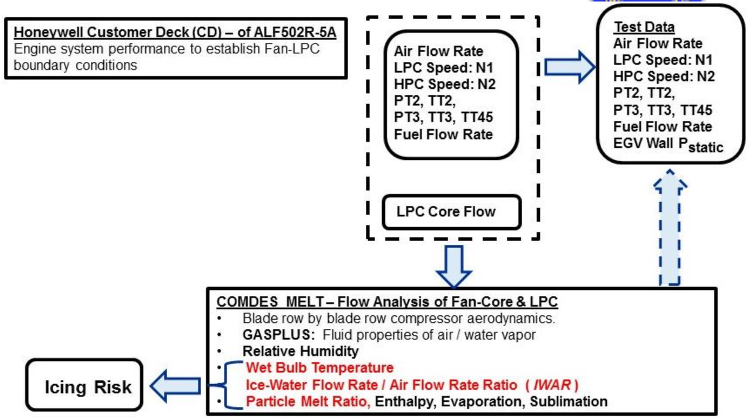
- Mean-line compressor flow analysis code was modified to include the effects of relative humidity on the fluid properties of air and water vapor mixture, and the subsequent effects on compressor performance (mass of water/mass of air) at the engine inlet, as well as the sublimation and evaporation of the particles through the flow path.
- Pre-test evaluation of the LF11 test points using COMES to predict the likelihood of rollback.
- Used code to guide the formulation of the altitude study test points.
- Post-test evaluation of the test points conducted and defined icing risk criteria using COMDES and the engine thermodynamic cycle code.

RESULTS

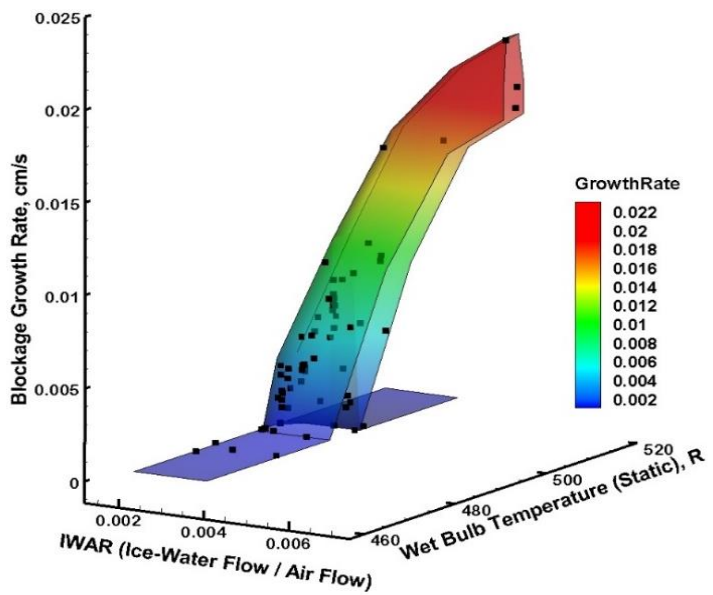
- A relationship between blockage growth rate, ice-water flow rate to air flow rate ratio (IWAR), and static wet bulb temperature was observed and plotted generating an "Icing Wedge".
- Correctly predicted rollback points with 80% accuracy.
- Code enhancements needed include: improved flow solver, increased fidelity in the stator flow model, improved code usability to enable use by non-experts.

SIGNIFICANCE

- The analysis provided additional validation of the icing risk parameters within the LPC, as well as the creation of models for estimating the rates of blockage growth and losses.
- Enables icing susceptibility assessments of current and advanced ultra-efficient engines.



Computational Process for the flow analysis of the Honeywell engine.



"Icing Wedge" – Risk of Ice Accretion Criteria

POC: Joe Veres and Phil Jorgenson

Most Significant Outcomes

GRC's most noteworthy FY17 Propulsion outcomes include:

1. **First-ever testing of Boundary Layer Ingesting Inlet with Distortion – Tolerant Fan (3-year effort resulting in a successful test).**
   - Data will be used to verify the system-level benefits for advanced vehicle configurations using embedded inlet architectures.
   - Could be used as a testbed to test improved designs of distortion-tolerant fans.
   - Operability and stability was well-behaved across the range of conditions tested.

Top/Major challenges

Organizational

- Limited number of technical leaders
  - Retirement of key senior personnel. Others eligible or soon-to-be eligible over next few years
  - Losses due to retirements and transfers backfilled with less experienced employees and "fresh-outs."
  - Development of new employees places additional demand on remaining experienced employees.

- Lack of institutional/project resources (institutional, or project)
  - Flight Demos are very expensive – requested budgets not adequate without substantial partnership from industry
  - Cost of running major wind tunnels and rigs increases every year – project funding does not keep up with cost increase – New AETC model could help

Technical

- Cruise Efficient propulsion for supersonic flight while meeting airport noise requirement (Affordable Supersonic flight Over land) and high altitude emissions
- Subsonic propulsion – Achieve High Thermal efficiency and Nox reduction simultaneously
- Low carbon propulsion - Electric Propulsion needs High Power densities to be comparable to gas turbines

Backup Charts

SCEPTOR X-57 Thermal Testing

Problem: Understand heating within electric aircraft wings

Objective: Validate an analytical heat transfer model's ability to accurately predict temperature of the X-57 traction bus throughout its mission profile. Determine the heat capacity and cooling rates of the flight wires and demonstrate an effective EMI shielding technique for vehicle thermal monitoring.

Approach:

- Construct a representative power source and load to match the X-57 vehicle configuration and flight profile.
- Instrument the wire with temperature sensors for open-air and insulated scenarios, using thermocouples and infra-red cameras.
- Run representative power profiles and track thermal loads
- Capture results into model parameters to better predict future flight scenarios.

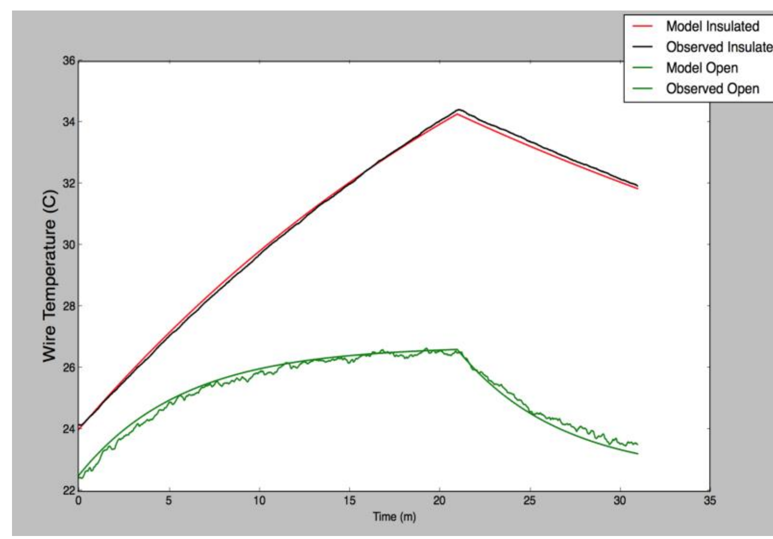
X57 Power Bus Thermal Testing at the NEAT facility

Results:

- Successfully completed testing - Test resulted in data that matched very closely with analytical models, and indicate that existing design will meet flight requirements
- Brass shielding over Type E over-braded Neoflon PFA thermocouples with perpendicularly oriented sensors provides sufficient EMI shielding
- Based on results, no additional thermal management methods will need to be employed to keep the wires within acceptable temperature limits.

Impact:

- Simplifies future X-57 thermal analyses, and eliminates the need for further wing ducting design.
- Provides a dataset to develop in-house thermal prediction tools for electric aircraft thermal management.



Results matched against analytical models

NASA Aeronautics Six Strategic Thrusts

6 Strategic Research and Technology Thrusts

Safe, Efficient Growth in Global Operations
- Enable full NextGen and develop technologies to substantially reduce aircraft safety risks

Innovation in Commercial Supersonic Aircraft
- Achieve a low-boom standard

Ultra-Efficient Commercial Vehicles
- Pioneer technologies for big leaps in efficiency and environmental performance

Transition to Low-Carbon Propulsion
- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Real-Time System-Wide Safety Assurance
- Develop an integrated prototype of a real-time safety monitoring and assurance system

Assured Autonomy for Aviation Transformation
- Develop high impact aviation autonomy applications

http://www.aeronautics.nasa.gov/pdf/armd-strategic-implementation-plan.pdf

ARMD Programs with Strategic Thrusts

MISSION PROGRAMS

Airspace Operations and Safety Program

- Safe, Efficient Growth in Global Operations
- Real-Time System-Wide Safety Assurance
- Assured Autonomy for Aviation Transformation

Advanced Air Vehicles Program

- Ultra-Efficient Commercial Vehicles
- Innovation in Commercial Supersonic Aircraft
- Transition to Low-Carbon Propulsion
- Assured Autonomy for Aviation Transformation

Integrated Aviation Systems Program

- Flight Research-Oriented Integrated, System-Level R&T support all six thrusts
- X-Planes / Test Environment

SEEDLING PROGRAM

Concepts Program

- High-risk, leap-frog ideas supporting all six thrusts
- Critical cross-cutting tools and technology development

FY 2017 President's Budget

$ Millions	FY 2015	Enacted FY 2016	FY 2017	FY 2018	FY 2019	FY 2020	FY 2021	FY 2022	FY 2023	FY 2024	FY 2025	FY 2026
Aeronautics	$642.0	$640.0	$790.4	$846.4	$1,060.1	$1,173.3	$1,286.9	$1,294.2	$1,307.6	$1,218.1	$829.7	$839.5
Airspace Operations and Safety	154.0		159.4	159.2	176.2	189.1	221.5	198.7	200.9	193.2	175.5	167.8
Advanced Air Vehicles	240.6		298.6	277.4	308.8	311.6	312.6	321.3	315.0	318.9	317.7	326.7
Integrated Aviation Systems	150.0		210.0	255.4	381.4	493.0	556.7	591.5	612.2	525.0	203.8	210.6
Transformative Aeronautics Concepts	97.4		122.3	154.4	193.8	179.7	196.2	182.8	179.4	181.0	132.7	134.4

Note that NASA is still under a Continuing Resolution at this point. This budget is included as a reference but is not enacted.

Summary – A New Era for NASA Aeronautics

Investing In Our Future - Investments in NASA's cutting edge aeronautics research today are investments in a cleaner, safer, quieter and faster tomorrow for American aviation:

- NASA is entering the Administration transition with a strong portfolio with good stakeholder support.
- No decisions have been made regarding the New Aviation Horizons (X-Plane) Initiative.
- The X-57 distributed propulsion electric aircraft was announced.
- The Hypersonic Technology Project (HTP) was approved for execution.
- The Advanced Composites Project is moving into Phase II
- Most key propulsion related research remains on track (e.g. Variable Speed Power Turbine, Small Core, Advanced Materials, etc)

Ten Year Investment Plan—FY 2017 Budget Accelerates Key Components of NASA Aeronautics Plan

Fund the Next Major Steps to Efficient, Clean and Fast Air Transportation Mobility

New Aviation Horizons

Start a continuing series of experimental aircraft to demonstrate and validate high impact concepts and technologies. Five major demonstrations over the next 10+ years in the areas of Ultra-Efficiency, Hybrid-Electric Propulsion, and Low Noise Supersonic Flight

Major New Initiative within IASP

Enabling Tools & Technologies

Major series of ground experiments to ready key technologies for flight

Research and ground demonstration for an advanced small engine core for very high bypass engines and as a hybrid-electric propulsion enabler

Development of next generation physics-based models needed to design advanced configurations

Increases to AAVP and TACP

Revolutionizing Operational Efficiency

Accelerate demonstration of full gate-to-gate Trajectory Based Operations

Increase to AOSP

Fostering Advanced Concepts & Future Workforce

Increased investment in new innovation through the NASA workforce and Universities

Leverage Non-Traditional Technology Advances

Pursue challenge prizes in areas such as energy storage, high power electric motors, advanced networking and autonomy

Increase to TACP

UAS

Strong continued research leadership in enabling UAS integration into the National Airspace. Extending the UAS in the NAS project for an additional 4 years

Hypersonics

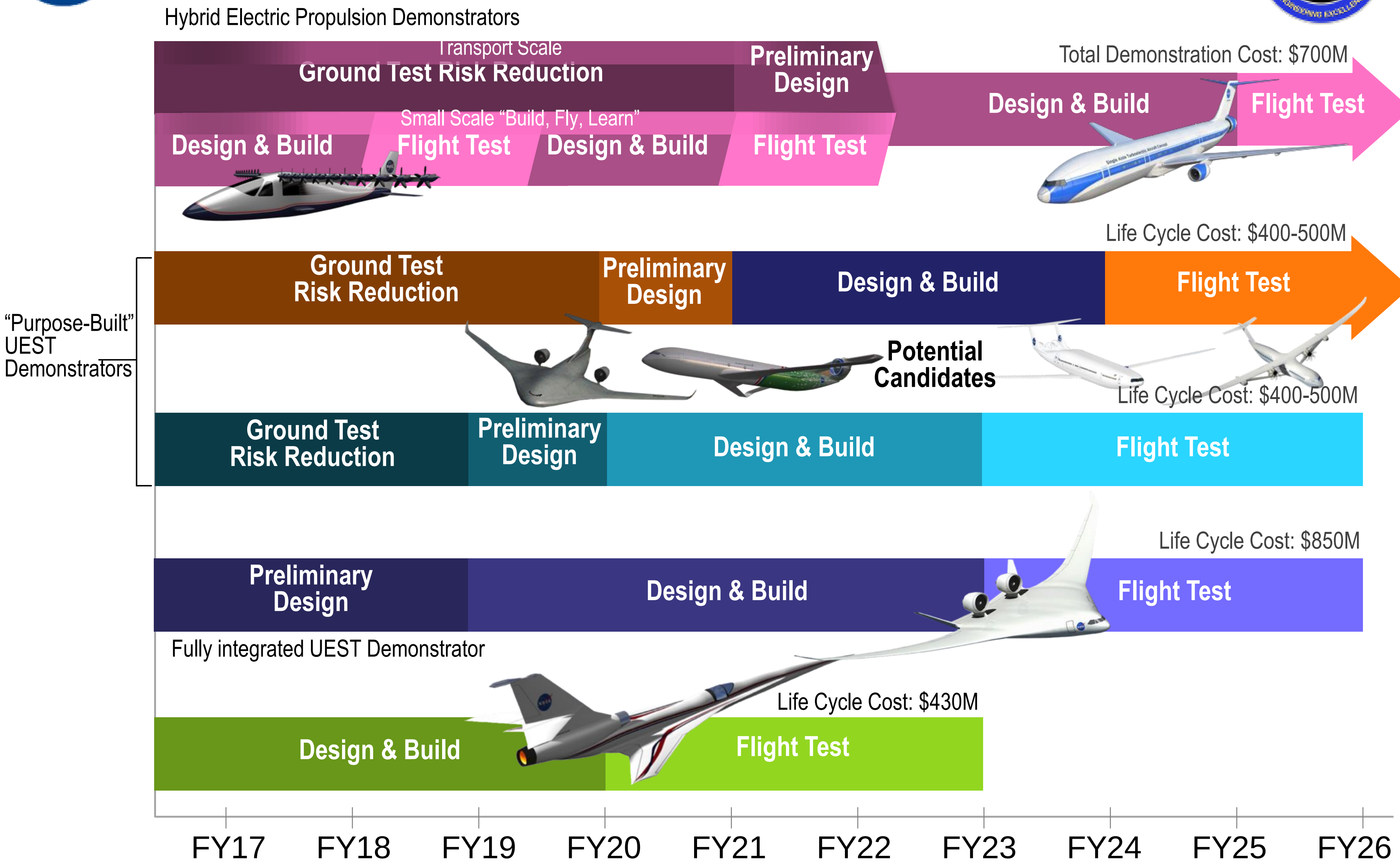
Increased investment to ensure a strong National fundamental research capability

Increases to IASP and AAVP

Build off of major current developments and accomplishments

Continue to incentivize new innovation

Flight Demo Plan



NASA Aeronautics Program Structure

Aeronautics Research Mission Directorate

Mission Programs

- **Advanced Air Vehicles (AAVP)**
  - Advanced Air Transport Technology (AATT)
  - Revolutionary Vertical Lift Technology (RVLT)
  - Commercial Supersonic Technology (CST)
  - Advanced Composites (ACP)
  - Aeronautics Evaluation and Test Capabilities (AETC)
- **Airspace Operations And Safety (AOSP)**
  - Airspace Technology Demonstration (ATD)
  - SMART NAS – Testbed for Safe Trajectory Operations
  - Safe Autonomous System Operations (SASO)
- **Integrated Aviation Systems (IASP)**
  - Environmentally Responsible Aviation (ERA)
  - UAS Integration in the NAS
  - Flight Demonstration and Capabilities (FDC)

Seedling Program

- **Transformative Aeronautics Concept (TACP)**
  - Transformational Tools and Technologies (TTT)
  - Convergent Aeronautics Solutions (CAS)
  - Leading Edge Aeronautics Research for NASA (LEARN)

GRC Propulsion Division Mission and Vision

Mission

Lead the development of significant research products, technologies and flight systems to meet the future needs of NASA and commercial aerospace

- Aeropropulsion Systems
- In-Space Propulsion Systems
- Fluid and Thermal Systems
- Multidisciplinary Systems (e.g., ISRU, Human Research Program, ECLSS, Fire Safety)

Thermosciences Based

Vision

Be broadly recognized for our:

- Technical leadership, excellence and unique contributions in research, technology development and systems development
- Ability to serve vital roles in meeting the most demanding goals of NASA and commercial aerospace