National Aeronautics and Space Administration

Aeropropulsion Technologies for Future Aircraft Generations

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Invited Lecture
Cranfield University, Cranfield, United Kingdom
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Advanced Air Transport Technology Project

Explore and Develop Technologies and Concepts for Improved Energy Efficiency and Environmental Compatibility for Fixed Wing Subsonic Transports

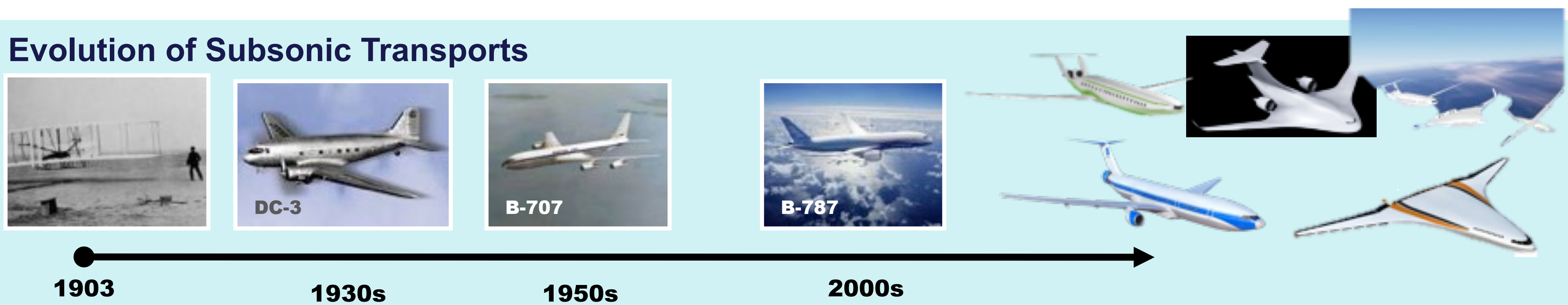
Vision

- Early-stage exploration and initial development of game-changing technology and concepts for fixed wing vehicles and propulsion systems

Scope

- Subsonic commercial transport vehicles (passengers, cargo, dual-use military)
- Technologies and concepts to improve vehicle and propulsion system energy efficiency and environmental compatibility without adversely impacting safety
- Development of tools as enablers for specific technologies and concepts

Evolution of Subsonic Transports



AATT and the NASA Aeronautics Context

Strategic Implementation Plan (SIP)

3 Mega-Drivers

6 Strategic Research & 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

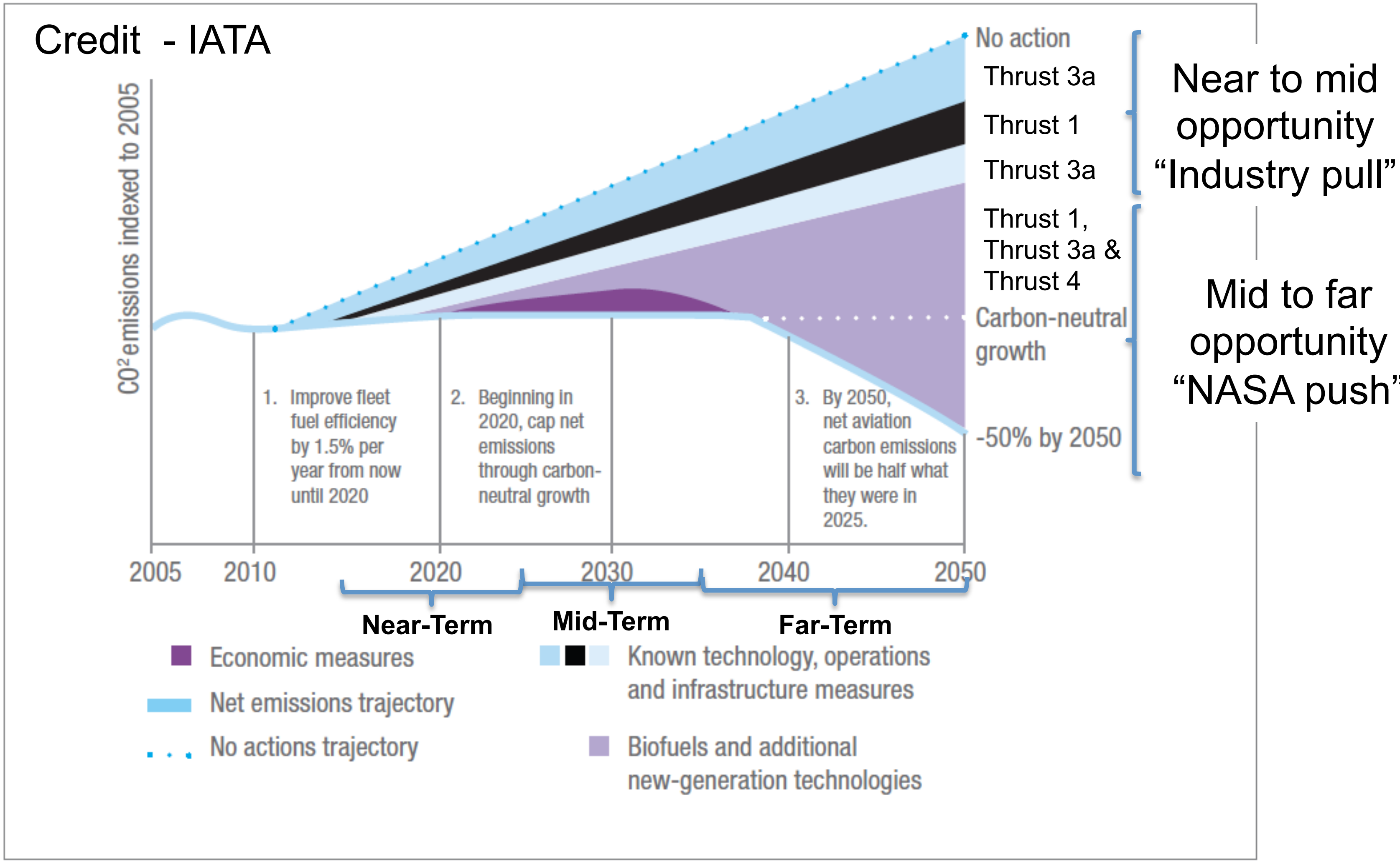
Ultra-Efficient Commercial Vehicles — AATT
- Pioneer technologies for big leaps in efficiency and environmental performance

Transition to Alternative Propulsion and Energy
- 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

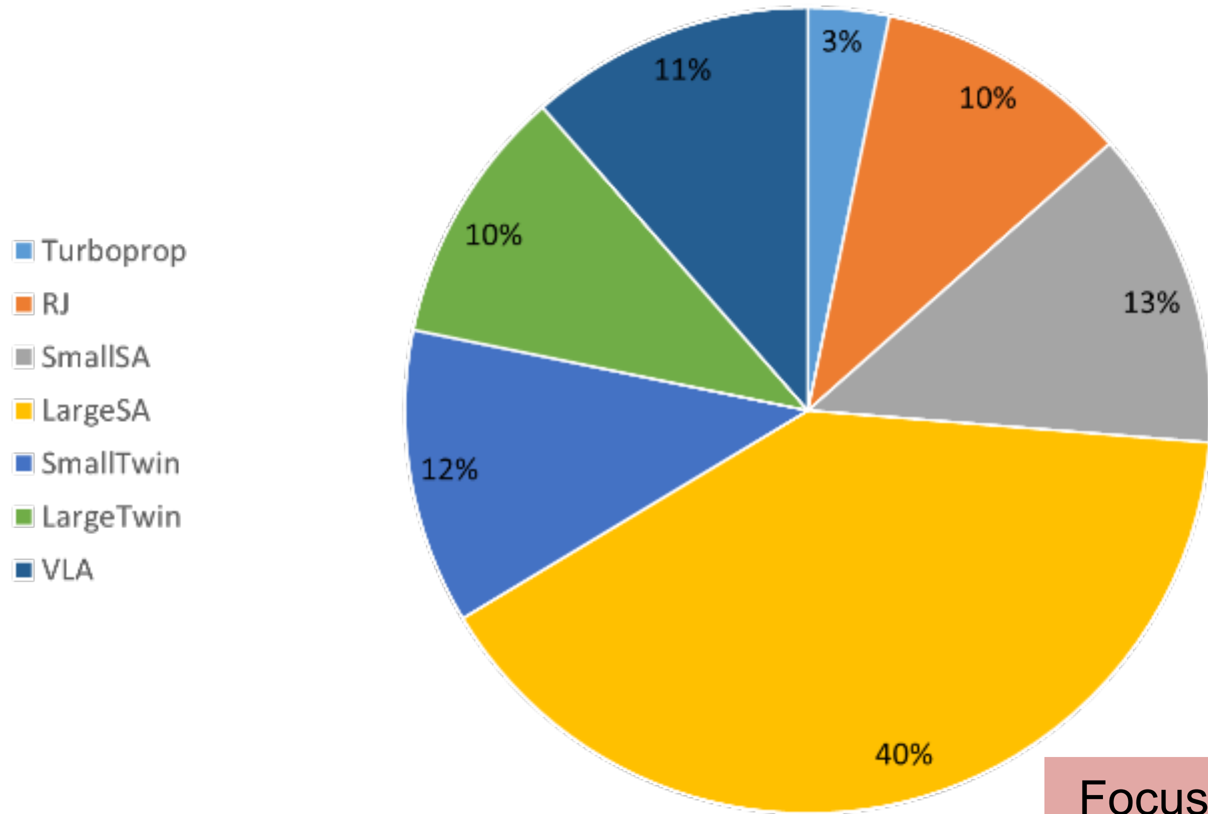
Assured Autonomy for Aviation Transformation
- Develop high impact aviation autonomy applications

Major Aviation Community "Driver"
Reduce Carbon Footprint by 50% by 2050…



…in the face of increasing demand, and while reducing development, manufacturing and operational costs of aircraft & meeting noise and LTO NOx regulations

Fuel Use by Vehicle Class



Focus on small single-aisle and larger vehicle classes for maximum community impact

40% of fuel use is in 150-210 pax large single aisle class
87% of fuel use is in small single-aisle and larger classes (>100 pax)
13% of fuel use is in regional jet and turboprop classes

Analysis based on FAA US operations data provided by Holger Pfaender of Georgia Tech

NASA Subsonic Transport
System Level Measures of Success

Use industry pull to mature technology that enables aircraft products that meet near-term metrics, enabling *community* outcome 1, and NASA push to mature technology that will support development of new aircraft products that meet or exceed mid- and far-term metrics, enabling *community* outcomes 2 and 3

v2016.1

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 NOx Emissions (below CAEP 6)	**70 - 75%**	**80%**	**> 80%**
Cruise NOx 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%**

Evolutionary Revolutionary Transformational

Portfolio Development:
N+3 Advanced Vehicle Concept Studies Summary

Advanced concept studies for commercial subsonic transport aircraft for 2030-35 Entry into Service (EIS)

Boeing, GE, GA Tech

NG, RR, Tufts, Sensis, Spirit

GE, Cessna, GA Tech

MIT, Aurora, P&W, Aerodyne

NASA, VA Tech, GT

NASA

Trends:

- Tailored/multifunctional structures
- High aspect ratio/laminar/active structural control
- Highly integrated propulsion systems
- Ultra-high bypass ratio (20+ with small cores)
- Alternative fuels and emerging hybrid electric concepts
- Noise reduction by component, configuration, and operations improvements

Advances required on multiple fronts…

AATT Project Technical Challenges

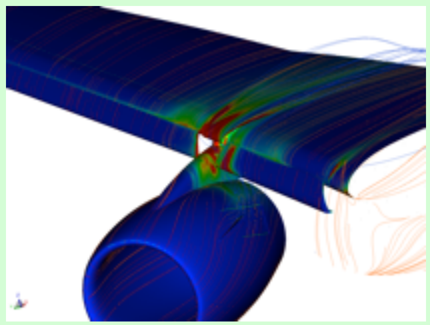
Based on Goal-Driven Advanced Concept Studies

Goals Metrics (Far Term)	Noise Stage 4, 42-52 dB cum	Emissions (LTO) CAEP6, >80%	Emissions (cruise) 2005 best, >80%	Energy Consumption 2005 best, 60-80%

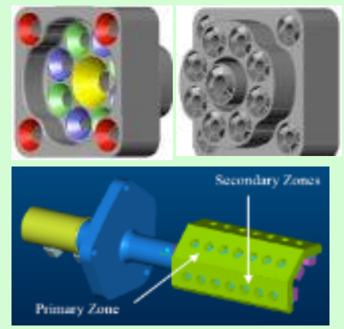
Goal-Driven Advanced (N+3) Concepts

Investments in both Near-Term Tech Challenges and Far-Term Vision

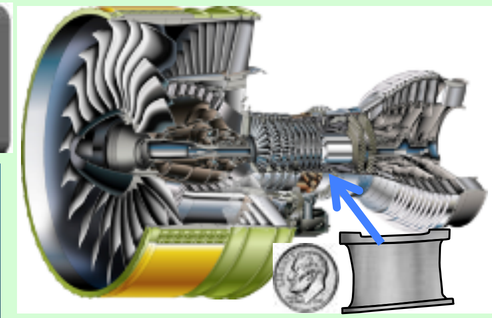
2.1 Higher Aspect Ratio Optimal Wing



3.1 Fan and High Lift Noise



4.1 Low NOx Fuel-Flex Combustor



4.2 Compact High OPR Gas Generator

5.2 Hybrid Gas Electric Propulsion Concept

6.1 Integrated BLI System

4.3 Engine Icing; 6.2 Airframe Icing

AATT Project Technical Challenges

Near-Term Impact Toward Long-Term Objectives

Goals Metrics (Far Term)	Noise		Emissions (LTO)	Emissions (cruise)		Fuel/Energy Consumption	
	Stage 4 – 42-52 dB cum		CAEP6 – 80%	2005 best – 80%		2005 best – 60-80%	
Technology Themes	Lighter-Weight Lower-Drag Fuselage	Higher Aspect Ratio Optimal Wing	Quieter Low-Speed Performance	Cleaner, Compact, Higher BPR Propulsion	Hybrid Gas-Electric Propulsion	Unconventional Propulsion-Airframe Integration	Alternative Fuel Emissions

Technical Challenges Near-Term (FY16-21) Project Focus

TC2.1 (FY19) Higher Aspect Ratio Optimal Wing: Enable a 1.5-2X increase in the aspect ratio of a lightweight wing with safe flight control and structures (TRL3).

TC3.1 (FY18) Fan & High-Lift Noise: Reduce fan (lateral and flyover) and high-lift system (approach) noise on a component basis by 4 dB with minimal impact on weight and performance (TRL5)

TC4.1 (FY19) Low NOx Fuel-Flex Combustor: Reduce NOx emissions from fuel-flexible combustors to 80% below the CAEP6 standard with minimal impact on weight, noise, or component life (TRL3).

TC4.2 (FY20) Compact High OPR Gas Generator: Enable reduced size/flow high pressure compressors and high temperature disk/seals that are critical for 50+ OPR gas generators with minimal impact on noise and component life (TRL4).

TC4.3 (FY21) Engine Icing: Predict likelihood of icing events with 90% probability in current engines operating in ice crystal environments to enable icing susceptibility assessments of advanced ultra-efficient engines. (TRL2)

TC5.2 (FY19) Hybrid Gas-Electric Propulsion Concept: Establish viable concept for 5-10 MW hybrid gas-electric propulsion system for a commercial transport aircraft (TRL2)

TC6.1 (FY17) Integrated BLI System: Achieve a vehicle-level net system benefit with a distortion-tolerant inlet/fan, boundary-layer ingesting propulsion system on a representative vehicle (TRL3).

TC6.2 (FY21) Airframe Icing: Enable assessment of icing risk with 80% accuracy for advanced ultra-efficient airframes operating in supercooled liquid droplet environments. (TRL2)

Note: Reference is best commercially available or best in class in 2005.

TC 2.1(FY19): Higher Aspect Ratio Optimal Wing, TRL 3

Objective

Enable a 1.5-2X increase in the aspect ratio of a lightweight wing with safe structures and flight control (TRL 3)

Technical Areas and Approaches

Performance Adaptive Aeroelastic Wing (PAAW)

- Distributed control effectors, robust control laws, mission-adaptation and optimization
- Actuator/sensor structural integration

Passive Aeroelastic Tailored Wing (PATW)

- Passive aeroelastic tailored loadpath structures

Transonic Truss-Braced Wing (TTBW)

- External bracing / Passive drag reduction concepts

Active Flow Control Wing (AFCW)

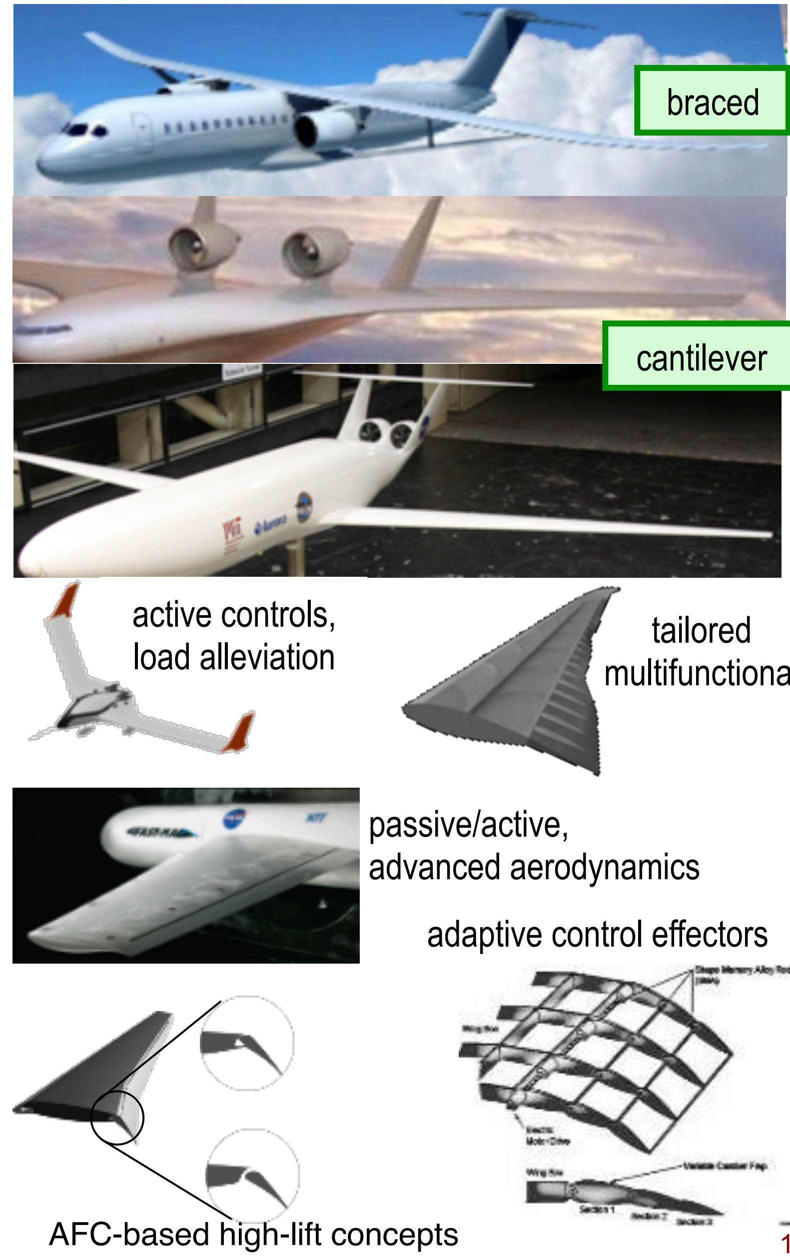
- Transonic drag reduction; simple high-lift system

Natural Laminar Flow Wing (NLFW)

- Design approaches for NLF on transports

Benefit/Payoff

- 20% wing structural weight reduction
- Wave drag benefits tradable for weight or other parameters
- Concepts to control and exploit structural flexibility
- Optimal wing AR increase (50% cantilever, 100% braced)



TC 3.1(FY18): Fan and High-Lift Noise, TRL 5

Objective

Reduce fan (lateral and flyover) and high-lift system (approach) noise on a component basis by 4 dB with minimal impact on weight and performance (TRL 5)

Technical Areas and Approaches

Airframe Noise

– Flap and slat noise reduction concepts
– Landing gear noise reduction concepts

Acoustic Liners and Duct Propagation

– Multi-degree-of-freedom, low-drag liners

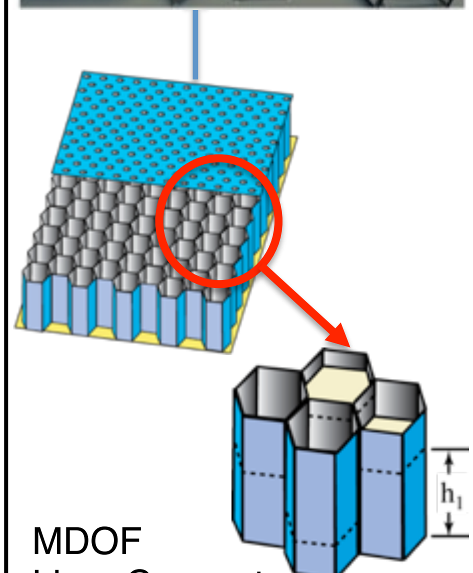
Benefit/Payoff

Component noise reduction with minimal impact on weight and performance

– 12 dB cum noise reduction
– Liner and non-active-flow-control high-lift system technology have early insertion potential

flap/slat
noise reduction
concepts

Liner Test Facility (LTF)



MDOF
Liner Concept

TC 4.1(FY19): Low NOx Fuel-Flex Combustor, TRL 3

Objective

Reduce NOx emissions from fuel-flexible combustors to 80% below the CAEP6 standard with minimal impact on weight, noise, or component life (TRL 3)

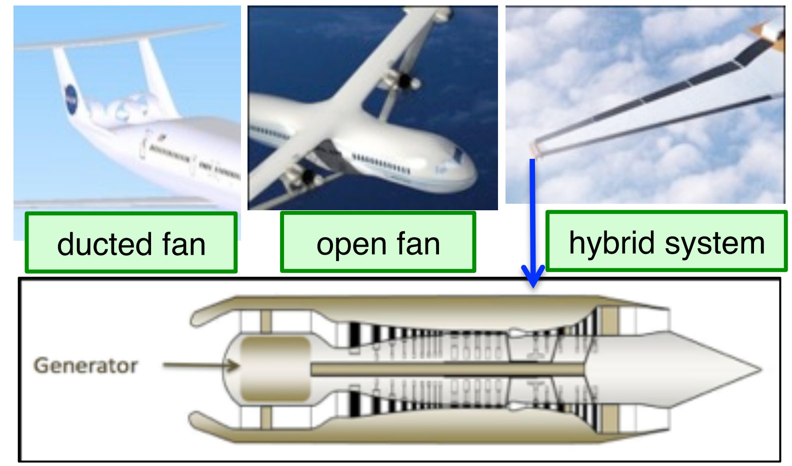
Technical Areas and Approaches

Fuel-Flexible Combustion

– Small core injection methods, alternative fuel properties, combustion stability techniques

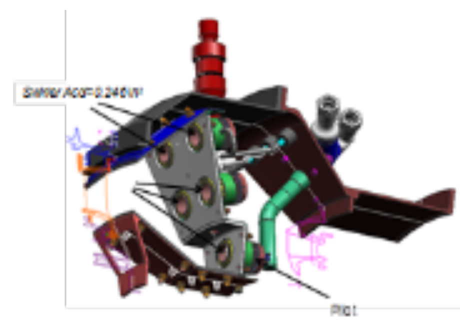
Benefit/Payoff

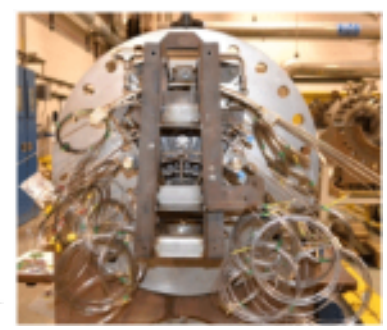
– Lower emissions: NOx reduction of 80% at cruise and 80% below CAEP6 at LTO and reduced particulates
– Compatible with thermally efficient, high OPR (50+) gas generators
– Compatible with gas-only and hybrid gas-electric architectures and ducted/unducted propulsors
– Compatible with alternative fuel blends



Advanced combustor required for gas-only and hybrid architectures

Low-emission flametube concepts





TC 4.2(FY20): Compact High OPR Gas Generator, TRL 4

Objective

Enable reduced size/flow high pressure compressors and high temperature disk/seals that are critical for 50+ OPR gas generators with minimal impact on noise and component life (TRL 4)

Technical Areas and Approaches

Hot Section Materials

- 1500°F hybrid disk and coatings
- 1500°F capable non-contacting seal

Reduced Size HPC for High OPR Engines

- Minimize losses due to short blades/vanes

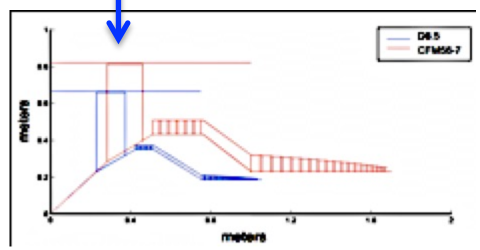
Benefit/Payoff

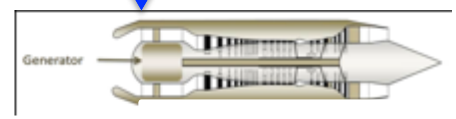
- Advanced compact gas-generator core architecture and component technologies enabling BPR 20+ growth by minimizing core size
- Thermally efficient, high OPR (50+) engines

ducted fan

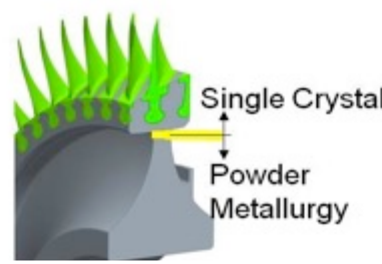
open fan

hybrid system

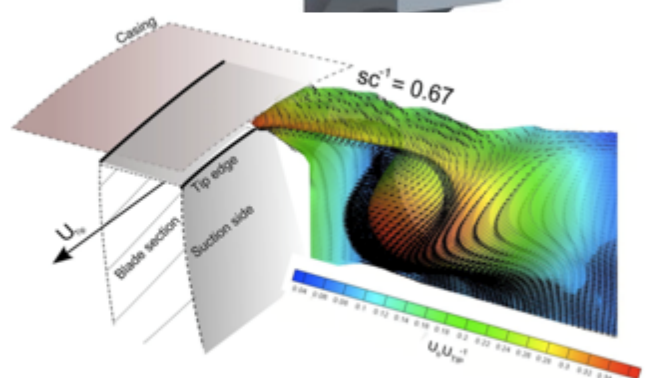




materials, aerodynamics, and control



1500°F, bonded hybrid disk concept



Tip/endwall aerodynamic loss mitigation

Wu et al. Exp. Fluids, 2010, 1011
Miorini et al., J. Turbomachinery 2012, AIAA Journal 2012

TC 4.3 (FY21): Engine Icing, TRL 2

Objective

Predict likelihood of icing events with 90% probability in current engines operating in ice crystal environments to enable icing susceptibility assessments of advanced ultra-efficient engines (TRL 2)

Technical Areas and Approaches

Icing Prediction Analysis Tool

- Engine conditions conducive to ice formation
- Rate of ice growth/engine effects

Fundamental Physics and Engine Icing Tests

- Study ice crystal icing in GRC Propulsion Systems Laboratory to validate tools

Benefit/Payoff

- Enable analysis of ice crystal icing effects on turbofan engines
- Design tools adapted for N+3, compact core, higher bypass ratio turbofan engines to assess icing impacts during development

Ice Formation inside Engine in PSL

Engine in Propulsion Systems Laboratory for Icing Test

Fundamental Physics Test Ice Accretion

Engine in Ice Crystal Cloud

TC 5.2 (FY19): Gas-Electric Propulsion Concept, TRL 2

Objective

Establish viable concept for 5-10 MW hybrid gas-electric propulsion system for a commercial transport aircraft (TRL 2)

Technical Areas and Approaches

Propulsion System Conceptual Design

- Early selection of system concepts that allow drill-down in issues of system interaction concept refinement

Integrated Subsystems

- Develop flight control and mission operations methodology for distributed propulsion
- Explore component interactions, power management, and fault management

High Efficiency/Power Density Electric Machines

- Explore conventional and non-conventional topologies
- Integrate novel thermal management
- Demonstrate component maturation

Flight-weight Power System and Electronics

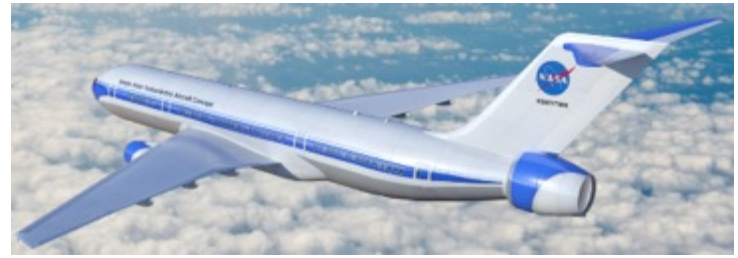
- Develop and demonstrate powertrain systems and components
- High voltage, MW power electronics, transmission, protection

Enabling Materials

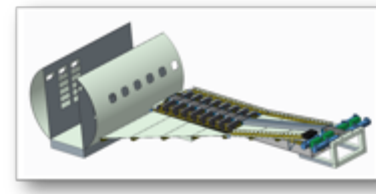
- Insulators and conductors for high power and altitude components
- Nanocomposite magnetic materials for targeted machines and drives

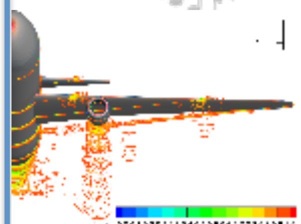
Benefit/Payoff

- Enable paradigm shift from gas-turbine to electrified propulsion
- Reduce fuel & energy consumption, emissions, and noise

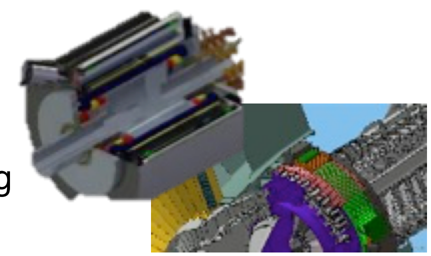


Exploring tube-and-wing architectures

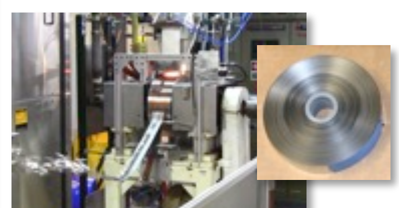




Powertrain, Controls and Flight Simulation Testbeds and advanced CFD



Superconducting and Ambient Motor Designs



Advanced Materials and Novel Designs for Flightweight Power

TC 6.1(FY17): Integrated BLI System, TRL 3

Objective

Achieve a vehicle-level net system benefit with a distortion-tolerant inlet/fan, boundary-layer ingesting propulsion system on a representative vehicle (TRL 3)

Technical Areas and Approaches

Aerodynamic Configuration

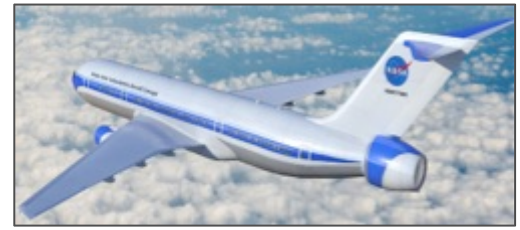
– Novel configurations and installations

Distortion-Tolerant Fan

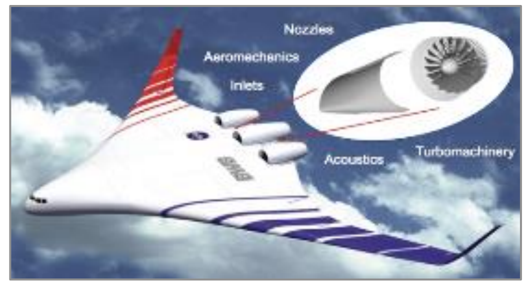
– Robust, integrated inlet/fan design

Benefit/Payoff

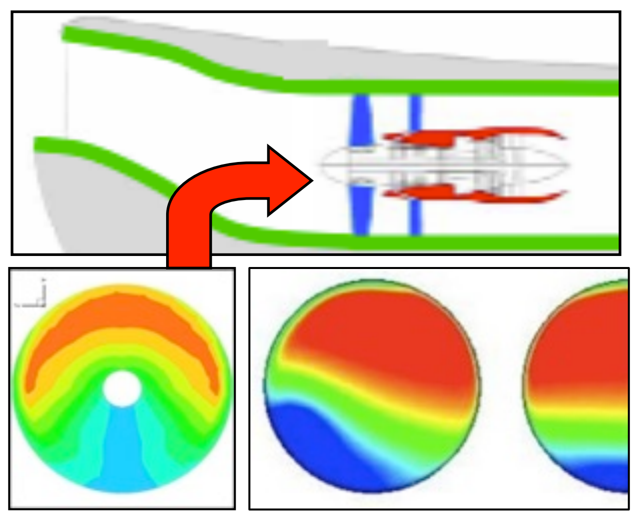
- Will demonstrate a net system-level performance benefit for BLI propulsion that is applicable and beneficial to a variety of mid-term and long-term advanced vehicle concepts
- Developing distortion-tolerant fan technology is relevant to near-term conventional, short-duct installations requiring enhanced operability capability

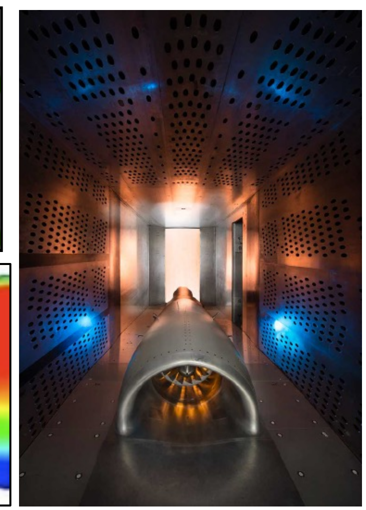


Boundary-layer ingestion for drag reduction



Distortion-tolerant fan required for net vehicle system benefit





TC 6.2(FY21): Airframe Icing, TRL 2

Objective

Enable assessment of icing risk with 80% accuracy for advanced ultra-efficient airframes operating in supercooled liquid droplet environments (TRL 2)

Technical Areas and Approaches

3D Ice Accretion Prediction Tool

– Develop LEWICE3D to assess ice accretion on complex airframe features

Ice Protection Systems

– Integrate assessment of ice protection systems into LEWICE3D as airframe design tool

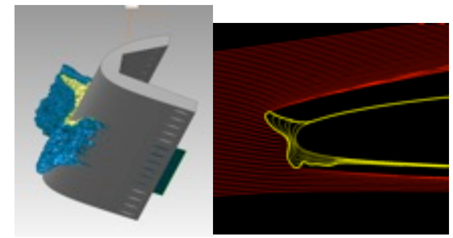
Benefit/Payoff

– LEWICE3D validated against experimental data to be used as design tool for advanced N+3 airframes

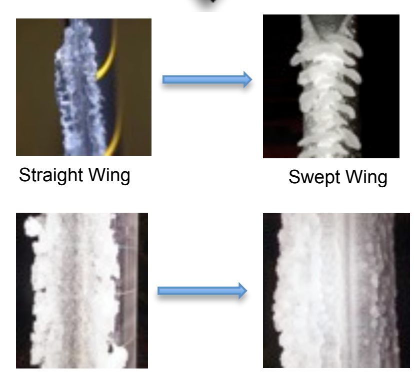
– Ice protection system evaluation capability to mitigate icing issues for N+3 airframes

Scalloped Ice Shape on Swept Wing

Current NASA Icing Simulation Tools Well Validated and Accepted by Aviation Community



Ice Growth on 65% Scale CRM Wing Section Model



Straight Wing

Swept Wing

MVD = 18.6 microns

MVD = 215.6 microns

Expanding Current Icing Simulation Tools to Swept Wing and Freezing Rain/Drizzle Icing

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

AATT Project Research Team

NASA Ames, Armstrong, Glenn, and Langley Research Centers

Three Main Components:

- NASA in-house research
- Collaborations with partners (OGA, Industry, Academia)
- Sponsored research by NASA Research Announcement (NRA)

NASA