National Aeronautics and Space Administration

The Environmentally Responsible Aviation (ERA) Project – A technology development project

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New Aviation Horizons

Turbine Engine Technology Symposium
Dayton, OH
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NASA Aeronautics Six Strategic Thrusts
ERA - Ultra Efficient Commercial Vehicles

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

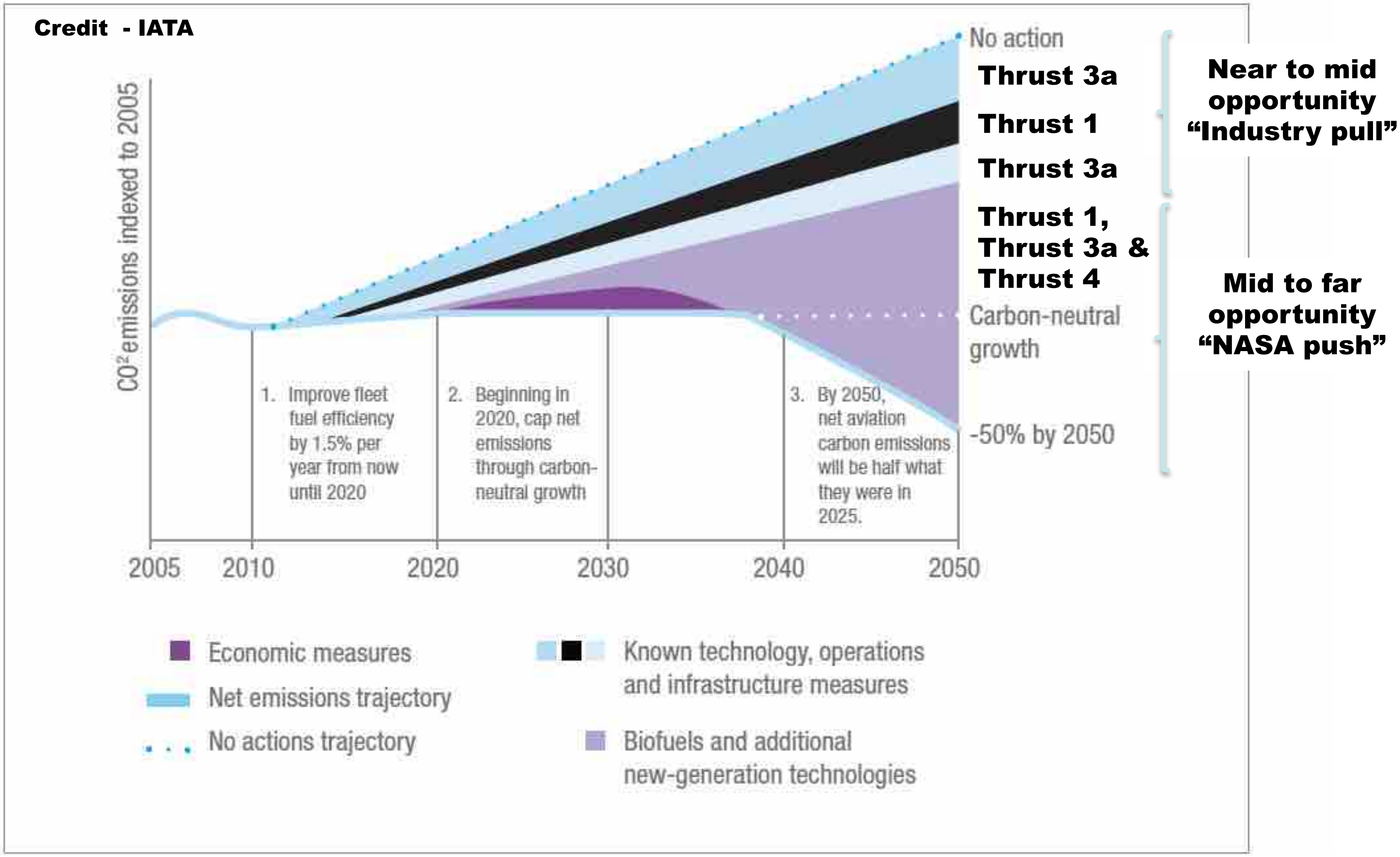
Transition to Low-Carbon Propulsion
- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

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

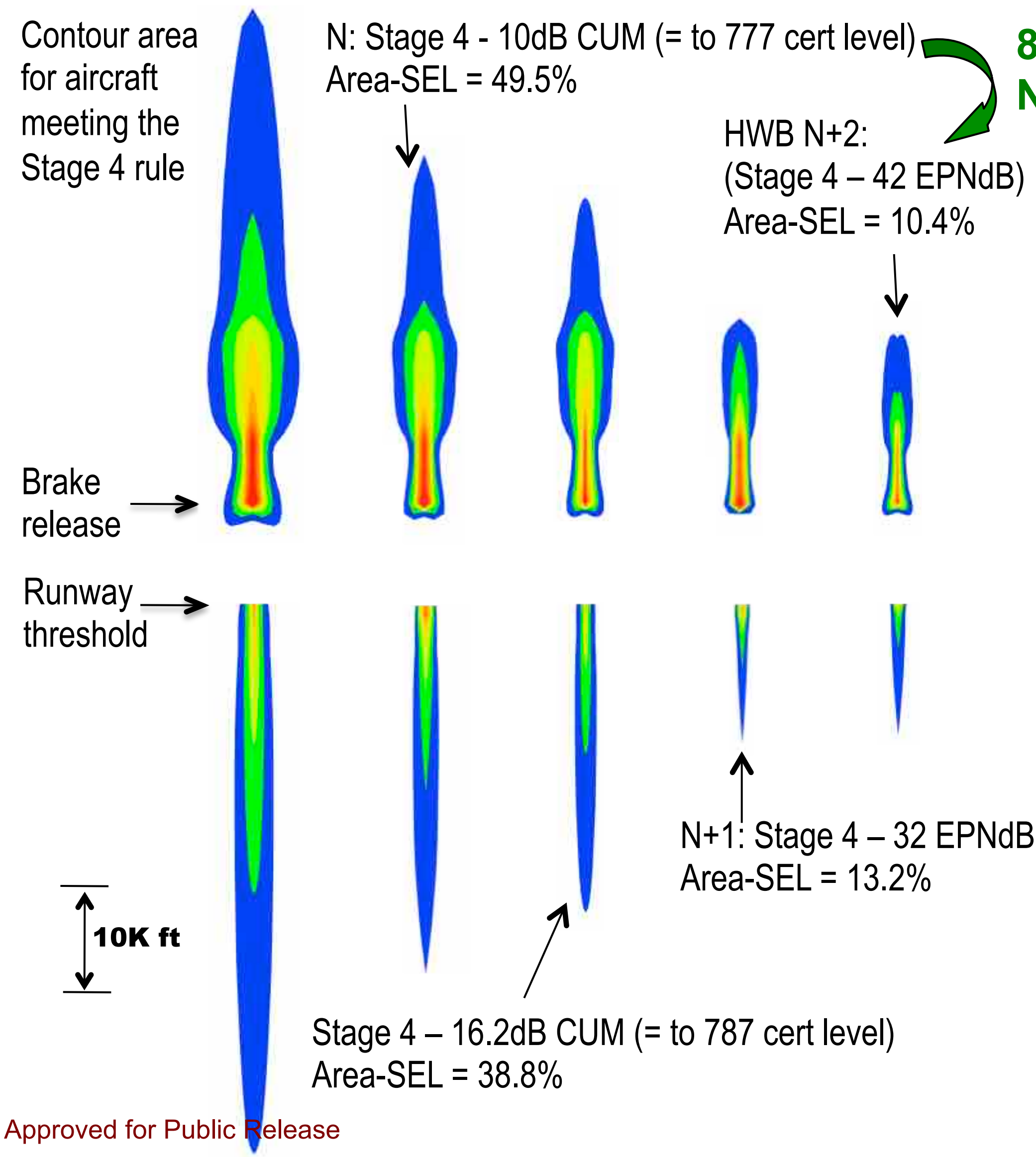
Grand Challenge for Commercial Aviation (1 of 2)
Reduce carbon footprint by 50 percent by 2050



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

Grand Challenge for Commercial Aviation (2 of 2) Contain objectionable noise within airport boundary

Change in noise "footprint" area (within 85 dB) **for a landing and takeoff**



80% Reduction in Noise Footprint Area

- **All contours are for a 777-like aircraft weight and mission, N+2 achieved with HWB aircraft for same 777-like mission**
- **N and N+2 areas are rigorous predictions using analytical tool (ANOPP) with measurements for key installation effects**
- **Stage 4 and N+1 areas are computed from N aircraft to meet required EPNL**
  - **Source levels changed, assumed even distribution between three certification points**
- **Effects of source component directivity and aircraft configuration are included.**
- **Auralizations of ANOPP predictions for straight and level flight at conditions of takeoff and approach**

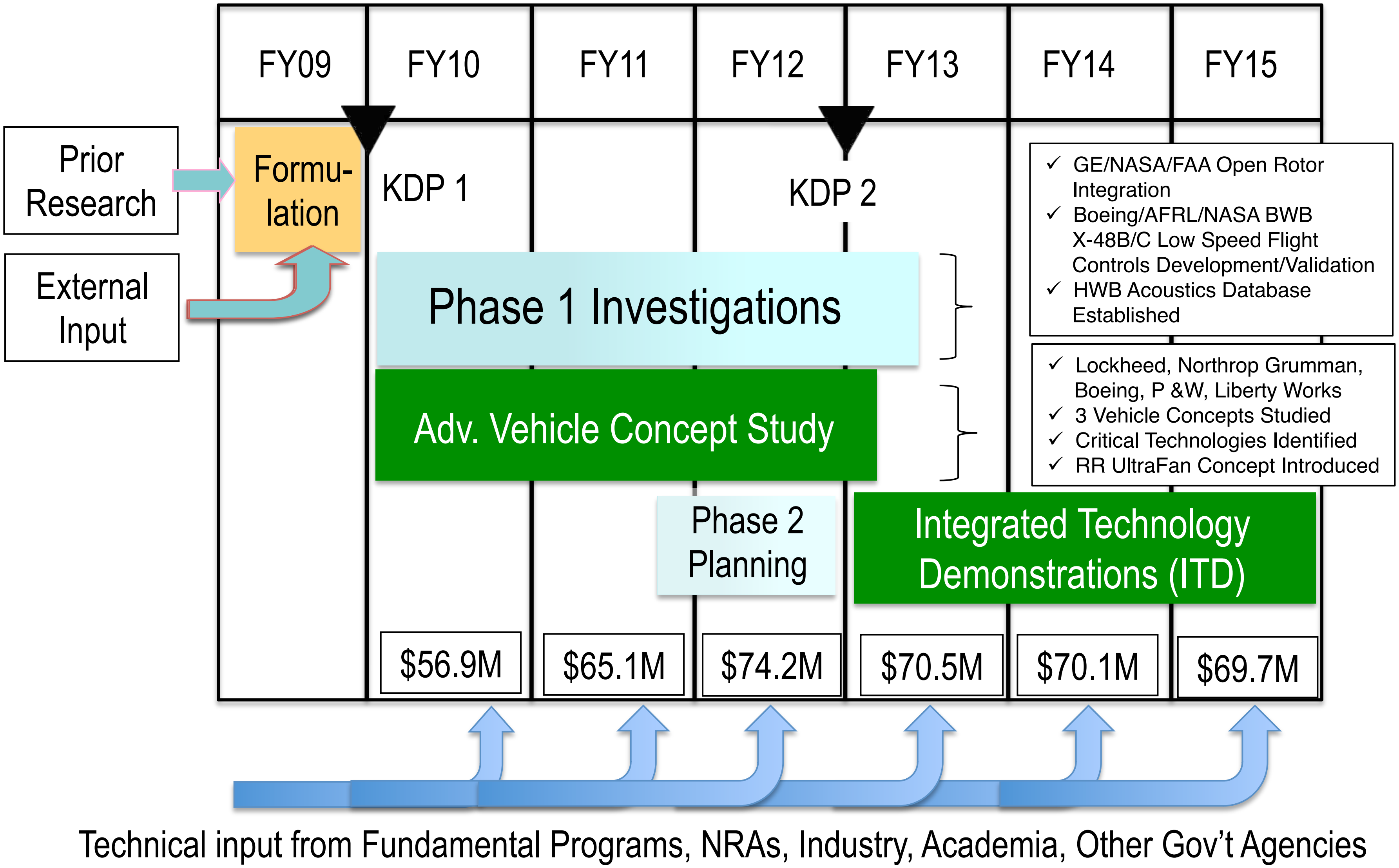
Thomas, R.H., Burley, C.L, and Olson, E.D., "Hybrid Wing Body Aircraft System Noise Assessment with Propulsion Aircraft Aeroacoustic Experiments," *International Journal of Aeroacoustics*, Vol 11 (3+4), pp.369-410, 2012.

Rizzi, S.A., Aumann, A.R., Lopes, L.V., and Burley, C.L.., "Auralization of Hybrid Wing Body Aircraft Flyover Noise from System Noise Prediction," AIAA Paper 2013-0542, January, *2013*.

Environmentally Responsible Aviation Vision, Mission, & Scope

- Vision
  - expand the viable and well-informed trade space for commercial transport design decisions
  - enable simultaneous realization of national noise, emissions, and performance goals (N+2 timeframe)
- Mission
  - Execute integrated technology demonstrations
  - Partner w/Industry/Academia/OGA and transfer knowledge
- Scope
  - Mature technology for application in the 2020+ time frame
    - Advance the state-of-the-art, reduce risk of application
  - Perform system/subsystem research in relevant environments

Environmentally Responsible Aviation Project Flow



ERA Phase 1 Completed Propulsion Activities

Open Rotor technologies were studied during ERA Phase 1 in partnership with GE and FAA. (Aeronautical Journal, Oct 2014)

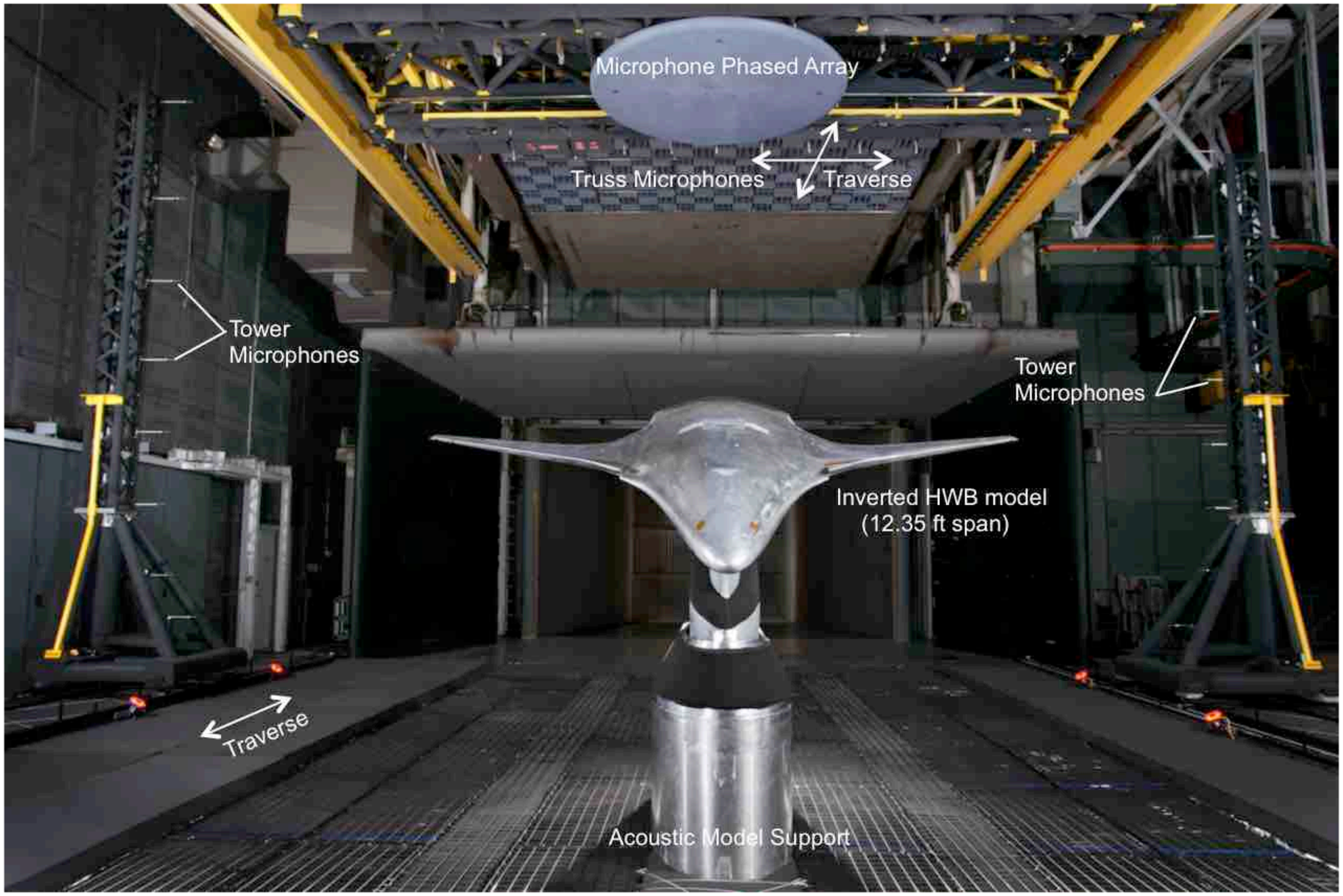
CMC mixer nozzle work in ERA Phase 1 in partnership with Rolls-Royce and AFRL.

+ CMC turbine vanes, CMC combustor liner, active combustion control, lean direct injection, boundary layer ingesting propulsor.

ERA Phase 1 Completed Airframe Activities

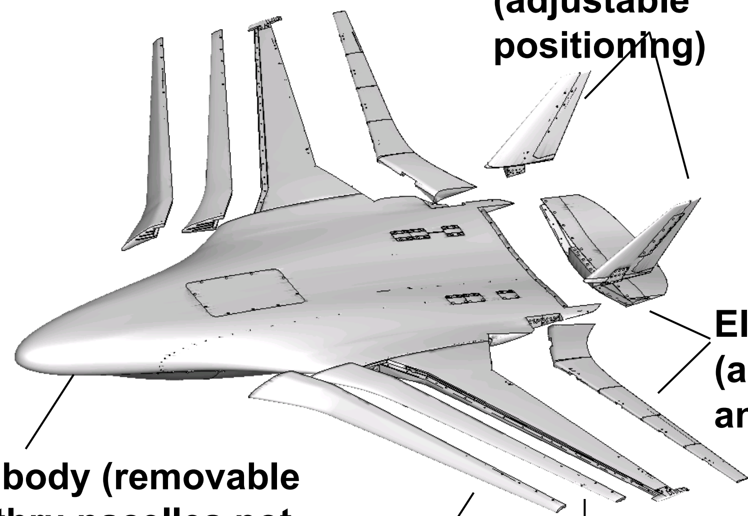
HYBRID WING BODY ACOUSTIC TEST

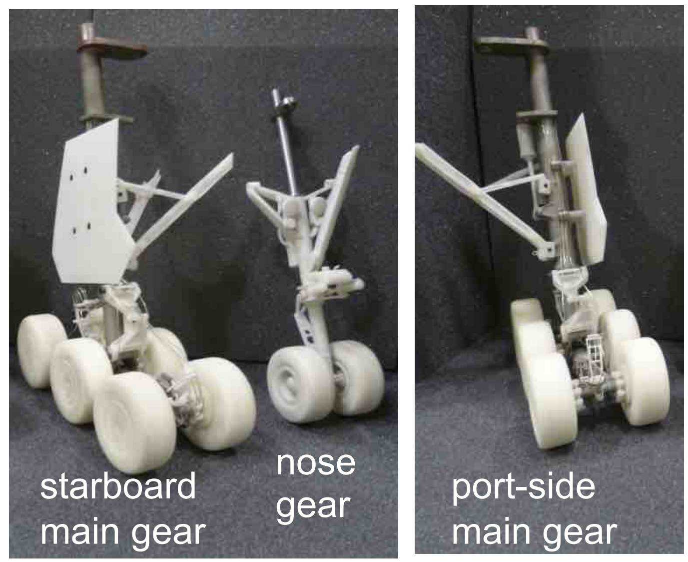
LaRC 14x22 ft. Subsonic Wind Tunnel



- Noise measurements were obtained from Tower and Truss microphones, and from Microphone Phased Array at key streamwise locations.

HWB AIRFRAME MODEL





5.8% scale (12.35 ft span)

Modular components (control surfaces and landing gear)

High fidelity of geometric details

Designed by a team led by Boeing under a NASA Research Announcement

Detailed characterization of :

- **Jet noise and its shielding**
- **Airframe noise**
- **Broadband noise shielding**

Measuring Progress in ERA Phase 2
Goal Decomposition and Technology Selection

2025 Vehicle System Level Goals

Fuel Burn	NO_x	Noise
-50%	-75%	-42EPNdB

Technical Challenge

Progress Indicators

Innovative Flow Control Concepts	Advanced Composites	Advanced UHB Engines	Advanced Combustors	Airframe & Engine Integration
TC 1: 8% Drag Reduction	TC 2: 10% Structural Weight Reduction	TC 3: 15% TSFC and 15 EPNdB Noise Reduction	TC 4: 75% LTO NOx Reduction	TC 5: 42 EPNdB Cum Noise Reduction and 50% Fuel Burn Reduction

P2 Integrated Technology Demonstrations (TRL 4-6)

12A+ AFC VT & Advanced Wing	KPP_{2025}	•Cruise Drag Reduction
21A PRSEUS	KPP_{2025}	•Structural Weight Reduction
21C ACTE	KPP_{2025}	•Wing Weight Reduction
30A Front Block Compressor	KPP_{2025}	•TSFC
35A UHB Propulsor	KPP_{2025}	•TSFC •Cumulative Noise Reduction
40A Low LTO NOx, Fuel Flex Combustor	KPP_{2025}	•LTO NOx
50A Low Noise Flap Edge & Landing Gear	KPP_{2025}	•Airframe Component Noise Reduction
51A UHB Engine Integration on HWB	KPP_{2025}	•Fuel Burn Reduction •Cumulative Noise Reduction

ERA Technology Development & Maturation Plans – Phase 1 and 2

Environmentally Responsible Aviation Technical Challenges

TC1 **Innovative Flow Control Concepts for Drag Reduction**

- Demonstrate drag reduction of 8 percent, contributing to the 50 percent fuel burn reduction goal at the aircraft system level, without significant penalties in weight, noise, or operational complexity

TC2 **Advanced Composites for Weight Reduction**

- Demonstrate weight reduction of 10 percent compared to SOA composites, contributing to the 50 percent fuel burn reduction goal at the aircraft system level, while enabling lower drag airframes and maintaining safety margins at the aircraft system level

TC3 **Advanced UHB Engine Designs for Specific Fuel Consumption and Noise Reduction**

- Demonstrate UHB efficiency improvements to achieve 15% TSFC reduction, contributing to the 50 percent fuel burn reduction goal at the aircraft system level, while reducing engine system noise and minimizing weight, drag, NOx, and integration penalties at AC system level

TC4 **Advanced Combustor Designs for Oxides of Nitrogen Reduction**

- Demonstrate reductions of LTO NOx by 75 percent from CAEP6 and cruise NOx by 70 percent while minimizing the impact on fuel burn at the aircraft system level, without penalties in stability and durability of the engine system

TC5 **Airframe and Engine Integration Concepts for Community Noise and Fuel Burn Reduction**

- Demonstrate reduced component noise signatures leading to 42 EPNdB to Stage 4 noise margin for the aircraft system while minimizing weight and integration penalties to enable 50 percent fuel burn reduction at the aircraft system level

Airframe Technology
Integrated Technology Demonstrators

ITD 21A: Damage Arresting Composite Demonstration

ITD 21A: Damage Arresting Composite Demonstration Overall Approach – Technology Maturation Plan

Weight | Drag | TSFC | Noise | NOx

End TRL: 5

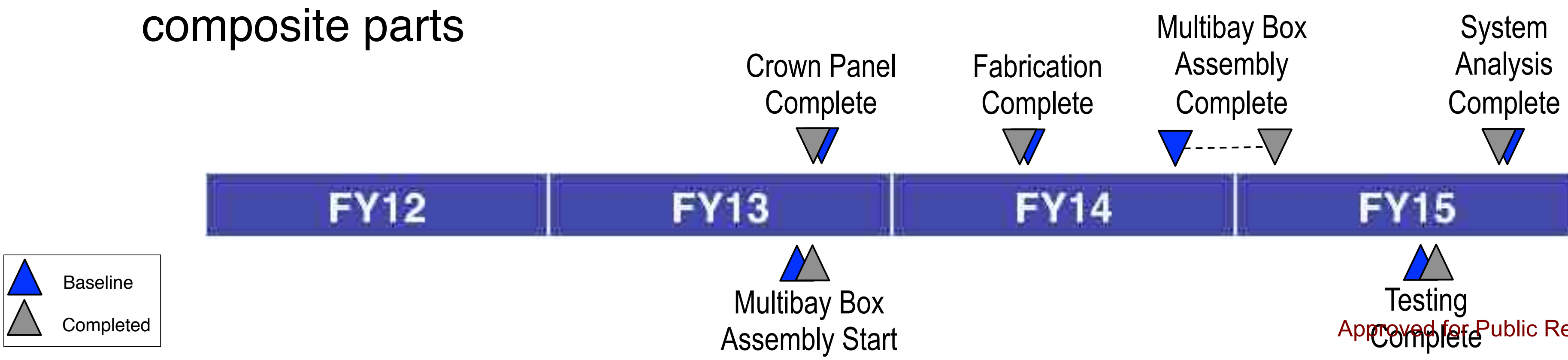
Key Performance Parameters

- Reduce structural weight by 20 percent for LTA Class Aircraft w/GTF Engine

Technology Insertion Challenges Addressed

- Damage tolerance
- Post-buckled composite structure
- Integrated system weight
- Large scale flight weight infused composite parts

Assembled Multi bay Box in C-17 Factory



ITD 21A: Damage Arresting Composites Demonstration Summary Technical Highlight

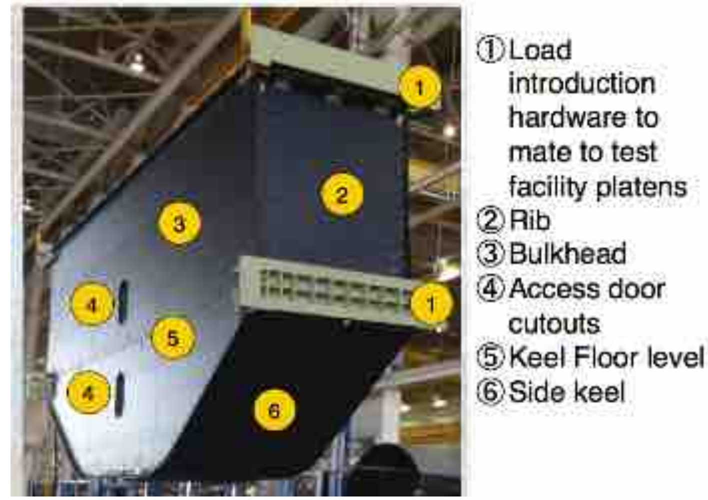
NASA Super Guppy Aircraft picked up the MBB at the Long Beach Airport in Calif. and delivered it to NASA LaRC

Where it was moved to COLTS and installed between the platens for testing

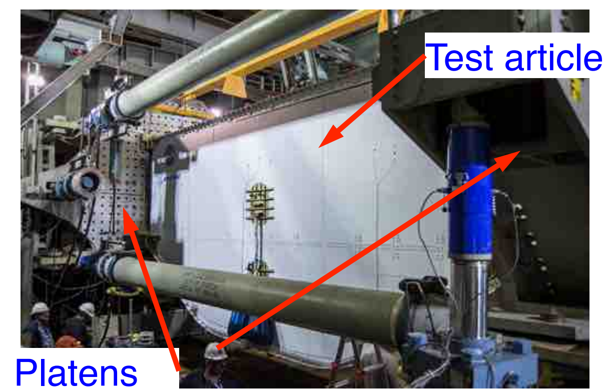
ITD 21A: Damage Arresting Composites Demonstration Summary Technical Highlight

Requirements
- Fabricate an aerospace-quality large-scale pultruded rod stitched efficient unitized structural (PRSEUS) test article representative of a HWB centerbody.
- Demonstrate that the pristine PRSEUS multi-bay pressure box could support design ultimate load in five critical loading conditions.
- Demonstrate that the damaged PRSEUS multi-bay pressure box could support design ultimate load in five critical loading conditions.
- Demonstrate that analytical tools and modeling techniques are adequate for predicting structural response of complex PRSEUS structures.

Accomplishments
- A high-quality 30-ft long, 6.5-ft wide, 13.5-ft tall multi-bay pressure box test article was fabricated from 11 PRSEUS panels, 4 sandwich panels, fasteners, metal fittings and load-introduction elements.
- The test article was installed in the NASA Langley Research Center Combined Loads Test System facility and loaded to design ultimate load in up-bending, down-bending, internal pressure and combinations of pressure and mechanical load in the pristine condition, with barely visible impact damage and with discrete source damage.
- Finite element analysis predictions showed good agreement with test data.



Test article



Test article mounted in COLTS

Propulsion Technology
Integrated Technology Demonstrators

30A: Highly Loaded Front Block Compressor (GE)
35A: 2nd Gen UHB Propulsor Integration (P&W and FAA)
40A: Low NOx, Fuel Flexible Combustor Integration (P&W)

Integrated Technology Demonstrator
Highly Loaded Front Block Compressor Demonstration

Weight | Drag | TSFC | Noise | NOx

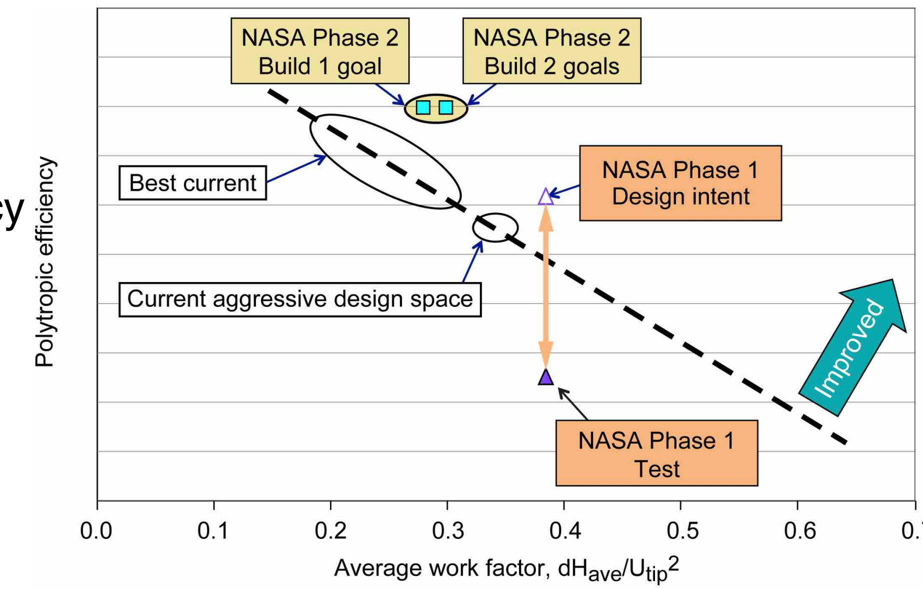
End TRL: 5

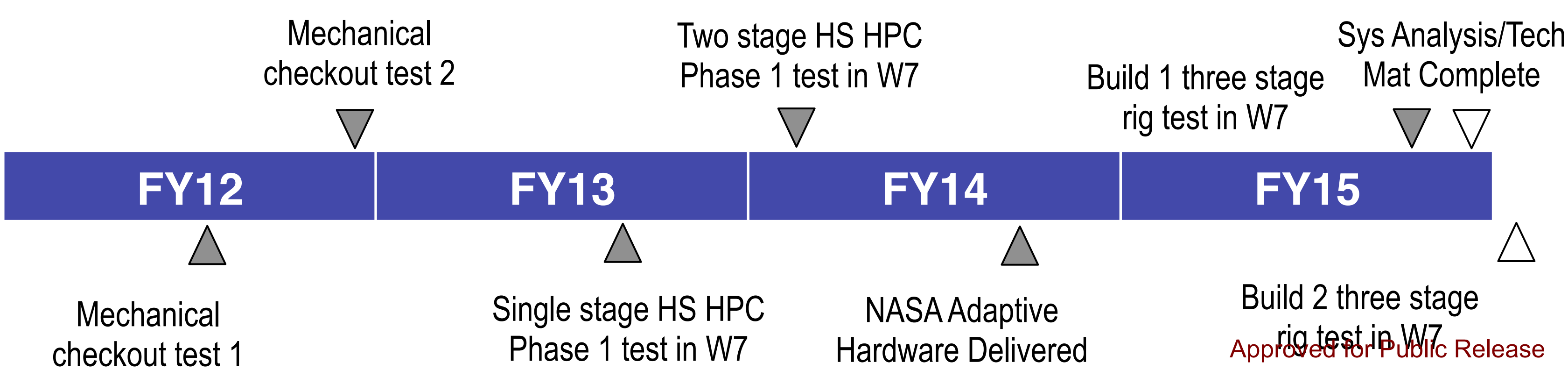
Key Performance Parameters

- Reduce TSFC by 2.5 percent

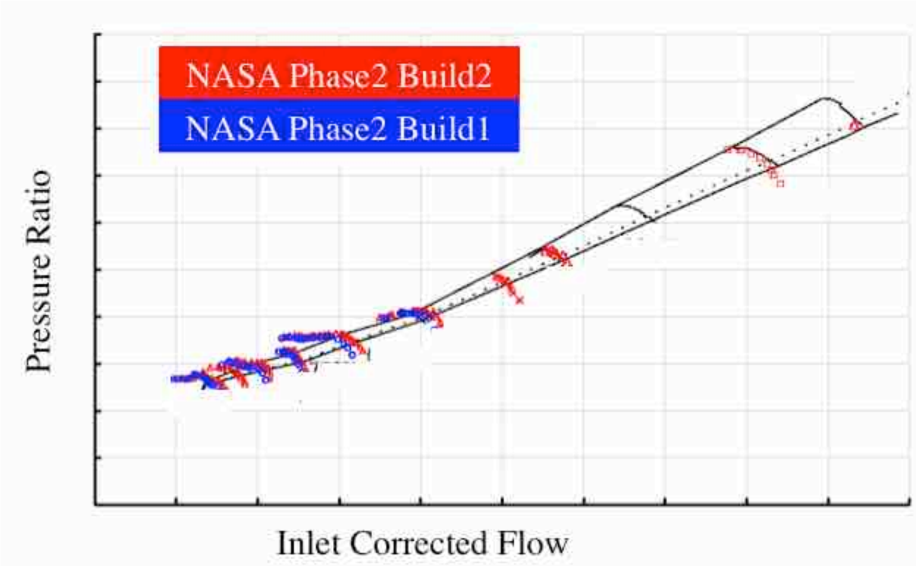
Technology Insertion Challenges Addressed

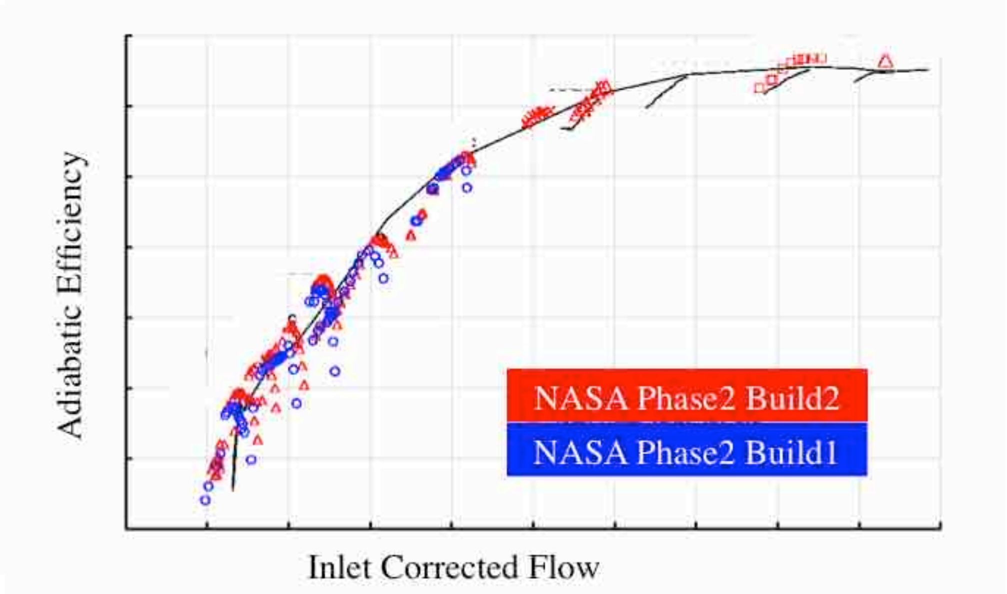
- Front block aerodynamic losses limit efficiency
- Identify loss mechanisms and interaction effects of highly-loaded compressor stages
- Trade-off OPR, Efficiency, and operability to optimize fuel burn
- Establish part-speed operability margin
- Integrated 1st 3 stages of HPC





Integrated Technology Demonstrator
Highly Loaded Front Block Compressor Demonstration





From Celestina, Green Aviation TIM, March 2016.

ITD30A validated a 2.9% TSFC reduction for the technology.

Integrated Technology Demonstrator
2nd Generation UHB Propulsor Integration

Weight | Drag | TSFC | Noise | NOx

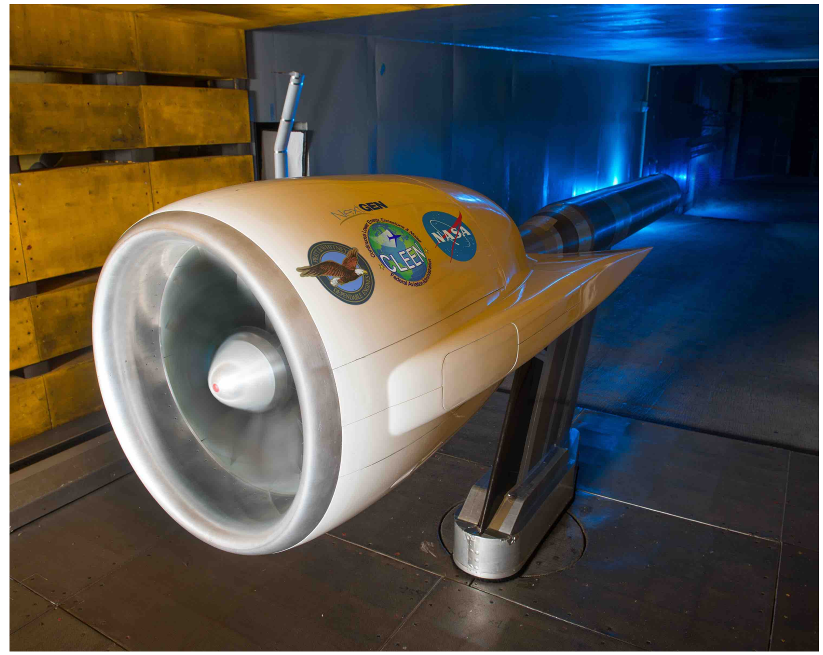
End TRL: 5

Key Performance Parameters

- Reduce noise by 15 EPNdB
- Reduce TSFC by 9 percent

Technology Insertion Challenges Addressed

- Noise reduction & aero performance of advanced liners validated: 1 – 2 EPNdB
- Comprehensive- modern database of propulsor multi-discipline performance characteristics for sys analysis created.
- Integrated performance of modern fan + advanced FEGVs + short inlet verified



FY12 | FY13 | FY14 | FY15

SMA VAN Prototype Demo

UHB OTR Perf. Risk Mitigation Test

UHB OTR/SV Noise Reductions Validation Test

Integrated System LS Test

UHB Gen 2 Test

Integrated Systems Design Task Start

UHB Integ. System DDR

UHB Low Loss FEGVs Test

Sys Analysis/Tech Mat Complete

Integrated Technology Demonstrator
2nd Generation UHB Propulsor Integration

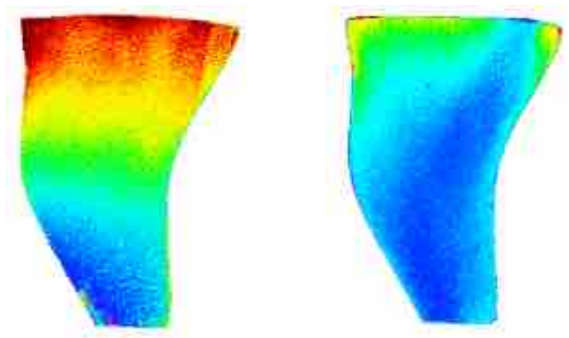


Image Credit: NASA

Pressure & temperature sensitive paint utilized over range of operating lines

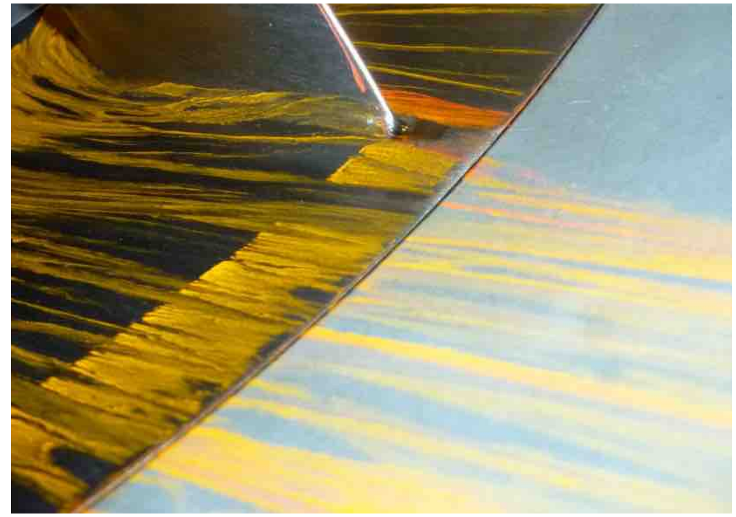


Photo Credit: Pratt & Whitney

Oil pigmentation gave insight into aerodynamic behavior

ITD35A validated performance and acoustics for the propulsor that exceeded the goals of 9% TSFC reduction and 15 EPNdB noise reduction for the technology.

Integrated Technology Demonstrator
Fuel Flexible, Low NOX Combustor Integration

Weight | Drag | TSFC | Noise | NOx

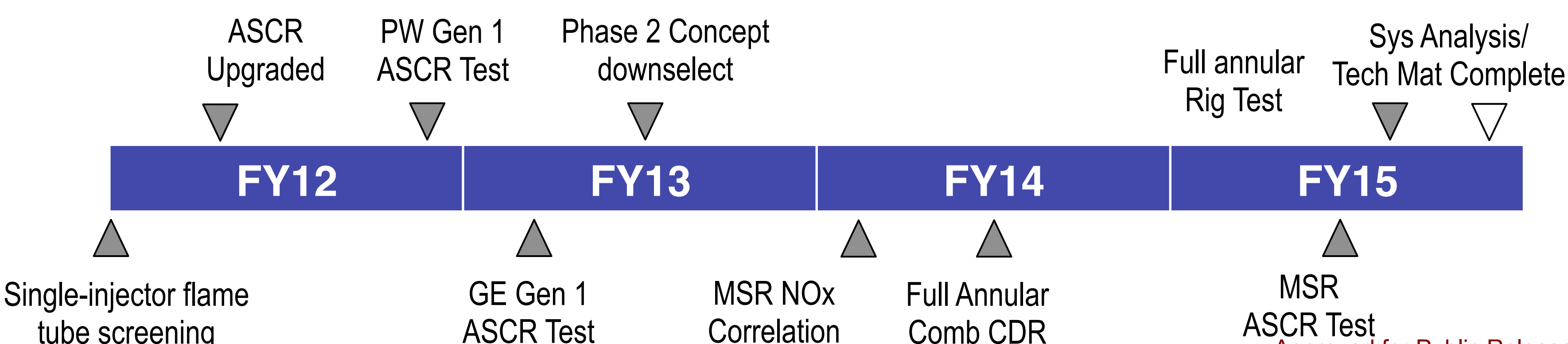
End TRL: 5

Key Performance Parameters

- Reduce LTO NOx by 75 percent

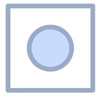
Technology Insertion Challenges Addressed

- Lean burn system operability concerns
  - Auto-ignition
  - Flame stability
  - Acoustic resonance
- Durability for lean burn configuration
- 50/50 jet/alt fuel mixture

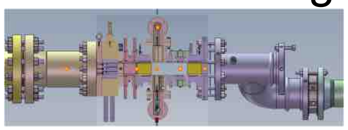


Integrated Technology Demonstrator
Fuel Flexible, Low NOX Combustor Integration

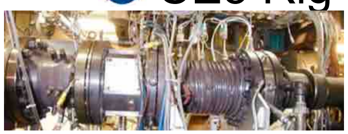
Single Sector



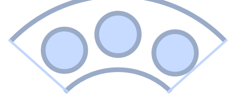
United Technologies Research Center AAC Rig



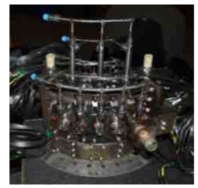
CE5 Rig



Multi-Sector

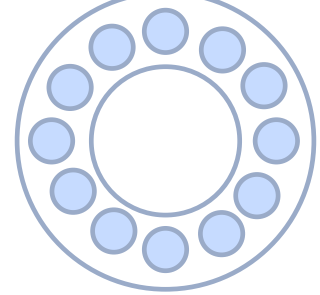


United Technologies Research Center Arc Sector Rig

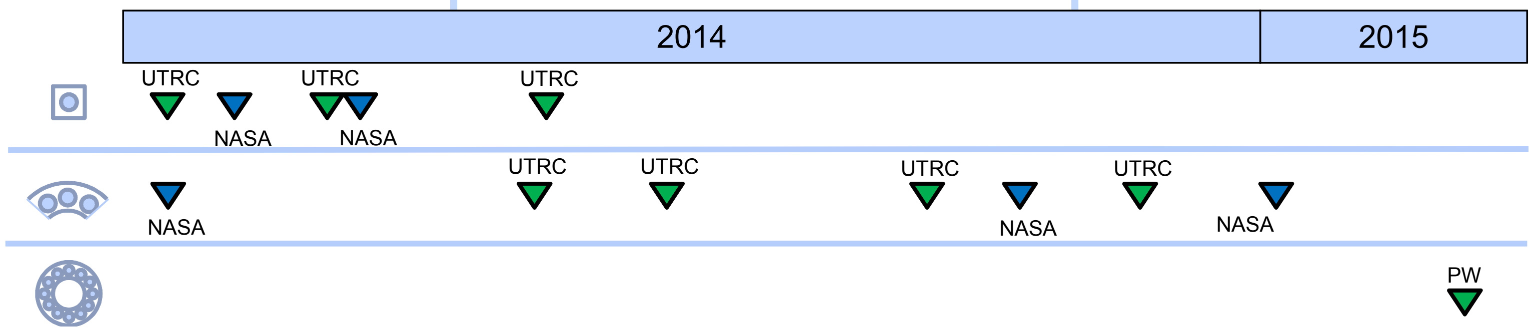


ASCR Rig

Full Annular



X960 Rig



ITD40A was fully successful in validating greater than 75% NOx reduction re/CAEP6 with a durable lean-lean combustor system that is compatible with alt fuel blends.

Integrated Technology Demonstrators Summary Performance

	Integrated Technology Demonstrators	Partner(s)	Min Success	Full Success	Plan/Actual Impact (2025)
12A+	AFC Enabled Vertical Tail and Advanced Wing Flight Test	Boeing			-1.5 / -0.92+% Tail Drag -3 / -3.3% Wing Drag (NLF)
21A	Damage Arresting Composites Demonstration	Boeing			-20 / - 20+ % Structural Weight
21C	Adaptive Compliant Trailing Edge Flight Test	AFRL/ FlexSys			-5 / -8+% Wing Weight
30A	Highly Loaded Front Block Compressor Demonstration	General Electric			-2.5 / -2.94% TSFC
35A	2nd Generation UHB Propulsor Integration	Pratt & Whitney/ FAA			-9 / -10.9% TSFC -15 / -20.9 EPNdB
40A	Fuel Flexible, Low NOX Combustor Integration	Pratt & Whitney			-75 / -81% LTO NOX
50A	Landing Gear and Flap Edge Noise Reduction Flight Test	Gulfstream			LG -1.0 / -1.0+ EPNdB FE -3.0 / -3+ EPNdB
51A	UHB Integration on Hybrid Wing Body Aircraft	Boeing			-42 / -40+ EPNdB -50 / -47+% Fuel Burn

Potential Impacts
Vehicle Level – AIAA 2016-1030 & 0863

Assessment of the Noise Reduction Potential of Advanced Subsonic Transport Concepts for the NASA Environmentally Responsible Aviation Project

Russell H. Thomas, Casey L. Burley, and Craig L. Nickol
NASA Langley Research Center

AIAA SciTech 2016
San Diego, California
January 5, 2016
AIAA Paper 2016-0863

Potential Impacts
Vehicle Level – AIAA 2016-1030 & 0863

Assessment of the Performance Potential of Advanced Subsonic Transport Concepts for NASA's Environmentally Responsible Aviation Project

Craig Nickol
NASA Langley Research Center

Bill Haller
NASA Glenn Research Center

AIAA SciTech 2016
San Diego, California
January 6, 2016

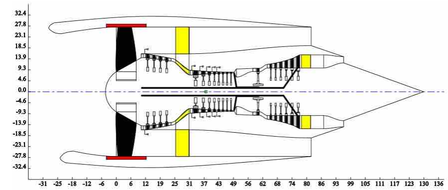
AIAA Paper 2016-1030

Potential Impacts
Vehicle Level – AIAA 2016-1030 & 0863

RJ

T+W98-DD
(2) Small DD

OWN98-DD
(2) Small DD

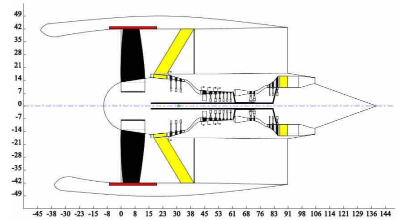


Small DD

SA

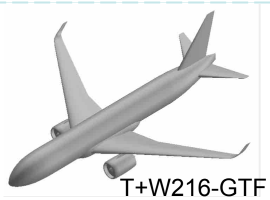
T+W160-GTF
(2) Small GTF

OWN160-GTF
(2) Small GTF

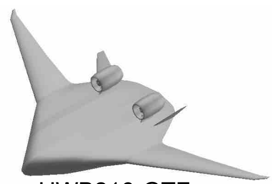


Small GTF

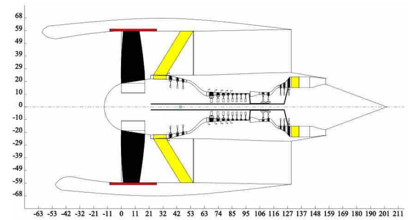
STA



T+W216-GTF
(2) Medium GTF

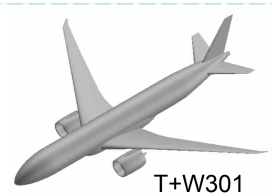


HWB216-GTF
(2) Medium GTF

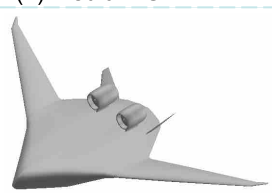


Medium GTF

LTA

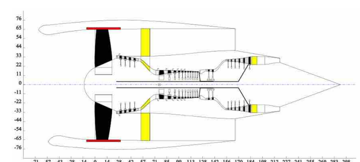


T+W301
(2) Large DD
(2) Large GTF

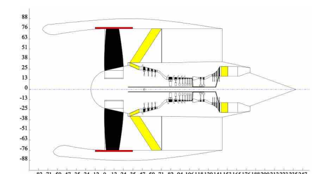


HWB301
(2) Large DD
(2) Large HWB GTF

MFN301-GTF
(2) Large GTF

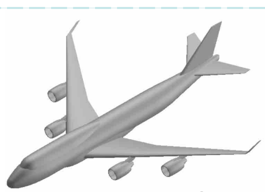


Large DD

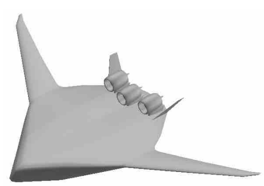


Large GTF T+W
Large HWB GTF (not shown)

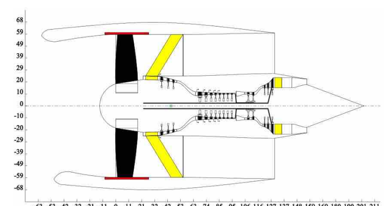
VLTA



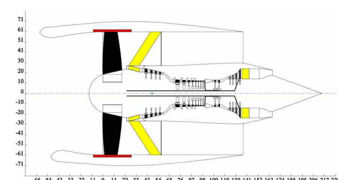
T+W400-GTF
(4) Medium GTF



HWB400-GTF
(3) Medium HWB GTF



Medium GTF



Medium HWB GTF

Potential Impacts
Vehicle Level - Best Performers

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6) v2013.1		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-52 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‡ (rel. to 2005 best in class)	-33%	-50%	-60%

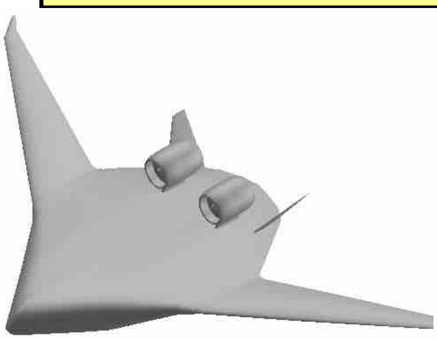
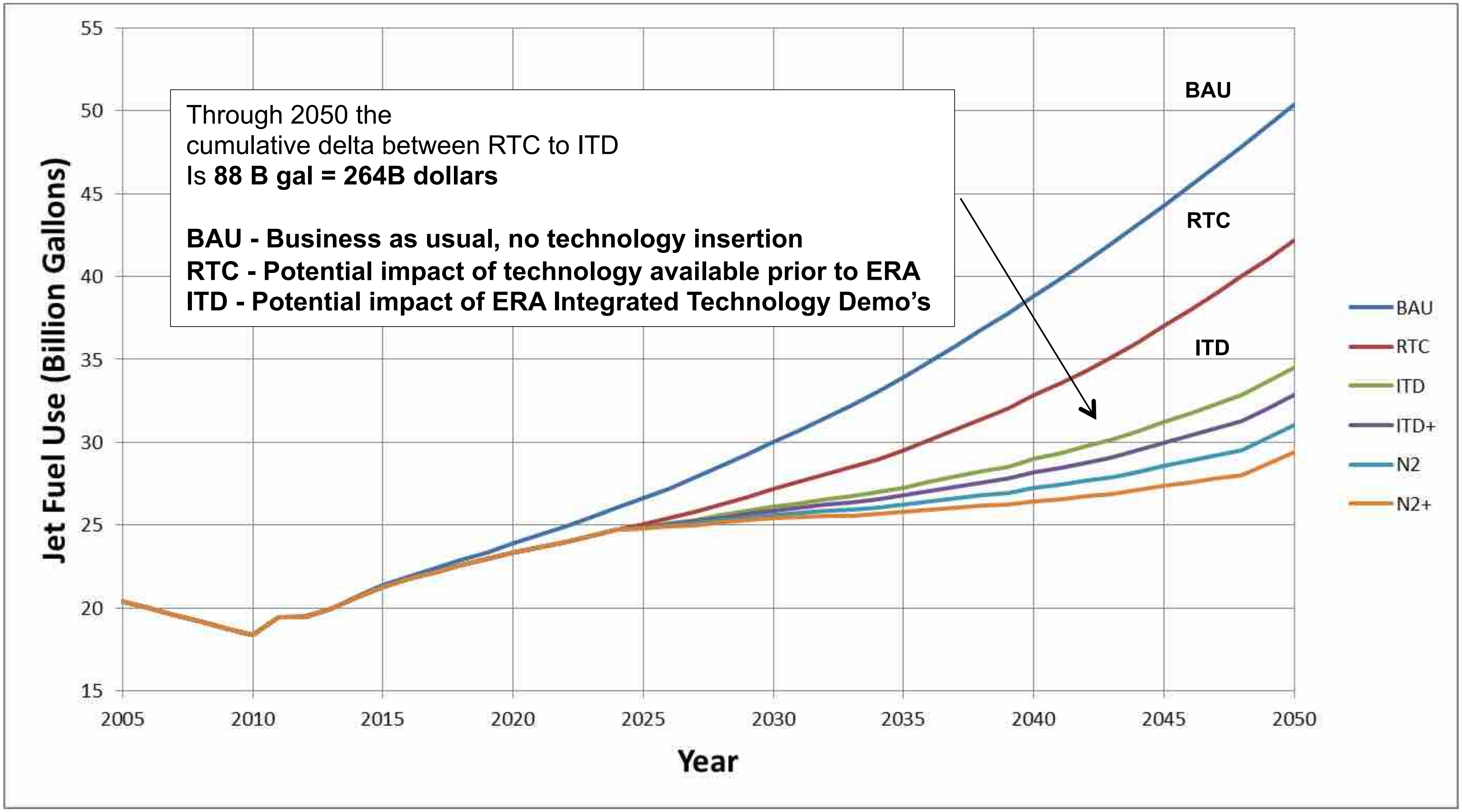


Table 15. N+2 HWB-GTF Concept Performance Summary

	Noise	Fuel Burn	Emissions
ERA Target	-42 dB Cumulative Margin to Stage 4	-50% Block Fuel Burn Relative to 2005 Best-in-Class	-75% LTO Nox relative to CAEP/6
HWB301-GTF	-40.3	-47	-79
HWB400-GTF	-40.3	-49.4	-79

Potential Impacts
US Fleet Level – Carbon Footprint



Notes – (1) This "what-if" scenario assumes ITD technology finds it way into the fleet in 2025. (2) ITD wedge above based on transition of ITD techs to tube and wing only in 2025.

Technical Accomplishments - Summary

- It is feasible that Open Rotor Systems will meet current noise standard
- Laminar flow applications have been applied by Boeing to B787
  - Main wing, high Rn applications are the final challenge
- Active flow control applications are still being investigated
- Compliant wing technology is feasible. Large impact on tube & wing
  - Aviation Partners has teamed with FlexSys
- A scalable low NOX, fuel-flexible combustor that exceeds the current regulation with an engine w/advanced fan blade system is feasible
  - Application to future engine products are being explored
- Highly loaded compressor blading is feasible
  - Application to future engine products are being explored
- The Rolls Royce UltraFan engine concept shows great promise
- Feasible noise reduction technologies for engine and airframe emerged
- The NASA/Boeing HWB / GTF configuration was matured further
  - Low speed aero, structures, and operability issues solved
- Less mature, over the wing configurations also show promise toward goals

Future work/Collaboration opportunities

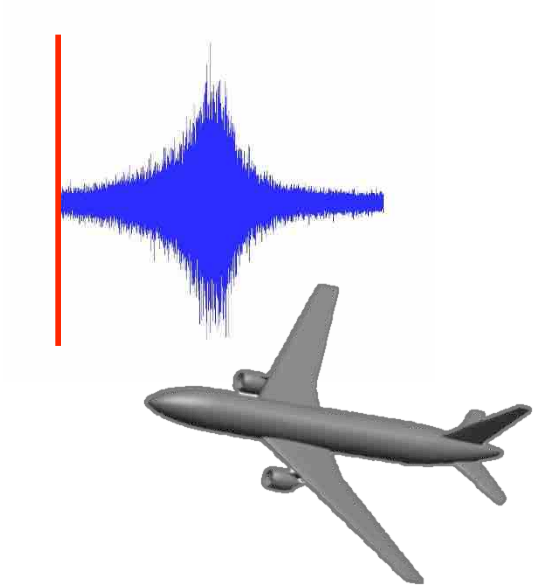
Propulsion specific

- Advanced Air Transport Technology Project (AATT)
  - Next Generation Propulsors – ducted/unducted propulsors and PAI
  - Boundary Layer Ingesting Propulsors – distortion tolerant
  - Advanced combustors – compact and low NOx for high P/T cores
  - Compact cores – stable and efficient
  - Hybrid Gas Electric Propulsion – new engine options

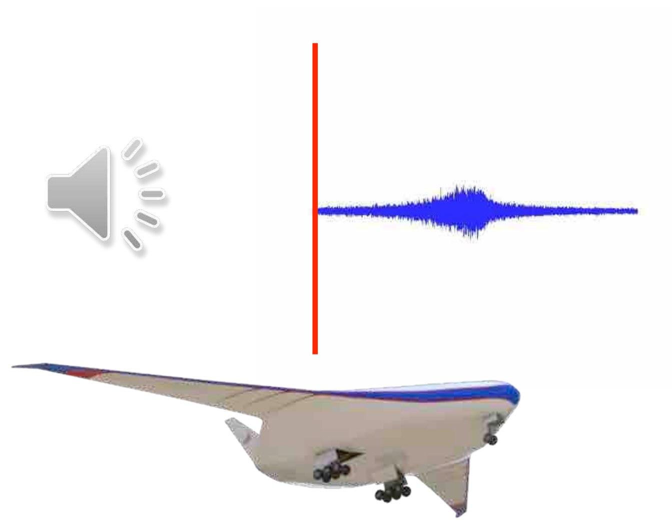
- Flight Demonstrations and Capabilities Project (FDC)
- New Aviation Horizons (NAH) – flight demonstrators

Potential Impacts
What does Stage 4 - 40 EPNdB sound like?

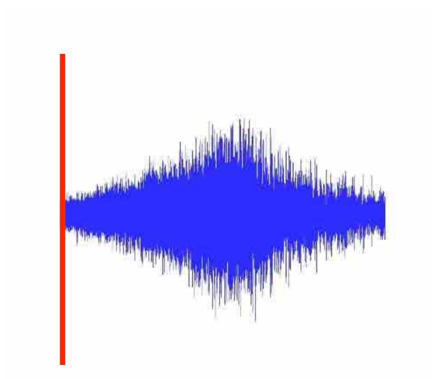
LTA Ref (NASA model of 777-GE90-110B) on Approach



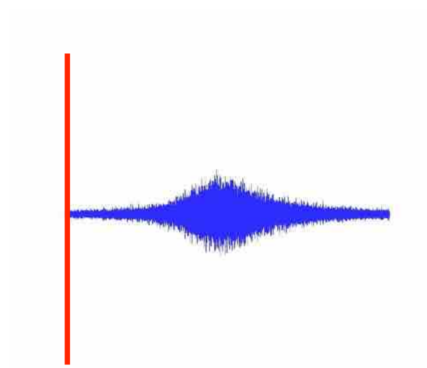
HWB301-GTF w/ITDNR on Approach



LTA Ref (NASA model of 777-GE90-110B) on Sideline



HWB301-GTF w/ITDNR on Sideline



"Auralization of NASA N+2 Aircraft Concepts from System Noise Predictions," Rizzi, Burley, and Thomas, 22nd AIAA/CEAS Aeroacoustics Conference, 30 May – 1 June, 2016, (accepted for publication).

Thrust 3 - Ultra-Efficient Commercial Vehicles ERA Project Focus

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6) v2013.1		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-52 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‡ (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_2 emission benefits dependent on life-cycle CO_2e per MJ for fuel and/or energy source used

ERA Focus

Complete Alignment with the NASA Strategic Implementation Plan & The National Aeronautics R& D Plan

Potential Impacts
Vehicle Level – AIAA 2016-1030 & 0863

- NPSS – Numerical Propulsion Simulation System
  - ITD and partner data utilized to help create input assumptions
- WATE++ - Weight Analysis for Turbine Engines
- FLOPS & OpenVSP – Flight Optimization System & Vehicle Sketch Pad
  - HCDStruct utilized for HWB weights analysis
  - FUN3D corrections utilized for HWB aero analysis
  - ITD and partner data utilized to help create input assumptions
- HCDStruct – Hybrid Wing Body Conceptual Design and Structural Optimization
  - New capability developed under ERA
  - Wing-tip to wing-tip HWB finite element model with NASTRAN solver
  - Validated using Boeing benchmark cases (OREIO, 9H1)
- MVL-15 – Modified Vortex Lattice for Low Speed Aerodynamic Performance Estimation
  - New semi-empirical capability developed under ERA
  - Provides low speed drag polars for tube+wing aircraft
  - Capable of analyzing multi-element high lift systems
- ANOPP2 – Aircraft Noise Prediction Program
  - ITD and partner data utilized to help create refined input assumptions and improved predictions
  - Shielding, fan noise, and noise reduction technology impact estimates supported by test data
  - New prediction capabilities developed

Potential Impacts
Vehicle Level – AIAA 2016-1030 & 0863

Table 13. N+2 Large Twin Aisle class T+W and HWB Concepts

		Large Twin Aisle			
					
	Units	T+W301-DD	T+W301-GTF	HWB301-DD	HWB301-GTF
TOGW	lb	570,195	570,533	537,641	534,491
OEW	lb	265,290	270,084	251,281	253,326
Payload	lb	118,100	118,100	118,100	118,100
# Pax		301	301	301	301
Range	nm	7500	7500	7500	7500
Total Fuel	lb	186,805	182,349	168,259	163,065
Block Fuel	lb	168,687 (-39.1%)	164,748 (-40.6%)	151,597 (-45.3%)	147,011 (-47.0%)
Wing Area	ft^2	4664	4670	10169	10169
Wing Span	ft	226.5	226.6	250	250
Wing Aspect Ratio		11	11.0	6.2	6.1
Wing Loading	lb/ft^2	122.2	122.2	52.9	55.9
Cruise Mach		0.84	0.84	0.84	0.84
Start of Cruise L/D		22.1	22.0	23.8	23.7
Number of Engines		2	2	2	2
Thrust per Engine	lb	71800	74,000	65,989	69,398
Start of Cruise SFC		0.483	0.467	0.49	0.475

Notes – (1) Impacts also modeled all other seat classes. (2) HWB- GTF vehicles provided the best overall performance