National Aeronautics and Space Administration

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

Fayette Collier, Ph.D., M.B.A.
Former ERA Project Manager

Currently, Associate Director for Flight Strategy
Integrated Aviation Systems Program
New Aviation Horizons

UTIAS Workshop
On Aviation and Climate Change
May 2016

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

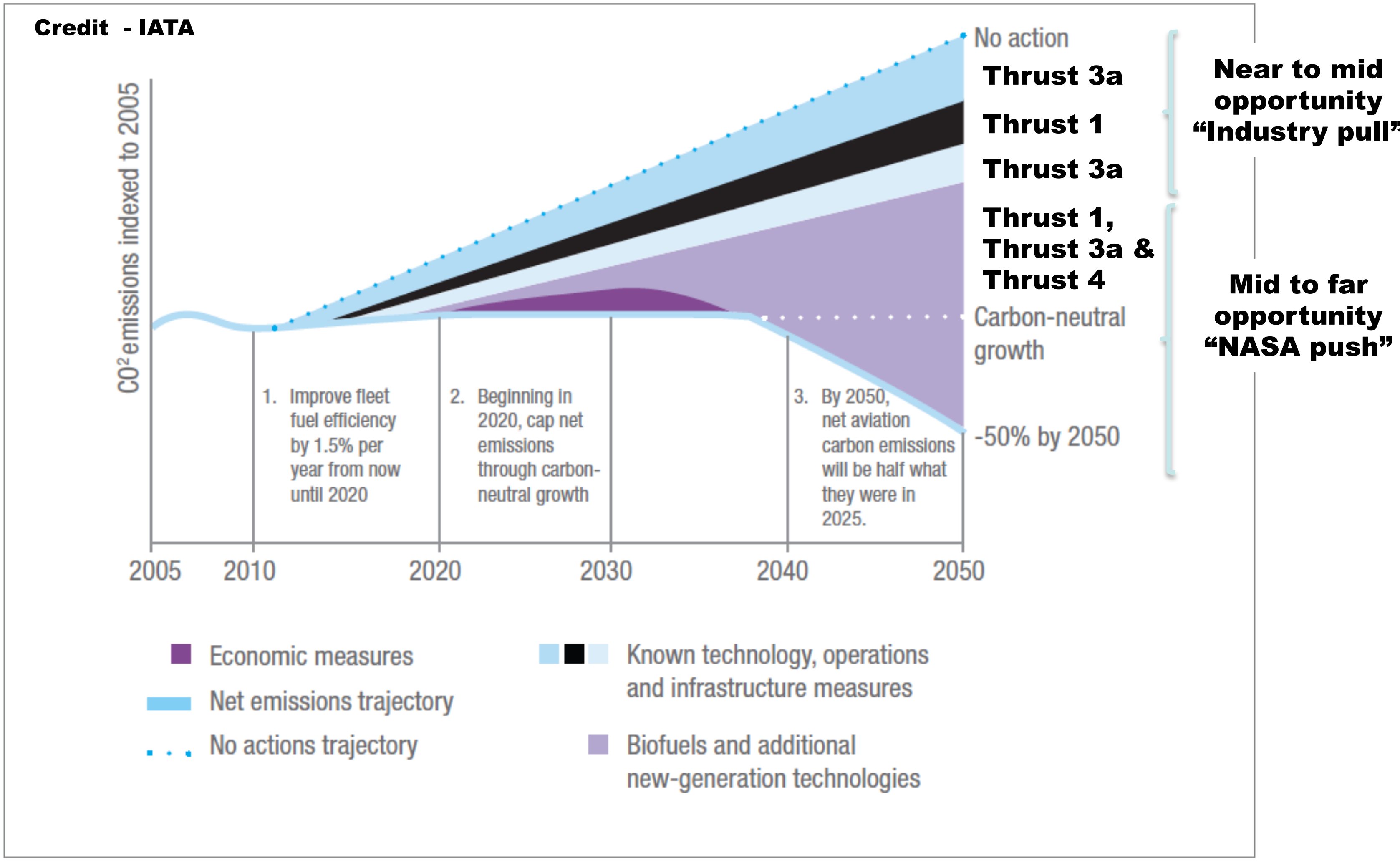
Transition to Low-Carbon Propulsion
- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

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

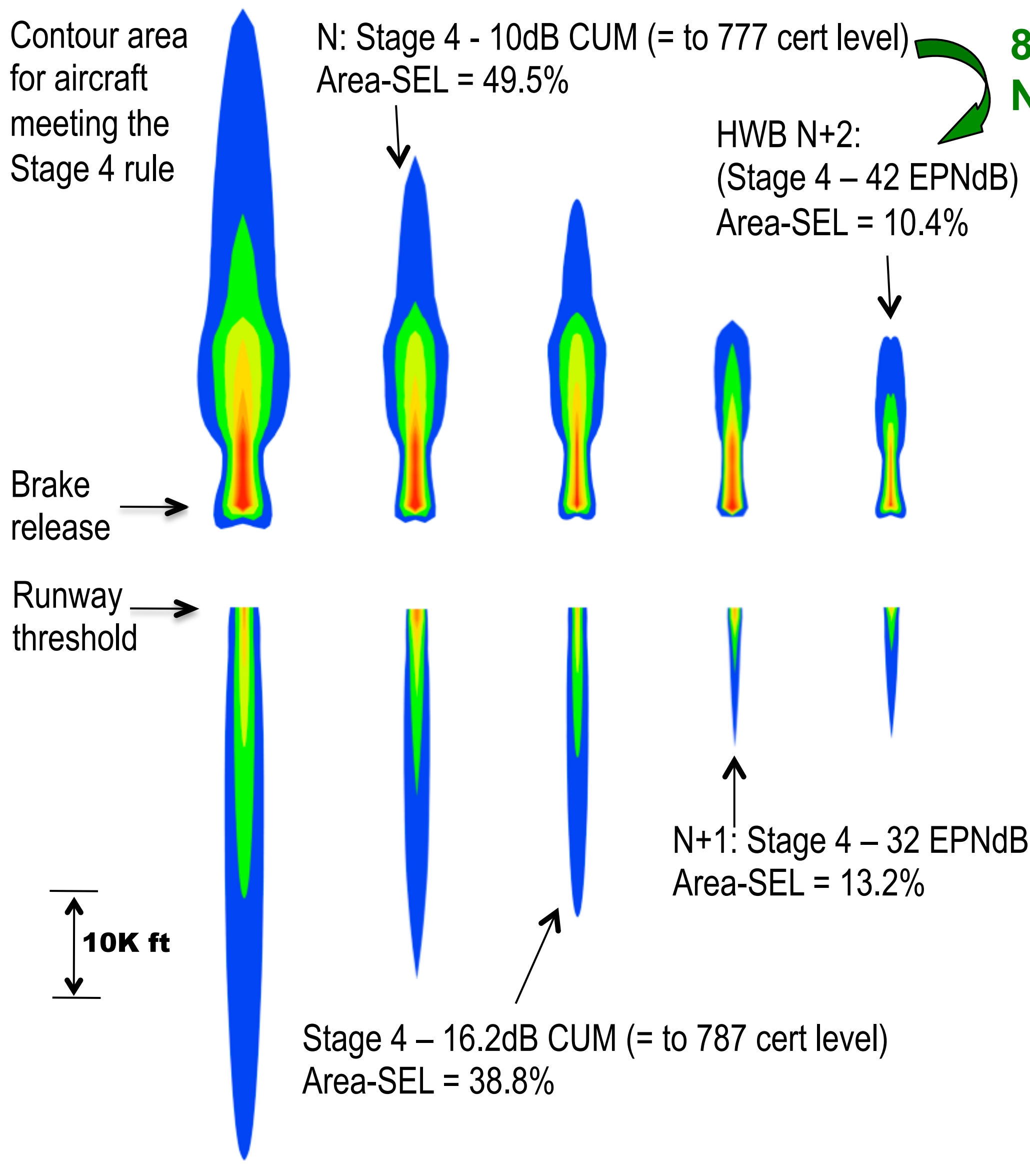
Grand Challenge for Commercial Aviation (2 of 2)
Reduce carbon footprint by 50 percent by 2050



…. 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 (1 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**

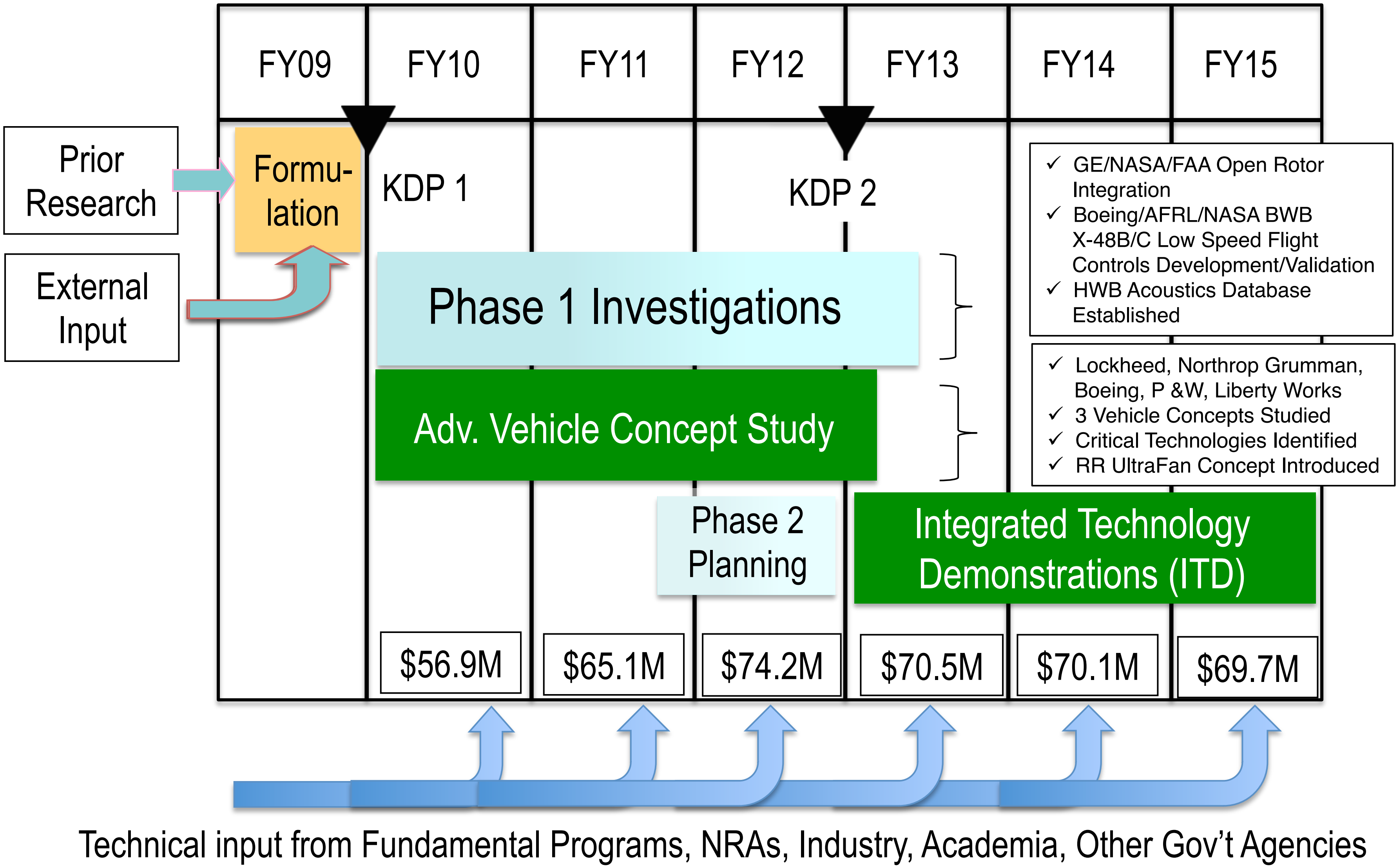
Thomas, R.H., Burley, C.L, and Olson, E.D., "Hybrid Wing Body Aircraft System Noise Assessment with Propulsion Aircraft Aeroacoustic Experiments," ***International Journal of Aeroacoustics*****, Vol 11 (3+4), pp.369-410, 2012.**

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-____, 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



Thrust 3 - Ultra-Efficient Commercial Vehicles ERA Project Focus

v2013.1

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	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 → (N+2 column)

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

Measuring Progress
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

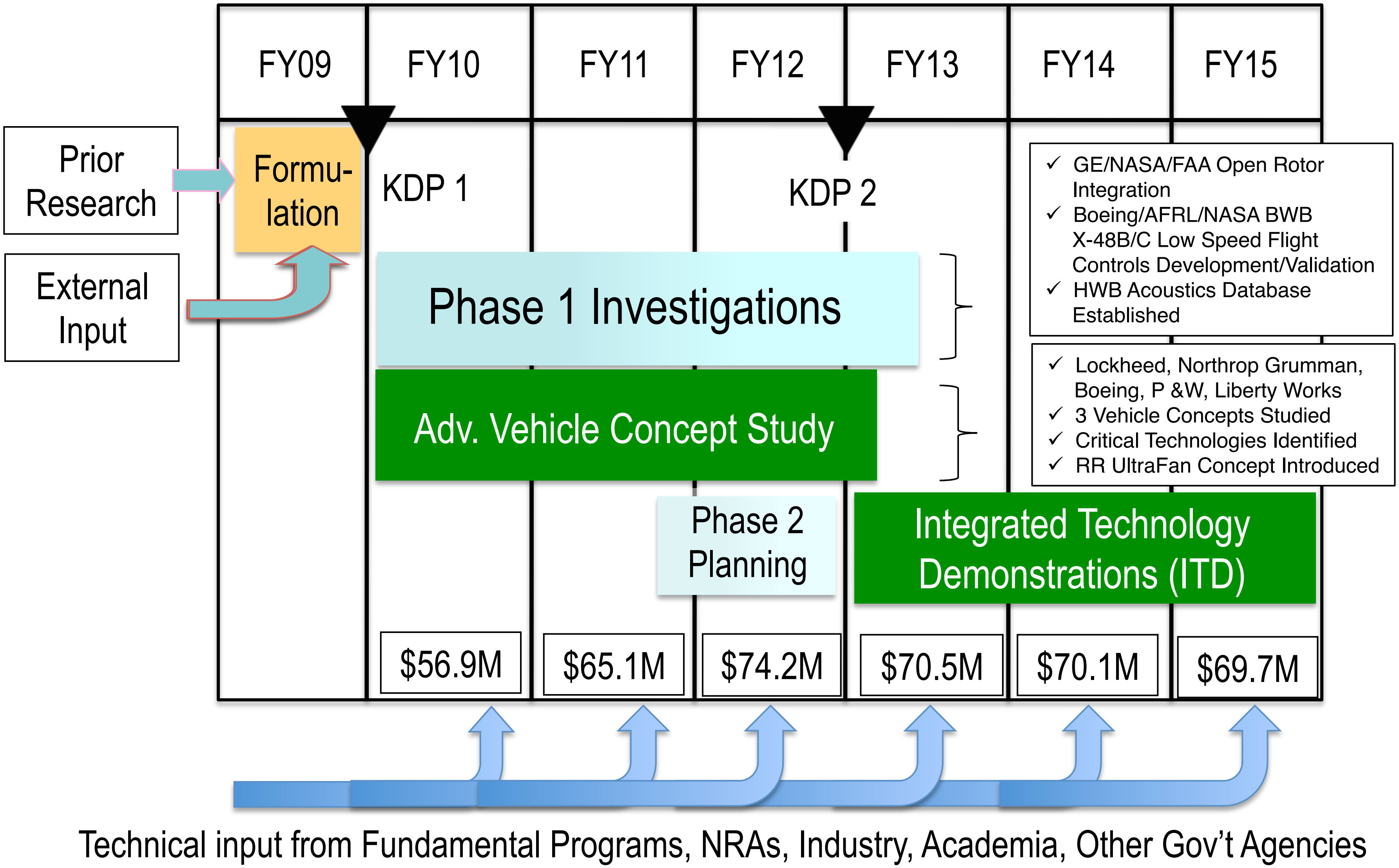
TC4 **Advanced Combustor Designs for Oxides of Nitrogen Reduction**
– Demonstrate reductions of LTO NOx by 75 percent from CAEP6 and cruise NOx by 70 percent while minimizing the impact on fuel burn at the aircraft system level, without penalties in stability and durability of the engine system

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

Integrated Technology Demonstrators Summary Performance Goals

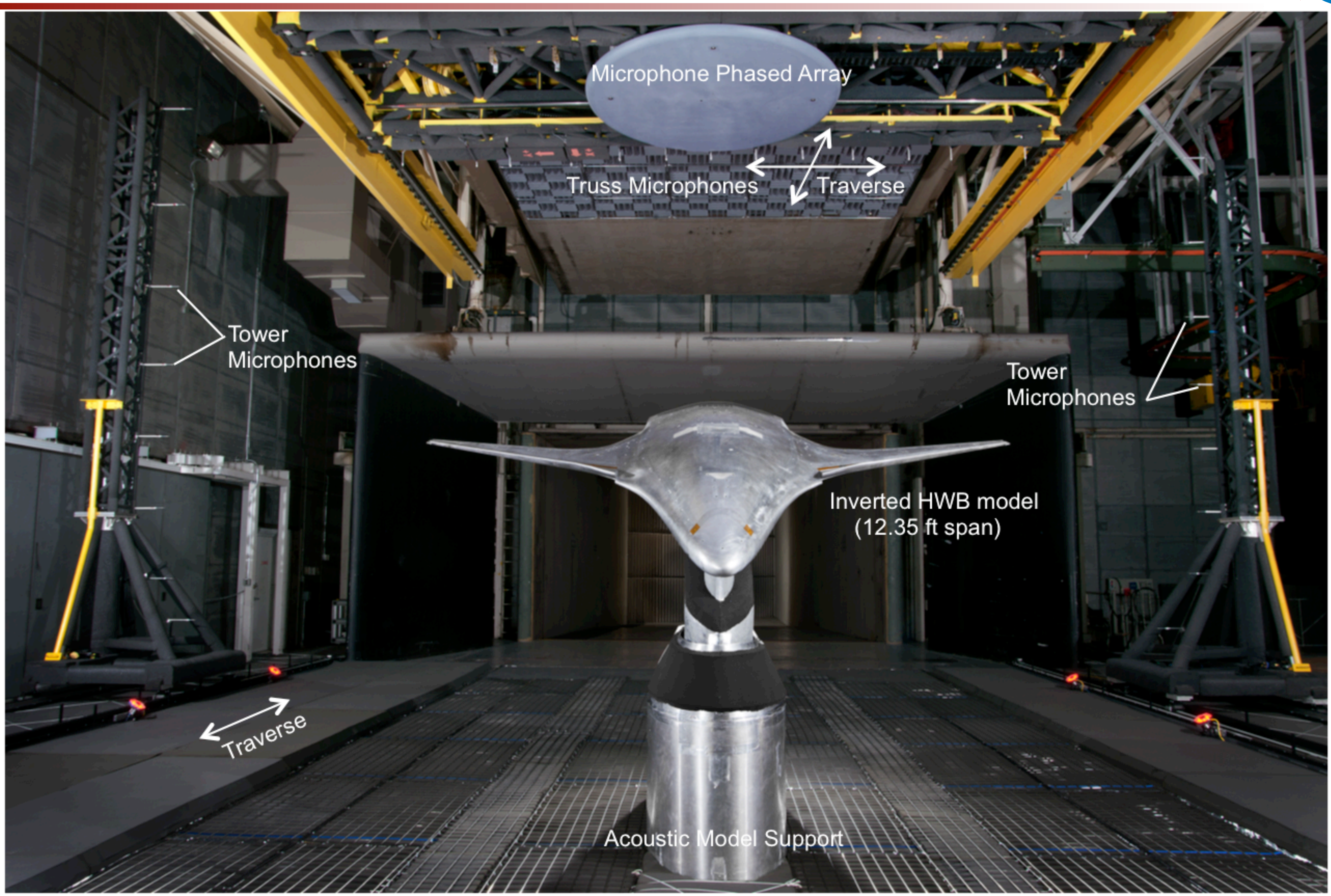
	Integrated Technology Demonstrators	Partner(s)	Min Success	Full Success	Planned Impact (2025)
12A+	AFC Enabled Vertical Tail and Advanced Wing Flight Test	Boeing			-1.5 Tail Drag -3 Wing Drag (NLF)
21A	Damage Arresting Composites Demonstration	Boeing			-20 % Structural Weight
21C	Adaptive Compliant Trailing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

Environmentally Responsible Aviation Project Flow



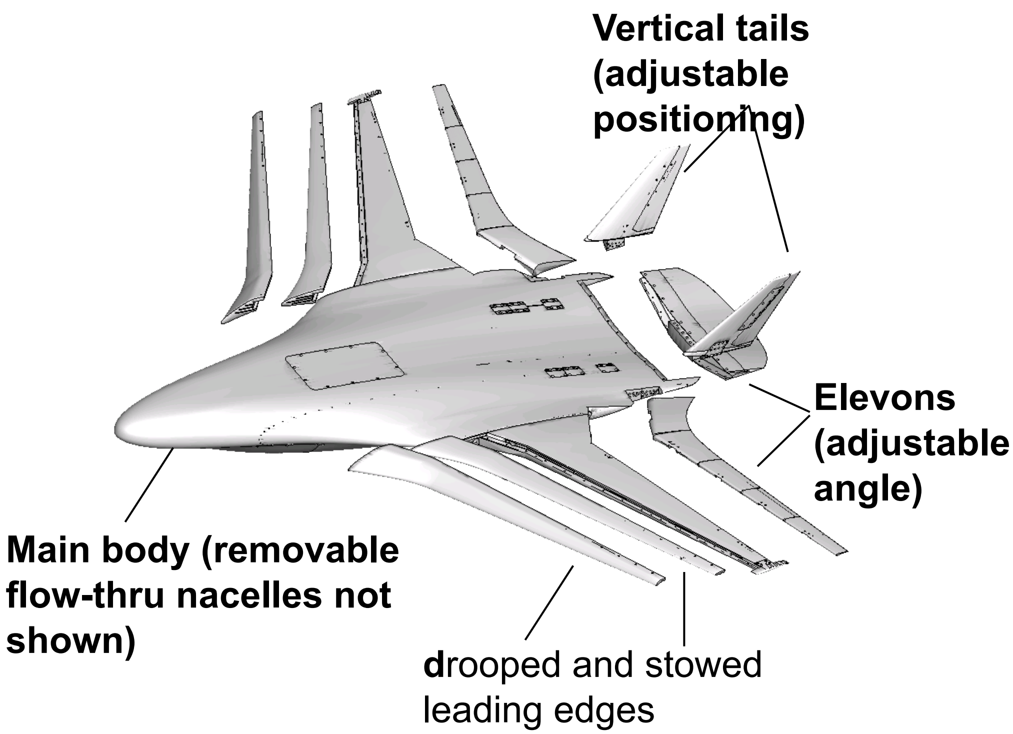
HYBRID WING BODY ACOUSTIC TEST

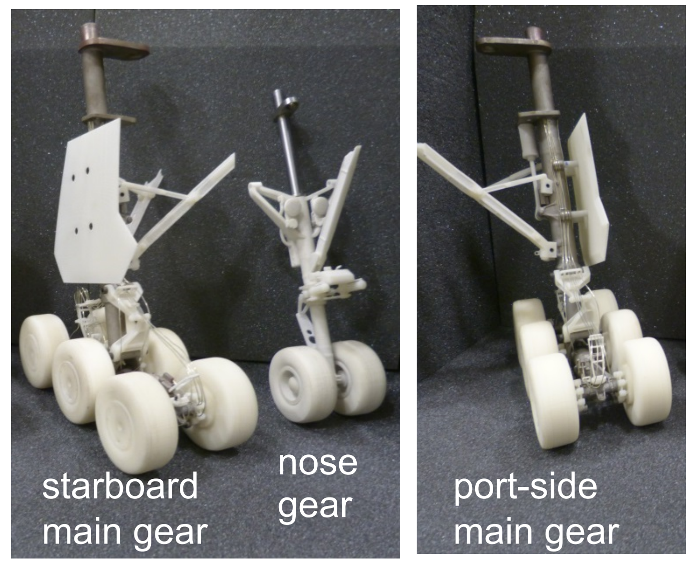
LaRC 14x22 ft. Subsonic Wind Tunnel



- 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

TEST RESULTS

This was a large and successful multi-year effort which resulted in:

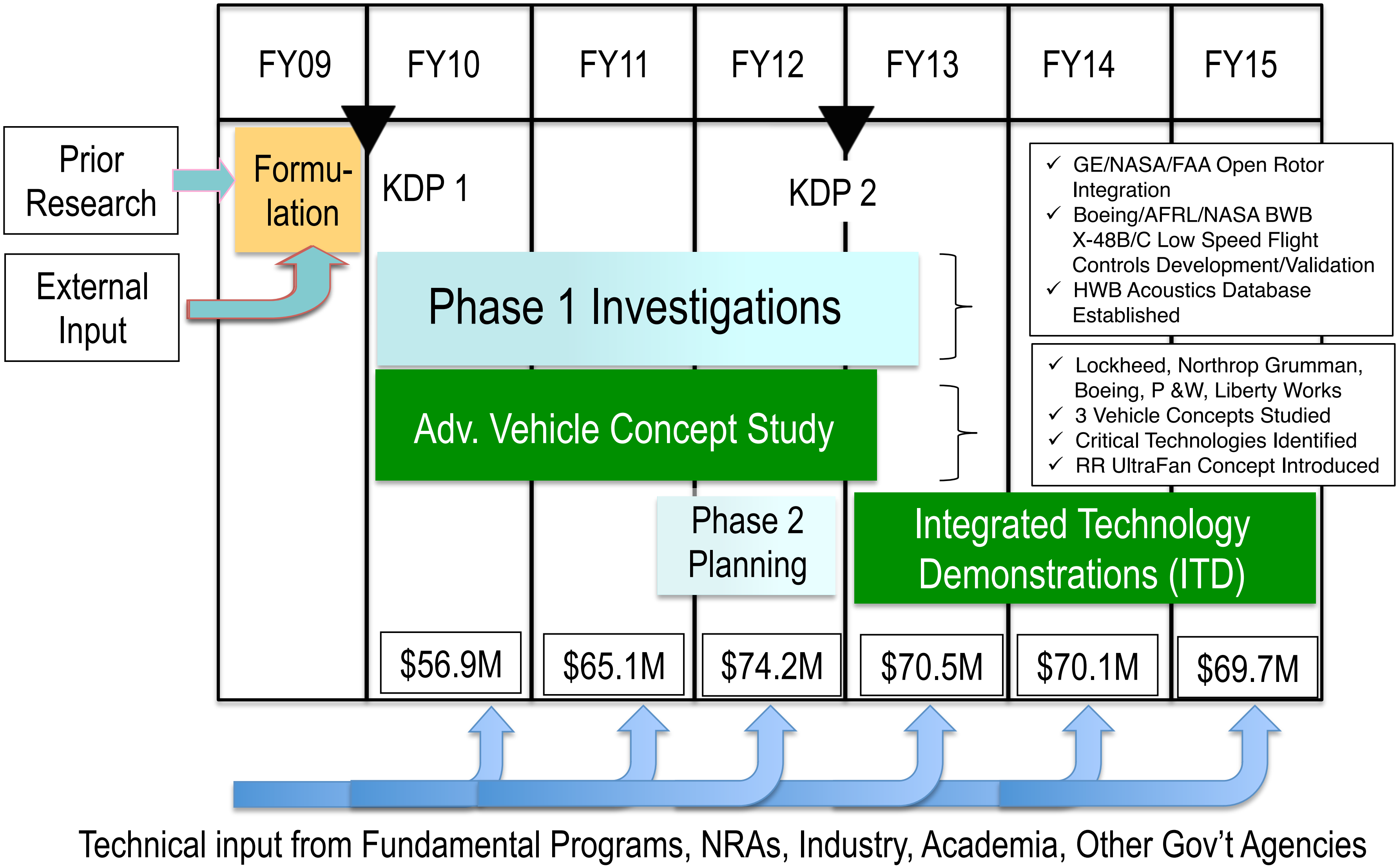
- Detailed characterization of :
  - Jet noise and its shielding
  - Airframe noise
  - Broadband noise shielding

  on a full span, high fidelity HWB aircraft configuration

- Acoustic database for system noise analysis and validation/ development of noise prediction capabilities to assess Environmentally Responsible Aviation (ERA) Project noise goals

- Improved testing capabilities of NASA Langley's 14 by 22-Foot Subsonic Tunnel

Environmentally Responsible Aviation Project Flow



Integrated Technology Demonstrators Partners & Performance Targets

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

ITD 12A+: AFC Enhanced Vertical Tail and Advanced Wing Overall Approach – Technology Maturation Plan

Weight | Drag | TSFC | Noise | NOx | **End TRL: 6**

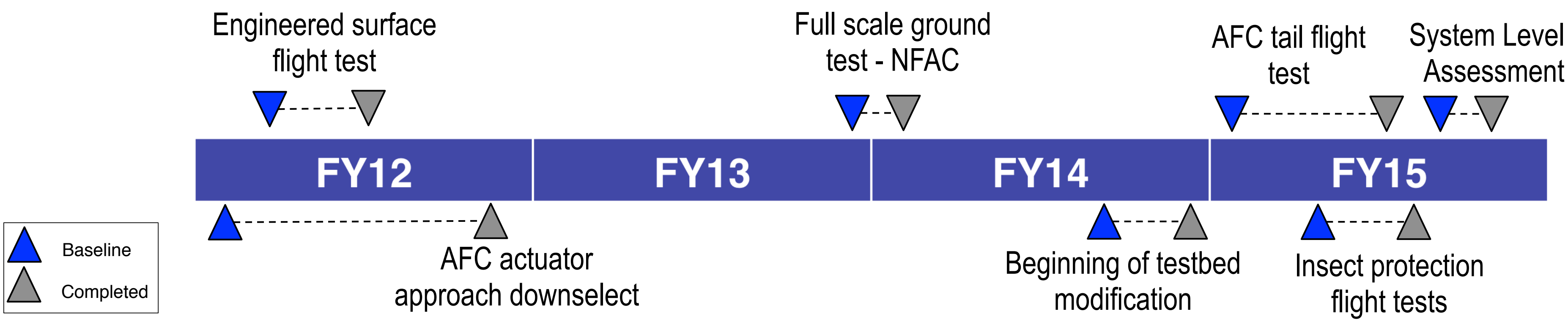
Key Performance Parameters

- Reduce total cruise drag by 1.5%
- Enable more laminar flow to reduce total cruise drag by at least 3 percent

Technology Insertion Challenges Addressed

- Full-scale AFC demonstration in flight
- Effect of flight profile on insect accumulation
- Durable, repairable insect adhesion mitigation surfaces

NASA/BOEING B757 ecoDemonstrator FCF March 2015



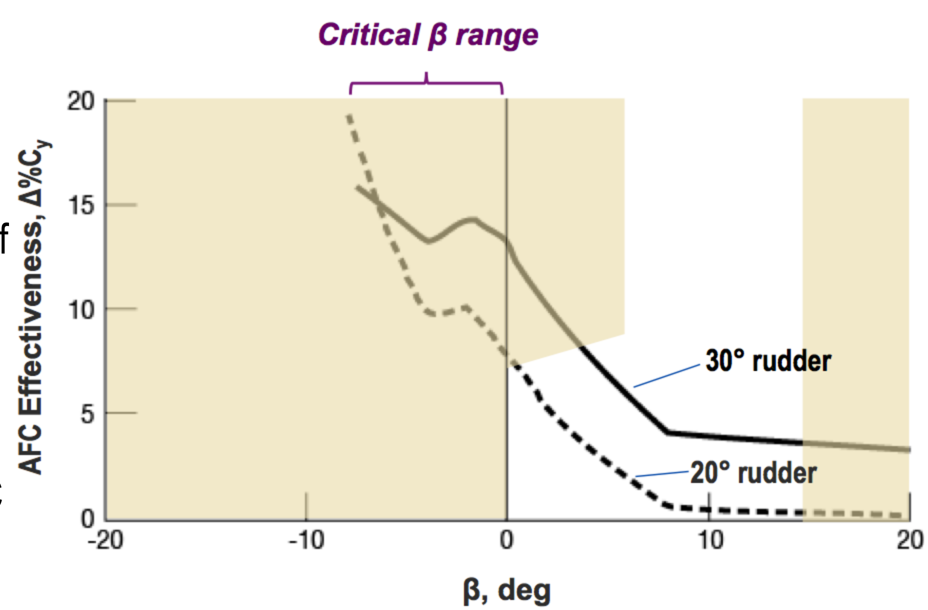
ITD 12A+: AFC Enhanced Vertical Tail and Advanced Wing Summary Technical Highlights

Goal

- Demonstrate AFC rudder effectiveness in-flight
  - Using available APU flow rates
  - Engine-out trims and decelerations
- Collect in-flight data for comparison to NFAC & CFD
- Integrate prototype AFC system into an airframe
  - Highlight key integration challenges

Summary

- Unique 757 eco Demonstrator AFC-enhanced vertical tail flight tests successfully completed
- AFC improved rudder effectiveness
  - A side force increase of 13% to16% was estimated at 30° rudder deflection between critical sideslip angles of β = 0° and -7.5°,
  - AFC increment on rudder effectiveness extracted from flight data at +β by using NFAC increment and reconciling with CFD
  - Tufts flow visualization on rudder consistent with NFAC
- Based on 13% side force increase, ERA system analysis estimated 0.92% drag reduction for a large twin aisle aircraft



% increase in rudder effectiveness due to AFC

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

Weight | Drag | TSFC | Noise | NOx

End TRL: 5

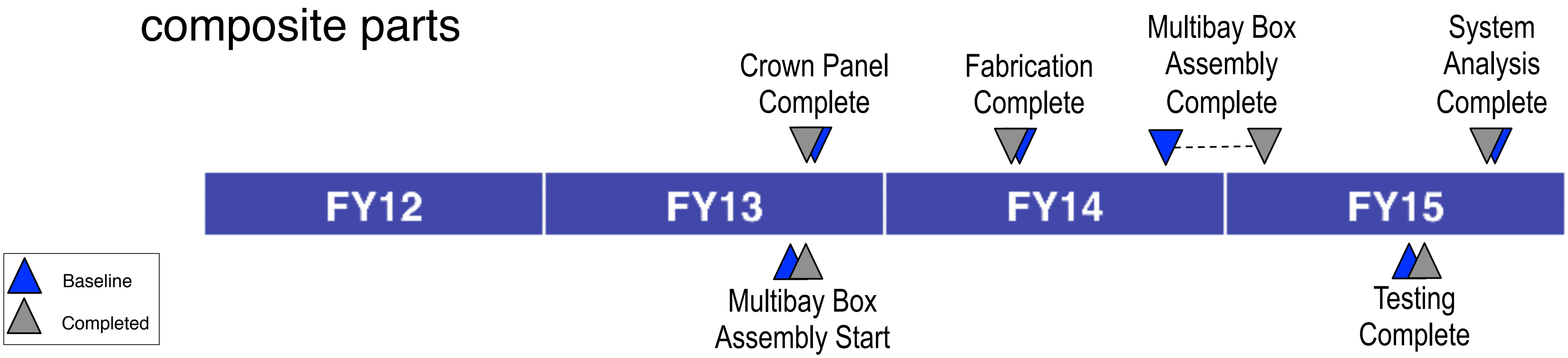
Key Performance Parameters

- 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



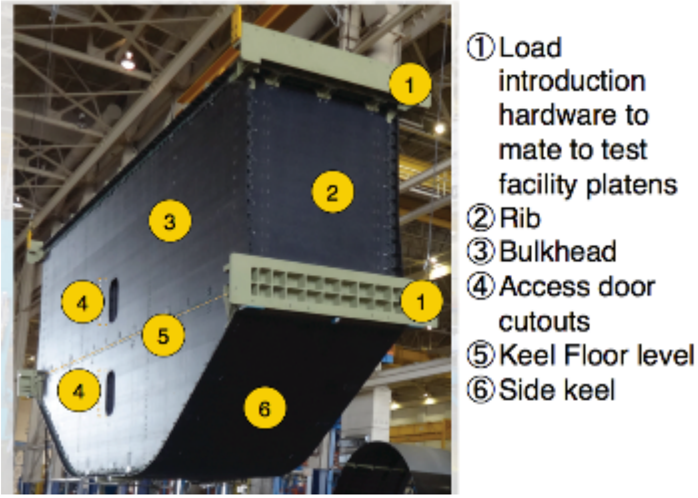
NASA Super Guppy Aircraft picked up the MBB at the Long Beach Airport in Calif. and delivered it to NASA LaRC




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

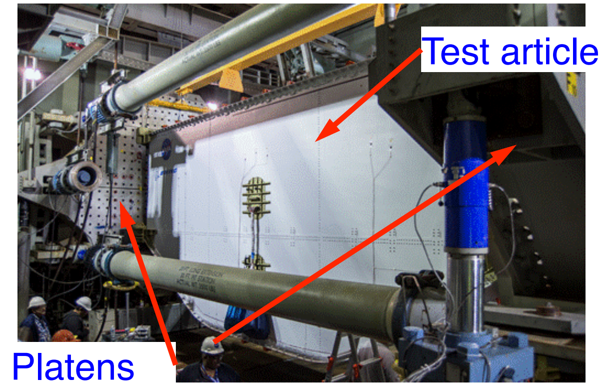
ITD 21A: Damage Arresting Composites Demonstration Summary Technical Highlight

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.



Test article

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 mounted in COLTS

ITD 51A: UHB Integration for Hybrid Wing Body
Overall Approach - Technology Maturation Plan

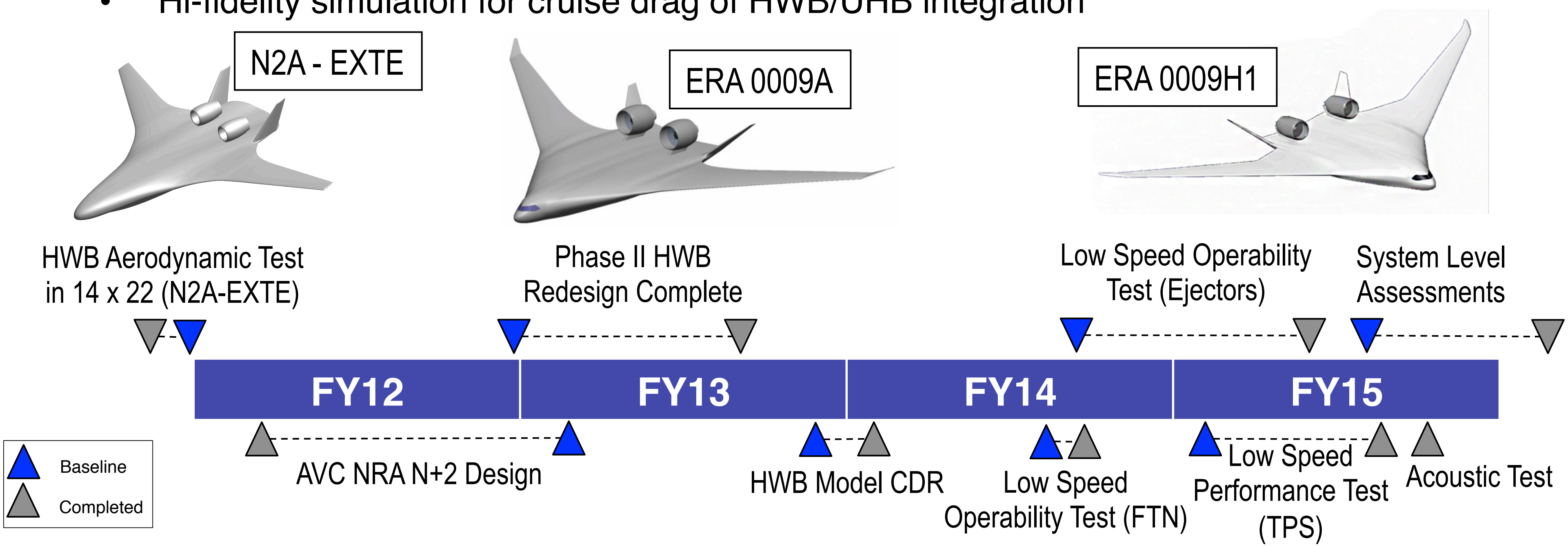
Weight | Drag | TSFC | Noise | NOx | End TRL: 5

Key Performance Parameters

- 42 EPNdB cummulative NR and 50 percent mission fuel burn reduction

Technology Insertion Challenges Addressed

- Optimization of engine Integration for all envelope performance & S&C
- UHB engine operability (pressure recovery, distortion, flow angularity) at low speed, high α and β
- Balance solution for low drag with low noise
- Hi-fidelity simulation for cruise drag of HWB/UHB integration



ITD 51A – UHB Engine Integration for HWB Summary Technical Highlight

- Three Major test campaigns planned using common model
- Tests Conducted at
  - NASA LaRC 14 x 22 Foot Subsonic Tunnel
  - National Full Scale Aerodynamics Complex (NFAC) 40 x 80 Foot Test Section at NASA ARC
- Flow Through Nacelle Test (FTN)
  - Define high lift system
  - Optimize Krueger position for takeoff and landing
- Ejector Powered Test
  - Characterize inlet flow distortion
  - Mitigate adverse PAI induced inlet flow distortion through inlet height and Krueger
- Turbine Powered Simulator Test (TPS) – Jet Effects on S&C
- Bonus 4th test: Phased Array Acoustic Test using FTN configuration

ITD 51A – UHB Engine Integration for HWB Summary

- Cooperative effort between NASA and Boeing and Pratt & Whitney successfully completed
- Design refinements to ERA PSC configuration to meet ERA Noise and Fuel Burn Metrics
- Cruise Drag, L/D, PAI drag assessed via CFD
- Low Speed Wind Tunnel test campaign completed on 5.75% HWB model
  - Flow Through Nacelle tests
    - Optimized high lift system
    - Aerodynamic and Stability & Control database
    - High lift system noise characterized
  - Ejector Powered test
    - Characterized Inlet distortion and swirl
    - Data used for Engine Operability Assessment
  - Turbine Powered Simulator test
    - Jet effects on Aero / S&C measured
- Extensive use of multiple CFD codes by NASA ARC, NASA LaRC and Boeing to guide testing and augment experimental data
- Engine operability analysis completed by P&W/UTRC
- Independent Boeing System Assessment Completed
  - Mission Fuel Burn Reduced by 53%
  - Noise reduction 38.4 dB cumulative margin below Stage 4

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

Progress – Technical Challenge Level Summary
Goal Decomposition and Technology Selection

2025 Vehicle System Level Goals

- **Fuel Burn** -50%
- **NO_x** -75%
- **Noise** -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)

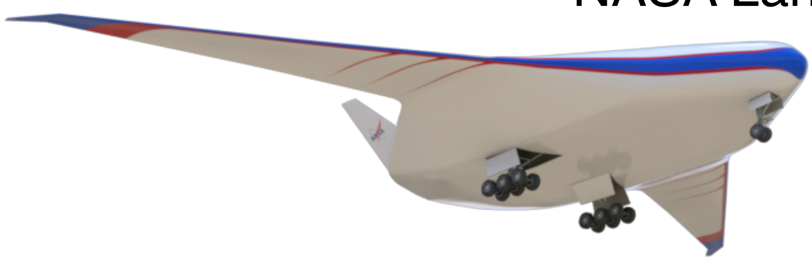
Demonstration	KPP_{2025}
12A+ AFC VT & Advanced Wing	•Cruise Drag Reduction
21A PRSEUS	•Structural Weight Reduction
21C ACTE	•Wing Weight Reduction
30A Front Block Compressor	•TSFC
35A UHB Propulsor	•TSFC •Cumulative Noise Reduction
40A Low LTO NOx, Fuel Flex Combustor	•LTO NOx
50A Low Noise Flap Edge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

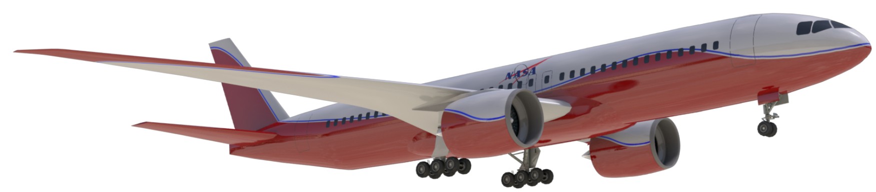
ERA Technology Development & Maturation Plans – Phase 1 and 2

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





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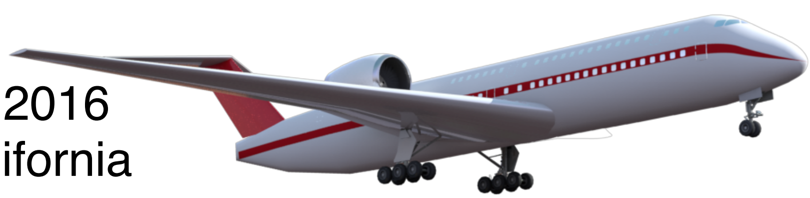
January 5, 2016
AIAA Paper 2016-0863

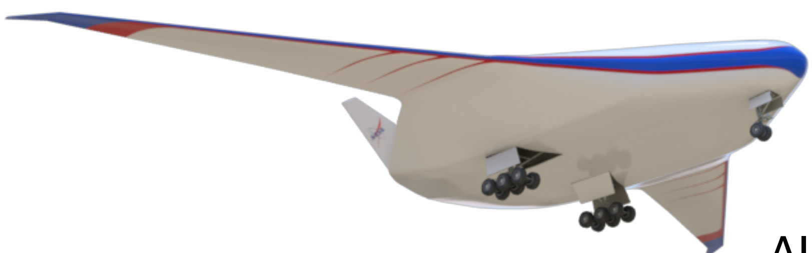


Potential Impacts
Vehicle Level – AIAA 2016-1030 & 0863

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

- 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)

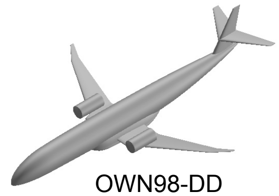
- MVL-15 – Modified Vortex Lattice for Low Speed Aerodynamic Performance Estimation
  - New semi-empirical capability developed under ERA
  - Provides low speed drag polars for tube+wing aircraft
  - Capable of analyzing multi-element high lift systems

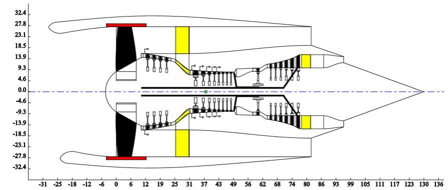
- ANOPP2 – Aircraft Noise Prediction Program
  - ITD and partner data utilized to help create refined input assumptions and improved predictions
  - Shielding, fan noise, and noise reduction technology impact estimates supported by test data
  - New prediction capabilities developed

Potential Impacts
Vehicle Level – AIAA 2016-1030 & 0863

RJ

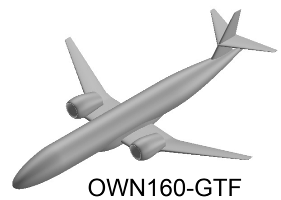

T+W98-DD
(2) Small DD


OWN98-DD
(2) Small DD


Small DD

SA


T+W160-GTF
(2) Small GTF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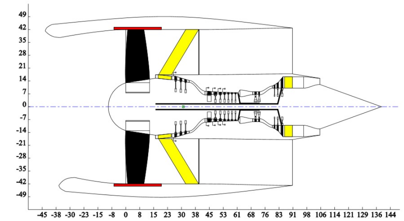
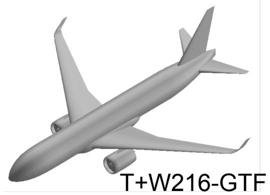
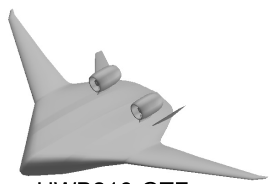
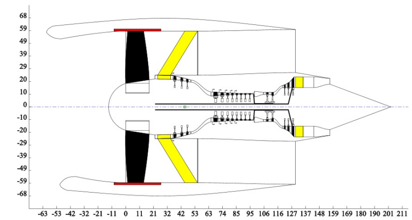
(2) Small GTF


Small GTF

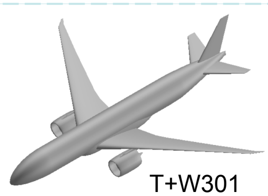
STA

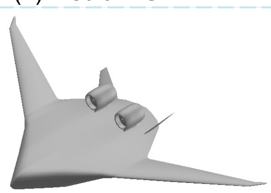

T+W216-GTF
(2) Medium GTF


HWB216-GTF
(2) Medium GTF

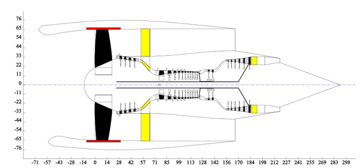

Medium GTF

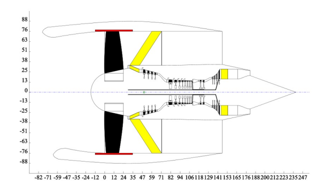
LTA


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

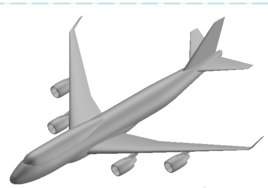

HWB301
(2) Large DD
(2) Large HWB GTF

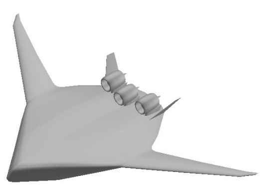

MFN301-GTF
(2) Large GTF

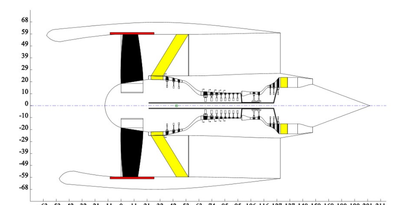

Large DD

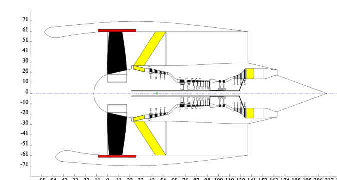

Large GTF T+W
Large HWB GTF (not shown)

VLTA


T+W400-GTF
(4) Medium GTF

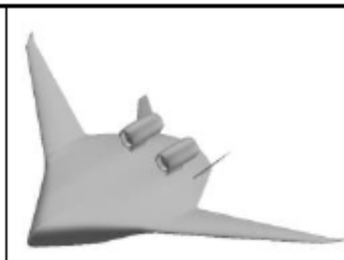
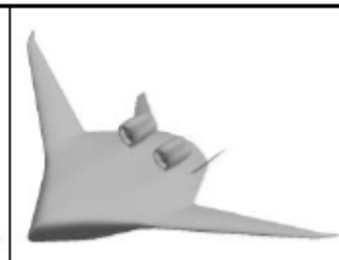

HWB400-GTF
(3) Medium HWB GTF


Medium GTF


Medium HWB GTF

Potential Impacts
Vehicle Level – 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

Potential Impacts
Vehicle Level - Best Performers

v2013.1

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	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%

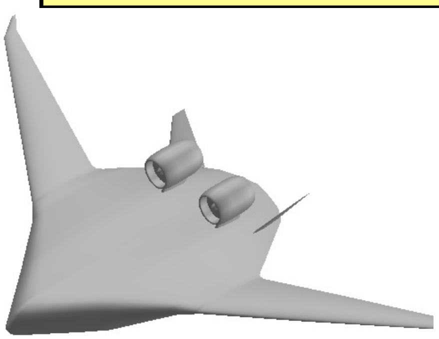
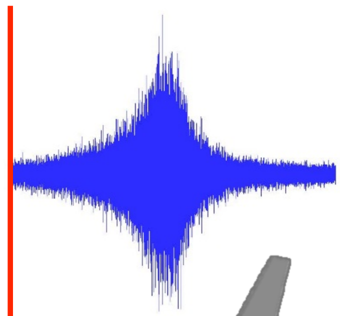


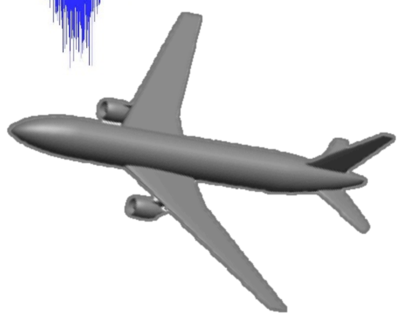
Table 15. N+2 HWB-GTF Concept Performance Summary

	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

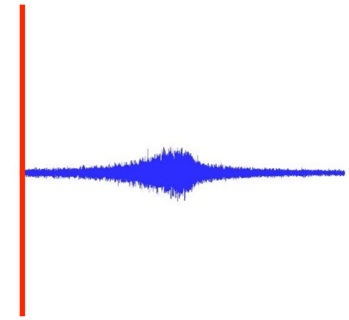
Potential Impacts
What does Stage 4 - 40 EPNdB sound like?

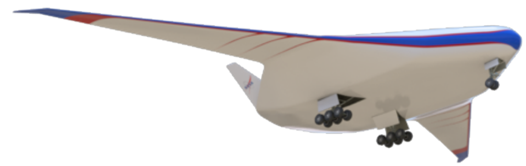
LTA Ref (NASA model of 777-GE90-110B) on Approach



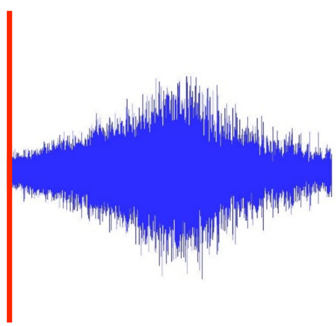


HWB301-GTF w/ITDNR on Approach

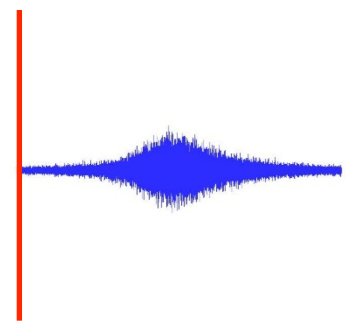




LTA Ref (NASA model of 777-GE90-110B) on Sideline

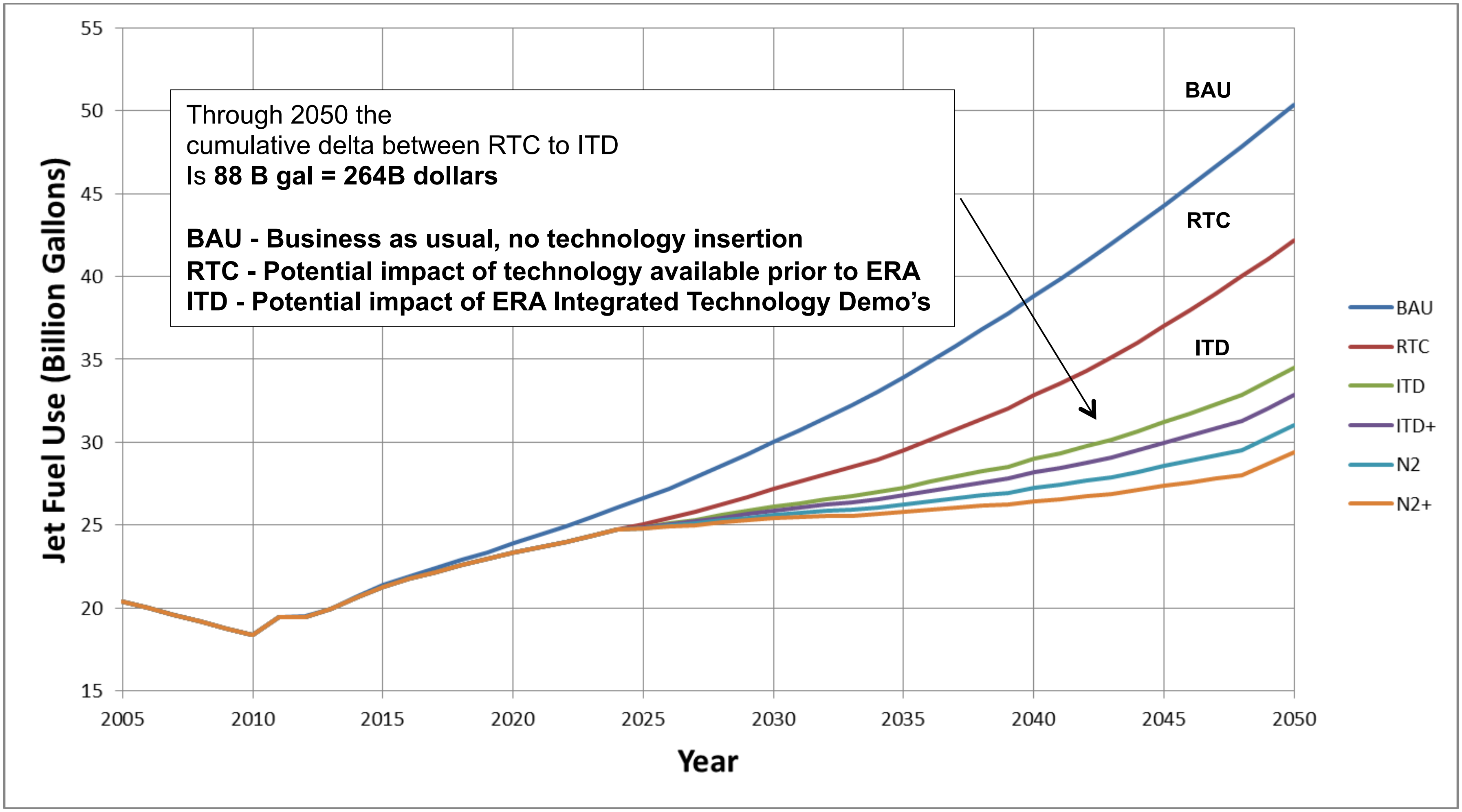


HWB301-GTF w/ITDNR on Sideline



"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).

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