National Aeronautics and Space Administration

Airframe Technologies for Aerodynamic and Structural Efficiency of N+3 Subsonic Transport Aircraft

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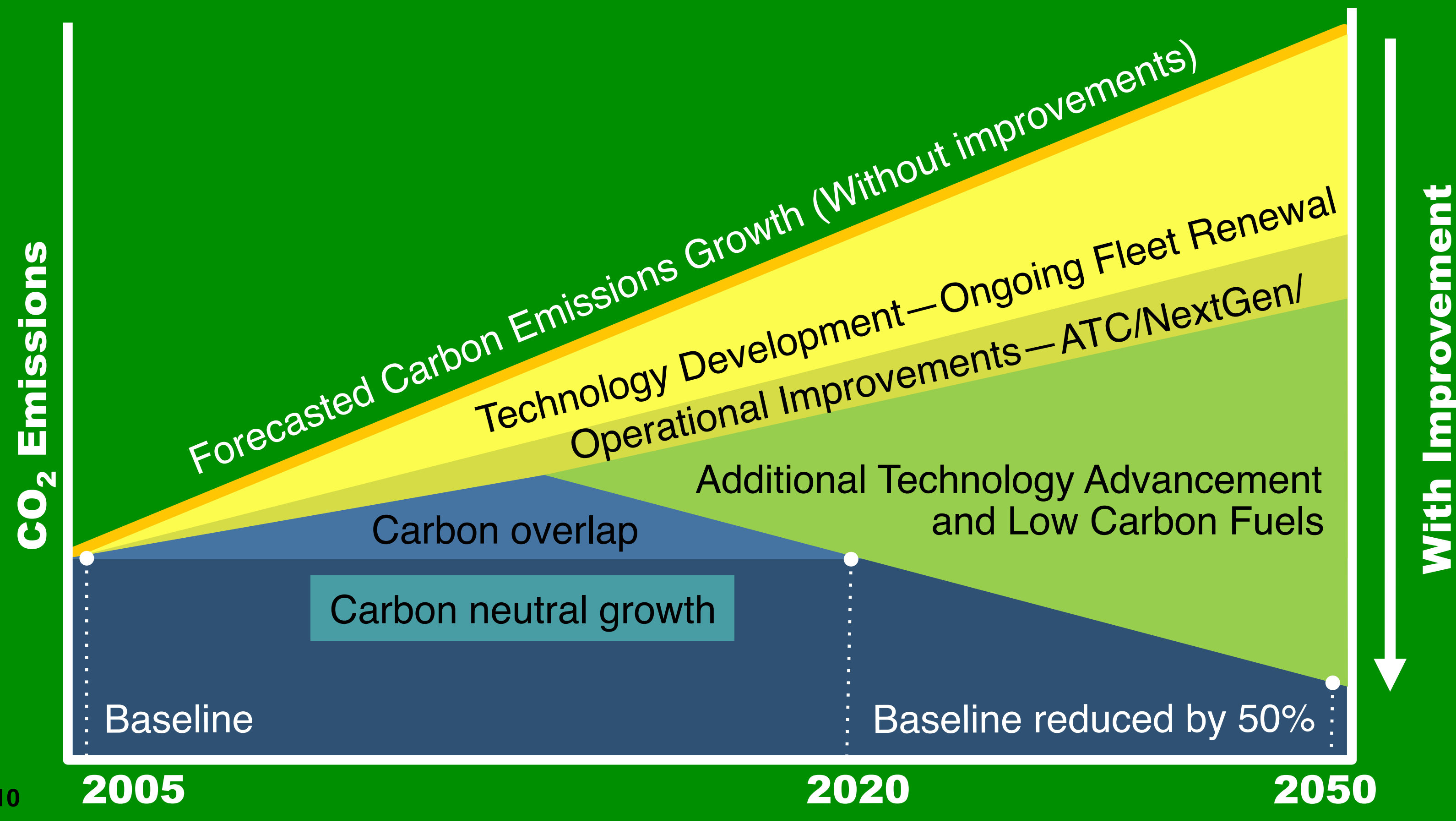
Outline

- Introduction
- Goal-Driven Advanced Concept Studies
- Enabling Technologies
- Concluding Remarks

Major Challenges for Aviation

By 2050, substantially reduce emissions of carbon and oxides of nitrogen and contain objectionable noise within the airport boundary



Source: IATA, 2010

NASA Aeronautics Programs

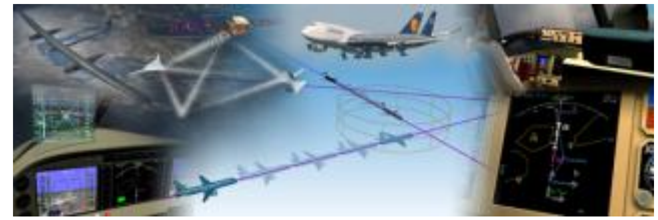
Subsonic Fixed Wing and other NASA Green Aviation emphasis

Fundamental Aeronautics Program

Conduct fundamental research that will produce innovative concepts, tools, and technologies to enable revolutionary changes for vehicles that fly in all speed regimes.

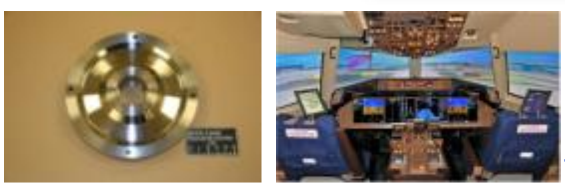
Integrated Systems Research Program

Conduct research at an integrated system-level on promising concepts and technologies and explore/assess/demonstrate the benefits in a relevant environment



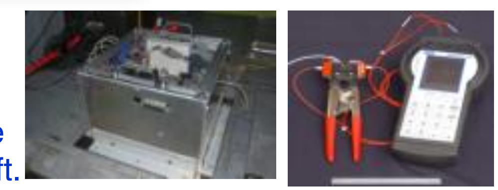
Airspace Systems Program

Directly address the fundamental ATM research needs for NextGen by developing revolutionary concepts, capabilities, and technologies that will enable significant increases in the capacity, efficiency and flexibility of the NAS.



Aviation Safety Program

Conduct cutting-edge research that will produce innovative concepts, tools, and technologies to improve the intrinsic safety attributes of current and future aircraft.



Aeronautics Test Program

Preserve and promote the testing capabilities of one of the United States' largest, most versatile and comprehensive set of flight and ground-based research facilities.

SFW Strategic Framework/Linkage

Strategic Thrusts	Strategic Goals	System Level Metrics
1. Energy Efficiency	1.1 Reduce the energy intensity of air transportation	• Fuel Burn • Energy Efficiency
2. Environmental Compatibility	2.1 Reduce the impact of aircraft on air quality around airports 2.2 Contain objectionable aircraft noise within airport boundaries 2.3 Reduce the impact of aircraft operations on global climate	• LTO NO_X Emissions • Other LTO Emissions • Aircraft Certification Noise • Cruise NO_X Emissions • Life-cycle CO_2e per Unit of Energy Used

The NASA Subsonic Fixed Wing Project

Explore and Develop Tools, Technologies, and Concepts for Improved Energy Efficiency and Environmental Compatibility for Sustained Growth of Commercial Aviation

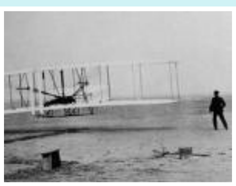
Objectives

- Prediction and analysis tools for reduced uncertainty
- Concepts and technologies for dramatic improvements in noise, emissions and performance

Relevance

- Address daunting energy and environmental challenges for aviation
- Enable growth in mobility/aviation/transportation
- Subsonic air transportation vital to our economy and quality of life

Evolution of Subsonic Transports



1903 — 1930s — 1950s — 2000s

NASA Subsonic Transport System Level Metrics

…. technology for dramatically improving noise, emissions, & performance

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	-71 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

Research addressing revolutionary N+3 Goals with opportunities for near term impact

Outline

- Introduction
- Goal-Driven Advanced Concept Studies
- Enabling Technologies
- Concluding Remarks

Goal-Driven Advanced Vehicle Concept Studies (N+3)

purpose/approach

- Leverage external and in-house expertise
- Stimulate thinking to determine potential aircraft solutions to address significant performance, environmental, and operations issues of the future
- Identify advanced airframe and propulsion concepts and corresponding enabling technologies for commercial aircraft anticipated for 2030-35 EIS (market conditions permitting)
- Identify key driving technologies (traded at the system level)
- Prime the pipeline for future, revolutionary aircraft technology developments
- Use to inform and define SFW research portfolio and investments

Goal-Driven Advanced Vehicle Concept Studies (N+3)

summary

Advanced concept studies for commercial subsonic transport aircraft for 2030-35 EIS

Boeing, GE, GA Tech

NG, RR, Tufts, Sensis, Spirit

GE, Cessna, GA Tech

MIT, Aurora, P&W, Aerodyne

Trends:

- Tailored/Multifunctional Structures
- High AR/Active Structural Control
- **Highly Integrated Propulsion Systems**
- **Ultra-high BPR (20+ w/ small cores)**
- **Alternative fuels and emerging hybrid electric concepts**
- Noise reduction by component, configuration, and operations

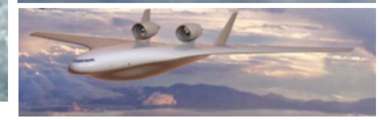
NASA, VA Tech, GT

NASA

Advances required on multiple fronts…

Goal-Driven Advanced Concepts (N+3)

TRL 6 2025-30 for EIS 2030-35



- Fuselages
  - remain large % of structural weight and wetted area
  - double-bubble and hybrid wing bodies may be uniquely enabling ideas

- Wings
  - higher AR, lighter, and more flexible than today, varying degrees of laminar flow
  - truss-bracing and hybrid wing bodies may be uniquely enabling ideas

- Propulsion
  - Systems of increasingly higher BPR from larger fans and/or smaller cores
  - game-changing architectures include hybrid electric and distributed propulsion concepts

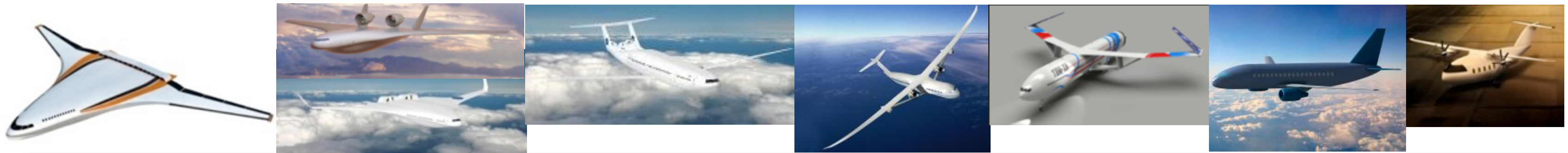
- Noise
  - reduction from component improvements, and configuration
- Emissions
  - reduction from efficient combustion, cleaner burning alternative fuels, more electric, less energy use
- Operations
  - Advanced concepts of operation can significantly contribute to meeting goals (e.g. steeper LTO angles, formation flight)

Advances required on multiple fronts…

Diversified Portfolio Addressing N+3 Goals

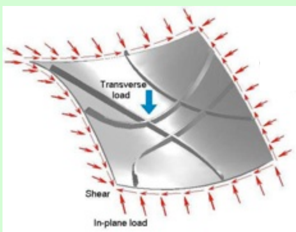
broadly applicable subsystems technical challenges

N+3 Vehicle Concepts

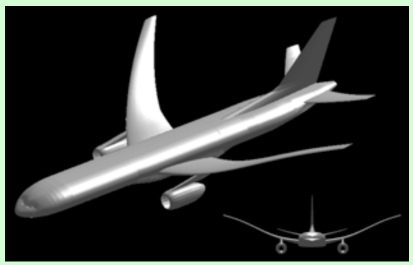


Technical Challenges

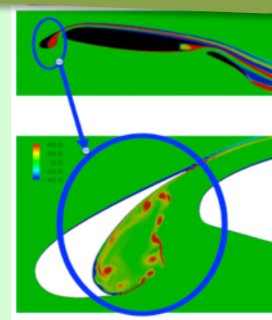
Reduce Drag, Weight, TSEC, Emissions and Noise



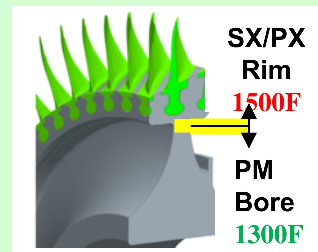
Tailored Fuselage



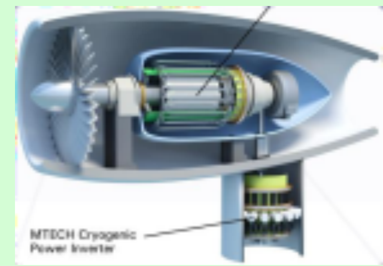
High AR Elastic Wing



Quiet, Simplified High-Lift



High Eff. Small Gas Generator



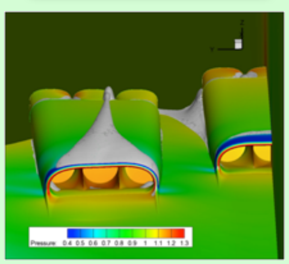
Hybrid Electric Propulsion

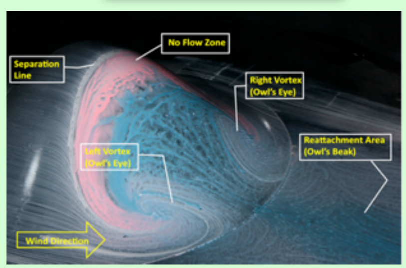
Propulsion Airframe Integration

Tools

Alternative Fuels

Research Areas





Outline

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- Goal-Driven Advanced Concept Studies
- Enabling Technologies
  - Overview
  - Examples
- Concluding Remarks

Tailored Fuselage

opportunity to reduce large structural weight, large wetted area

Objective

Drag | Weight | TSEC | Clean | Noise

Explore and develop technologies to enable direct structural weight and skin friction reduction

Approach/Challenges

Tailored Load Path Concepts & Design

- Curvilinear metallic stiffeners
- Tow-steered carbon fibers

Designer Materials

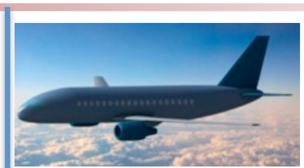
- Functionally graded metallics
- CNT hybrid composites

Turbulent Skin Friction Drag Reduction

- Direct skin friction drag reduction
- Fuselage wetted area reduction via flow control

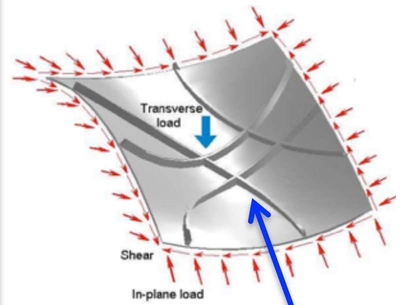
Benefit/Pay-off

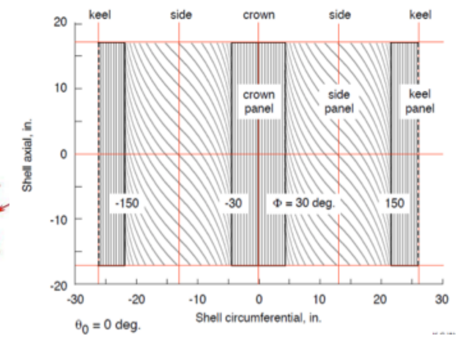
- 25% fuselage structural weight reduction
- 10% fuselage turbulent boundary-layer drag reduction



large structure
large area

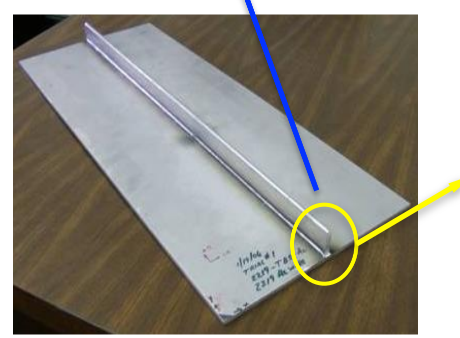
conventional and unconventional

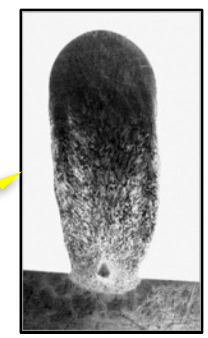




metallic & composites

tailored load path design/build
tailored materials





High Aspect Ratio Elastic Wing
changing the drag/weight trade space

Objective

Drag | Weight | TSEC | Clean | Noise

Explore and develop technologies to enable lightweight high aspect ratio wings

Approach/Challenges

Tailored Load Path Concepts & Design
- Passive aeroelastically tailored structures

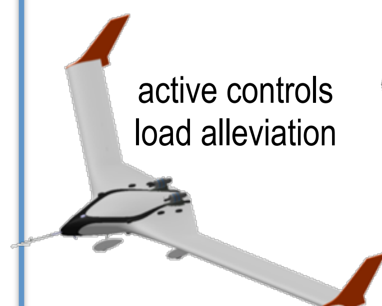
Designer Materials
- Varible stiffness flexible skins

Active Structural Control
- Structural adaptation to reduce loads, suppress flutter, and maintain optimal aerodynamics

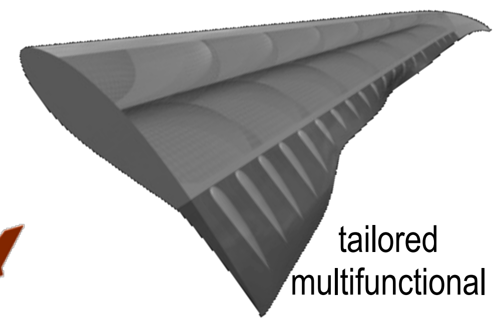
Aerodynamic Shaping
- Low interference external bracing
- Passive/Active concept to reduce wave drag

Elastic Aircraft Flight Control
- Control concepts, aeroservoelastic optimization

Benefit/Pay-off
- 25% wing structural weight reduction
- AR increase of 30-40% for cantilever wings, 2X+ for braced

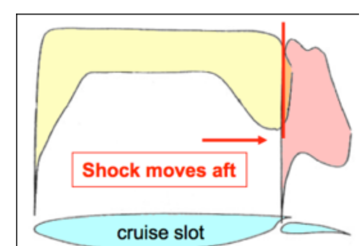


active controls
load alleviation



tailored
multifunctional

passive/active
advanced aerodynamics



Propulsion Airframe Integration

increasingly synergistic integration

Objective

Drag | Weight | TSEC | Clean | Noise

Explore and develop technologies to enable highly coupled, synergistic aero-propulsive-control

Approach/Challenges

Aerodynamic Configuration

- Novel configurations and installations (e.g. BLI, DP)

Adaptive, Lightweight Fan Blade

- SMA to twist blade (10 deg at tip)
- Nano-toughened composite blade

Distortion-Tolerant Fan

- Robust to unsteady and non-uniform inflow

Acoustic Liners

- Low drag, multi-degree-of-freedom

Propulsion Airframe Aeroacoustics

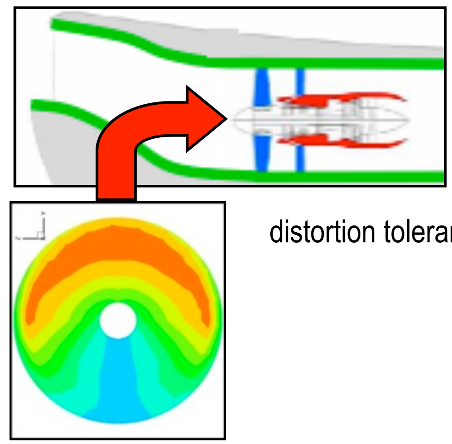
- Inlet distortion, jet-flap/surface interaction

Benefit/Pay-off

- Improved multidisciplinary performance and noise characteristics; benefits tradable for specific missions

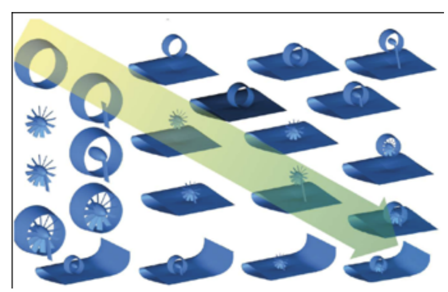
boundary-layer ingesting concepts

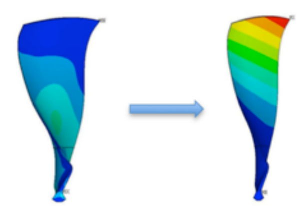
thrust vectoring



distortion tolerance

jet/surface interaction acoustics

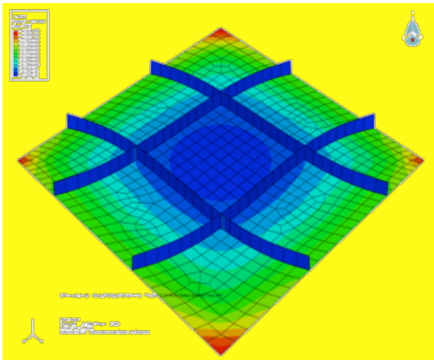


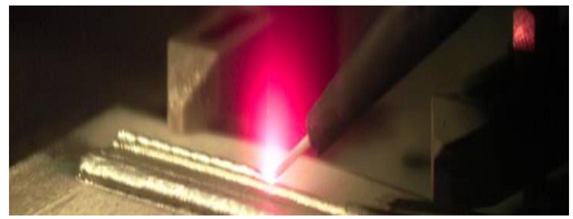


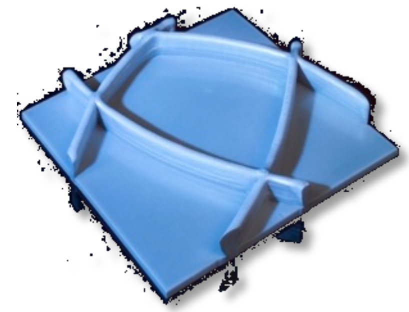
adaptive fan blades

Weight Reduction and Manufacturing

tailored metallic structures via electron beam free form fabrication (EBF3)

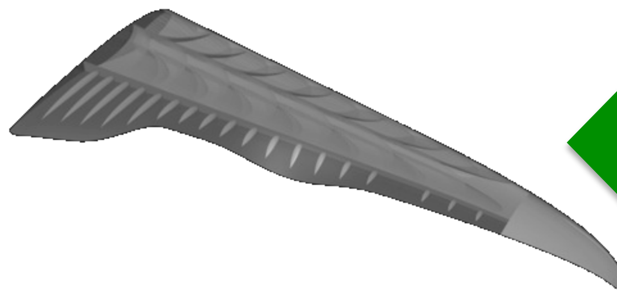


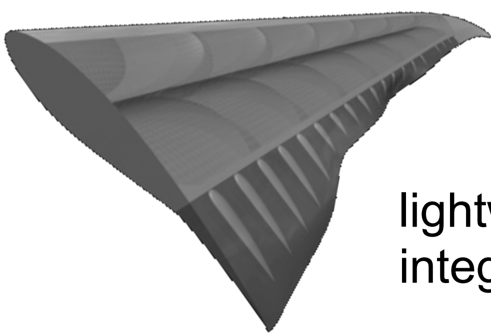




structural design optimization
with curvilinear stiffeners

fabrication & testing of structural designs

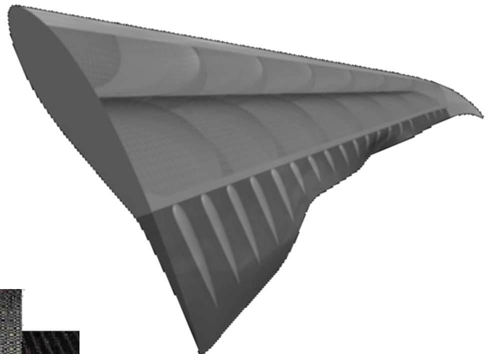


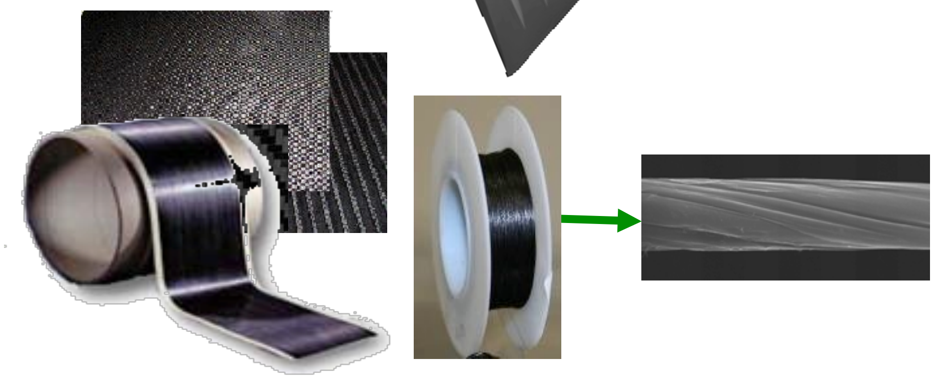


lightweight aeroelastically tailored wing structure with
integral control surfaces

Weight Reduction via
Advanced Multifunctional and Tailored Materials

Variable Stiffness
Hybrid CNT CFRP/ All CNT

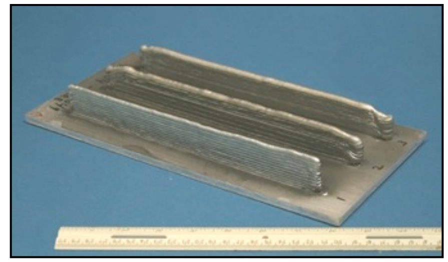


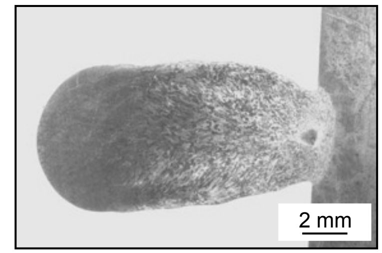


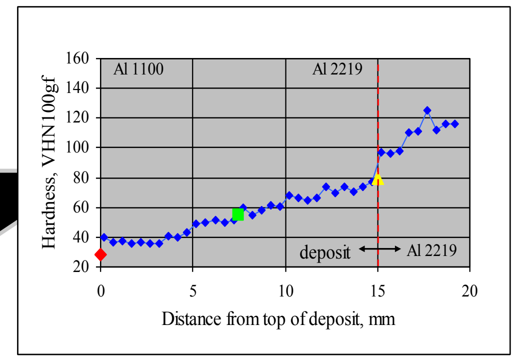
CNT Tapes and Yarns - *Nanocomp Technologies*

nano-structured elements within active
polymeric materials for active wing skin
(load bearing + electric conductivity)

Designer Metallics
Functionally Graded Metal Alloys



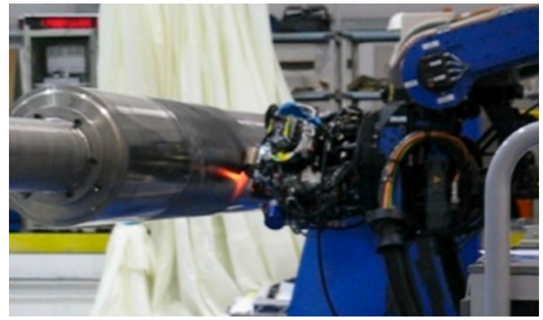




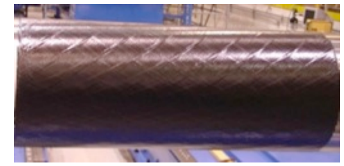
tailored metal alloys
vary material properties continuously
throughout a structure

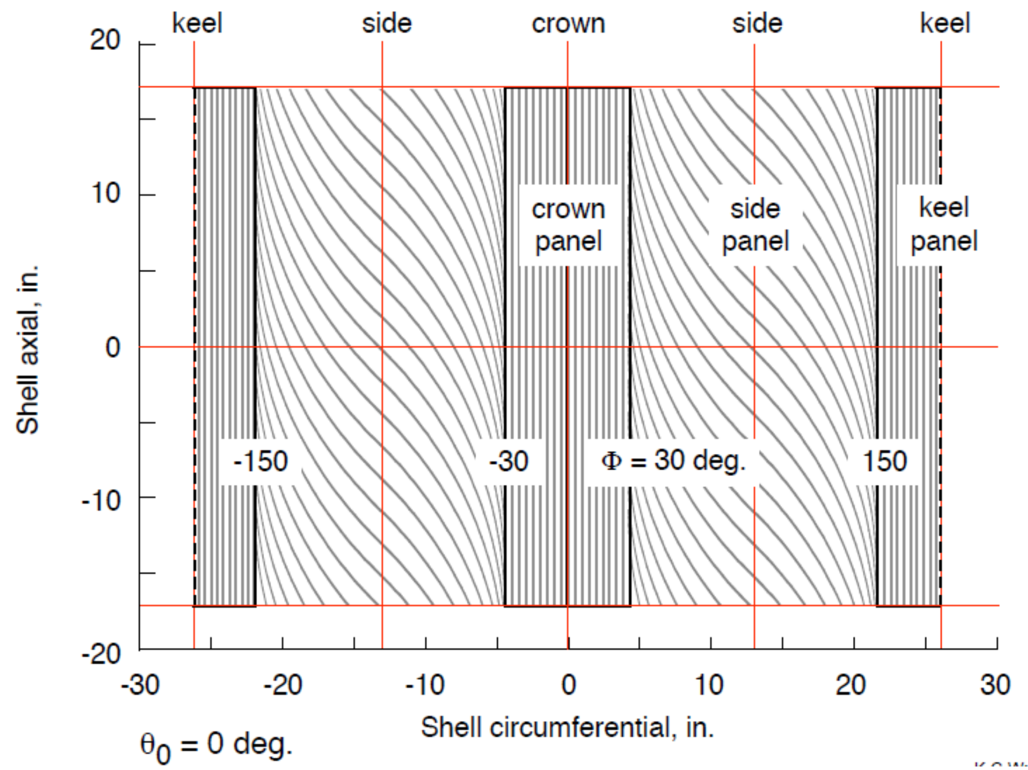
Composite Structural Design and Analysis Tool Development

- Fiber winding and automatic tape placement are industry standards
- Fiber tow steering places individual fiber tows, enabling tighter radii curves and control of fiber distribution
- Fiber tow steering equipment exists, but design and analysis tools to effectively tailor localized laminate properties are lacking
- Develop analysis and design tools to optimize structures through tailored placement of fibers within composite
- Fibers from axial along keel and crown to 45° along sides for shear; steer fibers around cutouts for continuity



Fabrication at NCAM/MAF

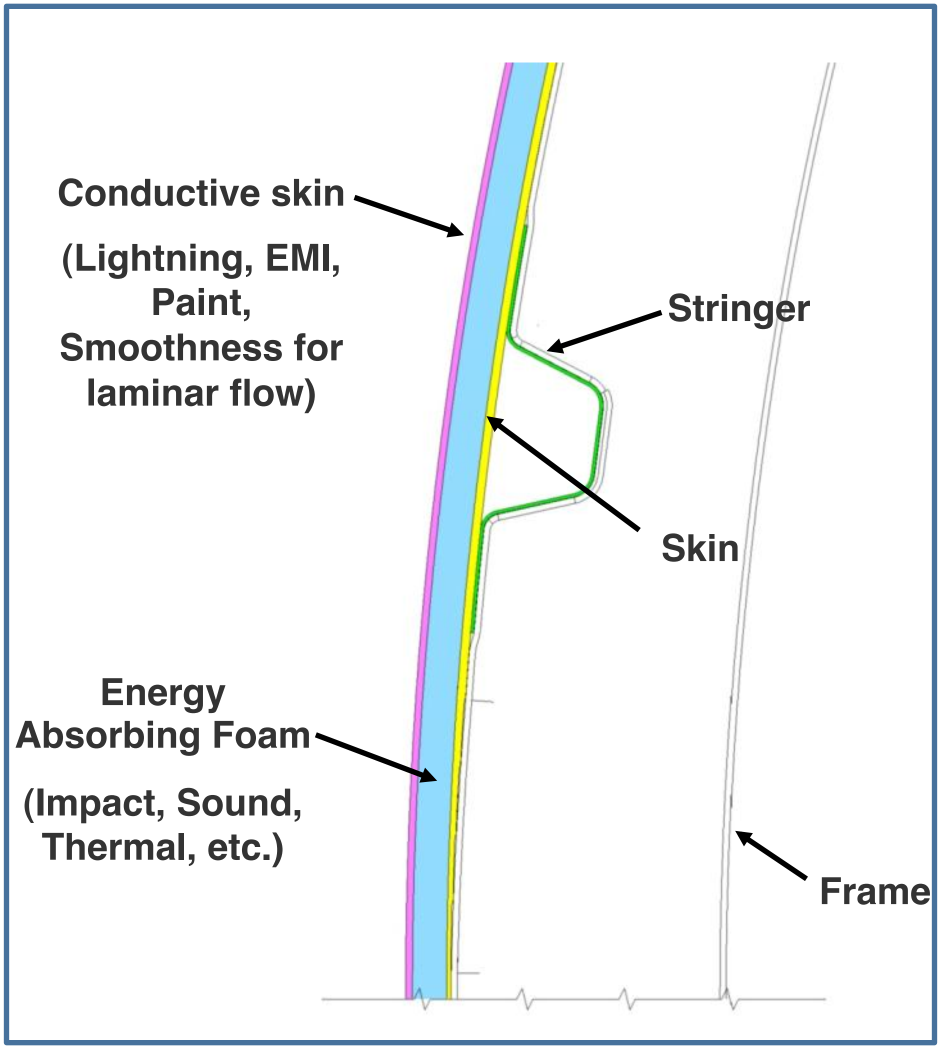




Fiber tow placement plan within a single ply (cylinder split along keel for purposes of image); validate through test of cylinders 28" dia. x 40"

Composite Protective Skin

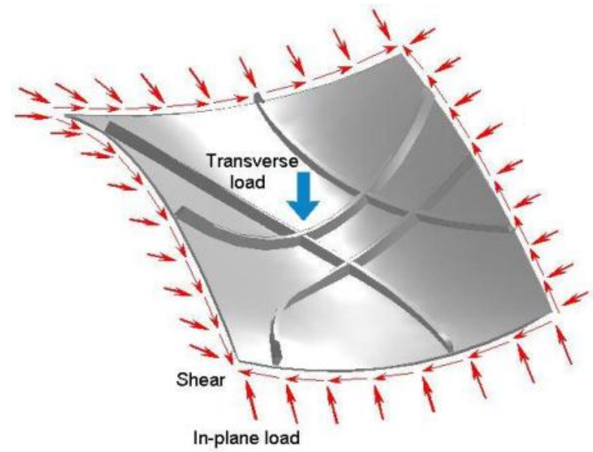
- Smoothing, Thermal, Absorbing, Reflective, Conductive, Cosmetic (STAR – C^2)
- Composite primary structure with external protective skin
- Multifunctional skin provides protection external to primary structure:
  - Cosmetic finish
  - Acoustic treatment
  - Thermal insulation
  - Lightning strike protection
  - Smoothness to facilitate laminar flow
  - Impact detection/indication
  - Ice protection
  - Easily produced and repaired
- Weight reduced by driving towards lighter gage primary structure and combining other functions in multifunctional skin



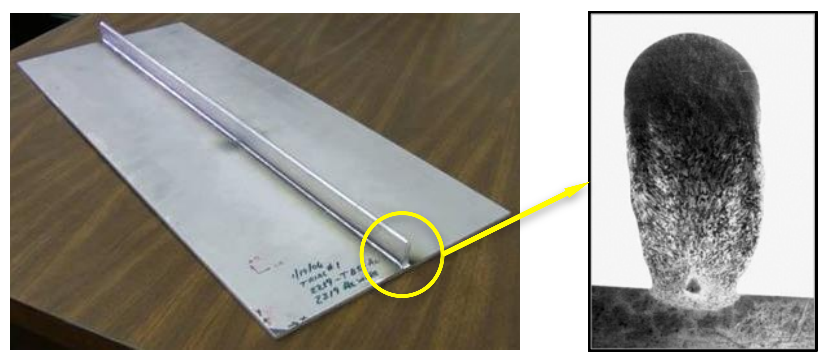
Schematic of STAR-C^2 concept (under development on Cessna NRA contract)

Metallic Fuselage Design and Fabrication

- Engineered materials coupled with tailored structural design enable reduced weight and improved performance
- Multi-objective optimization:
  - Structural load path
  - Acoustic transmission
  - Durability and damage tolerance
  - Minimum weight
  - Materials functionally graded to satisfy local design constraints
- Additive manufacturing using new alloys enables unitized structure with functionally graded, curved stiffeners
- Weight reduction by combined tailoring structural design and designer materials



Design optimization tools developed at VA Tech through NRA contract



High toughness alloy at stiffener base for damage tolerance, transitioning to metal matrix composite for increased stiffness and acoustic damping

Validated Design Tool for Improved Structural Efficiency EBF3PanelOpt

OBJECTIVE

Develop *structural design and optimization tool* and *validate* with experiment. Optimize aircraft structures using novel materials, manufacturing methods and structural configurations to carry comparable loads at *significantly lower weight.*

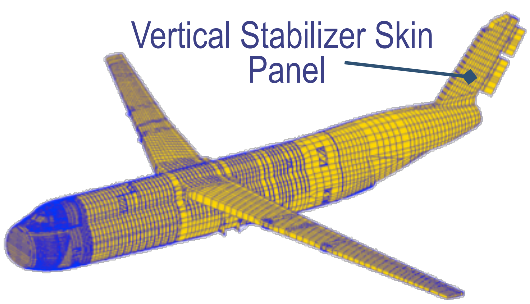
APPROACH

Validate EBF3PanelOpt (developed under NRA with Virginia Tech) design and optimization tool by designing, fabricating, and testing panel with six individually optimized T-stiffeners for a high compression load case with optimization constraints on buckling, stress, and crippling.

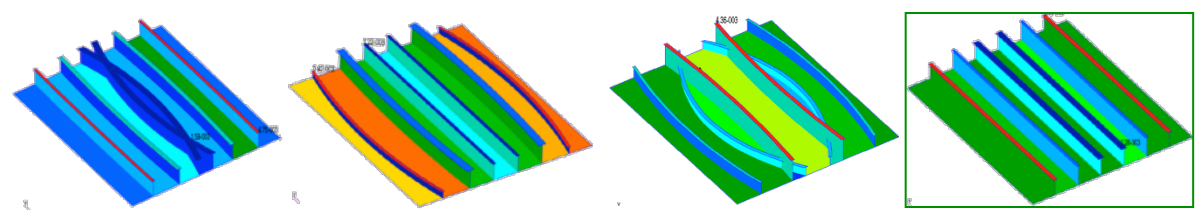
RESULTS

- EBF3PanelOpt was validated by experiment for several load conditions and multi-objective optimization.
- The final validation test showed that the aluminum panel with individually optimized stiffeners and skin thickness is 20% lighter than baseline with uniform stiffeners optimized with conventional design methods.
- Future plans include using EBF3PanelOpt to simultaneously optimize structure and functionally grading the materials for even larger weight reductions. Panels will be fabricated using Electron Beam Freeform Fabrication and tested to validate the methods and tool.

T-stiffened panel designed and optimized using EBF3PanelOpt, in compression test system



Design Candidates Using Several Variations of Geometry Input Parameters

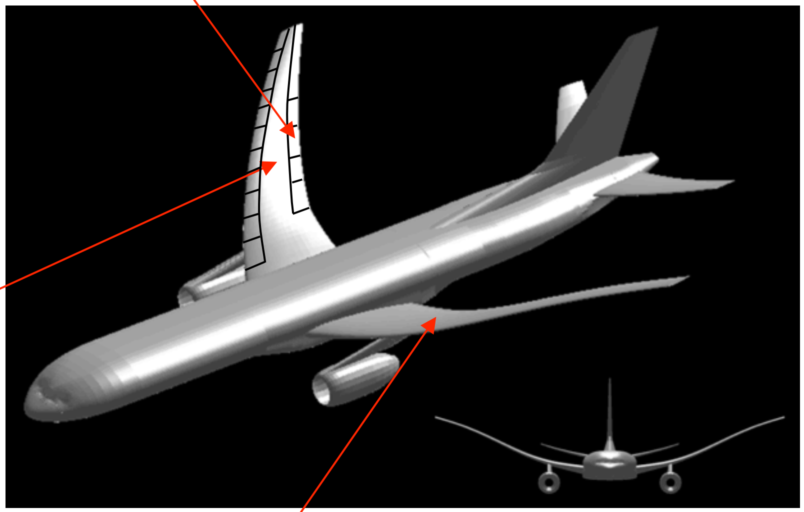


8.98 lb | 9.25 lb | 9.89 lb | 8.30 lb

Elastically Shaped Aircraft Concept (ESAC)

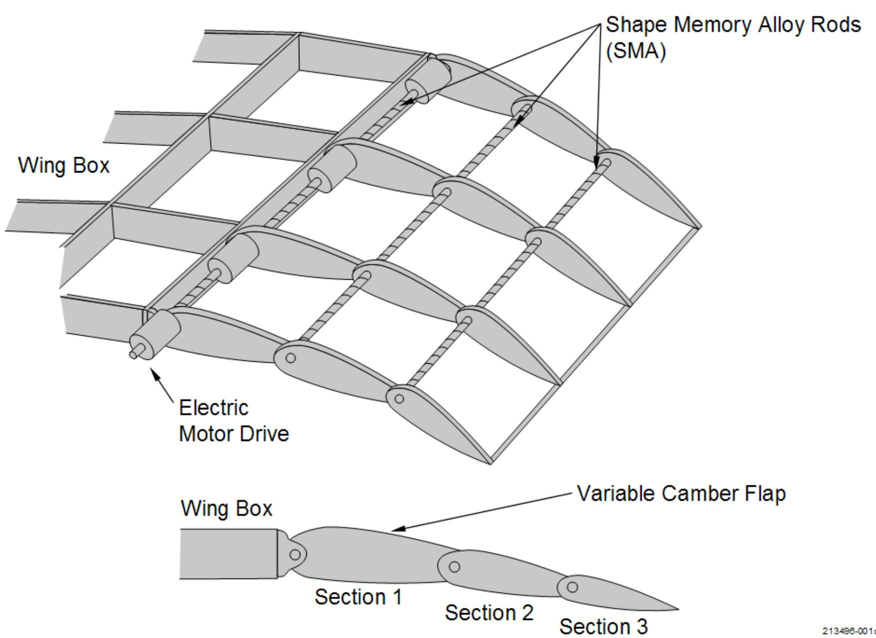
- Addressing SFW project goal of drag reduction for high-aspect ratio elastic wing configurations for current and future N+3 aircraft concepts

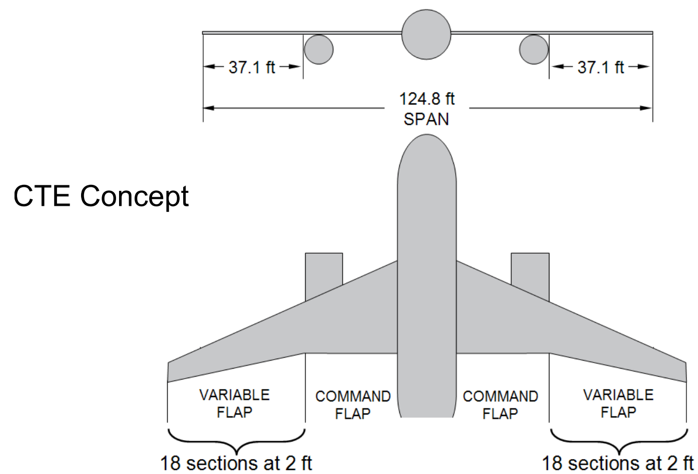
- Developing integrated MDAO solutions to drag reduction challenge
  - Aeoelastic wing optimization for cruise drag reduction
  - Active aeroelastic wing shaping control for drag reduction
  - Integrated aeroelastic flight dynamic modeling of current and N+3 aircraft concepts
  - Aeroelastic flight control solutions to enable operation of high-aspect ratio wing
    - Gust load alleviation
    - Modal suppression
    - Load limiting control allocation
  - Low-drag variable camber continuous trailing edge (VCCTE) flap device for wing shaping control

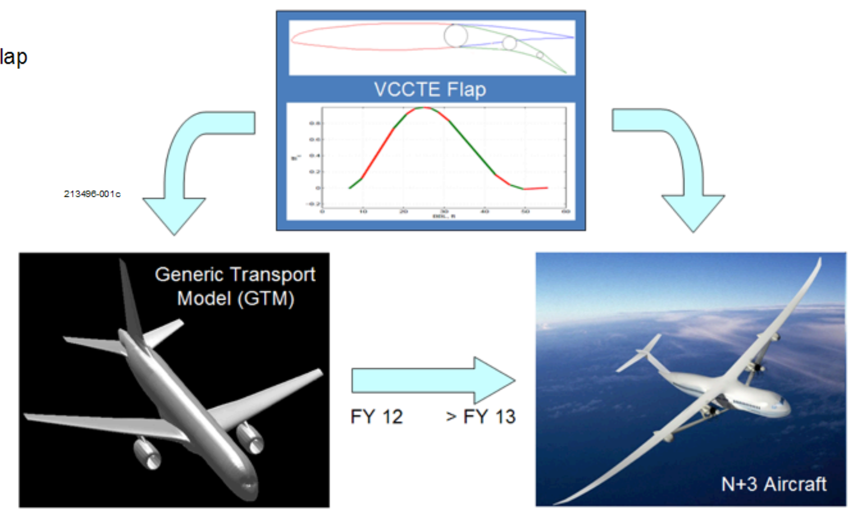


Variable Camber Continuous Trailing Edge Flap (VCCTE) System Partnership

- Collaboration with Boeing under SMAAART contract NNL11AD25T "Development of Variable Camber Continuous Trailing Edge Flap System"
  - Establishes a design of a VCCTE flap system that will act as the dominant control effector to shape the wings on a transport aircraft for the purpose of achieving minimum drag
  - Addresses the goal of the SFW project to reduce drag with minimal impact on weight



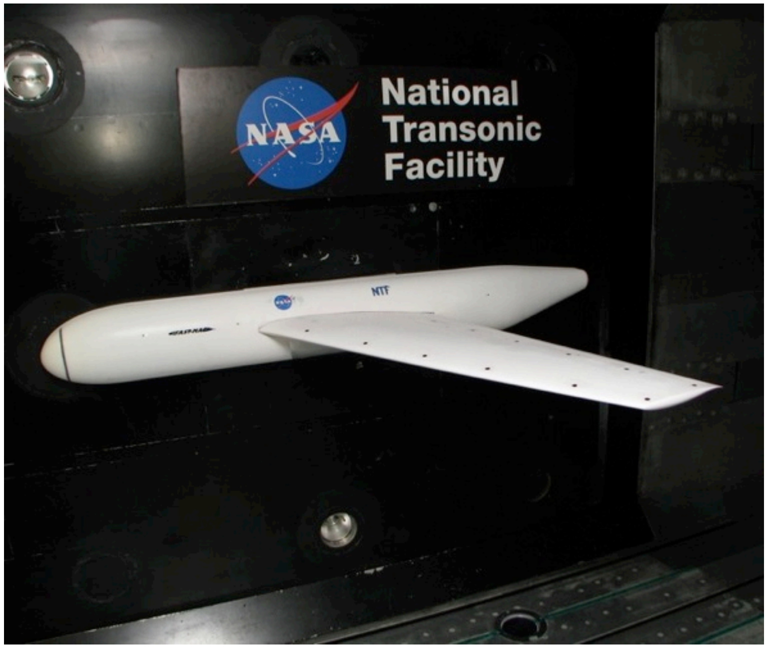


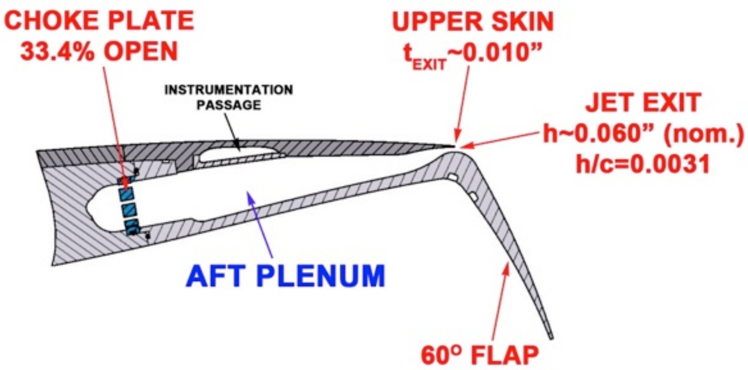


- Ultimate goal is to develop wing shaping control technology for N+3 aircraft design

Circulation Control Research – High Rn

- Technical Objectives
  - Cruise Drag Reduction
  - Low-Speed CLmax
  - Rn Scale Effects, Blowing Effects
- Test Technique
  - National Transonic Facility
  - Sidewall Model Support System
  - Flow Control System
- FAST-MAC Model
  - Mach 0.85 design, open geometry
  - Supercritical airfoil
  - Modular – future flow control and PAI research



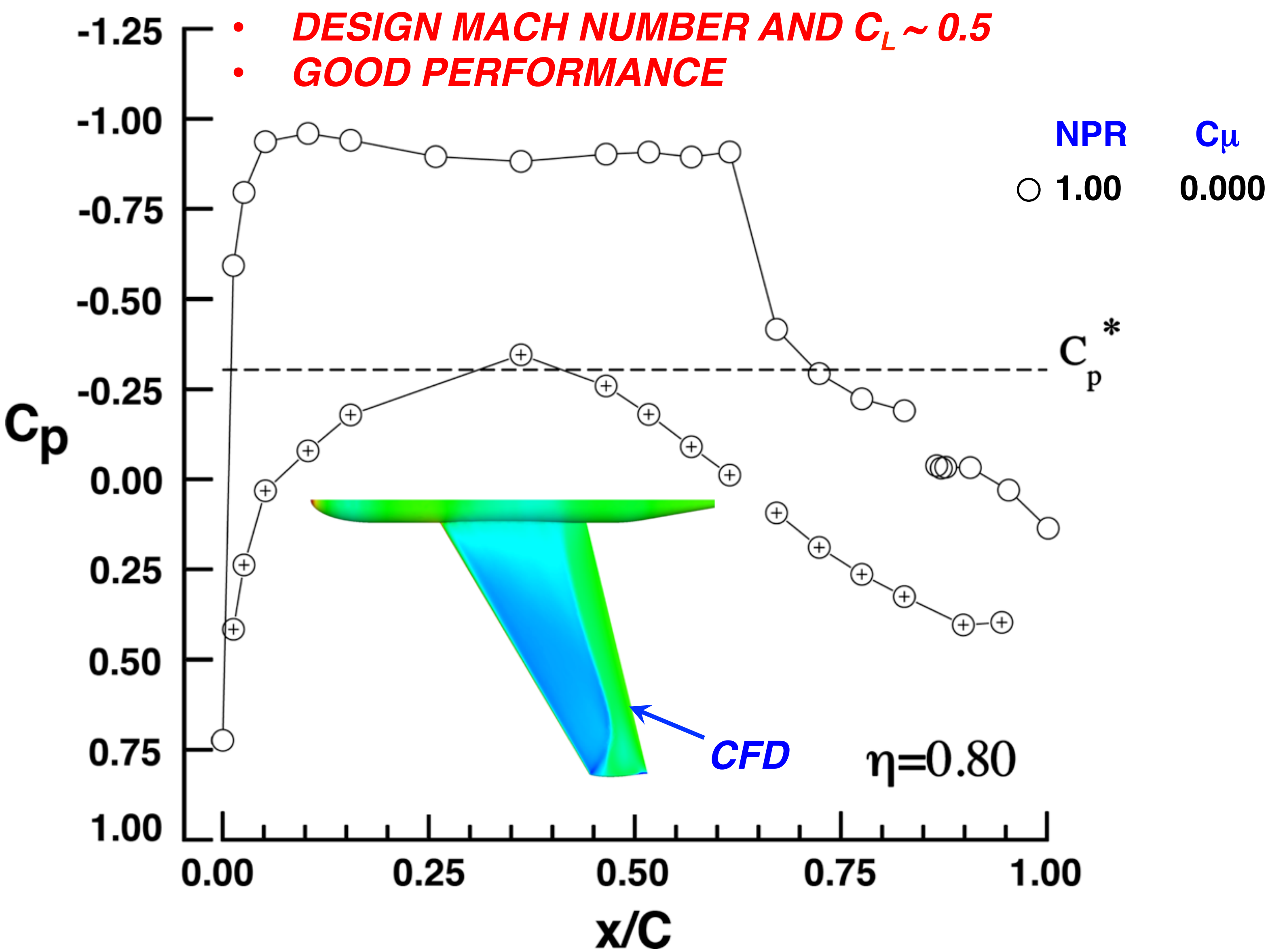


Fundamental **A**erodynamics **S**ubsonic/**T**ransonic-**M**odular **A**ctive **C**ontrol

POCs: W.Milholen, G.Jones, (NASA LaRC); see AIAA 2012-0103

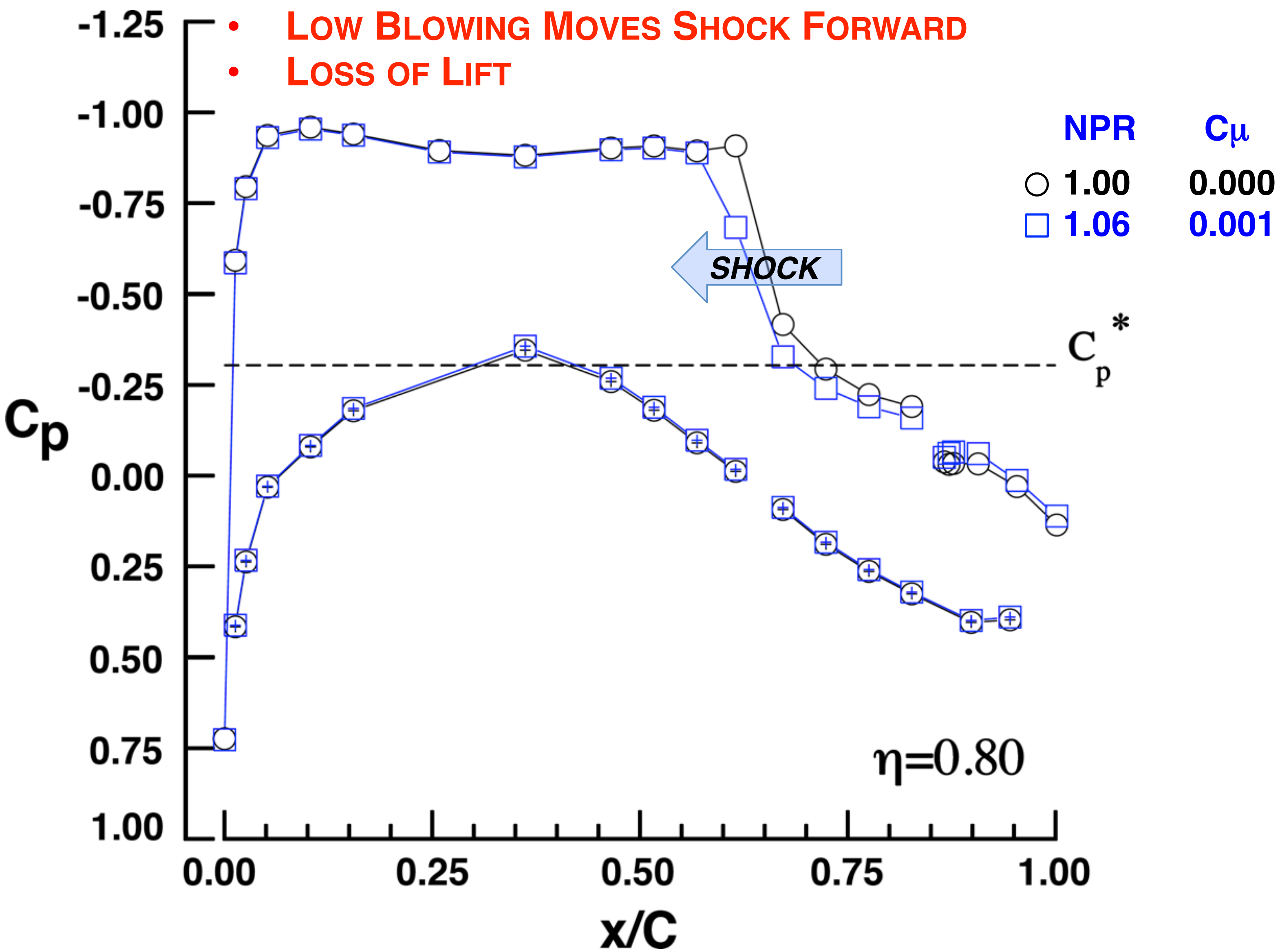
Design Point Wing Pressures

(M_{∞}=0.85, α = 3.00°, Rn=10×10^6)



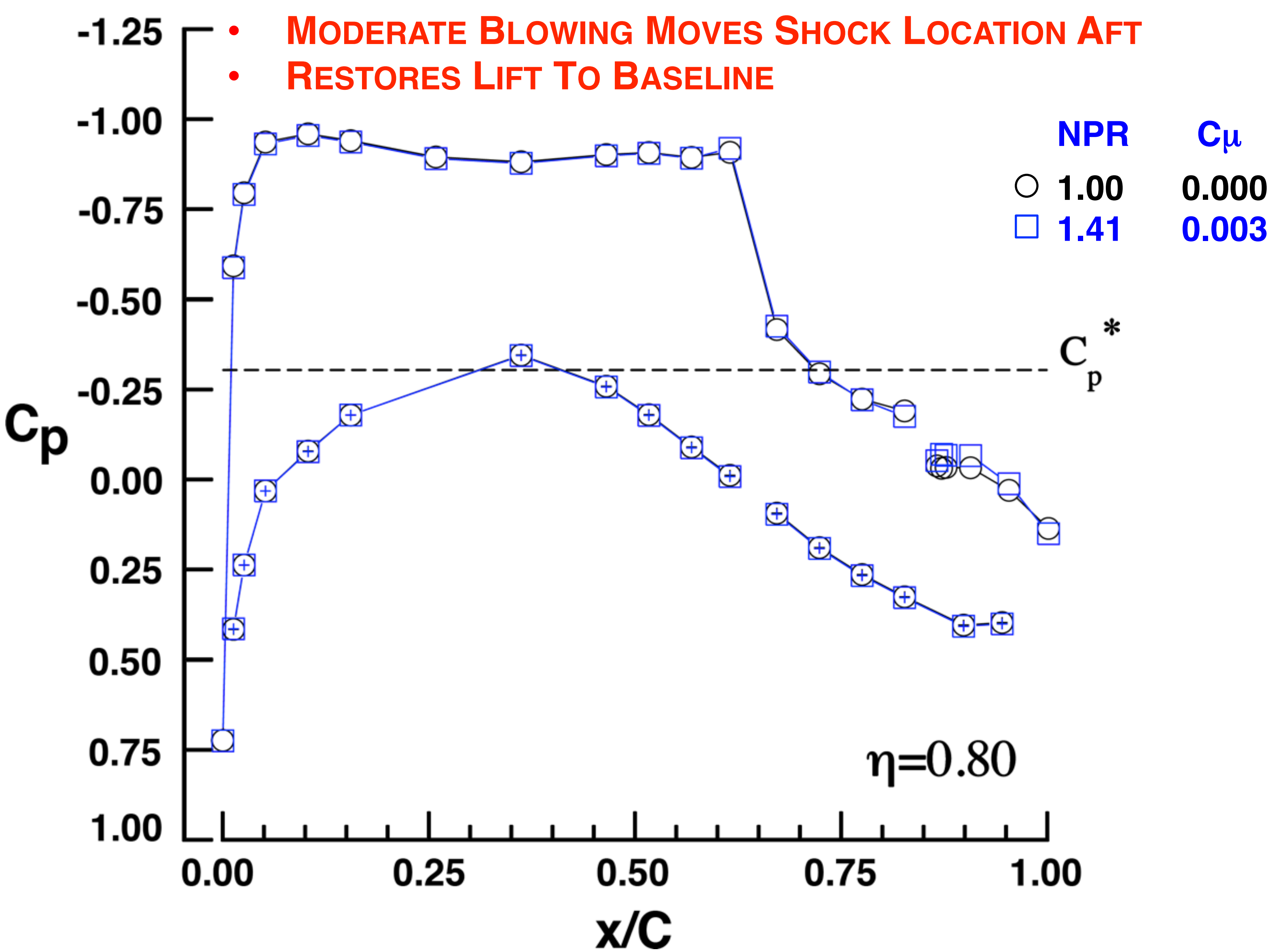
POCs: W.Milholen, G.Jones, (NASA LaRC); see AIAA 2012-0103

Effect of Low Blowing on Wing Pressures
(M_{∞}=0.85, α = 3.00°,Rn=10x10^6)



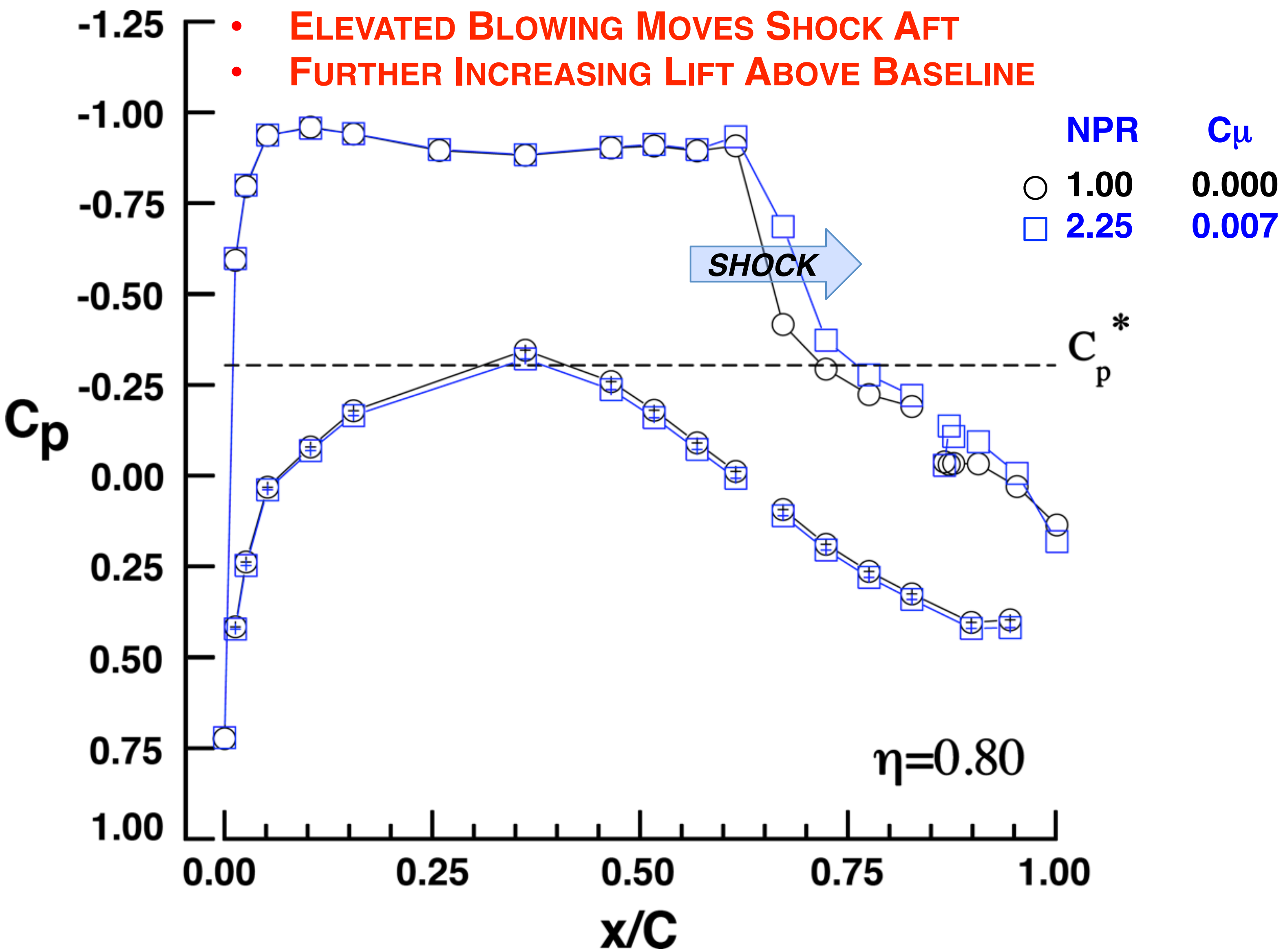
POCs: W.Milholen, G.Jones, (NASA LaRC); see AIAA 2012-0103

Effect of Moderate Blowing on Wing Pressures
(M_∞=0.85, α = 3.00°,Rn=10x10^6)



POCs: W.Milholen, G.Jones, (NASA LaRC); see AIAA 2012-0103

Effect of Elevated Blowing on Wing Pressures
(M_∞=0.85, α = 3.00°,Rn=10x10^6)



POCs: W.Milholen, G.Jones, (NASA LaRC); see AIAA 2012-0103

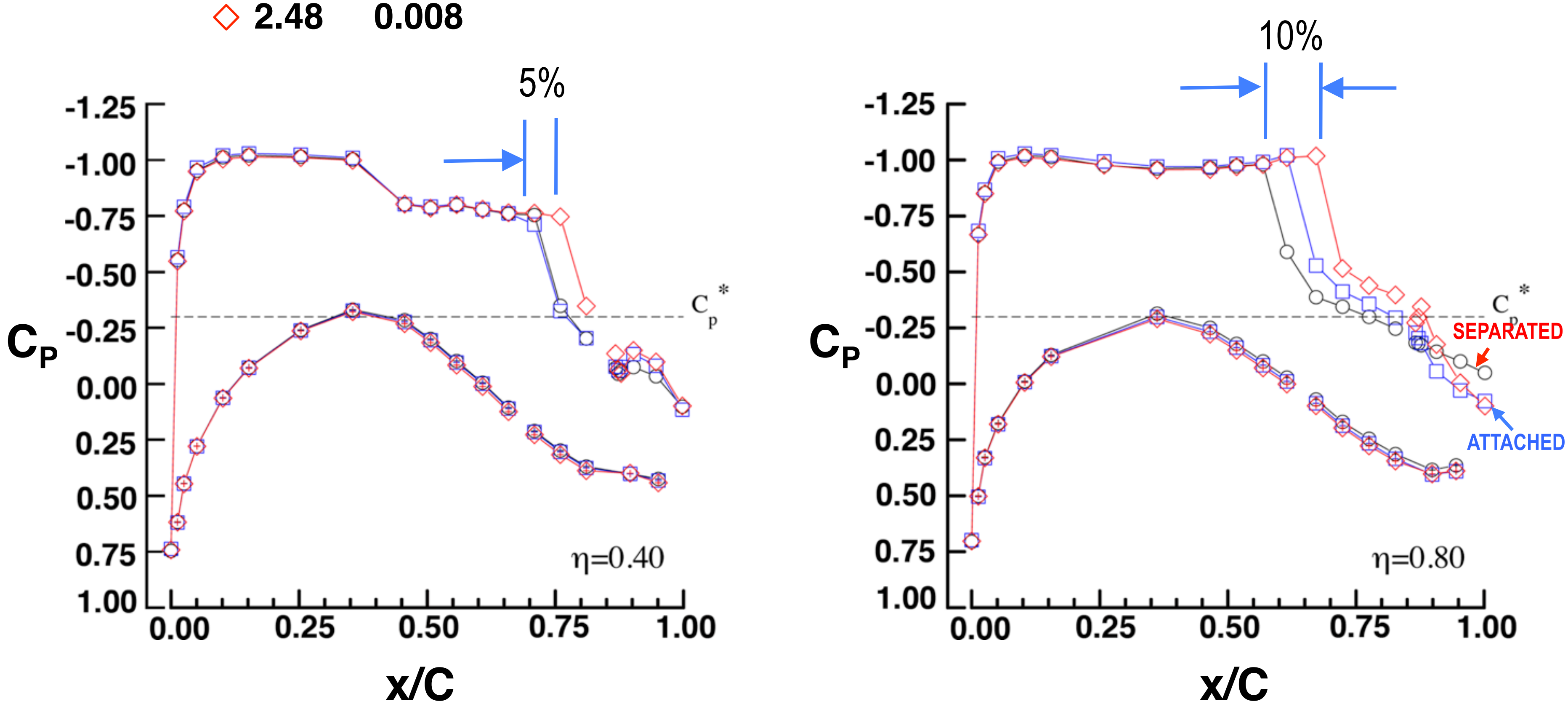
Effect of Blowing on Off-Design Wing Pressures

(M_∞=0.85, α = 3.92°,Rn=30x10^6)

	NPR	Cμ
○	1.00	0.000
□	1.53	0.004
◇	2.48	0.008

OFF-DESIGN C_L ~ 0.7

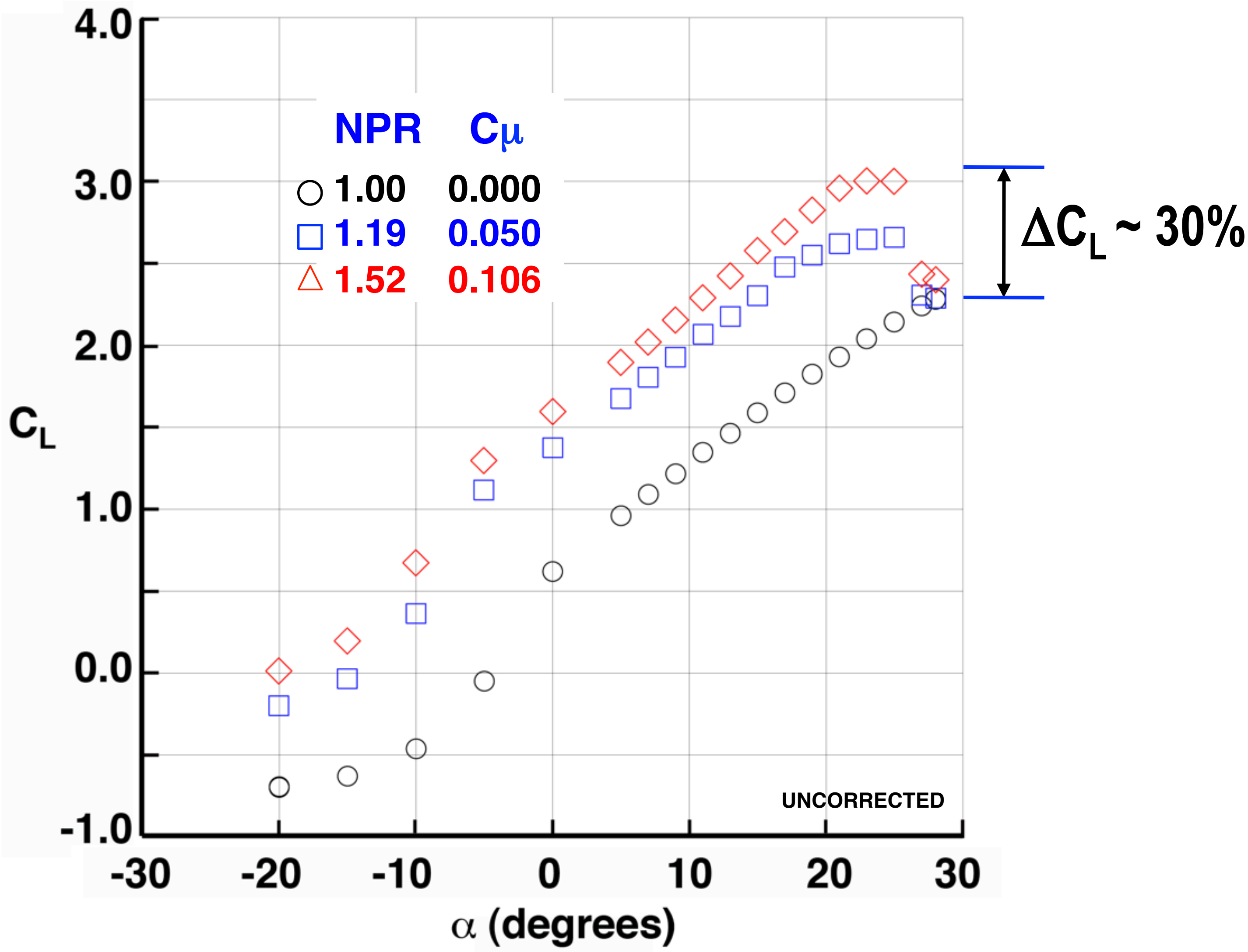
SIGNIFICANT SHOCK WAVE MOVEMENT
LITTLE CHANGE IN SHOCK STRENGTH



POCs: W.Milholen, G.Jones, (NASA LaRC); see AIAA 2012-0103

Effect of Blowing on Low-Speed Performance

60° Flap (M_∞=0.20,Rn=15x10^6)



POCs: W.Milholen, G.Jones, (NASA LaRC); see AIAA 2012-0103

"AMELIA" CESTOL Research

Low-Speed Performance and Acoustics w/ Flow Control

- Technical Objectives
  - Low-Speed Performance
  - Low-Speed Acoustics
  - Configuration, Flow Control, Propulsion
- Test Technique
  - National Full-Scale Aerodynamic Complex (40'x80')
  - Turbine Powered Simulators
  - Force/moment/pressures/skin friction/ acoustics, smoke/oil flow visualization
- AMELIA Model
  - CESTOL , open geometry

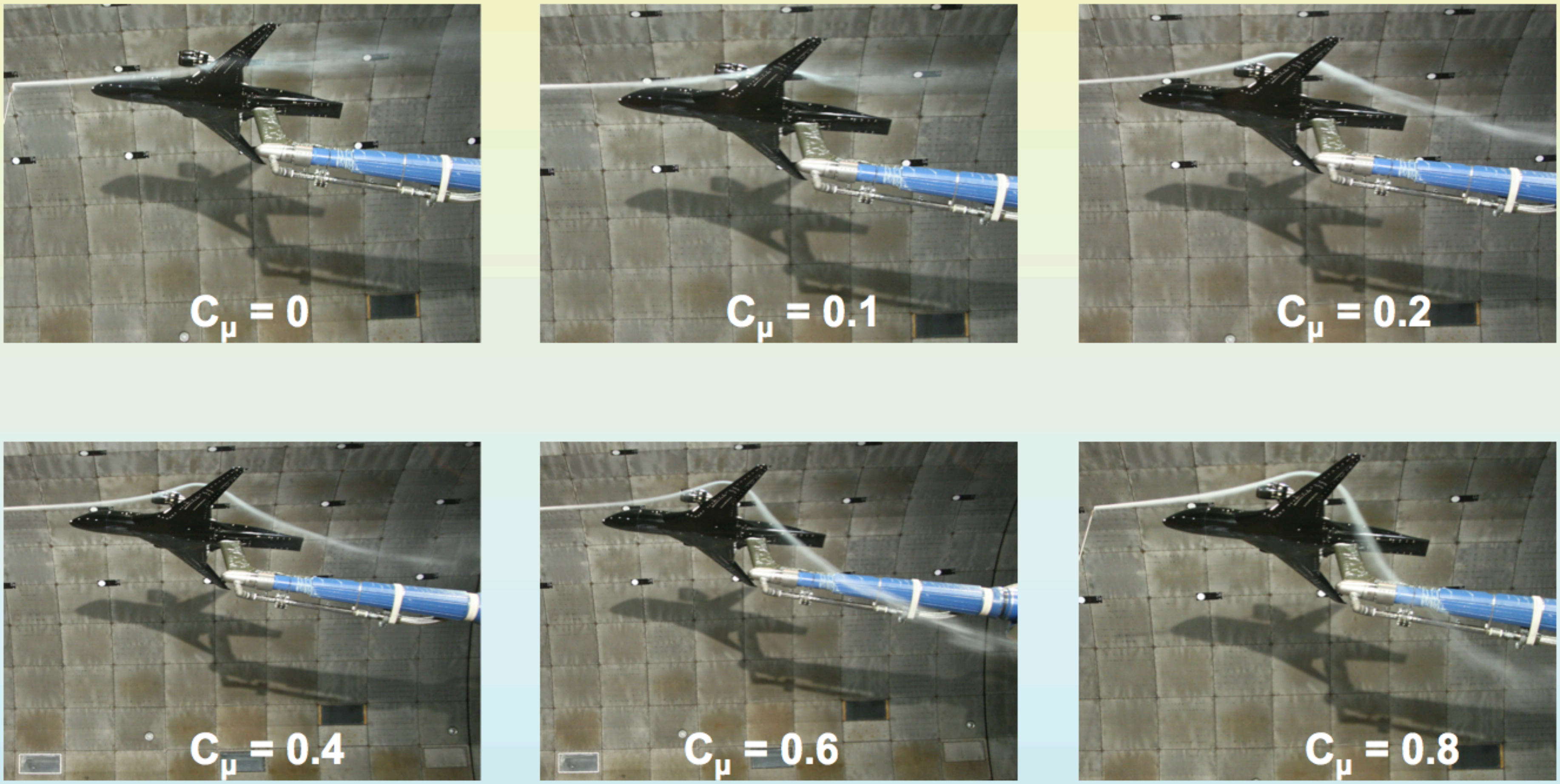
Advanced **M**odel for **E**xtreme **L**ift Improved **A**coustics

POCs: D. Marshall, T. Jameson (Cal Poly); R. Fong, N. Burnside, C. Horne (NASA ARC)

AMELIA – sample flow visualization

Flow Visualization- Momentum Sweep

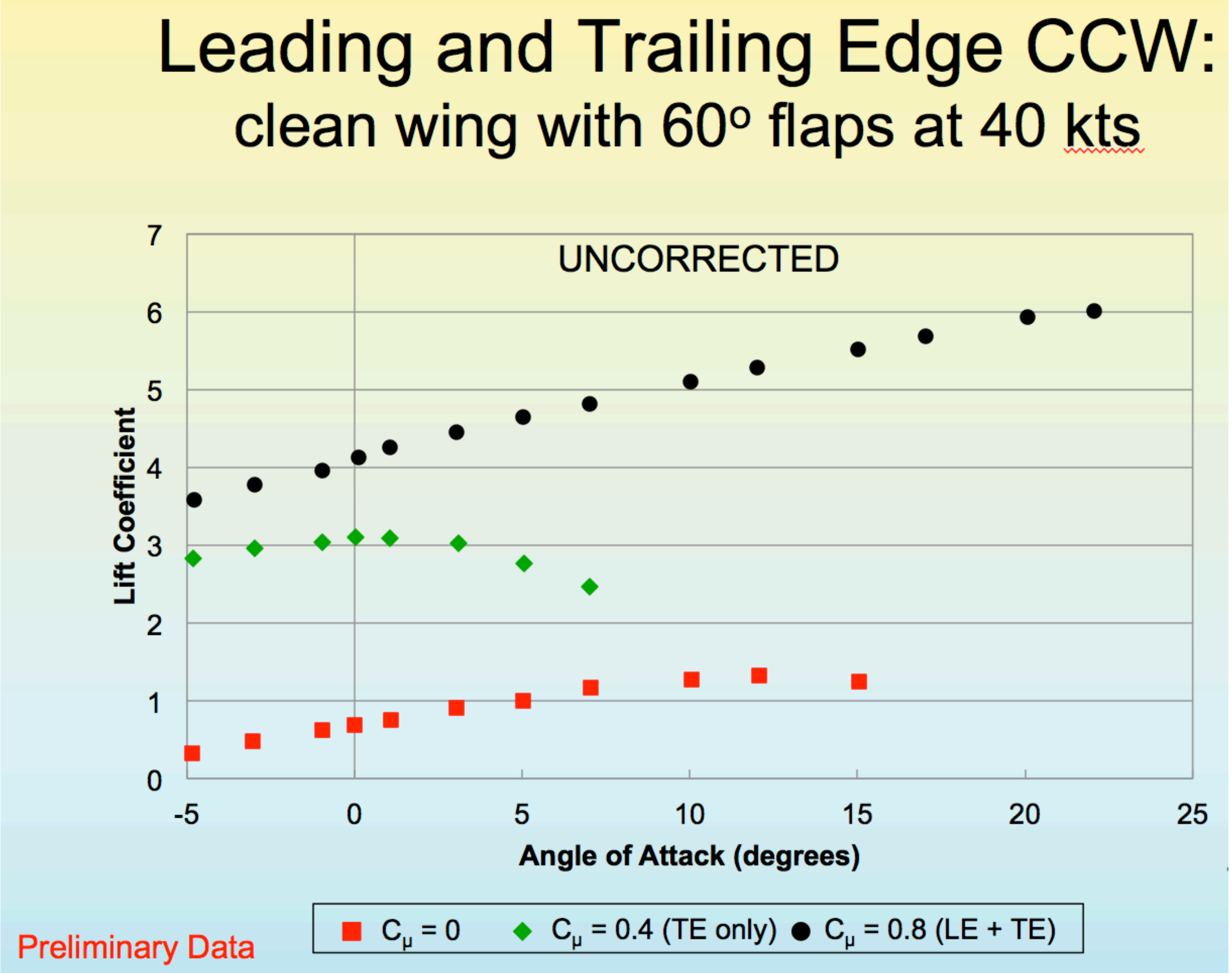
at 30 kts



POCs: D. Marshall, T. Jameson (Cal Poly); C. Hange, C. Horne (NASA ARC)

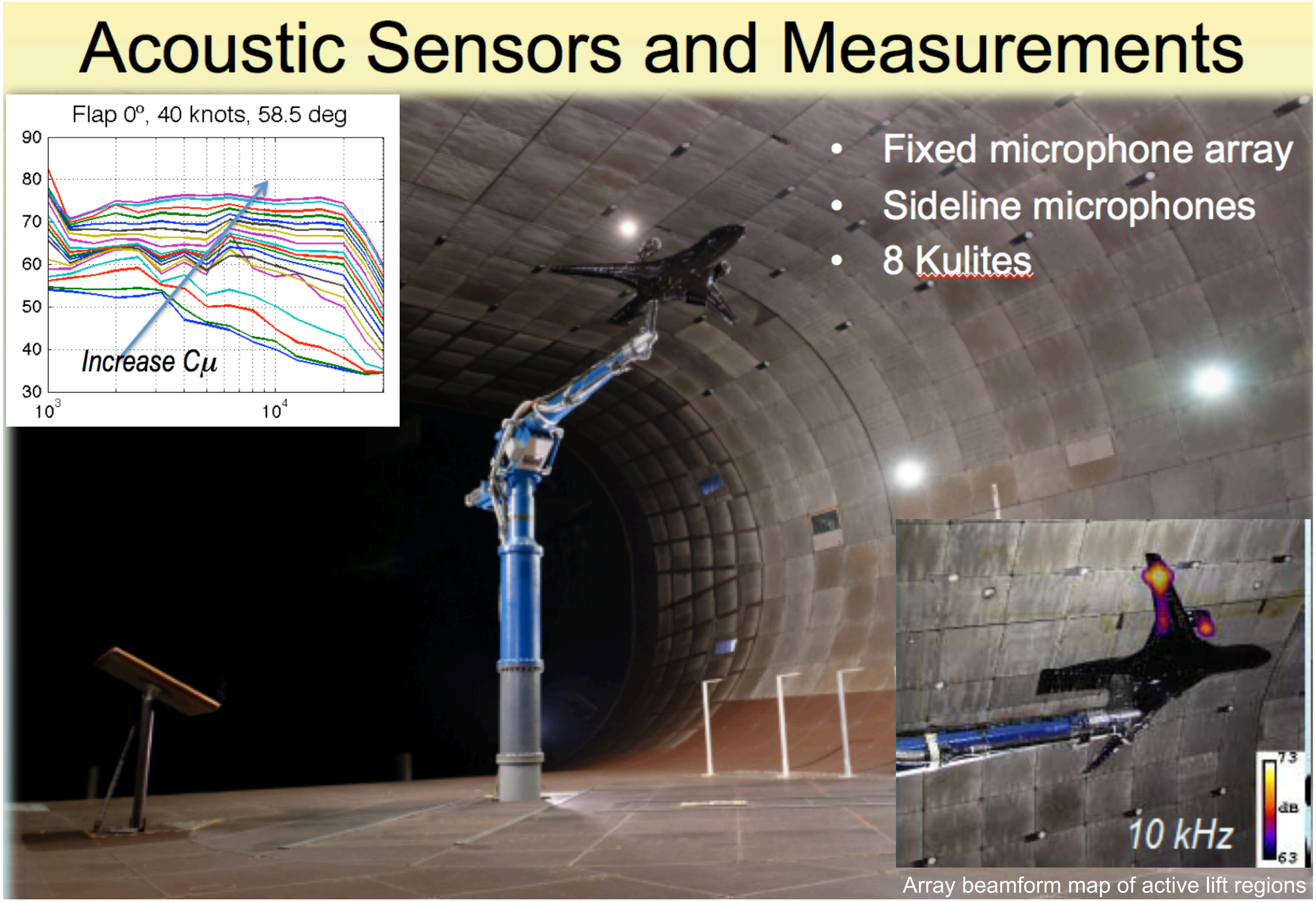
AMELIA – sample performance

- Leading-edge blow is important to overall system benefit



POCs: D. Marshall, T. Jameson (Cal Poly); C. Hange, C. Horne (NASA ARC)

AMELIA – sample acoustics data



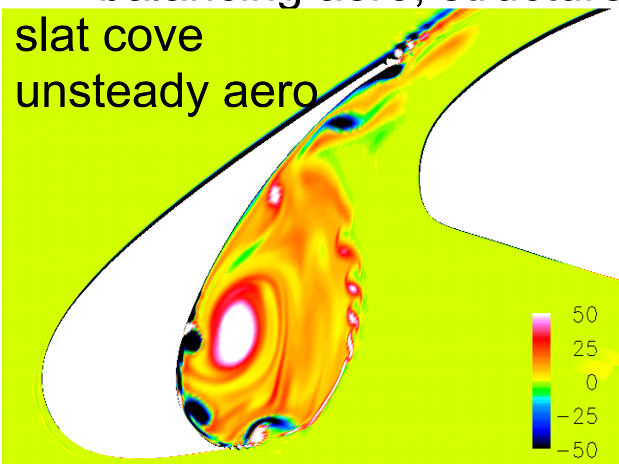
Array beamform map of active lift regions

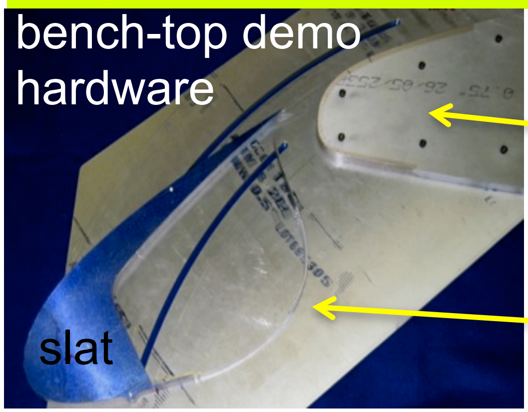
POCs: D. Marshall, T. Jameson (Cal Poly); C. Hange, C. Horne (NASA ARC)

Aero-Structures

changing the multidisciplinary trade space

Multi-Objective Leading Edge
balancing aero, structures,





main
element

cove filler
assembly

Truss-Braced Wing
balancing drag, weight, speed

low drag strut
wing/strut/truss optimization
wing weight uncertainty

Inviscid Simulation of the MIT N+3 D8 Double-bubble Aircraft External Aerodynamics Completed

PROBLEM

Model and simulate the MIT D8 “double-bubble” design in an inviscid code to obtain preliminary assessment of the aircraft’s external aerodynamics in support of the aircraft design team

OBJECTIVES

- Use accurate mesh refinement techniques to guide future (viscous) simulations
- Study the effects of wind tunnel walls, strut, and empennage on model aerodynamic loads
- Compare to experimental results and results from MIT’s Fluent simulations

APPROACH

- Generated geometries with and without wind tunnel walls as well as strut and empennage
- Used Cart3D code along with an adjoint-based mesh refinement method
- Compared results to data from the Wright Brothers wind tunnel at MIT as well as to MIT’s Fluent results

RESULTS

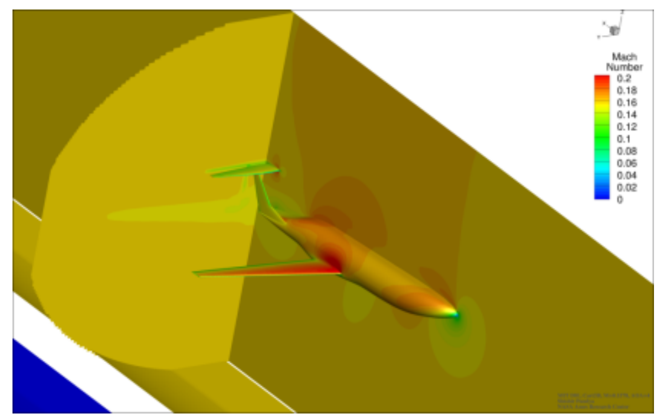
- Good CL agreement without WT walls; stall only predicted with WT walls, no stall in Fluent results.
- CD is over-predicted.
- Cm is good at low-α
- Strut effects are minimal, WT wall effects are substantial
- Empennage contributes significant loads

SIGNIFICANCE

Loads assumptions are verified, and guidance for mesh clustering is completed. Allows the group to move on to simulations with viscous effects and propulsion system integration.

D8 initial tests at the MIT Wright Bros WT

Mach contours on MIT D8 with wind tunnel walls



POC: Shishir A. Pandya (NASA ARC)

N+3 Integrated Vehicle Concepts

technology collectors … revolutionary performance … low TRL

Truss-Braced Wing with Hybrid Electric Propulsion

Boeing – NASA N+3 Study

Hybrid Wing Body w/ Turbo-Electric Distributed Propulsion

NASA in-house

D8 Double Bubble w/ high BPR BLI Propulsion

MIT – NASA N+3 Study

Significant technology development required by 2030,
but in the realm of the possible

Concluding Remarks

- Exciting times
  - Many opportunities … many challenges
- Technologies
  - Many broadly applicable technologies
  - Some uniquely enabling technologies
- Vehicles, Operations, Energy – no silver bullet

for more information:

- SFW presentations from AIAA Nashville Jan ’12
  http://www.aiaa.org/KeySpeeches2012/

- N+3 NRA Phase 1 studies see:
  http://www.nasa.gov/topics/aeronautics/features/future_airplanes_prt.htm

- Green Aviation Summit (Sept 8-9, 2010)
  http://www.aeronautics.nasa.gov/calendar/20100908.htm

NASA