National Aeronautics and Space Administration

NASA Sponsored Activities in Laminar Flow Technologies for Advanced Transport Aircraft

Fayette Collier, Ph.D., M.B.A.
Project Manager
Environmentally Responsible Aviation
(ERA) Project, NASA

2nd UTIAS-MITAS International Workshop on Aviation and Climate Change
MAY 27-28, 2010
Toronto, Canada

www.nasa.gov

Agenda

- NASA System Metrics and Technology Evaluations
- Laminar Flow Technology Background and Status
- NASA Activities to Advance Laminar Flow Technology
- Concluding Remarks

NASA Subsonic Transport System Level Metrics

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

Over the next 5 years:

- Explore and mature alternate unconventional aircraft designs and technologies that have potential to simultaneously meet community noise, fuel burn, and NOX emission midterm goals as described in the National Aeronautics R & D Plan
- Determine potential impact of these aircraft designs and technologies if successfully implemented into the Air Transportation System
- Determine potential impact of these technologies on advanced "tube and wing" designs

ERA focused subset of Metrics

CORNERS OF THE TRADE SPACE	N+1 = 2015*** Technology Benefits Relative To a Single Aisle Reference Configuration	N+2 = 2020*** Technology Benefits Relative To a Large Twin Aisle Reference Configuration	N+3 = 2025*** Technology Benefits
Noise (cum below Stage 4)	-32 dB	-42 dB	-71 dB
LTO NO_x Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%	-50%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts

***Technology Readiness Level for key technologies = 4-6. ERA will undertake a time phased approach, TRL 6 by 2015 for "long-pole" technologies

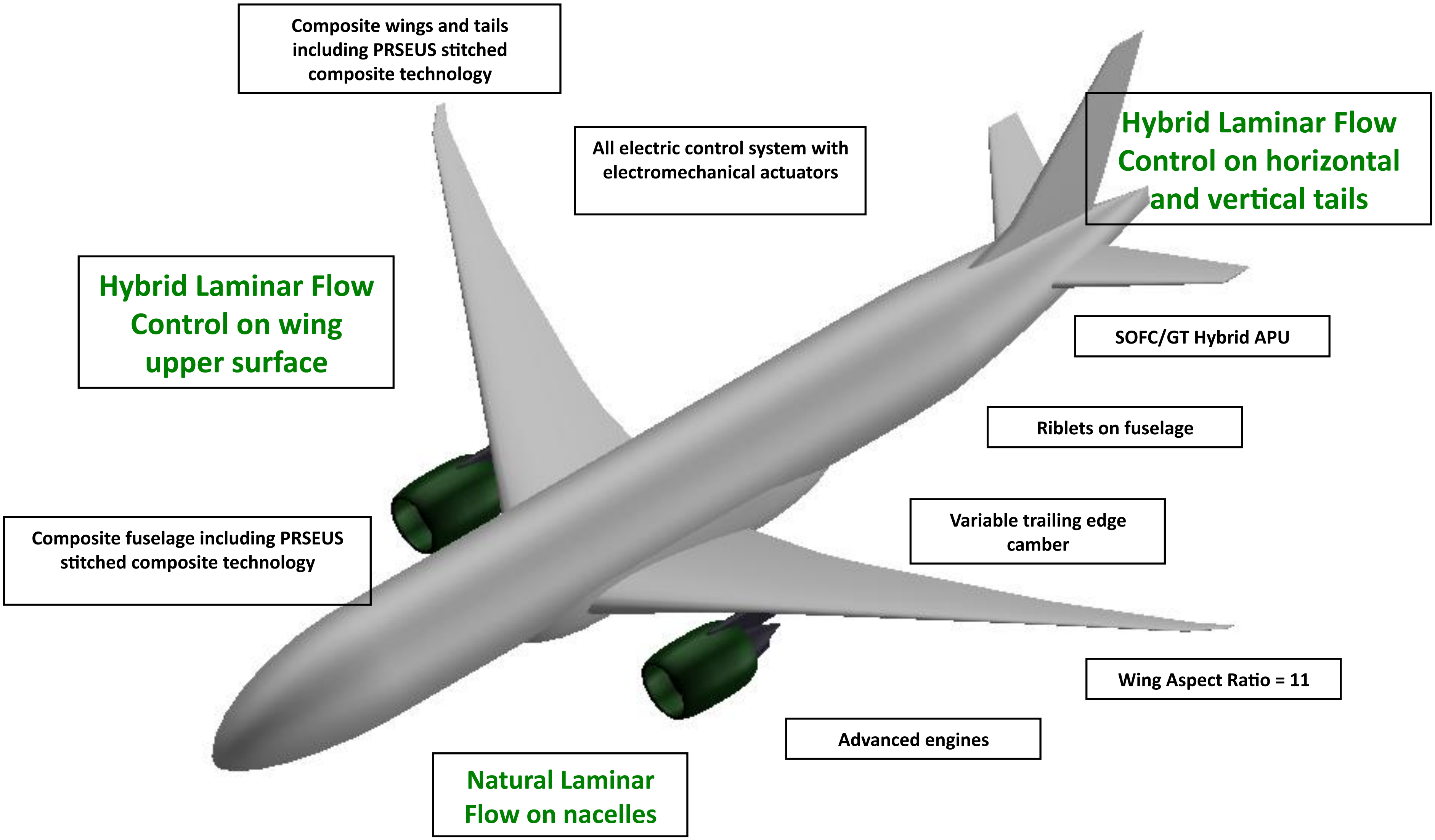
** RECENTLY UPDATED. Additional gains may be possible through operational improvements

* Concepts that enable optimal use of runways at multiple airports within the metropolitan area

2025 “Technology Collectors” – Current Set

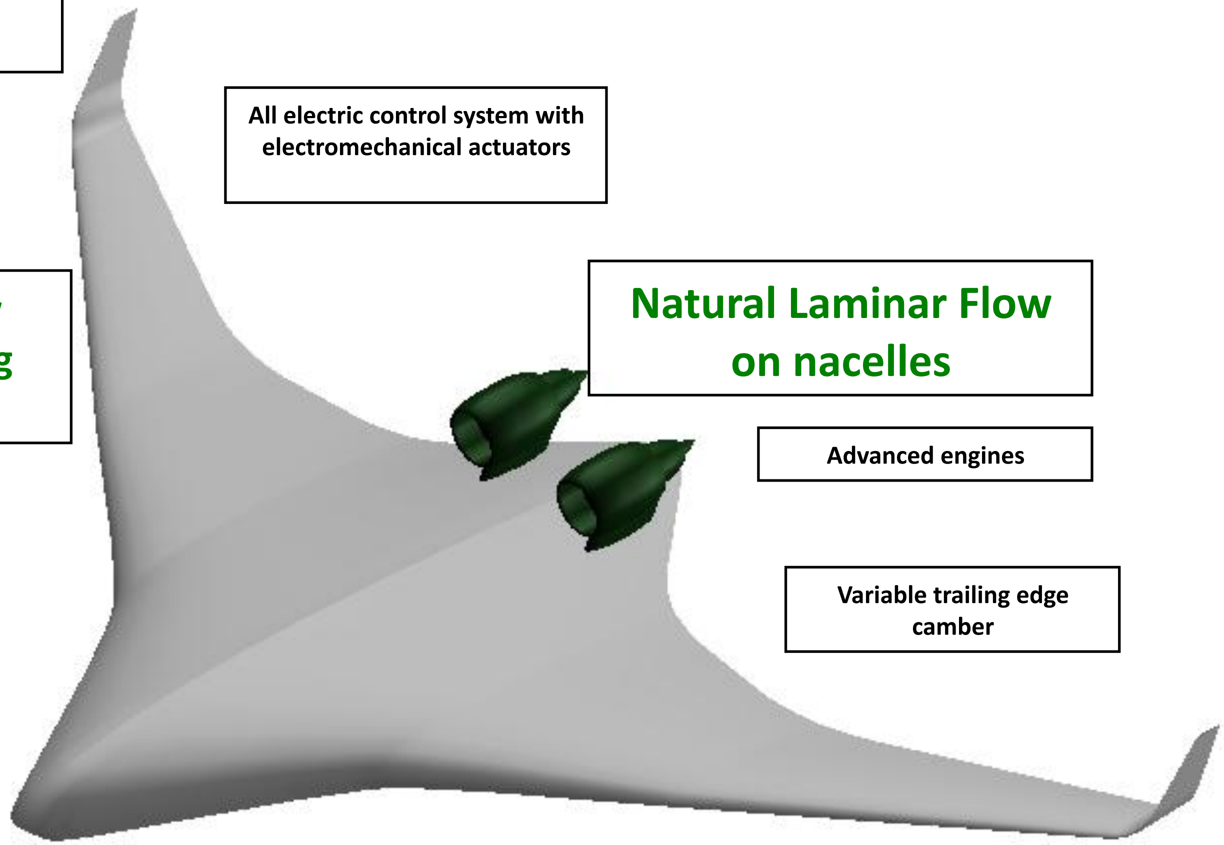
Advanced Configuration 1

N+2 Advanced "tube-and-wing" 2025 Timeframe



Advanced Configuration 2A

N+2 Advanced HWB 2025 Timeframe



Composite centerbody and wings including PRSEUS stitched composite technology

All electric control system with electromechanical actuators

Hybrid Laminar Flow Control on outer wing sections

Natural Laminar Flow on nacelles

Advanced engines

Variable trailing edge camber

Riblets on centerbody

SOFC/GT Hybrid APU

Advanced Configuration 2B

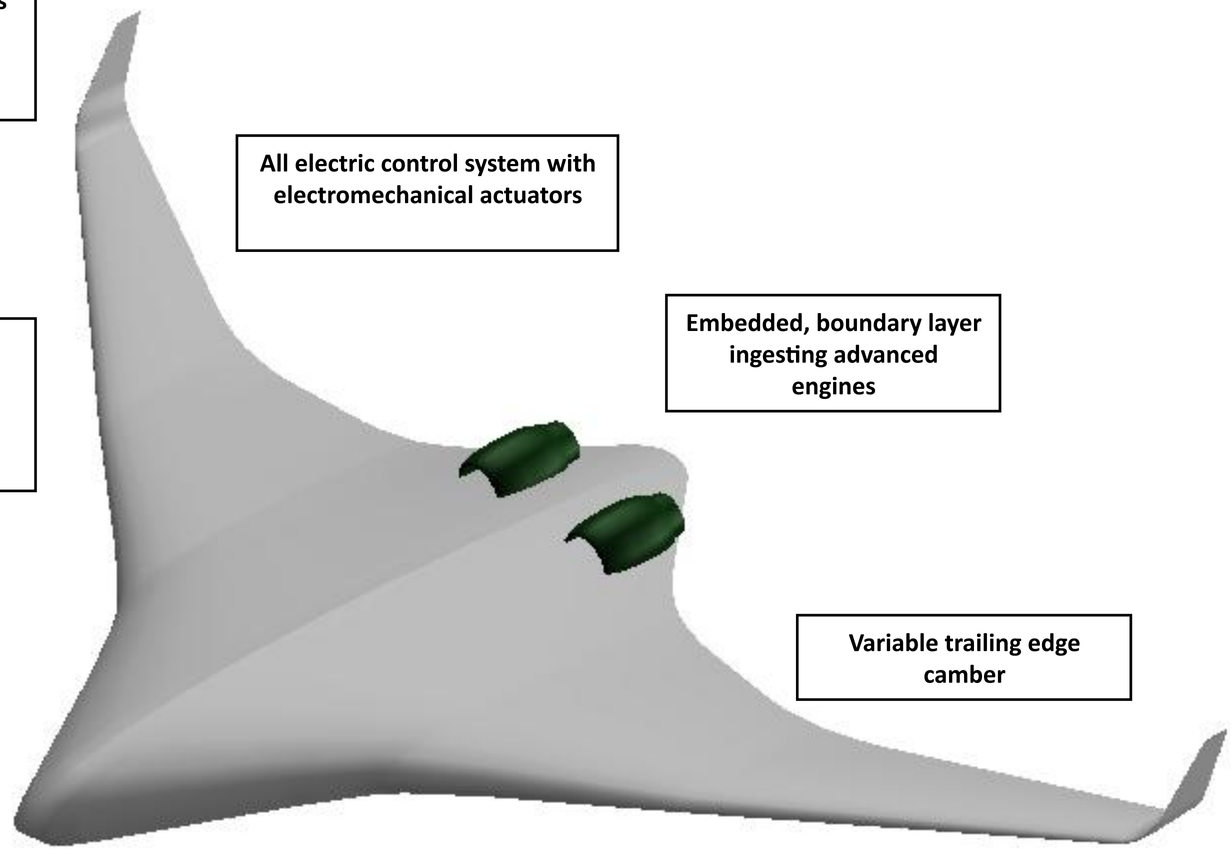
N+2 HWB300 2025+ Timeframe

Composite centerbody and wings including PRSEUS stitched composite technology

All electric control system with electromechanical actuators

Embedded, boundary layer ingesting advanced engines

Hybrid Laminar Flow Control on outer wing sections



Variable trailing edge camber

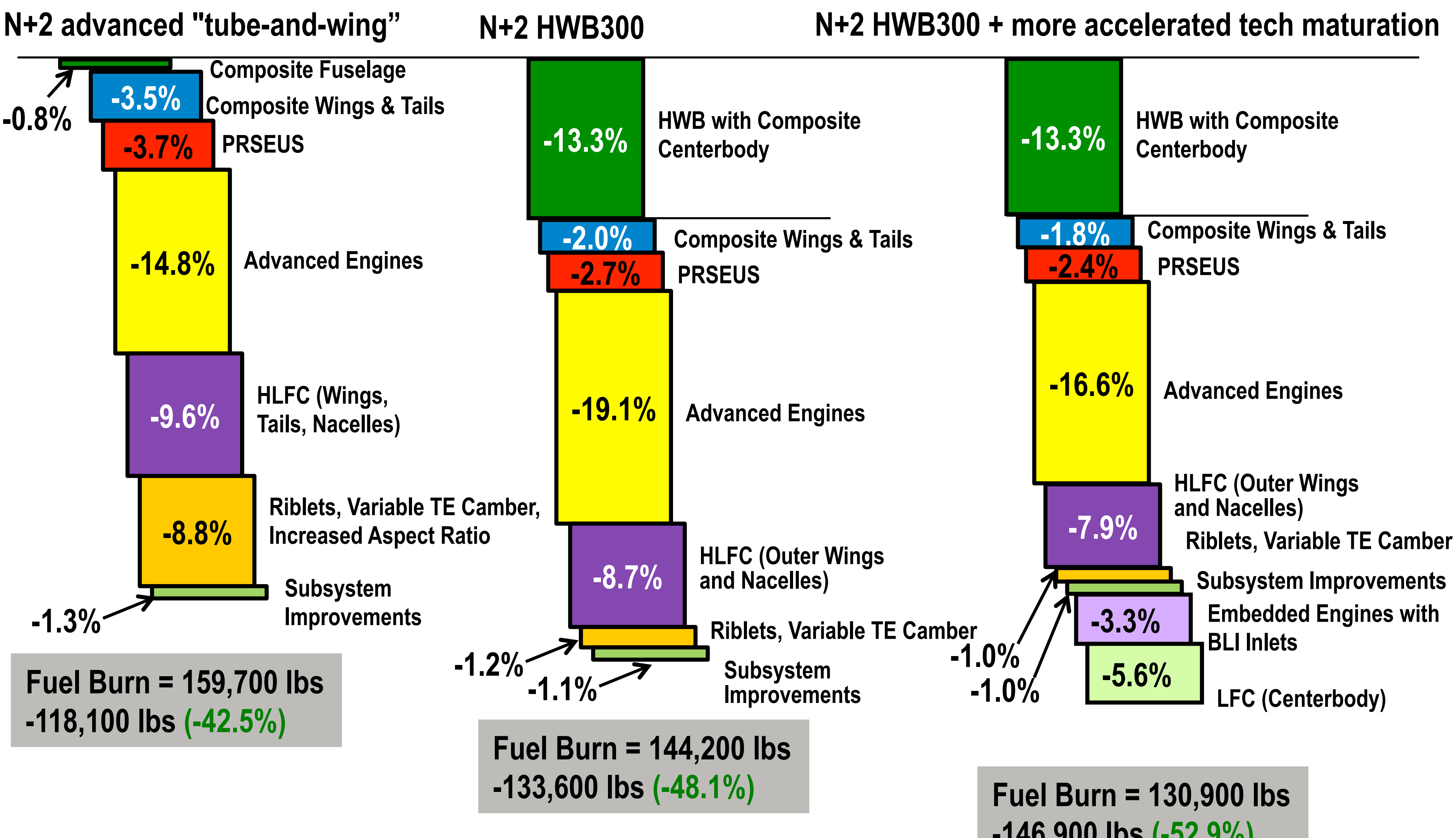
Laminar flow control on centerbody

SOFC/GT Hybrid APU

Potential Reduction In Fuel Consumption

2025 EIS (TRL = 6 in 2020)

Technology Benefits Relative to Large Twin Aisle (Reference: 777-200LR "like" Vehicle



Reference Fuel Burn = 277,800 lbs

Laminar Flow Technology

Fuel Burn Reduction via Laminar Flow Control

- Objective - Enable practical laminar flow for transport aircraft
  - LFC demonstrated in several flight experiments
  - Subsonic boundary layer transition mechanisms are sufficiently well understood for design
  - Swept-Wing laminar flow is design tradeoff between TS and CF modes

Laminar Flow

Attachment Line Instability/ Contamination
- Wing leading edge radius and sweep constraints
- R_θ< 100 for "no contamination" (empirical)
- Divert contamination i.e. "Gaster Bump"
- Suction at attachment line

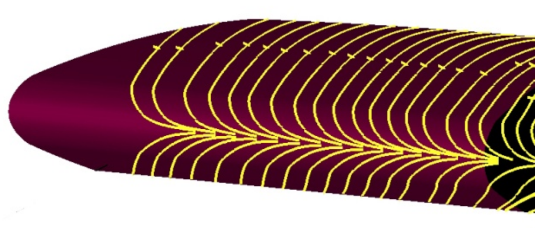
Tollmien-Schlichting (TS) Instability
- Viscous mode
- 2D BL transition mechanism
- Sensitive to surface waviness
- Stabilized by –dp/dx, suction, cooling
- For NLF, maximize (-dp/dx)

Crossflow (CF) Instability
- Inviscid instability of crossflow velocity profile
- Crossflow induced due to sweep and –dp/dx
- 3D BL transition mechanism
- Sensitive to surface roughness
- Stablized by wall suction
- For NLF, minimize sweep and/or dp/dx

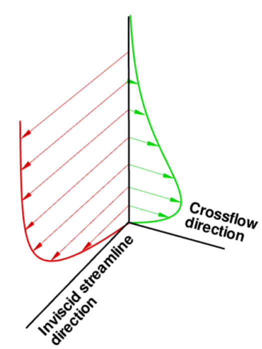
Secondary Instability

Breakdown ..

Turbulent Flow



Attachment line

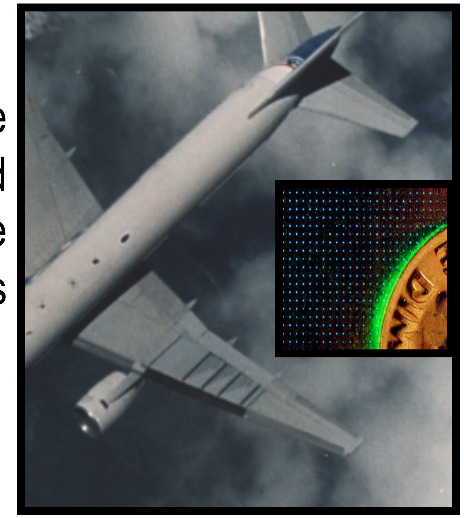


Crossflow Instability

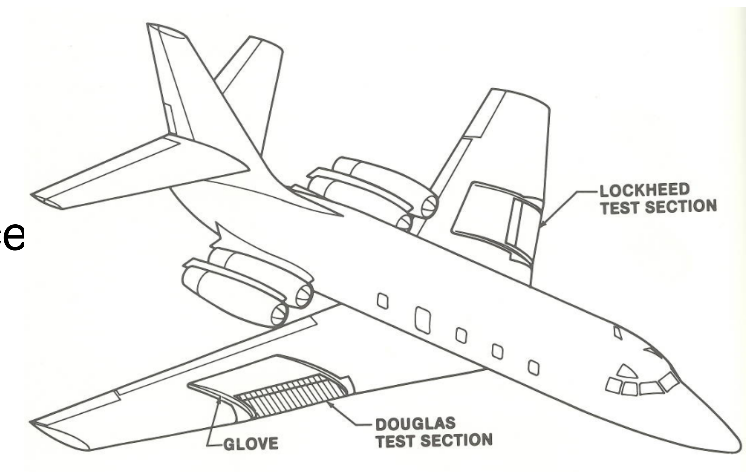
Status of Practical Laminar Flow Control

- Laminar flow has yet to be exploited on transonic transport aircraft
  - Laminar flow technology at TRL of 5-6. What needs to be done?
- Achieving LFC is a complex design challenge
  - Configuration trades between sweep, wing thickness, cruise Mach number, S&C (SRL ??)
  - System integration trades – high-lift performance, flight weight systems, structural stiffness (IRL ??)
  - Manufacturing of structures, joints, surface quality, etc. (IRL ??)
- Outstanding questions
  - Operational readiness
    - robustness to contamination, repair of surface damage, loss of LF due to clouds/ice
    - Examples: JetStar, A320 HLFC vertical tail
  - Pre-flight assessment – ability to ground test/ assess across full-flight envelop

Active and Passive Concepts



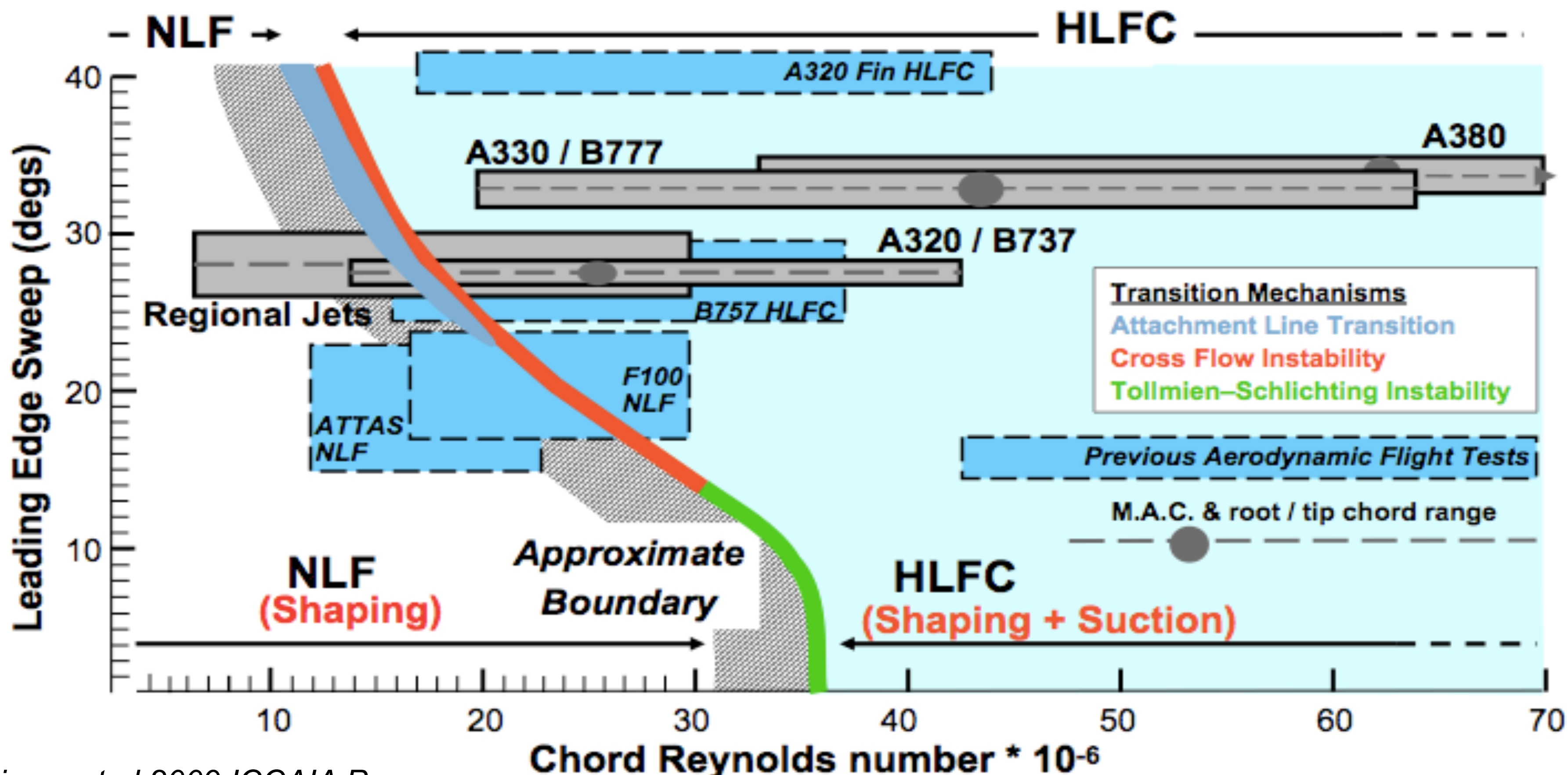
757 HLFC Experiments



JetStar Experiments

Laminar Flow Approach is Determined by Mission

- Approach dependent on system requirements and trades
- System design decisions/trades
  - Mach/Sweep, Rn, Cp distribution, high-lift system
  - Aircraft components, and laminar extent of each

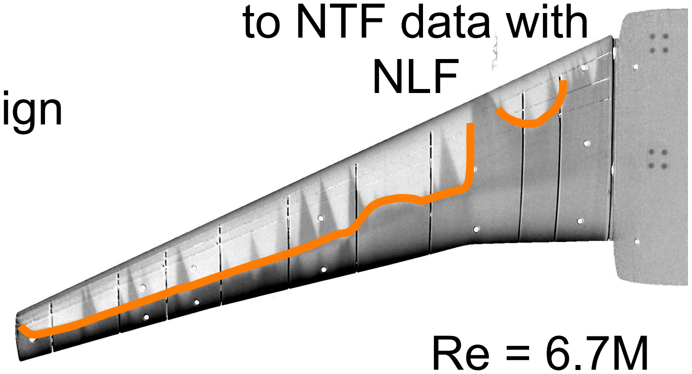


Vijgen, et al 2009 ICCAIA Paper

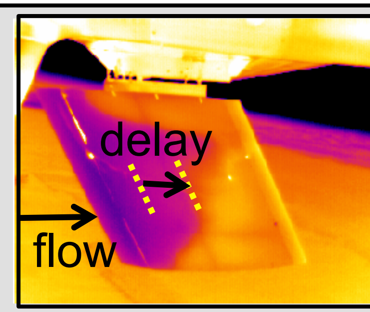
Laminar Flow Technology Maturation by NASA

- **Develop and demonstrate usable and robust aero design tools for NLF, HLFC**
  - Link transition prediction to high-fidelity aero design tools
- **Explore the limits of CF control through Discrete Roughness Elements (DRE)**
  - Practical Mach, Re demonstration at relevant C_L
  - Potential control to relax surface quality requirements
- **NASA NRA to develop N+2 concepts to PDR**
  - Integration of NLF, HLFC, and/or DRE into flight weight systems
  - Understand system trades
- **Assess and develop high Reynolds number ground test capability**

Analysis compared to NTF data with NLF



Re = 6.7M



DRE effect, low M, low Rn

Aero Tools for LFC Design

Some Aerodynamic Trades in Transonic NLF Design

Challenges:

- Longer extent of favorable pressure gradient can increase shock Mach number (M_1) and wave drag

$$\Delta c_{dw} = .04/(t/c)^{1.5} * (M_1 - 1)^4$$

- Thinning an airfoil can reduce M_1, but thinness is limited by need for favorable gradient, especially if NLF is also desired on lower surface

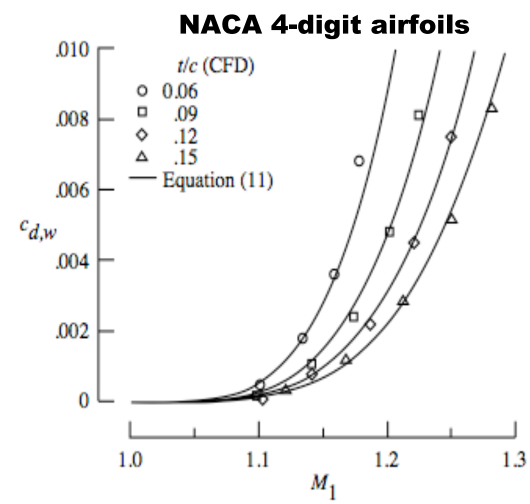
$\Delta M_1 = 7\ \Delta(t/c)$

- Small leading edge radius for NLF and/or thin airfoil can adversely impact low-speed, high-lift characteristics
- Design must be multipoint in the traditional sense as well as minimizing impact if NLF is lost

Note: the above equations were empirically derived (by Dick Campbell) and may not be generally applicable.

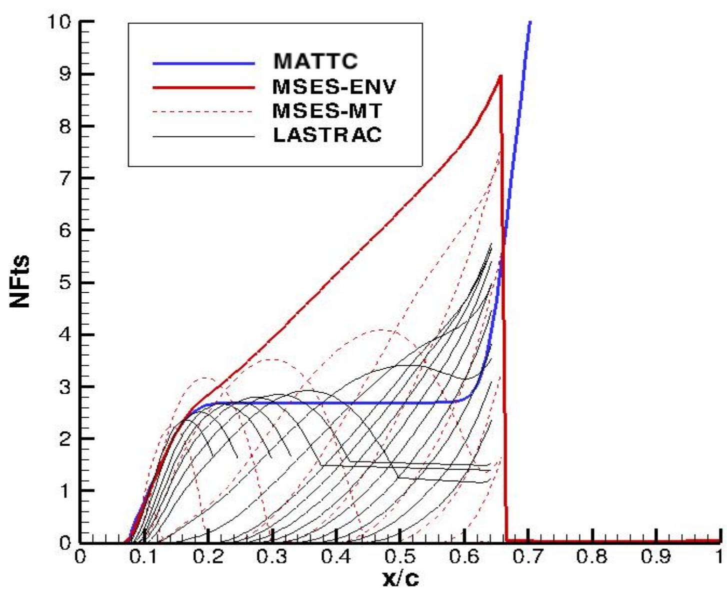
For t/c=0.10, increasing M_1 from 1.10 to 1.18 gives Δc_{dw} = 0.0012

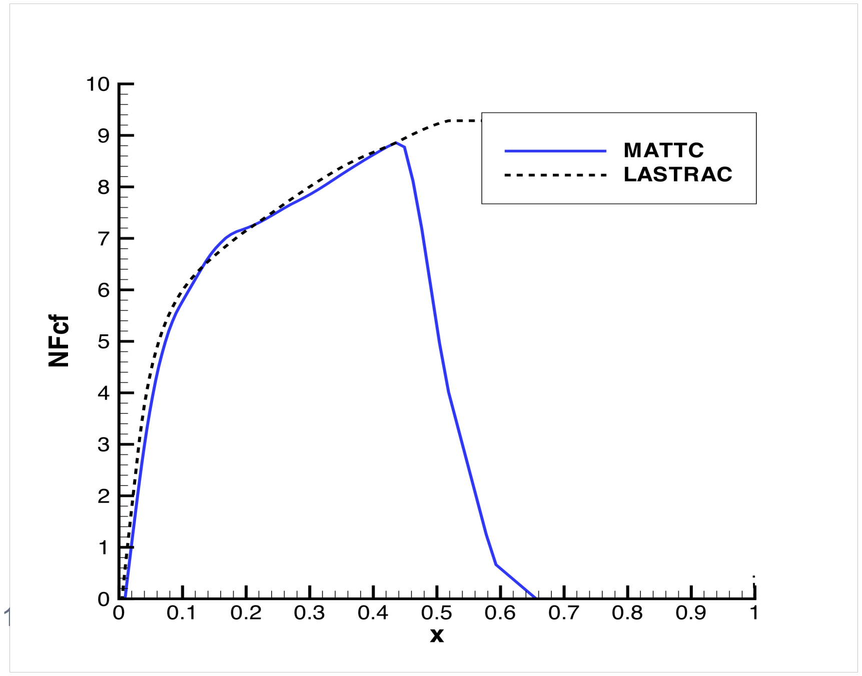
Thinning airfoil to t/c=.09 may remove this wave drag penalty



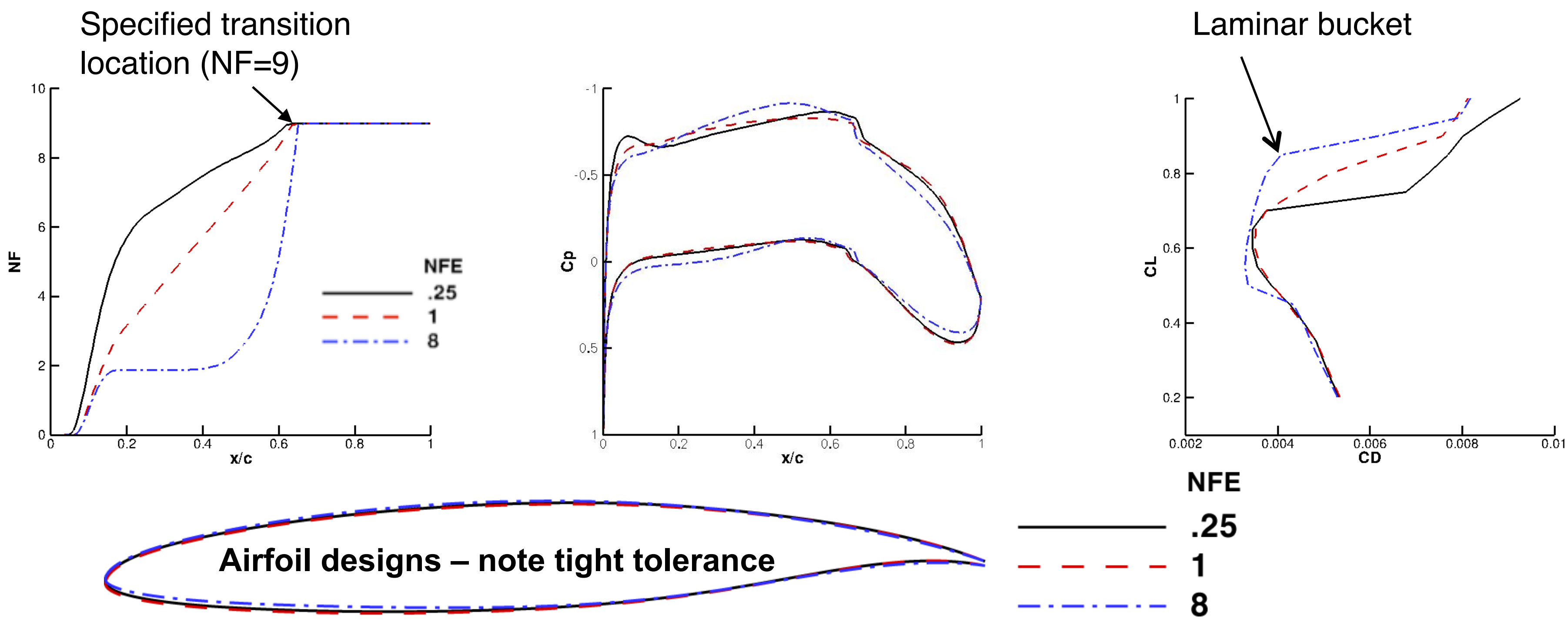
MATTC Transition Prediction Method

- Modal Amplitude Tracking and Transition Computation
- Computes transition location based on empirical correlations
  - transition studies using 3 airfoils run in MSES and LASTRAC
  - TS: Re = 0.25 - 30 million
  - CF: Re = 10 - 30 million, sweep = 10 - 30 degrees
- x_{tr} = f(Re,dCp/dx,x), with sweep included for CF
- No boundary layer information required, provides n-factor envelope



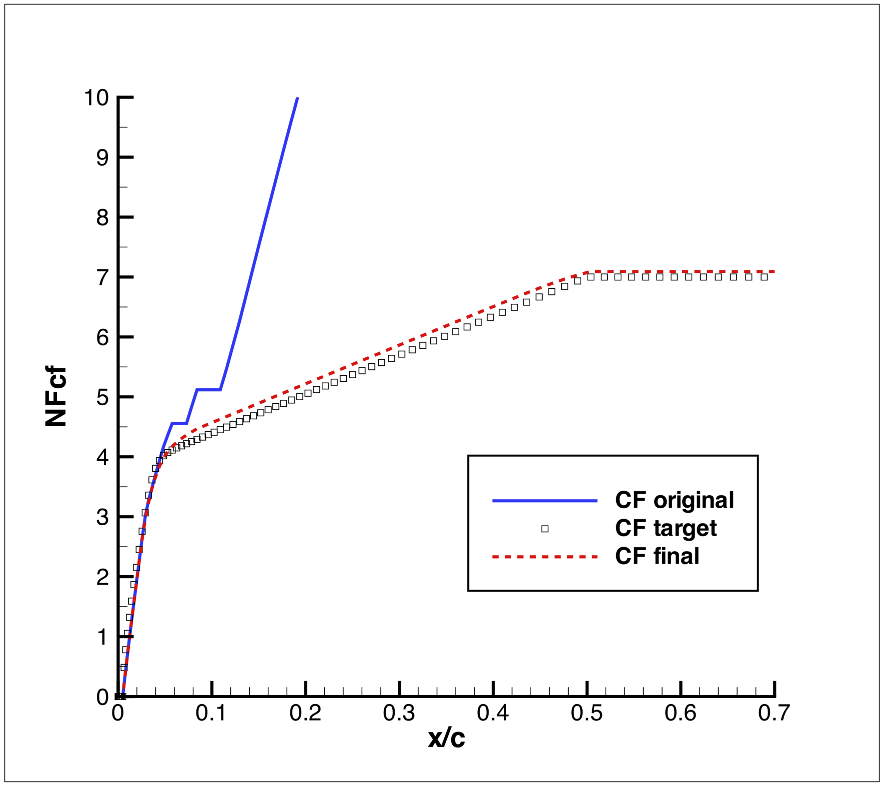


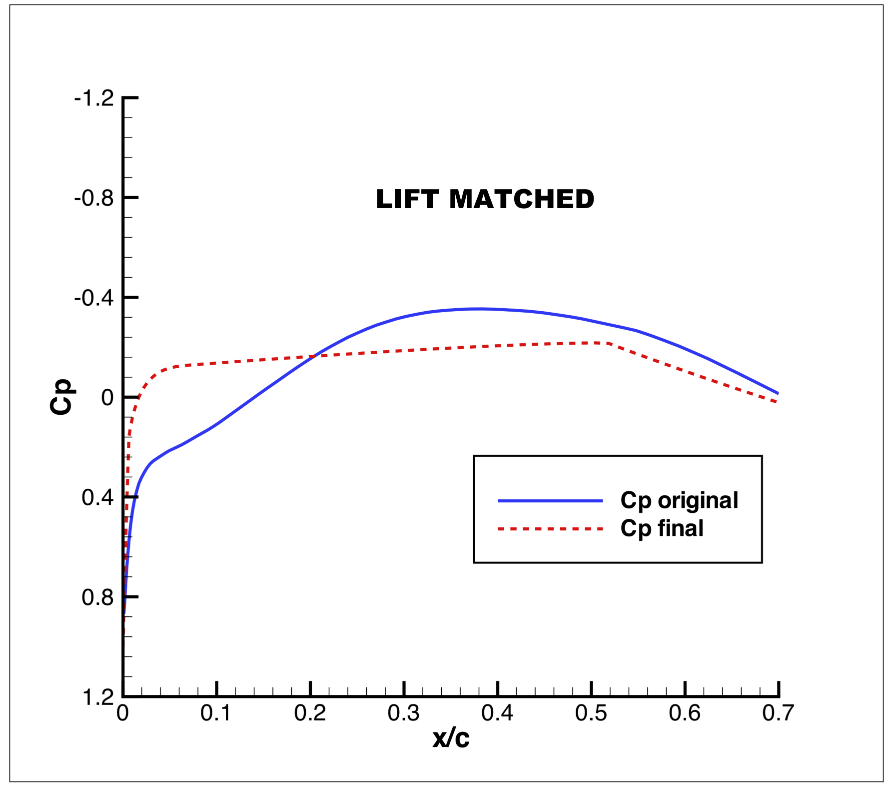
“Knowledge-Based” NLF Airfoil Design with CDISC NLFCP Constraint



- New knowledge-based approach for design to a specified TS n-factor distribution
- Laminar “drag bucket” characteristics can be related to the n-factor family exponent (NFE)
- New approach compatible with other CDISC design method flow and geometry constraints for practical 3-D design
- Independent analysis by Streit at DLR using Schrauf’s LILO method confirmed TS results and indicated robust CF performance

New NLF Target Pressure Generator

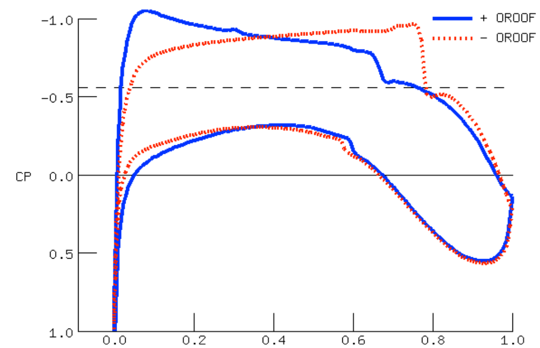


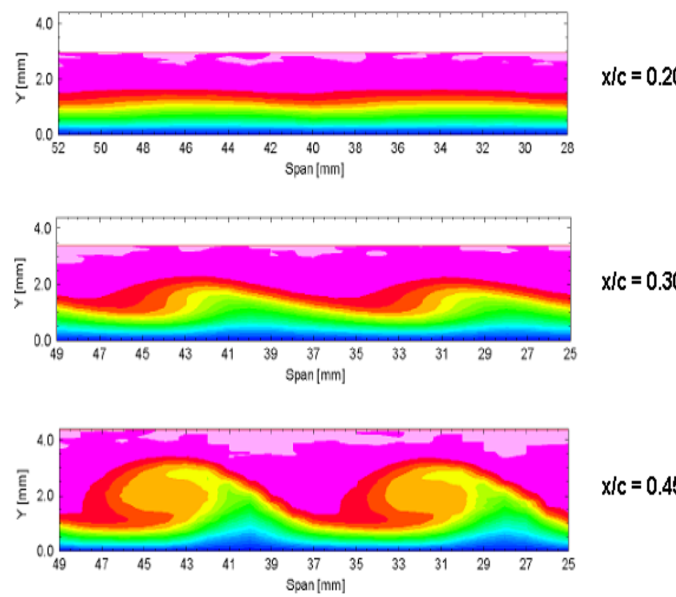


- New tool creates a target pressure distribution for CDISC design for a specified TS or CF n-factor distribution
- Utilizes MATTC transition prediction method for rapid estimation of n-factors
- Options available for independent or combined TS/CF targets, with or without lift constraint

Delay of Crossflow Transition with DRE

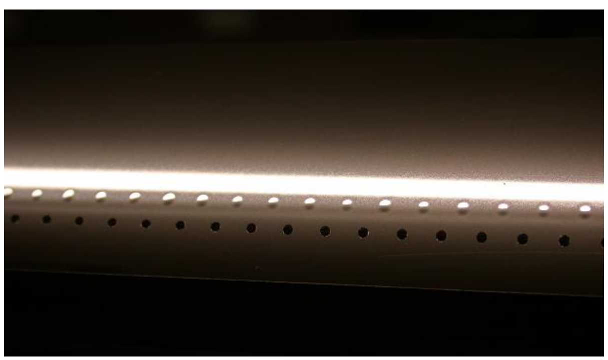
- The stationary crossflow vortex modifies the mean boundary layer flow
- Discrete Roughness Elements (DRE) used to control growth of spanwise periodic CF instability
  - Introduce weakly growing wavelength at half most amplified wavelength through stability analysis
  - modified mean flow is stable to all greater wavelengths
  - Restricts TS waves due to more stable 3D wave
- Design philosophy
  - *t/c* and C_L are design points
  - Design pressure minimum as far aft as possible (potential wave drag penalty)
    - Subcritical to TS instability
    - Restrict leading edge radius to R_θ<100 for subcritical attachment line
  - Iterate *Cp* distribution with stability calculations for crossflow control
    - Euler and Navier-Stokes for Cp and BL
    - Orr-Sommerfeld for stability
    - Parabolized Navier-Stokes for final assessment



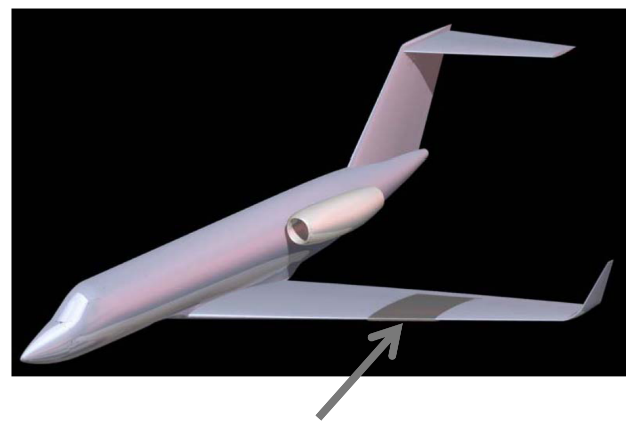


Flight Demonstration of DRE

- To date, DRE technology demonstrated at low Re only (~ 8M)
- NASA/TAMU/AFRL to fly DRE on NASA DFRC G-III Wing Glove
  - Leading edge sweep 31.5°, Mach number 0.75
  - Span approximately 2 meters
- Primary goal: Demonstrate DRE increases extent of laminar flow by 50%
  - Design for NLF to 15 – 20M Re_c with transition at x/c = 60%
  - Use DRE to delay transition at 22 - 30M Re_c to x/c = 60%
- Secondary goal: Demonstrate ability of DRE to control CF with relaxed surface quality on leading edge by textured paint finishes
- DRE geometry: Appliqué with DRE with diameter of 1.5 mm, height of 6-12 microns, wavelength of 4 mm along x/c = 1%



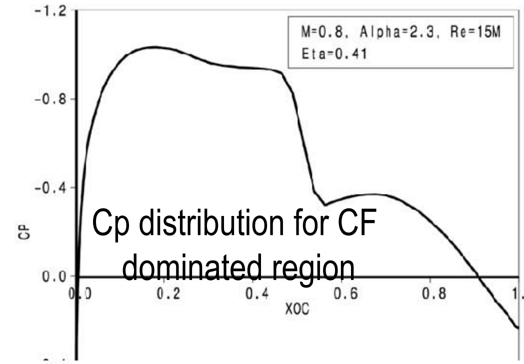
Discrete Roughness Elements

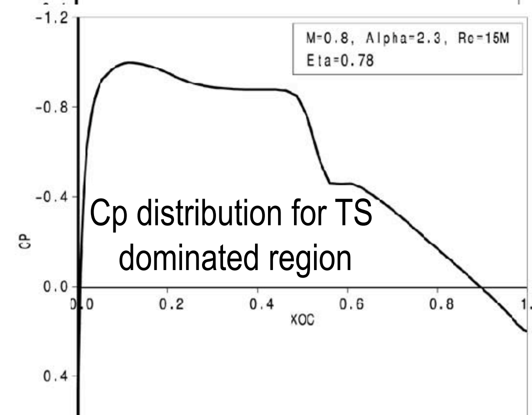


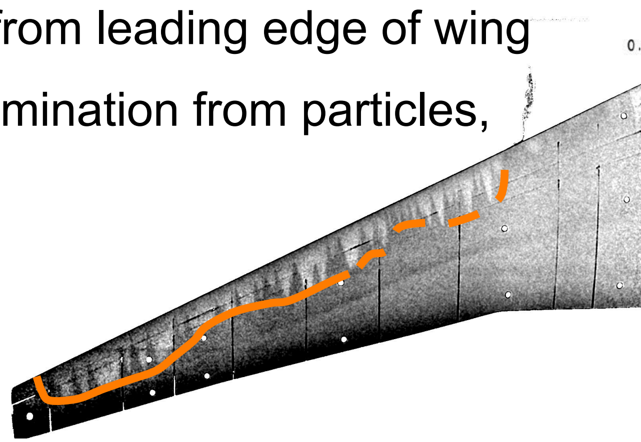
Laminar Flow Glove

Ground Facility Capability for Laminar Flow Testing

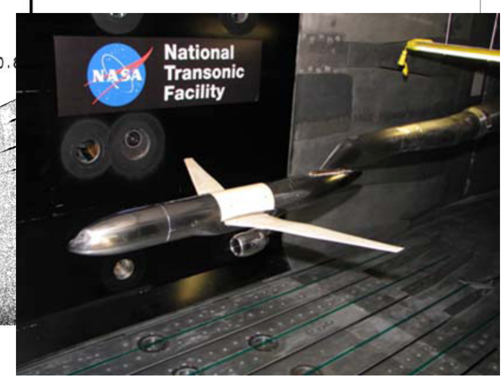
- Boeing/NASA test in NASA National Transonic Facility (NTF) at High Re
- Wing design for laminar flow with mix of TS and CF transition at Re between 11 – 22 million at Mach = 0.8, 25° leading edge sweep
- Designed with non-linear full potential equations with coupled integral boundary layer code
- Instability growth and transition prediction calculations by compressible linear stability code
- Laminar flow lost at higher Re numbers
  – Turbulent wedges emanating from leading edge of wing
  – Suspect attachment line contamination from particles, frost, and/or oil







Analysis compared to NTF transition measurements at Re = 22 M/ft

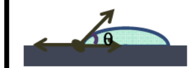
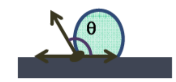
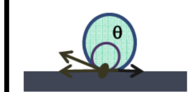


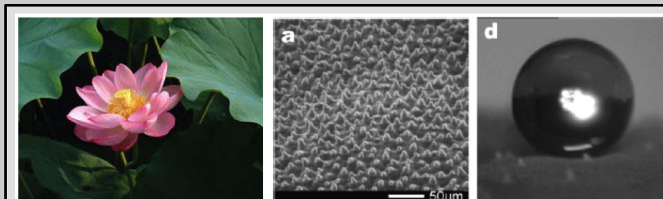
NLF model in NTF

Supporting Technology for Practical LFC

– **Low-Surface Energy Coating/Finishes**
  - Self-cleaning surfaces, insect/ice protection
  - Demonstrate coatings for insect and ice protection on NASA G-III
  - Develop abhesives with very low surface energy
  - Surface engineering for controlled roughness to enhance hydrophobicity

– **Lightweight Structural Concepts Suitable for LFC Applications**
  - Rethink structural design to meet NASA System Metrics – multi-functional teams and enablers
  - Tailored load paths, stitching, free-form fab, integral curvilinear stiffeners, materials
  - Aeroelastically tailored laminar flow wing structures team

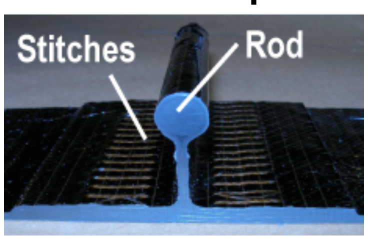
Classification	Contact Angle	Example
Hydrophilic	θ< 90	
Hydrophobic	150>θ> 90	
Super-Hydrophobic	θ> 150	

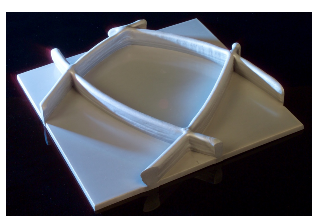


Controlled roughness example

Internal structure of bird bones

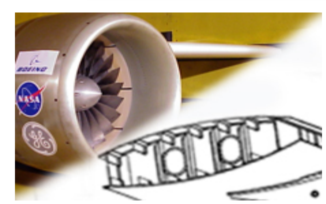
Stitched Composites





Integrated Curvilinear Stiffeners

HLFC - Insect Adhesion



Component Integration

Summary of Practical Barriers to LFC

- **Most system studies require integration of laminar flow to meet fuel burn goals**
- **Surface tolerances, fit, and finish**
  - Front spar joint may trip boundary-layer limiting laminar flow to 15% to 30% of chord
  - CF sensitive to surface finish in range of few microns, TS sensitive to surface waviness
  - Attachment line contamination and CF sensitive possible due to insects, dents/ damage, or other excrescences
  - Leading edge high lift device integration (joints, discontinuities)
- **Configuration aero design**
  - Laminar flow inboard of wing mounted nacelle difficult due to interference and leading edge radius
  - Conflicting design requirements. Example: CF (minimize –dp/dx) and TS (maximize –dp/dx)
  - Effect of loss of laminar flow en route – stability, fuel burn
  - Account for aeroelastic effects
- **Maintenance and operations**
  - Maintenance access panels on laminar flow surfaces
  - Maintenance of suction systems
  - Surface cleaning

NASA

Summary of Technology Maturation (Fuel Burn)

Technology being researched	Description of Research	Test bed or facility	Technology Readiness in 2012
Drag Reduction			
Discrete Roughness Elements	Flight test at high RN.	NASA Gulfstream-III	5-6
Natural Laminar Flow	High RN wind tunnel testing. Qualify wind tunnel for laminar flow design/testing. T/W, HWB models	National Transonic Facility	5
Decision Point Hybrid Laminar Flow	Define and address barriers to certification using a multi-disciplinary approach	TBD – Future flight test bed	Currently 3-5
Decision Point AFC for Rudders	Practical integration of AFC for increased rudder performance	TBD - Future flight test bed	Currently 3

Summary of Technology Maturation (Fuel Burn)

Technology being researched	Description of Research	Test bed or facility	Technology Readiness in 2012
Resin Infused Stitched Composites			
Pultruded rod stitched efficient unitized structure	Flat panel testing	NASA COLTS	4
	Curved panel test	FAA FASTER	4
	Multi-bay pressurized test of a center-body section – HWB Focus	NASA COLTS	5
Decision point	Full PRSEUS Wing with laminar flow	TBD – Flight test bed	Beyond 2012 Target 6-7

Summary of Technology Maturation (Fuel Burn)

Technology being researched	Description of Research	Test bed or facility	Technology Readiness in 2012
Propulsion System			
Open Rotor	System studies. Tube and wing and HWB	N/A	N/A
	(Re)baseline performance and acoustics (uninstalled/ installed)	NASA 9 x 15 NASA 8 x 6	5
	Noise shielding optimization testing (tube and wing and HWB)/propulsion aero-acoustics testing	Boeing Low Speed Acoustic Facility/ NASA 14x22	5

Summary of Technology Maturation (Fuel Burn)

Technology being researched	Description of Research	Test bed or facility	Technology Readiness in 2012
Propulsion System			
UHB	System studies. Tube and wing and HWB	N/A	N/A
	UHB performance/ acoustics	NASA 9 x 15	5
	UHB (BPR = 18) Integration Testing	Ames 11-ft Transonic Test	4
	Noise shielding optimization test/PAA	Boeing LSAF/14x22	5
Embedded Engine	Fan tolerant design and test	NASA 9x15	4
Decision Point	Open rotor/UHB/ embedded integration testing	TBD – Flight test bed	Beyond 2012 Target 6-7