



Overview of NASA Circulation Control Research (CFD and Experiments)

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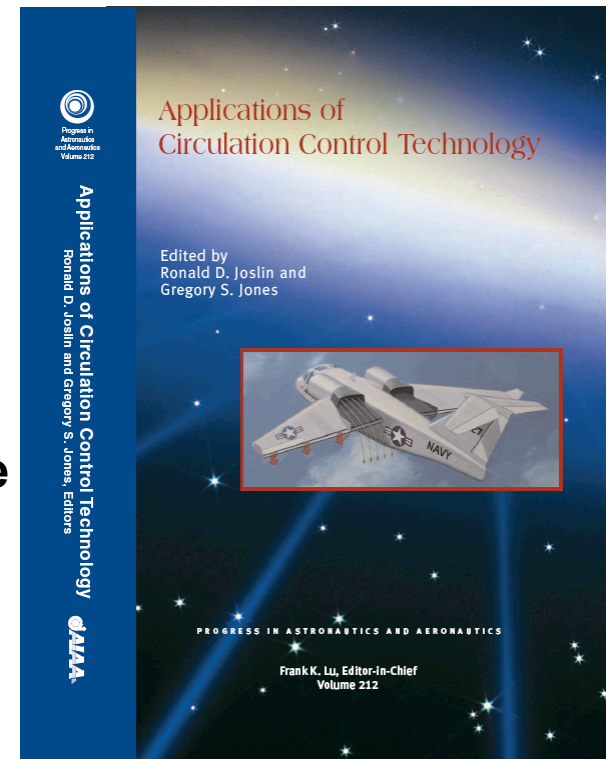
OUTLINE

- Background
 - 2004 NASA/ONRCC Workshop
- Low Speed Activities
 - 2D CC flow physics – NASA BART
 - 2D CC performance – GTRI (MTF)
 - 2D CC aeroacoustics – UoF (AFF)
 - 3D Powered Lift Semi-Span – NTF (Future)
- High Speed Activities
 - 2D CC Airfoil
 - 3D CC Cruise Semi-Span – NTF (Future)
- Concluding Remarks



2004 NASA/ONR CIRCULATION CONTROL WORKSHOP

- **Experiments**
 - Long history that includes small scale to flight demonstrations
 - Limited data sets available for modern CFD validation for fixed wing aircraft.
- **CFD**
 - Comparisons of different techniques resulted in inconsistencies of performance prediction (turbulence models, grid generation related to jets and wakes, etc)
 - Need better prediction tools and high-quality experimental data bases to quantify and optimize CC performance.
- **Workshop conclusions related to fixed wing applications**
 - CC has not been implemented on production aircraft (Why?)
 - Conventional high lift systems meet the current take-off and landing requirements
 - *CC becomes a viable option for short runways*



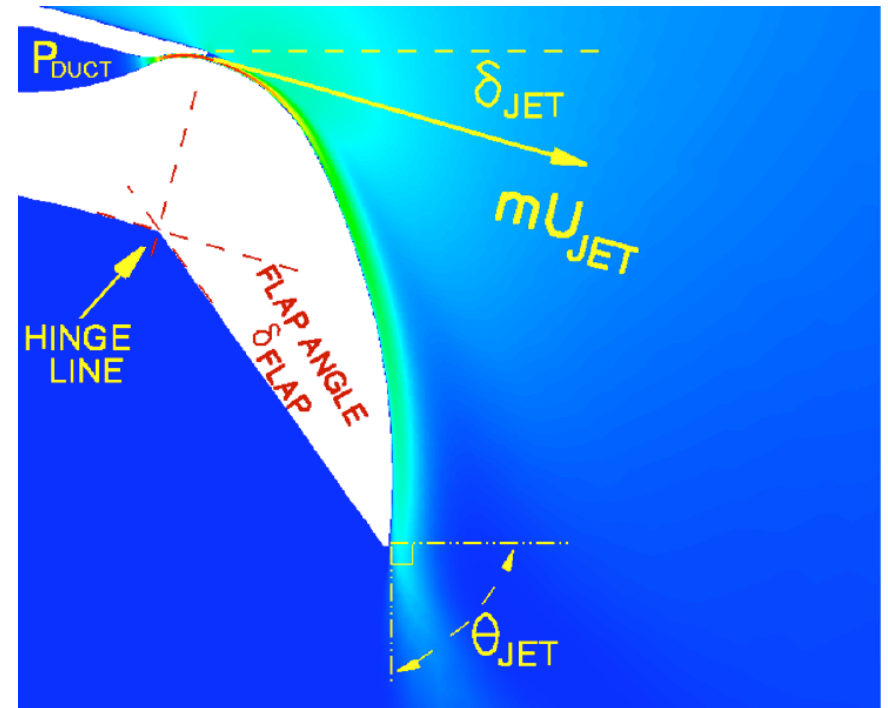
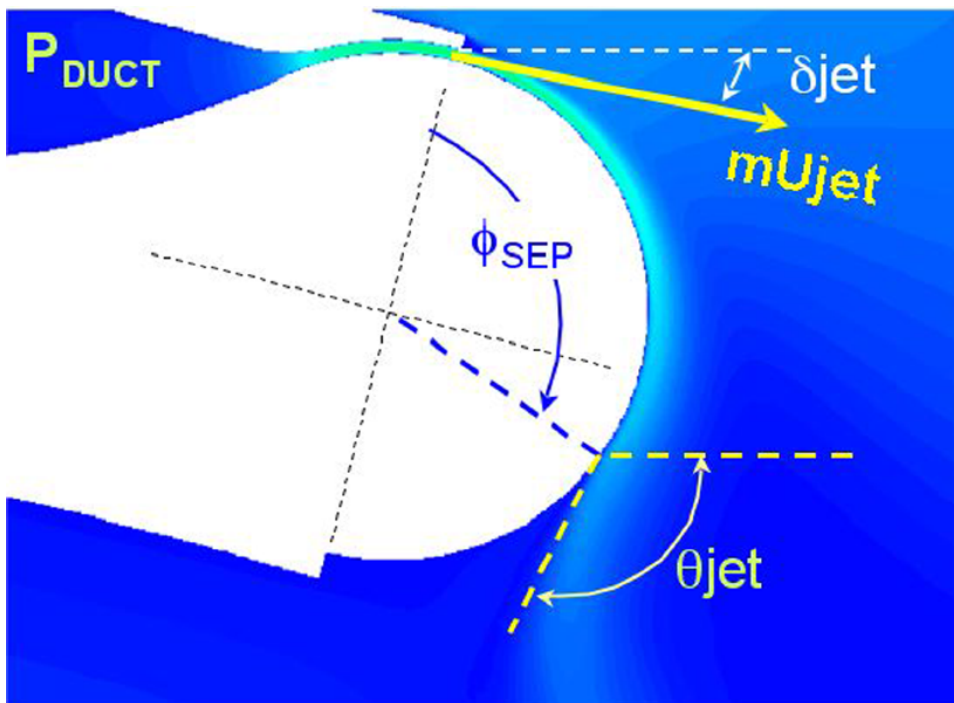


CIRCULATION CONTROL TERMINOLOGY

- Circulation control devices are typically related to actively blown systems (e.g. pneumatic flaps)
- Circulation control surfaces can have almost any curved shape

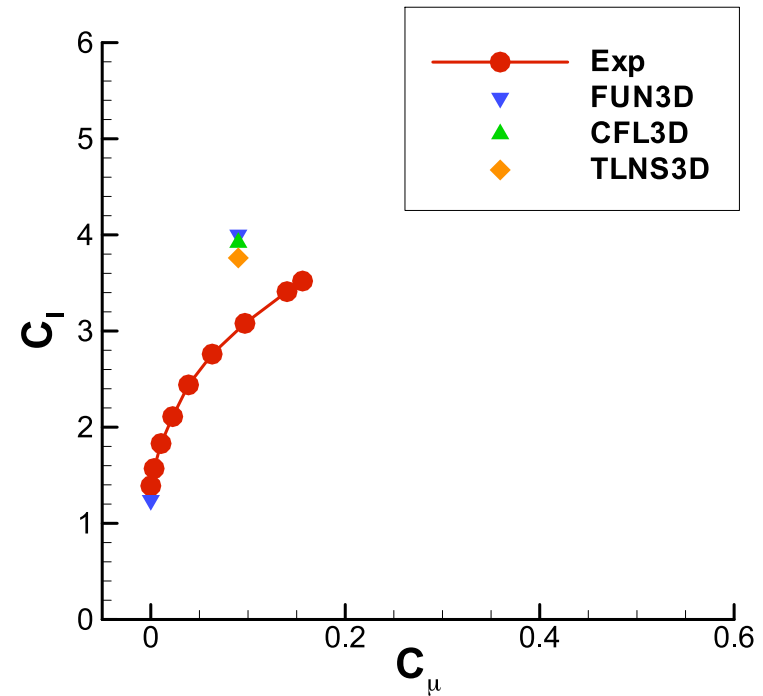
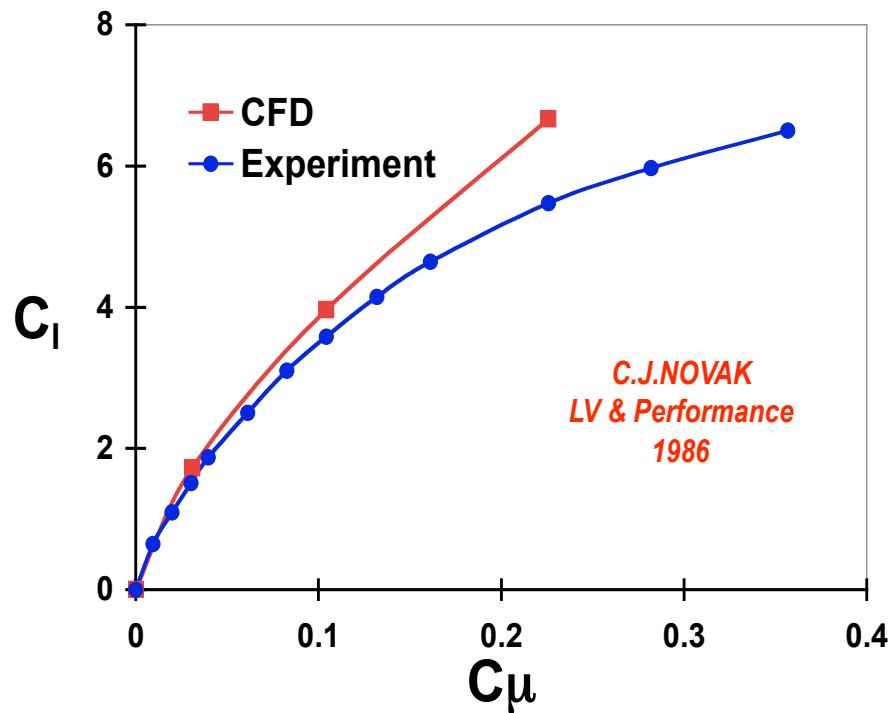
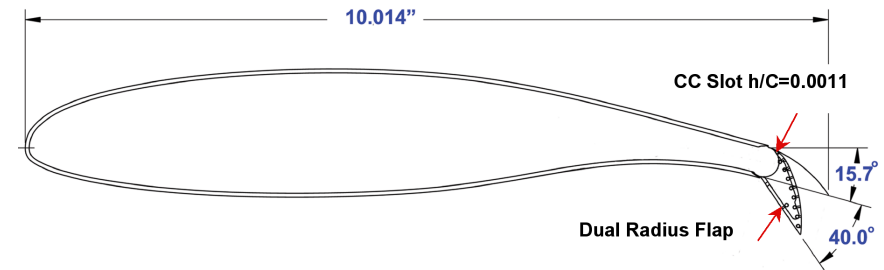
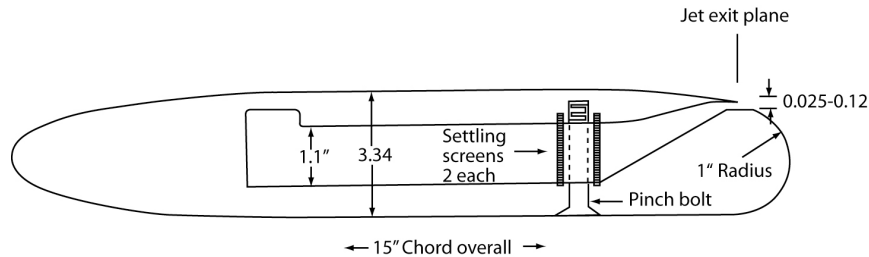
Circular TE - jet separation is not fixed

Internally Blown Flap - jet separation can be fixed to TE flap





CAN WE PREDICT CC PERFORMANCE





OBJECTIVES FOR VALIDATION DATA BASE

- Characterize model performance
 - Parametric study of slot height (h) for LE and TE blowing
- Select limited configurations for detailed study
 - Document boundary conditions (emphasizing C_μ variables)
 - Document flow field using multiple measurement techniques including uncertainty analysis

$$C_\mu = \frac{\text{THRUST}}{q_\infty S} = \underbrace{\frac{2hb_{\text{JET}}}{cb} \frac{\rho_{\text{JET}}}{\rho_\infty} \frac{U_{\text{JET}}^2}{U_\infty^2}}_{\text{Local measurements}} = \underbrace{\frac{\dot{m}U_{\text{JET}}}{q_\infty S}}_{\text{Global measurements}}$$

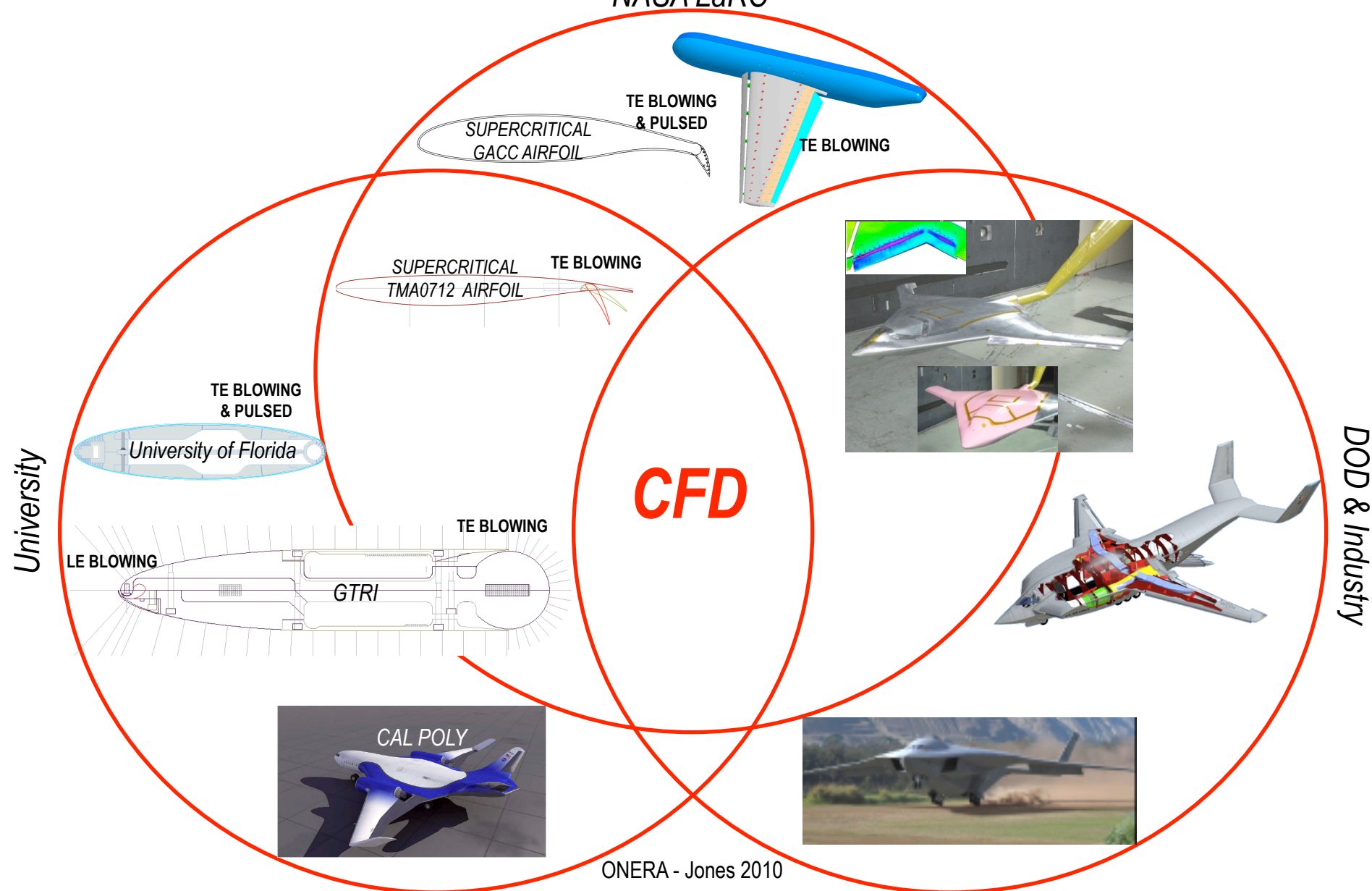
Local measurements
 U_{JET} profile characterizes h
captures variations in
slot height (h) w/ duct pressure
(b = slot width; S = wing area)

Global measurements
assumes mass flow and U_{JET}
uniform along span



PARTNERSHIPS

NASA LaRC



ONERA - Jones 2010



SYSTEM LEVEL METRICS

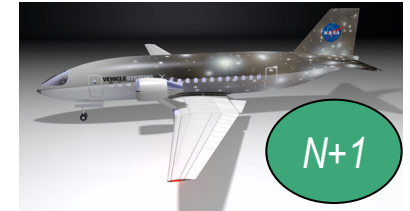
.... *TECHNOLOGY FOR DRAMATICALLY IMPROVING NOISE, EMISSIONS, & PERFORMANCE*

CORNERS OF THE TRADE SPACE	N+1 (2015) ^{***} Generation Conventional Tube and Wing (relative to B737/CFM56)	N+2 (2020) ^{***} Generation Unconventional Hybrid Wing Body (relative to B777/GE90)	N+3 (2025) ^{***} Generation Advanced Aircraft Concepts (relative to user defined reference)
Noise	- 32 dB (cum below Stage 4)	- 42 dB (cum below Stage 4)	55 LDN (dB) at average airport boundary
LTO NO _x Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33% ^{**}	-40% ^{**}	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts

^{***} Technology readiness level for key technologies = 4-6

^{**} Additional gains may be possible through operational improvements

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



Approach

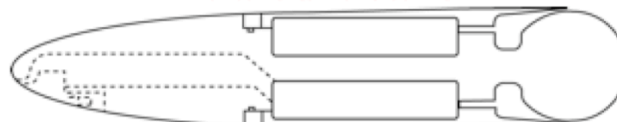
- Enable Major Changes in Engine Cycle/Airframe Configurations
- Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes
- Develop/Test/ Analyze Advanced Multi-Discipline Based Concepts and Technologies
- Conduct Discipline-based Foundational Research



CFD VALIDATION

Benchmark Cases

Fundamental Powered Lift



2-D CC Airfoil w/ Upper and Lower Blowing

GTRI/NASA LaRC – MTF/BART

Complete System

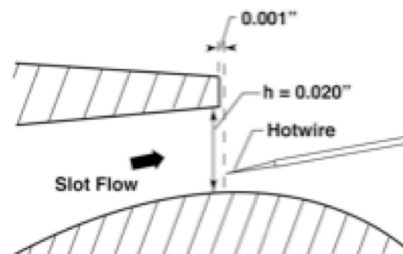
Integrated Powered Lift



3-D Hybrid Wing Body w/ USB augmented w/ CC Wing
Cal Poly/NASA ARC - NFAC

Unit Problems

Fundamental Wall Bounded Jet

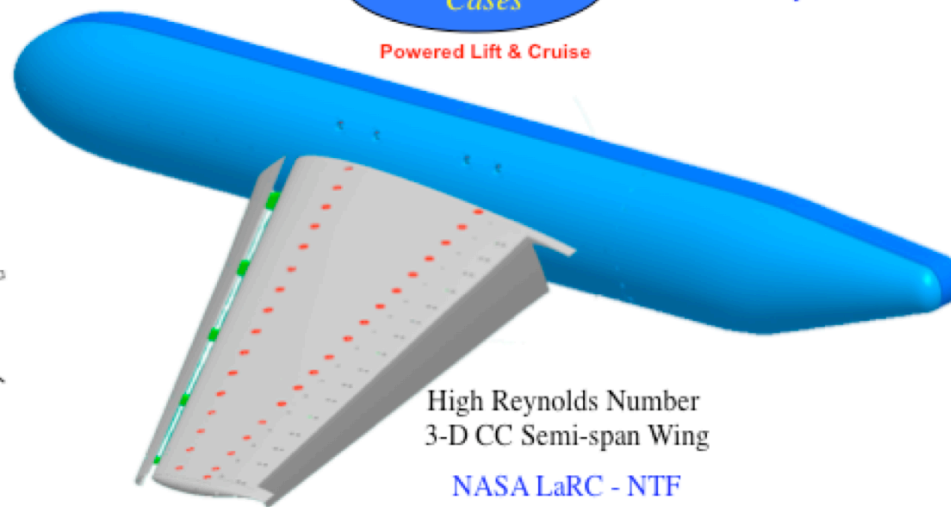


Jet Exit Velocity Profile

NASA LaRC – CC Lab

Subsystem Cases

Powered Lift & Cruise



High Reynolds Number
3-D CC Semi-span Wing

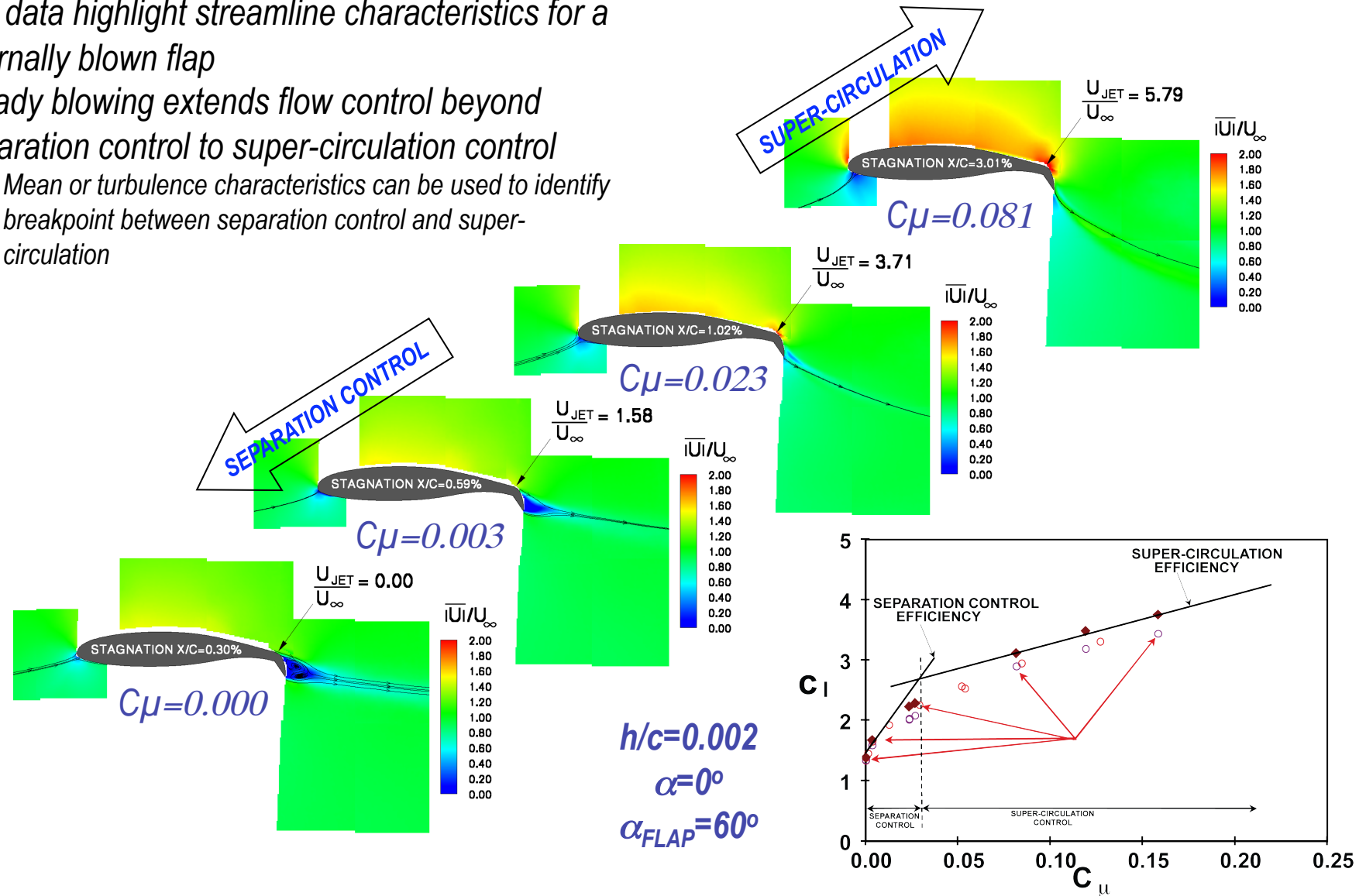
NASA LaRC - NTF

Increasing Geometric And Flow Complexity



EXAMPLE OF PIV MEAN VELOCITY FOR INTERNALLY BLOWN FLAP

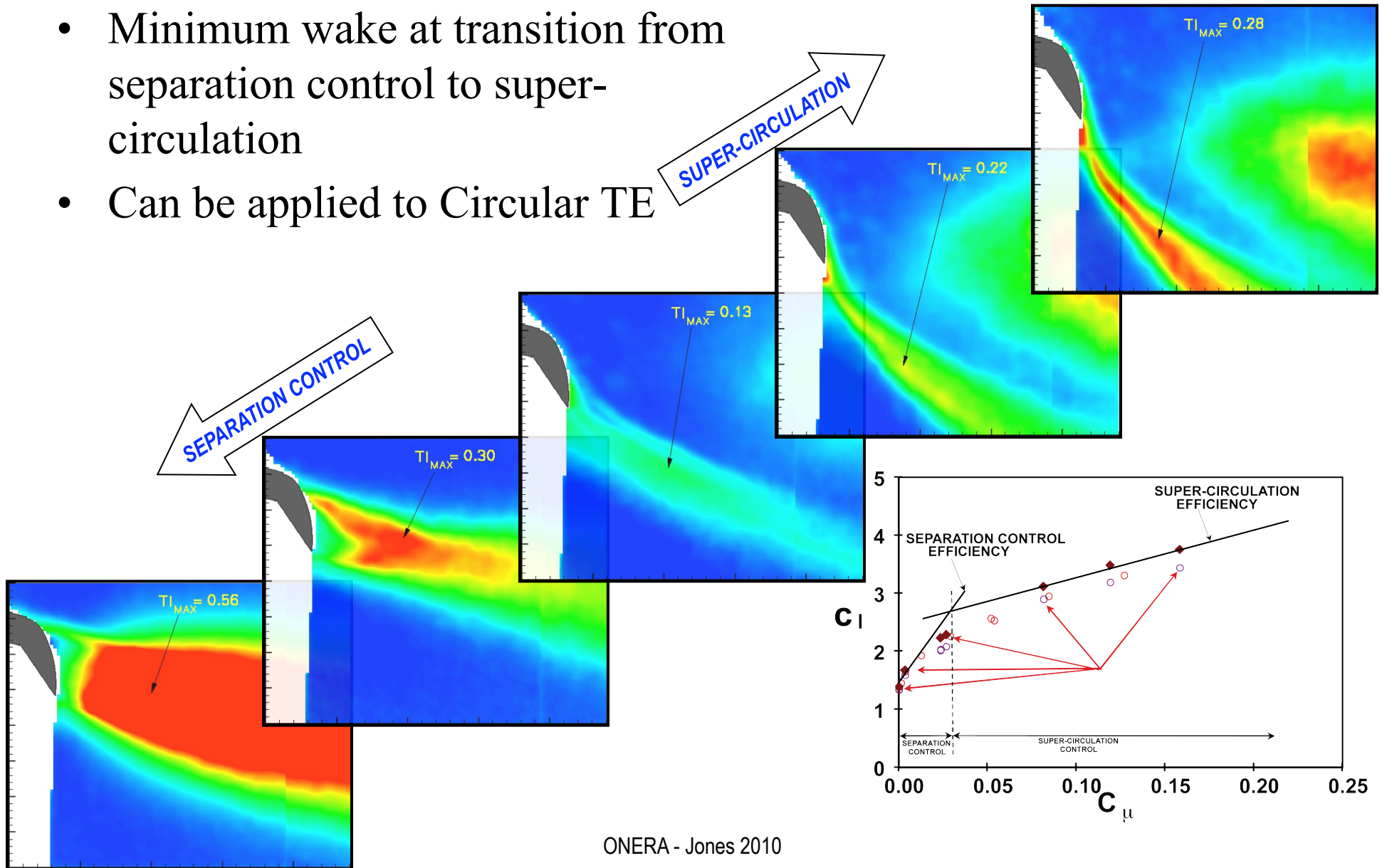
- PIV data highlight streamline characteristics for a internally blown flap
- Steady blowing extends flow control beyond separation control to super-circulation control
 - Mean or turbulence characteristics can be used to identify breakpoint between separation control and super-circulation





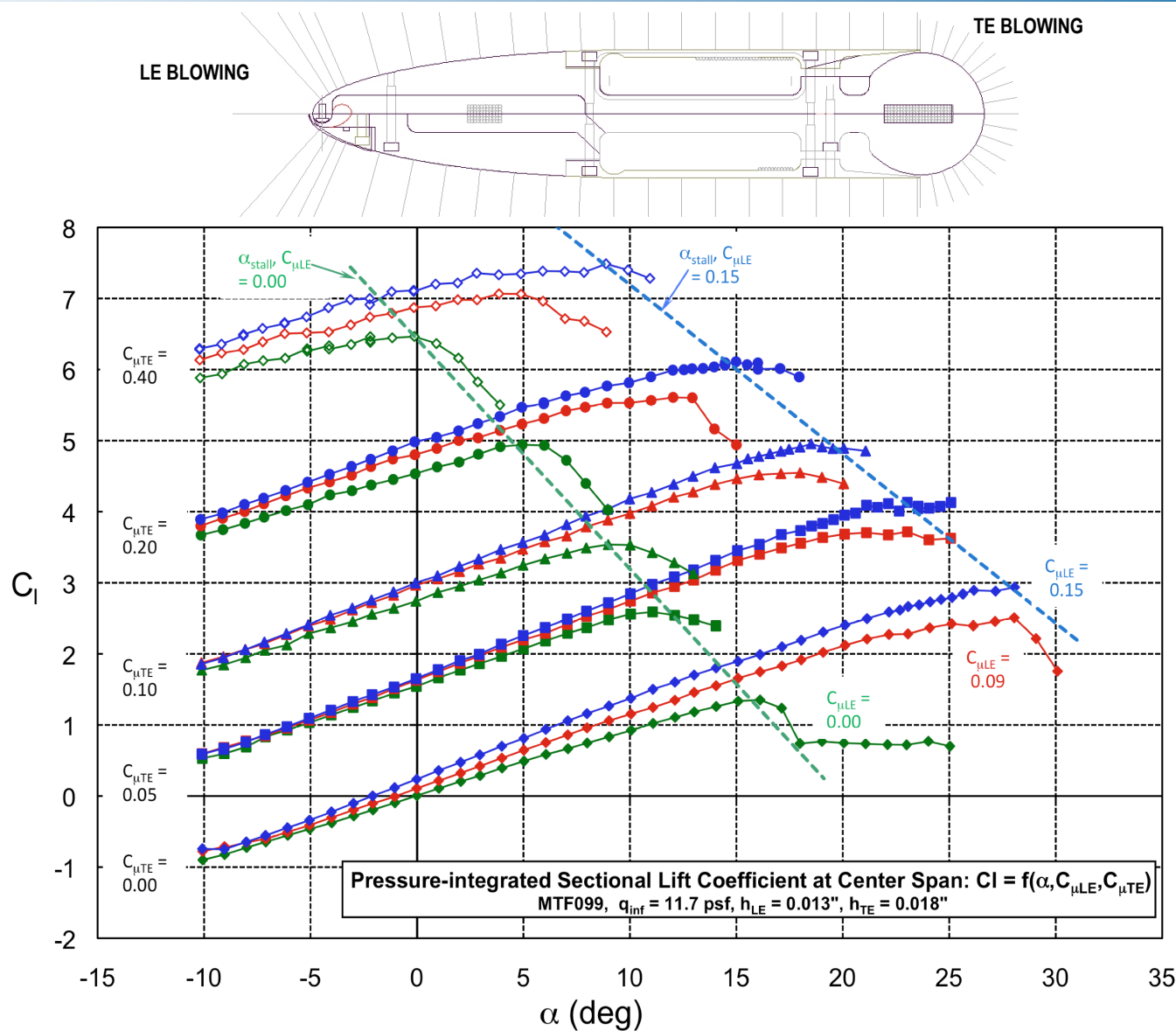
WAKE TURBULENCE FUNCTION OF C_μ

- Minimum wake at transition from separation control to super-circulation
- Can be applied to Circular TE





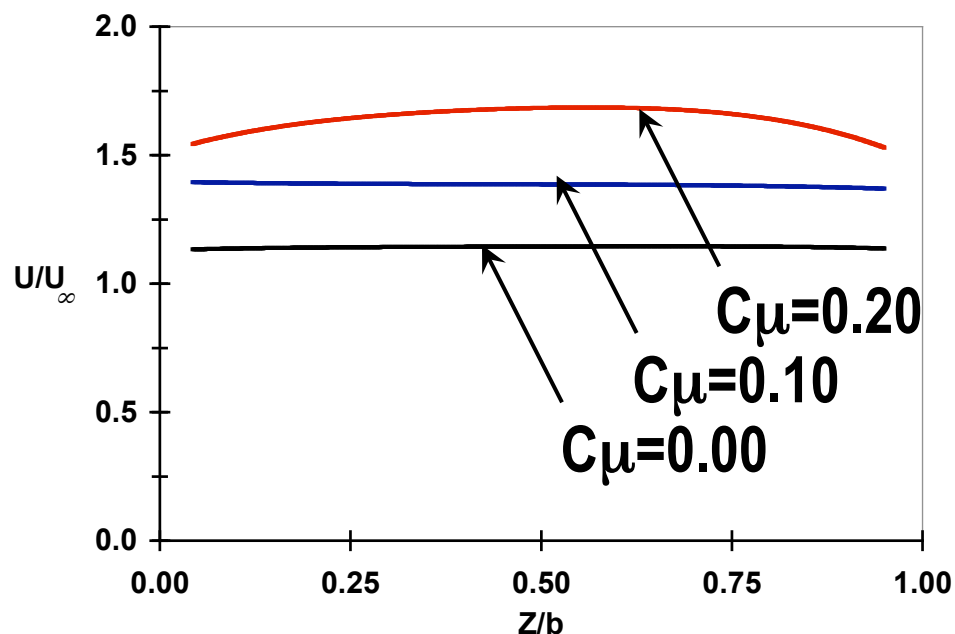
CC-E0020EJ w/ LEADING EDGE BLOWING





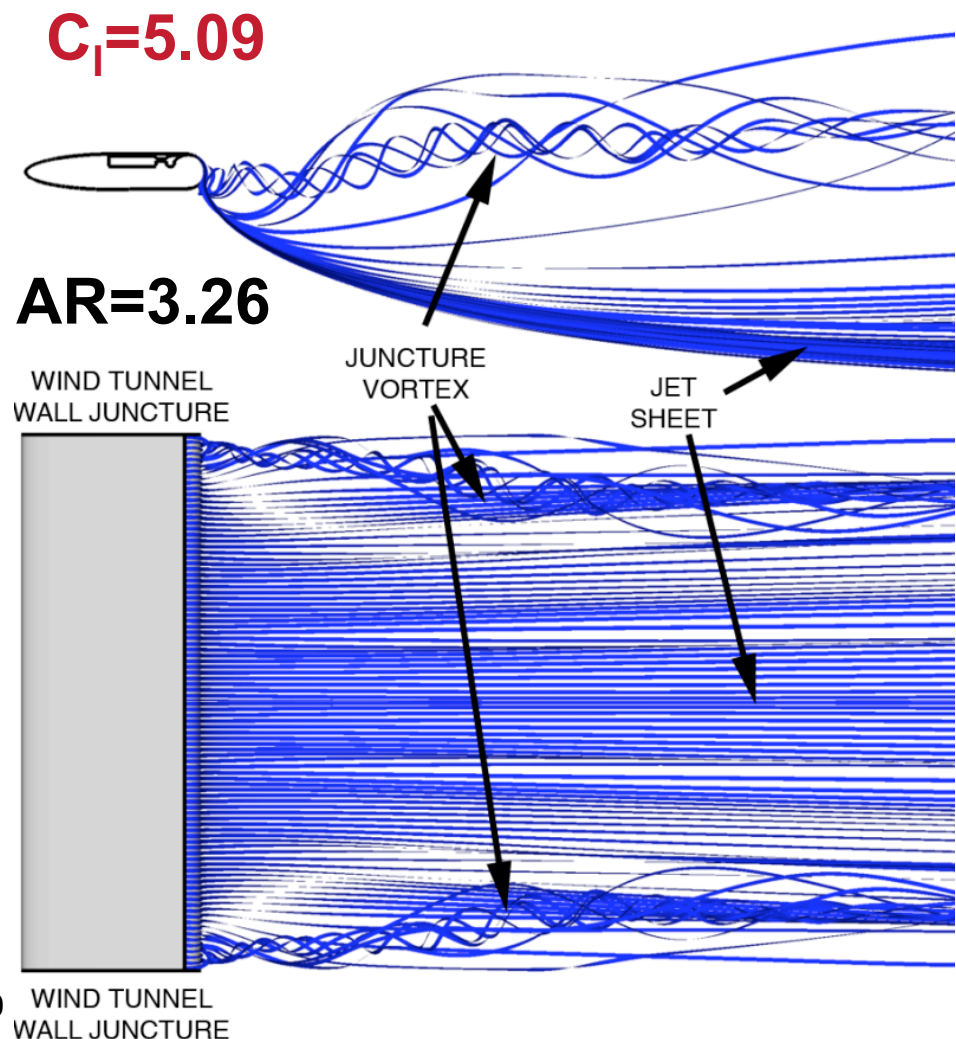
CFD VALIDATION- 3-D JUNCTURE EFFECTS

Juncture flow influence on two-dimensionality increases with blowing



Pitot Static $x/c = 0.5$ $y/b = 0.5$ $y = 1.0$

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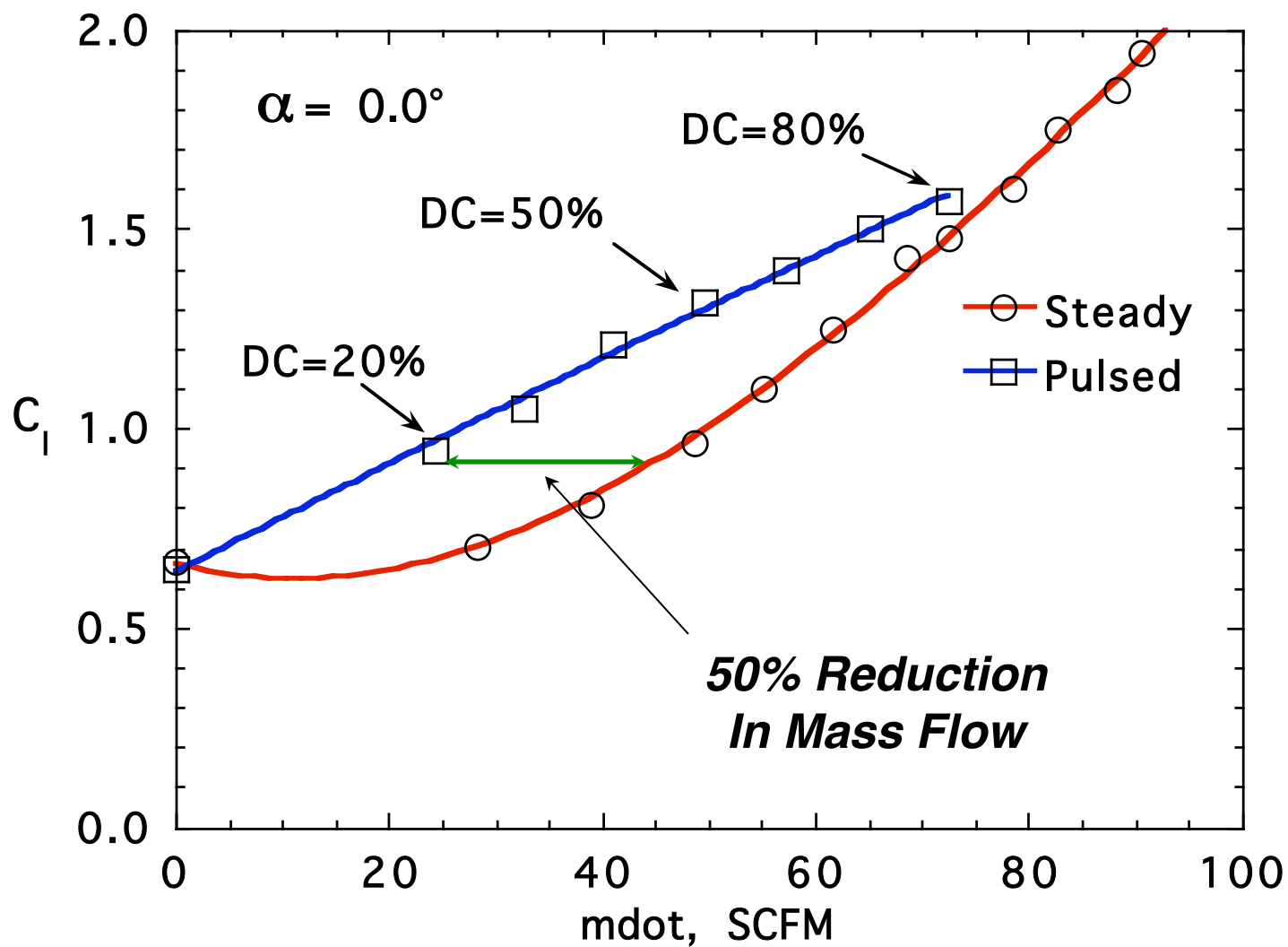


$C_\mu = 0.23$



PERFORMANCE BENEFIT OF PULSED BLOWING

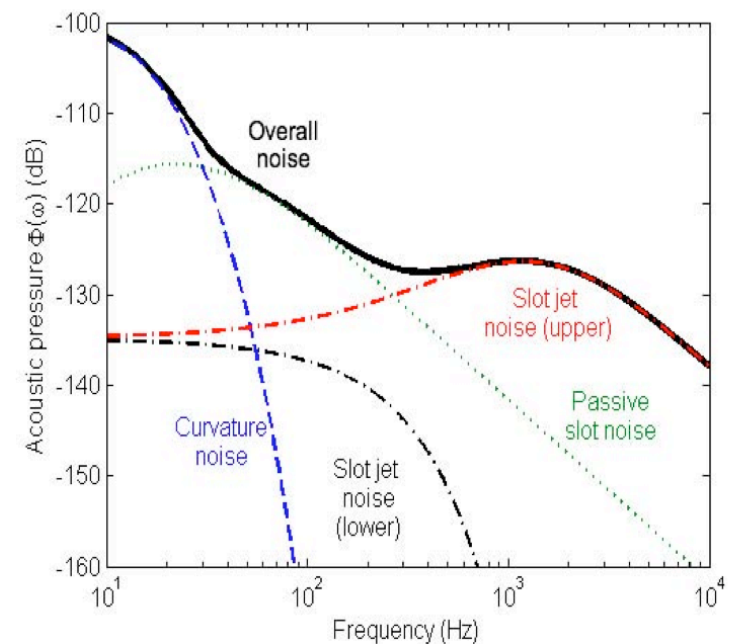
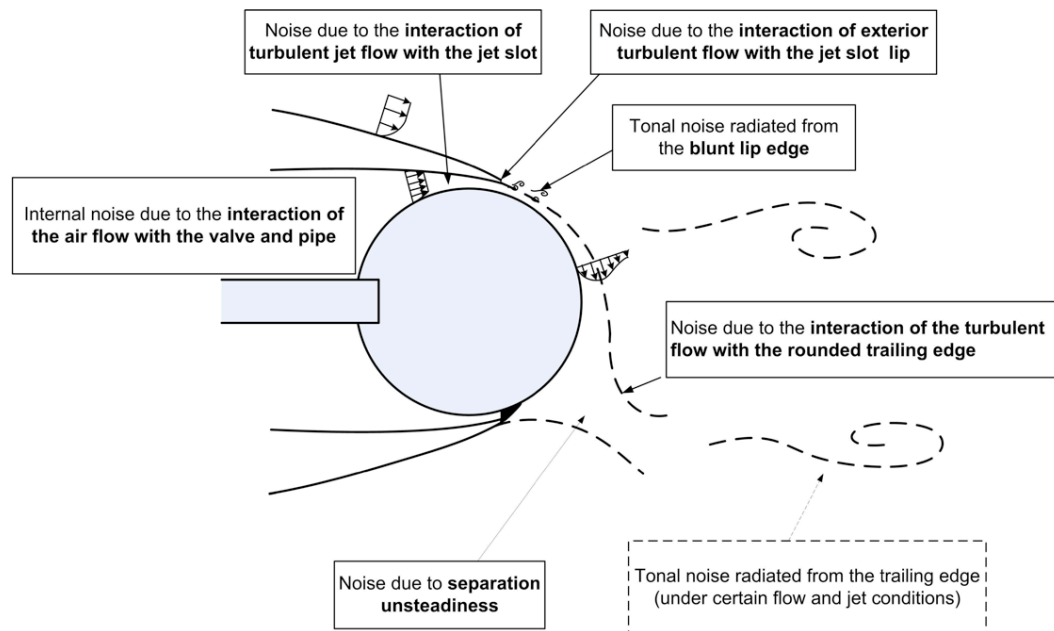
35 Hz w/ Varying Duty Cycle





NRA – FLOW MECHANISMS RESPONSIBLE FOR THE OBSERVED TONAL AND BROADBAND NOISE

University of Florida Aeroacoustic Flow Facility
POC: Dr. Louis Cattafesta

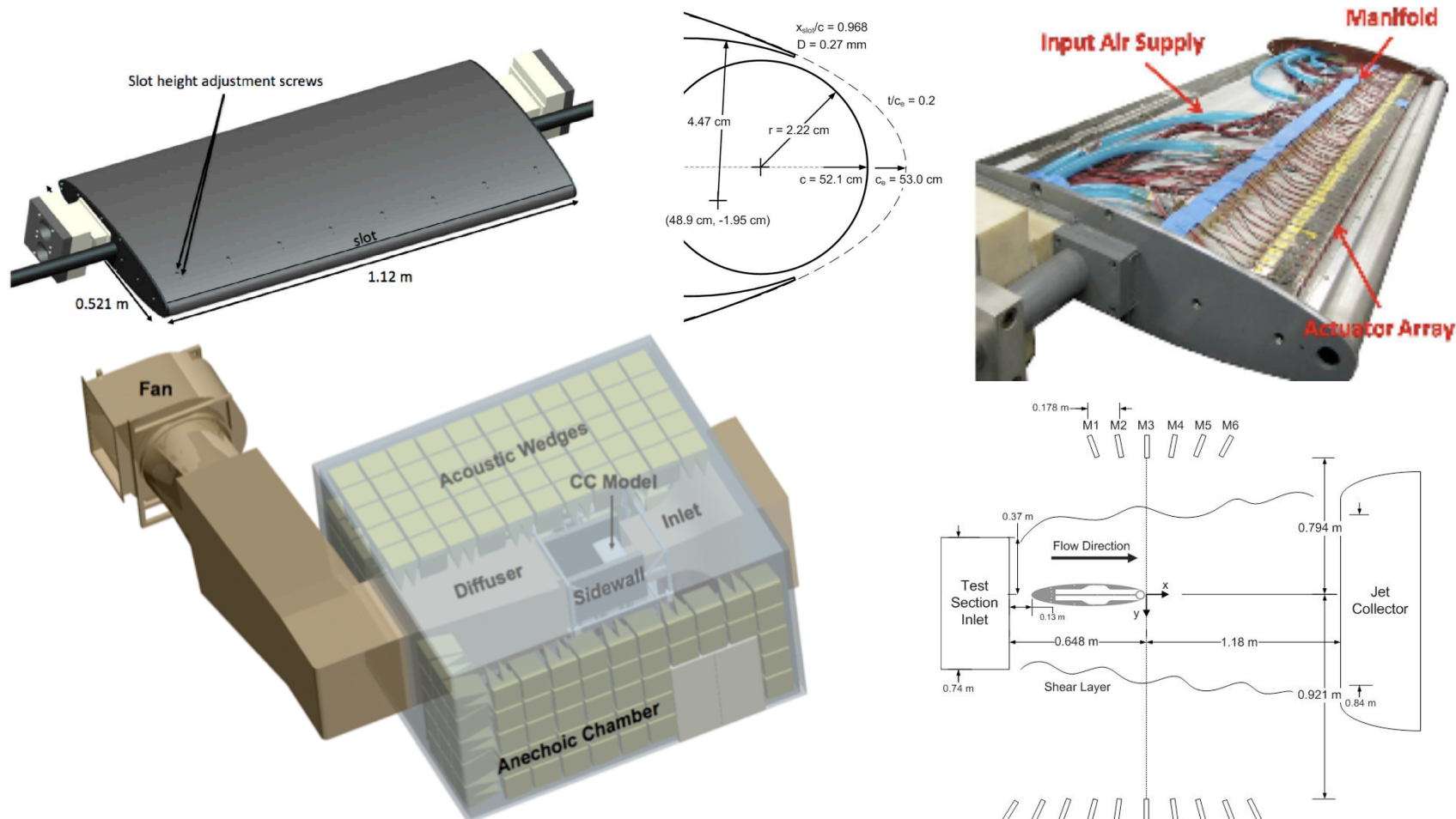




NRA – ACOUSTICS SETUP FOR PULSED BLOWING

Reference: Ashley Jones, et. al., AIAA 2010-0346

POC: Dr. Louis Cattafesta



University of Florida Aeroacoustic Flow Facility

ONERA - Jones 2010



PERFORMANCE OF ELLIPTIC AIRFOIL PIV DATA

Reference: Drew Wetzel, et. el., AIAA 2009-4280
POC: Dr. Louis Cattafesta

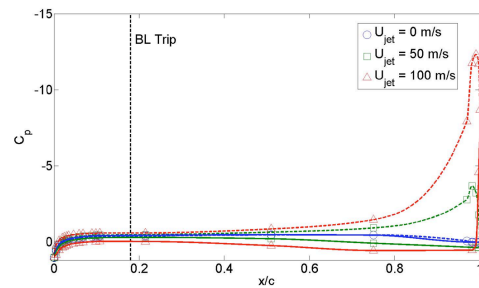


Fig. 7. C_p distributions, $Re_c = 0.65M$, $h = 1.0$ mm.

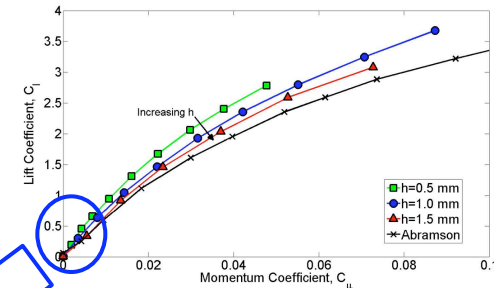
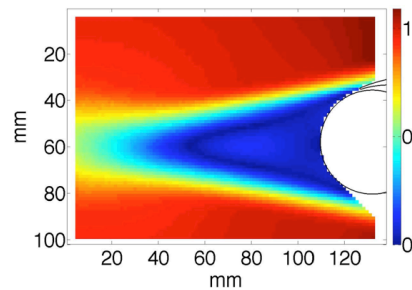
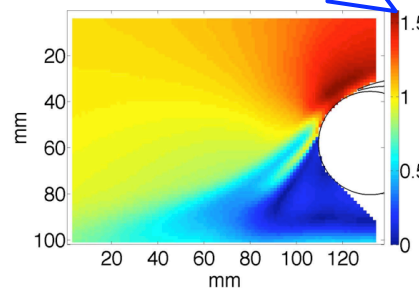


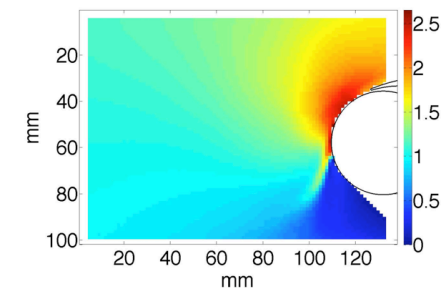
Fig. 8. Lift performance, $Re_c = 0.65M$, varying slot height.¹³



(a) $C_\mu = 0.0$



(b) $C_\mu = 0.015$.



(c) $C_\mu = 0.057$



2D CC LESSONS LEARNED

- Experiment

- Measured slot height along span critical ... Large Slot heights correspond to large models
- Small scale experiments plagued with 3D effects (Small AR leads to juncture flow influences in lift and drag)
- Pulsed blowing reduces mass flow requirements
- Classic wall corrections are inadequate for super-circulation conditions

- CFD

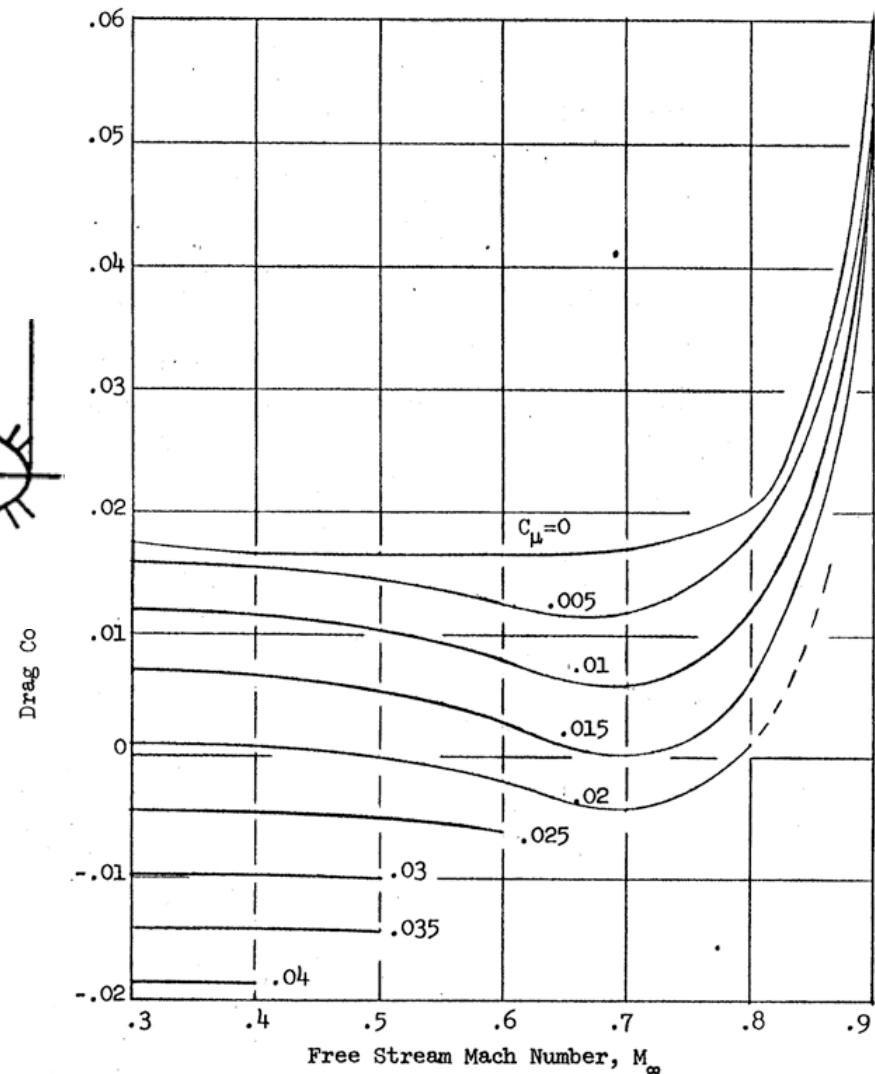
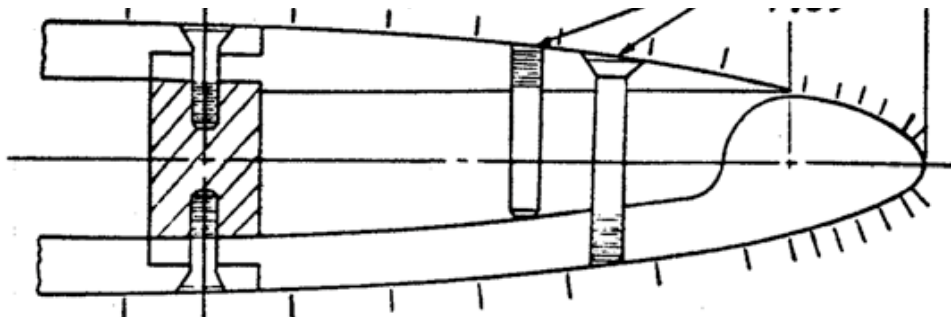
- CFD codes over-predict CC airfoil lift performance
 - Turbulence Modeling
 - Grid Generation
 - Need to eliminate boundary conditions and 2D modeling issues as source difference
- Limited experimental data base with appropriate boundary conditions for CFD benchmarking
 - Must validate jet velocity profile and mass flow with experiment for a given NPR and jet total temperature
- 3D CFD simulations being pursued to eliminate 2D modeling issues (α and q corrections)
 - Introduces the need to resolve complex juncture flows at a significant simulation cost



PNEUMATIC CAPABILITY FOR C_D REDUCTION AT HIGHER MACH NO.

(CC Ellipse Symmetric Airfoil at $\alpha = -1.2^\circ$)

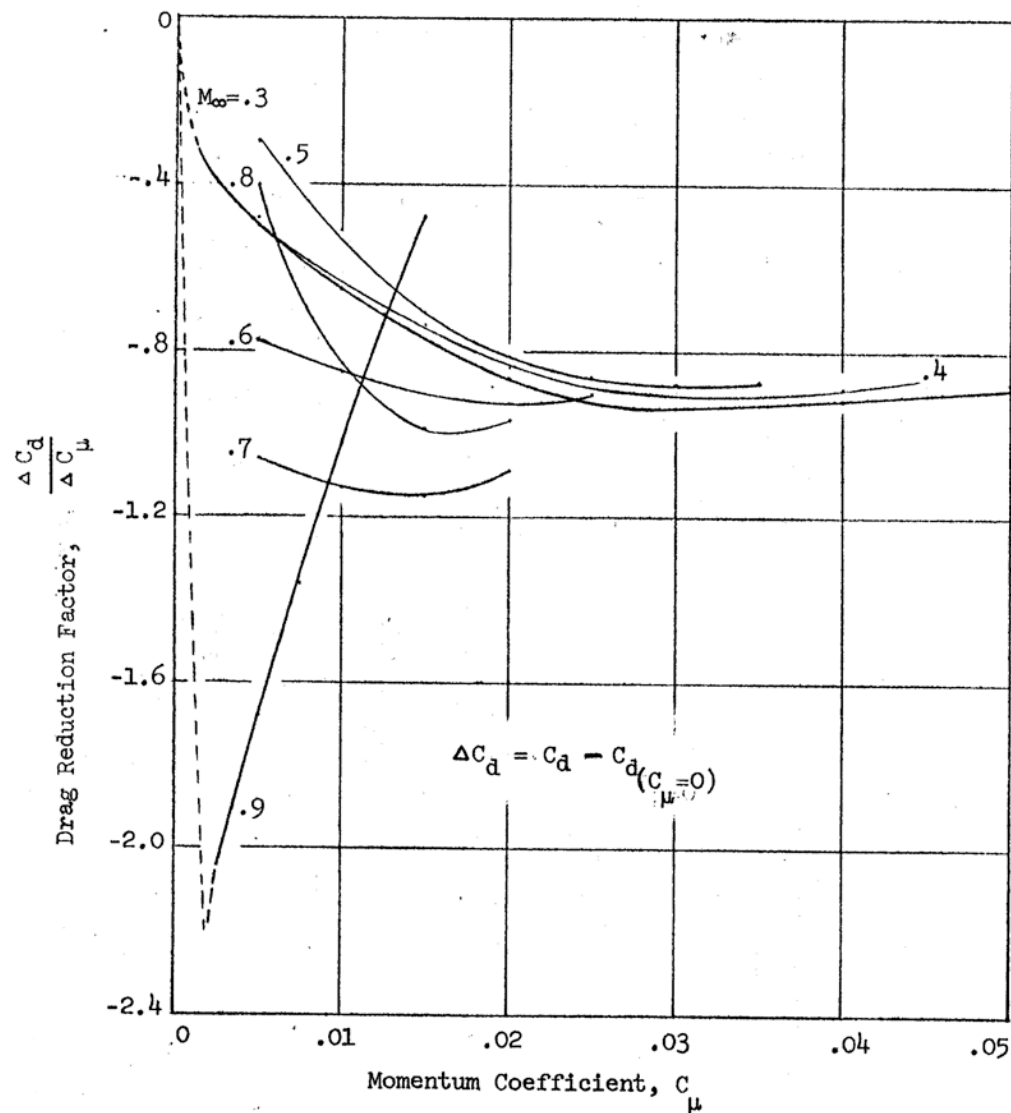
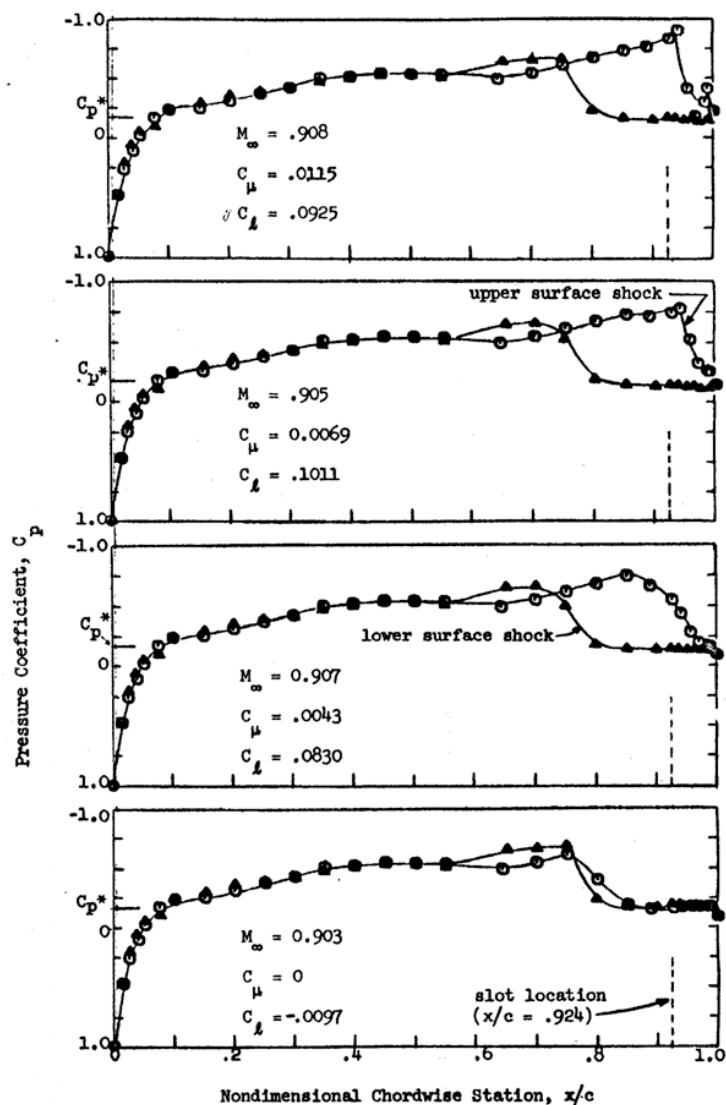
*David Taylor
Helicopter Section
(1970)*





Transonic CC Elliptic Airfoil

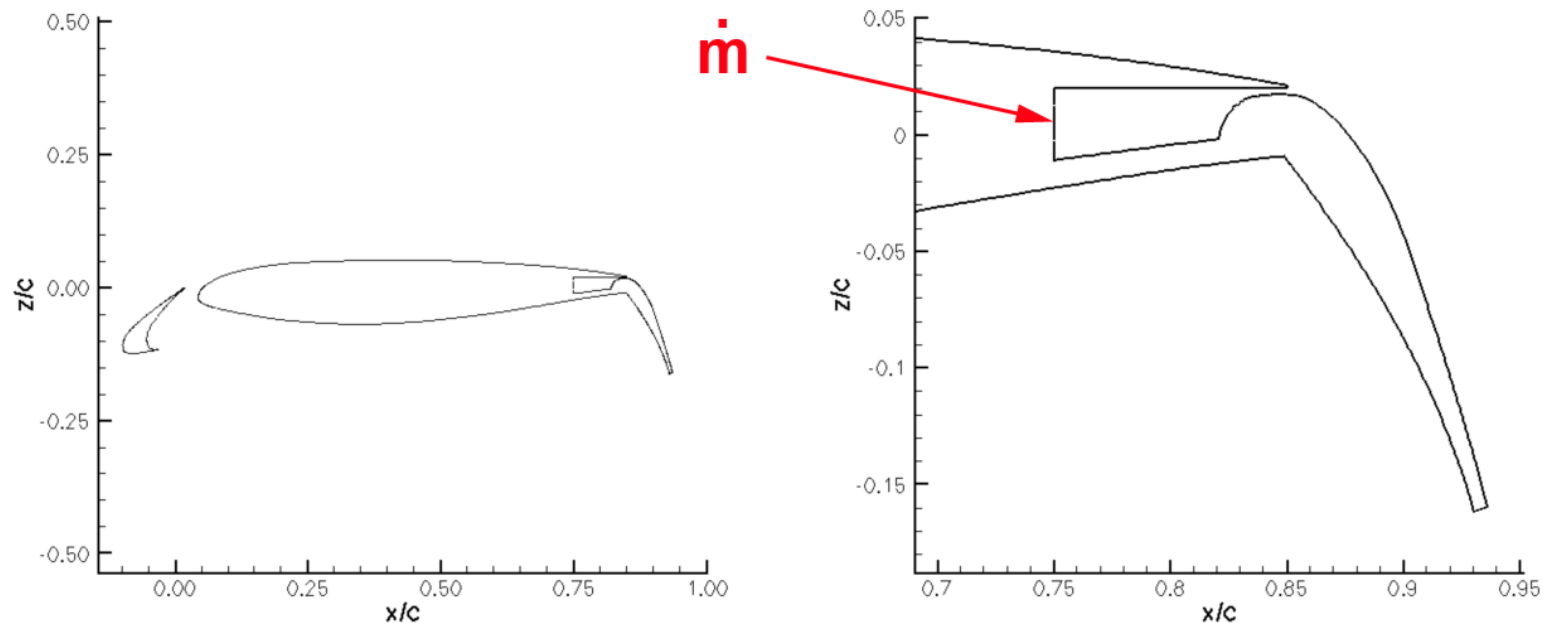
C_D reduction due to Aft Shock Movement





Open Geometry

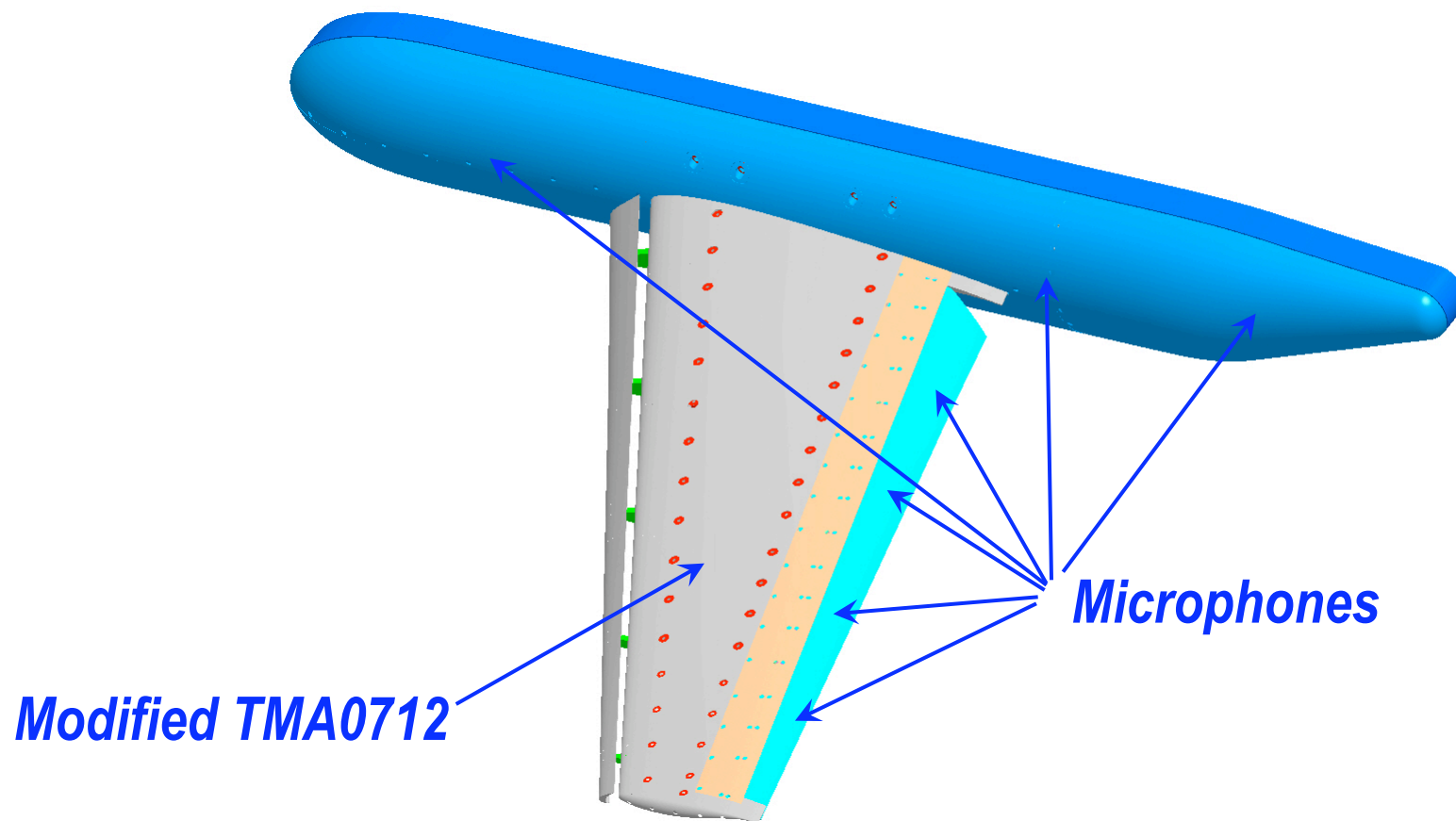
- Need to develop an advanced wing section with blowing capability
 - Develop a 3D Semi-Span Model based on TMA0712 (0.3m TCT)





HIGH REYNOLDS POWERED LIFT AND CRUISE

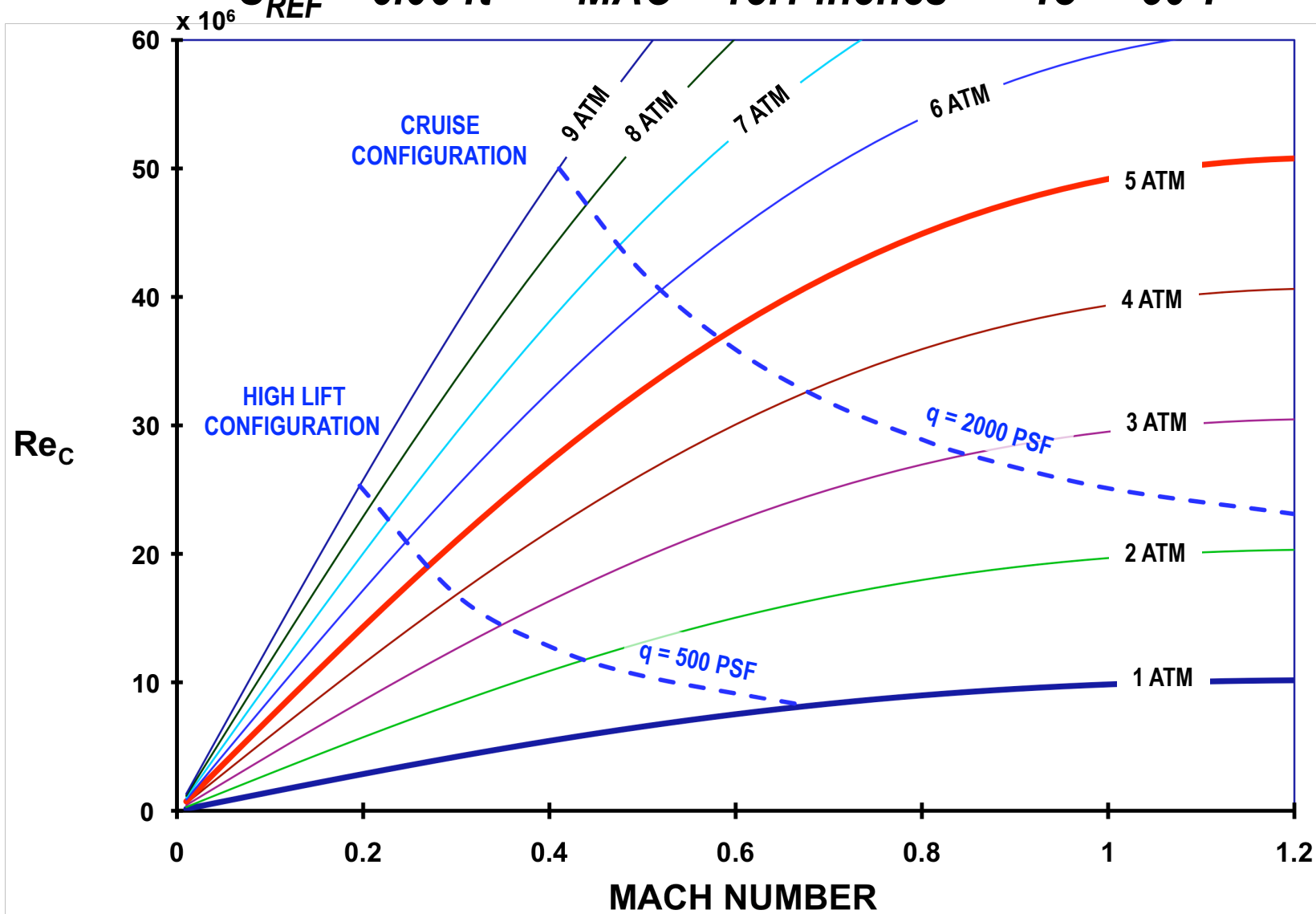
HIGH LIFT CONFIGURATION





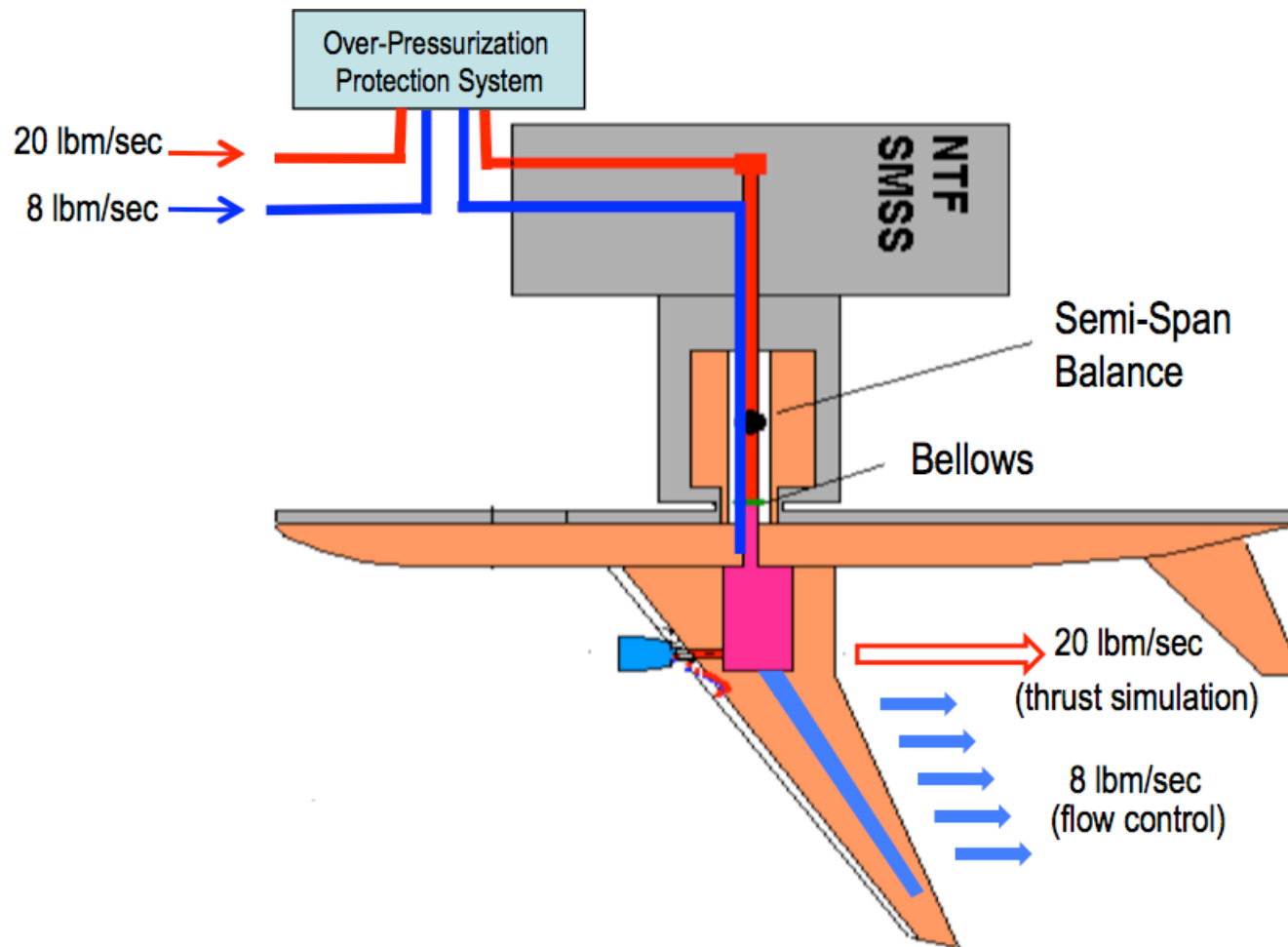
NTF OPERATING ENVELOPE USING SIDE MOUNTED SUPPORT SYSTEM

$S_{REF} = 6.06 \text{ ft}^2$ $MAC = 18.1 \text{ inches}$ $T_o = -50^\circ\text{F}$





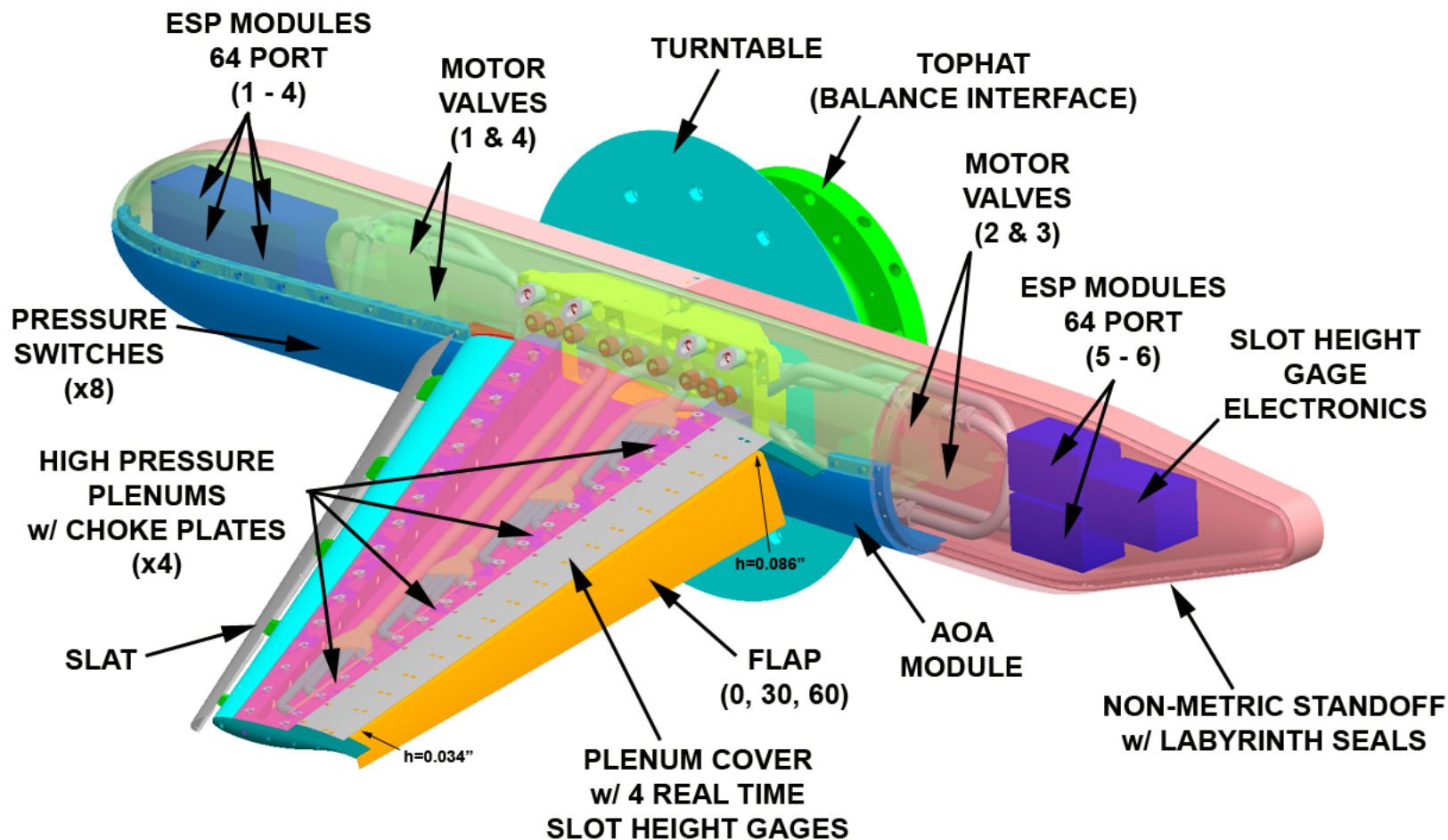
SIMPLIFIED SCHEMATIC OF HIGH PRESSURE AIR DELIVERY FOR SEMI-SPAN MODEL IN THE NTF



- Mild cryogenic testing (-50° F) to avoid frost formation

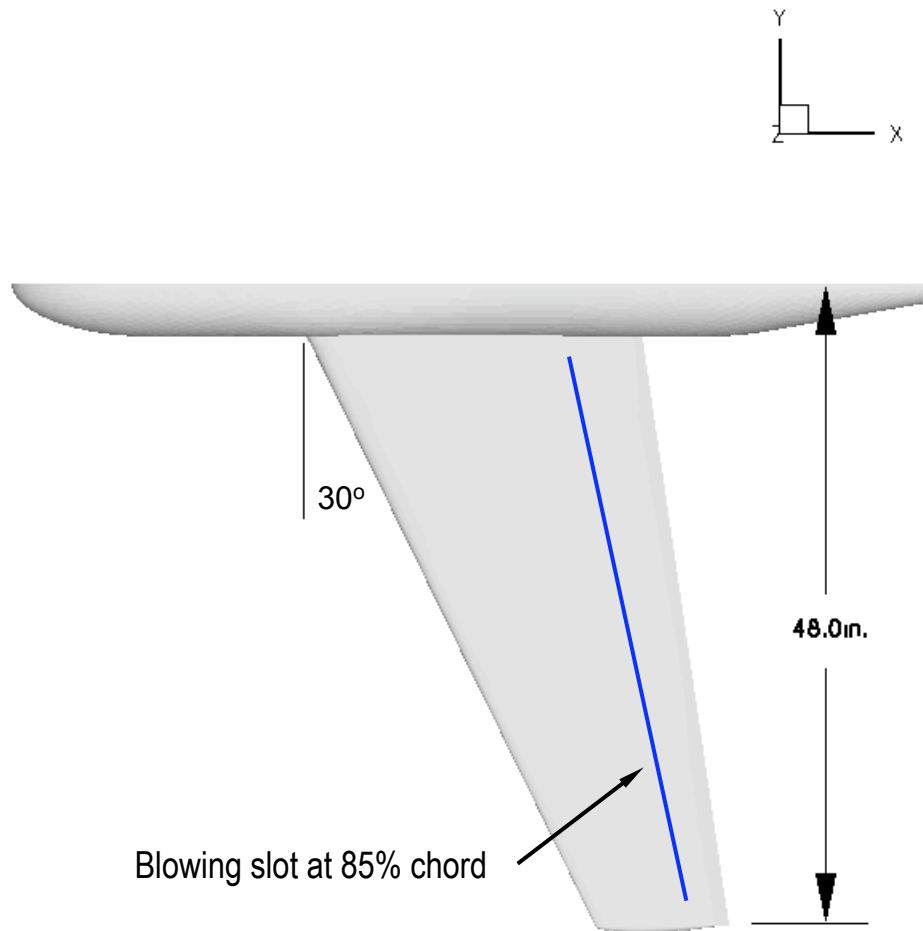


INTERNAL FEATURES OF NTF SEMI-SPAN MODEL ASSEMBLY





SEMI-SPAN TRANSONIC WING DESIGN



Wing planform parameters:
 $AR=5.0$, $\lambda=0.40$
 $cbar = 18.1$ in.

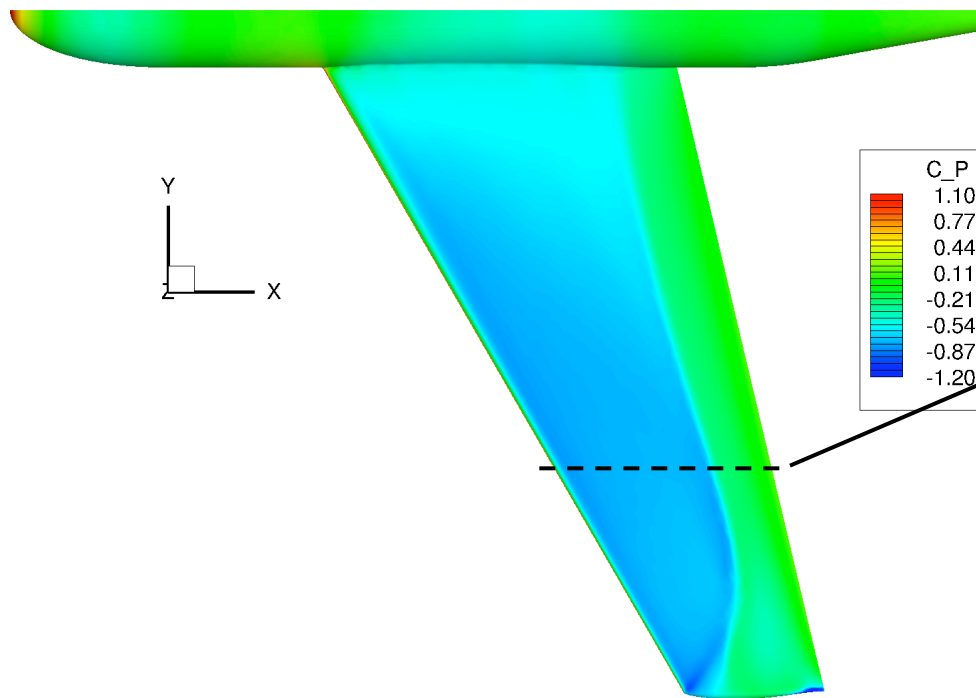
Design conditions:
 $M=0.85$, $Re = 30 \times 10^6$
 $C_L = 0.50$

Flow solver:
USM3D, fully turbulent,
S-A turb model with wall
functions,
~5 million cells

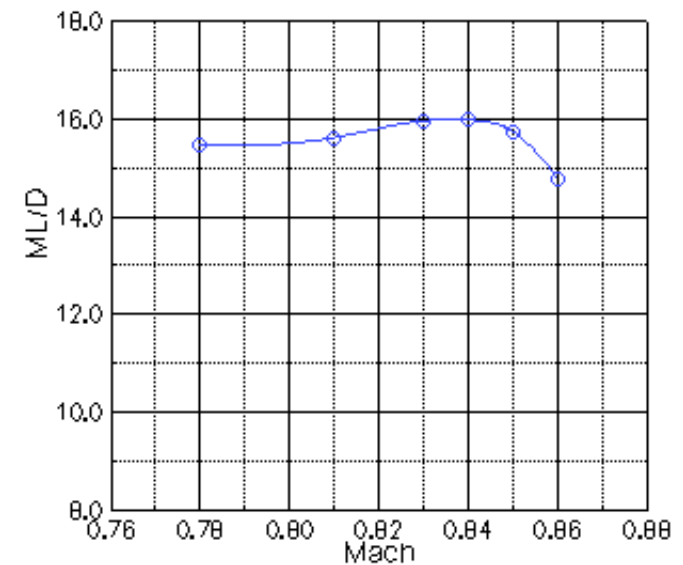
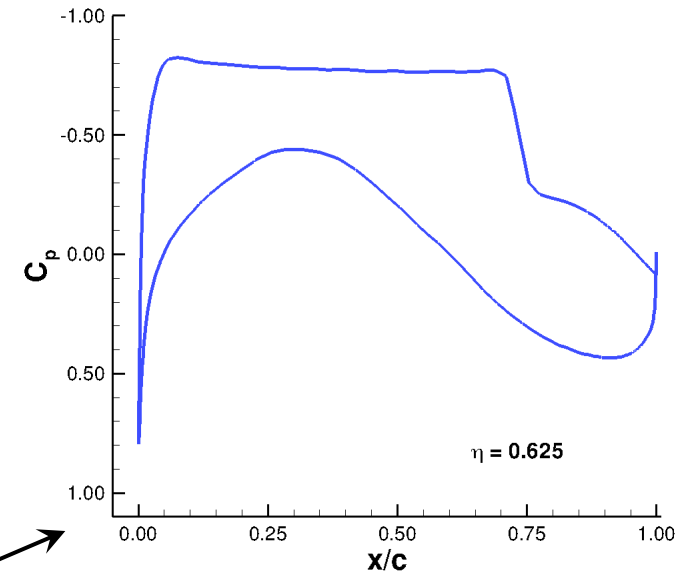
Inverse design using CDISC



AERODYNAMIC CHARACTERISTICS OF SEMI-SPAN TRANSONIC WING DESIGN (NO BLOWING)

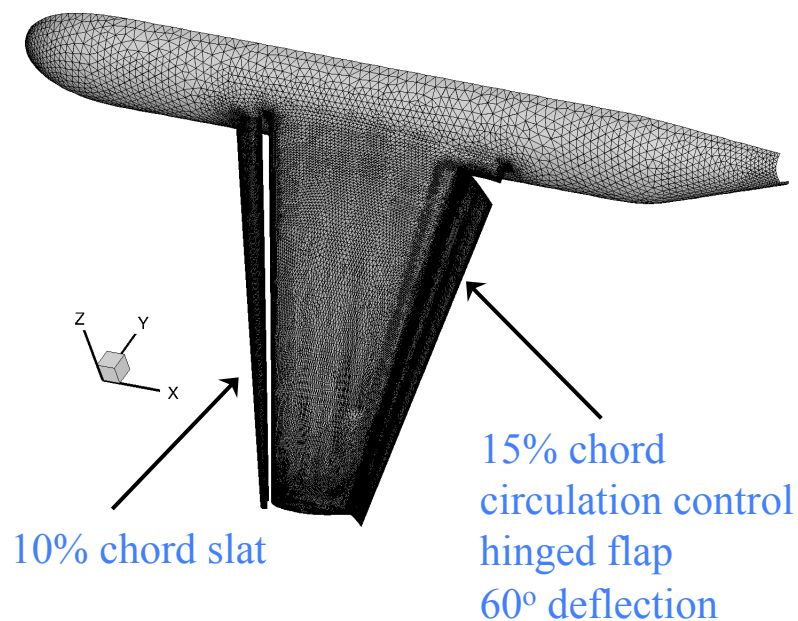


$M=0.85$, $C_L=0.50$, $Re = 30 \times 10^6$

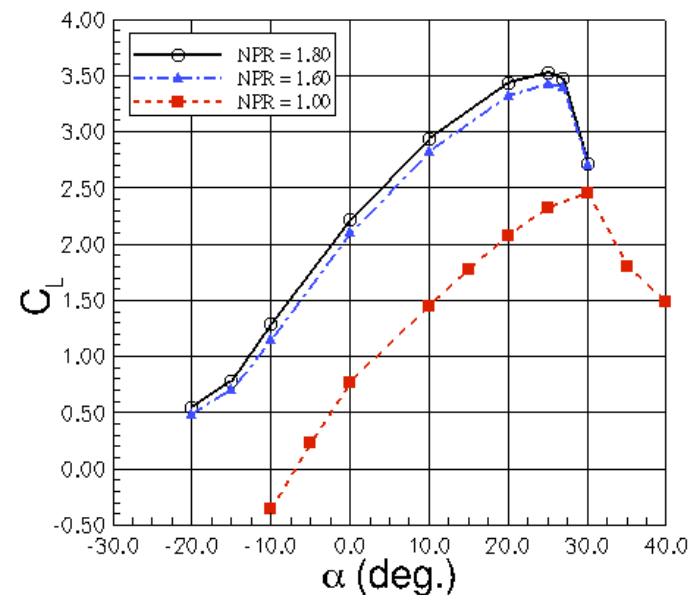




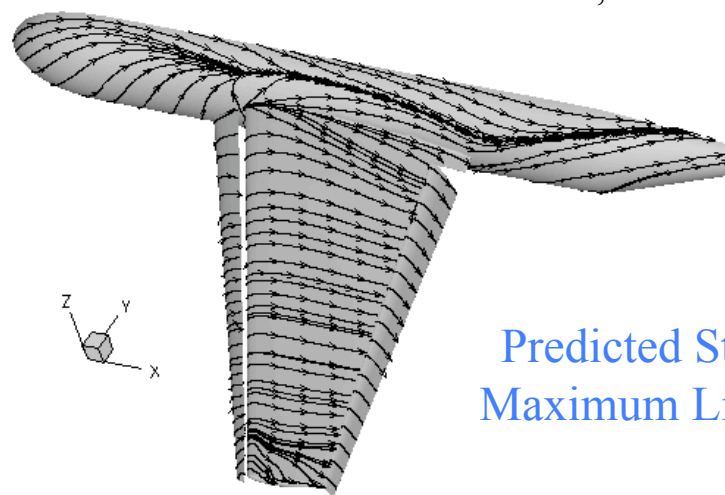
AERODYNAMIC CHARACTERISTICS OF SEMI-SPAN HIGH-LIFT DESIGN WITH BLOWING



USM3D, full-viscous
simulation, S-A
turbulence model
(35×10^6 cells)



$M=0.20$, $Re=20 \times 10^6$



Predicted Streamlines at
Maximum Lift Coefficient

$M=0.20$, $\alpha=25^\circ$, $NPR=1.80$, $Re=20 \times 10^6$
ONERA - Jones 2010



FUTURE

Work with Industry, DOD, and University partners to advance scaling of Active Flow Control and Propulsion Airframe Integration configurations.

Develop high Reynolds number testing techniques for flow physics based research in active flow control

Provide high Reynolds number benchmark data bases for advancing CFD

Evaluate different AFC techniques to improve performance and or reduce mass flow characteristics (e.g. sweeping jets, pulsed jets, synthetic jets, etc.)



QUESTIONS