Turboelectric Distributed Propulsion Test Bed Aircraft

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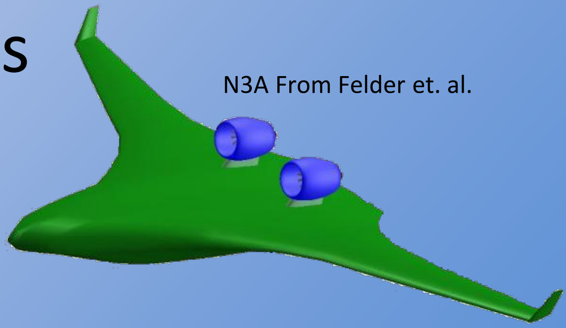
Outline

- Introduction
- Turboelectric Distributed Propulsion (TeDP)
- Subscale Test Bed
- Scaling From Test Bed Aircraft to Full Scale
- Phase I Technical Approach
- Results to Date
- Next steps

Introduction

- NASA Subsonic Fixed Wing (SFW) Project N+3 Goals
  - 2025 Timeframe, Based on B777-200LR Baseline
  - Noise: -52dB Reduction
  - Emissions: -80% Reduction
  - **Fuel Burn: -60% Reduction**
- In Order To Meet Goals ⇒ New Configurations, Materials, and Propulsion Technologies
  - Hybrid Blended Wing Body (HBWB) Config.
  - HBWB Provides High Cruise L/D, Noise Shielding With Upper Surface Mounted Engines
    - With Pylon Mounted UHB Engines, HBWB Provides -52% Fuel Burn Reduction[1]
    - Still Requires Additional 8% Fuel Burn Reduction to Meet N+3 Goals



N3A From Felder et. al.

1) Felder et al. ISABE-2011-1340

TeDP

- HBWB Fuel Burn Can Be Further Reduced 18%-20%** Using TeDP Propulsion Concept[1]
- **Total Fuel Burn Reduction HBWB+TeDP = 70%-72%****
- TeDP Uses Electric Motor Driven Fans Coupled To Gas Turbine Generators Via Transmission Lines

** Assumes Superconducting Motors and Generators

1) Felder et al. ISABE-2011-1340

TeDP Advantages

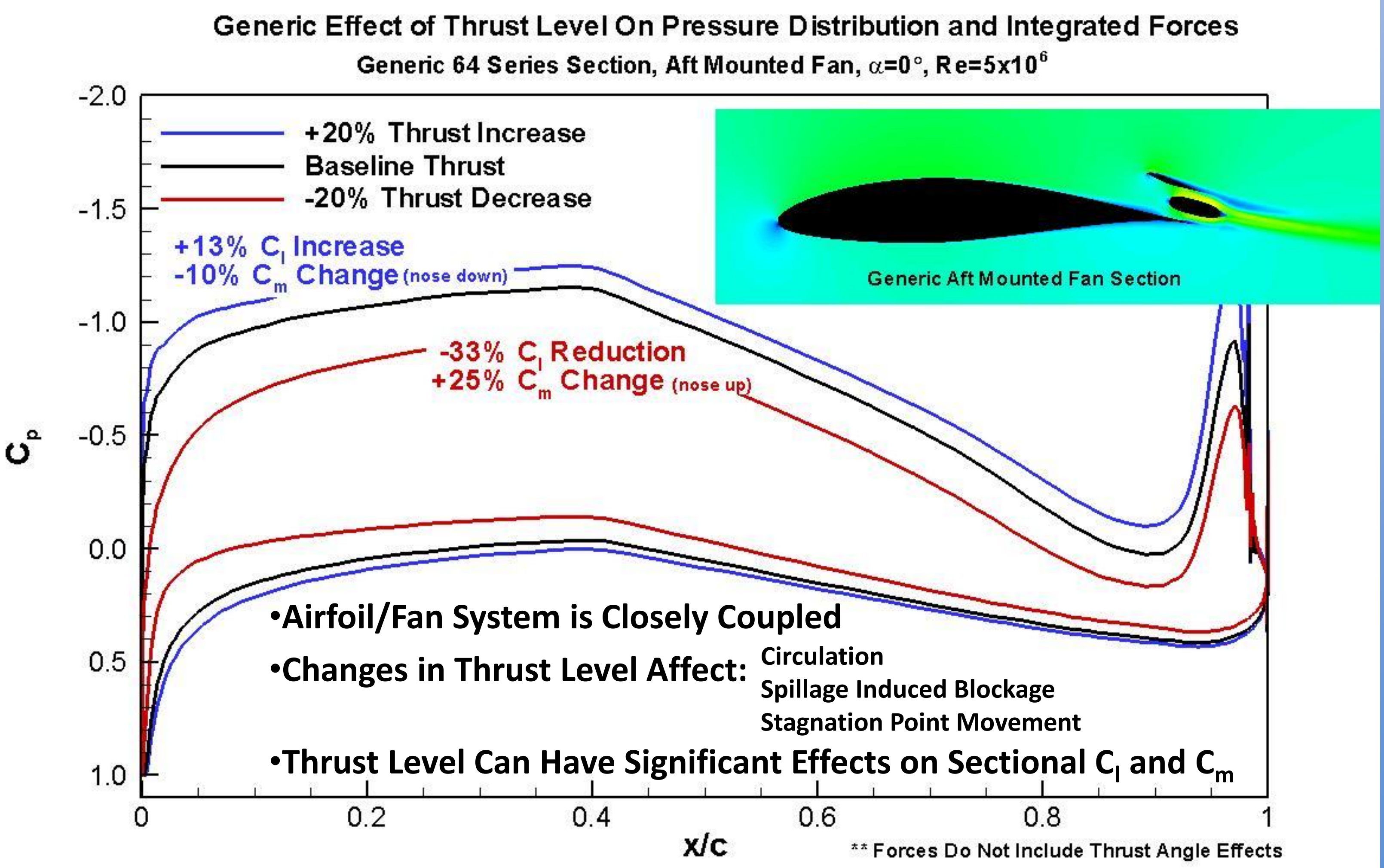
- Boundary Layer Ingestion (BLI)
  - Reduces Average Inlet Velocity and Drag of Inlet
  - Reduces Fuel Burn Compared to Pylon Mounted Design
- Reduces Wake Drag of Vehicle
  - Re-energizes Wake of Airframe With Fan Thrust Stream
- Decouples Propulsion From Power
  - Power and Propulsion Can be Placed at Optimum Locations
  - RPM of Power Generating Turbine Independent of Fan RPM
- Very High Effective Bypass Ratio
- Safety: Redundancy For Both Propulsion and Power
- Differential Thrust For Trim and Possible Yaw Control

1) Felder et al. ISABE-2011-1340

TeDP Challenges

- Inlet Distortion Due to BLI and Inlet Geometry
  - Reduced Fan Performance, Increased Blade Fatigue Due to BLI and Inlet Secondary Flows
- Aerodynamics and Propulsion Closely Coupled
  - Possible Nonlinear Interaction Between Sectional Aero Performance and Thrust Level (Mass Flow and Spillage Vary With Thrust Level)
- Effect of Individual Fan Thrust Level/Mass Flow on Adjacent Fan Performance and Distortion
- Reliance on Superconducting Motors/Generators to Reduce Propulsion System Weight Fraction
- Increased System Complexity and New Technologies

TeDP Challenges



- Airfoil/Fan System is Closely Coupled
- Changes in Thrust Level Affect:
  - Circulation
  - Spillage Induced Blockage
  - Stagnation Point Movement
- Thrust Level Can Have Significant Effects on Sectional C_l and C_m

Subscale Test Bed

- **LEARN Project: Design Distributed Propulsion System For Small Test Bed Aircraft**
- Successful TeDP Implementation Poses Significant Challenges, Even For N+3 2025 Time Frame
- Develop a Flying Demonstrator For TeDP Concepts, Systems, and Technologies
  - Allows Early Investigation of Complex Aerodynamics, Propulsion, and Systems Vital to Success of a TeDP Configuration
  - Reduce Development Risk of Larger, Dedicated TeDP Configuration by Converting Small, Single Engine Aircraft Already in NASA's Inventory

Subscale Test Bed

- Test Bed Aircraft Allows Early Assessment of Multiple TeDP Technologies and Challenges
  - BLI
    - Distortion Challenges
  - Aerodynamic/Thrust Coupling
    - Effect of Thrust Level and Mass Flow on Sectional Aerodynamic Characteristics (C_l, C_m, Trim and Trim Drag)
    - Approach and Landing Configurations
    - High Angle-of-Attack Behavior, Stall, Separation and Effect on Thrust Level
  - Spanwise Differential Thrust
    - For Trim and Possible Yaw Control
    - Effect of Changing Spanwise Thrust Levels, Mass Flow and Spillage on Neighboring Fans Thrust and Performance
  - Inlet Area Design
    - Changes in Mass Flow With Thrust Effect Spillage and Blockage
    - Is Moveable Inlet Lip Required to Adjust For Various Flight Conditions?

Scaling

- Technologies Developed On Test Bed Need To Scale To Full Scale Transport Configuration
- **Scalable Technologies**
  - BLI Effects: Match BL Height to Inlet Height Ratio, Shape Factor
  - Aerodynamic/Propulsive Coupling
    - Effect of Fan Thrust/Mass Flow on Circulation, C_l, C_m, Stagnation Point
      - Approach/Landing Configurations, Climb, High Lift/Angle-of-Attack
    - Adjacent Fan's Thrust/Spillage Level on Neighboring Fan Performance Distortion Characteristics
    - Movable Inlet Lip Geometry to Adjust For Flight Conditions
    - Power Distribution Topology
- **Scaling Challenges**
  - Low Speed Converging vs. High Speed Diverging Inlet
    - Distortion Levels
  - Electric Power Levels
  - Shock Upstream of Inlet at Transonic Speeds

Phase I Technical Approach

- Phase I Goal: Test Multi-Fan Model Based On Conceptual Test Bed Aircraft Installation
  - Measure Installed Thrust, Inlet Distortion, Surface Pressures, Boundary Layer Profiles, and Required Fan Power
  - Examine Effect of Adjacent Fan Thrust Level on Neighboring Fan Distortion and Performance
    - Increased Scope of Program to Examine Multiple Fans
- Phase I Major Tasks
  - Select Proposed Test Bed Aircraft
  - Evaluate Required Performance of TeDP System to Replace Baseline IC/Propeller Based Propulsion
  - Select COTS Electric Ducted Fan/Motor
  - Design BLI Inlet/S-Duct, and Exhaust
  - Design Wind Tunnel Test Model of Propulsion System
  - Generate 3D CFD Model of Wind Tunnel Test Article
  - Perform Wind Tunnel Test of Model Propulsion System

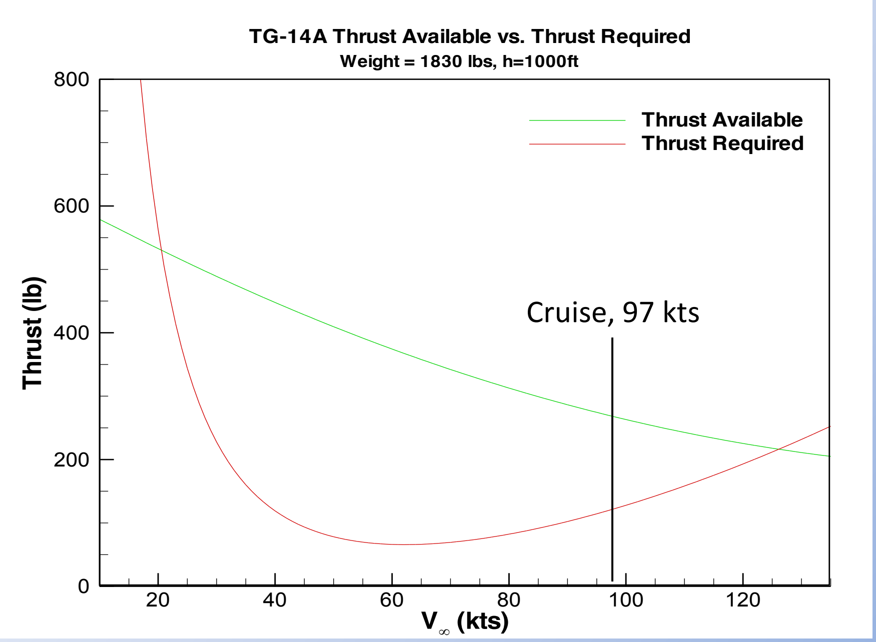
Test Bed Aircraft

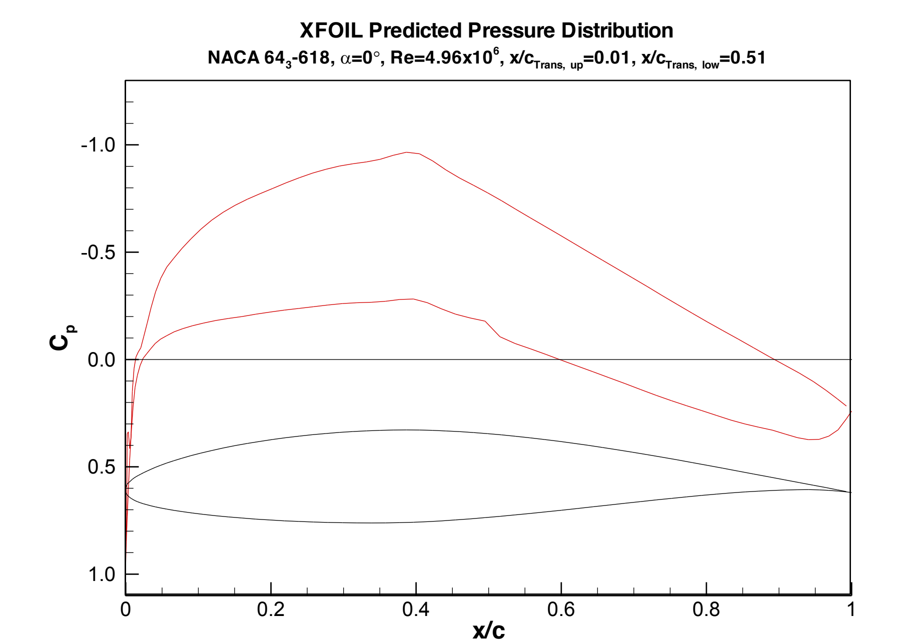
- TG-14A Motor Glider
  - Previously Selected as an Excellent Candidate For Conversion to an Electric Aircraft Test Bed Under Previous Program
  - Chosen For a Combination of Aerodynamic Performance, Available Space, and High MTOGW/Useful Load

Aircraft	Manufacturer	Type	# of Seats	Motor	
TG-14A	Grupo Aeromot	Motor Glider	2	Rotax 912	
				100 HP (74 kW)	
Wingspan	57.3 ft	**Max Speed (V_{NE})**	132 kts		
Length	26.5 ft	**Maneuver (V_A)**	97 kts	**Propeller**	
Height	6.3 ft	**Stall**	39 kts	Hoffmann HO-V62R-1/170FA	
Width	42.5"				
		Glide Ratio	31-1	**Endurance**	5 hrs
Empty Wt	1334 lbs	**Airfoil**	NACA 64_3-618		
Takeoff Wt	1874 lbs				

Test Bed Aircraft

- Baseline Power plant
  - 100 Hp (74 kW) Rotax 912
  - Take-Off Thrust ~ 550 lbs
  - Cruise Speed 97 kts
    - T_a=270 lbs
    - T_r=120 lbs
- Airfoil and Design Conditions
  - NACA 643-618, 18% Thick
  - TG-14A Root Chord ~ 57.25 Inches
  - $Re_c=4.96\times10^6$ at Cruise, STP
  - To Maximize BLI Benefit, Want Fan Inlet at $C_p \geq 0 \Rightarrow x/c \geq 0.90$

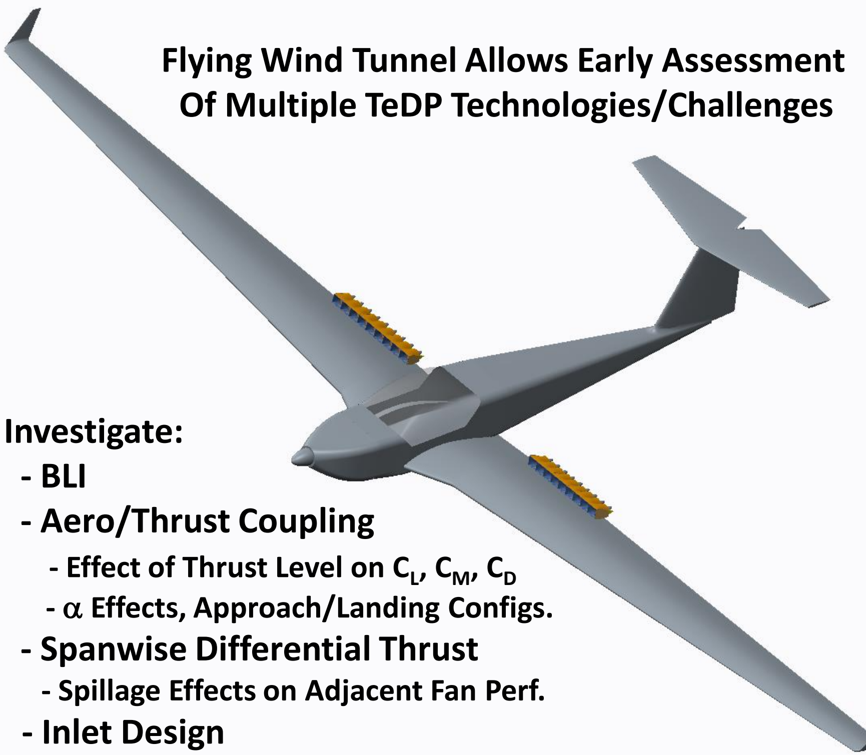




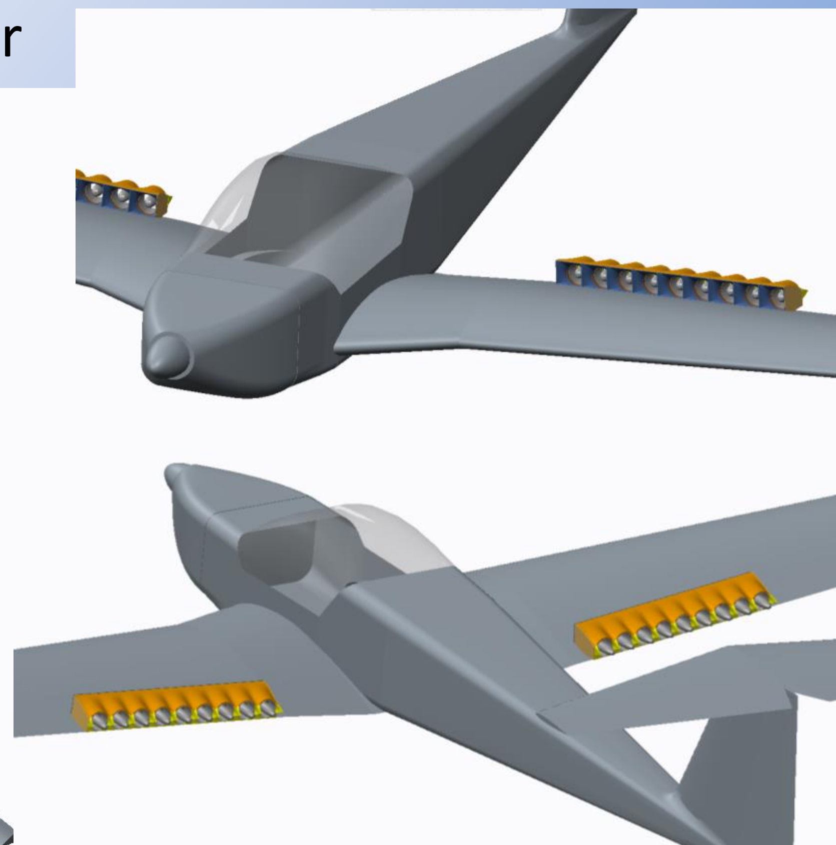
Notional Test Bed TeDP System

- Based on COTS Electric Ducted Fans
- Compromise Between Available Fan Thrust, # of Fans, Fan Efficiency and Required Power

Flying Wind Tunnel Allows Early Assessment Of Multiple TeDP Technologies/Challenges



Investigate:
- **BLI**
- **Aero/Thrust Coupling**
  - **Effect of Thrust Level on C_L, C_M, C_D**
  - **α Effects, Approach/Landing Configs.**
- **Spanwise Differential Thrust**
  - **Spillage Effects on Adjacent Fan Perf.**
- **Inlet Design**



EDF Fan Choice

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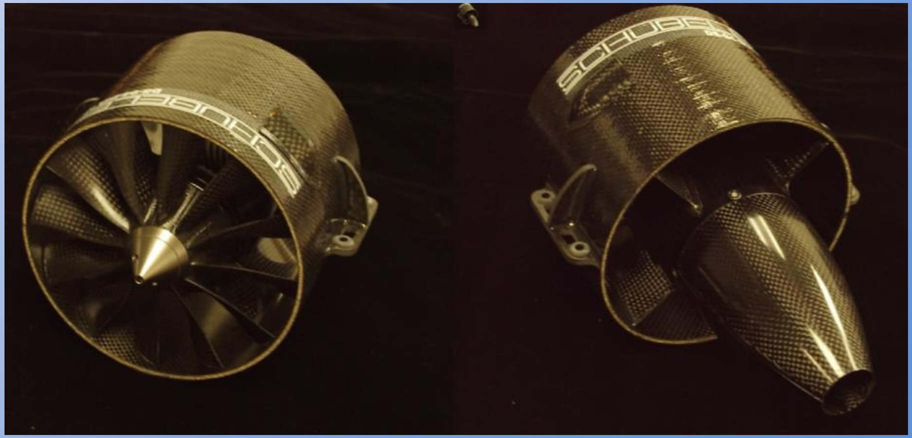
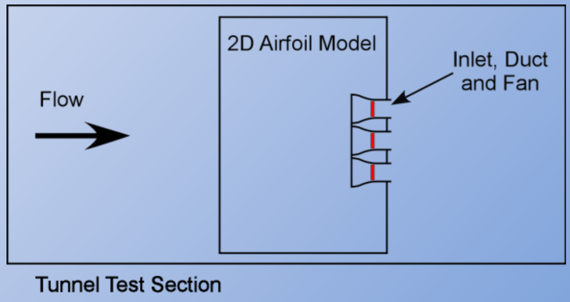
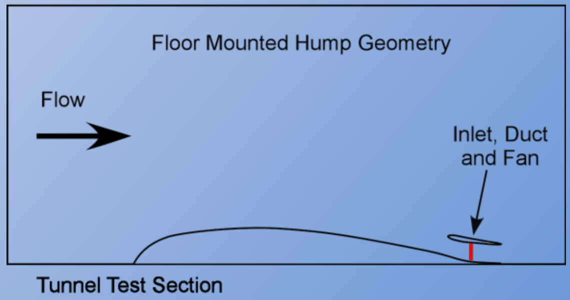
- Investigated COTS EDF Fans
  - Produced For R/C Hobby Enthusiasts
  - Come In Several "Standard Sizes" From 30mm to 140mm With Thrust Levels From Less Than 1 lbs to 46 lbs
- Chose Schuebeler DS-94-DIA HST DSM6745-700
  - Best Combination of Thrust, Efficiency, Power Required, and Number of Required Fan Units
  - 5.04 inch ID, 14.57 in^2 FSA
  - Thrust = 29 lbs Static @ 9.8 kW
  - Efficiency 70%, FPR ~ 1.1
  - 18 Individual Fans Required to Replace TG-14A 100 HP Rotax

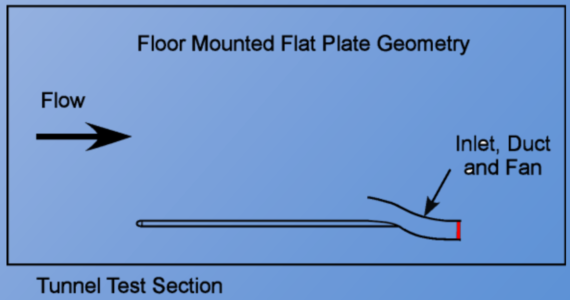


Model Design and Duct Sizing

- Model Designed For 3ft x 4ft Low Speed Wind Tunnel
- Test 3 Fan, Multi-Inlet Geometry
- Three Configurations Considered
  - 2D Airfoil Vertical Mount
    - Determine Effect of Thrust on C_l, C_m, C_d
    - Reduced Chord, Reynolds #, Subscale Fan
  - Floor Mounted Hump Geometry
    - Full Scale Chord/Fan, Reynolds Number
    - No Lift, Drag, Moment
  - Floor Mounted Flap Plate Geometry
    - Simple, Inexpensive
    - No Pressure Gradient Effects
- Chose Hump Geometry
  - Allows Full Scale Fans, Flight Reynolds #
  - Correct BL and Pressure Gradient







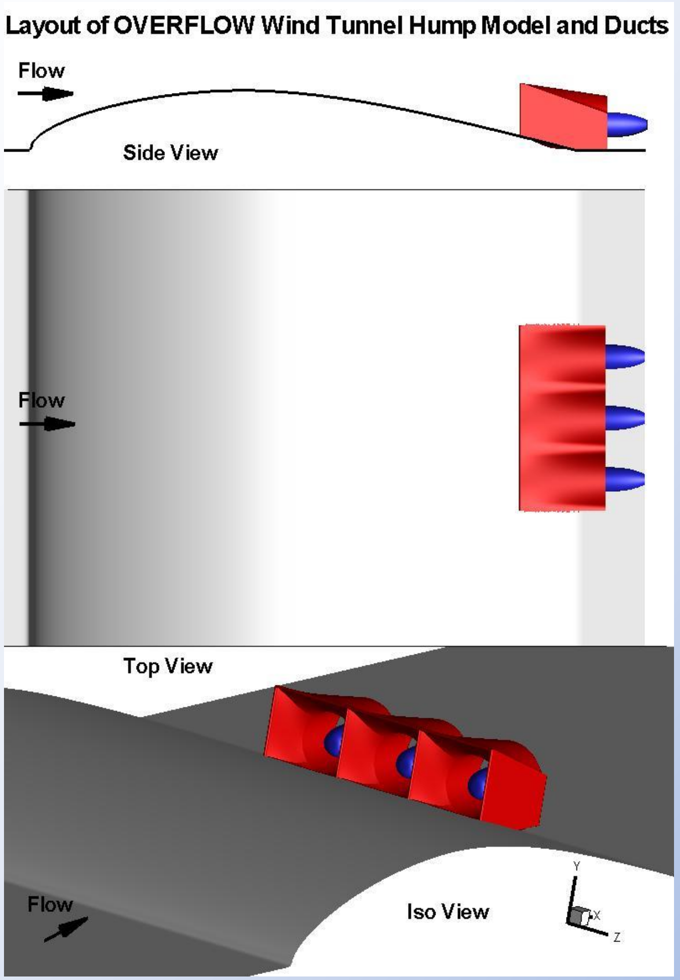
Model Design and Duct Sizing

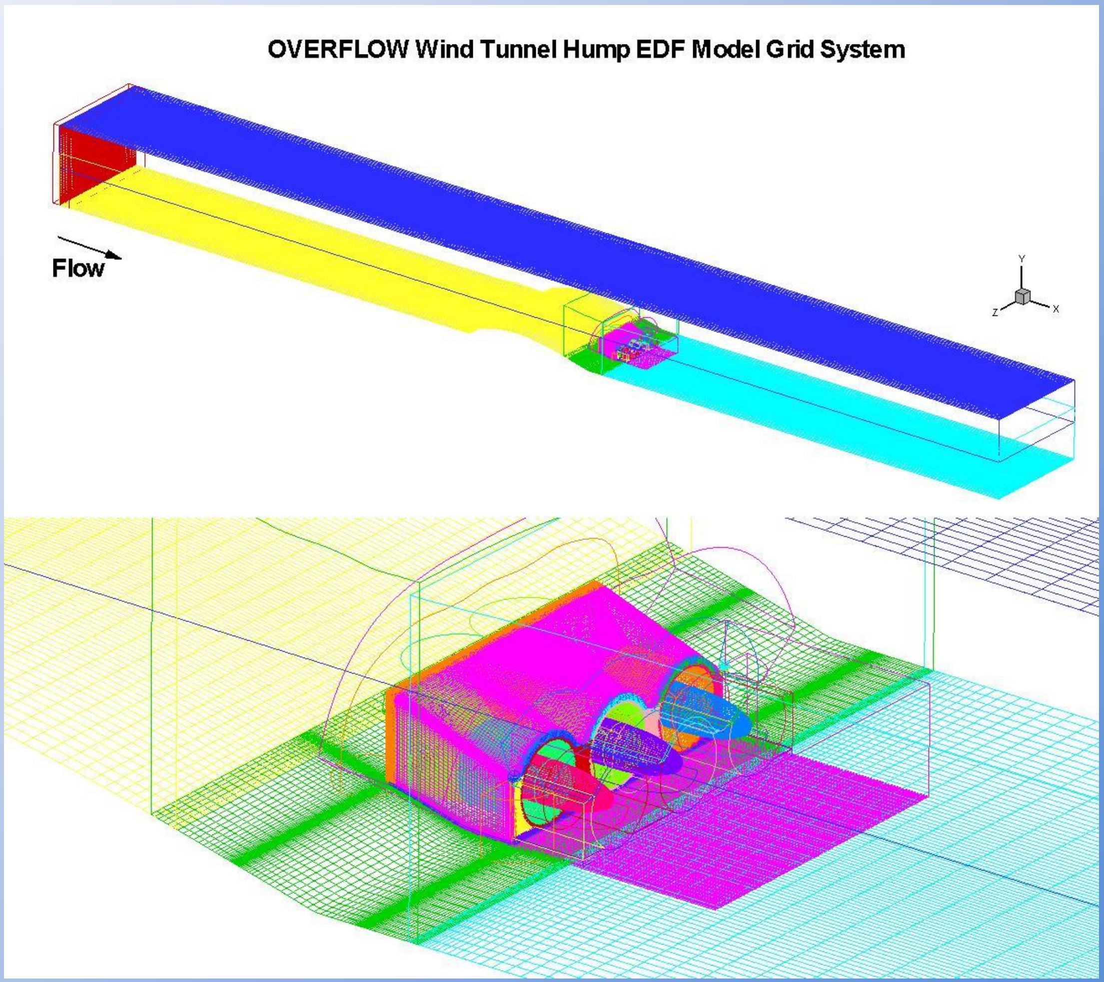
- Initial Estimate of Boundary Layer From XFOIL
  - Re_c=4.96x10^6 at TG-14A Cruise of 97 kts
  - Assumed Turbulent Boundary Layer
  - TG-14A Root Chord = 57.25 inches
  - At x/c=0.90, $\delta \sim$ 1.4 inches
- Duct Design
  - TG-14A is Low Subsonic → Converging Duct
  - Duct Capture Area Based on Required Mass Flow Estimate For TG-14A Thrust Available at Cruise T_a=15 lbs/fan, $\dot{m}$ = 0.0828 slugs/s
  - For Required Mass Flow, Inlet Area Estimated to be 32.8 in^2
  - Duct Width 6.0 inches (Minimum Δ Between Fans), Height 5.47 Inches
  - 25% of Inlet Height Occupied by Boundary Layer
  - Inlet to Fan Face L/D $\sim$ 1 Used

CFD Model

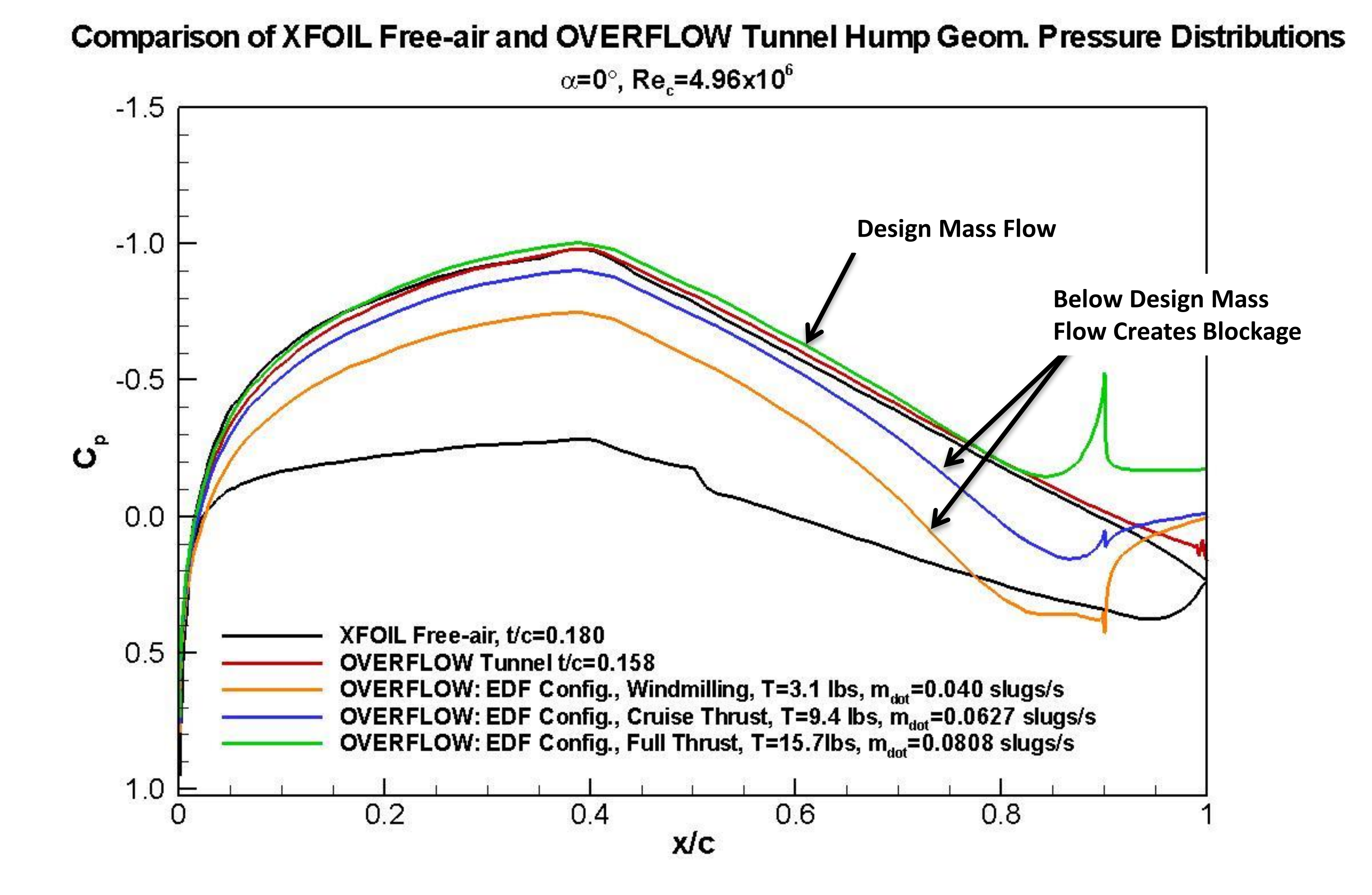
- CFD Model of Wind Tunnel Experiment Developed To Provide Insight Into EDF Duct Flowfield
  - Model Includes Tunnel Walls, Inlets, Duct System, and Motor/Fan Plug
  - Provide Guidance in Inlet/Duct Design, Inlet Distortion Estimates
- Simulations Run Using OVERFLOW CFD Code
  - To Match Free Air Pressure Distribution, Model t/c Reduced From 18% to 15.8% Due to Model Blockage
  - Cases Investigated
    - Full Cruise Thrust Available T_a=270 lbs → 15 lbs/fan, $\dot{m}$ = 0.0828 slugs/s
    - Cruise Thrust Required T_r=120 lbs → 6.6 lbs/fan, $\dot{m}$ = 0.0642 slugs/s
    - Windmill
    - Differential Thrust: Full/Cruise on Center and Left Duct, Right Duct Idle
  - EDF Modeled as an Actuator Disk in Fan Annulus
    - Actuator Disk Δp Specified as BC, Δp Adjusted to Obtain Desired Mass Flow

CFD Model


Layout of OVERFLOW Wind Tunnel Hump Model and Ducts
Flow
Side View
Flow
Top View
Flow
Iso View
Y
X
Z


OVERFLOW Wind Tunnel Hump EDF Model Grid System
Flow
Y
Z
X

CFD Model Results



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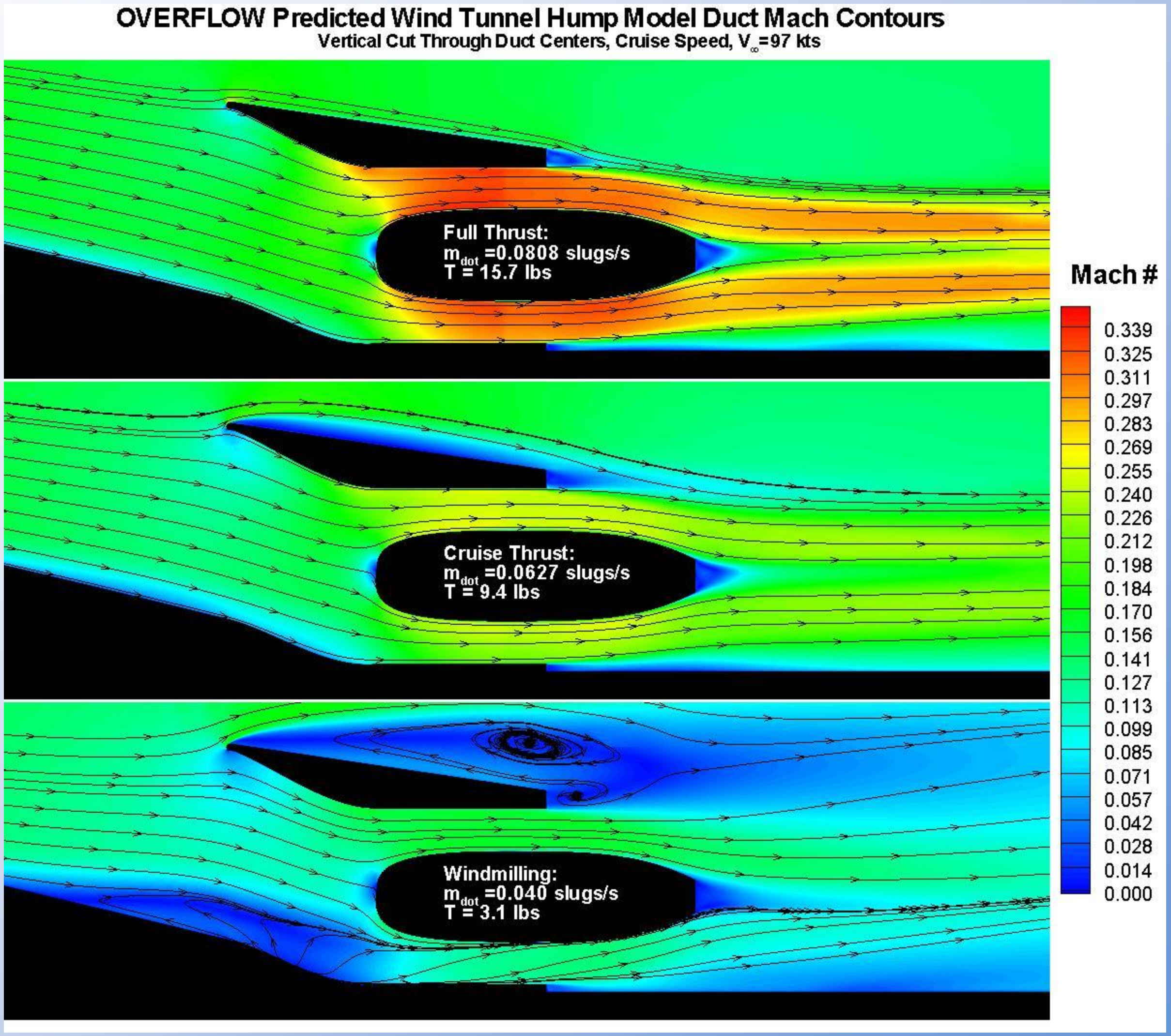

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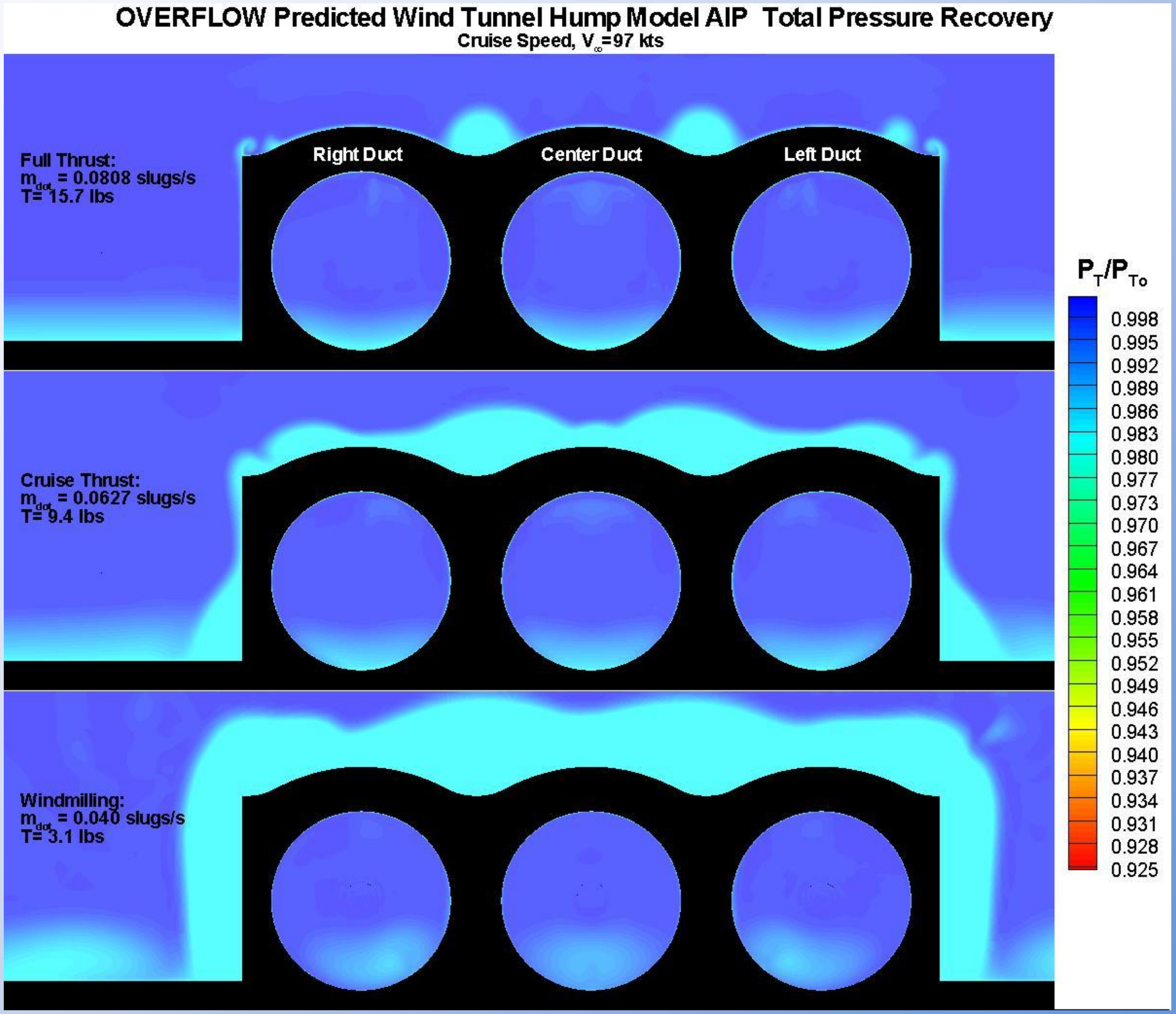

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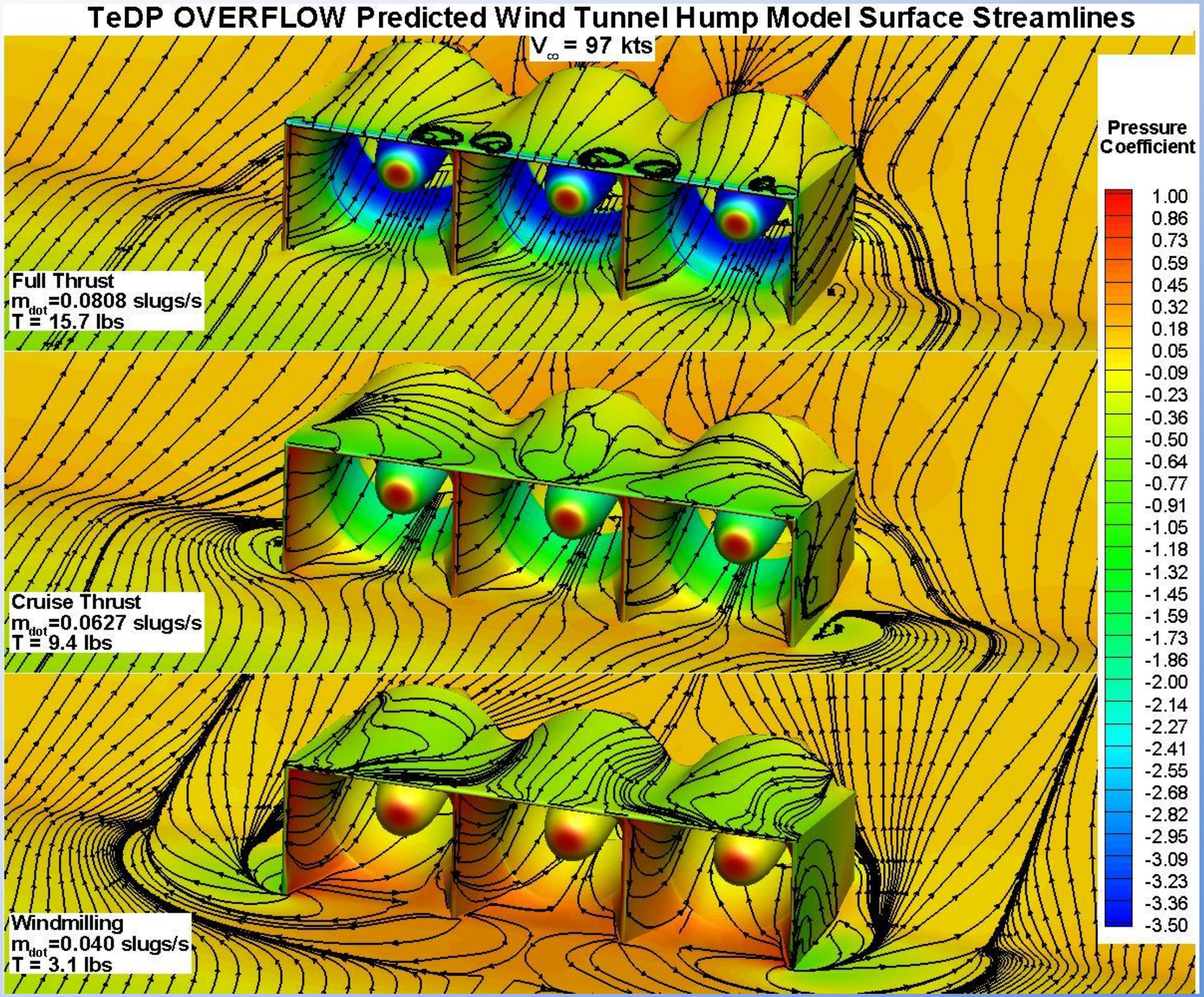

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CFD Model Results

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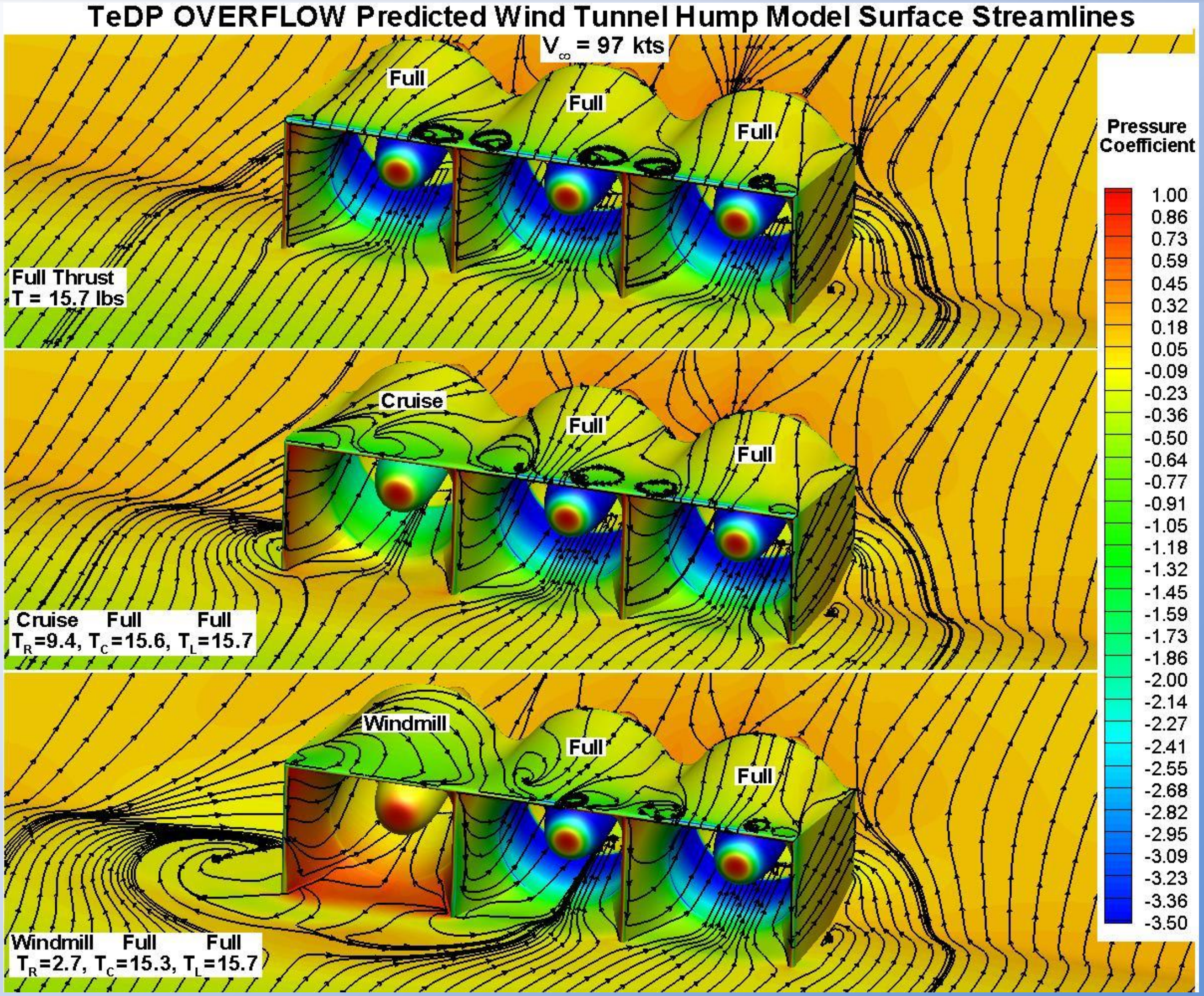

CFD Model Results

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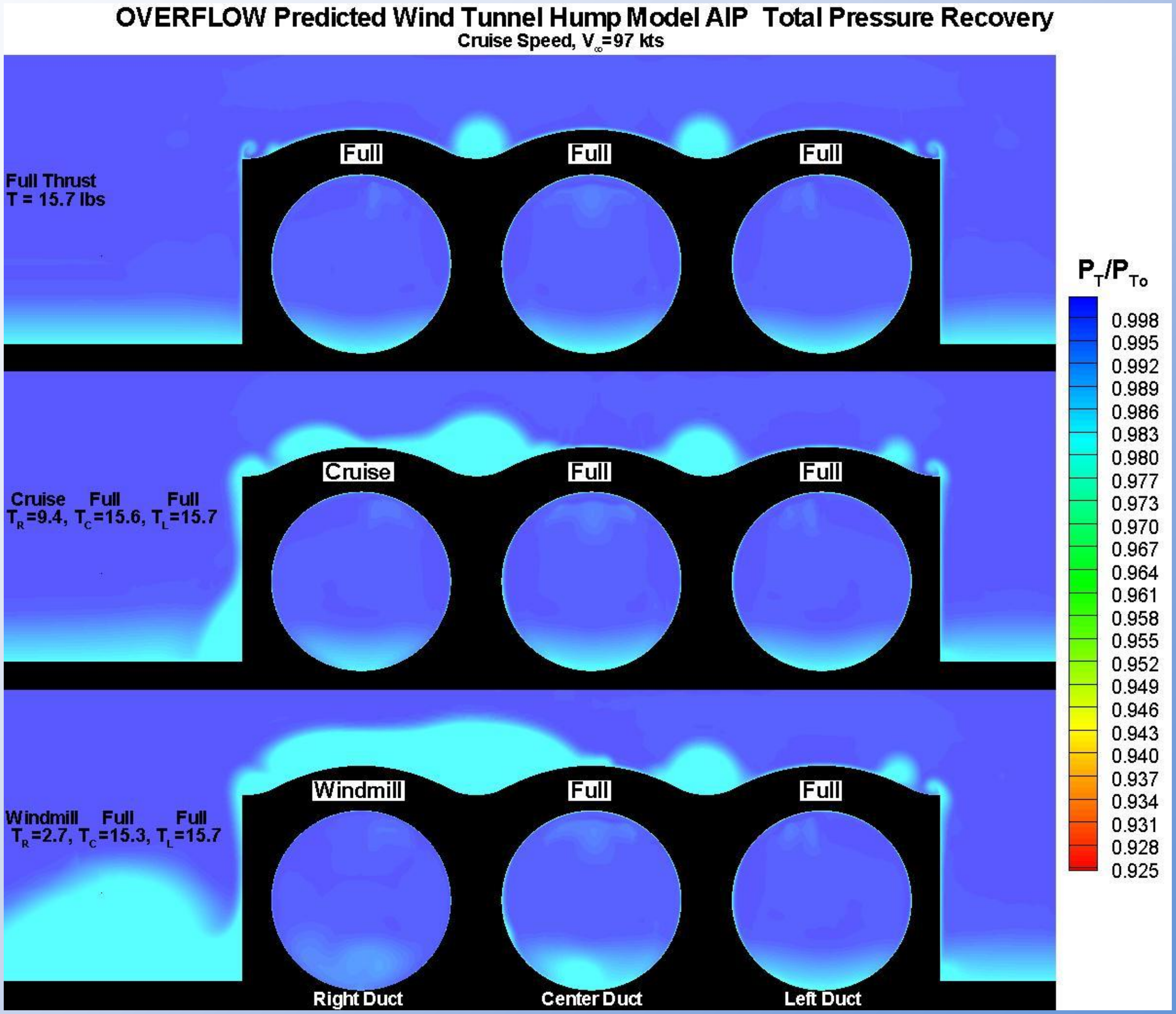

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CFD Model Results

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- Overall CFD Results Positive
  - At Design Point (T_a) and Cruse (T_r) Inlet, Distortion Low For Aggressive L/D
  - No Separation In Duct For T_a and T_r Cases, Only Separation at Windmilling
  - Large Pressure Distribution Effect For Increased Blockage Below Design $\dot{m}$
  - Predicted Thrust Levels Higher Than Estimated Based On Mass Flow
    - Increased Blockage Below Design Mass Flow
    - Positive BLI Effect
- Differential Thrust Results Show Adjacent Fan Impacted
  - Increased Distortion Observed For Large Differential, But Still Small
  - CFD Predicts Increased Lip Separation on Adjacent Fan and Small Thrust Reduction
- Based On CFD Results Some Minor Mods Made
  - S-Duct Inlet and Exit Transition Smoothed, Outer Lip Geometry Adjusted

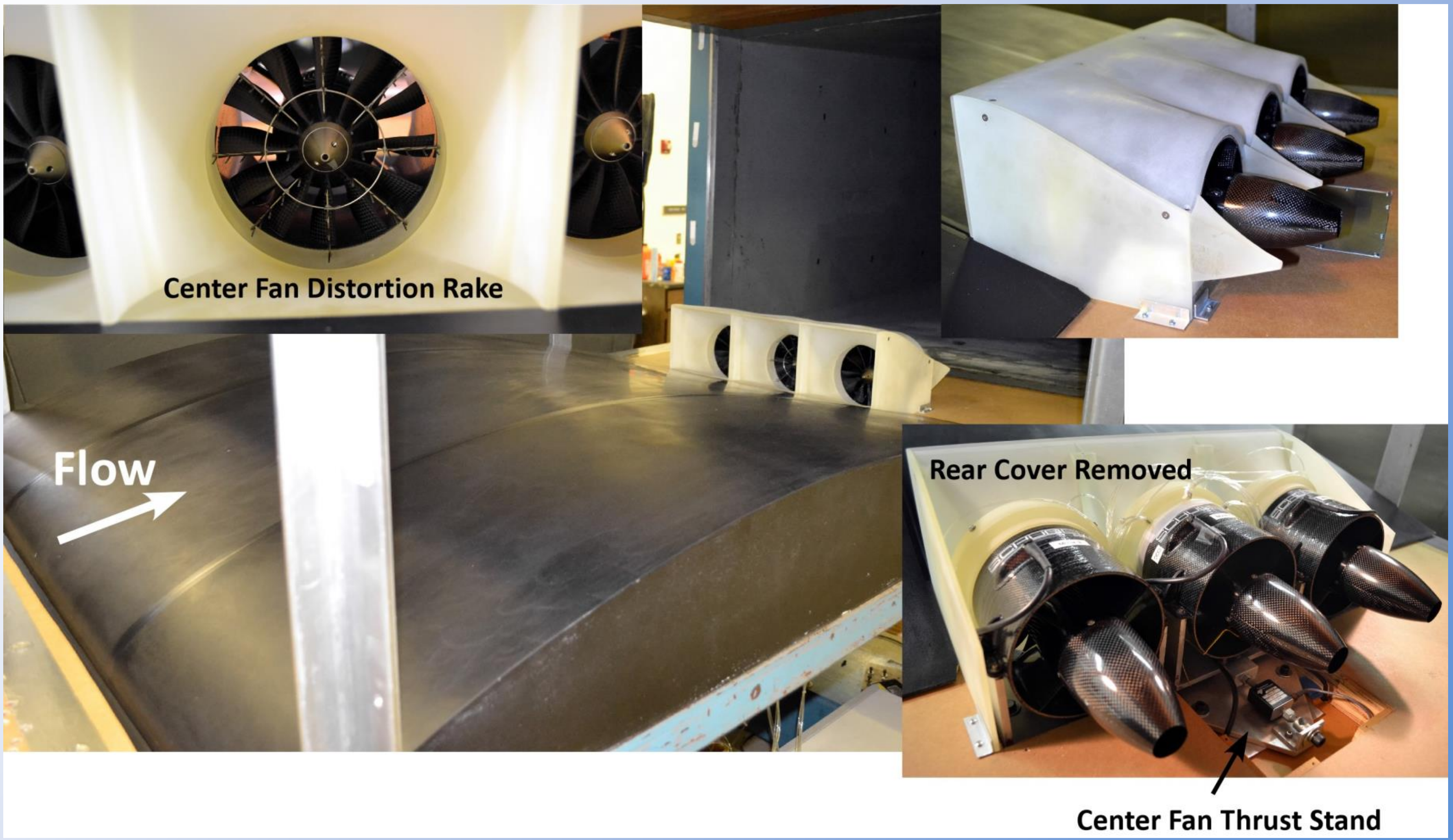
Wind Tunnel Model/Test

- Model Tested In UIUC 3’x4’ Low Speed Tunnel
  - Airfoil Manufactured Using CNC Sculpting From High Density Urethane
  - Duct System Manufactured Using Stereo Lithography
- Power Required For Full Rated Fan Thrust is 52 Volts at 190 Amps
  - Preliminary Runs Made Using 4 Deep Cycle Marine Batteries in Series
    - Not Enough Power, Only Able To Obtain 44 Volts at 130 amps at Full Load (5.7 kW)
  - Investigated DC Power Supply – Too Costly
  - Used Lithium Polymer Battery Packs Obtained From Fan Manufacturer (14s 7800 mAh)
    - Produced 49 volts at 136 amps (6.7 kW)
    - Available Power 30% Below 9.75 kW Required To Achieve Full Rated Power
    - Run Times Limited to Approximately Two Minutes at Full Power

Wind Tunnel Model/Test

- Instrumentation
  - Center Duct Fan Mounted on a Thrust Balance
  - Center Duct Equipped With 40 Port Miniature Inlet Distortion Rake
  - Surface Static Pressure Taps Along Model Centerline
  - Traversing Pitot Probe to Measure BL Thickness Upstream of Centerline Duct Entrance
  - Left and Right Ducts Have Static Pressure Ports to Measure Flow Rates
  - Suction Used Upstream of Model to Remove Tunnel Floor BL
- Two Week Entry Completed Sept. 27th
  - Tunnel Speed Set to Match TG-14A Cruise Reynolds No. (~ 164 ft/s)
  - Conditions Included
    - All Fans Running: Static Thrust, 100% - 75% - 50% Power and Windmill
    - Differential Thrust Combinations Using 100%, 50% Power and Windmill Settings
  - Smoke Flow Visualization

Wind Tunnel Set-Up



Test Results

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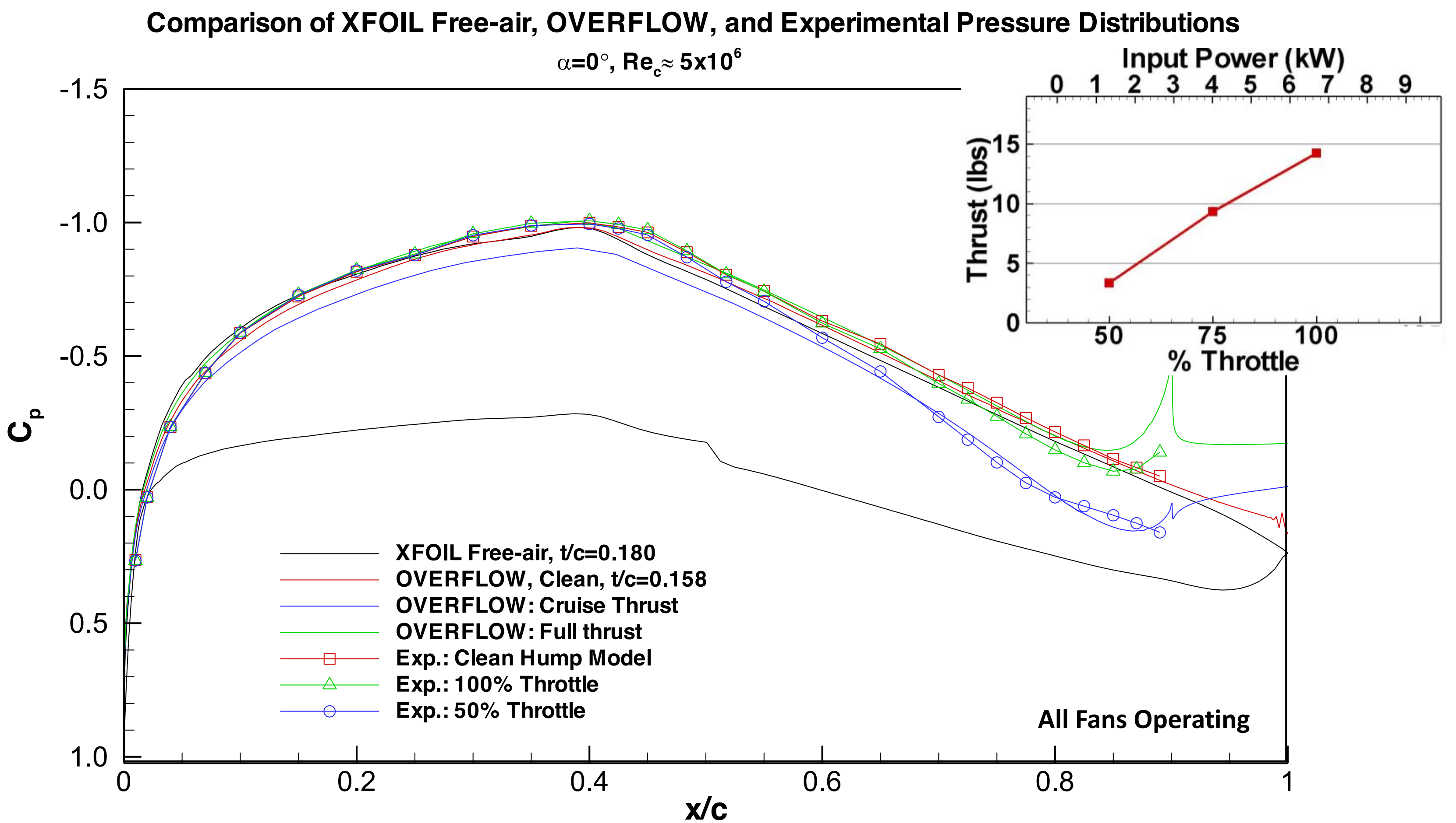

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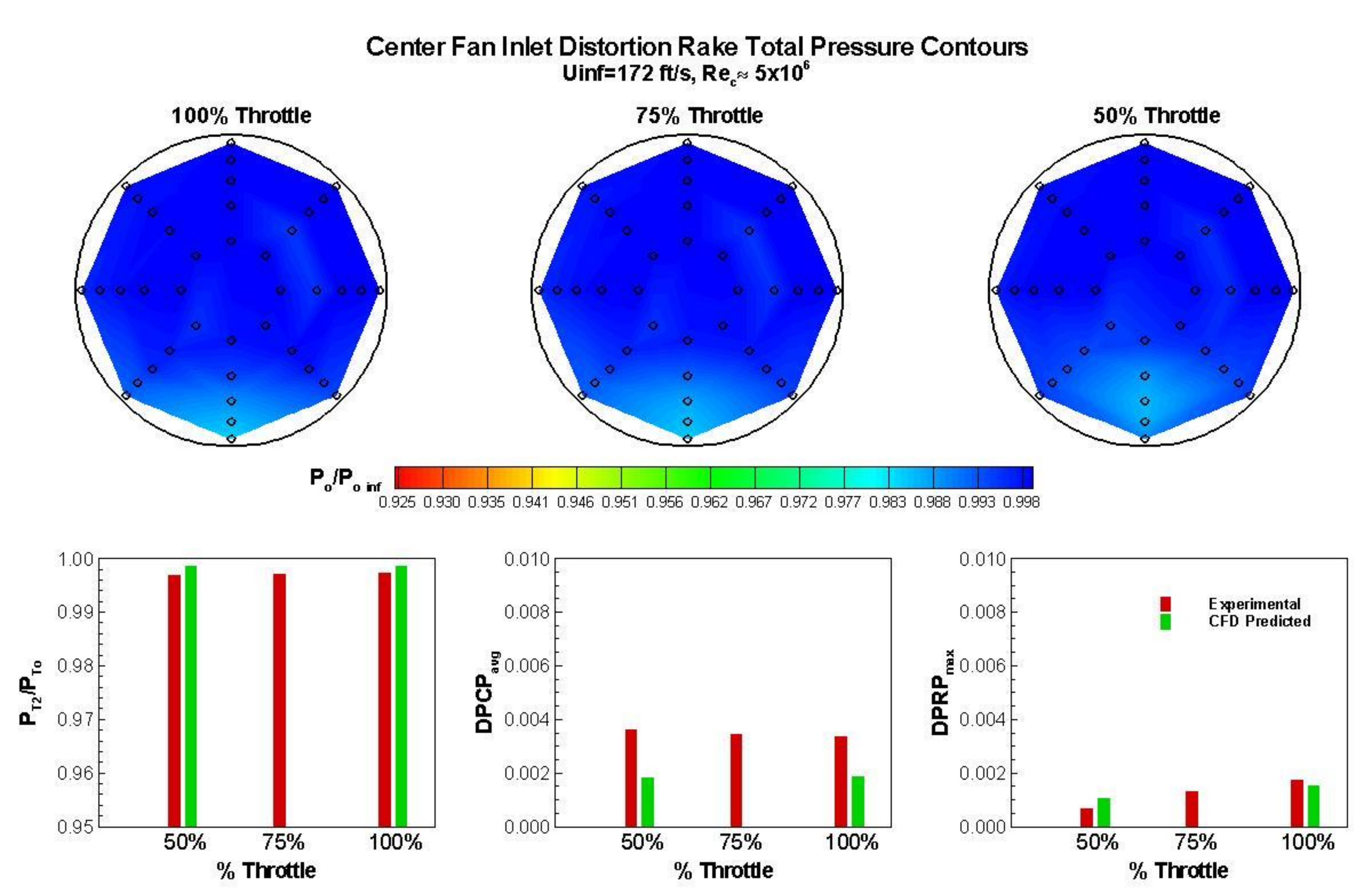

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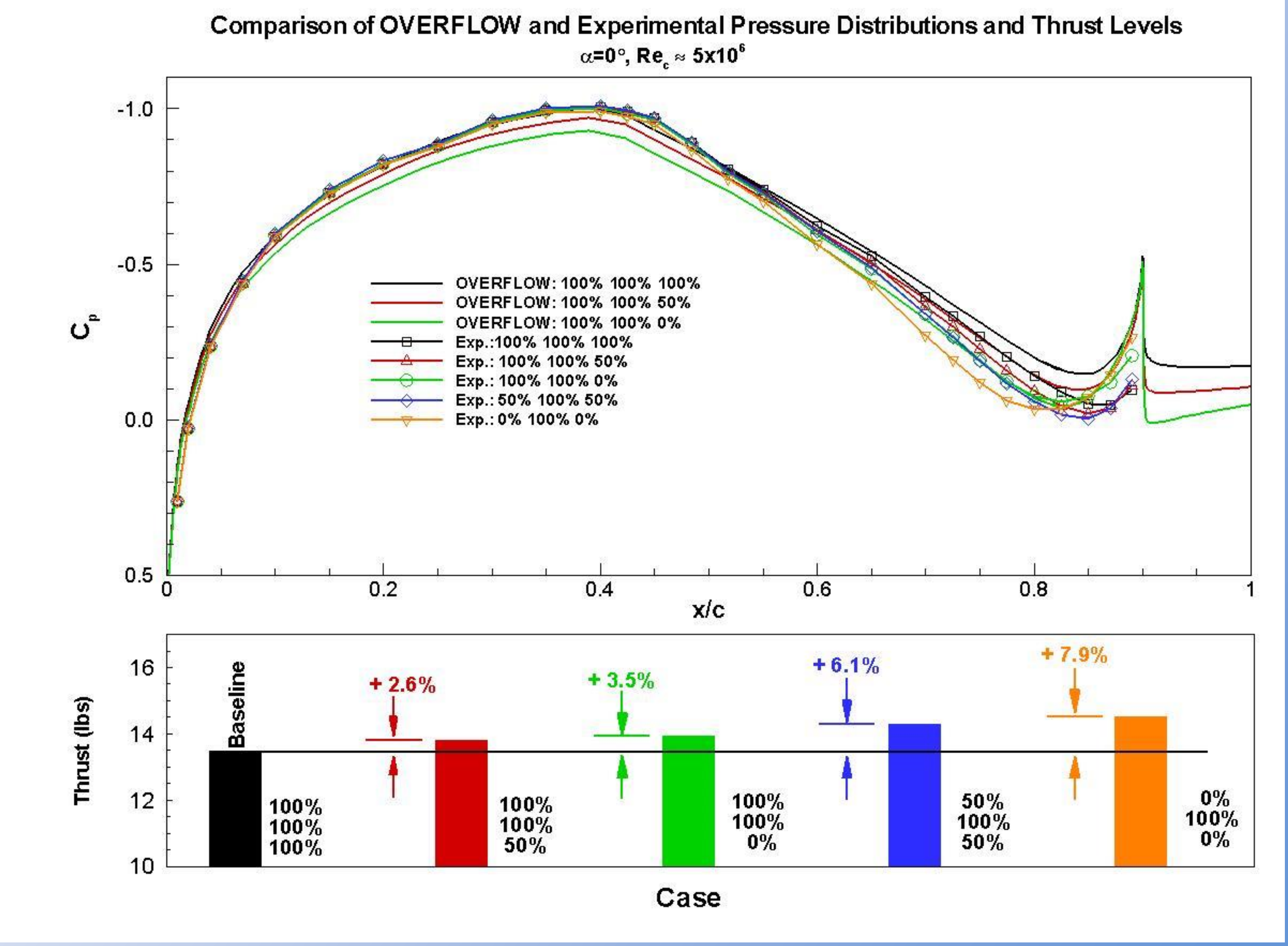

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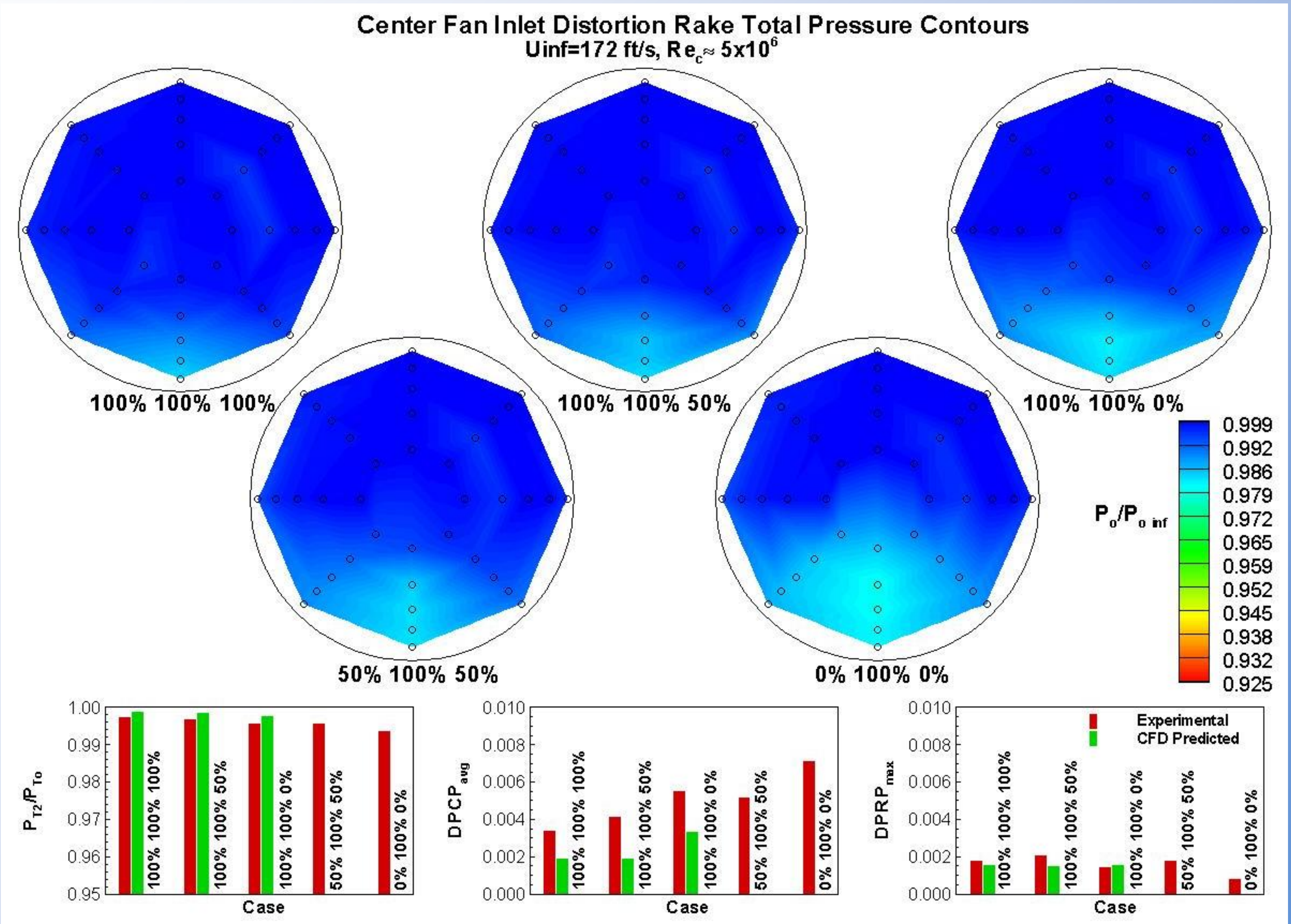

Summary and Lessons Learned

- Test Results Positive
  - Experimental Results Generally Compared Well to CFD Predictions
  - Thrust Level at Design Point ~ 8% Below Predicted
    - Lower Thrust a Result of Inadequate Battery Power
  - Significant Blockage Effect on Surface Pressures at $\dot{m}$ Below Design $\dot{m}$
  - Distortion Levels Low
    - Effect of Converging Duct and Low Mach Number
  - Moveable Inlet Lip Would Minimize Off Design Mass Flow Effects
- Differential Thrust Has Significant Effect On Adjacent Fan
  - Although Levels Still Low, Adjacent Fan Distortion Does Increase
  - Spillage From Decreased Mass Flow Affects Adjacent Fan Incoming Pressure Distribution, Reducing Effective Inlet Velocity $\Rightarrow$ Increases Thrust
  - Should Increase Inlet Lip Radius to Better Account for Changes in Effective Lip Angle-of-attack Due to Neighboring Fan Spillage

Next Steps

- Overall Phase II Investigation Goals
  - 2D Airfoil, Five Fan/Prop Configuration (~ 3D Effects)
    - Investigate Multiple Fan/Prop, Differential Thrust Effect on 2D Airfoil
    - Aero/Thrust Coupling Effect on Lift, Drag, and Moment (Overall and Sectional)
    - Multi-Fan Circulation Effect … Linear?
    - Neighboring Fan/Prop Spillage Effect on Thrust, Distortion and Unsteady (Overall and Sectional)
    - Moveable Inlet Lip To Adjust For Off Design Conditions?
- Approach
  - CFD Investigation: OVERFLOW Model and Inlet Design
    - Effects of Movable Inlet Lip
    - Spillage Tolerant Lip Design
    - Effect of Changing Angle-of-Attach, High Angle-of-Attack
  - Subscale Wind Tunnel Test: 5 Fan 2D Airfoil Model
    - Measure Overall and Sectional Lift, Drag, Moment, and BL Profiles Upstream of Inlets
    - Measure Individual Fan Thrust
    - Test Differential Thrust Effects: Steady and Unsteady Effects
    - Test Angle-of-Attack Effects, Including Approach to Stall and Stall
  - Phase II Option: Full Scale Transport to Subscale Test Bed CFD Based Scaling Study
- Phase III: Flying Test Bed Implementation