

Use of CFD in the Design of the 10- by 10-Foot Supersonic Wind Tunnel Characterization Array

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Outline

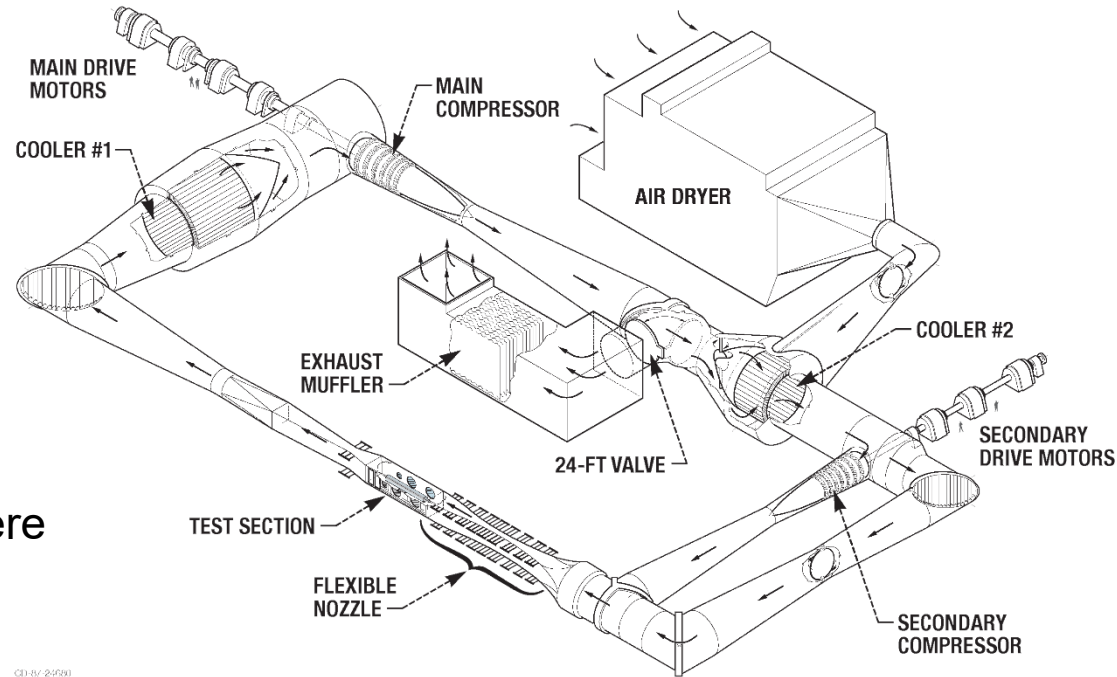
- Introduction
- Facility Overview
- Past Characterizations
- Characterization Array Overview
- CFD-Aided Design
 - Pitot-Static Probe Sizing & Spacing
 - Variable-Angle-Wedge Probe Design
 - Drag & Blockage Estimates
 - 5-Hole Cone Probe Calibration
- Future Work

Introduction

- Previous full characterization of the 10- by 10-Foot Supersonic Wind Tunnel (10x10 SWT) test section occurred in 1993 and 1995.
- Upcoming facility modifications presented opportunity to fully characterize test section again:
 - Data system, control system, pressure measurement system, etc.
- To capitalize on the opportunity, new characterization hardware recommended to improve uncertainty estimates, flow quality/uniformity understanding, etc.

Facility Overview

- Mach Number:
 - 2.0 – 2.6 (main compressor)
 - 2.5 – 3.5 (both compressors)
- Open-loop or closed-loop operation
- Total pressure:
 - 200 psf
 - Up to 2.5 standard atmosphere
- Total temperature:
 - Up to 300°F at Mach 3.5
 - Up to 680°F with tunnel air heater



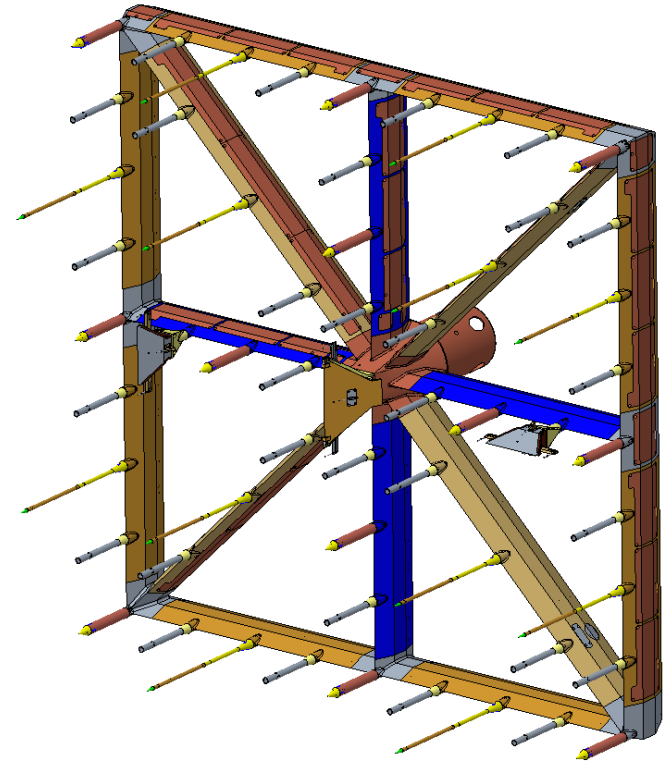
Past Characterizations

- Since the 1960's, 17-wedge array has been used to calibrate/characterize test section flow field.
- 4- by 4-ft array of 20° half-angle supersonic wedge probes and thermocouples.
- Probes refurbished prior to the 1991 test entry (right).
- 1993/1995 Full Characterization.
- Most recently used in 1999.



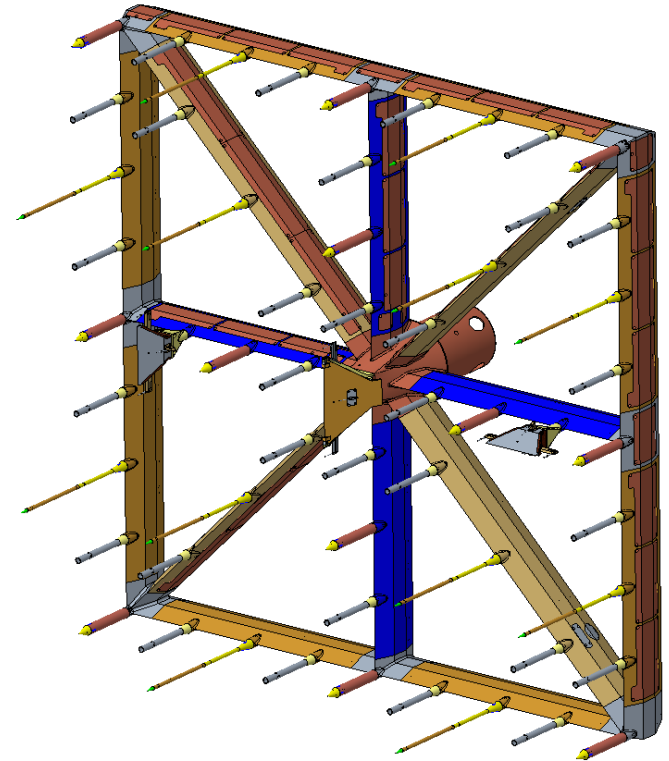
Characterization Array Overview

- Design Considerations/Objectives:
 - Survey full operating envelope
 - Max dynamic pressure: 735 psf
 - Max total temperature: 680 °F
 - Full Mach & Reynolds number range
 - Survey test section volume
 - Cross-sectional area (5- x 5-ft)
 - 96-inch Translation System
 - Interchangeability



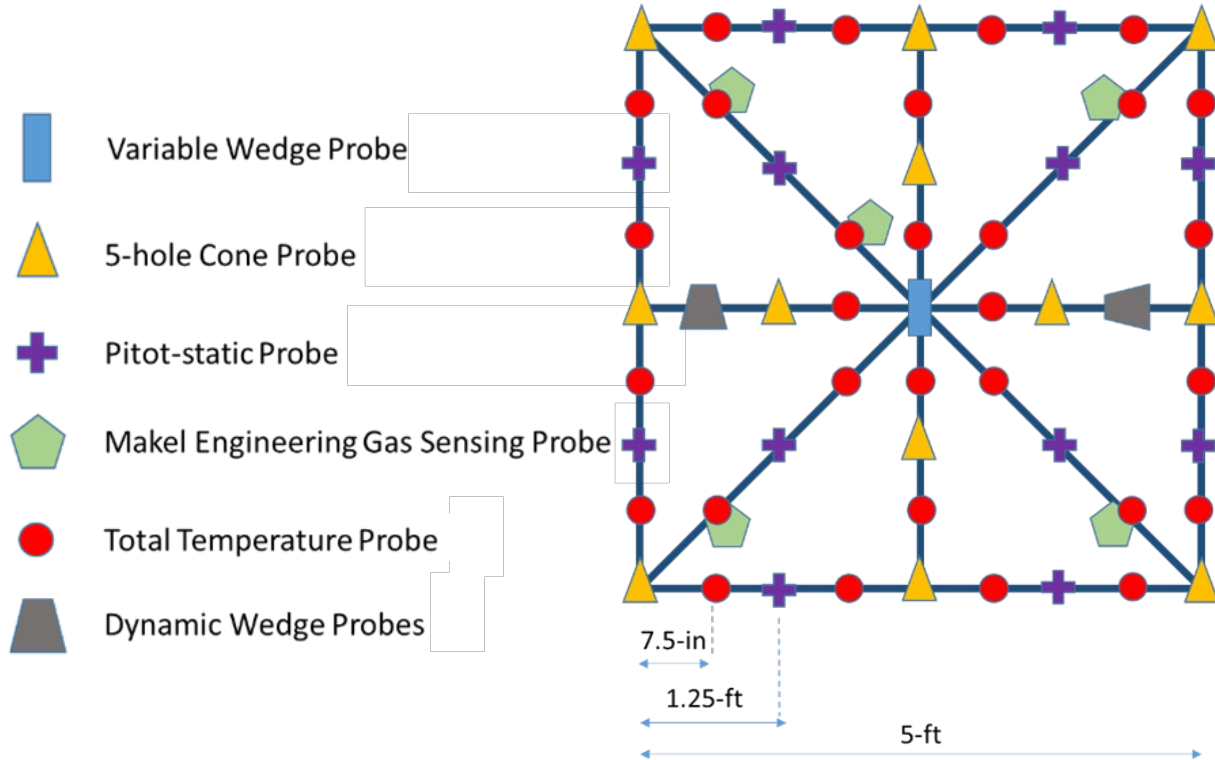
Characterization Array Overview

- Design Considerations/Objectives:
 - Reduce calibrated Mach number uncertainty estimate
 - Local Mach number estimates to avoid isentropic nozzle assumptions
 - Two-components of flow angularity simultaneously
 - Direct static pressure measurement
 - Optional gas sensing probe mounts (tunnel air heater operations only)



Characterization Array Overview

- Initial probe arrangement
- Flexibility for future surveys to account for unique customer requirements



CFD-Aided Design

- Traditional resources used for preliminary design work:
 - Best practices & lessons learned from NASA AETC-sponsored Wind Tunnel Characterization Working Group (WTCWG)
 - Recommended practices
 - NASA CR-2920
 - AGARDograph-22
 - AGARDograph-54
 - AEDC TR's
- Validation of design choices through CFD simulations



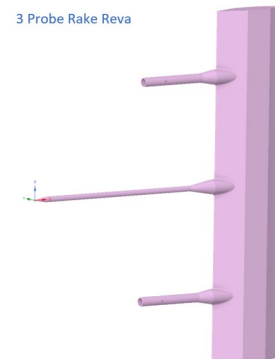
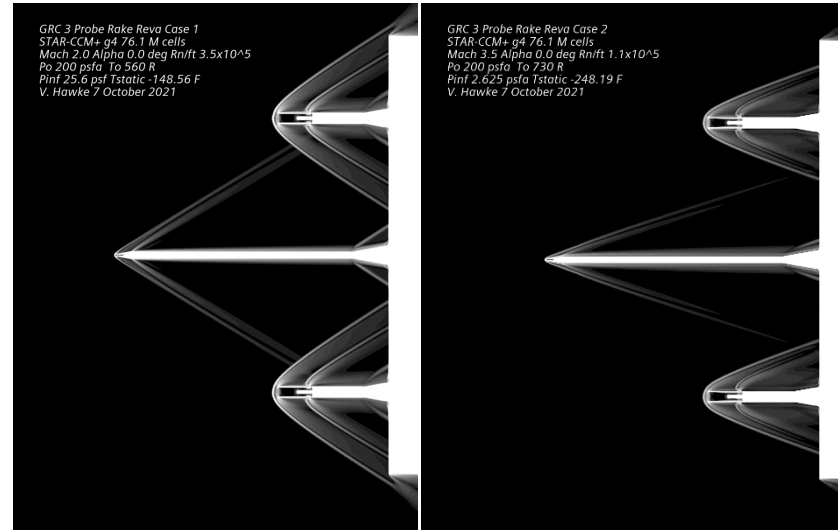
Pitot-Static Probe Sizing & Spacing

- Static pressure measurements can be biased from:
 - Poor flow recovery along probe body
 - Rake support back-pressuring
 - Probe-to-probe interference
- Simulations generated to:
 - Validate preliminary pitot-static probe design decisions
 - Verify probe spacing is adequate to avoid interference

CASE NUMBER	MACH NUMBER []	TOTAL PRESSURE [PSFA]	STATIC PRESSURE [PSFA]	REYNOLDS NUMBER [10 ⁶ /FT]	TOTAL TEMPERATURE [R]	TOTAL ITERATIONS
1	2.0	200.1	25.578	0.34	560.0	800
2	3.5	200.2	2.625	0.11	729.6	1477
3	2.0	2066.3	264.079	3.50	560.0	2948
4	3.5	4721.4	61.901	2.50	729.6	1515

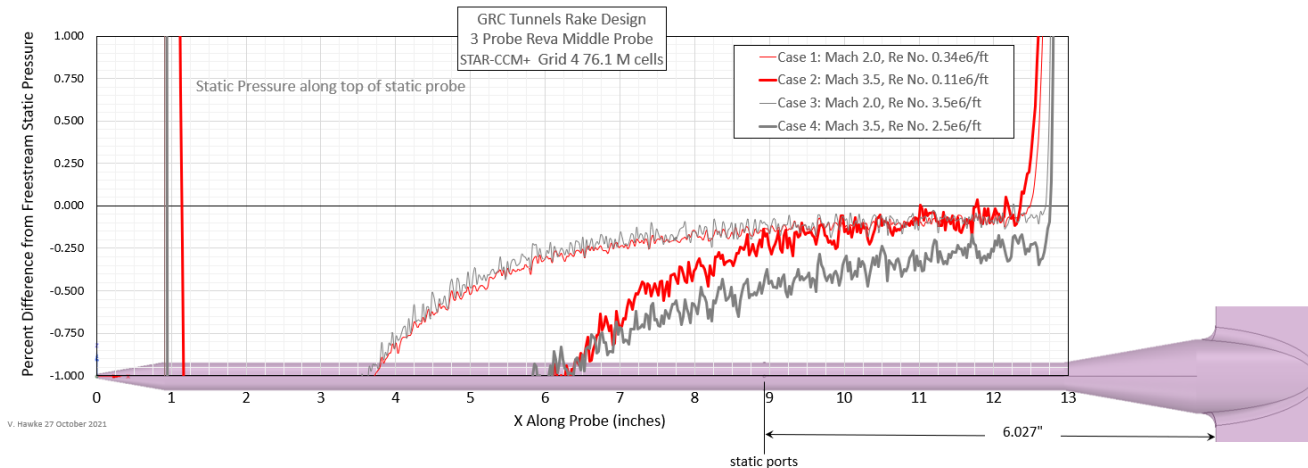
Pitot-Static Probe Sizing & Spacing

- Model included one pitot-static and two aspirated-tip total temperature probes
- Lack of probe-to-probe interference; oblique shocks:
 - Do not impact aspiration hole effectiveness
 - Do not create additional back-pressure on pitot-static probe



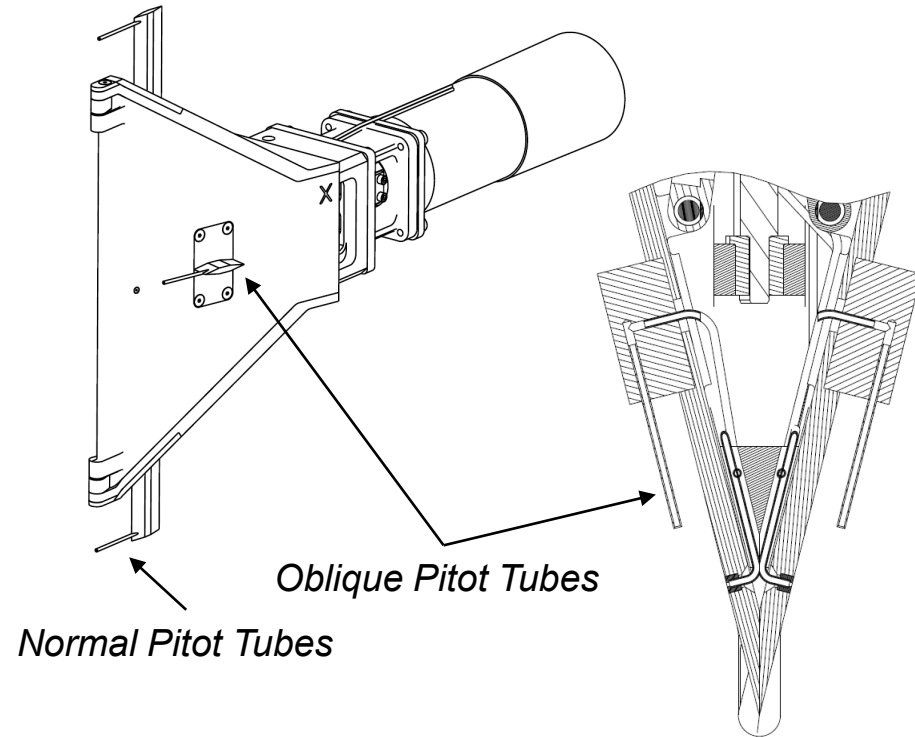
Pitot-Static Probe Sizing & Spacing

- Static pressure recovery acceptable at chosen 16 probe diameters aft of conical tip
- ~ 0.002 psia delta for high-Reynolds number cases



Variable-Angle-Wedge Probe Design

- Placement of the Variable-Angle-Wedge (VAW) probe oblique pitot tubes is critical to estimating Mach number.
- Locate pitot between boundary layer developing on wedge surface and oblique shock from wedge vertex.



Variable-Angle-Wedge Probe Design

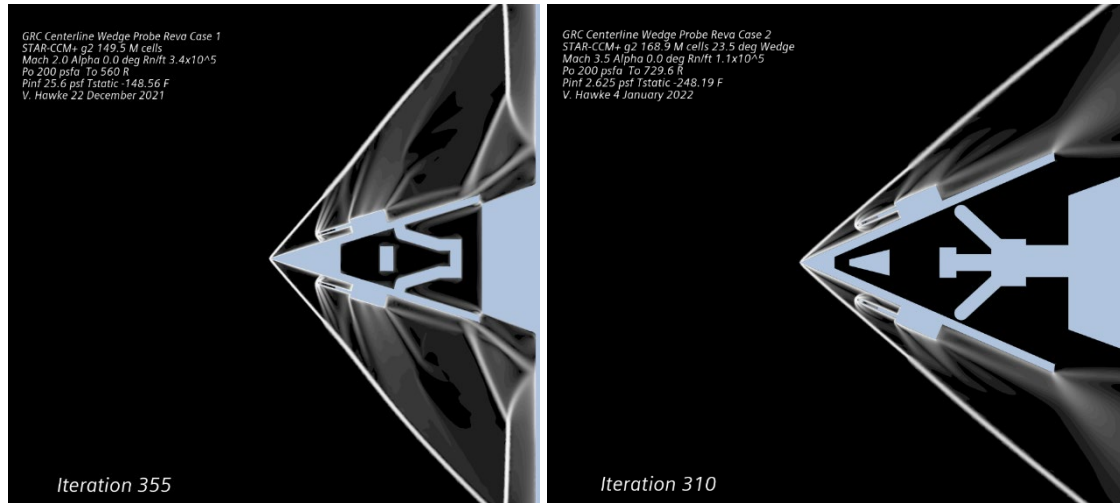
- Simulations conducted at several conditions:

CASE NUMBER	MACH NUMBER []	TOTAL PRESSURE [PSFA]	STATIC PRESSURE [PSFA]	REYNOLDS NUMBER [10 ⁶ /FT]	TOTAL TEMPERATURE [R]	TOTAL ITERATIONS
1	2.0	200.1	25.578	0.34	560.0	435
2	3.5	200.2	2.625	0.11	729.6	310
3	2.0	2066.3	264.079	3.50	560.0	1000
4	3.5	4721.4	61.901	2.50	729.6	1452

- Wedge half-angle set to 16.5° and 23.5° for Mach 2.0 and 3.5 simulations, respectively.

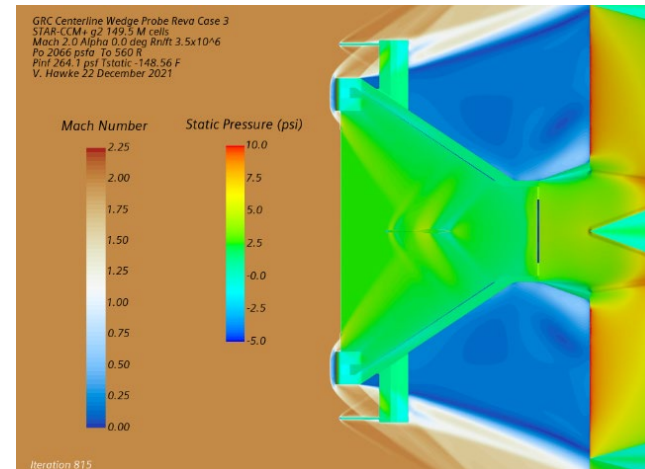
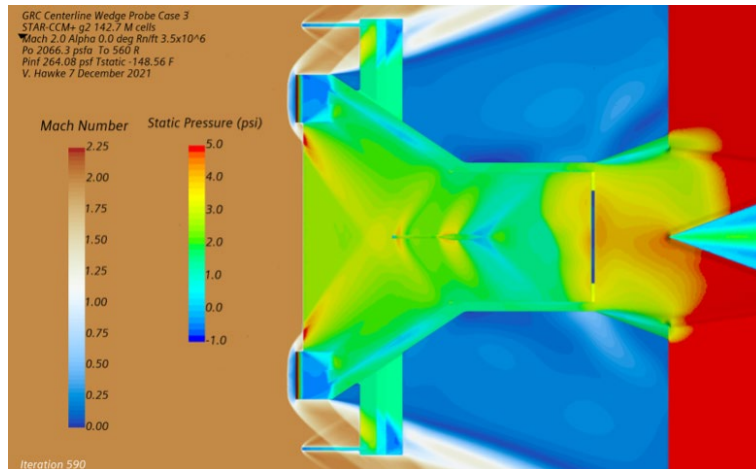
Variable-Angle-Wedge Probe Design

- Shock patterns and sampled data indicate oblique pitot tubes are not influenced by wedge surface boundary layer growth or vertex-generated oblique shock



Variable-Angle-Wedge Probe Design

- Influence of hinge-generated disturbance observed (left)
- Design modified to resolve issue (right):
 - Wedge vertex lengthened; oblique pitot tube moved upstream



Drag & Blockage Estimates

- Preliminary design review comments on model blockage & drag generated concern
- Consulted reference provided by WTCWG member:
 - *Correlation of Wind Tunnel Blockage Data, ASD-TDR-63-230*
- Required estimate of C_D to estimate allowable blockage to 'start' the 10x10 SWT at Mach 2.0.

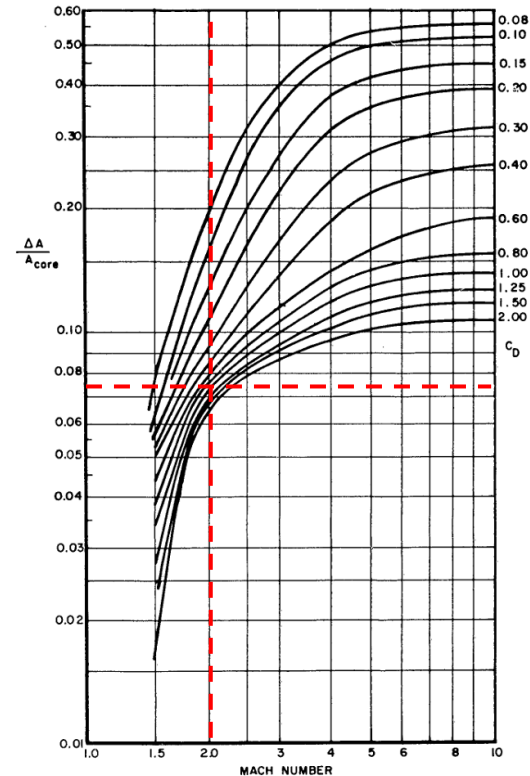
Drag & Blockage Estimates

- Simulation conducted at:
 - Mach 2.0
 - $P_T = 200$ psfa
 - $q = 71.68$ psf
- Drag estimate: 375 lbf
- Cross-sectional area: 805.13 in²
- C_D : 0.936



Drag & Blockage Estimates

- Using historical boundary layer information to estimate A_{core}
- $\Delta A/A_{\text{core}} = 7.44\%$
- Conclusion: Possible at Mach 2.0
- 10x10 SWT has historically 'started' the tunnel at higher Mach numbers (Mach 2.0 – 2.5) for large blockage models



ASD-TDR-63-230

5-Hole Cone Probe Calibration

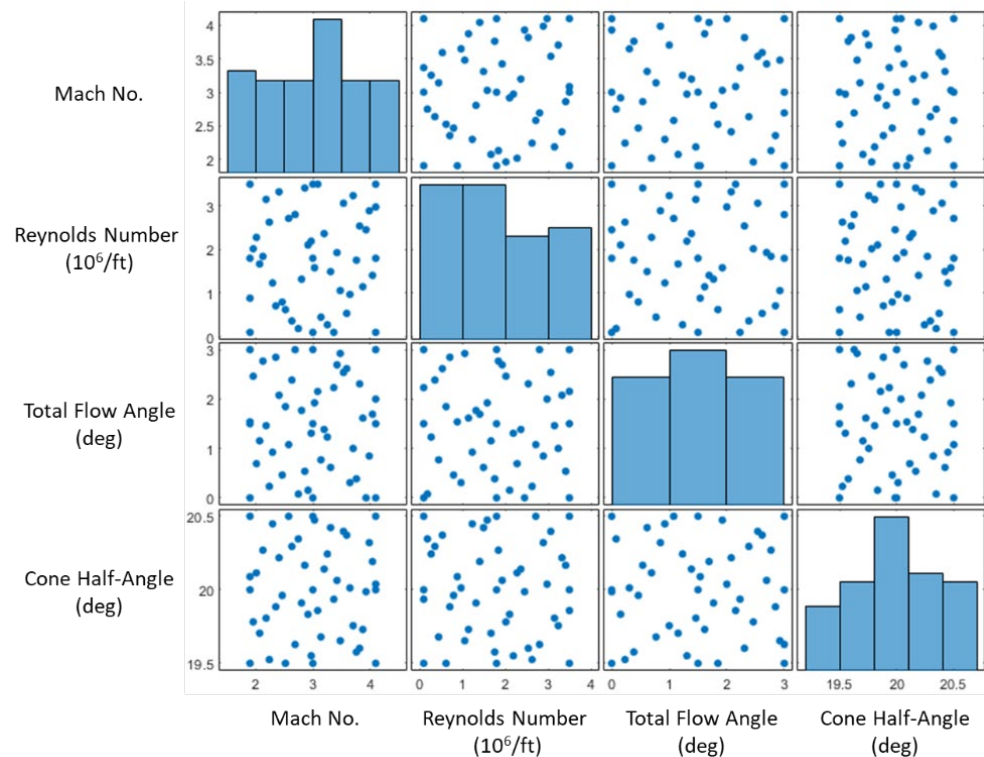
- 5-hole Cone Probes will measure/estimate Mach number and two components of flow angularity
- To achieve optimal condition estimate accuracies, probe calibrations required over expected operating range:
 - In-situ probe calibrations \$\$\$
 - Small-scale facility calibrations \$\$
 - “CFD-calibration” \$
 - CFD validation test entry strongly recommended

5-Hole Cone Probe Calibration

- CFD-calibration DOE test matrix developed
 - 21 CCD cases
 - 40 space-filling cases
 - 9 validation cases
- Design variables & ranges:
 - Mach number 1.9 – 4.1
 - Reynolds number $0.1 - 3.5 \times 10^6$ per ft
 - Probe AoA/flow angle 0 – 3.0 degrees
 - Cone half-angle 19.5 – 20.5 degrees

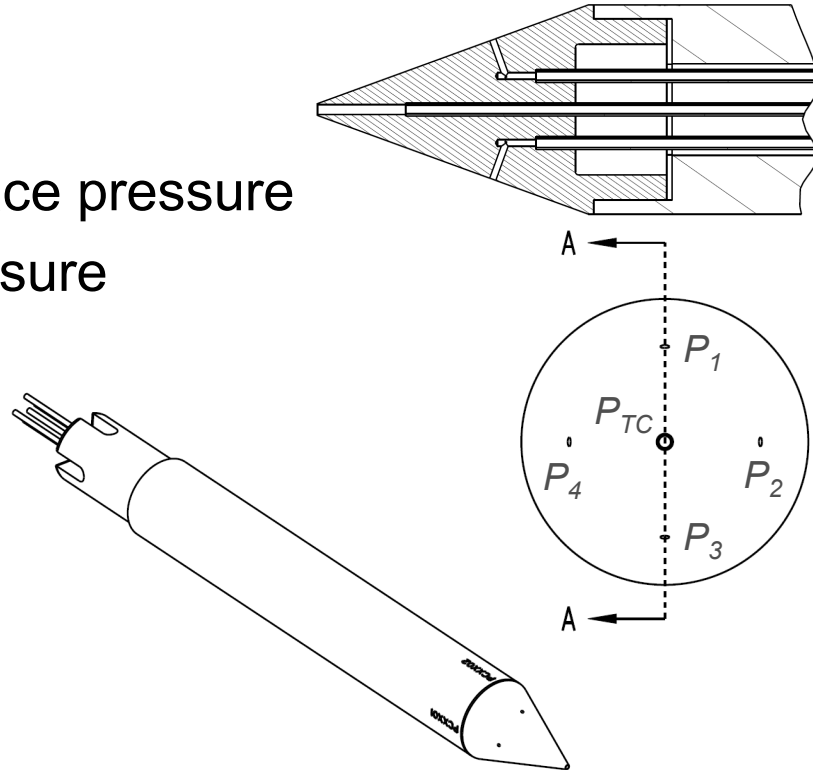
5-Hole Cone Probe Calibration

- Design space
 - Does not include validation cases
- Cone surface pressures sampled at 3-degree increments around half of the cone produces 60 “cases” within each



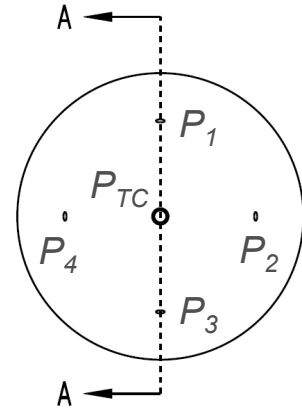
5-Hole Cone Probe Calibration

- Mach Number Calibration
 - $P_C = \text{avg}(P_1, P_2, P_3, P_4) =$ cone surface pressure
 - $P_{TC} =$ post-normal-shock pitot pressure
 - $\theta_C =$ cone half-angle
 - $M =$ freestream Mach number
 - $Re =$ Reynolds number per foot
- $1/M^2 = f(P_C/P_{TC}, Re, \theta_C)$



5-Hole Cone Probe Calibration

- Total Flow Angle & Roll Angle Calibration
 - $RDP_{13} = (P_1 - P_3)/P_{TC}$
 - $RDP_{24} = (P_2 - P_4)/P_{TC}$
 - $RDP = (RDP_{13}^2 + RDP_{24}^2)^{0.5}$
 - $\Phi = \tan^{-1}(-RDP_{24}/RDP_{13} + (\pi/2)*(|RDP_{13}|/RDP_{13} + 1))$
- Total flow angle = $f(RDP, P_C/P_{TC}, Re, \theta_C)$
- Roll angle = $f(\Phi, \theta_C)$



Future Work

- Develop regression models for Mach number, total flow angle, and roll angle for 5-hole cone probes
- Request resources for 5-hole cone probe validation test entry in small-scale supersonic facility
- Document & present on lessons learned through CFD analyses of various aspects of the 10x10 Characterization Array and its various probe types
- Pursue uncertainty estimates related to CFD-calibration



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