Mechanisms of Hypersonic Boundary Layer Transition on Two Generic Vehicle Geometries

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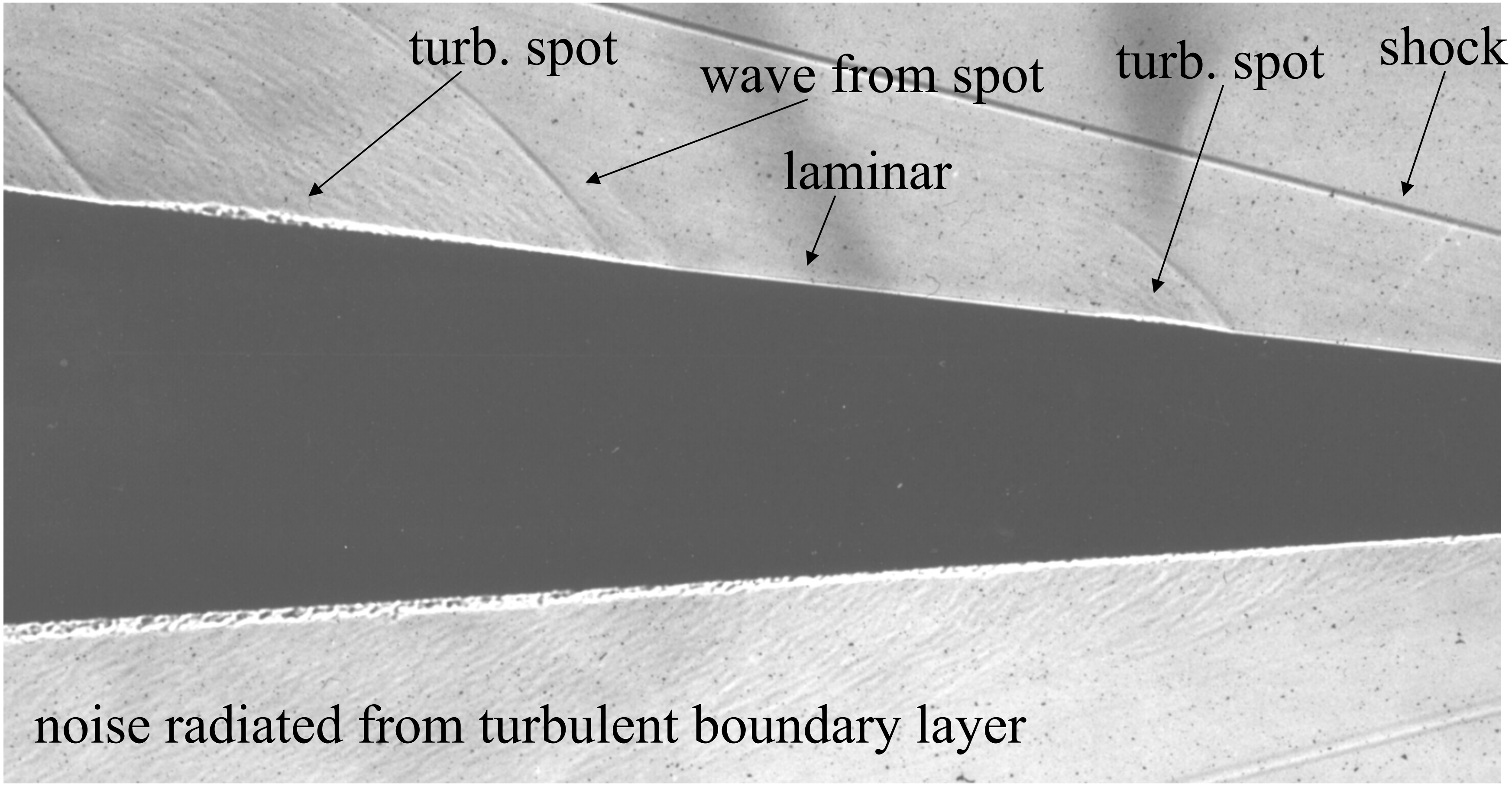
AFOSR Contractors Meeting
12 September 2003
San Destin, Florida

Acknowledgements

- Boeing/AFOSR/BMDO/Purdue/Sandia/Langley development of Mach-6 Quiet Ludwieg Tube, based on previous LaRC work. $1m, 1995-2001.
- Cooperative funding by Sandia and Northrop-Grumman (ballistic RV's/blunt cones, flight data review), NASA Langley (scramjet forebodies)
- Graduate students Craig Skoch (AFOSR), Erick Swanson (NG/AFOSR), Shann Rufer (Sandia), Shin Matsumura (Langley)
- advice from Jim Kendall, Scott Berry, etc.

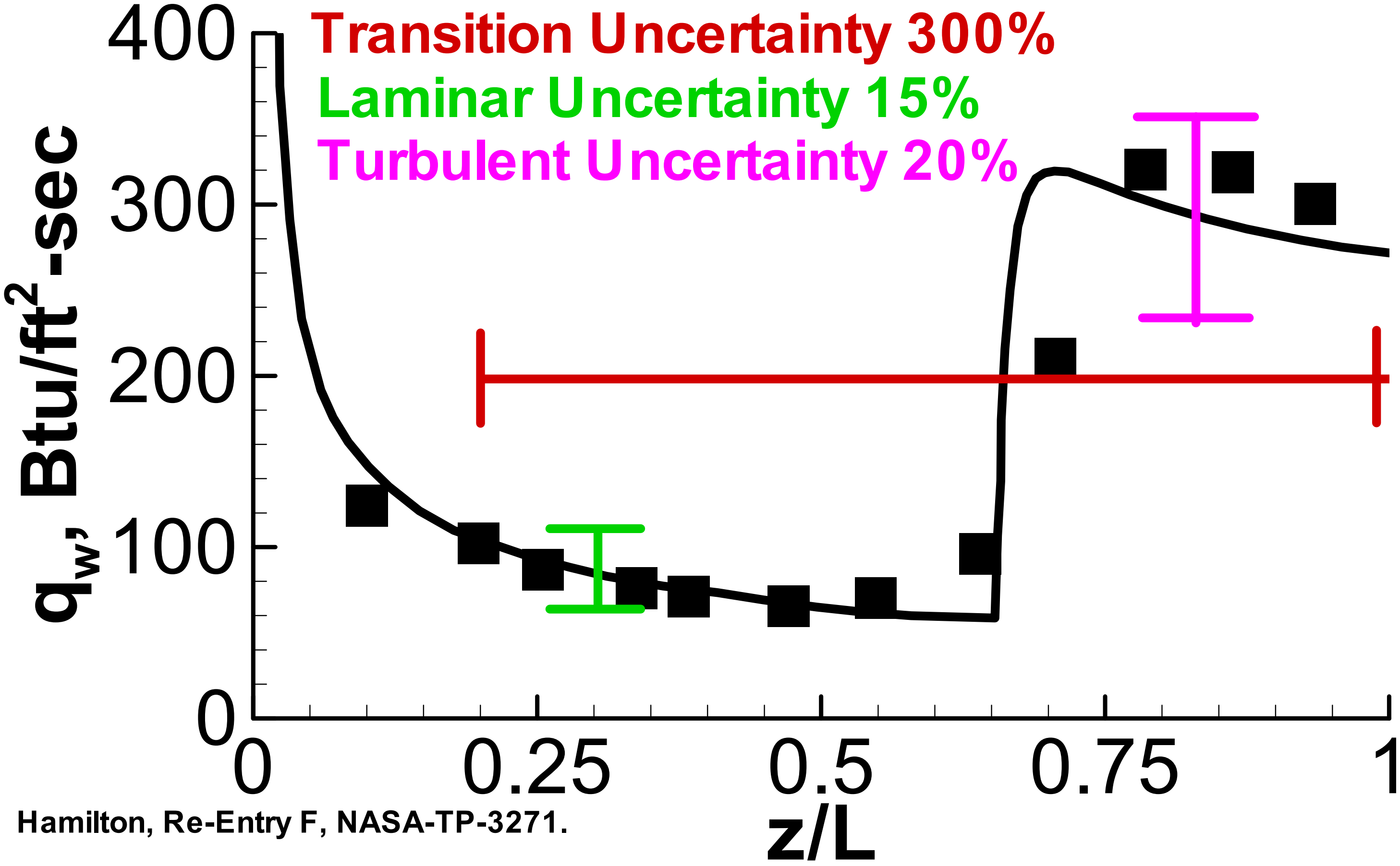
Shadowgraph of Transition on Sharp Cone at Mach 4



5-deg. half-angle cone in NOL Ballistics Range at Mach 4.31. Shot 6728, Dan Reda, AIAA Journal v. 17, number 8, pp. 803-810, 1979. Re_∞=2.66E6/inch, cone length is 9.144 inches. From Ken Stetson. Cropped

Aeroheating Rises By a Factor of 3-8 at Transition

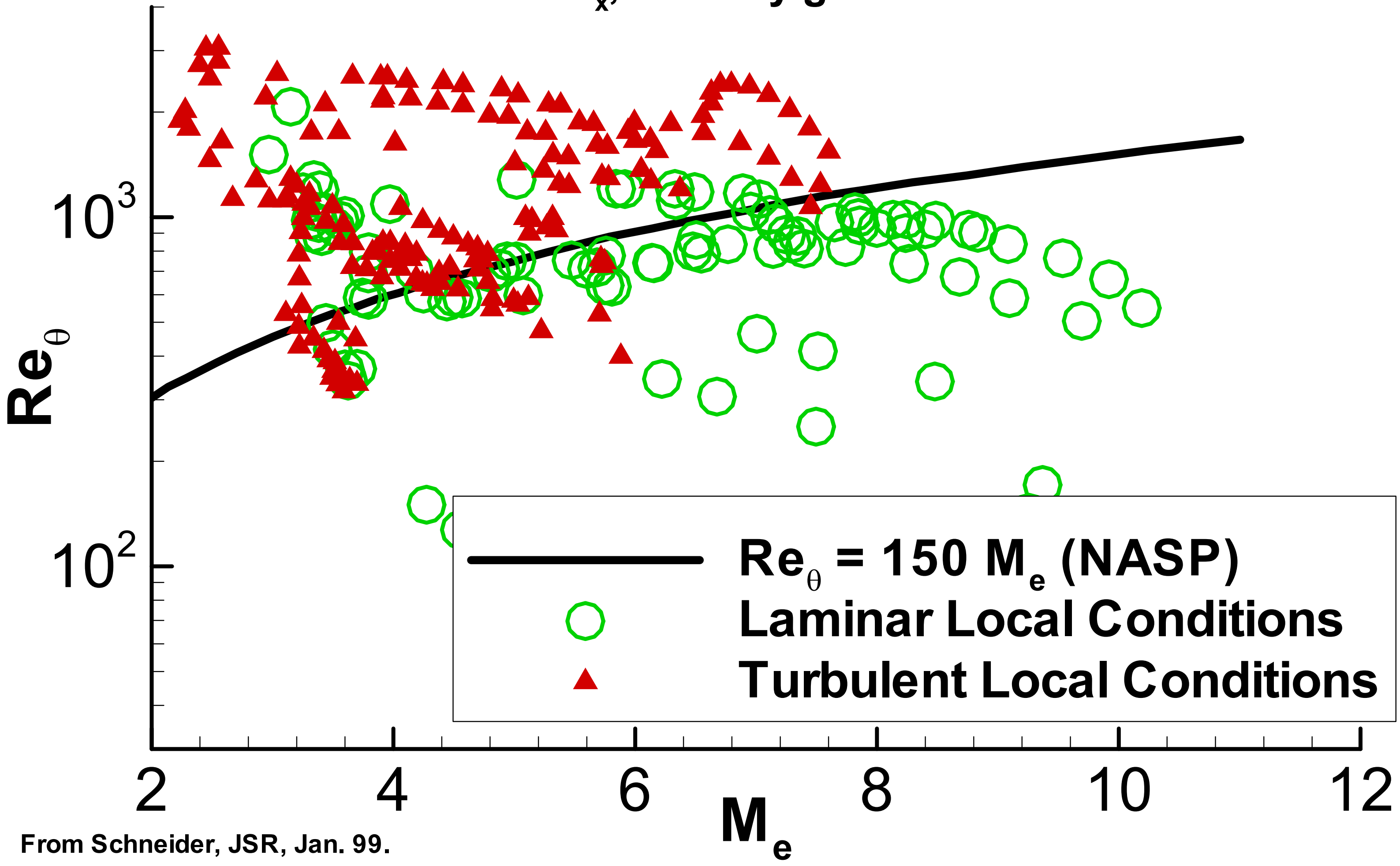
13-foot Beryllium Cone at Mach 20 in Reentry
CFD predicts heating well --ONLY IF--
transition location picked to match flight



Hamilton, Re-Entry F, NASA-TP-3271.

Existing Correlations Have a Large Uncertainty

Kuntz, Sandia SWERVE maneuvering flight vehicle
Empirical Correlations Typically Scatter by a Factor 3 in Re_θ, or a factor 10 in Re_x, for fairly general datasets



From Schneider, JSR, Jan. 99.

Conventional Noise Corrupts Transition Expts: Quiet Tunnels Needed

1. Conventional fluctuation level typically 1%
2. Major Source: Acoustic radiation from the nozzle walls
3. Causes early transition
4. Can change trends in transition
5. Transition in Conventional Facilities is NOT a reliable predictor for flight!
6. Quiet tunnels require laminar nozzle-wall boundary layers
7. Quiet tunnel development is an expensive and risky exercise in laminar flow control
8. Langley developed quiet tunnels in 1970-1990, but only Mach 3.5 is operational
9. Purdue effort leads hypersonic q.t. dev. Langley may restart

Need Measurements of the Mechanisms of Transition

- Transition data by itself is ambiguous. What caused the transition? Roughness? Crossflow? 1st mode? All 3? Tunnel noise? stray roughness? AOA errors?
- Need detailed measurements of the transition mechanisms (rare field measurements of small fluctuations, preferably with controlled disturbances).
- Detailed measurements and computations of the mechanisms can provide physical understanding.
- Can improve scaling from wind-tunnel to flight conditions
- Such measurements are difficult; development of the capability requires a sustained effort. Purdue presently has the only lab making hypersonic hot-wire measurements

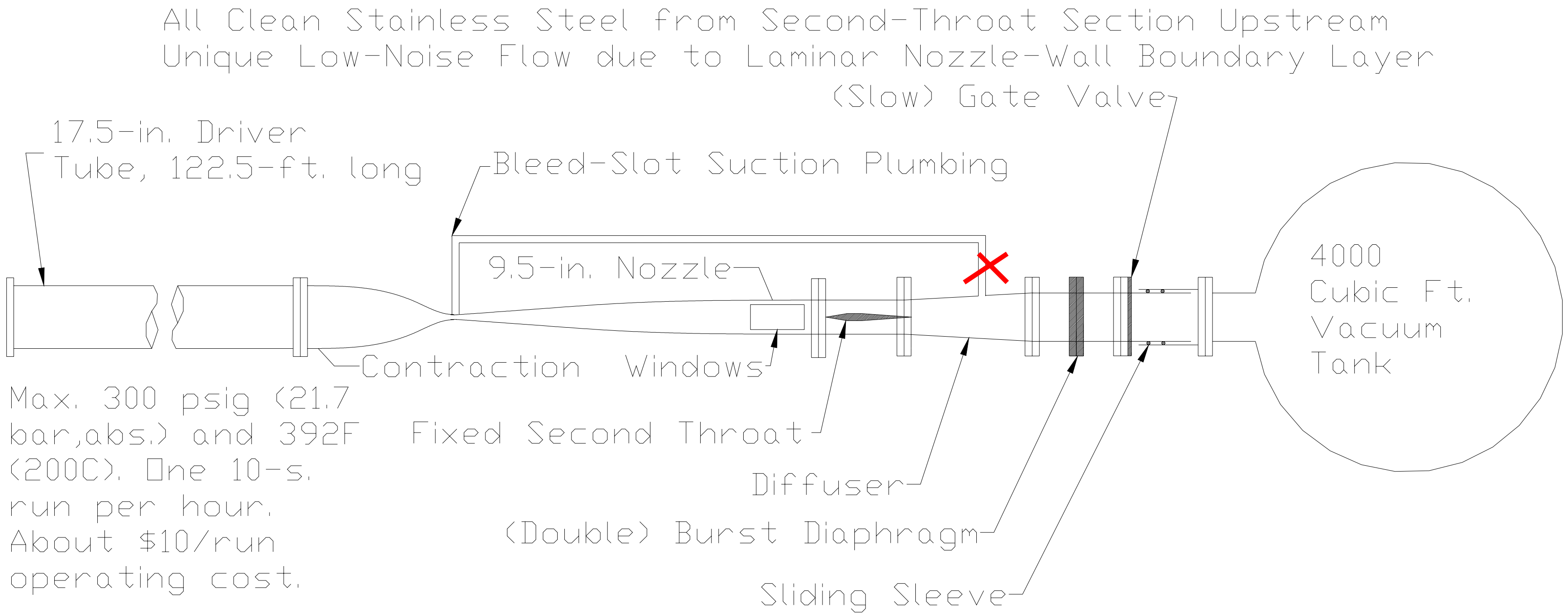
Reliable Predictions Must Be Based on Mechanisms

- Instabilities that lead to transition can be computed (now or soon) (1st & 2nd mode, crossflow, Gortler, algebraic, etc.)
- Seek semi-empirical mechanism-based methods similar to e**N, where N=ln(A/A0) is the integrated growth of the most-amplified instability, incorporates mean-flow effects on wave growth
- Computations must be developed and validated based on detailed measurements in ground facilities
- Computations must be compared to flight data
- Dominant Mechanisms on RLV's, airbreather forebodies, and RV's remain to be determined; little or no data at present
- Bridge gap between users and researchers

Three Primary AFOSR-Funded Tasks

1. **Obtain quiet flow at high Reynolds number in the Mach-6 Ludwieg tube.** Craig Skoch and now also Matt Borg. Joint with NASA Langley and Sandia.
2. **Measure mechanisms of transition on a generic RV: a blunt cone including angle of attack.** Shann Rufer and Erick Swanson. Joint with Sandia and Northrop-Grumman.
3. **Measure mechanisms of transition on a generic scramjet forebody.** Shin Matsumura, M.S., but work now suspended. AIAA 2003-3592, 2003-4583. Joint with NASA Langley.

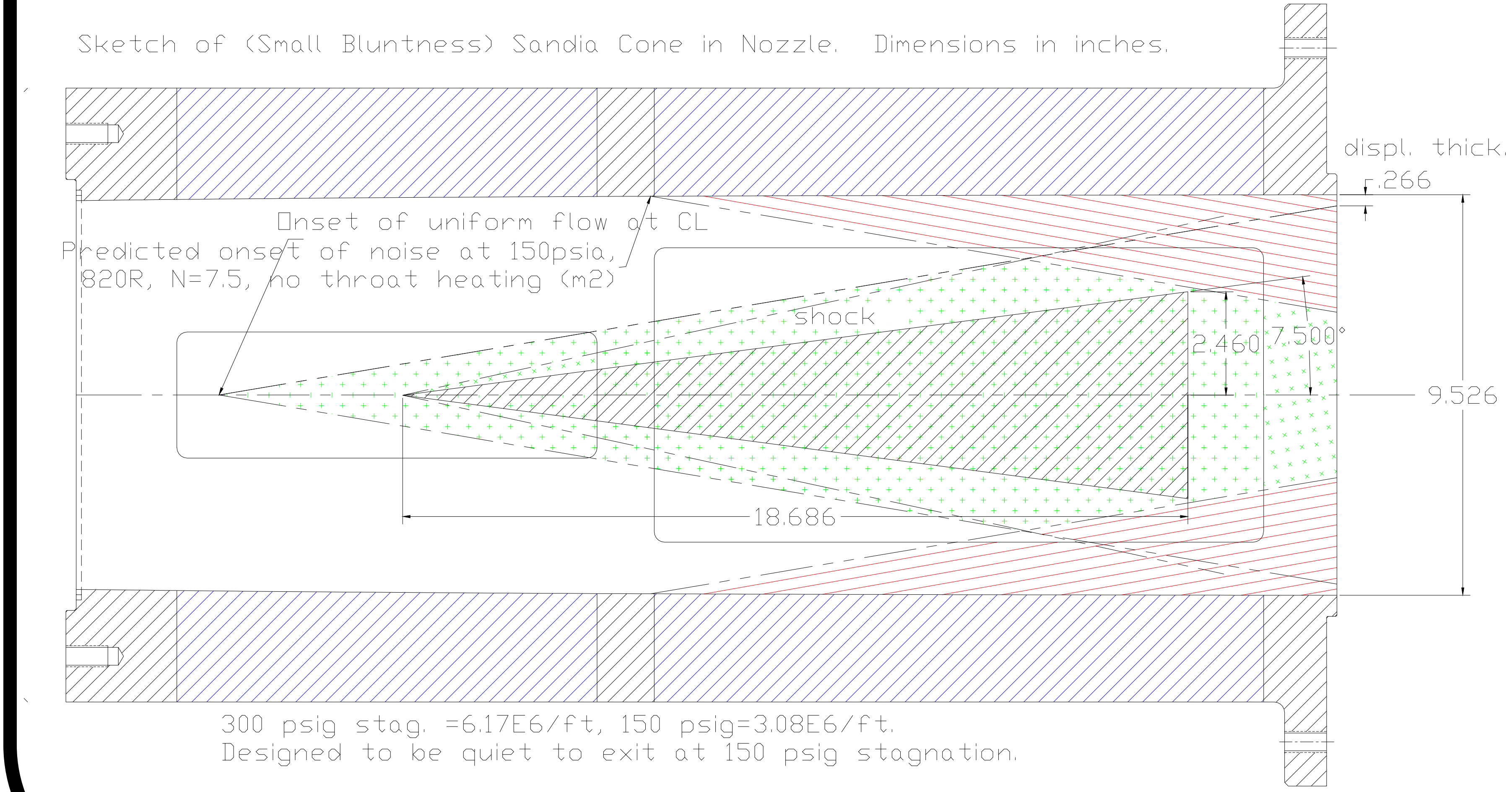
Boeing/AFOSR Mach-6 Quiet Tunnel



So Far, Quiet Only at Low Reynolds Number

Pressure Drops 30-40% During 10-sec. Run

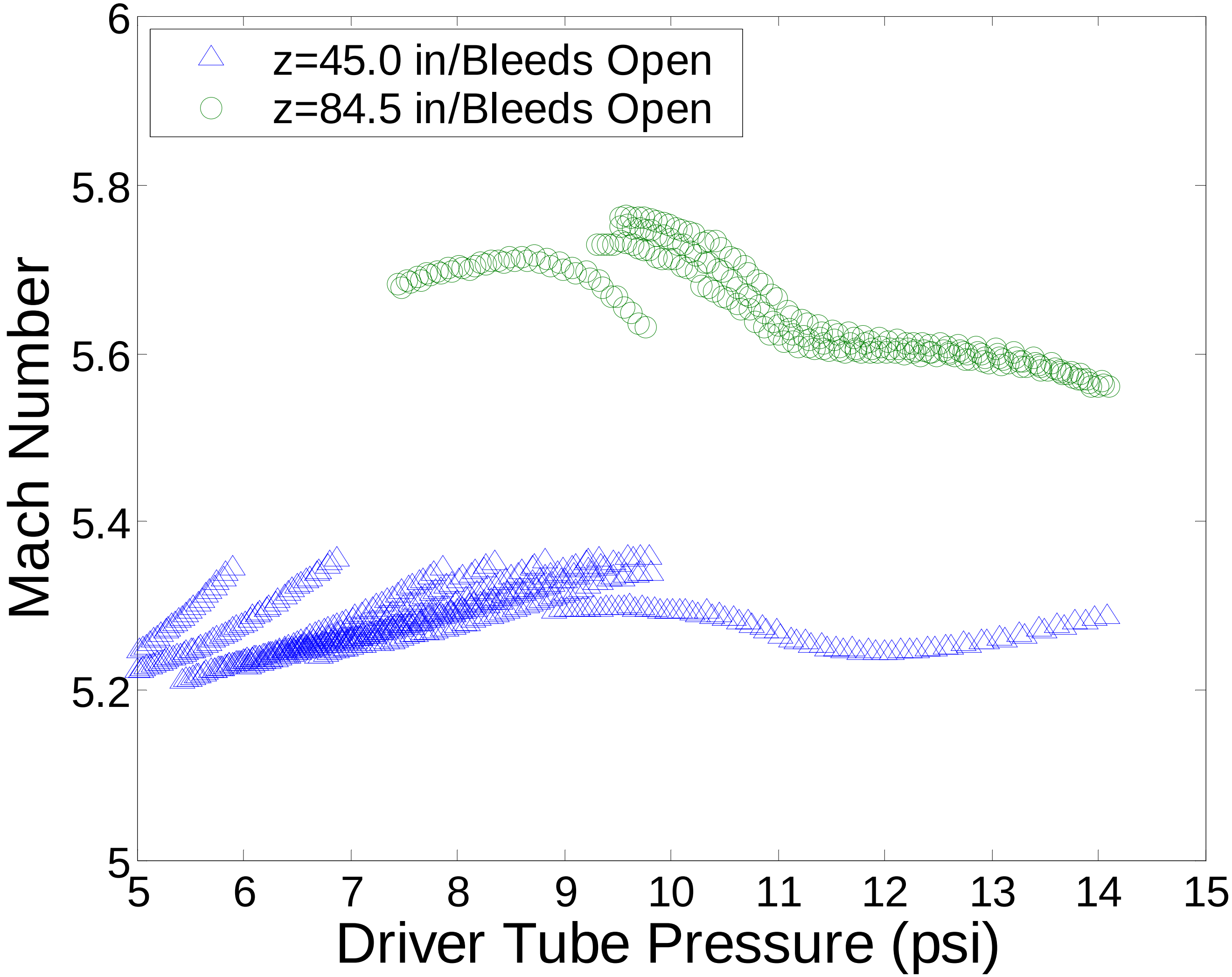
Schematic of Mach-6 Quiet Nozzle



Tunnel Quiet Only at Low Reynolds No. – Why?

1. Nozzle length twice Langley Mach-6 quiet nozzle (was quiet to 145 psia). We drop quiet at 8 psia in downstream half of nozzle. Bypass!?
2. Fluctuations generated at bleed-slot lip? (Tried Case 7)
3. 0.001-0.002-in. step at aft end of electroform? Lack of polish on downstream sections? (Polished downstream)
4. Leaks which we have not found yet?
5. Upstream effect of diffuser fluctuations? (current focus) LaRC quiet tunnels all open jet
6. Vibrations of tunnel & bleed lip?? M4 had no lip. But these damp with time, no time dependence observed
7. Residual noise in driver? Plan hot-wire measurements
8. Something else?

Pitot Measurements on Nozzle Center, Near Exit and 40 Inches Upstream. Mach Varies Slowly



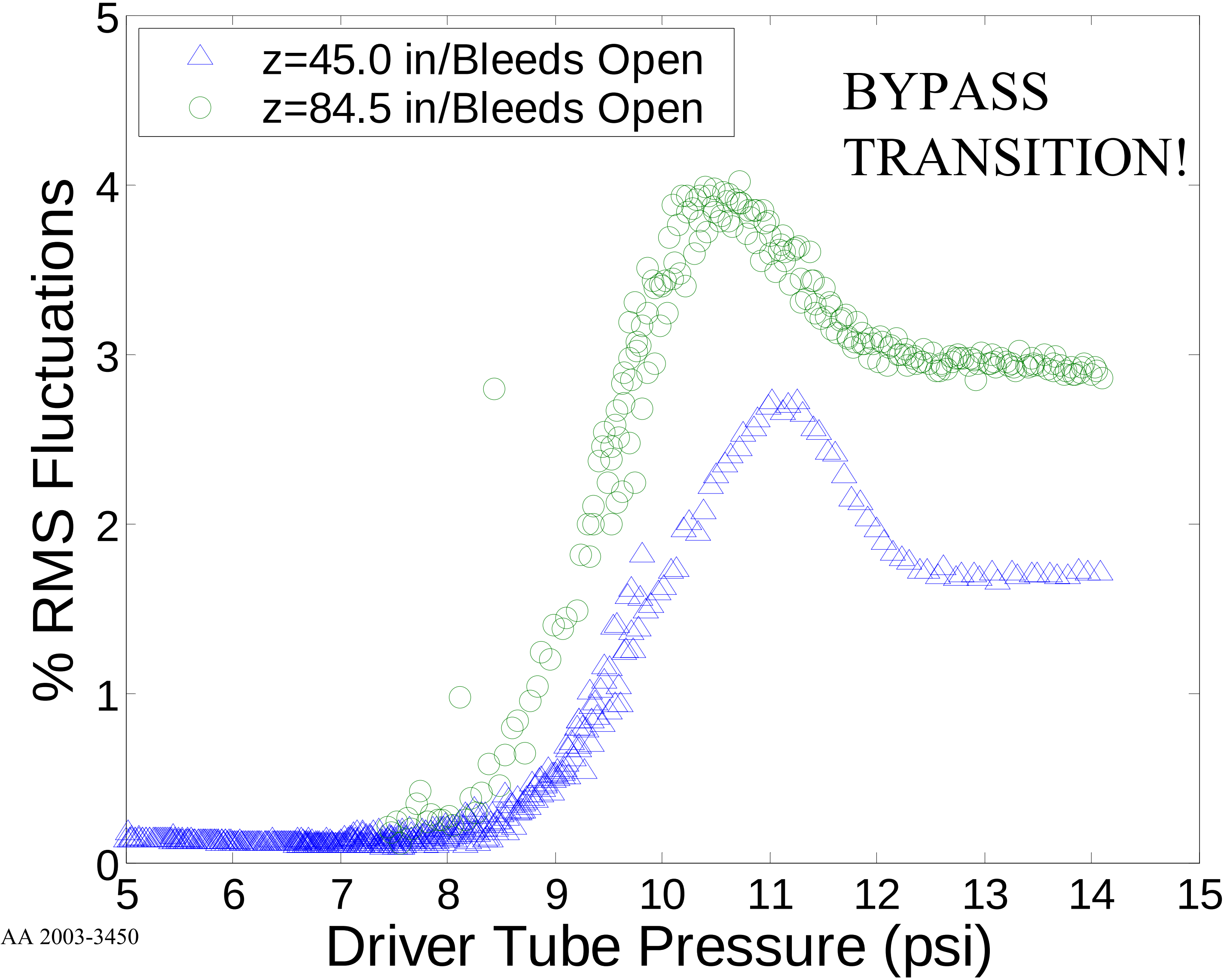
nozzle end at z=102 in.

throat at z=0

Empty tunnel

AIAA 2003-3450

Pitot Fluctuations Drop at Nearly Same Pressure Near the Nozzle Exit and Halfway Up the Nozzle



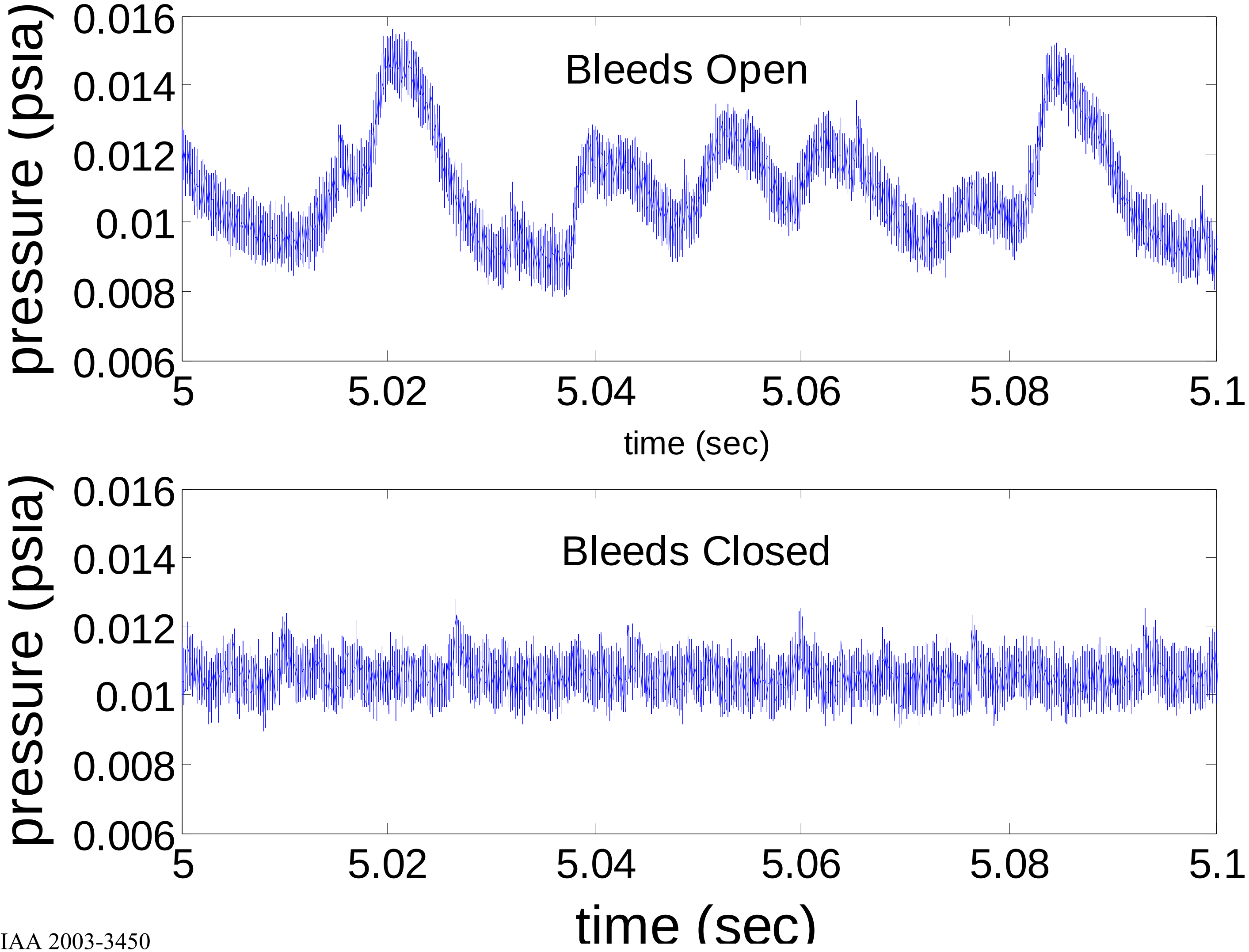
noz. end at z=102 in. throat at z=0. empty tunnel

T0=160C

centerline

AIAA 2003-3450

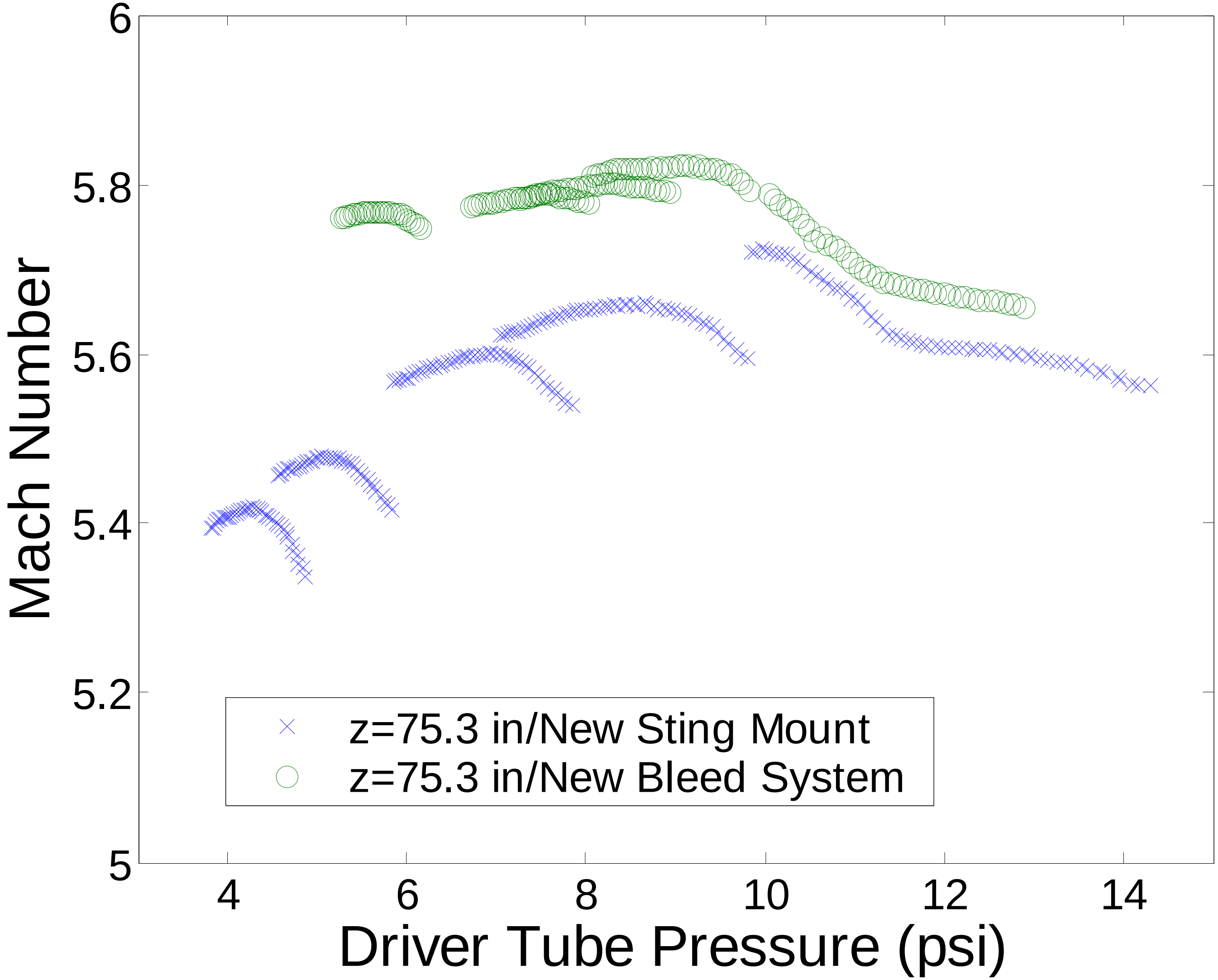
Diffuser-Entrance Static Pressure Fluctuations are 50% when Bleeds are Open: Due to Bleed-Air Jets in Diffuser? Fed Upstream? Trip BL?



z=104.85
inches

AIAA 2003-3450

Bleeds Plumbed Direct to Vacuum Tank: Mean Mach number higher!



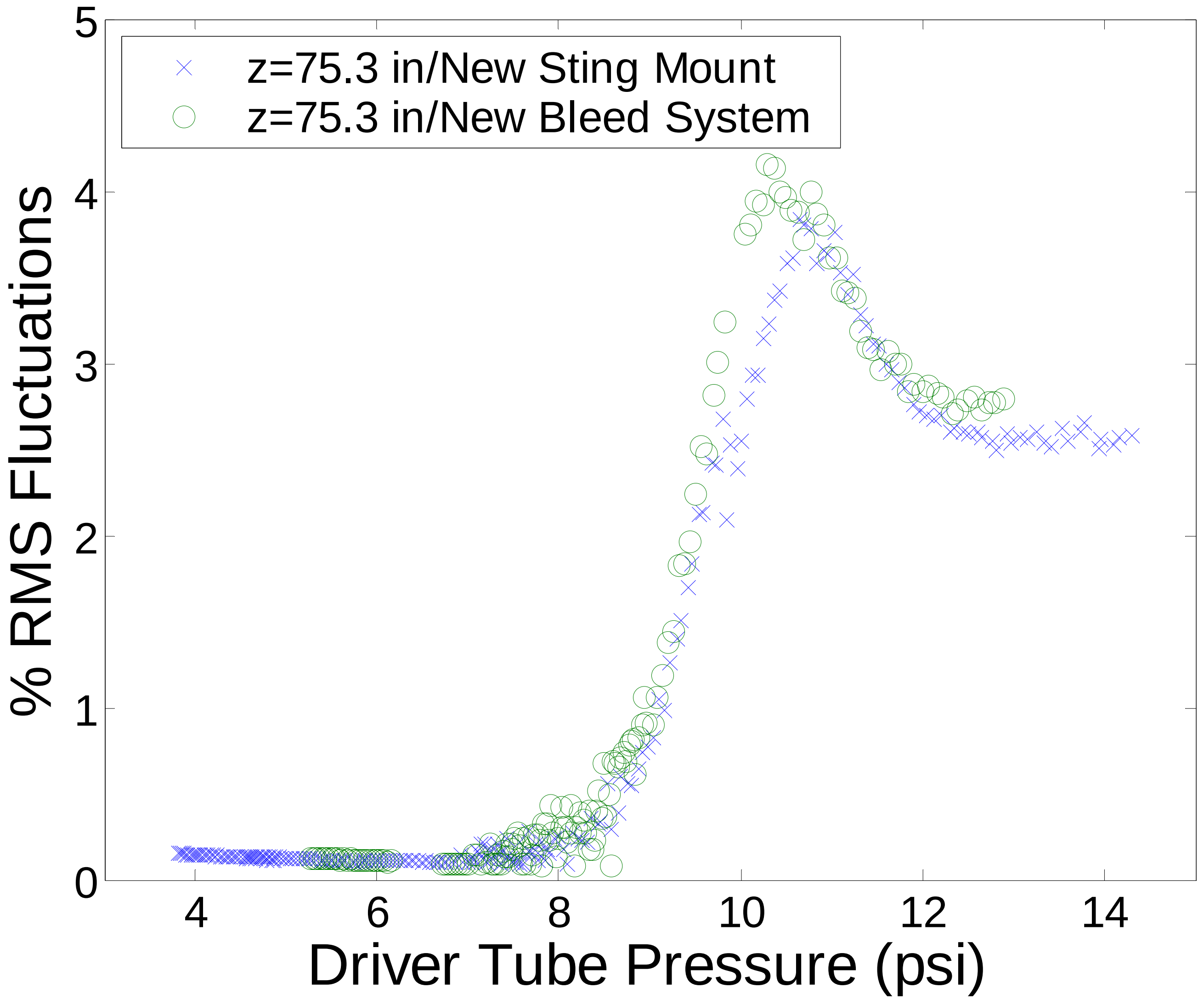
T0=160C

Probe on CL

Reduced B.L. thickness?

First results

Bleeds Plumbed Direct to Vacuum Tank: Noise Unchanged!

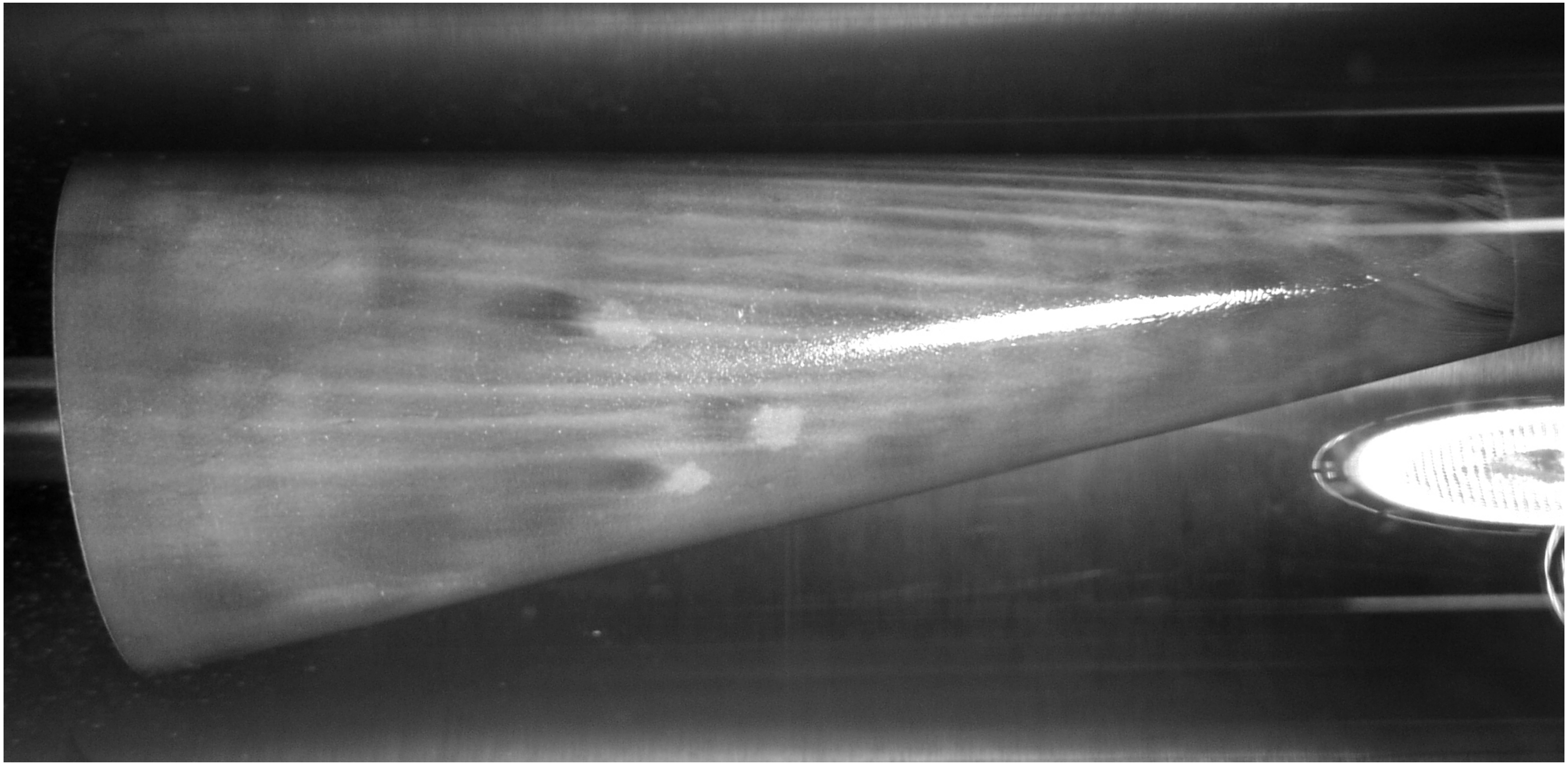


T0=160C

Probe on CL

New results, preliminary

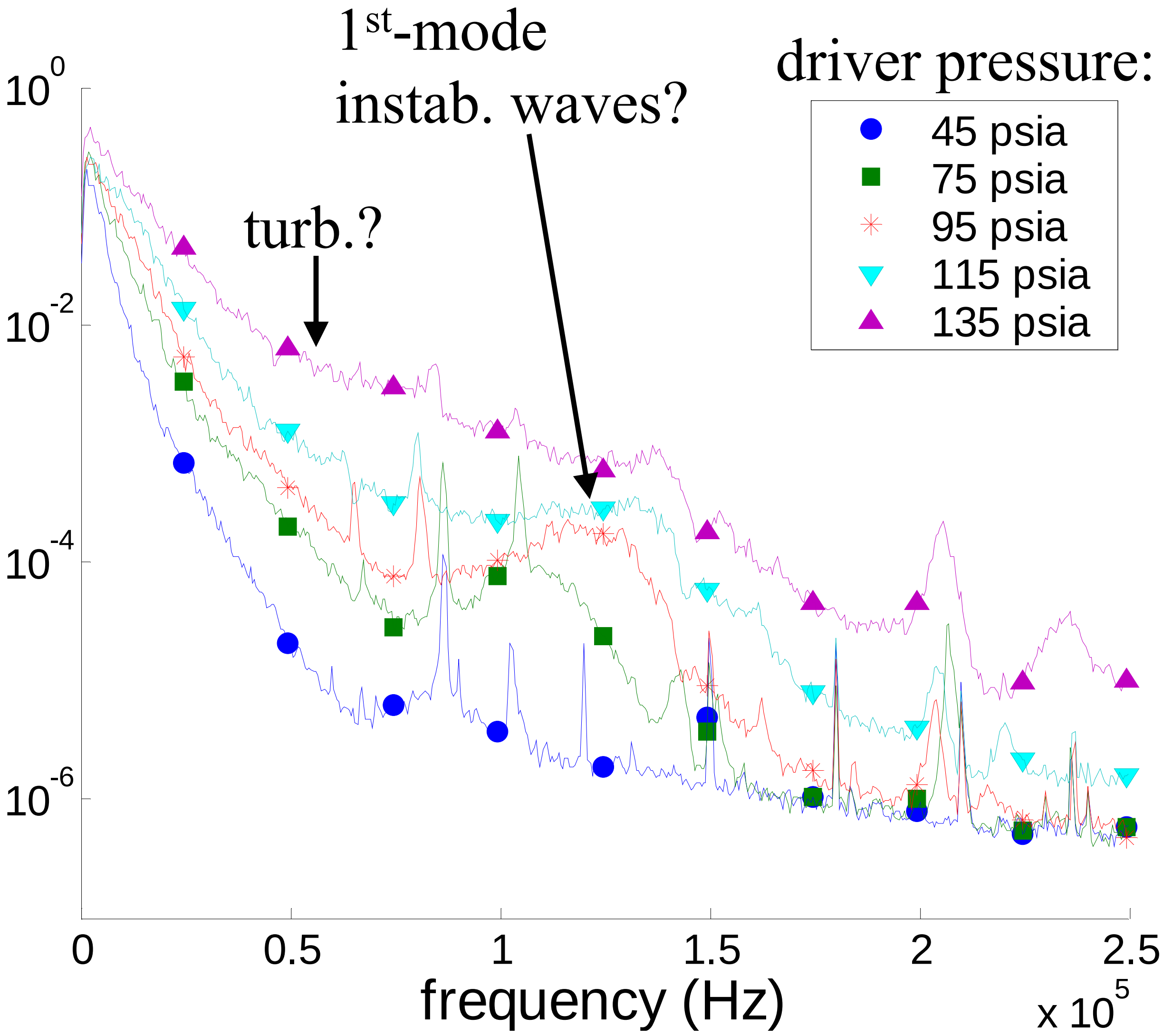
Crossflow Vortices on a Cone at Angle of Attack at Mach 6



Re = 3 x 10^6/ft, 7-deg. half-angle sharp cone, 6-deg. AOA, T_D=160C, AIAA 2003-3450

Oil applied in smooth layer by brushing crosswise. Streaks develop ala china clay

Hot-Wire Spectra on Sharp Cone Showing Waves



1^{st}-mode instab. waves?

turb.?

x=11.7 in.

7-deg. half-angle cone

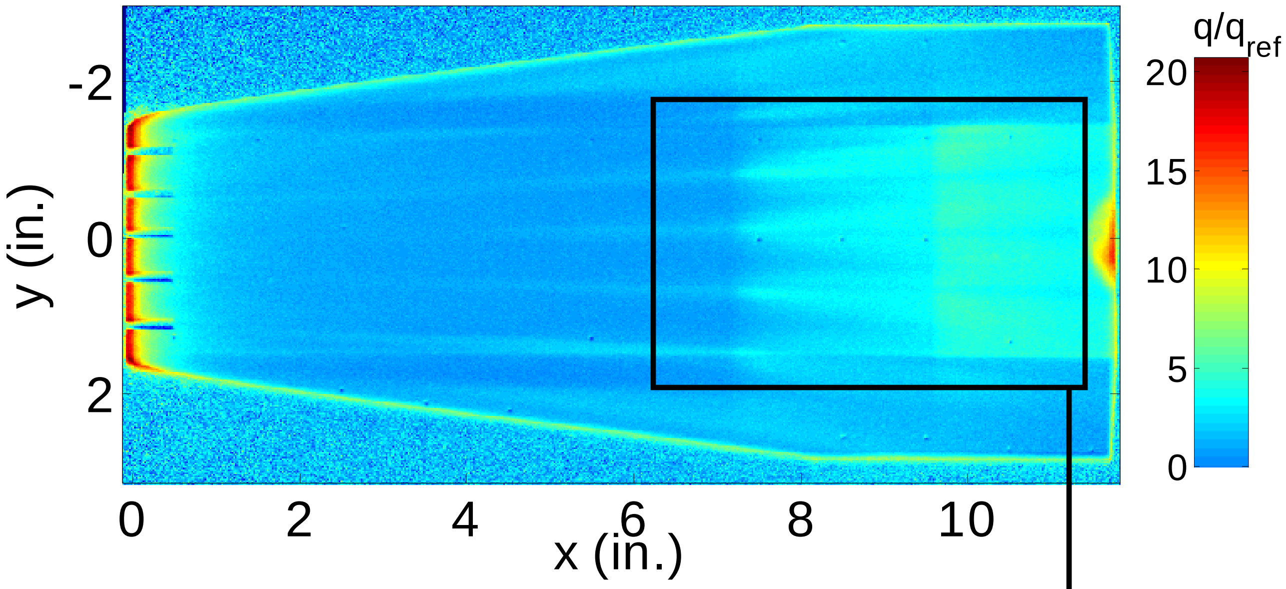
O.H. 1.8

l/d=140

225kHz

T0=160C

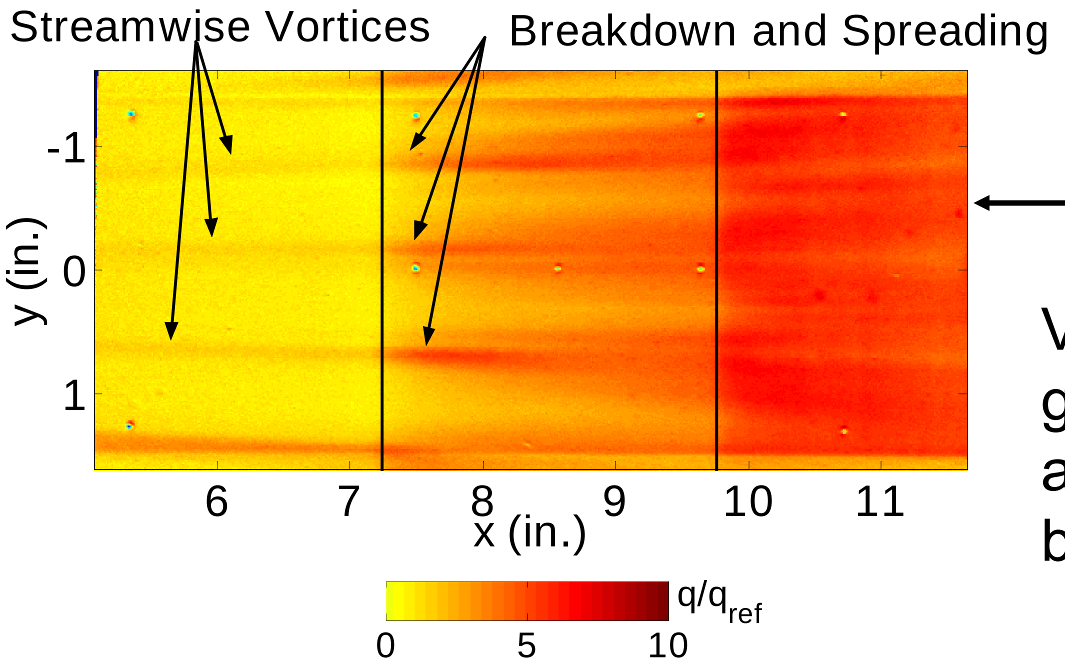
TSP IMAGES ON HYPER-2000 SCRAMJET FOREBODY (VORTEX BREAKDOWN)



P_0 : 120 psia
unit Re : 2.57 million/ft

thick. : 4 mils
spacing : 5/8 inch

AIAA Papers
2003-3592, 2003-4583


Streamwise Vortices

Breakdown and Spreading

Vortices generated at LE grow, break down and spread across the corner. Followed by onset of turbulence?

Summary

- Tunnel runs quiet, now without separation at 8 psia, Mach 5.7. Model support/second throat had excessive blockage. A new streamlined support avoids blockage problems.
- Bypass causes nozzle-wall transition at 8 psia
- Prime suspect is still fluctuations from downstream
- Work toward quiet flow continues
- Bypassing bleed-slot air direct to vacuum tank through fast valve does not affect noise much.
- Oil flow shows crossflow vortices on cone at AOA
- Hot wire appears to show instability waves on sharp cone
- Hot-wire frequency response needs improvement for measurements of second-mode waves
- TSP and oil-flow measurements on scramjet forebody

What Next?

- Are Disturbances Fed from Downstream Tripping the Upstream Boundary Layer? Centerbody DID cause separation. Plumbed bleed air direct to vac. tank, but this shows limited effect so far
- Modify diffuser further? How?
- Measure in diffuser and with hot-wire on nozzle wall
- Measure flow in contraction entrance, confirm low noise
- Check for leaks with helium sniffer
- Touch up throat polish, bleed-lip bump
- Need computation of flow in Bleed Slots,
  more measurements
- Hot-wire, oil-flow, temp. paints on blunt cones incl. AOA

Backup Slides

General 3D Tunnel Data Scatter Over $Re_x = 10^5$ to 10^7

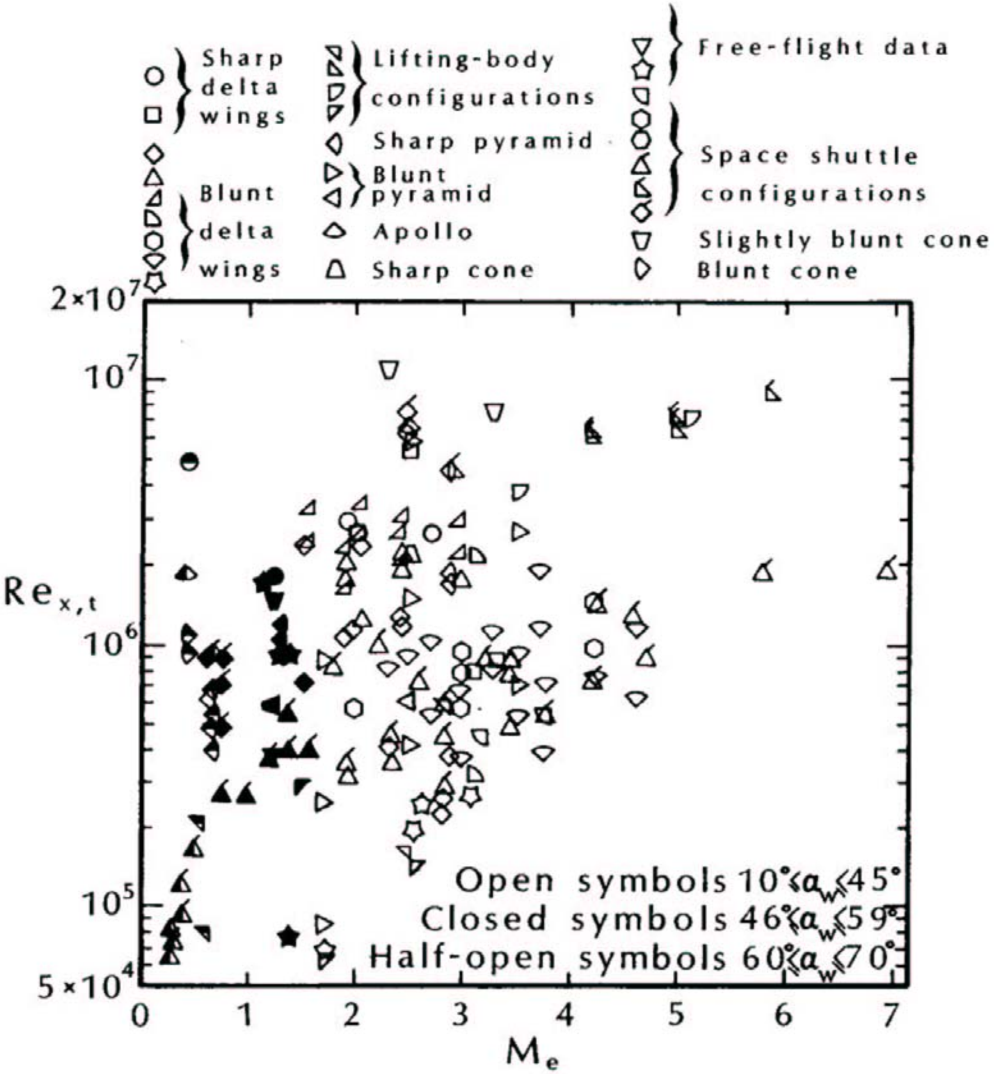


Fig. 7.27 Transition Reynolds number as a function of local Mach number, as taken from Ref. 48.

Depending on Noise, Configuration, Roughness, etc.

From "A Survey of NASA Langley Studies on High-Speed Transition and the Quiet Tunnel", NASA TM-X-2566, Beckwith and Bertram, as reproduced in Bertin, "Hypersonic Aerothermodynamics", AIAA, 1994, p.379.

Context for Blunt Cone Research

1. Interest in gliding RV's from Air Force (CAV) and DARPA (Falcon). Transition is critical to aeroheating during extended glide. A cone at AOA is one such glider.
2. Interest in HyFly and similar airbreathing missiles
3. Flight data review (incl. classified) provides:

   a) suggestions regarding research directions

   b) test cases for development/validation of mechanism-based computational prediction methods
3. Connections to user community at Sandia, Northrop-Grumman, etc.
4. Sandia work now joint with Candler at Minnesota

Transition Critical to Scramjet Cruise Vehicles

1. Multistage airbreathing to orbit will still be similar to NASP – a large scramjet-powered vehicle
2. NASP review by DSB, 1988: "*Estimates [of transition] range from 20% to 80%*", affects GTOW by factor 2
3. NASP review by DSB, 1992: Two most critical tech. areas are scramjet engines and boundary layer transition
4. Propulsion has made great progress under Hyper-X, HyTECH, related programs. Engine works in direct connect tests.
5. Will transition technology be ready when the engine is?

DTIC citations AD-A201124, AD-A274530

Conventional Wind and Shock Tunnels are Noisy!

1. **Fluctuation level typically 1%**: > 10 times higher than flight
2. **Major Source: Acoustic radiation** from turbulent boundary layers on the nozzle walls.
3. **Causes early transition:** perhaps 3-10 times earlier than in flight.
4. **Can change trends in transition:**
   a) Sharp cone transition data in conventional tunnels scales with noise parameters alone, independent of Mach number.

   b) $Re_{T,\ CONE} = 2\ Re_{T,\ PLATE}$ in conv. tunnel, but $Re_{T,\ CONE} = 0.7\ Re_{T,\ PLATE}$ in quiet tunnel and e**N analysis. Flat Plate is later, NOT cone!

   c) Bluntness, crossflow, and roughness effects all differ in quiet and noisy conditions.

   d) Transitional extent typ. 2-4 times longer in conv. tunnel than in flight or quiet tunnel.
5. **Transition in Conventional Facilities is NOT a reliable predictor for flight!** Except for certain limiting cases, such as transition that occurs at a roughness element.

Quiet Tunnels Have Been Under Development Since the 1960's to Address the Noise Problem

1. Must solve the Acoustic Radiation Problem
2. Must Control Laminar-Turbulent Transition on the nozzle walls!
3. Quiet Tunnels also require low-noise core flows.
4. Laminar Nozzle-Wall Boundary Layers requires mirror-finish nozzle walls, specially designed nozzles, particle-free flow
5. Accurate Fabrication of the Nozzle with tight tolerances and a mirror finish is expensive and risky.
6. NASA Langley built a dozen nozzles between 1970 and 1990, and worked out many of the problems: **Mach 3.5** since 1982, **Mach 6** from 1990-97 (presently boxed)
7. No High Reynolds Number Hypersonic Quiet Tunnel presently in operation anywhere. Purdue effort leads. Langley Mach-6 may be reinstalled ca. 2004.

Hypersonic Transition is Critical to Large Scramjet Accelerator Vehicles

- Multistage Airbreathing to Orbit will still be similar to NASP -- a large hypersonic scramjet-powered vehicle
- National Aerospace Plane Review by Defense Science Board, 1988: *Estimates [of transition] range from 20% to 80% along the body … The estimate made for the point of transition can affect the design vehicle gross take off weight by a factor of two or more.*
- National Aerospace Plane Review by Defense Science Board, 1992: *The two most critical [technology areas] are scramjet engine performance and boundary layer transition… Further design development and increased confidence in these two technical areas must be of paramount importance to the NASP program.*
- The propulsion problems are being worked under various programs. However, transition research is reduced to a shell. Will transition technology be ready when the combustor is?

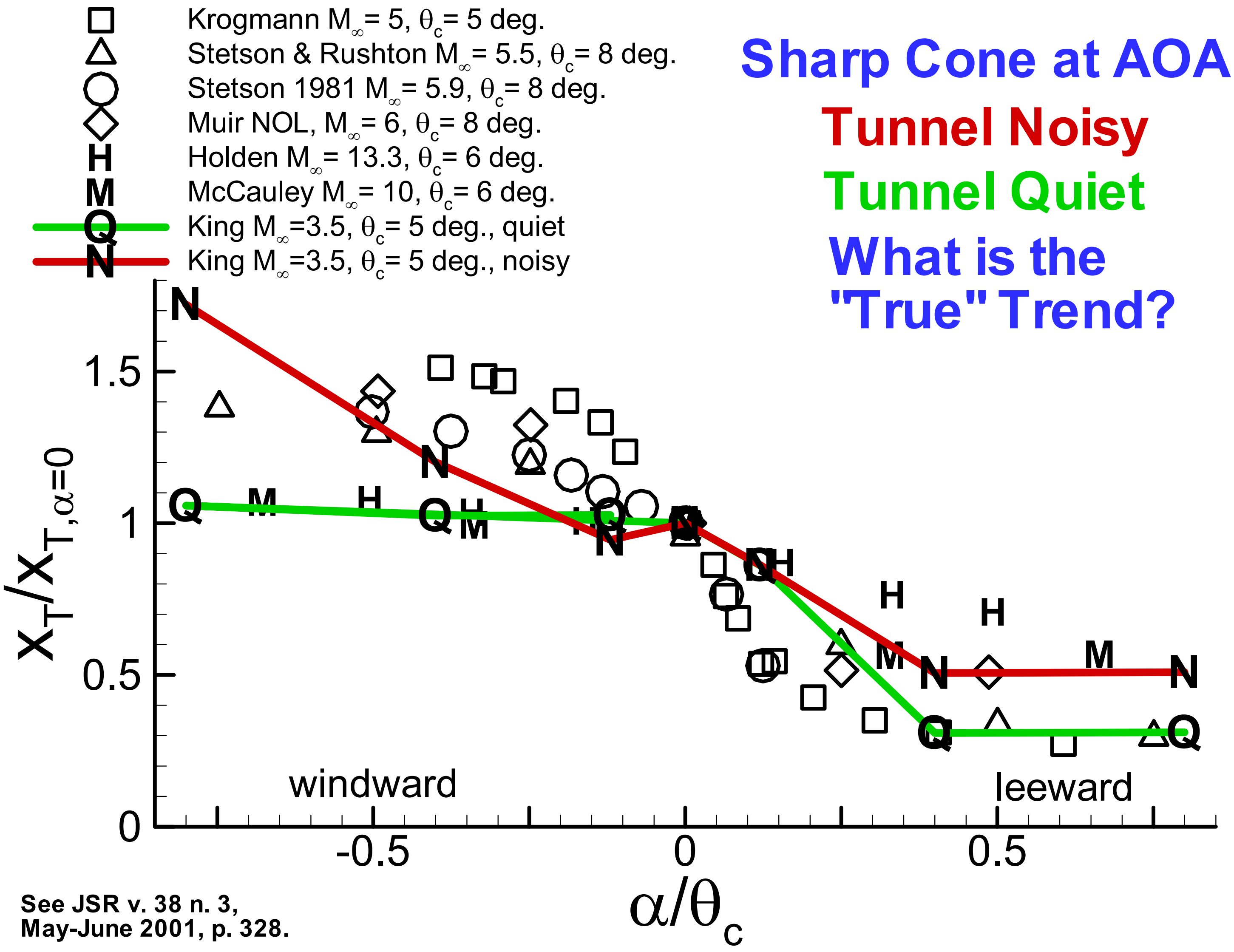
AD-A201124, Report of the DSB Task Force on the NASP Program, Sept. 1988

AD-A274530, Report of the DSB Task Force on the NASP Program, Nov. 1992

Transition is Critical to RLV Reentry Aeroheating

- Aeroheating affects TPS weight, type, and operability – a low-maintenance metallic TPS may not be possible if transition occurs early
- Reentry trajectory is iterated to achieve acceptable aeroheating, and therefore depends on transition
- Crossrange is critically dependent on aeroheating
- TPS selection affects roughness and surface temperature and therefore boundary-layer transition
- Uncertainty in transition drives TPS temperature margin, 200+F for shuttle (per Stan Bouslog)
- A metallic TPS may have a more repeatable and smaller roughness which might permit delaying transition

Simple Conventional Transition Measurements Often Don't Give "Correct" Trends



Sharp Cone at AOA.

Tunnel Noisy

Tunnel Quiet

What is the "True" Trend?

See JSR v. 38 n. 3, May-June 2001, p. 328.

Bridge the Gaps in Hypersonic BLT

- Designers using Empirical Methods/
  Researchers doing PSE and DNS etc.
- Designers using CFD, often 3D/
  But still crude models for BLT
- Improve BLT models at all levels:
  Simple for conceptual design to
  Complex for advanced design
- Improve coordination between researchers and designers
- Improve coordination among researchers

Summary of Purdue Effort, 1990-99

1. Development of Mach-4 Ludwieg Tube, Quiet to Re = 400,000, 1990-94.
2. Tests of Heated Driver Tube (Munro, 1996)
3. Development of Hot-Wire and Glow-Perturber Technique
4. Controlled Wave Growth of factor 2-3 on Cone at AOA under quiet conditions (Ladoon Ph.D., 1998)
5. Development of Pulsed Laser-Perturber for Generating Local Perturbations in Freestream for Receptivity Work (Schmisseur Ph.D., 1997)
6. Controlled Measurements of Damping in Forward-Facing Cavity, Explained Low Heat Transfer in 1961 Flight Data (1997-99)
7. Developed of High-Sensitivity Laser Differential Interferometer ala Smeets. Receptivity on Blunt Nose. (Salyer Ph.D., 2002)
8. Development of High-Reynolds Number Mach-6 Quiet Ludwieg Tube (1995-present)

Summary of Purdue Effort, 1999-2002

1. **Completion of Mach-6 Quiet-Flow Ludwieg Tube**. Rufer, M.S. 2000, burst diaphragm tests. Skoch, M.S. 2001, heaters and initial tests. Initial Operation, April 2001.
2. **Development of Automated Vertical-Plane Traverse** (probe profile in single run). Swanson, M.S. Dec. 2002
3. **Modifications to Bleed-Slot Throat Yield Initial Quiet Flow** (but only at low Reynolds number).
4. **Hot-wires survive in Mach-6 flow, stable CTA operation,** 2001-2002 (still not at full pressure).
5. **Skoch/Rufer operate Ladoon's glow perturber** and hot wire apparatus in Mach-4 tunnel, 2002. (New student education).
6. **Matsumura/Swanson develop temperature-sensitive paints** for measuring stationary vortex growth, 2001-2002.
7. **Matsumura measures streak/vortex growth on Hyper2000** with controlled roughness perturbers.
8. **Schneider surveys classified flight data,** summer 2002

Need National Plan for Hypersonic Transition Research for Airbreathers and RLV’s

- Further development of existing mechanism-based prediction methods
- Detailed measurements on generic geometries in quiet and conventional tunnels to develop & validate the mechanism-based methods
- Comparisons of mechanism-based methods against existing flight data
- Industry has long used mechanism-based methods for transonic speeds – how long before they are available for the more critical hypersonic problems?

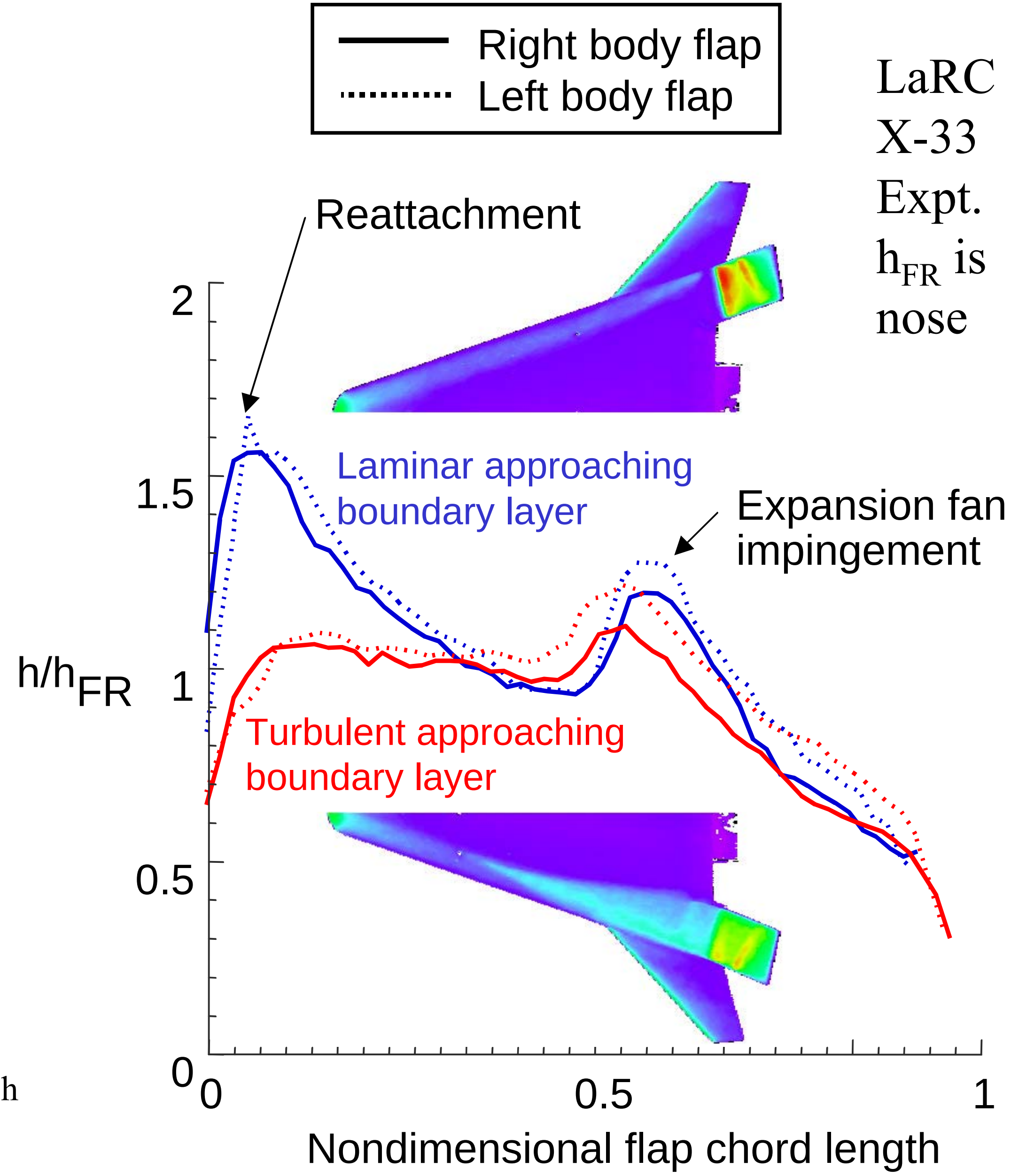
Deflected Control Surfaces with Compression-Corner Separations:

-Transitional Heating Can be 50% Larger than Turbulent Heating

-Transition Occurs at Low Reynolds Numbers

-Improved Predictions Can Reduce Control Surface TPS Requirements

Horvath et al., AIAA 99-3558, Fig. 14. Mach 6, 40-deg. AOA, Re=2E6/ft., δ_{BF}=20 deg.

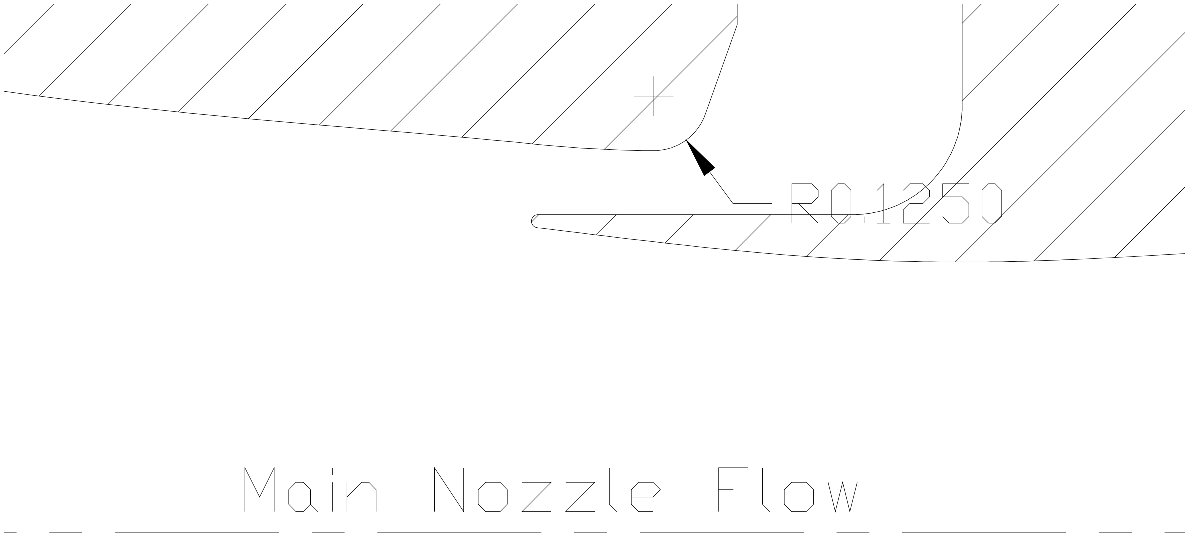


LaRC X-33 Expt. h_{FR} is nose

S.P. Schneider, Purdue AAE

Design of Seventh Bleed Slot Throat

- 1D streamtube analysis ala Beckwith, full 1D both sides of bleed lip. See paper
- Increase from 30% to 38% suction
- Move stagnation point from 2/3 below top of hemicircle to 4/5 below top

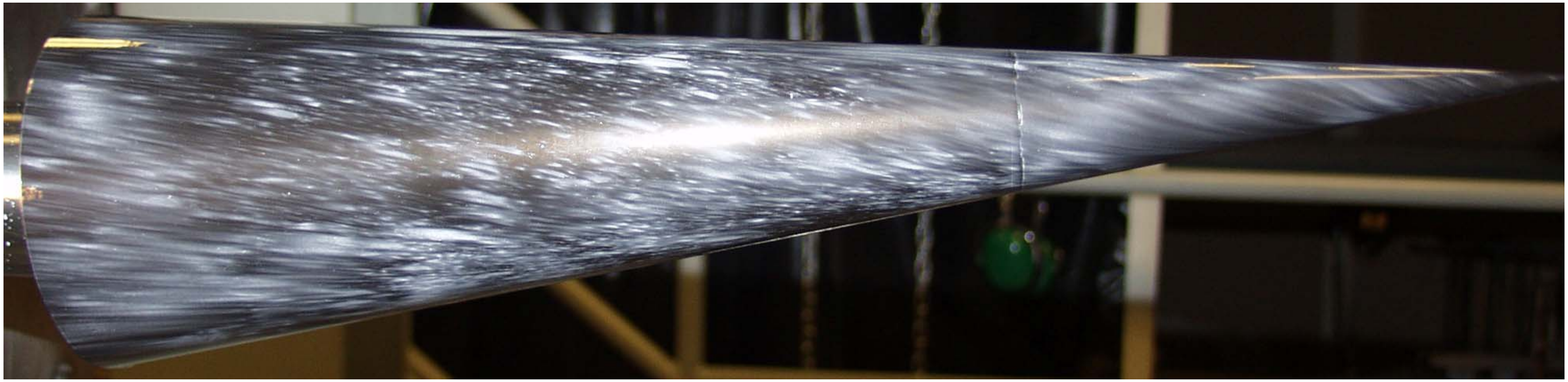


Crossflow Vortices on a Cone at Angle of Attack at Mach 6

Re = 2.6 x 10^6/ft, 7-deg. half-angle sharp cone, 6-deg. AOA, T_D=160C,

AIAA 2003-3450. Oil applied in smooth layer by brushing crossways.

Oil-Flow Image of Streamlines on a Cone at Angle of Attack at Mach 6



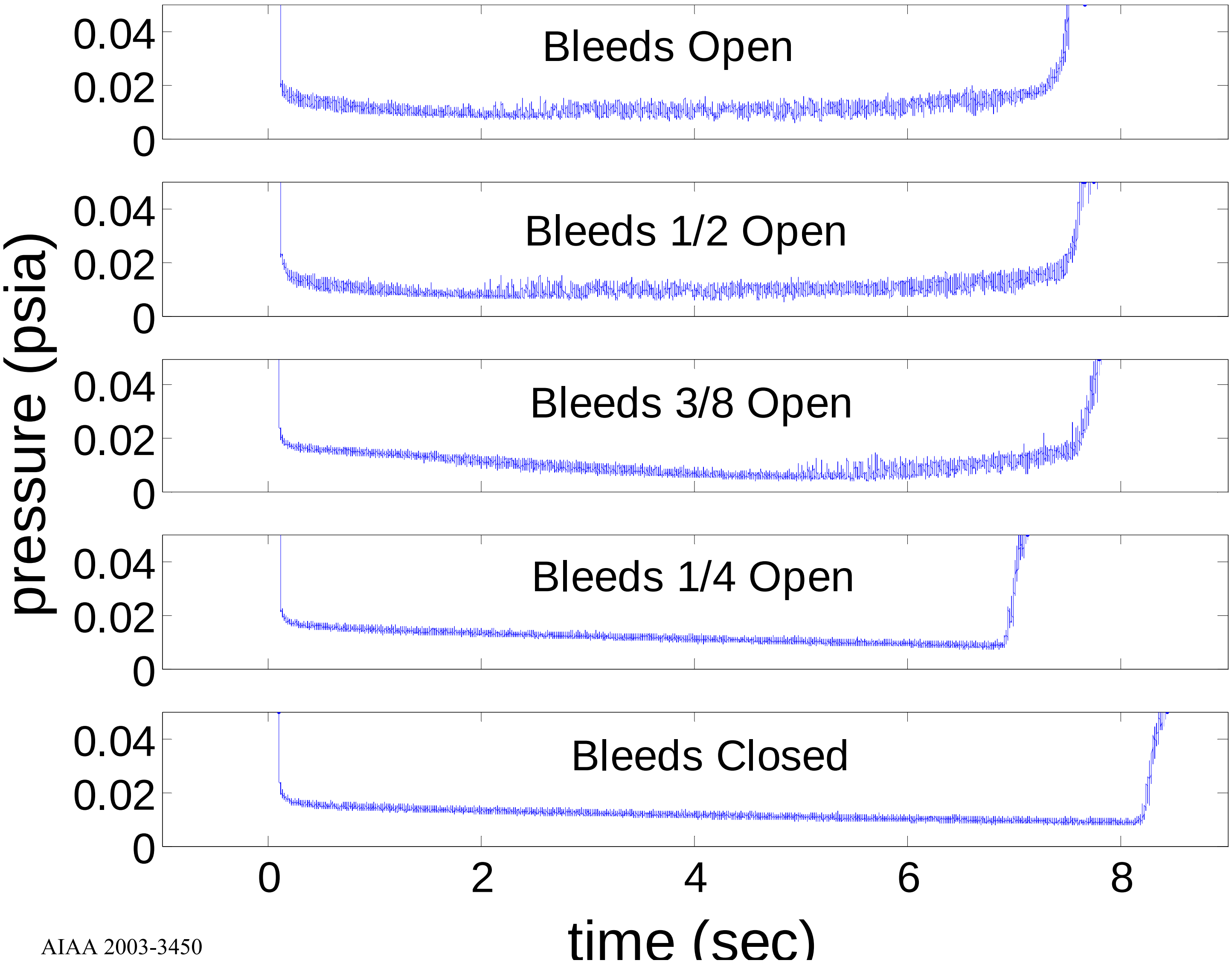
Re = 3 x 10^6/ft, 7-deg. half-angle sharp cone, 6-deg. AOA, T_D=160C, AIAA 2003-3450.

Oil Flow. In this case, oil was applied in dots, movement of dots shows streamlines.

Near-Term Mechanism-Based Prediction Approach

- Compute approximate aeroheating and 1D heat conduction, down the trajectory
- Compute accurate 3D mean flow (with chemistry) at possible transition altitudes
- Compute 1st & 2nd mode instabilities on wind & lee planes
- Compute crossflow Reynolds number off centerplane. Later compute crossflow instability growth
- Compute Gortler when relevant
- Compute Re_k, k/theta, etc. for roughness.
- Use linear instability, also PSE & nonlinear when needed
- Compare details to ground expts, results to flight & ground

Diffuser Static Pressures with Throttled Bleeds



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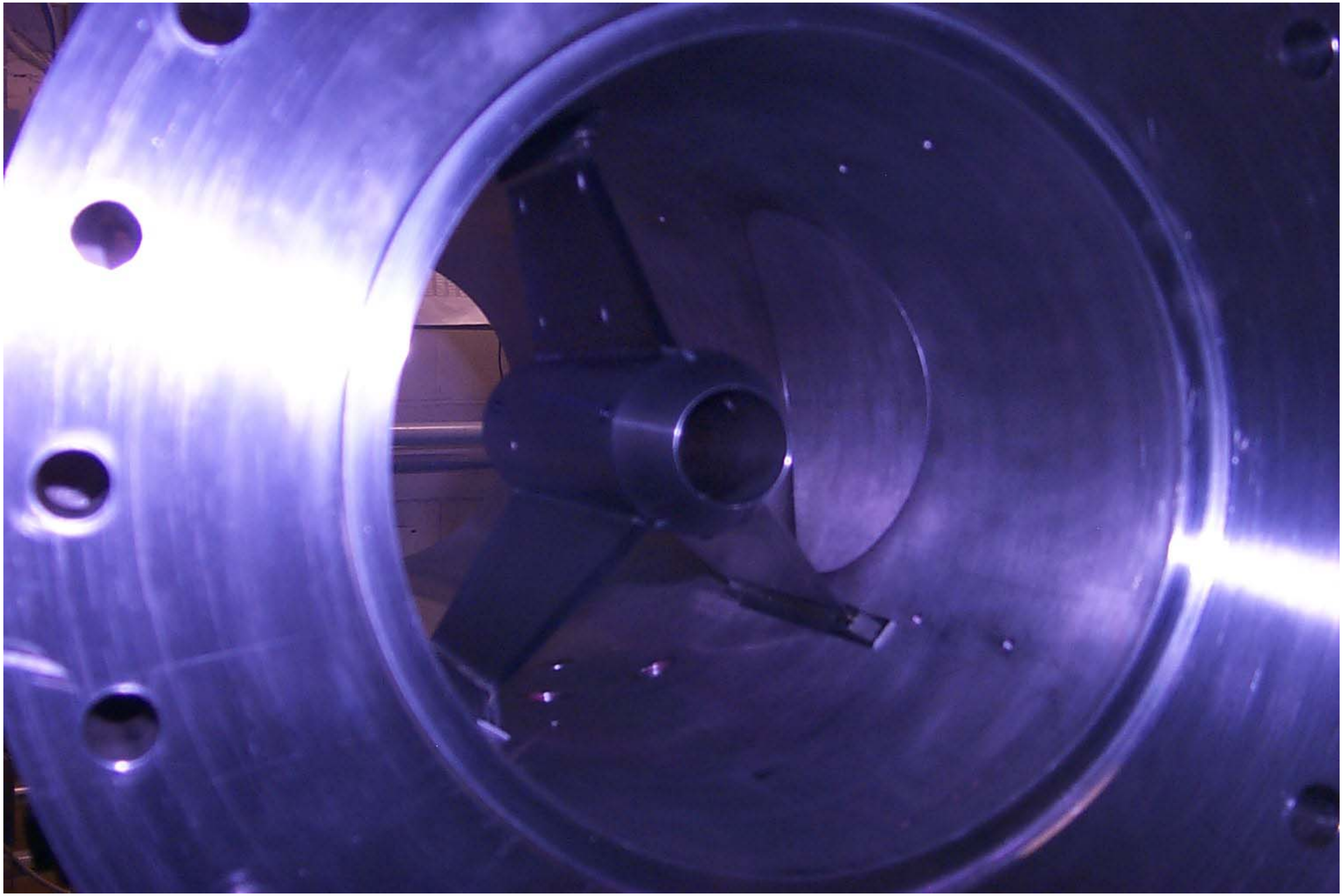
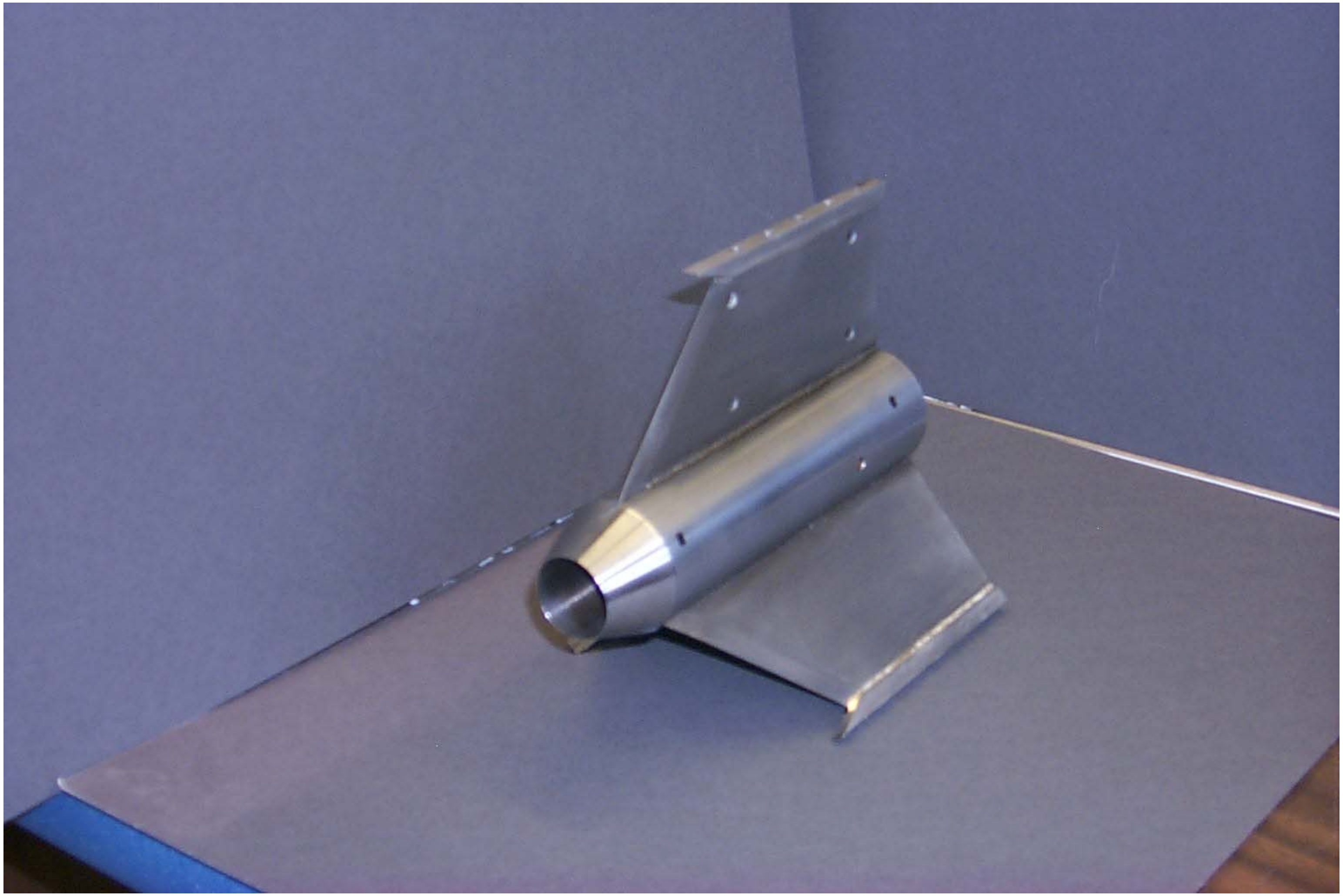
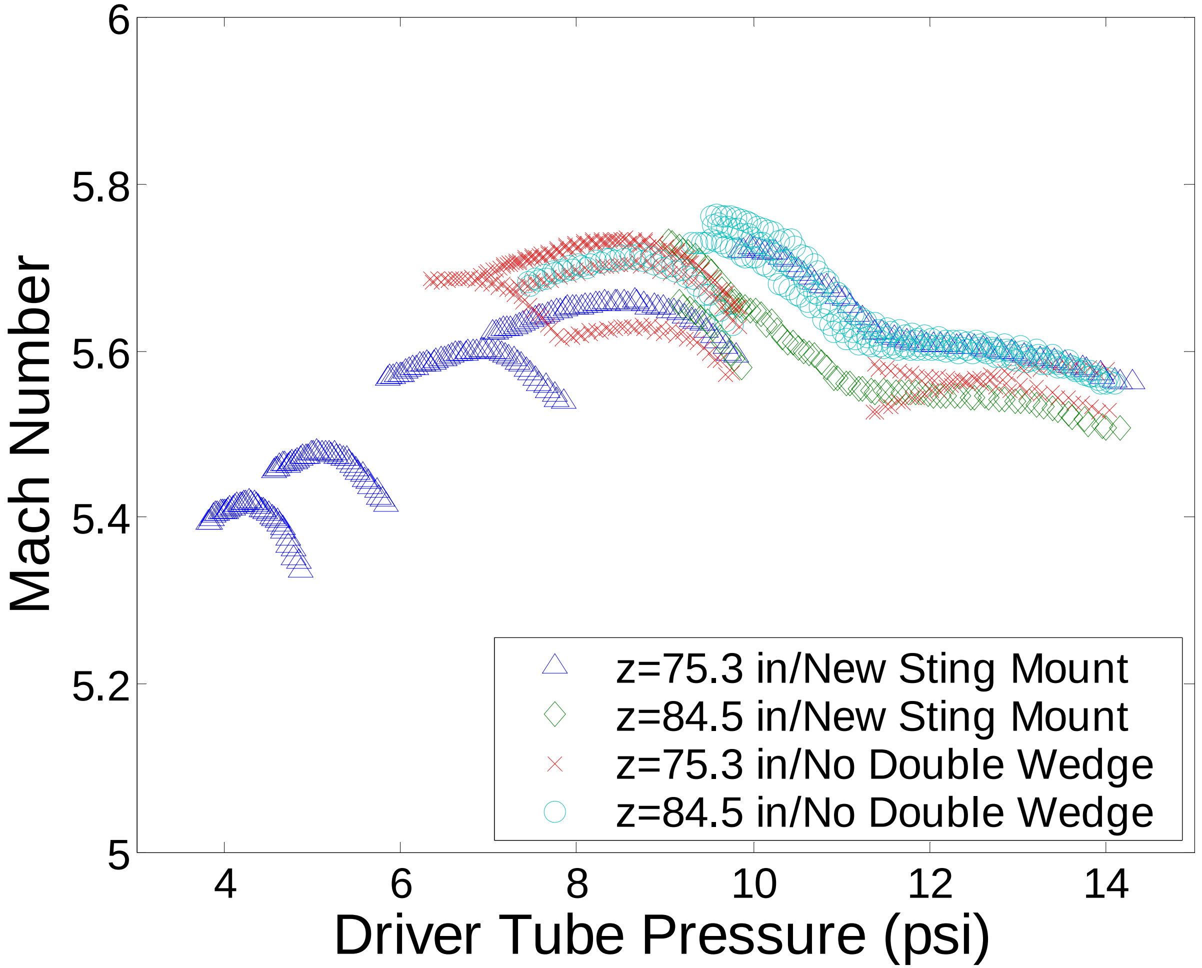
New Streamlined Sting Support, Installed



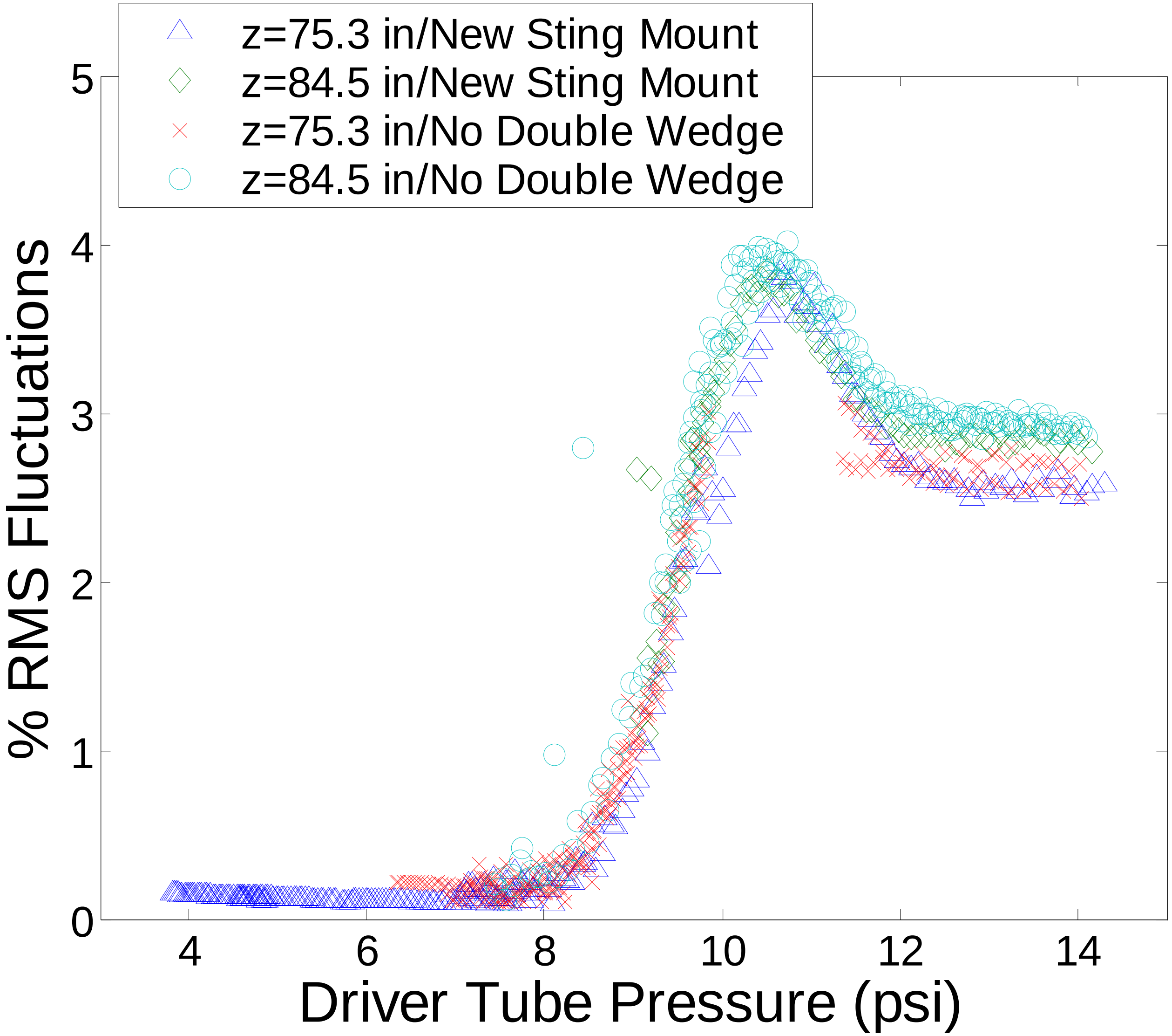
New Streamlined Sting Support on Bench



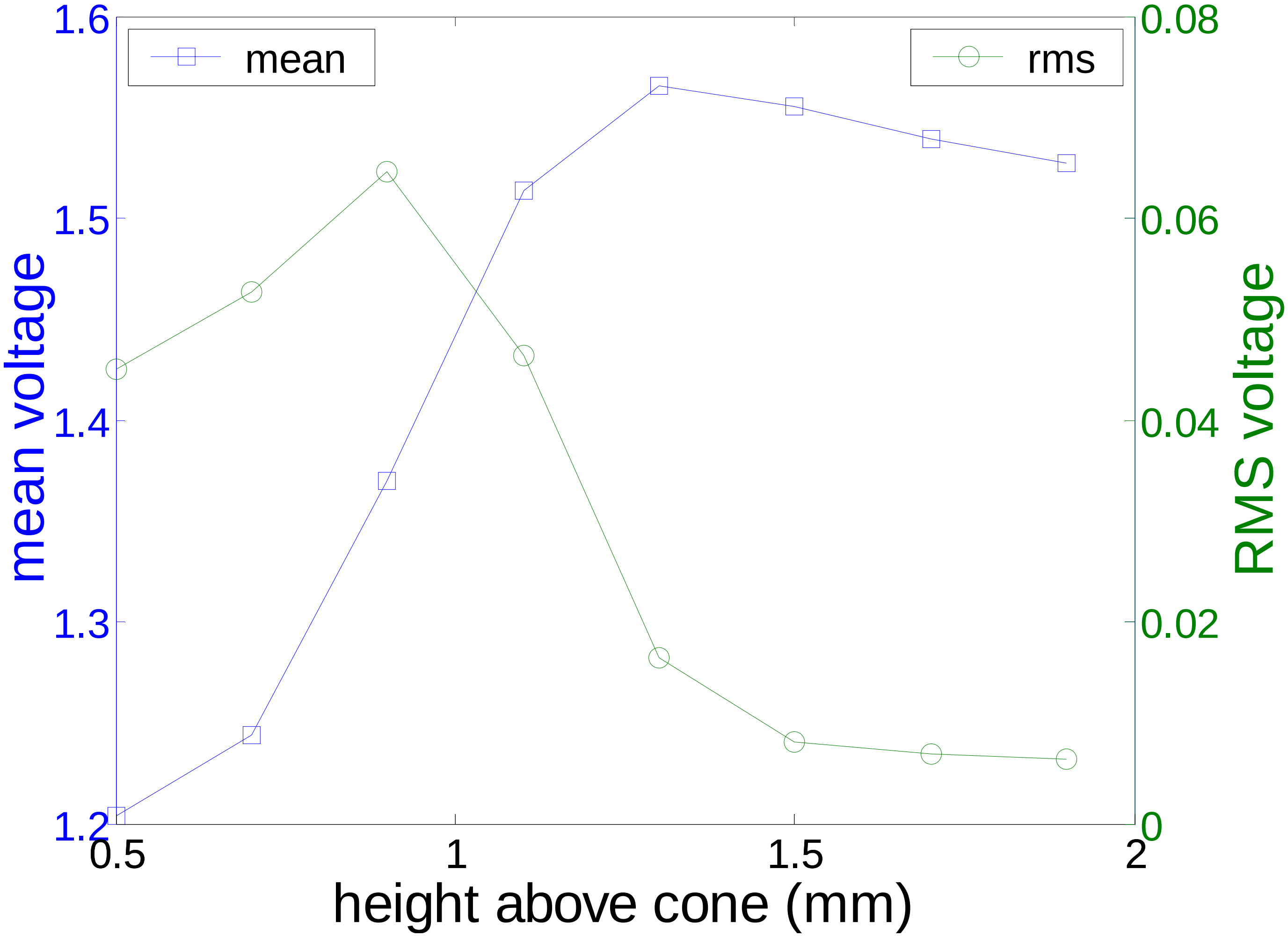
Mean Mach Number from Pitot on Centerline
New Streamlined Model Support Stops Separation



Pitot on Centerline: Noise Onset is Same for Empty Tunnel and New Sting Support



Single-Run Hot-Wire Profile on Sharp Cone at Pd=95 psia



x=11.7 in.

7-deg. half-angle cone

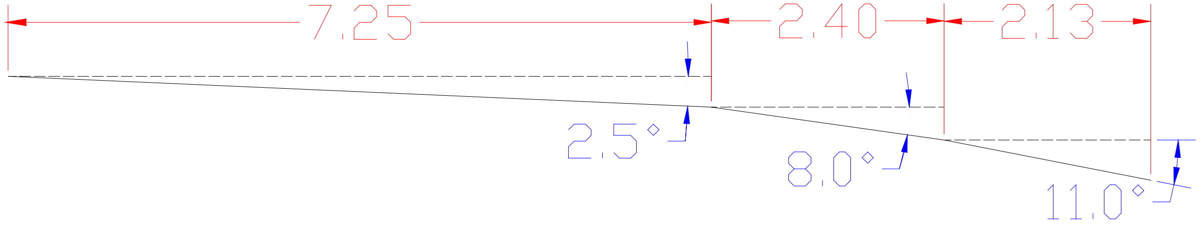
O.H. 1.8

l/d=140

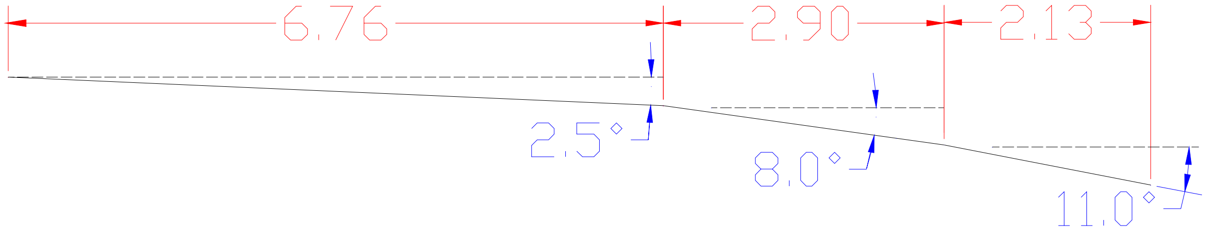
225kHz

HYPER-2000 MODEL GEOMETRY

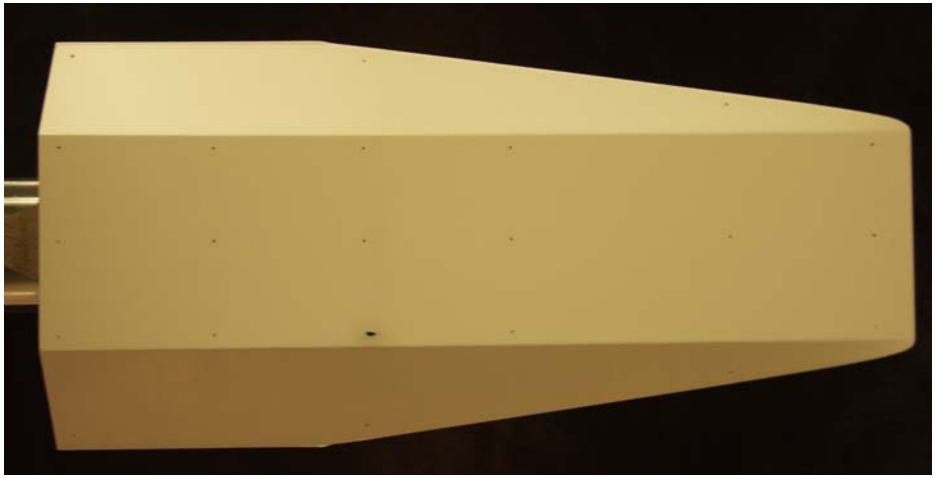
Hyper-2000



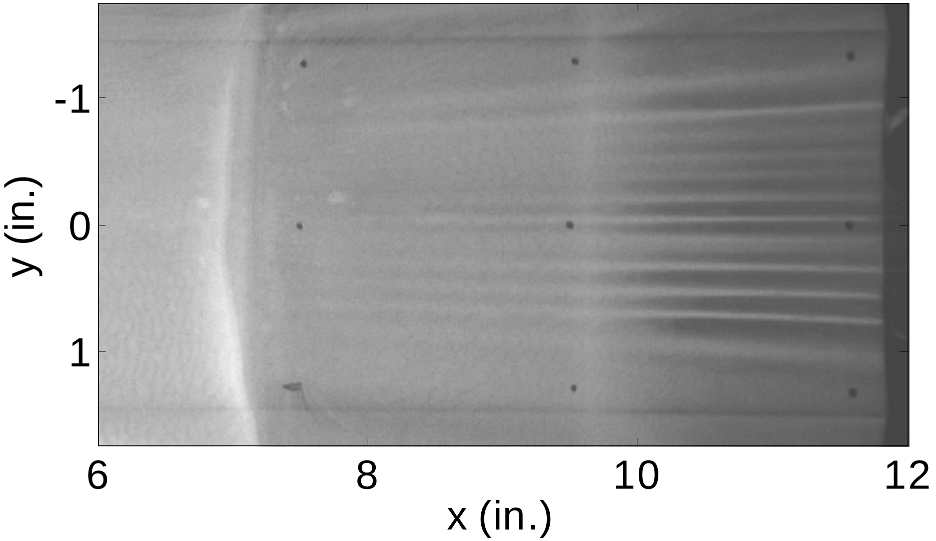
Hyper-X



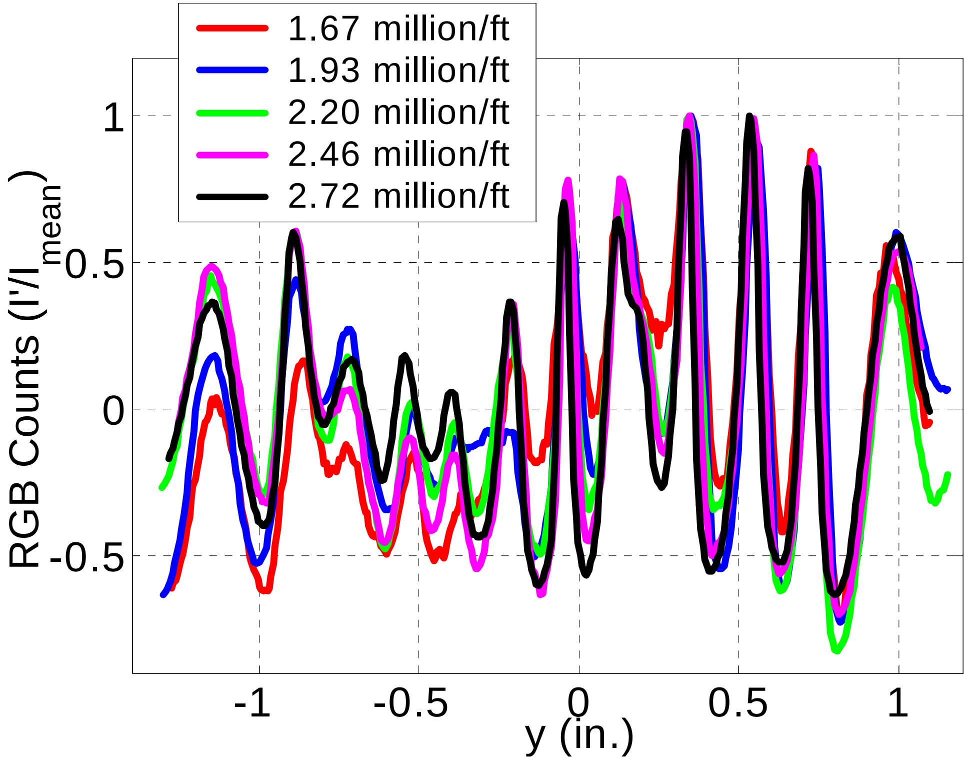
- Obtained from Hyper-X program office
- Representative geometry of current vehicles of this class
- Approx. 1/5th scale of 12 ft. full-scale vehicle
- Slightly longer first compression ramp than the Hyper-X



OIL-FLOW VISUALIZATION (“SMOOTH” MODEL)



Appearance of streamwise vortices immediately downstream of first compression corner



- Location and spacing of vortices independent in this unit Re range.
- Effect of leading edge variation
- Suggests most amplified vortex spacing of 0.19 inches (5.6 cycles/inch)