Hypersonic Boundary-Layer Transition on Reusable Launch Vehicles

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Presented at the RLV/SOV Airframe Technology Review, NASA Langley, 19-22 November 2002. Meeting is ITAR restricted.

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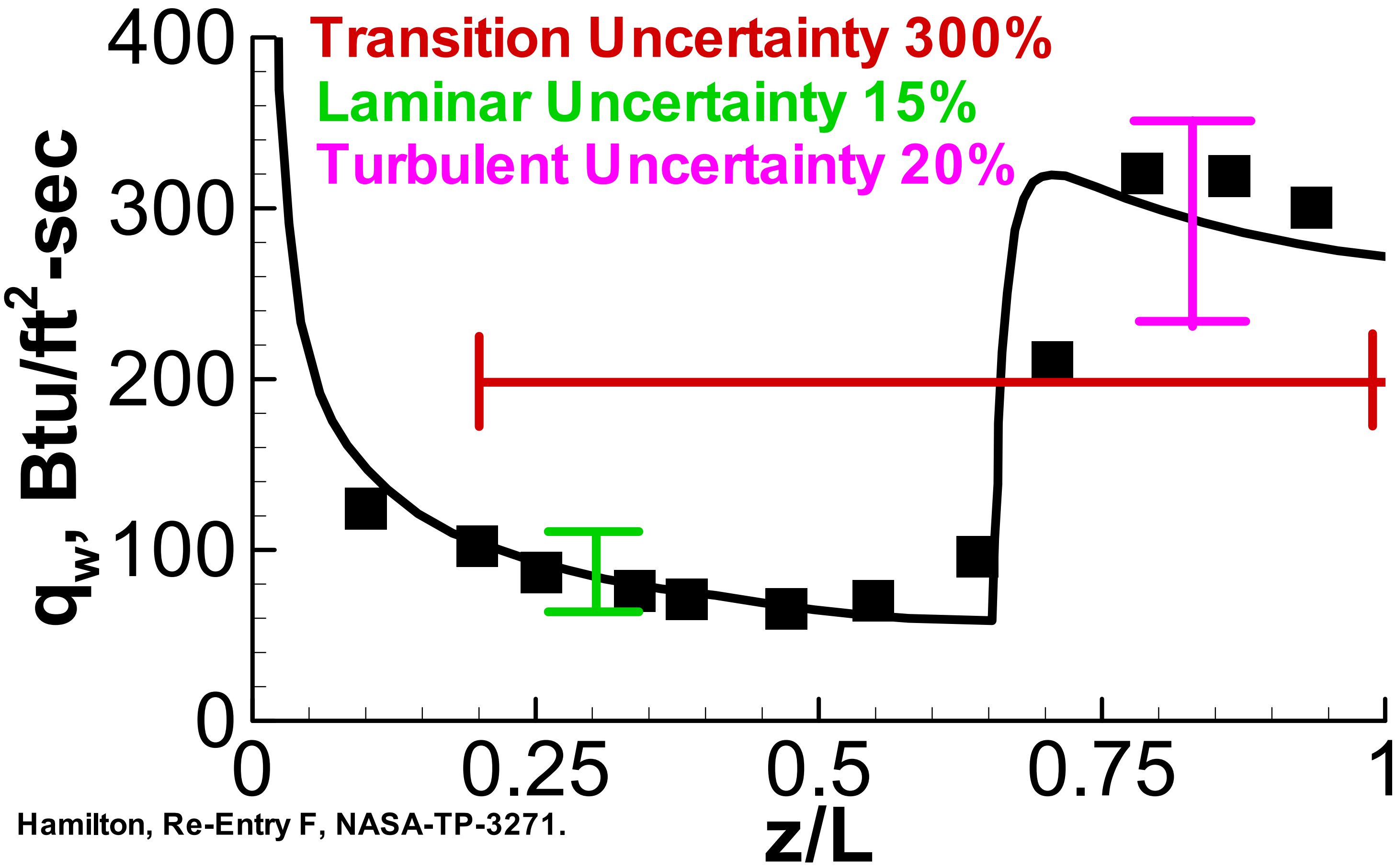
All viewgraphs in this talk are for unlimited distribution, except as specifically marked otherwise

Acknowledgements

- Boeing/AFOSR/BMDO/Purdue/Sandia/Langley, Development of Mach-6 Quiet Ludwieg Tube ($1m, 1995-2001)
- Based on three decades of work by NASA Langley and others
- AFOSR research, transition on generic scramjet forebody
- Generic forebody geometry from the Hyper-X program office
- Langley research, transition on generic RLV
- Johnson Space Center research on lifting-body aeroheating
- Sandia/TRW research, transition on RV's

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

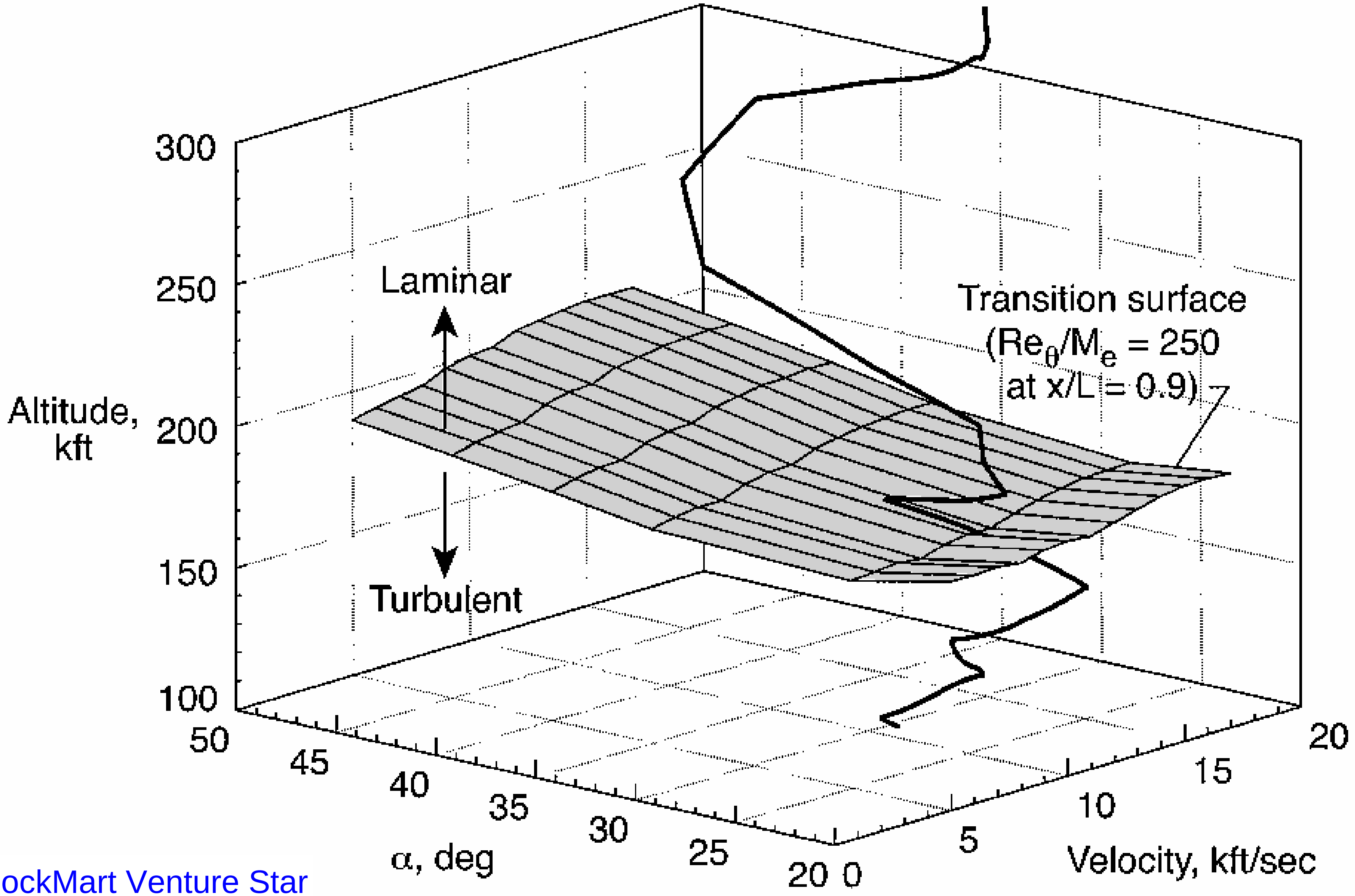


Hamilton, Re-Entry F, NASA-TP-3271.

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
- A metallic TPS may have a more repeatable and smaller roughness which might permit delaying transition

To Avoid Overheating and Improve Crossrange, Reliable Transition Prediction Should be Part of the Multidisciplinary Design



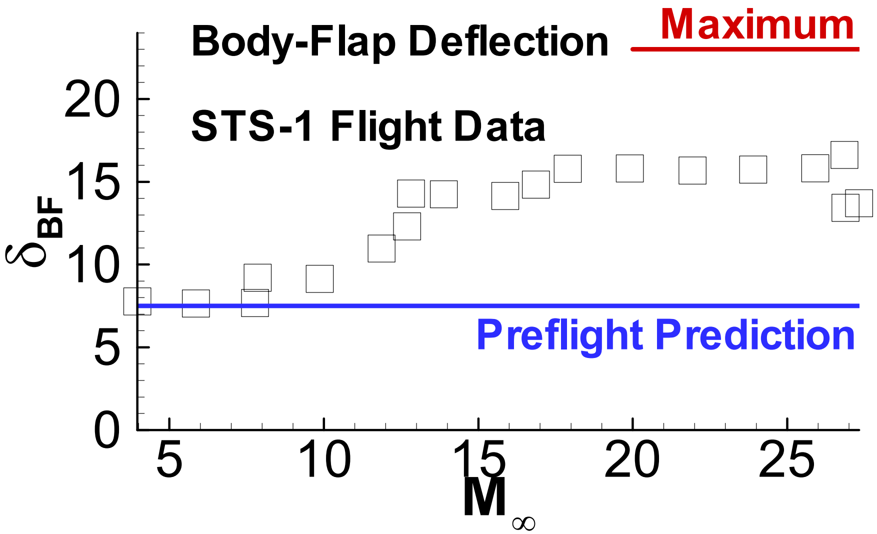
LockMart Venture Star

Trajectory Optimized for Acceptable Heating; Requiring Estimate of Transition

From Tartabini, Wurster, Korte, and Lepsch, "Multidisciplinary Analysis of a LIfting Body Launch Vehicle"., J. Spacecraft and Rockets, Sept.-Oct. 2002, pp. 788-795

Transition Also Affects RLV Controllability

- Asymmetrical transition caused Shuttle flight STS-50 to use [??] extra RCS fuel to correct the yawing moment
- Body-flap effectiveness is dramatically affected by transition – a laminar incoming boundary layer increases corner-flow separation and reduces flap effectiveness.



Shuttle Pitchup Anomaly.

-Mostly due to Real-Gas Effects on C_M.
-However, Body-Flap Effectiveness is also Hard to Predict, due in part to Transition

NASA CP-2283 p. 343
NASA TM-4499 p. 15

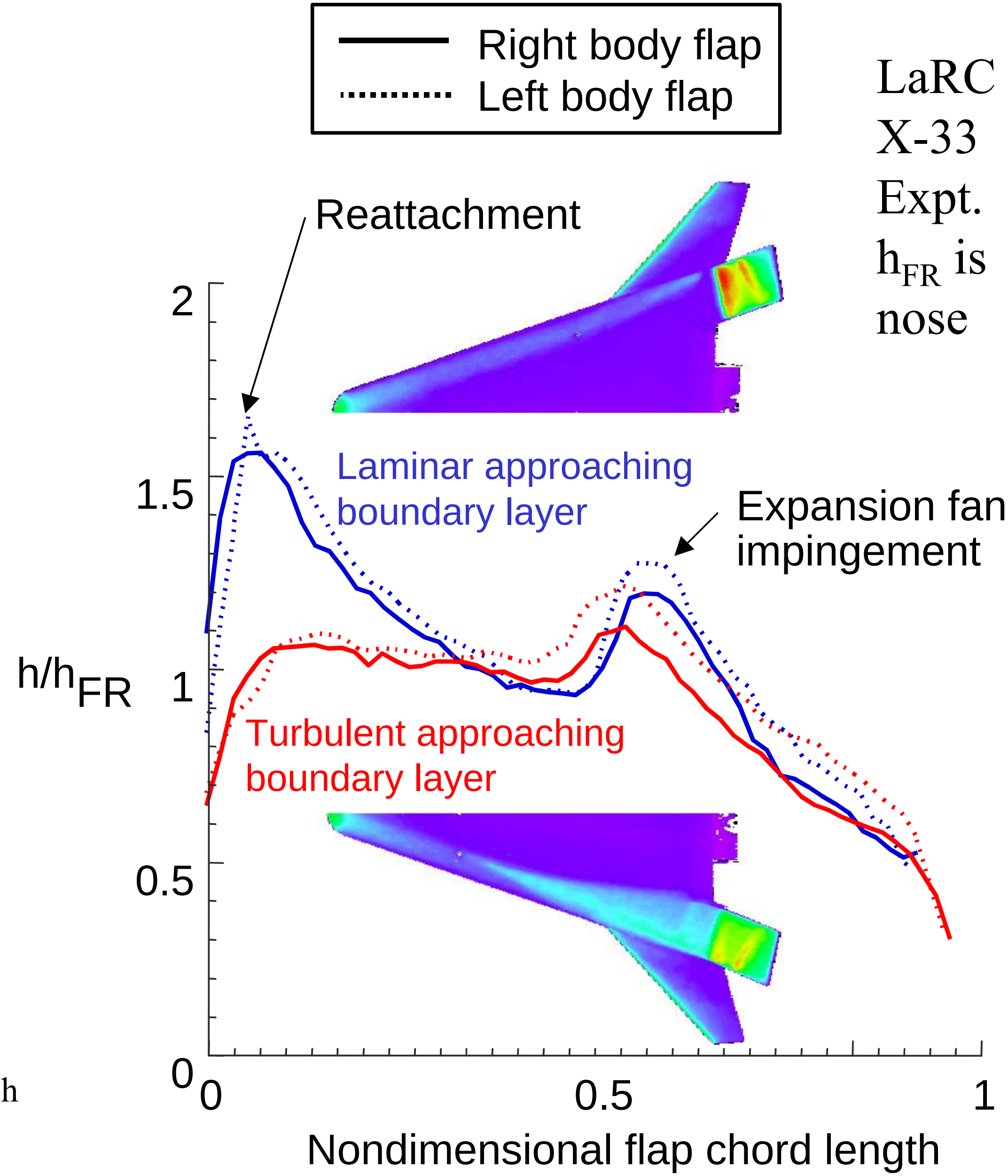
RCS fuel usage data is ITAR, omitted here

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



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

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

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?

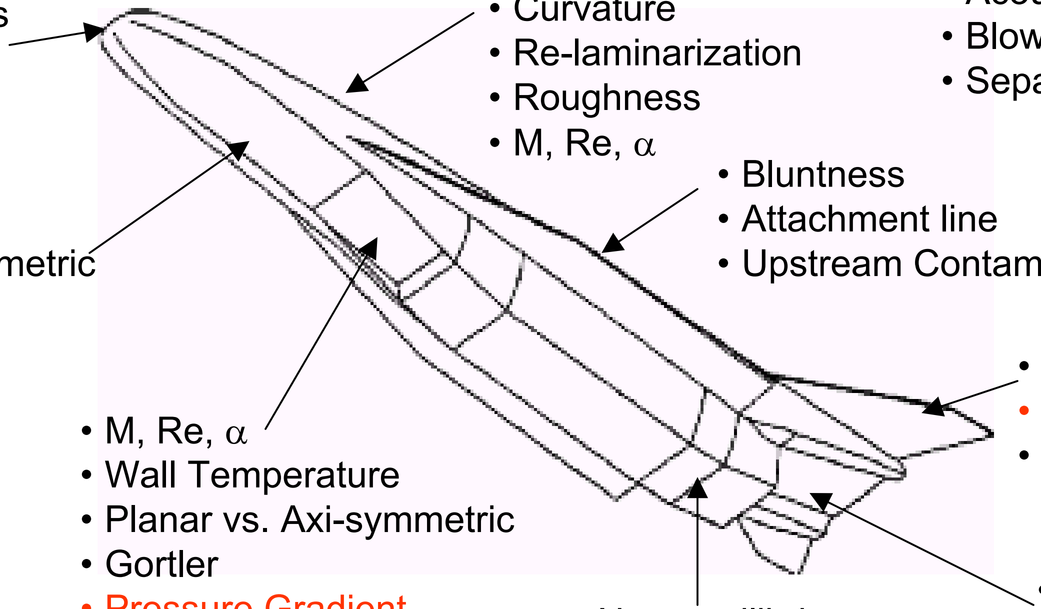
AD-A201124, Report of the DSB Task Force on the NASP Program, Sept. 1988
AD-A274530, Report of the DSB Task Force on the NASP Program, Nov. 1992

Hypersonic Boundary Layer Transition

Integrated Defense Advanced System

Bowcutt/Lau Sept. 2002

- **Boundary Layer Transition Has First Order Impact On:**
  - **Aerodynamic Drag and Control Authority**
  - **Engine Performance and Operability**
  - **Thermal Protection Requirements**
  - **Structural Materials, Concepts and Weight**



Inside Scramjet

- Shock-BL Interaction
- Acoustics
- Blowing
- Separation

- Bluntness
- Blowing

- Curvature
- Re-laminarization
- Roughness
- M, Re, α

- M, Re, α
- Wall Temperature
- Planar vs. Axi-symmetric
- LE/nose Bluntness
- Pressure Gradient
- Roughness

- Bluntness
- Attachment line
- Upstream Contamination

- Trim
- Shock-BL Interaction
- Roughness

- M, Re, α
- Wall Temperature
- Planar vs. Axi-symmetric
- Gortler
- Pressure Gradient
- Roughness
- Shock-BL Interaction

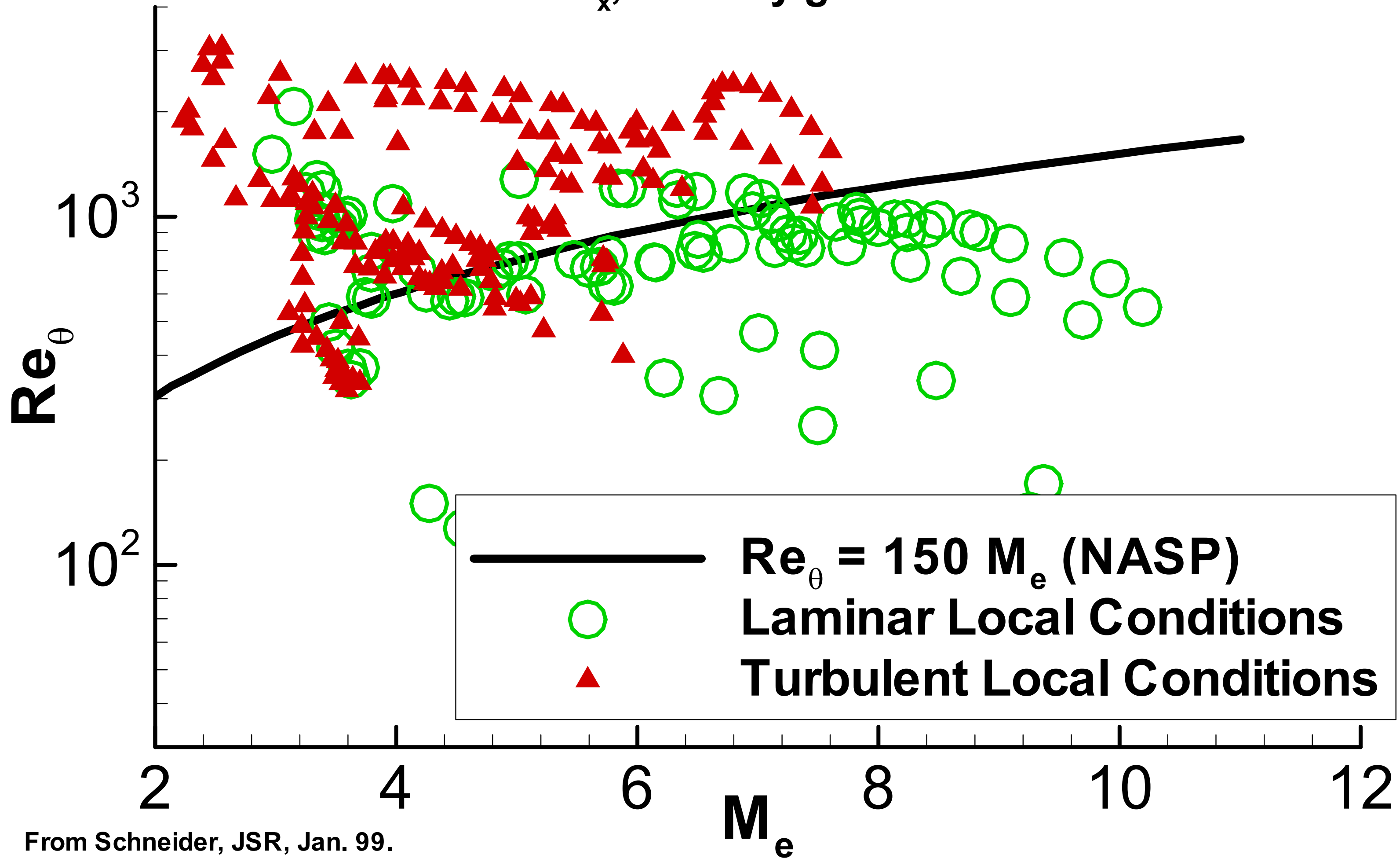
- Non-equilibrium
- Free Shear Layer
- Acoustics
- Pressure Gradient

- Non-equilibrium
- Re-laminarization
- Acoustics
- Film Cooling

Many Factors Influence Boundary Layer Transition

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.

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

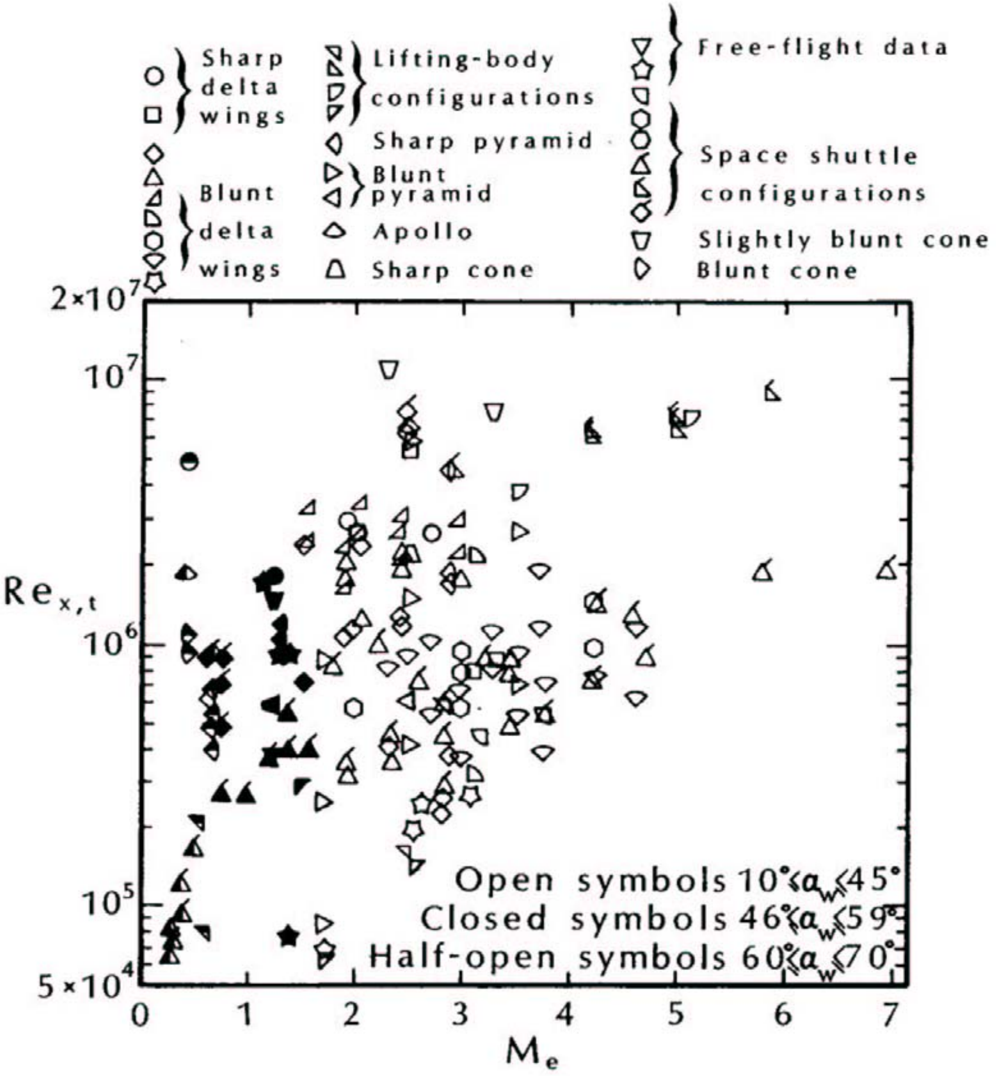


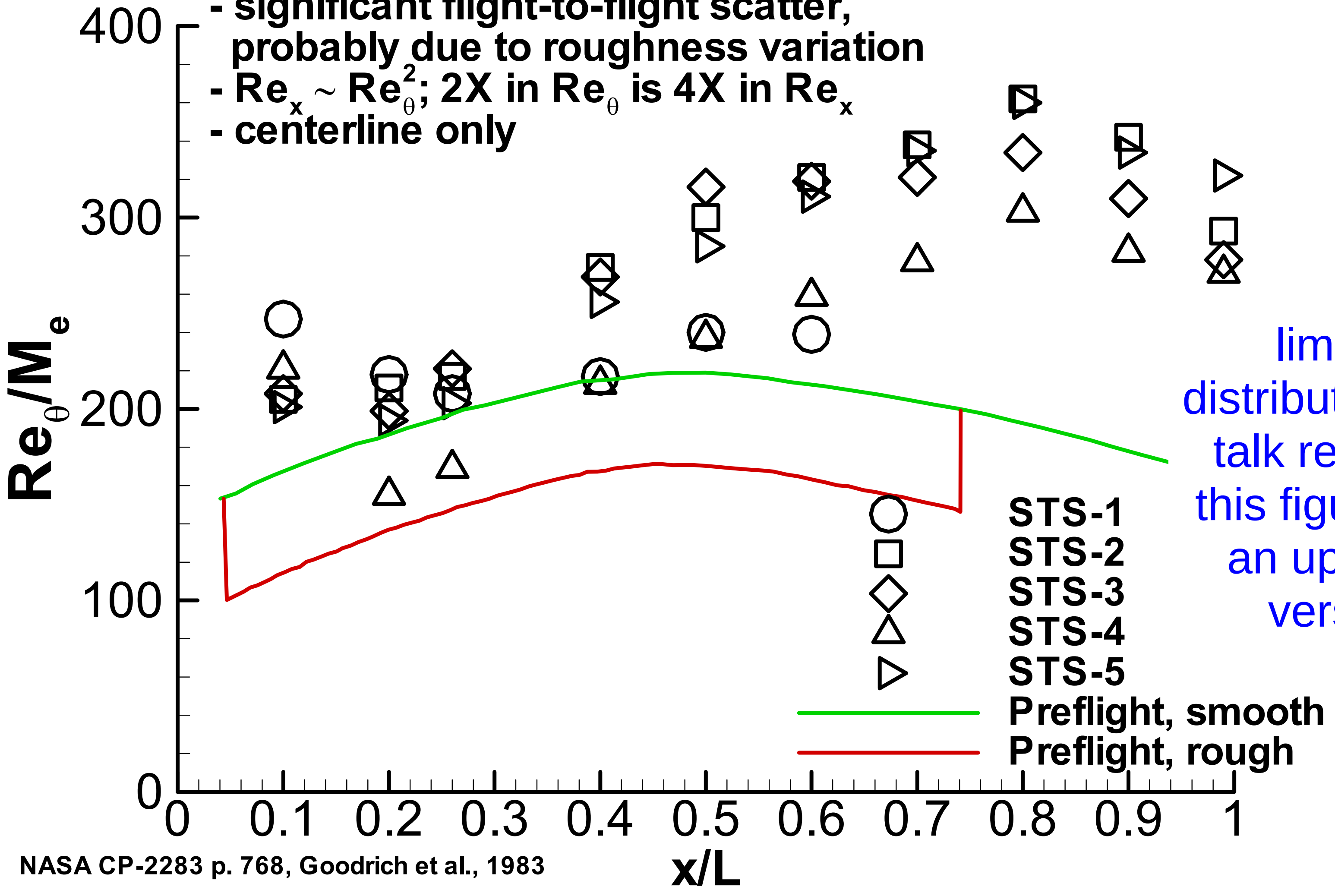
Fig. 7.27 Transition Reynolds number as a function of local Mach number, as taken from Ref. 48.

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.

Flight Data for Hypersonic Transition on the Shuttle

- Re_θ/M_e varies by a factor of 2 along the vehicle
- significant flight-to-flight scatter, probably due to roughness variation
- $Re_x \sim Re_\theta^2$; 2X in Re_θ is 4X in Re_x
- centerline only



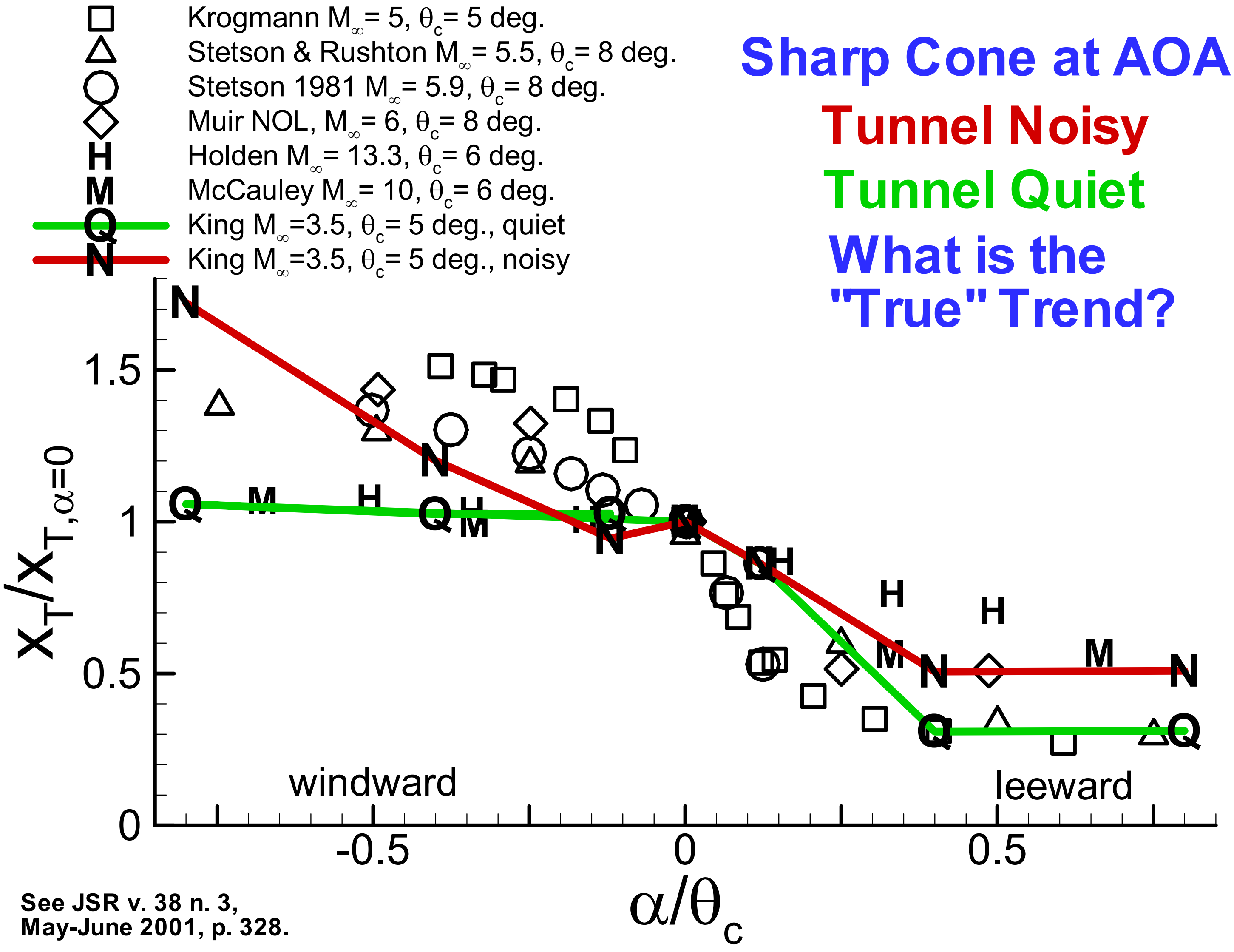
limited distribution final talk replaces this figure with an updated version

NASA CP-2283 p. 768, Goodrich et al., 1983

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.

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.

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.

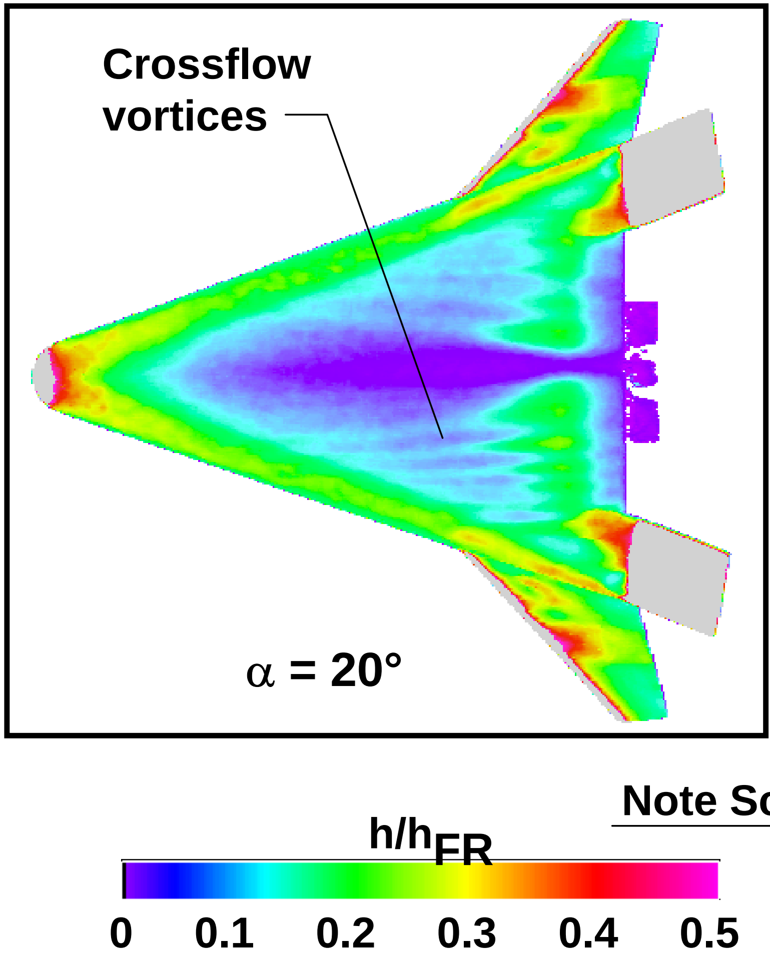
Need Measurements of the Mechanisms of Transition

- 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

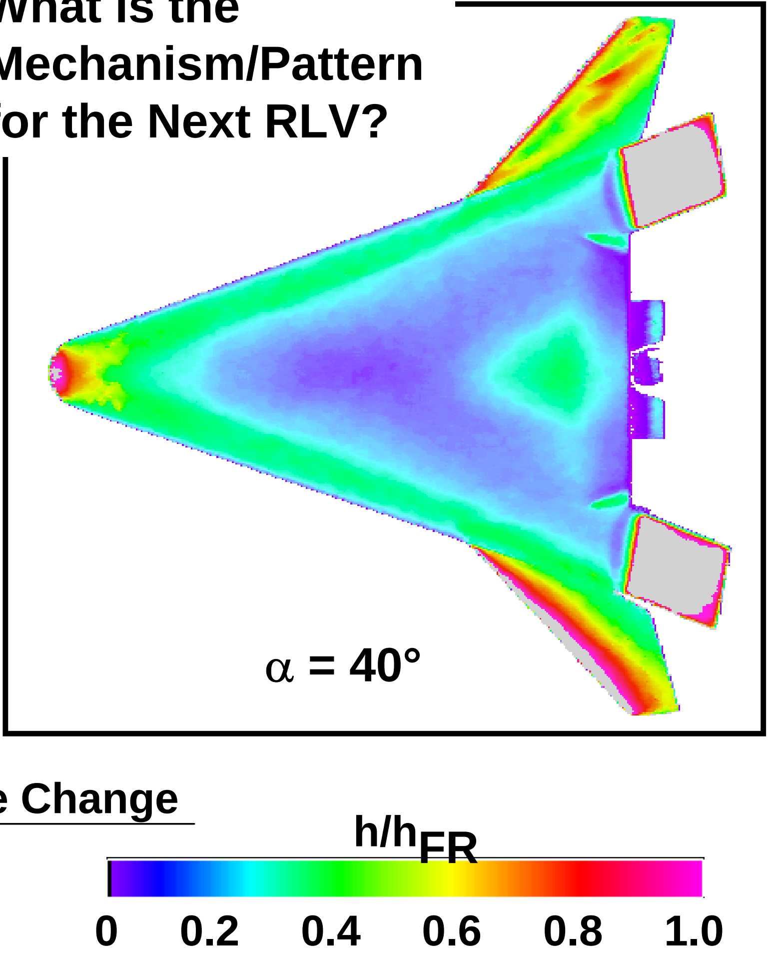
Effect Of Angle-of-Attack on Transition Mechanism for X-33 Rev-F

Mach 6 Expts, Color Prop. to Heating Rate

$M_\infty = 6$ $\delta_{BF} = 10°$ $Re_\infty/ft = 6x10^6$



What is the Mechanism/Pattern for the Next RLV?



Note Scale Change

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 all 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 Shuttle, X-33, X-38, Hyper-X remain to be determined; little or no data at present
- Bridge gap between users and researchers

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

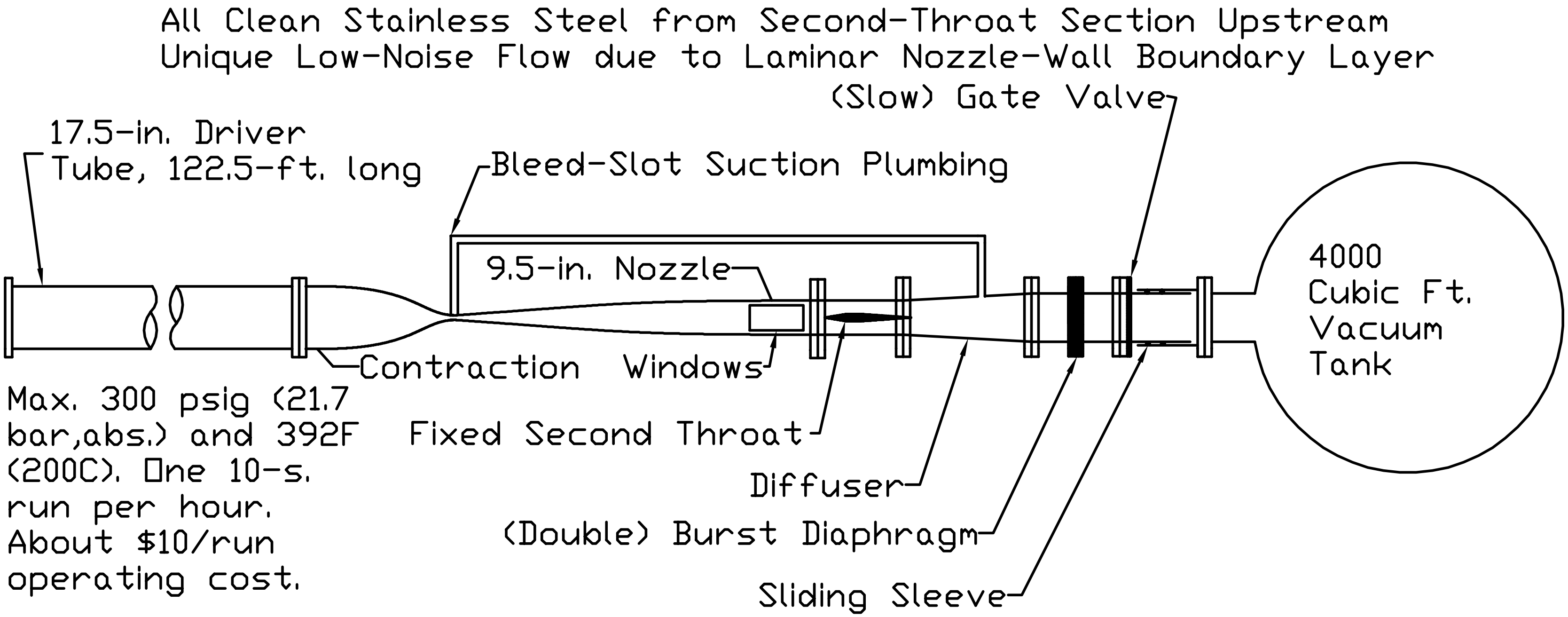
Summary of Purdue Effort, 1990-99

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

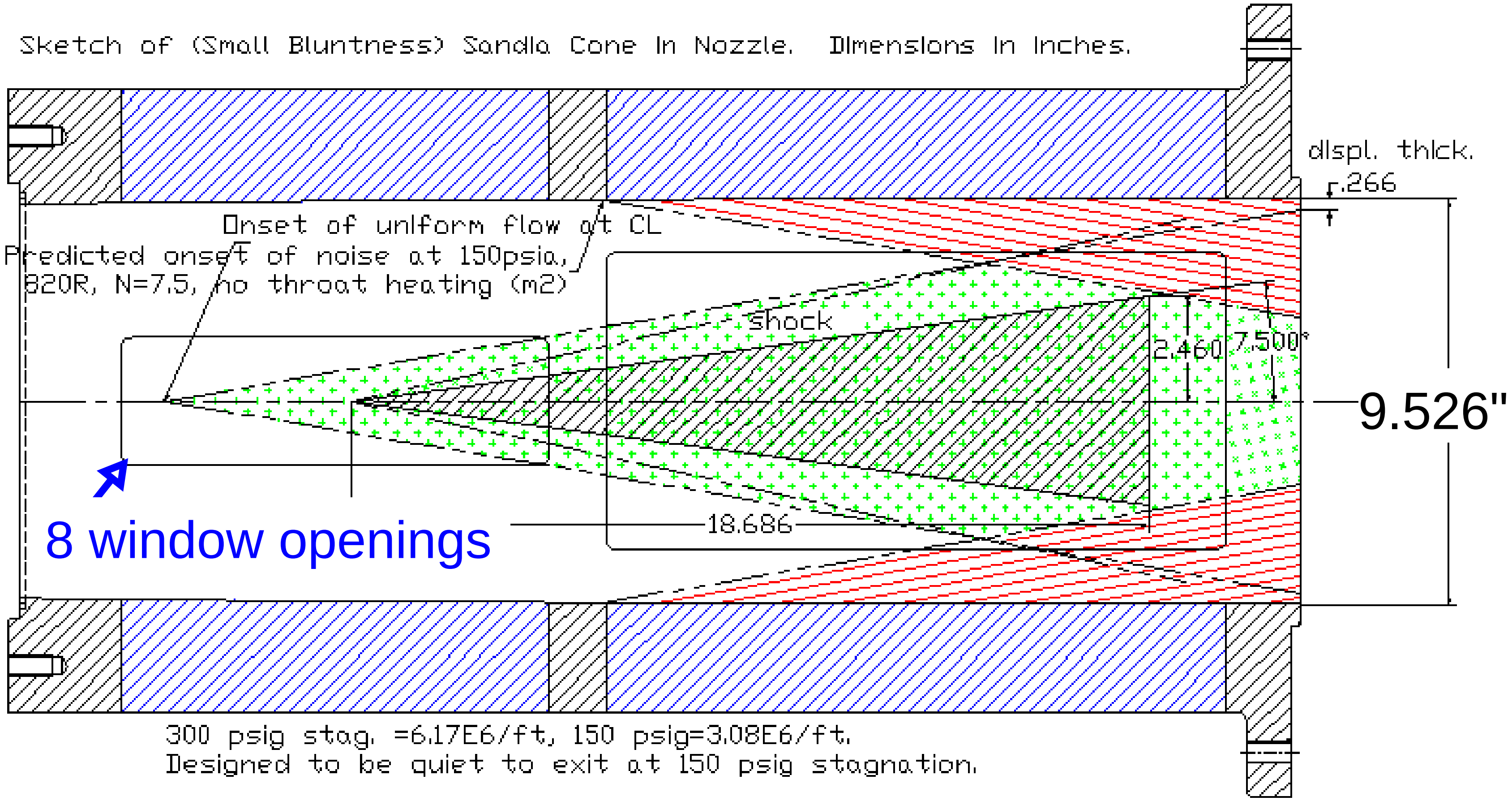
Boeing/AFOSR Mach-6 Quiet Tunnel



All Clean Stainless Steel from Second-Throat Section Upstream
Unique Low-Noise Flow due to Laminar Nozzle-Wall Boundary Layer

Max. 300 psig (21.7 bar,abs.) and 392F (200C). One 10-s. run per hour. About $10/run operating cost.

Schematic of Mach-6 Quiet Nozzle



Sketch of (Small Bluntness) Sandia Cone in Nozzle. Dimensions in Inches.

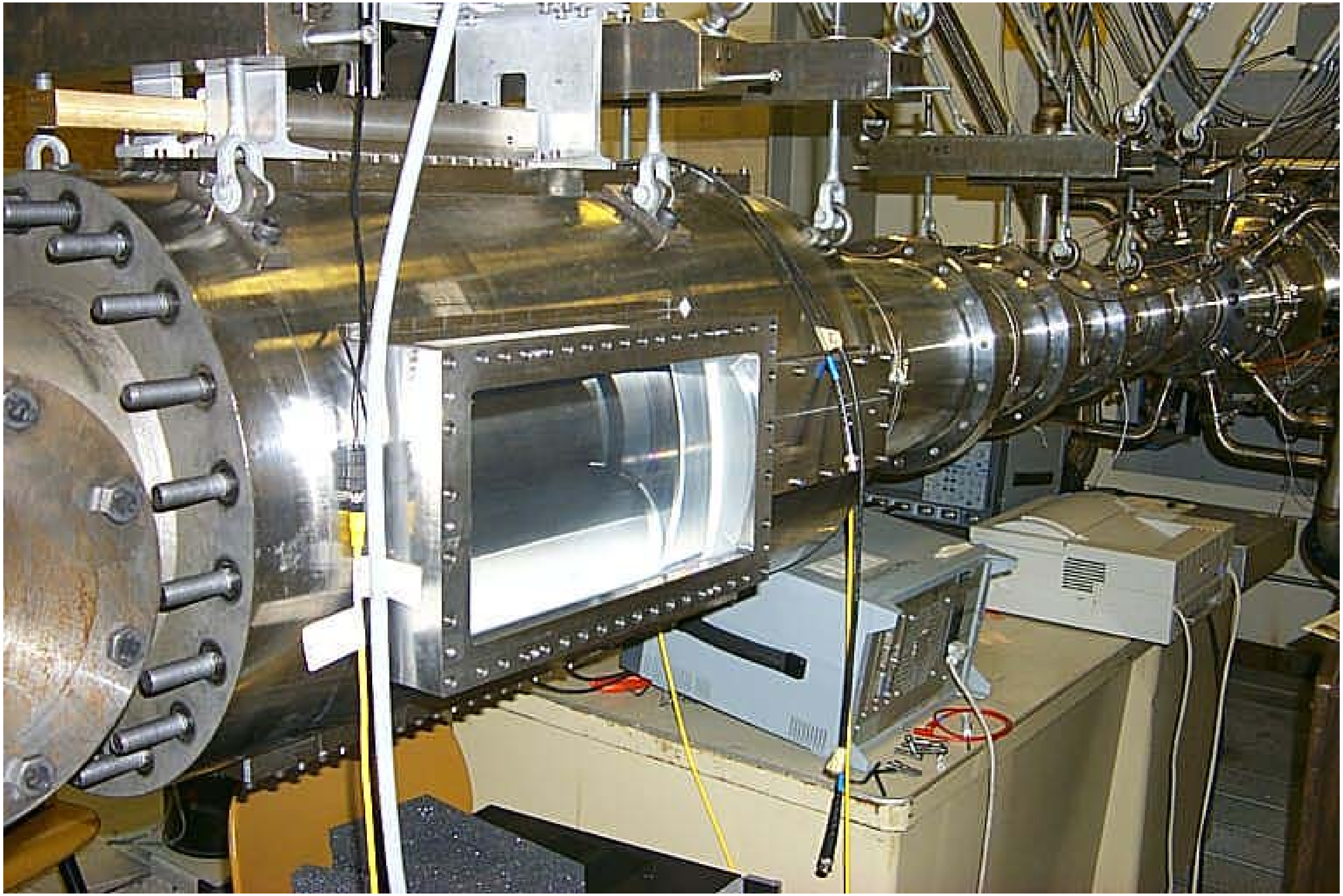
Onset of uniform flow at CL

Predicted onset of noise at 150psia, 820R, N=7.5, no throat heating (m2)

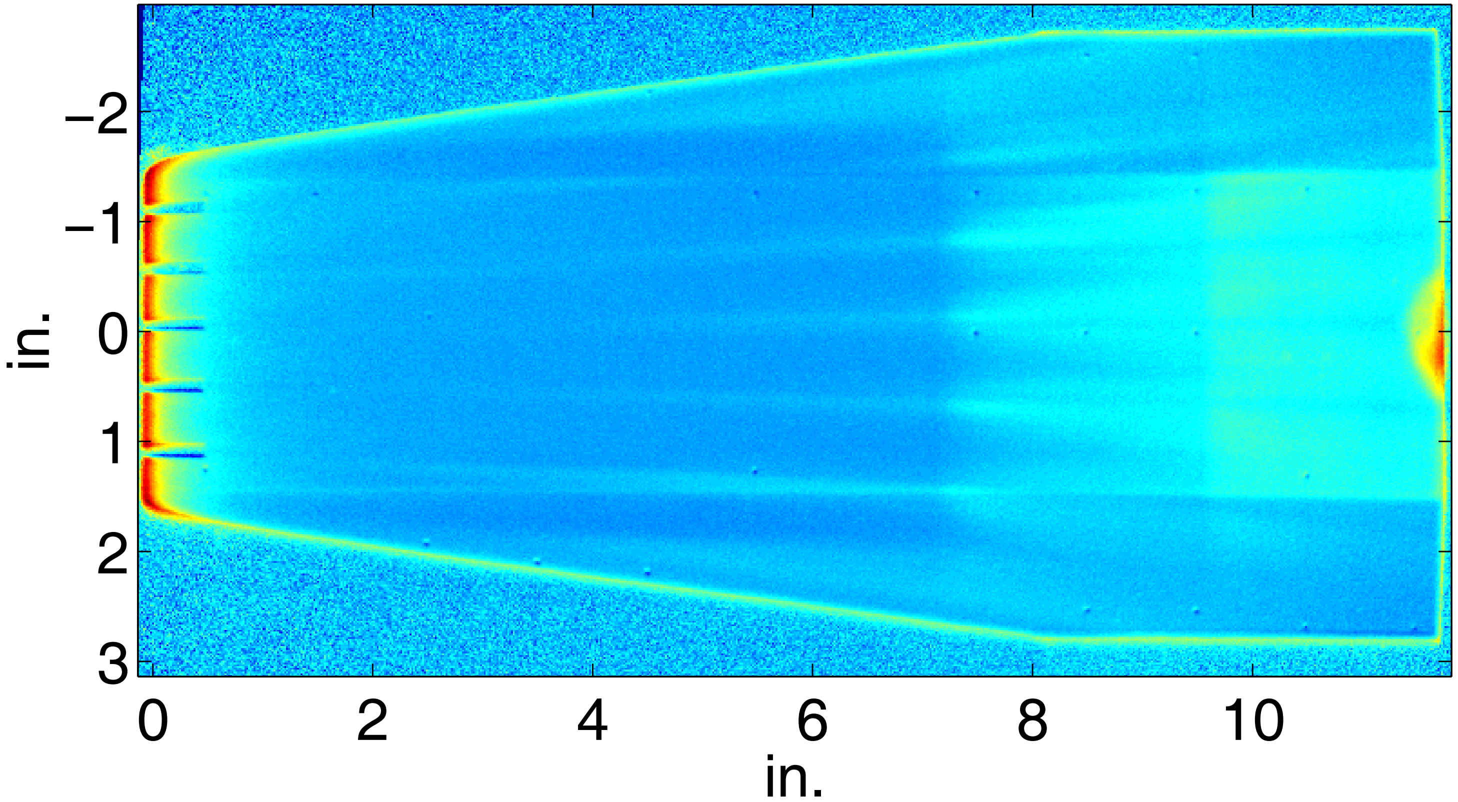
8 window openings

300 psig stag. =6.17E6/ft, 150 psig=3.08E6/ft.
Designed to be quiet to exit at 150 psig stagnation.

Plexiglas Window Inserted in Nozzle

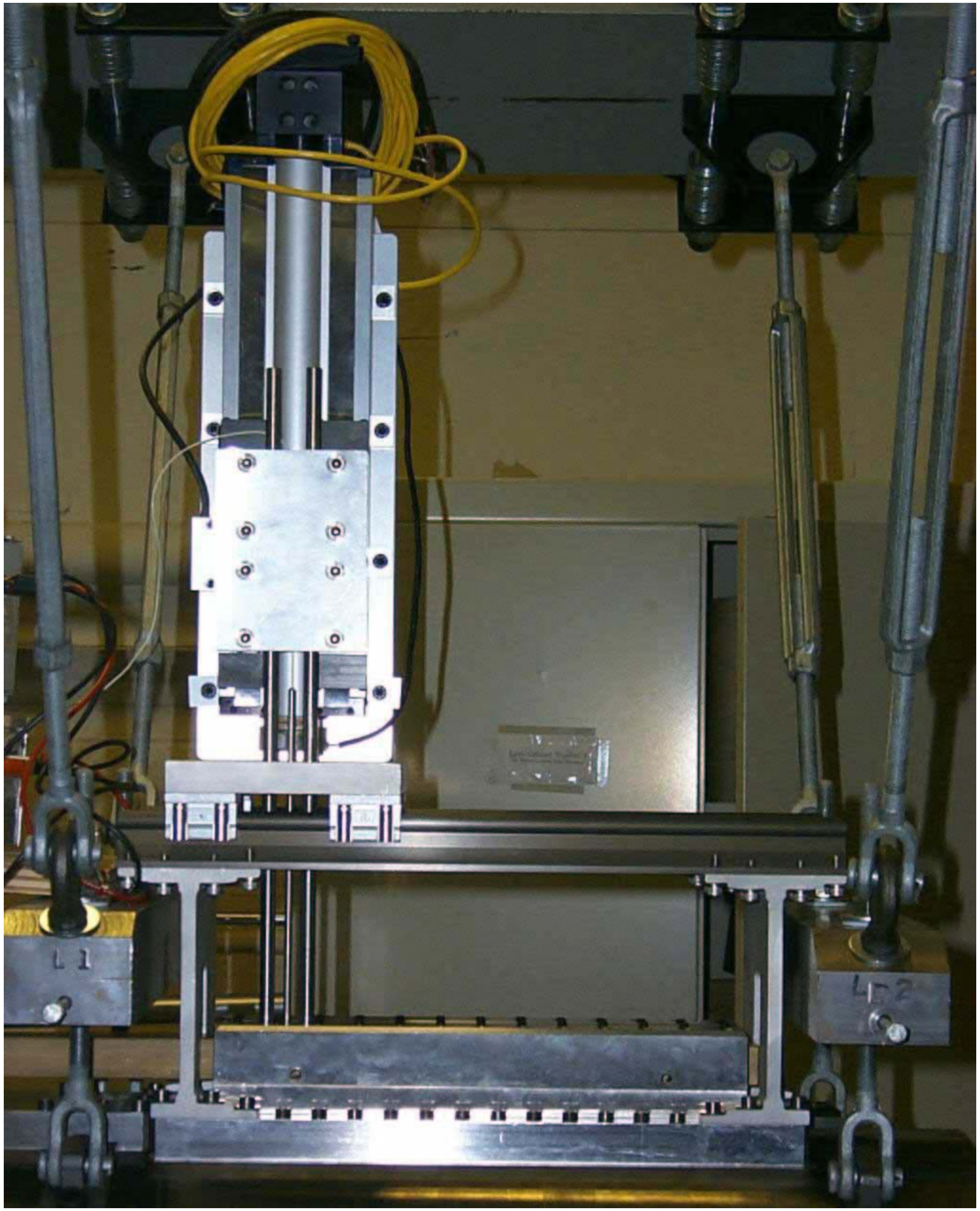


Streamwise-Vortex-Induced Transition on Hyper2000

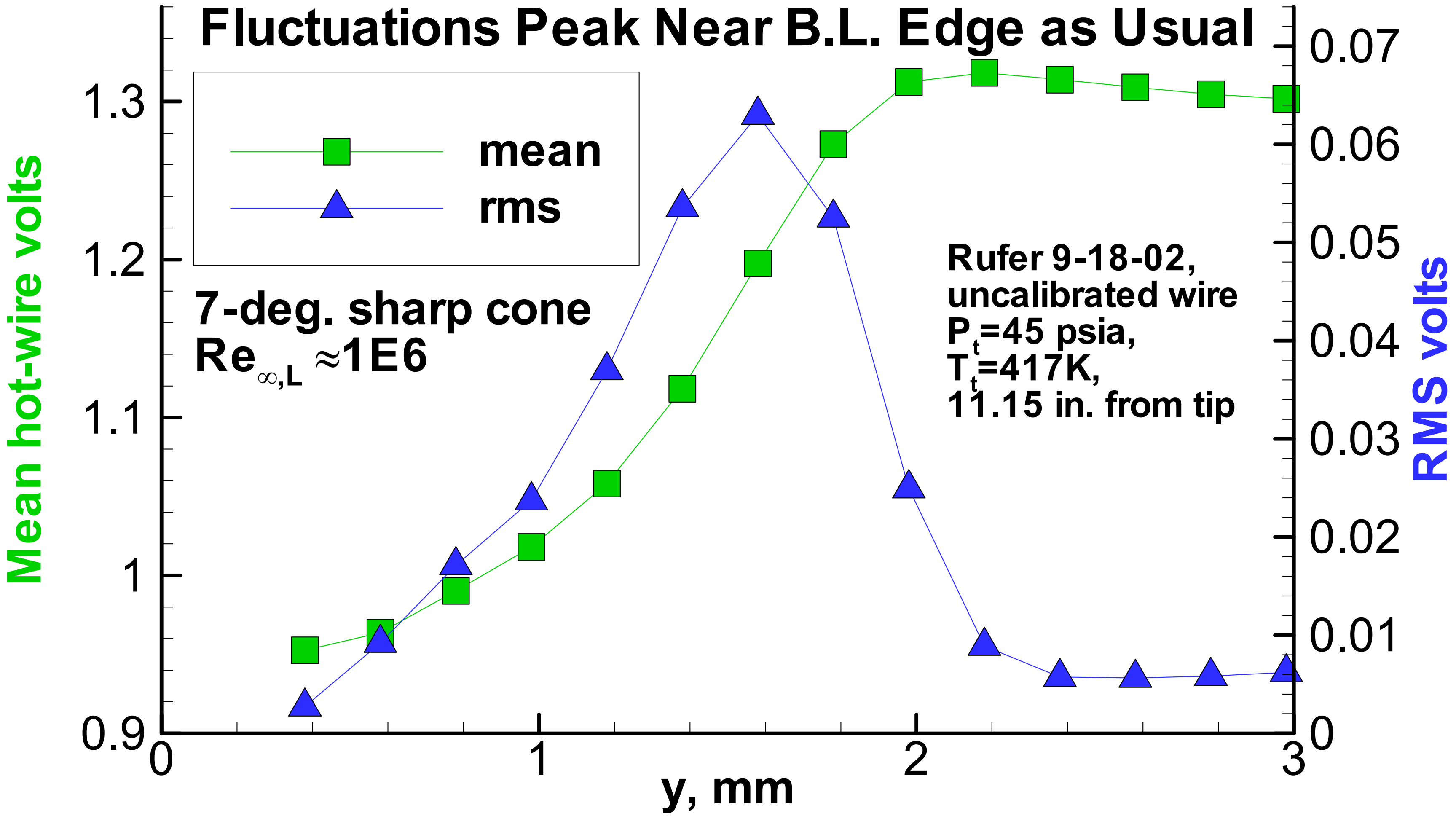


--Color Proportional to Heat-Transfer Rate, from Temp. Paints
--Hyper2000 is Generic for Hyper-X Class, Same Centerline Shape
--Roughness on Leading Edge Makes Small Vortices,
Which Grow Dramatically Past First Corner

Probe Traverse with Vertical Automation



Mach-6 Boundary-Layer Profile in One Run



Uncalibrated Preliminary; Uncorrected for Drop in Total Pressure

Summary of Purdue Effort

1. The $1m 9.5-inch Mach-6 tunnel runs reliably for about $10/shot
2. Extending quiet flow from low to high Reynolds number may yet be a simple modification
3. Tunnel noise is affected by temperature as well as unit Re. no.
4. An accurate large cone with a 5.5-in. base diameter has been built.
5. A 4-inch slab-delta model may start at 40-deg. AOA, although fluctuations high
6. Streamwise-vortex mechanisms can be studied with temp. paints
7. Hot wires can survive OK;   calibrations still needed
8. Automated traversing allows probing a full profile in one run
9. Hot-wire measurements of wave growth at Mach 6 are beginning
10. Everything is taking longer than planned, but there are no show-stoppers yet. Cost remains low.

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?

BACKUP SLIDES

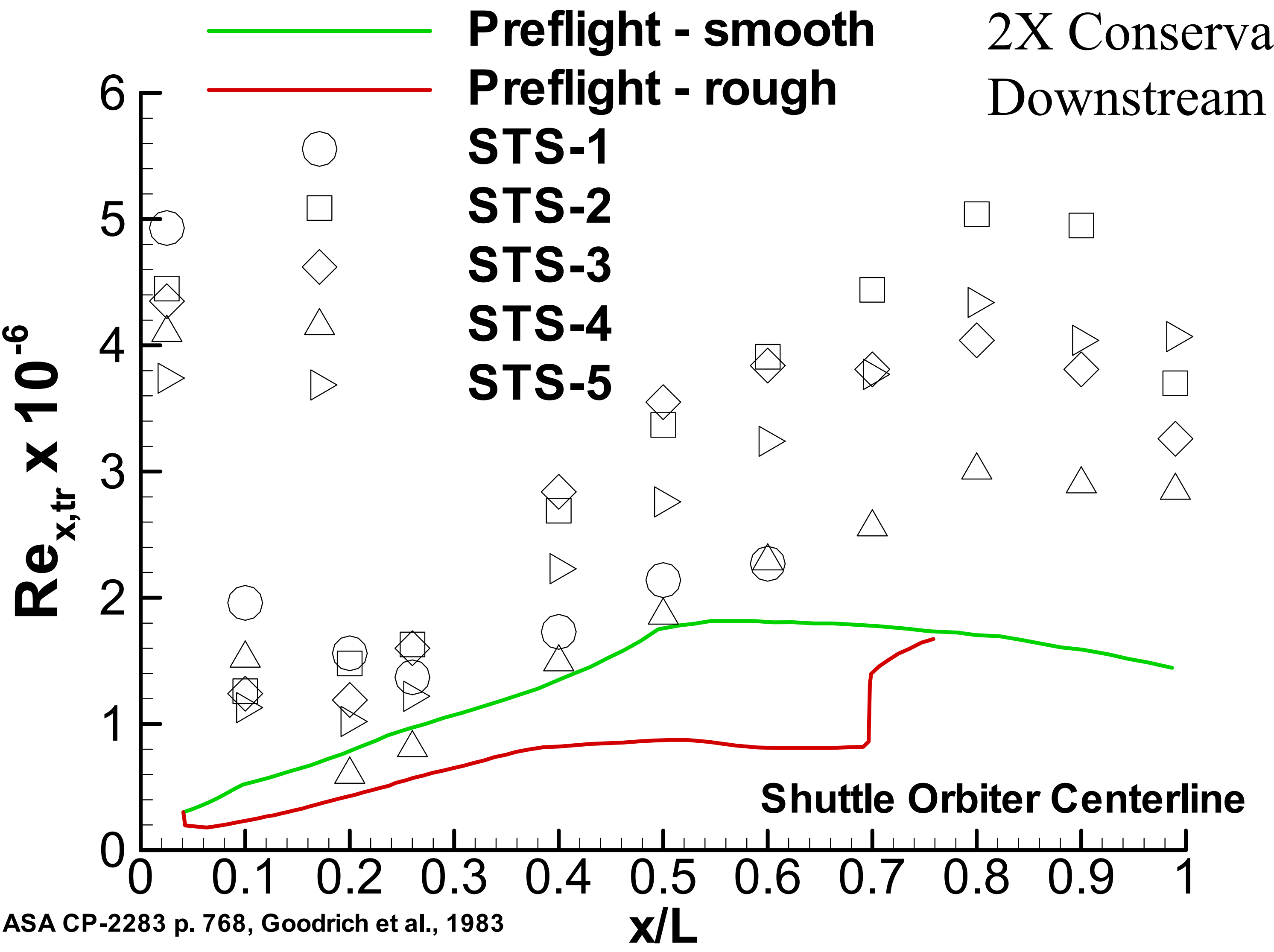
Aerothermal Loads Have 1st Order Impact on Airframe Weight Optimization

Bowcutt/Lau Sept. 2002

- Fully turbulent flow analysis
  - Does not permit accurate thermal gradient predictions
  - Results in excessive TPS weight penalties

- Must also account for heating amplification mechanisms
  - Shock/boundary layer interaction (e.g., inlet shocks)
  - Fin shocks
  - Fin gap heating
  - Corner flow
  - Free shear flows
  - Vortex impingement
- Heating distribution effects
  - Thermal expansions at component joints
  - Stress induced by temperature gradients in & between components
  - Shape distortion by thermal/pressure gradients

Shuttle Transition – Preflight Predictions Compared

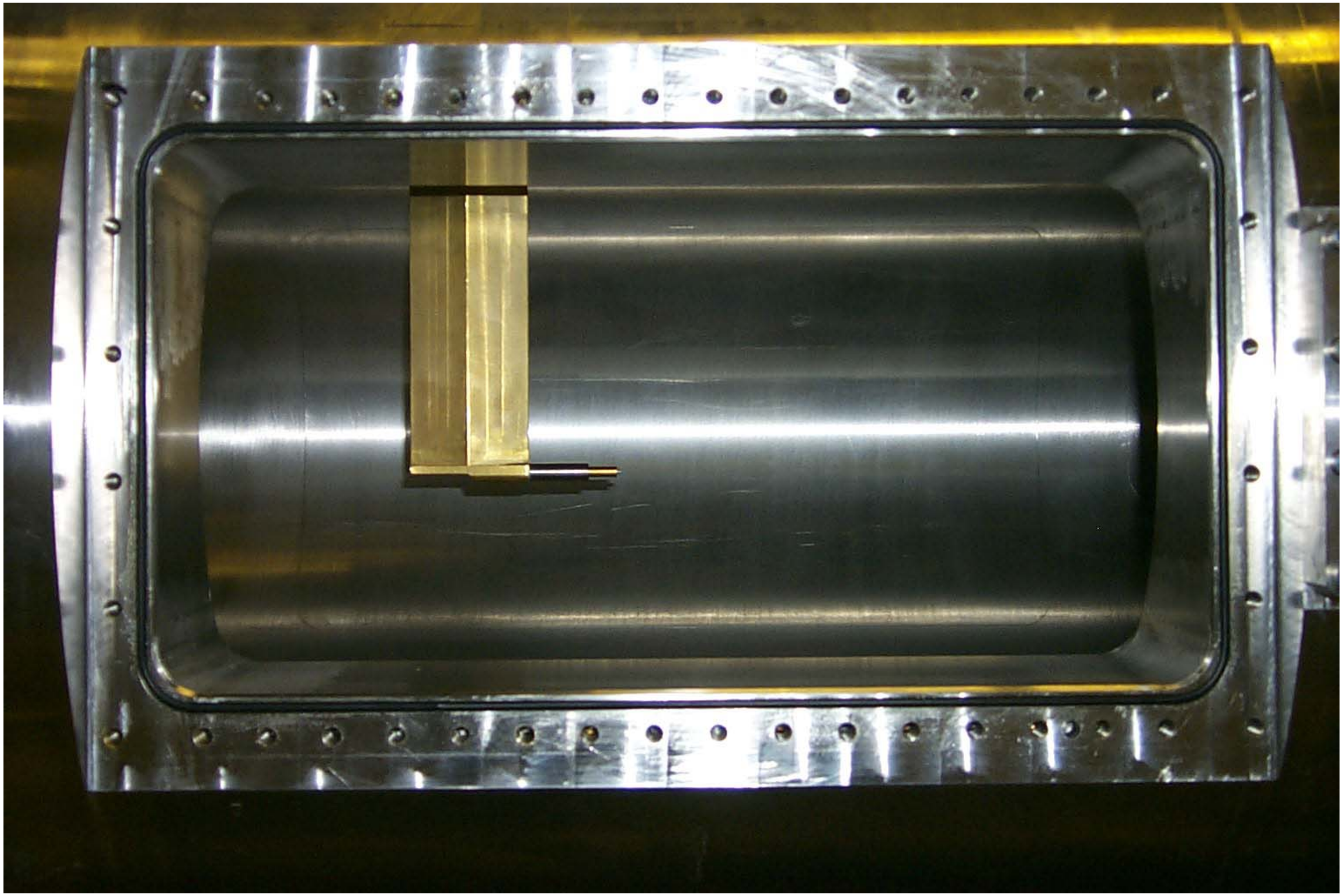


2X Conservative Downstream

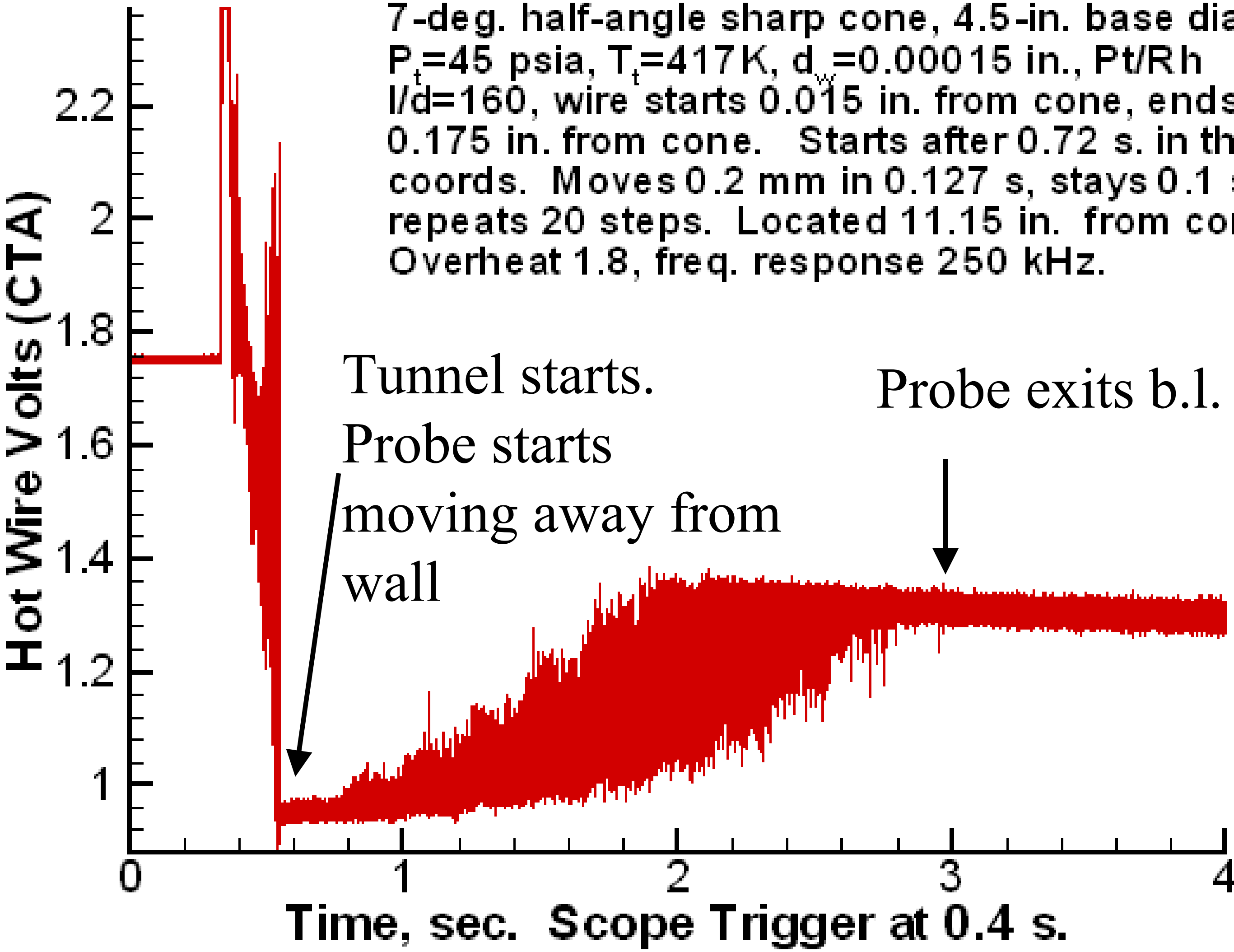
NASA CP-2283 p. 768, Goodrich et al., 1983

S.P. Schneider, Purdue AAE

Pitot Probe in Nozzle, Window Removed



Single-Run Hot Wire Profile of Mach-6 Boundary Layer



7-deg. half-angle sharp cone, 4.5-in. base diam., P_t=45 psia, T_t=417K, d_w=0.00015 in., Pt/Rh l/d=160, wire starts 0.015 in. from cone, ends 0.175 in. from cone. Starts after 0.72 s. in these coords. Moves 0.2 mm in 0.127 s, stays 0.1 s, repeats 20 steps. Located 11.15 in. from cone tip. Overheat 1.8, freq. response 250 kHz.

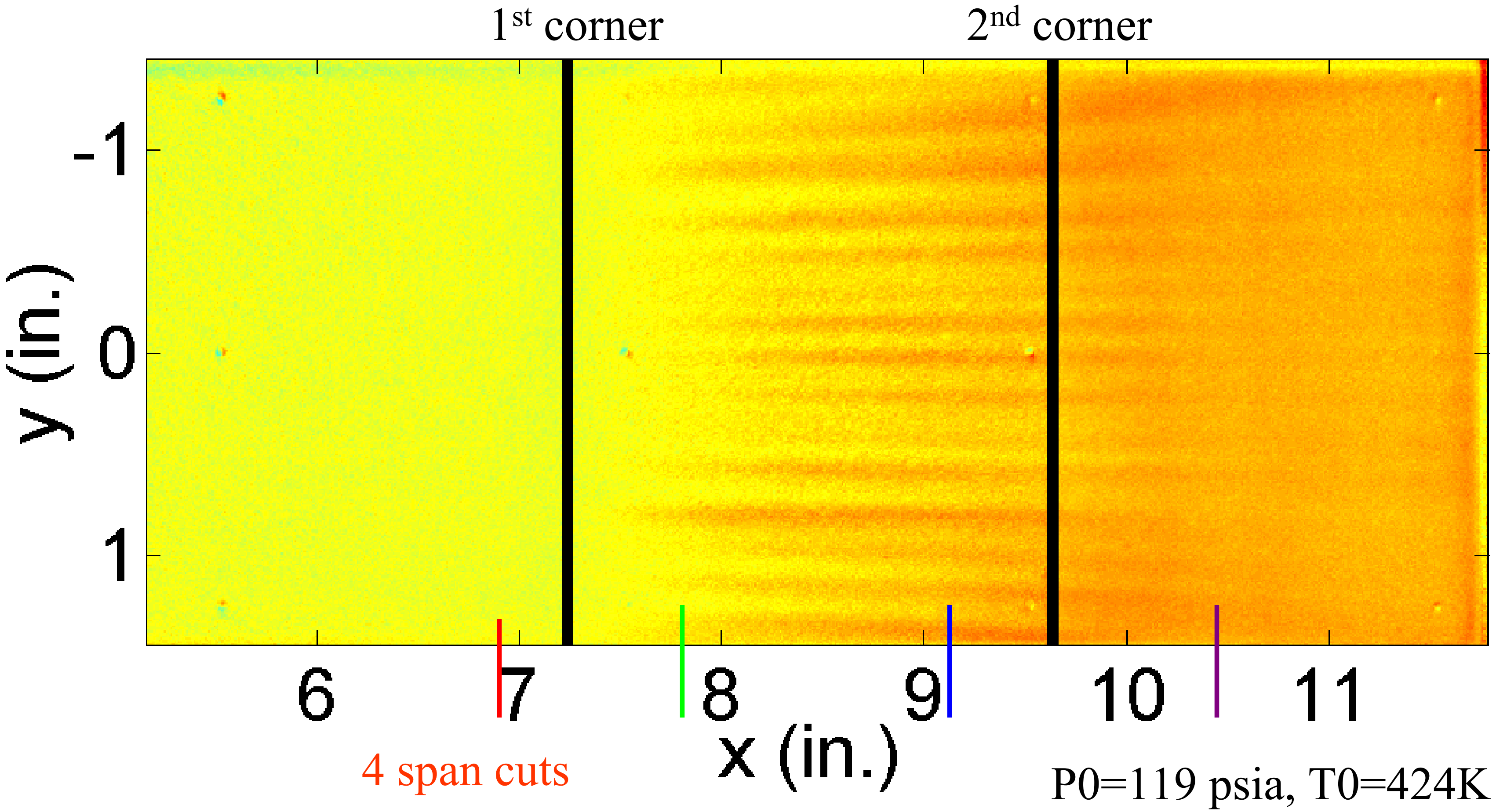
Tunnel starts. Probe starts moving away from wall

Probe exits b.l.

sampled 500kHz for 4 s, 9/18/02

Streamwise Streaks in Hyper2000 Heating Rates

17 roughness strips on LE, 0.00015-in. high, 0.16 on centers, 0.03 wide

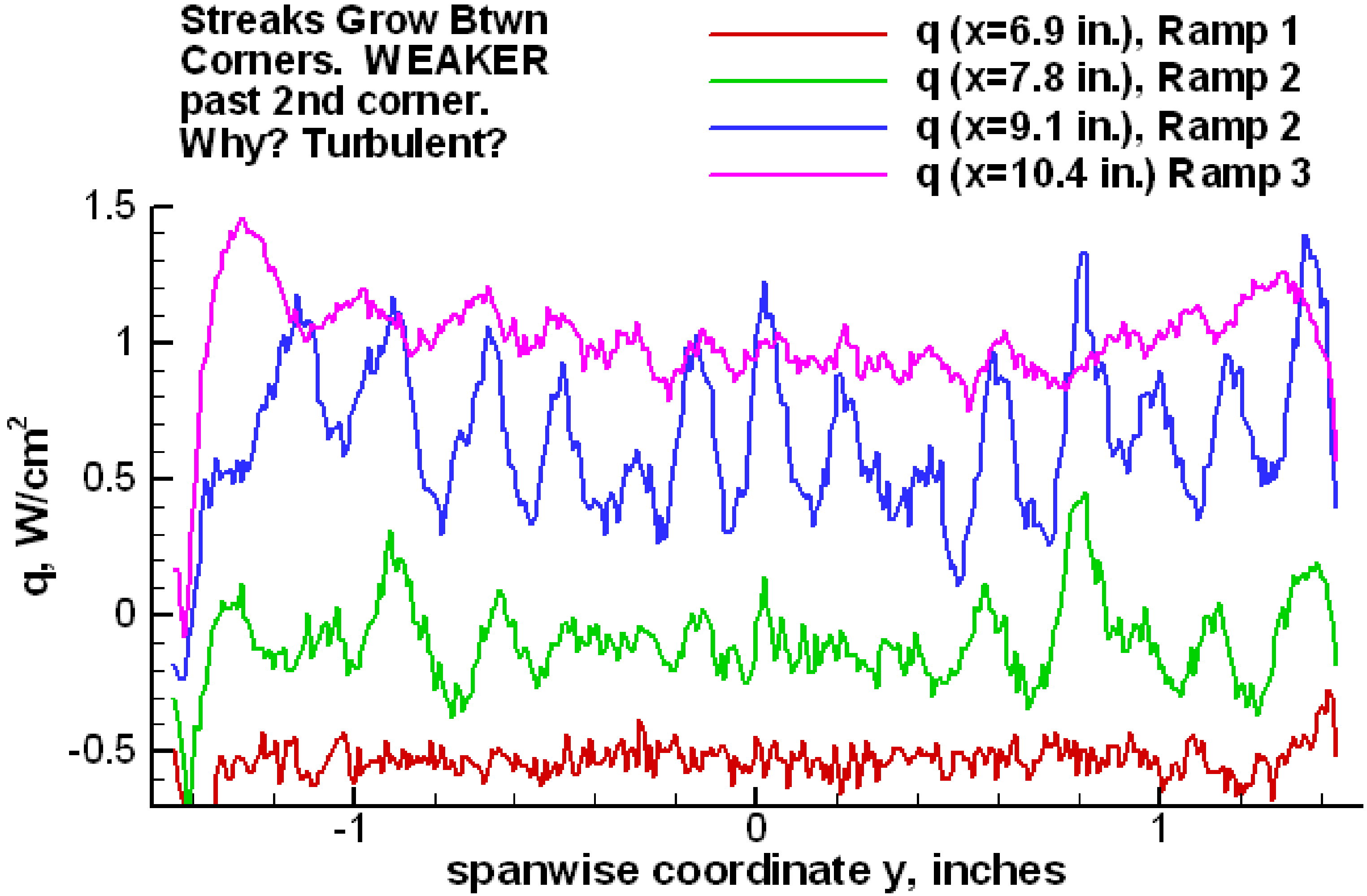


4 span cuts

P0=119 psia, T0=424K

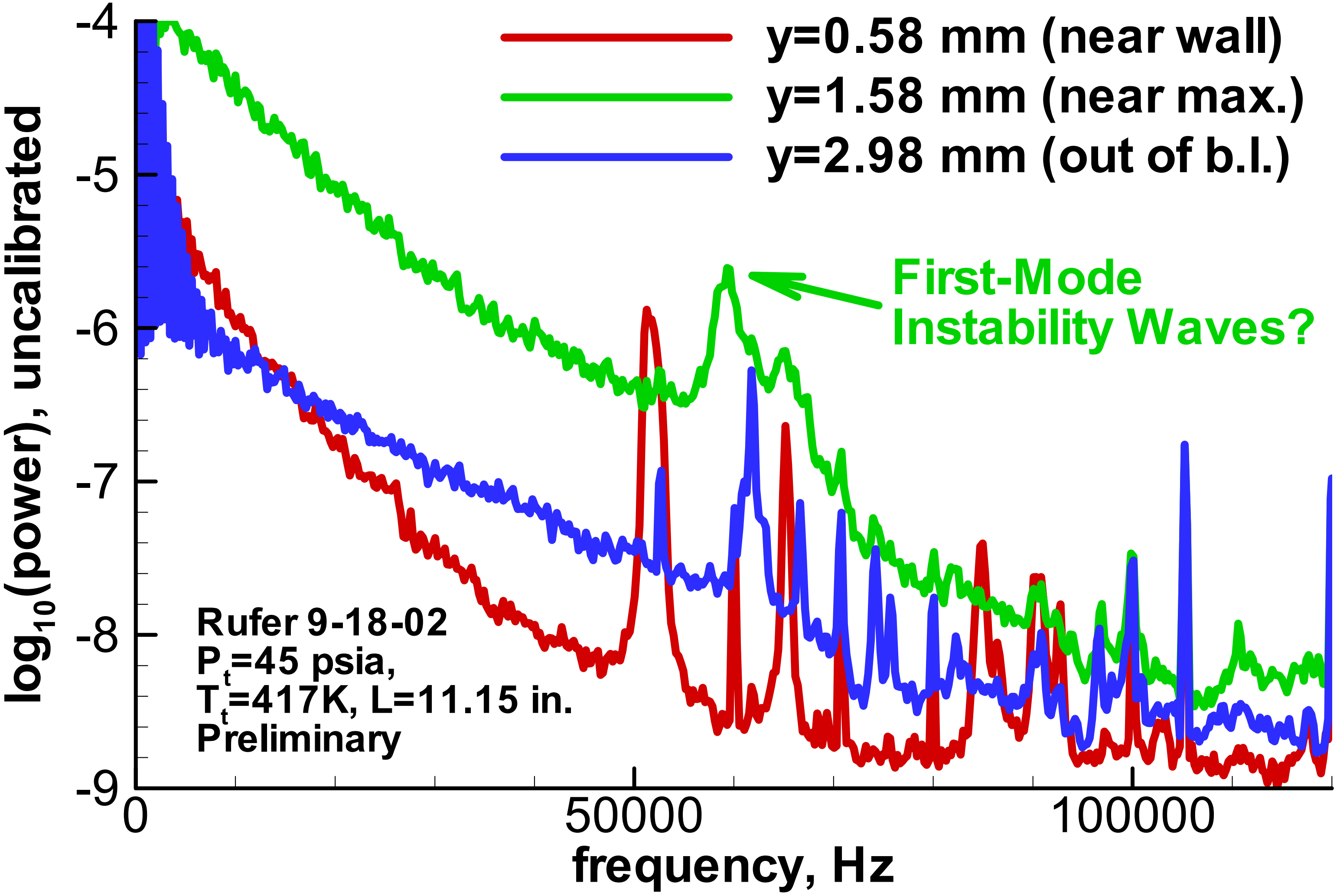
Spanwise Variation of Heat Transfer on Hyper2000

P_0=119 psia, T_0=424K, 17 roughness strips on l.e., 0.0015-in. thick, strips 0.03-in. wide, 0.16-in. o.c., extend 1/64-in. downstream of l.e., 1st corner at 7.24 in., 5.5°, 2nd corner at 9.64 in. 3°



Streaks Grow Btwn Corners. WEAKER past 2nd corner. Why? Turbulent?

Hot-Wire Spectra from Boundary Layer



Some References

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1. Steven P. Schneider, "Flight Data for Boundary-Layer Transition at Hypersonic and Supersonic Speeds," *J. of Spacecraft and Rockets*, 36, no. 1, January-February 1999, pp. 8-20.

2. Steven P. Schneider, "Effects of High-Speed Tunnel Noise on Laminar-Turbulent Transition," *J. of Spacecraft and Rockets*, 38, no. 3, May-June 2001, pp. 323-333.

3. Takeshi Ito, Laura A. Randall, and Steven P. Schneider, "Effect of Noise on Roughness-Induced Boundary-Layer Transition for Scramjet Inlet," *J. Spacecraft and Rockets*, 38, no. 5, September-October 2001, pp. 692-698.

4. Steven P. Schneider, Shann Rufer, Craig Skoch, Shin Matsumura, and Erick Swanson, "Progress in the Operation of the Boeing/AFOSR Mach-6 Quiet Tunnel," AIAA Paper 2002-3033.