Performance Improvements in Boeing/AFOSR Mach 6 Quiet Wind Tunnel Based on CFD Predictions

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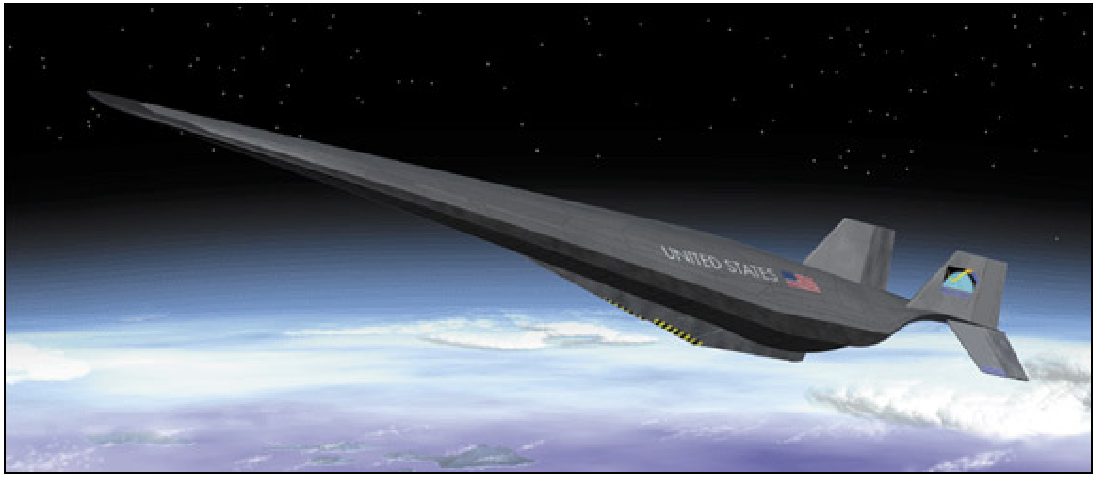
Motivation

- Importance of quiet tunnels for hypersonic research

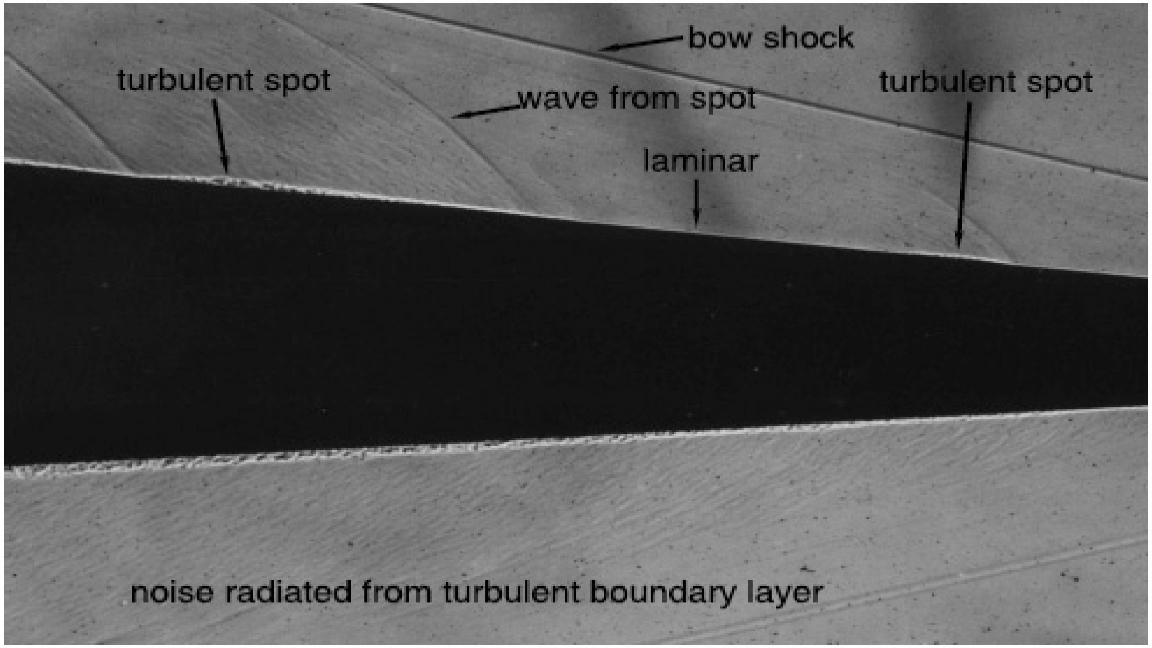
  Understanding the nature of laminar-to-turbulent transition is crucial for:

  - Reusable launch vehicles
  - Hypersonic reconnaissance aircraft
  - Hypersonic cruise vehicles
  - Ballistic reentry vehicles
- Current Programs
  - *DARPA FALCON* glide vehicle
  - X-51
  - Orion

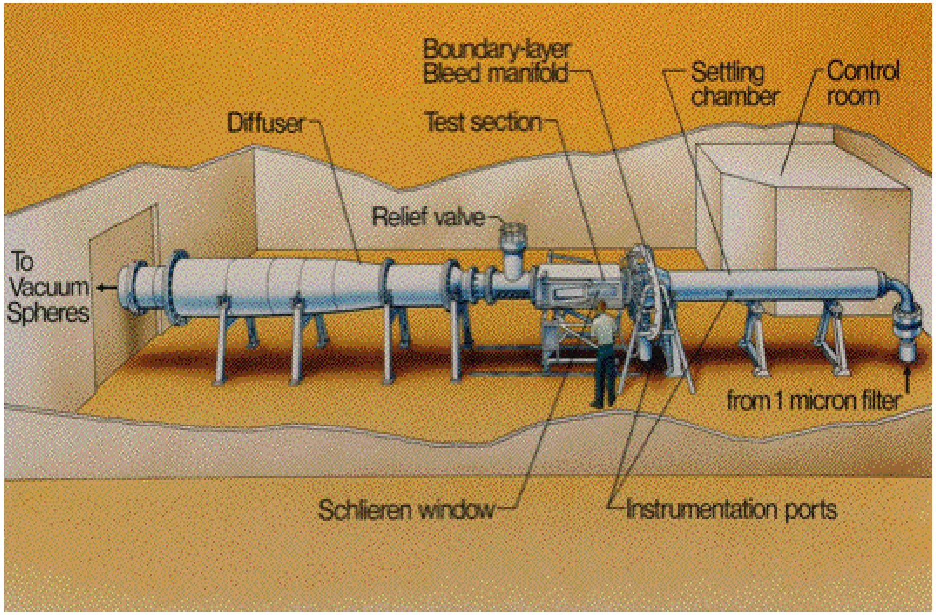


- Transition location affects data
  - Aerodynamic Heating
  - Skin Friction Drag
  - Heat Shield Weight, Materials
- Conventional wind tunnel

  Contaminated by high noise levels
  - Location of transition
  - Parametric trends for transition

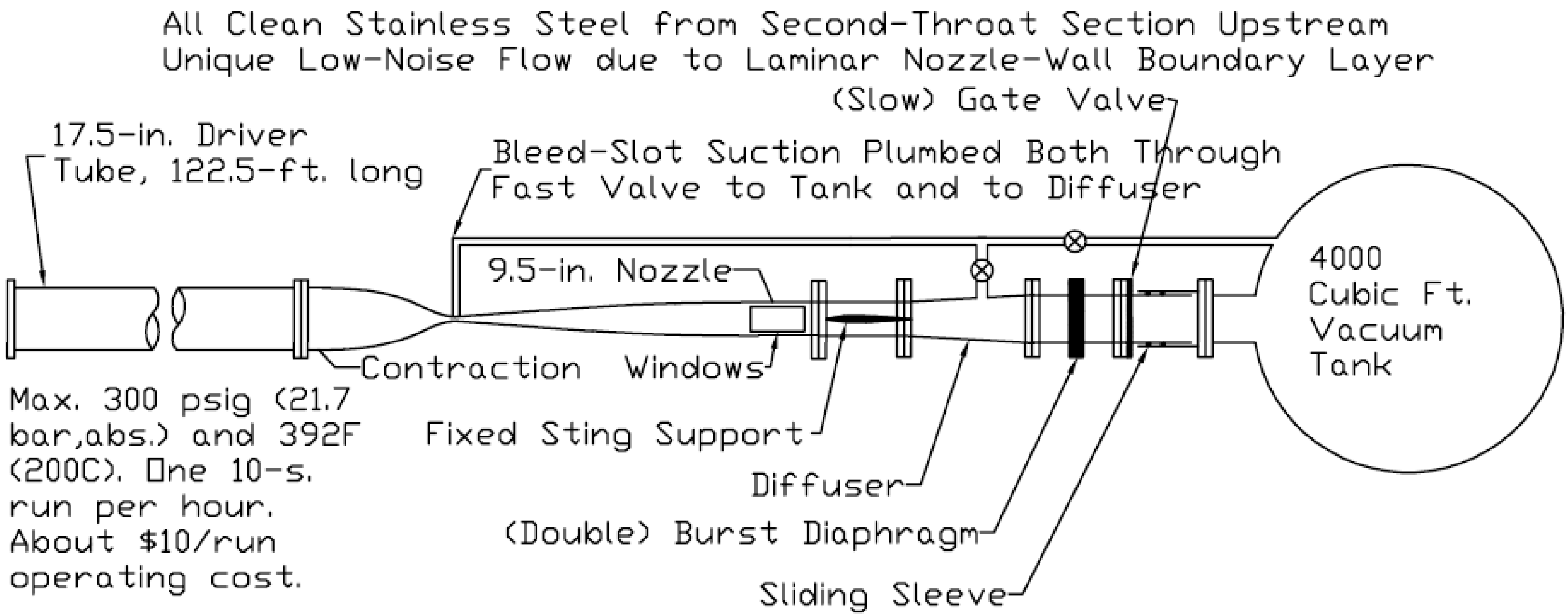


- *Quiet Flow* Wind Tunnel
  - Simulate hypersonic flight where the noise levels are very low
  - Laminar boundary layers in the test section
- Quiet Facilities
  - NASA Langley -- *M=3.5*
  - NASA Langley -- *M=6*
    - Reassembled at Texas A&M
  - NASA Langley -- *M=8*
    - Abandoned, 2001
  - Boeing/AFOSR Mach-6 Quiet Tunnel (BAM6QT)
    - 145 psia, Re ~ 13 x 10^6



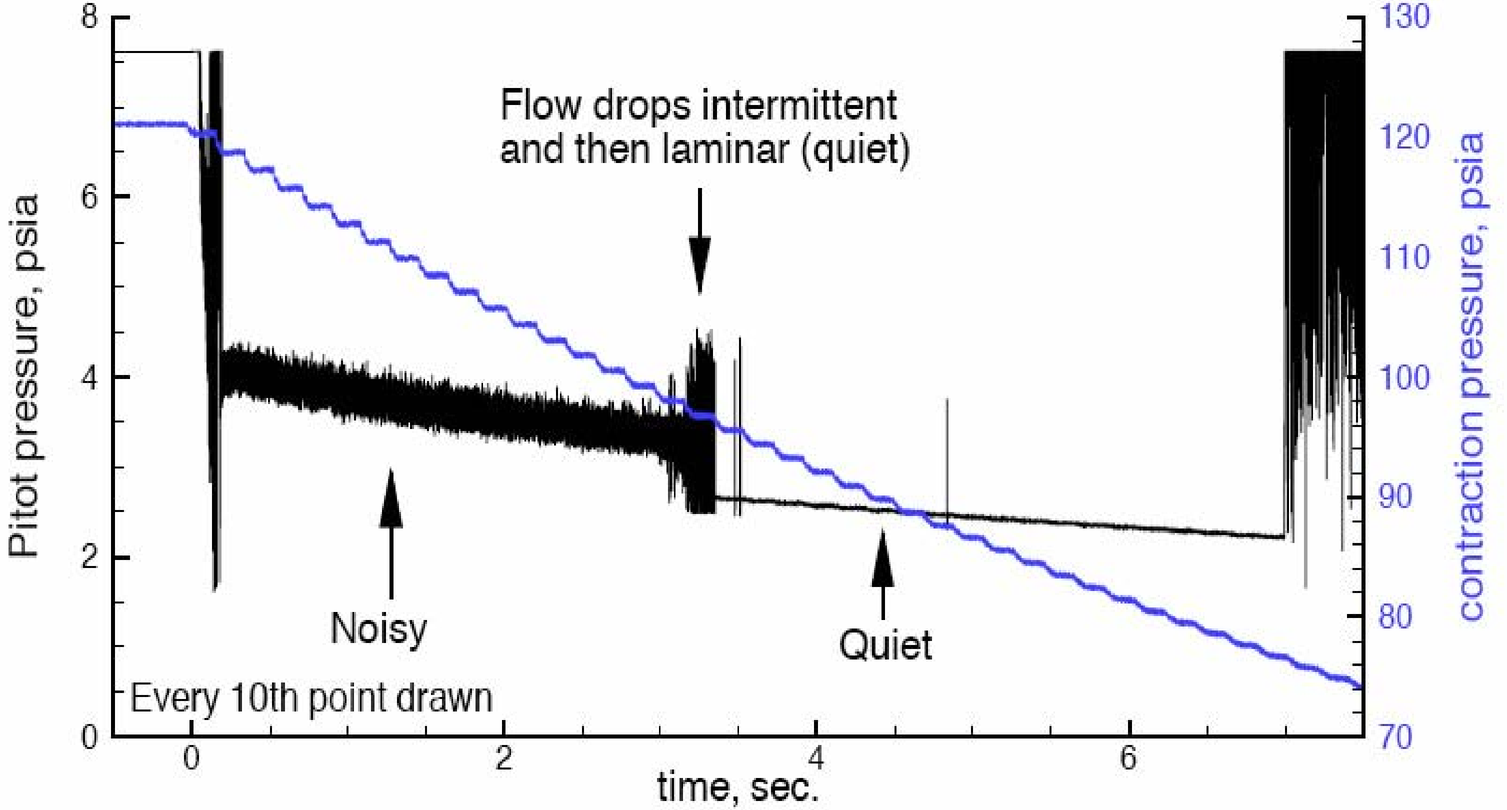
The Development of Hypersonic Quiet Tunnels, S. P. Schneider
37th AIAA Fluid Dynamice Conference, June 2007

Ludwieg Tube

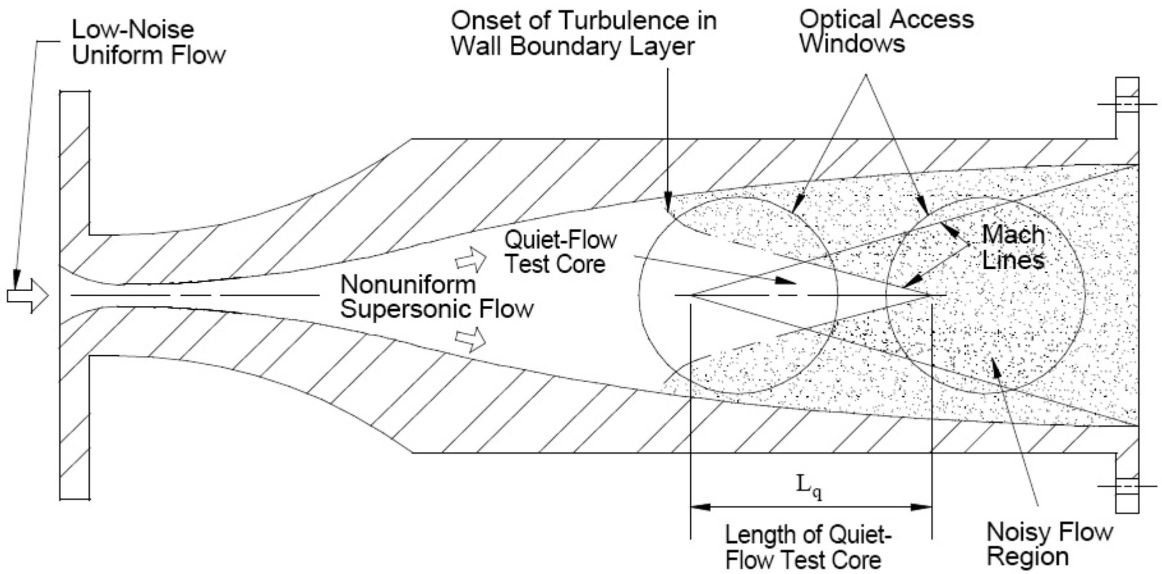


Typical Oscilloscope Output

- During many cycles of expansion-wave reflection, the pressure drops in stair-step fashion

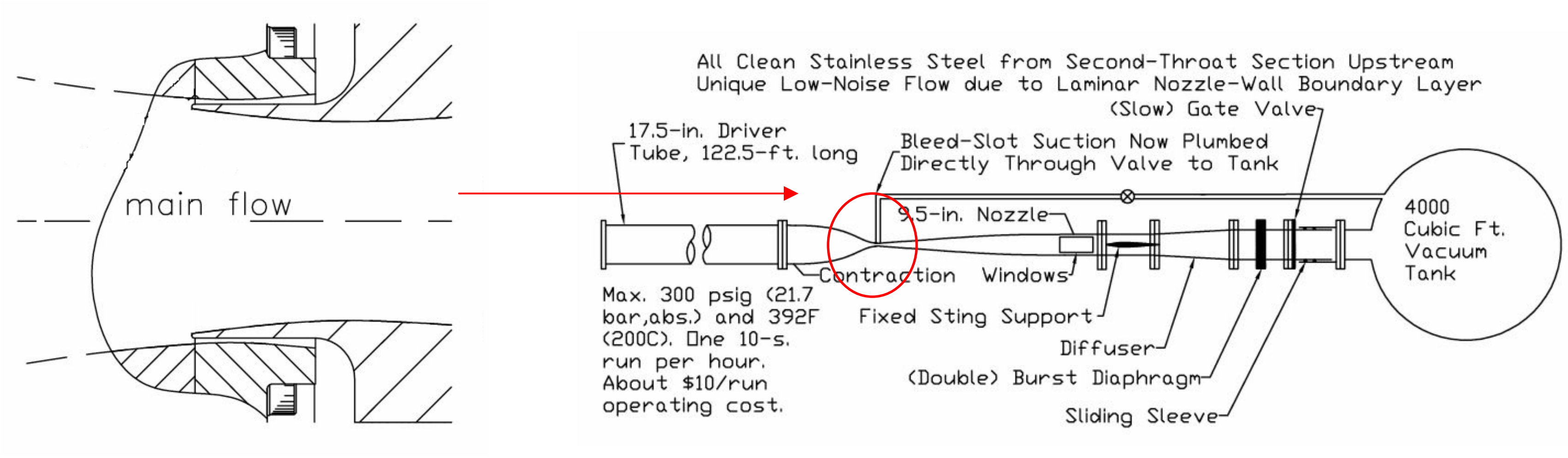


Quiet Test Section



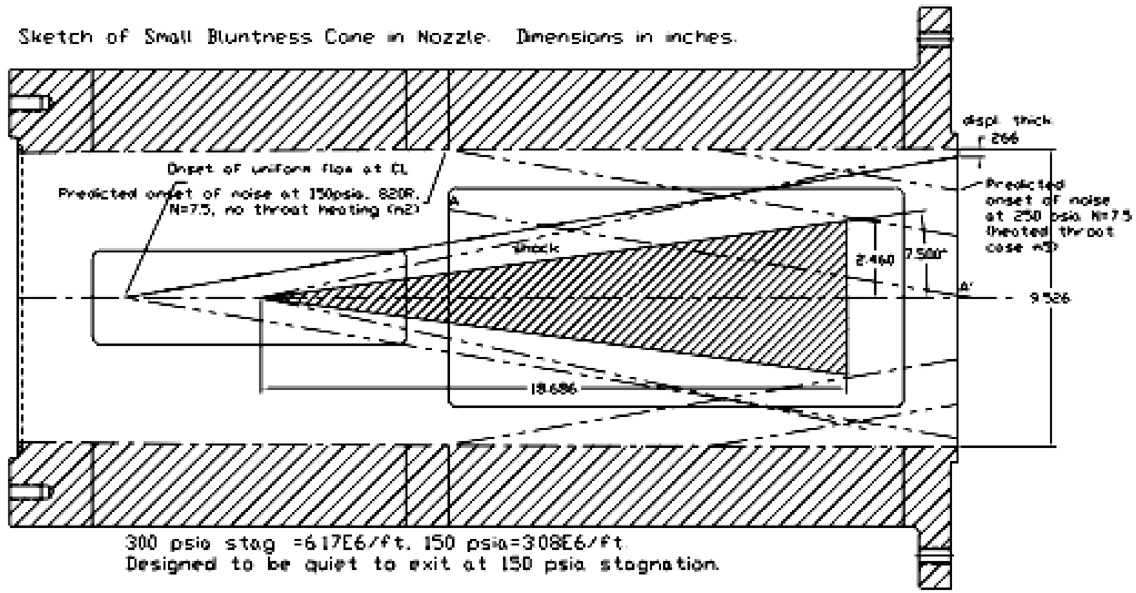
- Quiet flow region in test section is determined by
  - Characteristics marking onset of uniform flow
  - Characteristics marking beginning of acoustic radiation from onset of turbulence

Bleed Slot



- Bleed slot before the throat removes contraction-wall boundary layer
- Purpose: reduces noise by delaying boundary layer transition

Test Section Expansion



- Shocks emanating from a model interact with nozzle wall boundary layer, causing separation for blunter models
- Expand the test section diameter and determine the largest model that can be started in the tunnel

Objectives

Two cases that used CFD to improve performance of the BAM6QT:

- The effect of bleed lip geometry on nozzle wall boundary layer transition
- The effect of a test section expansion on the ability to test larger blunt models

Bleed Lip Redesign

As of 2005, the tunnel was not yet quiet for the desired range of pressures up to 150 psi.

Cause of test section noise:

• Early transition of the nozzle wall boundary layer.

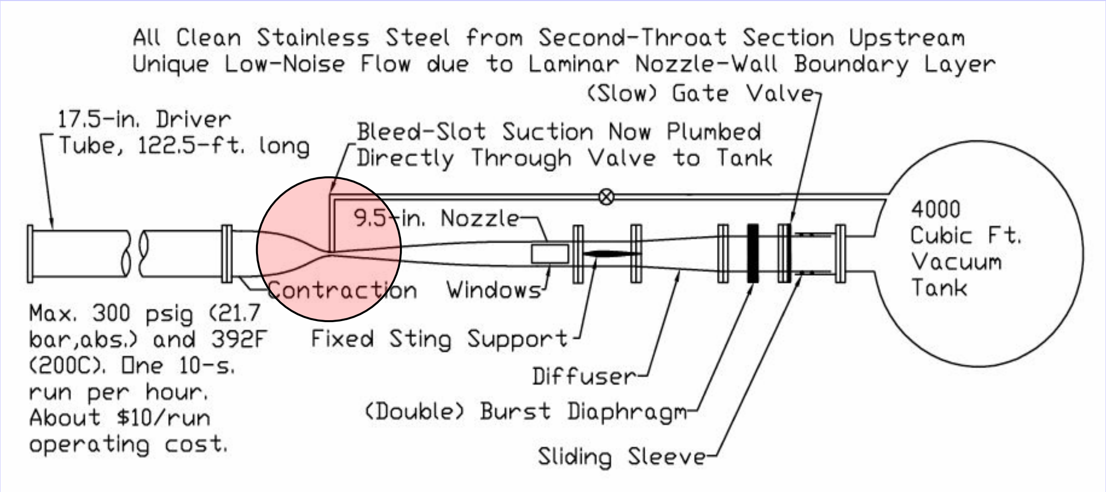
Cause of early transition:

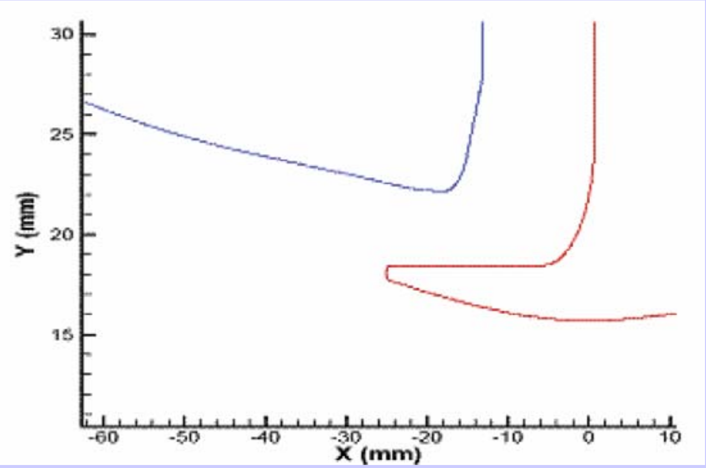
• Separation bubbles on the bleed lip and associated fluctuations induced near the bleed lip.

Bleed Lip Redesign

- Use CFD to
  - Investigate numerically the existence of steady and unsteady separation bubbles on the main flow and/or the bleed flow side of the original nozzle lip
  - Design a new geometry to eliminate or reduce the size of the separation bubbles

Analysis of Existing Bleed Lip

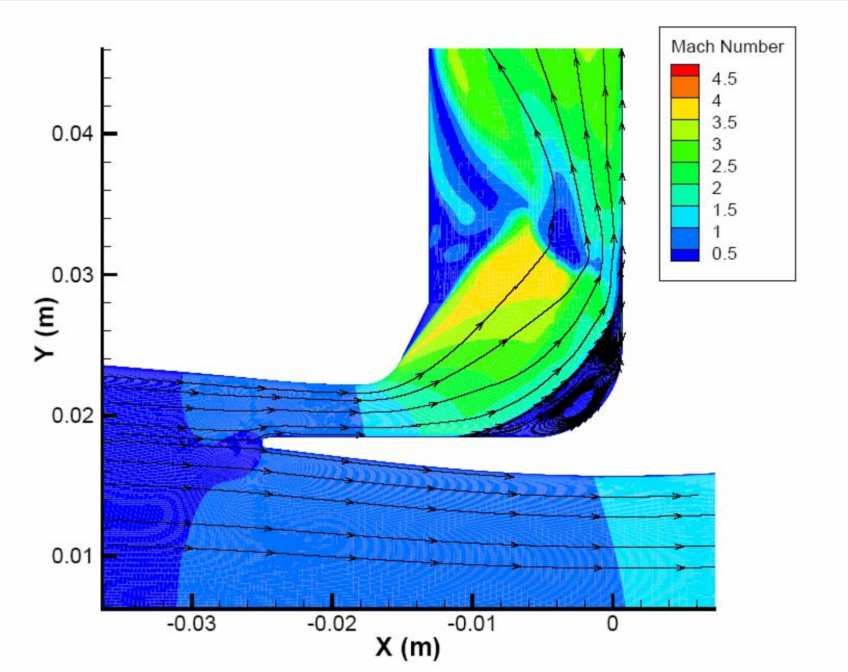


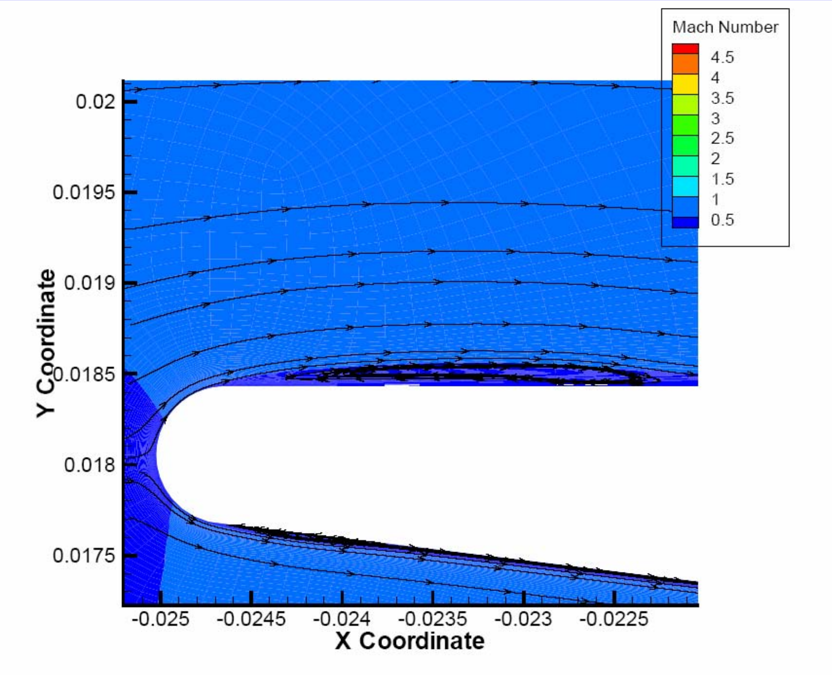


The geometry is represented by two surfaces.

Analysis of Existing Bleed Lip

- Separation bubbles exist on both the main flow and bleed flow sides for all the stagnation pressures tested.



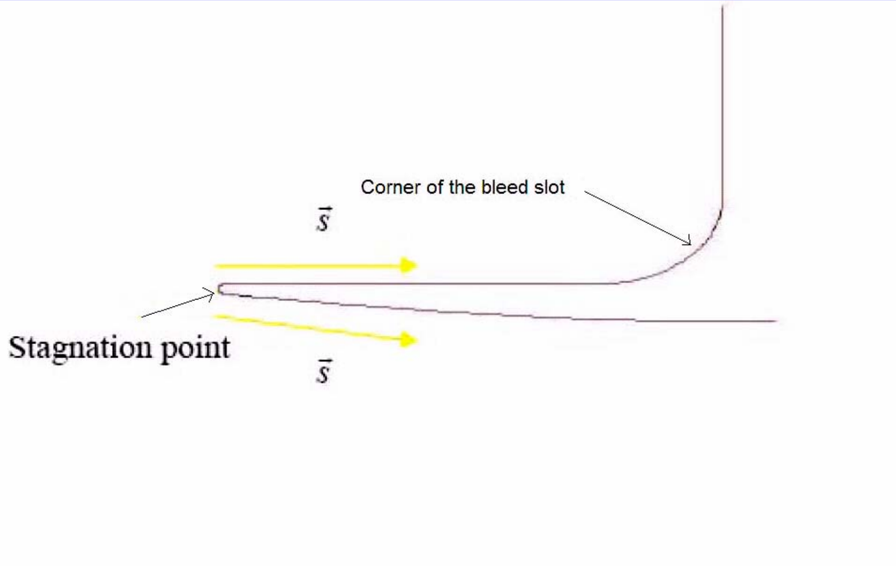


Mach number contours and streamlines for 150 psi.

Analysis of Existing Bleed Lip

- Separation bubbles exist on both the main flow and bleed flow sides for all the stagnation pressures tested.

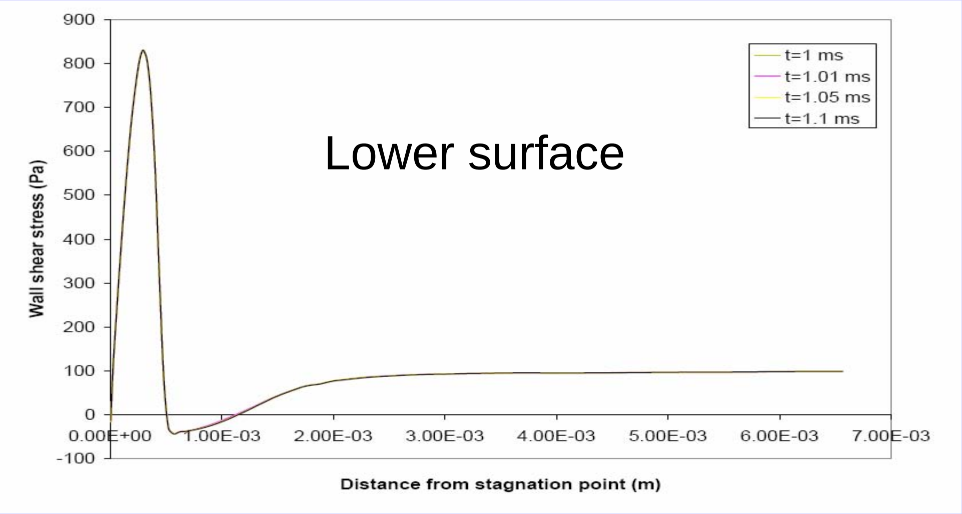
$$\Gamma_w = \mu_w \frac{\vec{s}.\vec{V}}{\Delta n}$$

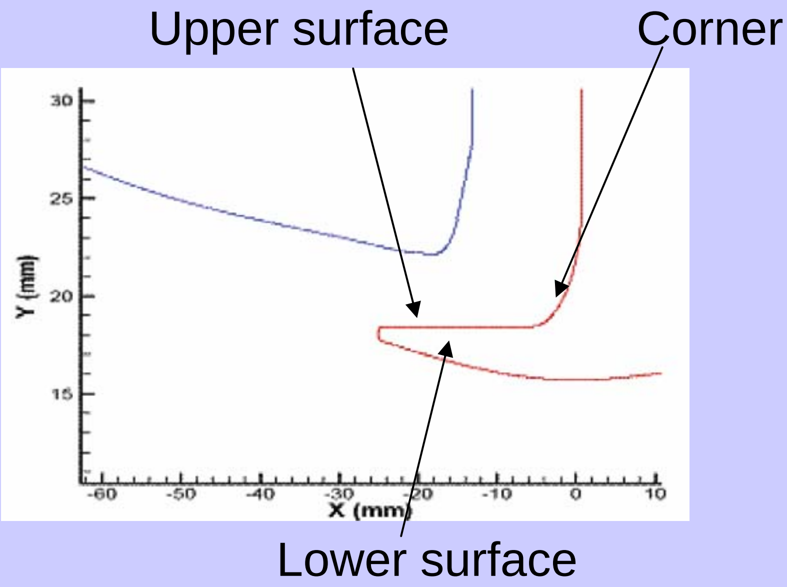


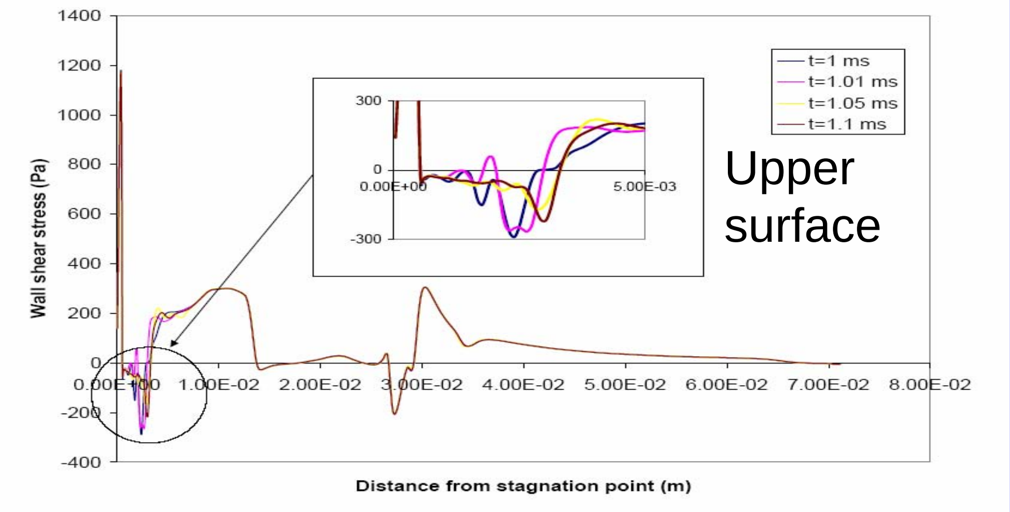
Mach number contours and streamlines for 150 psi.

Results of Original Bleed Lip

14 psi





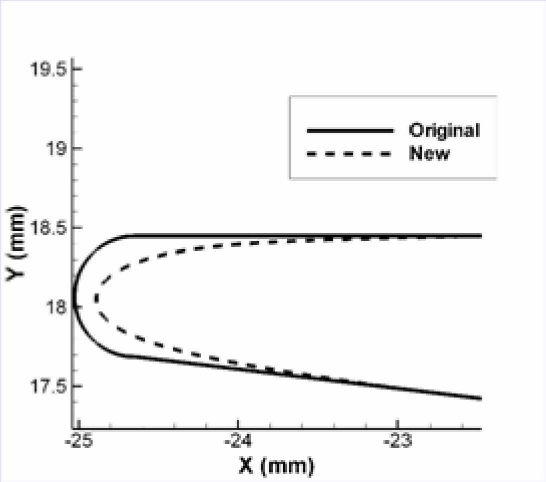


Separation bubbles:

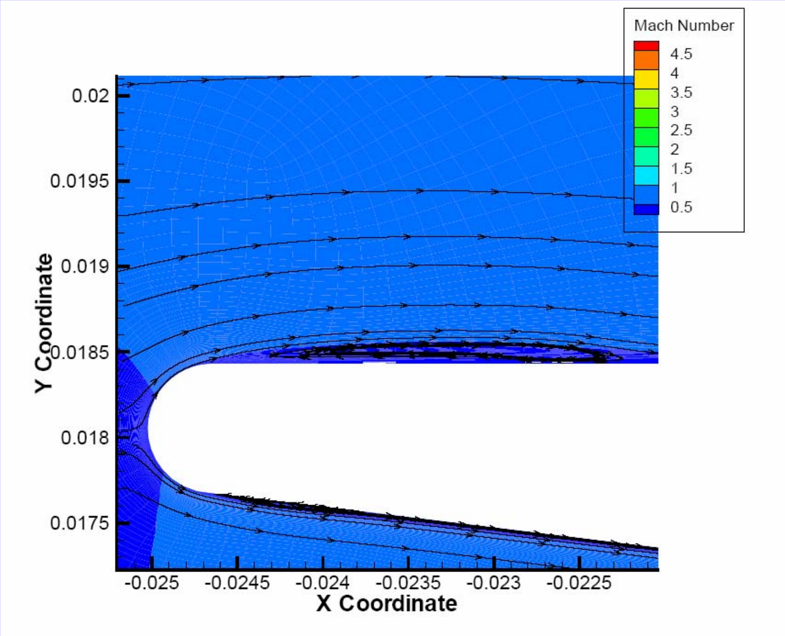
- Unsteady on bleed flow side (upper surface)
- Steady on main flow side (lower surface)

Redesign of Bleed Slot

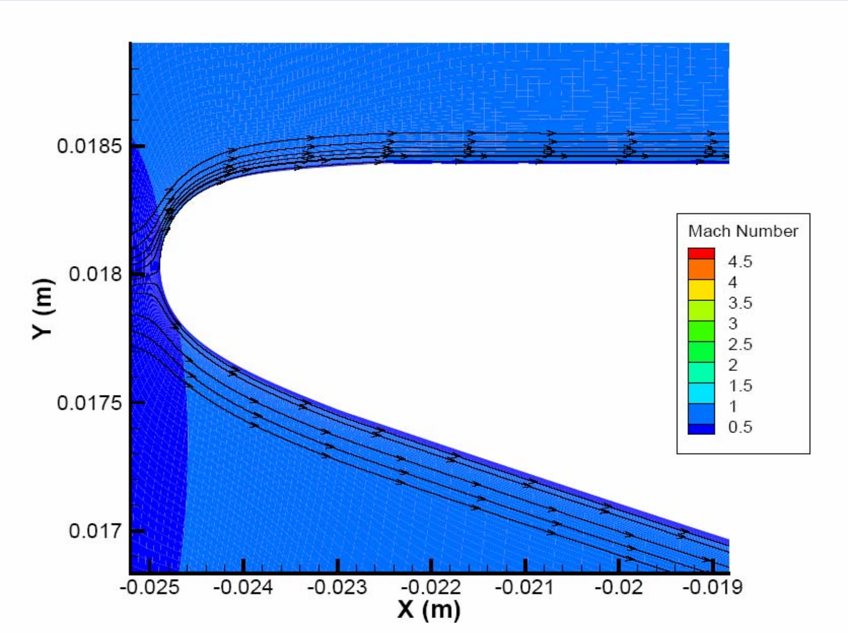
- The bleed lip was cut less than 0.1 in (2.54 mm)
- An adverse pressure gradient is present just aft of the blunt nose on a flat plate in uniform flow. As a semi-elliptical nose becomes more slender, this gradient reduces. (Hess and Smith, 1967)
- The basic idea in the modifications of the bleed lip is to make the lip more slender to eliminate the separation bubbles.



Mach Contours for Modified Geometry



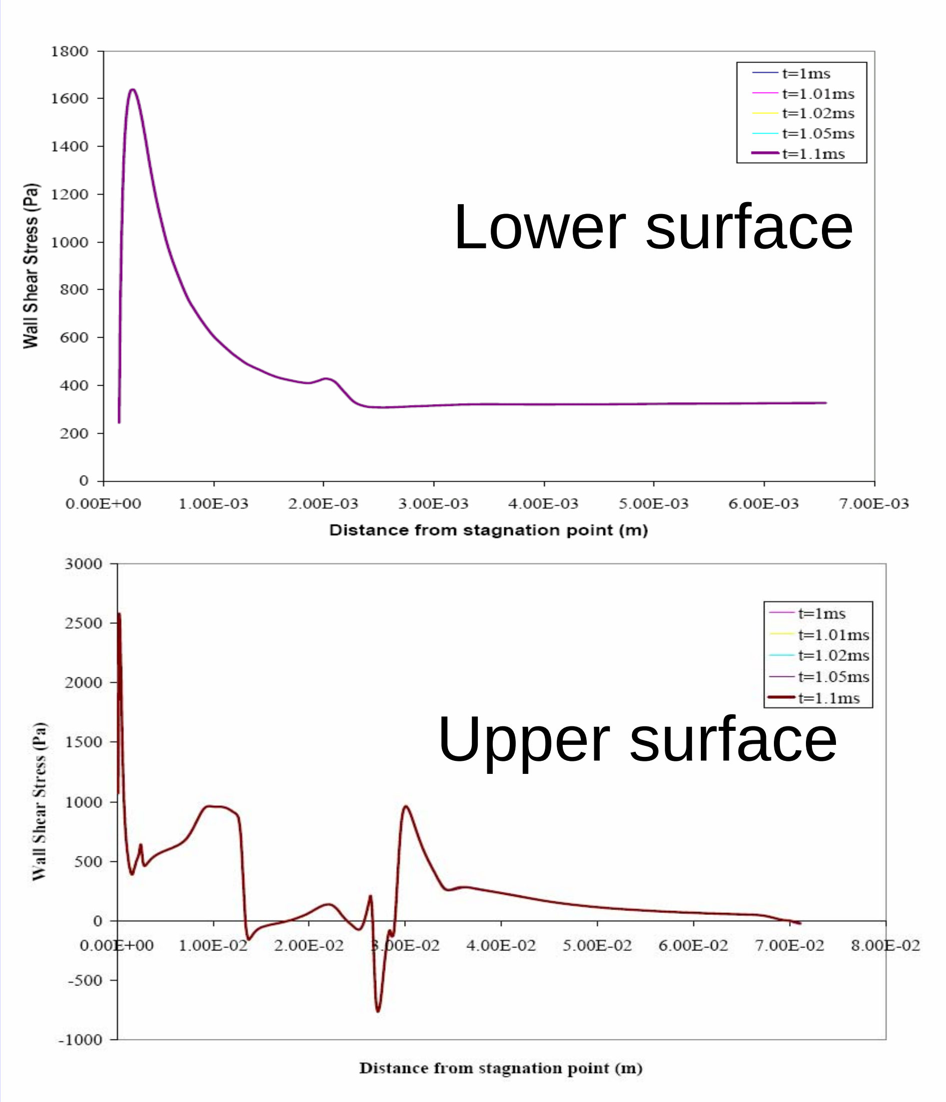
- Original Design – 150 psi



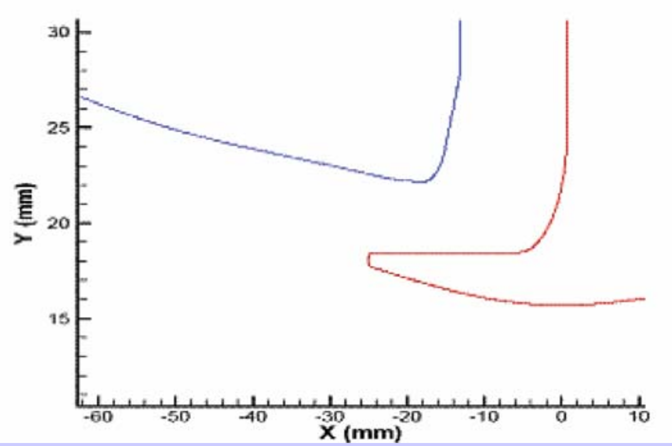
- Modified Design – 150 psi

There is no separation bubble on both the main flow and bleed flow sides of the bleed lip with the modified geometry up to a stagnation pressure of 300 psi.

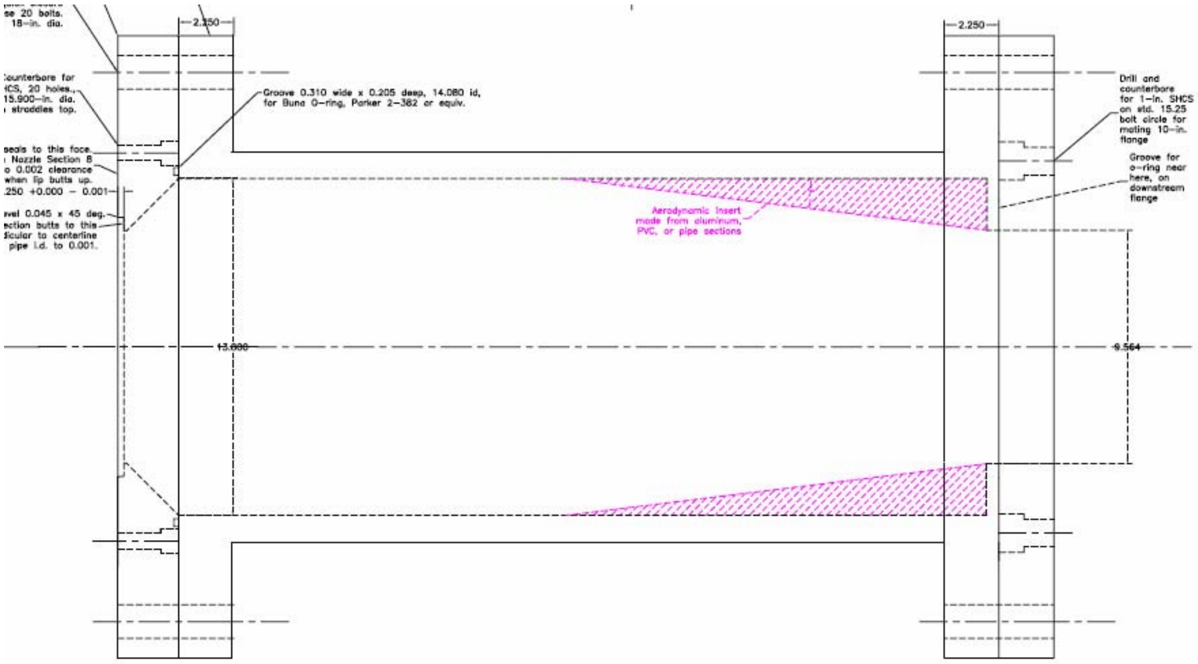
Redesign of Bleed Slot



- No separation bubble on either the upper or the lower surface
- Wall shear stress is always positive around the bleed lip

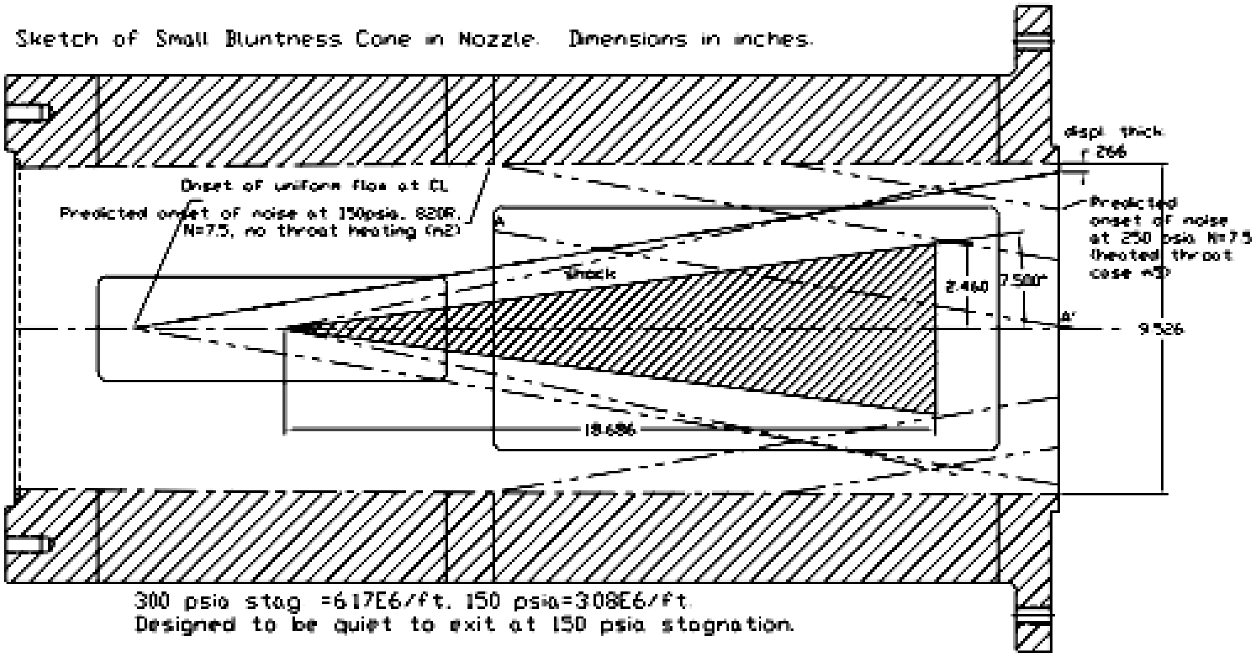


Test Section Expansion



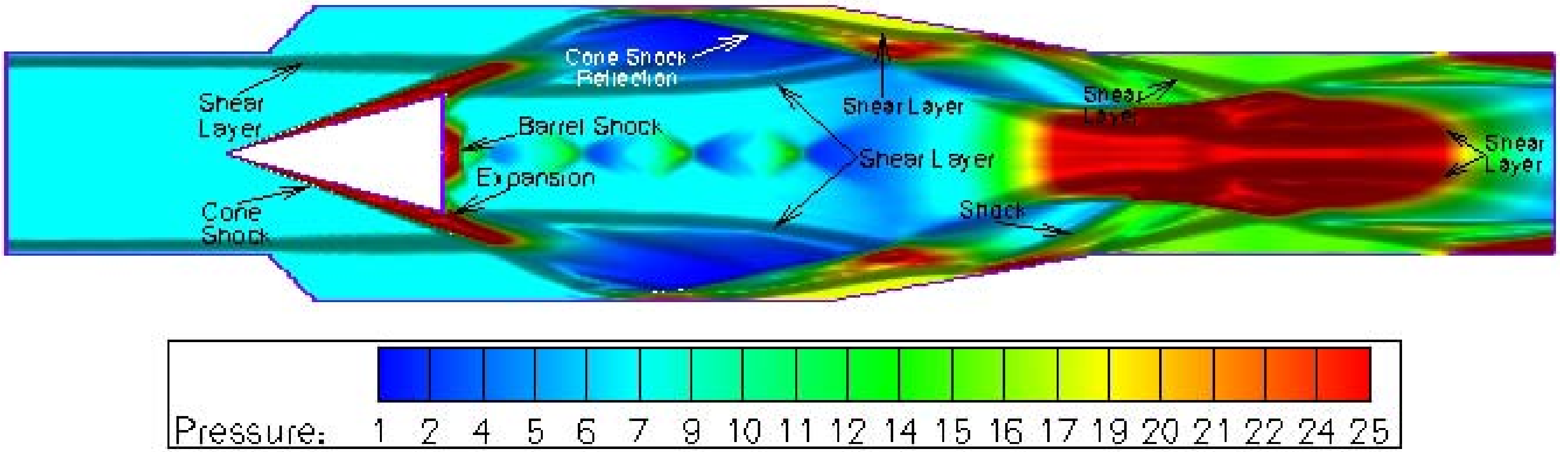
<u>Goal</u>: Expand Diameter to fit larger, blunter models

Test Section Expansion

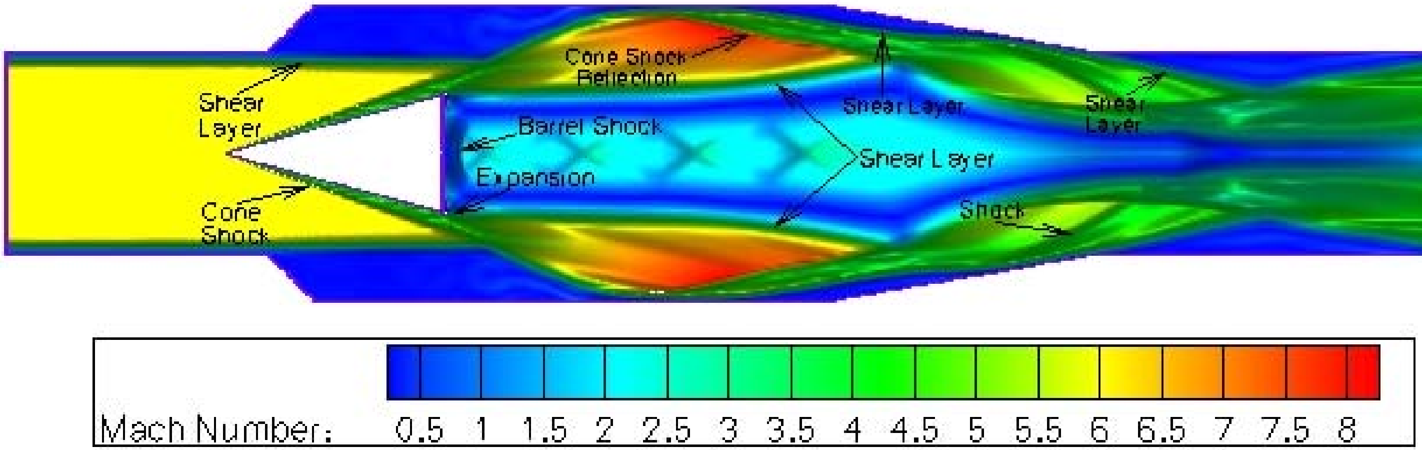


- Separation of the upstream boundary layer is often induced when strong bow shocks from blunt models interact with the nozzle wall boundary layer
- If the bow shock impinges on a shear layer before reaching the wall separation might be avoided (Skoch, Schneider & Borg, 2005)

Results

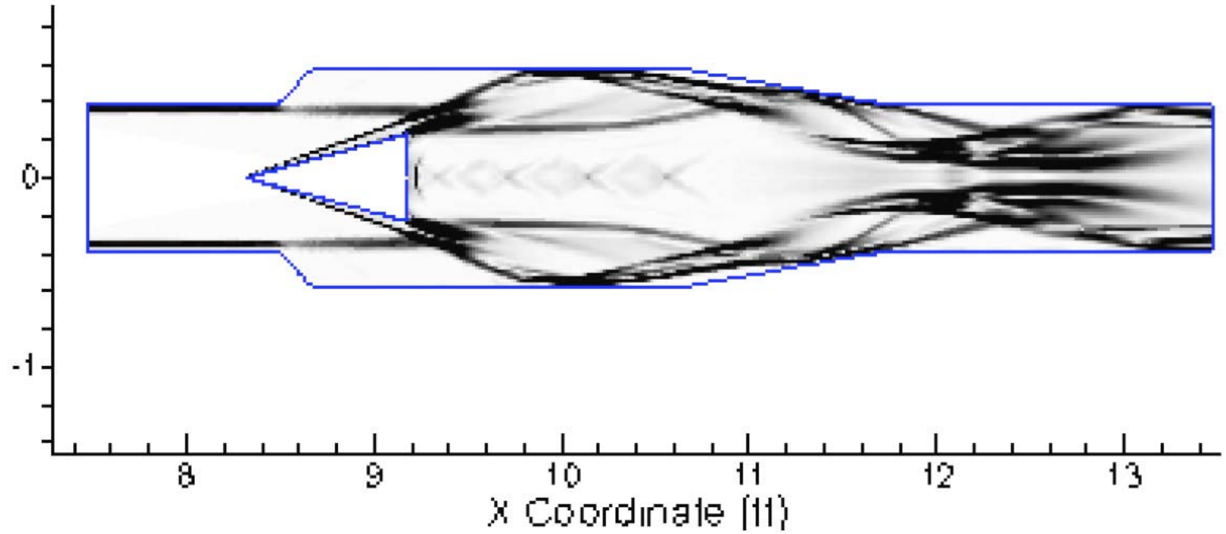


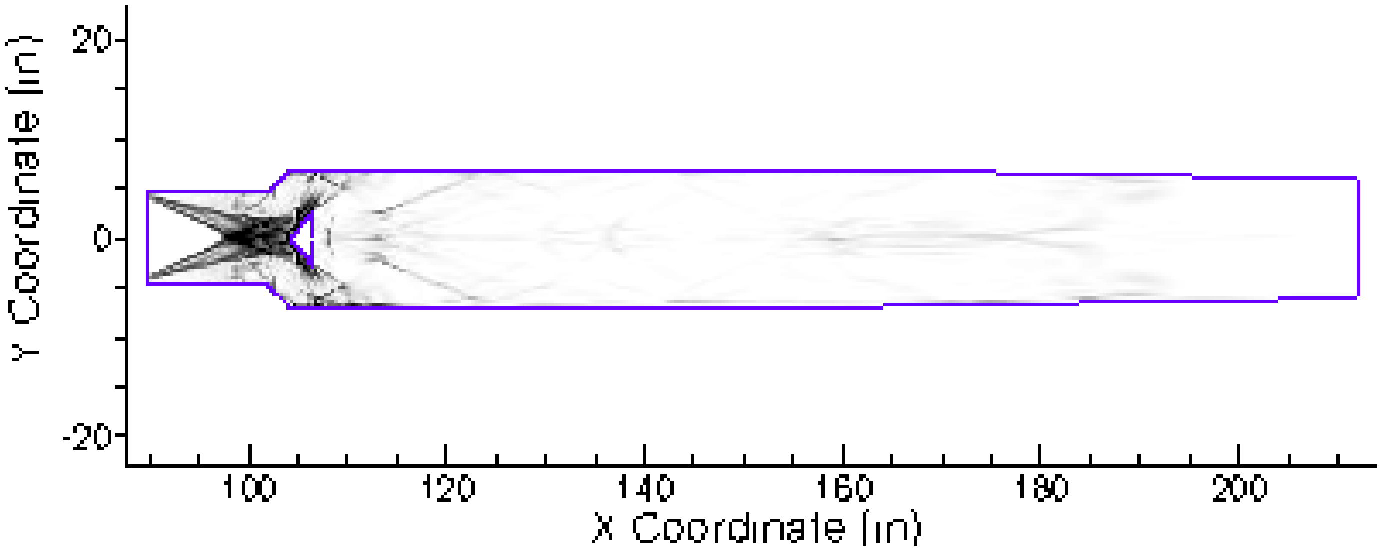
Cone Shock
Reflection
Shear
Layer
Barrel Shock
Expansion
Cone
Shock
Shear Layer
Shear Layer
Shear
Layer
Shock
Shear
Layer
Pressure: 1 2 4 5 6 7 9 10 11 12 14 15 16 17 19 20 21 22 24 25



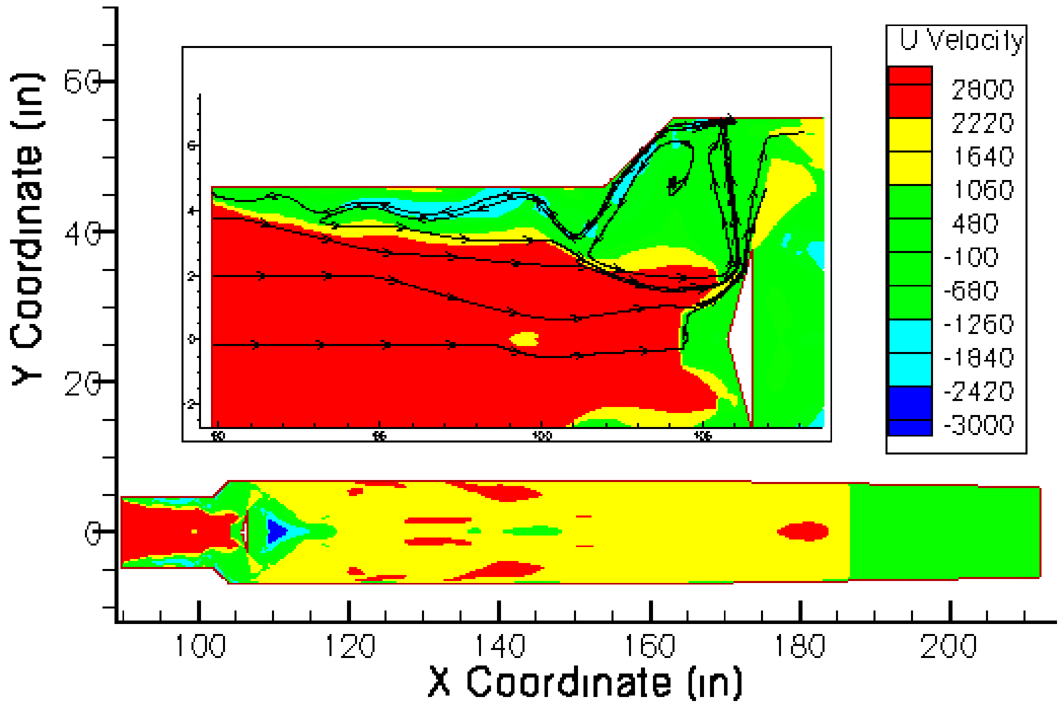
Cone Shock
Reflection
Shear
Layer
Barrel Shock
Expansion
Cone
Shock
Shear Layer
Shear Layer
Shear
Layer
Shock
Shear
Layer
Mach Number: 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8

Unstart


0
-1
8
9
10
11
12
13
X Coordinate (ft)

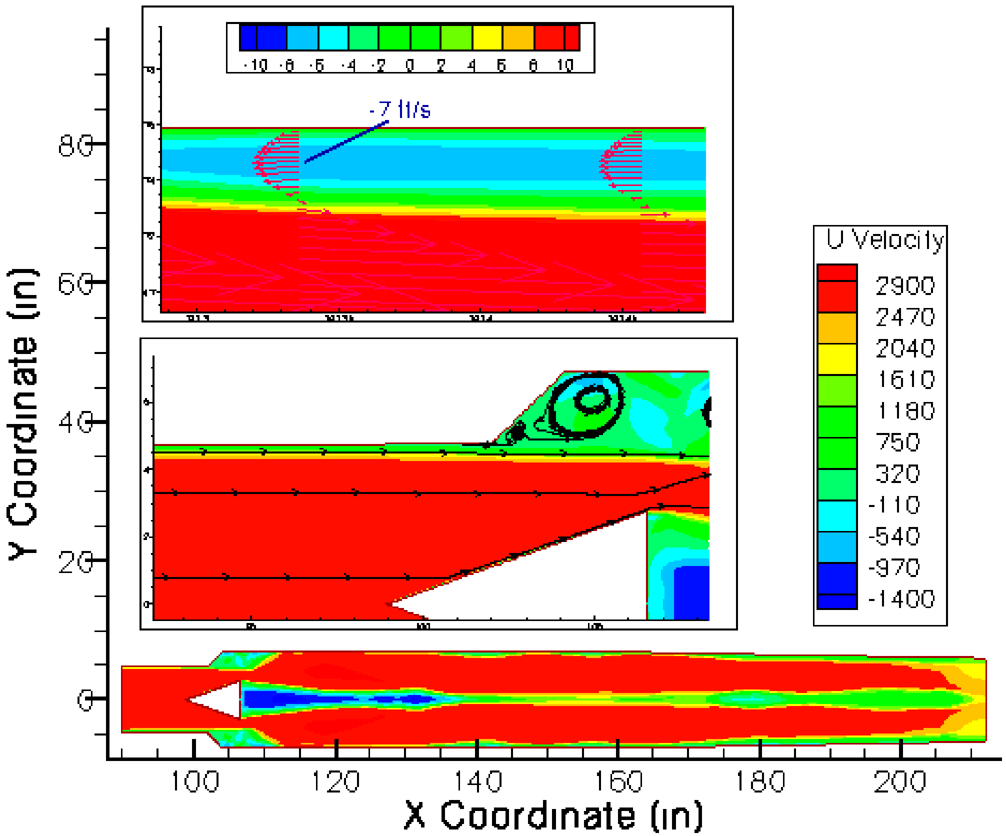

Y Coordinate (in)
20
0
-20
100
120
140
160
180
200
X Coordinate (in)

Results



- U Velocity contours of 75º cone unstarting the tunnel
- Separation bubble forms at expansion corner and grows until inflow boundary

- Separation bubble moves slightly upstream and remains in place
  - tunnel is not unstarted
  - may cause noise and interfere with quiet flow measurements



Summary

Two examples of design modification based on CFD analysis:

- Bleed slot modification
  - Separation bubbles were shown to exist on both the main flow and the bleed flow sides of the bleed lip
  - Separation bubbles are eliminated up to 300 psi (operational limit of the tunnel)
  - BAM6QT was remachined in 2006 and quiet flow was subsequently achieved at 150 psi
- Test Section Expansion
  - Bow shocks from large models cause the flow upstream to separate
  - 15° cone fit into modified section without causing unstart – an improvement over the 7° cone currently used