Some Hypersonic Aerodynamics

W.H. Mason

Configuration Aerodynamics Class

Hypersonics!

- Lots of hypersonics
  - Missiles
  - Rockets
  - Entry (re-entry?)
- How fast is hypersonic anyway?
  - Mach numbers at which supersonic linear theory fails
  - Where γ is no longer constant, and we must consider temperature effects on fluid properties.
  - Mach numbers from 3 - 5, where Mach 3 might be required for blunt bodies causing large disturbances to the flow, and Mach 5 might be the starting point for more highly streamlined bodies.
- Shocks curved, typically close to the body
  - Stagnation pressure varies from body to shock
    - Rotational flow and entropy variation

5 things to know about hypersonics

1. Temperature and heating become critical
2. Blunt shapes are common
   – And in fact required to withstand heating
3. Many times pressure can be easily estimated
4. Control and stability lead to different shapes at hypersonic speeds
5. Engine-Airframe Integration is key
   – Systems are so tightly coupled the aero and propulsion cannot be separated from each other

Review Chapter 12 of Bertin and Cummings, your aerodynamics text and Anderson, *Modern Compressible Flow*, your compressible aero text

Board Work

- Newtonian Impact Theory

Surface pressure estimation

Local slope rules differ in supersonic and hypersonic flows

Linearized supersonic flow

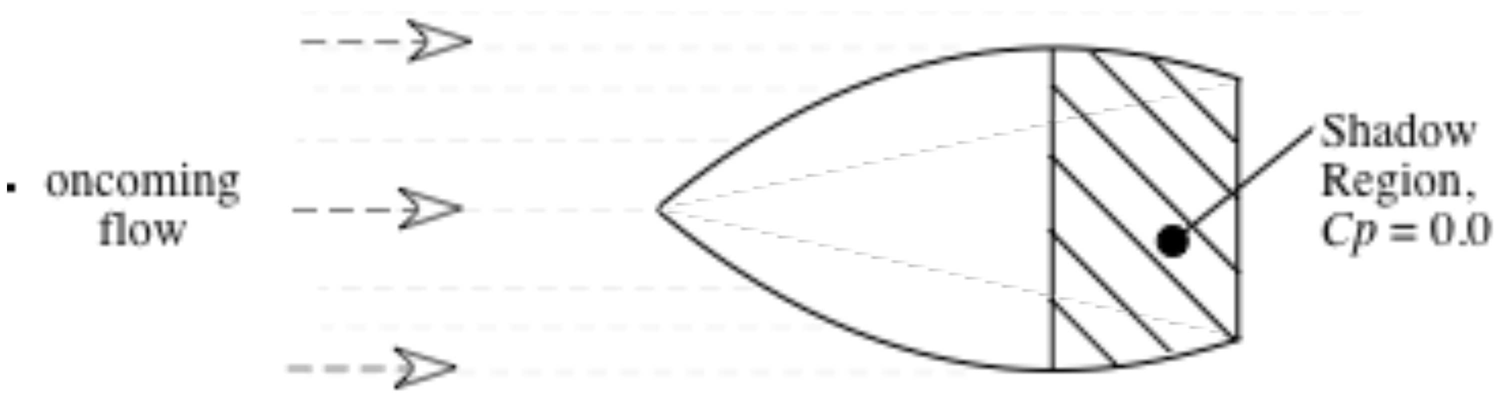
$$C_p = \frac{2\theta}{\sqrt{M_\infty^2 - 1}}$$

Hypersonics: Newtonian flow rule

$$C_p = 2\sin^2\theta$$

No Mach number!
Nonlinear! ($M = \infty$, $\gamma = 1$)

Many other hypersonic "rules" available



Modified Newtonian

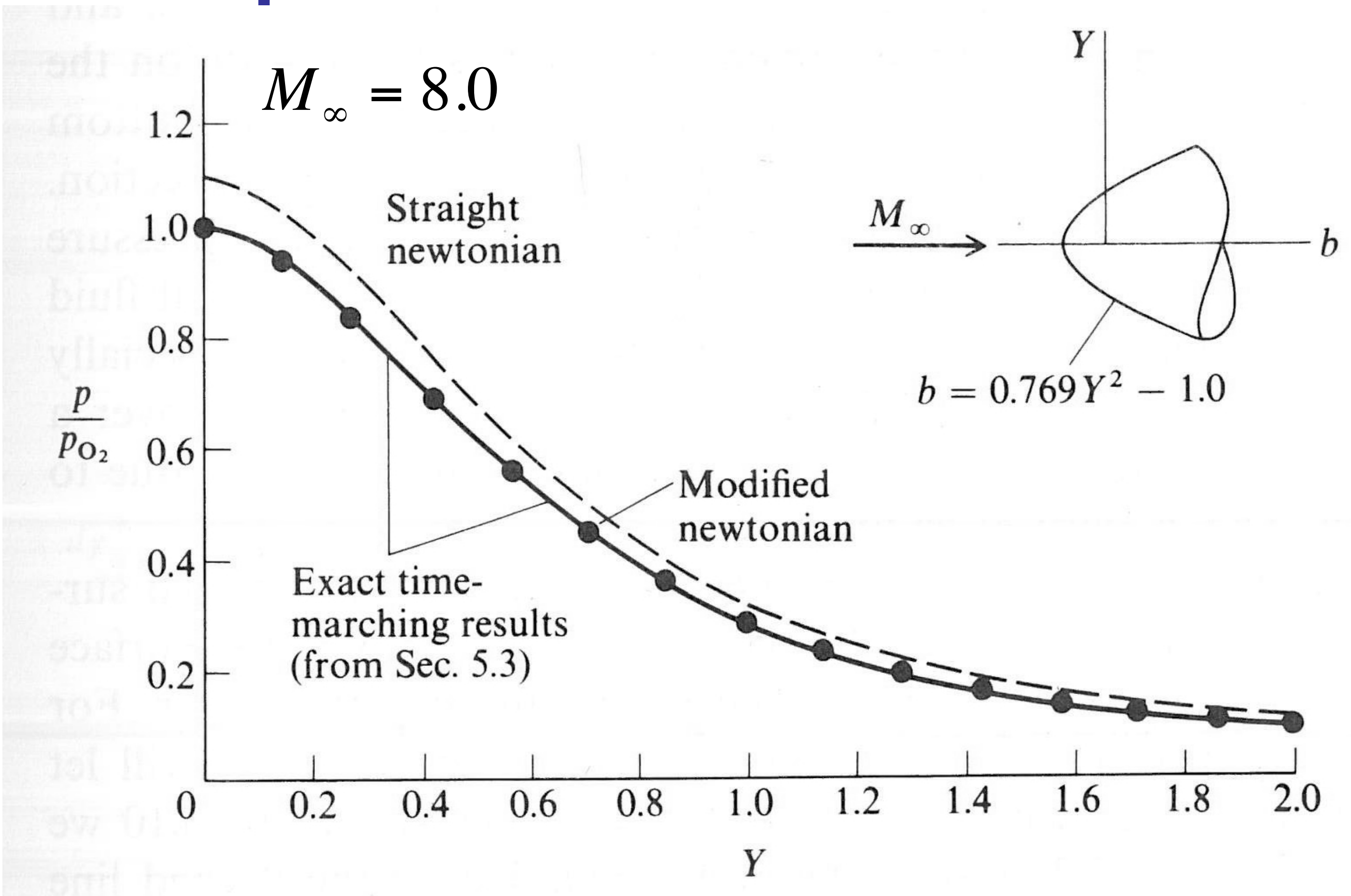
$$C_p = C_{p_{\max}} \sin^2 \theta$$

- Cp_{max} is Cp behind a normal shock
  - For $\gamma = 1.4$, Cp_{max} at $M = \infty$ is 1.84, at $M = 4$, $Cp_{max=}$ 1.79

Newtonian/Modified Newtonian is typically good for blunt bodies with large inclination angles, and better for axisymmetric bodies than 2D

- A good homework problem is to show for $\gamma = 1$, $M = \infty$, $Cp_{max}=2$

Comparison: Newtonian w/CFD



p_{0_2} is the total pressure behind a normal shock at M_∞ = 8.0

John D. Anderson, Jr., *Hypersonic and High Temperature Gas Dynamics*, McGraw Hill, 1989 (now 2nd Ed. From AIAA)
See also your Bertin and Cummings Aerodynamics book for derivations

Other Surface Inclination Methods (Approximations developed before CFD)

For bodies with attached shocks (nominally pointed bodies)

- Tangent Cone
  - Pressure locally equal to a cone with the same slope
- Tangent Wedge
  - Pressure locally equal to a 2D wedge with the same slope
- Shock Expansion
  - Compute pressure behind shock and then do a P-M expansion

Thus, in the first approximation you only need the vehicle geometry
(just like the Harris Wave Drag code)

- Essentially, the standard code is known as the Hypersonic Arbitrary Body Program (HABP)
- Also known as the S/HABP or "the Gentry code"
  - Developed by Gentry of Douglas Aircraft for the Air Force, with a date of about 1973 or so
  - Has a list of flow inclination – pressure formulas
    - the user chooses (once again, the burden is placed on "the user")
  - Available as part of PDAS

The Hypersonic Challenge of the ’50s: Ballistic Missile Atmospheric Entry

1st thought: a slender shape with pointed nose would be best

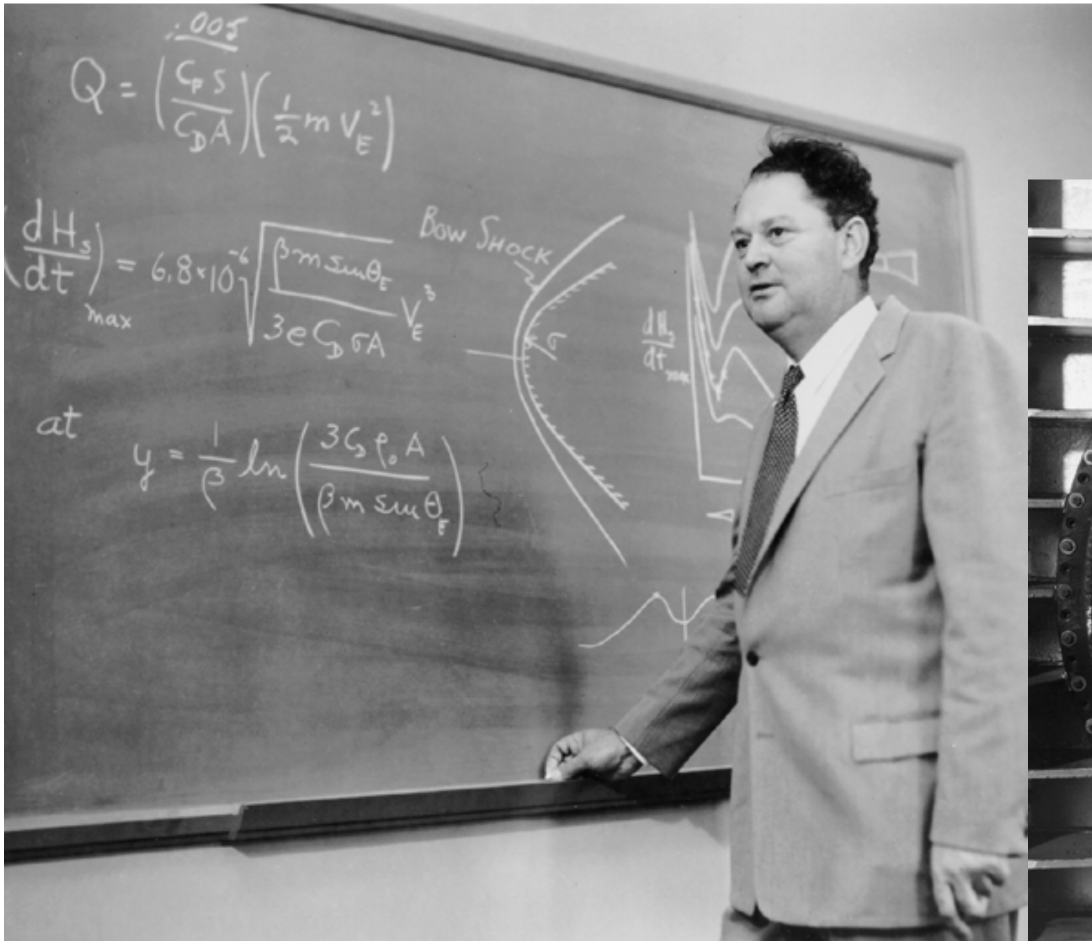
But! H. Julian Allen and A.J. Eggers, Jr.:

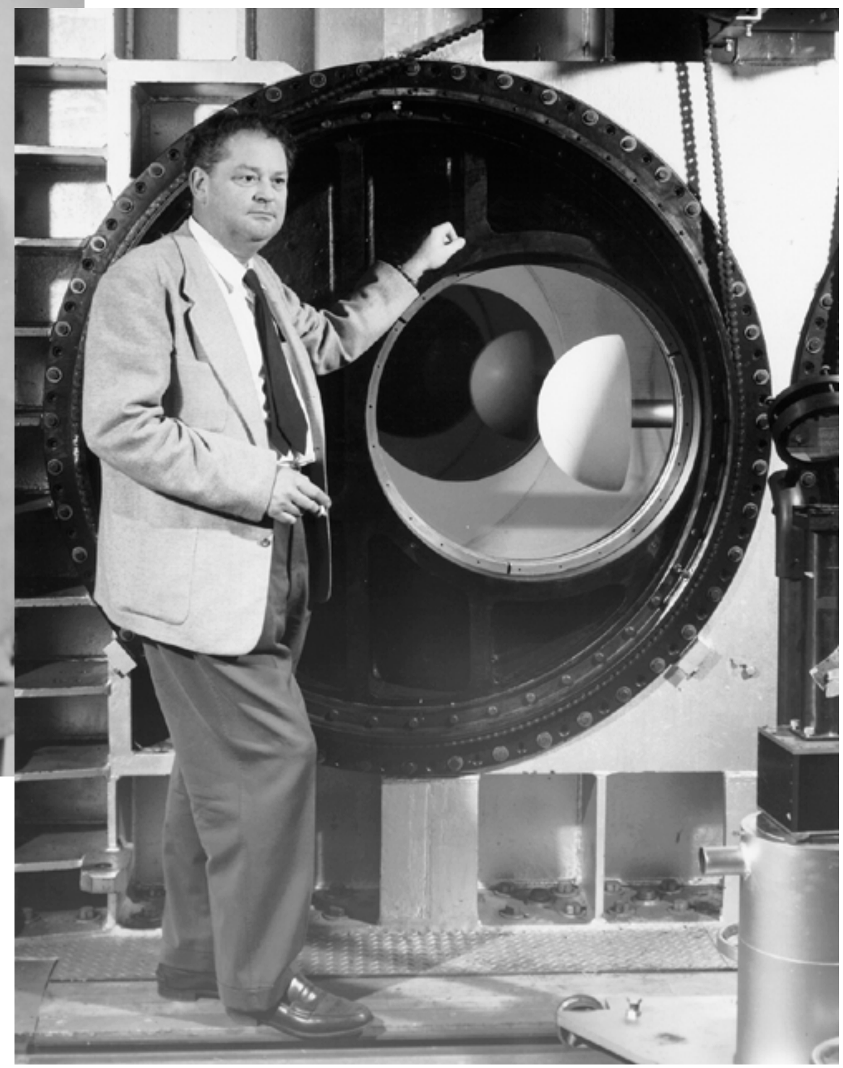
A blunt nose forces a detached shock and most of the heat goes off the surface and into the flowfield, not the vehicle, and enables practical re-entry “vehicles”

This was the major theoretical advance in the 1950s

NACA R 1381, H. Julian Allen and A.J. Eggers, Jr., “A Study of the Motion and Aerodynamic Heating of Ballistic Missiles Entering the Earth’s Atmosphere at High Supersonic Speeds,” 1953 (declassified and publicly released in 1958)

Harvey Allen, NASA Ames





Photos from the NASA web site

Allen showed:

$$\dot{q}_{\substack{\max \\ \text{laminar}}} \sim \frac{1}{\sqrt{R_{LE}}}$$

- *q-dot* is the heating rate
- R_{LE} is the leading edge radius at the stagnation point
  - – ***and should be large!***
  - \- Think Mercury, Gemini, Apollo
- Still requires a thermal protection system: ablative material
- Finally, on fast (lunar) re-entry, radiation is important!

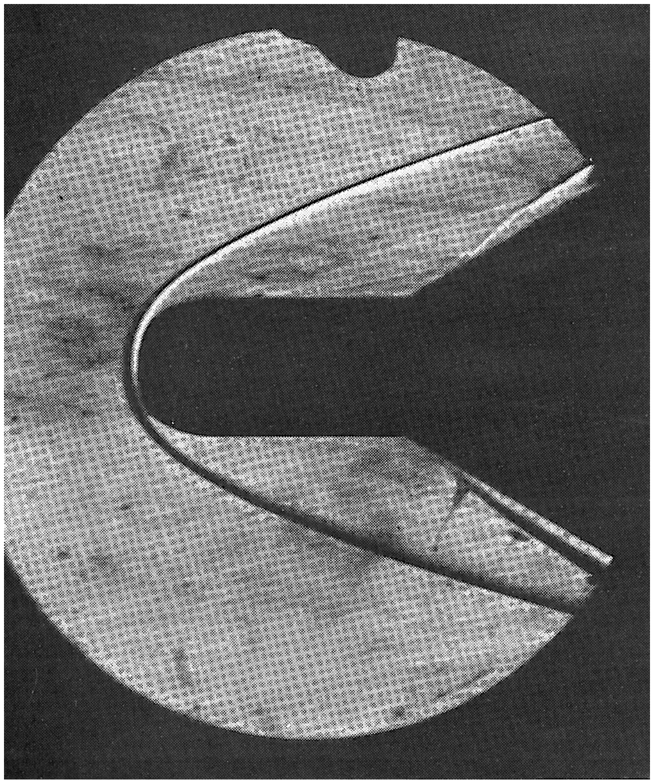
This was the first real CFD problem:

"the blunt body problem"

Gino Moretti solved (1966) by realizing that you should march forward in time to get to the steady state solution

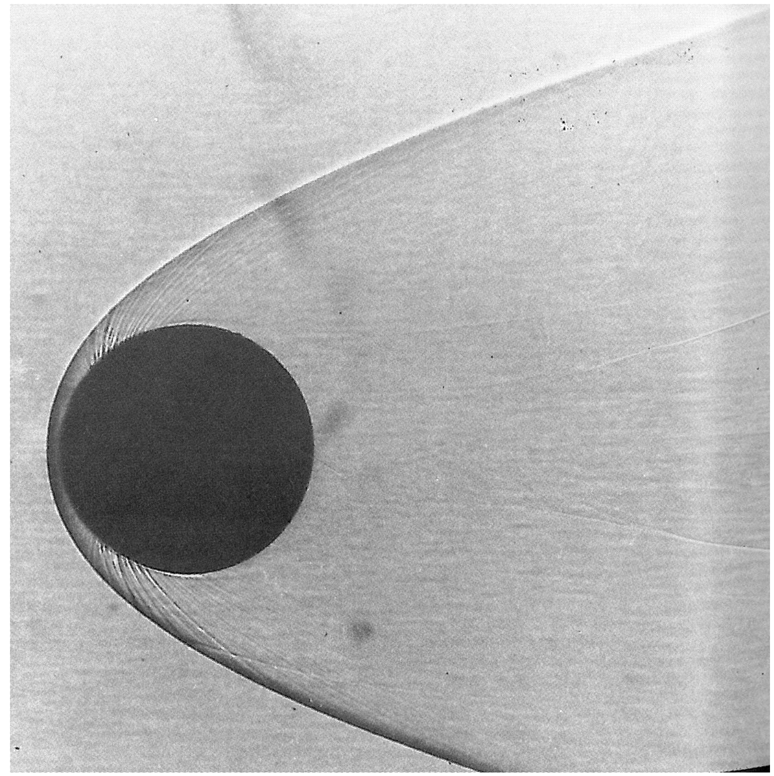
Blunt Body Flowfield

$M = 6.85$



From Cox and Crabtree, *Elements of Hypersonic Flow*, Academic Press, 1965

$M = 7.6$

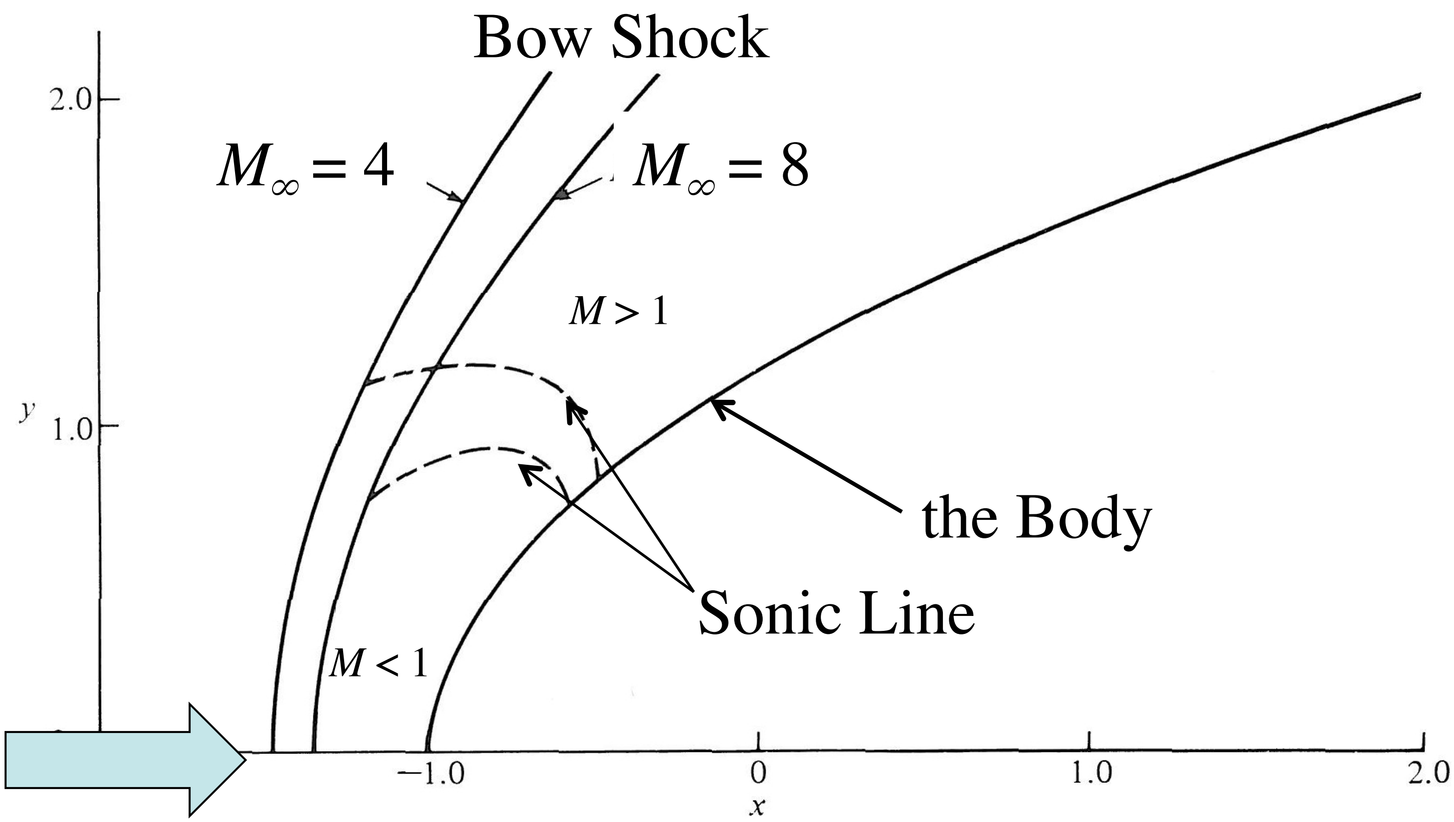


From Van Dyke, *An Album of Fluid Motion*, The Parabolic Press, 1982

Key item of interest: Stagnation Point Heat Transfer

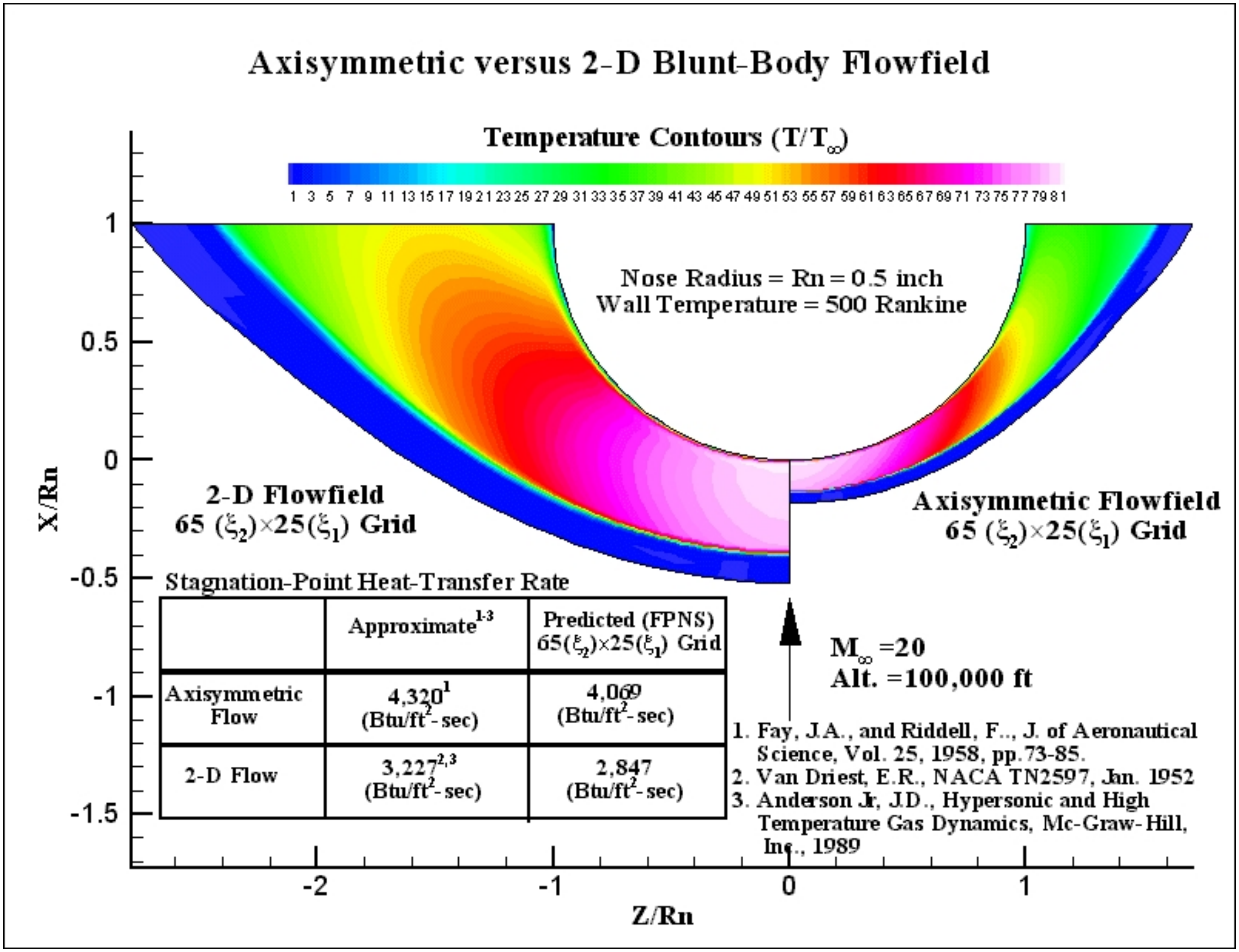
The sketch of the physics

The mixed supersonic/subsonic flow caused the same problem that arose for transonic calculations



From Anderson, *Modern Compressible Flow*

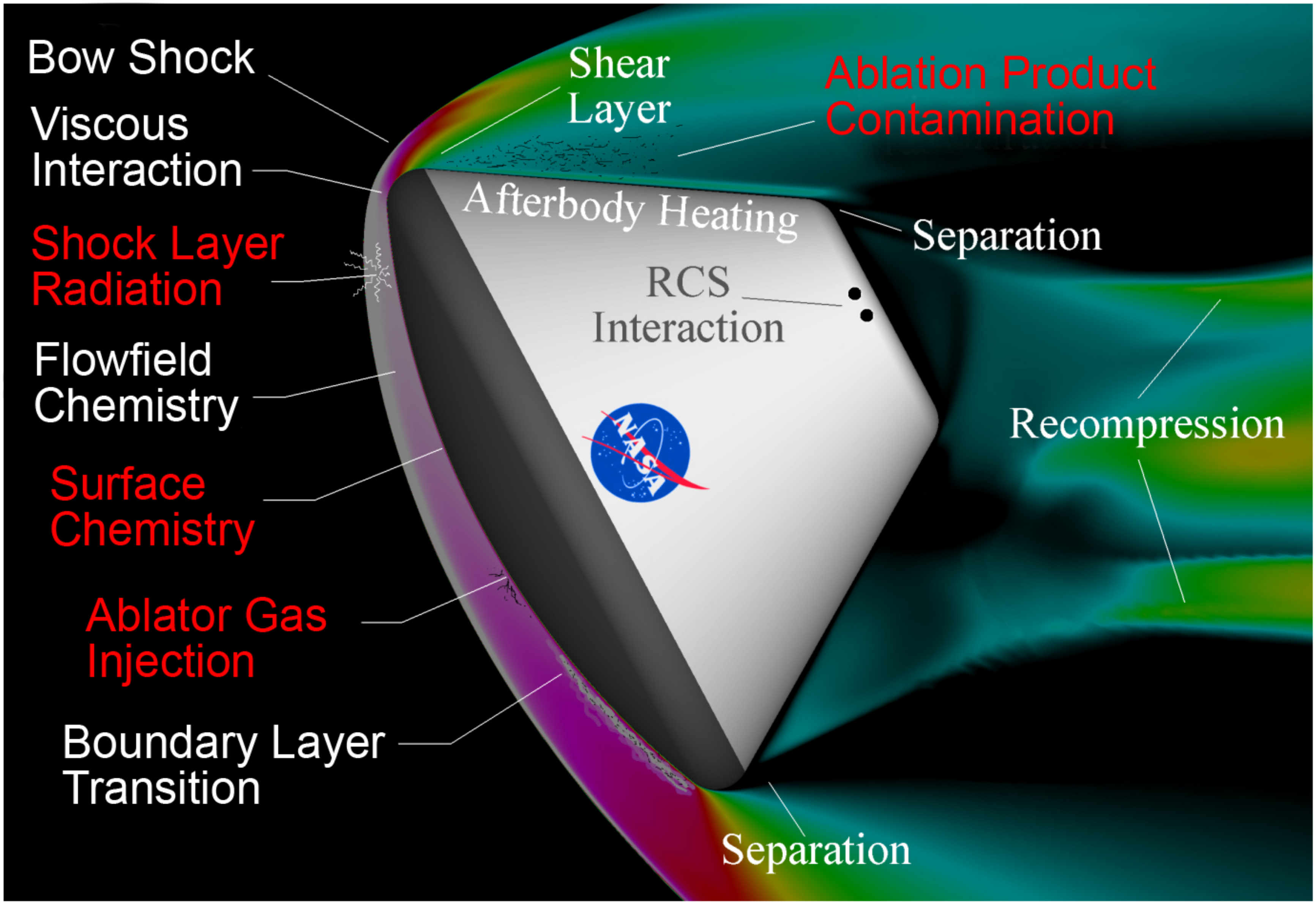
And CFD Solutions



	Approximate[1-3]	Predicted (FPNS) $65(\xi_2)\times25(\xi_1)$ Grid
Axisymmetric Flow	4,320[1] (Btu/ft^2-sec)	4,069 (Btu/ft^2-sec)
2-D Flow	3,227[2,3] (Btu/ft^2-sec)	2,847 (Btu/ft^2-sec)

From AeroTechnologies Inc. on Google images

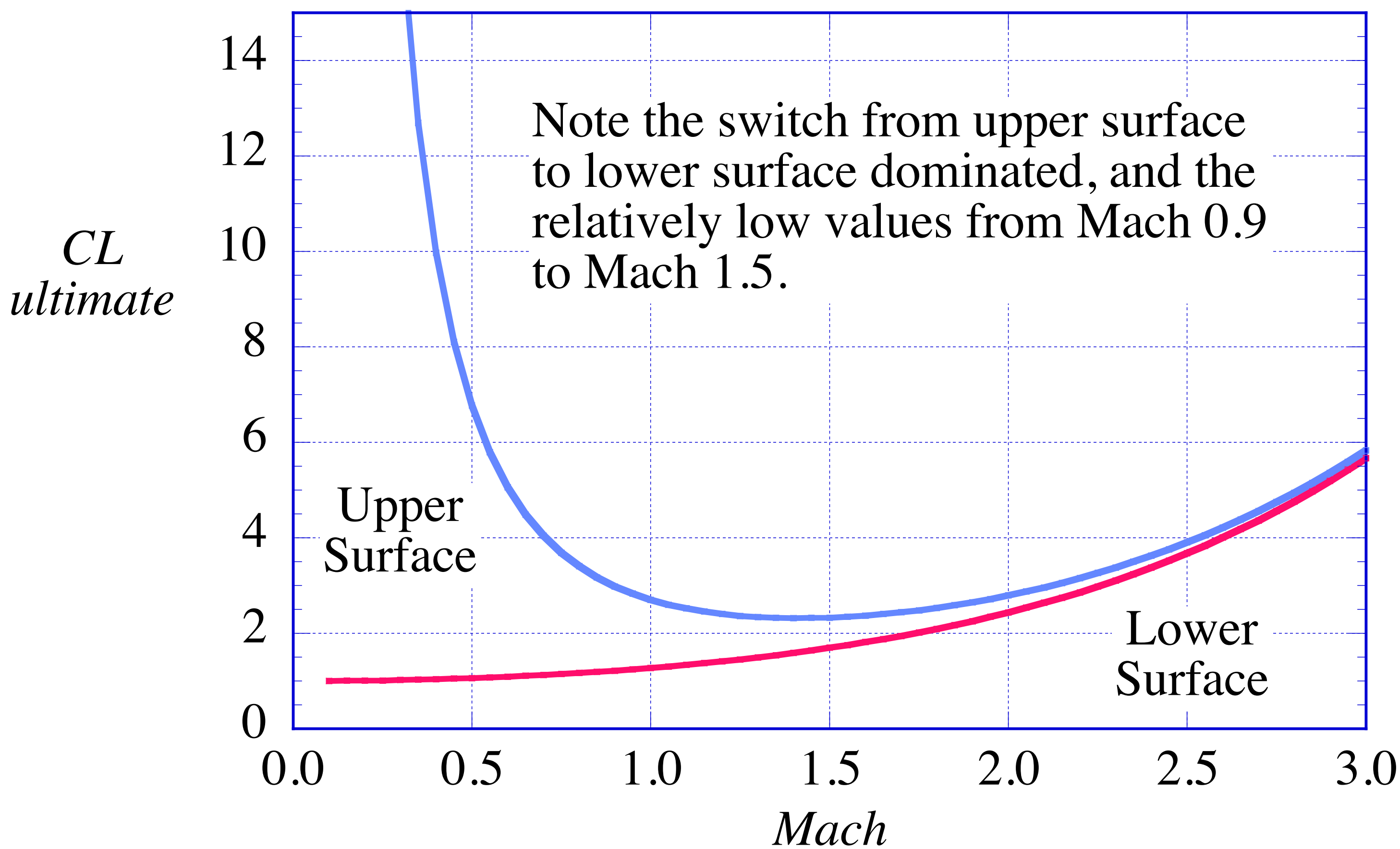
From Chris Johnston, VT BS, MS, PhD



The surface pressure story changes

from an upper surface story to a lower surface story

$C_{p_{VAC}} = -\frac{2}{\gamma M_\infty^2}$ shows why



Vacuum pressure on top surface, stagnation pressure on bottom surface

Gas Dynamics Issues

- A new type of viscous-inviscid interaction can occur: what's the value of "Chi bar"? (We'll explain later)
  - Greater or less than 3 changes the type of interaction
- Lots of laminar flow situations, and the boundary layer is thicker: high altitudes lead to low Reynolds numbers
  - Transition occurs over a long distance, it is not assumed to occur at a "point"
- Go high enough, and the mean free path of a molecule may be significant compared to the vehicle characteristic length: the Knudson number, Kn, is the ratio of a molecule's mean free path to a characteristic vehicle length
  - $Kn > 1$ implies the rarefied gas dynamics regime
  - $Kn < 0.03$ is "normal" continuum flow

Chi-bar

- At low speeds, we often estimate the pressure distribution using inviscid flow models as a start.
- At hypersonic speeds, sometimes the boundary layer influences the pressure distribution immediately.
- The value of chi-bar is used to tell when the boundary layer effects are of first order importance – a "strong interaction"

$$\bar{\chi} = \frac{M_\infty^3}{\sqrt{\mathrm{Re}}}\sqrt{C}, \quad C = \frac{\rho_w \mu_w}{\rho_e \mu_e}$$

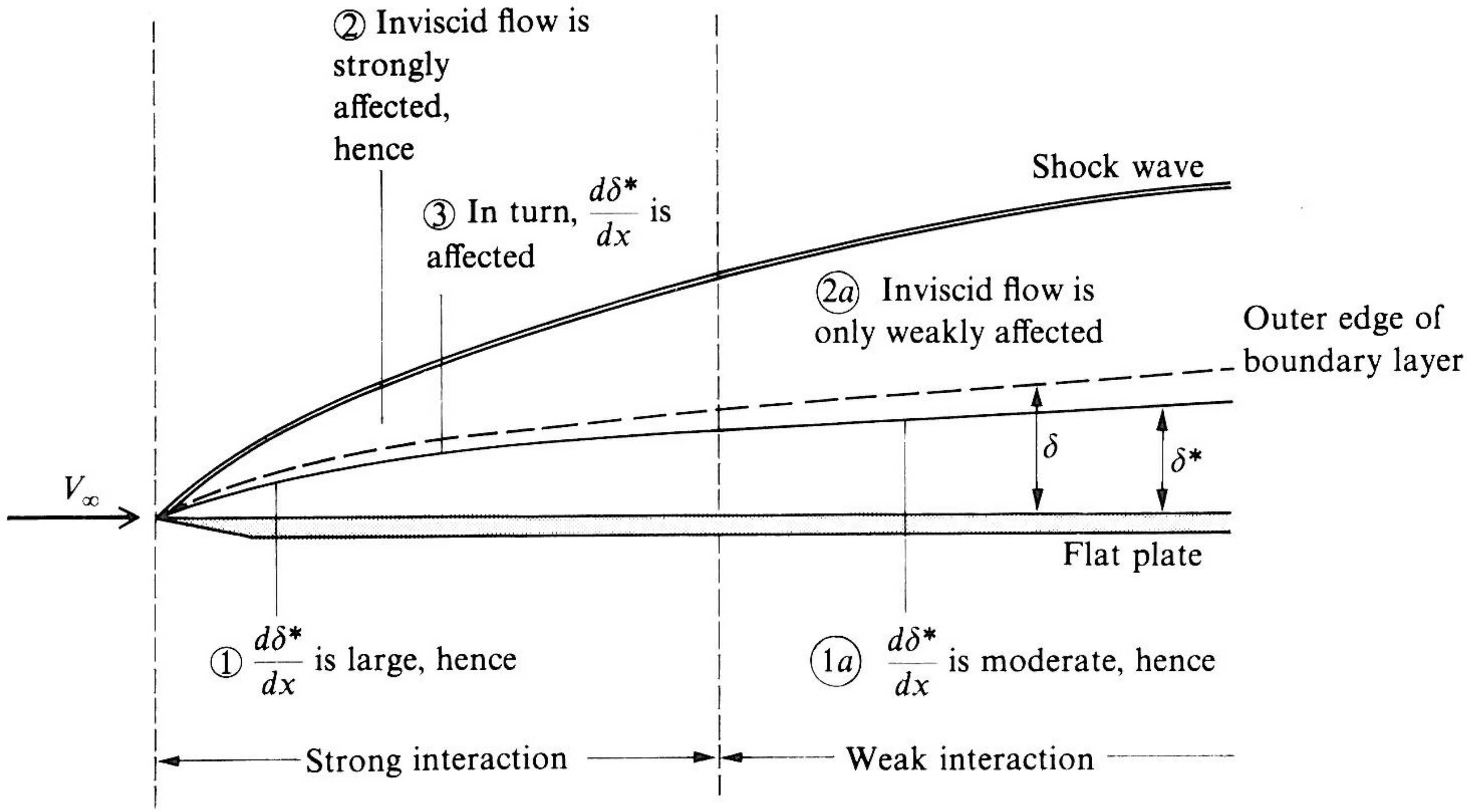
$$\bar{\chi} > 3 \quad \text{a strong interaction}$$

$$\bar{\chi} < 3 \quad \text{a weak interaction}$$

Note: recall that viscous effects are also found to be important at transonic speeds

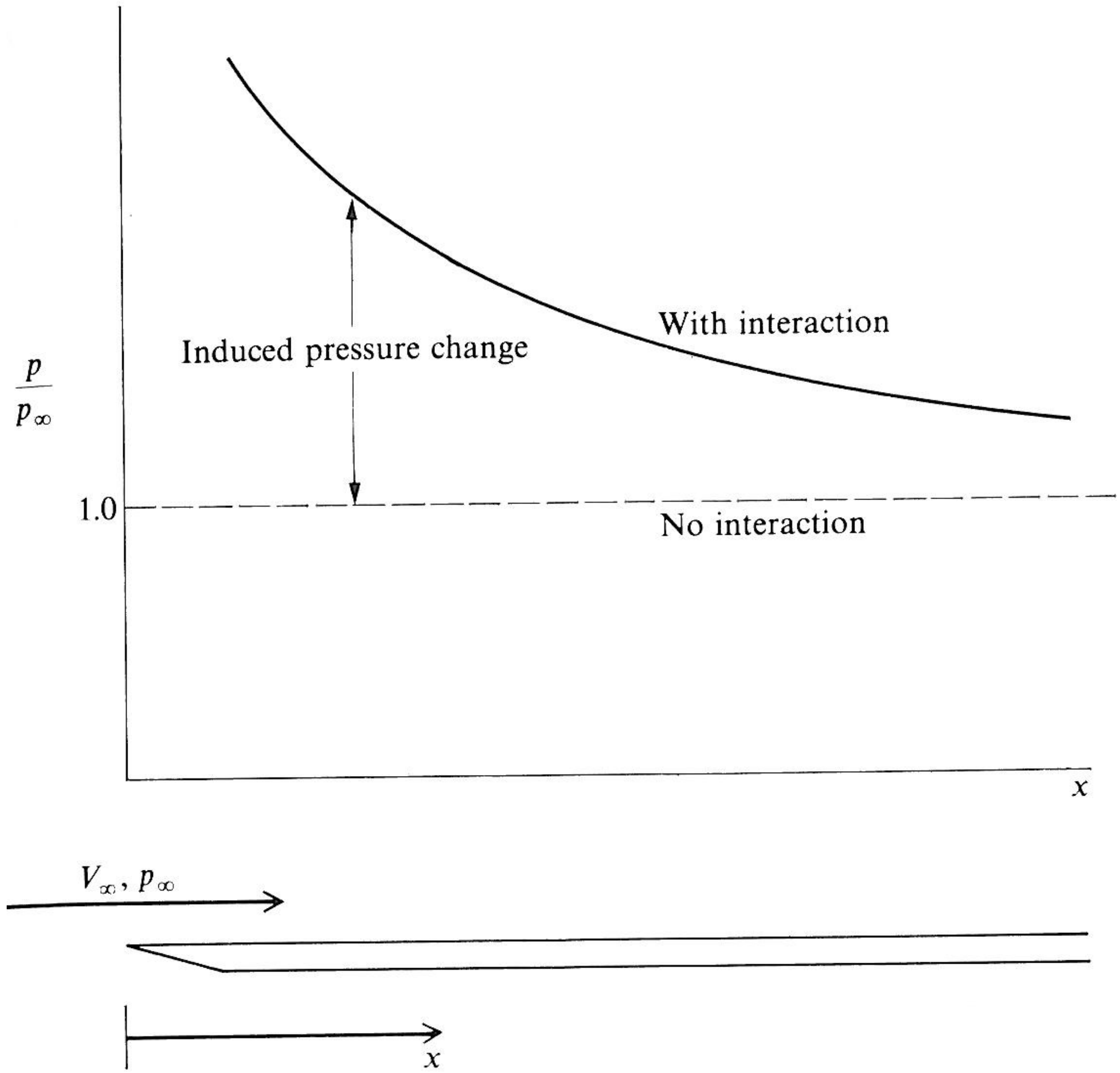
Hypersonic Strong Viscous interaction

Boundary layer much thicker at hypersonic speed



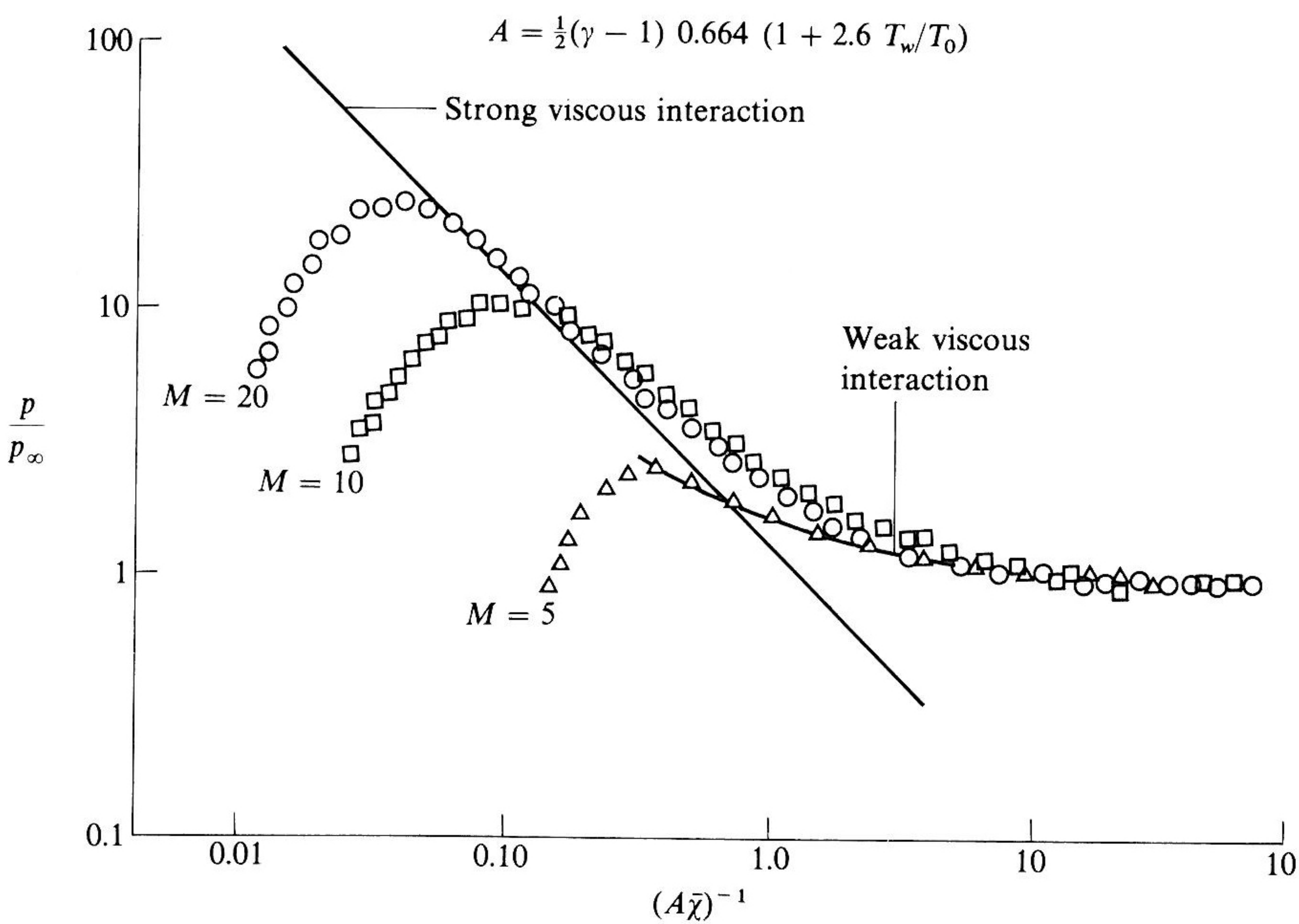
John D. Anderson, Jr., *Hypersonic and High Temperature Gas Dynamics*, McGraw Hill, 1989 (now 2nd Ed. From AIAA)

Viscous effects induced pressures –



John D. Anderson, Jr., *Hypersonic and High Temperature Gas Dynamics*, McGraw Hill, 1989 (now 2nd Ed. From AIAA)

Experimental Demonstration



John D. Anderson, Jr., *Hypersonic and High Temperature Gas Dynamics*, McGraw Hill, 1989 (now 2nd Ed. From AIAA)

X-15

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: E-5251 Date: 1960

X-15 ship #1 on lakebed

Dropped from a B-52

6/8/59: first drop/glide
Scott Crossfield

With bigger tanks,

8/22/63: Max altitude - Joe Walker, 354k ft

10/3/67: Max speed - Pete Knight, Mach 6.70 @ 100k ft

XLR-99 Rocket Motor
- anhydrous ammonia
- liquid oxygen

The hypersonic stability story

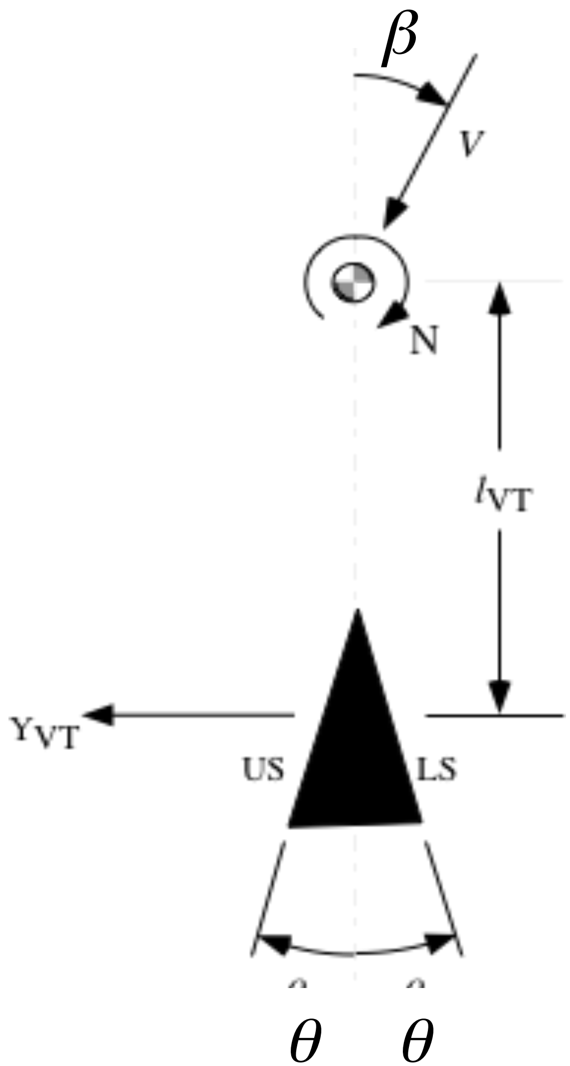
The change in pressure rules supersonic - hypersonic are important

- the difference in physics changes the shape
- exploitation actually made the X-15 practical
- consider the directional stability problem
- the yawing moment due to the vertical tail is:

$$C_{n_{VT}} = \frac{l_{VT} S_{VT}}{b_{ref} S_{ref}} \frac{q_{VT}}{q_{ref}} C_{Y_{VT}}$$

- The first term is the vertical tail volume coefficient, V_{VT}
- The second term is the ratio of dynamic pressures, assumed unity here
- $C_{Y_{VT}} = C_{p_{LS}} - C_{p_{US}}$ with correct interpretation of *"us* and *ls"*

For directional stability



$$\text{if } C_p = \frac{2\theta}{\sqrt{M_\infty^2 - 1}},$$

$$C_{n_{\beta_{VT}}} = V_{VT} \frac{4}{\sqrt{M_\infty^2 - 1}}$$

- goes to 0 as M increases

$$\text{if } C_p = 2\sin^2\theta,$$

$$C_{n_{\beta_{VT}}} = 8V_{VT}\theta$$

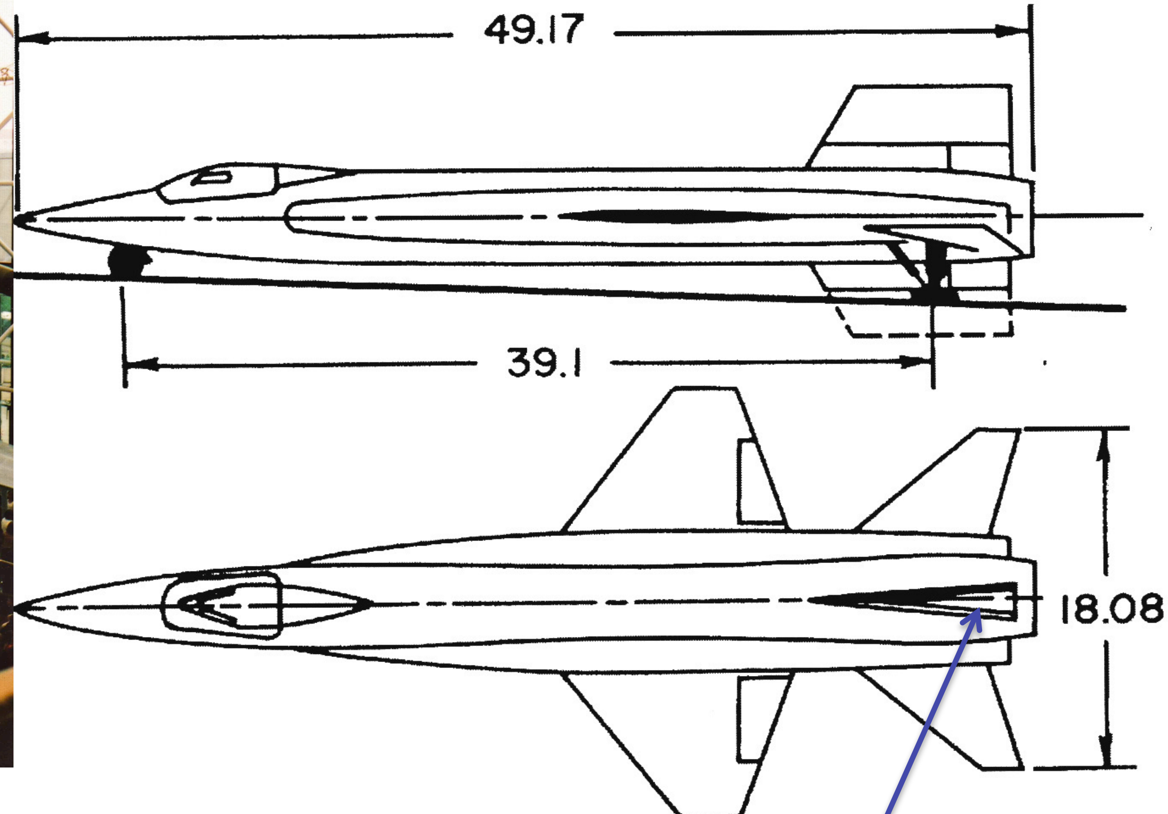
- increases with θ !
- no Mach sensitivity

Realization essentially saved the X-15

Example: the X-15 vertical tail

Mason took this at the NASM on the Mall in DC

A little hard to see, shows up in the top view below



Note also the ventral fin

Wedge Tail

Also explains "Missile Skirts"

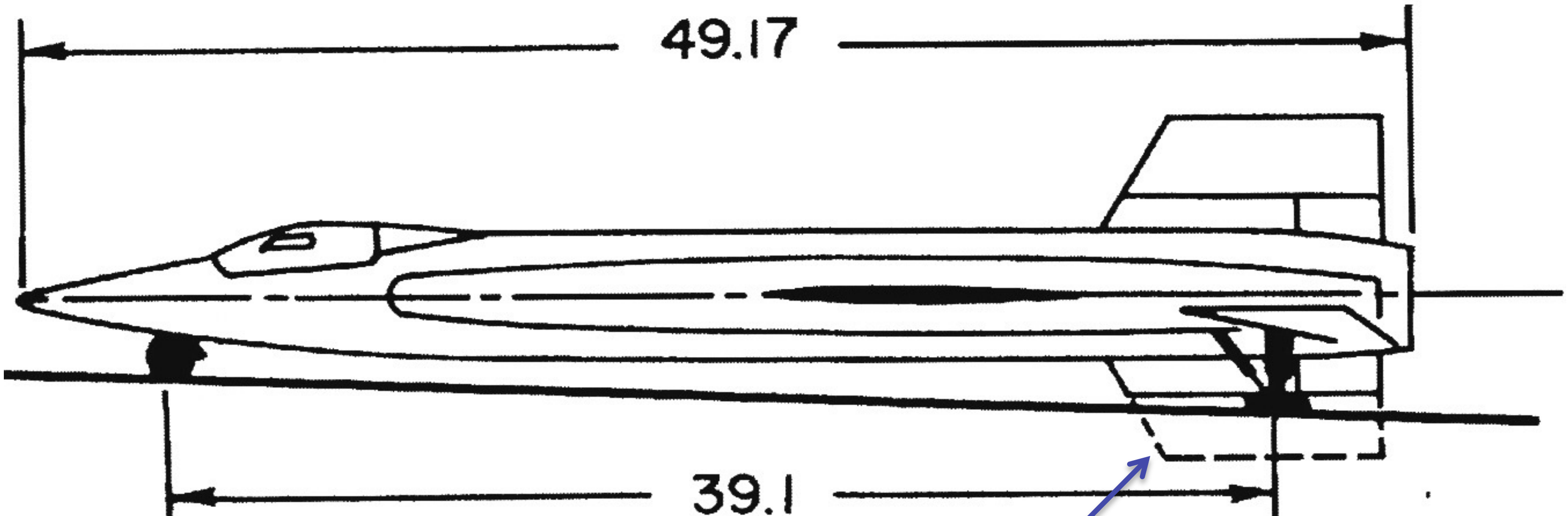
Side and top views from NASA TN D-2532

X-15 Roll Instability and Aero Fix

Above 15° α, a PIO with SAS off, roll damper is flight critical

- good $C_{n\beta}$, but bad $C_{l\beta}$.

The fix: leave lower ventral, that had to be jettisoned to land, off



Just leave the lower part of the ventral off

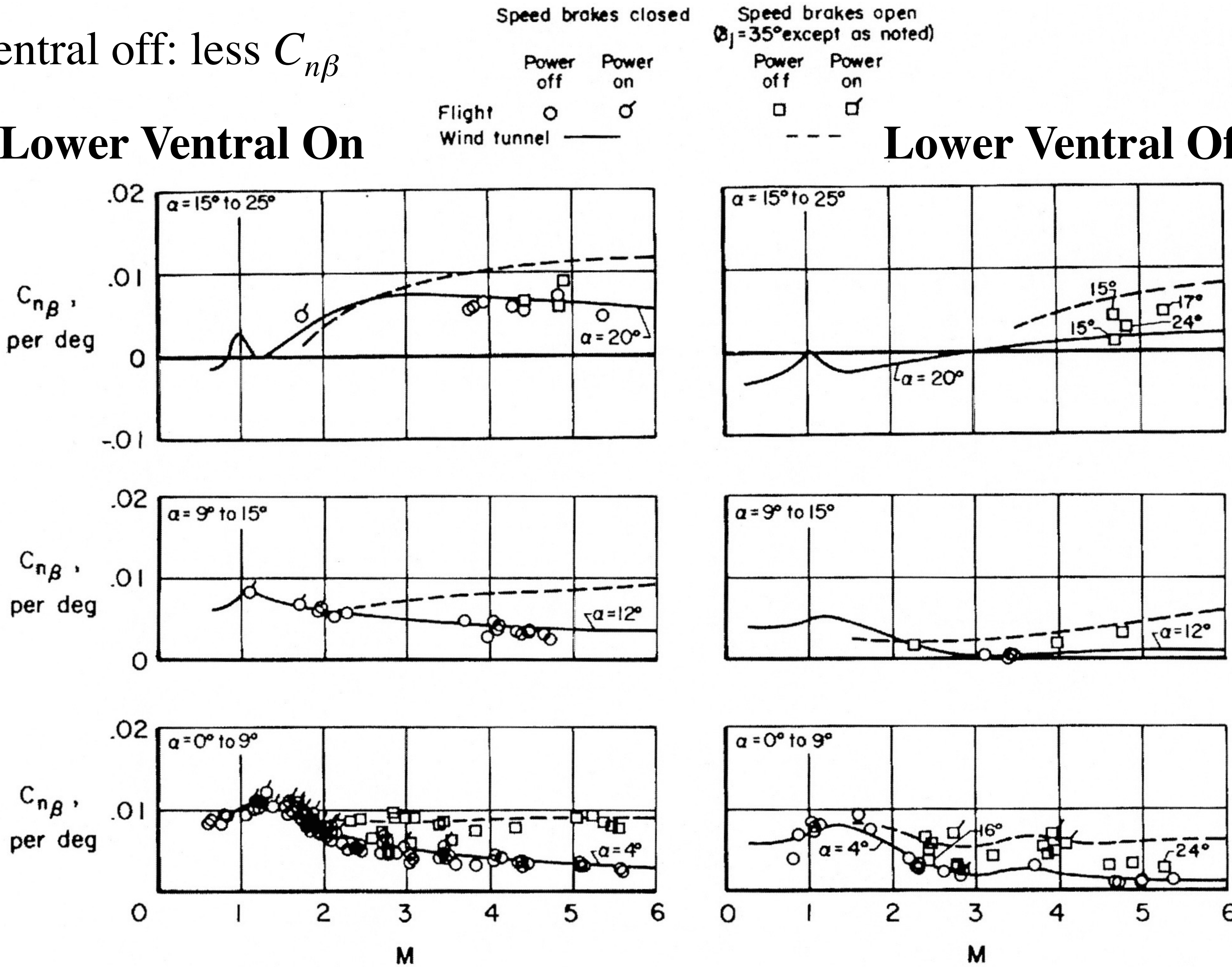
Note: SAS is the Stability Augmentation System

The story is in *Flight Testing at Edwards*, Ed. by Fred Stoliker, Bob Hoey and Johnny Armstrong, Flight Test Historical Foundation, 1996.

The directional data: NASA TN D-2532

Ventral off: less $C_{n\beta}$

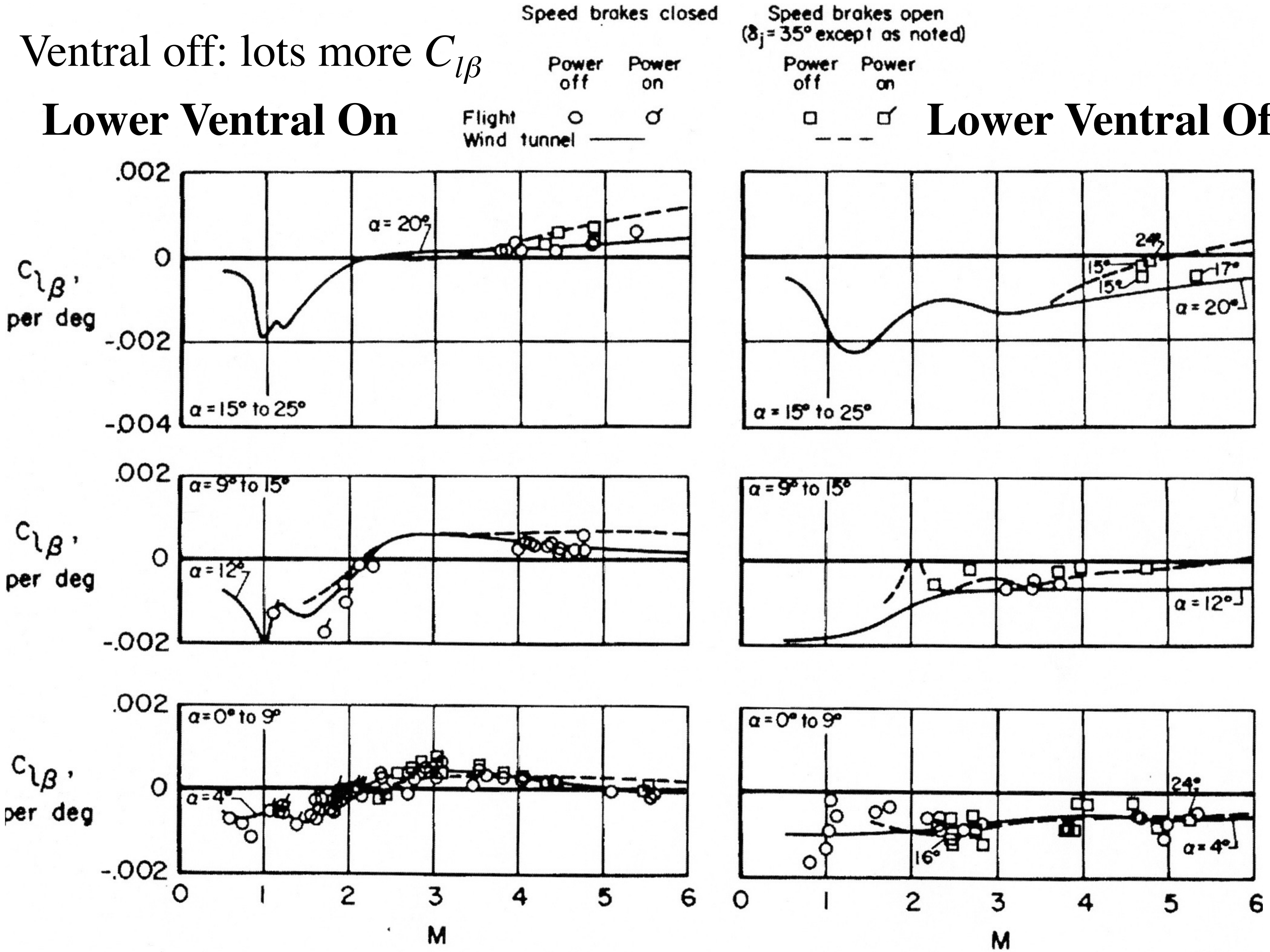
Lower Ventral On **Lower Ventral Off**



The lateral data: NASA TN D-2532

Ventral off: lots more $C_{l\beta}$

Lower Ventral On **Lower Ventral Off**



X-15 Heating Problems: They' re Real

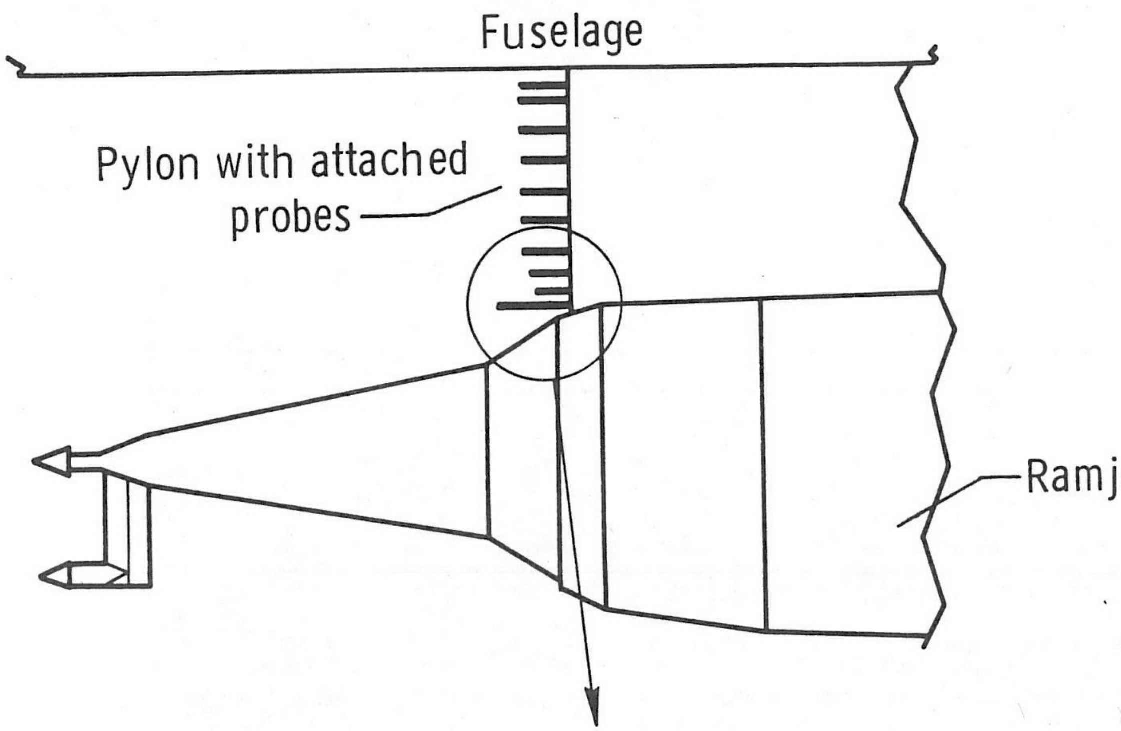
- "normal" surface temps reached around 1350° F
  - Milt Thompson said it snapped and crackled like a tin can tossed into a fire
    - *the simulator never did that!*
  - The skin buckled due to heating
  - Twice a window crazed because the Inconel X frame buckled, and had to be replaced with titanium

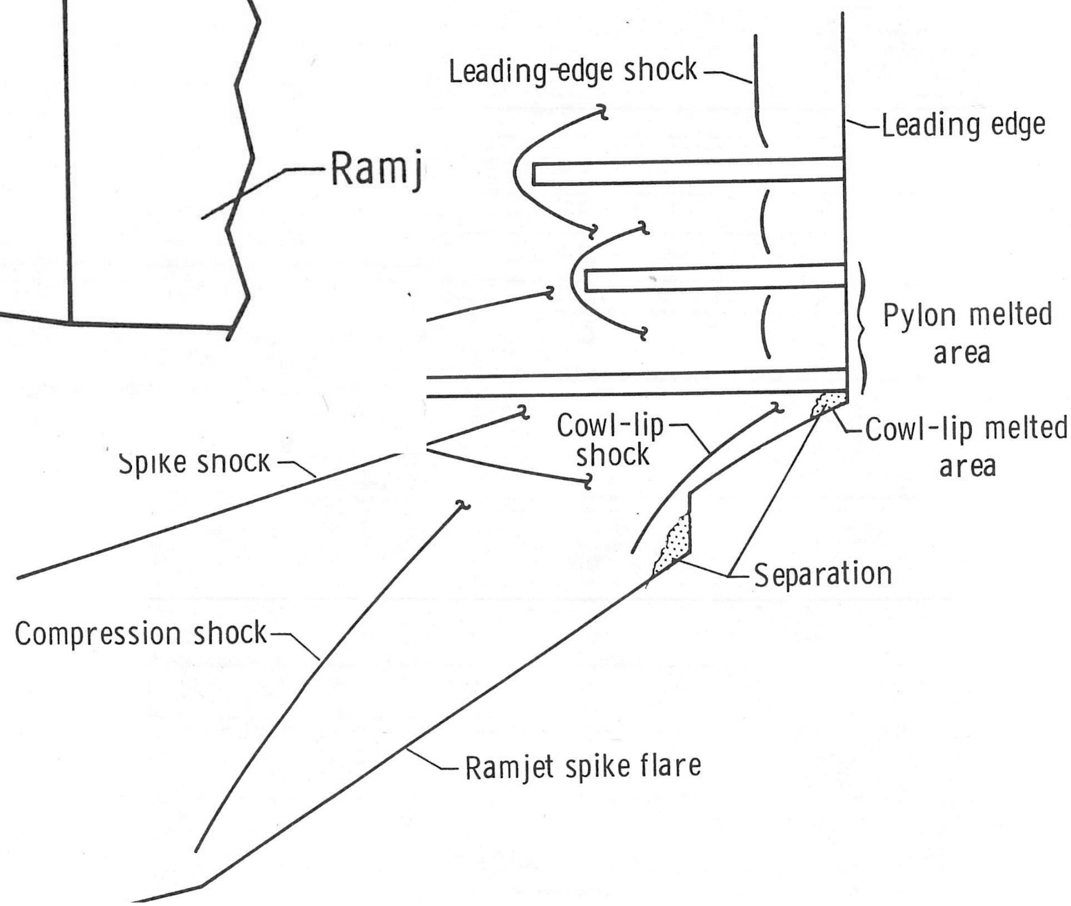
•Shock-shock interference heating resulted in local temperatures above 2795° F (see below)

X-15 dummy ramjet fiasco: a famous aero heating problem

Dryden Flight Research Center EC88-180-2
Photographed Early 1960's X-15

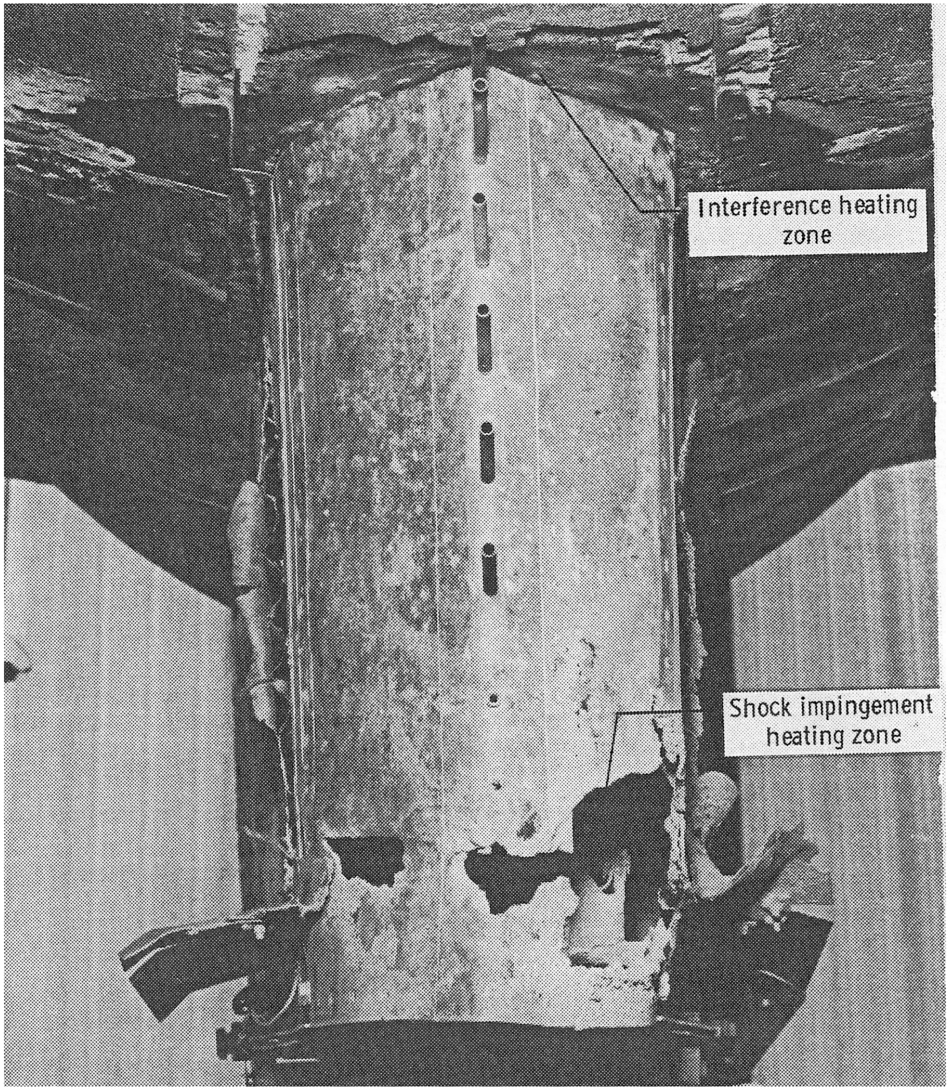
Installation w/o analysis!

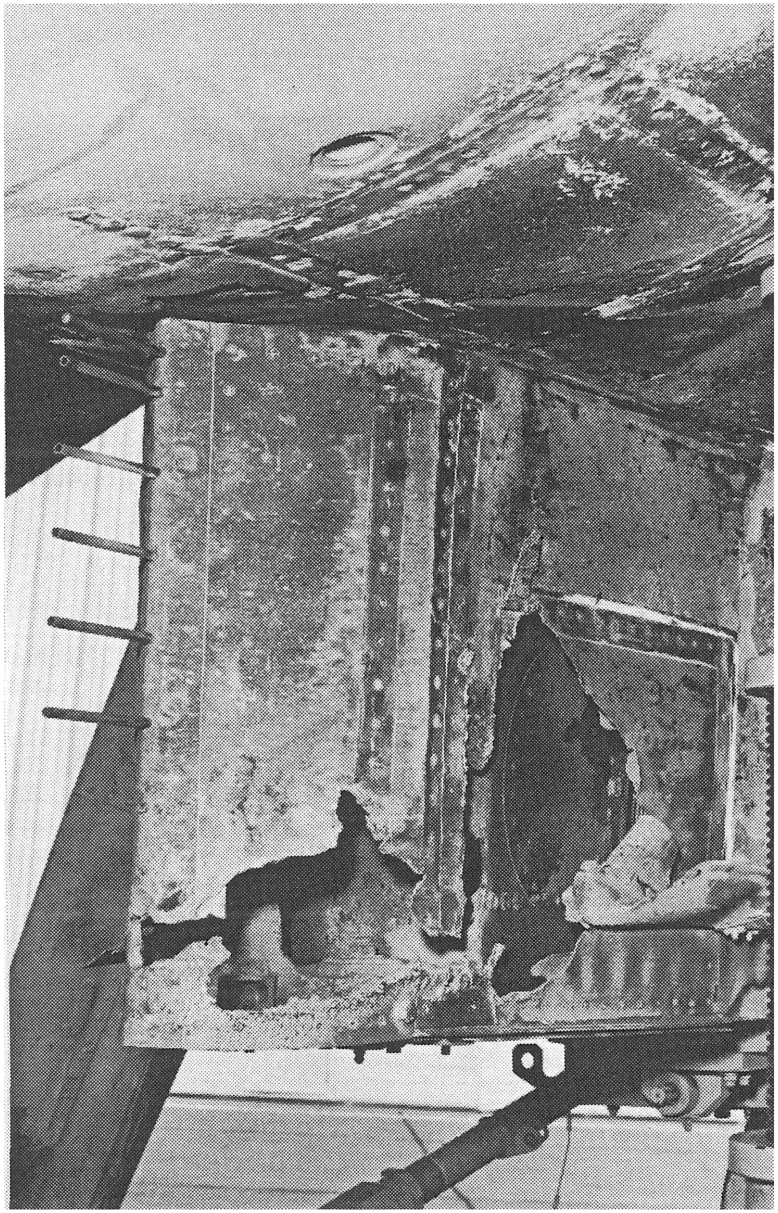




From Iliff and Shafer, AIAA Paper 93-0311

The result melted the metal with temps > 2795° F, 10/3/67





Structure: Inconel X (a nickel-chromium alloy) plus an ablative cover

From Iliff and Shafer, AIAA Paper 93-0311and NASA TM X-1669

Some X-15 Pilots

Dryden Flight Research Center E-1020 Photographed 1966
X-15 Pilots Milt Thompson, Bill Dana, and Jack McKay

Note: Jack McKay was a graduate of VPI Aeronautical Engineering Dept.

X-15 crashes when engine stops and fuel remains, so lands heavy and fast

Dryden Flight Research Center E-9149 Photographed 1962
X-15 after engine failure forced pilot Jack McKay
to land at Mud Lake, Nevada. NASA photo

Aero Heating

Recall: $$\frac{T_0}{T} = 1 + \frac{\gamma - 1}{2} M_\infty^2$$

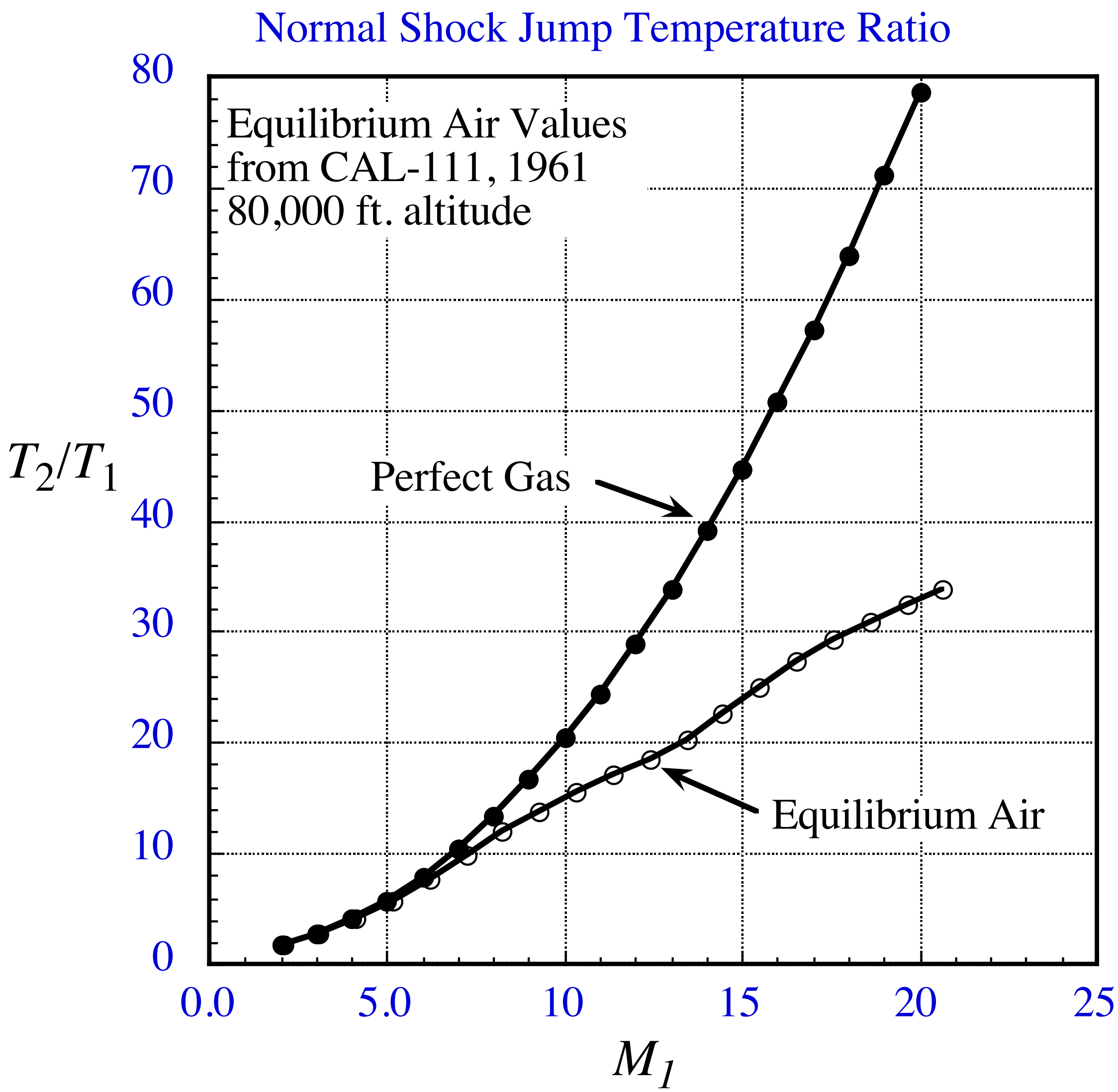
or: $$T_{\substack{adiabatic \\ wall}} = \left(1 + r\frac{\gamma - 1}{2} M_\infty^2\right) T_e$$

r = about 0.85 for laminar flow, about 0.88 for turbulent flow

The air actually starts to vibrate, then dissociate, then ionize at high temperatures, and must be treated as a chemically reacting flow!

Temperature quickly exceeds material limits, walls must be cooled!

Example High Temperature Effects on Shock Jump

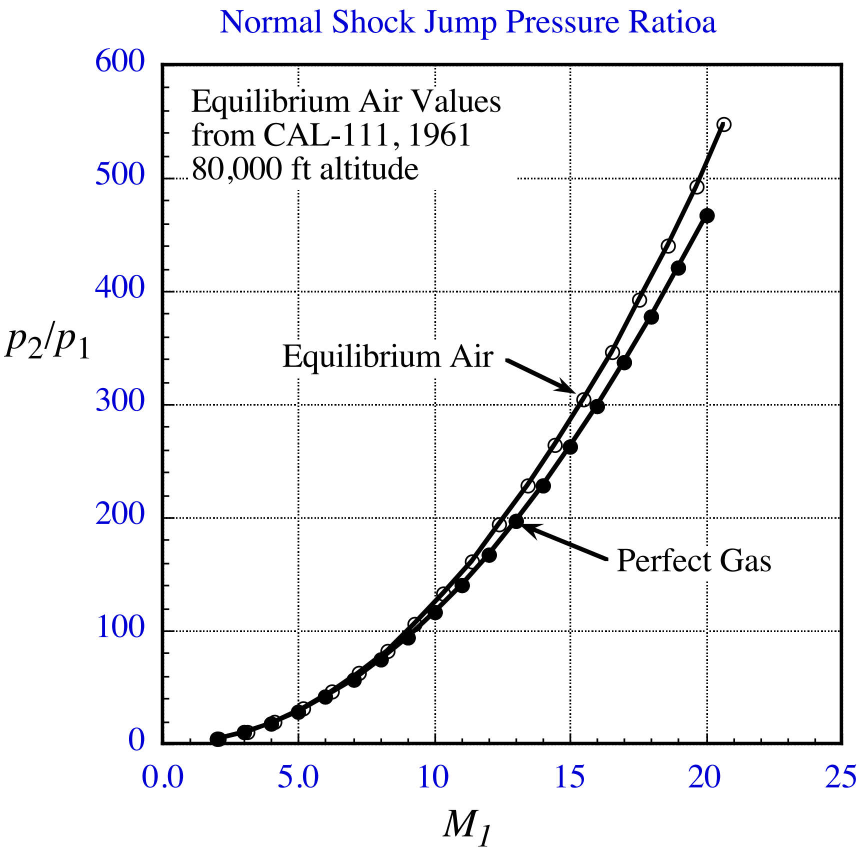


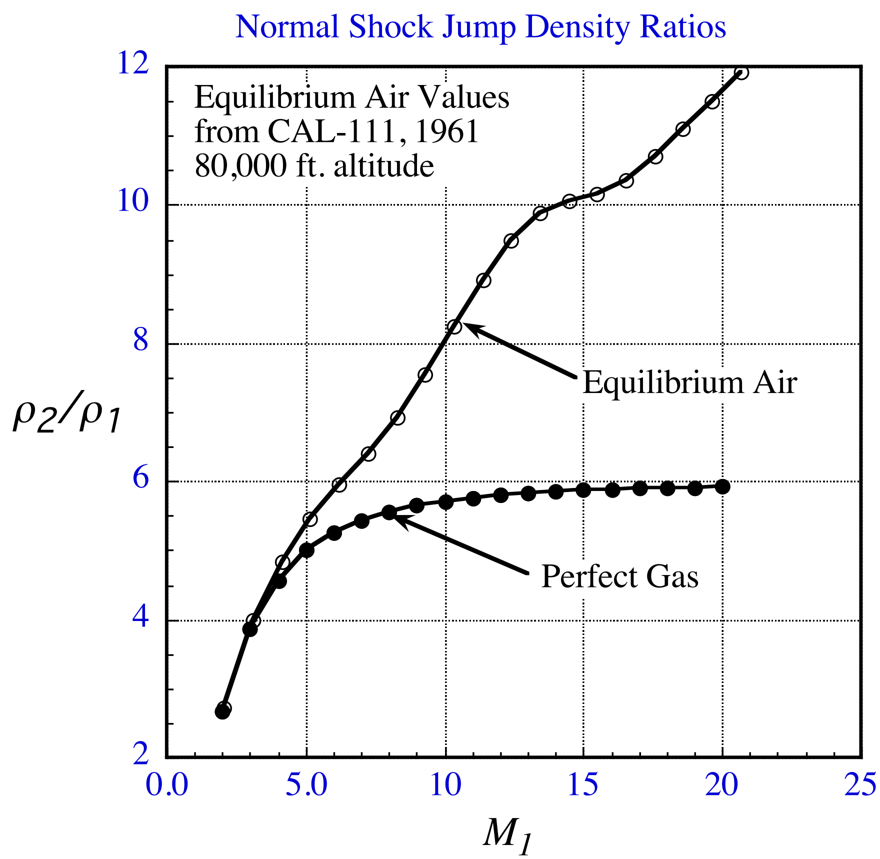
- γ not constant above about 800°K
- Oxygen starts to dissociate above about 2000°K, completed at 4000°K
- Nitrogen dissociation begins at 9000° K
- > 9000° K, gas starts to ionize and become a plasma

According to Anderson, *Hypersonic and High Temperature Gas Dynamics*

Representative: equilibrium air values also depend on the altitude

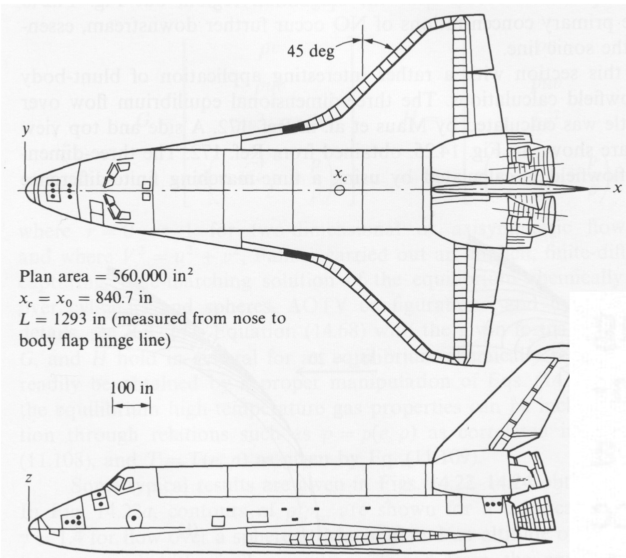
Example High Temperature Effects on Shock Jumps



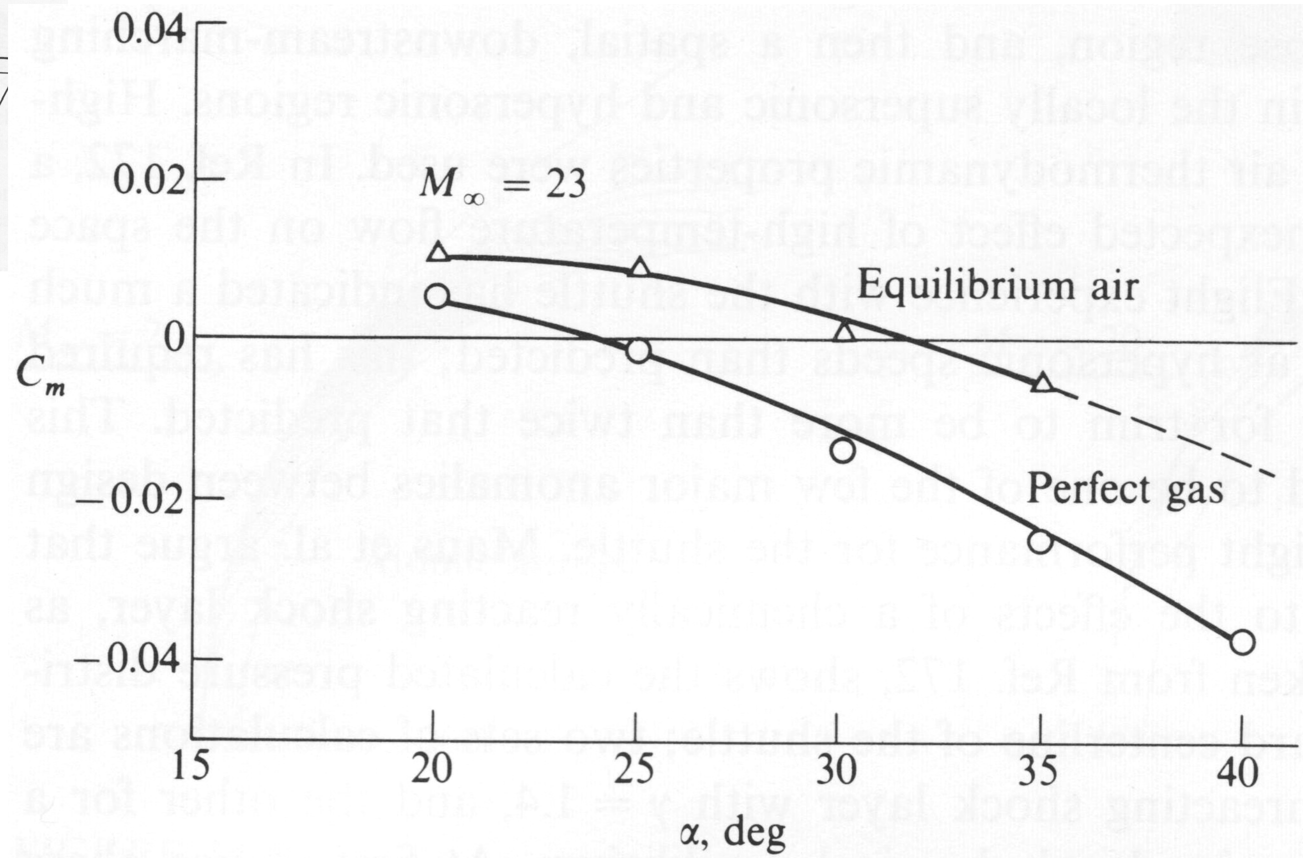


Note that equilibrium air values also depend on the altitude

Space Shuttle Anomaly from high temp gas effects

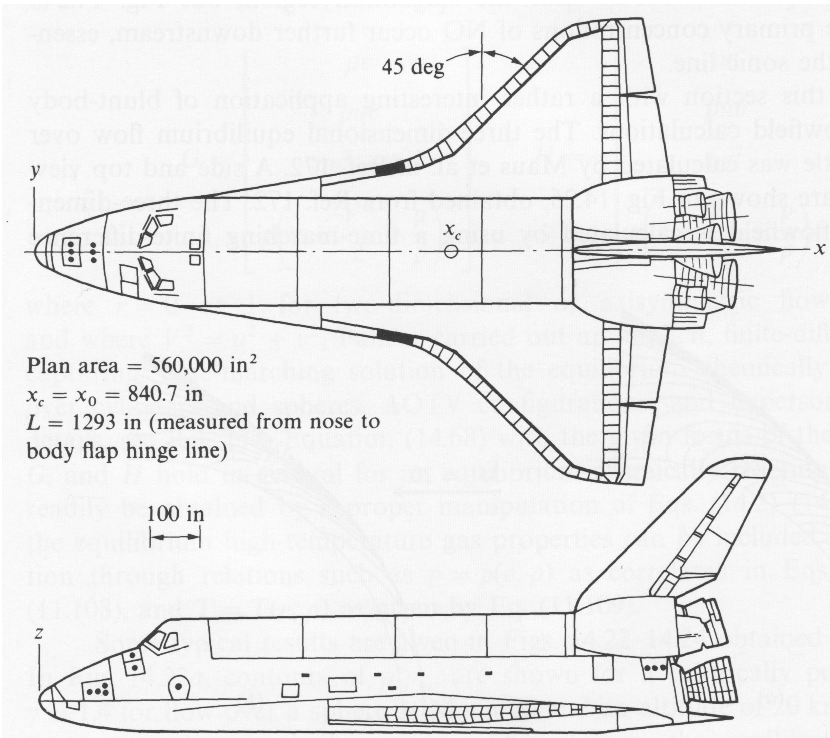


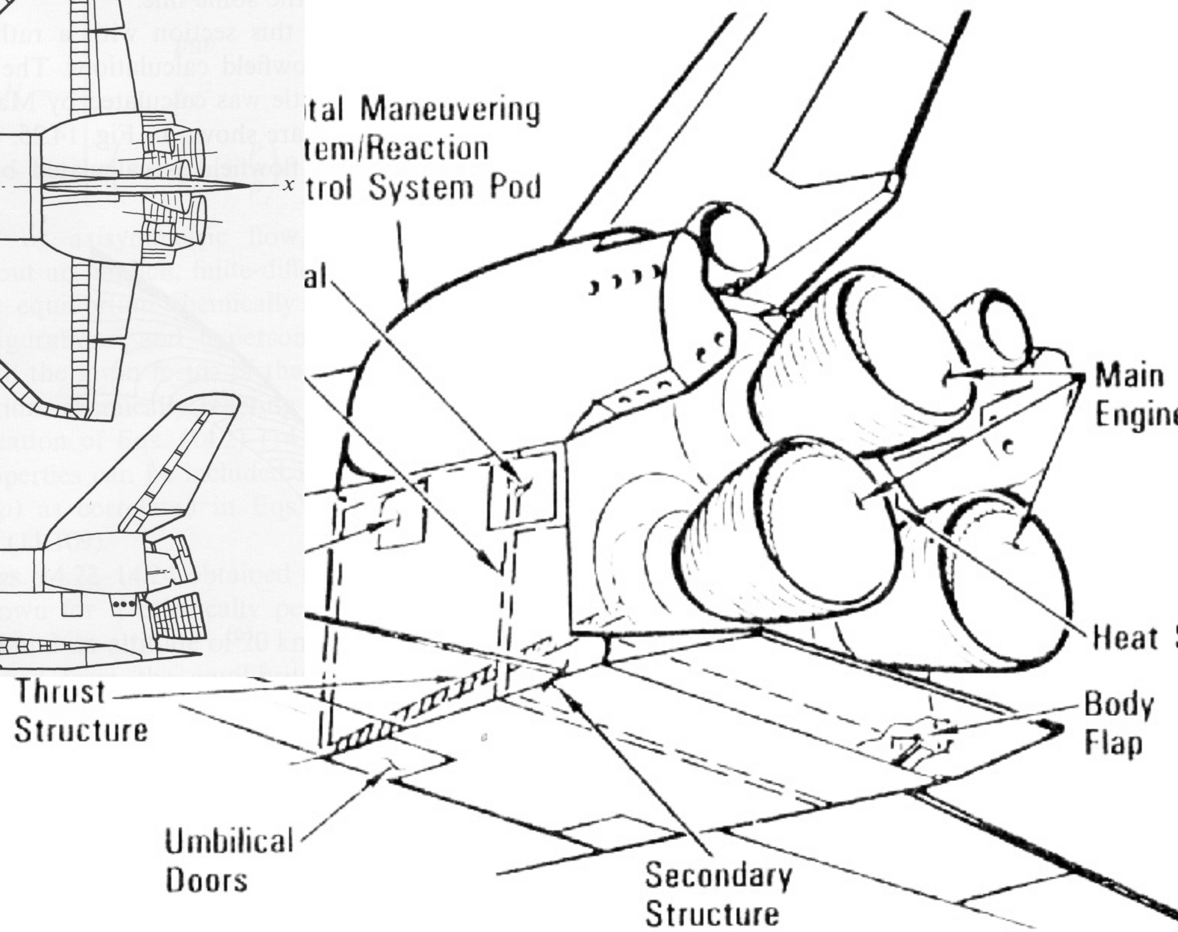
They almost ran out of deflection to trim - could have been a disaster!



From Anderson, *Hypersonic and High Temperature Gas Dynamics*, but originally from Maus, et al, *JSR* Mar-Apr 1984, pp 136-141

The Space Shuttle Body Flap

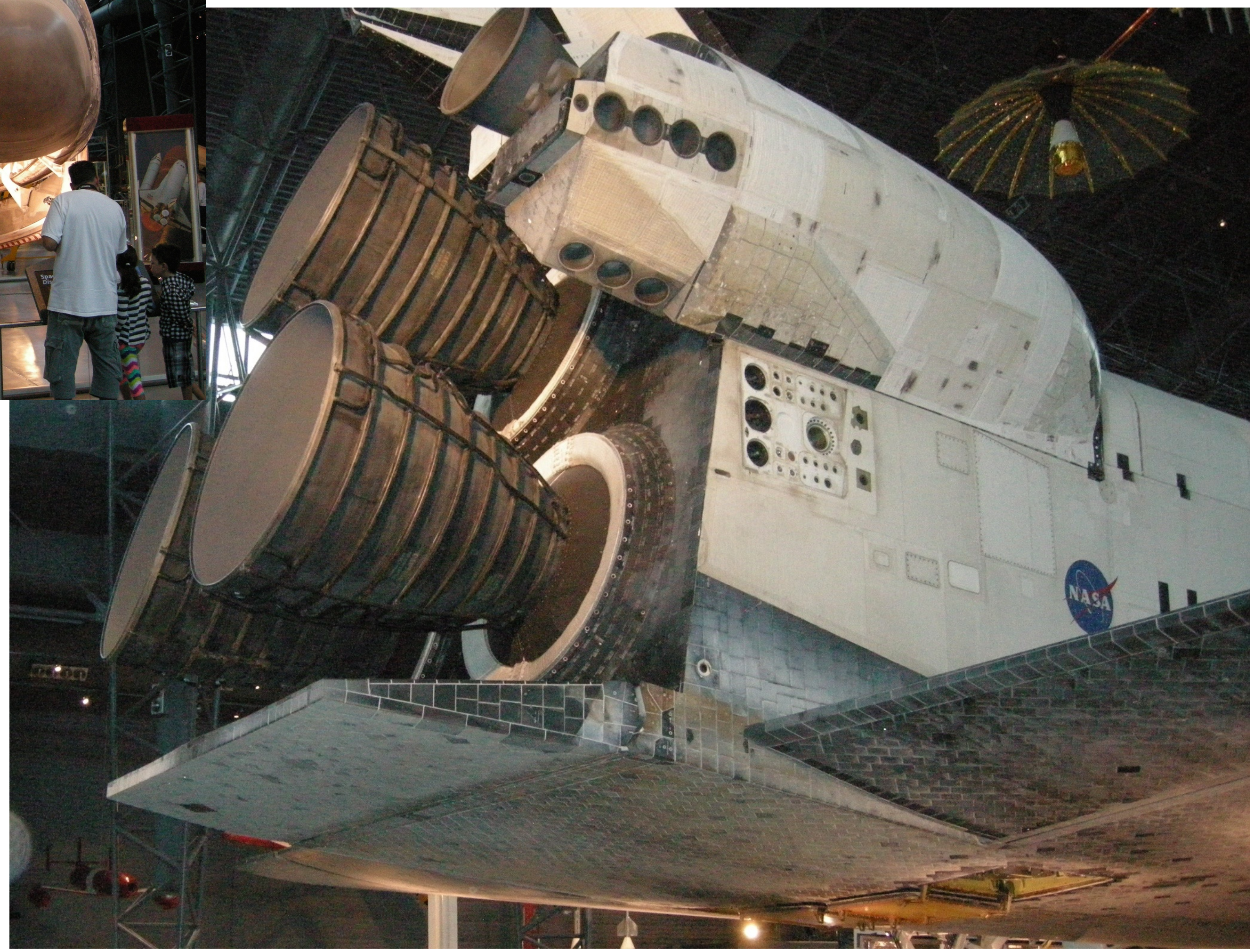




Aft Fuselage Structure

Mason's Picture of the Body Flap

Discovery is now
at the Udvar-Hazy



Discovery
39 flights
Last Flight:
Feb. 24, 2011

Scramjet Idea

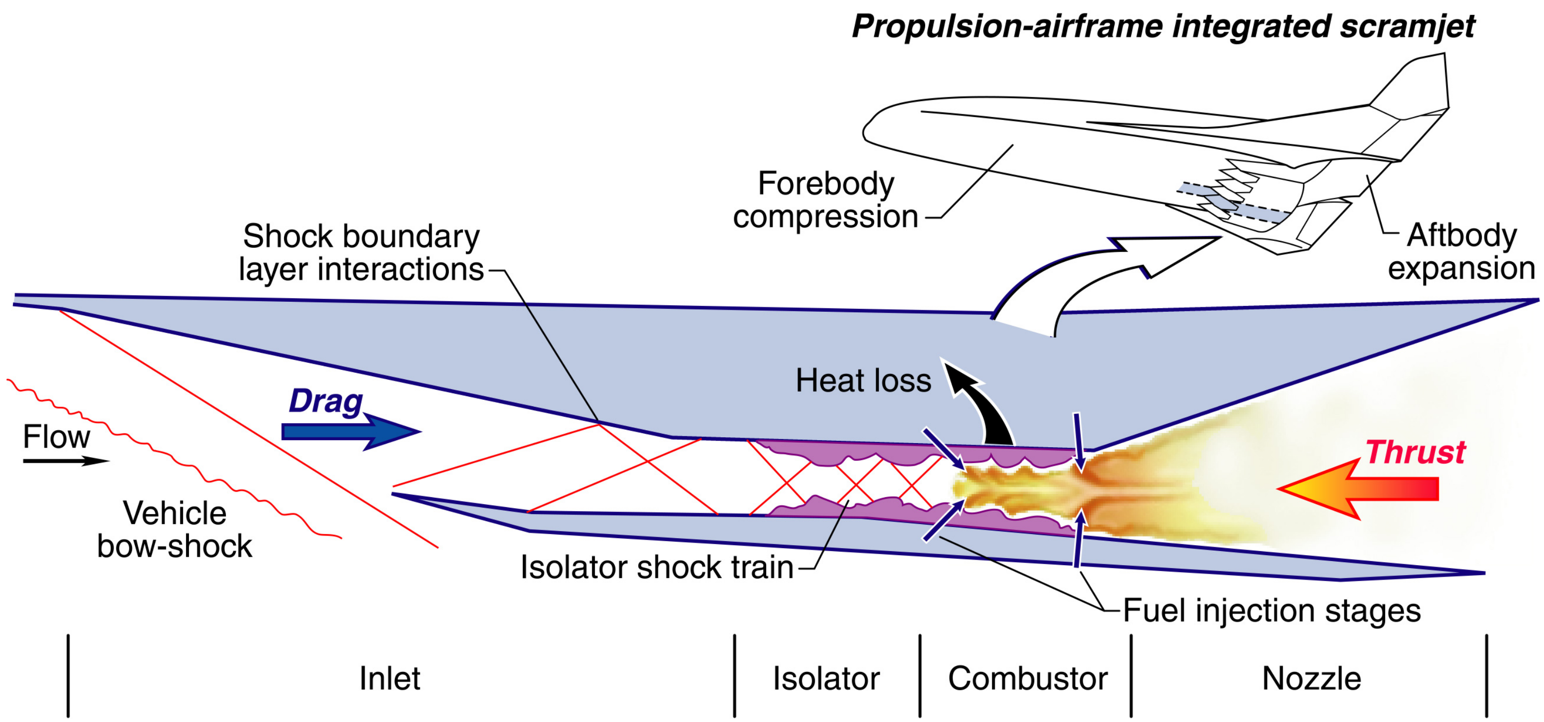
Suppose you could get propulsion from a ramjet that only slows the flow in the combustor down to moderate supersonic speeds? a ***Scramjet***

- more efficient at Machs 7 - 10 and up
- has been a challenge
- Prof. Schetz, a key contributor for 50 years

Corin Segal, *The Scramjet Engine*, Cambridge Univ. Press, 2009

From the talk to our class by Walt Engelund

Scramjet Features



Important Terms/Concepts for the X-43 Experiment

Inlet starting	Combustor/isolator interaction
Ignition/Flameout/Flameholding	Fuel equivalence ratio/Φ

Artist's Concept: X-43 (Hyper X)

Dryden Flight Research Center ED98-44824-1
X-43/Hyper -X aircraft. NASA/Dryden Illustration by Steve Lighthill

12 feet long, 5 foot span, weighed 3,000 lb

Dryden Flight Research Center EC99-45265-14 Photographed DEC1999
X-43 ground testing.
NASA/Dryden photo by Tom Tschida

X-43 prep NASA Dryden Research Center, Edwards AFB, CA

12 feet long
5 foot span
3,000 lb

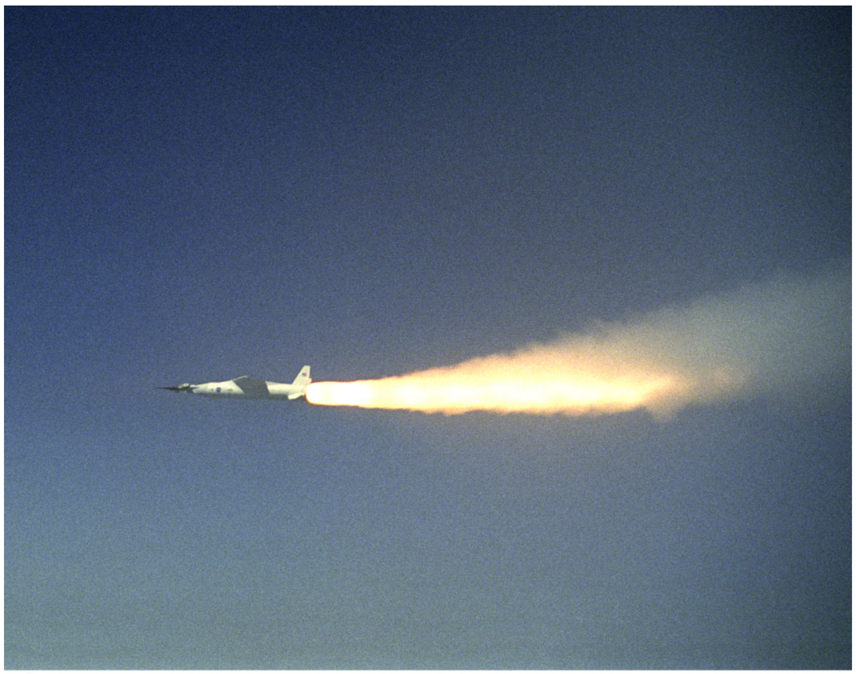
X-43 - dropped from NASA's B-52
and propelled to hypersonic speed by a Pegasus

Dryden Flight Research Center ED97 43968-04
B-52 CARRY-ALL: This artist's concept depicts the Hyper-X research vehicle riding on a booster rocket prior to being launched by Dryden Flight Research Center's B-52 at about 40,000 feet.

X-43 – Flight History

1st attempt – Pegasus failed, June 2, 2001

2nd attempt - success, Mar. 27, 2004



NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: EC04–0092–32 Date: March 27, 2004 Photo By: Jim Ross

A modified Pegasus rocket ignites moments after release from the B–52B, beginning the acceleration of the X–43A over the Pacific Ocean on March 27, 2004.

2nd flight: $M = 6.83$,
10 seconds of powered flight,
$q = 980$ psf (95K ft)

3rd flight: M = 9.68
11 seconds of powered flight,
$q = 930$ psf (110K ft)

3rd attempt – success, Nov. 16, 2004

See McClinton's Dryden Lecture, AIAA Paper 2006-1, Jan. 2006

The X-51 - a "Wave Rider"

A "wave rider" is a very efficient way to use the shock to generate lift on the lower surface.

- Originally based on conical flow ideas
- some say the XB-70 was "Waverider-like"
- 1st flight – May 26, 2010, 2nd flight – June 13, 2011
- 3rd flight – Aug. 14, 2012, 4th flight – Spring or Sum. 2013

***The 4th flight May 1, 2013: Success! M* = 5.1, 210 sec**

1st flight: 200 seconds of powered flight

2nd flight: Scramjet unstart when switched from ethylene to JP-7

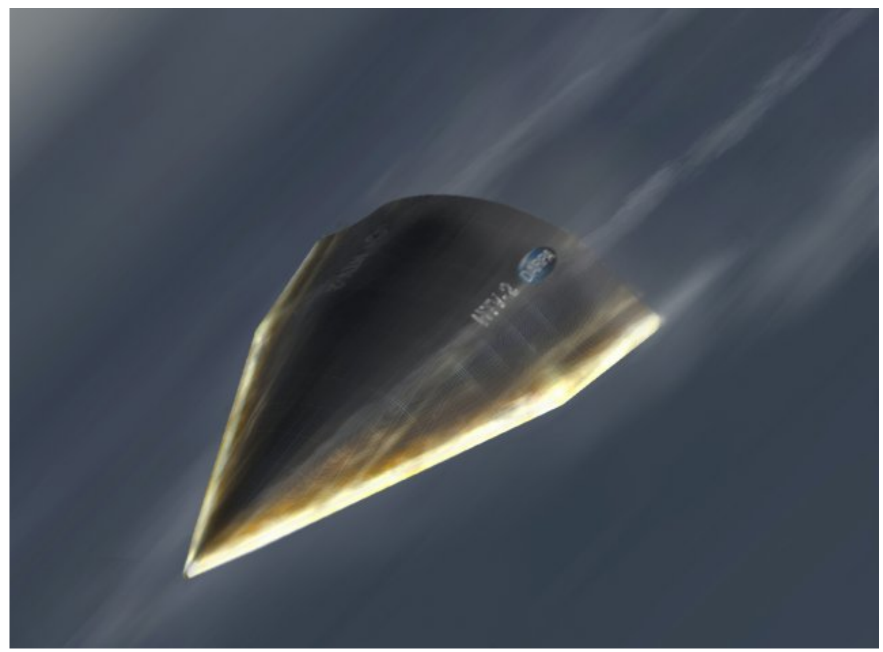
3rd flight: a fin locked up and it went out of control

HTV-2 Falcon DARAP-USAF Lockheed Hypersonic Glider

Launched from a missile

-11 April 2010
-11 Aug 2011

Both "Flew" at Mach 20



In both cases the flight ended prematurely.

It appears that asymmetric disintegration due to aero heating caused loss of control.

To Conclude Hypersonics

- Scramjet research continues
- If scramjets become practical, a new era in flight will begin

For more info:

- Aero: John D. Anderson, Jr., *Hypersonic and High Temperature Gas Dynamics*, 2nd Ed. From AIAA
- See the Walt Engelund and Chris Cotting presentations on Hyper-X (X-43) on the class website
- Vehicles: http://www.aerospaceweb.org/design/waverider/main.shtml
  - this is a good overview across the board
- Air Force and NASA histories on the class website