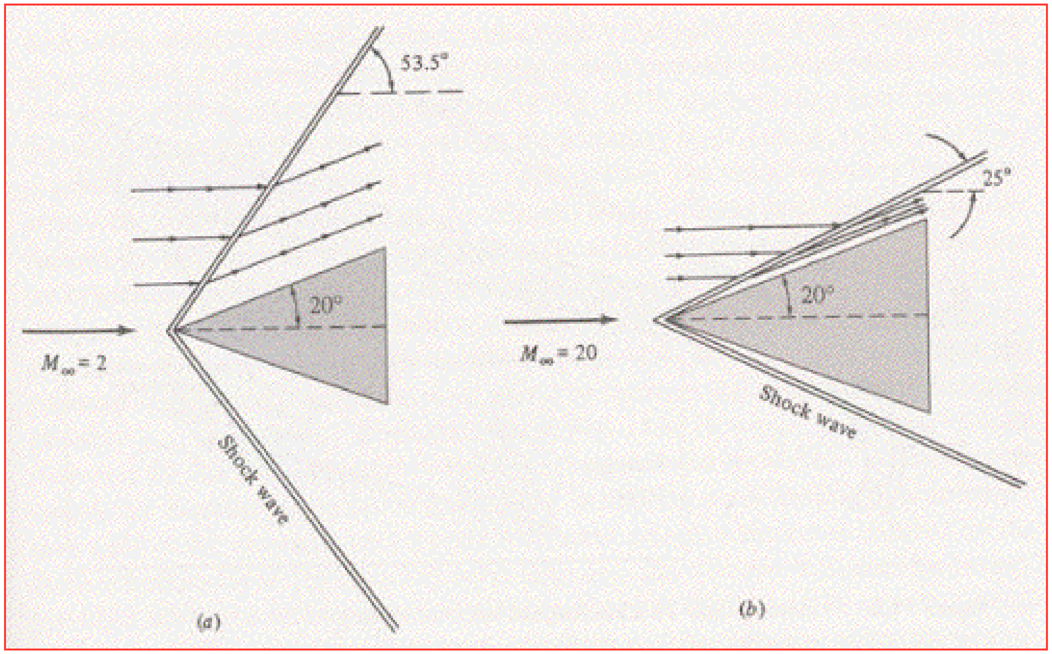
Utah State University

Mechanical & Aerospace Engineering

Section 12 Lecture 1: Introduction to Hypersonic Flight

Anderson: Chapter 16 pp. 610-613, Chapter 3 pp. 102-111
Chapter 17 pp. 648-658

What Characterizes Hypersonic Flow



- As the Mach number increases, the shock angle becomes smaller, and distance between surface and shock wave decreases with increasing speed.

What Characterizes Hypersonic Flow

(cont'd)

• For a hypersonic body, shock distance from surface can become very small over a large portion of the body

-- resulting flowfield between the surface and shock is often referred to as a shock layer.

• Thin layer can produce many complications in vehicle design, e.g. the shock layer may merge with the boundary layer at low Reynolds numbers to form a fully viscous shock layer.

• In the limit as Mach number goes to infinity, the shock layer forms an infinitely thin, infinitely dense sheet, or, essentially, a flat plate.

What Characterizes Hypersonic Flow

(cont'd)

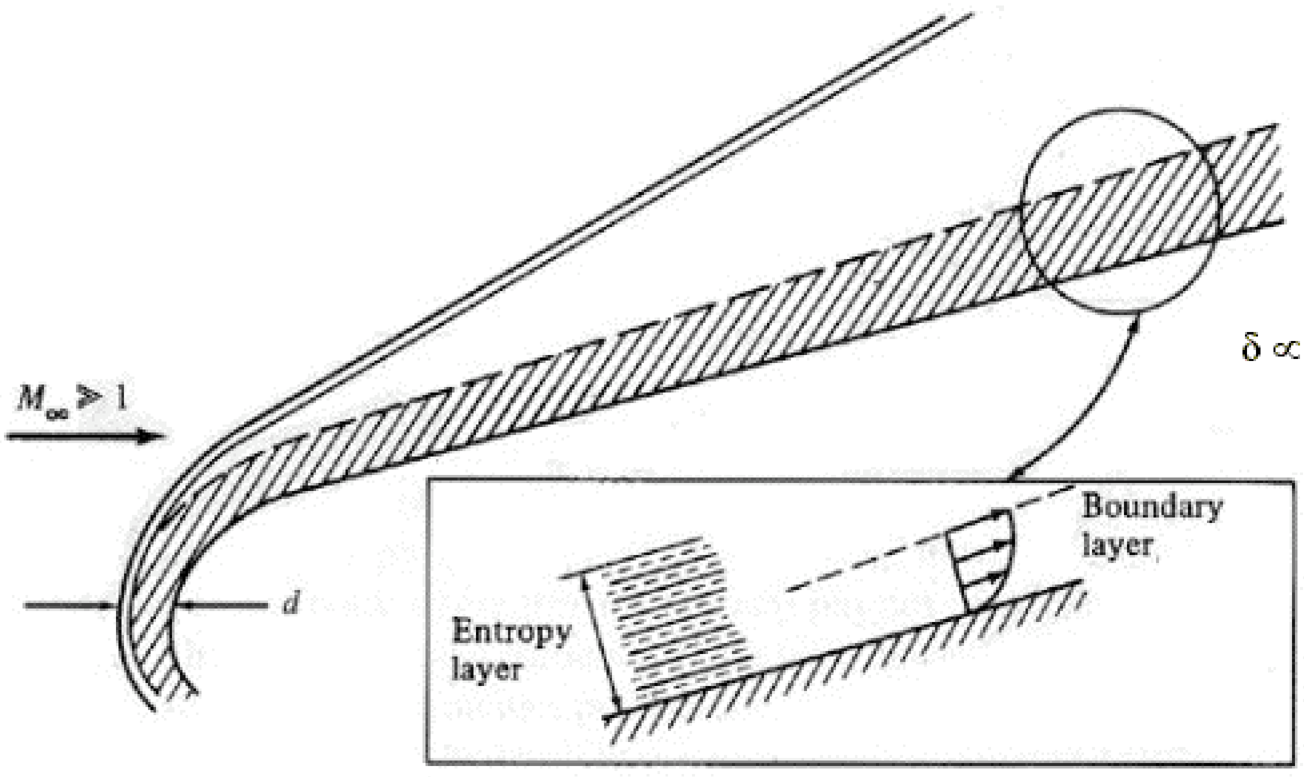
•Close to a blunt leading edge, detached shock becomes highly curved.

• Since flow near the nose passes through a nearly normal shock, it will experience a much greater change in entropy compared to flow passing through the much shallower shock angle further from the body centerline.

• Thus, strong entropy gradients exist near the leading edge generating an "entropy layer" that flows downstream along the body surface.

What Characterizes Hypersonic Flow

(cont'd)



$$\delta \propto \frac{M^2}{\sqrt{Re_x}}$$

What Characterizes Hypersonic Flow

(cont'd)

• As Mach number increases, the boundary layer can grow rapidly … resulting in very high drag.

• If boundary layer becomes thick enough, it may affect the inviscid flowfield far from the body, ………a phenomenon called viscous interaction.

• Viscous interaction can have a great influence on the surface pressure distribution and skin friction on the body thereby affecting the lift, drag, stability, and heating characteristics of the body.

What Characterizes Hypersonic Flow

(cont'd)

•Hypersonic vehicles create so much heat and such high temperatures due to shock wave compression and boundary Layer frictional heating that they cause chemical changes to occur in the fluid through which they fly.

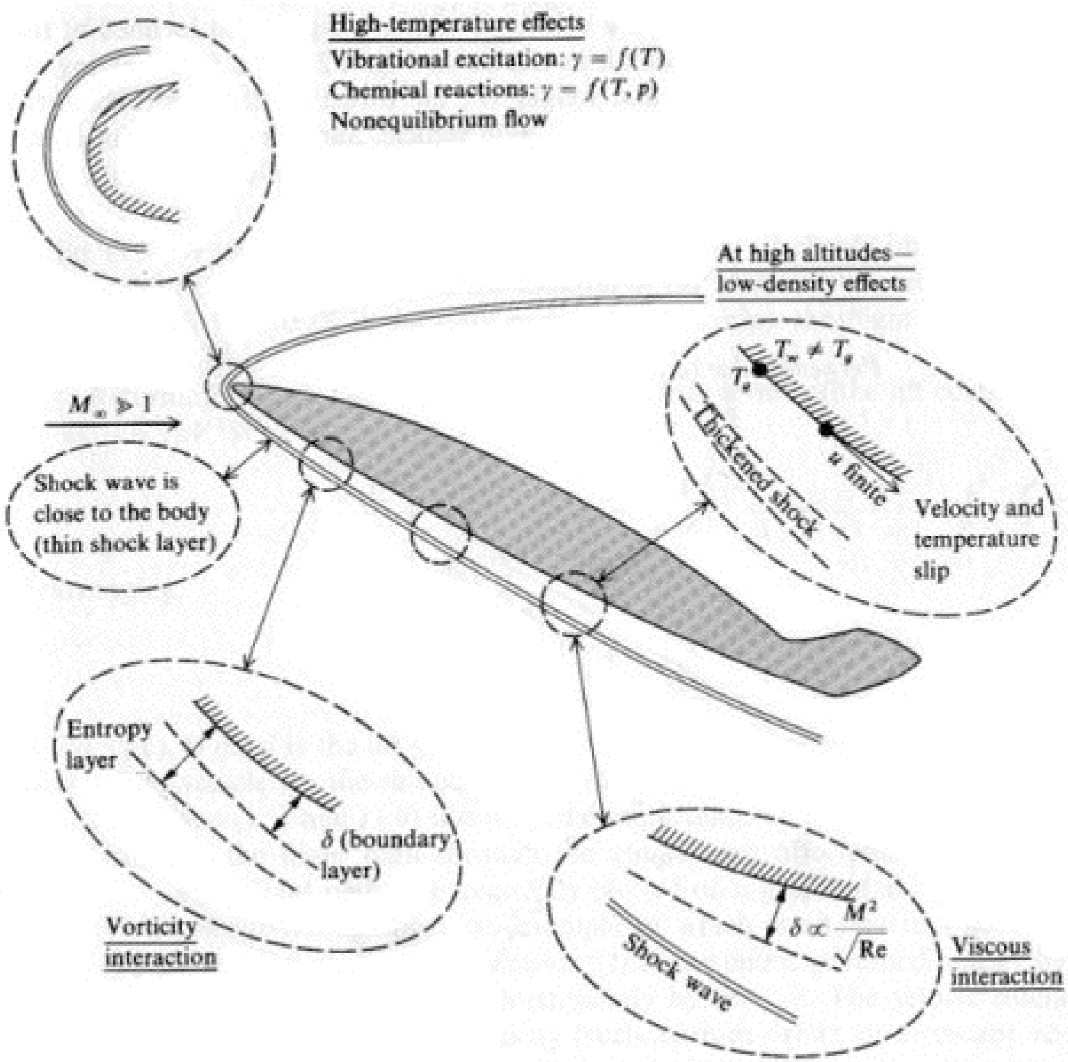
High Temperature Effects on Air

Temperature [K]	Chemical Change
800	Molecular vibration
2000	Oxygen molecules (O_2) dissociate
4000	Nitrogen molecules (N_2) dissociate
	Nitric oxide (NO) forms
9000	Oxygen and nitrogen atoms ionize

• Gas chemistry effects are important factor in dissipation of heat on hypersonic vehicles

What Characterizes Hypersonic Flow

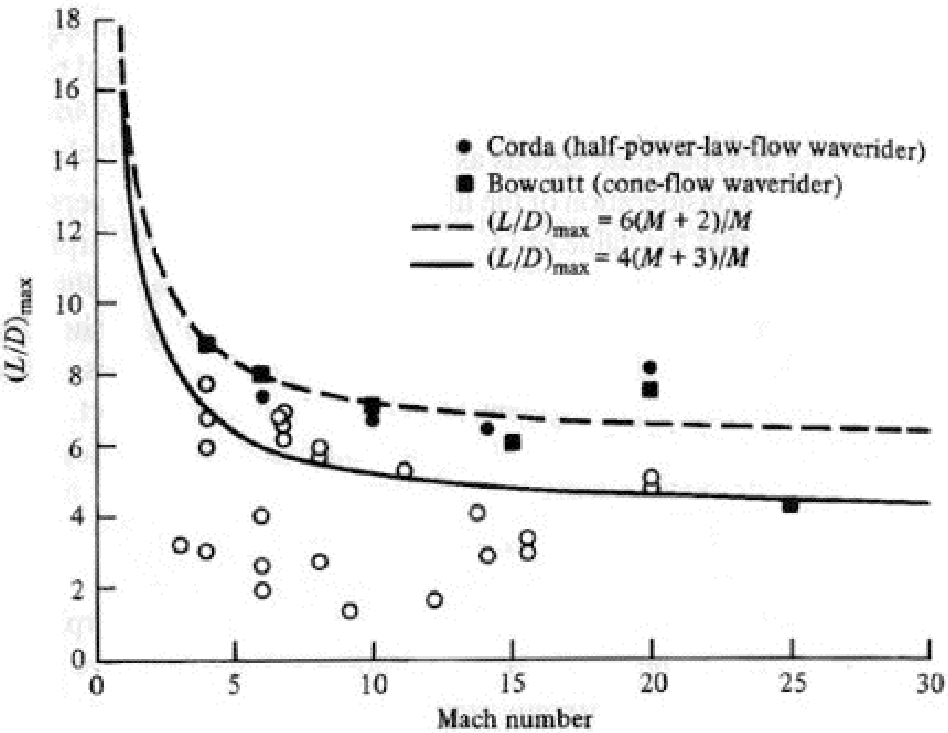
(cont'd)



- Combined effects … the big picture

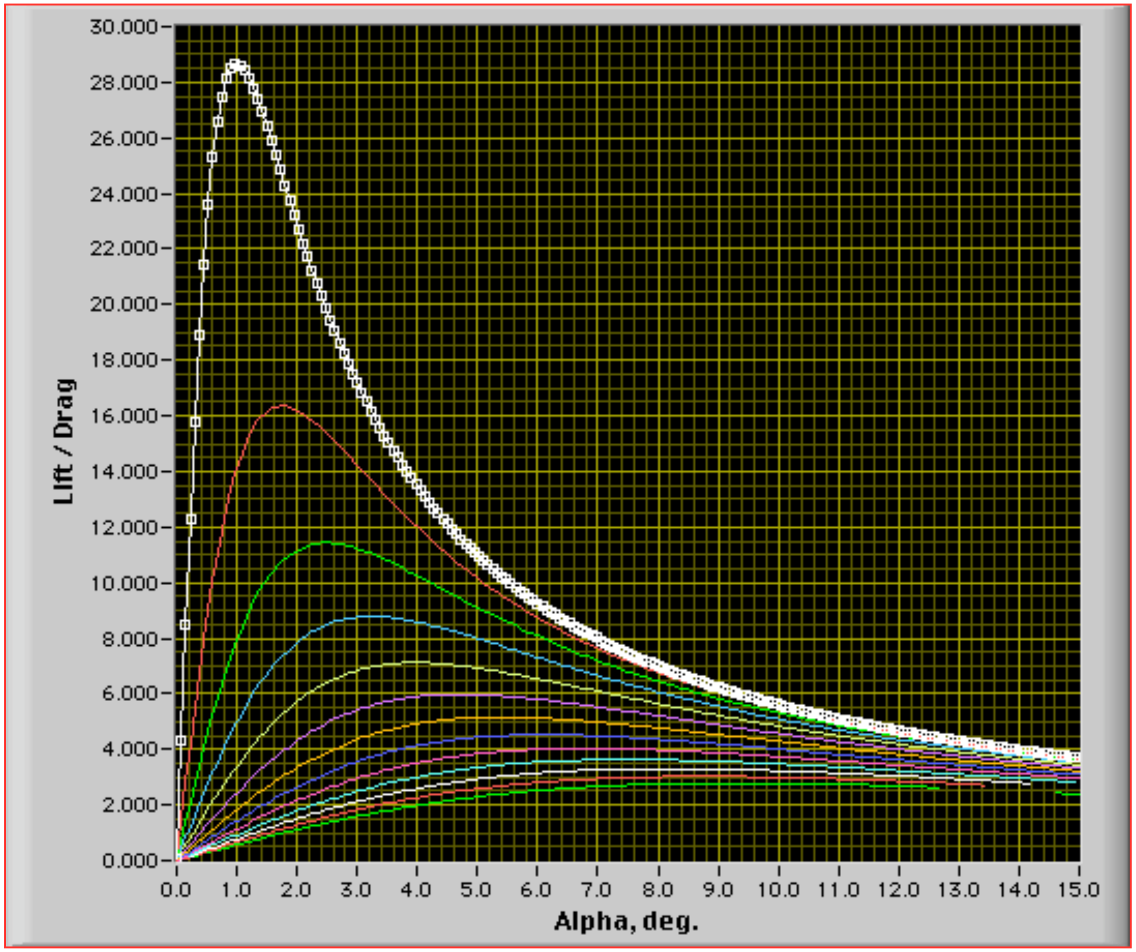
Hypersonic Vehicle Characteristics

• Hypersonic vehicles are capable of L/D ratios far below those typical of subsonic and low supersonic aircraft.



• Viscous effects within boundary layer cause friction effects to Skyrocket

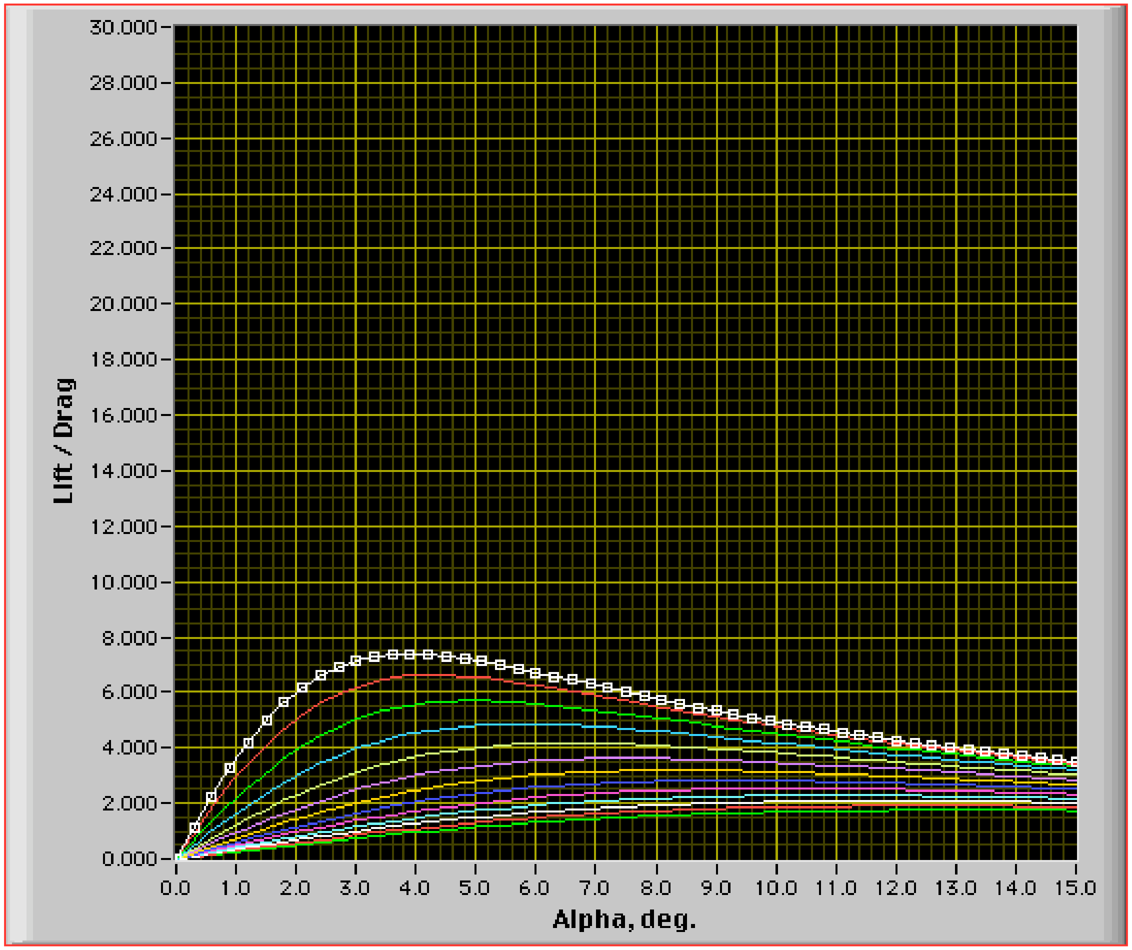
Symmetric Double-wedge Airfoil … L/D (revisited)



- Inviscid Analysis

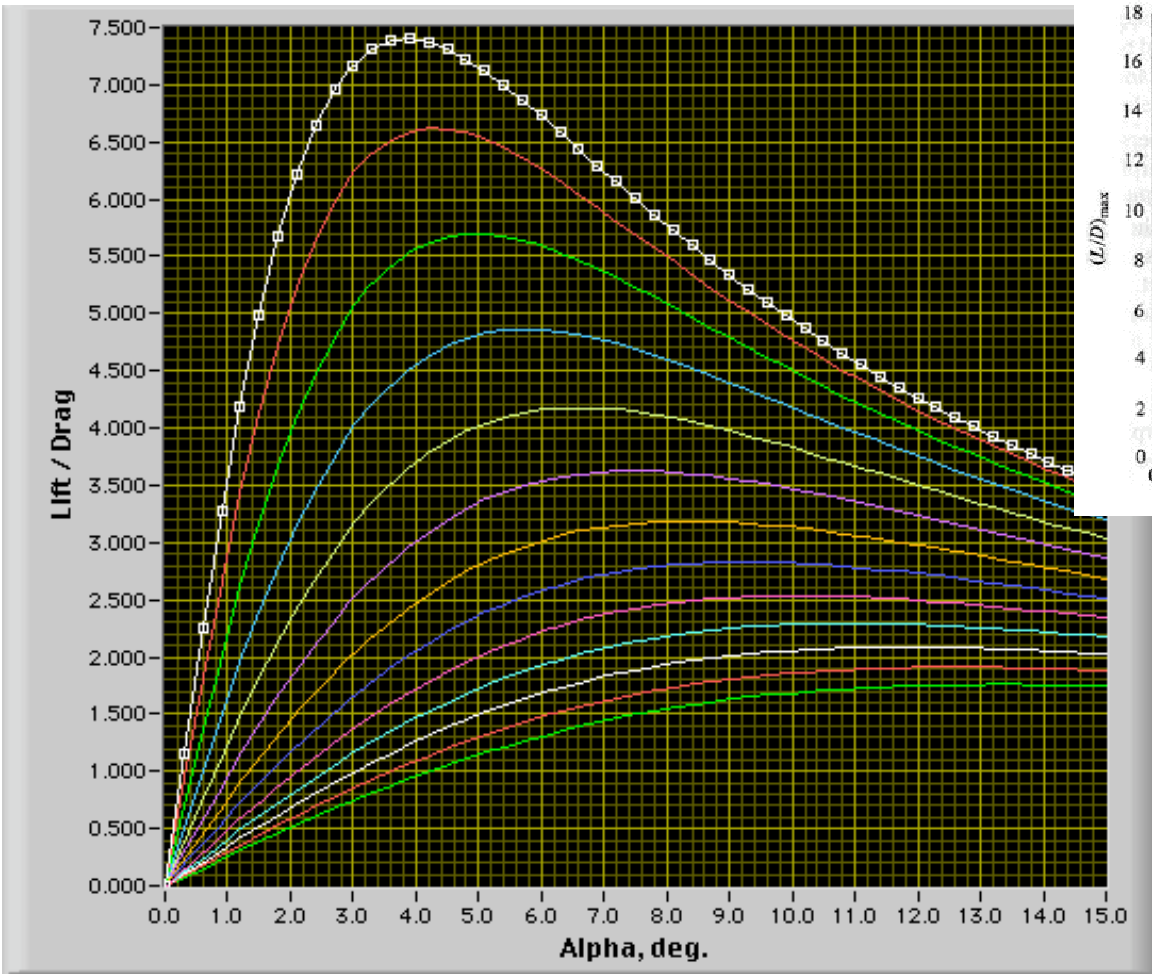
- Mach 3

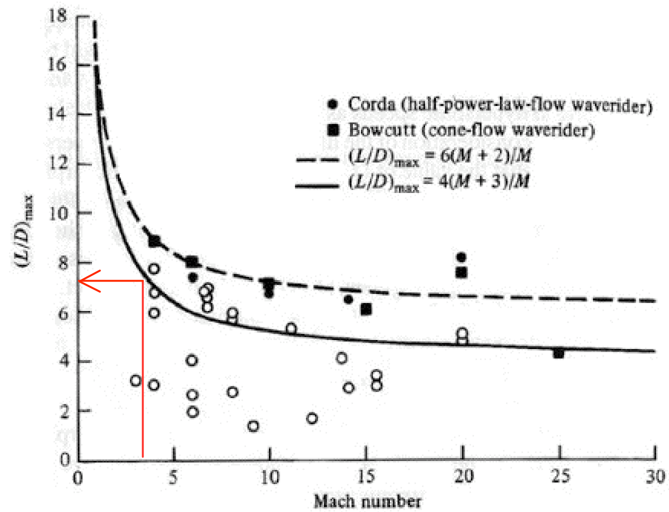
Symmetric Double-wedge Airfoil … L/D (revisited)



- Analysis Including skin Friction Model
- Wow!
- Mach 3

Symmetric Double-wedge Airfoil … L/D (revisited)



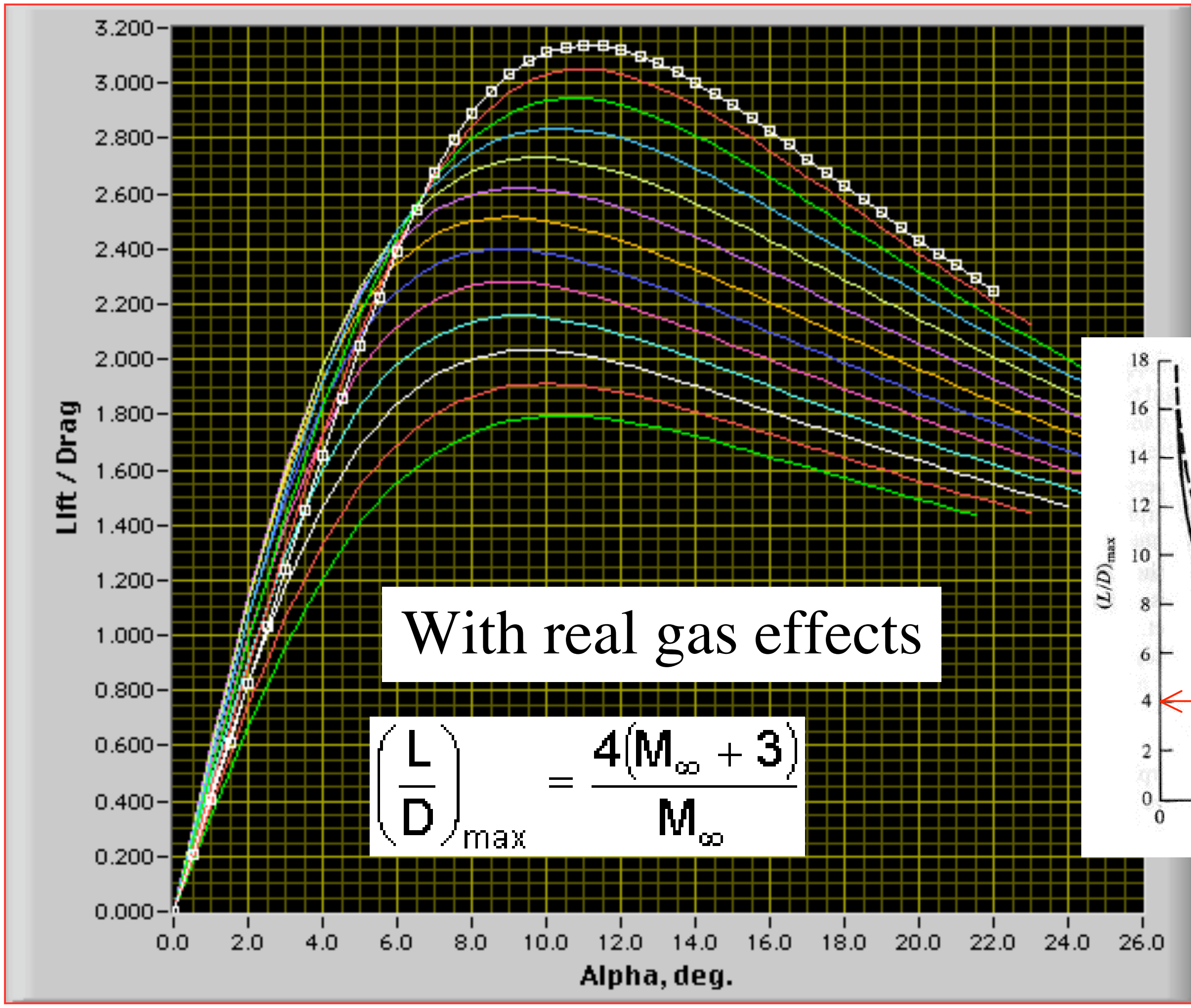


- Mach 3

$L/D_{max} = 7.4$

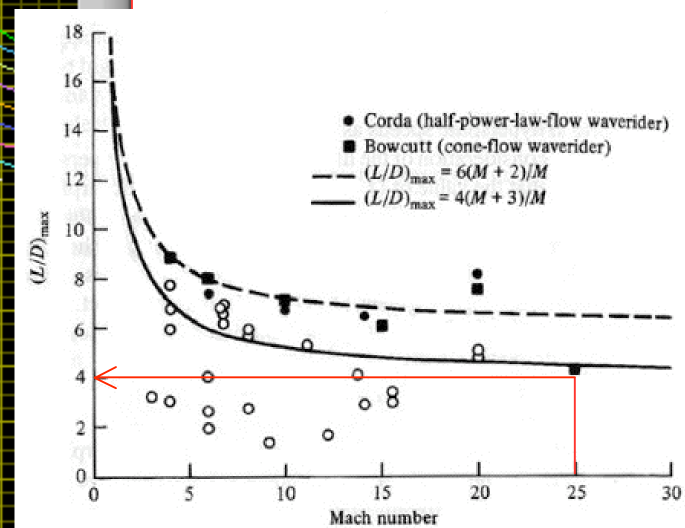
Symmetric Double-wedge Airfoil … L/D (revisited)

- Mach 25
- 60 km Altitude

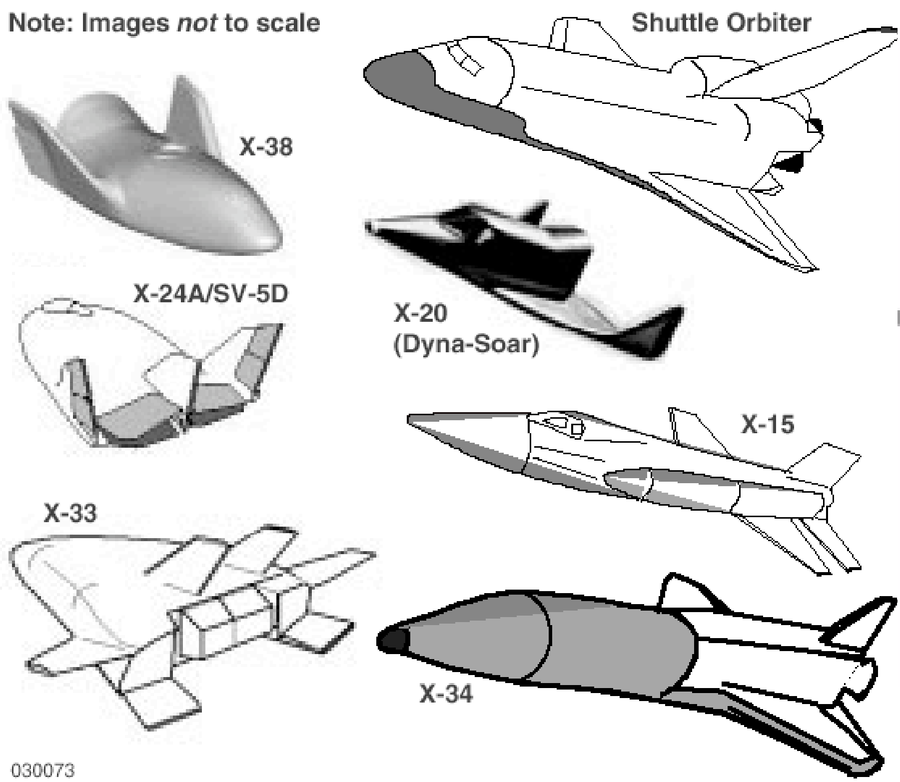


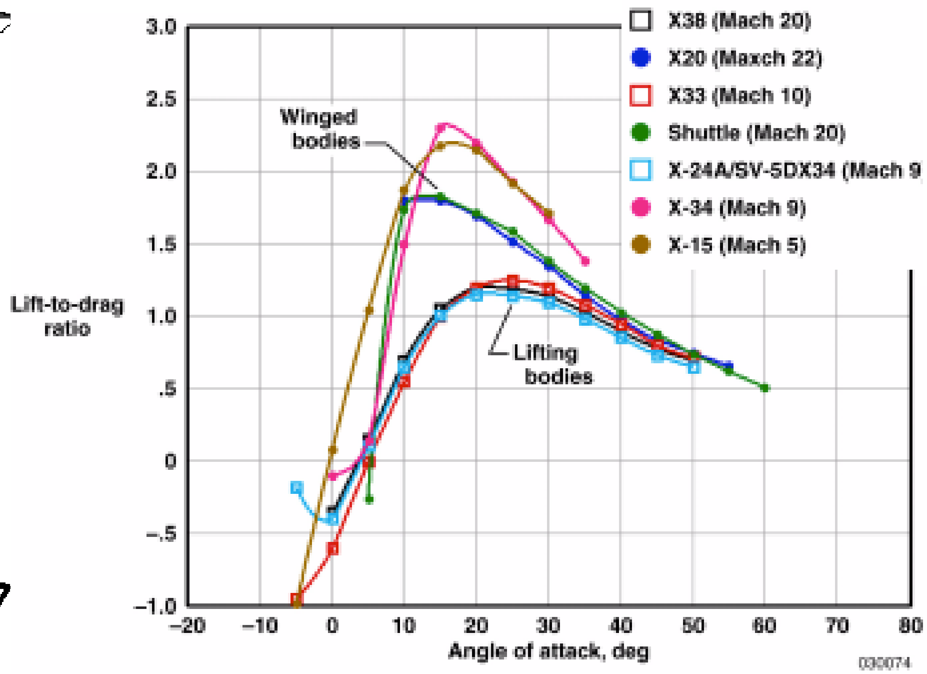
With real gas effects

$$\left(\frac{L}{D}\right)_{max} = \frac{4(M_\infty + 3)}{M_\infty}$$



Hypersonic L/D Comparisons for seven lifting reentry configurations.

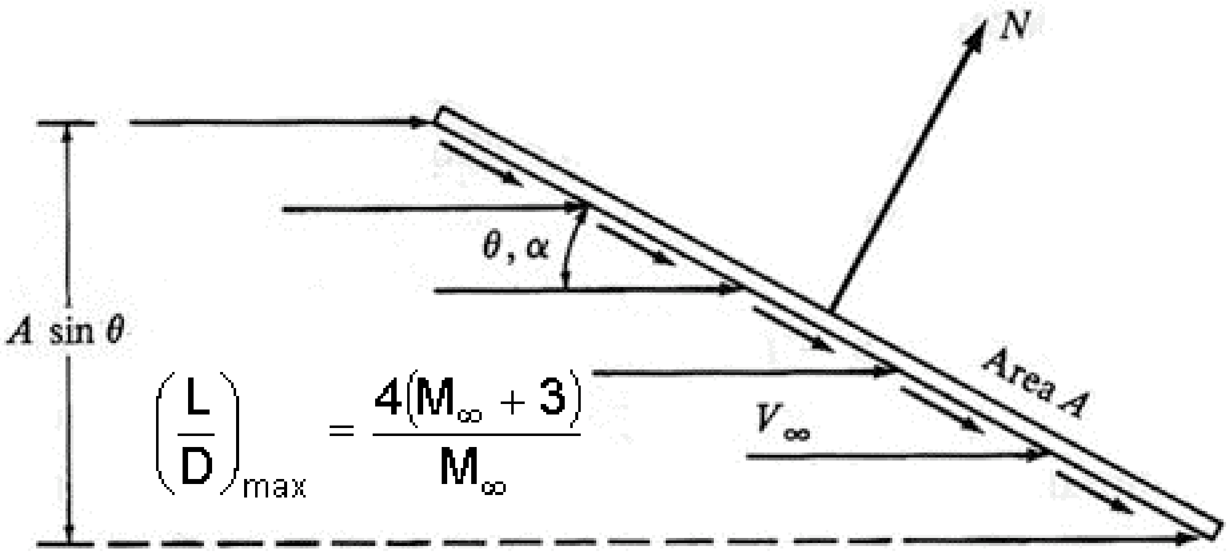




Hypersonic L/D ratio

Hypersonic Vehicle Design

- Flat plate is best hypersonic airfoil



$$\left(\frac{L}{D}\right)_{max} = \frac{4(M_\infty + 3)}{M_\infty}$$

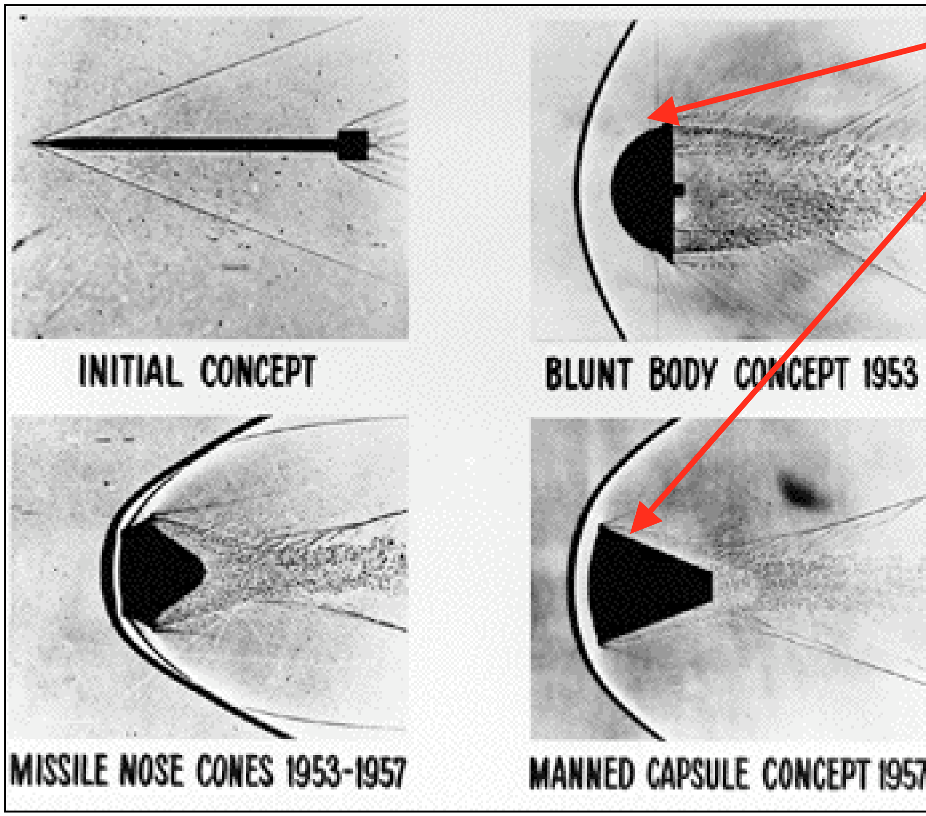
- But impractical

Hypersonic Vehicle Design

(cont'd)

- Heating vs. performance (Hypersonic Aerodynamics)

Heating is Minimized by Blunt Body
.. But so is Lift-to-Drag ratio



- Detached Normal Shockwave On Blunt Leading Edge Dissipates significant Portion of heat into flow

- But Also .. Produces High level of Drag

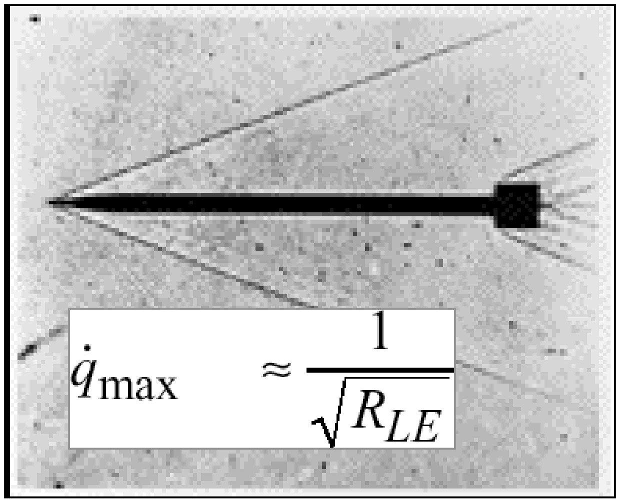
Heating proportional to

$1/R_{le}^{\,1/2}$

Hypersonic Vehicle Design

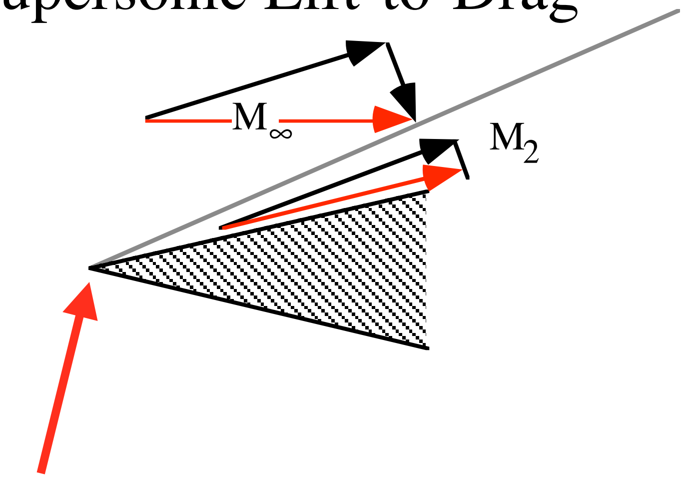
(cont'd)

- Sharp leading Edge has very high heating
  But Much Lower Hypersonic Supersonic Lift-to-Drag



$$\dot{q}_{max} \approx \frac{1}{\sqrt{R_{LE}}}$$

Oblique Shockwave

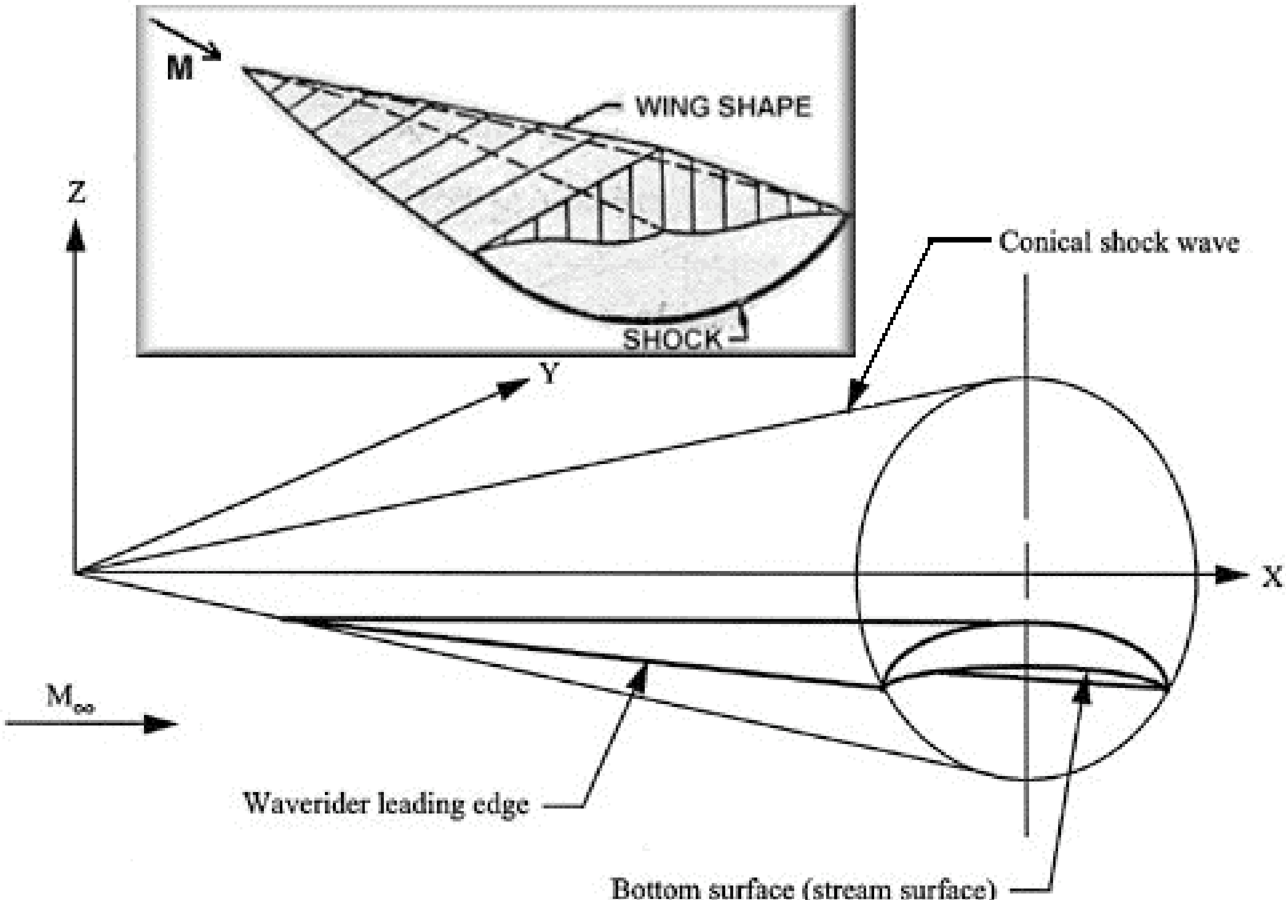


- Flow attached at leading edge
  Heating impinges directly

- More Exotic Thermal Protection
  Systems Required

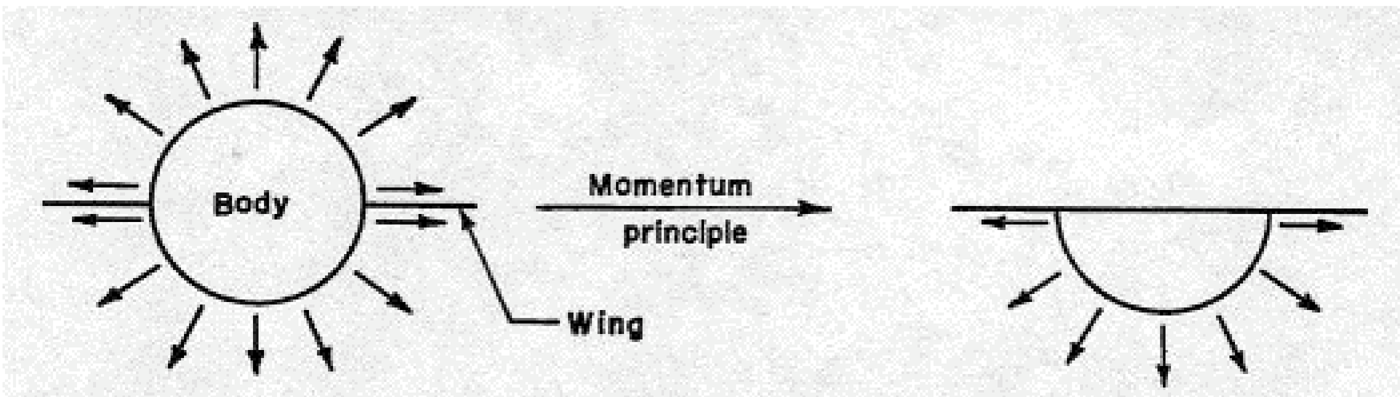
Hypersonic Vehicle Design (cont'd)

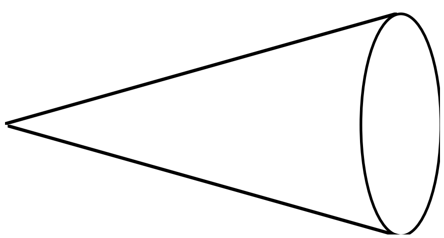
- High performance hypersonic vehicles designs are "carved" out of conical flow fields

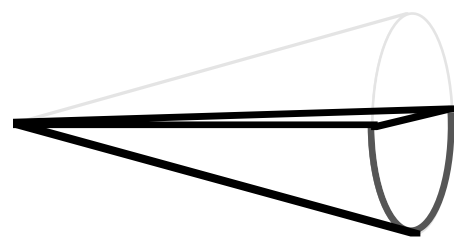


Hypersonic Vehicle Design (cont'd)

- Lower Body doesn't "see" effects of lower Body
  we can "chop off" top and still have conical flow field

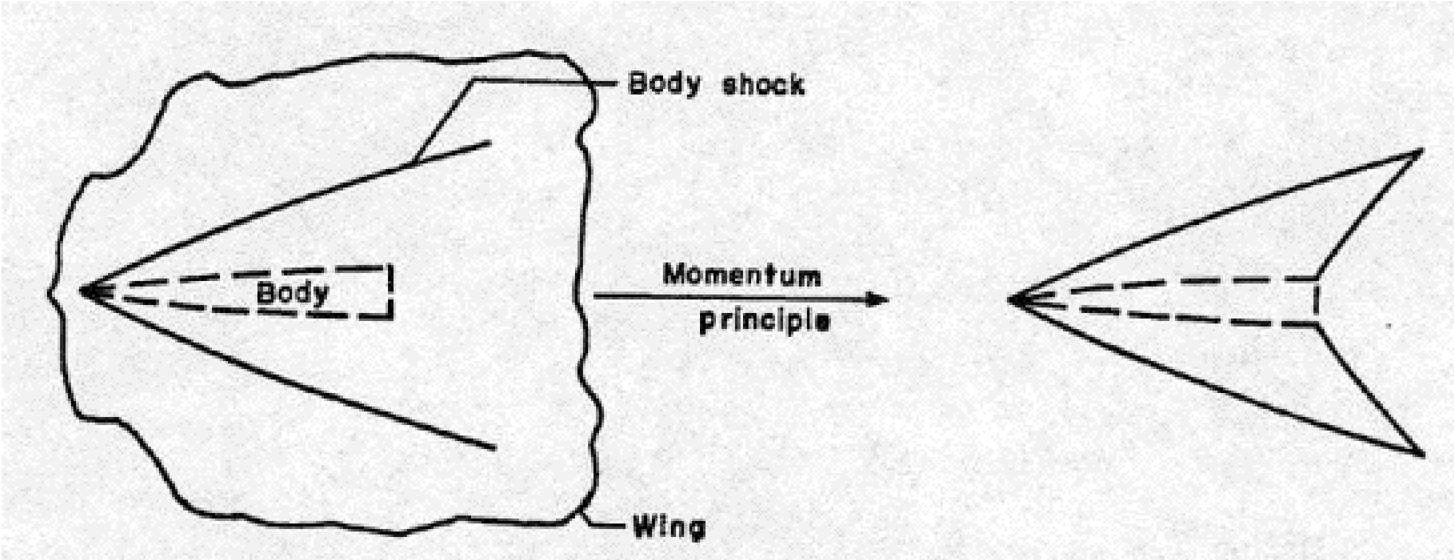






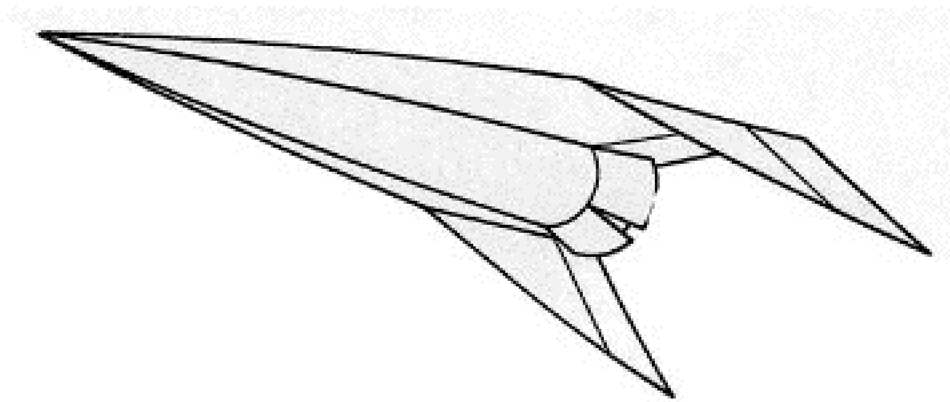
Hypersonic Vehicle Design (cont'd)

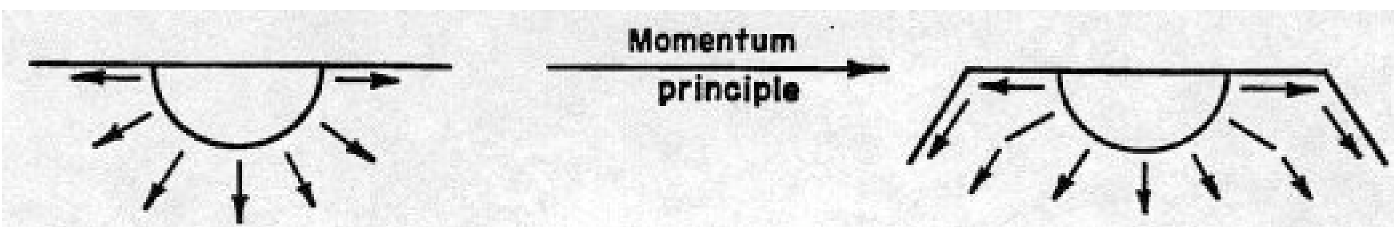
- Wing can extend to edge of conical shock wave without effecting conical flow field



Hypersonic Vehicle Design (cont'd)

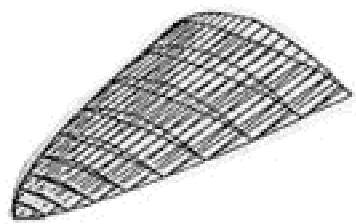
- Wing tips can be contoured along stream lines to capture "extra lift"



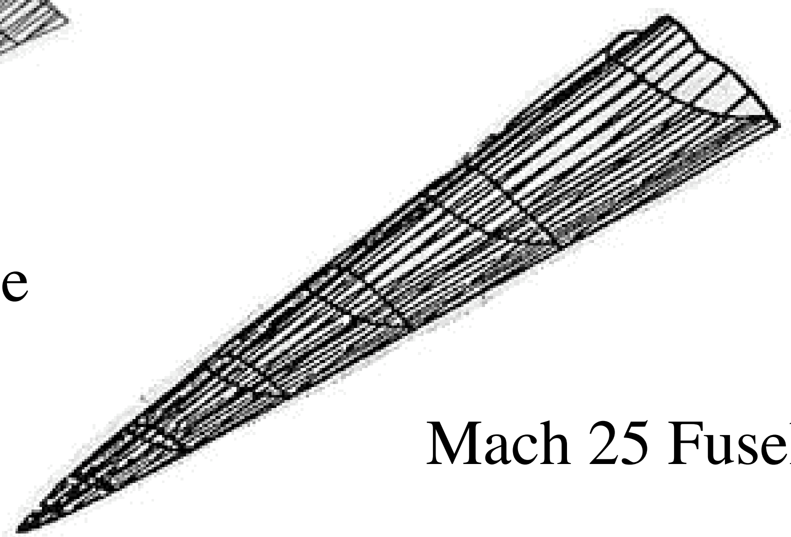


Hypersonic Vehicle Design (cont'd)

- Example Hypersonic vehicle designs … mach number drives the shape



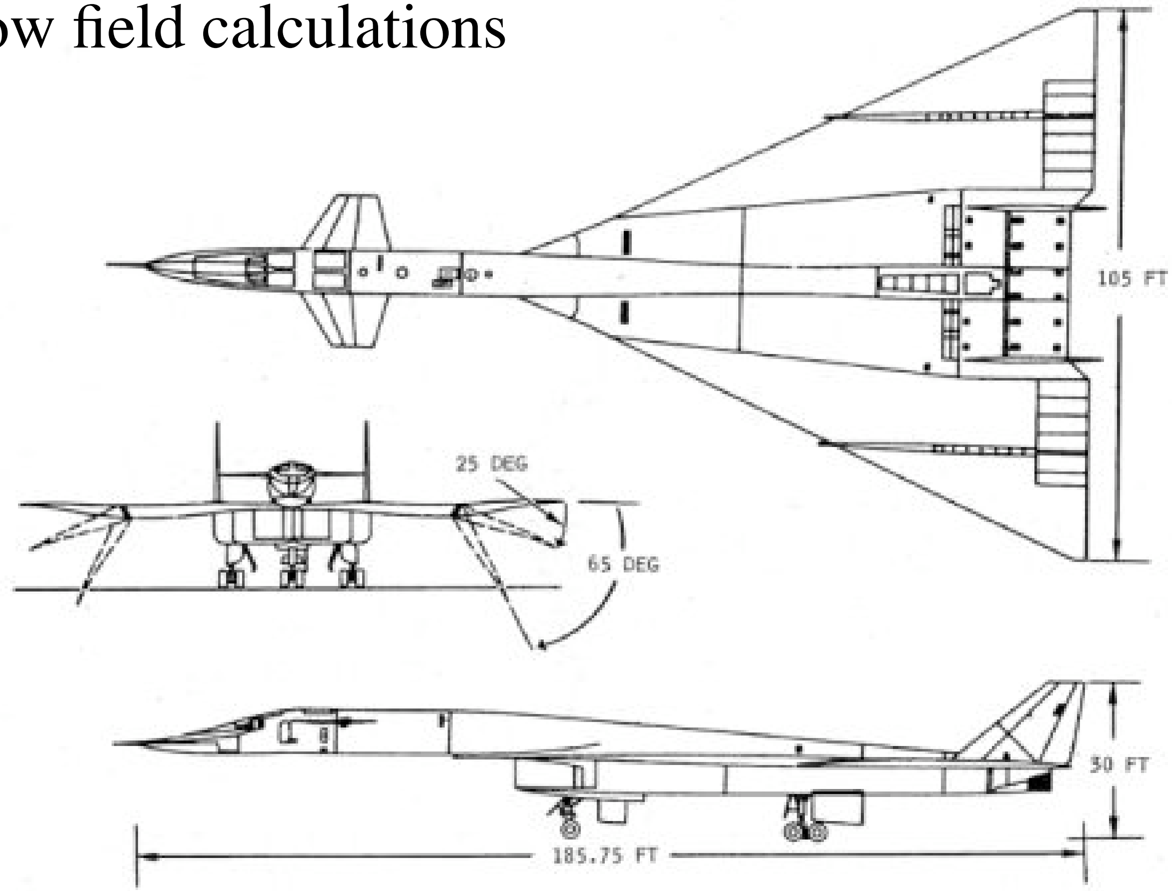
Mach 6 Fuselage



Mach 25 Fuselage

Hypersonic Vehicle Design (concluded)

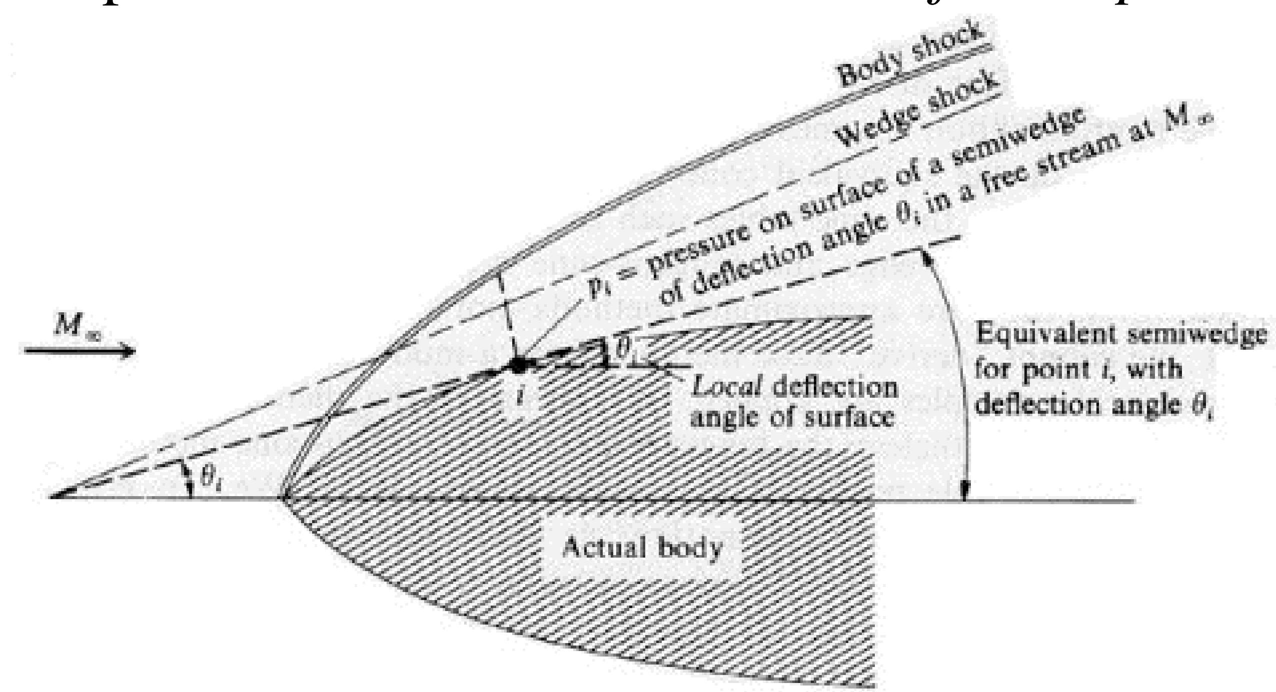
- XB-70 Valkyrie … Mach 3 design basically exploited conical flow field calculations



Analysis Tools

- Tangent Wedge … works well on 2-D surfaces

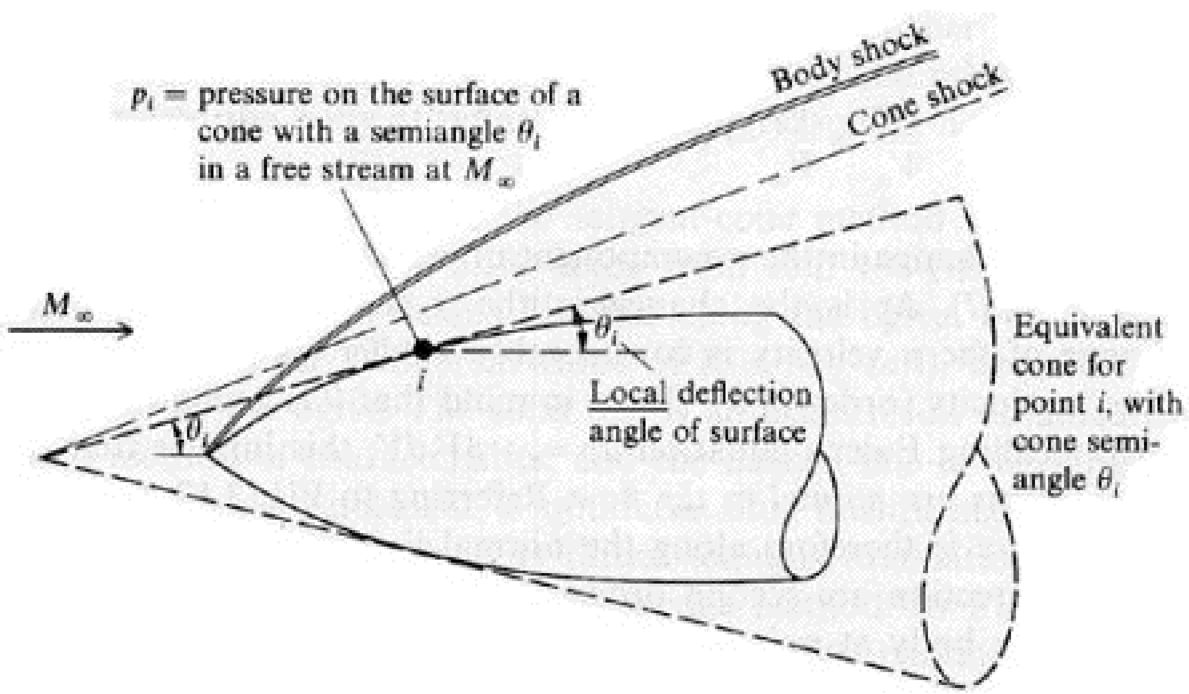
- Uses Oblique shock wave theory to predict surface pressures … *does not work well for temperatures*



Analysis Tools (cont'd)

- Tangent Cone … Apply to low inclination 3-D surfaces

- Uses Conical shock wave theory to predict surface pressures …



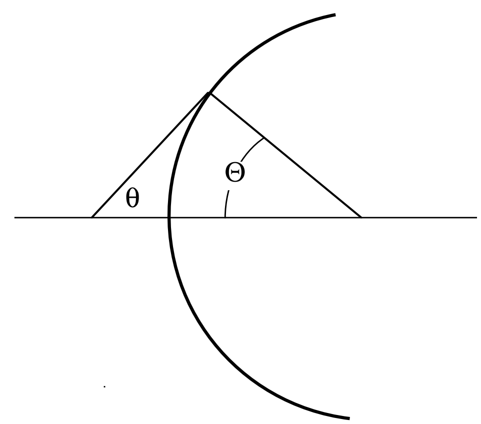
Analysis Tools (cont'd)

- Newtonian Flow … Apply to blunt 3-D surfaces

$$\frac{p_\Theta - p_\infty}{\frac{\lambda}{2} M_\infty^{\ 2} p_\infty} = Cp_{Max}\left[\cos^2\Theta\right]$$

$$Cp(\Theta) = Cp_{Max}\left[\cos^2\Theta\right] = Cp_{Max}\left[\sin^2\theta\right]$$

- *"Modified Newtonian Flow"*
Semi-empirical model
Valid for very high speeds, 3-D
And 2-D blunt bodies … accurate
For both sonic and supersonic regions
Behind detached shock wave



Analysis Tools (cont'd)

- How do theories compare to observations?

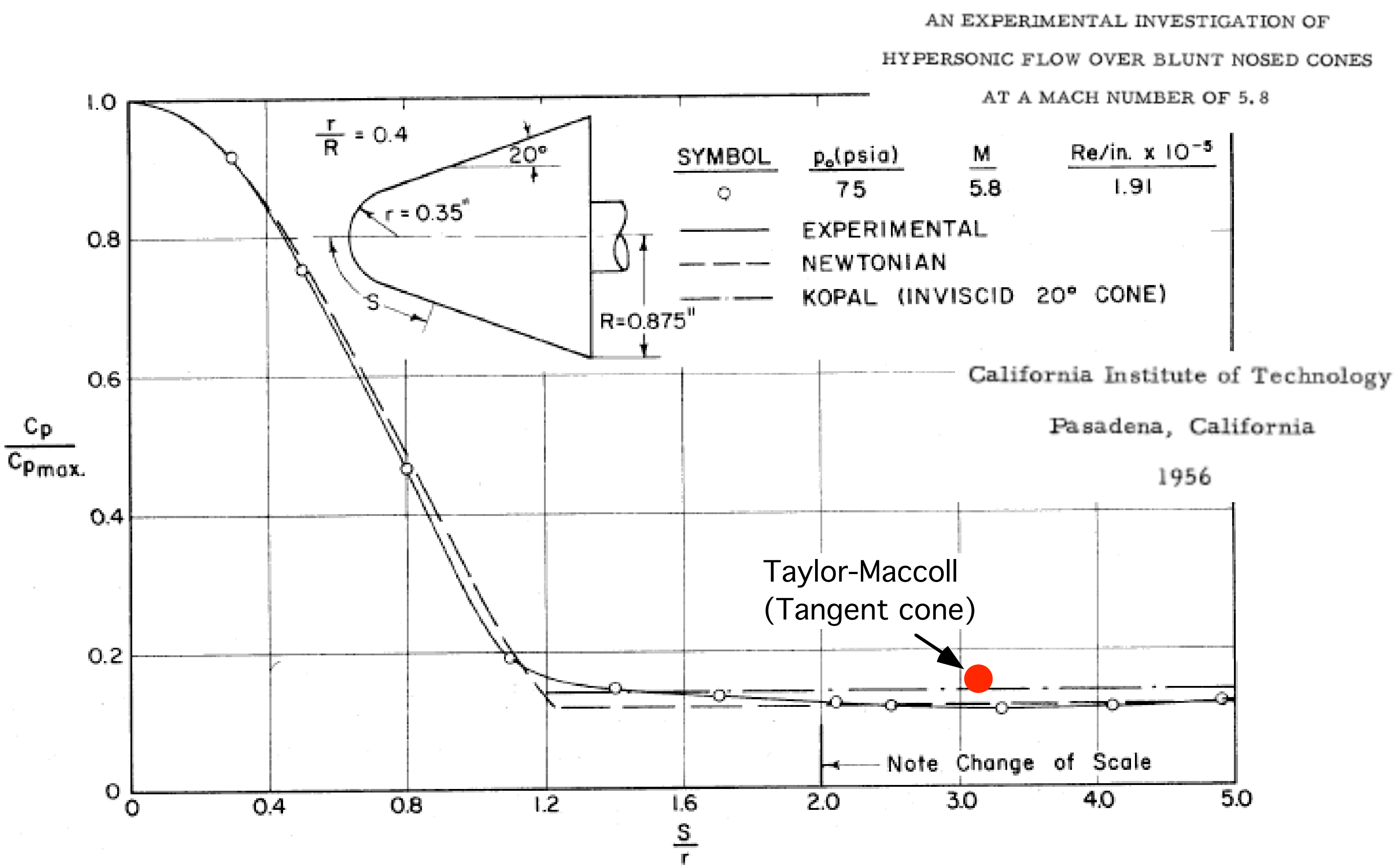


FIG. 20 SURFACE PRESSURE DISTRIBUTION, $\alpha = 0°$

Analysis Tools (cont'd)

- How do theories compare to observations?

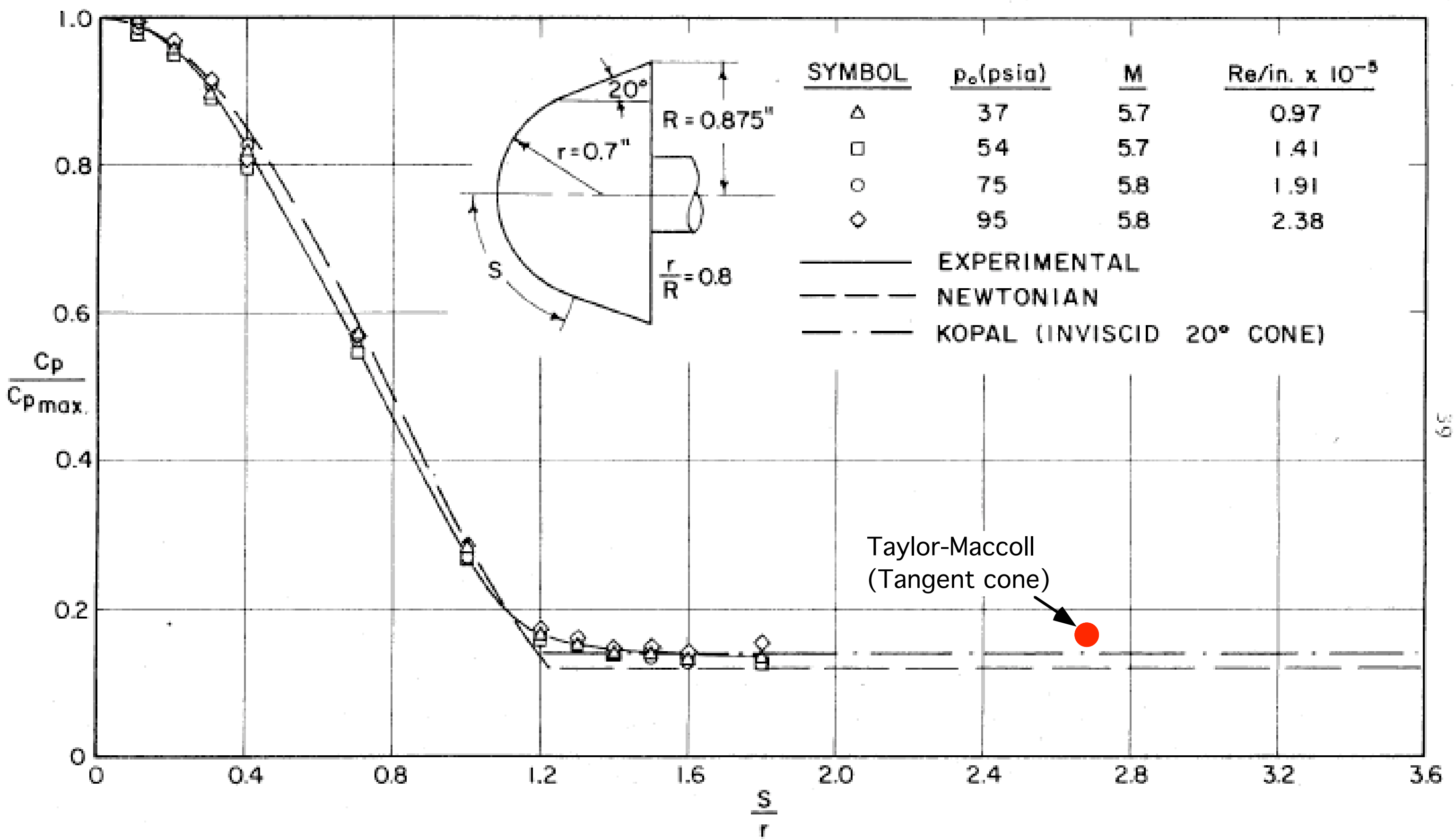


FIG. 21 SURFACE PRESSURE DISTRIBUTION, α = 0°

Analysis Tools (cont'd)

- Ideal gas ....

$$C_{p_{\max}} = \frac{1}{\frac{\gamma}{2} M^2} \left\{ \frac{\left(\frac{\gamma + 1}{2} M^2 \right)^{\left(\frac{\gamma}{\gamma - 1} \right)}}{\left(\frac{2\gamma}{(\gamma + 1)} M^2 - \frac{(\gamma - 1)}{(\gamma + 1)} \right)^{\left(\frac{1}{\gamma - 1} \right)}} - 1 \right\}$$

- Buuut ....

Flow Across a Hypersonic Shock Wave

- Across a Hypersonic Shock Wave, Temperature Rises Dramatically

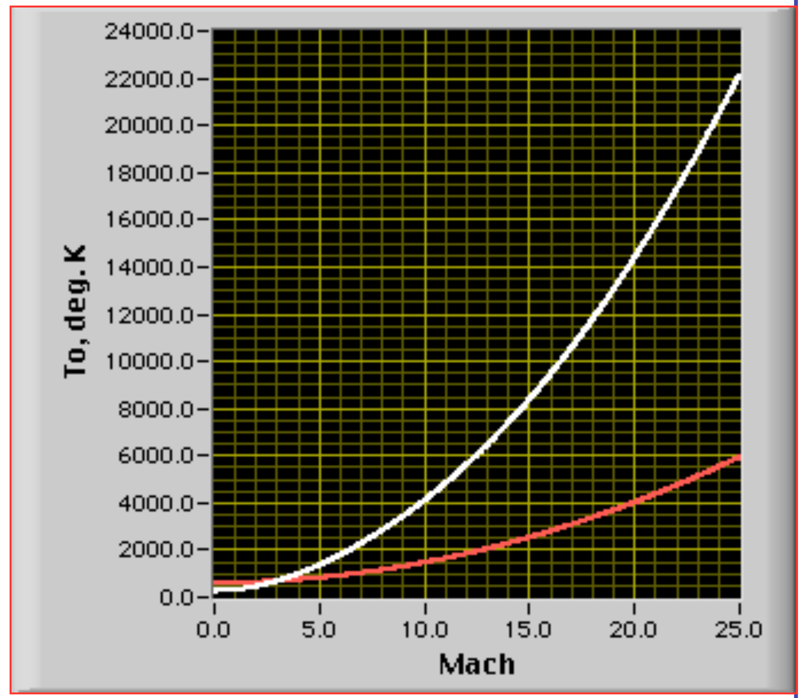
- Thermal Properties (c_p, c_v, γ) of Gas Change

- T_0 not constant across shock

- Gas Dissociation, chemical reaction, molecular Vibration Significantly lower the Stagnation temperature Behind the shock wave when compared To "calorically perfect" gas

- In general Enthalpy is implicit function of Pressure and temperature

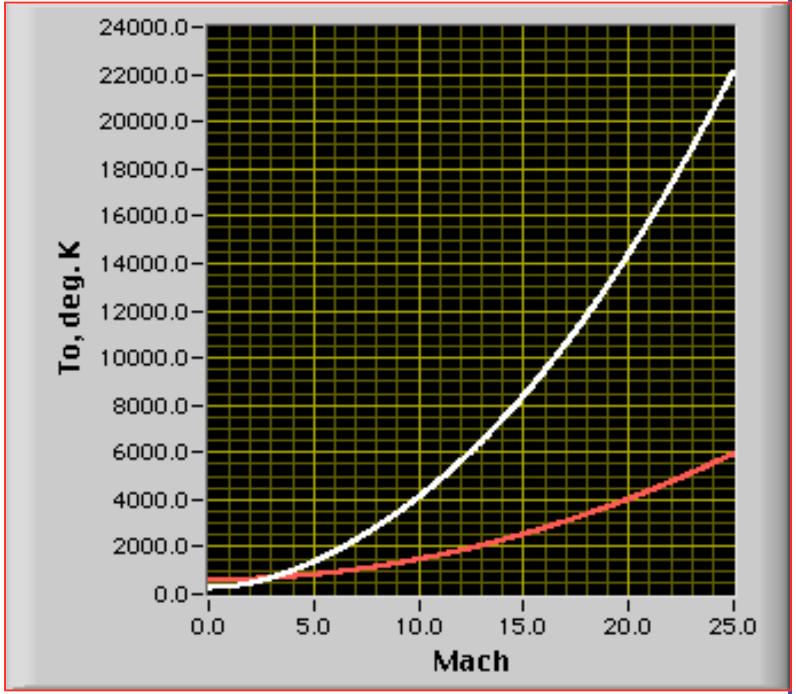
$$h = \eta(T, P) \Rightarrow \text{"}non - analytical - function\text{"}$$



Flow Across a Hypersonic Shock Wave

(cont'd)

• Across a Hypersonic Shock Wave, Temperature Rises Dramatically



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$$h = \eta(T, P) \Rightarrow "non-analytical-function"$$

Flow Across a Hypersonic Shock Wave

(cont'd)

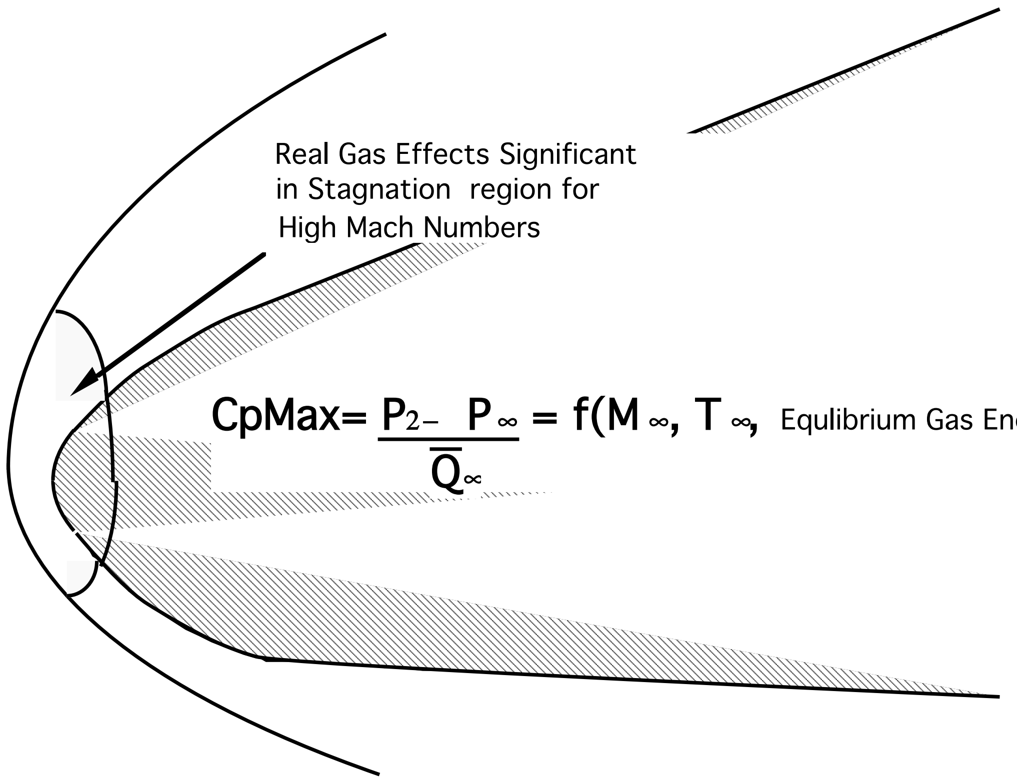
- Across a Hypersonic Shock Wave, Temperature Rises Dramatically

- γ .. Changes across shock wave … normal shock wave equations need to be reformulated to account for this change

P_∞, T_∞

Q_∞, Pt_∞,

$M_\infty >> 1$



$$C_{pMax} = \frac{P_2 - P_\infty}{\bar{Q}_\infty} = f(M_\infty, T_\infty, \text{Equlibrium Gas Energy, State Equations})$$