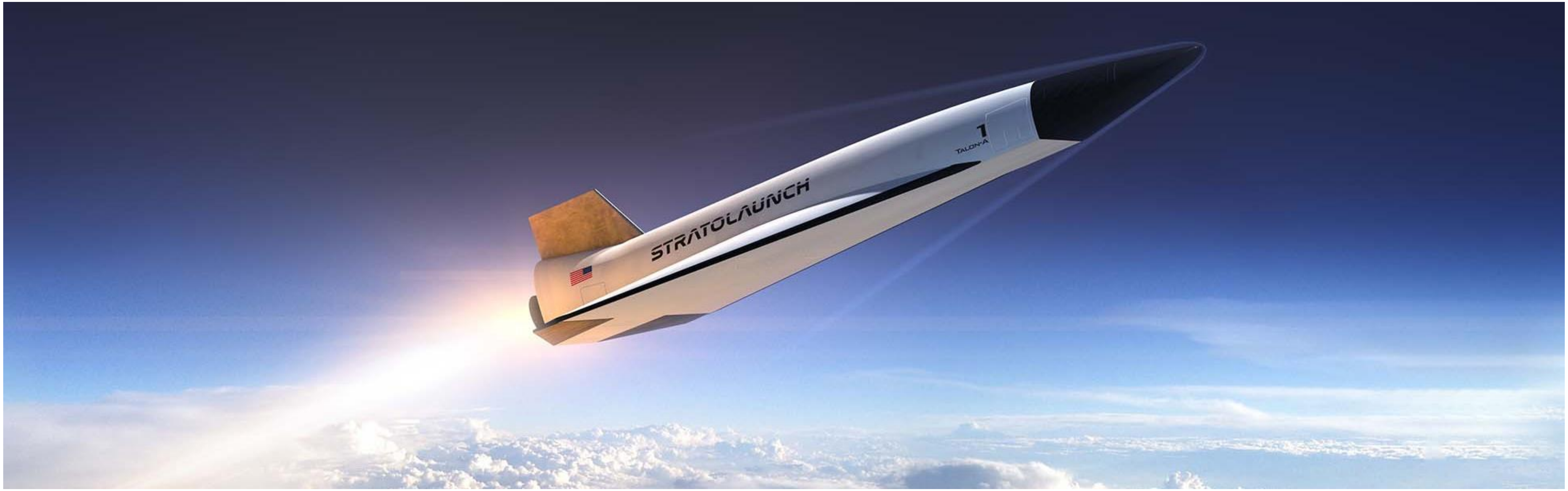

2022 NDIA Aircraft Survivability Workshop
Hypersonic Vehicles Tutorial

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Chief Technology Officer, Stratolaunch

16 March 2022

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What's all the Hype?

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Media Coverage Underscores Growing Awareness of the Challenge

"China's most recent successful test of a nuclear-capable hypersonic missile has shaken American military officials and politicians, putting a fresh focus on America's own hypersonic programs which appear—at least publicly—to lag those in Russia and China." **- Newsweek**

"The Russian navy is getting hypersonic missiles in 2022 in a bid to outpace Washington in the next missile race…Beijing's FOBS delivery system could provoke an arms race—or a more stable deterrence relationship." **- Foreign Policy Magazine**

"The push towards hypersonic military technologies has never been as pronounced as it is now. After years of being on the fringe, the capability is now receiving major pushes from the Pentagon, the U.S. Congress — and potential adversary nations." **– National Defense**

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Hypersonic Weapon Systems Are a National Security Imperative

- Hypersonic demonstrations by China and Russia have emphasized a national security mandate for the United States and its allies.
- To address this imperative, the Department of Defense (DOD) has stated that the U.S. will deliver hypersonic strike capability to its warfighters in the early- to mid-2020s, as well as a layered-hypersonic defense capability.

> “What we saw [from China] was a very significant event of a test of a hypersonic weapon system. And it is very concerning…
> close to a Sputnik moment.”
>
> **General Mark Milley**
>
> *Chairman of the Joint Chiefs of Staff*

> “Hypersonic technology needs to be cost-effective and mixed with other systems to be a useful tool in the Air Force's arsenal.”
>
> **The Honorable Frank Kendall**
>
> *Secretary of the Air Force*

Pictured Above: Chinese DF-17 and Russian 3M22 Zircon

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The Threat – the Ability to Flight Test

- China has flown 60+ hypersonic flight tests over the last two years – averaging one flight every two weeks.
- Chinese and Russian hypersonic flight-testing pace prompted the U.S. to initiate several prototyping efforts – HAWC, TBG, ARRW, LRHW, CPS
- The U.S. 50% flight-test success rate, low pace of testing, and lack of formalized CONOPS will not deter China or Russia.

> “[The U.S.] has conducted nine hypersonic tests in the last five years, while the Chinese have done hundreds. Single digits versus hundreds is not a good place. Now it doesn't mean that we're not moving fast in the development process of hypersonics, what it does tell you is that our approach to development is fundamentally different."
>
> **General John E. Hyten**
> *Vice Chairman of the Joint Chiefs of Staff*

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What is Hypersonic Flight?

- Flight greater than Mach 5?
  - Ballistic missiles reenter at numbers above Mach 20
  - The Space Shuttle reentered at Mach 25
  - The Orion Spacecraft reentered at Mach 30
- The reentry vehicles quickly decelerate at high altitudes
- They required thermal protective systems to survive the harsh reentry environment
- They generate plasmas which block radio communications
- Is this what we mean by hypersonic flight?

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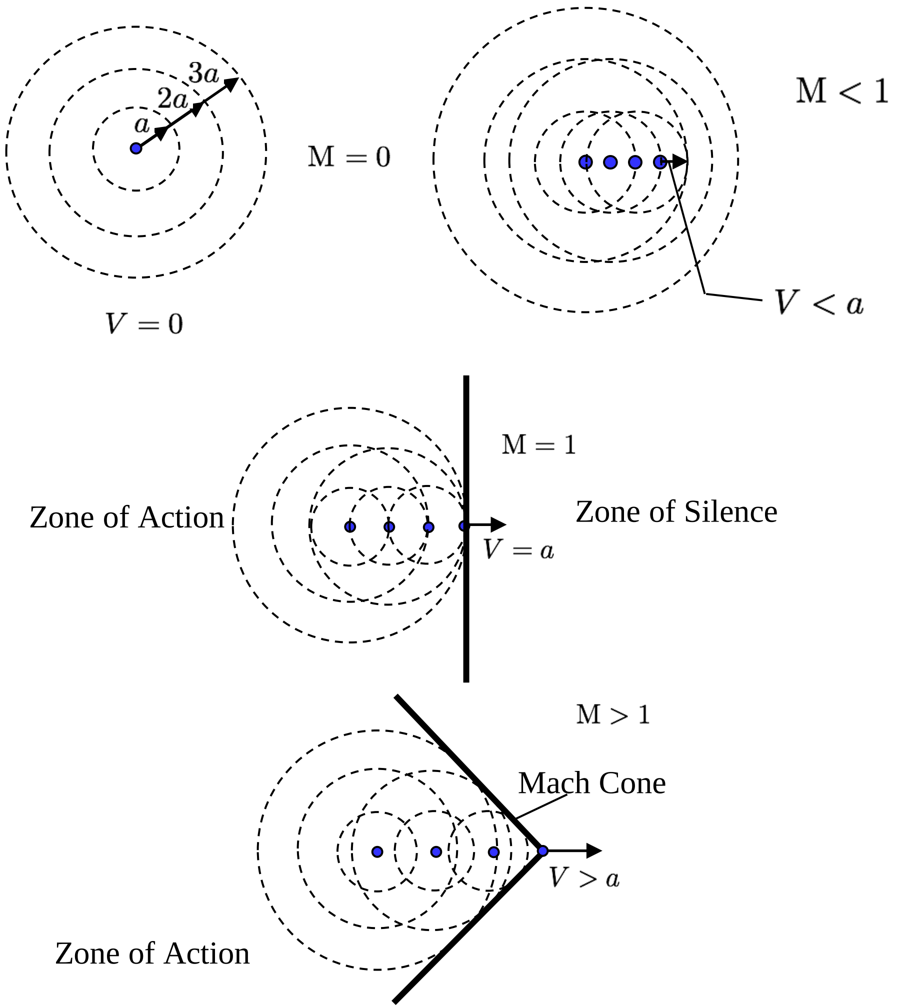
Mach Number

- If a vehicle is moving at a velocity V and the local speed of sound is given by
$$a = \sqrt{\gamma R T} = \sqrt{\gamma \frac{p}{\rho}}$$
where γ is the ratio of specific heats, R is the gas constant for air, and T is the temperature of the air the vehicle is flying in, then the Mach number is defined as
$$\mathrm{M} = \frac{V}{a}$$
- The Mach number is the most important parameter in compressible flow theory. It relates how information propogates through the flow. We use it to explicitly define three different Mach regimes.
  - If $\mathrm{M} < 1$, the flow is *subsonic*
  - If $\mathrm{M} = 1$, the flow is *sonic*
  - If $\mathrm{M} > 1$, the flow is *supersonic*
- Mach number is not an inertial term. It is an *energy* term.



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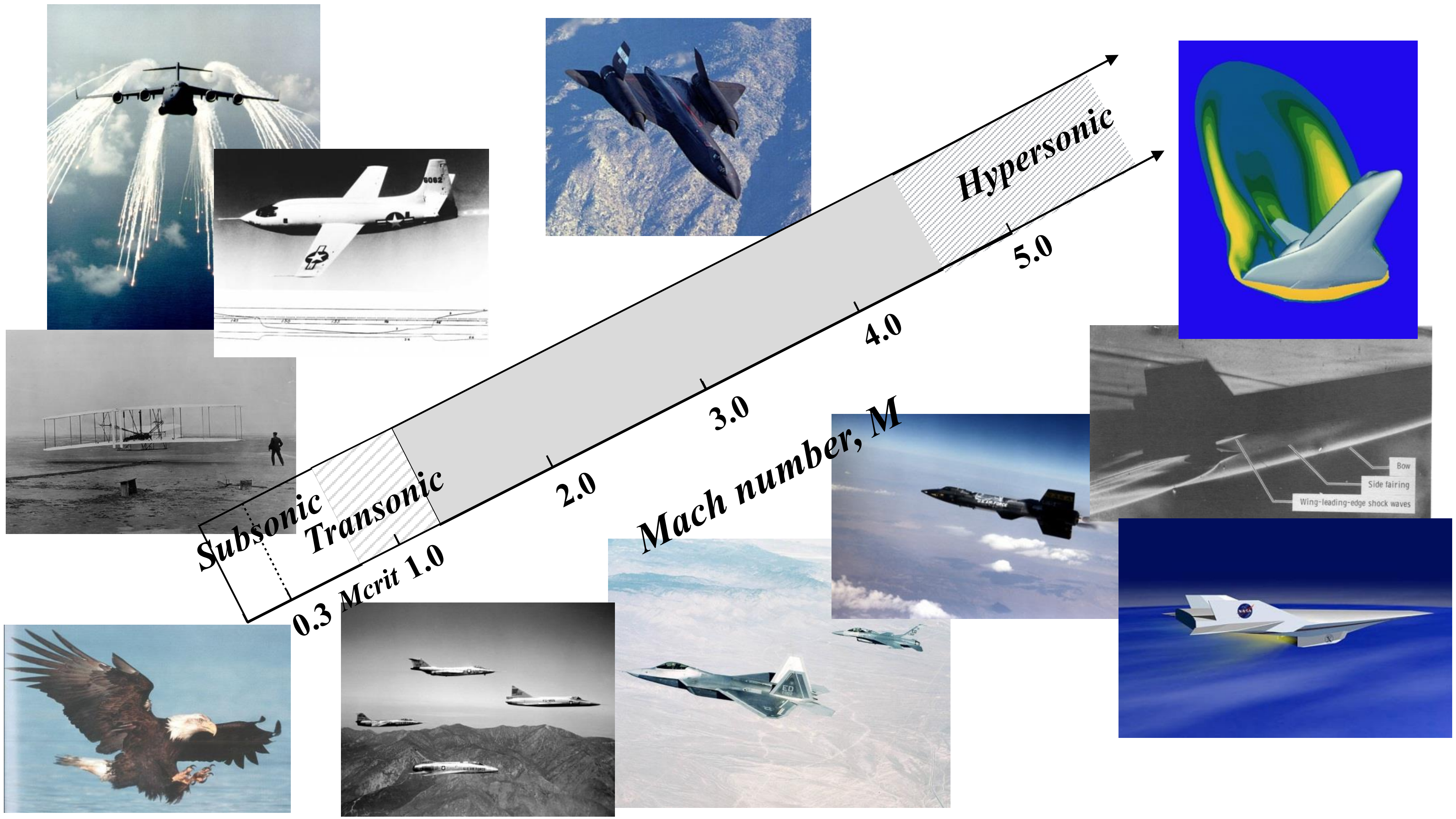
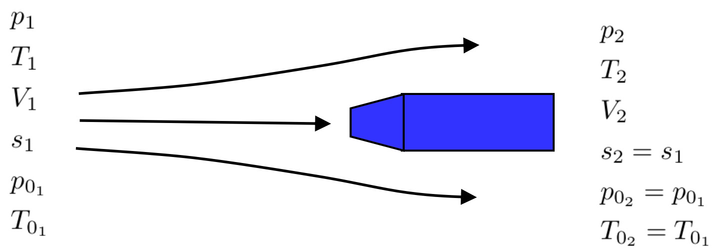
Mach Regimes

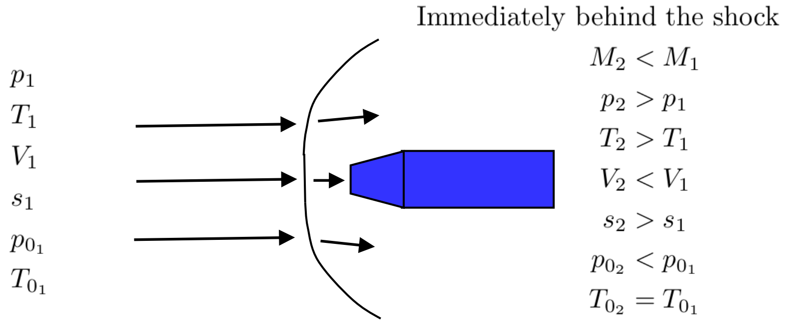


Shock Waves

- Shock waves modify flow direction and static pressure to satisfy downstream conditions.
- Whenever a solid body is placed in a supersonic stream, shock waves will occur.
- The flow upstream of the shock wave is isentropic (no change in entropy). Typically the flow downstram of the shock wave can also be considered isentropic.
- A shock wave is adiabatic, which means the total temperature across the shock does not change.
- A shock wave is entropy producing (nonisentropic) which causes a loss of total pressure (the amount of work a flow is capable of doing).
- A shock wave can be treated as a discontinuity in the flow properties.
  - Shock thickness on the order of 10^{-5} cm
  - The processes in the shock are dominated by viscous losses



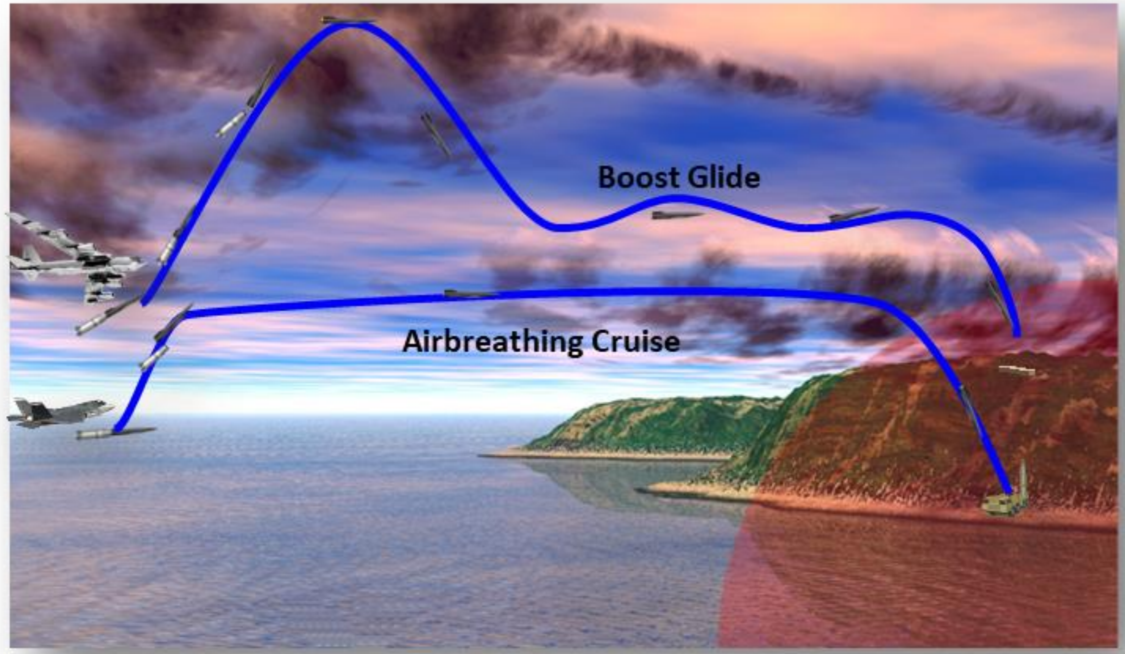
$M_1 < 1$



$M_1 > 1$

Hypersonic Weapons

- Hypersonic flight
  - Always includes a high speed component ($M \gtrsim 5$)
  - Lower altitude employment, which complicates the heat problem
  - Maneuverability
- Critical Flow Phenomena
  - Shock-shock and shock-boundary layer interactions
  - Non-equilibrium effects
  - Flow-structure interactions
  - Ablation
  - Flight controls
  - Atmospheric Noise
- Thermal Management, external and internal
- Multidisciplinary due to fully-coupled physics
  - Coupling effects can be beneficial or adverse
  - Systems level analysis and design optimization



Breaking the Heat Barrier!

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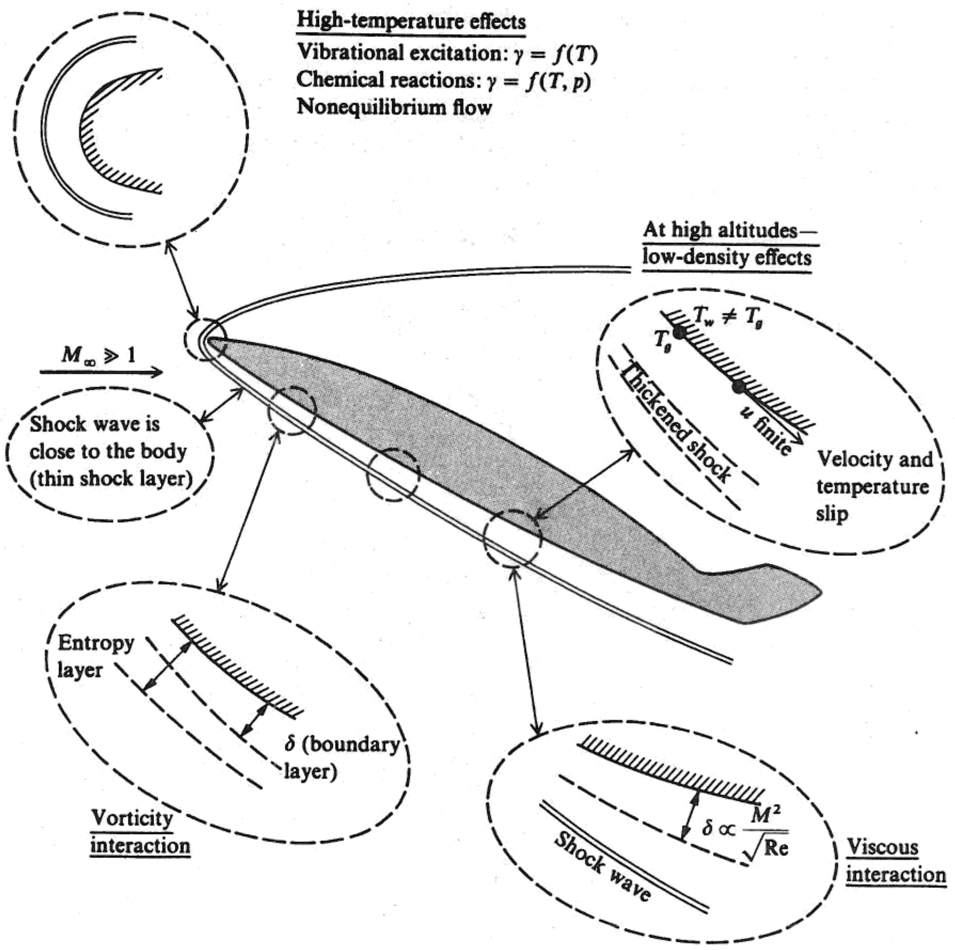
Hypersonic Flow Features

- Hypersonic flow begins when the simplifying assumptions of supersonic flow are no longer valid
- Distinguishing features
  - Thin Shock Layer: The region between the the shock wave and the vehicle surface.
  - Entropy Layer: Strong entropy gradients leading to significant vorticity generation and propagation.
  - Viscous Interaction: Standard boundary layer transition analysis fails.
  - High Temperature Effects: The ratio of specific heats, γ, is no longer constant. Air must be treated with all the different possible species that form due to dissociation (O_2, N_2, N, O, NO) and ionization.
  - Usually low density flow due to the high altitudes that hypersonic vehicles tend to fly. However...



Ref: John D. Anderson, *Hypersonic and High Temperature Gas Dynamics*

Historical Perspective

1959-1968 X-15

- Joint NACA, USAF, Navy program; North American Aviation selected Sep 55
- Three flight vehicles produced; 199 flights; 1 fatality
- Conventional aero controls plus reaction control system
- Heat sink structure with Inconel X skin; ablative with sealant for high Mach
- Initially 2 XLR-11 engines (16 klb thrust); later XLR-99 engine (67 klb thrust)
- First application of hypersonic theory and wind tunnel work to actual flight
- Max altitude: 354,200 feet on 22 Aug 1963
- Max Mach: 6.72 on 3 Oct 1967

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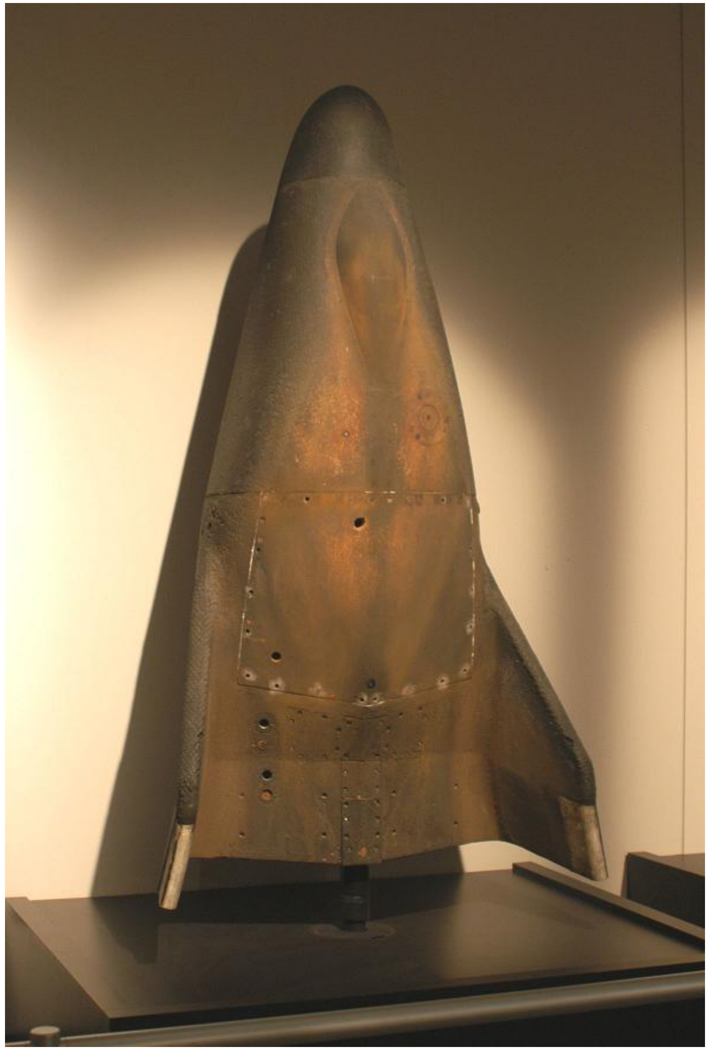
1966-1967 Precision Recovery Including Maneuvering entry (PRIME)

- The Martin X-23 PRIME was a small uncrewed lifting body re-entry vehicle.
- PRIME was developed to study the effects of maneuvering during re-entry of Earth's atmosphere, including cross-range maneuvers.
- It was built from titanium, beryllium, stainless steel, and aluminium. It consisted of two sections: the aft main structure and a removable forward "glove section." The body of the X-23 was completely covered with a Martin-developed ablative heat shield 20 to 70 mm thick, and the nose cap was constructed of carbon phenolic material.
- At Mach 2 a drogue ballute deployed and slowed the vehicle's descent. As it deployed, its cable sliced the upper structure of the main equipment bay, allowing a 16.4 m recovery chute to deploy. It was to be recovered in midair by a specially-equipped JC-130B Hercules aircraft.



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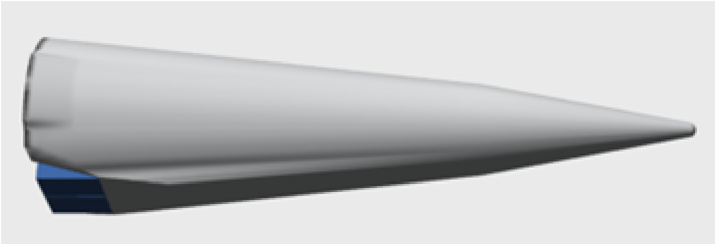
1979-1981 Advanced Maneuvering Reentry Vehicle (AMaRV)

- Advanced Maneuverable Reentry Vehicle (AMaRV) was a prototype MaRV built by McDonnell-Douglas Corp.
- Four AMaRVs were made and represented a significant leap in Reentry Vehicle sophistication.
- Three of the AMaRVs were launched by Minuteman-1 ICBMs on 20 December 1979, 8 October 1980 and 4 October 1981.
- AMaRV had an entry mass of approximately 470 kg, a nose radius of 2.34 cm, a forward frustum half-angle of 10.4°, an inter-frustum radius of 14.6 cm, aft frustum half angle of 6°, and an axial length of 2.079 meters.
- Trajectory plots showing hairpin turns have been published.

Ref: Frank J. Regan and Satya M. Anadakrishnan, *Dynamics of Atmospheric Re-Entry*



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X-43A (Hyper-X)

- Four decades of supersonic-combustion ramjet propulsion research culminated in a successful flight of the X-43A hypersonic technology demonstrator in March 2004, the first time a scramjet-powered aircraft had flown freely.
- After being launched by Dryden's venerable B-52B mothership off the coast of Southern California, a modified first-stage Pegasus booster rocketed the X-43A to 95,000 feet before the X-43A separated and flew under its own scramjet power at an airspeed of Mach 6.8, or about 5,000 mph, for about 11 seconds.
- On Nov. 16, another identical scramjet-powered X-43A did it again, this time reaching hypersonic speeds above Mach 9.6, or about 6,800 mph, in the final flight of the X-43A project.
- Both flights set world airspeed records for an aircraft powered by an air-breathing engine, and proved that scramjet propulsion is a viable technology for powering future space-access vehicles and hypersonic aircraft.

Source:

https://www.nasa.gov/centers/armstrong/history/experimental_aircraft/X-43A.html

2010-2013 X-51A Wave-rider

- Four powered flights over four years
- First Flight – May 26th, 2010
  - 143 seconds of scramjet operation
  - Peak Mach of 4.87; 150 nm traveled
  - Seal/nozzle breach ended flight early
- Second Flight – June 13th, 2011
  - Engine "unstarted" nine seconds after scramjet ignition
  - Post-flight investigation and ground testing yielded several scramjet operability lessons learned
- Third Flight – August 14th, 2012
  - Booster run-away control fin actuator and loss of control prior to engine light
- Fourth Flight – May 1st, 2013
  - Full duration flight: ∼209 seconds of scramjet operation and 377 seconds of controlled flight
  - Peak Mach of 5.1; ∼240 nm travelled in six minutes

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2011 Advanced Hypersonic Weapon

- The AHW technology demonstration programme is managed by the US Army Space and Missile Defence Command (USASMDC) / Army Forces Strategic Command (ARSTRAT).
- In November 2011, AHW was launched from the Pacific Missile Range Facility in Kauai, Hawaii, to the Reagan Test Site on the Marshall Islands. The glide vehicle successfully hit the target, which is located about 3,700km away from the launch site.
- The test was conducted to demonstrate hypersonic boost-glide technologies and demonstrate the capability for atmospheric flight at long-ranges.

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2021 Hypersonic Airbreathing Weapon Concept (HAWC)

- A classified DARPA program
- Raytheon indicated the vehicle did exceed Mach 5 with its scramjet propulsion system

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Hypersonic Aerothermodynamics

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Hypersonic Flow Characteristics

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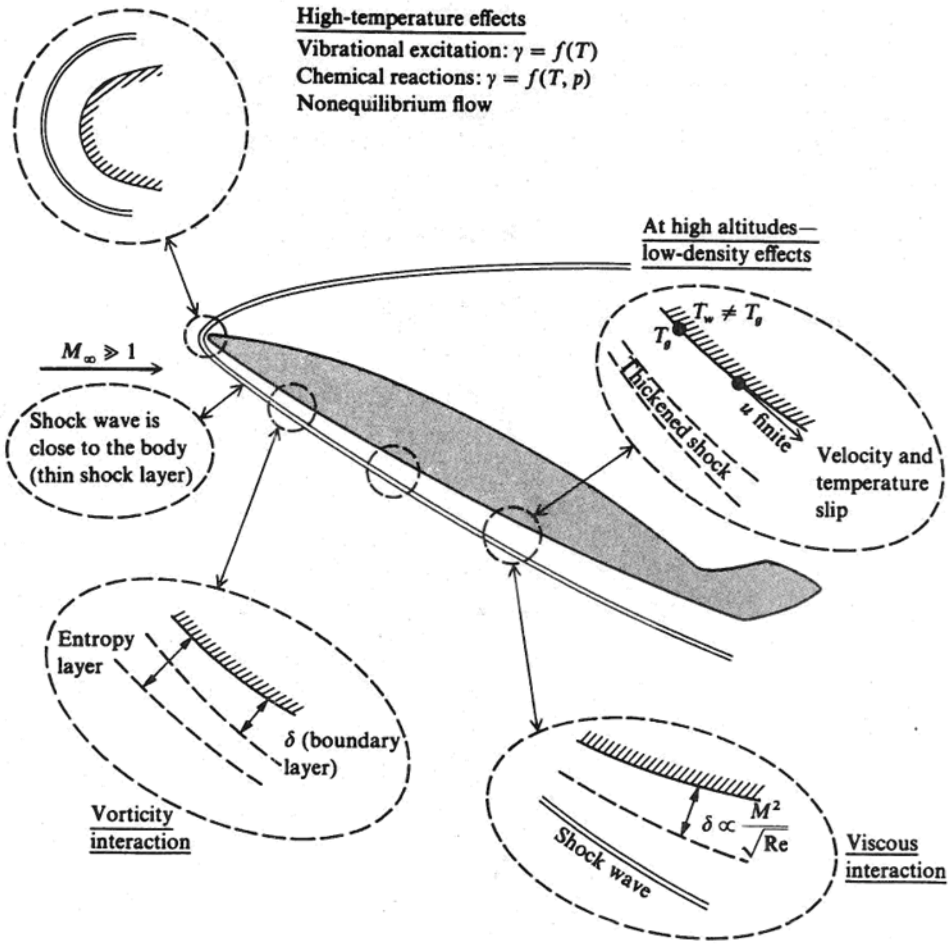

Ref: John D. Anderson, *Hypersonic and High Temperature Gas Dynamics*

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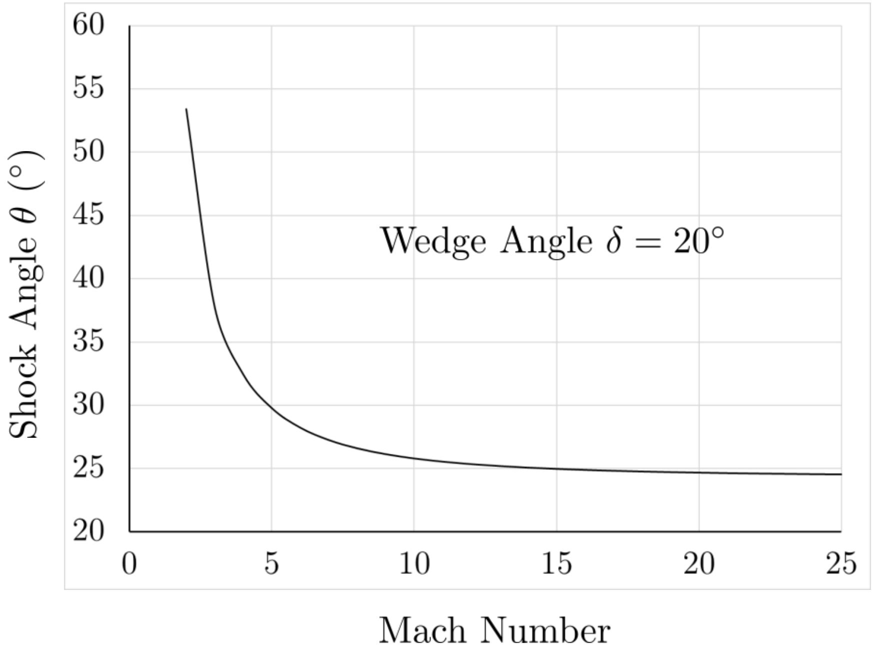
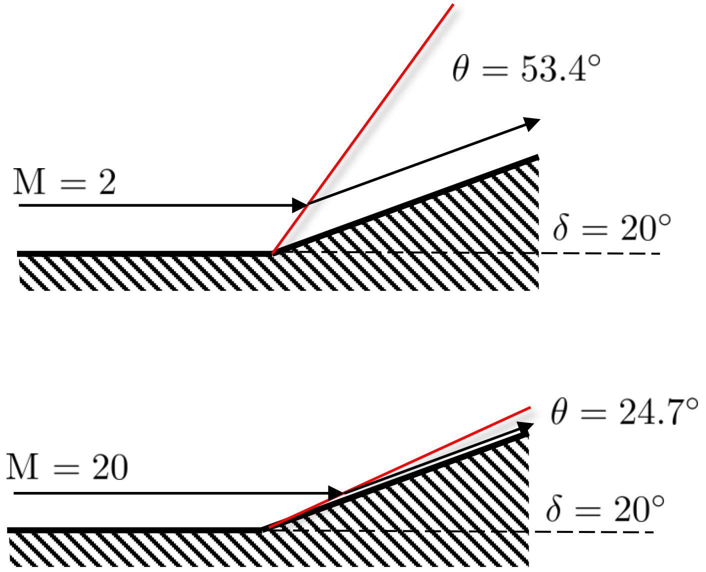
Thin Shock Layers

- Shock Layer – Flowfield region between the shock wave and the body surface
- Compare the shock wave on a wedge with a half-angle of 20° at Mach = 2 and Mach = 20
- At low Reynolds numbers, the thick boundary layer can merge with the shock wave to form a fully viscous shock layer





Shock angles obtained from equations in NACA-1135

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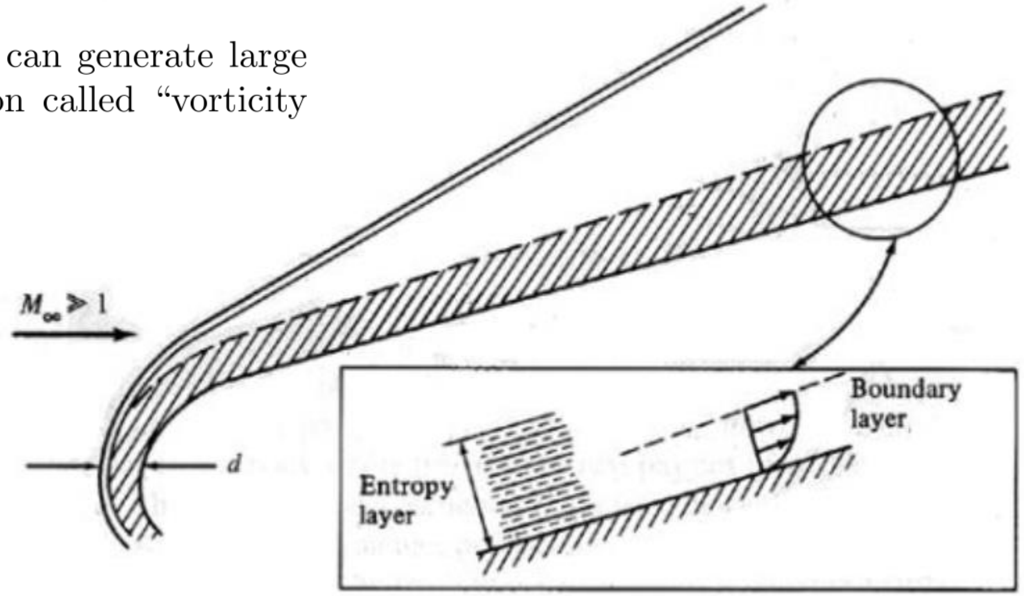
Entropy Layer

- Entropy Layer – Region of strong gradients (vorticity)
- For supersonic flow, the entropy is assumed to be constant inside the boundary layer since the leading edges are assumed to be sharp
- For hypersonic flow the leading edge must be rounded or blunted both for practicality of manufacture and to ease heat fluxes (more on this later). Close to this blunt leading edge, the oblique shock becomes highly curved. Entropy increases across a shock, and the entropy increase becomes greater as the shock strength increases. 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 downstream. Strong entropy gradients exist near the leading edge generating an ”entropy layer” that flows downstream along the body surface.
- In addition, the entropy layer is a region of strong vorticity that can generate large gradients in the velocity flowfield near the surface, a phenomenon called “vorticity interaction.”



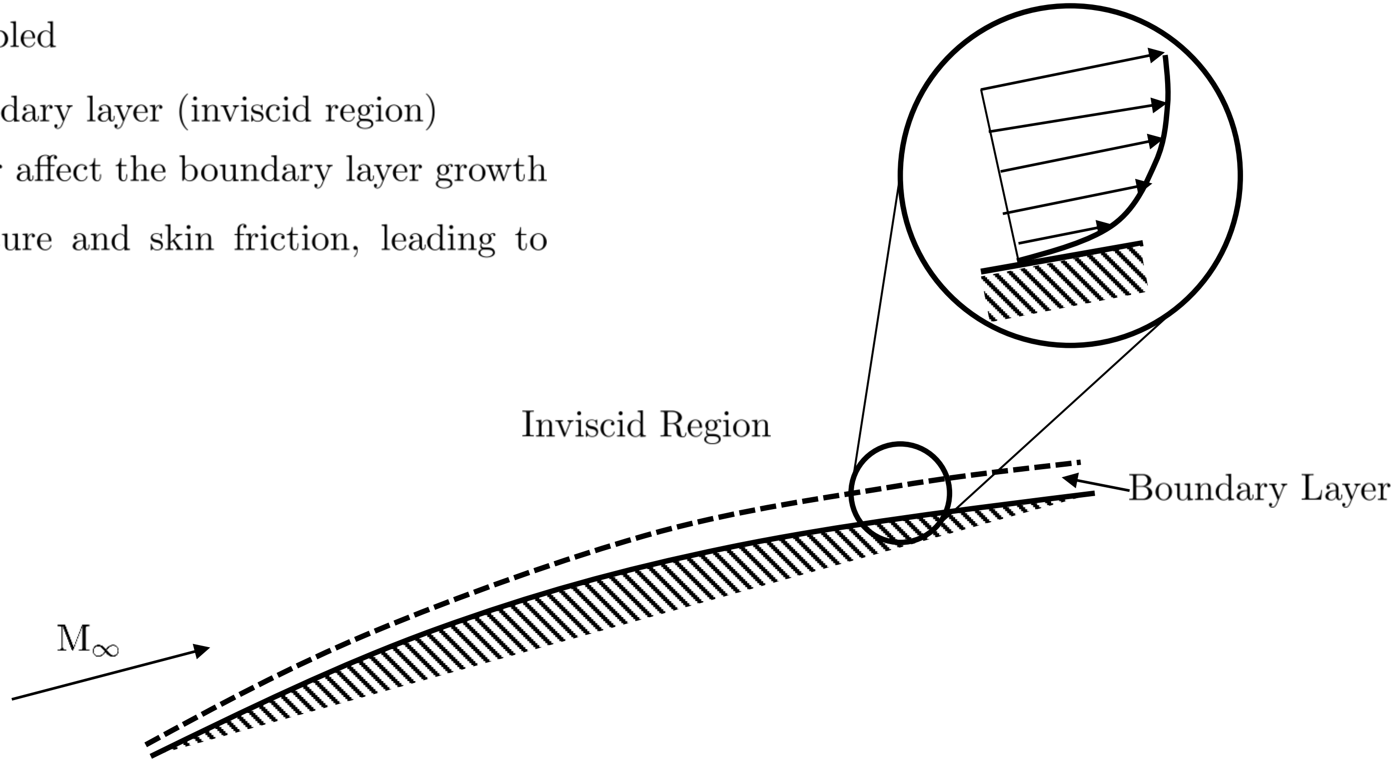
Ref: John D. Anderson, *Hypersonic and High Temperature Gas Dynamics*

Viscous Interaction

- For compressible flow, boundary layer thickness is proportional to the Mach number squared

$$\delta \propto \frac{\mathrm{M}^2}{\sqrt{\mathrm{Re}}}$$

- Viscous-Inviscid interaction can no longer be decoupled
  - Thick boundary layer affects flow outside boundary layer (inviscid region)
  - Changes in the flow outside the boundary layer affect the boundary layer growth
- Consequently there is an increase in surface pressure and skin friction, leading to increased drag and increased aerodynamic heating



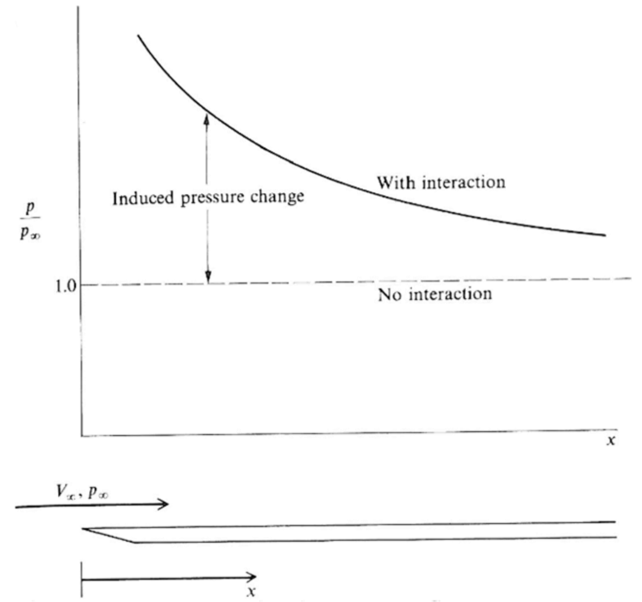
Quantifying Viscous Interaction

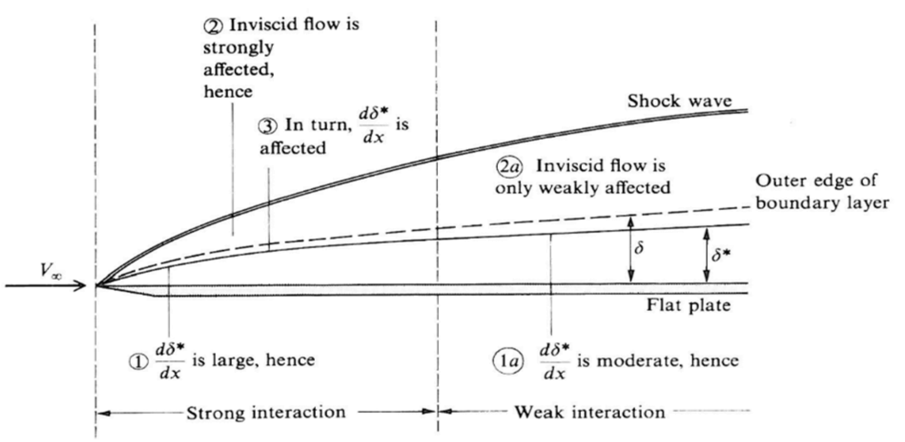
- At low speeds, the pressure distribution at the edge of the boundary layer is assumed to be the same as the pressure distribution on the wall from an inviscid flow analysis.
- At hypersonic speeds, the boundary layer influences this pressure distribution starting at the stagnation point.
- The value of $\overline{\chi}$ is used to determine when the boundary layer effects are of first order importance – a "strong interacton."

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

$\overline{\chi} \geq 3$ a strong interaction

$\overline{\chi} < 3$ a weak interaction

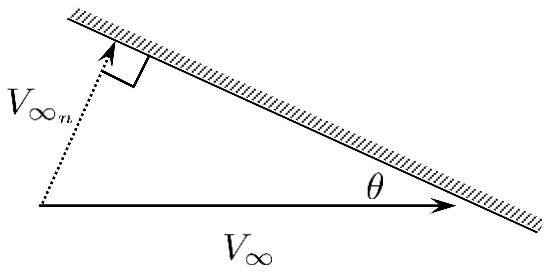




Ref: John D. Anderson, *Hypersonic and High Temperature Gas Dynamics*

Newtonian Flow

- In 1687, Newton postulated the following model of fluid flow (he was actually trying to estimate forces on ships)
  - When a fluid with a velocity of V_∞ strikes a suface of area A inclined at an angle θ to the flow, the normal momentum of the fluid is totally transfered to the surface while the tangential momentum is preserved
  - Thus the coefficient of pressure is determined from the normal portion of the flow only.



- The normal force can be equated to the pressure difference on the surface. Dividing by dynamic pressure yields the desired result for the coefficient of pressure.

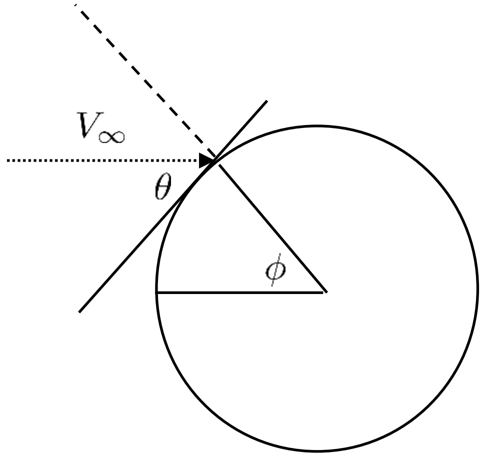
$$\begin{aligned} N &= \dot{m}_n V_{\infty_n} \\ &= (\rho_\infty A V_\infty \sin\theta)(V_\infty \sin\theta) \\ &= \rho_\infty A V_\infty^2 \sin^2\theta \end{aligned}$$

$$N = (p - p_\infty)A$$

$$\begin{aligned} (p - p_\infty)A &= \rho_\infty A V_\infty^2 \sin^2\theta \\ (p - p_\infty) &= \rho_\infty V_\infty^2 \sin^2\theta \end{aligned}$$

$$\begin{aligned} c_p &\equiv \frac{p - p_\infty}{\bar{q}_\infty} \\ &= \frac{\rho_\infty V_\infty^2 \sin^2\theta}{\frac{1}{2}\rho_\infty V_\infty^2} \end{aligned}$$

$$\boxed{c_p = 2\sin^2\theta}$$



$\theta = 90° - \phi$

The same results are obtained if you use the shock relations and assume Mach number approaches infinity and γ approaches 1

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Modified Newtonian Flow

- Newtonian Flow:

$$c_p = 2\sin^2\theta$$

- Newtonian flow indicates that performance is independent of Mach number!
- We can modify the Newtonian flow by limiting the value of 2 with a physics model. If we assign p_{0_2} as the total pressure behind the normal shock determined by the freestream Mach number, then

$$c_{p_{\max}} = \frac{p_{0_2} - p_\infty}{\frac{1}{2}\gamma p_\infty \mathrm{M}_\infty^2}$$

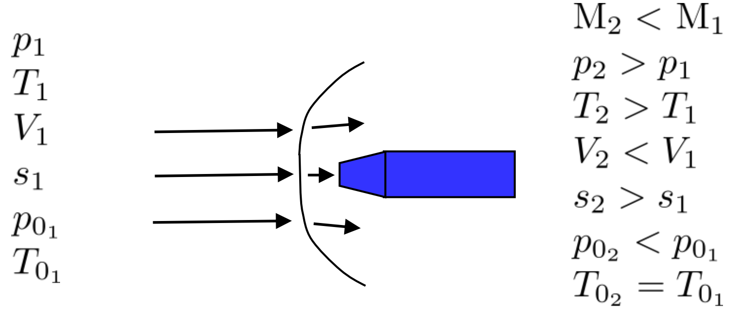
  and the modified Newtonian flow becomes

$$\boxed{c_p = c_{p_{\max}} \sin^2\theta} \, .$$

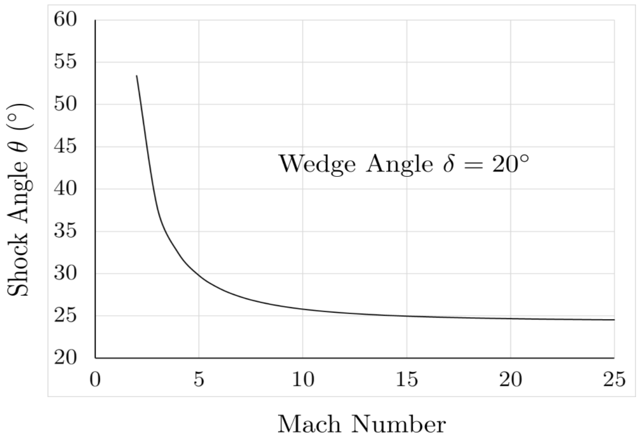
- It turns out, for hypersonic flow, $c_{p_{\max}} \approx 1.83$, so still Mach number independent!
- Recall, Mach number relates information propogation. Above about Mach 5, only so much information about the flow can be transmitted.
- Modified Newtonian flow gives more accurate results for the c_p calculation around blunt bodies.

$\mathrm{M}_1 > 1$

Immediately behind the shock



The properties at $()_1$ are the same as the freestream properties $()_\infty$



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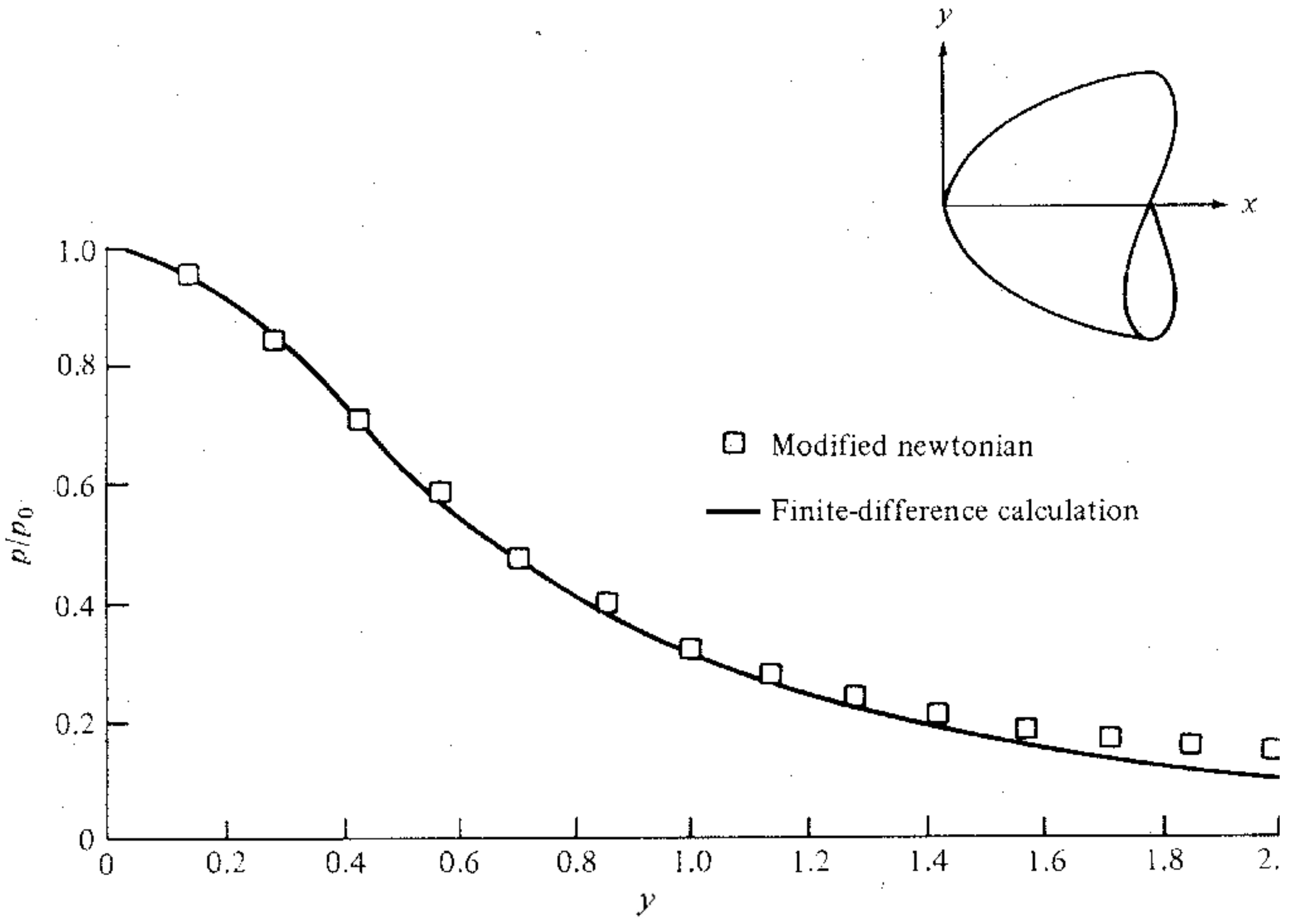
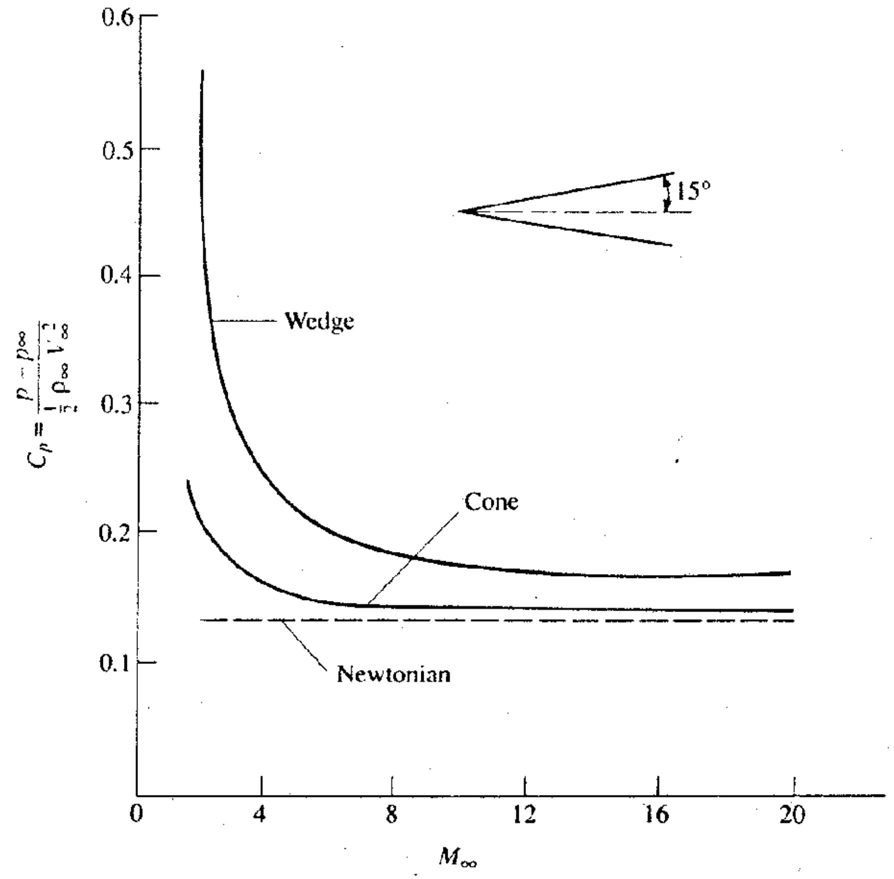
Comparison of Modified Newtonian Law with Computational Fluid Dynamics



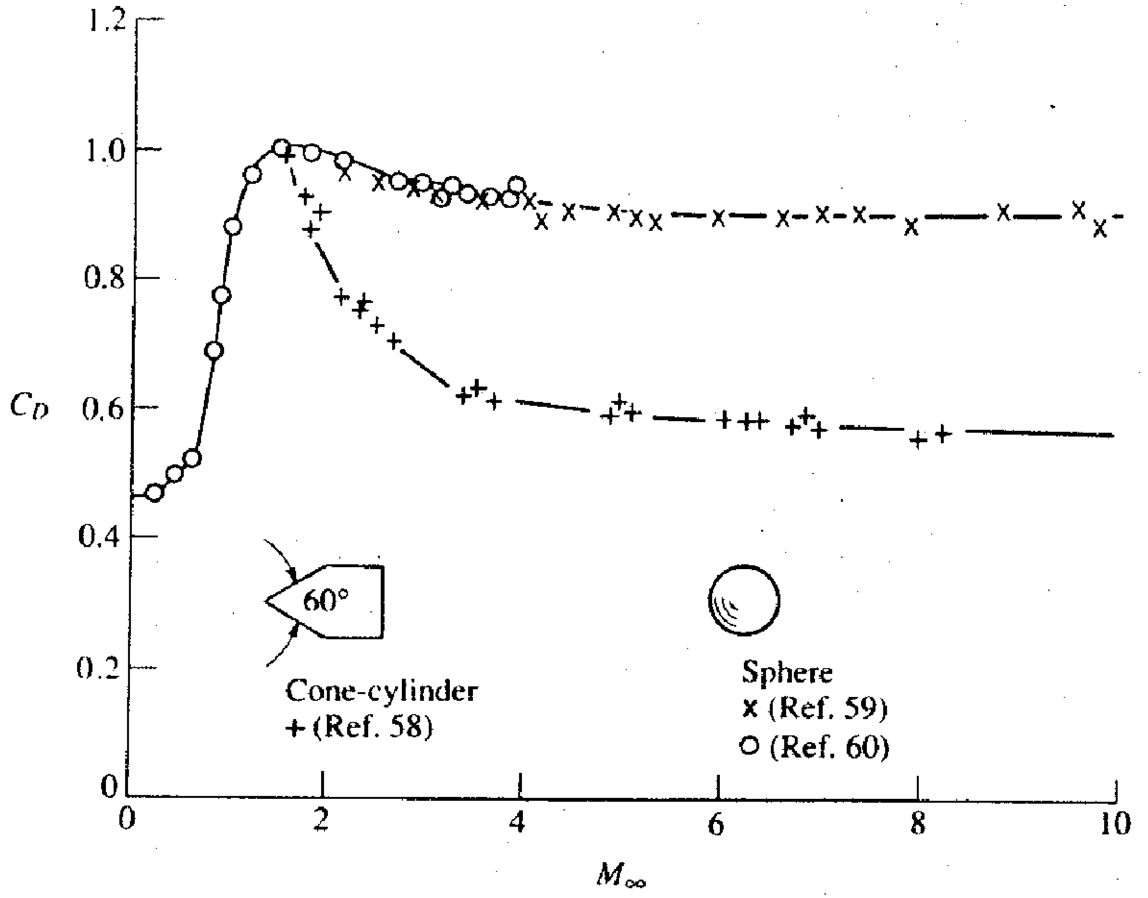
Ref: Anderson, Fundamentals of Aerodynamics, Figure 10.10. Surface-pressure distribution on an axisymmetric body of parabolic shape, M=4.

Mach Number Independence Principle



Ref: Anderson, Fundamentals of Aerodynamics, Figure 14.13.Comparison between Newtonian and exact results for the pressure coefficient on a sharp wedge and a sharp cone.

Mach Number Independence Principle



Ref: Anderson, Fundamentals of Aerodynamics, Figure 14.14. Drag Coefficient for a sphere and a cone cylinder from ballistic range measurements.

Hypersonic Flow over a Flat Plate

- Consider the hypersonic flow over a flat plate where

$$c_n = c_p$$
$$\theta = \alpha \; .$$

- We can write the lift and drag coefficients as

$$c_l = c_n \cos\alpha$$
$$c_d = c_n \sin\alpha \; .$$

- According to Newtonian flow, we then have

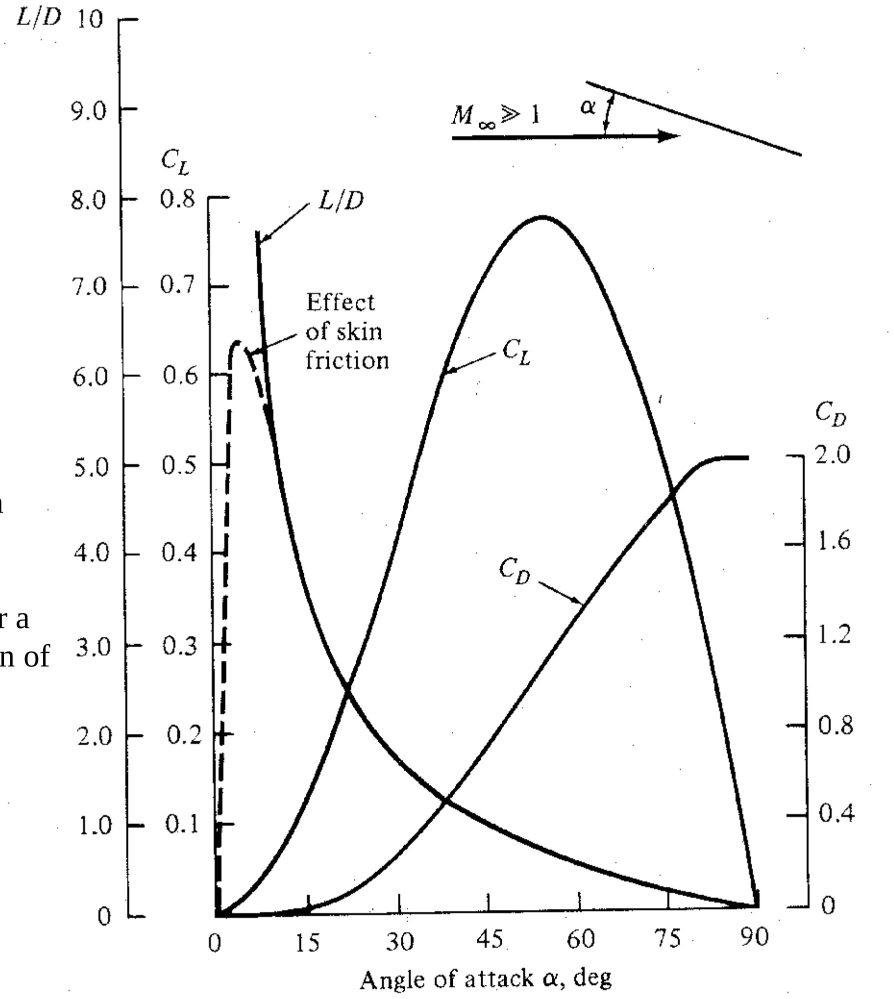
$$\boxed{c_l = 2\sin^2\alpha\cos\alpha}$$

$$\boxed{c_d = 2\sin^3\alpha}$$

$$\boxed{l/d = \cot\alpha}$$

- We often speak of the hypersonic lift to drag ratio, because the ratio is no longer dependent on Mach number, just on angle of attack.

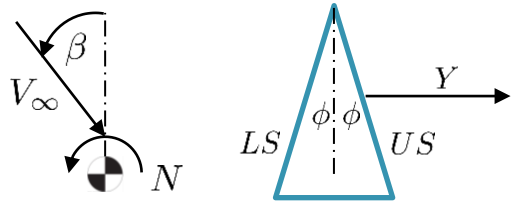
Ref: Anderson, Hypersonic and High Temperature Gas Dynamics, Fig. 3.6, Newtonian results for a flat plate as a function of angle of attack.



Directional Stability

- Consider the directional stability problem. The yawing moment due to the vertical tail is given by

$$C_{N_{\beta_{VT}}} = V_{VT}\frac{\overline{q}_{VT}}{\overline{q}_{\text{ref}}}C_{Y_{VT}}\,.$$



The first term is the vertical tail volume coefficient. The second term is the ratio of dynamic pressures. The third term is given by $C_{Y_{VT}} = c_{p_{LS}} - c_{p_{US}}$, with the correct interpretation of the lower surface and upper surface.

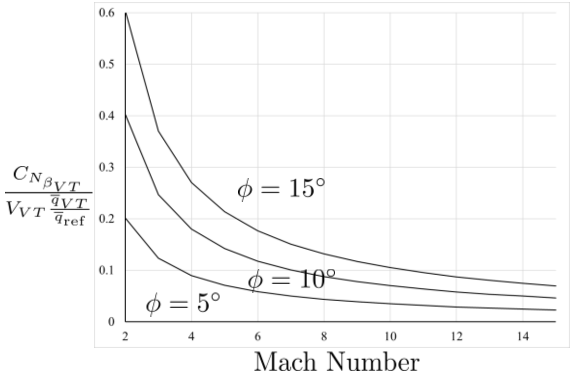
$$\theta_{LS} = \beta + \phi$$
$$\theta_{US} = \beta - \phi$$

- Lineraized supersonic thin airfoil theory predicts

$$c_p = \frac{2\theta}{\sqrt{\mathrm{M}_\infty^2 - 1}}\,,$$

which would result in a restoring moment of

$$C_{N_{\beta_{VT}}} = V_{VT}\frac{\overline{q}_{VT}}{\overline{q}_{\text{ref}}}\frac{4\phi}{\sqrt{\mathrm{M}_\infty^2 - 1}}$$



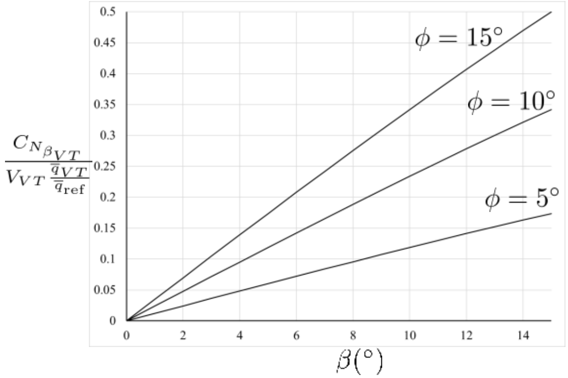
Thus, supersonic flow theory predicts that the restoring moment goes to zero as the Mach number increases!

- However, Newtonian flow predicts

$$c_p = 2\sin^2\theta$$

and the resulting restoring moment is

$$C_{N_{\beta_{VT}}} = 2V_{VT}\frac{\overline{q}_{VT}}{\overline{q}_{\text{ref}}}\sin(2\beta)\sin(2\phi)$$



Now the restoring moment increases with increasing wedge angle and increasing sideslip!

- Academic exercise?

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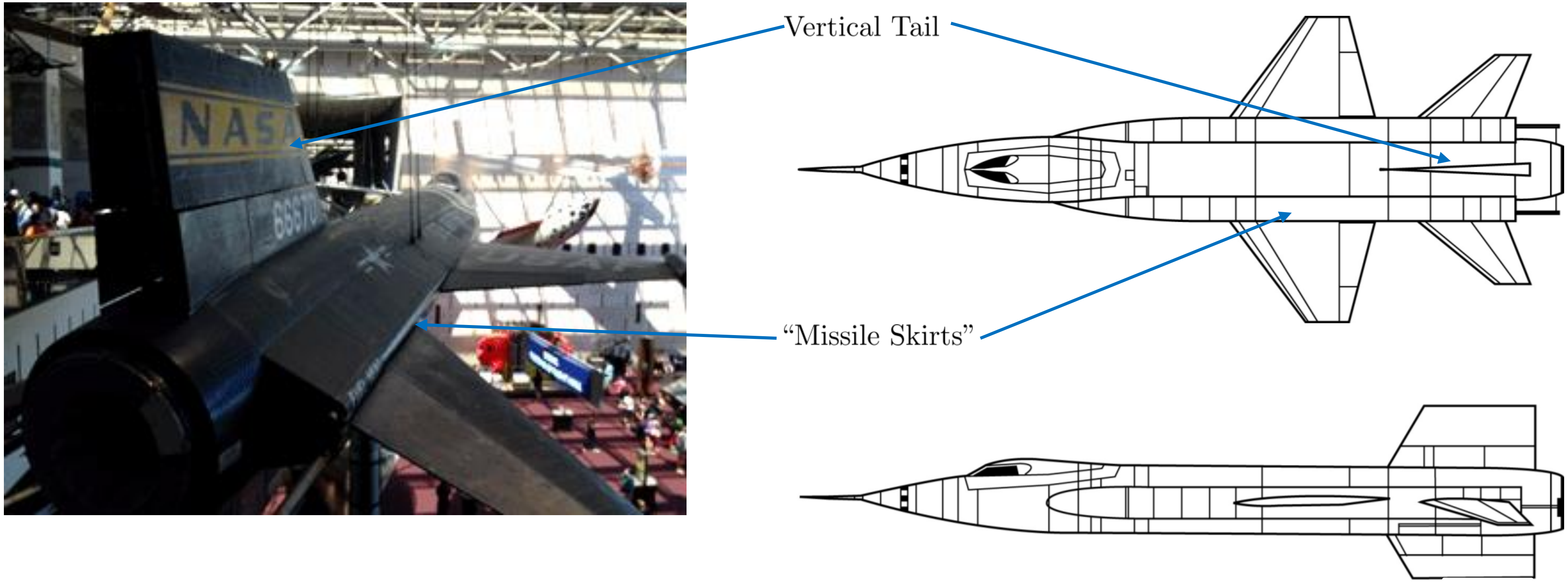
X-15 Vertical Tail



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1950's Hypersonic Challenge

- The hypersonic challenge of the 1950's: Ballistic Missile Atmospheric Re-Entry
- Based of supersonic theory, hypersonic vehicles would need to be even more slender and sharp
- The major theoretical advance came with the publication of
  - 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," NACA R 1381, 1953
- Allen and Eggers showed

$$\dot{q}_{\max,laminar} \sim \frac{1}{\sqrt{R_N}}$$

- They concluded *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.*
- Experimental evidence suggests the heat flux (heat transfer per unit area) can be approximated based on the following relationship:

$$\dot{q}_{\max,laminar} \sim \sqrt{\frac{\rho_\infty}{R_N}} V_\infty^3$$

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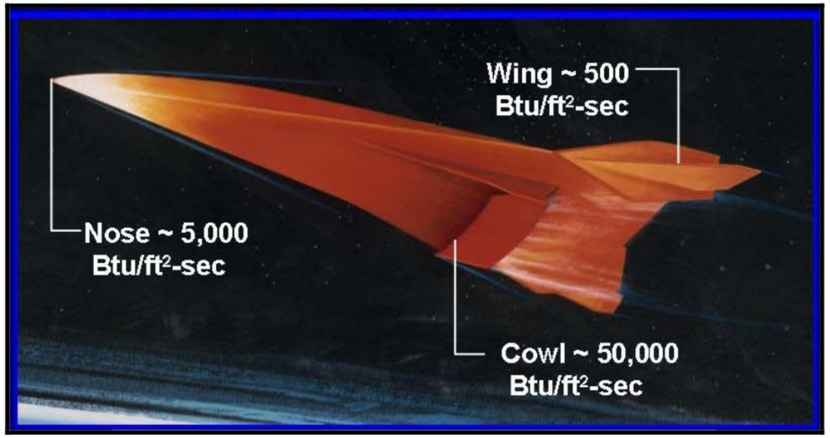
Estimating Heat Flux

- The three modes of heat transfer are given by
  - *Conduction* - heat transfer through a substance due to a temperature gradient:
  $$\dot{q}_{\text{cond}} = k\frac{T_2 - T_1}{x_2 - x_1} \ ,$$
  where k is the coefficient of thermal conductivity.
  - *Forced Convection* - heat transfer due a moving fluid over a solid body:
  $$\dot{q}_{\text{conv}} = h\left(T_\infty - T_w\right) \ ,$$
  where h is the convective heat transfer coefficient.
  - *Radiative Cooling* - heat transfer by electromagnetic waves:
  $$\dot{q}_{\text{rad}} = \epsilon\sigma T_w^4 \ ,$$
  where ϵ is the emmisivity of the material and σ is the Stefan-Boltzmann constant.
- The heat flux balance is
$$\dot{q}_{\text{cond}} + \dot{q}_{\text{conv}} - \dot{q}_{\text{rad}} = 0$$



David E. Glass, "Ceramic Matrix Composite (CMC) Thermal Protections Systems (TPS) and Hot Structures for Hypersonic Vehicles," AIAA-2008-2682

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Estimating Heat Flux

- If we assume the thermal protection system has low conductivity (a pretty good assumption), then we can neglect $\dot{q}_{\text{cond}}$. *Sans shock-to-shock interactions*, the maximum heat flux is typically at the stagnation point, so we focus our approximation there.

$$\dot{q}_s = \left(\dot{q}_{\text{conv}}\right)_s = \left(\dot{q}_{\text{rad}}\right)_s$$

- There are many empirical approaches for estimating the convective stagnation point heat flux, such as Fay-Riddell, Chapman, Hildago, and Sutton & Graves. The latter is the simplest to use and still gives good engineering predictions.

$$\boxed{\dot{q}_s = 1.74153 \times 10^{-4} \sqrt{\frac{\rho_\infty}{R_N}} V_\infty^3 \ \text{W/m}^2}$$

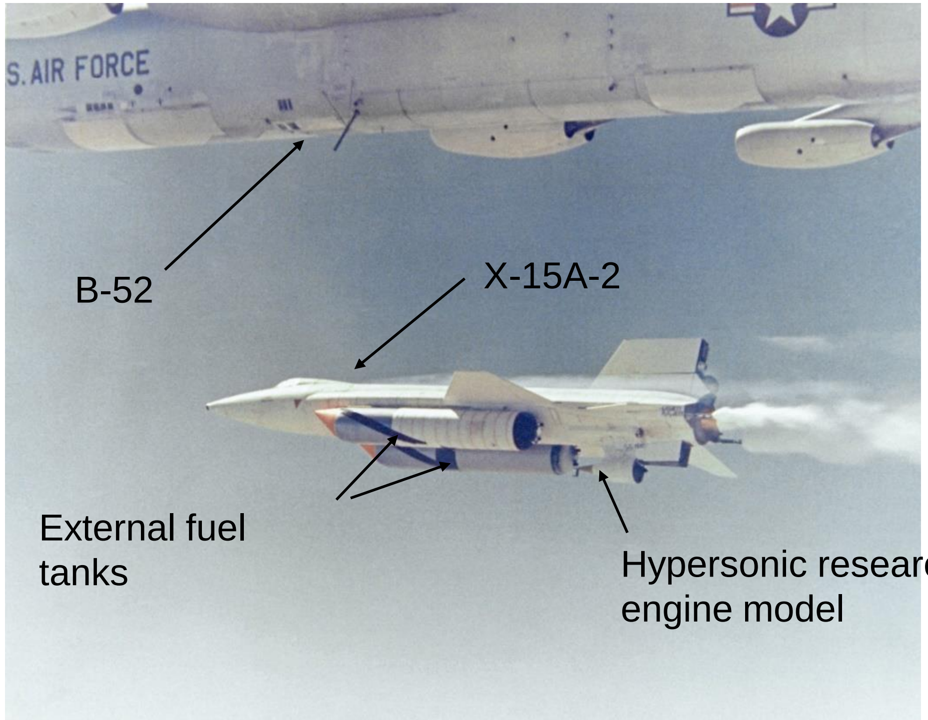
- With the defintion of $\dot{q}_{\text{rad}}$, the wall temperature at the stagnation point can also be estimated.

$$\boxed{T_s = \left(\frac{\dot{q}_s}{\epsilon\sigma}\right)^{1/4}}$$

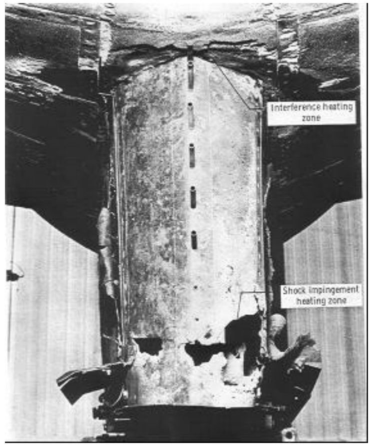
where ϵ is typically in the range of 0.8 to 0.9, and $\sigma = 5.6704 \times 10^{-8}$ W/m^{2}K^4 is the Stefan-Boltzmann constant.

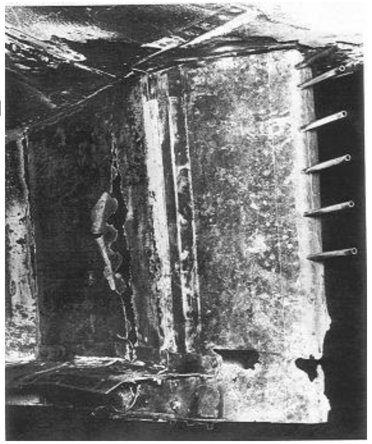
- These types of estimations are very important when, in the absence of flight test data, deciding if high fidelity simulations, such as computational fluid dynamics, are providing a realistic answer.
- How do shock-to-shock interactions affect the heat flux?

Pete Knight’s Mach 6.7 Flight in the X-15A-2

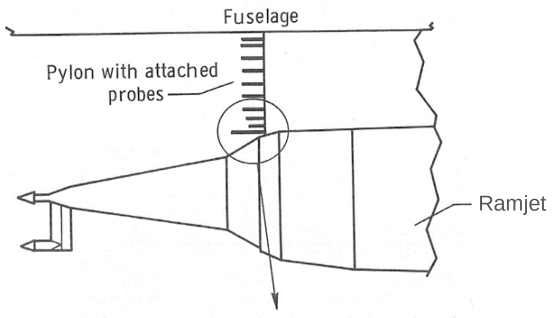


If there had been any question that the airplane was going to come back in that shape, we never would have flown it.
Jack Kolf
X-15 Project Engineer





As a point of reference, the entire output of a moderate-size nuclear power plant would be required to provide this heating rate to a 1-m^2 piece of material.
van Wie *et al*



Structure: Inconel X (a nickel-chromium alloy) plus an ablative cover.
From Iliff and Shafer, AIAA Paper 93-0311 and NASA TM X-1669

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High Temperature Effects

- High temperature flows are fundamentally different than classical thermodynamics
  - The thermodynamic properties (p, ρ, T, e, h, s, etc.) behave differently
  - The transport properties (μ and k) also behave differently. Diffusion becomes important.
  - High heat transfer rates are usually a dominant aspect of any high-temperature application.
  - The ratio of specific heats is no longer constant.
  - Due to the items listed above, virtually all analyses of high temperature gas flows require some type of numerical simulation rather than closed-form solutions.
  - If the temperature is high enough to cause ionization, the gas becomes a partially ionized plasma, which has a finite electrical conductivity. In turn, if the flow is in the presence of an exterior electric or magnetic field, then electromagentic body forces act on the fluid elements. This the purview of an area called magnetohydrodynamics.
  - If the gas temperature is high enough, there will be nonadiabatic effects due to radiation to or from the gas.

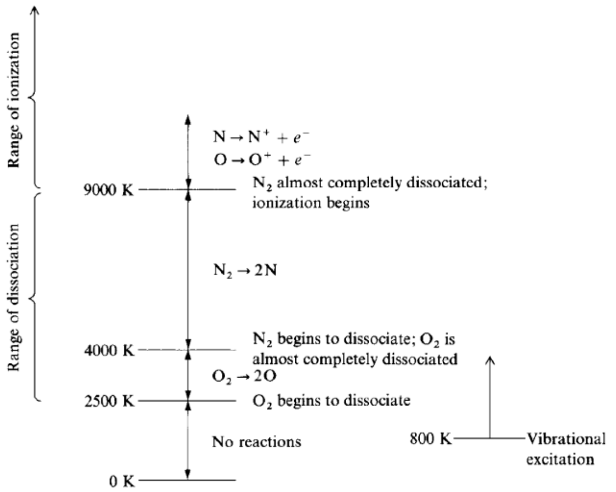


Fig. 9.12 Ranges of vibrational excitation, dissociation, and ionization for air at 1 atm pressure.

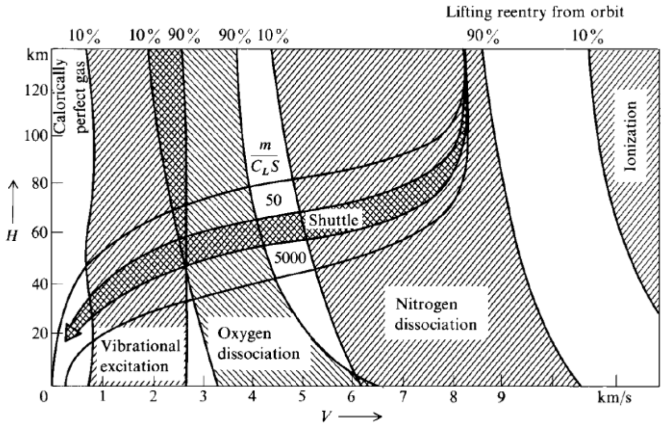


Fig. 9.13 Velocity-amplitude map with superimposed regions of vibrational excitation, dissociation, and ionization (from [79]).

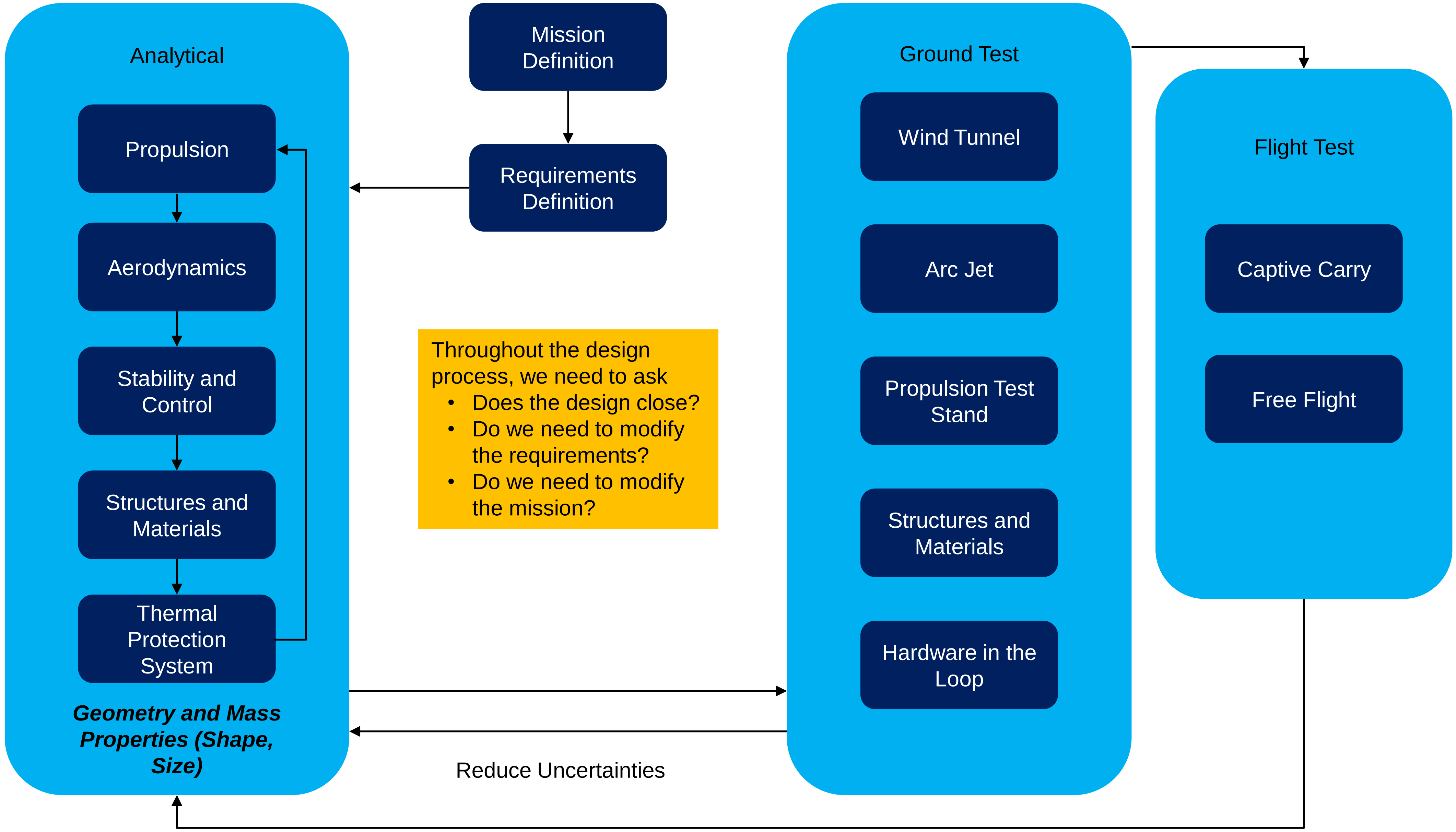
Ref: John D. Anderson, *Hypersonic and High Temperature Gas Dynamics*

Design Considerations

Design Challenges

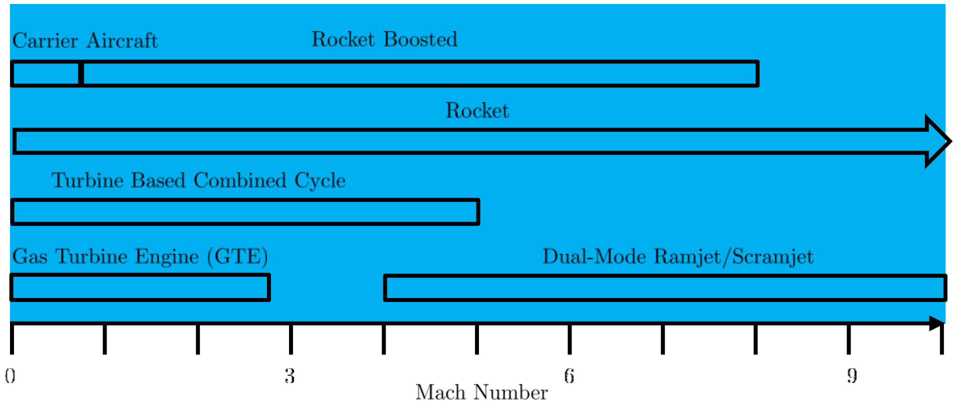
- Design is difficult due to
  - Viscous interactions
  - High temperatures
  - Trajectory shaping
  - Predicting shock/shock interactions
- Design considerations
  - Integrate wing and fuselage
  - Reduce shock wave impingement/interference
  - Integrate propulsion system fully with the airframe
  - Increase L/D with waveriders
- Tool consideration
  - The tools need to talk to each other
  - High fidelity analysis is needed early in the design cycle
  - High fidelity tools need to anchor medium fidelity tools to decrease time to explore the design space

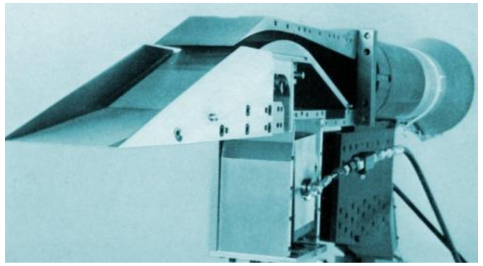
Systems Engineering Approach



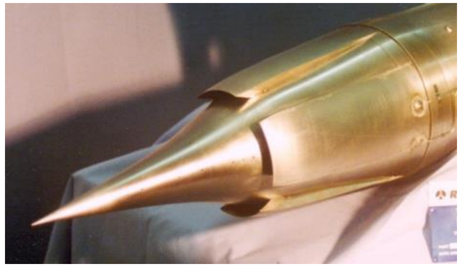
Propulsion

- Multiple engine options
  - Boost-glide vehicles – tend to be larger and require bomber platforms
  - Air-breathers - TBCC, ramjets, scramjet – tend to be smaller allowing fighter employment
- Inlet design driven by inlet performance, drag, weight, and complexity tradeoffs
- Optimum nozzle size is a tradeoff between vehicle drag, nozzle overexpansion and underexpansion losses – all a function of body cross-sectional area
- The fuel (hydrocarbon or cryogenic) is now integral to the thermal management system



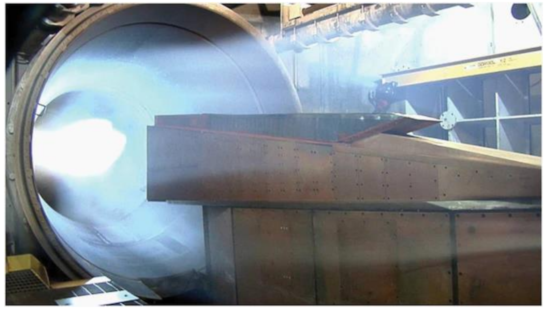


2-D Planer



Axisymmetric

	Advantage
Spillage drag	Axisymmetric
Bleed drag	Axisymmetric
Wetted area/corner flow	Axisymmetric
Angle of attack sensitivity	2-D Planer
Airflow capability with variable geometry	2-D Planer
Mechanization for variable geometry	Axisymmetric
Leakage and spilling	Axisymmetric
Reentry closure	2-D Planer

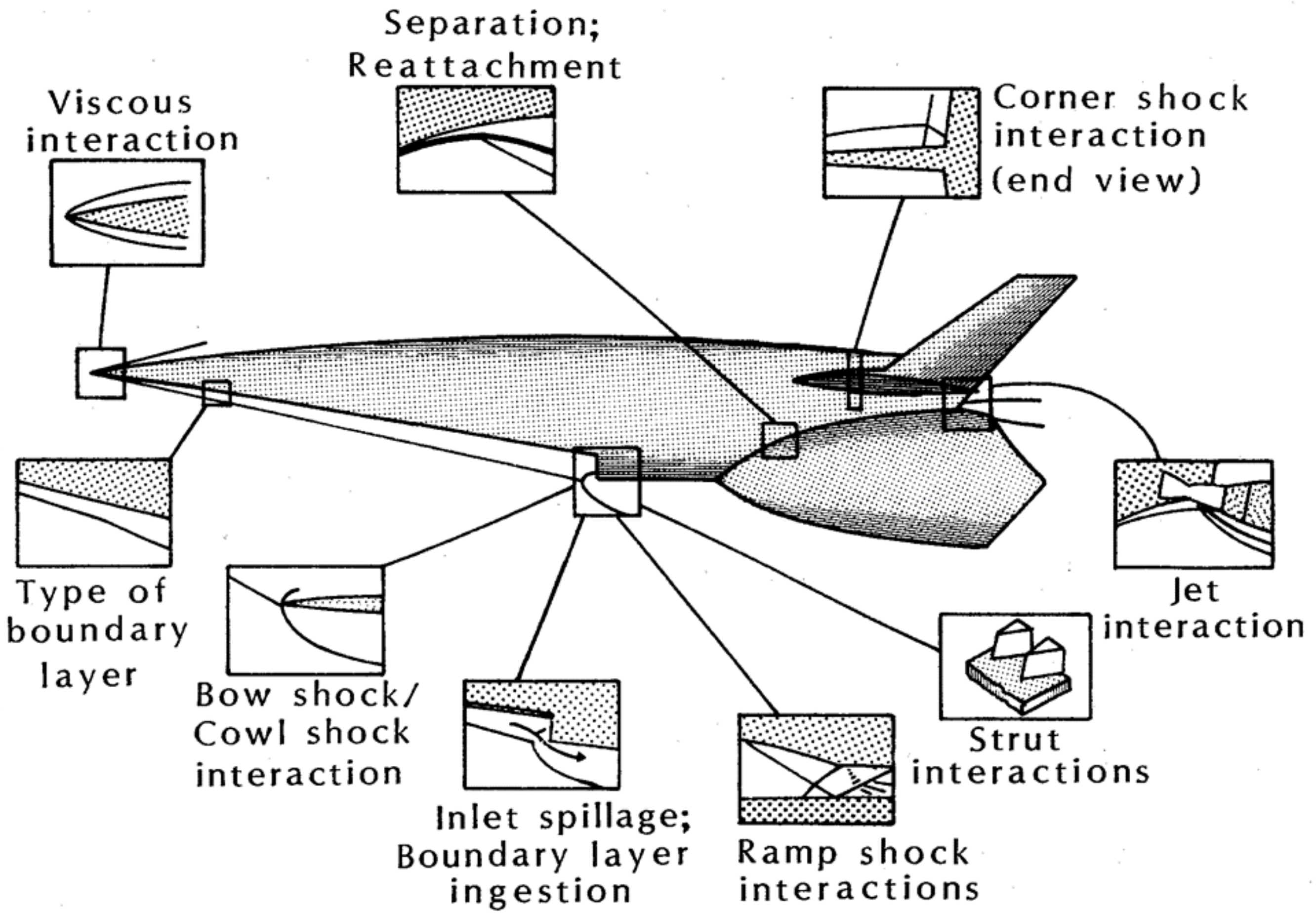


Pratt & Whitney Rocketdyne SJX61-2 Mach 5 ground test under way at the NASA Langley Research Center's 8 ft high-temperature tunnel. (U.S. Air Force)

Vehicle Shape

- Physics drives the vehicle shapes
  - Liquid rocket-powered vehicles can be cylindrical, although a low drag profile can be used
    - Fins sufficient for control.
    - A wing is needed for a reusability.
  - Boost-glide vehicles use a solid rocket motor for acceleration and have a low drag profile
    - Von Karman ogives provide the lowest drag profile at hypersonic speeds.
    - The bottom of the vehicle is usually flat, giving these vehicles a wedge shape.
  - Air breathing vehicles are tightly integrated with the propulsion system
    - The forebody of the vehicle is also the engine inlet
    - The aft body of the vehicle is also the nozzle
    - Requires a rocket to get to scramjet start box

Critical design issues for a hypersonic air-breathing aircraft



Integrated design of the propulsion system and the airframe is critical with hypersonic vehicles

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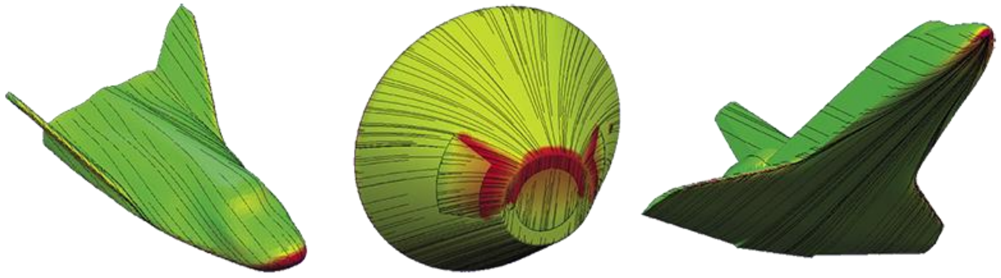
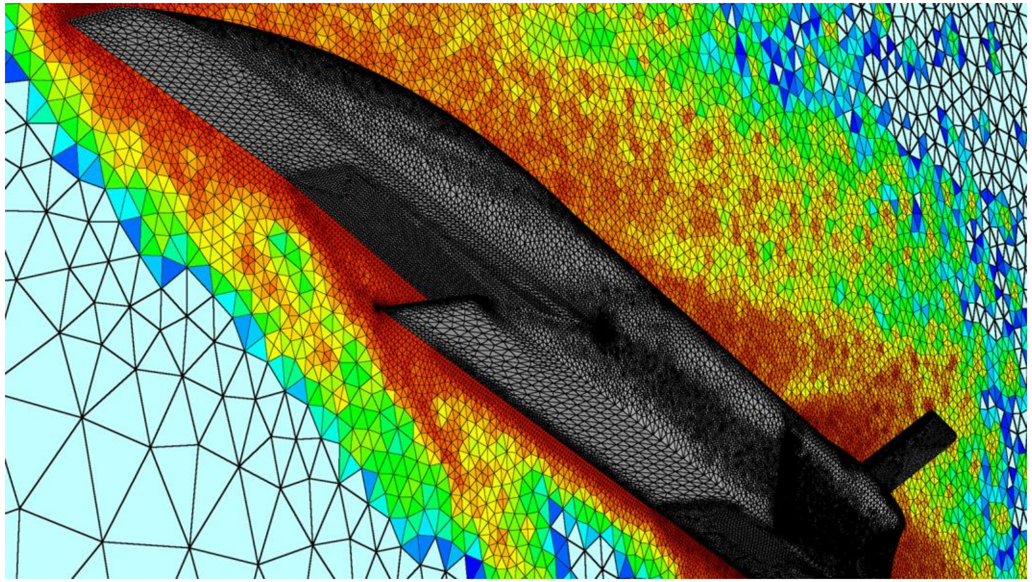
Aerodynamics

- The complexities of hypersonic flow require high fidelity simulations early in the design cycle
- There are numerous codes with different strengths for capturing flow physics - FUN3D, STAR-CCM+, USM3D, OVERFLOW...
- Impractical to perform CFD analysis throughout the entire trajectory
- NASA developed a code called CBAERO which uses just the surface mesh to estimate forces, moments, stability derivatives, and heating on the vehicle
  - Techniques include Newtonian flow, tangent wedge, and tangent cone
  - By itself CBAERO tends to be inaccurate since flowfield information is missing
- CFD simulations at different points in the trajectory anchors the CBAERO solutions providing much better estimates
- Now with just a few CFD solutions it's possible to explore a larger design space with greater accuracy





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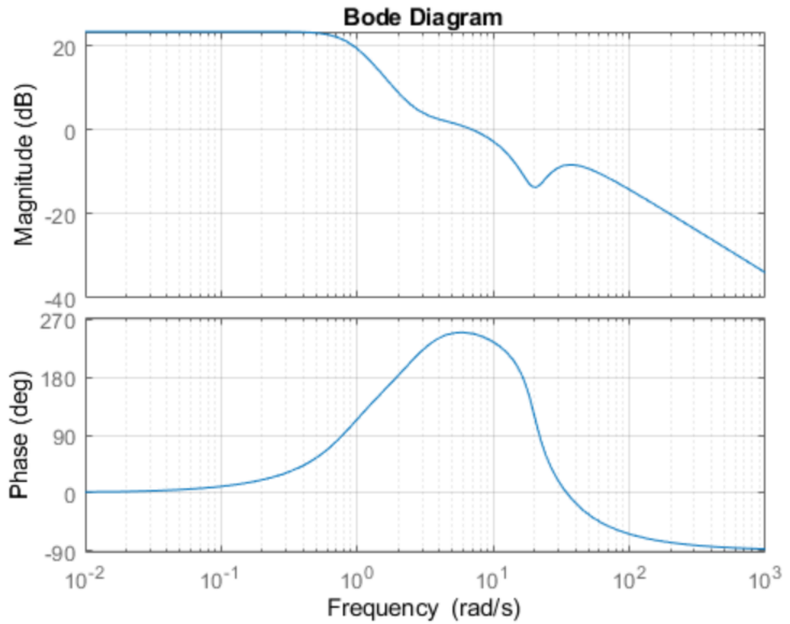
Stability and Control

- Vehicle requirements derived from low speed powered approach, maximum angle of attack, maximum dynamic pressure, and maximum Mach number
- General statements about hypersonic stability
  - Stabilizing effect of tails or fins and control surface effectiveness are dependent on windward side pressure
  - High-speed vehicles typically exhibit negative static margin
  - Hypersonic vehicles are generally stable in roll, however roll-yaw coupling can be an issue due to moment of inertia distribution (fuselage heavy)
  - Crossflow lift and sideforce on long, slender fuselages with integrated inlets may be difficults to overcome with tail aerodynamics
- To estimate the stability of the vehicle
  - Design Reference Missions (DRMs) are chosen
  - The full aero-database is determined from analytical, CFD, and wind tunnel data
  - A Flight Control System (FCS) is developed – Proportional-Integral-Differential (PID) or Nonlinear Dynamic Inversion (NDI)
  - Monte Carlos of the DRMs are simulated that include uncertainties in the aerodatabase, atmospheric conditions, etc.
  - Phase and gain margins are determined to see if the vehicle remains stable in each of the DRMs



Note that there are two 180 deg phase crossings with corresponding gain margins of -9.35dB and +10.6dB. Negative gain margins indicate that stability is lost by decreasing the gain, while positive gain margins indicate that stability is lost by increasing the gain.

MATLAB™ example

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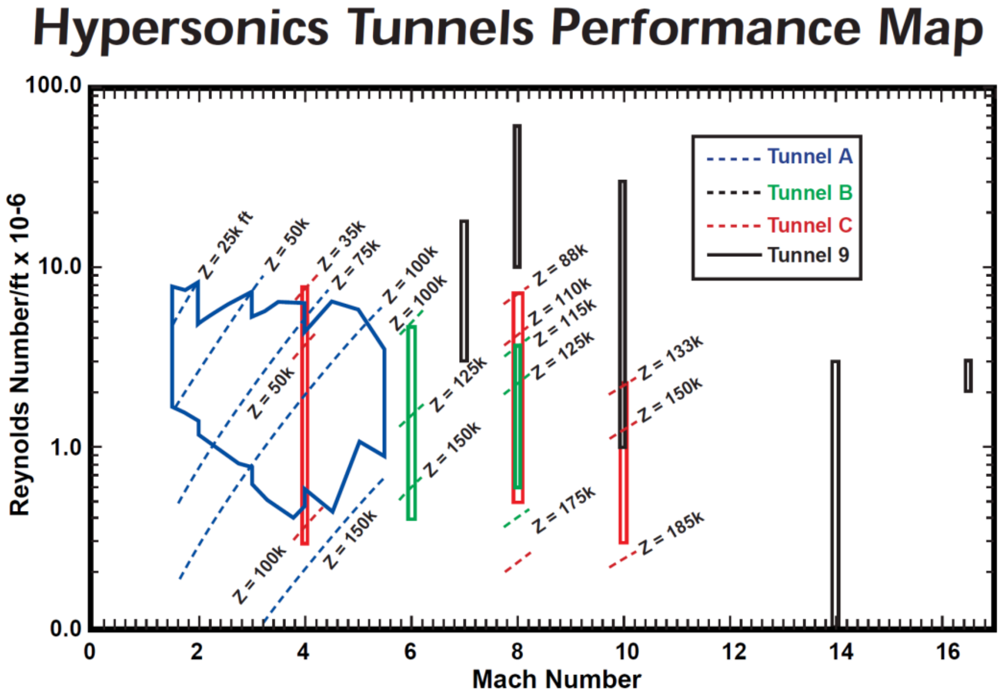
Ground Test

- Infrastructure upgrades provide opportunities to reduce flight test risks
  - Aerodynamic performance
  - Static Stability
  - Store Separation
  - Vehicle Staging
  - Flutter and Aeroelastic
  - Inlet Performance
  - Material Sampling
  - Thermal Mapping
  - Shroud Separation



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Ground Test Limitations

- Wind tunnels test around the boundaries of the hypersonic environment
- No single ground-test facility can fully simulate all aspects of hypersonic flight.
  - Flow duration, velocity, gas chemistry effects, Mach number, altitude or Reynolds number, model surface temperature, ablation effects, and the quality of the freestream flow cannot be controlled simultaneously in any single facility, if at all.
  - Nearly all tunnels suffer from noise levels much higher than flight.
  - All tunnels simulating gas chemistry effects also have freestream chemistry contaminants.
- Tunnel time and scheduling are a challenge
  - Tens of thousands of dollars per hour in government tunnels
  - Years-long backlog and growing
  - Von Karman Facility Tunnel A (VKF-A) at the Arnold Engineering Development Center (AEDC) has a 3.5 year wait

> "Ground test simulations are an exercise in the art of combining partial simulations each having different advantages and disadvantages."
>
> **Steven P. Schneider**
>
> *Hypersonic and Hypervelocity Ground Test Facilities: A Brief Informal Summary; 2007*

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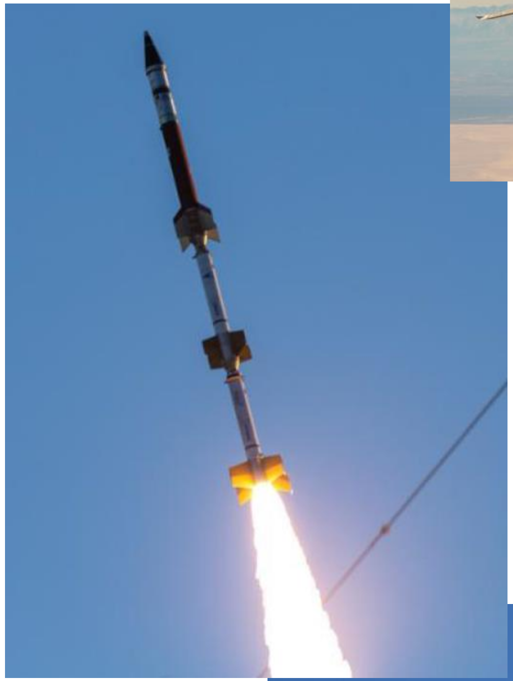
Flight Test

- Options are limited and typically expensive
- Sounding rockets can get to the necessary speeds but typically do not fly operationally relevant trajectories
- Air-launch provides more operationally relevant trajectories, but usually at an increased cost over sounding rockets
- The B-52H is the typical threshold platform for hypersonic weapons
  - Undergoing engine modifications, radar, and electronic warfare upgrades
  - Multiple conventional programs
  - Limited number of B-52Hs dedicated to flight test
- Other low-cost options are needed to increase the frequency of flight test



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Questions?