AAE 538: Air-Breathing Propulsion

Lecture 23: Supersonic Aerothermodynamics and Inlets

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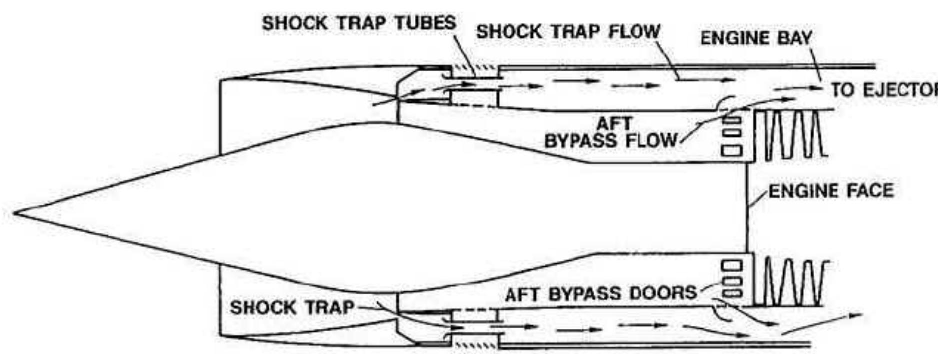
Introduction

Ramjet Engines

- The ramjet engine is the simplest air-breathing engine that can be built
  - In conceptual form, the ramjet engine has no moving parts, since the compressor is effectively ____.
  - Because the ramjet has no turbine, it can operate at higher temperatures (like an afterburner)
    -
  - Very economical due to simplicity
    -



Introduction

Ramjet Engines

- The greatest disadvantage of the ramjet is the fact that it
  - Limited to operation at Mach numbers
  - At high Mach numbers, diffuser and combustion design challenges become severe
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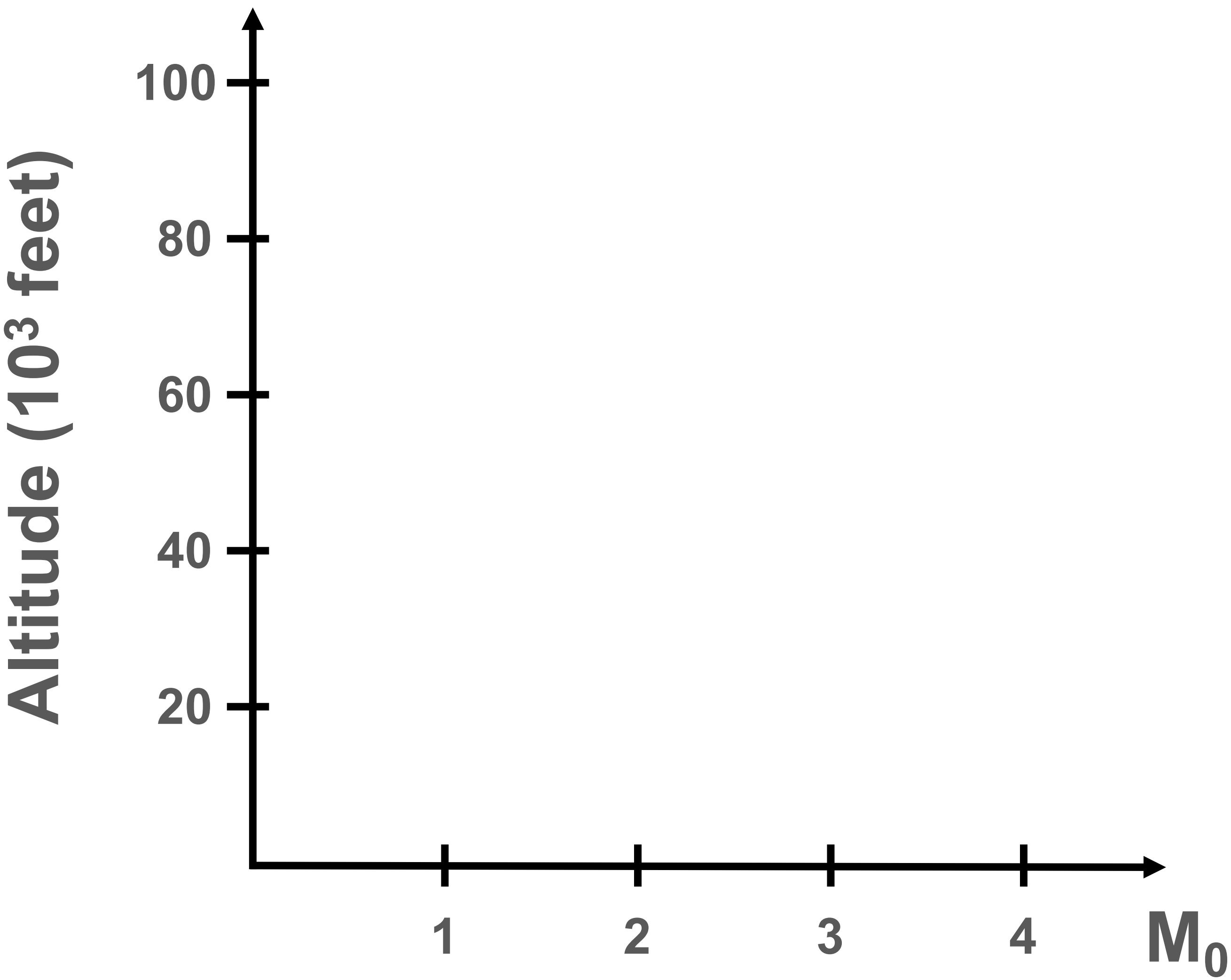
Introduction

Typical Subsonic Combustion Limits



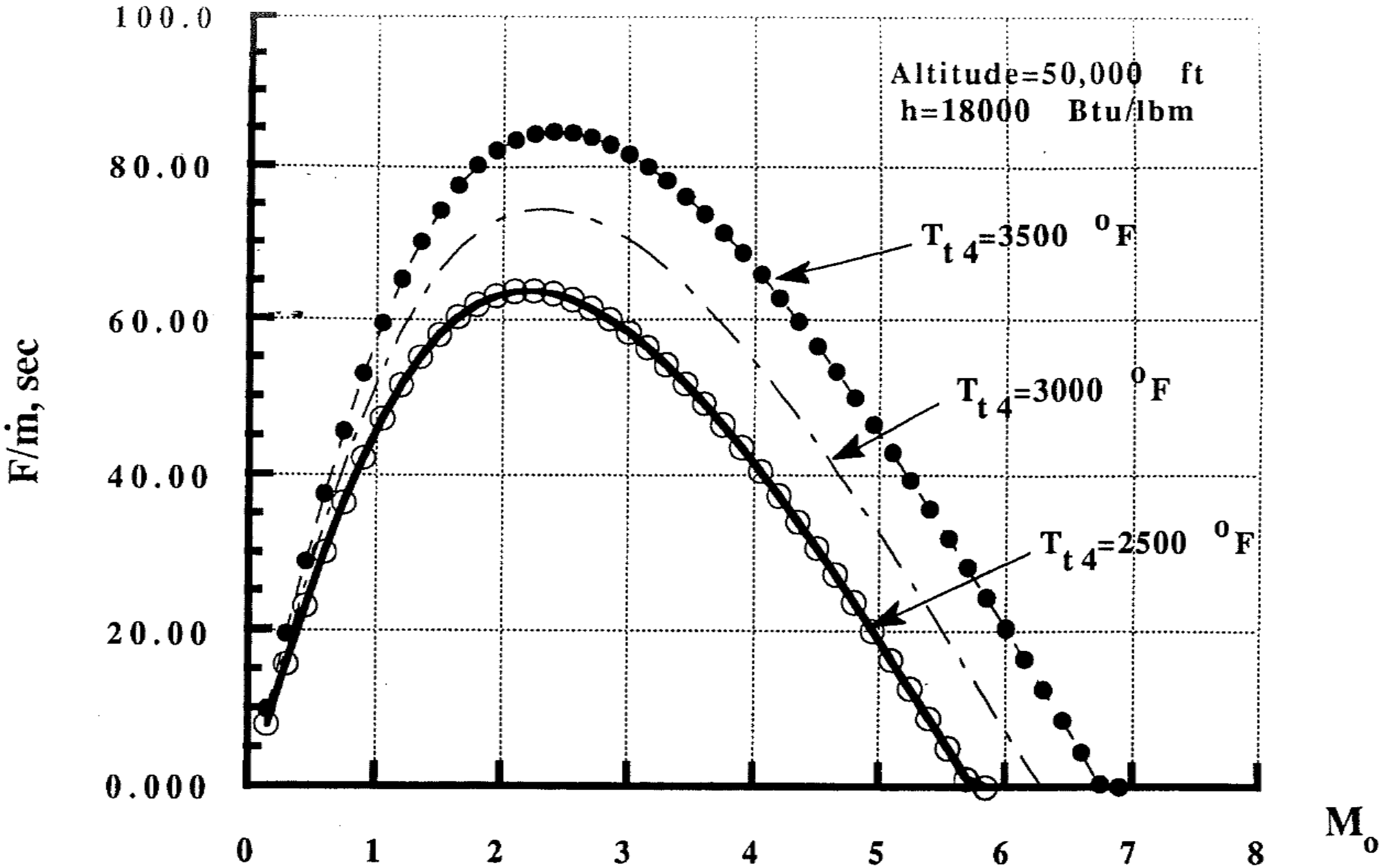
Ideal Ramjet Performance

- The ideal ramjet was implicitly covered as an ideal turbojet.
  -
  - Under this condition, the turbine temperature ratio becomes

$$\tau_t =$$

  - Under these conditions, the specific thrust becomes
  - We can also write

Ideal Ramjet Performance



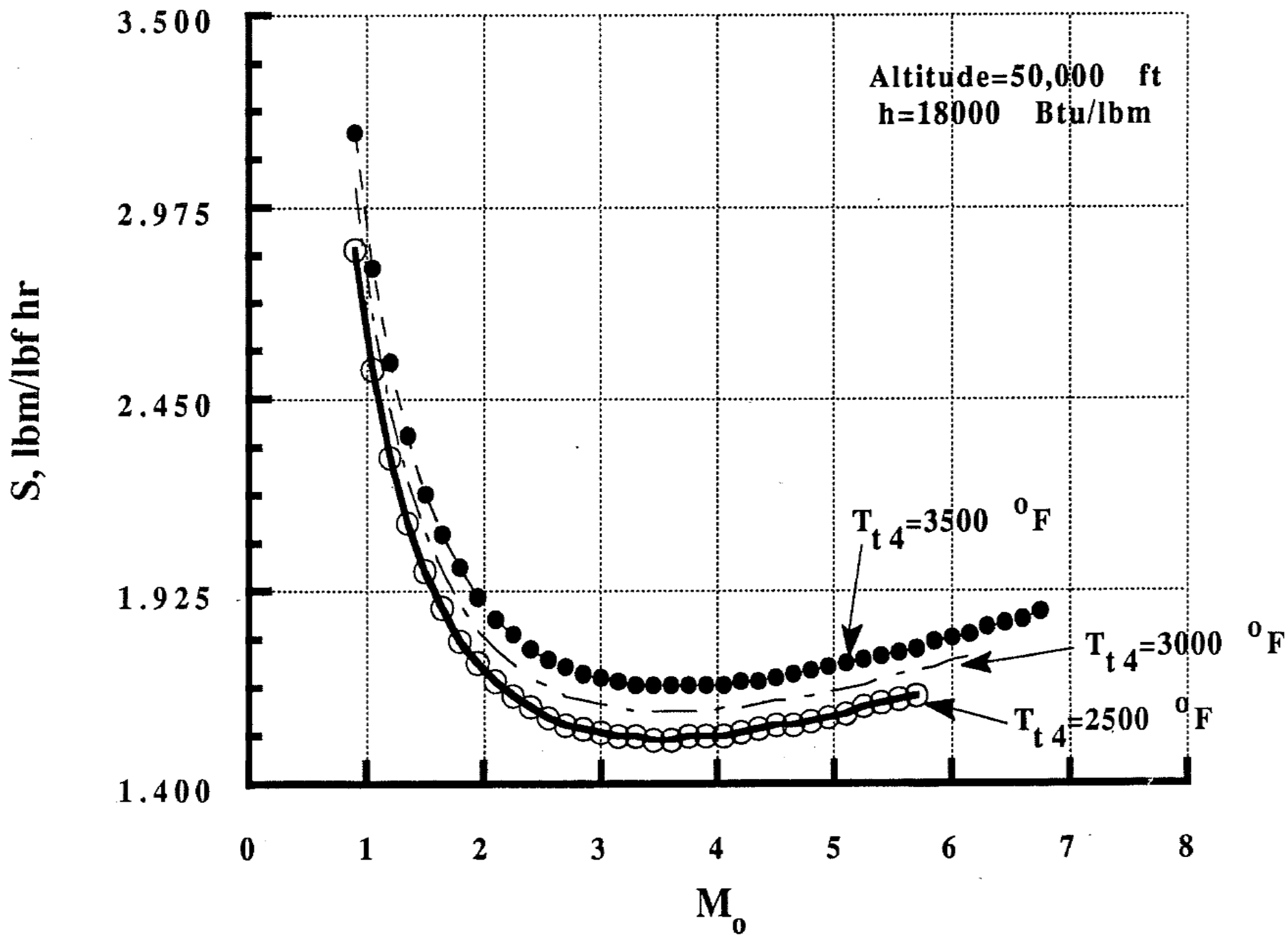
Ideal Ramjet Performance

- The fuel/air ratio can be derived as it was for the ideal turbojet
  - By considering the energy balance across the combustor, we showed that

$$f = \frac{c_p T_0}{h} \tau_r \tau_c (\tau_b - 1) =$$

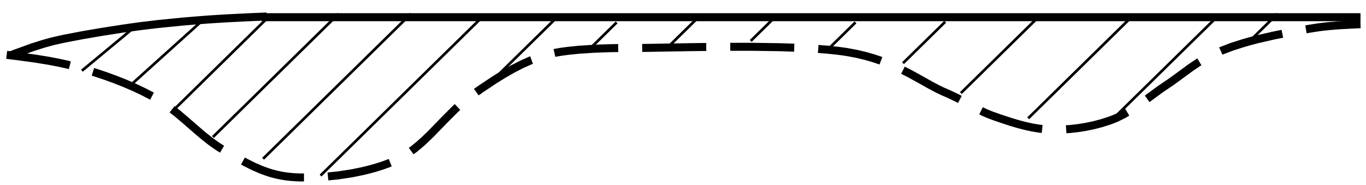
  - Such that the specific fuel consumption for this simple device can be written as

Ideal Ramjet Performance



Semi-Ideal Ramjet Analysis

- Kantrowitz–Donaldson Inlet
  - A geometry for a ramjet engine using a reverse Delaval nozzle.
  - Under proper flight and design conditions, a normal shock will reside downstream of the inlet throat.
  - We can analyze the performance of this semi-ideal ramjet design with the following assumptions
    -
    -
    -
    -



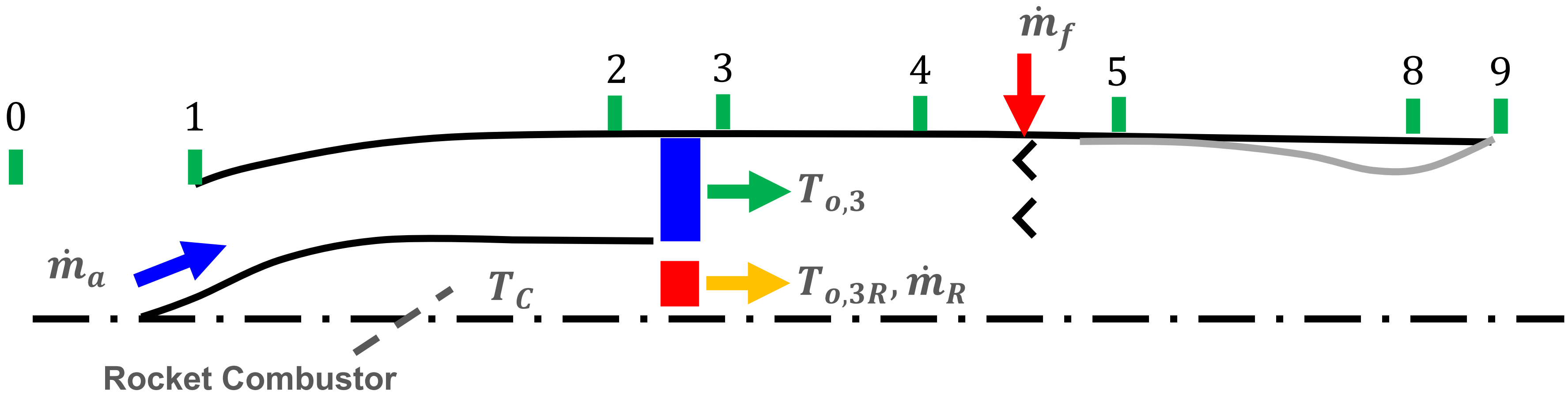
Semi-Ideal Ramjet Analysis

Final Notes on Ramjets

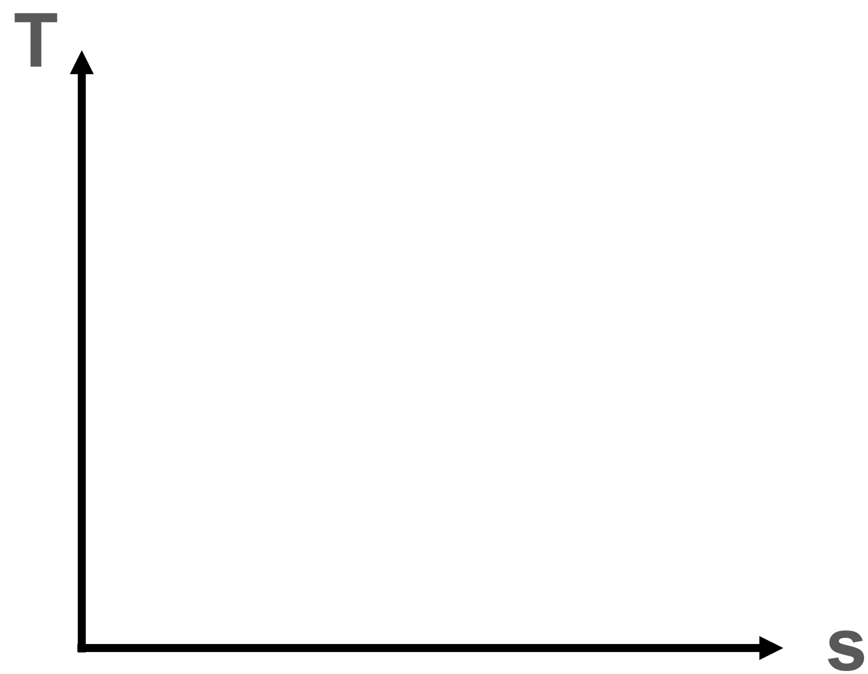
- Performance of these ramjets is extremely sensitive to the position of the shock.
- As the ramjet accelerates, the shock is ‘swallowed’ beyond a critical Mach number
  -
  - Operation near the swallowing point is not possible, where the stagnation pressure losses are minimized, because the shock is highly sensitive to small disturbances and the shock can be ____________________________ resulting in a large loss of thrust.
- By varying the amount of heat addition through the fuel flow rate, we can position the shock far enough away from the throat to promote stable operation and still maintain small losses in the shock.
  -
  - Decreased heat addition results in the opposite effect.

Example

Air-Turbo-Rocket Example



- $0 \rightarrow 2$:
- $2 \rightarrow 3$:
- $\mathrm{C} \rightarrow 3$:
- $3 \rightarrow 4$:
- $4 \rightarrow 5$:
- $5 \rightarrow 9$:



Example

- **Inlet** $(0 \rightarrow 2)$
  - For an adiabatic process with no shaft work, that the ______________________ is constant, such that

- **Fan** $(2 \rightarrow 3)$
  - The fan is modeled as an adiabatic, reversible (hence, isentropic) compression device.

Example

- **Turbine** $(\mathrm{C} \rightarrow 3')$
  - P_C is the rocket combustion chamber pressure (design input). T_C is a function of the rocket propellants. For an isentropic expansion process

- **Mixer** $(3 \rightarrow 4$ and $3' \rightarrow 4)$

Example

- **Burner** $(4 \rightarrow 5)$
  - From the energy balance:

$$(\dot{m}_f + \dot{m})c_p T_{o,5} = \dot{m} c_p T_{o,4} + \dot{m}_f \Delta H_B$$

- **Nozzle** $(5 \rightarrow 9)$
  - For an adiabatic process with no shaft work, that the stagnation enthalpy is constant, such that

Example

- **Computing Performance Parameters**

Example

- **Computing Performance Parameters**

Introduction

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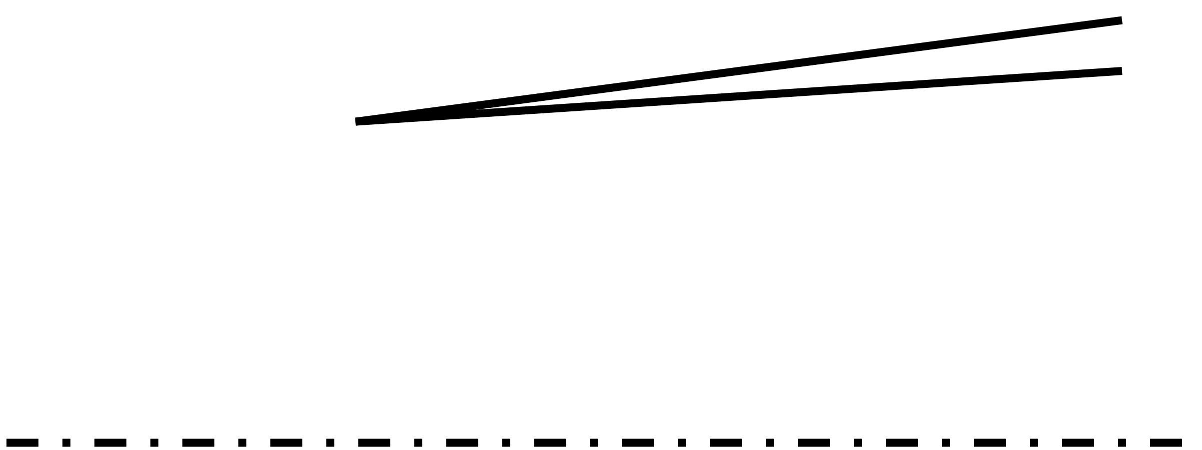
Supersonic Diffusers

- The design of supersonic inlets is governed by the shock structure associated with the operational flight envelope of the aircraft.
  - Aircraft with supersonic dash capabilities: e.g. F-15 or F-16
  - Aircraft with supersonic cruise capabilities: e.g. F-22 (Ma=1.5) or SR-71 (Ma=3.2)

- The design of supersonic inlets is fraught with compromises

Supersonic Diffusers

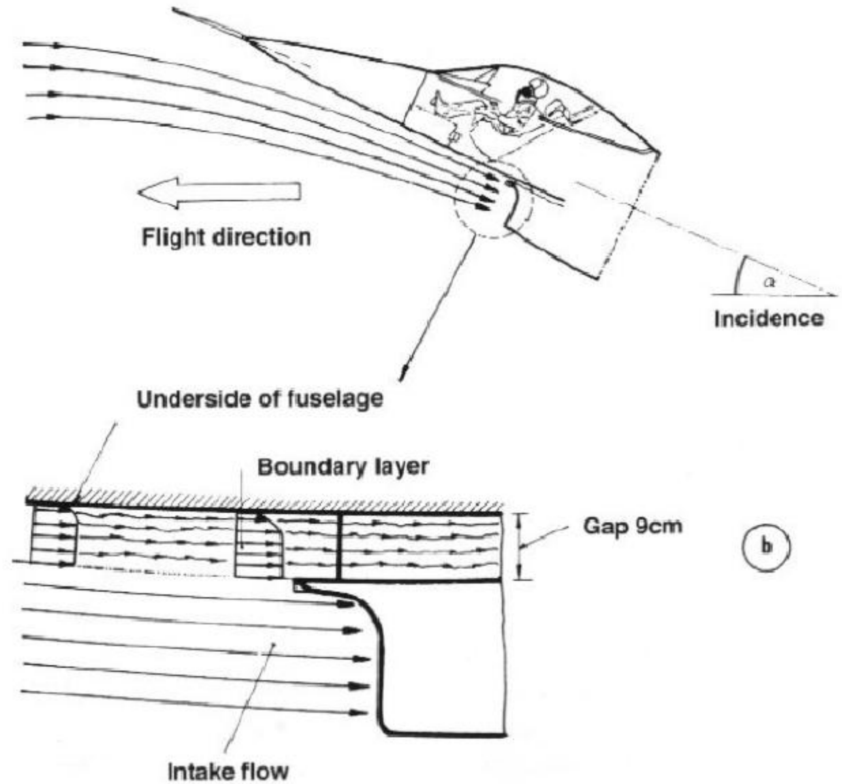
- Four examples of supersonic inlets
  - Simple, slightly diverging inlet
    - Found in aircraft with only ______________________________ performance



Simple, Diverging Inlet

Supersonic Diffusers

- General Dynamics F-16 Falcon
  - One GE F-110 Turbofan
  - Optimized for Mach 0.6 to 1.6



Supersonic Diffusers

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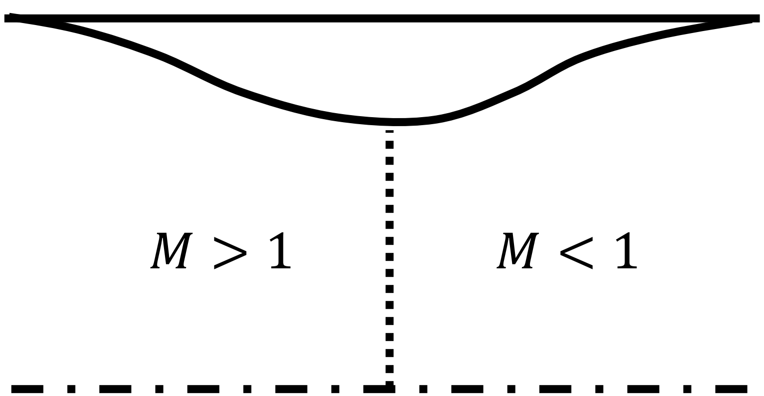
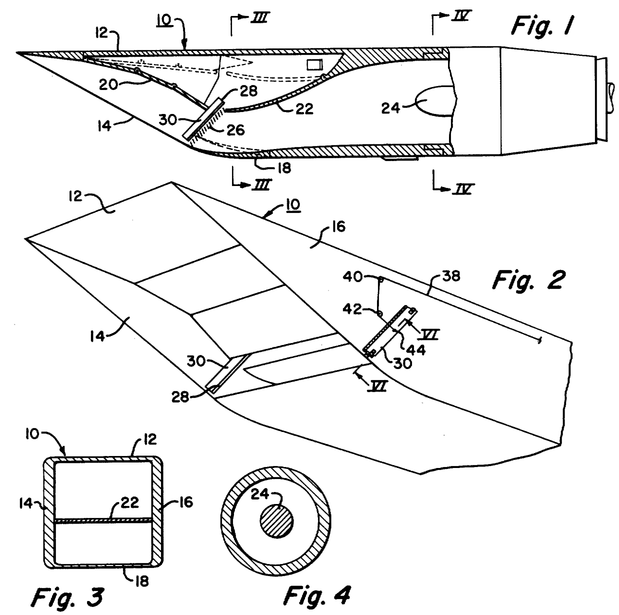
- Reverse de Laval Inlet
  - Upcoming discussion in the context of inlet starting, where we note the possibility of disgorging the shock if the backpressure increases for an instant.
  -



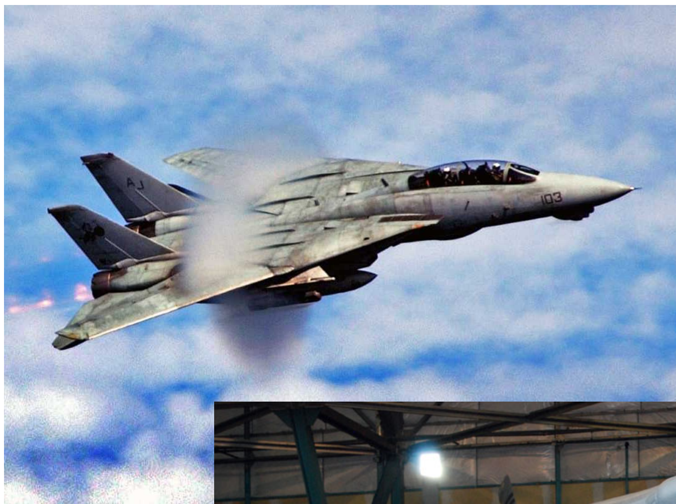
Reverse de Laval Inlet

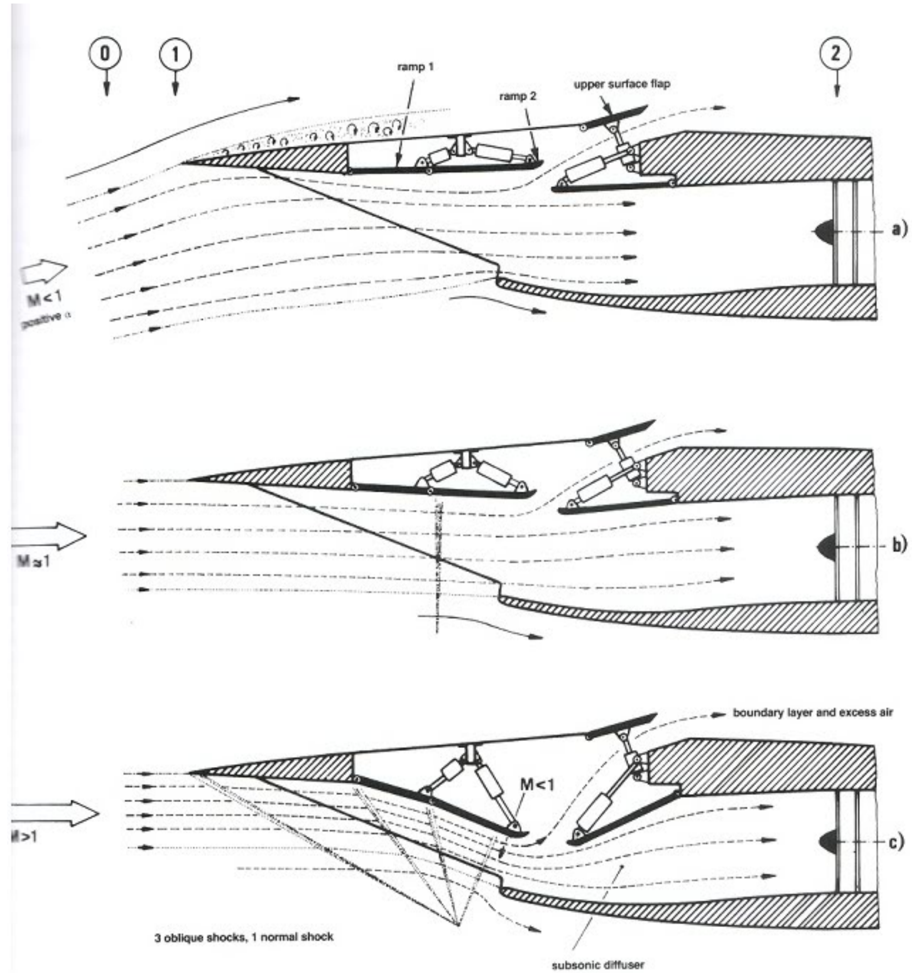


US PTO 4372505 (Boeing, 1979)

Supersonic Diffusers

- Grumman F-14 Tomcat
  - Two GE F-110 Turbofans
  - Mach 2.1 Top Speed





26 Inlet of the F-14
Ramp positions and flow at various flight conditions: a) subsonic speed and high angle-of-attack (typical manoeuvre case); b) transonic flow; c) supersonic flow.

Supersonic Diffusers

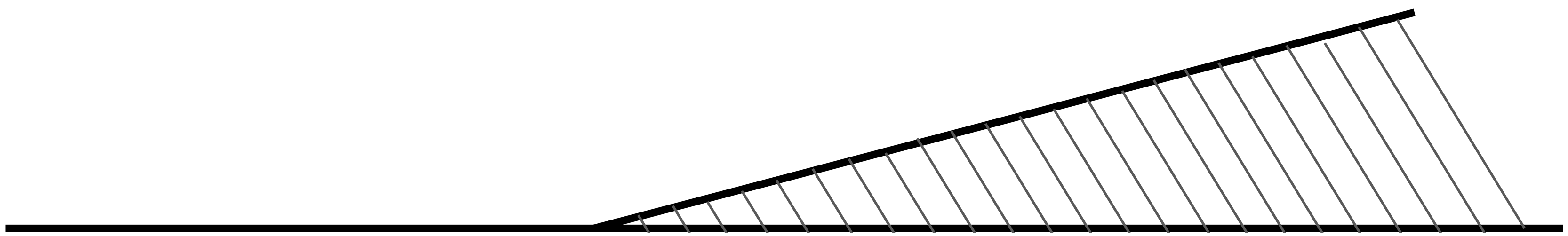
- A more clever approach to high Mach number inlets is to take advantage of your expert knowledge of gas dynamics!
  - Use a center-body, inlet lip, or some other geometric feature (upstream) to generate one or more oblique shocks and decelerate the flow prior to the normal shock near the inlet lip.
  -

Two-Dimensional, Ramp Inlet

Conical, or ‘Spike’ Inlet

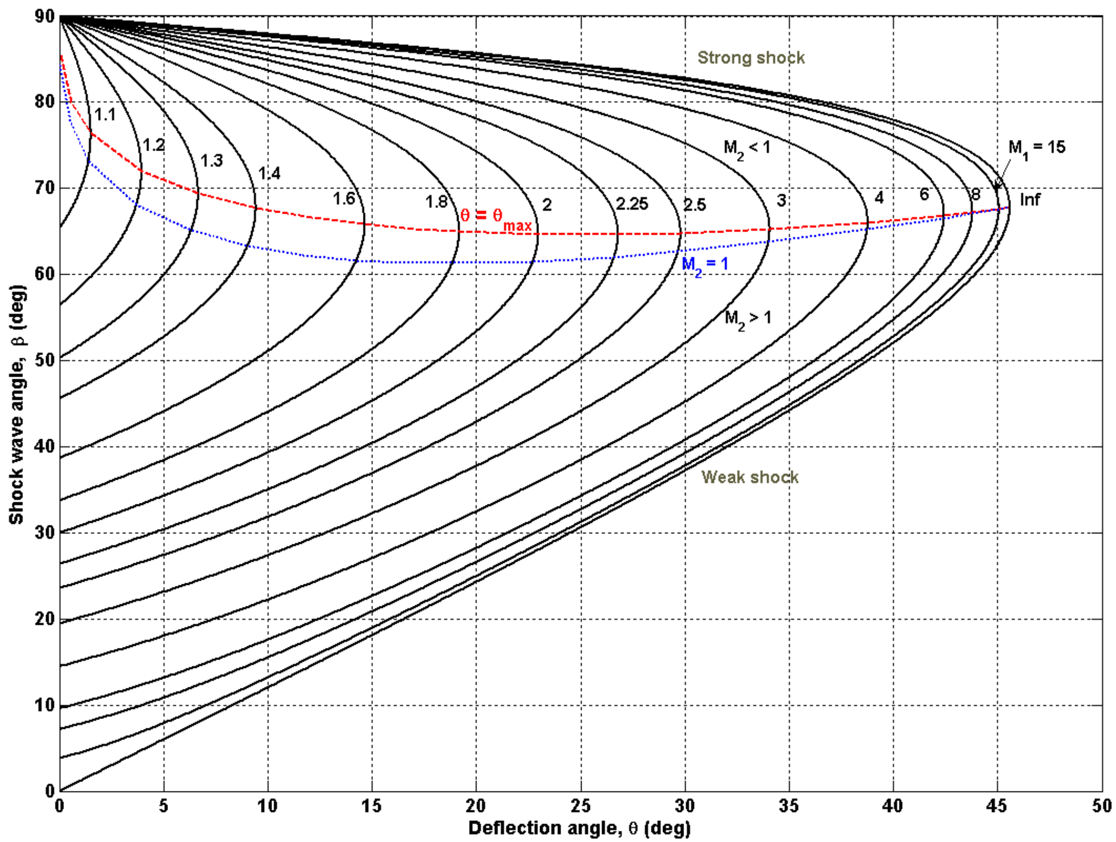
Ramp Inlet Design

- Focusing on the most frequently used inlet for modern supersonic vehicles, we will perform a brief analysis of the ramp inlet.
  - Consider the situation where a supersonic flow encounters a wedge of angle θ.



  - Since the flow is 2D, the fluid must be turned through the angle θ.
  - The solution to the governing equations gives two shocks that could provide the required turning angle change (change in momentum normal to the shock).
    - In nature, it is the weak solution that is almost always observed.

$$\tan(\theta) = 2\cot(\beta)\frac{M_1^2\sin^2(\beta) - 1}{M_1^2(\gamma + \cos(2\beta)) + 2}$$



Ramp Inlet Design

- Shock losses across oblique shock wave are a function of the Mach number normal to the wave, so we can find the change in stagnation pressure, for example, by using the normal shock table with the normal Mach number

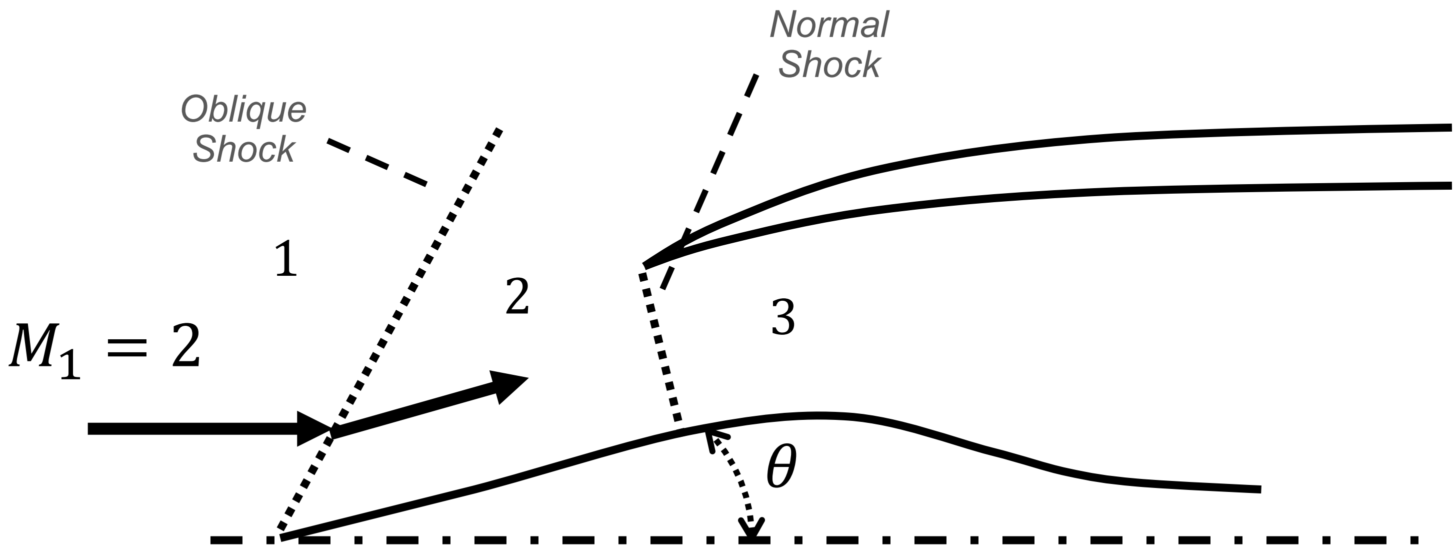
- The normal shock tables also give us the normal Mach number behind the shock, M_{2n}. This quantity can be related to the actual M_2 value through geometry

Ramp Inlet Design

- Treatment of losses across the normal shock follow directly from the normal shock tables for an entering Mach number M_2.
- With this, the overall stagnation pressure ratio can be written:

- For a given free-stream condition, the inlet can be optimized using a series of wedge angles to further reduce the overall pressure loss.
  - In doing this, we achieve lower losses with more shocks because each of the shocks is weaker than a single oblique shock.

Ramp Inlet Example



From the oblique shock chart: $M = 2, \theta = 8° \Rightarrow$

Normal shock tables:

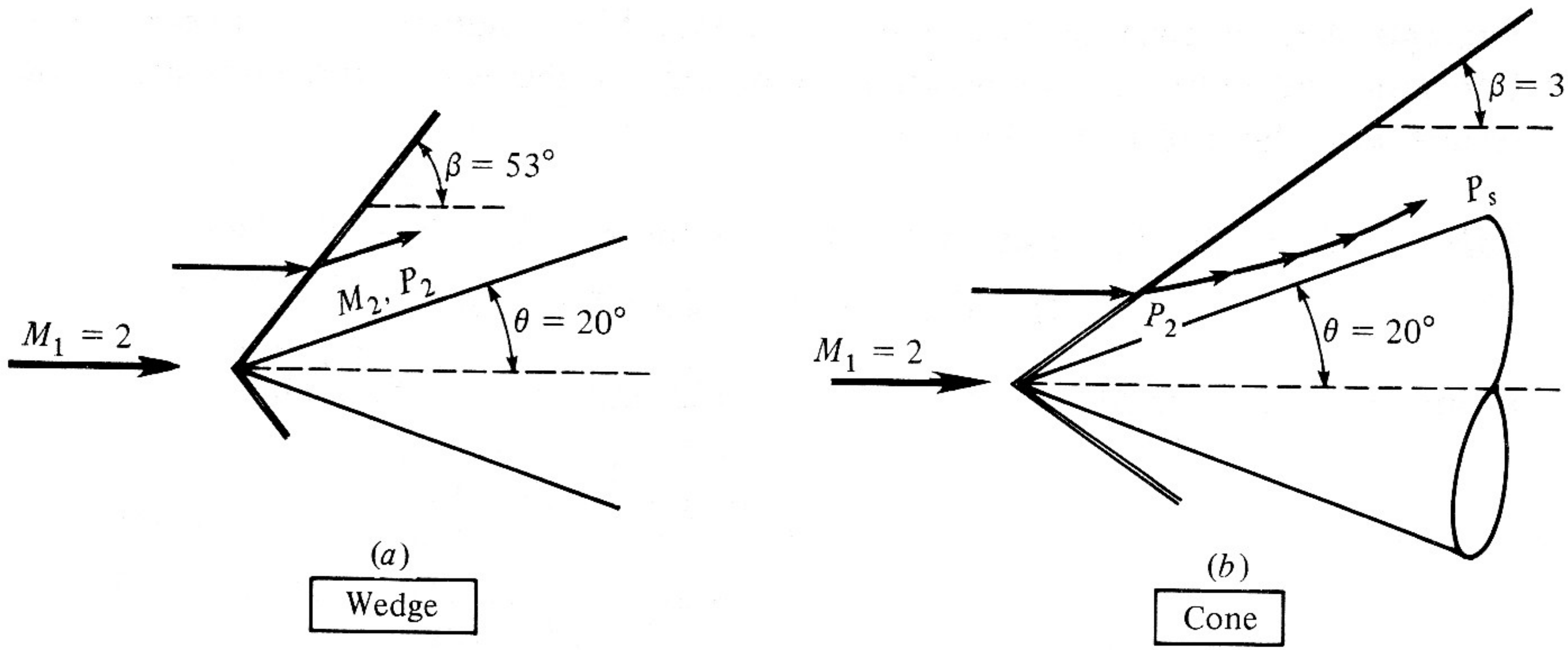
Ramp Inlet Example

Normal shock tables:

Overall stagnation pressure loss (r_d):

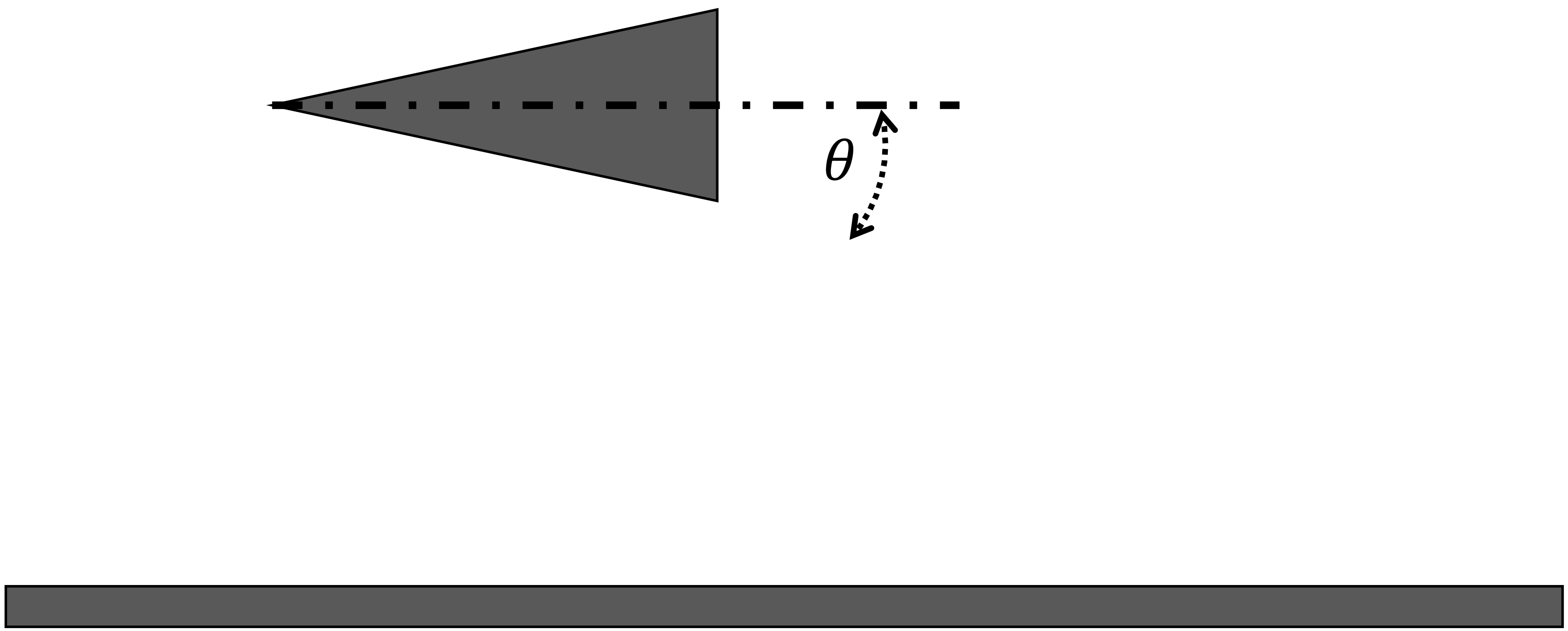
Wedge Versus Conical Center-body

- A conical center-body generates a conical shock surface
  - The flow is axisymmetric, as opposed to being 2D in the case of the wedge.
  - The flow area increases as a second-order function with increasing axial distance
    - Conservation of mass requires that the streamlines curve – work backwards to a lower turning angle and, effectively, a lower shock angle. The shock doesn't have to effect the entire turning angle… streamlines converge because annular streamtubes are stretched to a larger radius.
    -



Reflected Shock Waves

- When an oblique shock encounters another change in material density,
  - The reflected shock angle will be reduced from the preceding oblique shock waves since the incoming 'free-stream' Mach number has been lowered by the previous shock processes.



Shock Wave Interactions