Aerospace Propulsion

Lecture 17

Airbreathing Propulsion VII

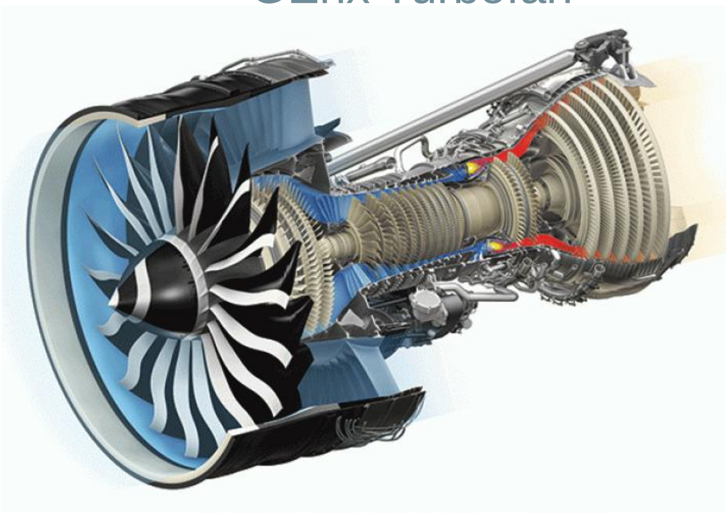
Airbreathing Propulsion: Part VII

- Supersonic turbojets and turbofans
- Ramjets
- Scramjets
- Rotating Detonation Engines

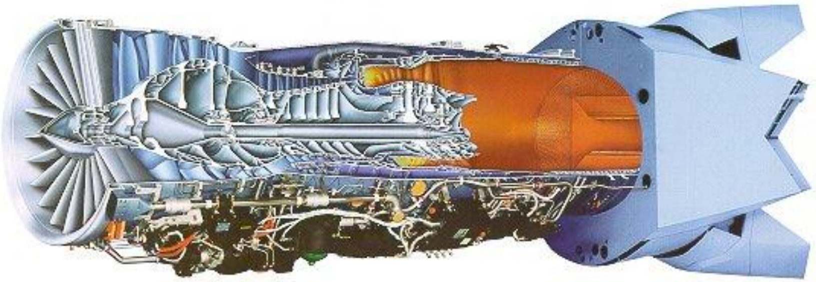
Supersonic turbojets and turbofans

- Subsonic vs. supersonic turbojet/fan
  - Fundamentally, identical behavior and analysis between fan/compressor inlet to turbine exit
  - Two key differences:
    - Flow needs to decelerate from supersonic flight velocity to subsonic velocity before compressor
      - Remember, compressor inlet limited to ~Ma=0.6
    - Flow needs to accelerate from subsonic velocities at turbine exit to supersonic velocities at nozzle exit
  - Engine inlets and outlets need to be designed differently for supersonic flight

GEnx Turbofan



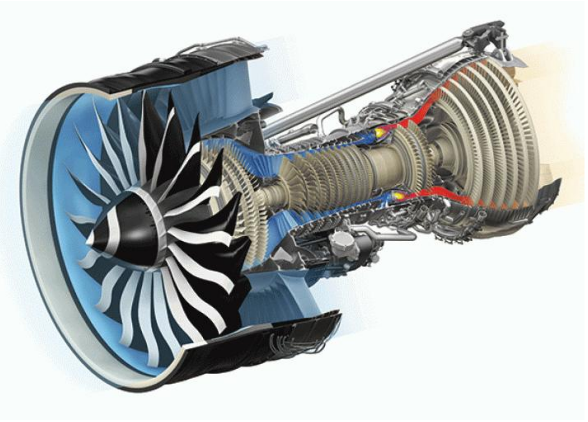
F119-PW-100 TURBOFAN



Supersonic turbojets and turbofans

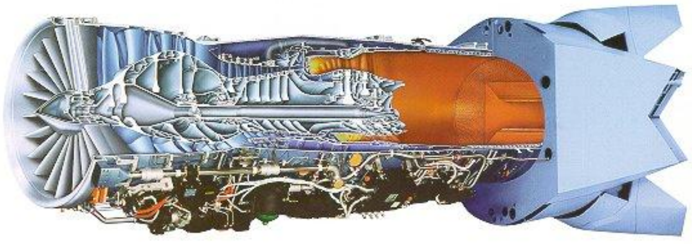
- Turbojets/fans can achieve supersonic flight without afterburners
  - Presuming inlets and outlets designed for supersonic…
- Bypass ratio much smaller for supersonic turbofans
  - Bypass stream primarily used for cooling/afterburner
  - Massive drag penalty with large fan at supersonic speeds

GEnx Turbofan



Engine	Application	Bypass Ratio	Pressure Ratio	Flight Speed
RR Trent 1000	787	11	52	0.85
GEnx	787	9.6	43	0.85
PW F119	F-22	0.2	27	1.82(D) /2.40(W)
PW F135	F-35	0.56	28	1.20(D)/1.60(W)

F119-PW-100 TURBOFAN



Supersonic turbojets and turbofans

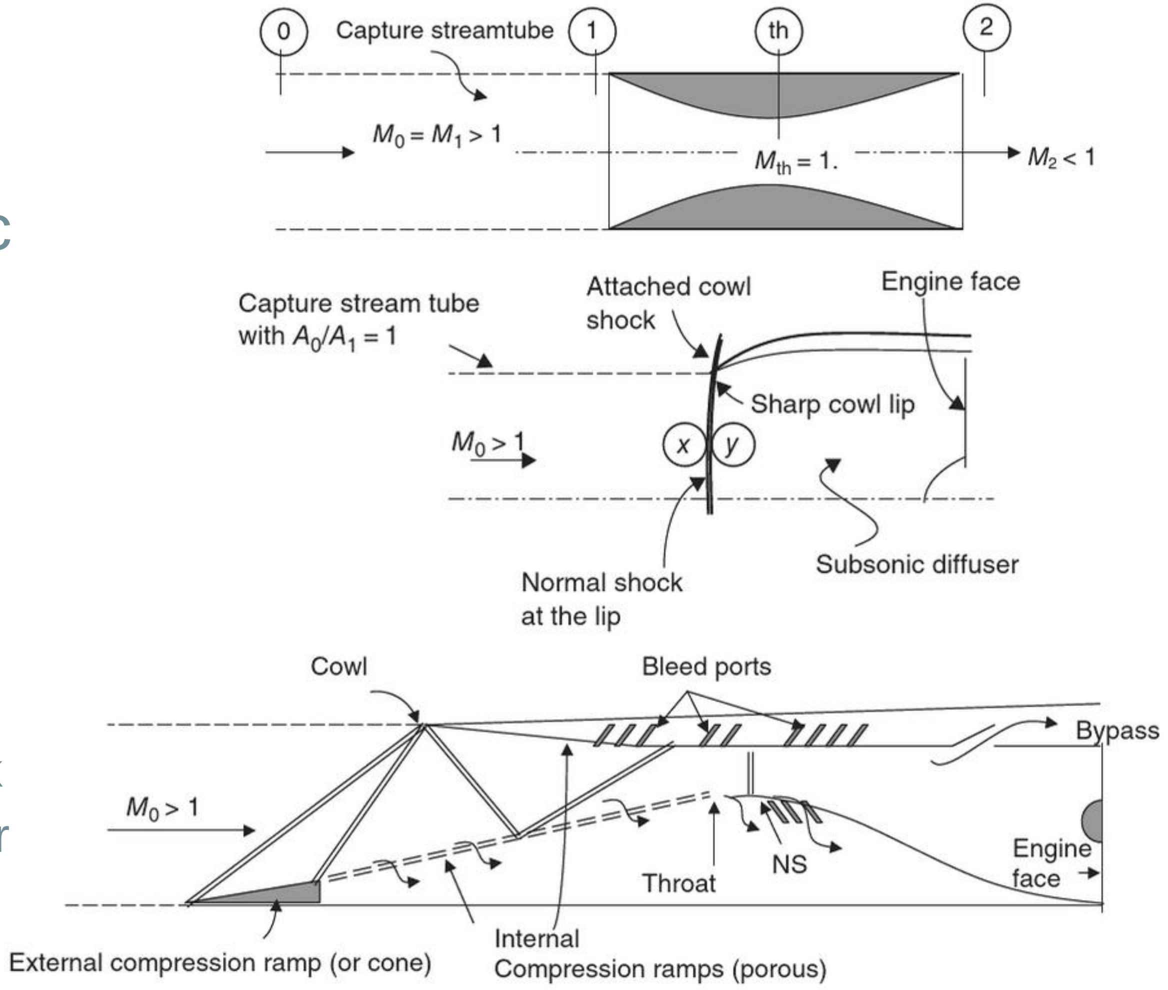
- Inlets
  - Subsonic
    - Inlet provides small decrease in flow velocity to prepare for compressor inlet
      - Remains subsonic entire time
    - Streamlined to minimize flow separation
  - Supersonic
    - Inlet provides large decrease in flow velocity through carefully designed shockwaves
      - Supersonic to subsonic
    - Corners to stabilize desired shock patterns
    - Often have variable geometry since shock properties change at different flight speeds

Boeing 787 (M=0.85)

Concorde (M=2.0)

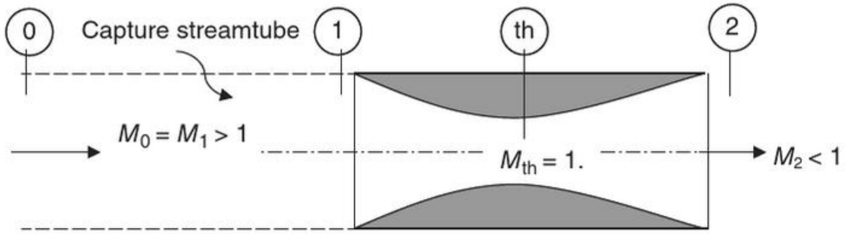
Supersonic turbojets and turbofans

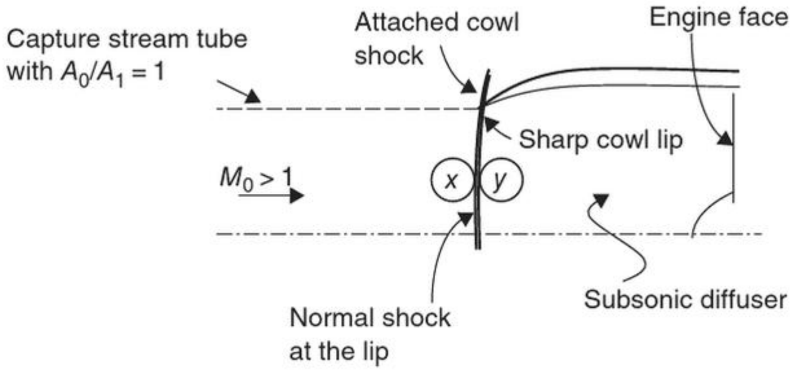
- Inlets
  - Need to slow flow from supersonic to subsonic through inlet
  - Two possible inlet categories
    - Isentropic (no shocks) diverging-converging diffuser
      - Opposite of converging-diverging nozzle to slow flow
    - Shock based inlet
      - One very strong normal (bow) shock
      - Series of oblique shocks and weaker normal shock

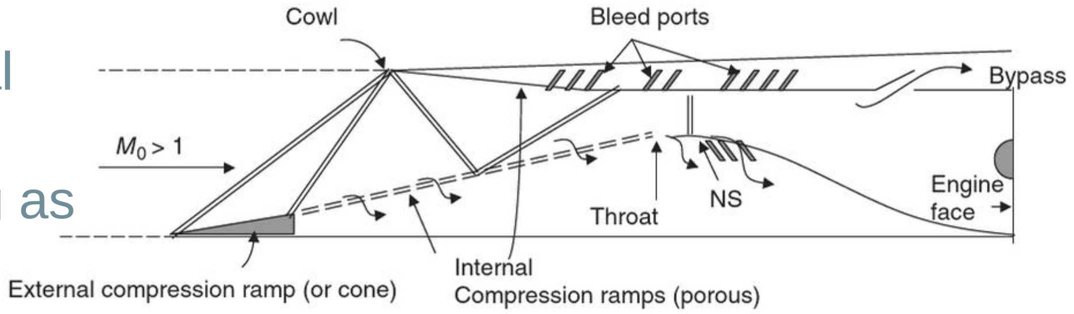


Supersonic turbojets and turbofans

- Inlets
  - Diverging-converging diffuser
    - Only optimized to one flight speed
      - Variable-area throat possible but complicated
    - Any other speed leads to normal shock
  - Upstream normal bow shock
    - Extremely high stagnation pressure losses
  - Series of oblique shocks
    - Lower stagnation pressure loss than normal shock
    - Can adjust to range of flight speeds as long as individual deflection angles aren't too large







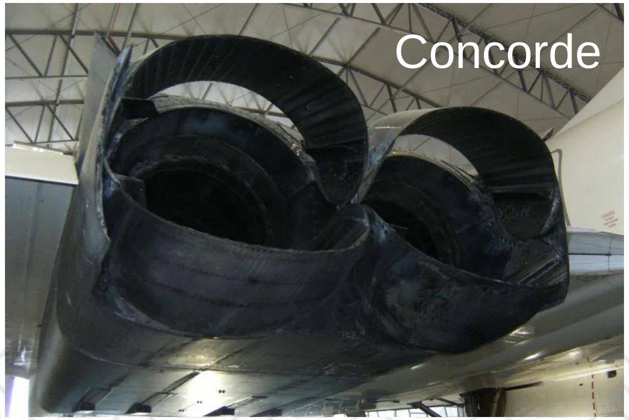
Supersonic turbojets and turbofans

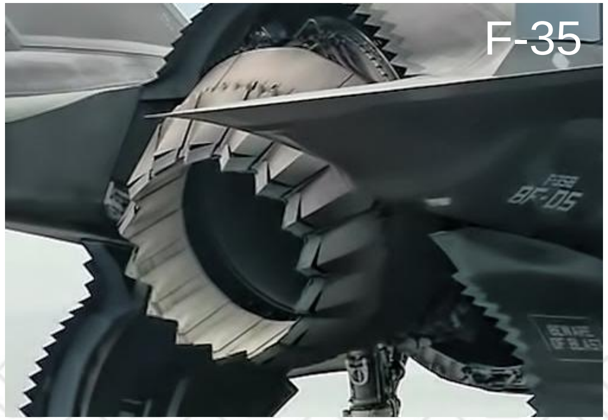
- Inlets
  - Series of oblique shocks is typically used
    - Efficient and easier to control
  - Shock properties change with flight speed
    - Variable inlet geometries <u>required</u>

  - Example: RR Olympus 593
    - Inlet for Concorde aircraft adjusts as needed

Supersonic turbojets and turbofans

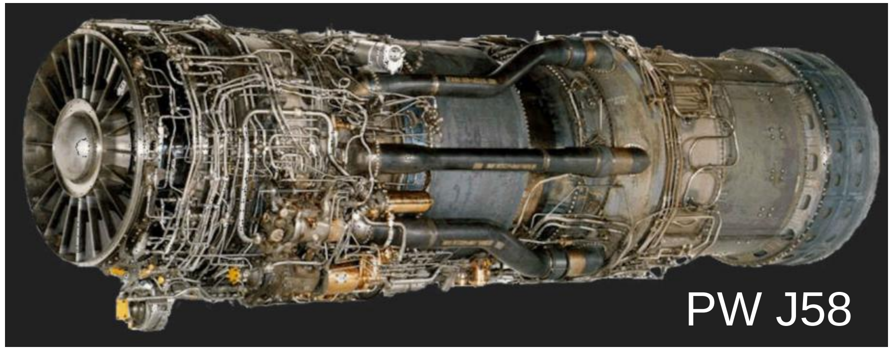
- Nozzles
  - Exhaust gas velocity > flight velocity
    - For supersonic flight, need supersonic exhaust
  - Flow at turbine outlet is subsonic
  - For supersonic flight, require converging-diverging nozzle
  - Area ratios need to be adjusted for different flight speeds
    - All supersonic engine nozzles are variable-area





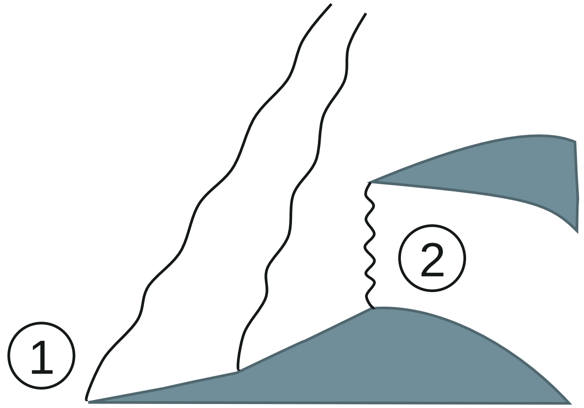
Ramjets

- Motivation
  - Consider very high-speed flight
  - Example: SR-71 Mach 3.3 @ 80,000 ft
  - Records: Still fastest and highest *sustained* air-breathing flight
    - New York to London in less than 2 hours
  - “If a surface-to-air missile launch was detected, the standard evasive action was simply to accelerate and outpace the missile.”
  - “A total of 32 aircraft were built; 12 were lost in accidents with none lost to enemy action.”



Ramjets

- Consider Mach 3.3 flight @ 80,000 ft
  - $T_a = 221.03$ K, $p_a = 2761.5$ Pa
- Approximate inlet as two oblique shocks with $15°$ flow deflection angles followed by a normal shock
  - We'll see what the actual inlet looks like for the SR-71 later, but this is representative of supersonic flight
  - $\frac{T_2}{T_a} \approx 3$
  - $\frac{p_2}{p_a} \approx 28.6$
  - $M_2 \approx 0.6$

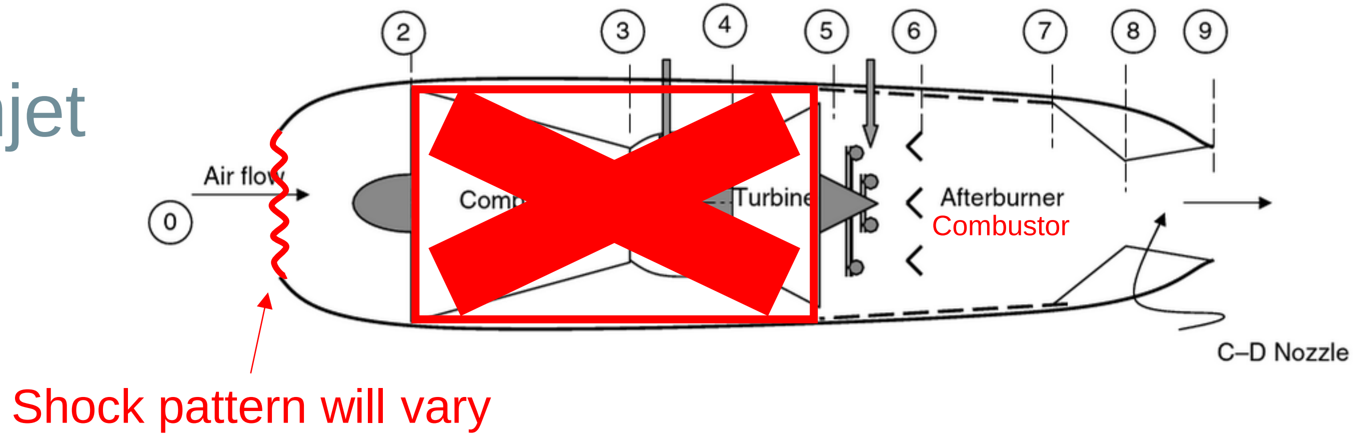


Ramjets

- We just found that the shocks alone give us a pressure increase of 28x
- Increased pressure with better designed inlet
  - Best case: isentropic (no shock) C-D inlet with no stagnation pressure losses
- Increased pressure with increased flight speed
- If we’re fast enough, do we even need a compressor?
  - Eliminate compressor and rely on shocks for compression
  - No compressor also means no need for a turbine

Ramjets

- (Basic) components of a ramjet
  - Inlet
  - Combustor
    - More like afterburner
  - Nozzle



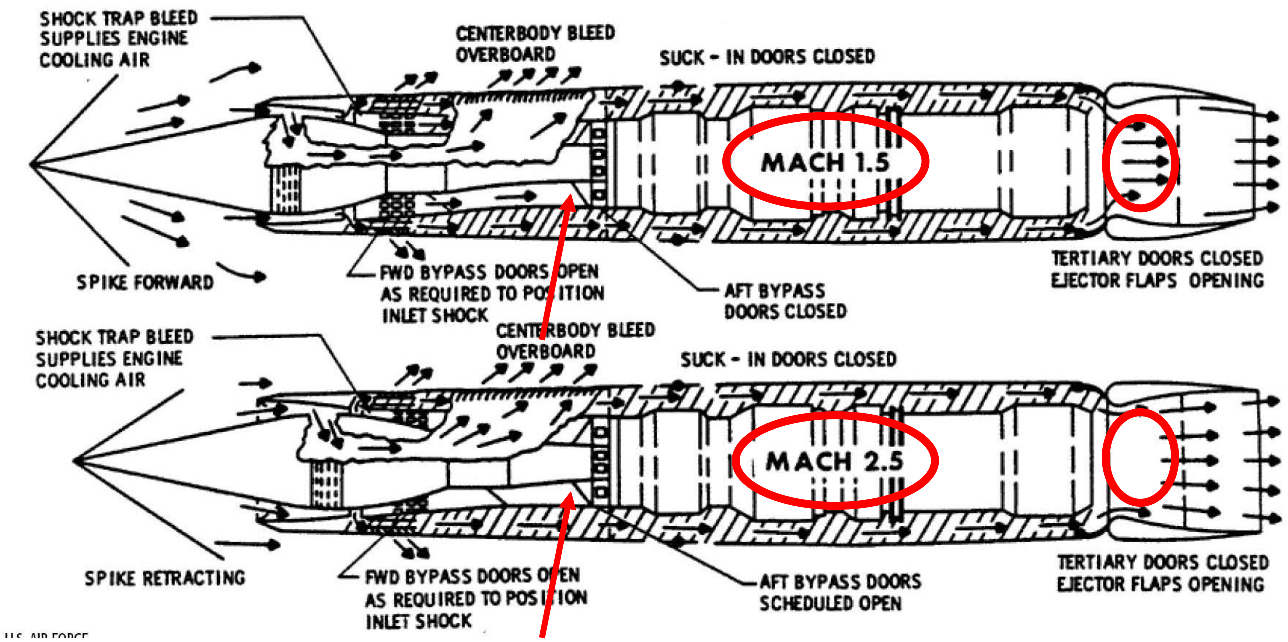
- Ramjet analysis:
  - Must analyze effect of shocks at inlet (see compressible flows)
  - Otherwise, exactly the same as for supersonic turbojet with afterburner, except that the core is completely skipped
  - $p_{t5} = p_{t2}$
  - $T_{t5} = T_{t2}$

Ramjets

- Advantages
  - Few moving parts (simpler and lighter)
  - More efficient at very high speeds
    - No need to cool a turbine!!!
- Disadvantages
  - Very inefficient at low flight speeds (very little compression)
  - Zero thrust at zero flight speed
    - Take-off thrust must come from somewhere else
- Applications
  - Missiles (with rocket assist) and…

Ramjets

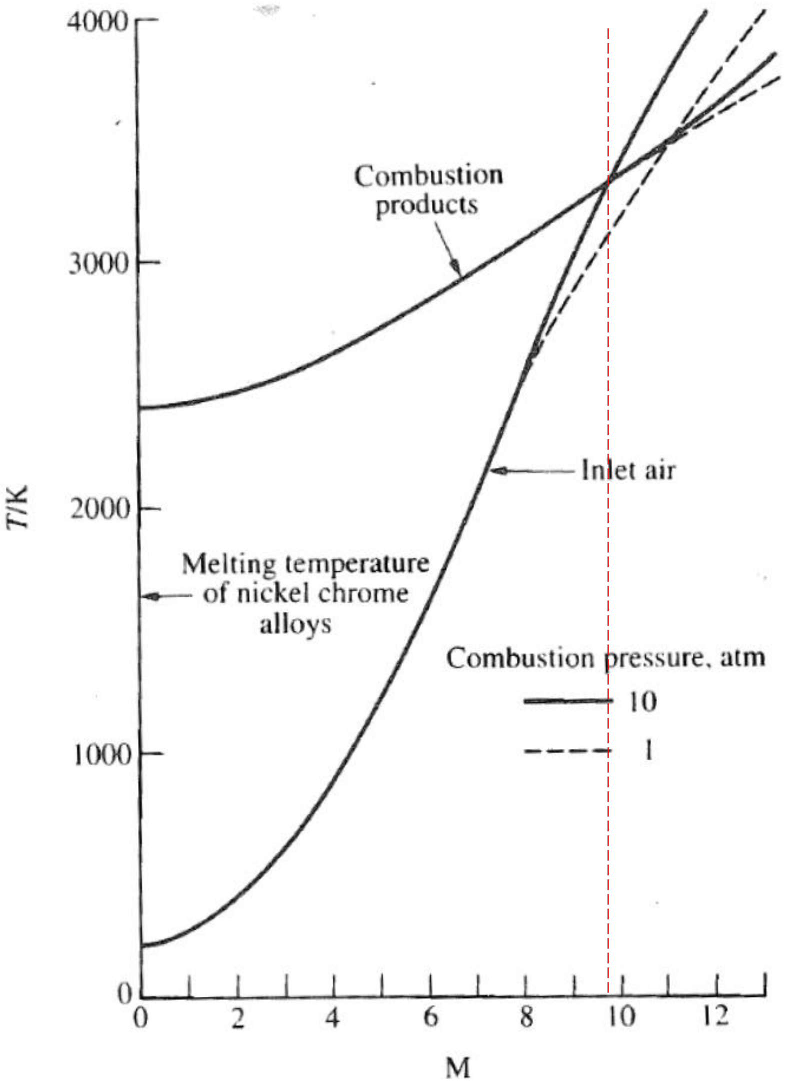
- Back to the SR-71 (and PW J58)
  - The J58 is a combination of turbojet/ramjet
  - At low flight speed, flow goes through core
    - Typical turbojet
  - At high flight speed, flow bypasses the core
    - Only goes through afterburner and nozzle
    - Acts as a ramjet



Youtube: The Mighty J58 - The SR-71's Secret Powerhouse

Scramjets

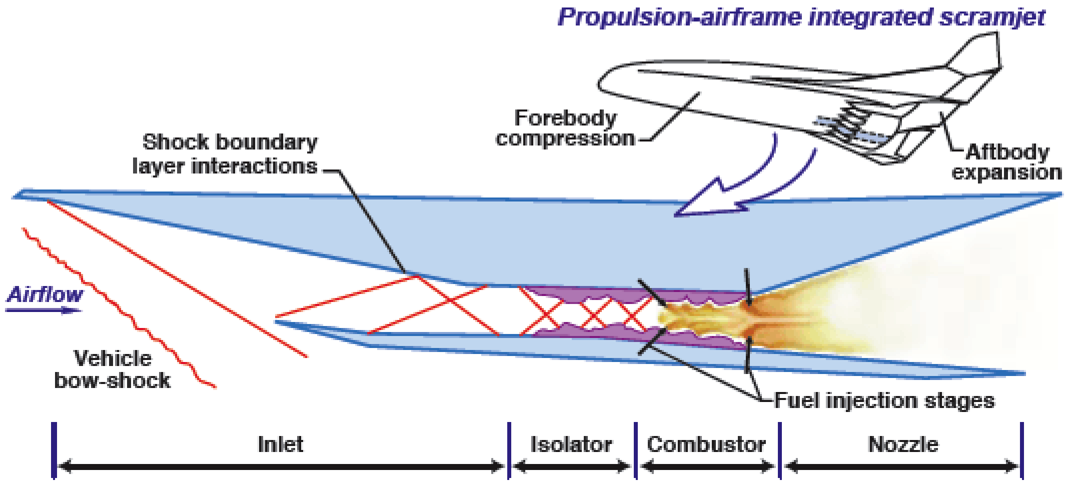
- Hypersonic Propulsion
  - What happens if we go even faster?
    - Large stagnation losses through inlet
    - Assuming we slow the flow down, combustion becomes **endothermic**
      - Energy input is required to burn fuel
  - For hypersonic flight ($M > 5$), combustion of decelerated flow does not really provide energy to engine
  - Can we do combustion in supersonic flow?



Temperature of gases decelerated to a certain pressure adiabatically (Jet fuel/Air)

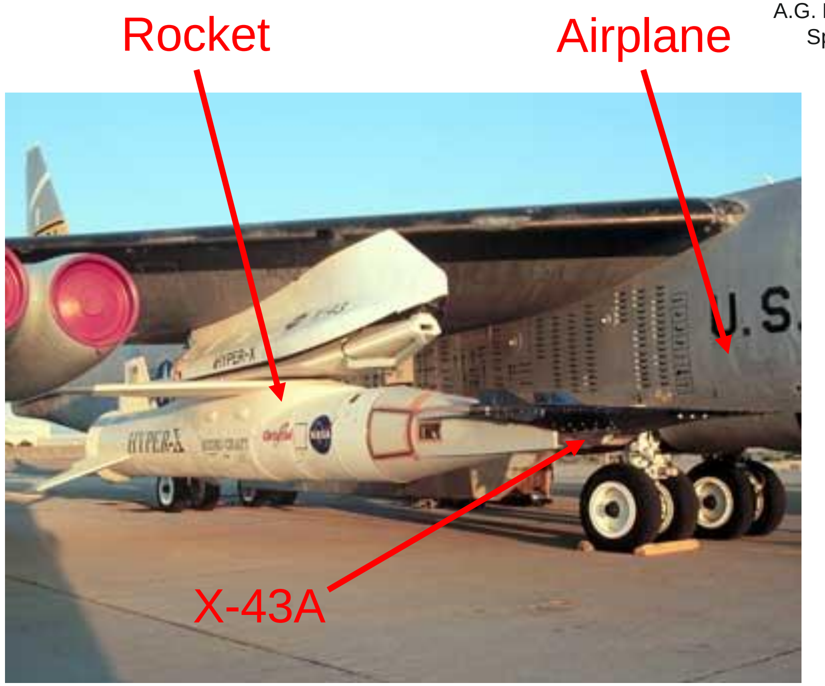
Scramjets

- Supersonic Combustion Ramjets
  - No normal shock is present
    - Flow remains supersonic even in combustor
  - Practical Issues
    - Flame holding
      - How can the flame be stabilized at such massive flow velocities and short time scales
    - Unstart
      - Ejection of shock train and loss of compression



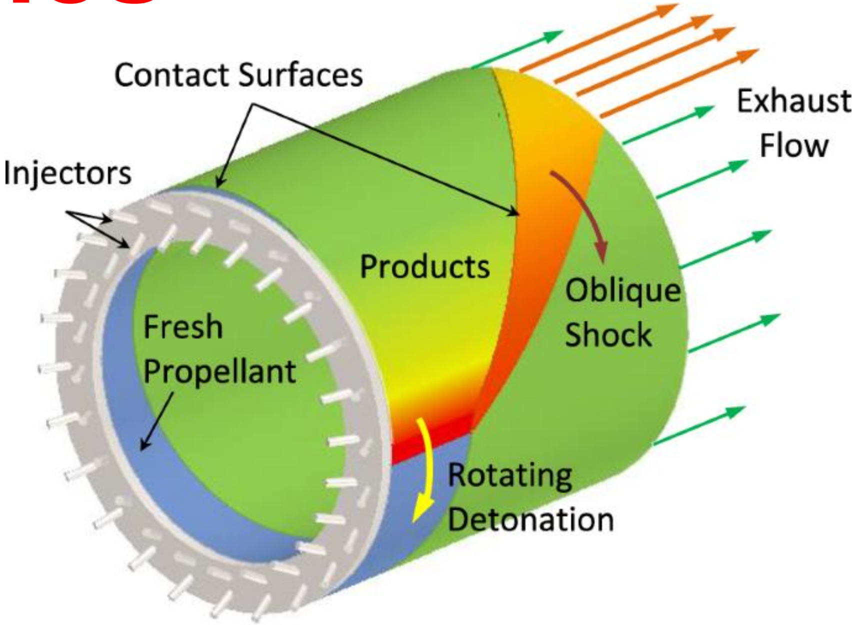
Scramjets

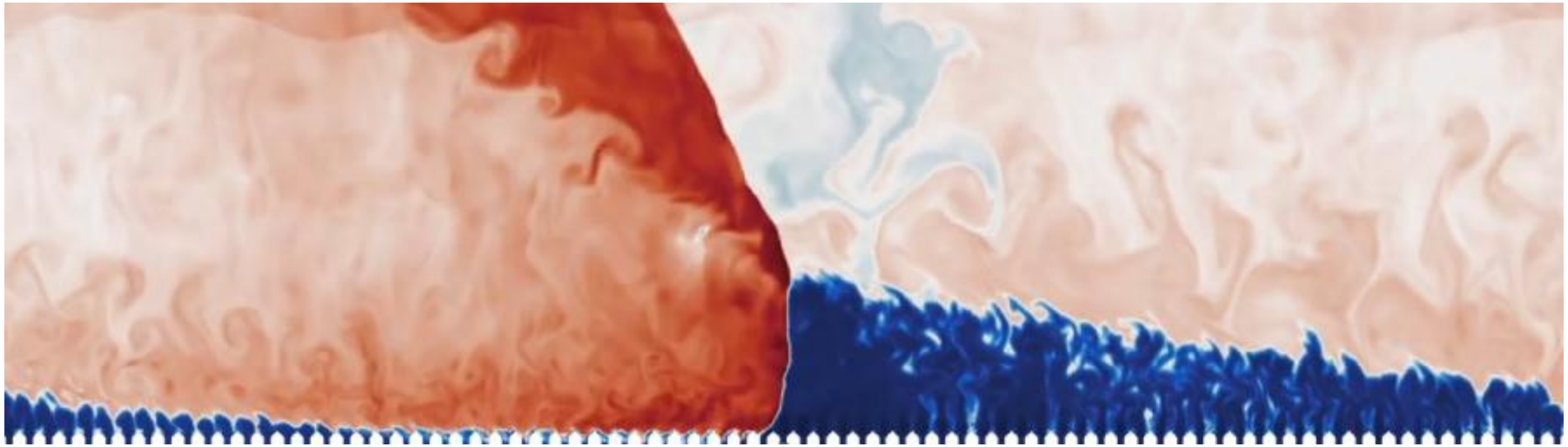
- NASA: X-43A
  - Record for highest speed air-breathing flight (November 16, 2004)
  - Mach 9.68 at 112,000 ft
    - Only flew for a few seconds
  - Mach 7 for 11 seconds
- Boeing/USAF/DARPA/NASA/UTX: X-51
  - Mach 5.1 at 60,000 feet for 210 seconds
  - Record for longest air-breathing flight over Mach 5 (May 1, 2013)



Rotating Detonation Engines

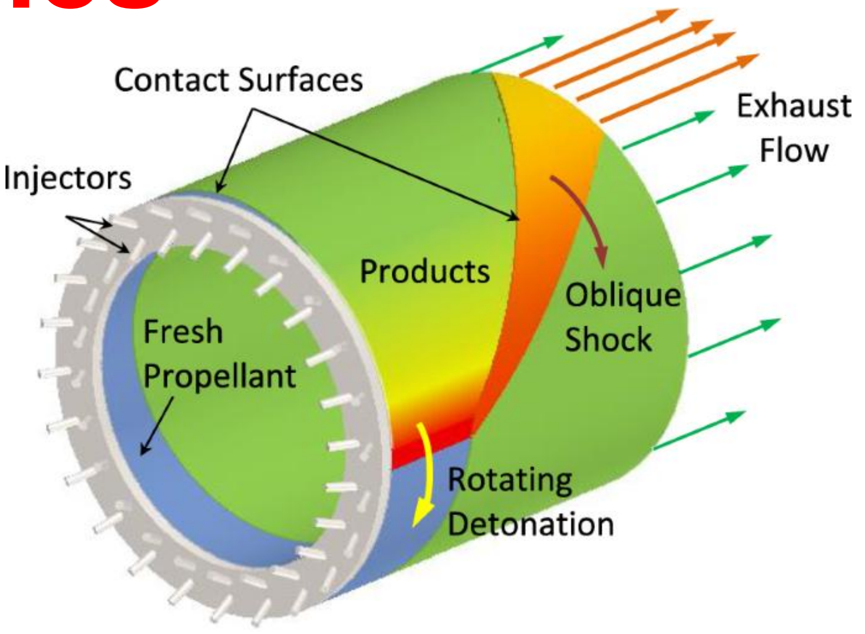
- How else can we stabilize combustion at high speeds?
- Detonations!
  - Shockwave coupled with combustion
  - High temperature after shock leads to very fast combustion





https://www.youtube.com/watch?v=7Q2d9vlWdNQ

Rotating Detonation Engines



- Pros
  - Detonations are *fast*, so can be used in very high speed flight
    - Potentially allows for hypersonics ($M > 5$)
  - In theory, up to 25% more efficient
  - Useable at very small size
  - No moving parts

- Cons
  - Very hard to actually build
  - Few actual demonstrations

https://www.youtube.com/watch?v=7Q2d9vlWdNQ