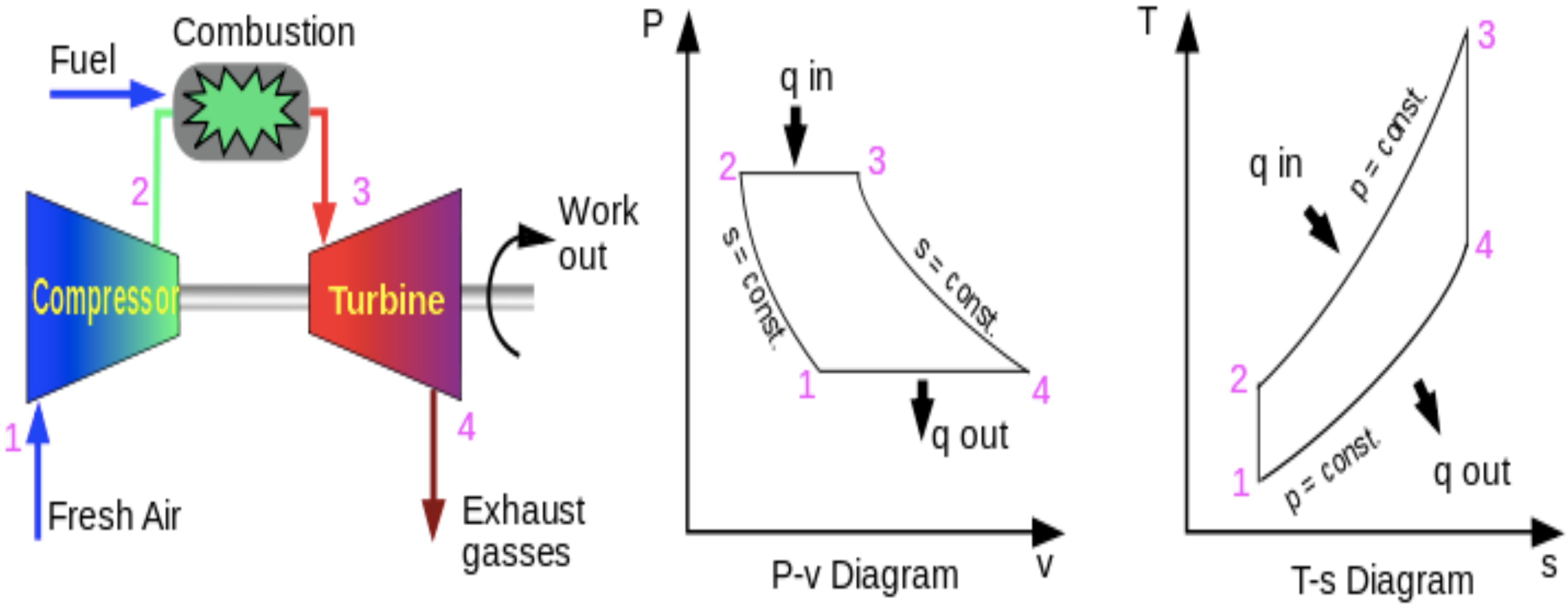
# Lecture 13

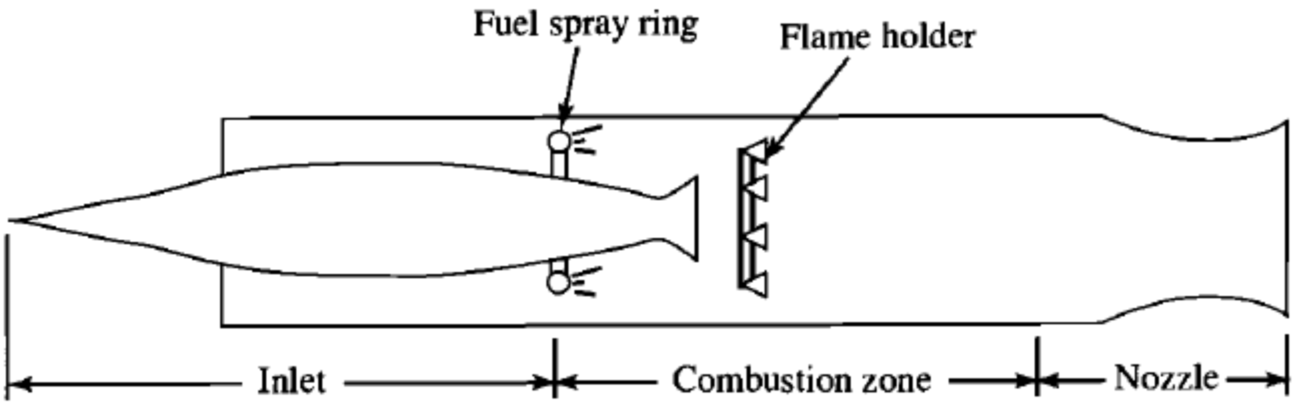
Ramjet Cycle Design

# Review: Brayton Cycle for Gas Turbines




- Ideal, no losses in compression or expansion
- Efficiency = 1 – 1/TR

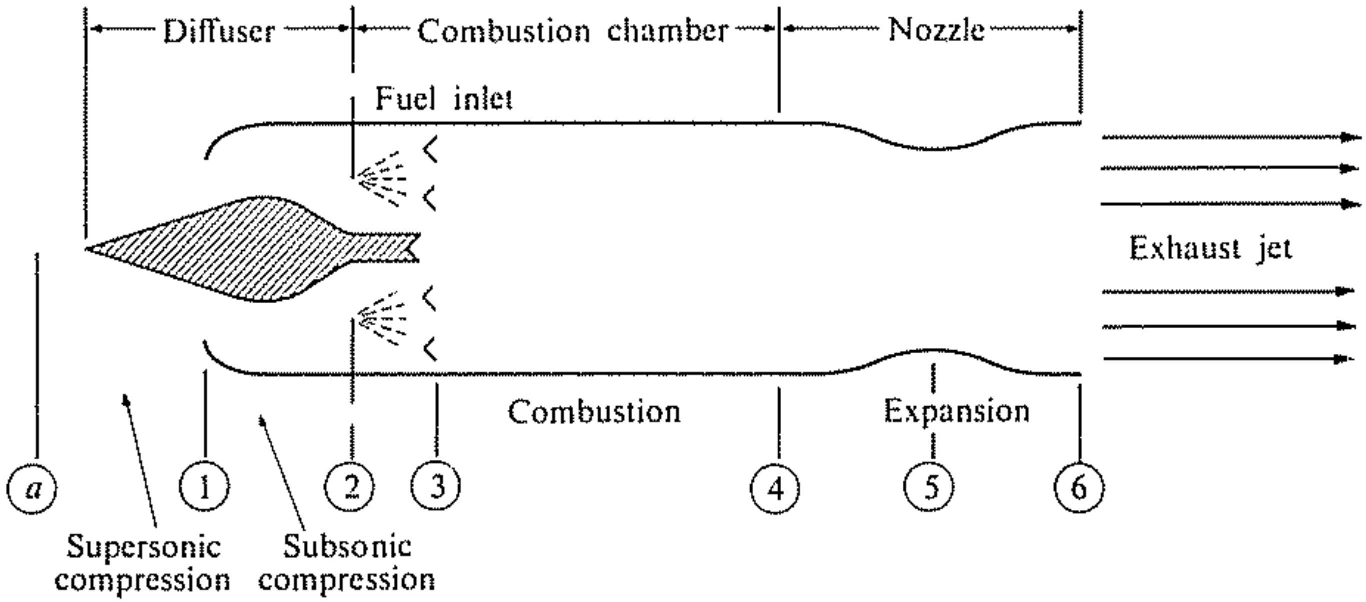
# Ramjet Cycle is the Brayton Cycle

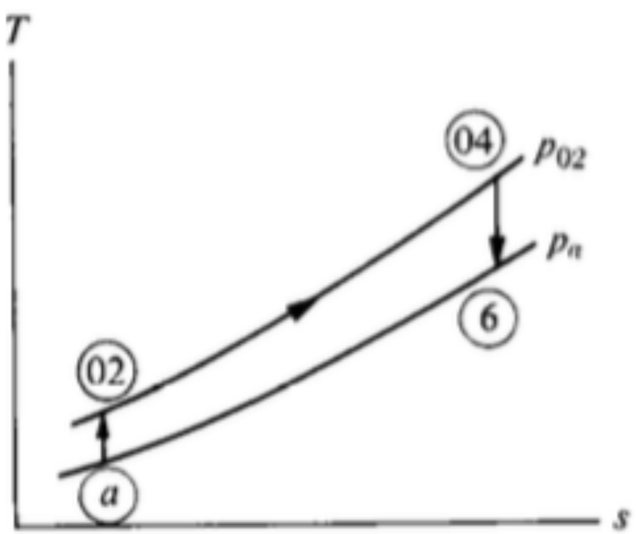



**Compression** **Heat Input** **Expansion**

- The ramjet does not have the compressor and turbine as the turbojet does.
- Air enters the inlet where it is compressed and then enters the combustion zone where it is mixed with the fuel and burned.
- The hot gases are then expelled through the nozzle, developing thrust.
- The operation of the ramjet depends on the inlet to decelerate the incoming air to raise the pressure in the combustion zone.

# Ideal Ramjet

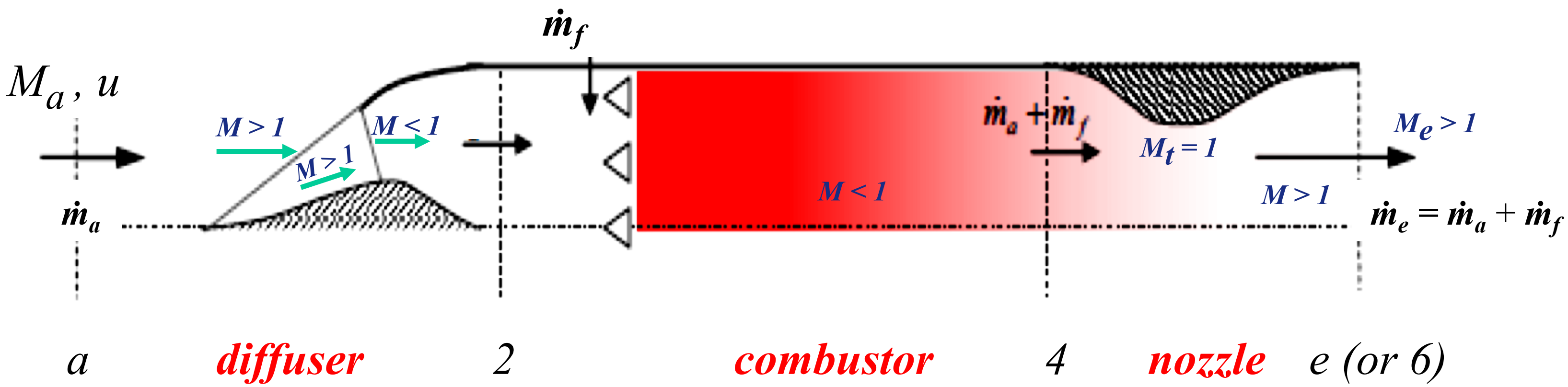



Important: Note the nomenclature change compared to the Brayton Cycle

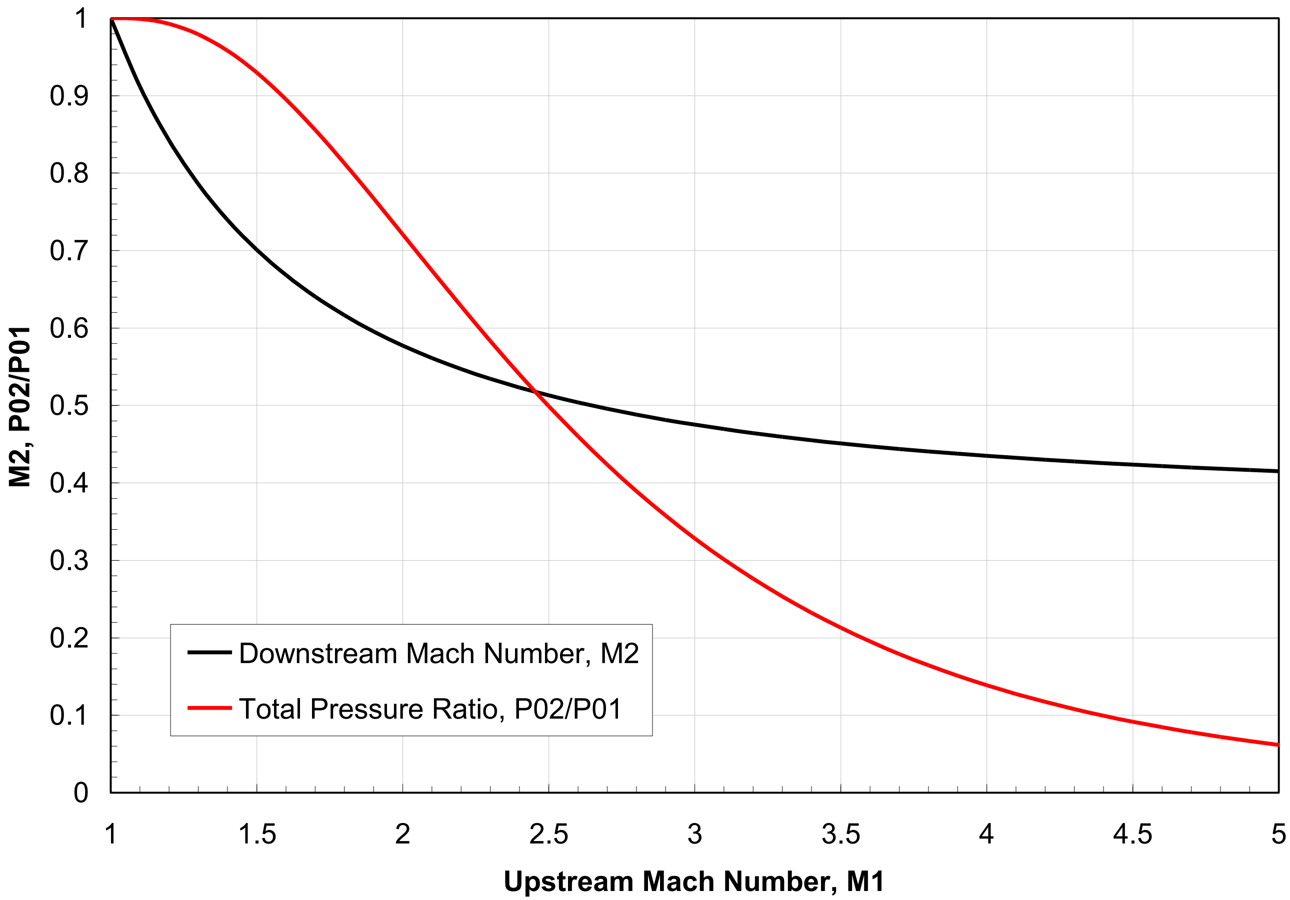
- **We are starting to look at stagnation properties**
- **Assume heat addition at near zero velocity (otherwise have to look at flow with heat addition, Rayleigh Flow**
- **Station 2 to 4 is at stagnation conditions (follow the 02, 04 terminology)**

# Ramjets : Mach Number Variation




- Non-isentropic compression and expansion: losses lead to lowered total pressure and temperature
- Define total pressure ratios before and after components to quantify the efficiency:
  - $r_d$, total pressure loss in the diffuser
  - $r_c$, total pressure loss in the combustor
  - $r_n$, total pressure loss in the nozzle

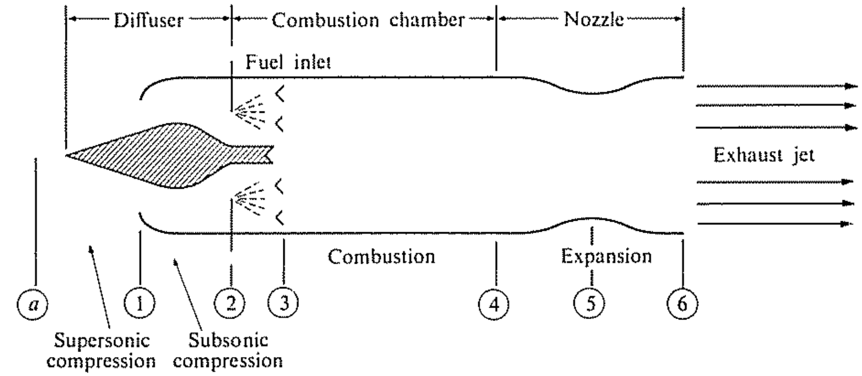
# Normal Shock Total Pressure Loss

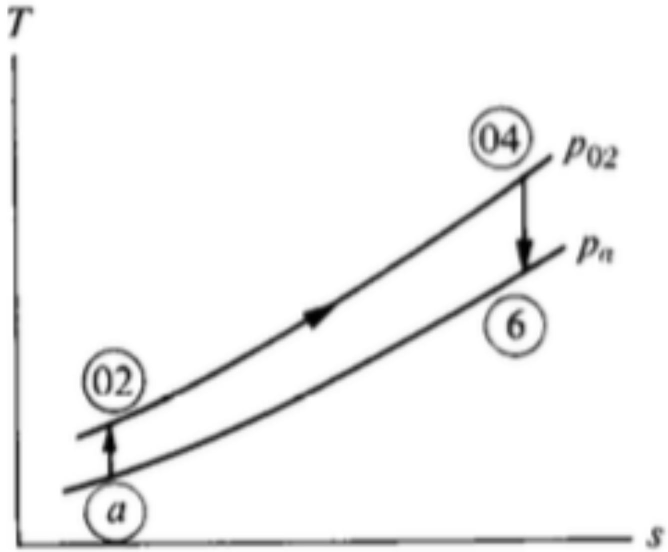



- Modern combustors desire entrance Mach numbers of around 0.2 to 0.3, so flow must be decelerated from supersonic flight speed
- Process is accomplished much more efficiently (less total pressure loss) by using series of multiple oblique shocks, rather than a single normal shock wave

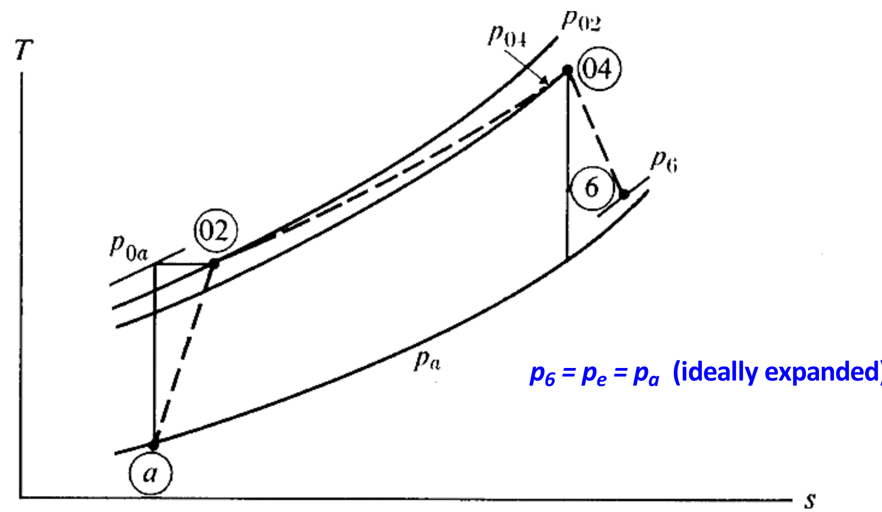
- As $M_1 \uparrow$ $p_{02}/p_{01} \downarrow$ very rapidly
- Total pressure is indicator of how much useful work can be done by a flow
  - Higher $p_0 \rightarrow$ more useful work extracted from flow
- Loss of total pressure is a measure of efficiency of flow process

# T-S Diagrams




Ideal Ramjet




Ramjet with losses

$P_{06} = P_{04} = P_{02} = P_{0a}$

$P_{06} < P_{04} < P_{02} < P_{0a}$

$r_d$, total pressure loss in the diffuser = $P_{02}/P_{0a}$
$r_c$, total pressure loss in the combustor = $P_{04}/P_{02}$
$r_n$, total pressure loss in the nozzle = $P_{06}/P_{04}$

Therefore, $P_{06}/P_{0a} = P_{06}/P_{04} \times P_{04}/P_{02} \times P_{02}/P_{0a}$

# Non-ideal Ramjet Performance

The overall stagnation pressure ratio is therefore

$$\frac{p_{06}}{p_{0a}} = r_d r_c r_n .$$

From isentropic stagnation to static relationships

$P_{06}/P_6 = [\ 1 + (\gamma - 1)\ M_e^2/2\ ]^{\ (\gamma - 1/\gamma)}$ $P_{0a}/P_a = [\ 1 + (\gamma - 1)\ M^2/2\ ]^{\ (\gamma - 1/\gamma)}$

$$M_e^2 = \frac{2}{\gamma - 1}\left[\left(1 + \frac{\gamma - 1}{2}M^2\right)\left(\frac{p_{06}}{p_{0a}}\frac{p_a}{p_e}\right)^{(\gamma-1)/\gamma} - 1\right]$$

Thus, in terms of the component stagnation pressure ratios,

$$M_e^2 = \frac{2}{\gamma - 1}\left[\left(1 + \frac{\gamma - 1}{2}M^2\right)\left(r_d r_c r_n \frac{p_a}{p_e}\right)^{(\gamma-1)/\gamma} - 1\right].$$

From energy balance across combustor (refer Ideal Ramjet lecture). Also, adding a parameter for combustion efficiency, different from $r_c$ which is due the aerodynamic losses in the combustor

$$f = \frac{(T_{04}/T_{0a}) - 1}{(\eta_b Q_R/c_p T_{0a}) - (T_{04}/T_{0a})},$$

# Non-ideal Ramjet Performance

$$\frac{\mathcal{T}}{\dot{m}_a} = [(1 + f)u_e - u] + \frac{1}{\dot{m}_a}(p_e - p_a)A_e$$

$$\frac{\mathcal{T}}{\dot{m}_a} = (1 + f)\sqrt{\frac{2\gamma R T_{04}(m - 1)}{(\gamma - 1)m}} - \mathrm{M}\sqrt{\gamma R T_a} + \frac{p_e A_e}{\dot{m}_a}\left(1 - \frac{p_a}{p_e}\right),$$

in which

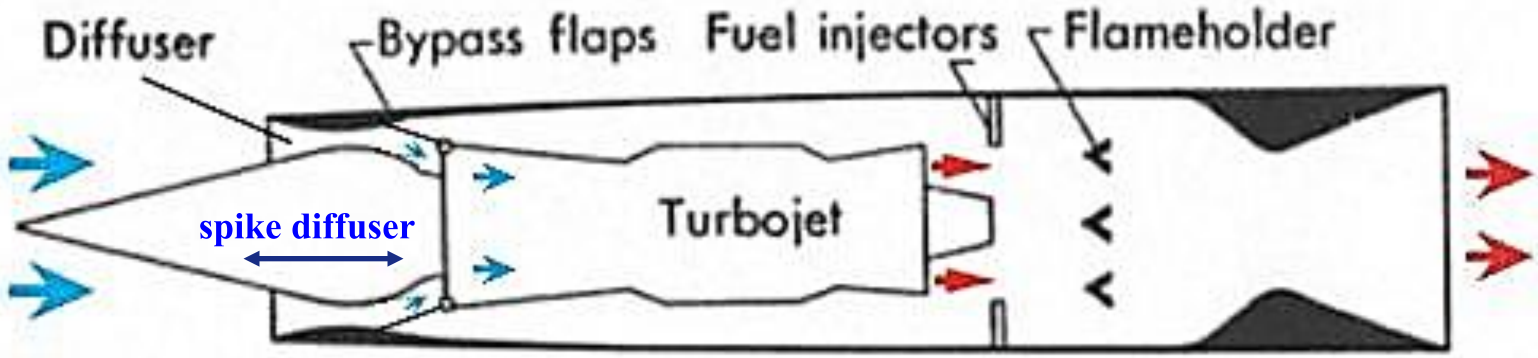
$$m = \left(1 + \frac{\gamma - 1}{2}\mathrm{M}^2\right)\left(r_d r_c r_n \frac{p_a}{p_e}\right)^{(\gamma-1)/\gamma}.$$

$$f = \frac{(T_{04}/T_{0a}) - 1}{(\eta_b Q_R/c_p T_{0a}) - (T_{04}/T_{0a})},$$

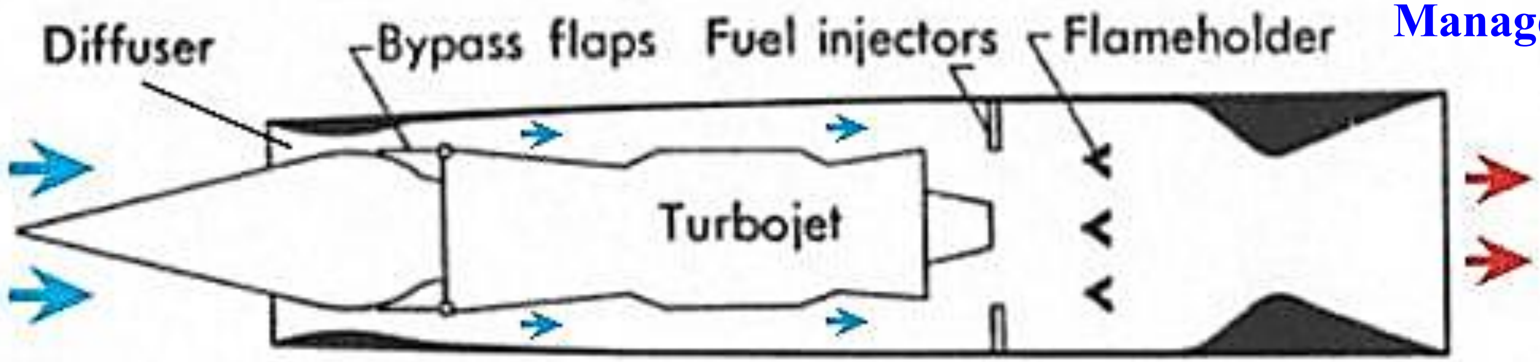
# Ramjet Summary

- A ramjet develops no static thrust
- Uses "ram compression"; requires high speed flight;
  flight performance limited by pressure ratio;
  pressure ratio limited by flight Ma#
- Performance depends on increase in stagnation temperature across burner (combustor)
- Efficiencies (thermal, propulsive, and overall) increase with increasing flight Mach number
- Next step: an engine that develops static thrust
  - put in a device to mechanically compress air (compressor)
  - put in a device to power compressor (turbine)
- Result: Turbo-Ramjet

# Turbo-Ramjet



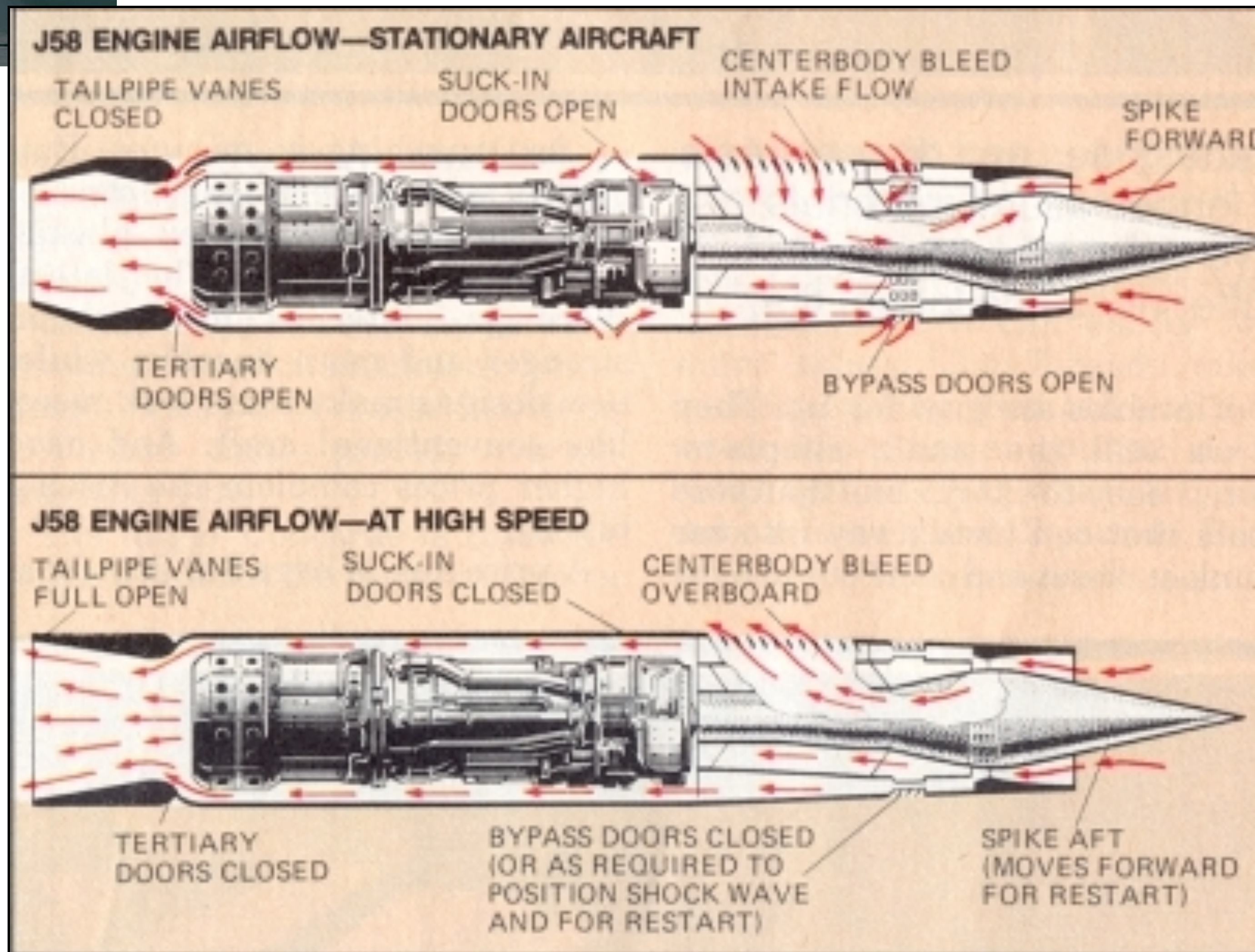

a) Bypass flaps allow flow into turbojet




b) Bypass flaps block flow into turbojet during ramjet mode

**It's all about Air Management!**

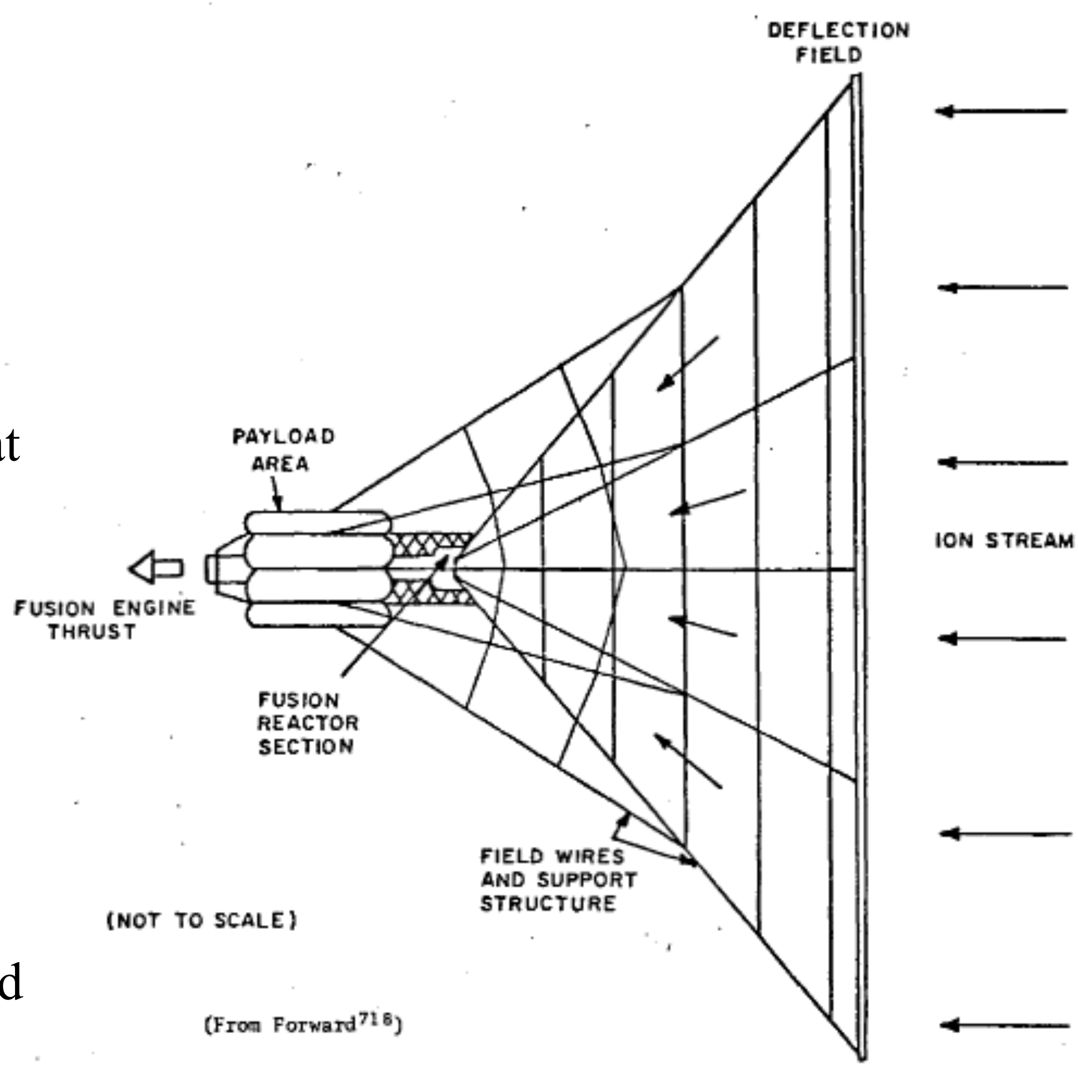
# J58 SR-71 Engine: Ramjet/Turbojet Hybrid Engine




http://aerostories.free.fr/technique/J58/J58_01/page8.html

# Interstellar Ramjet: 'Hydrogen Breathing Engine'

- In this concept, interstellar hydrogen is scooped to provide propellant mass
  - Hydrogen is ionized and then collected by an electromagnetic field
- Onset of ramjet operation is at a velocity of about 4% speed of light
- Typically, interstellar ramjets are very large systems
- A ramjet sized for a 45-year manned mission to Alpha Centauri would have a ram intake 650 km in diameter and weigh 3000 metric tons including payload



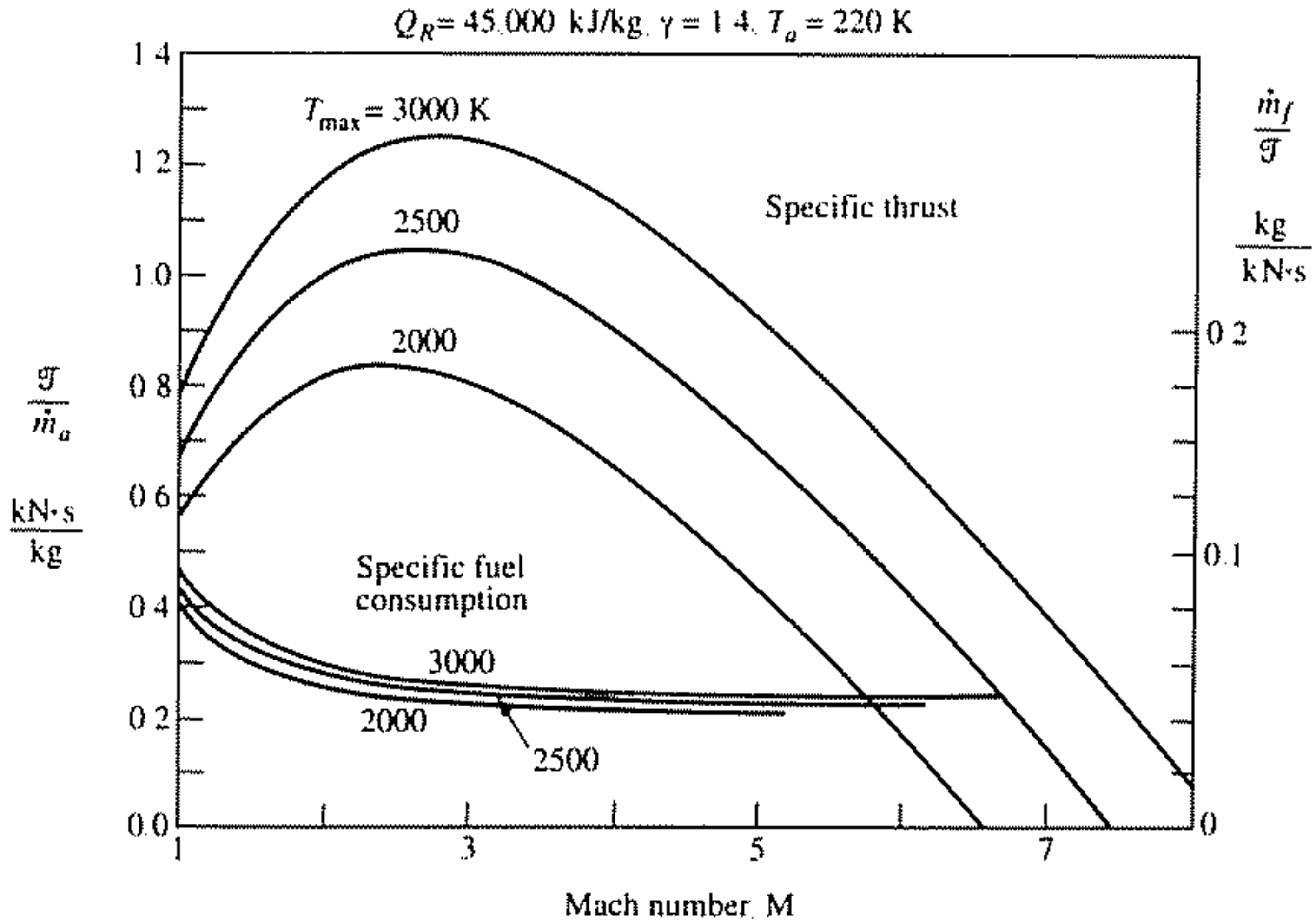

http://www.xenology.info/Xeno/17.3.3.htm

# Homework Assignment: Ramjet Analysis

- Use the equations developed (see Slide 9) to write a computer program to perform a Ramjet Analysis to plot **TSFC and Isp** as a function of different parameters – you can use Excel, Matlab, Python or any other programming language of your choice. Label the axis and Label the plots. Explain briefly what you see in the plots.

1. Plot TSFC and Isp vs M, from 1.5 to 4.5 in steps of 0.25
   - Set all inefficiencies to 1.
   - Incoming static temperature = 220K.
   - T04 (Tmax) = 3400K
   - Perfectly expanded nozzle, so pa=pe
   - Heat of combustion, Qr = 45 MJ/kg/K
   - Cp = 1005 J/kg/K, R = 287 J/kg/K, $\gamma$ = 1.4
2. Plot TSFC and Isp vs $T_{04}$ (i.e., maximum allowable temperature at the exit of the combustor), vary from 1000K to 4000K in steps of 200K.
   - Set all inefficiencies to 1.
   - Incoming static temperature = 220K.
   - Perfectly expanded nozzle, so pa=pe
   - Heat of combustion, Qr = 45 MJ/kg/K
   - Cp = 1005 J/kg/K, R = 287 J/kg/K, $\gamma$ = 1.4
   - incoming Mach number of 3
3. Plot TSFC and Isp vs $r_d$, and $\eta_b$ individually by varying them one at a time from 0.6 to 1 (in steps of 0.1). Hold the other inefficiencies at 1. For example, if you are looking at the effect of $r_d$, make all other at 1 and vary $r_d$ from 0.6 to 1.
   - incoming Mach number of 3.
   - perfectly expanded nozzle, so pa=pe
   - T04 (Tmax) < 3400K
   - Incoming static temperature, 220K
   - Heat of combustion, Qr = 45 MJ/kg/K
   - Cp = 1005 J/kg/K, R = 287 J/kg/K, g = 1.4

# Thrust and TSFC Performance Summary




- Ramjet performance parameters vs. flight Mach number
- Specific thrust has peak value for set $T_{max}$ and Ta
- Specific thrust increases as maximum allowable combustor exit temperature increases
- Specific fuel consumption decreases with increasing flight Mach number

# Thrust per unit Mass and Efficiency Summary

- Ramjet performance parameters vs. flight Mach number
- Specific thrust has peak value for set $T_{max}$ and Ta. Peak is around Mach 2.5
- Propulsive, thermal and overall efficiencies increase continually with increasing Flight Mach number