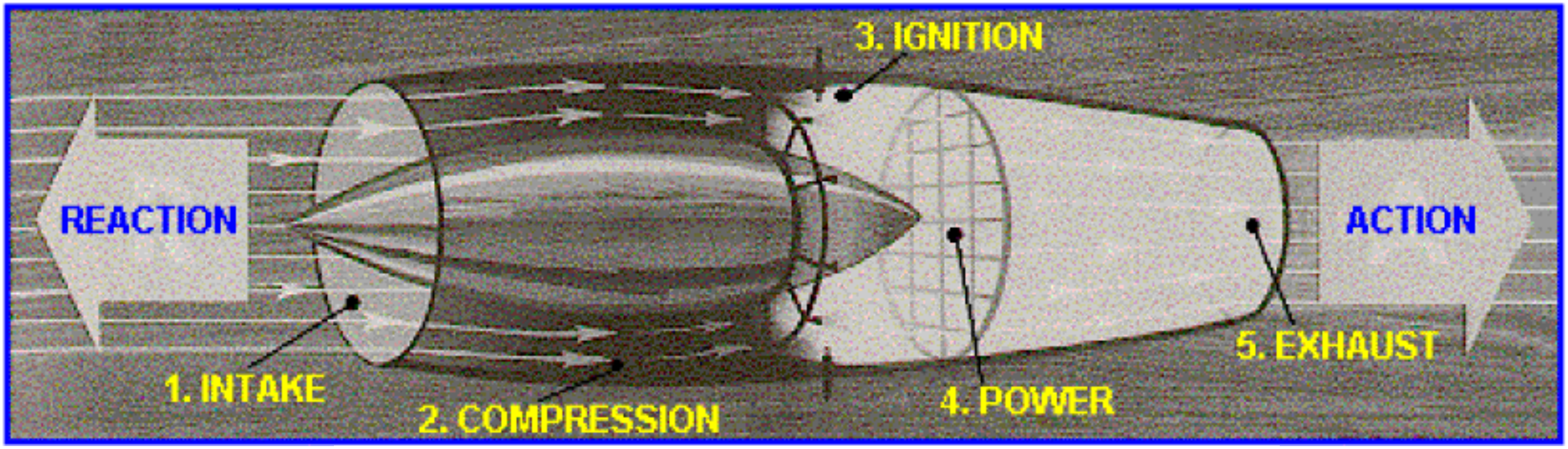
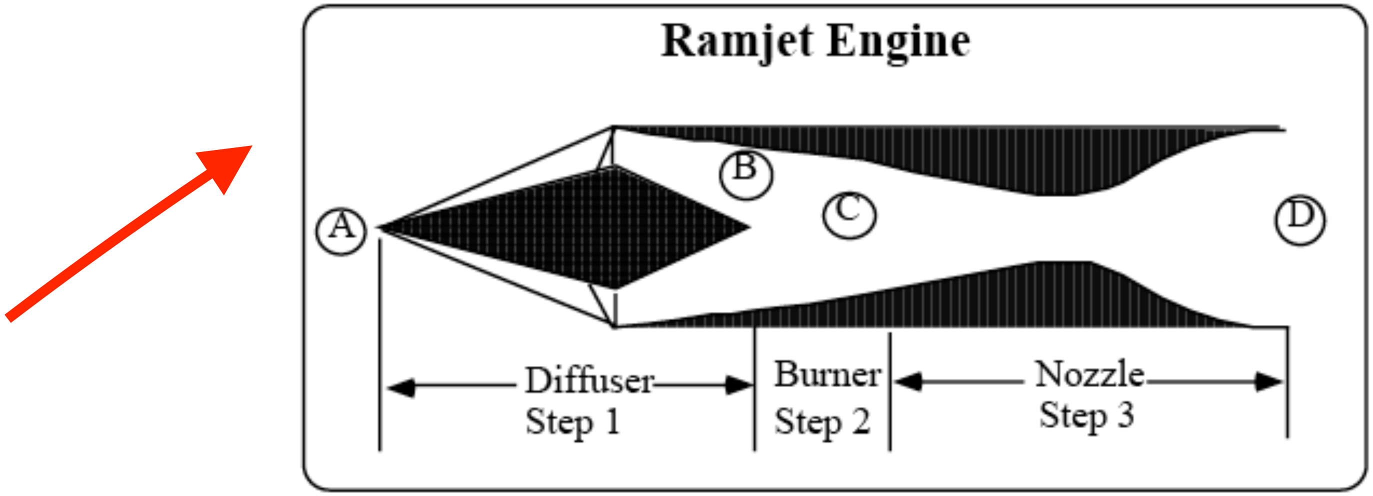
Section 4.3: The RamJet Propulsion Cycle

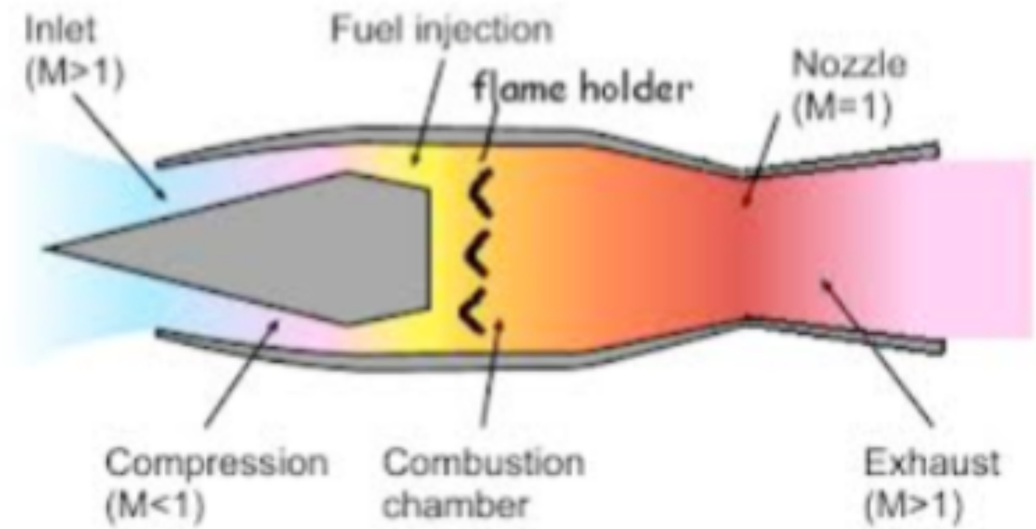




Background on RamJets

• Ramjets are a very simple jet engine configuration that are capable of high speeds

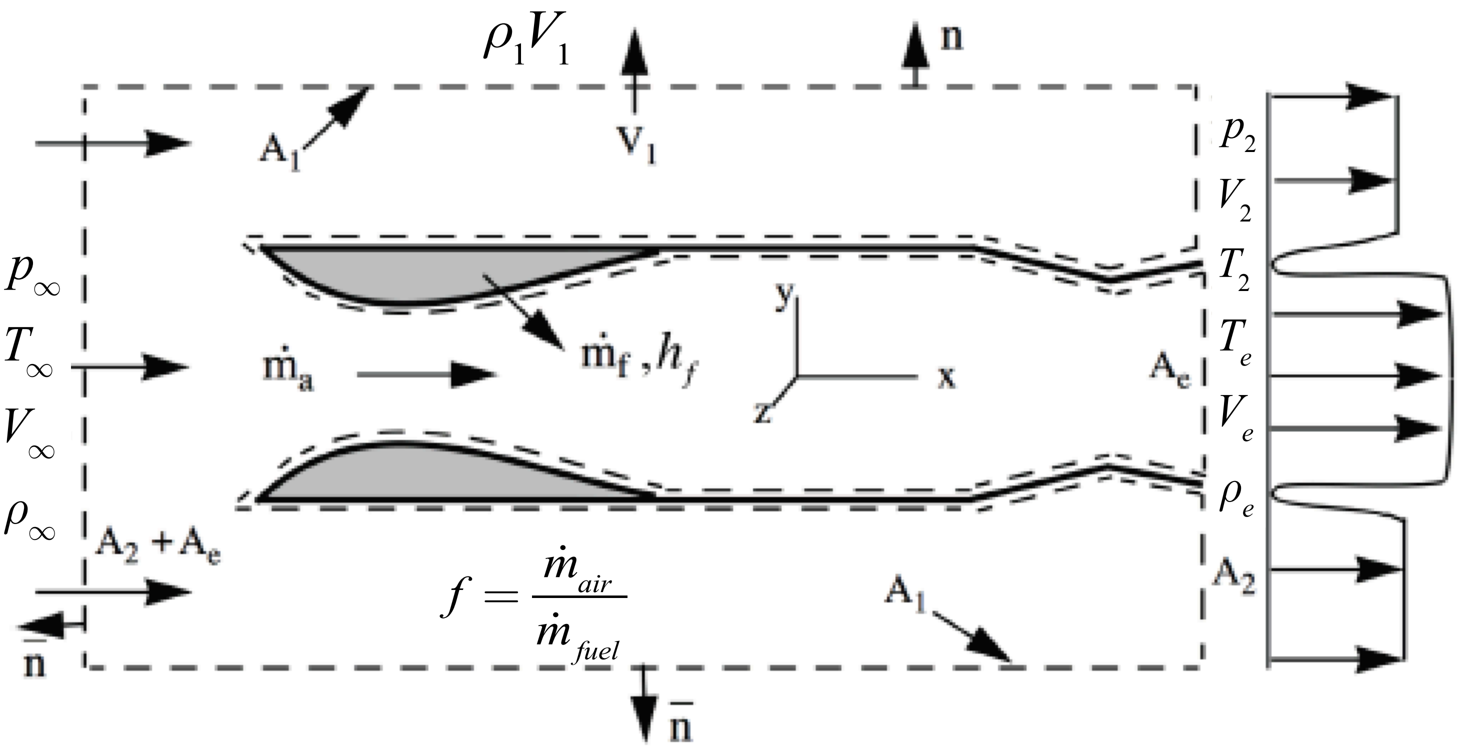
• Ramjets cannot produce thrust at zero airspeed; they cannot move an aircraft from a standstill.



• A ramjet powered vehicle, therefore, requires an assisted take-off like a rocket assist to accelerate it to a speed where it begins to produce thrust.

• Inherently constrained to "combined cycle" applications for flight

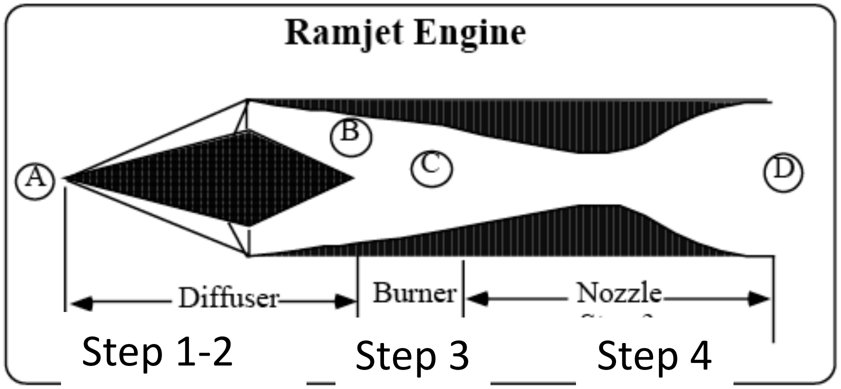
Control Volume for a Ramjet



$$F_{thrust} = \frac{\left(\dot{m}_{air} + \dot{m}_{fuel}\right)\cdot V_{exit} - \left(\dot{m}_{air}\right)\cdot V_{\infty} + A_{exit}\cdot\left(p_{exit} - p_{\infty}\right)}{p_{\infty}\cdot A_0} =$$

$$F_{thrust} = \dot{m}_{air}\cdot V_{\infty}\left[\left(\frac{f+1}{f}\right)\cdot\frac{V_{exit}}{V_{\infty}} - 1\right] + \frac{A_{exit}}{A_0}\cdot\left(\frac{p_{exit}}{p_{\infty}} - 1\right)$$

Ideal Ramjet Thermodynamic Cycle Analysis



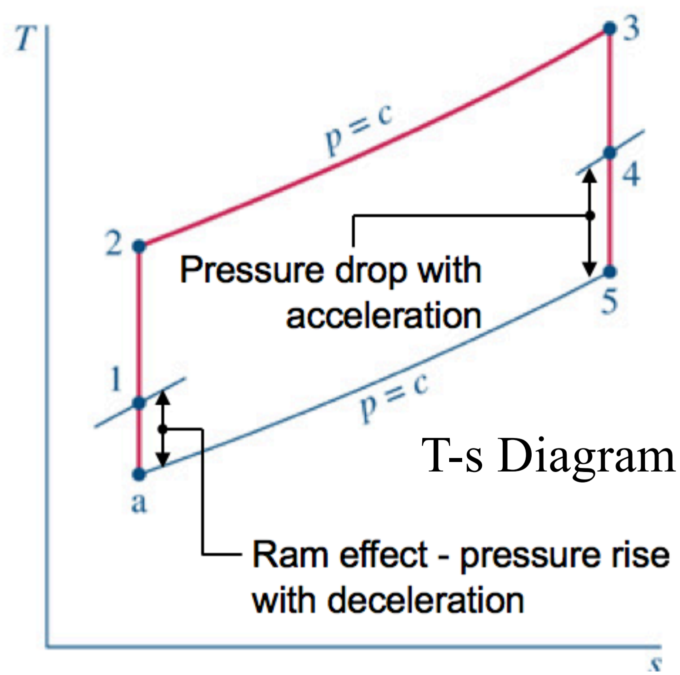
Region	Process	Ideal Behavior	Real Behavior
A to 1(inlet)	Isentropic flow	P_0,T_0 constant	P_0 drop
∞-1-2 (diffuser)	Adiabatic Compression	P,T increase P_0 drop	P_0 drop
2-3 (burner)	Heat Addition	P_0 constant, T_0 s Increase $\Delta s = \left(\frac{\Delta q}{T}\right)_{rev} > 0$	P_0 drop
3-4 (nozzle)	Isentropic expansion	T_0,P_0 constant $\Delta s > \Delta s_{rev}$	s Increase T_0 drop

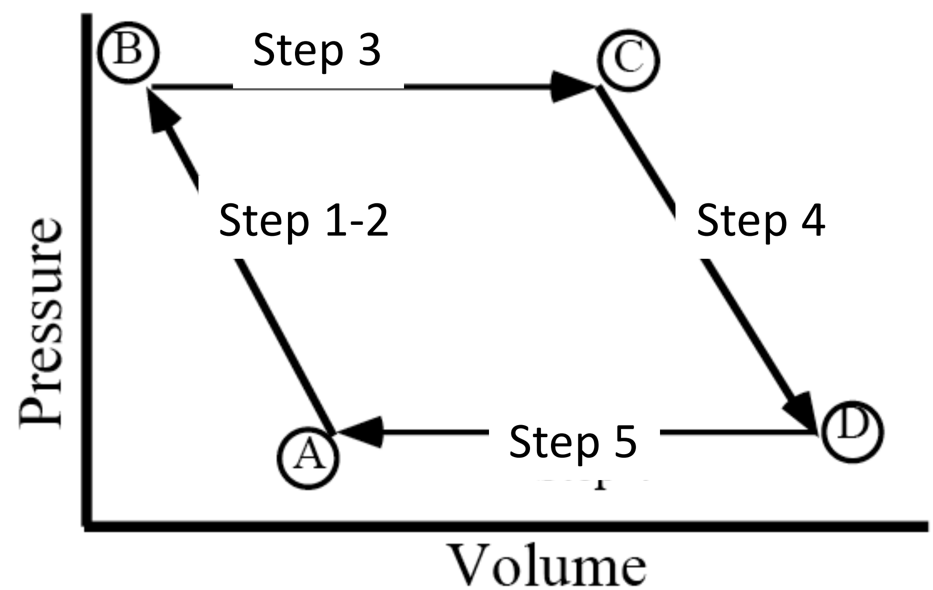
UtahState UNIVERSITY

Mechanical & Aerospace Engineering

Ideal Ramjet Cycle Analysis (2)

Step	Process
1) Intake *(suck)*	Isentropic Compression
2) Compress the Air *(squeeze)*	Adiabatic Compression
3) Add heat *(bang)*	Constant Pressure Combustion
4) Extract work *(blow)*	Isentropic Expansion in Nozzle
5) Exhaust	Heat extraction by surroundings





Cycle Efficiency of Ideal Ramjet

$$\eta_{propulsive} \times \eta_{\sout{propulsive}\ \text{thermal}} =$$

$$\frac{\dot{W}_p}{\left(K.E._{exit} - K.E._{\infty}\right)} \times \frac{\left(K.E._{exit} - K.E._{\infty}\right)}{\dot{m}_{fuel} \cdot h_{fuel}} = \frac{\dot{W}_p}{\dot{m}_{fuel} \cdot h_{fuel}}$$

6

- Propulsive Power Output--> work perform by system in step 4 minus work required for step 1-2

- Net Heat Input --> heat input during step 3 (combustion) - heat lost in exhaust plume

Cycle Efficiency of Ideal Ramjet (2)

$$\frac{Net\ Power}{\dot{m}_{air}} = \left(h_A - h_B\right) + \left(\frac{f+1}{f}\right) \cdot \left(h_C - h_D\right)$$

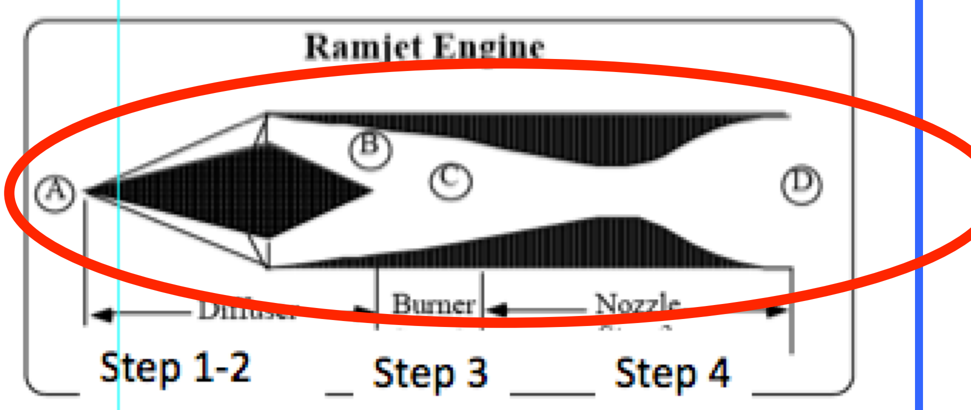
$$\frac{Net\ Heat\ Input}{\dot{m}_{air}} = \left(\frac{f+1}{f} h_C - h_B\right)$$

$$\eta_{total} = \frac{\left(\frac{Net\ \text{~~Work~~ Power}}{\dot{m}_{air}}\right)}{\left(\frac{Net\ Heat\ Input}{\dot{m}_{air}}\right)} = \frac{\left(h_A - h_B\right) + \left(\frac{f+1}{f}\right) \cdot \left(h_C - h_D\right)}{\left(\frac{f+1}{f}\right) \cdot h_C - h_B}$$

Cycle Efficiency of Ideal Ramjet (3)

Add and Subtract $\left(\frac{f+1}{f}\right)\cdot h_C - h_B$ From Right Hand Side

$$\eta_{total} = \frac{\left(h_A - h_B\right) + \left(\frac{f+1}{f}\right)\cdot\left(h_C - h_D\right)}{\left(\frac{f+1}{f}\right)\cdot h_C - h_B} =$$



$$1 + \frac{\left(h_A - h_B\right) + \left(\frac{f+1}{f}\right)\cdot\left(h_C - h_D\right) - \left[\left(\frac{f+1}{f}\right)\cdot h_C - h_B\right]}{\left(\frac{f+1}{f}\right)\cdot h_C - h_B} = 1 - \frac{\left(\frac{f+1}{f}\right)\cdot h_D - h_A}{\left(\frac{f+1}{f}\right)\cdot h_C - h_B}$$

Cycle Efficiency of Ideal Ramjet (4)

- ***Assume … calorically perfect gasses → h ~ Cp•T***

$$\eta_{total} = 1 - \frac{\left(\frac{f+1}{f}\right) \cdot C_{p_{products}} T_D - C_{p_{air}} T_A}{\left(\frac{f+1}{f}\right) \cdot C_{p_{products}} T_C - C_{p_{air}} TB} = 1 - \frac{T_D - \left(\frac{f}{f+1}\right)\left(\frac{C_{p\,air}}{C_{p\,products}}\right) T_A}{T_C - \left(\frac{f}{f+1}\right)\left(\frac{C_{p\,air}}{C_{p\,products}}\right) T_B}$$

- For conceptual simplicity … let … ~~$f >> 1$~~ … and … $Cp_{air} \sim Cp_{products}$

$$\eta_{total} \approx 1 - \frac{\left(T_D - \frac{C_{p\,air}}{C_{p\,products}} T_A\right)}{\left(\frac{C_{p\,air}}{C_{p\,products}} T_C - T_B\right)} = 1 - \frac{(T_D - T_A)}{(T_C - T_B)} = 1 - \frac{\left(\frac{T_D}{T_C} - \frac{T_A}{T_B}\frac{T_B}{T_C}\right)}{\left(1 - \frac{T_B}{T_C}\right)}$$

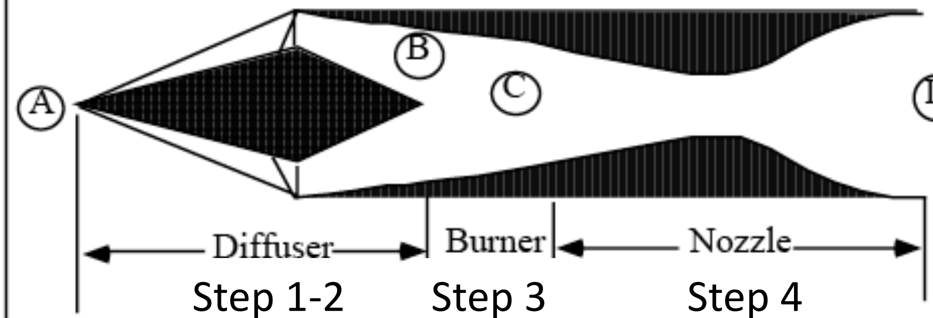
Cycle Efficiency of Ideal Ramjet (5)

- From C-->D flow is isentropic …

$$\rightarrow \frac{T_D}{T_C} = \left(\frac{P_D}{P_C}\right)^{\frac{\gamma-1}{\gamma}}$$

Ramjet Engine

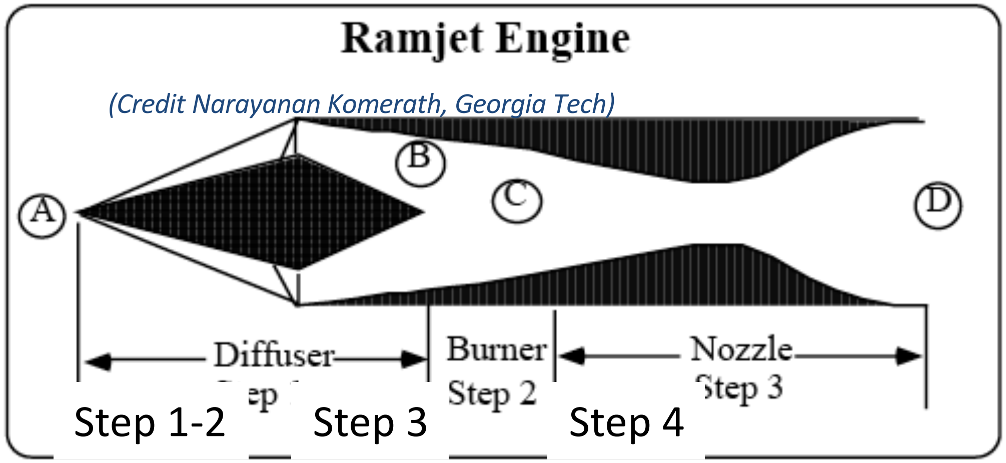
(Credit Narayanan Komerath, Georgia Tech)



$$\eta_{total} = 1 - \frac{\left(\frac{T_D}{T_C} - \frac{T_A}{T_B}\frac{T_B}{T_C}\right)}{\left(1 - \frac{T_B}{T_C}\right)} = 1 - \frac{\left(\left(\frac{P_D}{P_C}\right)^{\frac{\gamma-1}{\gamma}} - \frac{T_A}{T_B}\frac{T_B}{T_C}\right)}{\left(1 - \frac{T_B}{T_C}\right)}$$

Cycle Efficiency of Ideal Ramjet (6)

- Approximate as Adiabatic compression across diffuser



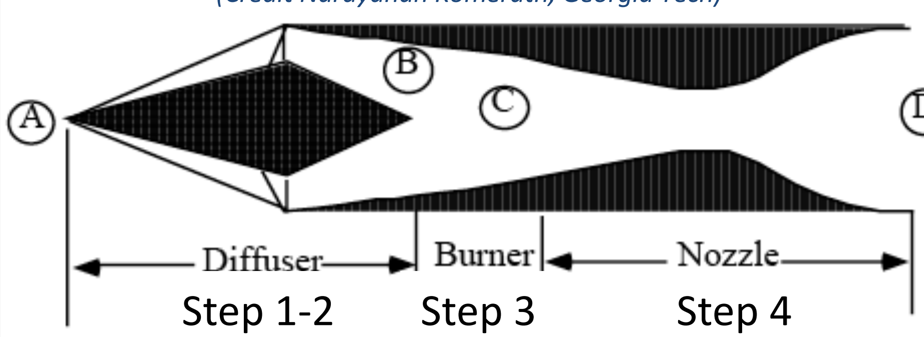
$$\left(\frac{P_A}{P_B}\right)=\left(\frac{P_A}{P_{0_A}}\times\frac{P_{0_A}}{P_{0_B}}\times\frac{P_{0_B}}{P_B}\right)=\left(\frac{T_A}{T_{0_A}}\right)^{\frac{\gamma}{\gamma-1}}\times\frac{P_{0_A}}{P_{0_B}}\times\left(\frac{T_{0_B}}{T_B}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\rightarrow T_{0_A}=T_{0_B}\rightarrow solve\ for\rightarrow\frac{T_A}{T_B}=\left(\frac{P_A}{P_B}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{P_{0_B}}{P_{0_A}}\right)^{\frac{\gamma-1}{\gamma}}$$

Cycle Efficiency of Ideal Ramjet (7)

- Sub

$$\frac{T_A}{T_B} = \left(\frac{P_A}{P_B}\right)^{\frac{\gamma-1}{\gamma}} \left(\frac{P_{0_B}}{P_{0_A}}\right)^{\frac{\gamma-1}{\gamma}}$$



into efficiency equation

$$\eta = 1 - \frac{\left(\left(\frac{P_D}{P_C}\right)^{\frac{\gamma-1}{\gamma}} - \left(\frac{P_A}{P_B}\right)^{\frac{\gamma-1}{\gamma}} \left(\frac{P_{0_B}}{P_{0_A}}\right)^{\frac{\gamma-1}{\gamma}} \frac{T_B}{T_C}\right)}{\left(1 - \frac{T_B}{T_C}\right)}$$

Cycle Efficiency of Ideal Ramjet (8)

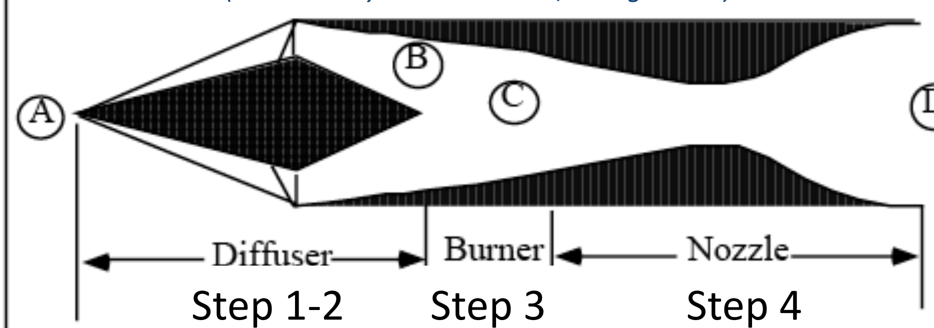
$$\text{Assume ideal nozzle} \rightarrow P_A = P_D$$

$$\text{ideal burner} \rightarrow P_B = P_C$$

Factor Out $\left(\frac{P_A}{P_B}\right)^{\frac{\gamma-1}{\gamma}}$

Ramjet Engine

(Credit Narayanan Komerath, Georgia Tech)



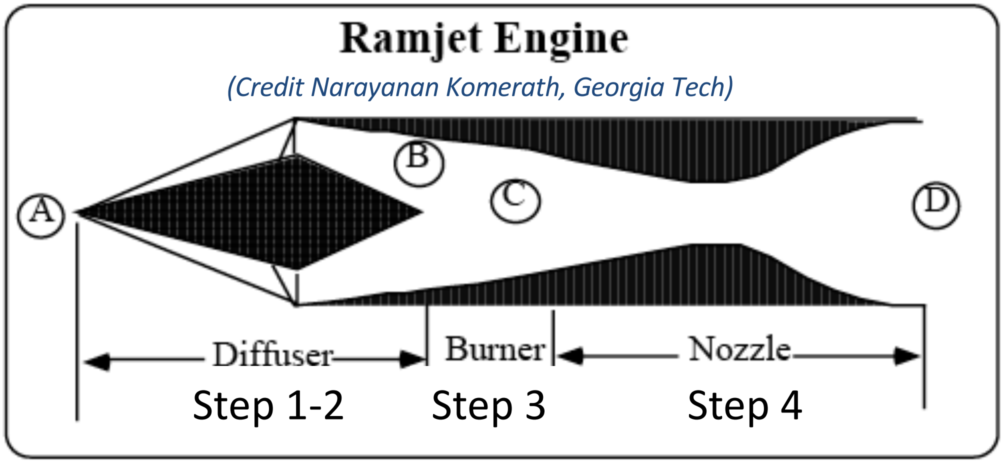
$$\eta = 1 - \left(\frac{P_A}{P_B}\right)^{\frac{\gamma-1}{\gamma}} \frac{\left(1 - \left(\frac{P_{0_B}}{P_{0_A}}\right)^{\frac{\gamma-1}{\gamma}} \frac{T_B}{T_C}\right)}{\left(1 - \frac{T_B}{T_C}\right)} = 1 - \left(\frac{P_A}{P_B}\right)^{\frac{\gamma-1}{\gamma}} \frac{\left(T_C - \left(\frac{P_{0_B}}{P_{0_A}}\right)^{\frac{\gamma-1}{\gamma}} T_B\right)}{\left(T_C - T_B\right)}$$

Utah State University

Mechanical & Aerospace Engineering

Cycle Efficiency of Ideal Ramjet (9)

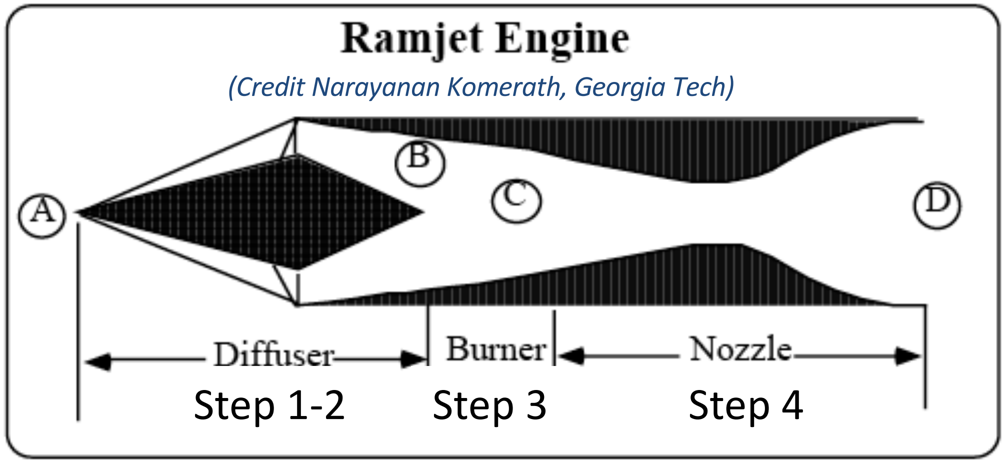
$$\eta = 1 - \left(\frac{P_A}{P_B}\right)^{\frac{\gamma-1}{\gamma}} \frac{\left(T_C - \left(\frac{P_{0_B}}{P_{0_A}}\right)^{\frac{\gamma-1}{\gamma}} T_B\right)}{\left(T_C - T_B\right)}$$



1. Cycle Efficiency Proportional to Inlet Pressure ratio, P_B/P_A
2. Cycle Efficiency Proportional to combustor temperature difference T_C-T_B
3. As inlet total pressure ratio ($P0_B/P0_A$) goes down … Cycle Efficiency Drops
4. Characteristic of a Brayton process, the cycle efficiency is anchored by the inlet compression process.

Cycle Efficiency of Ideal Ramjet (10)

$$\eta = 1 - \left(\frac{P_A}{P_B}\right)^{\frac{\gamma-1}{\gamma}} \frac{\left(T_C - \left(\frac{P_{0_B}}{P_{0_A}}\right)^{\frac{\gamma-1}{\gamma}} T_B\right)}{\left(T_C - T_B\right)}$$



1. High Inlet Compression Ratio Desirable
2. Low Stagnation Pressure Loss Desirable
3. Large Temperature Change across Combustor Desirable
4. Ramjets Cannot Start from Zero Velocity

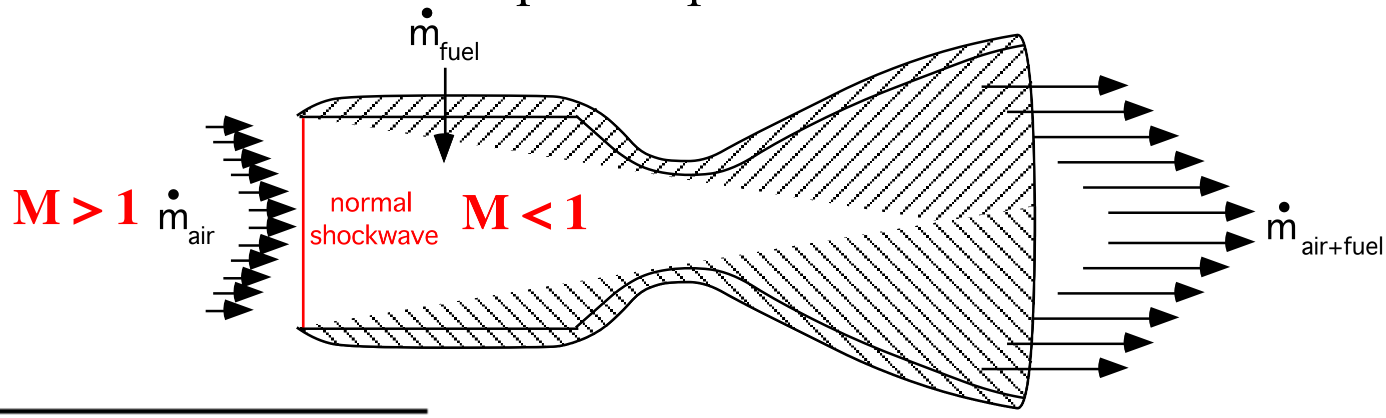
$$When\ M_\infty \to 0 \to \to \eta_{total} \to \left| 1 - \frac{\left(T_C - T_B\right)}{\left(T_C - T_B\right)} = 0 \right.$$

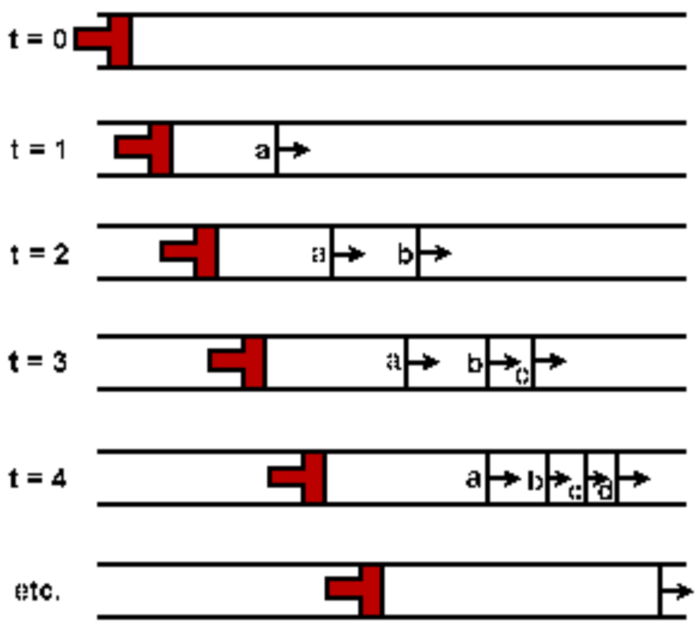
UtahState UNIVERSITY

Mechanical & Aerospace Engineering

Ideal Ramjet Example: *Inlet and Diffuser*

- Take a Rocket motor and "lop the top off"

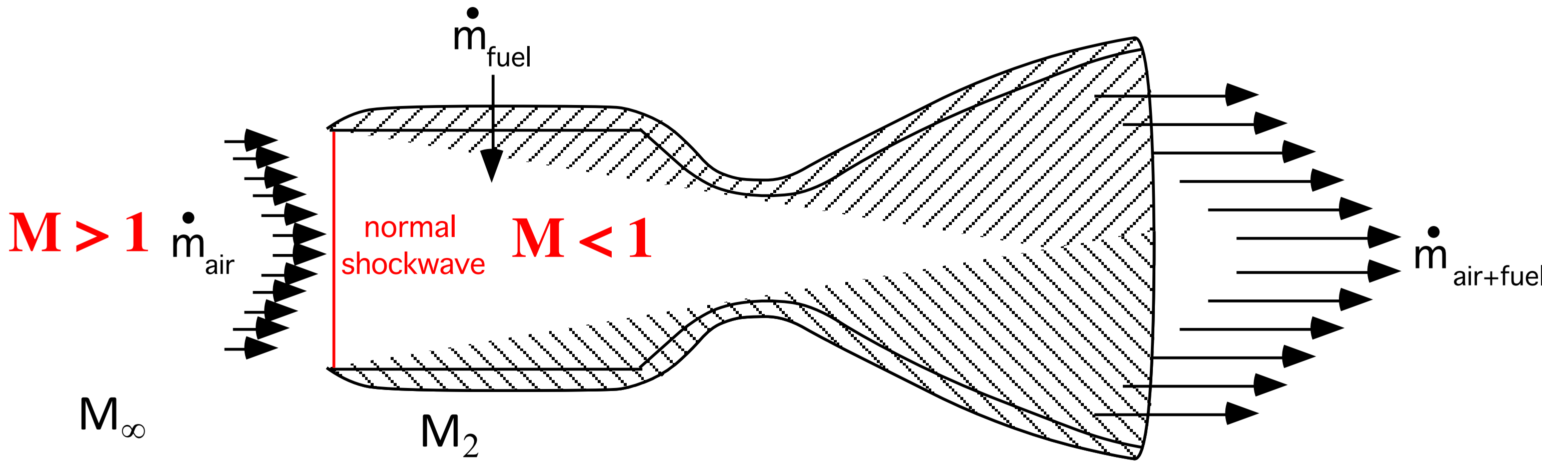




- Works Ok for subsonic, but for supersonic flow … can't cram enough air down the tube

- Result is a *normal shock wave* at the inlet lip

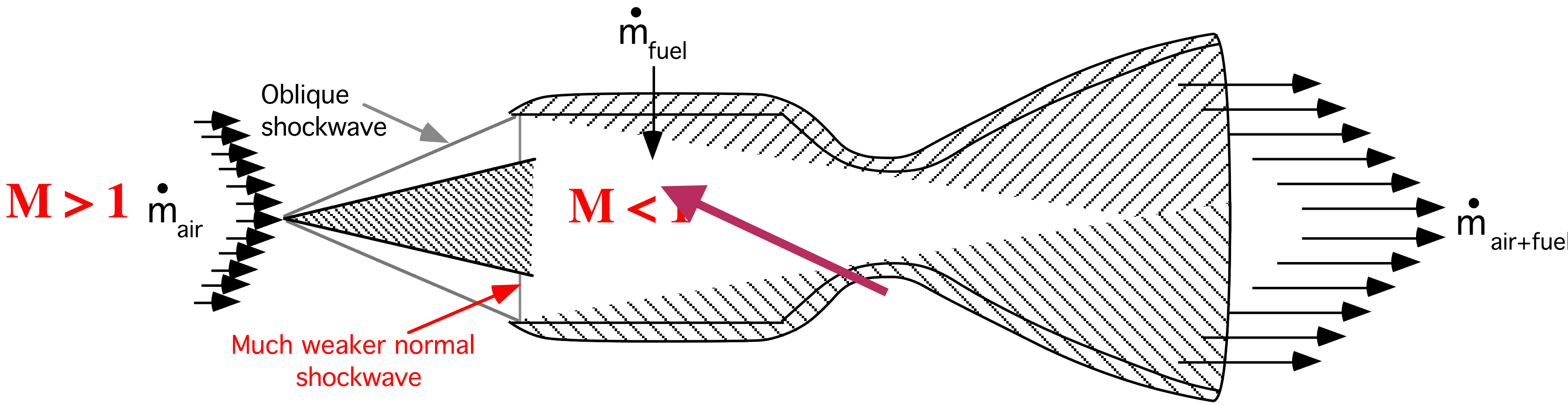
Ideal Ramjet Example: *Inlet and Diffuser (2)*

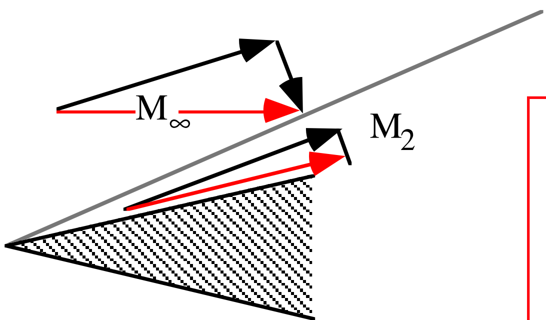


- Mechanical Energy is Dissipated into Heat
- Huge Loss in Momentum

Ideal Ramjet Example: *Inlet and Diffuser (3)*

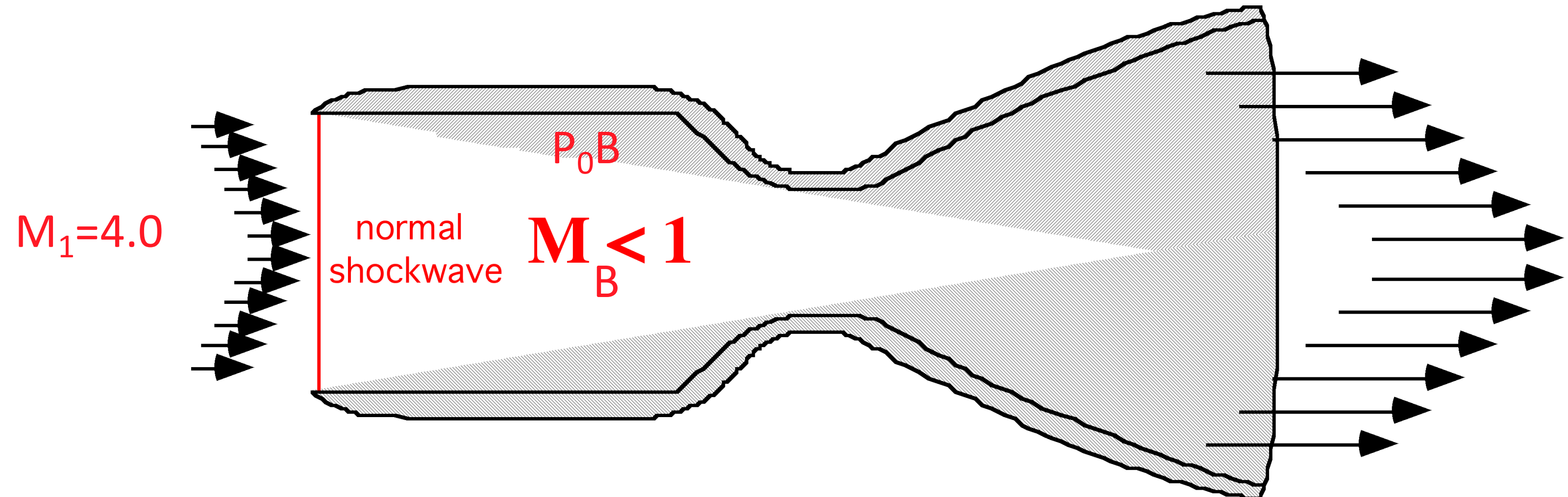
- So … we put a spike in front of the inlet



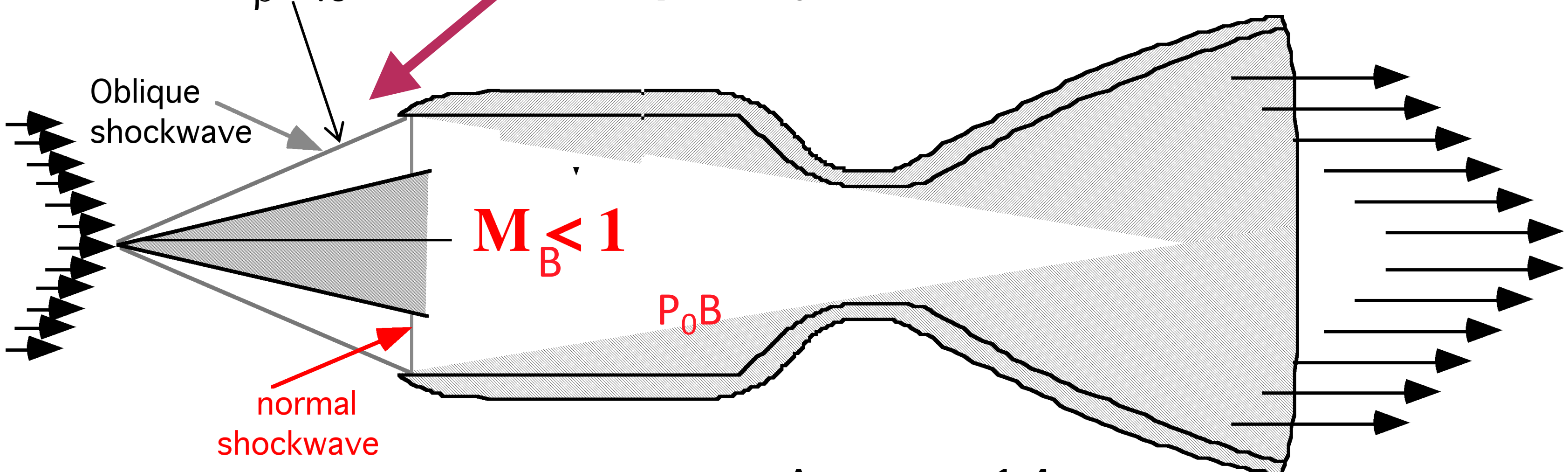


- How does this spike Help?
- By forming an Oblique Shock wave ahead of the inlet

2-D Ramjet Inlet Example

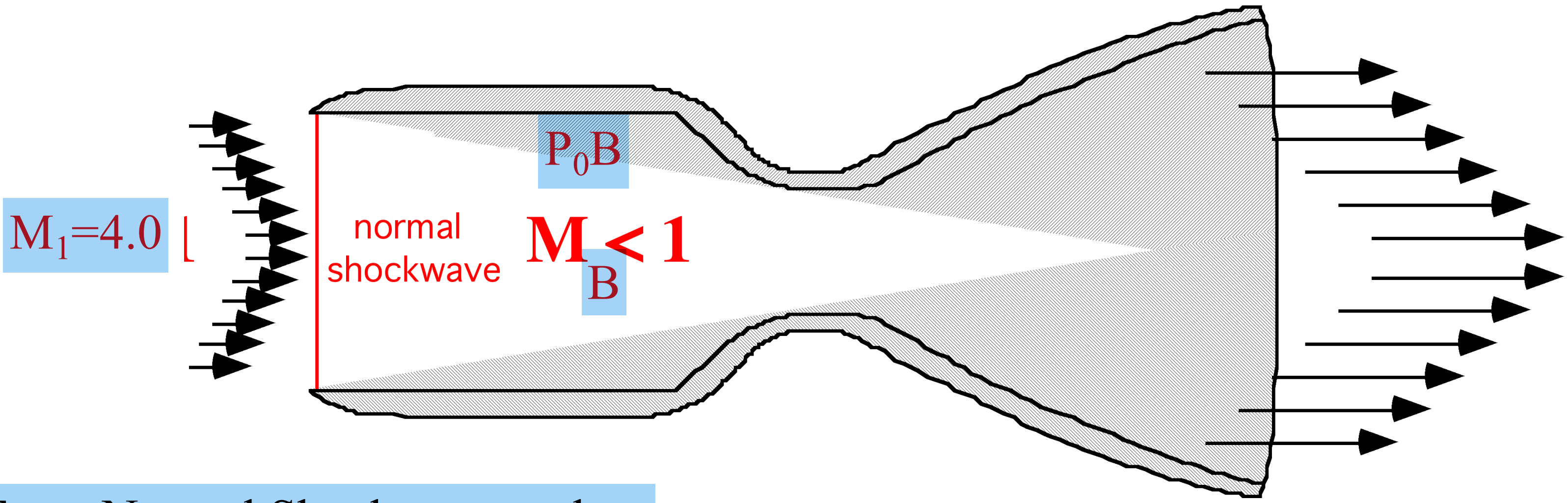


- Compare M_B and P_0 behind normal shockwaves



Assume γ=1.4

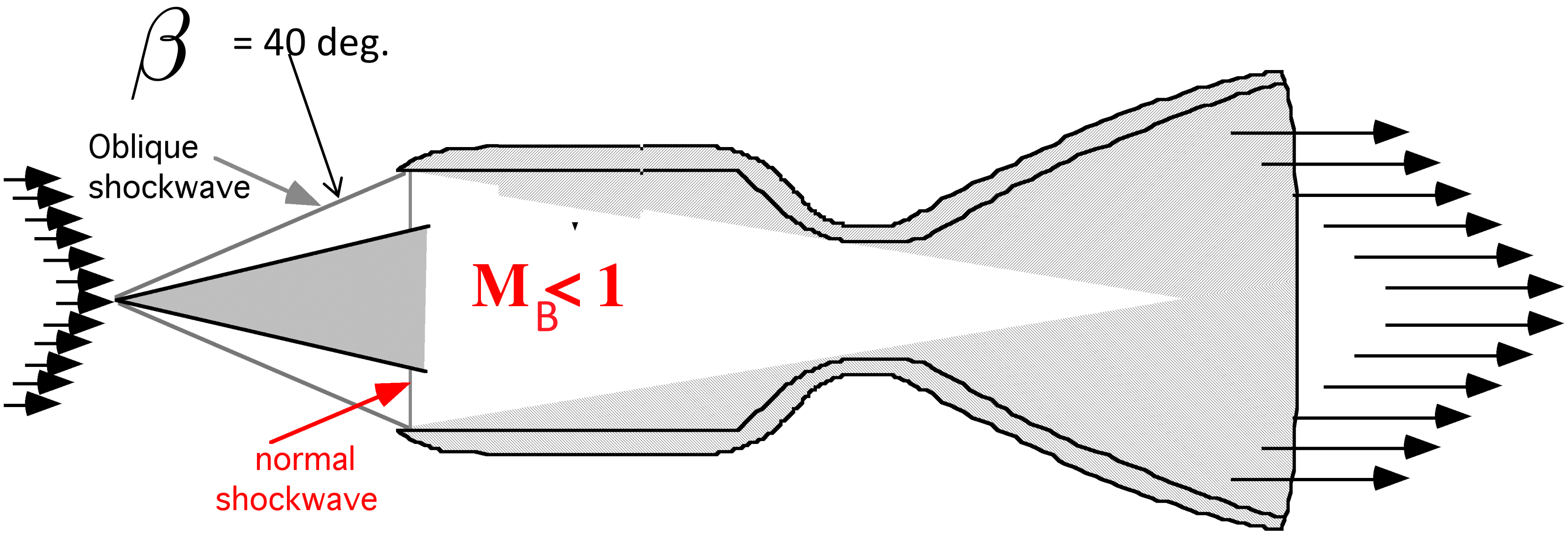
2-D Ramjet Inlet Example (3)



- From Normal Shock wave solver

$$M_\infty \xrightarrow{normal..shock} M_B = 0.434959 \Rightarrow \begin{bmatrix} \frac{P_{0_B}}{P_{0_\infty}} = 0.1388 \\ \frac{p_B}{p_\infty} = 18.5 \end{bmatrix}$$

2-D Ramjet Inlet Example (4)



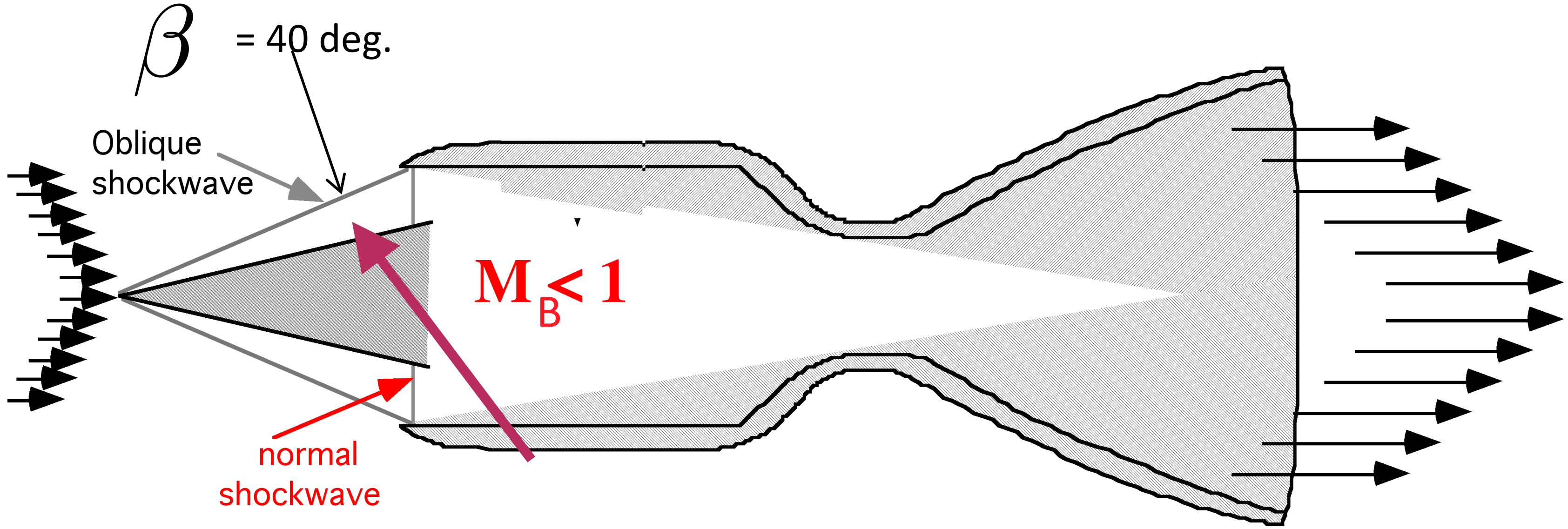
- Across Oblique Shock wave

- $M_{1n} = M_1 \sin \beta_1 = 4 \sin\left(\frac{\pi}{180} 40\right) = 2.571 \longrightarrow M_2n = 0.5064$

$$\tan(\theta) = \frac{2\left\{M_1^2 \sin^2(\beta) - 1\right\}}{\tan(\beta)\left[2 + M_1^2\left[\gamma + \cos(2\beta)\right]\right]} \rightarrow \frac{180}{\pi} \operatorname{atan}\left(\frac{2\left(4^2 \sin^2\left(\frac{\pi}{180} 40\right) - 1\right)}{\left(\tan\left(\frac{\pi}{180} 40\right)\right)\left(2 + 4^2\left(1.4 + \cos\left(\frac{\pi}{180} 2 \cdot 40\right)\right)\right)}\right)$$

θ = 26.2 δεγ

2-D Ramjet Inlet Example (5)

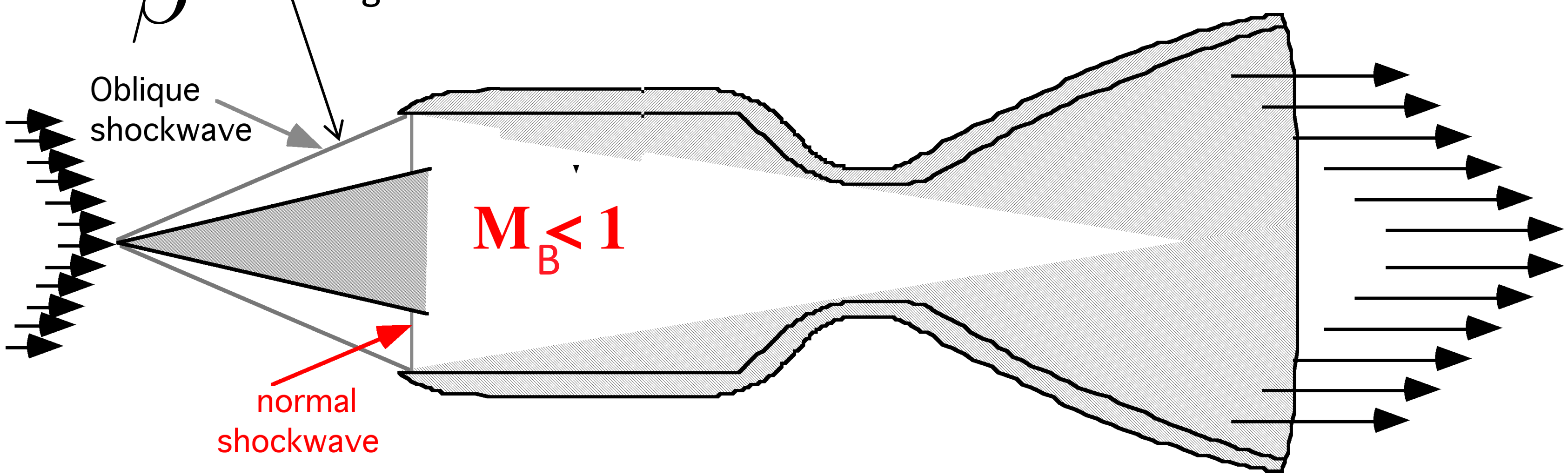


- Across Oblique Shock wave

$$M_2 n = 0.5064 \rightarrow M_2 = \frac{M_2 n}{\sin(\beta_1 - \theta)} = \frac{0.5064}{\sin\left(\frac{\pi}{180}(40 - 26.2)\right)} = 2.123$$

$P_0 2 / P_0 \infty = 0.4711$

2-D Ramjet Inlet Example (6)



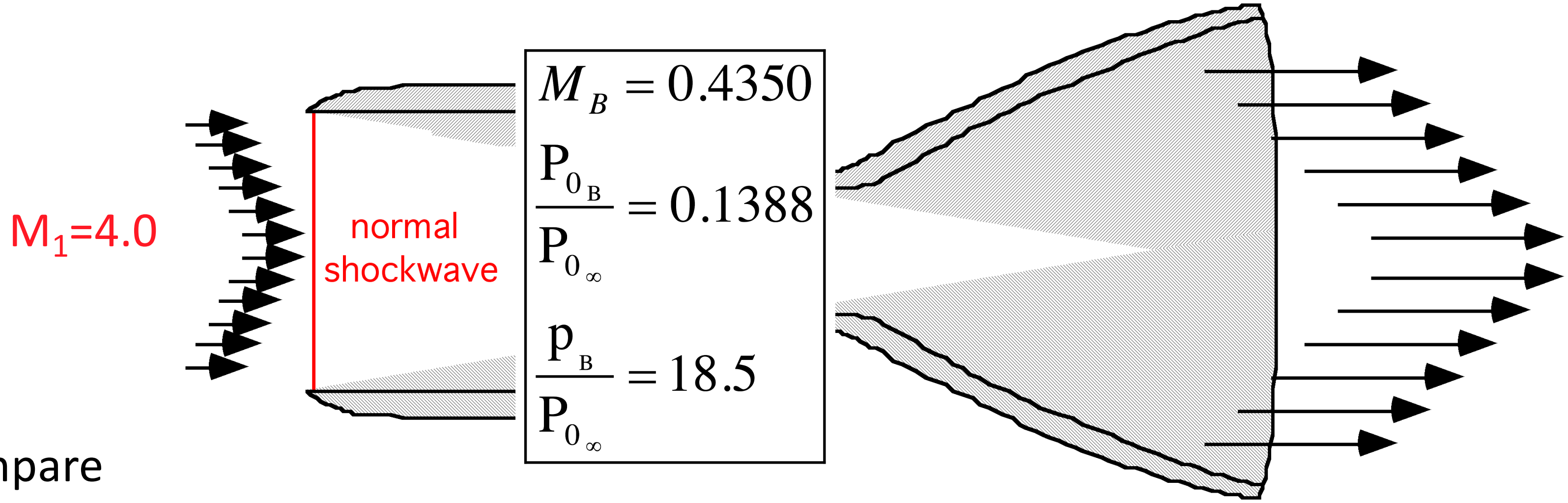
- Across Oblique Shock wave

$$M_2 = 2.123 \overset{normal..shock}{\longrightarrow} M_B = 0.557853 \Rightarrow$$

$$\frac{P_{0_B}}{P_{0_2}} = 0.663531 \Rightarrow \frac{P_{0_B}}{P_{0_\infty}} = \frac{P_{0_B}}{P_{0_2}}\frac{P_{0_2}}{P_{0_\infty}} = (0.663531)(0.4711) = 0.3126$$

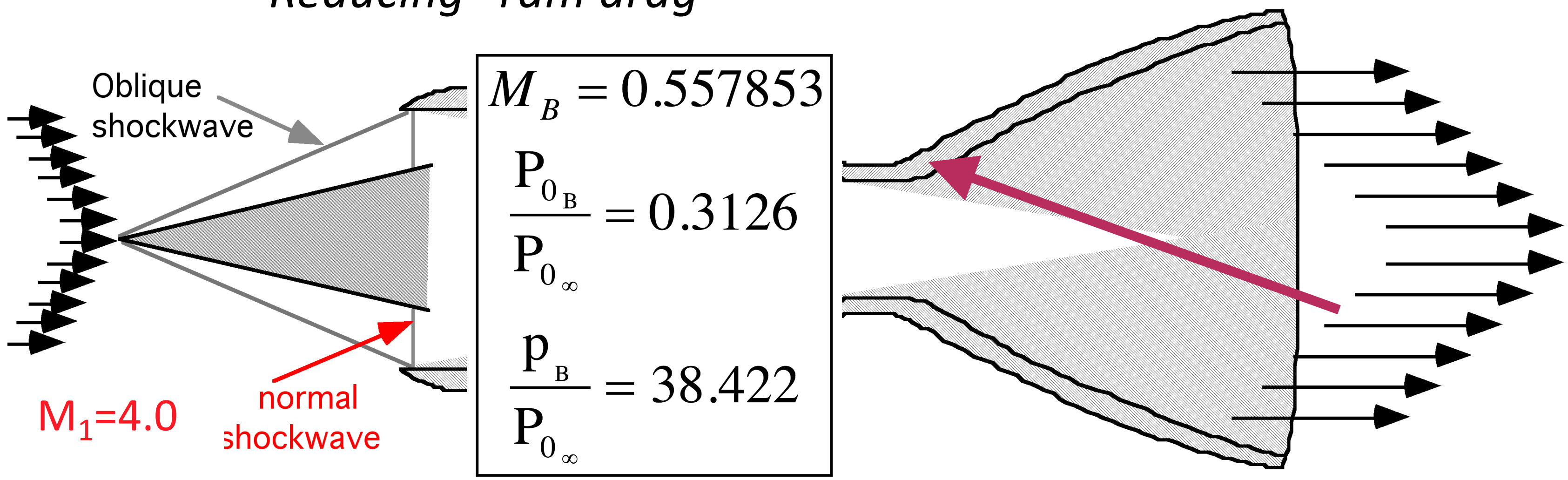
$$\frac{p_B}{p_\infty} = \frac{p_B}{P_{0_B}} \times \frac{P_{0_B}}{P_{0_\infty}} \times \frac{P_{0_\infty}}{p_\infty} = \frac{0.3126\left(\left(1+\frac{1.4-1}{2}4^2\right)^{\frac{1.4}{(1.4-1)}}\right)}{\left(\left(1+\frac{1.4-1}{2}0.557853^2\right)^{\frac{1.4}{(1.4-1)}}\right)} = 38.422$$

2-D Ramjet Inlet Example (7)



- Compare

  - *Spike aids in increasing Total Pressure recovery Reducing "ram drag"*



2-D Ramjet Inlet Example (8)

- … Continuing example … **Incoming Air to Ramjet**

- Molecular weight = 28.96443 kg/kg-mole
- γ = 1.40
- R_g = 287.056 J/°K-(kg)
- T_∞ = 216.65 °K
- p_∞ = 19.330 kPa
- Combustor $\dot{q} = \dot{q}/\dot{m} =$ 500 kJ/kg

- *Assume that mass of added fuel is negligible, exhaust and γ, R_g are the same*

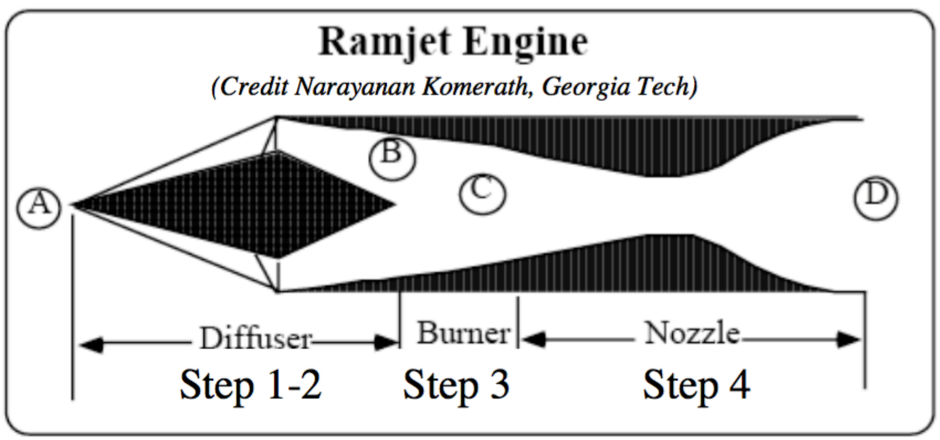
2-D Ramjet Inlet Example (cont'd)

- Compute free stream stagnation temperature

$$T_{0_\infty} = T_\infty \left[1 + \frac{\gamma - 1}{2} M_\infty^{\ 2}\right] = 216.65\left(1 + \frac{1.4-1}{2}4^2\right) = 909.93^\circ K$$

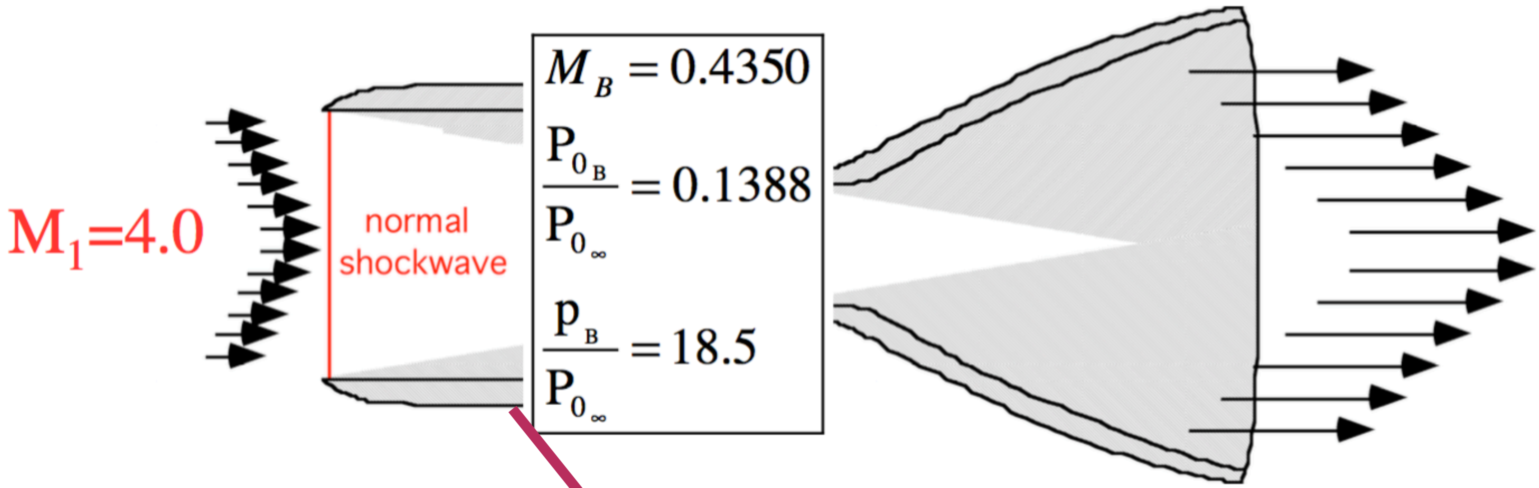
- Compute BURNER stagnation temperature

$$T_{0_C} = \frac{q + c_p T_{0_\infty}}{c_p} = \frac{500 \cdot 10^3 + 1004.696\,(909.93)}{1004.696} = 1407.6\ ^\circ K$$



2-D Ramjet Inlet Example (cont'd)

- Compute efficiency …. Normal shock inlet



- Compute T_C, T_B

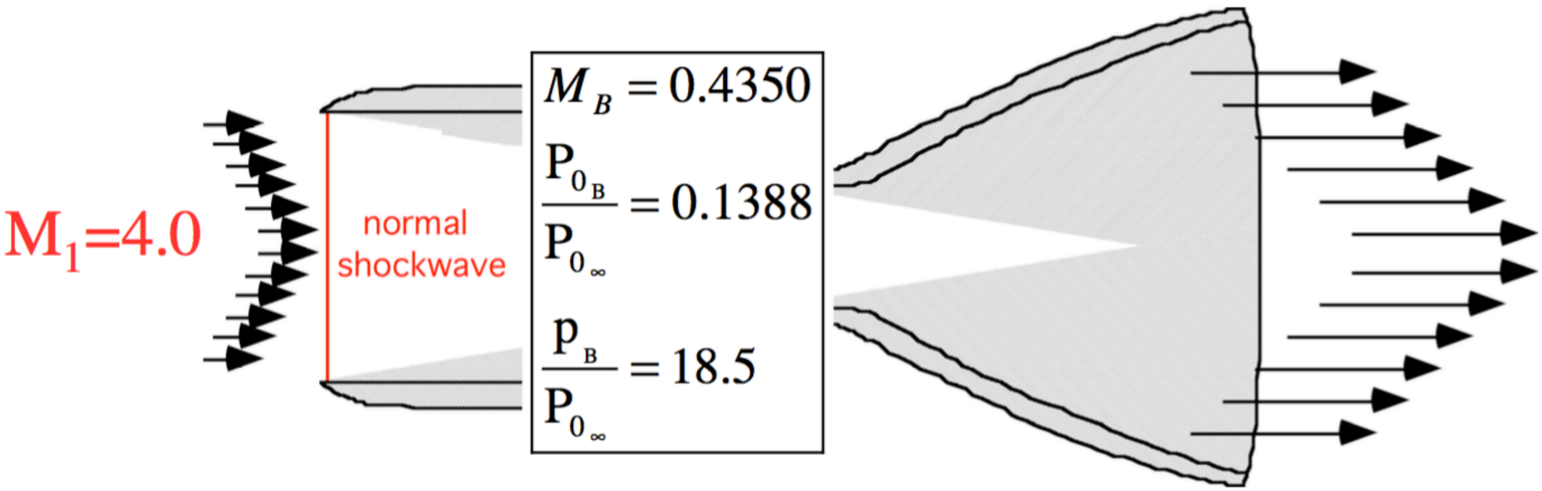
$$T_B = \frac{909.93}{\left(1 + \frac{1.4-1}{2}0.435^2\right)} = 867.75°K$$

$$T_C = \frac{1407.6}{\left(1 + \frac{1.4-1}{2}0.435^2\right)} = 1356.3°K$$

Text

2-D Ramjet Inlet Example (cont'd)

- Compute efficiency …. Normal shock inlet



- Compute T_C, T_B

T_B = 867.75°K

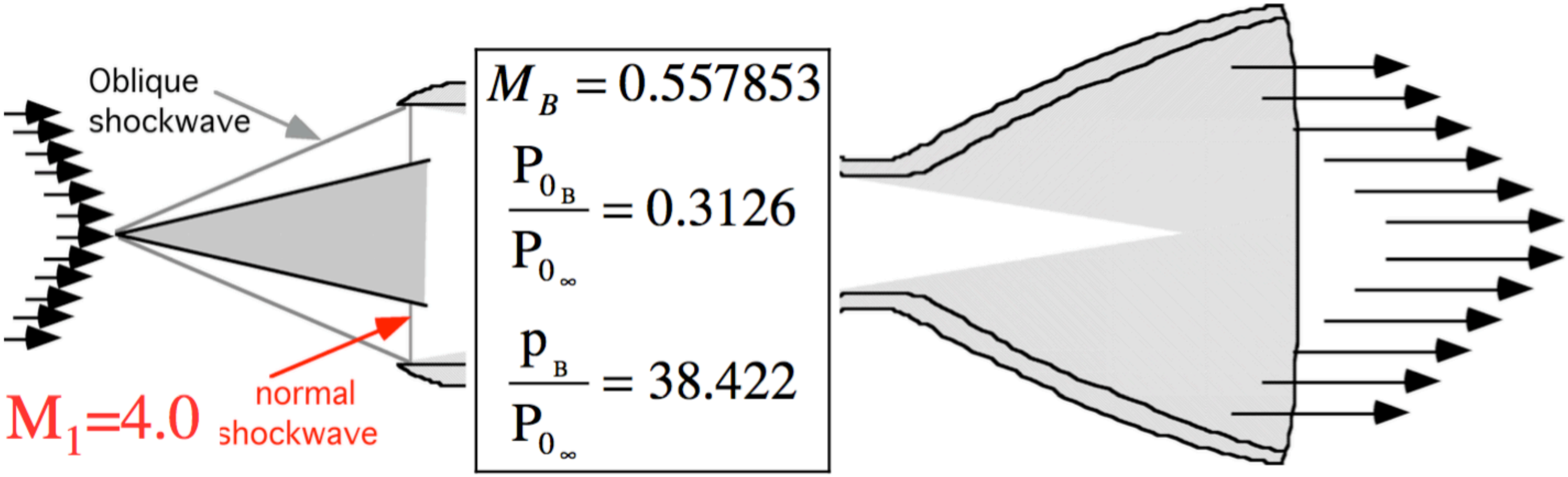
T_c = 1356.3°K

$$\eta = 1 - \left(\frac{P_A}{P_B}\right)^{\frac{\gamma-1}{\gamma}} \frac{\left(T_C - \left(\frac{P_{0_B}}{P_{0_A}}\right)^{\frac{\gamma-1}{\gamma}} T_B\right)}{\left(T_C - T_B\right)} =$$

$$1 - \frac{18.5^{\frac{-(1.4-1)}{1.4}}\left(1356.3 - \left(0.1388^{\frac{(1.4-1)}{1.4}}\right)867.75\right)}{(1356.3 - 867.75)} = 0.2328$$

2-D Ramjet Inlet Example (cont'd)

- Compute efficiency …. Oblique shock inlet



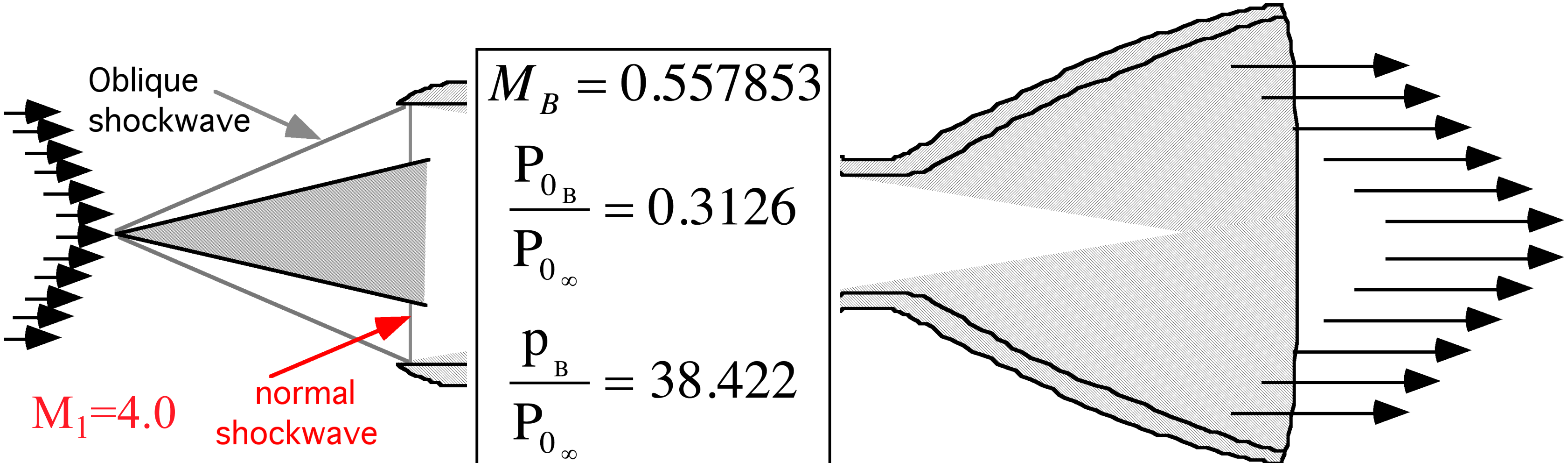
- Compute T_C, T_B

$$T_B = \frac{909.93}{\left(1 + \frac{1.4-1}{2}0.557853^2\right)} = 856.61°K$$

$$T_C = \frac{1407.6}{\left(1 + \frac{1.4-1}{2}0.557853^2\right)} = 1325.1°K$$

2-D Ramjet Inlet Example (cont'd)

- Compute efficiency …. Oblique shock inlet



$$M_B = 0.557853$$

$$\frac{P_{0_B}}{P_{0_\infty}} = 0.3126$$

$$\frac{p_B}{P_{0_\infty}} = 38.422$$

- Compute T_C, T_B

$T_C =$ 856.61 °K

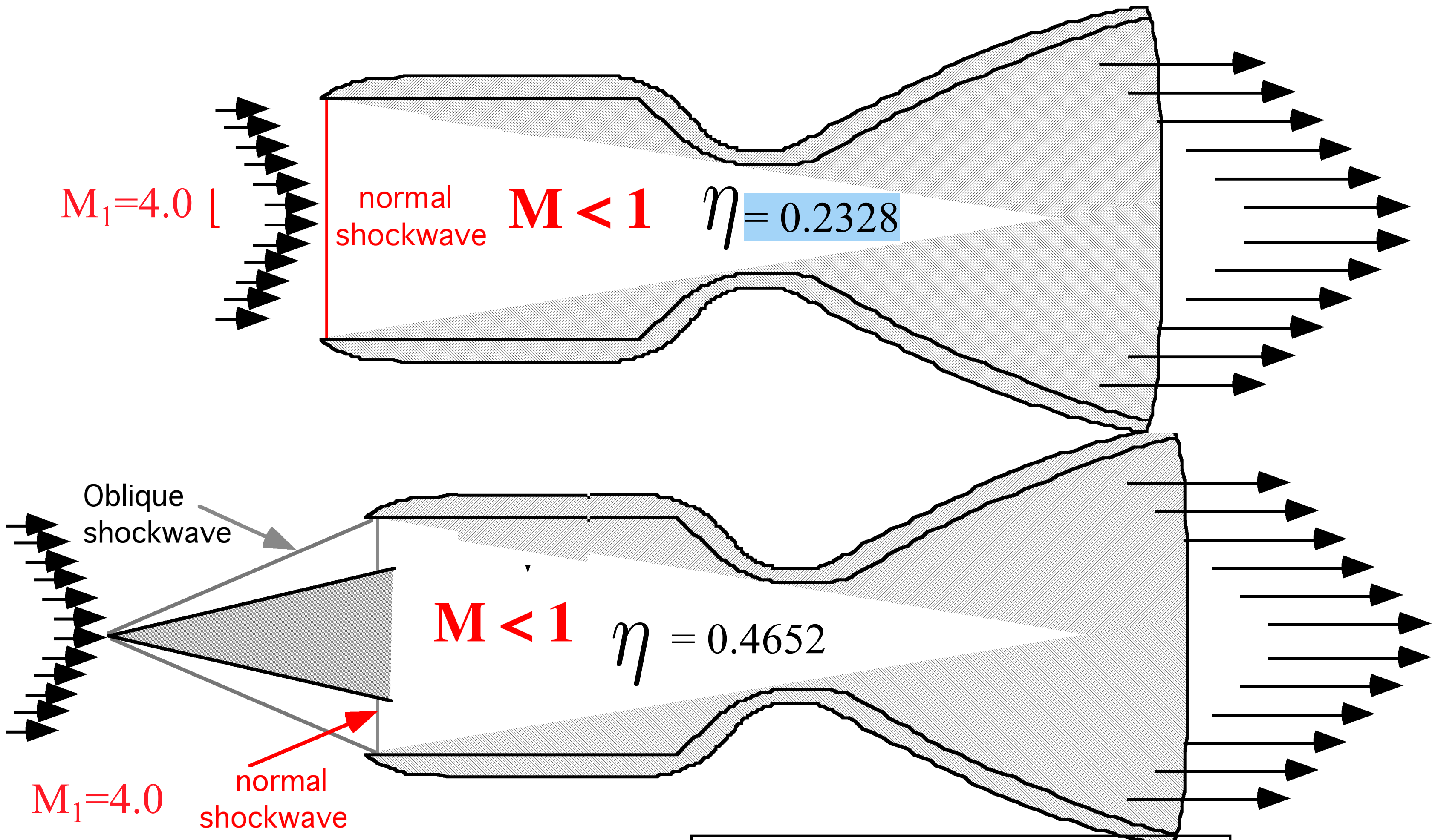
$T_B =$ 1325.1°K

$$\eta = 1 - \left(\frac{P_A}{P_B}\right)^{\frac{\gamma-1}{\gamma}} \frac{\left(T_C - \left(\frac{P_{0_B}}{P_{0_A}}\right)^{\frac{\gamma-1}{\gamma}} T_B\right)}{(T_C - T_B)} =$$

$$1 - \frac{38.422^{-\frac{(1.4-1)}{1.4}} \left(1325.1 - \left(0.3126^{\frac{(1.4-1)}{1.4}}\right) 856.61\right)}{(1325.1 - 856.61)} = 0.4652$$

2-D Ramjet Inlet Example (cont'd)

- Compute efficiency …. Oblique shock inlet

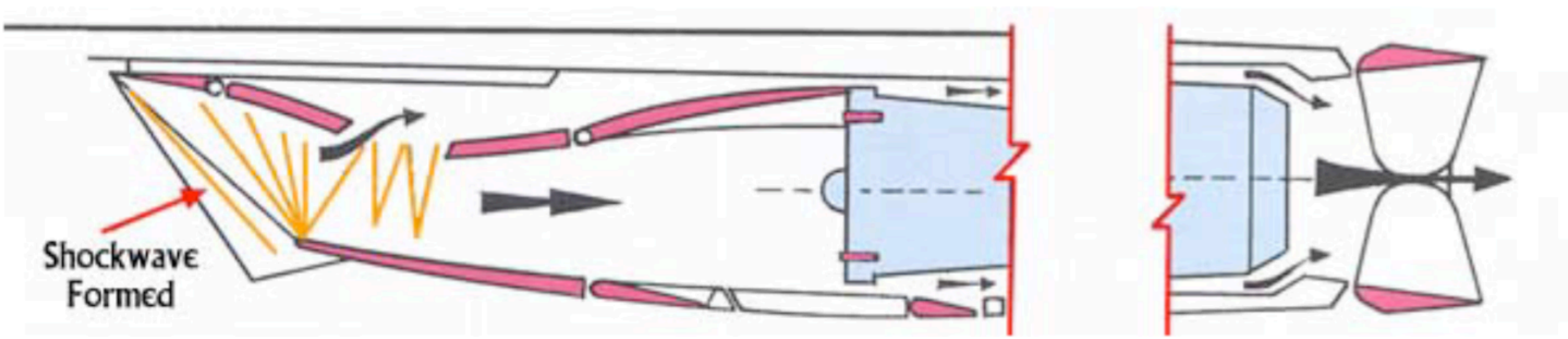


200% increase in efficiency!

Supersonic Inlet:
Condorde Inlet Design

Multi-stage Compression always Works Best For Stagnation Pressure Recovery!

- Mach 2 Cruise



"Starting" a Constant Geometry Ramjet Inlet

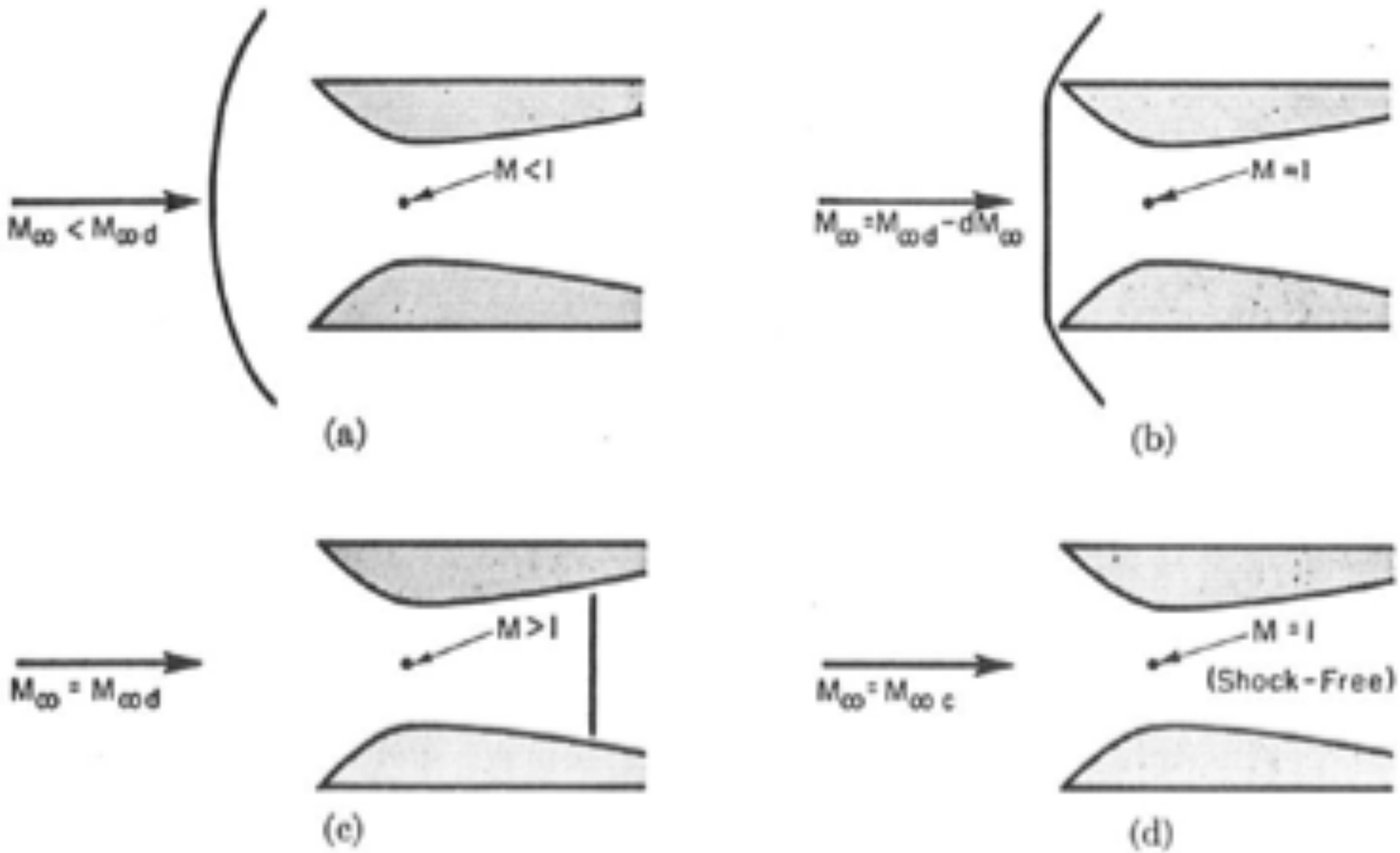


FIG. 5.33. Overspeed starting of fixed-geometry supersonic inlet, designed for free-stream Mach Number $M_{\infty d}$, and having contraction ratio $(A_2/A_1)_c$.


Questions??