Ramjet Overview

- Original idea predates turbojet
  - 1913: French patent (Lorin)
  - 1930’s and early 1940’s: development work in Soviet Union and Germany, including engine flight tests
  - late 1940’s: first flight of ramjet powered winged aircraft

US Navy Gorgon IV (missile/drone)

Smithsonian Air and Space

Leduc 0.10 (France)

Ramjet Overview

- Basic layout

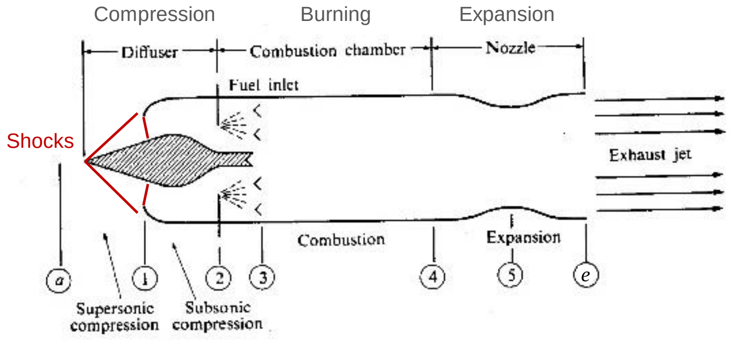
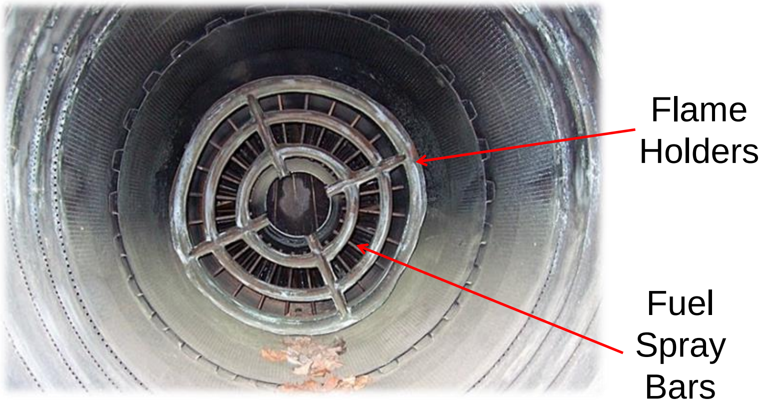


FIGURE 5.6 Schematic diagram of a ramjet engine. *from Hill and Peterson*

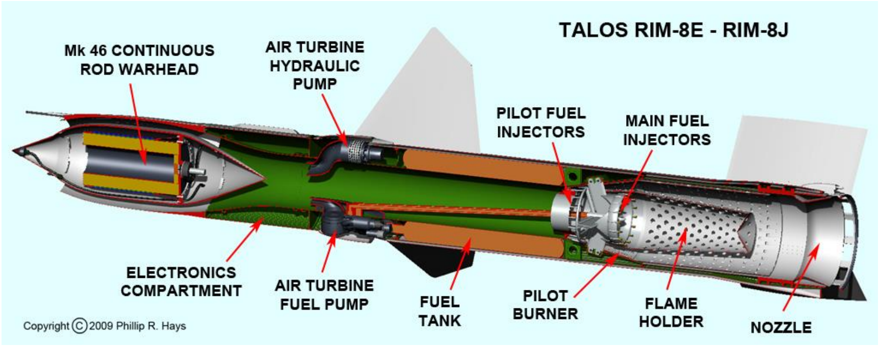
J57-P-55 Afterburner

- This afterburner arrangement of fuel injection/bluff body flame stabilizers was used in many ramjets



Ramjet in Missile

- Early ramjet application (1950's, US Navy SAM)



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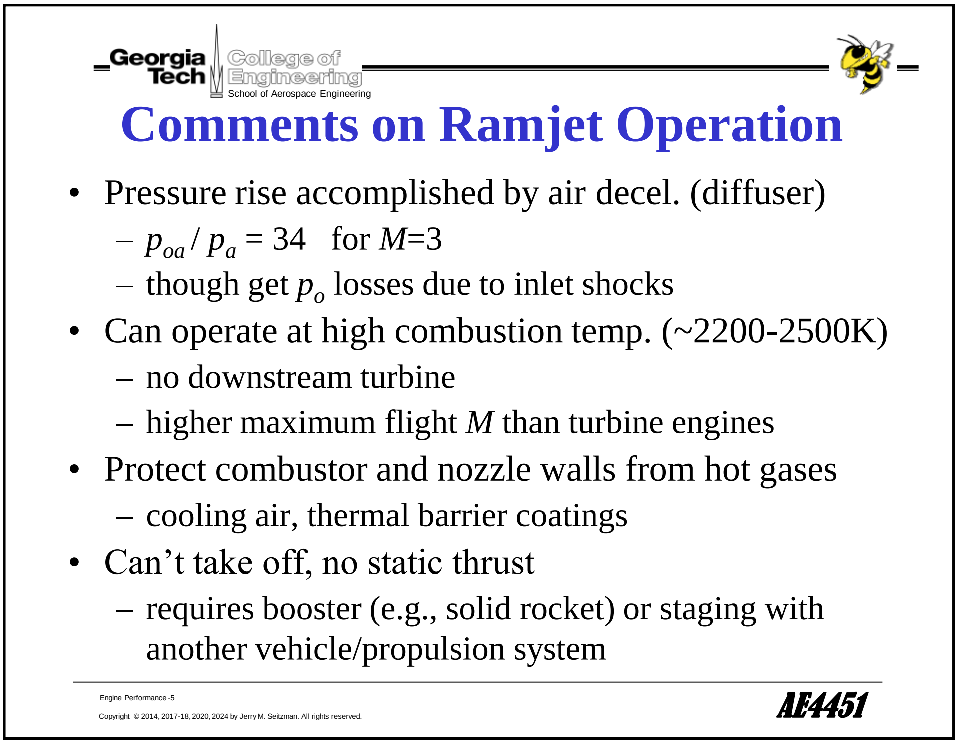
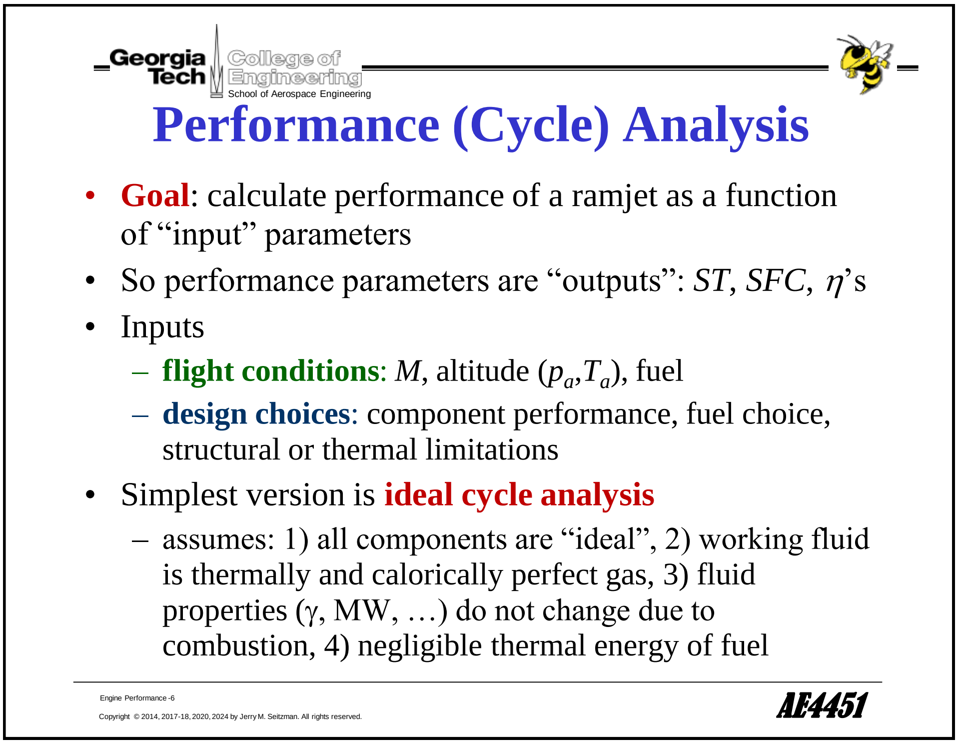
- Actually layout more complicated than simple schematic



Comments on Ramjet Operation

- Pressure rise accomplished by air decel. (diffuser)
  - $p_{oa} / p_a = 34$ for M=3
  - though get p_o losses due to inlet shocks
- Can operate at high combustion temp. (~2200-2500K)
  - no downstream turbine
  - higher maximum flight M than turbine engines
- Protect combustor and nozzle walls from hot gases
  - cooling air, thermal barrier coatings
- Can't take off, no static thrust
  - requires booster (e.g., solid rocket) or staging with another vehicle/propulsion system



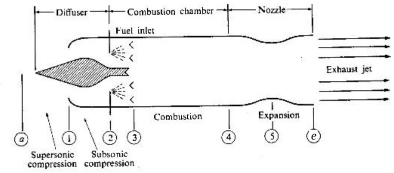
Performance (Cycle) Analysis

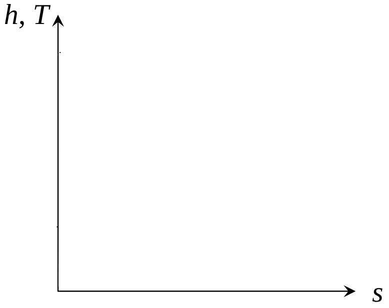
- **Goal**: calculate performance of a ramjet as a function of "input" parameters
- So performance parameters are "outputs": ST, SFC, η's
- Inputs
  - **flight conditions**: M, altitude (p_a,T_a), fuel
  - **design choices**: component performance, fuel choice, structural or thermal limitations
- Simplest version is **ideal cycle analysis**
  - assumes: 1) all components are "ideal", 2) working fluid is thermally and calorically perfect gas, 3) fluid properties (γ, MW, …) do not change due to combustion, 4) negligible thermal energy of fuel

Ideal Ramjet Cycle Analysis

- Good way to start is by sketching process on *T*-*s* (or *h*-*s*) diagram
  - begin with air at ambient conditions (far in front of engine)
- Want to find parameters like ST and SFC
  - so consider τ (III.1)

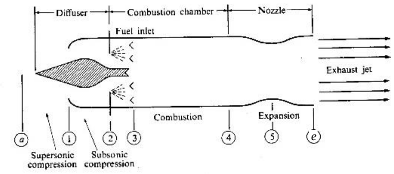
$$\tau = \underset{?}{\dot{m}_a}\left[\left(1+\underset{?}{f}\right)\underset{?}{u_e}-\underset{?}{u}\right]+\left(p_e-p_a\right)A_e$$

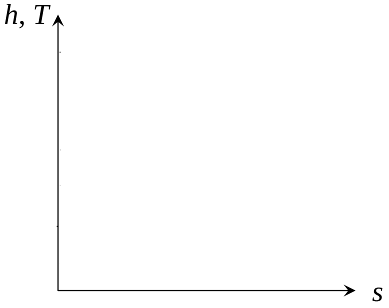




Ideal Ramjet Cycle Analysis

- So need u_e
  - short-cut method for *ideal* cases (isentropic compression and expansion, reversible heating)





Ideal Ramjet Performance

- So we get

$$\boxed{ST=\frac{\tau}{\dot m_a}=u\left[(1+f)\frac{u_e}{u}-1\right]=\overbrace{M\sqrt{\gamma R T_a}}^{u}\left[(1+f)\overbrace{\sqrt{\frac{T_{o4}}{\underbrace{T_a\left(1+\frac{\gamma-1}{2}M^2\right)}_{T_{o2}=T_{oa}}}}}^{u_e/u}-1\right]}\quad\textbf{(III.8)}$$

  - and from (II.15b)

$$f=\frac{T_{o4}-T_{o2}}{\Delta h_R/c_p-T_{o4}}=\frac{T_{o4}/T_a-\left(1+\frac{\gamma-1}{2}M^2\right)}{\Delta h_R/c_pT_a-T_{o4}/T_a}$$

choose T_{o4} (e.g., $=T_{max\ matl}$)

  - so $ST=ST(\underbrace{M,T_a}_{flight},\underbrace{T_{o4},\Delta h_R/c_p}_{design})$

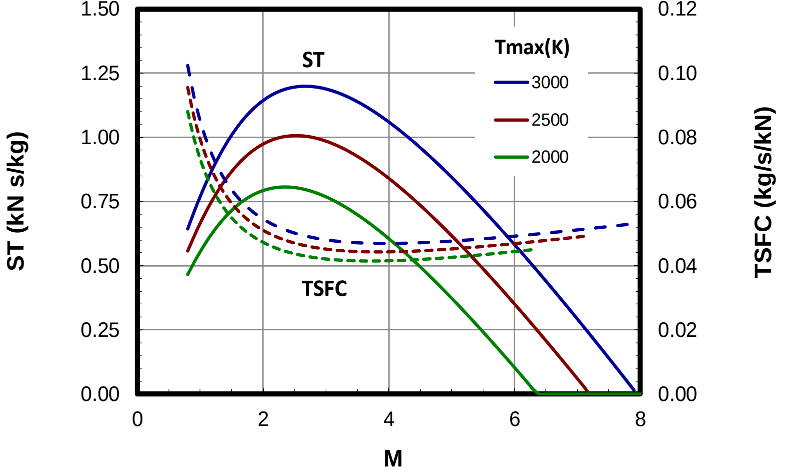
- Other parameters (from III.4-7)

$$TSFC=\frac{f}{ST}\qquad \eta_o=\frac{ST}{f}\frac{u}{\Delta h_R}=\frac{1}{TSFC}\frac{u}{\Delta h_R}$$

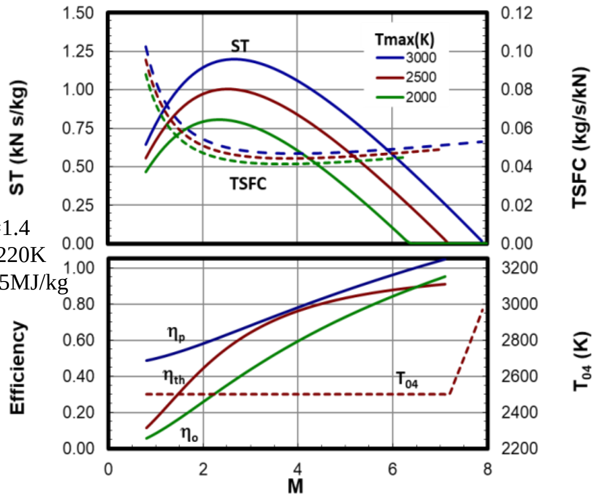
$$\eta_p=\frac{\tau u}{\Delta\dot{KE}}=\frac{\tau u}{\frac{1}{2}\dot m_a\left[(1+f)u_e^2-u^2\right]}=2\frac{ST}{u\left[(1+f)(u_e/u)^2-1\right]}\qquad \eta_{th}=\frac{\eta_o}{\eta_p}$$

Ideal Ramjet Performance

Δh_R=45MJ/kg, γ=1.4, T_a=220K



Ideal Ramjet Performance



γ=1.4
T_a=220K
HV=45MJ/kg

- Poor subsonic performance
- ST_{max} @ M~2.6 but SFC_{min} @ M~4
- For given M, T_{max}↓⇒SFC↓ but ST↓

What are the design tradeoffs?

- For given T_{max}, there is max M

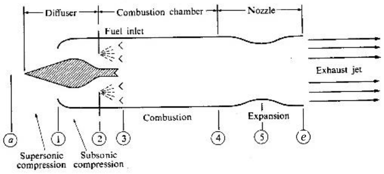
Why?

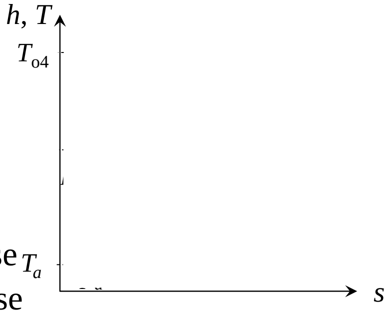
"Real" Ramjet Cycle Analysis

- Want to remove some of the idealizations in the previous analysis
  - – inlet/diffuser, combustor and nozzle are no longer reversible
    - will experience p_o losses
  - – combustor does not achieve ideal heat release
    - some of the fuel is unburned and/or the combustion is "incomplete" (e.g., made some CO instead of CO_2)
  - – nozzle not perfectly expanded
- But will keep other idealizations
  - – no heat losses, c_p= constant,…

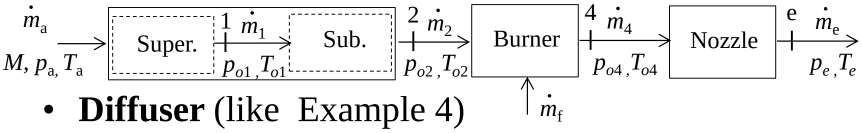
“Real” Ramjet Cycle Analysis

- Can’t use “short cut” based on isentropic processes
  - now need to perform CV analysis for each component, e.g., inlet to exit
- But again useful to examine *T*-*s* diagram to understand process
  - let’s use same p_a, T_a, *M* and T_{o4} as in ideal case
  - show underexpanded case





“Real” Ramjet Cycle Analysis



- **Diffuser** (like Example 4)

Mass $\dot m_a = \dot m_1 = \dot m_2$

Energy $\dot m_a h_{oa} = \dot m_a h_{o1} = \dot m_a h_{o2} \Rightarrow T_{o2} = T_{oa} = \overset{\checkmark}{T_a}\left(1+\frac{\gamma-1}{2}\overset{\checkmark}{M}{}^2\right)$

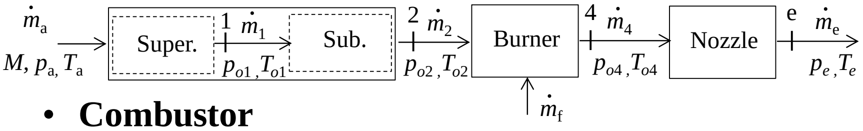
Entropy

- to get stagnation pressure, use adiabatic efficiency to compare to isentropic case, similar to (II.12)

$$\boxed{\frac{p_{o2}}{\underset{\checkmark}{p_a}} = r_d\left\{1+\eta_d\left(\frac{T_{o_2}}{T_a}-1\right)\right\}^{\gamma/\gamma-1} = \overset{\checkmark}{r_d}\left\{1+\overset{\checkmark}{\eta_d}\,\frac{\gamma-1}{2}M^2\right\}^{\gamma/\gamma-1}} \quad \textbf{(III.9)}$$

- but modified by *ram recovery factor* ($r_d(M) \le 1$) to account for shock losses

“Real” Ramjet Cycle Analysis



- **Combustor**

Mass $\dot{m}_a + \dot{m}_f = \dot{m}_4 = \dot{m}_a(1+f)$

Energy $\eta_b \dfrac{\dot{m}_f \Delta h_R}{c_p} = \dot{m}_a\left[(1+f)T_{o4} - T_{o3}\right]$

like (II.15) *but with*
***η_b*≡combustion efficiency**
how much available chem. energy is converted to thermal energy, ≤1

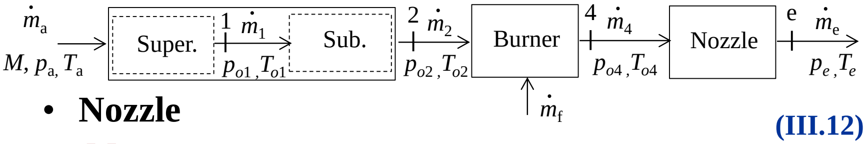
(III.10) $$\boxed{f = \frac{\overset{\checkmark}{T_{o4}}/T_{o2} - 1}{\left(\underset{\checkmark}{\eta_b}\underset{\checkmark}{\Delta h_R}/c_p \underset{\checkmark}{T_{o2}}\right) - T_{o4}/T_{o2}}}$$

- can’t use efficiency to get pressure loss (not compression or expansion process)

(III.11) $$\boxed{\frac{p_{o4}}{p_{o2}} = \overset{\checkmark}{\pi_{rb}}}$$

***π_{rb}*≡burner pressure ratio**
≤1

“Real” Ramjet Cycle Analysis



- **Nozzle**

Mass

Energy

Entropy

(III.12) $$\boxed{u_e = \sqrt{2c_p\left(\overset{\checkmark}{T_{o4}} - \overset{?}{T_e}\right)}}$$

(III.13) $$\boxed{T_e = \overset{\checkmark}{T_{o4}}\left\{1 - \overset{\checkmark}{\eta_N}\left[1 - \left(\frac{\overset{\checkmark}{p_e}}{p_{o4}}\right)^{\gamma-1/\gamma}\right]\right\}}$$

"Real" Ramjet Performance

- So we get

depends on nozzle design

$$ST=\frac{\tau}{\dot{m}_a}=\left[(1+\overset{\checkmark}{f})\overset{\checkmark}{u_e}-\underbrace{\overset{\checkmark}{M}\sqrt{\gamma R\overset{\checkmark}{T_a}}}_{u}\right]+\frac{(p_e-p_a)A_e}{\dot{m}_a}$$

$$TSFC=\frac{f}{ST}$$

$$\eta_o=\frac{1}{TSFC}\frac{u}{\Delta h_R}\checkmark$$

$$\eta_p=\frac{\tau u}{\Delta\dot{KE}}=2\frac{ST}{u\left[(1+f)(u_e/u)^2-1\right]}$$

$$\eta_{th}=\frac{\eta_o}{\eta_p}$$

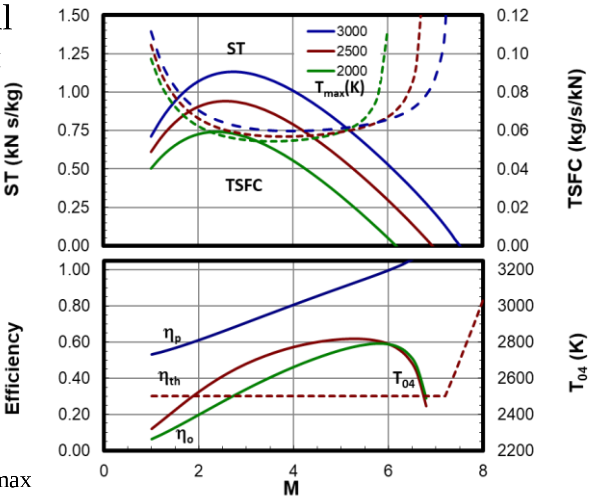
no change in these expressions compared to ideal case

Real vs Ideal Ramjet Performance

vs. ideal ramjet:

- $ST\downarrow$
- $SFC\uparrow$
- $\eta_o\downarrow$
- $\eta_{th}\downarrow$
- $\eta_p\uparrow$

- $\tau\to 0$ *before* $T_{o2}=T_{max}$



γ=1.3-1.4
T_a=220K
HV=45MJ/kg
η_D=0.92&ram recovery
η_B=0.99
p_{rb}=0.98
η_N=0.95