Turbojet Overview

- Development of the turbojet is credited independently to two individuals in the 1930's
  - Frank Whittle
  - Hans-Joachim Pabst von Ohain

Von Ohain **Whittle**

Ohain's 1st Experimental Turbojet (1935)

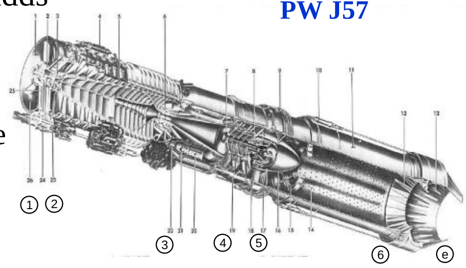
Whittle W2/700

  - 1st jet flight: He178 1939

Turbojet Overview

- vs. ramjet, basic layout adds
  1. **compressor**(s)
     - not relying on ram compression to achieve high pressure (and thus high η_{th})
  2. **turbine**(s)
     - needed to run compressor(s)
     - connected by shaft(s)
  3. **afterburner**/ augmentor/reheater
     - produces "peak" thrust
     - resembles ramjet burner

PW J57



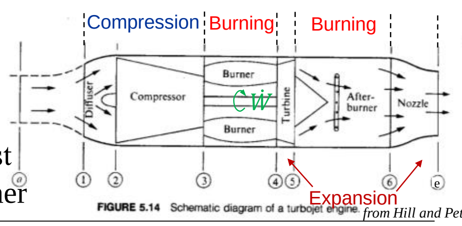
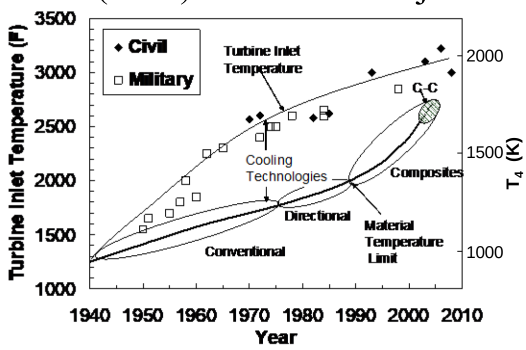


FIGURE 5.14 Schematic diagram of a turbojet engine. *from Hill and Peterson*

Comments on Turbojet Operation

- Unlike ramjets, compressors allow turbojet to operate efficiently at lower Mach numbers
  - can also produce static (takeoff thrust)
- Max. (main) combustion T ("T4") lower than ramjets
  - limited by turbine materials (stresses)
  - 1939: 1300F (1000K) von Ohain/Whittle
  - current: 3200-3500F (2000-2200K)



Adapted from Ballal and Zelina

"Real" Turbojet Cycle Analysis

- As with ramjet analysis
  - components are NOT assumed to be reversible, will experience p_o losses
    - for expansion/compression components, use adiabatic efficiency approach
    - for burners, use stagnation pressure ratio factors
  - combustors (burner, afterburner) do not achieve ideal heat release
    - include burner efficiencies
  - still assume no heat losses
- But for this analysis, will NOT assume c_p= constant throughout engine
  - use appropriately "averaged" c_p for each component

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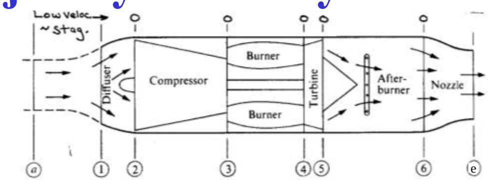
"Real" Turbojet Cycle Analysis



- Step 1:
  - draw cycle on *T-s* diagram
- Step 2:
  - component by component analysis to find u_e
- Step 3:
  - calculate engine performance parameters

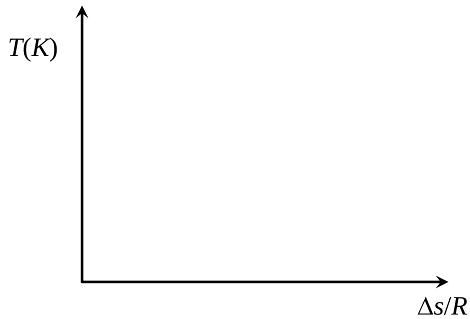


FIGURE 5.18 Turbojet *T–s* diagram. *from Hill and Peterson*

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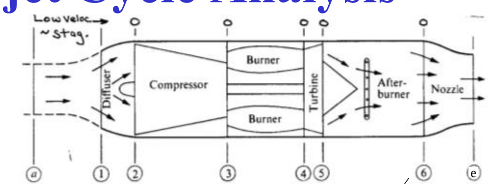
"Real" Turbojet Cycle Analysis



- **Diffuser**
  - same as ramjet

$$\dot{m}_2 = \dot{m}_a$$

$$T_{o2} = T_a\left(1 + \frac{\gamma_d - 1}{2} M^2\right) \quad p_{o2} = p_a r_d \left(1 + \eta_d \frac{\gamma_d - 1}{2} M^2\right)^{\gamma_d / \gamma_d - 1}$$

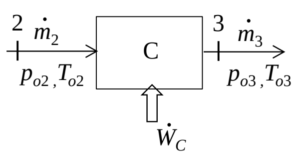
- **Compressor**
  - from class example (e.g., II.11)

$$\frac{p_{o3}}{p_{o2}} = design\,choice = P_{rc}$$

$$\dot{m}_3 = \dot{m}_2$$

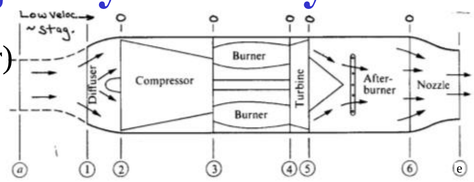
$$T_{o3} = T_{o2}\left\{1 + \frac{1}{\eta_c}\left[\left(\frac{p_{o3}}{p_{o2}}\right)^{\frac{\gamma_c - 1}{\gamma_c}} - 1\right]\right\}$$

$$\dot{W}_c = \dot{m}_3 c_{p_c}\left(T_{o3} - T_{o2}\right)$$



"Real" Turbojet Cycle Analysis

- **Burner** (main combustor)
  - similar to ramjet



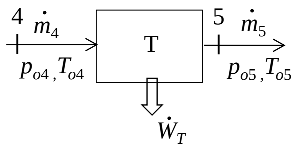
$$\dot{m}_4 = \dot{m}_a\left(1+f\right)$$

$$f = \frac{T_{o4}/T_{o3} - 1}{\left(\eta_b \Delta h_R / c_{pb} T_{o3}\right) - T_{o4}/T_{o3}} \qquad \frac{p_{o4}}{p_{o3}} = P_{rb}$$

- **Turbine**

(III.14)

(III.15)



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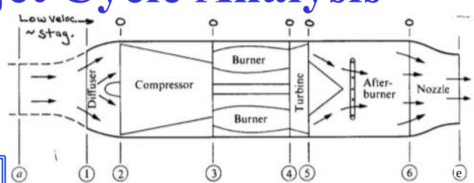
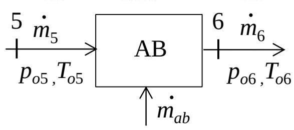
"Real" Turbojet Cycle Analysis

- **Afterburner** $f_{ab} \equiv \dfrac{\dot{m}_{f_{ab}}}{\dot{m}_a}$



(III.16)



- **Nozzle**
  - similar to ramjet

$$\dot{m}_e = \dot{m}_6 \qquad T_e = T_{o6}\left\{1 - \eta_n\left[1 - \left(\frac{p_e}{p_{o6}}\right)^{\frac{\gamma_n - 1}{\gamma_n}}\right]\right\}$$

$$u_e = \sqrt{2 c_{p_n}\left(T_{o6} - T_e\right)}$$

Turbojet Performance

- Performance parameters
  - similar to ramjet, just need to add afterburner (ab) fuel

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

$$TSFC = \frac{\dot{m}_f + \dot{m}_{f_{ab}}}{\tau} = \frac{f + f_{ab}}{ST}$$

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

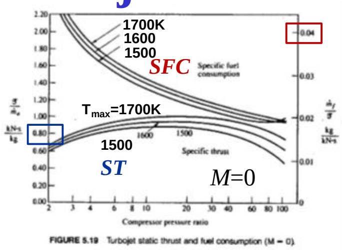
$$\eta_{th} = \frac{\Delta \dot{KE}}{\left(\dot{m}_f + \dot{m}_{f_{ab}}\right)\Delta h_R} = \frac{\left(1 + f + f_{ab}\right)u_e^2 - u^2}{2\left(f + f_{ab}\right)\Delta h_R}$$

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

Turbojet Performance

- $T_{max}\uparrow \Rightarrow ST\uparrow$ but $SFC\uparrow$
  - same as ramjet
- Can choose Pr_c for "optimum" performance
  - optimum $Pr_c\downarrow$ as $M\uparrow$

    why?



from Hill and Peterson