Airbreathing Propulsion

- Overview
  - we will be examining a number of airbreathing propulsion systems
    - ramjets, turbojets, turbofans, turboprops
- Performance parameters
  - to compare them, useful to define some parameters that are relevant to making a "good" propulsion system
  - helpful if they don't depend on engine size
    - **Specific Thrust (ST)**
    - **Specific Fuel Consumption (SFC)**
    - Various **engine efficiencies, η**
- Then we will use cycle analysis to predict performance as function of various design variables

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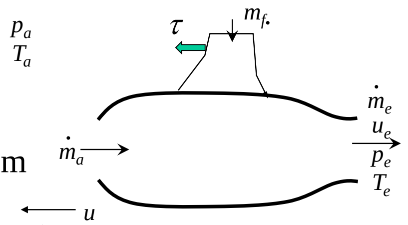
Jet Engine Thrust

- From momentum conservation
  - steady, uniform, inviscid
  - single nozzle exhaust stream



$$\tau = (\dot m_a + \dot m_f)u_e - \dot m_a u + (p_e - p_a)A_e$$

$$\tau = \dot m_a\left[(1+f)u_e - u\right] + (p_e - p_a)A_e$$

(III.1)

$$\boxed{\textit{Specific Thrust (ST)} \equiv \frac{\tau}{\dot m_a} = \left[(1+f)u_e - u\right] + \frac{(p_e - p_a)A_e}{\dot m_a}}$$

for subsonic nozzle exhausts, $p_e = p_a$

Overall Efficiency

- How to characterize an aircraft propulsion system based on how well it produces the desired output (thrust) given the "cost" input (fuel)
- Similar to a cycle efficiency, $\dot{W}_{out}/\dot{Q}_H$ we can define an **Overall Efficiency**
  - for thrust producing engines

$$\text{(III.2)}\quad \boxed{\eta_o \equiv \frac{\tau u}{\dot{m}_f \Delta h_R}} \quad \begin{matrix} \leftarrow \textit{thrust power} \\ \leftarrow \textit{heating rate from fuel} \end{matrix}$$

  - for turboshafts

goal of engine is to produce shaft power

$$\eta_o \equiv \frac{\dot{W}_{shaft}}{\dot{m}_f \Delta h_R}$$

Thermal and Propulsive Efficiencies

- We can also break down the overall process of how an engine produces thrust into two steps

fuel energy → ΔKE of propellant → thrust work

thermal efficiency propulsive efficiency

- **Thermal Efficiency**
  - for thrust produced using nozzles

$$\boxed{\eta_{th} \equiv \frac{\Delta \dot{KE}}{\dot{m}_f \Delta h_R}} \quad \Delta \dot{KE} = \dot{KE}_{out} - \dot{KE}_{in} \quad \text{(III.3)}$$

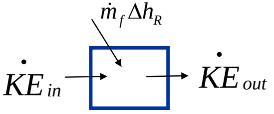
    - e.g., simple turbojet

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

Thermal Efficiency

- for thrust produced using a nozzle
  - this is just the cycle efficiency for a cycle that outputs kinetic energy (nozzle) instead of work (turbine)
  - nozzle exhaust contains gas that is fast (KE) **but also hot** (thermal energy), so $\eta_{th} < 100\%$

(III.4) $$\boxed{\eta_{th} \equiv \frac{\Delta \dot{KE}}{\dot{m}_f \Delta h_R}}$$



- for a turboshaft engines (and turboprops where most of the output power is to the drive shaft)

$$\eta_{th} \equiv \frac{\dot{W}_{shaft}}{\dot{m}_f \Delta h_R}$$

fuel energy → shaft power

Propulsive Efficiency

- How "efficient" is kinetic energy change in producing thrust
  - e.g., simple turbojet

$$\boxed{\eta_p \equiv \frac{\tau u}{\Delta \dot{KE}}}$$ **(III.5)**

$$\Delta \dot{KE} = \frac{1}{2}\left(\dot{m}_a + \dot{m}_f\right)u_e^2 - \frac{1}{2}\dot{m}_a u^2$$

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

if $p_e = p_a$

$$\eta_p = \frac{2\left(\tau/\dot{m}_a\right)u}{\left(1+f\right)u_e^2 - u^2}$$

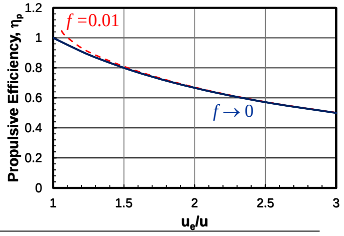
$$\eta_p = 2\frac{\left(1+f\right)u_e/u - 1}{\left(1+f\right)\left(u_e/u\right)^2 - 1}$$

little KE change **→1** ***as*** $u_e \rightarrow u$

lots of "wasted" KE **→0** ***for*** $u_e \gg u$

for static thrust case **=0** ***for*** $u=0$

η_p can be >1 since fuel is being ejected too



Propulsive Efficiency

- For **turboprop** engines, it is typical to replace propulsive efficiency with a **propeller efficiency**

$$\boxed{\eta_{pr} \equiv \frac{\tau_{pr} u}{\dot{W}_{shaft}}}$$

$\tau_{pr} \equiv$ thrust from propeller

  - if turboprop derives significant thrust from an engine exhaust nozzle (in addition to the propeller), then sometimes useful to define an equivalent shaft power

$$\dot{W}_{shaft,equiv} = \dot{W}_{shaft}\left(1 + \frac{\tau_{nozzle}}{\tau_{pr}}\right) \qquad \text{then } \eta_{pr} \equiv \frac{\tau u}{\dot{W}_{shaft,equiv}}$$

total thrust power

Efficiency Relations

- From our definitions

$$\eta_{th} n_p = \frac{\Delta \dot{KE}}{\dot{m}_f \Delta h_R} \quad \frac{\tau u}{\Delta \dot{KE}}$$

$$= \frac{\tau u}{\dot{m}_f \Delta h_R} \quad = \eta_o$$

(III.6) $$\boxed{\eta_o = \eta_{th} n_p}$$

only need to know 2 of the efficiencies to find the 3rd

  - or for turboprop

$$\eta_o = \eta_{th} n_{pr}$$

Specific Fuel Consumption, SFC

- How much does a given amount of thrust “cost” in fuel?
- **Thrust Specific Fuel Consumption (TSFC)**

lower SFC ⇒ greater range for an aircraft

$$\boxed{TSFC \equiv \frac{\dot{m}_f}{\tau}} \quad \textbf{(III.7)}$$

SFC has units

also related to ST

$$= \frac{\dot{m}_f / \dot{m}_a}{\tau / \dot{m}_a} = \frac{f}{ST}$$

where f represents all the fuel added

$$\eta_o \equiv \frac{\tau u}{\dot{m}_f \Delta h_R}$$

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

if you know η_o you know TSFC

Specific Fuel Consumption

- For turboshaft engines, can define a shaft power based SFC

$$BSFC \equiv \frac{\dot{m}_f}{\dot{W}_{shaft}}$$

  - this metric can be applied to any type of fuel-burning (combustion) engine that produces shaft power (diesels, spark-ignition, …)
  - “brake” is a hold-over name from the way that shaft-power was typically tested
    - on a dynamometer where the shaft power is absorbed (a “brake”) and measured

Jet Engine Performance History

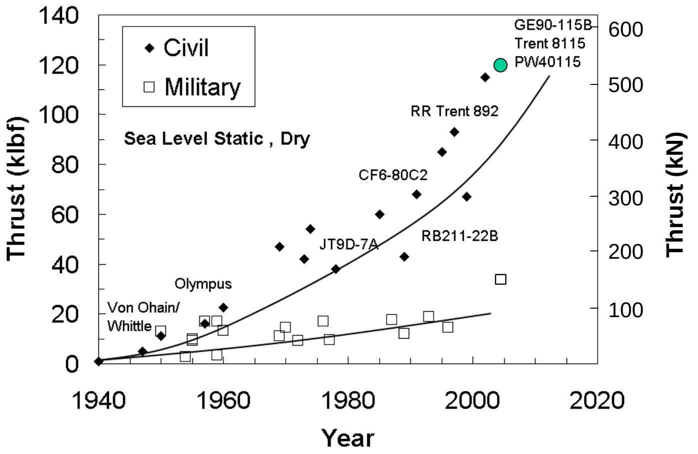
- How has jet engine performance improved since turbojet were first developed in the 1930’s
- The following information is adapted from *Progress in Aero Engine Technology (1939-2003)* by Dilip R. Ballal (University of Dayton) and Joseph Zelina (AFRL)

Search for Higher Thrust

- 1903: 134 lb_f Wright Flyer
- 1939: 1,000 lb_f (~4450N) von Ohain/Whittle
- 2004
  - 35,000 lb_f Military Engine
  - 115,000 lb_f (GE90-115B) *~8% of single F-1 engine in Saturn V*
    - tested up to 120,000 lb_f

Adapted from Ballal and Zelina

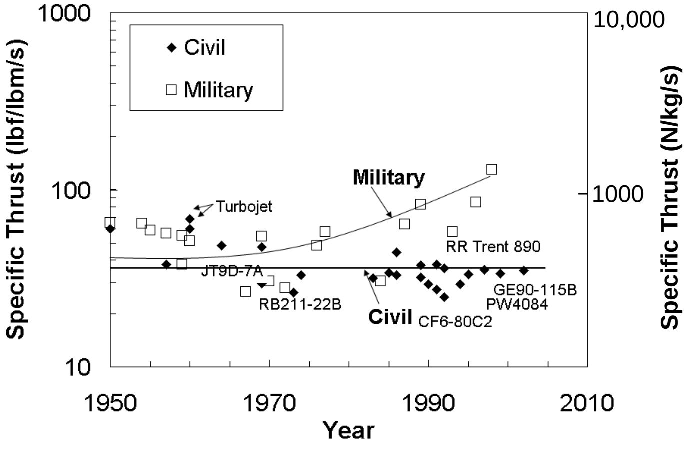
Gas Turbine Thrust Improvements



Since 1939, static thrust increased >110× for civil engines and 20× for military engines

Adapted from Ballal and Zelina

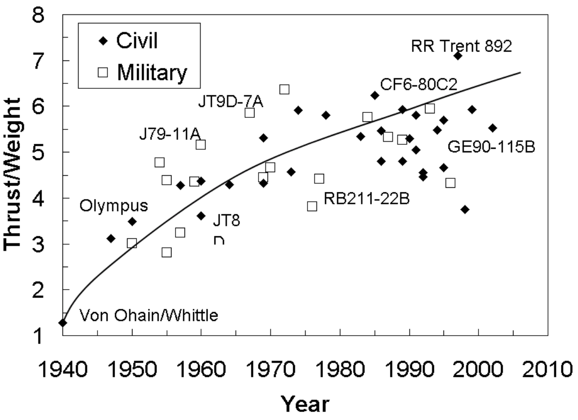
Specific Thrust Improvements



Adapted from Ballal and Zelina

Thrust/Weight

- 2003: 7
  Rolls Royce Trent
- 2003: 6.5
  Military Engine
- 1939: 1.2
  von Ohain/Whittle
- 1903: 0.67
  Wright Flyer

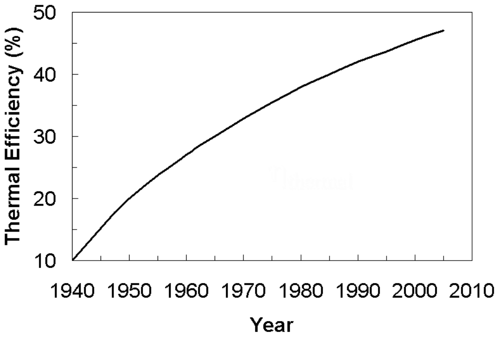


For comparison ~85 for Saturn V F-1 Engine

Adapted from Ballal and Zelina

Efficiencies

- $$\eta_{th} = \frac{\Delta \dot{K}_e}{\dot{m}_f \Delta h_r}$$



- Overall efficiencies

  1903: 10% (Wright Flyer)

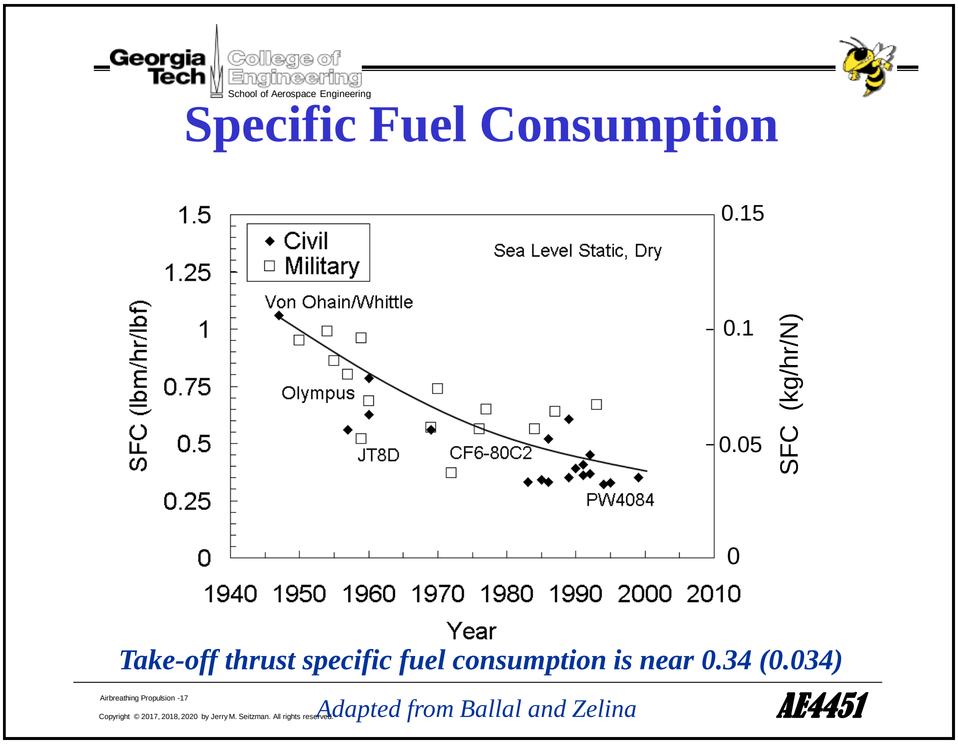
  1939: 15% (von Ohain and Whittle)

  2003: 30% (Military Engine)

  40% (Civil Engine)

Modern aeroengine thermal efficiency approaching 50%

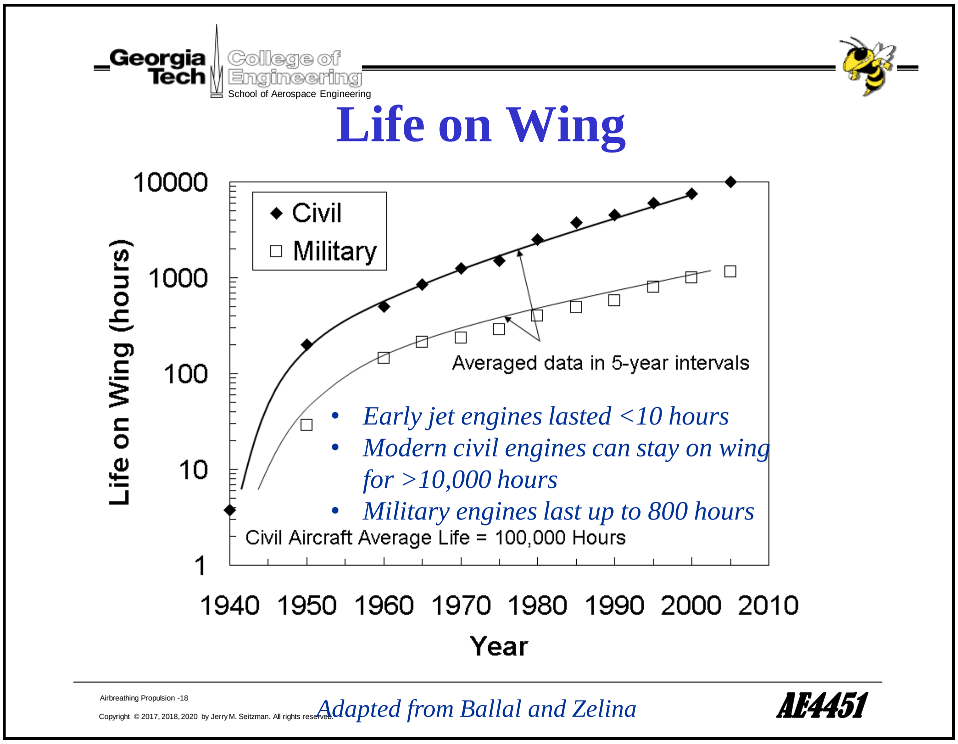
Adapted from Ballal and Zelina



Specific Fuel Consumption

Take-off thrust specific fuel consumption is near 0.34 (0.034)

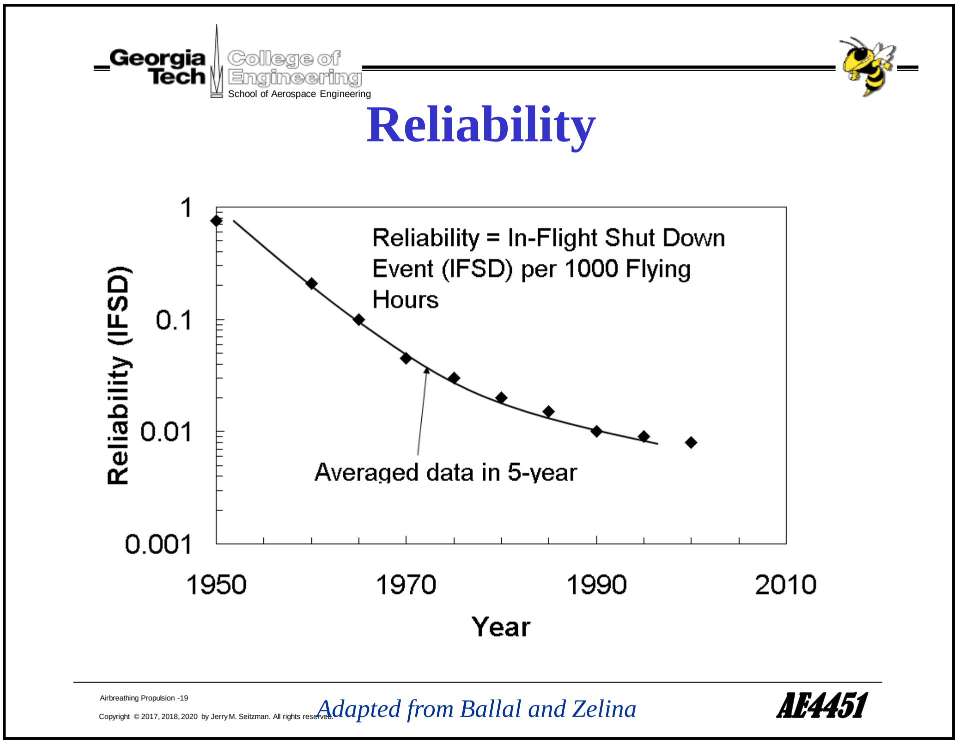
Adapted from Ballal and Zelina



Life on Wing

- *Early jet engines lasted <10 hours*
- *Modern civil engines can stay on wing for >10,000 hours*
- *Military engines last up to 800 hours*

Adapted from Ballal and Zelina



Reliability

Adapted from Ballal and Zelina