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Jet and Rocket Propulsion

AE4451

LECTURE 11

Sedina Tsikata – February 3, 2023

Overview

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what we saw last time:

- cycle analysis
  - in-class example determining product composition where iteration necessary
    - idea:
      - find mole fractions using imposed combustion temperature
      - find enthalpy release and compare to expected
      - if different, give another temperature estimate and recalculate

today:

- efficiencies and other performance metrics
- performance progress for air-breathing technologies

Air-breathing system performance

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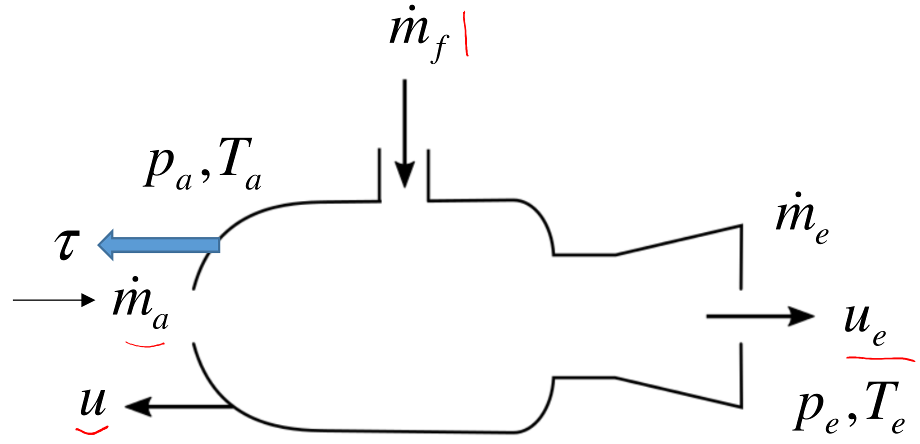
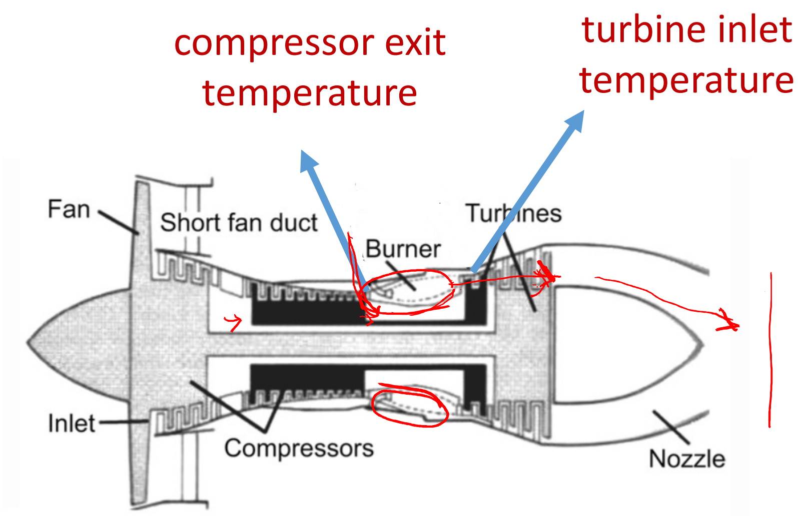
- Thermal efficiency

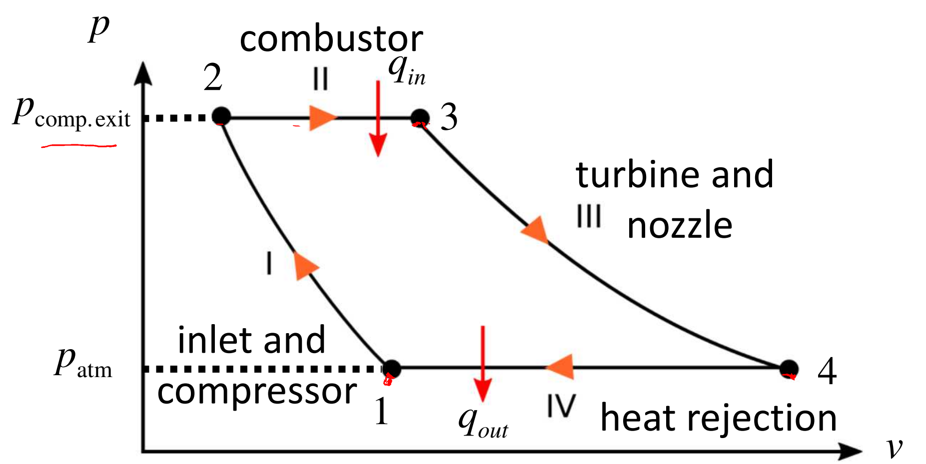
efficiency of conversion of fuel energy to k.e or shaft work

$$\eta_{th} = \frac{(1+f)u_e^2 - u^2}{2 f \Delta h_R} \qquad \eta_{th} \equiv \frac{\dot{W}_{shaft}}{\dot{m}_f \Delta h_R}$$

fuel to air ratio (f)







Air-breathing system performance

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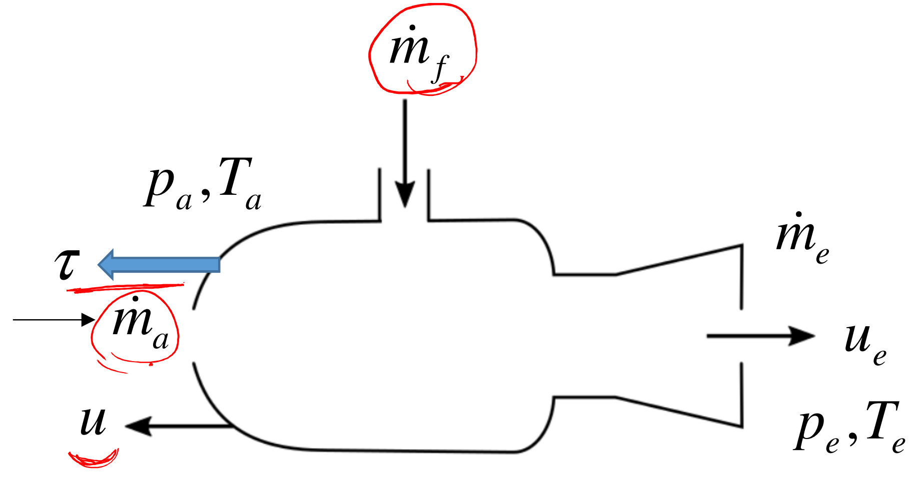
- Propulsive efficiency

a measure of how effective the system is in producing thrust

$$\eta_p = \frac{\tau u}{\Delta \dot{KE}}$$



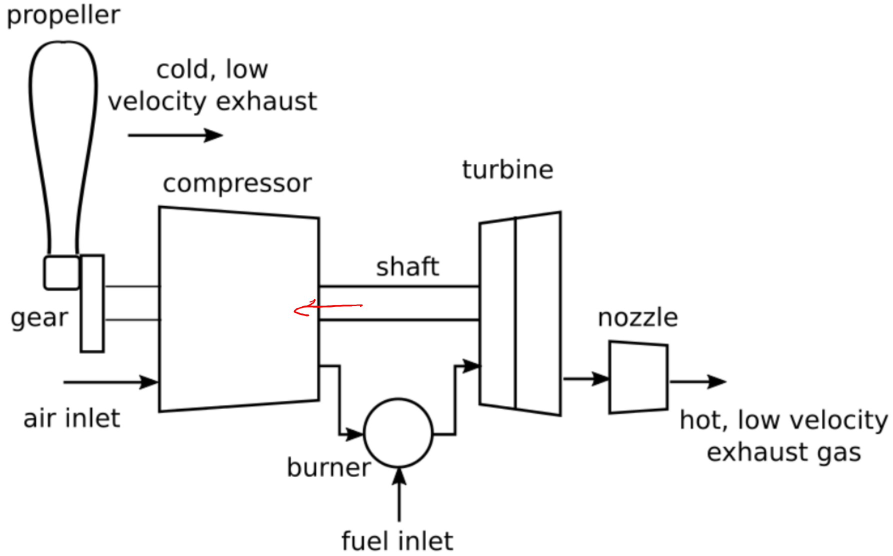
$$\Delta \dot{KE} = \frac{1}{2}(\dot{m}_a + \dot{m}_f)u_e^2 - \frac{1}{2}\dot{m}_a u^2$$ while specific thrust is $$\frac{\tau}{\dot{m}_a} = [(1+f)u_e - u] + \frac{(p_e - p_a)A_e}{\dot{m}_a}$$

if $p_e = p_a$ then $$\eta_p = \frac{2(\tau/\dot{m}_a)u}{(1+f)u_e^2 - u^2}$$ or $$\eta_p = 2\frac{(1+f)u_e/u - 1}{(1+f)(u_e/u)^2 - 1}$$

Air-breathing system performance

- Propulsive efficiency

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



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

τ_{pr} thrust from propeller

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

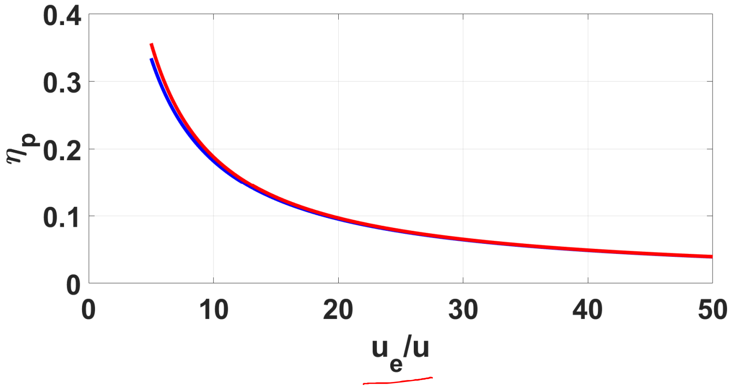
$$\dot{W}_{shaft,equiv} = \dot{W}_{shaft}\left(1 + \frac{\tau_{nozzle}}{\tau_{pr}}\right)$$

$$\text{then } \eta_{pr} \equiv \frac{\tau u}{\dot{W}_{shaft,equiv}}$$

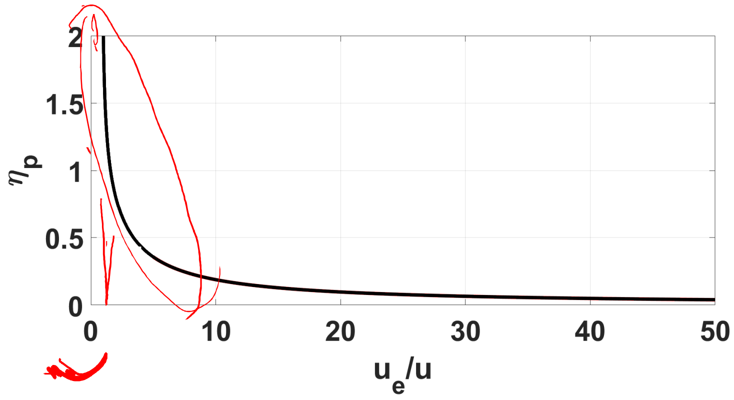
Air-breathing system performance

- Propulsive efficiency η_p

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



- f of 0.01 and 0.5
- here, significant increase in f leads to only minimal change to efficiency
- efficiency decreasing as $u_e \gg u$



- f of 0.5
- here, as $u_e \rightarrow u$, efficiency increasing
- η_p can be > 1 since fuel is being ejected

Air-breathing system performance

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- Simplified expressions for the propulsive and thermal efficiencies

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

assuming f << 1 (usually the case),

$\frac{\text{fuel}}{\text{air}} \sim$ few %

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

thus

$$\eta_p \approx \frac{2u}{(u_e + u)}$$

This assumption also gives, for the thermal efficiency,

$$\eta_{th} = \frac{(1+f)u_e^2 - u^2}{2f\Delta h_R} \Rightarrow \eta_{th} = \frac{u_e^2 - u^2}{2f\Delta h_R}$$

$f \ll 1$

Air-breathing system performance

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- Let's consider both efficiency contributions

in terms of the kinetic energy, we saw earlier:

$$\eta_{th} = \frac{\Delta \dot{KE}}{m_f \Delta h_R} \quad \text{and} \quad \eta_p = \frac{\tau u}{\Delta \dot{KE}}$$

previously, we saw the overall efficiency

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

i.e. thrust power/heating rate from fuel

for thrust producing engines

or, simply:

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

(for turboprop) $\eta_o = \eta_{th} n_{pr}$

$$(\eta_o = \eta_{th}\eta_p\eta_{tr})$$

η_{tr} transmission efficiency close to 1

i.e., we only need to know two of the efficiencies to find the third

Specific fuel consumption, SFC

- How much does a given amount of thrust cost in fuel?

lower specific fuel consumption (SFC) → greater aircraft range

thrust specific fuel consumption (TSFC), or just SFC

$$TSFC \equiv \frac{\dot{m}_f}{\tau}$$

since $\eta_o \equiv \dfrac{\tau u}{\dot{m}_f \Delta h_R}$ (overall efficiency)

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

can also write TSFC in terms of the specific thrust,

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

(fuel/air ratio)

Specific fuel consumption, SFC

- as before, we need to consider equivalent expressions for turboshaft engines,

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

"brake specific fuel consumption (BSFC)"

- 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

Aircraft range

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- the aircraft range is another way to express the aircraft fuel efficiency

- it can be calculated from the Breguet range equation:

$$\text{aircraft range} = \frac{u}{TSFC}\left(\frac{Lift}{Drag}\right)\ln\left(\frac{W_{fuel}}{W_{PL}+W_0}\right)$$

W_{fuel} = fuel weight

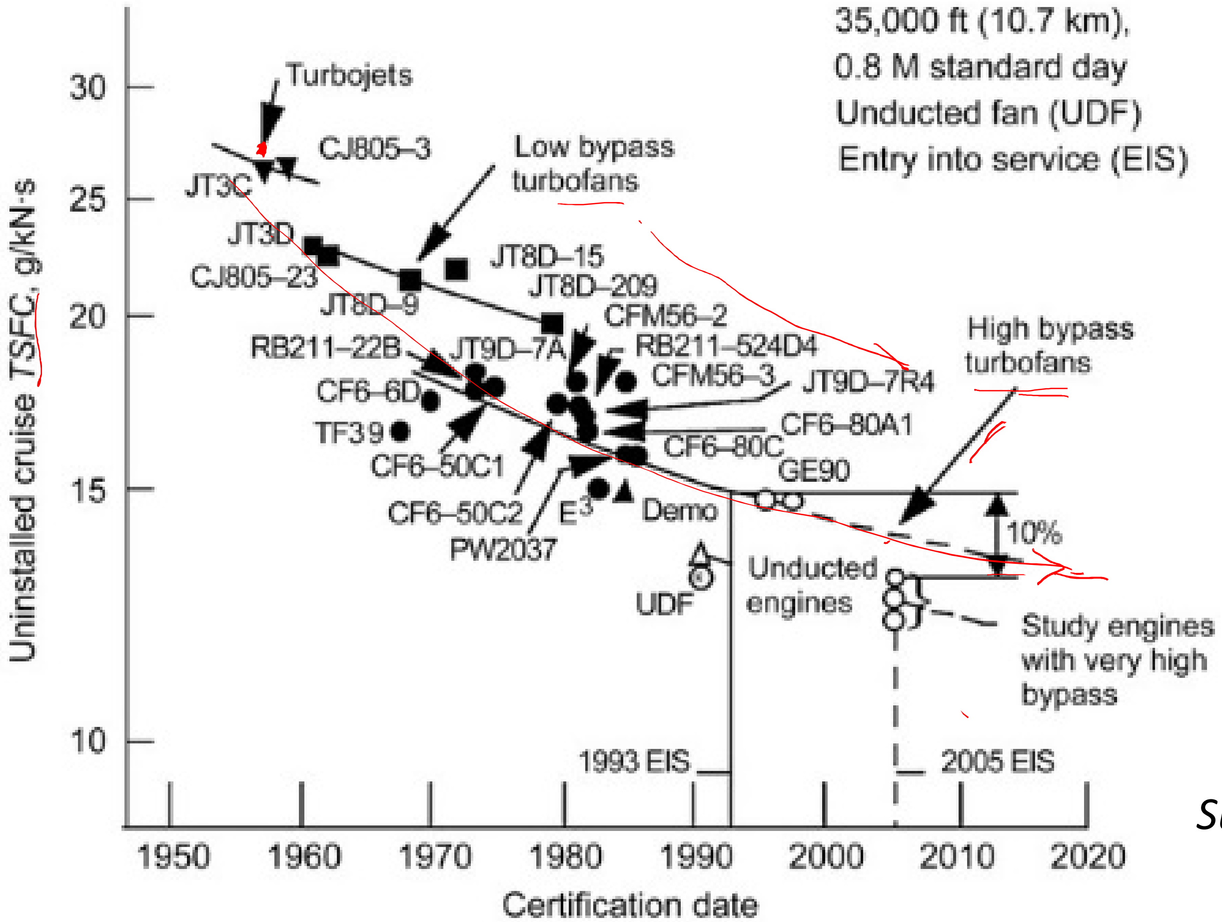
W_{PL} = payload weight

W_0 = aircraft empty weight

- improvements in range chiefly from:
  - decrease in TSFC
  - decrease in engine weight

Jet engine performance history

- uninstalled TSFC versus engine certification date



$$TSFC \equiv \frac{\dot{m}_f}{\tau}$$

"uninstalled" thrust: measured with thruster system not attached to vehicle

Suder and Heidmann, 2018

Jet engine performance history

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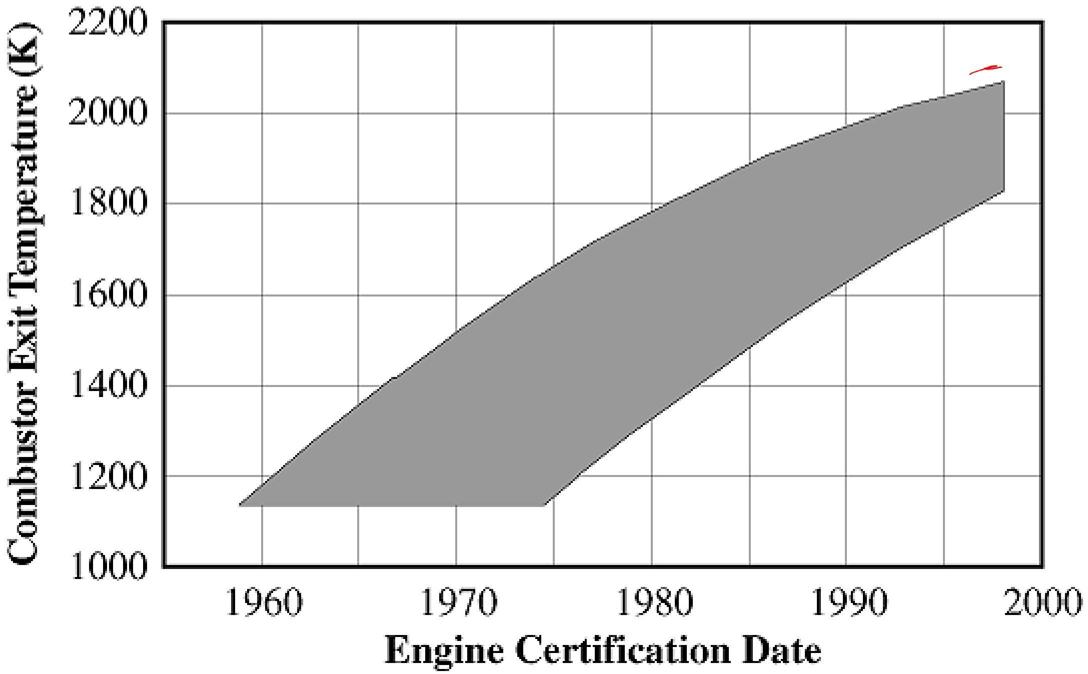
- combustor exit temperature



$$\eta_B = 1 - \frac{T_1}{T_2} = 1 - \frac{T_{\text{atmosphere}}}{T_{\text{compressor exit}}}$$

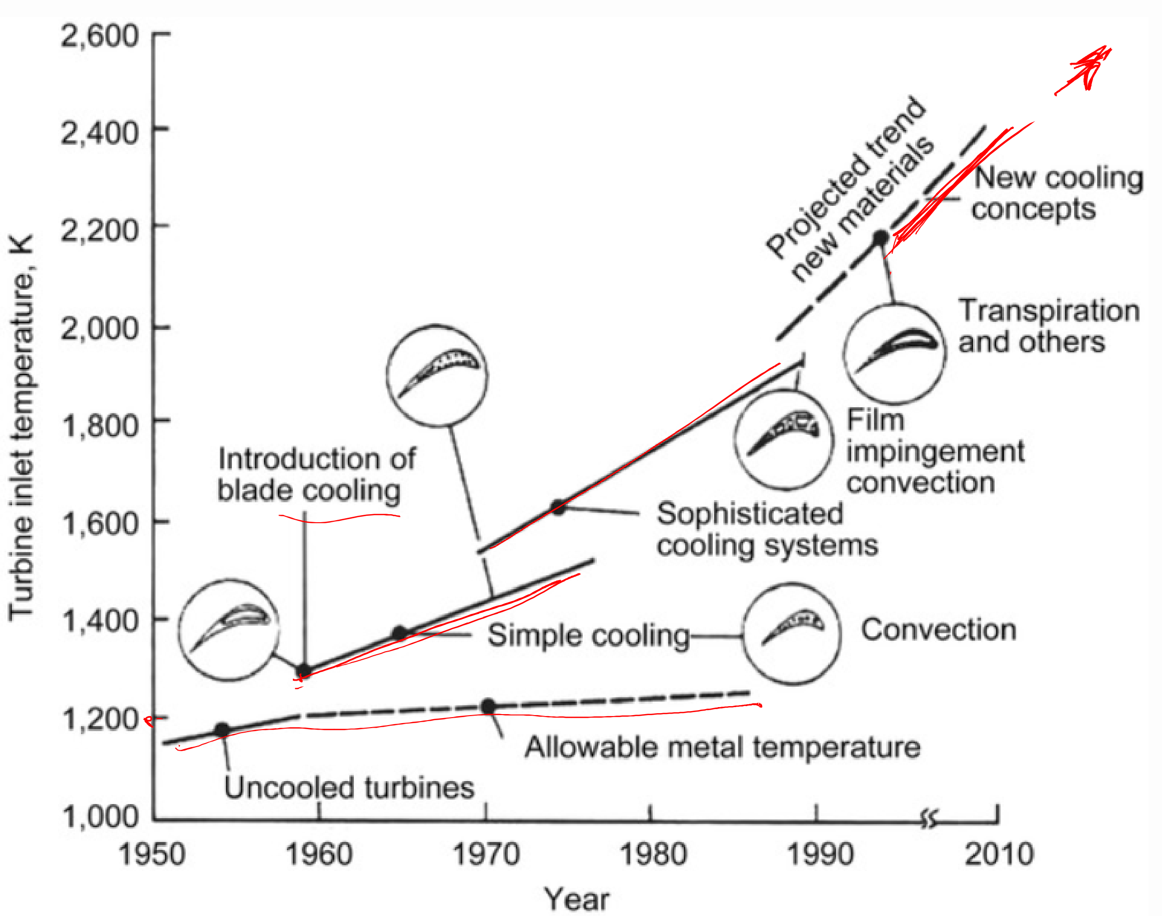
- notice this thermal efficiency was based on the compressor exit temperature (< the combustor exit temperature)

- compressor exit temperature limited to ~ 1000 K

- turbine inlet temperature limited to ~ 2000 K

Jet engine performance history

- turbine inlet temperature



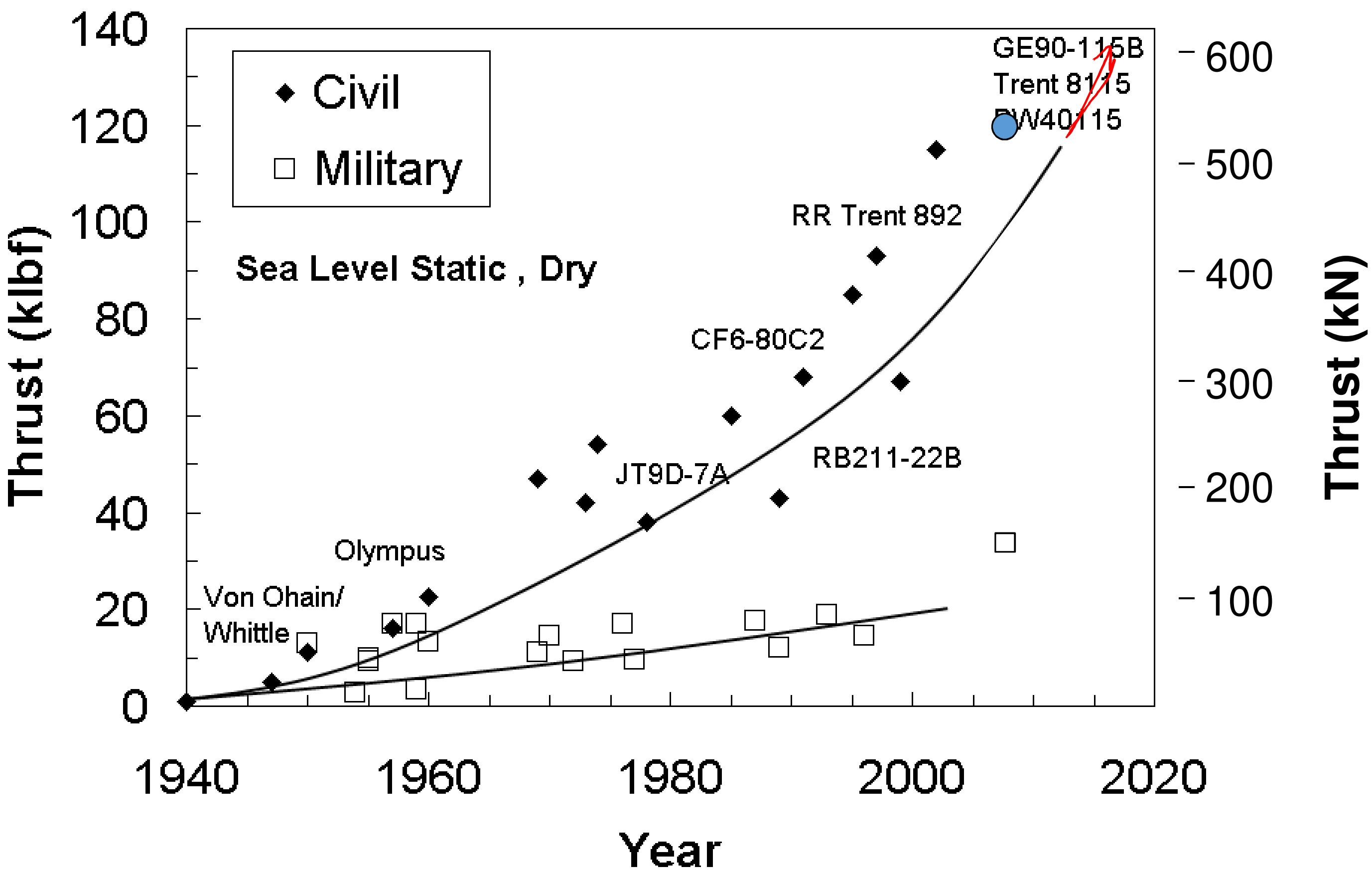
- advanced cooling systems have allowed the turbine inlet temperatures to be increased

recently: thermal barrier coatings (ceramic coatings providing insulation)

- in future: ceramic base materials

Jet engine performance history

- evolution in thrust level



Ballal and Zelina, 2003

- since 1939, static thrust increase by > 110 × for civil engines and 20 × for military engines

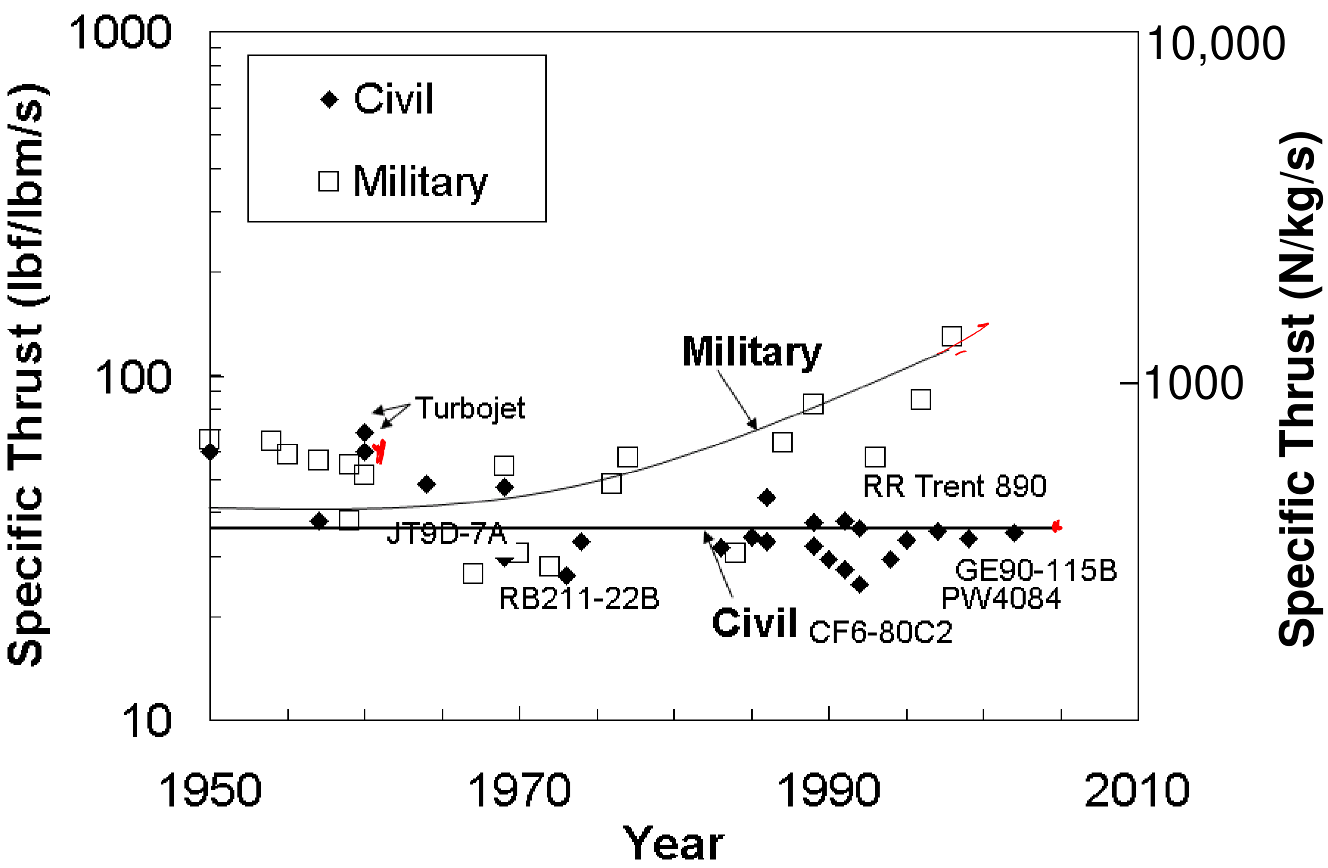
- 1903:
  - 134 lbf Wright Flyer

- 1939:
  - 1,000 lbf (~4450N) von Ohain/Whittle

- 2004:
  - 35,000 lbf Military Engine
  - 115,000 lbf (GE90-115B) tested up to 120,000 lbf

Jet engine performance history

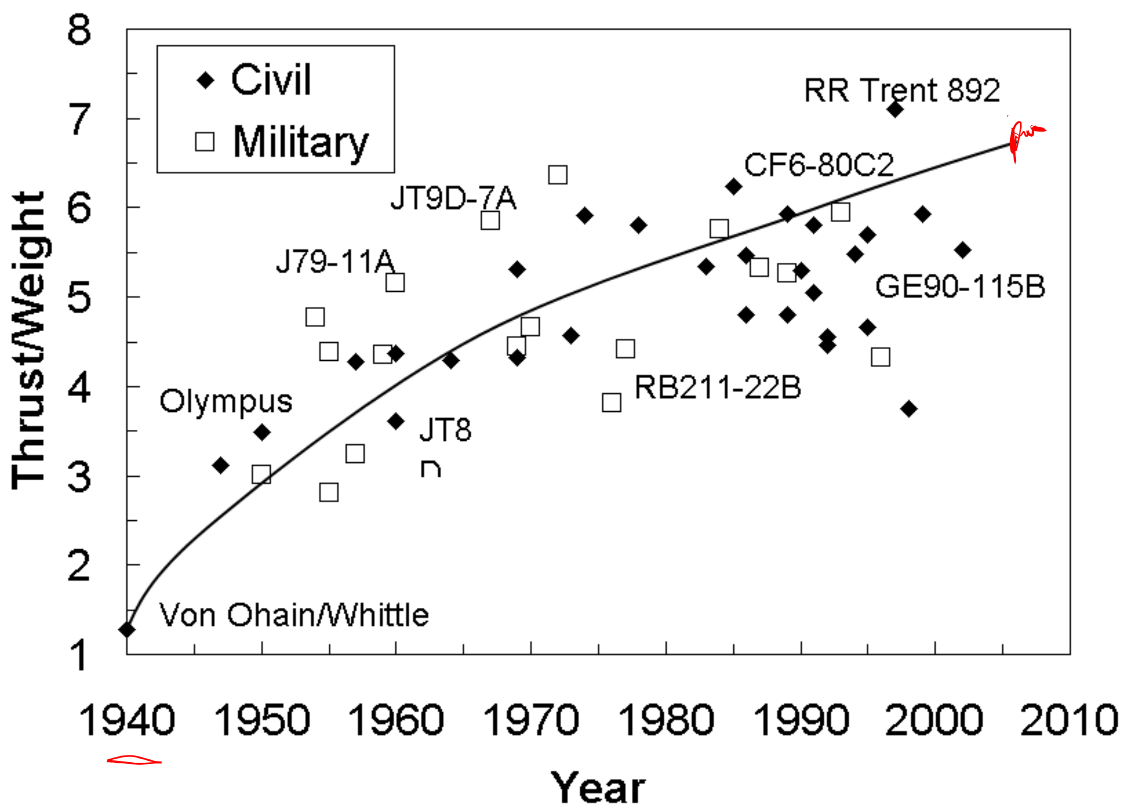
- evolution in specific thrust level



Ballal and Zelina, 2003

Jet engine performance history

- thrust-to-weight evolution



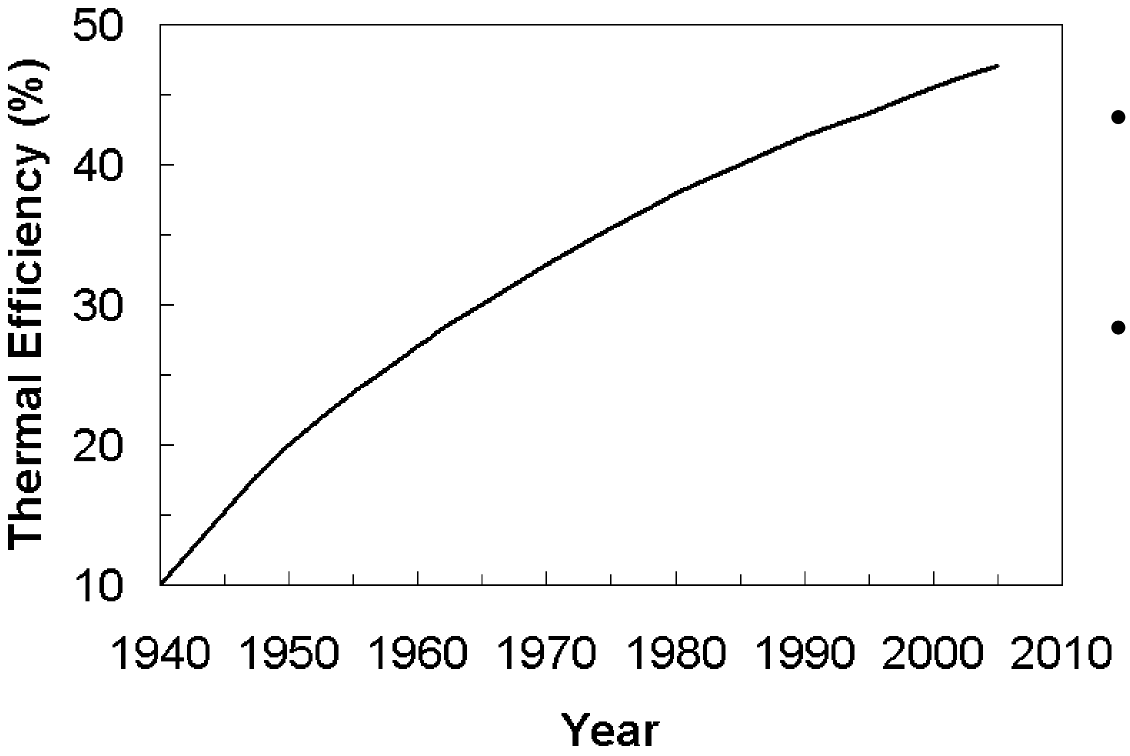
- 1903: 0.67
  Wright Flyer
- 1939: 1.2
  von Ohain/Whittle
- 2003: 6.5
  Military Engine
- 2003: 7
  Rolls Royce Trent

for comparison, ~85 for Saturn V F-1 Engine

Ballal and Zelina, 2003

Jet engine performance history

- evolution in efficiency



$$\eta_{th} = \frac{\Delta \dot{KE}}{m_f \Delta h_R}$$

- modern aeroengine thermal efficiency approaching 50%

- for overall efficiency $\eta_o \equiv \dfrac{\tau u}{\dot{m}_f \Delta h_R}$

1903: 10% (Wright Flyer)

1939: 15% (von Ohain and Whittle)

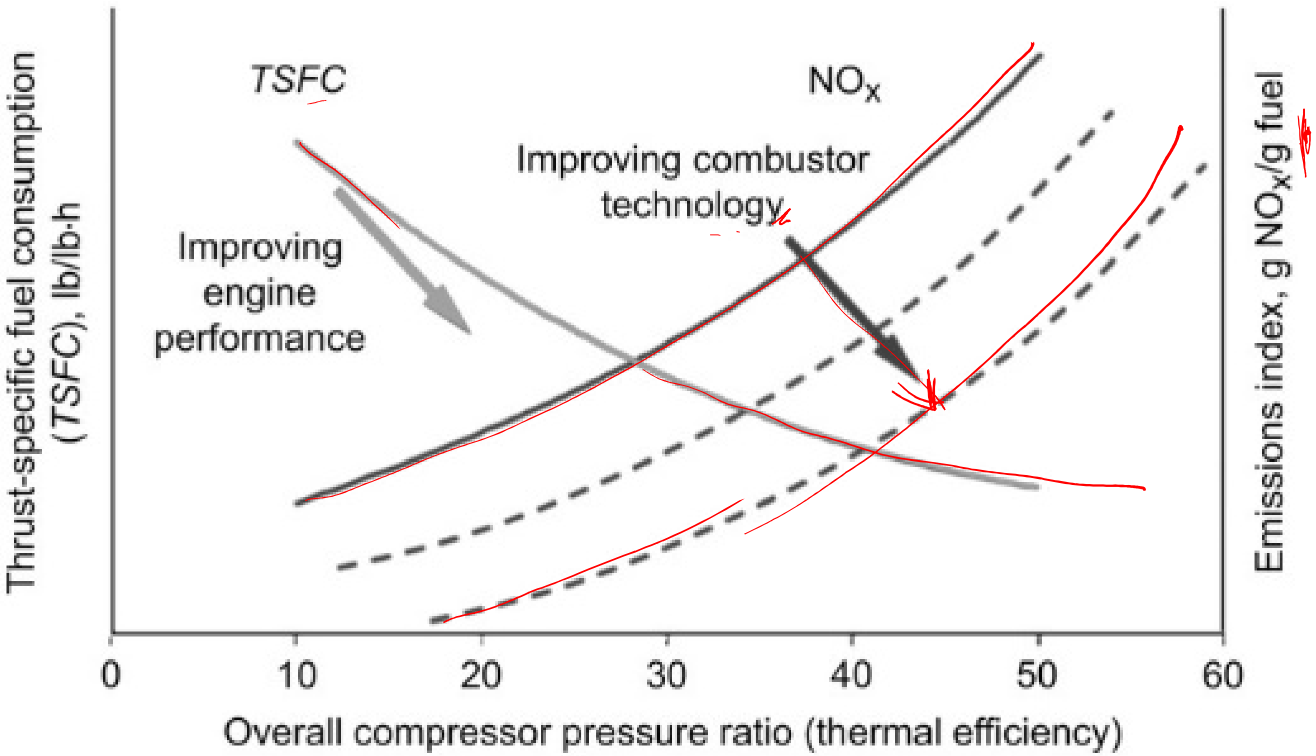
2003: 30% (Military Engine)

40% (Civil Engine)

Ballal and Zelina, 2003

Jet engine performance history

- evolution in emissions



- increasing cycle temperature good for thermal efficiency, but increases NOx emissions
- NOx from nitrogen and oxygen reaction during combustion of fuels in air

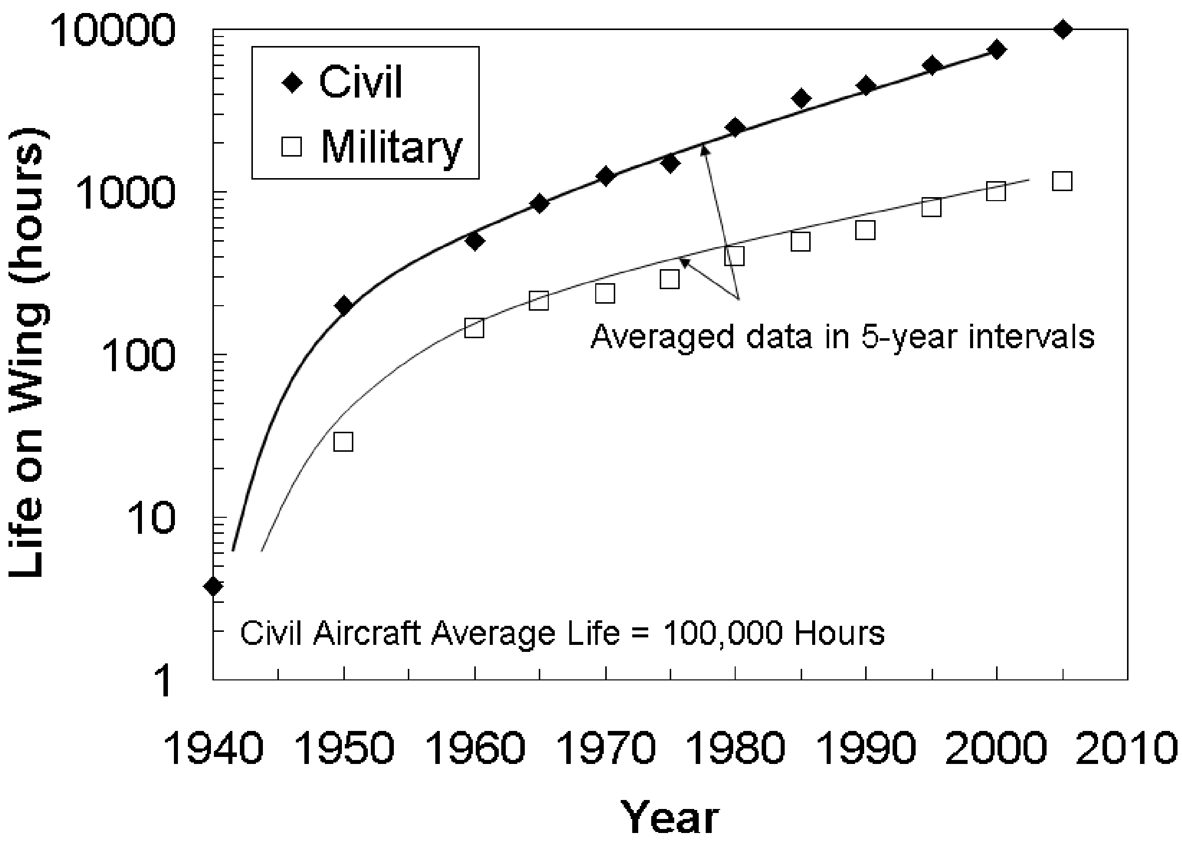
$$\eta_B = 1 - \frac{T_1}{T_2} = 1 - \frac{T_{\text{atmosphere}}}{T_{\text{compressor exit}}}$$

$$\eta_B = 1 - \frac{1}{TR} = 1 - \frac{1}{PR^{(\gamma-1)/\gamma}}$$

Routledge, 2017

Jet engine performance history

- 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

Ballal and Zelina, 2003

Jet engine performance history

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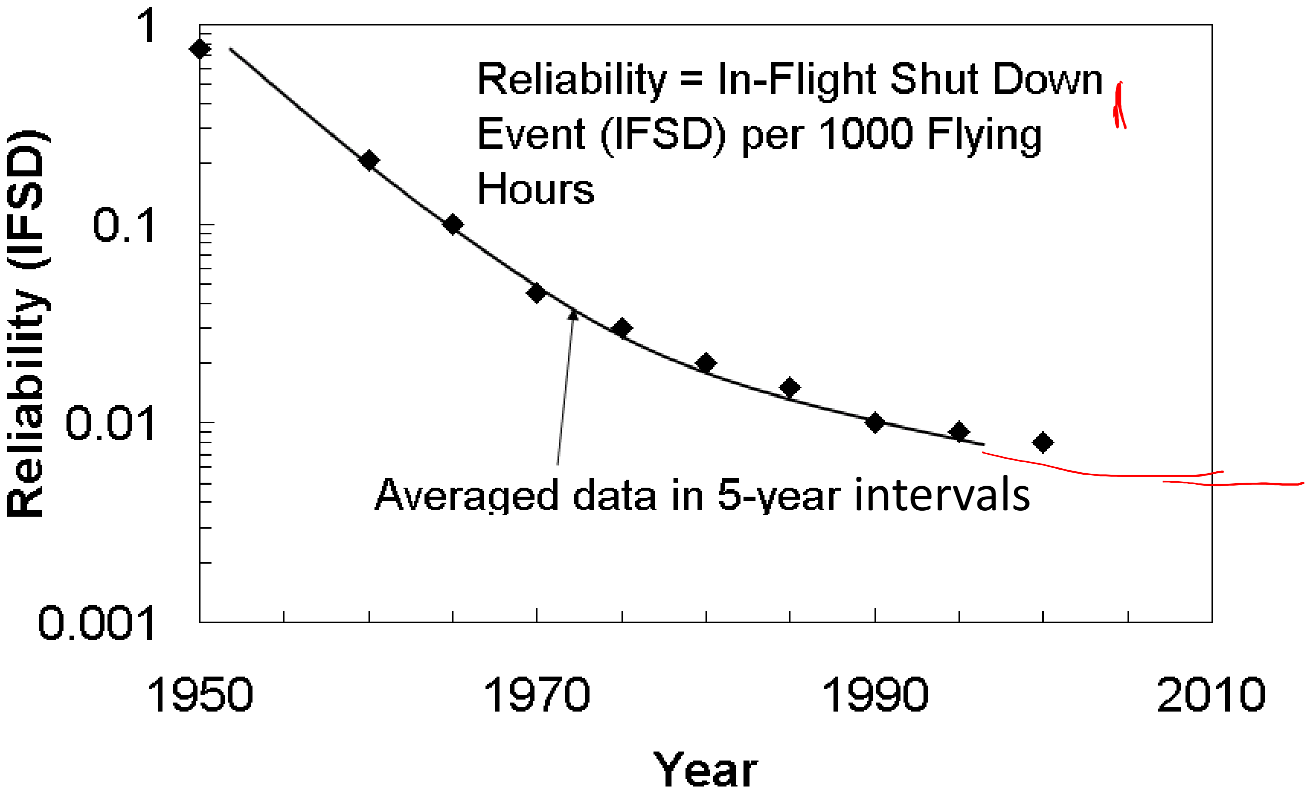
- reliability



Ballal and Zelina, 2003