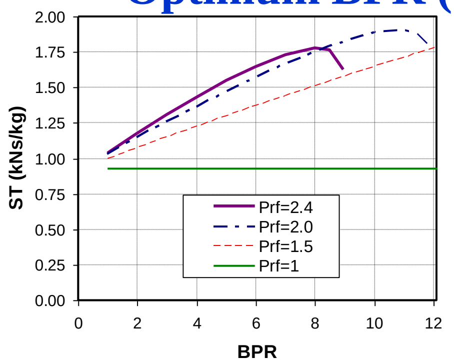
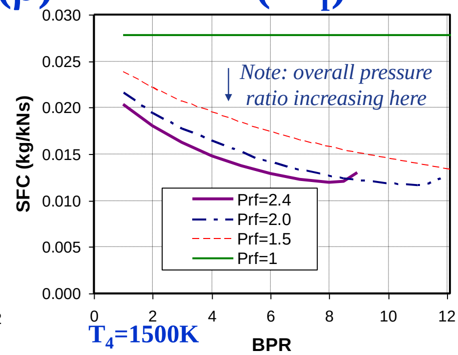
Optimum BPR (β) and FPR (Pr_f)

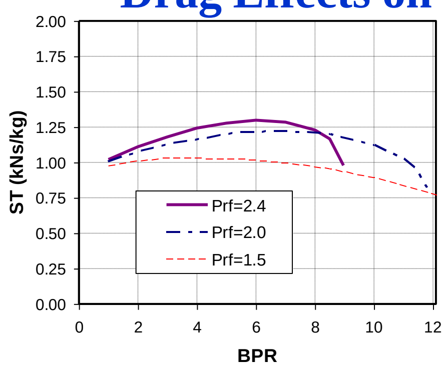


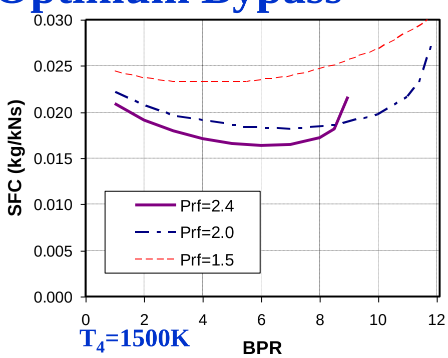


T_4=1500K
Pr_c=20
M=0.85

- Results for ideal turbofan
  - "optimum" BPR depends on FPR (+ M, T_4, Pr_c) e.g., 10-20 here for $Pr_f < 2$
- Thrust drops at high BPR (and SFC increases) due to __?
- Actual "optimum" also depends on component η's AND

Drag Effects on Optimum Bypass





T_4=1500K
Pr_c=20
M=0.85

- Results for ideal turbofan, **but**
  - includes additional drag induced with larger inlet
- Changes "optimum" bypass ratio now 4-7 for $Pr_f < 2$

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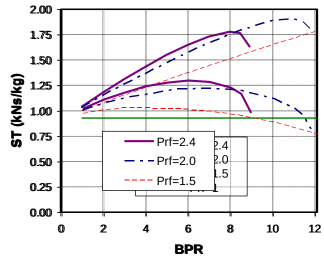
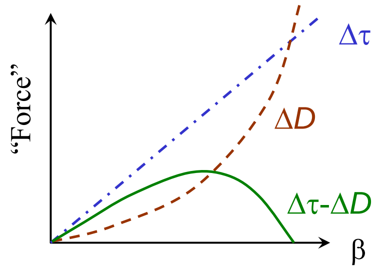
Effective Thrust

- Added thrust ($\Delta\tau$) developed with bypass scales roughly linearly with bypass ratio β
- Drag induced in flight (for given *u*, altitude, …) increases with inlet size
  - and larger inlet needed as β increases
    - *if core size not reduced*
  - increased drag (ΔD)$\propto\beta^n$ with $n>1$
- Effective thrust increment is difference, $\Delta\tau$-ΔD





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Takeoff vs. Cruise Bypass

- **Takeoff**
  - usually maximum power requirement (commercial/civilian aircraft)
    high thrust need
  - relatively low aircraft velocity ($D \propto u^2$)
    low drag conditions

  ⇒Effective thrust is large
- **Cruise**
  - low thrust required (less β needed) and higher drag conditions **higher effective thrust penalty**
- **Optimum bypass ??? (tradeoff)**

Other Issues Related to Turbofans

- **Clearance**
  - larger bypass (without reducing core size) limits engine placement
- **Noise**
  - lower jet exit velocities greatly reduce engine noise
- **Nozzles**
  - mixed exhaust vs. separate nozzles (thrust and noise improvements)
- **Optimum Operating RPM**
  - large fans typically do not operate "optimally" at the same RPMs as the smaller compressors
    - advantages if they are driven by independent turbine OR geared down

What are Typical Values for Turbofans?

- What are typical values for bypass ratios and pressure ratios?
- How has turbofan development impacted jet engine emissions (noise, pollutants)
- How have these changed over time?

- The following information is adapted from *Progress in Aero Engine Technology (1939-2003)* by Dilip R. Ballal (University of Dayton) and Joseph Zelina (AFRL)

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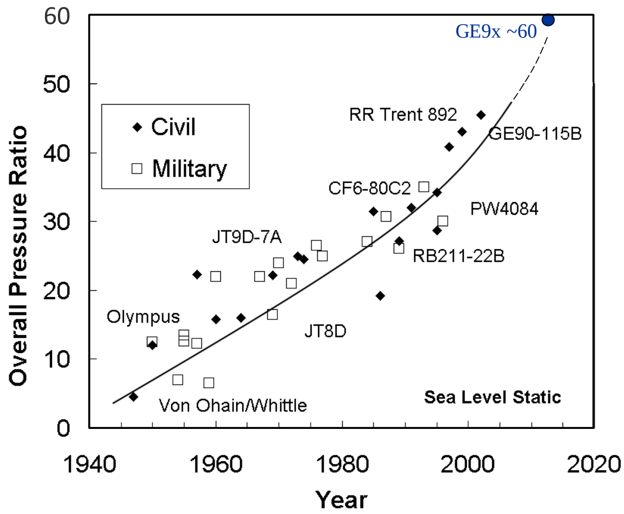
Overall Pressure Ratio (OPR)

- Increases from
  - # stages
  - increasing *p* ratio per stage
- Current technology
  - max. OPR ~50-60



Adapted from Ballal and Zelina

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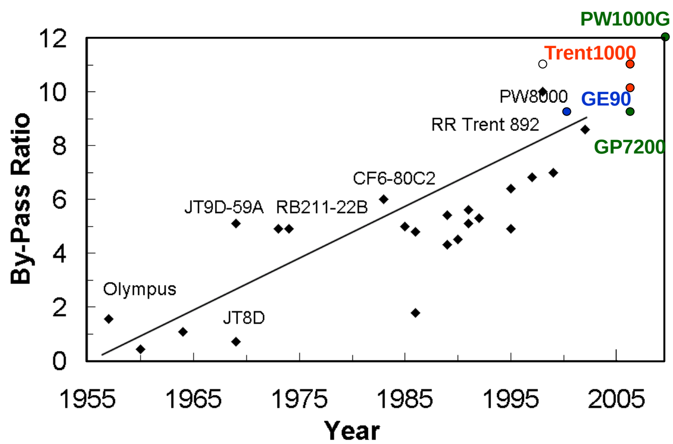
Bypass Ratio (BPR)

- Current technology max. BPR ~12-13



Adapted from Ballal and Zelina

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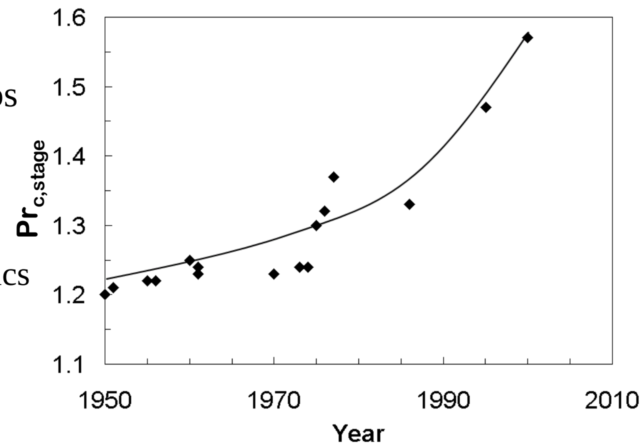
Compressor Stage Pressure Ratio

- Higher stage pressure ratios due to improved blade design
  - aerodynamics
  - materials



Adapted from Ballal and Zelina

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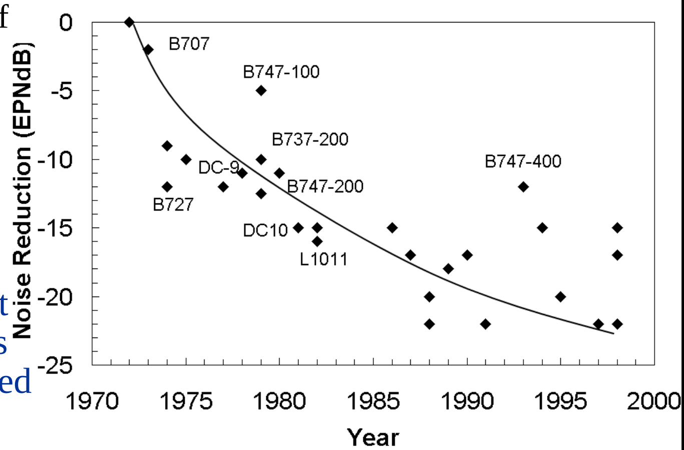
Engine Noise Reduction

- **EPNdB** ≡ effective perceived noise in decibels
  - measure of relative noise of aircraft pass-by event
- Drop due in great part to turbofans and increased BPRs



Adapted from Ballal and Zelina

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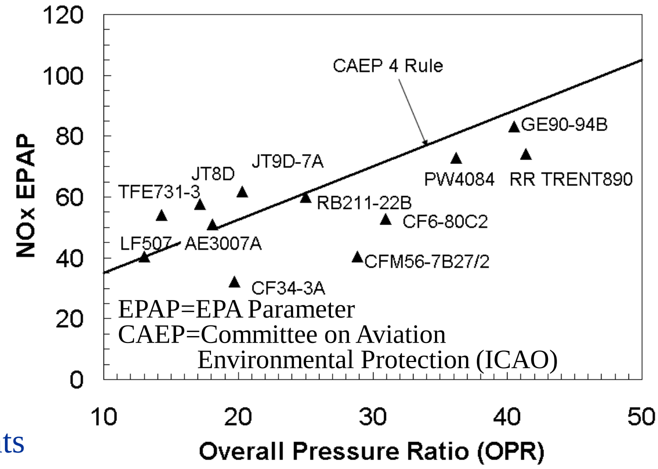
NOx Emissions

- EPAP measures g of NOx emitted per kN of thrust
- Reduction due to decreasing SFC and combustor improvements



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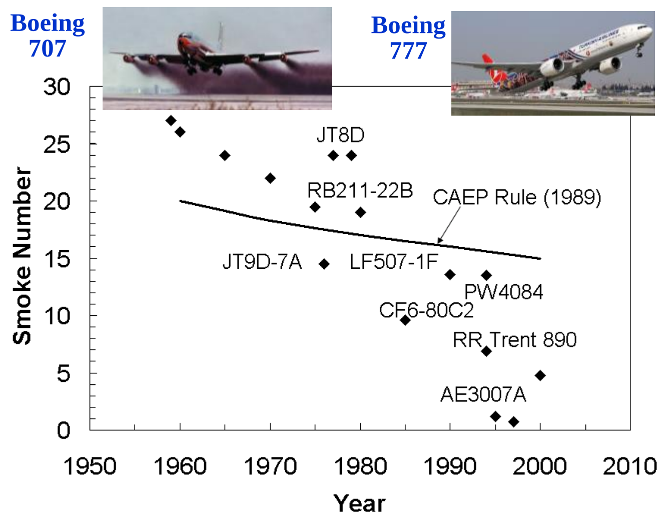
Smoke Number

- "Measure" of amount/ size of soot emitted by engine
- Reduction due to improved combustor designs



Adapted from Ballal and Zelina