TURBOFAN ENGINE

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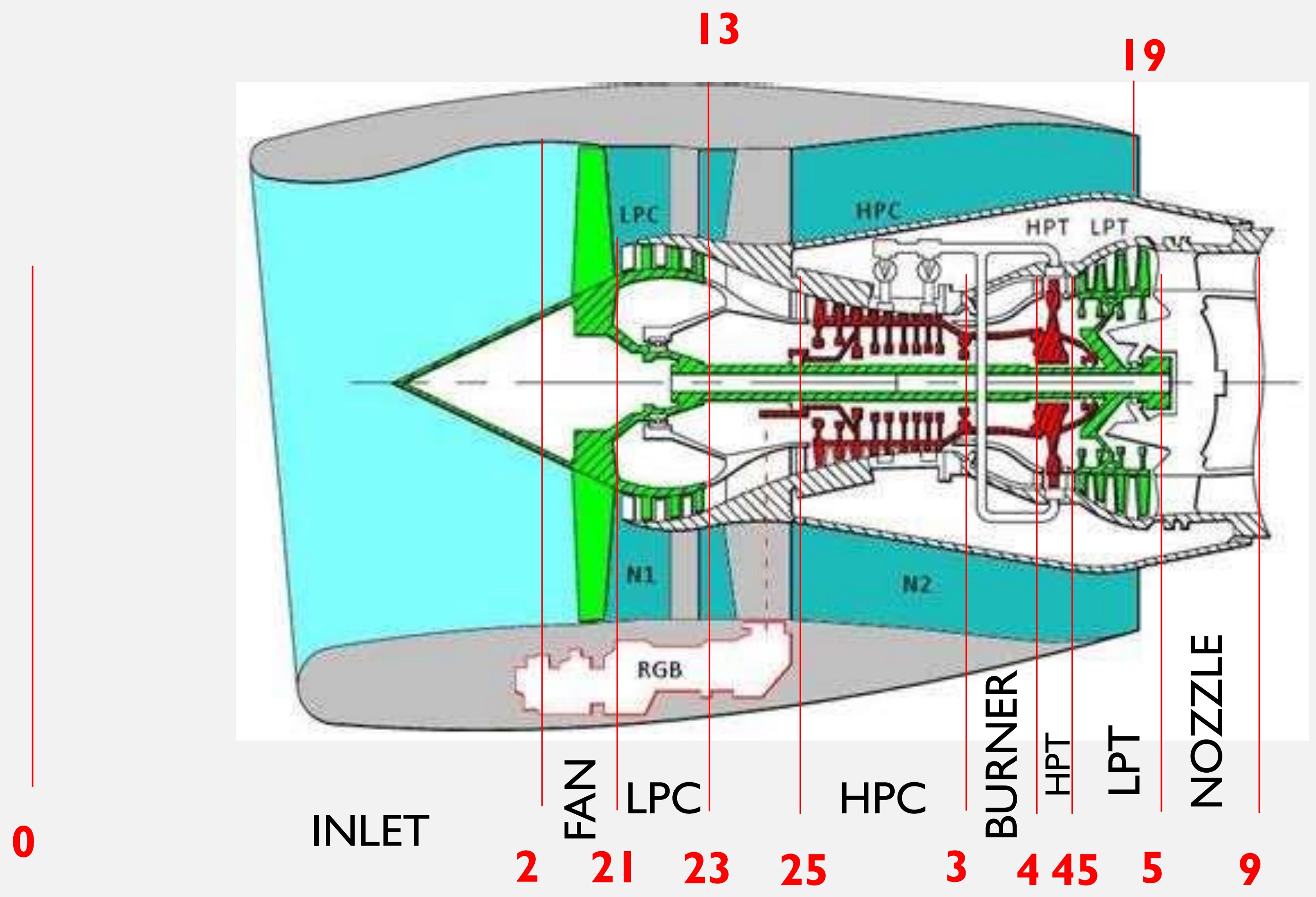
LITERATURE:

- **Jack D. Mattingly, Elements of Propulsion: Gas Turbines and Rockets, AIAA Education Series 2006 (Chapter 7)**
- **Jack D. Mattingly, Elements of Gas Turbine Propulsion, Tata McGraw Hill Education Private Limited, 2013 (Chapter 7)**
- **Gordon C. Oates, Aerothermodynamics of Gas Turbine and Rocket Propulsion, AIAA Education Series, 1997 (Chapter 7)**

CLASSICAL TURBOFAN ENGINE



TURBOFAN ENGINES REVIEW

MIDDLE BPR TURBOFAN ENGINE

JT15D-5D

$T_{take\ off}$ = 13,54 kN

SFC=0.55 daN/h

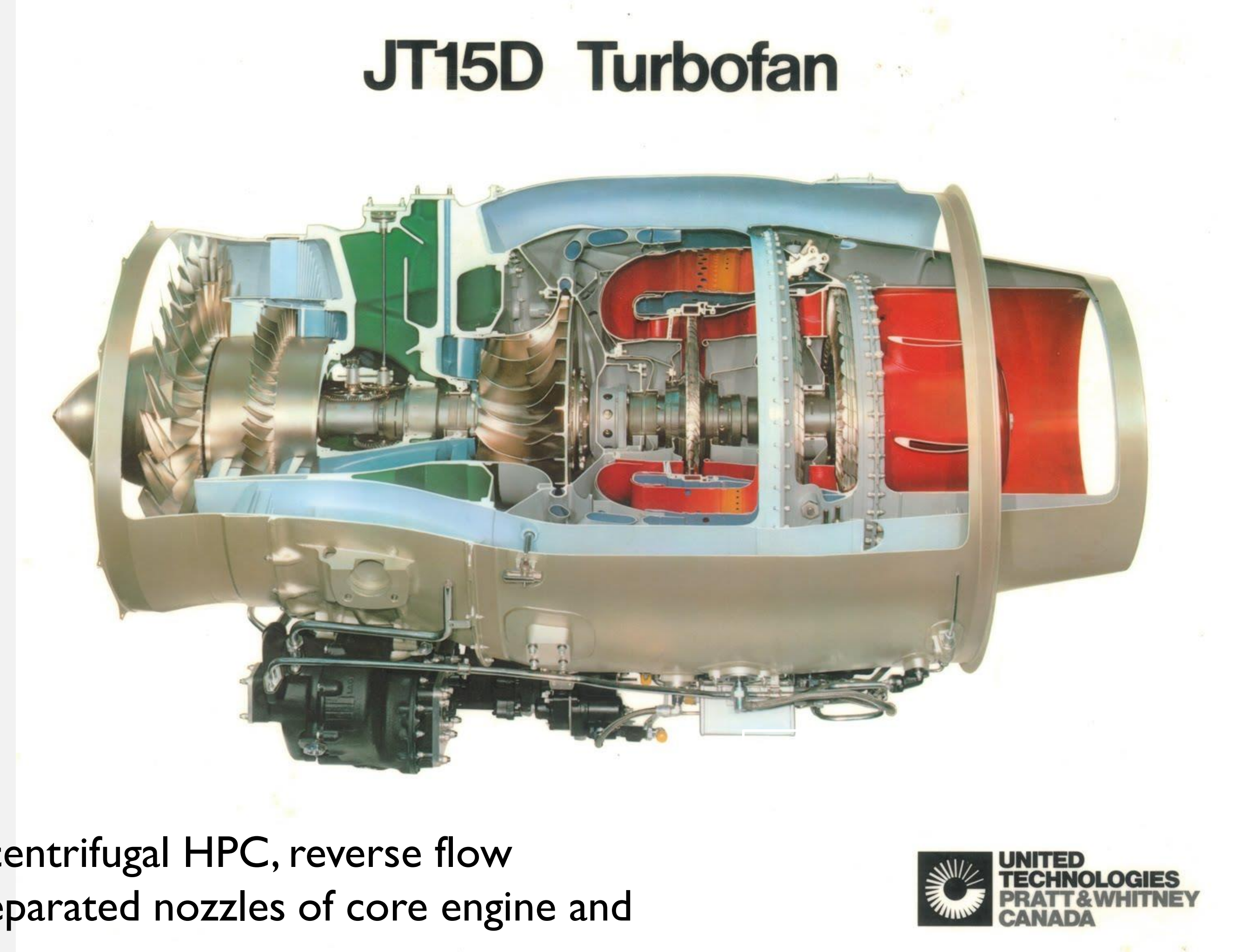
BPR=3,3

Mass = 292,6 kg

Length/Diameter=1531/520mm

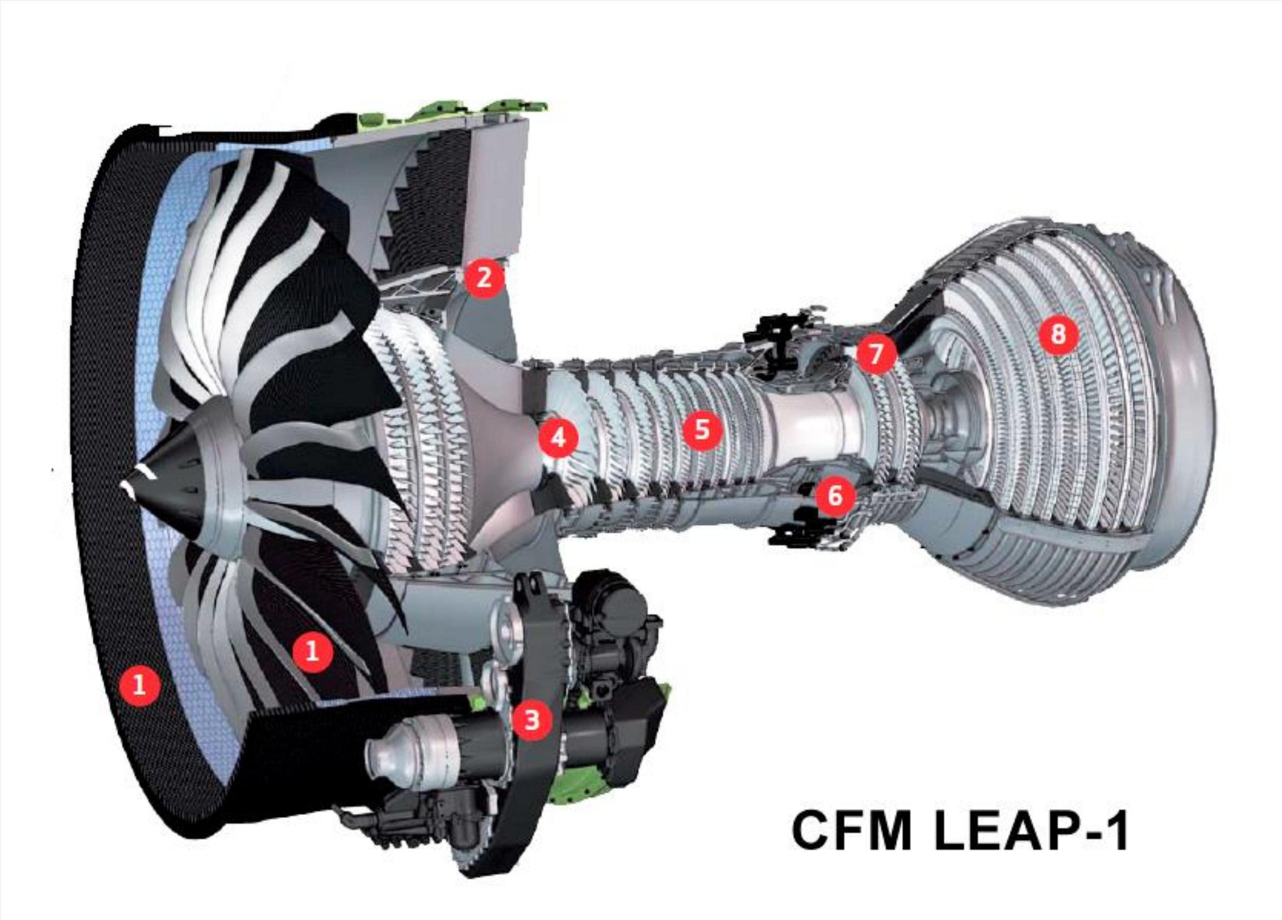
N1=15,900 RPM, N2= 32,760 RPM

Application: Cesna CitationV, Hawker 400



Two shaft engine.
It consist of: single stage fan, single stage LPC, centrifugal HPC, reverse flow combustor, single stage HPT, two stages LPT, separated nozzles of core engine and external duct

HIGH BYPASS-RATIO TURBOFAN



LEAP A1

Compressors: OPR=40:

F – Single stage, LPC – 3 stages, HPC - 10 stages

Combustor – second generation Twin-Annular

Turbines HPT – 2 stages, LPT – 7 stages

BPR 11

Length 3,328 m/ Diameter 1,93 m

MTO 143 kN

MCT 141 kN

N1=3894 RPM, N2=19391 RPM

Application A-320

GEARED TURBOFAN (GTF)

PW1100G

F – 1 stage LPC 3 stage, HPC 8 stage

Turbines: HPT – 2 stages, LPT – 3 stages

Gear 3,3:1

BPR – 12,5

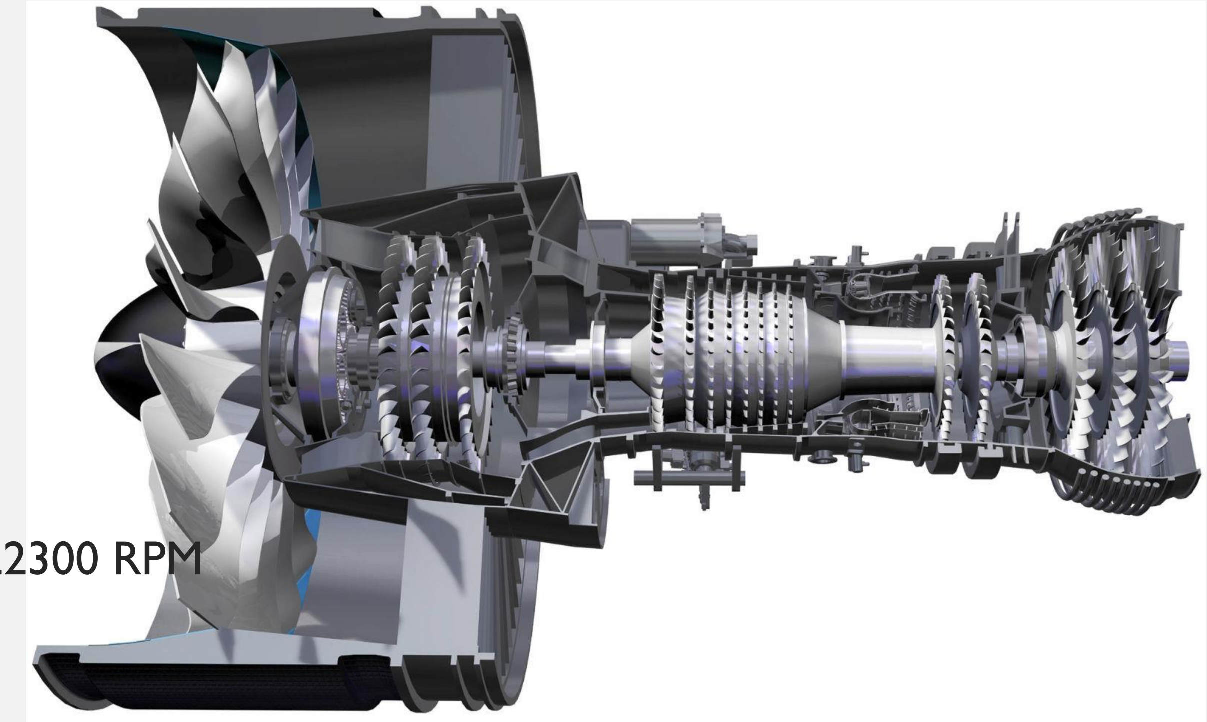
Lenth/Diameter 3,4 m / 2,224 m

Weight 2857 kg

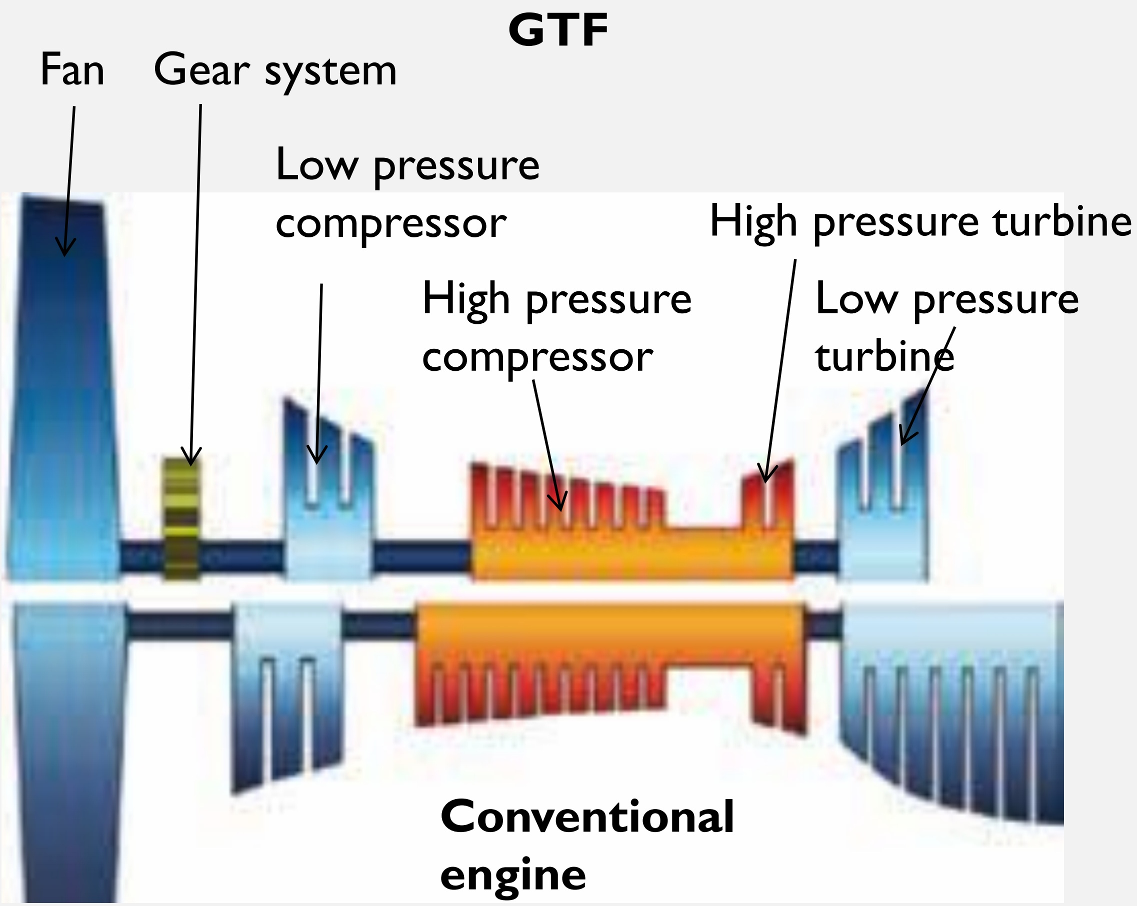
MTO 147 kN (33G) 120 kN (27G) 108 kN (24G)

Rotor speed: Fan – 3281 RPM, LP – 10047 RPM, HP 22300 RPM

Application: A320 Neo



GTF VS CLASSICAL TURBOFAN

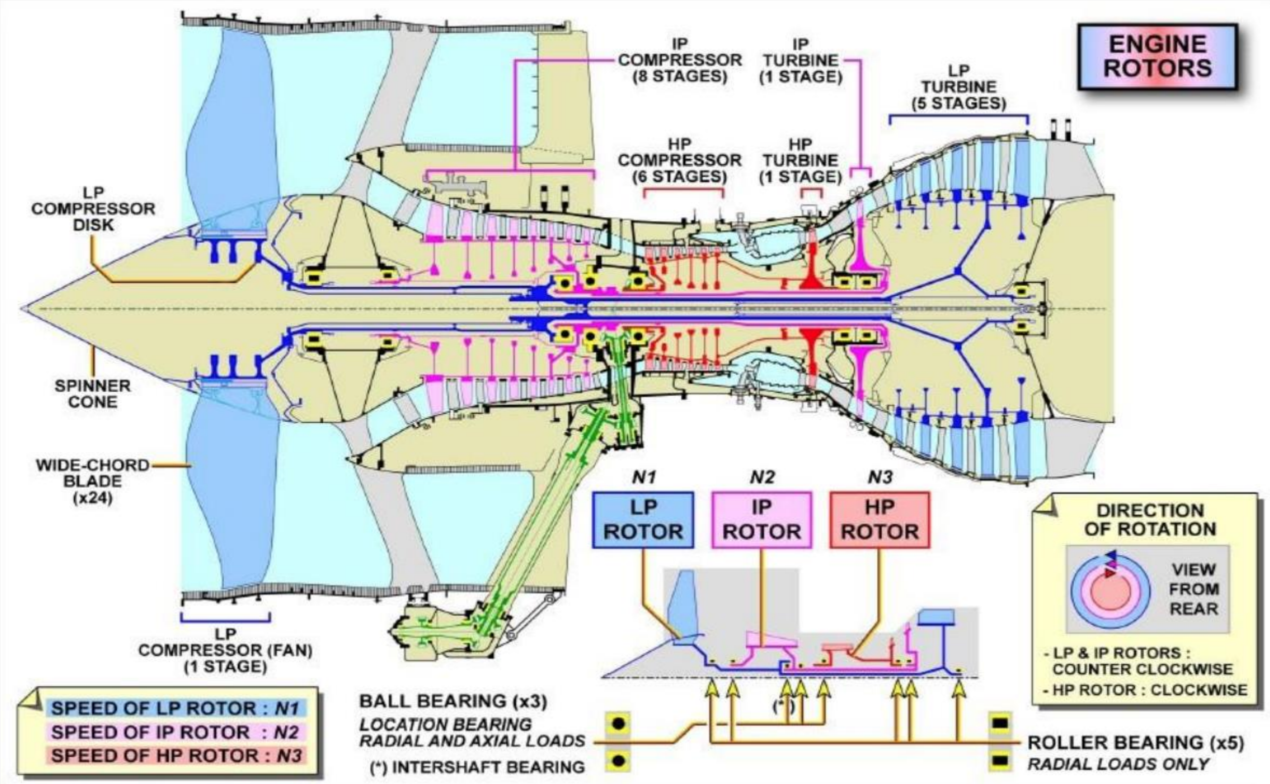


GTF got:

- Higher work of single LPT stage
  - Less LPT stages
- Higher LPC pressure of single stage
  - Less HPT stages

THREE SPOOL TURBOFAN ENGINE

Rolls-Royce Trent 7000



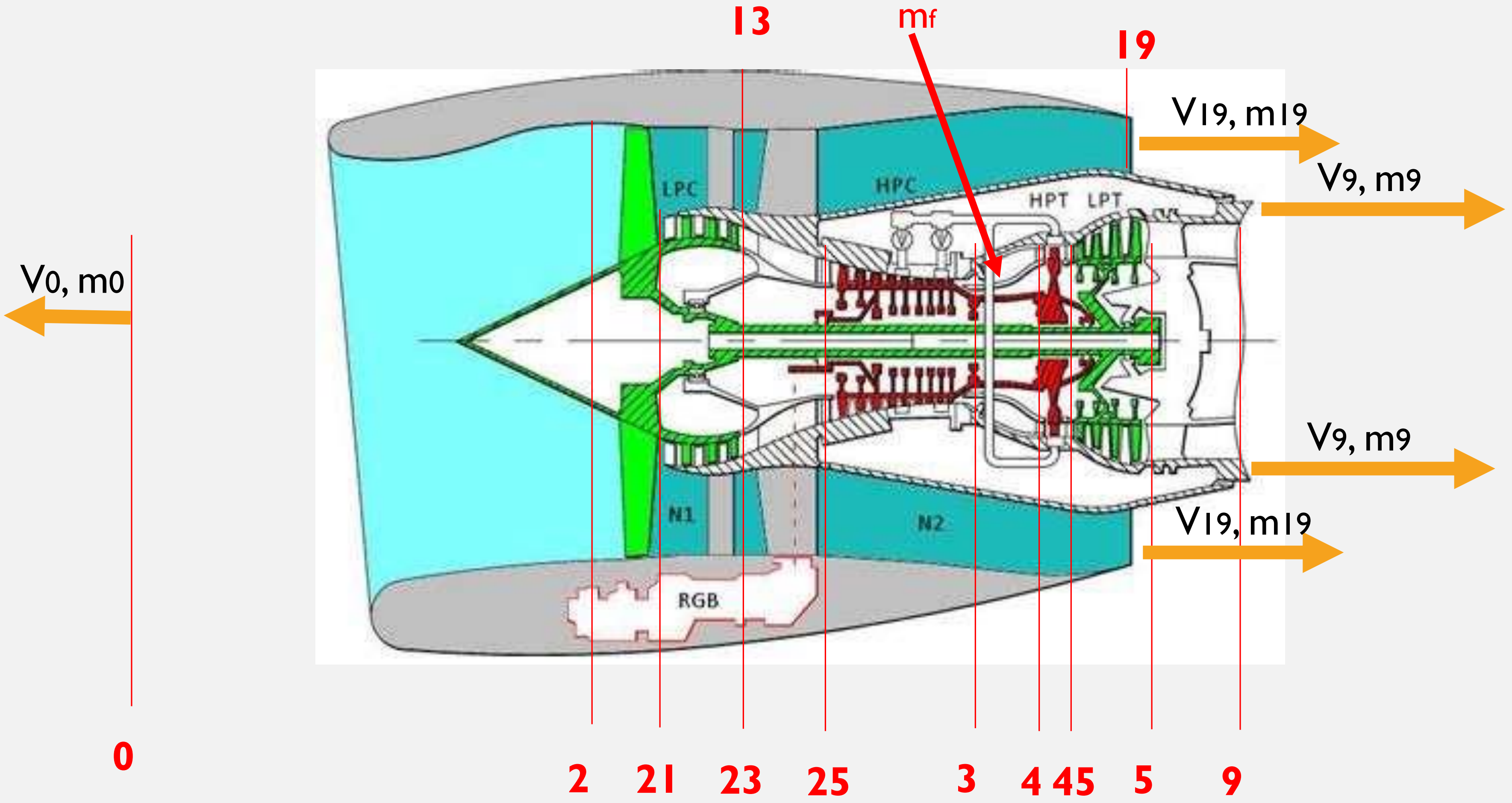
- **MTO:** 324,0 kN / 72 834 lbf
- **MCT:** 289,2 kN / 65 005 lbf
- **Pressure ratio :** 50:1
- **BPR :** 10:1
- **TIT:** > 1835 K (1562 °C; 2843 °F
- **SFC** (curse) = 14,4 g/kN/s
- **Stosunek ciągu do masy :** 5,13
- **Rotation:** (100%):
- HP 13 391 RPM, IP 8937 RPM, LP 2683 RPM

Application: **A330 neo**

<u>Coppressors:</u>
F – single stage
IP – 8 stages
HP – 6 stages

<u>Turbines:</u>
LP – 6 stages
IP – single stage
HP – single stage

TURBOFAN ENGINE THRUST



THTUST

$$T = \dot{m}_9 V_9 + A_9(P_9 - P_0) + \dot{m}_{19} V_{19} + A_{19}(P_{19} - P_0) - \dot{m}_0 V_0$$

effective exhaust velocity

$$V_{e9} = V_9 + A_9(P_9 - P_0)/\dot{m}_9$$

$$V_{e19} = V_{19} + A_{19}(P_{19} - P_0)/\dot{m}_9$$

$$T = \dot{m}_9 V_{e9} + \dot{m}_{19} V_{e19} - \dot{m}_0 V_0$$

Core engine exit mass flow

$$\dot{m}_9 = \dot{m}_{21} + \dot{m}_f$$

External exit mass flow

$$\dot{m}_{19} = \dot{m}_{13}$$

Bypass Ratio $BPR = \frac{\dot{m}_{13}}{\dot{m}_{21}}$

SPECIFIC THRUST AND SPECIFIC FUEL CONSUMPTION

SPECIFIC THRUST

$$ST = T/\dot{m}_0 = \frac{\dot{m}_9 V_{e9} + \dot{m}_{19} V_{e19} - \dot{m}_0 V_0}{\dot{m}_{21} + \dot{m}_{13}} = \frac{(1 + f_B)V_{e9} + BPR * V_{e19} - (1 + BPR)V_0}{1 + BPR}$$

Fuel/air ratio $$f_B = \frac{\dot{m}_f}{\dot{m}_{21}}$$

ST of turbofan engine goes down for higher BPR

SPECIFIC FUEL CONSUMPTION

$$\mathrm{SFC} = \dot{m}_f/T = \frac{\dot{m}_f}{\dot{m}_9 V_{e9} + \dot{m}_{19} V_{e19} - \dot{m}_0 V_0} = \frac{f_B}{(1 + f_B)V_{e9} + BPR * V_{e19} - (1 + BPR)V_0} =$$

$$= \frac{\frac{f_B}{1 + BPR}}{\frac{(1 + f_B)V_{e9} + BPR * V_{e19} - (1 + BPR)V_0}{1 + BPR}} = \frac{f_B}{(1 + BPR) * ST}$$

SFC goes down for higher BPR

TURBOFAN ENGINE EFFICIENCIES

Thermal efficency

$$\eta_{TH} = \frac{\text{Power imparted to engine airflow}}{\text{Rate of energy supplied in the fuel}}$$

$$\eta_{TH} = \frac{0,5 * (\dot{m}_9 {V_{9e}}^2 + \dot{m}_9 {V_{9e}}^2 - \dot{m}_0 {V_0}^2)}{\dot{m}_f FHV} = \frac{0,5 * ((1 + f_B){V_{9e}}^2 + BPR * {V_{9e}}^2 - (1 + BPR){V_0}^2)}{f_B FHV}$$

Due to the fact, that the high BPR turbofan engine produces a lot of thrust by cold streem (external duct), therfore a significant amount of exit gas temperature is clouse to the ambient temperature. This generate low heat losses and high thermal efficiency.

Propulsive efficency

$$\eta_P = \frac{\text{Thrust power}}{\text{Power imparted to engine airflow}}$$

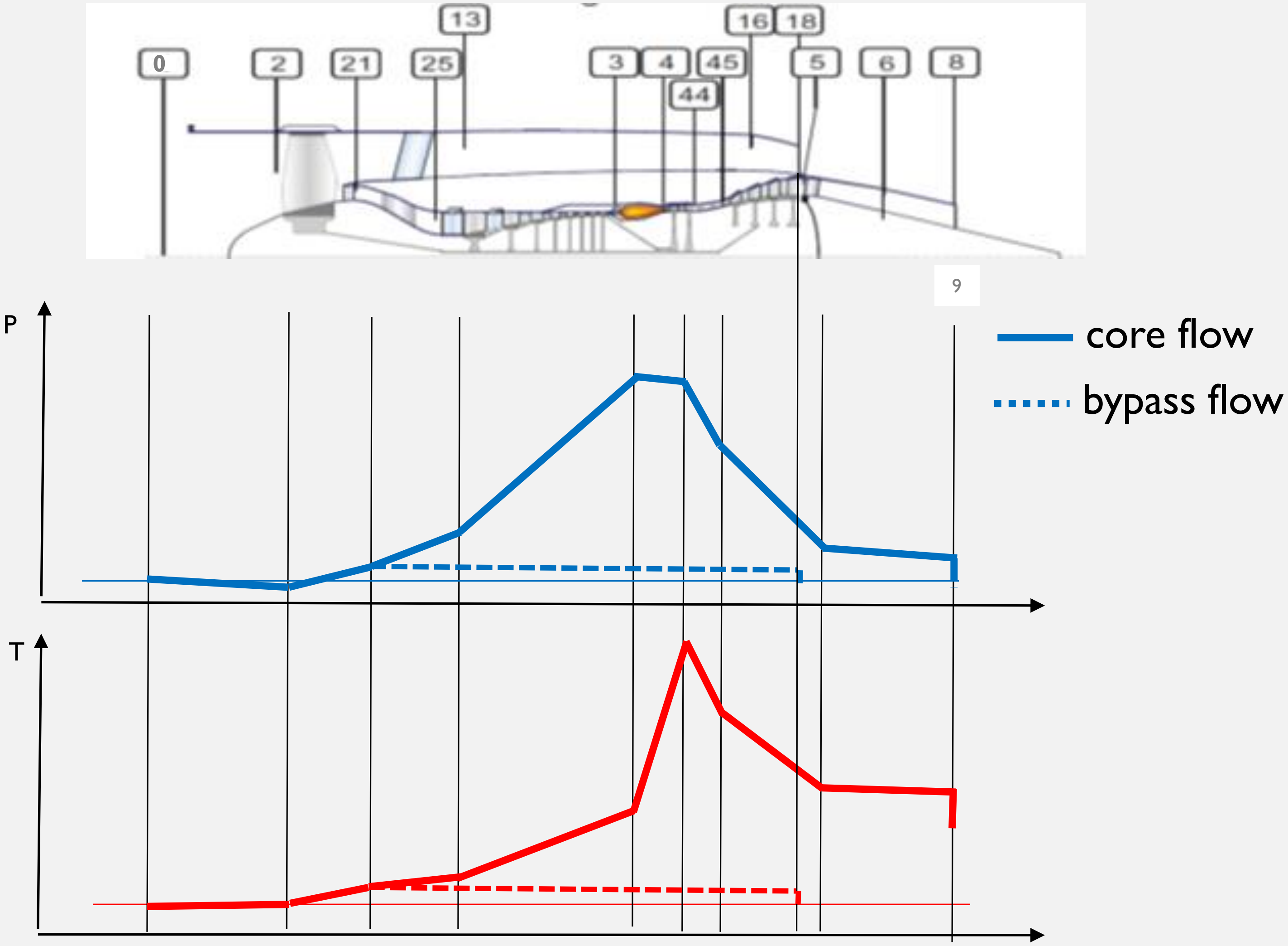
Huge amount of exit flow of the high BPR turbofan engine passes through the external duct of low temeparture therefore exit gas speed is low and only slightly higher than flight speed. By this way propulsive efficiency is high.

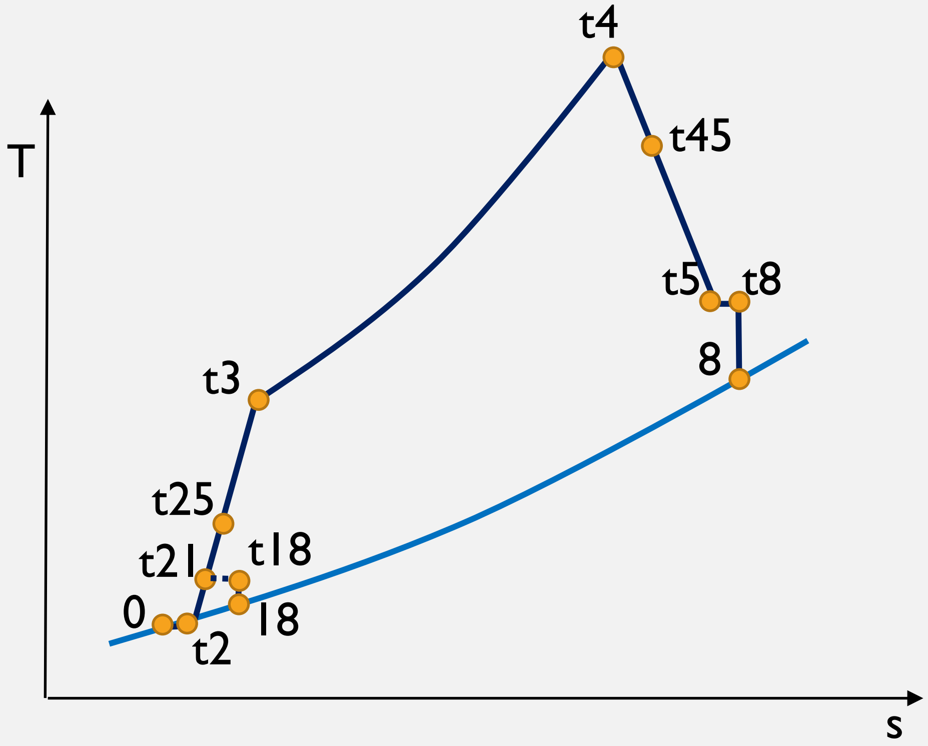
$$\eta_P = \frac{V_0 * T}{0,5 * (\dot{m}_9 {V_{9e}}^2 - \dot{m}_0 {V_0}^2)} = \frac{\dot{m}_0 V_0 * \frac{T}{\dot{m}_0}}{0,5 * (\dot{m}_9 {V_{9e}}^2 - \dot{m}_0 {V_0}^2)} = \frac{(1 + BPR) * V_0 * ST}{0,5 * ((1 + f_B){V_{9e}}^2 + BPR * {V_{9e}}^2 - (1 + BPR){V_0}^2}$$

Overall efficency

$$\eta_O = \eta_{TH} * \eta_P = \frac{V_0 * T}{\dot{m}_f FHV} = \frac{(1 + BPR) * V_0 * ST}{\dot{m}_f FHV}$$

TURBOFAN TEMPERATURE & PRESSURE DISTRIBUTION

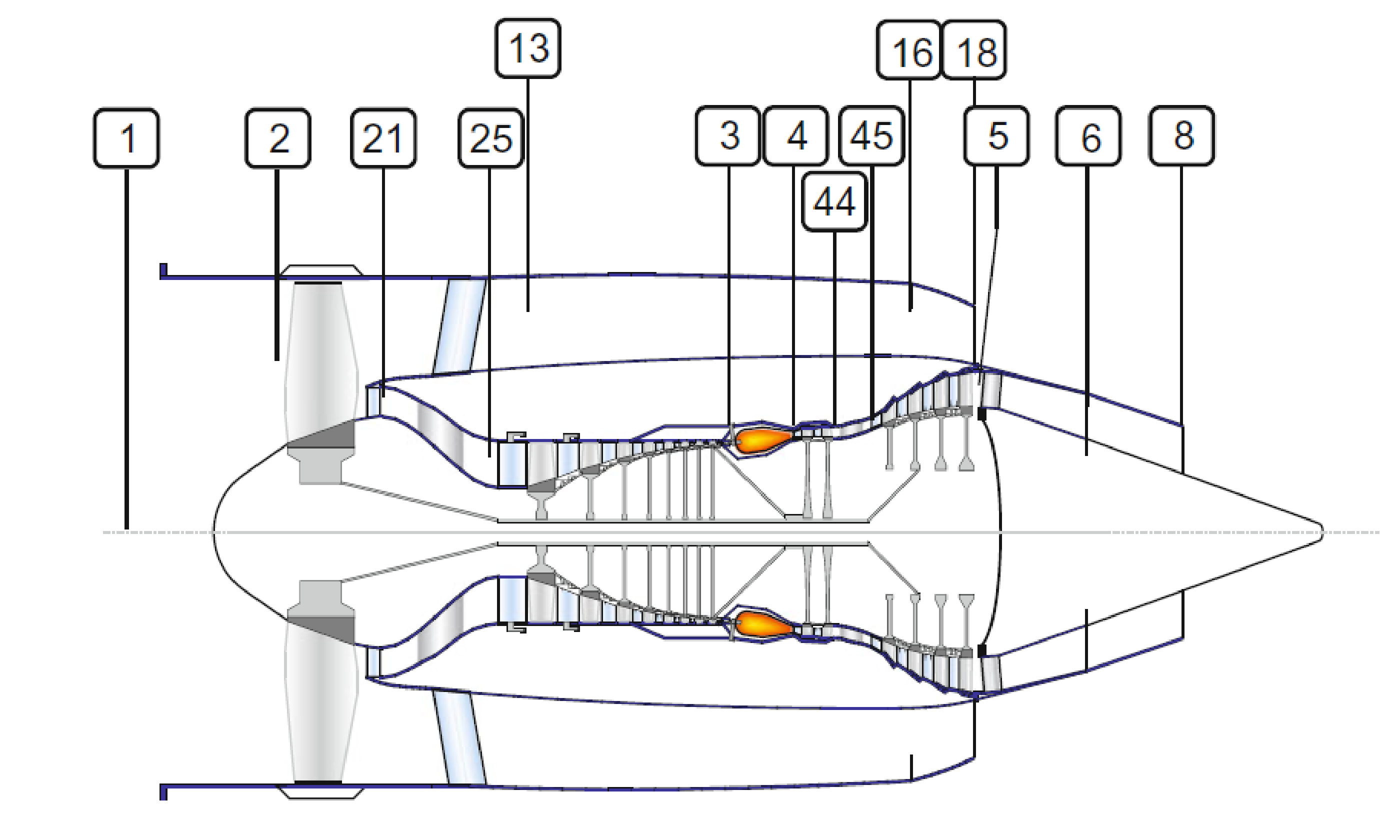




TURBOFAN ENGINE CALCULATION

Required data

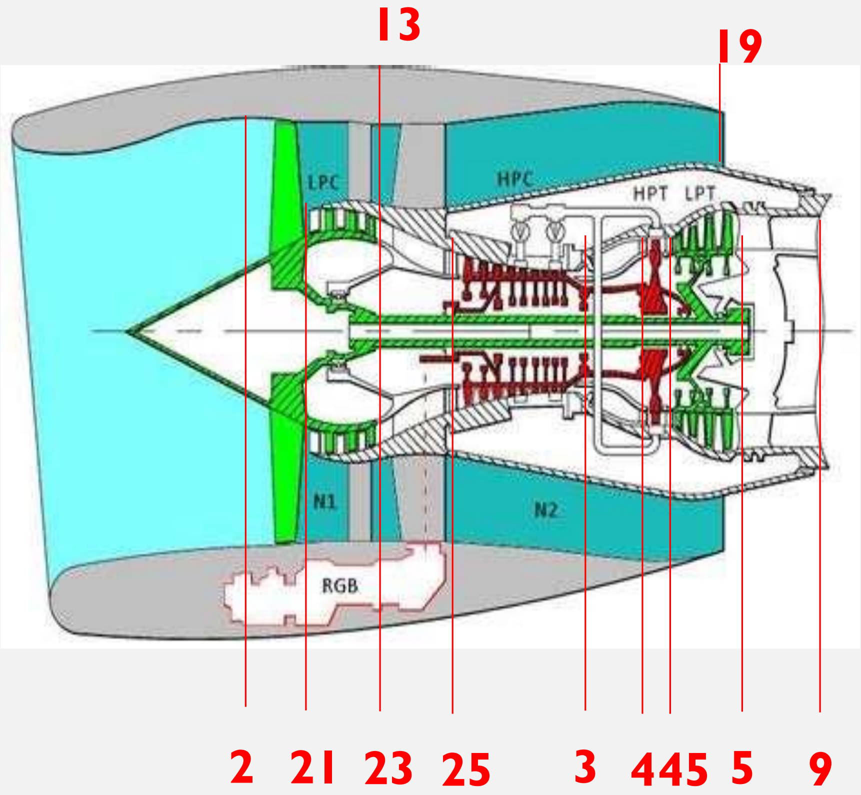
- Ambient and flight conditions: H, M_0
- Engine cycle parameters: FPR, LPCPR, HPCPR, BPR, TIT
- Pressure losses: inlet, burner, exterenal and internal nozzles, ducts
- Efficiences: fan, LPC, HPC, LPT, HPT, burner, mechanical of spool1 and spool2



Assumptions:

- Fan and LPC and HPC are calculated according compressor standard
- External nozzle calculation is provided according nozzle calculation standard, but gas paramethers specification is for air
- Mass flow related parameters are calculated on the mass flow in the core engine inlet m_{21}, therefore $f_B = m_f / m_{21}$.
- Nozzles are typically convergent, but often model is simplified by full expansion assumption

TURBOFAN ENGINE – SHAFTS POWER BALANCE



LP spool

$$P_F + P_{LPC} = T_{LPT}$$

$$\dot{m}_2 * cp(T_{t21} - T_{t2}) + \dot{m}_{21} * cp(T_{t23} - T_{t25}) = \dot{m}_{45} * cp_t(T_{t45} - T_{t5})$$

$$\dot{m}_{45} = \dot{m}_{21} + \dot{m}_f$$

$$(1 + BPR) * cp(T_{t21} - T_{t2}) + cp(T_{t25} - T_{t23}) = (1 + f_B) * cp_t(T_{t45} - T_{t5})$$

HP spool

$$\dot{m}_{21} * cp(T_{t3} - T_{t25}) = \dot{m}_4 * cp_t(T_{t4} - T_{t45})$$

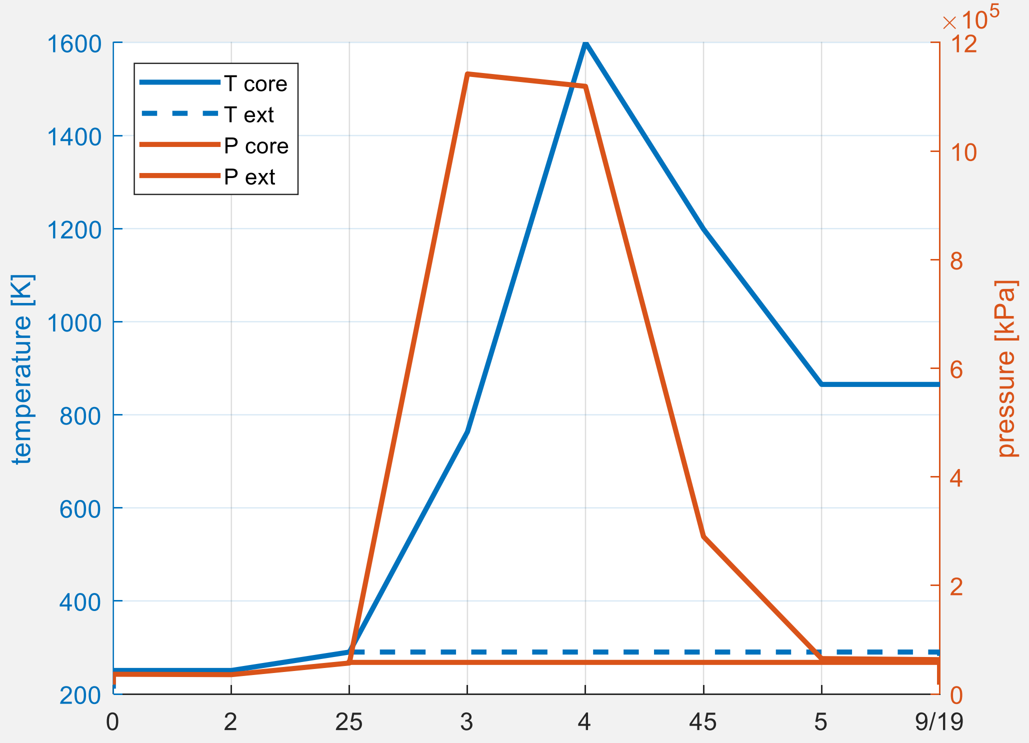
$$\dot{m}_{45} = \dot{m}_{21} + \dot{m}_f$$

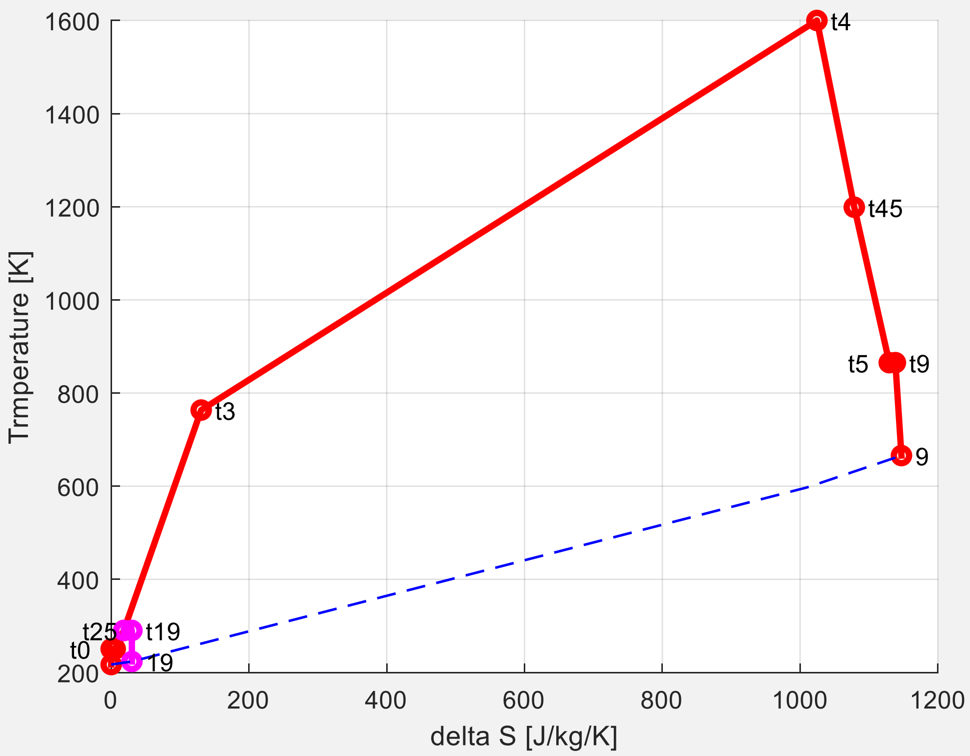
$$cp(T_{t3} - T_{t25}) = (1 + f_B) * cp_t(T_{t4} - T_{t45})$$

EXAMPLE OF TURBOFAN ENGINE CYCLE CALCULATION

GIVEN:

- Flight conditions: T0=217 K, P0=22 kPa, M0=0.88, BPR=9, FPR=1.6, CPR=20, TIT(Tt4)=1600 K, mass flow m=100 kg/s.
- π_{IN} =0.98, π_B =0.98, $\pi_{IN} = 0.97, \pi_{EN} = 0.96, \eta_F = 0{,}91, \eta_C = 0.83,\ \eta_{HPT} = 0.88,\ \eta_{LPT} = 0.9,$ $\eta_{mHP} = 0.99, \eta_{mLP} = 0.995$





TURBOFAN ENGINE PERFOTMANCE

	Parameter	Unit	Value
1	'Thrust'	'kN'	13.9345
2	'Specific Thrust'	'N*s/kg'	139.3452
3	'Fuel consumption'	'kg/s'	0.2382
4	'Specific fuel consump'	'kg/N/h'	0.0615
5	'therm. efficiency'	'-'	0.4915
6	'prop. efficiency'	'-'	0.7192
7	'overall efficiency'	'-'	0.3535
8	'V9'	'm/s'	682.8899
9	'V19'	'm/s'	365.8624
10	'HPT_PR'	'-'	3.8618
11	'LPT_PR'	'-'	4.4430

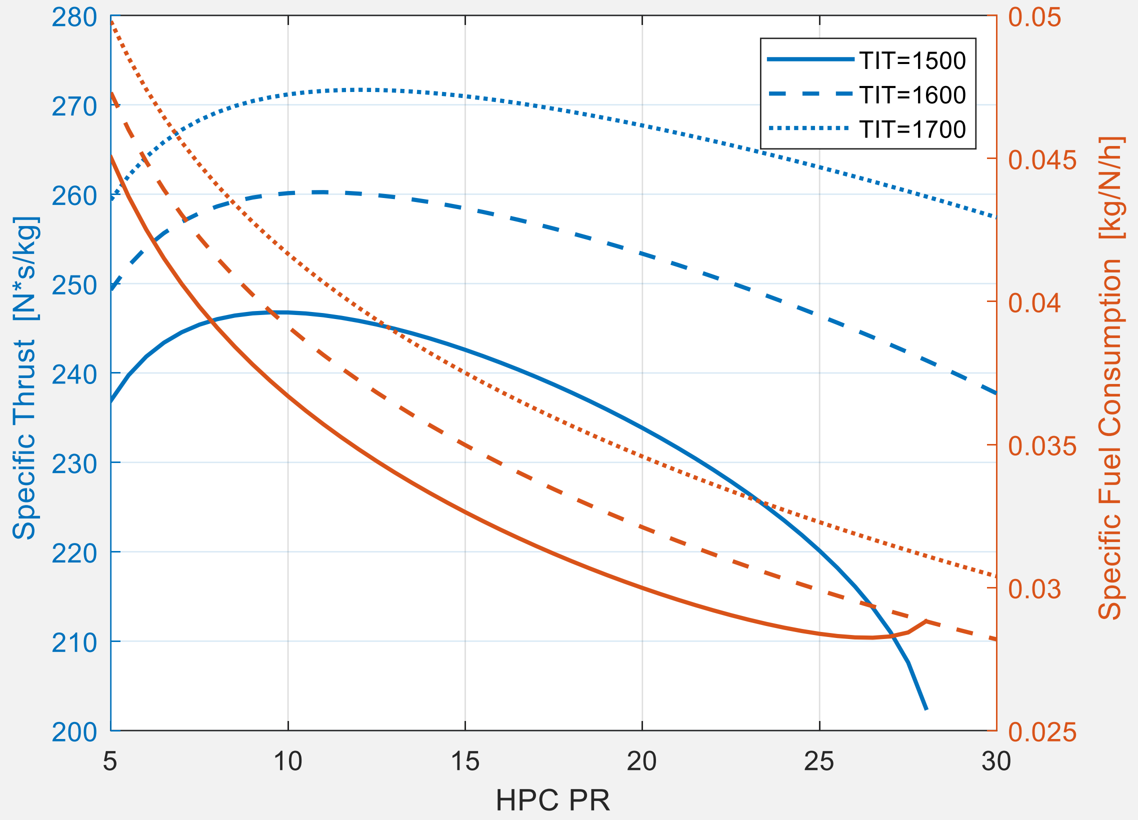
Results discusion:

- Specific thrust is significantly lower than in the turbjet engine
- Specific fuel consumption is lower than in the turbojet engine
- All efficiences are higher than in the turbojet engine for specified flight condition

Link to example of turbofan engine calculation:
https://robert-jakubowski.v.prz.edu.pl/download/task_no_4_turbofan_engine.pdf

TURBOFAN ENGINE CYCLE OPTIMISATION

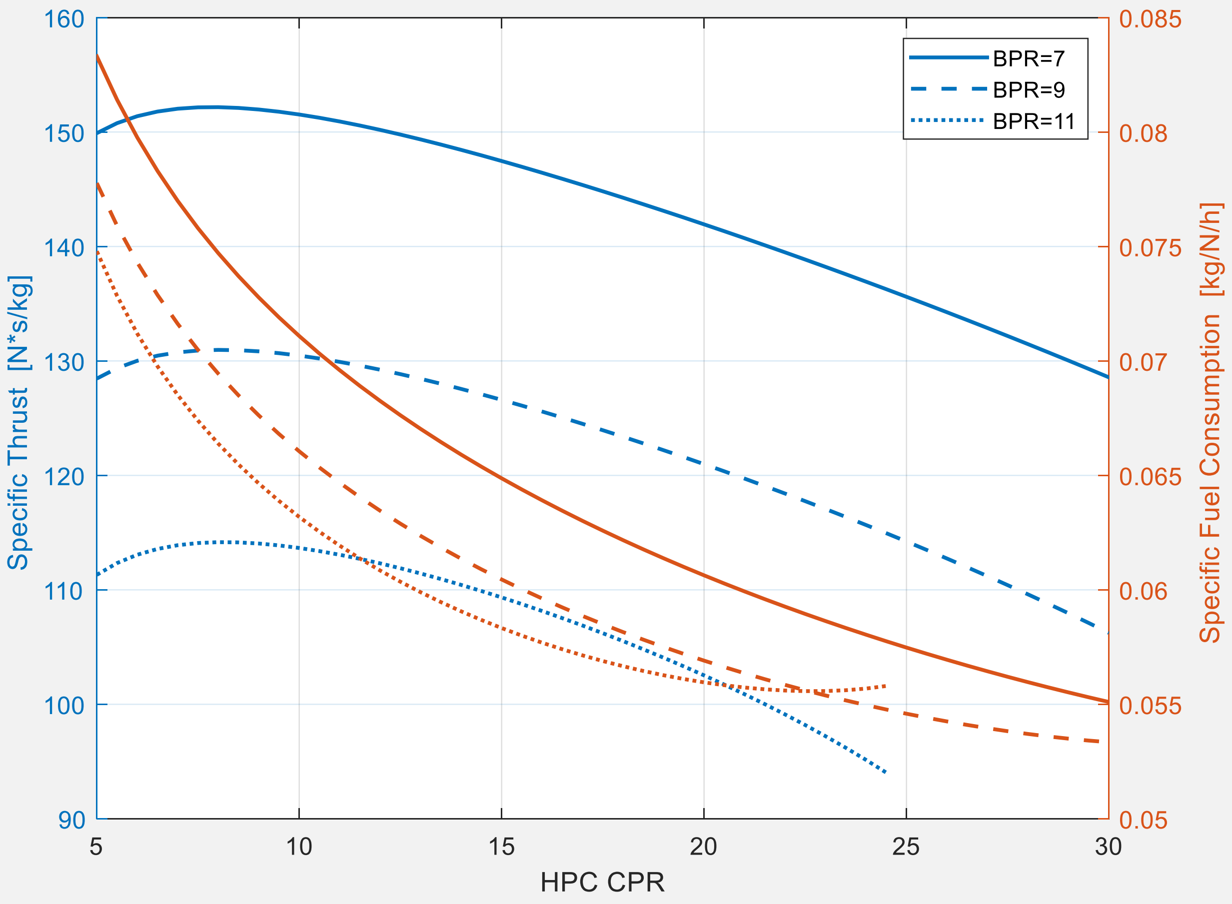
ST & SFC vs. HPC PR for constant BPR and FPR & three different TIT



- ST initially grows, gets maximum for low HPC PR, then goes down
- SFC decreases and achieves minimum for high HPC PR then grows
- Higher TIT causes higher SFC & lower ST
- Higher BPR leads to PR distans grow between maximum ST and minimum SFC
- Presented dependencies are similar to turbojet engine

TURBOFAN ENGINE CYCLE OPTIMISATION

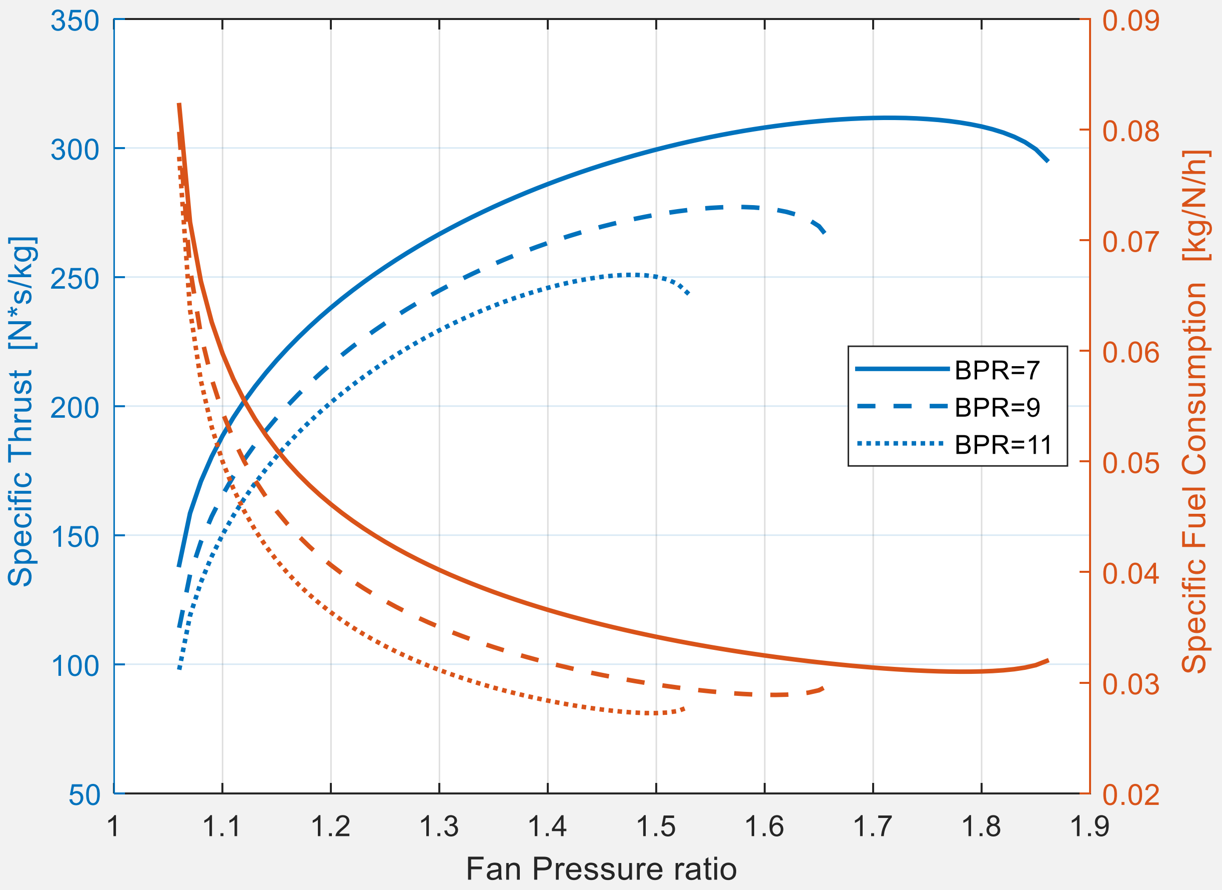
ST & SFC vs. HPC PR for constant TIT and FPR & three different BPR



- ST initially grows, gets maximum for low HPC PR, then goes down
- SFC decreases and achieves minimum for high HPC PR then grows
- Higher BPR causes lower SFC & lower ST
- Higher BPR leads to less PR distans between maximum ST and minimum SFC

TURBOFAN ENGINE CYCLE OPTIMISATION

ST & SFC vs. FPR for constant TIT and FPR & three different BPR



- ST gets maximum for the same FPR than SFC achieves minimu value.
- Lower BPR leads to FPR grow of maximum SF and minimum SFC
- It shows that it is possible to find optimal FPR for some BPR. FPR should be lower for higher BPR

THANKS FOR YOUR ATENTION

Questions and Comments ?

1. …….
2. …….
3. …….