TURBOFAN ENGINE

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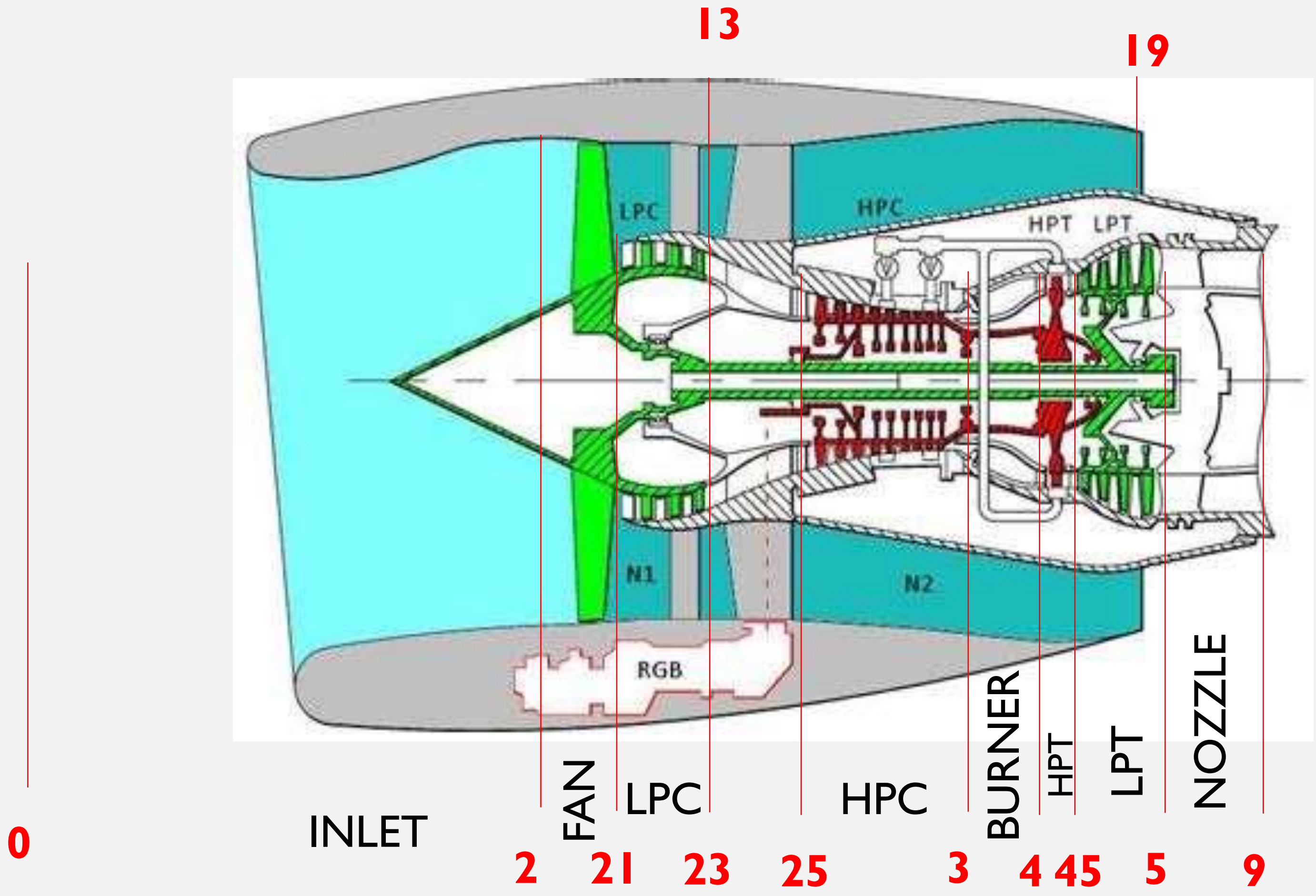
LITERATURE:

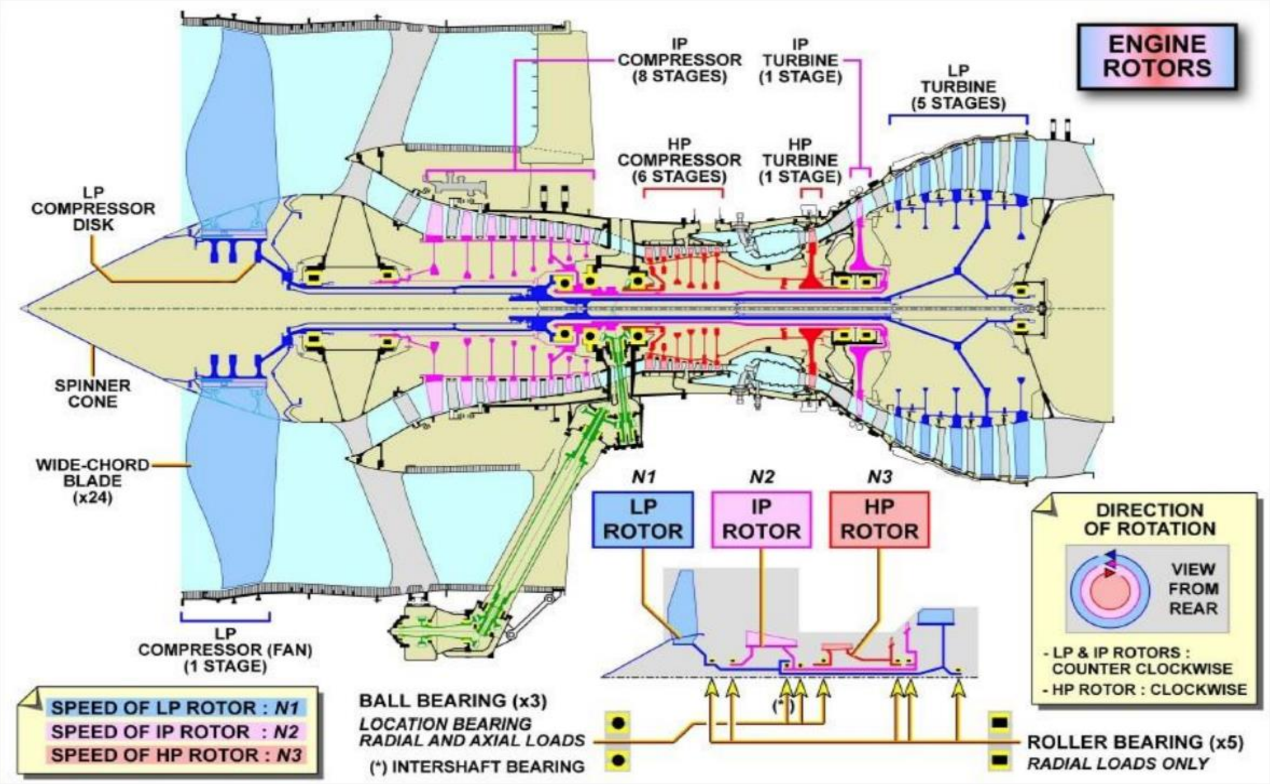
- **Jack D. Mattingly, Elements of Propulsion: Gas Turbines and Rockets, AIAA Education Series 2006 (Chapter 7)**
- **Jack D. Mattingly, Elements of Gas Turbine Propulsion, Tata McGraw Hill Education Private Limited, 2013 (Chapter 7)**
- **Gordon C. Oates, Aerothermodynamics of Gas Turbine and Rocket Propulsion, AIAA Education Series, 1997 (Chapter 7)**
- Jack D. Mattingly, William H. Heiser, David T. Pratt, **Aircraft Engine Design, Second Edition,** American Institute of Aeronautics and Astronautics, Inc. 2002 (**Chapter 4**)
- Joachim Kurzke • Ian Halliwell, Propulsion and Power, An Exploration of Gas Turbine Performance Modeling Springer International Publishing AG, part of Springer Nature 2018

CLASSICAL TURBOFAN ENGINE



THREE SPOOL TURBOFAN ENGINE

Rolls-Royce Trent 7000



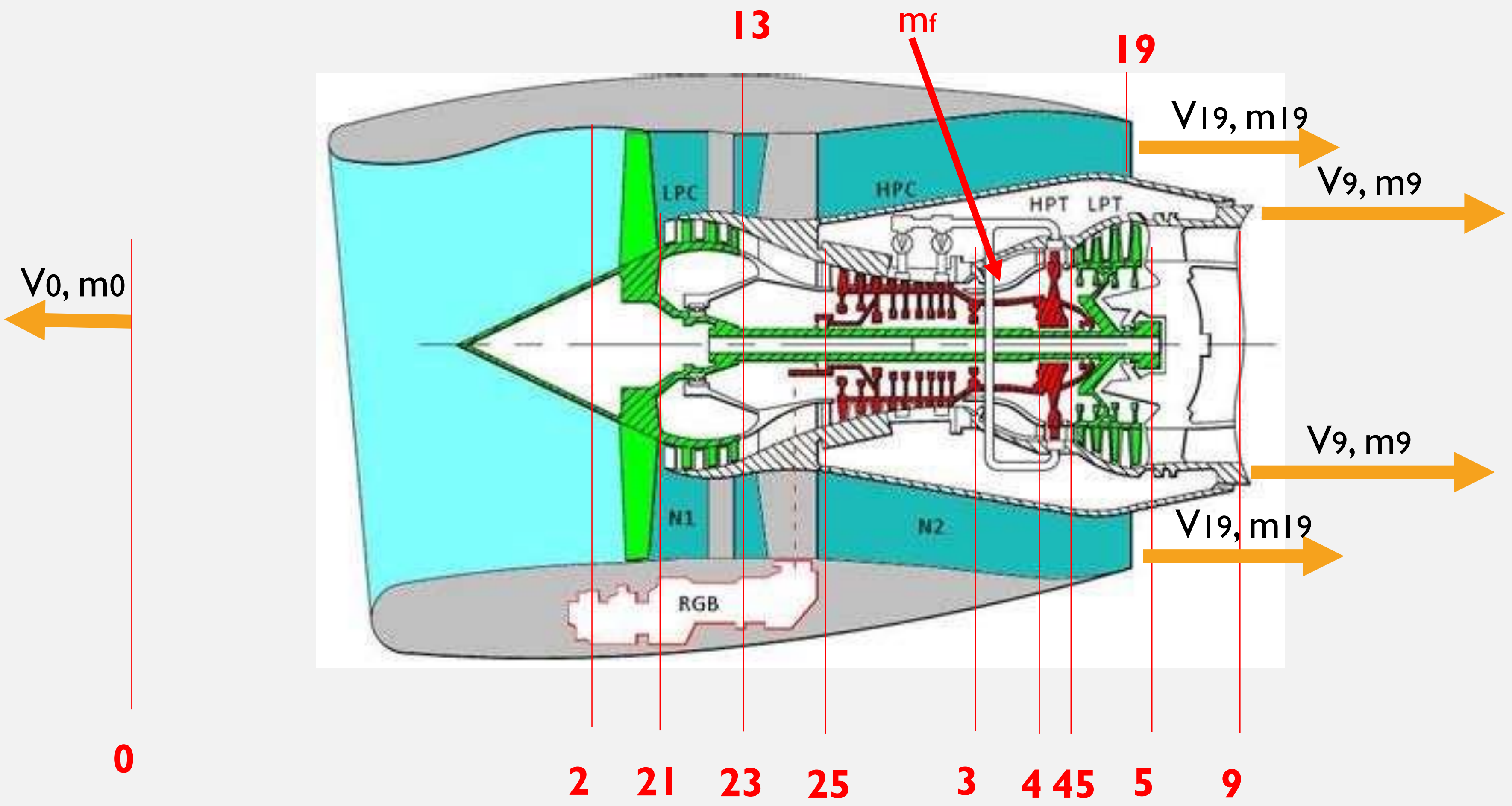
- **MTO:** 324,0 kN / 72 834 lbf
- **MCT:** 289,2 kN / 65 005 lbf
- **Pressure ratio :** 50:1
- **BPR :** 10:1
- **TIT:** > 1835 K (1562 °C; 2843 °F
- **SFC** (curse) = 14,4 g/kN/s
- **Stosunek ciągu do masy :** 5,13
- **Rotation:** (100%):
- HP 13 391 RPM, IP 8937 RPM, LP 2683 RPM

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

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

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

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

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 $BPR = \dfrac{\dot{m}_{13}}{\dot{m}_{21}}$

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

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

$$\eta_{TH} = \frac{0{,}5 * (\dot{m}_9 {V_{9e}}^2 + \dot{m}_{19} {V_{19e}}^2 - \dot{m}_0 {V_0}^2)}{\dot{m}_f FHV} = \frac{0{,}5 * ((1 + f_B){V_{9e}}^2 + BPR * {V_{19e}}^2 - (1 + BPR){V_0}^2)}{f_B FHV}$$

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

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

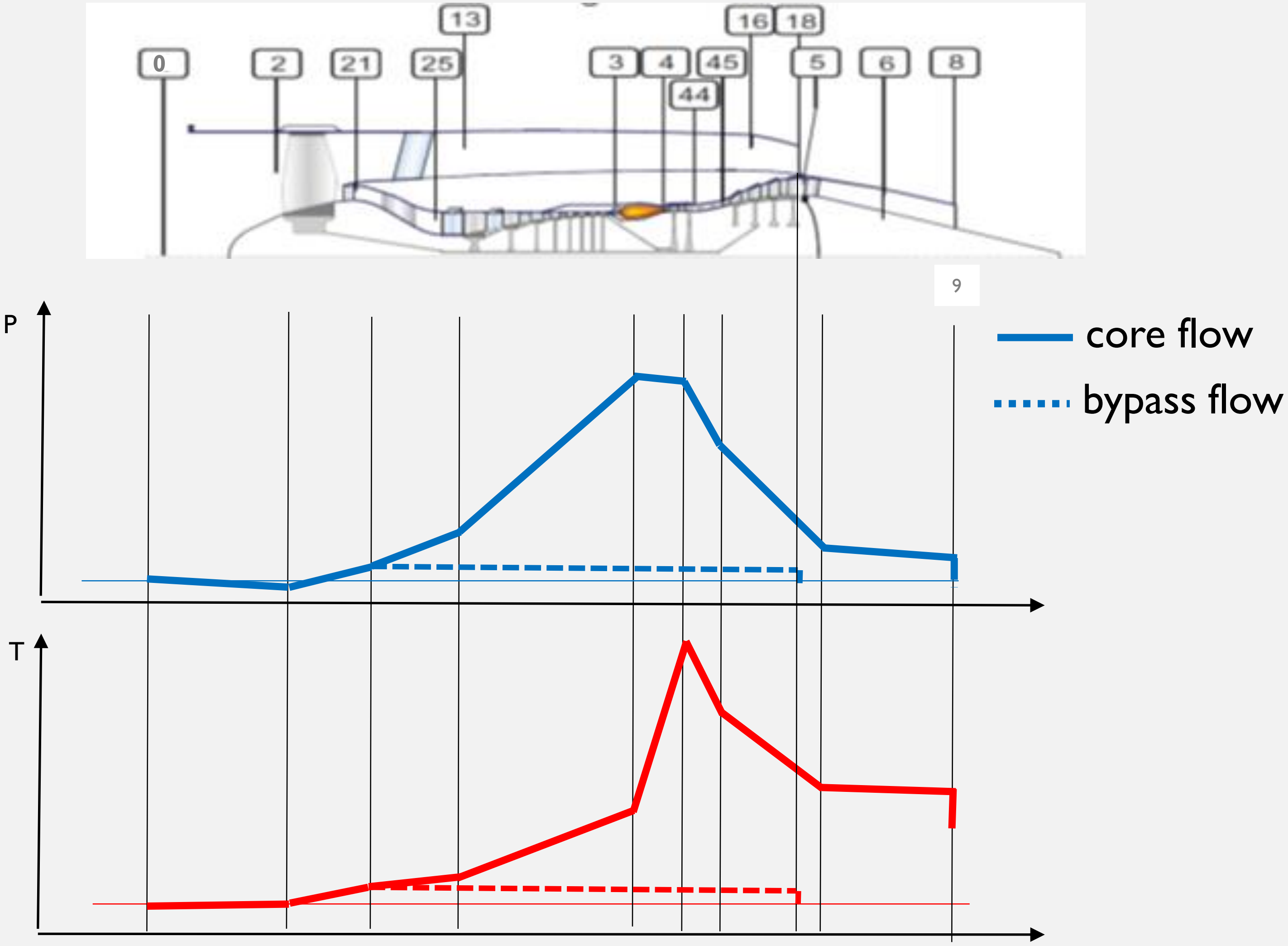
Huge amount of exit flow of the high BPR turbofan engine passes through the external duct of low temeparture therefore exit gas speed is low and only slightly higher than flight speed. By this way propulsive efficiency is high.

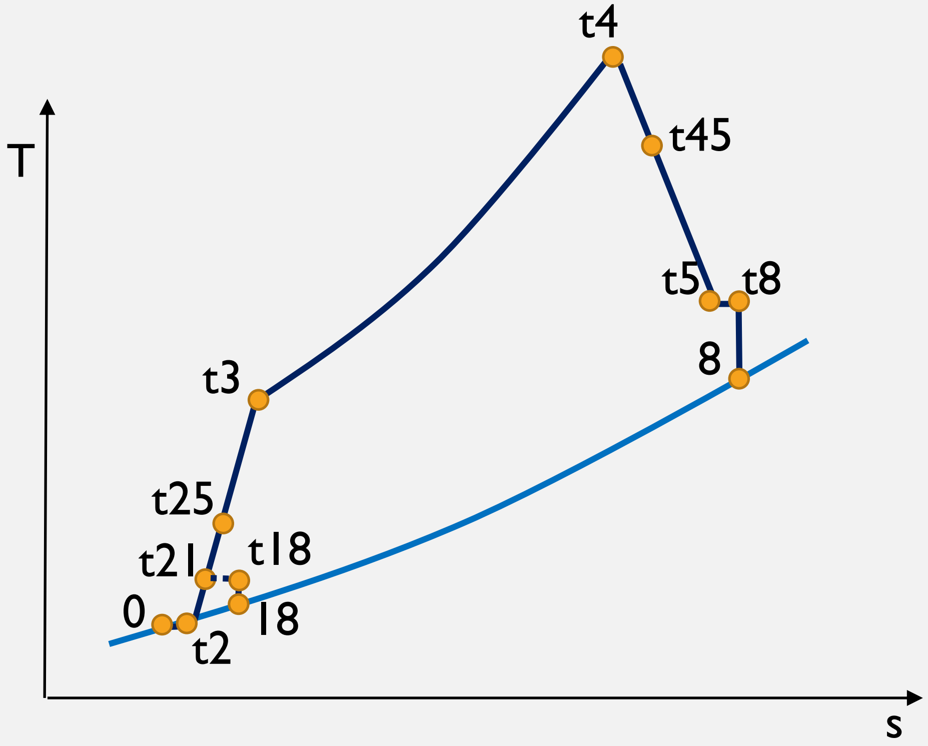
$$\eta_P = \frac{V_0 * T}{0{,}5 * (\dot{m}_9 {V_{9e}}^2 + \dot{m}_{19} {V_{19e}}^2 - \dot{m}_0 {V_0}^2)} = \frac{\dot{m}_0 V_0 * \frac{T}{\dot{m}_0}}{0{,}5 * (\dot{m}_9 {V_{9e}}^2 + \dot{m}_{19} {V_{19e}}^2 - \dot{m}_0 {V_0}^2)} = \frac{(1 + BPR) * V_0 * ST}{0{,}5 * ((1 + f_B){V_{9e}}^2 + BPR * {V_{19e}}^2 - (1 + BPR){V_0}^2}$$

Overall efficency

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

TURBOFAN TEMPERATURE & PRESSURE DISTRIBUTION

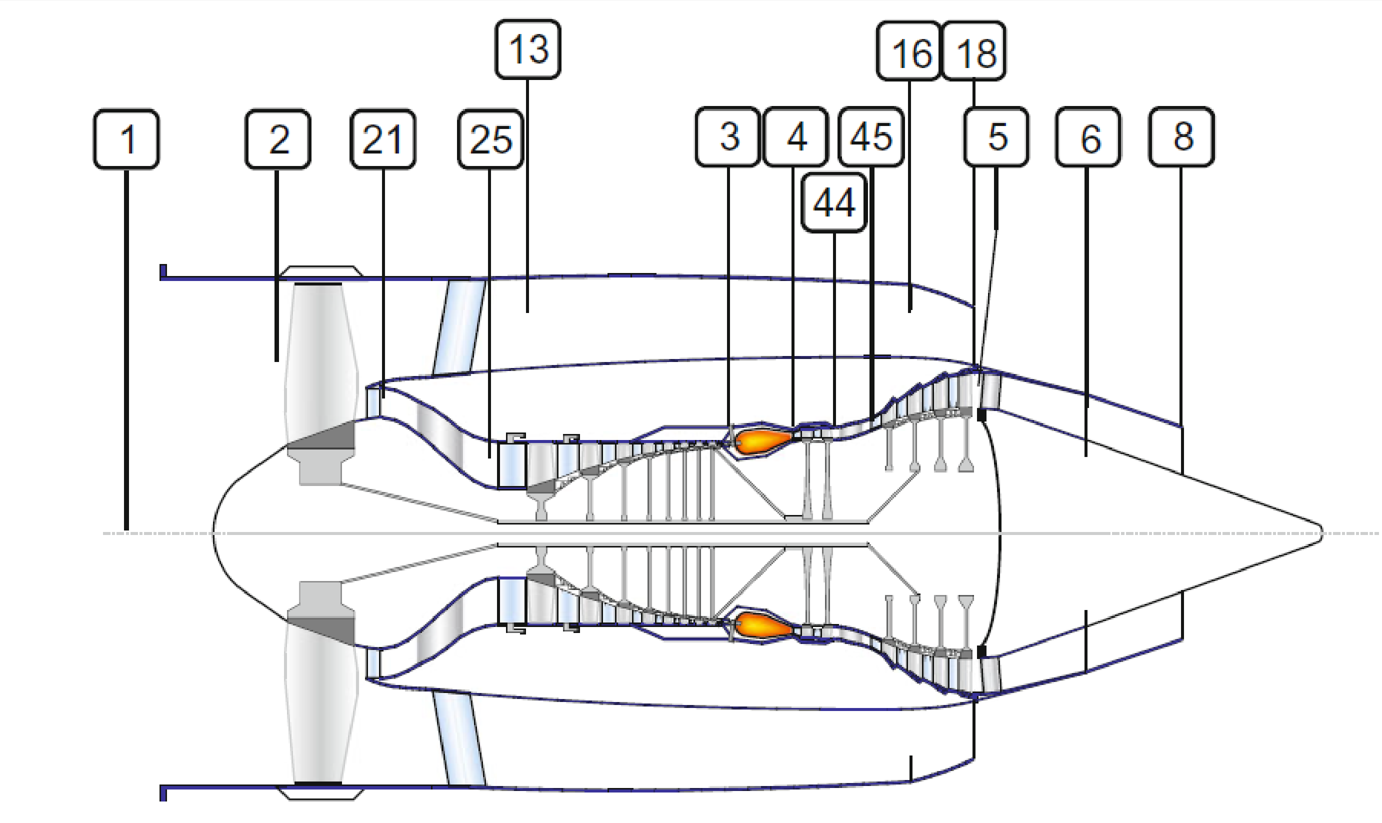




TURBOFAN ENGINE CALCULATION

Required data

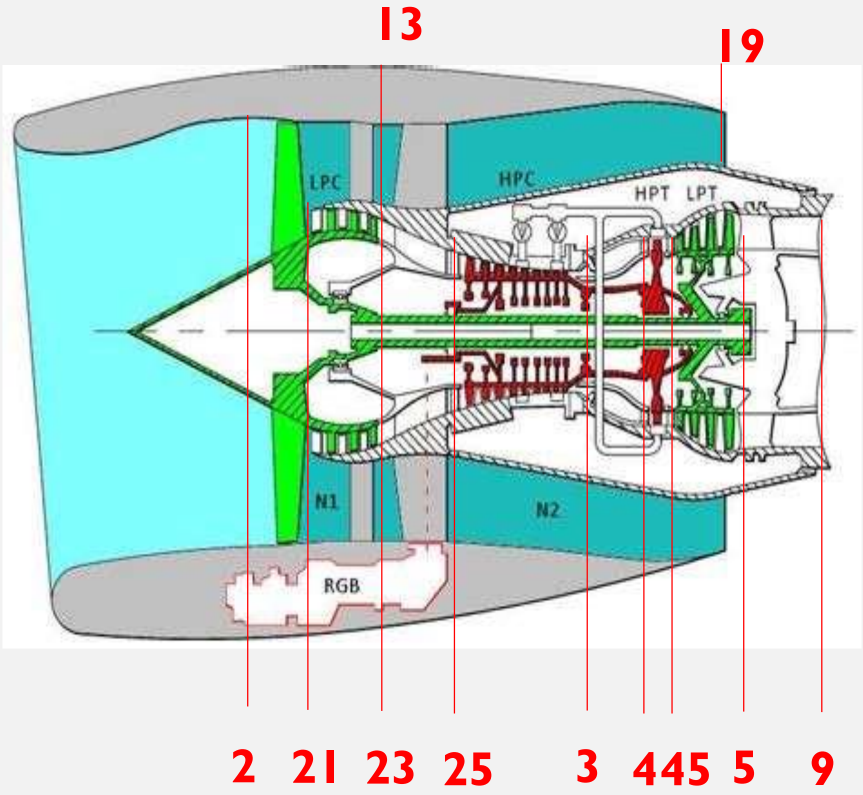
- Ambient and flight conditions: H, M_0
- Engine cycle parameters: FPR, LPCPR, HPCPR, BPR, TIT
- Pressure losses: inlet, burner, exterenal and internal nozzles, ducts
- Efficiences: fan, LPC, HPC, LPT, HPT, burner, mechanical of spool1 and spool2



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

$P_F + P_{LPC} < P_{LPT}$ $\qquad P_F + P_{LPC} = P_{LPT} * \eta_{mLP}$

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

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

$(1 + BPR) * cp(T_{t21} - T_{t2}) + cp(T_{t25} - T_{t21}) =$

$= (1 + f_B) * cp_t(T_{t45} - T_{t5}) * \eta_{mLP}$

HP spool

$P_{HPC} < P_{HPT}$ $\qquad P_{HPC} = P_{HPT} * \eta_{mHP}$

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

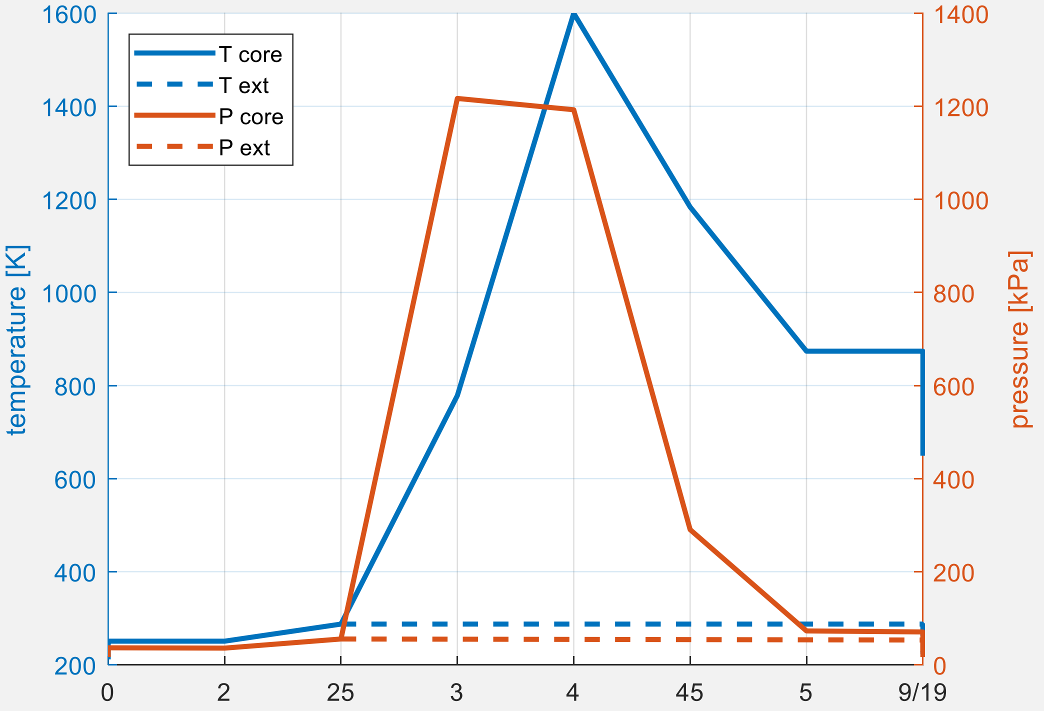
$\dot{m}_4 = \dot{m}_{21} + \dot{m}_f$

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

EXAMPLE OF TURBOFAN ENGINE CYCLE CALCULATION

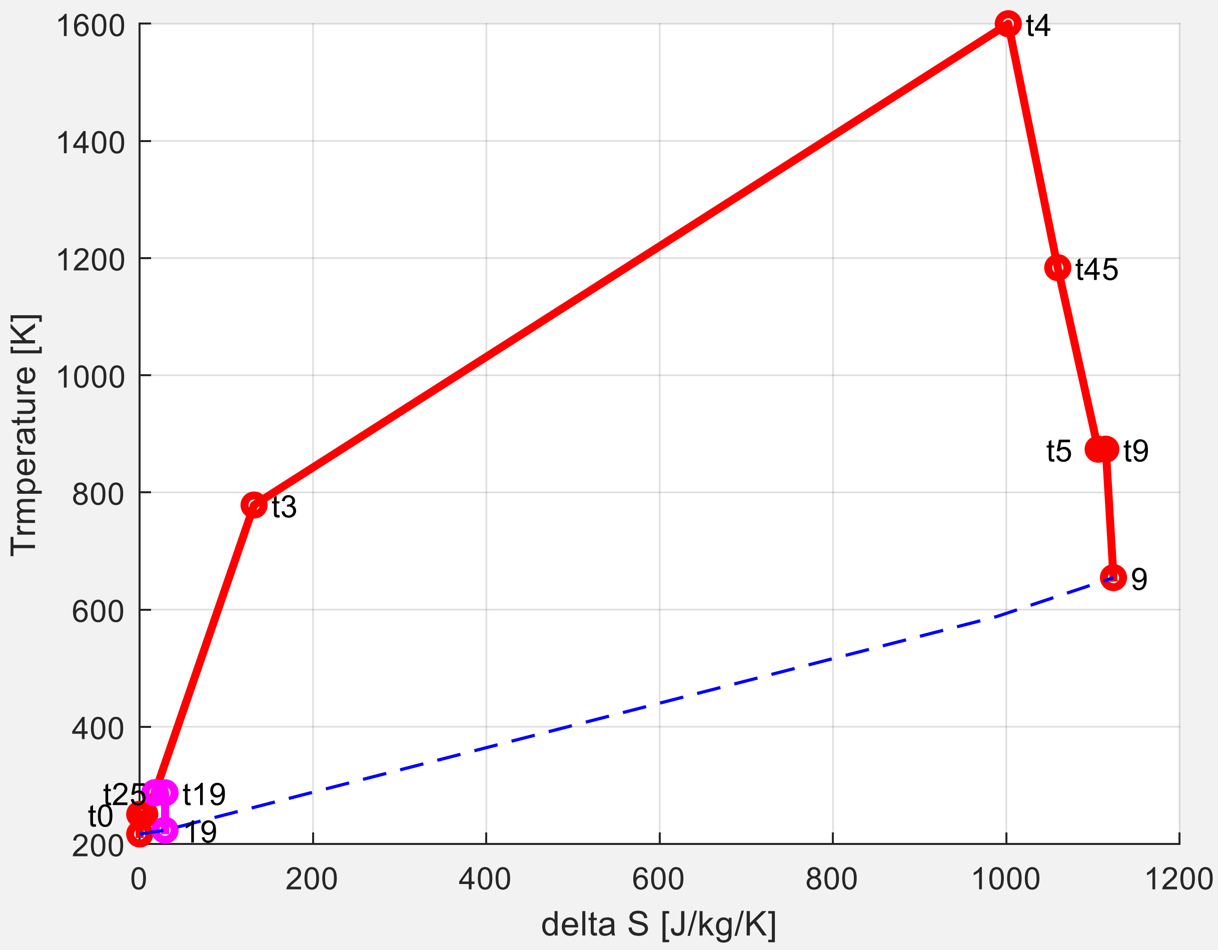
GIVEN:

- Flight conditions: T0=217 K, P0=22 kPa, M0=0.88, BPR=9, FPR=1.55, CPR=22, TIT(Tt4)=1600 K, mas flow m=60 kg/s.
- π_{IN} =0.98, π_B =0.98, $\pi_{IN} = 0.97$, $\pi_{EN} = 0.96$, $\eta_F = 0{,}91$, $\eta_C = 0.83$, $\eta_{HPT} = 0.88$, $\eta_{LPT} = 0.9$, $\eta_{mHP} = 0.99$, $\eta_{mLP} = 0.995$



	Section	T real [K]	P real [kPa]
1	'0'	217	22
2	't0'	251	36
3	't2'	251	36
4	't25'	287	55
5	't3'	778	1217
6	't4'	1600	1193
7	't45'	1184	290
8	't5'	874	73
9	't9'	874	70
10	'9'	655	22
11	't19'	287	53
12	'19'	223	22

TEMPERATURE ENTROPY PLOT



	Parameter	entropy [J/kg/K]
1	'ds_IN'	6
2	'ds_F'	12
3	'ds_C'	114
4	'ds_B'	870
5	'ds_HPT'	57
6	'ds_LPT'	47
7	'ds_N_int'	9
8	'ds_N_ext'	12

TURBOFAN ENGINE PERFOTMANCE

	Parameter	Unit	Value
1	'Thrust'	'kN'	8.1612
2	'Specific Thrust'	'N*s/kg'	136
3	'Fuel consumption'	'kg/s'	0.1404
4	'Specific fuel consump'	'kg/N/h'	0.0619
5	'therm. efficiency'	'-'	0.4998
6	'prop. efficiency'	'-'	0.7030
7	'overall efficiency'	'-'	0.3513
8	'V9'	'm/s'	716
9	'V19'	'm/s'	358
10	'HPT_PR'	'-'	4.1077
11	'LPT_PR'	'-'	3.9965

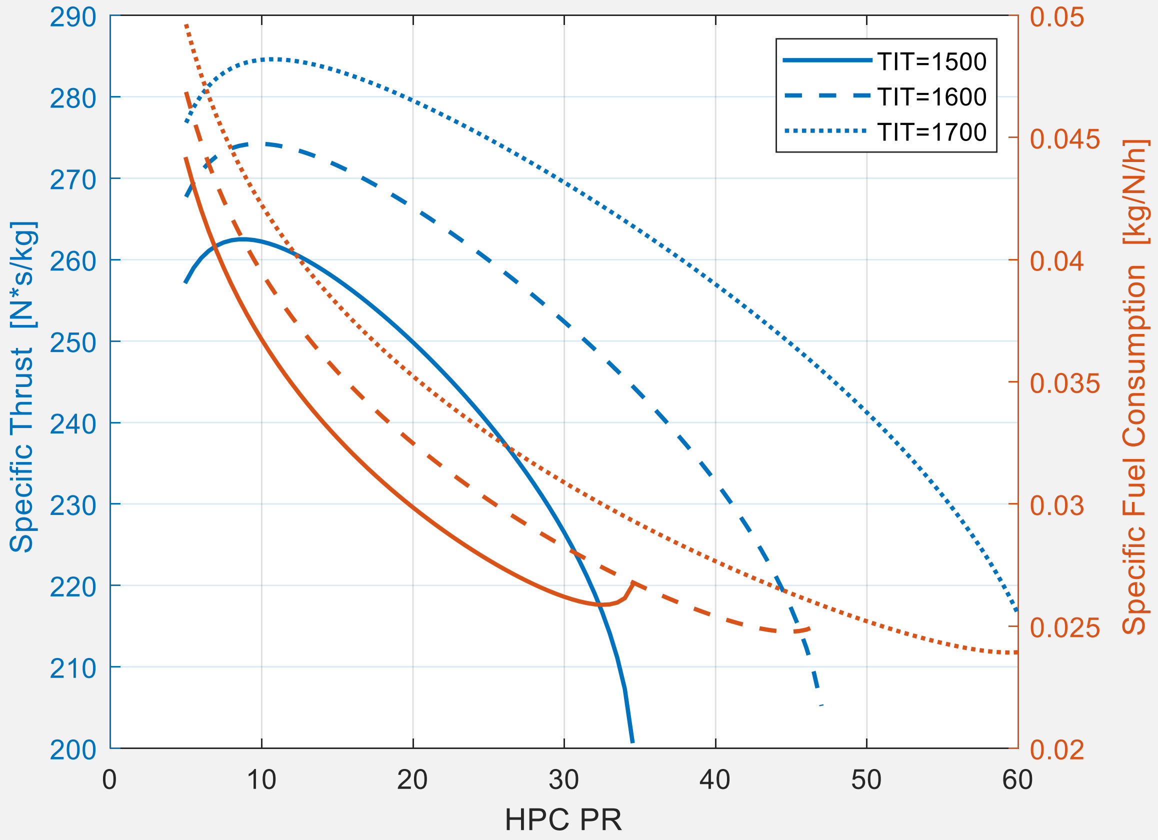
Results discusion:

- 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

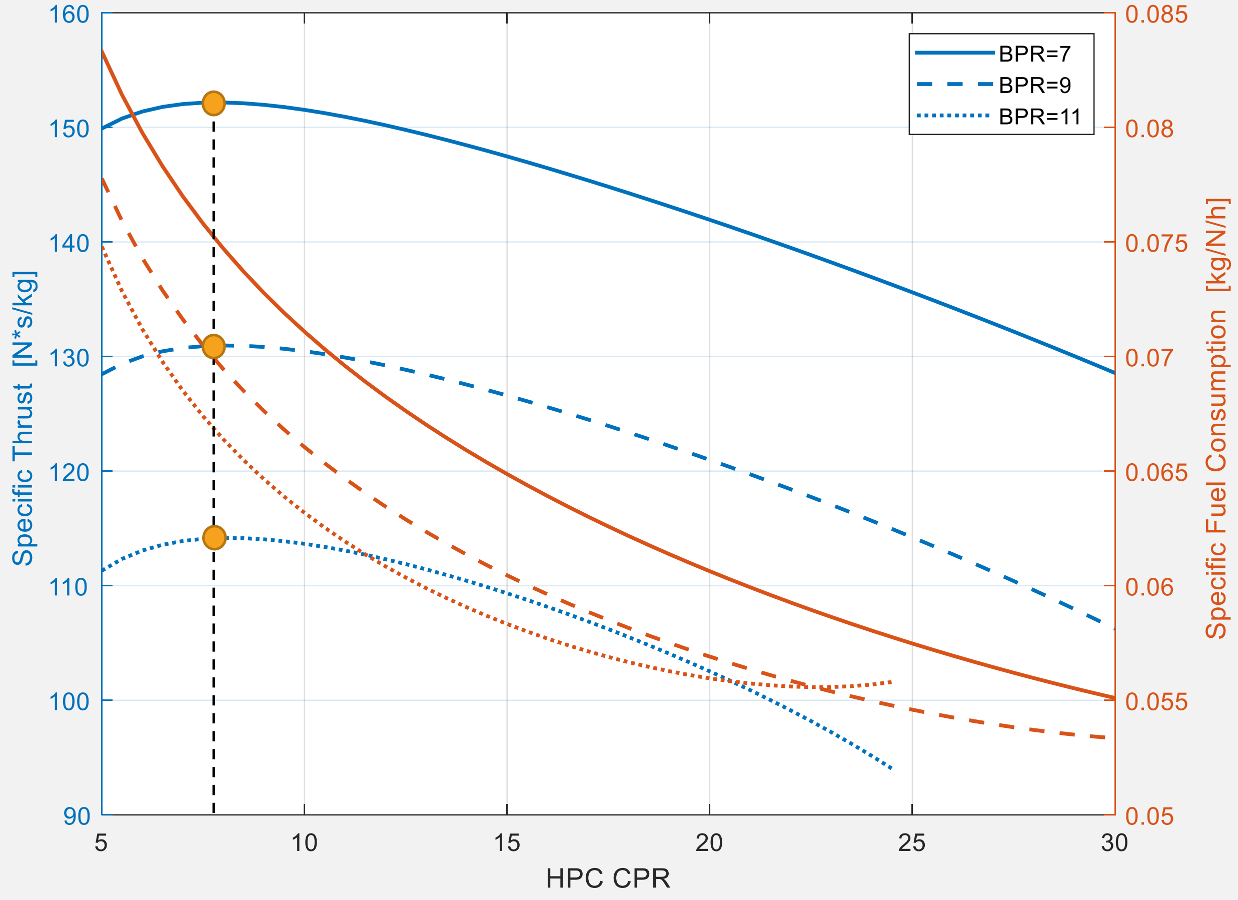


- ST initially grows, gets maximum for low HPC PR, then goes down
- SFC decreases and achieves minimum for high HPC PR then grows
- Higher TIT causes higher SFC & lower ST
- Higher TIT leads to PR distans grow between maximum ST and minimum SFC
- Presented dependencies are similar to turbojet engine

	TIT	HPC PR	ST_max	HPC PR	SFC_min
1	1500	9	262.4947	32.5000	0.0259
2	1600	10	274.2245	45	0.0248
3	1700	10.5000	284.5968	59.5000	0.0239

TURBOFAN ENGINE CYCLE OPTIMISATION

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

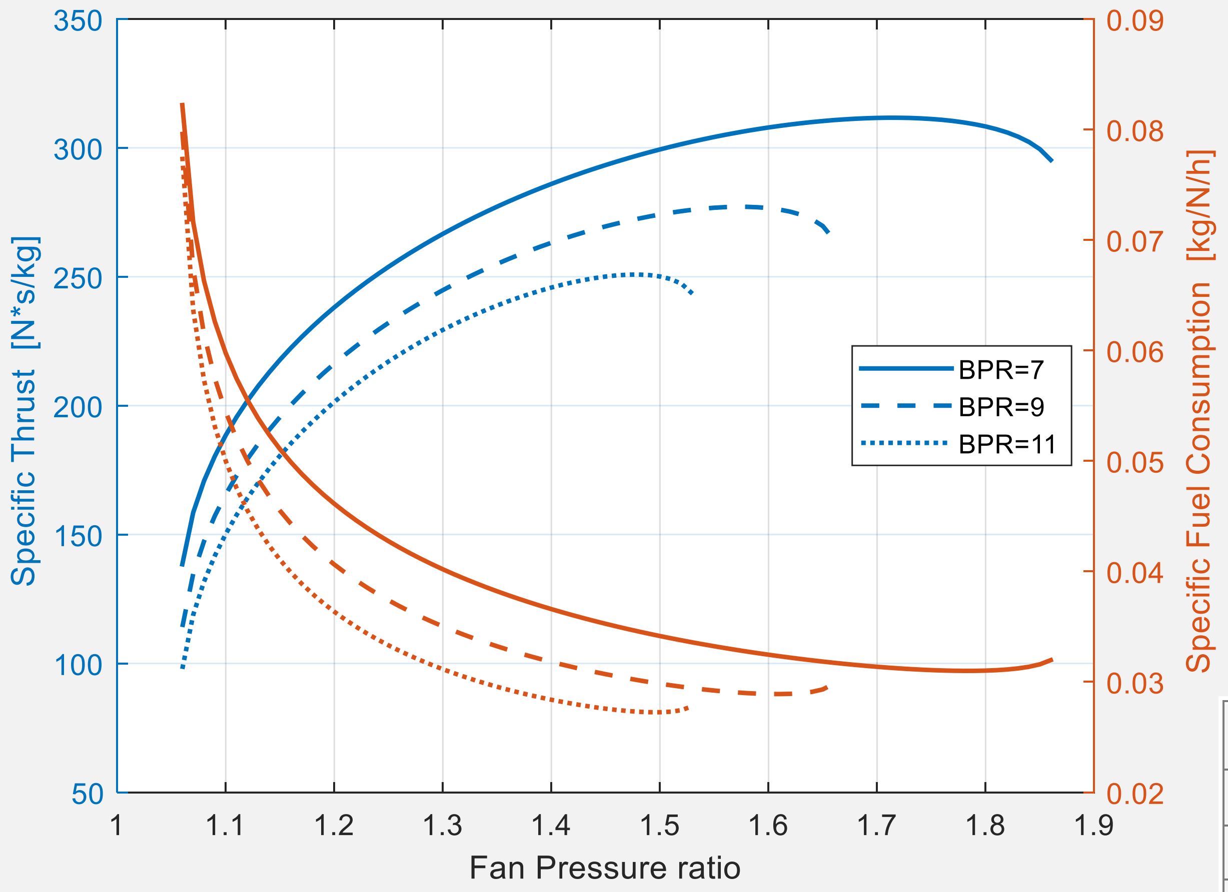


- ST initially grows, gets maximum for low HPC PR, then goes down
- SFC decreases and achieves minimum for high HPC PR then grows
- Higher BPR causes lower SFC & lower ST
- Higher BPR leads to less PR distans between maximum ST and minimum SFC
- BPR doesn't influence HPC PR of ST_max

	BPR	HPC PR	ST_max
1	7	8	152.1715
2	9	8	130.9649
3	11	8	114.1647

TURBOFAN ENGINE CYCLE OPTIMISATION

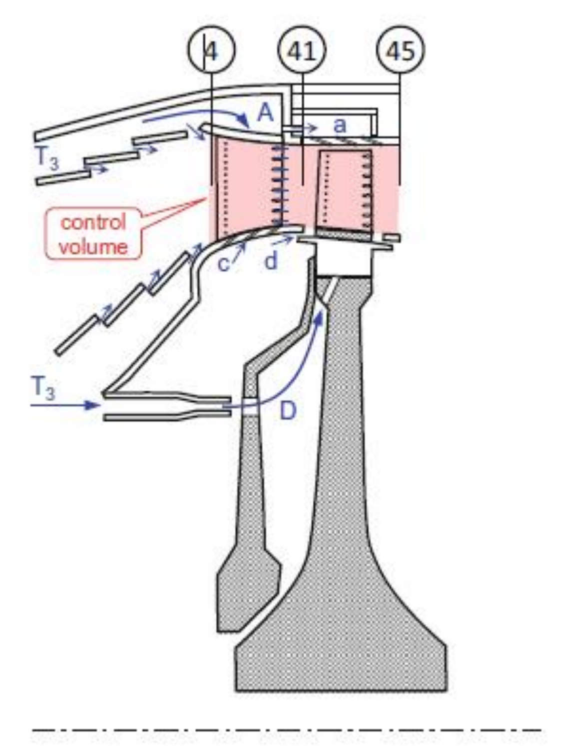
ST & SFC vs. FPR for constant TIT and FPR & three different BPR

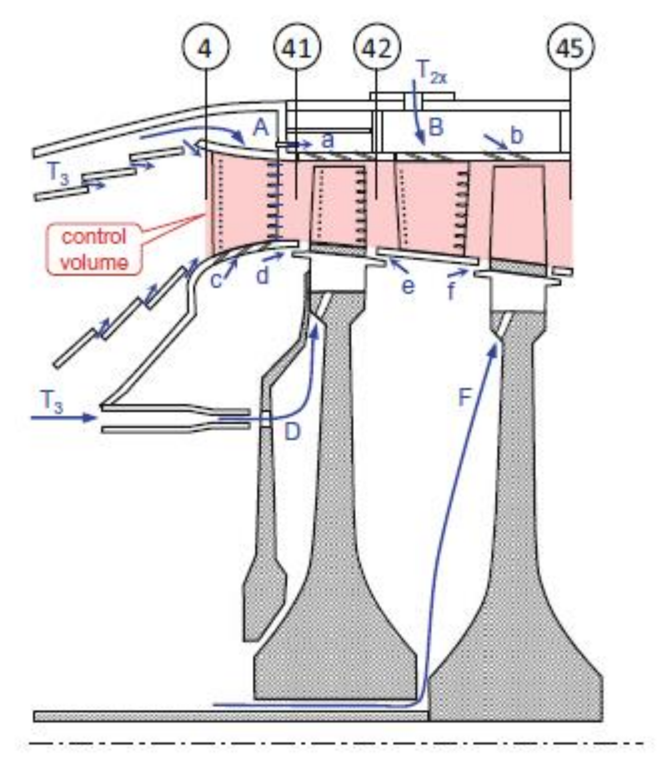


- ST gets maximum for the same FPR than SFC achieves minimu value.
- Lower BPR leads to FPR grow of maximum SF and minimum SFC
- It shows that it is possible to find optimal FPR for some BPR. FPR should be lower for higher BPR

	BPR	FPR	ST_max	FPR	SFC_min
1	7	1.7100	311.6837	1.7800	8.6090e-06
2	9	1.5700	277.1315	1.6100	8.0257e-06
3	11	1.4800	250.8528	1.5000	7.5688e-06

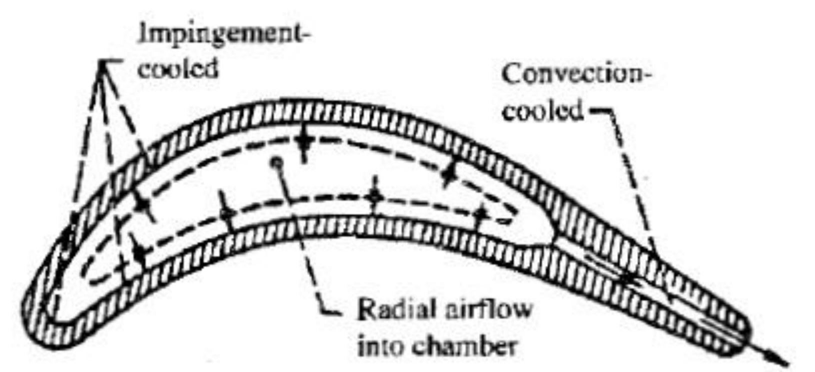
MODERN TURBOFAN EGNINE - TURBINE COOLING



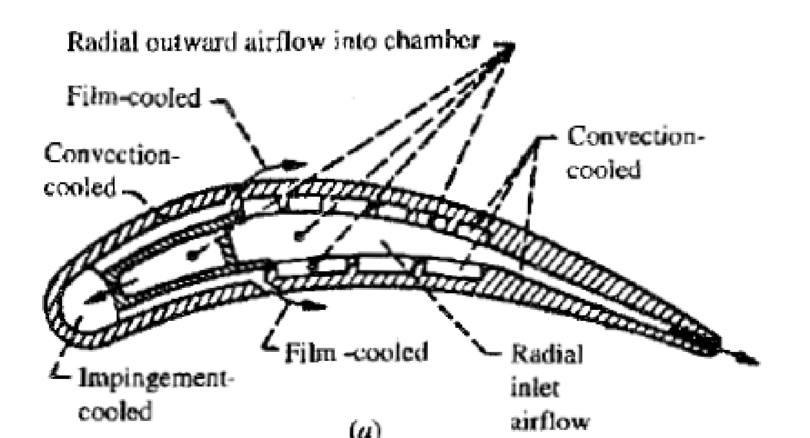


TURBINE COOLING TECHNIQUES

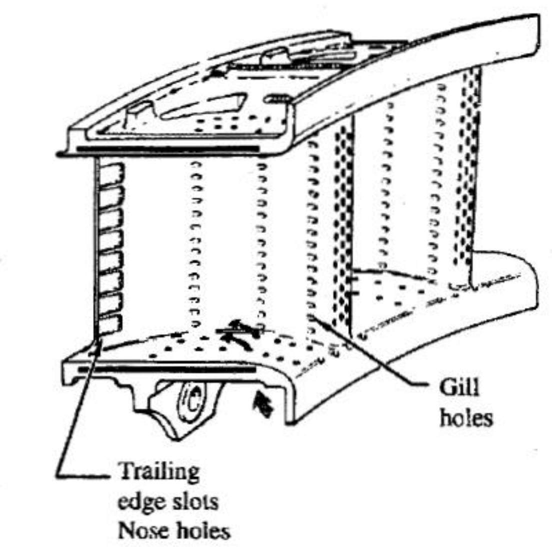
- 1. Convection
- 2. Impingement
- 3. Film cooling
- 4. Full coverage film cooling
- 5. Transpiration

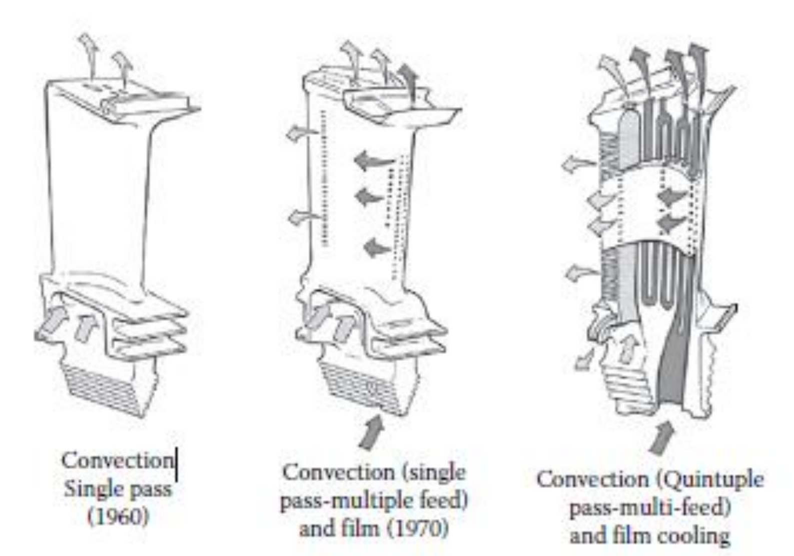


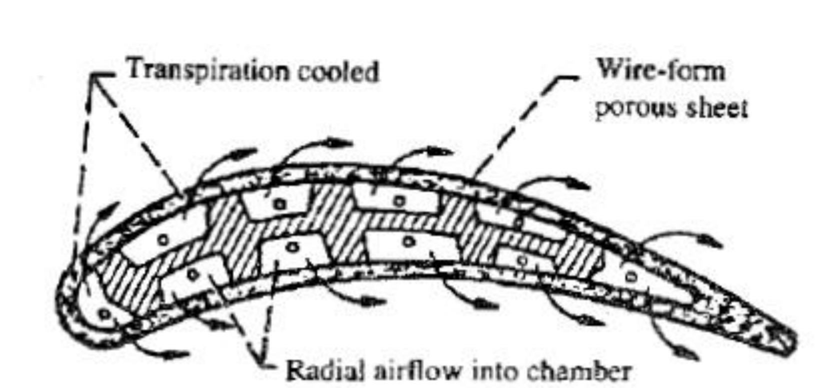
Impingement cooling



Impingment film cooling

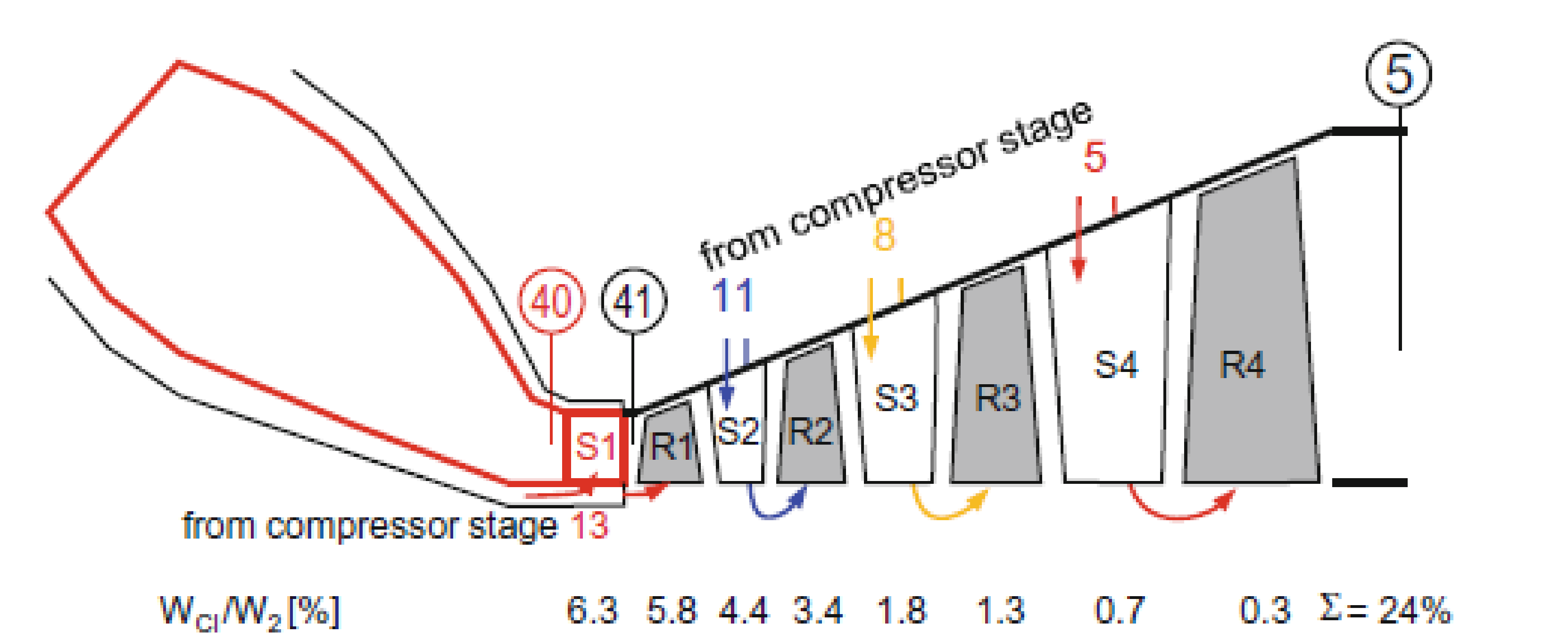




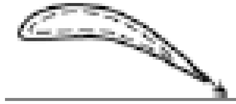
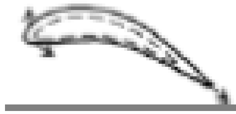
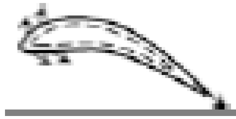
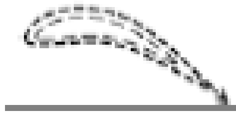


.Transpiration cooling

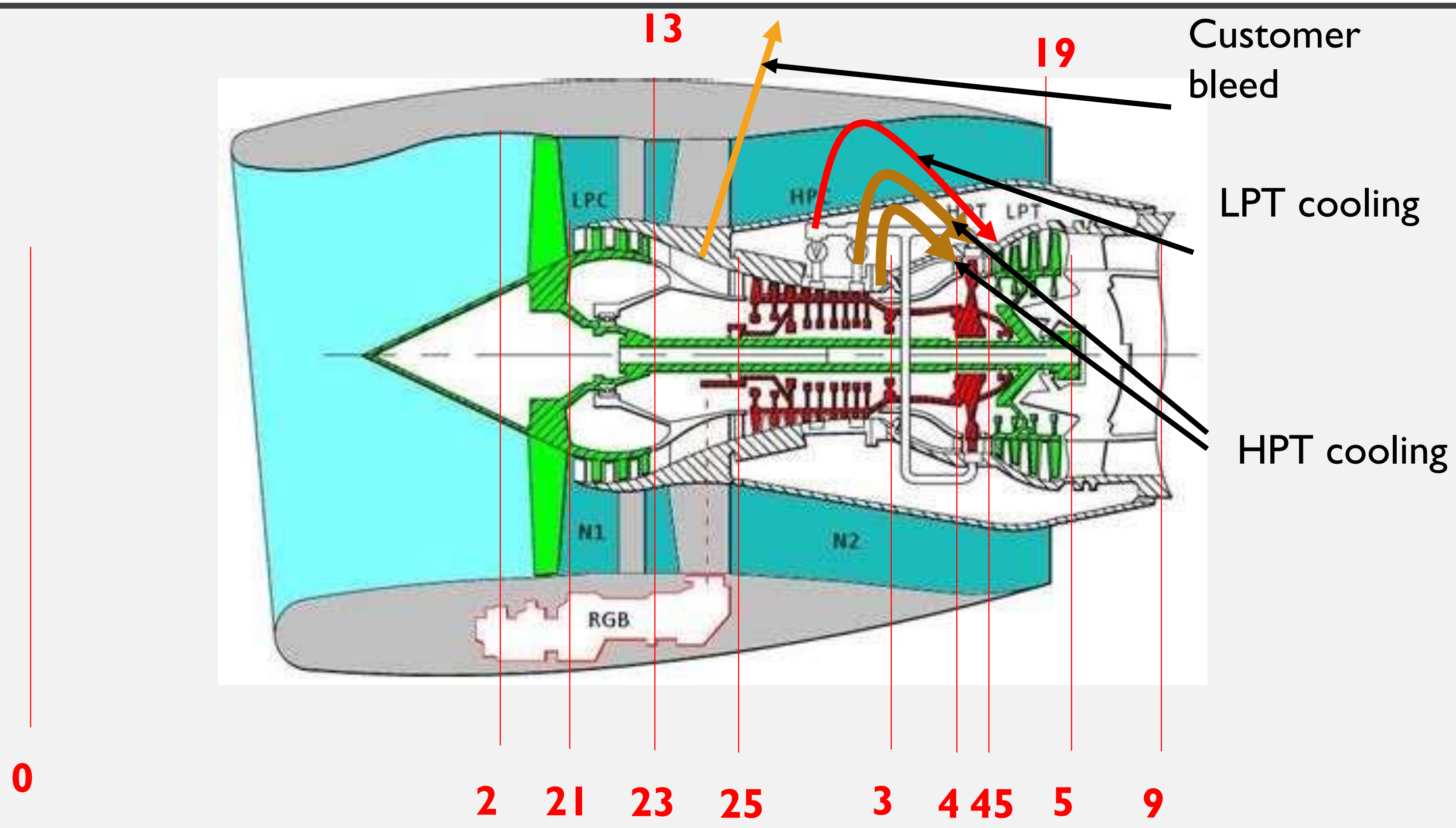
MULTISTAGE TURBINE COOLING EXAMPLE



EFFICIENCY LOSS FOR 1% COOLING AIR

		% Trailing edge ejection	Rel. cooling flow	$\Delta\eta_{stage}$	
				Stator	Rotor
	Advanced convection	100	1.5	0.001	0.002
	Film with convection	75	1.4	0.0012	0.0024
	Film with convection	50	1.3	0.0015	0.003
	Film with convection	25	1.0	0.0018	0.0036
	Transpiration with convection	25	0.8	0.005	0.01

TURBOFAN ENGINE WITH SECONDARY FLOW



Cooling of HPT: Bcool1 – turbine nozzle cooling (air from section 3)

Bcool2, PRB2 – cooling of next parts of HPT

Cooling of LPT: Bch3, PRBch3

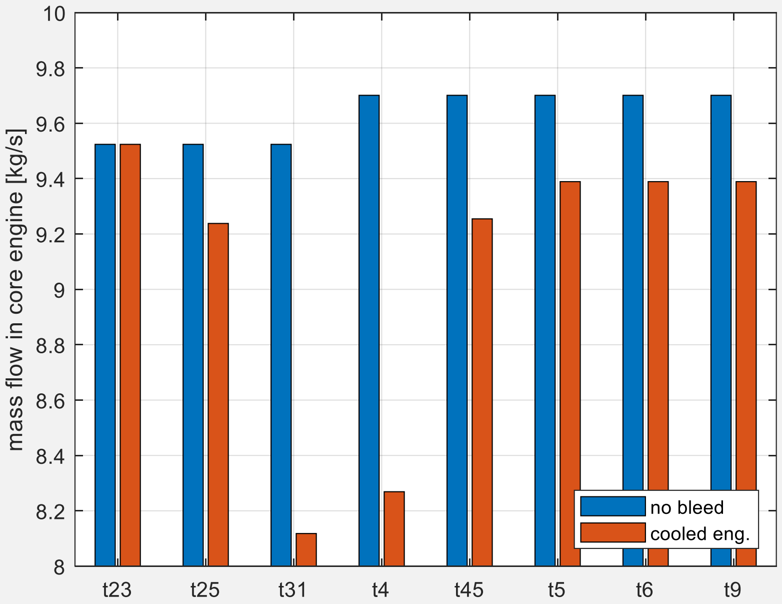
Customer bleed B_bleed, PR_bleed - bleed from LPC

RESULTS COMPARISON OF ENGINE WITH AND WITHOUT COOLING CALCULATION

	Parameter	customer bleed	LPT cool.	HPT cool.	HPTN cool.
1	'relative mass'	0.0300	0.0150	0.0300	0.0800
2	'mass flow [kg/s]'	0.2857	0.1344	0.2688	0.7169
3	'Temperature [K]'	389.4948	513.9169	755.9731	990.2732
4	'Pressure [kPa]'	149.6221	353.1082	1.1671e+03	2.6932e+03

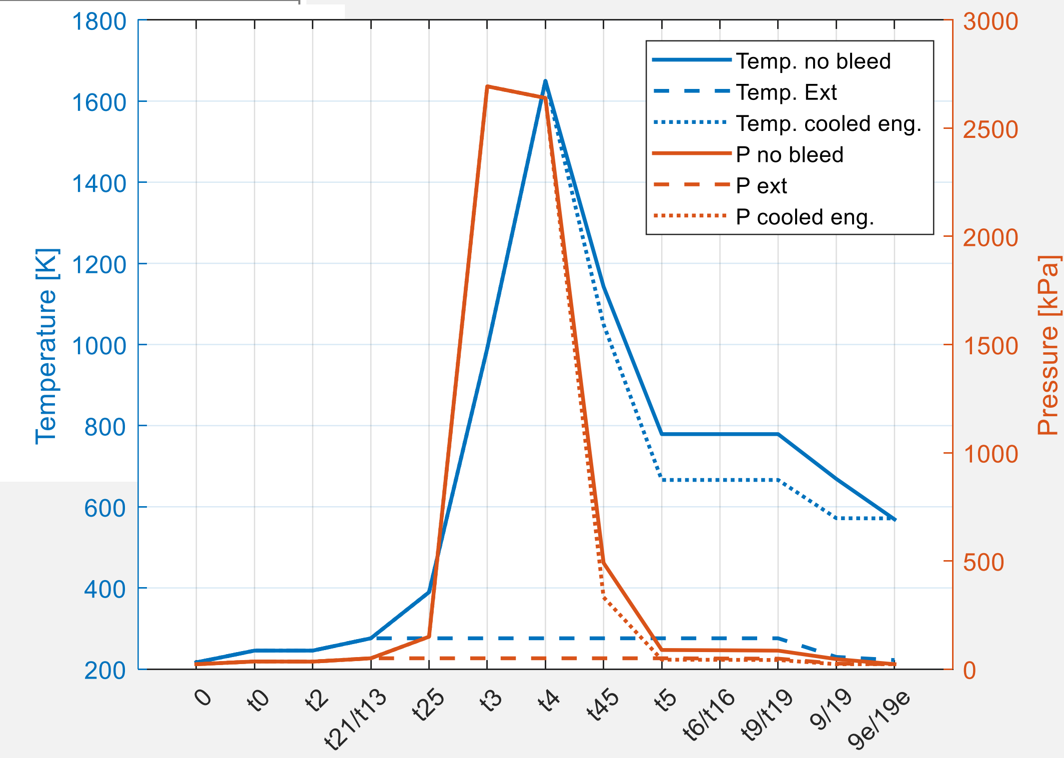
Mass flow discusion in the engine with bleeds and turbine cooling

- Air mass flow decreases in section 25 due to customer bleed
- Significant air mass flow drop is in HPC and after it therefore in section 31 it is the lowest.
- In section 3 mass flow grow is caused by fuel
- Mass flow grow in sections 45 and 5 is coused by turbines coolant which is transfered to main flow



RESULTS COMPARISON OF ENGINE WITH AND WITHOUT SECONDARY AIR SYSTEM

	section	T. [K] no bleed	T. [K] cooled engine	P [kPa] no bleed	P [kPa] cooled engine
1	'0'	216.4	216.4	22.57	22.57
2	't0'	245.5	245.5	35.1	35.1
3	't2'	245.5	245.5	34.4	34.4
4	't21/t13'	275.9	275.9	49.87	49.87
5	't25'	389.5	389.5	149.6	149.6
6	't3'	990.3	990.3	2693	2693
7	't4'	1650	1650	2639	2639
8	't45'	1143	1049	490.4	331.9
9	't5'	779.1	666.1	88.27	43.39
10	't6/t16'	779.1	666.1	86.94	42.74
11	't9/t19'	779.1	666.1	85.2	41.89
12	'9/19'	668.7	571.8	46.04	22.64
13	'9e/19e'	569	571.4	22.57	22.57



Temperature and pressure in cooled engine starting from section 45 are lower than in engine without bleed

Due to significant pressure drop in the cooled engine the full expansion is observed in convergent nozzle, instead of chocked nozzle in the engien without bleeds and cooling.

RESULTS COMPARISON OF ENGINE WITH AND WITHOUT COOLING CALCULATION

- Thrust and specific thrust of the cooled engine is lower
- Fuel consumption of the cooled engine is lower however SFC is higher
- Thermal and overall efficiencies are lower while propulsive efficiency is higher of of the cooled engine

	Parameter	Unit	no bleed engine	cooled engine
1	'Altitude'	'km'	11	11
2	'Mach No'	'-'	0.82	0.82
3	'm0'	'kg/s'	100	100
4	'Thrust'	'kN'	12.37	9.978
5	'Specific Thrust'	'N*s/kg'	123.7	99.78
6	'fuel consumption'	'kg/s'	0.1771	0.151
7	'Specific fuel consump'	'kg/N/h'	0.05155	0.05447
8	'therm. efficiency'	'-'	0.5727	0.4632
9	'prop. efficiency'	'-'	0.6856	0.8023
10	'overall efficiency'	'-'	0.3927	0.3716

Compressor air blieeds and turbines cooling are typical for modern engine of high TIT. Contemporarry engnes typically got very high TIT, significantly higher than the turbine material durability allow, therefore turbine cooling system is required.

COMPONENT POLYTROPIC EFFICIENCIES AND TOTAL PRESSURE LOSSES

Component	Figure of merit	Type	Level of technology 1	2	3	4
		A[a]	0.90	0.95	0.98	0.995
Diffuser	$\pi_{d\ \max}$	B[b]	0.88	0.93	0.96	0.97
		C[c]	0.85	0.90	0.94	0.96
Compressor	e_c	——	0.80	0.84	0.88	0.90
Fan	e_f	——	0.78	0.82	0.86	0.89
Burner	π_b	——	0.90	0.92	0.94	0.96
	η_b		0.88	0.94	0.99	0.995
Turbine	e_t	Uncooled	0.80	0.85	0.89	0.91
		Cooled		0.83	0.87	0.89
Afterburner	π_{AB}	——	0.90	0.92	0.94	0.95
	η_{AB}		0.85	0.91	0.96	0.97
		D[d]	0.95	0.97	0.98	0.995
Nozzle	π_n	E[e]	0.93	0.96	0.97	0.985
		F[f]	0.90	0.93	0.95	0.98
Maximum T_{t4}		(K)	1110	1390	1780	2000
		(°R)	2000	2500	3200	3600
Maximum T_{t7}		(K)	1390	1670	2000	2220
		(°R)	2500	3000	3600	4000

A = subsonic aircraft with engines in nacelles.
B = subsonic aircraft with engine(s) in airframe.
C = supersonic aircraft with engine(s) in airframe.
D = fixed-area convergent nozzle.
E = variable-area convergent nozzle.
F = variable-area convergent-divergent nozzle.
G Stealth may reduce Jrd max, 7rAB, and zrn.

Note: The levels of technology can be thought of as representing the technical capability for 20-year increments in time beginning in 1945. Thus level 3 technology presents typical component design values for the time period 1985-2005.

Jack D. Mattingly, William H. Heiser, David T. Pratt, **Aircraft Engine Design,**

THANKS FOR YOUR ATENTION

Questions and Comments ?

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