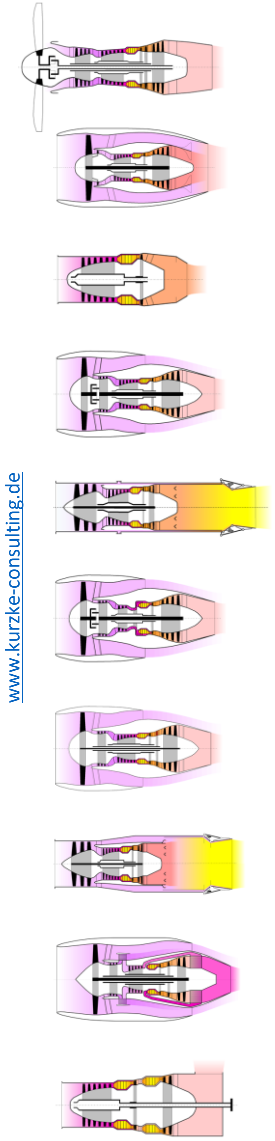
www.kurzke-consulting.de



Basics of Gas Turbine Performance

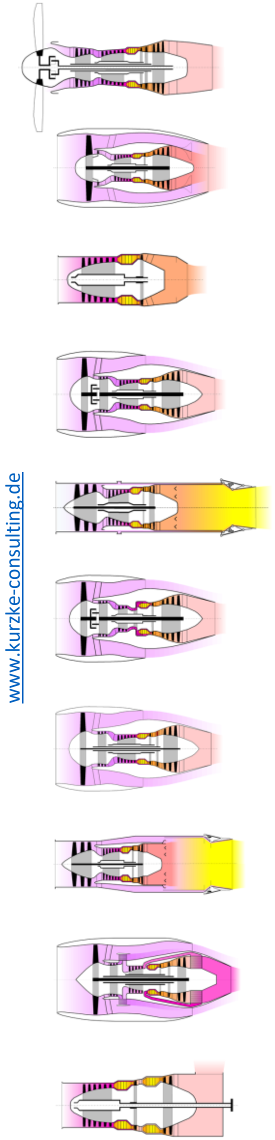
GT2024-TOB002

Joachim Kurzke – the inventor of GasTurb

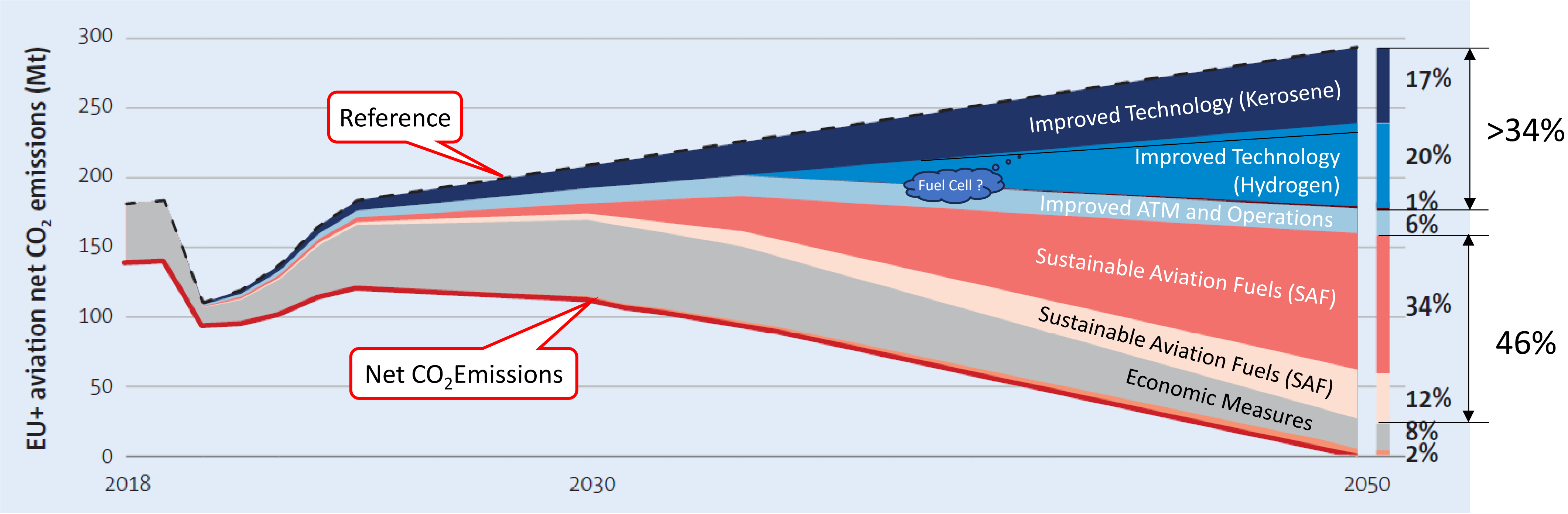
www.kurzke-consulting.de

Sustainable Aviation

More Than 80% of All Measures Have to do With Gas Turbines!

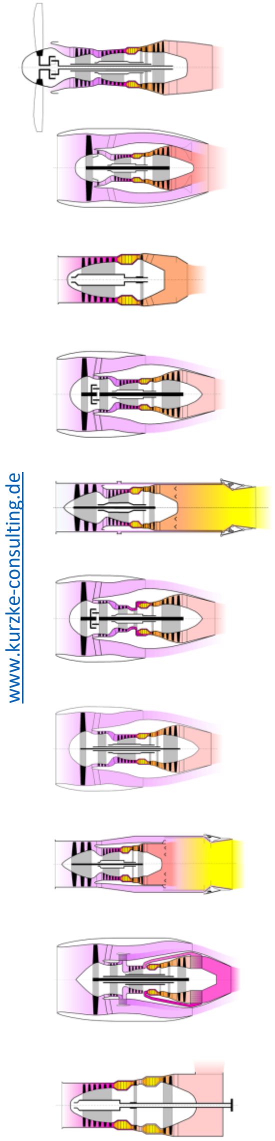


www.kurzke-consulting.de



Gas Turbine Related Σ= >80%

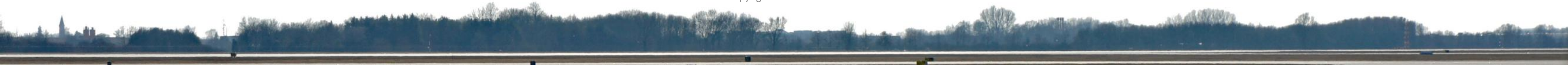
https://www.easa.europa.eu/eco/eaer/topics/introduction/industry-goals



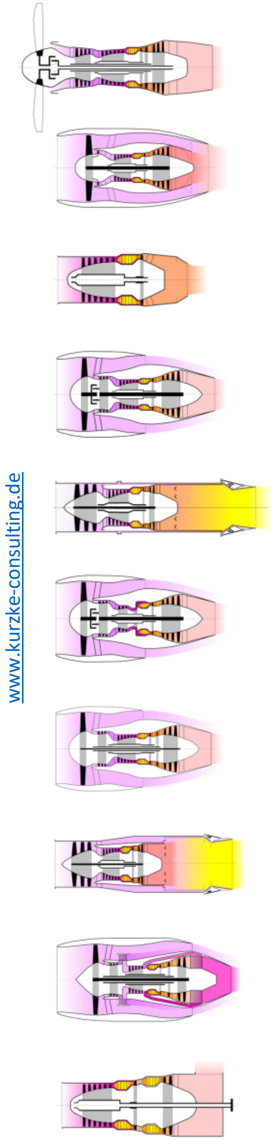
www.kurzke-consulting.de

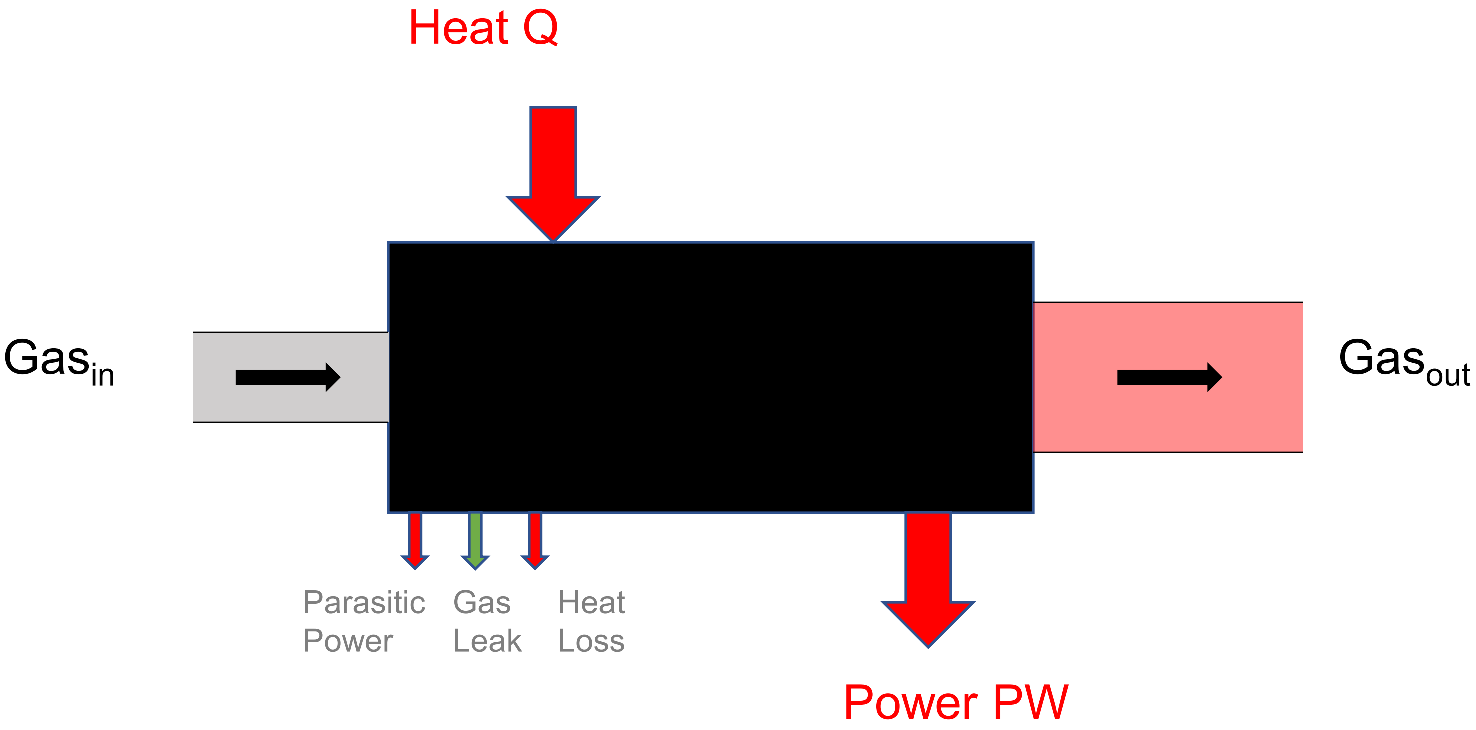
Outline

- Fundamentals
- Ideal Cycles
- Thermal Efficiency
- Power Generation
- Aircraft Propulsion
- Fundamental Design Decisions
- Non-Dimensionals
- Turbojet Off-Design

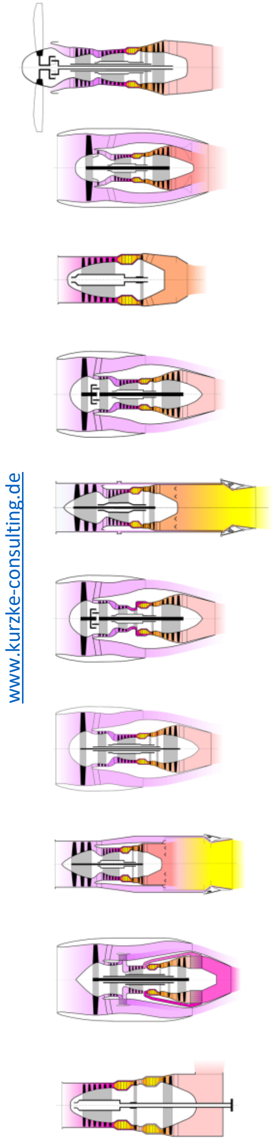


Thermodynamics of a Continuous Through Flow Machine





www.kurzke-consulting.de

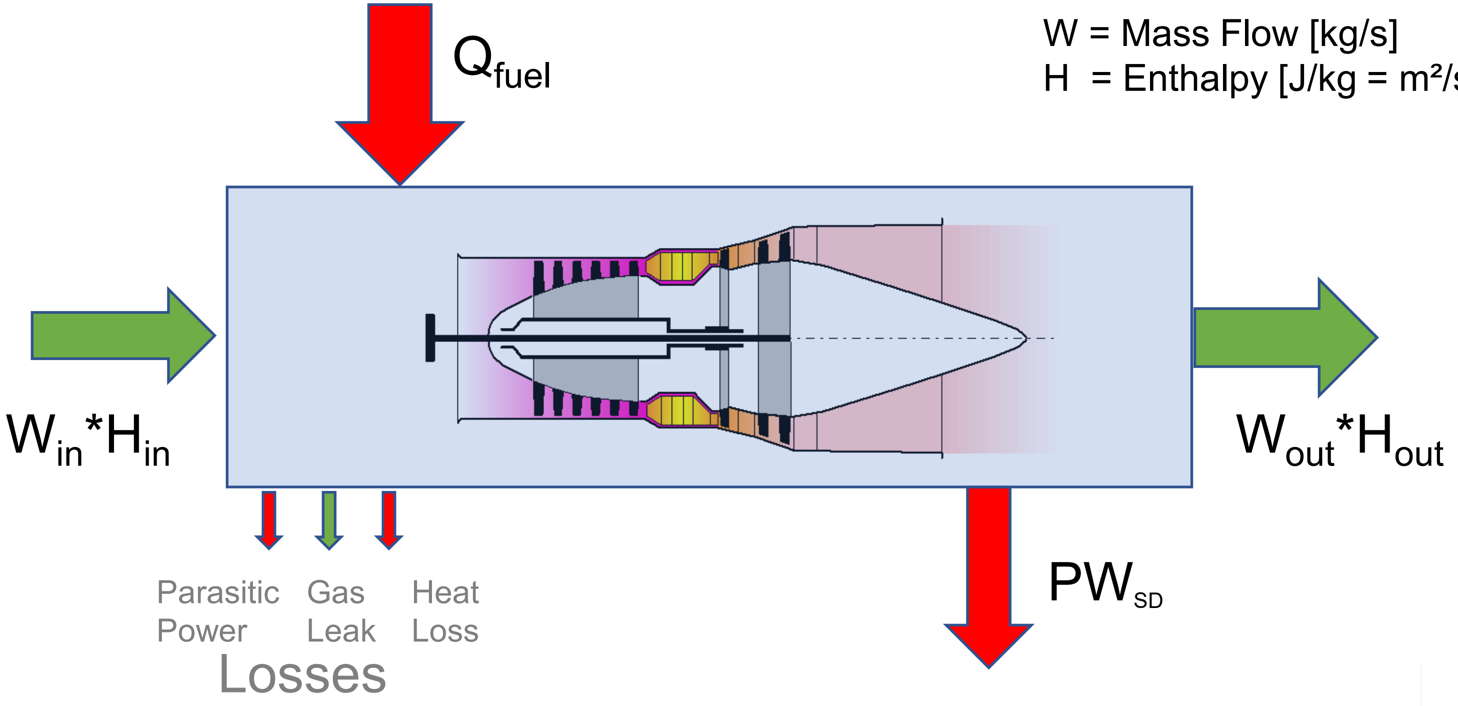


First Law of Thermodynamics

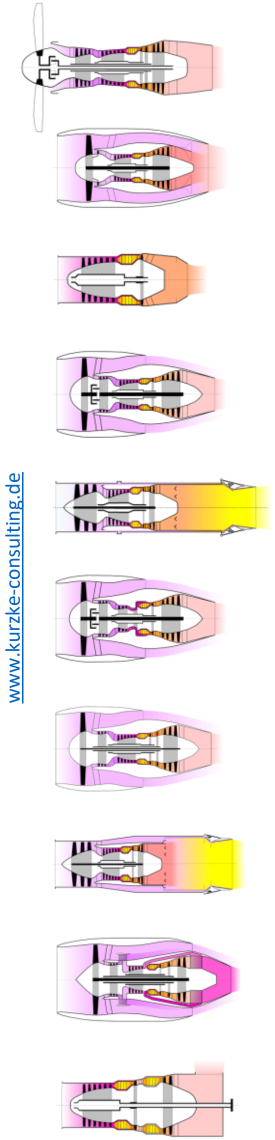
Energy in = Energy out

$$W_{in}*H_{in} + Q_{fuel} = PW_{SD} + W_{out}*H_{out} + \text{Losses}$$

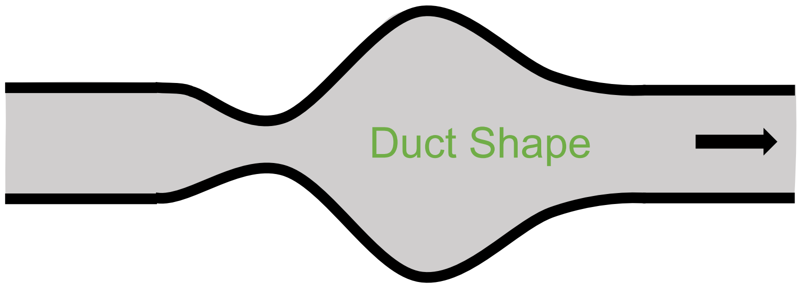
W = Mass Flow [kg/s]
H = Enthalpy [J/kg = m²/s²]



Flow in a Duct, no Heat Losses



www.kurzke-consulting.de



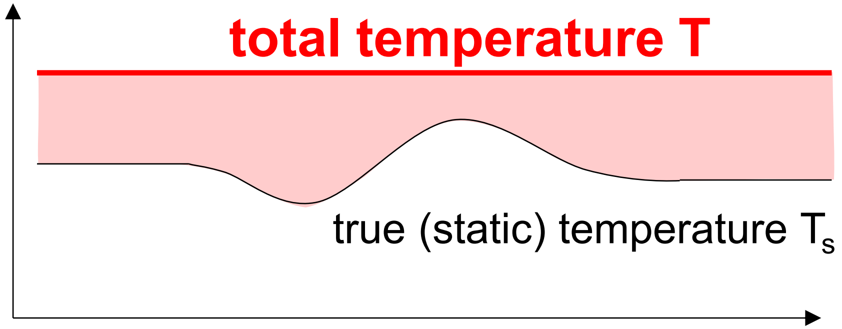
Total Energy = W*H = const

Mass Flow W = const

Total Enthalpy H = const

$H = c_P * \mathbf{T}$ = const

Total Temperature T = const

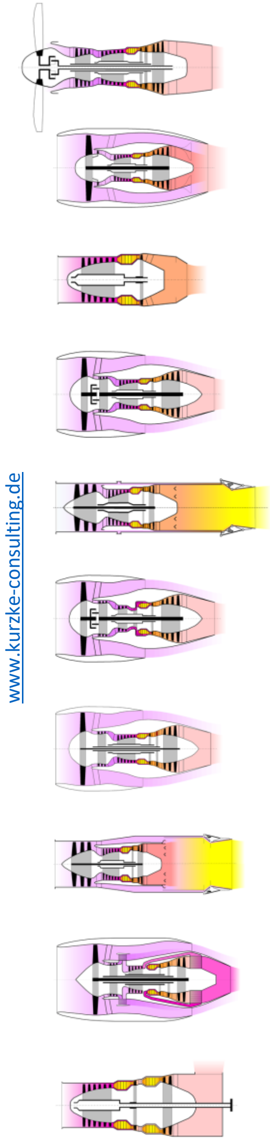


Static Temperature T_s varies:

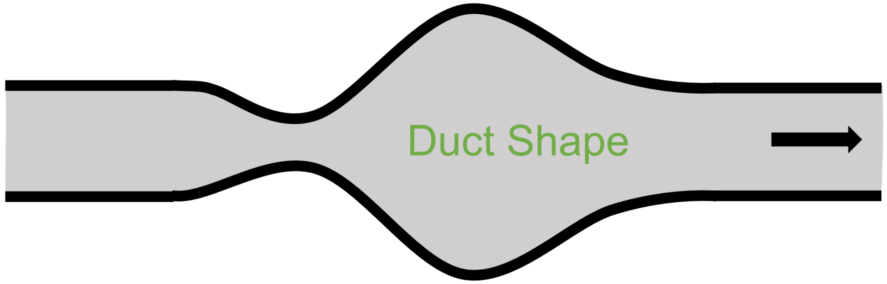
$$c_P * T_s = c_P * \mathbf{T} - V^2/2$$

Static and Total Pressure

Flow in a Duct, no Heat Losses



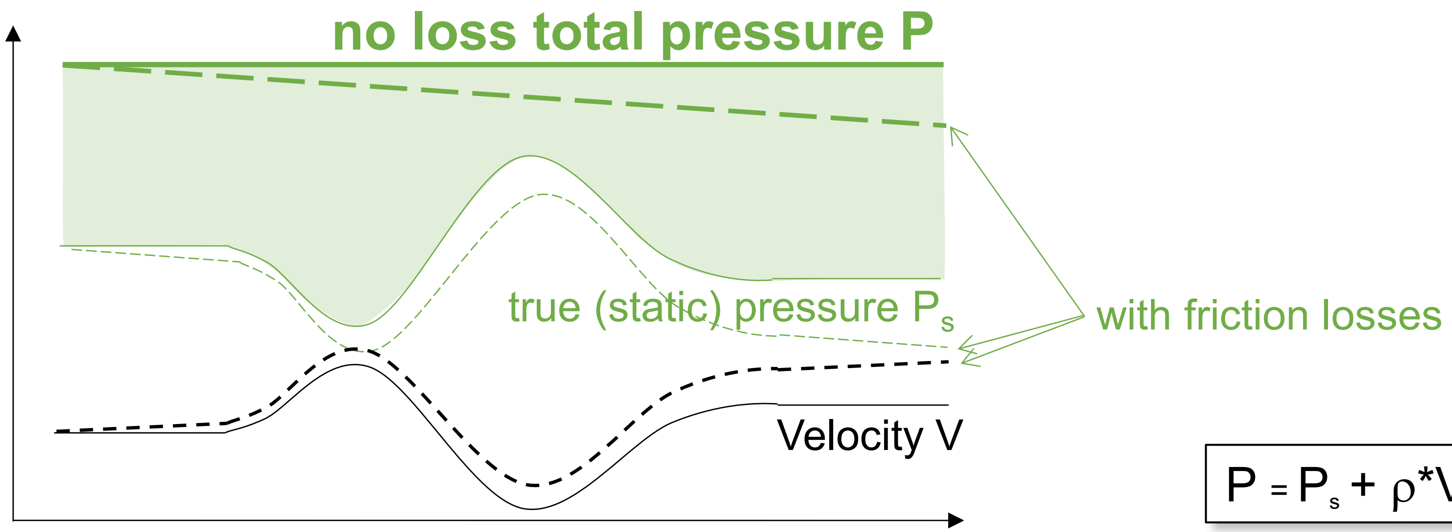
www.kurzke-consulting.de

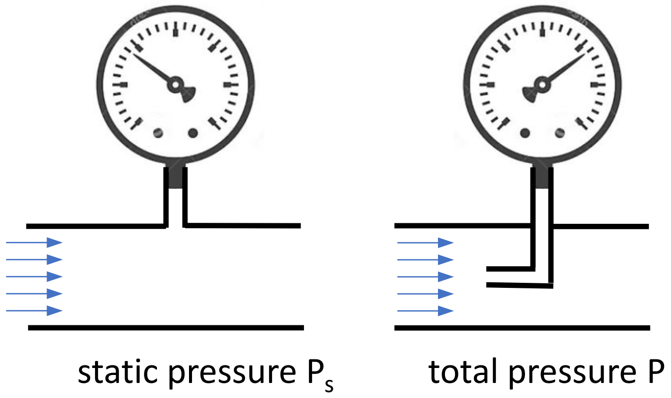


Energy = W*H = constant

$H = c_P * T$

T = constant

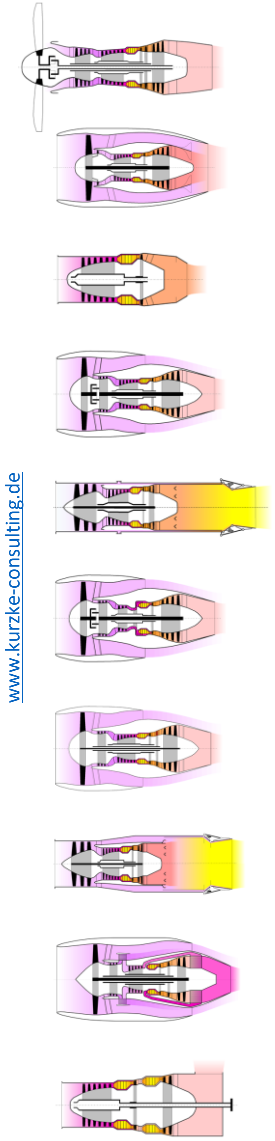




$$P = P_s + \rho * V^2/2$$

dynamic pressure

Correlations Between Static and Total Quantities



www.kurzke-consulting.de

Constant Gas Properties:

$$H = c_P * T = c_P * T_s + \frac{V^2}{2}$$

Isentropic Exponent:

$$\gamma = \frac{c_p}{c_p - R}$$

Mach Number:

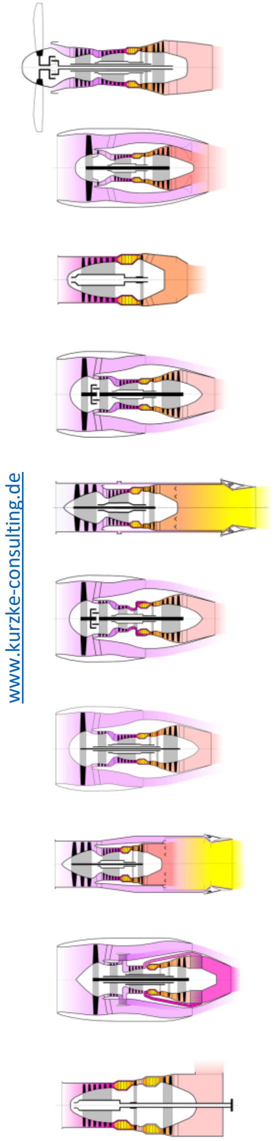
$$M = \frac{V}{V_{sonic}} = \frac{V}{\sqrt{\gamma * R * T_s}}$$

$$\frac{T}{T_s} = 1 + \frac{\gamma - 1}{2} M^2$$

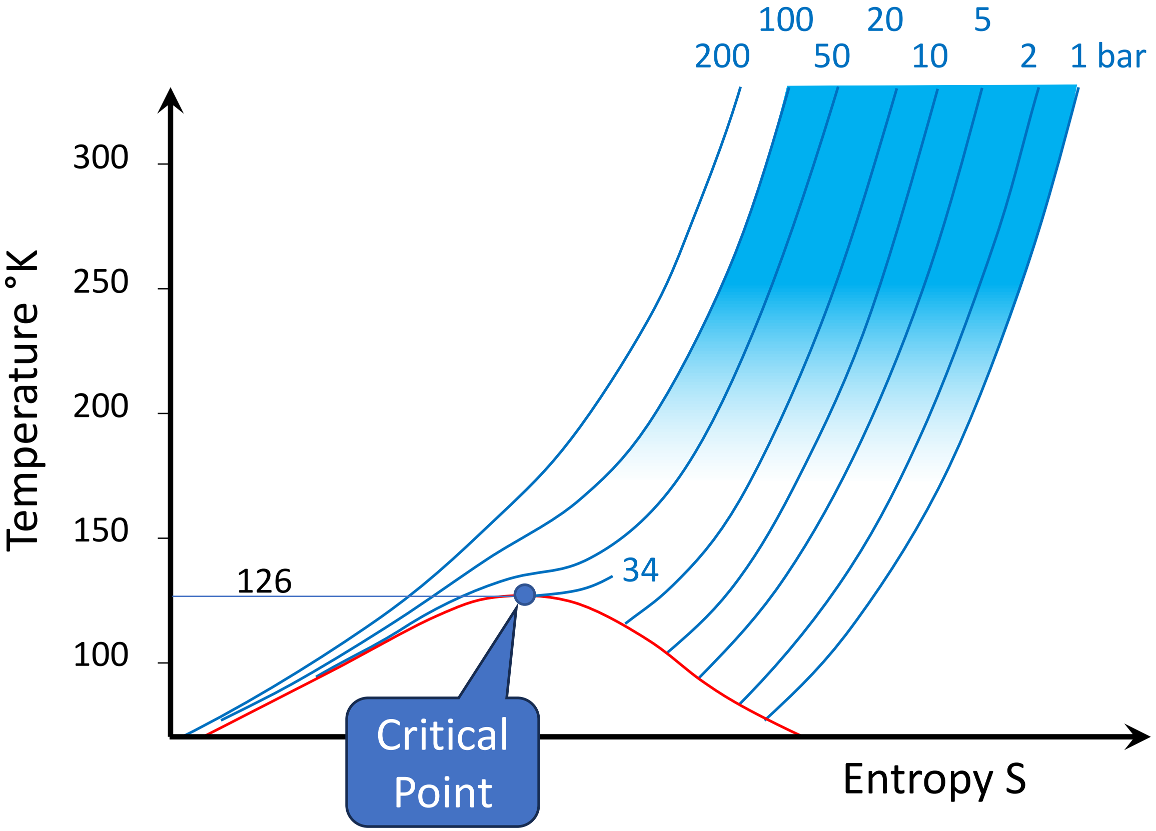
$$\frac{P}{P_s} = \left(\frac{T}{T_s}\right)^{\frac{\gamma}{\gamma - 1}} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}$$

R = Gas Constant
R_{air} = 287 J/(kg*K)
c_P = Specific Heat @ Constant Pressure
$c_{P,air}$ = 1004 J/(kg*K)
γ_{air} = 1.4

T-S Diagram of Nitrogen



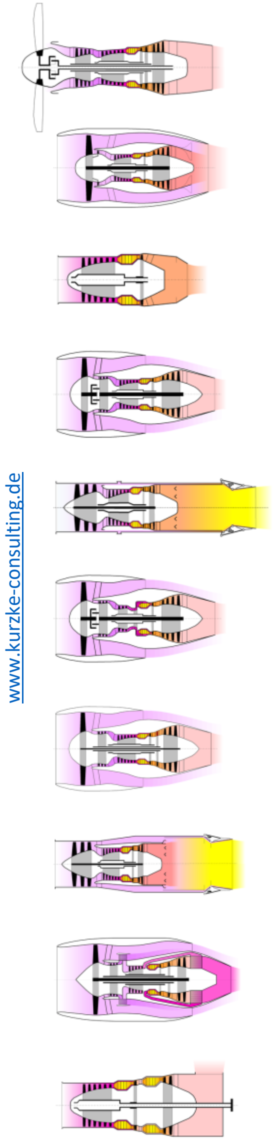
www.kurzke-consulting.de



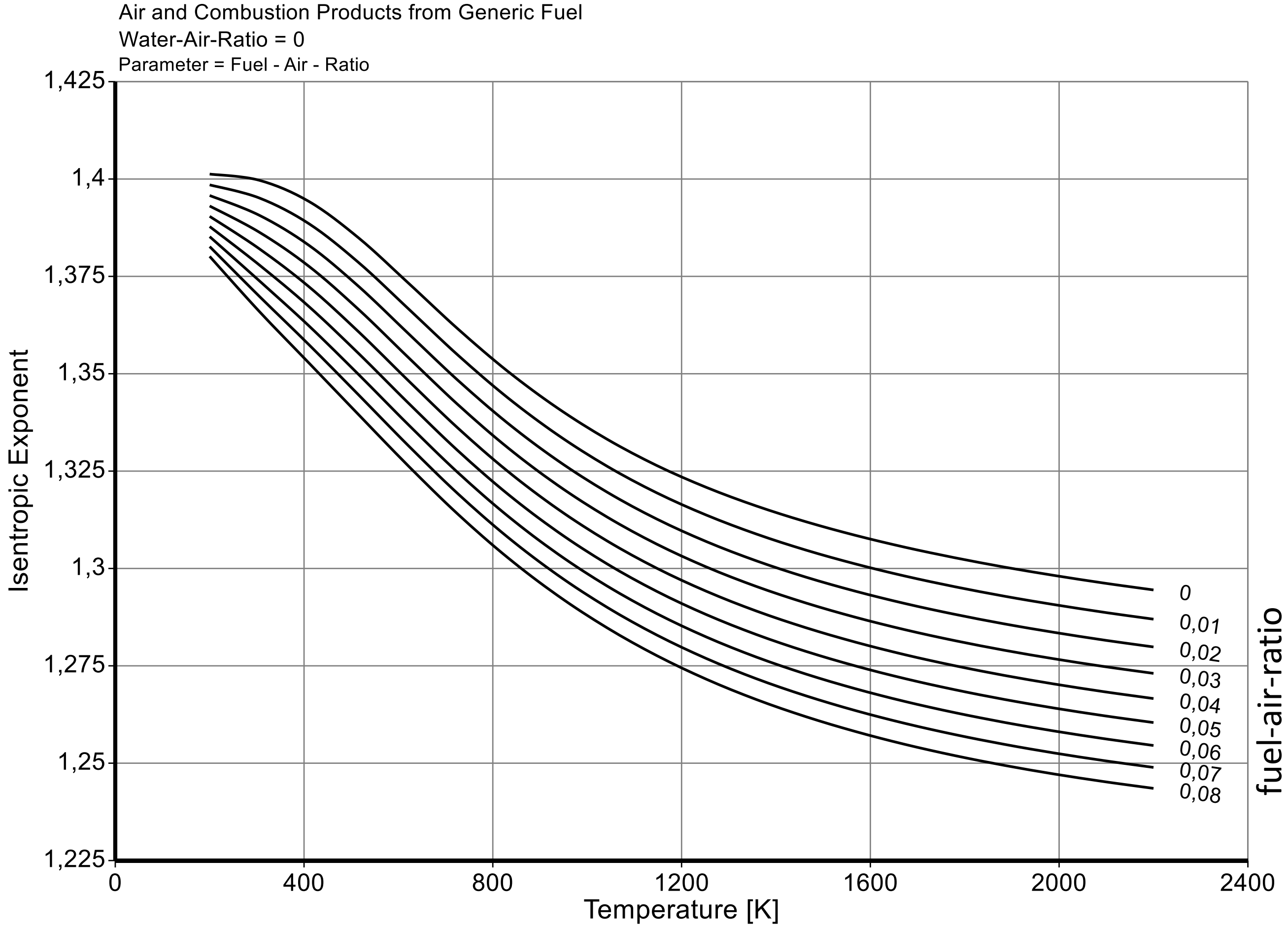
Gas	Critical Temp	Critical Pressure
Air	133K	37.7 bar
Nitrogen	126	34
CO_2	304	73.8
H_2O	647	221.2

True Gas Properties

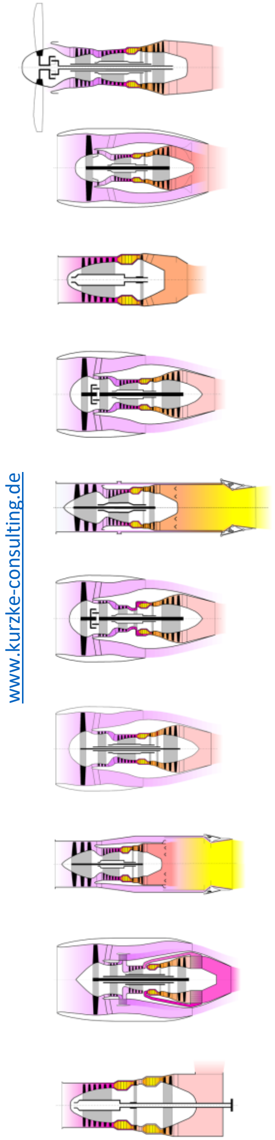
Isentropic Exponent $\gamma = c_p/(c_p - R)$

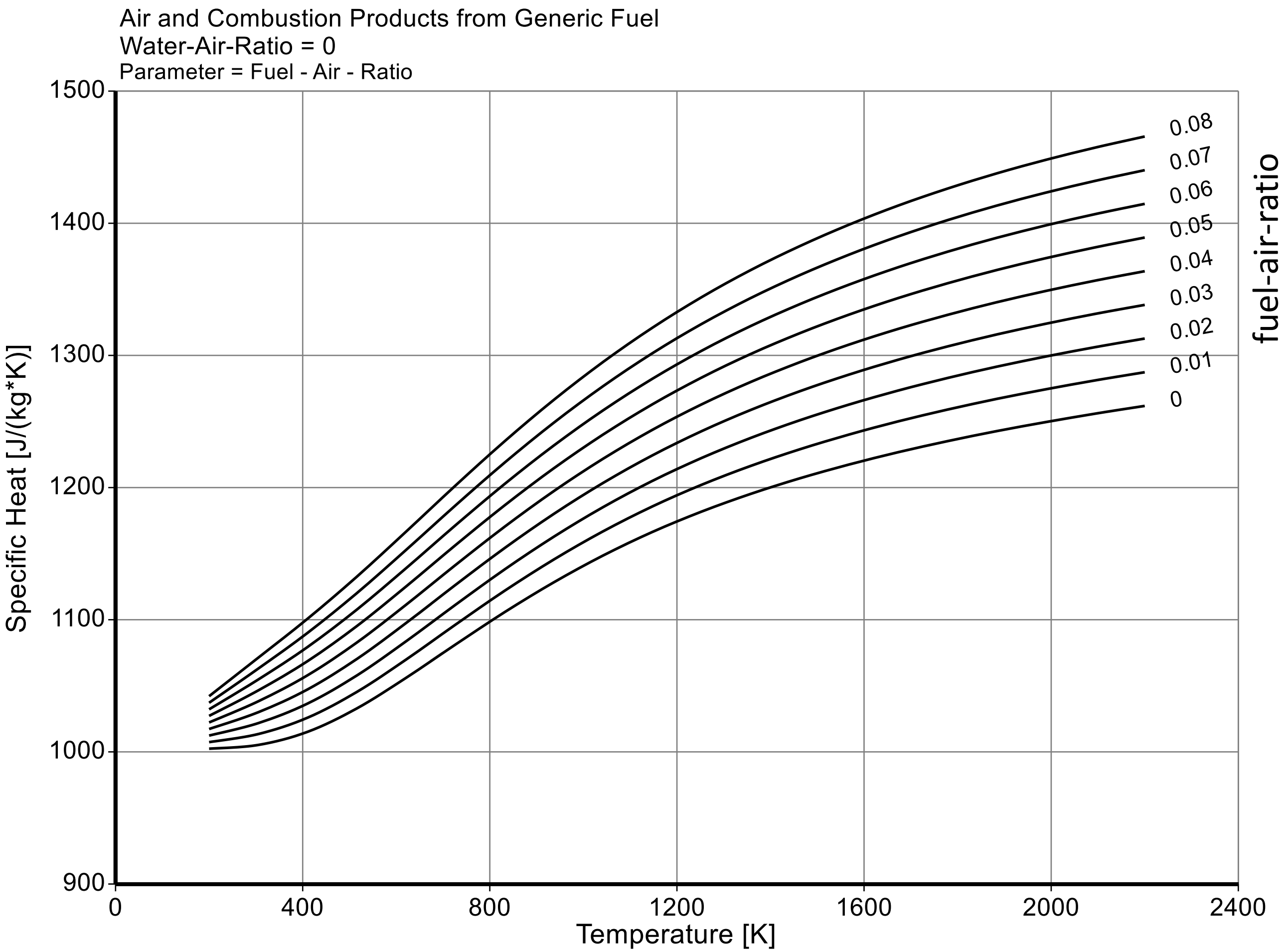


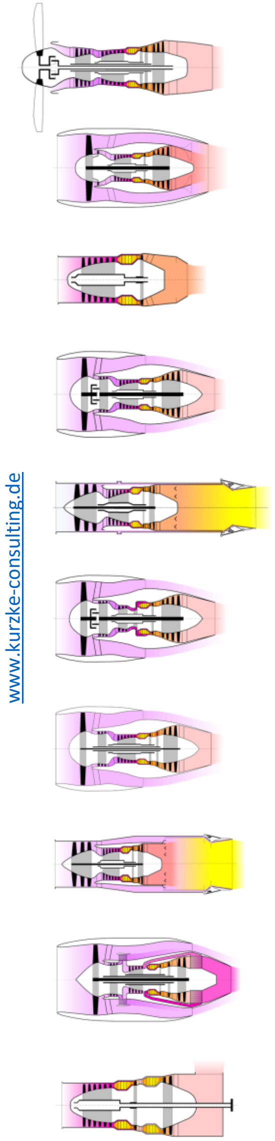
www.kurzke-consulting.de



Specific Heat c_p

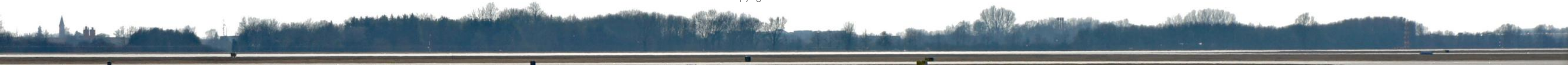






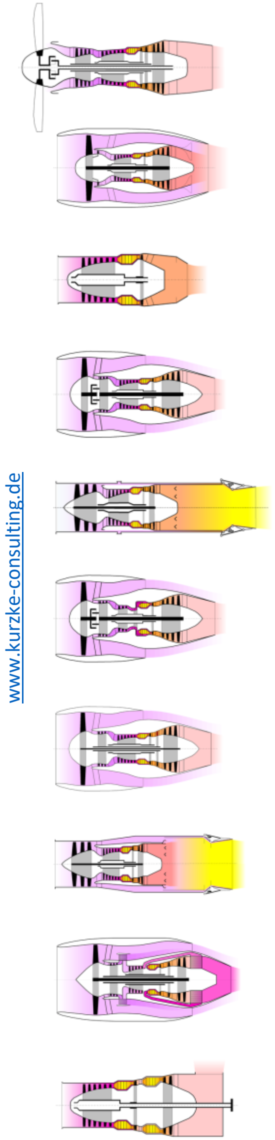
Outline

- Fundamentals
- **Ideal Cycles**
- Thermal Efficiency
- Power Generation
- Aircraft Propulsion
- Fundamental Design Decisions
- Non-Dimensionals
- Turbojet Off-Design

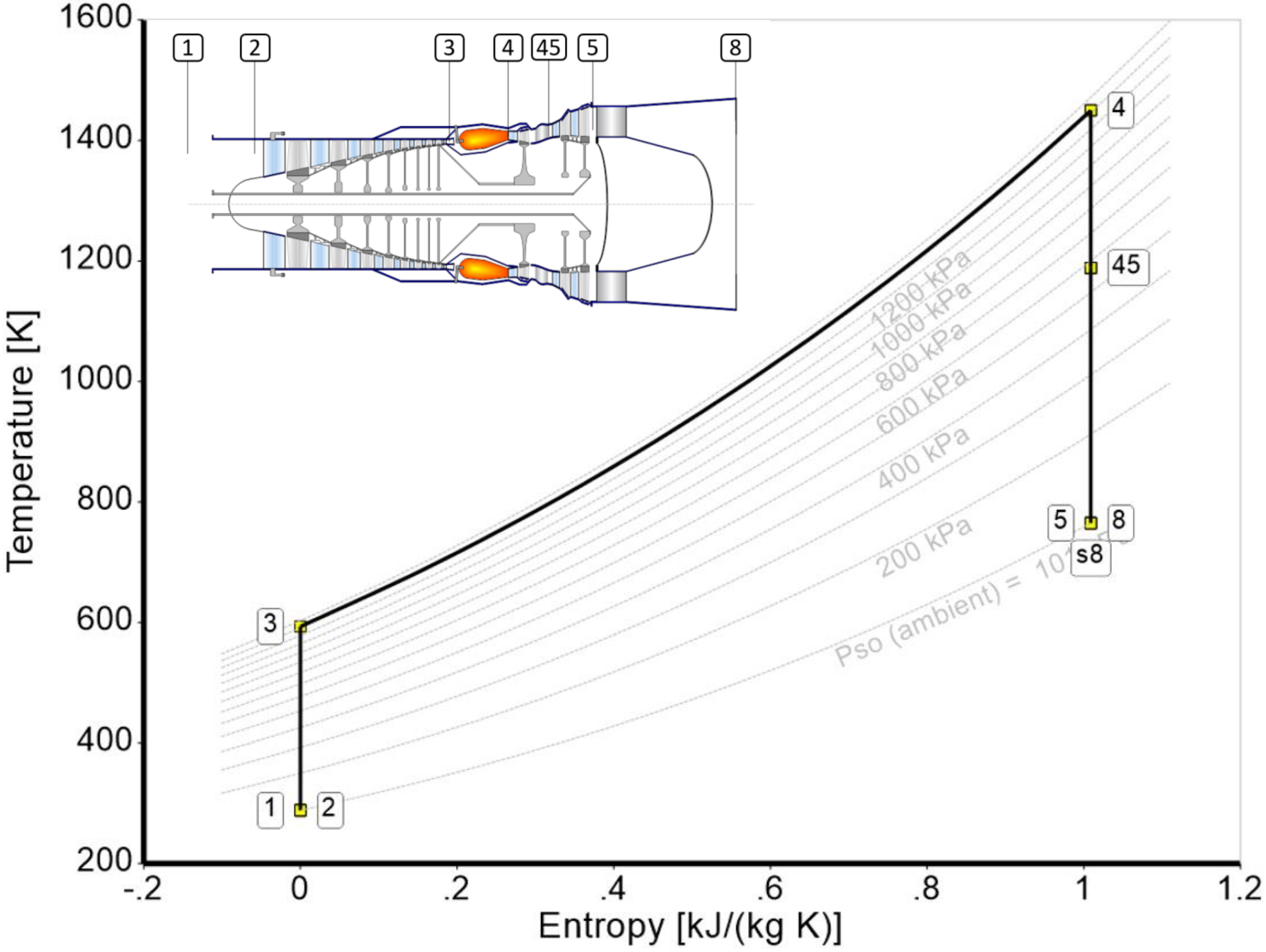


Temperature - Entropy Diagram

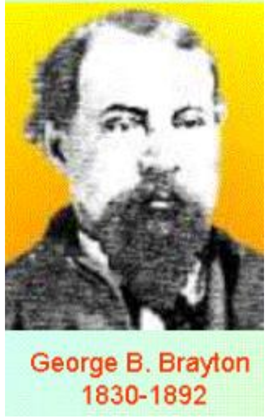
Ideal Joule (Brayton) Process



www.kurzke-consulting.de

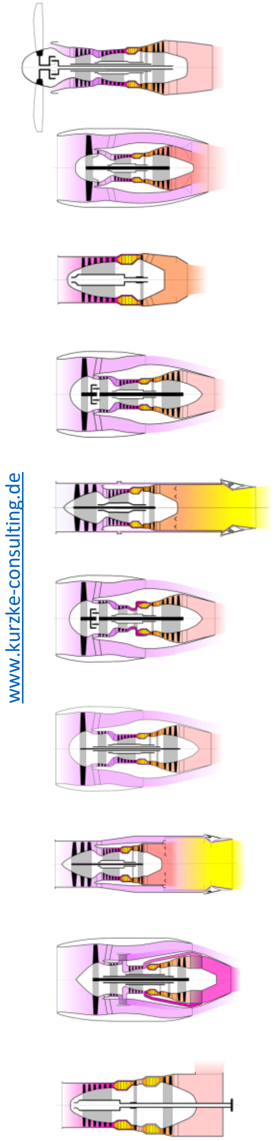


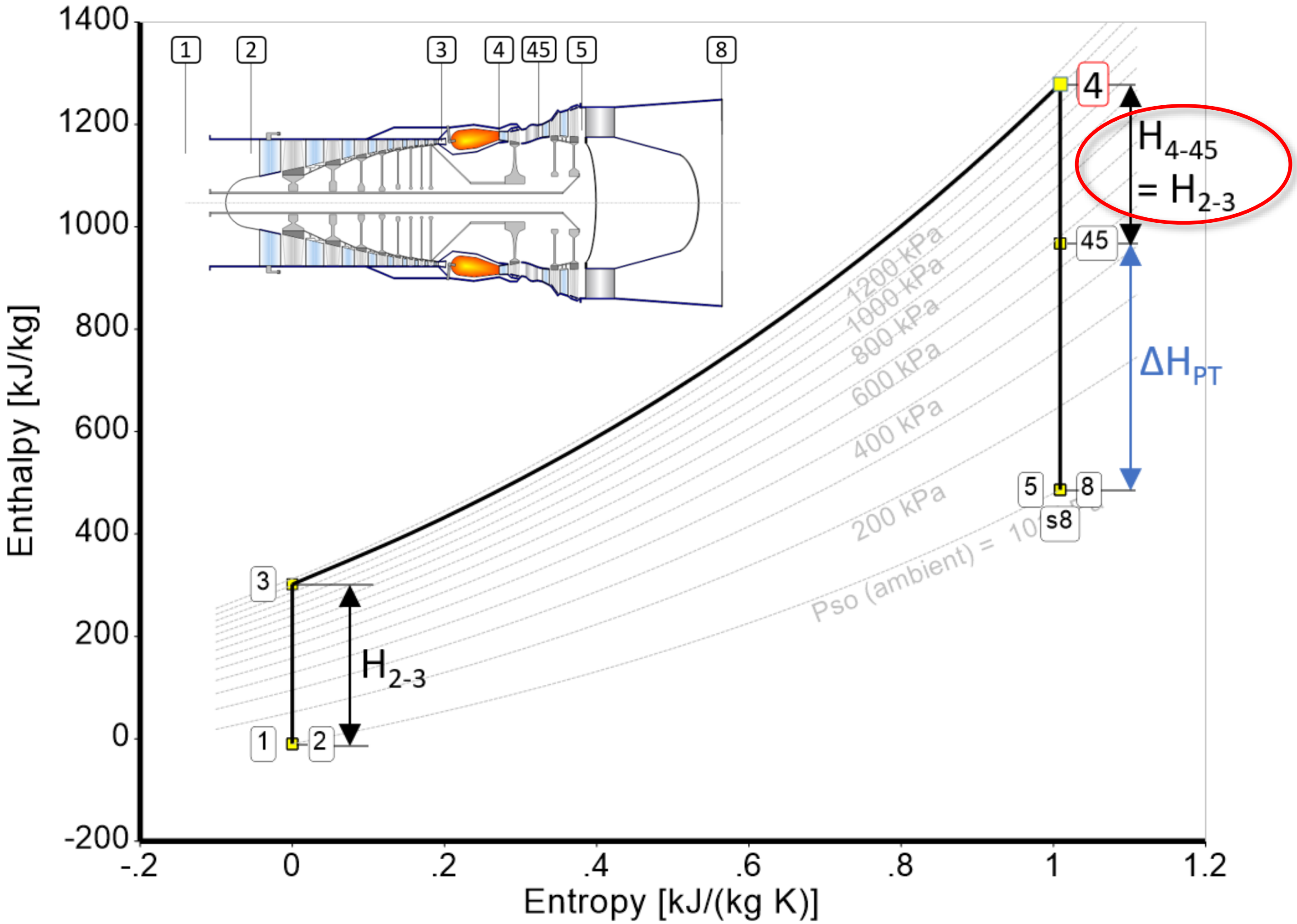
James P. Joule
1818-1889

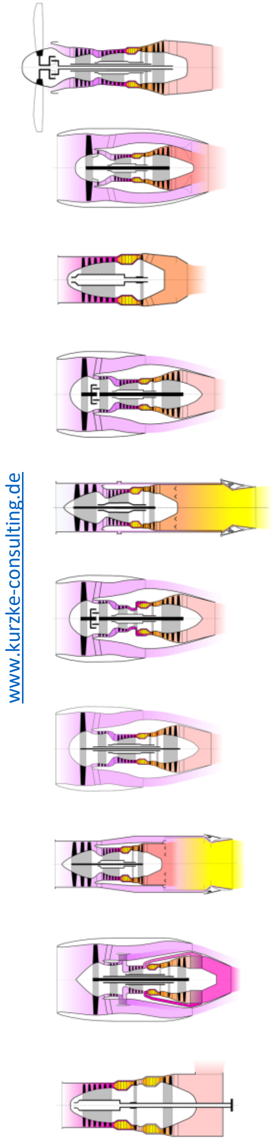


Enthalpy - Entropy Diagram

Ideal Joule (Brayton) Process

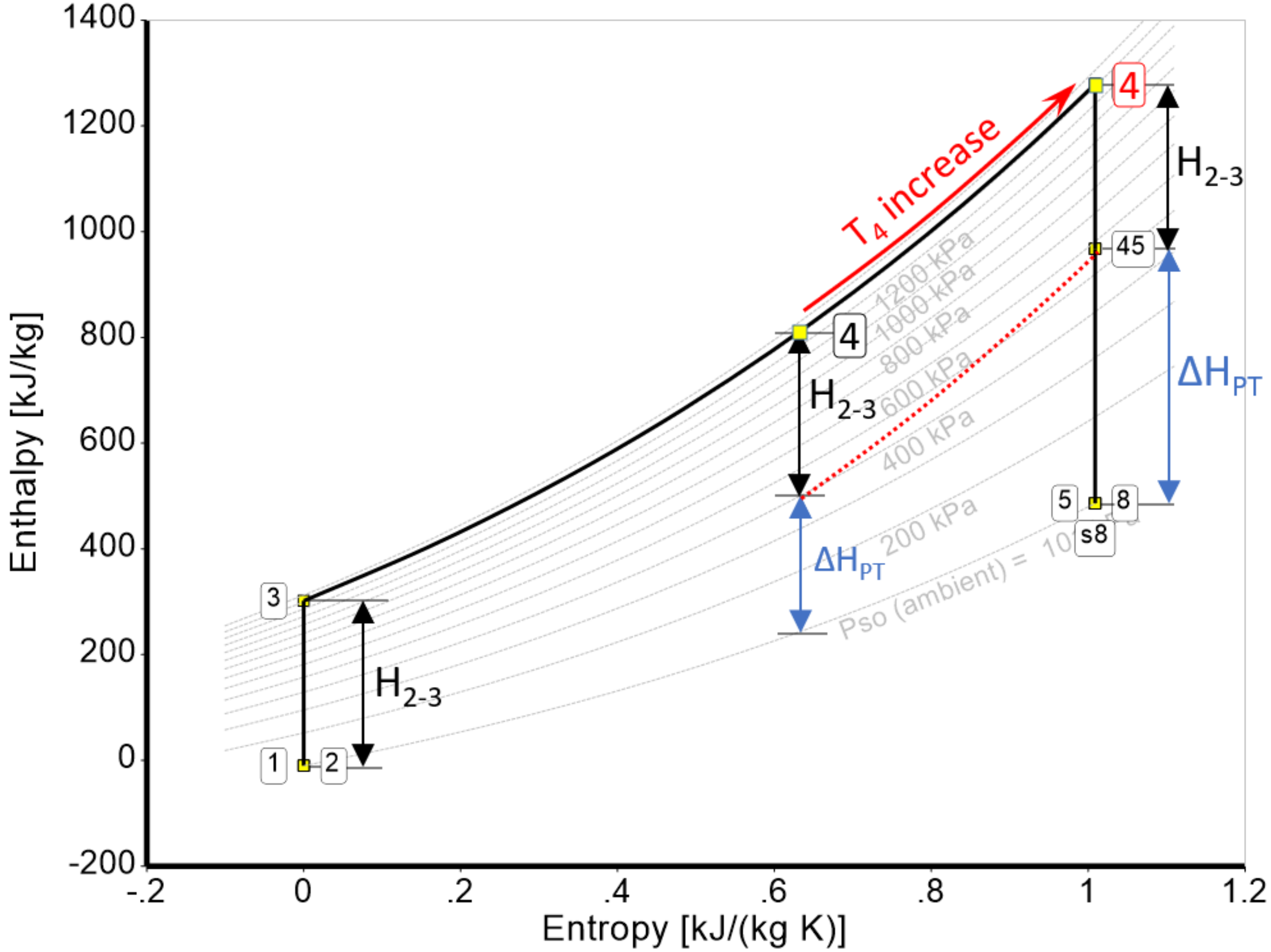




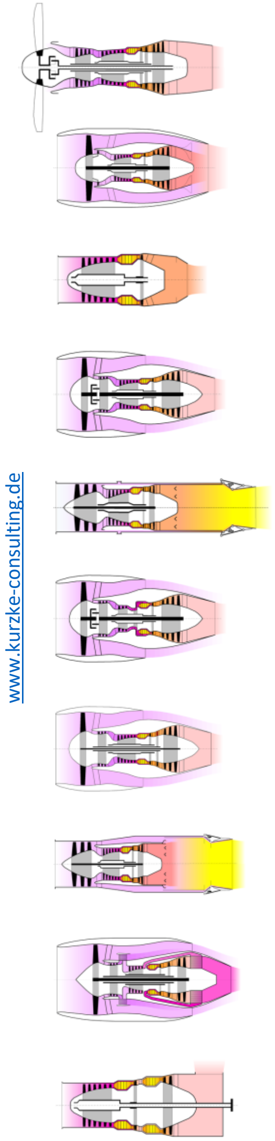


www.kurzke-consulting.de

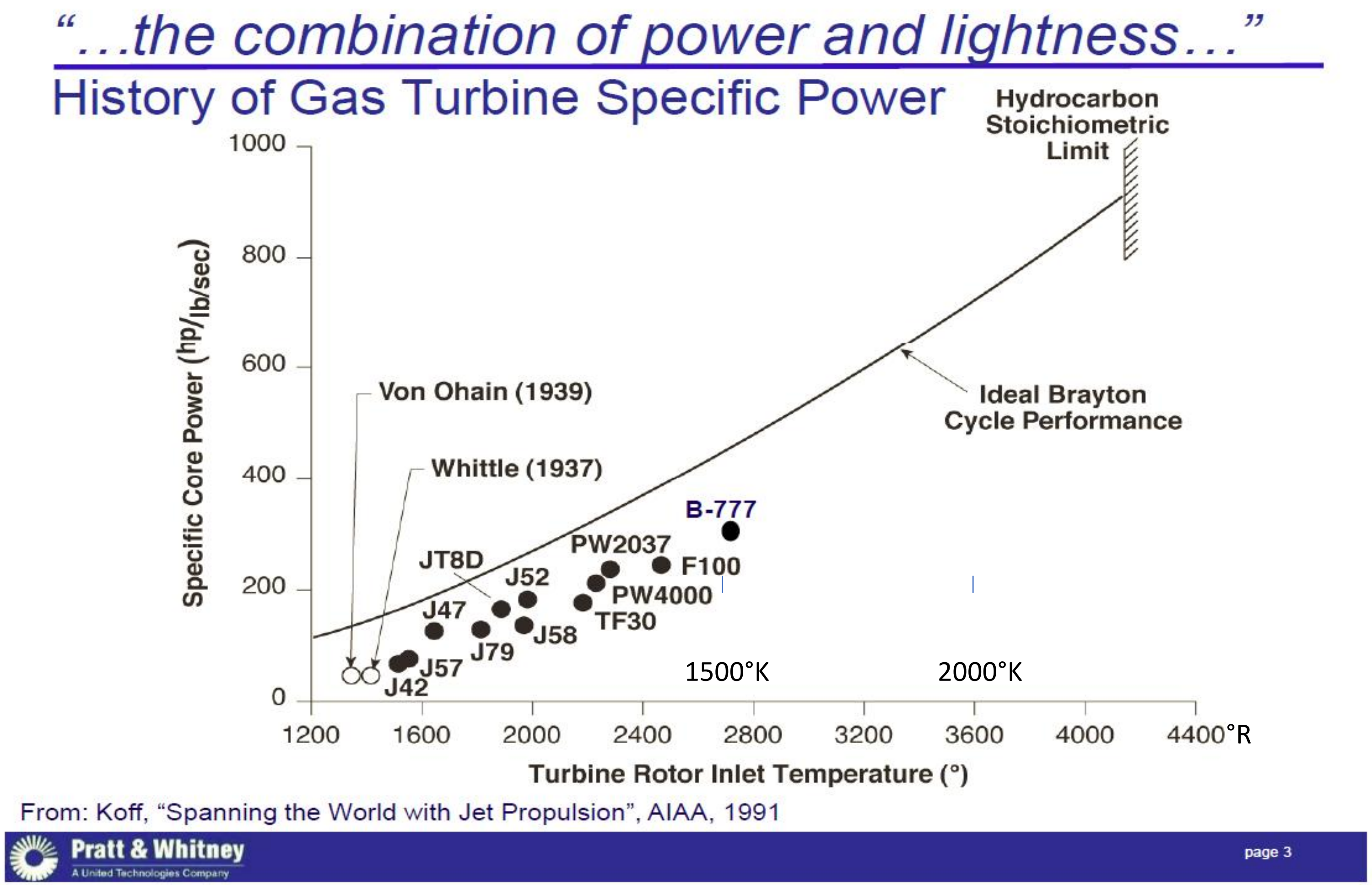
Ideal Joule Process
Influence of T_4

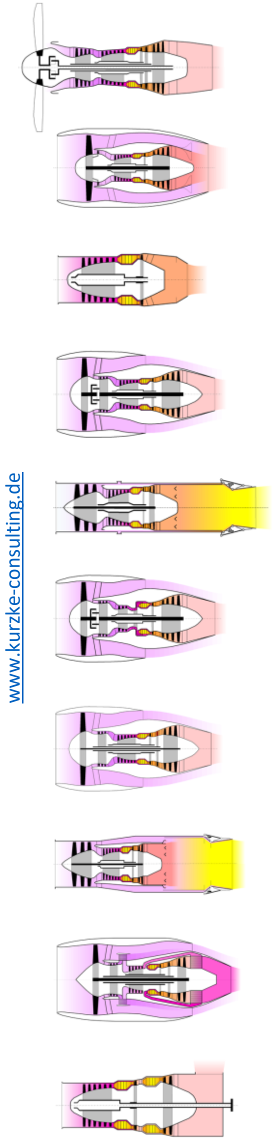


History



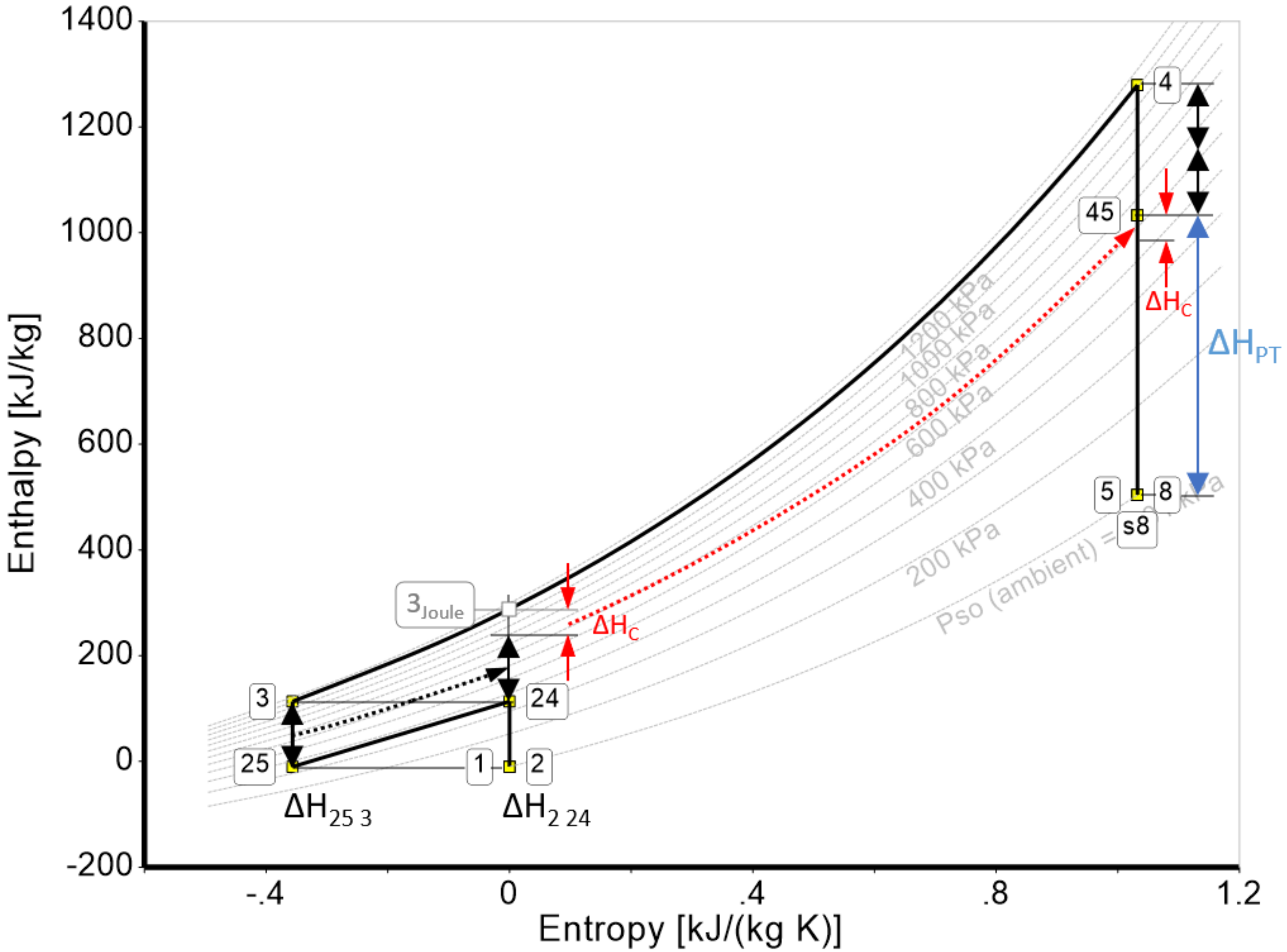
www.kurzke-consulting.de



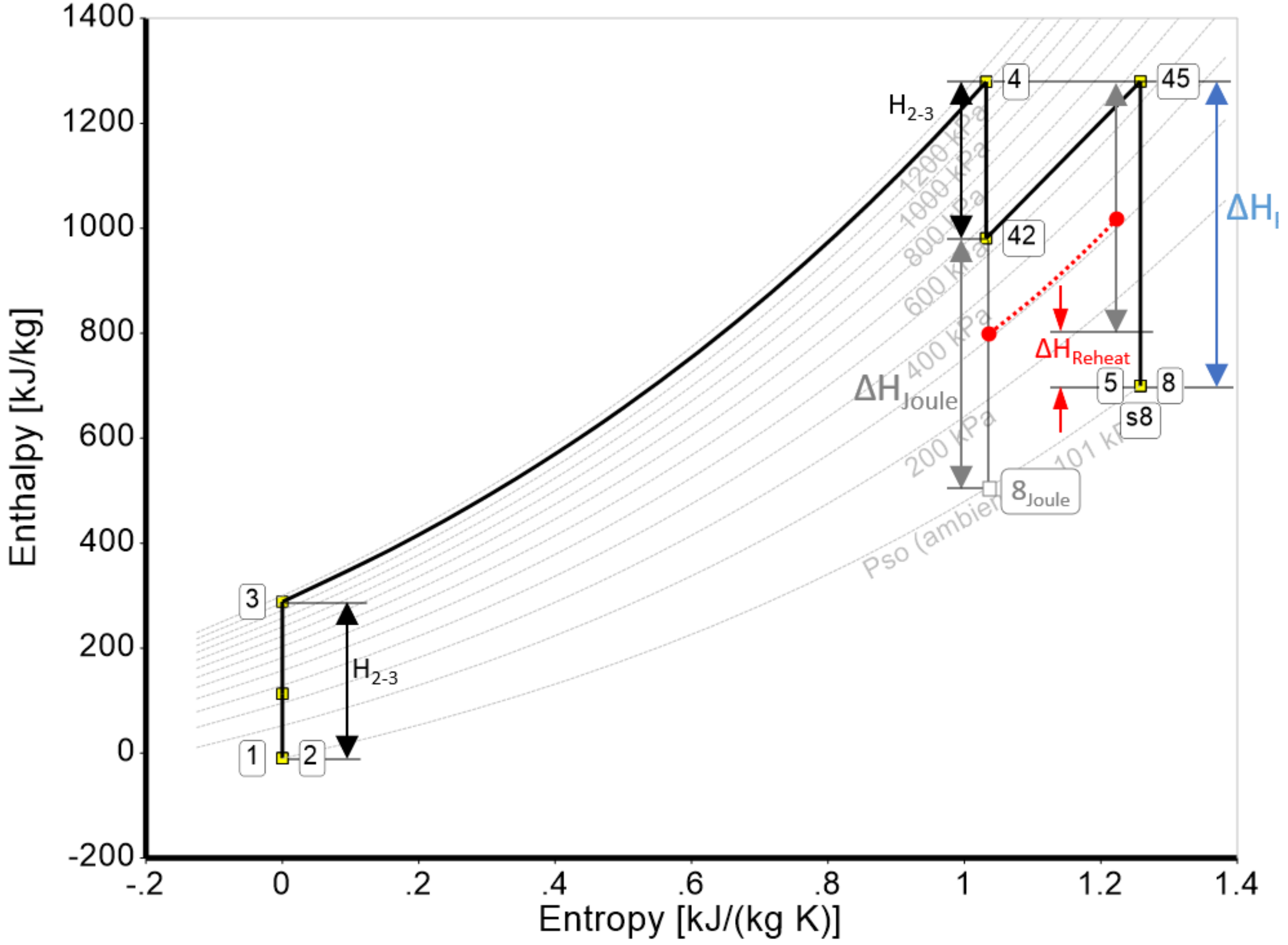


www.kurzke-consulting.de

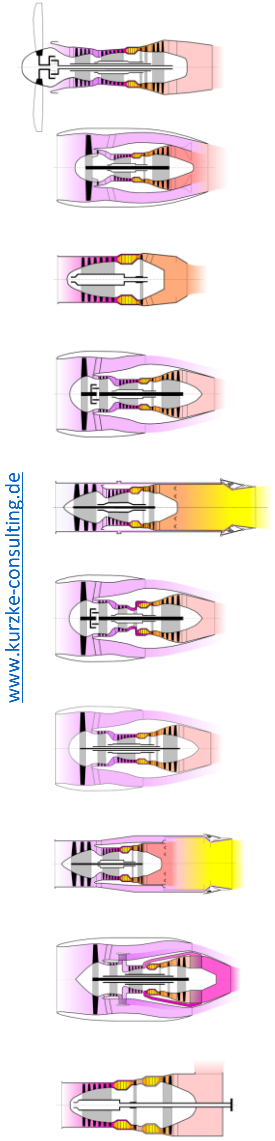
Increasing Power Output
Intercooling



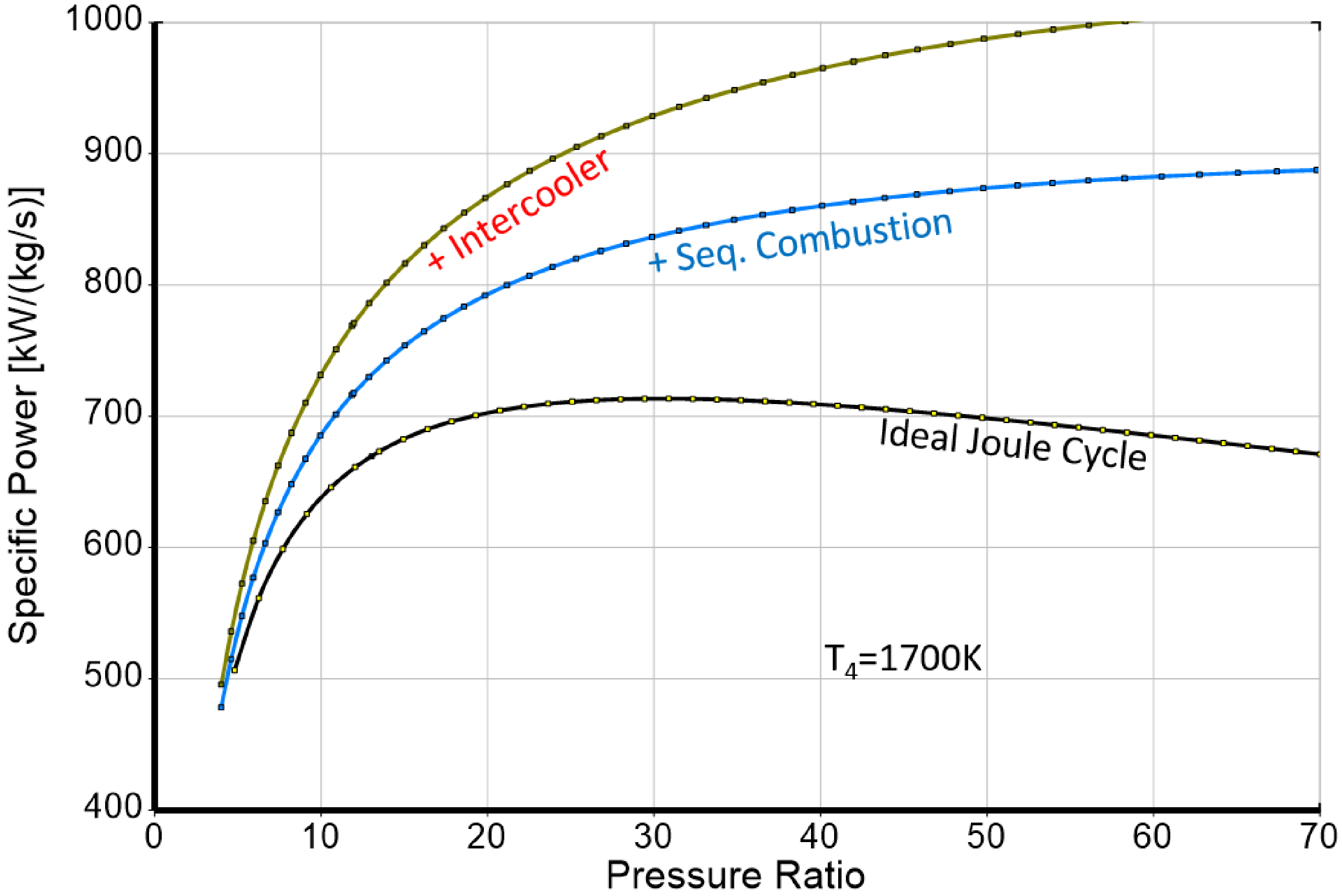
Increasing Power Output
Sequential Combustion

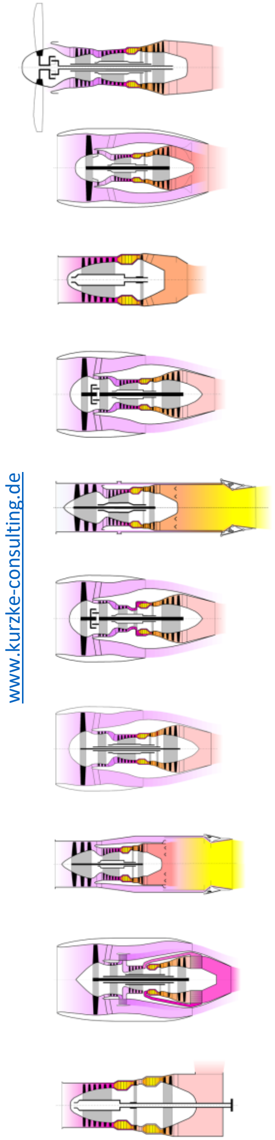


www.kurzke-consulting.de



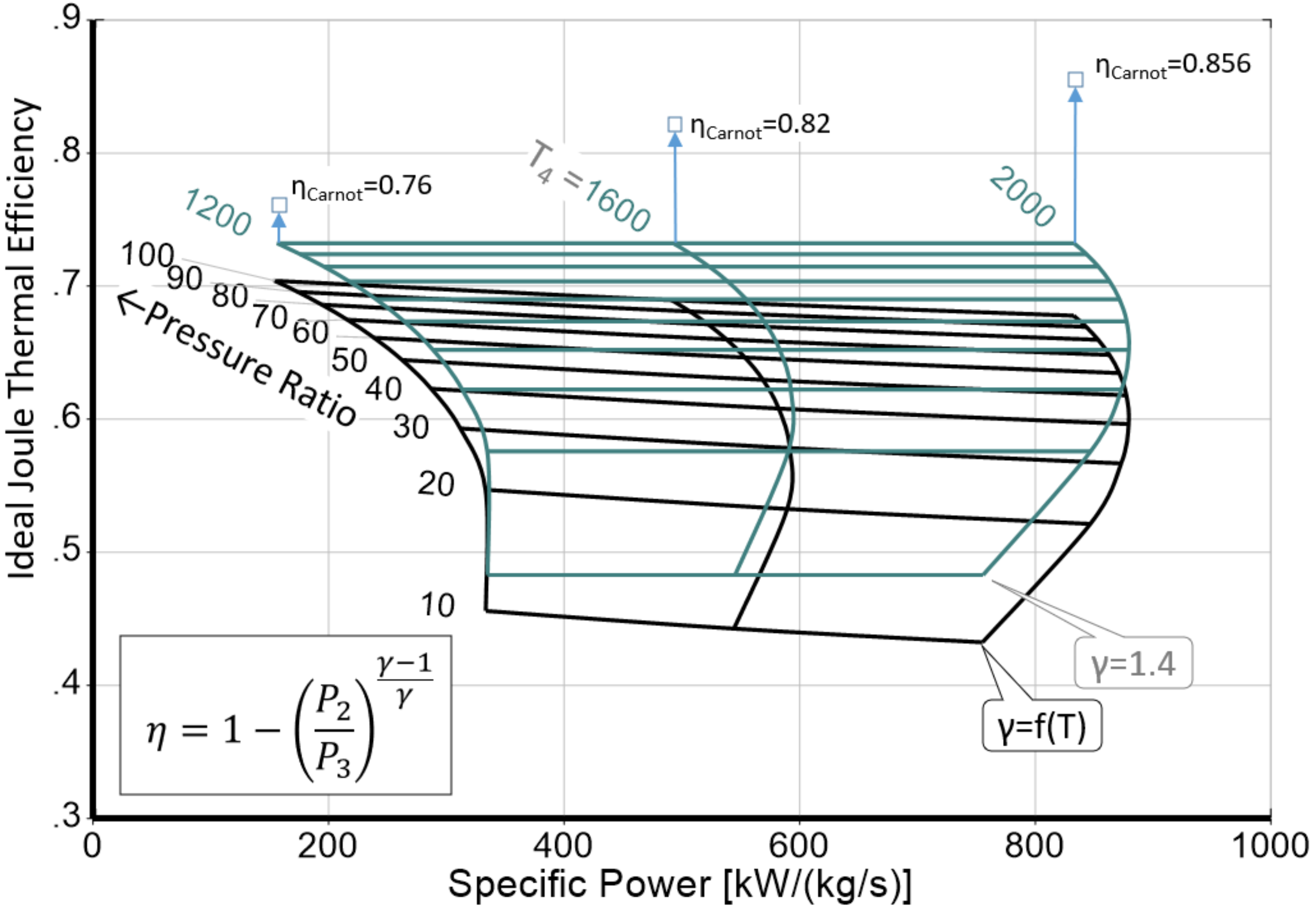
Increasing Power Output
Overview

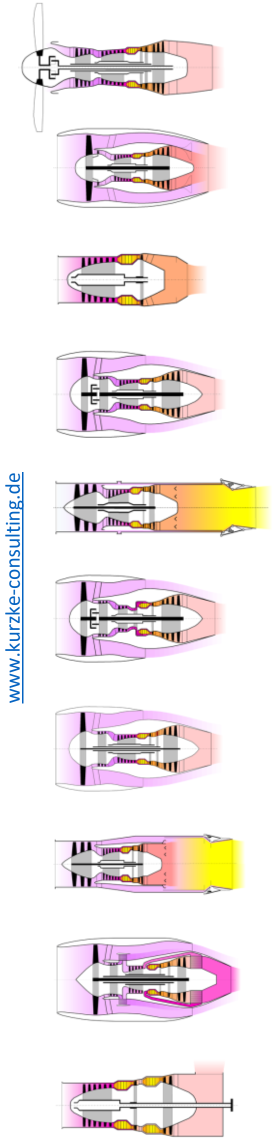




Ideal Joule Process

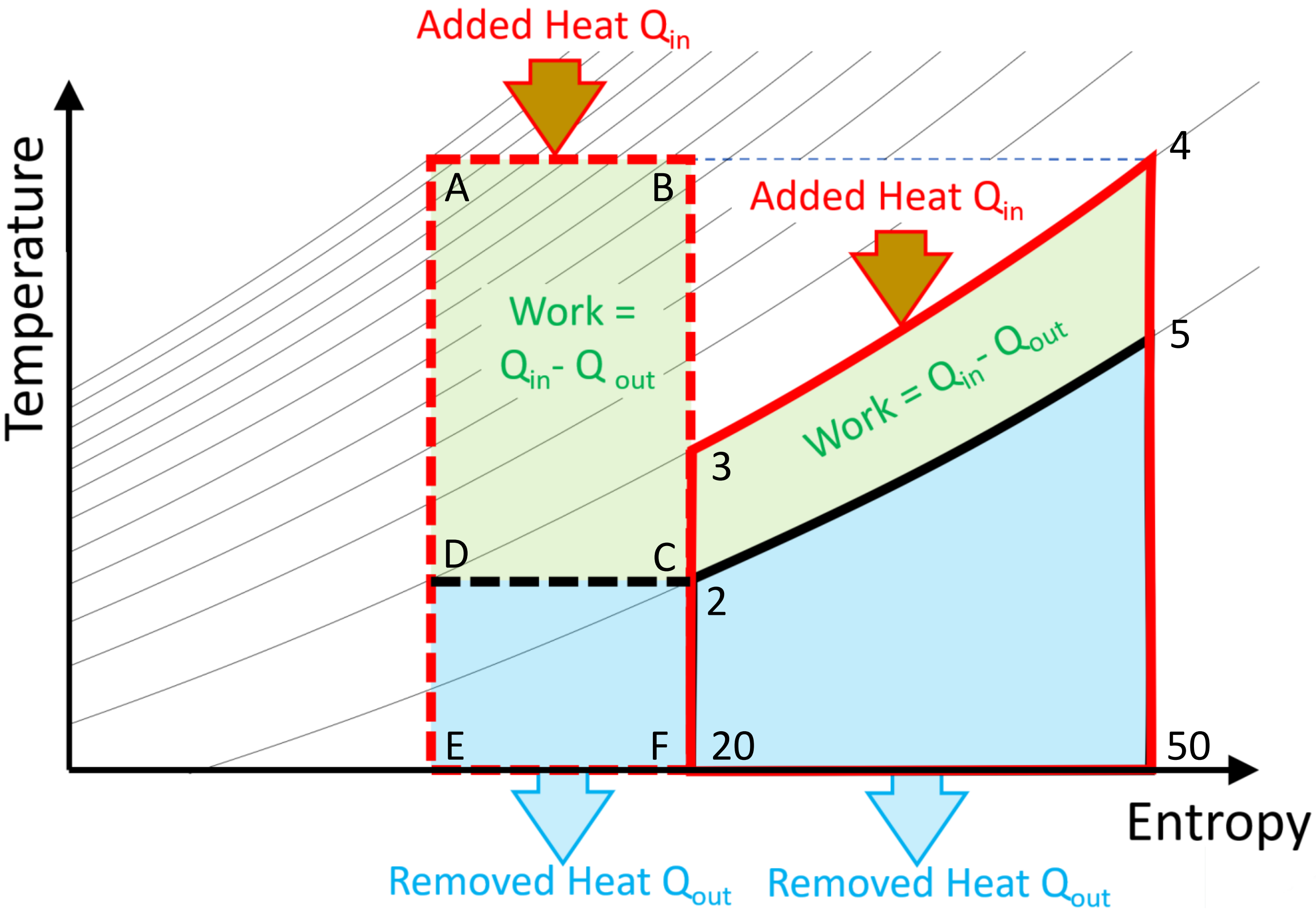
Thermal Efficiency





Carnot and Joule Cycle

Thermal Efficiency

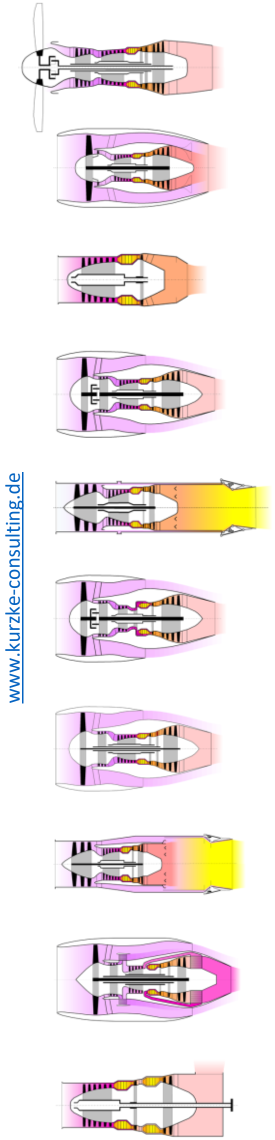


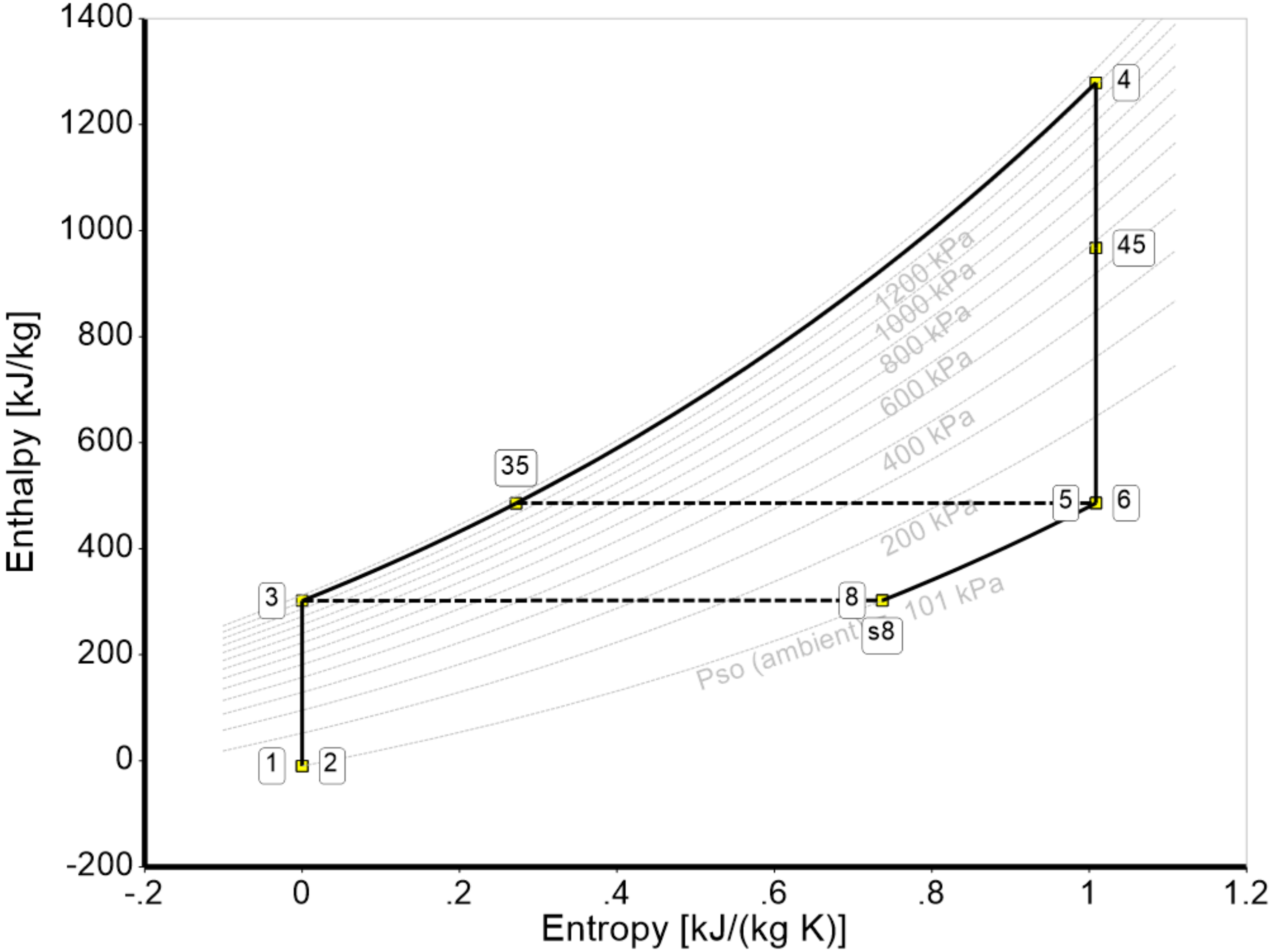
Carnot:
Added Heat = A-B-F-E
Removed Heat = C-D-E-F
Work = A-B-C-D

Joule:
Added Heat = 3-4-50-20
Removed Heat = 2-5-50-20
Work = 3-4-5-2

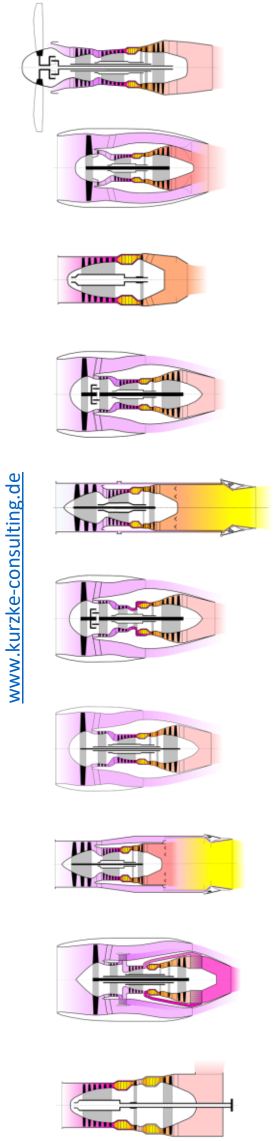
$$\eta = \frac{W}{Q_{in}}$$

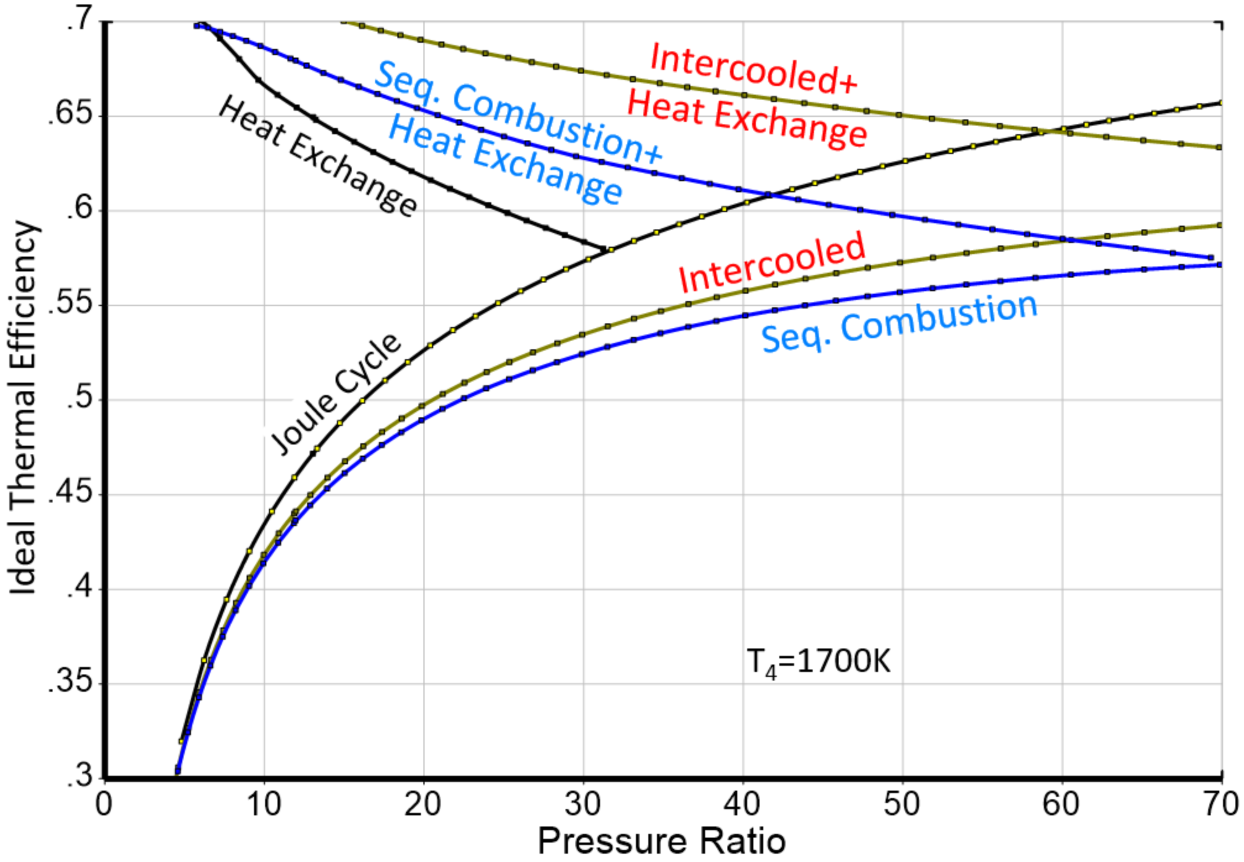
Reducing Fuel Consumption
Heat Exchanger

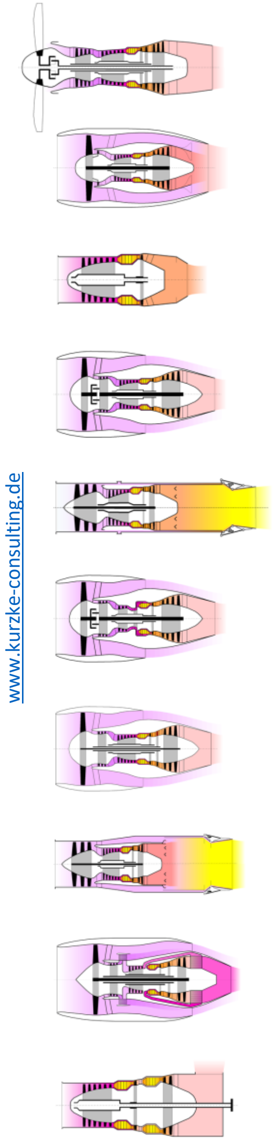




Ideal Cycles
Efficiency of Shaft Power Generation

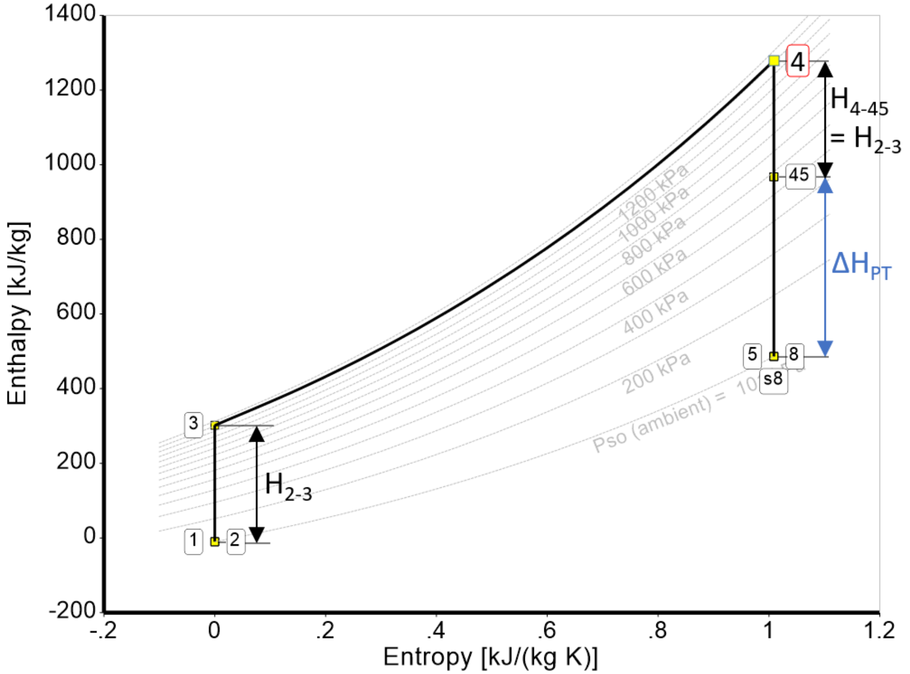


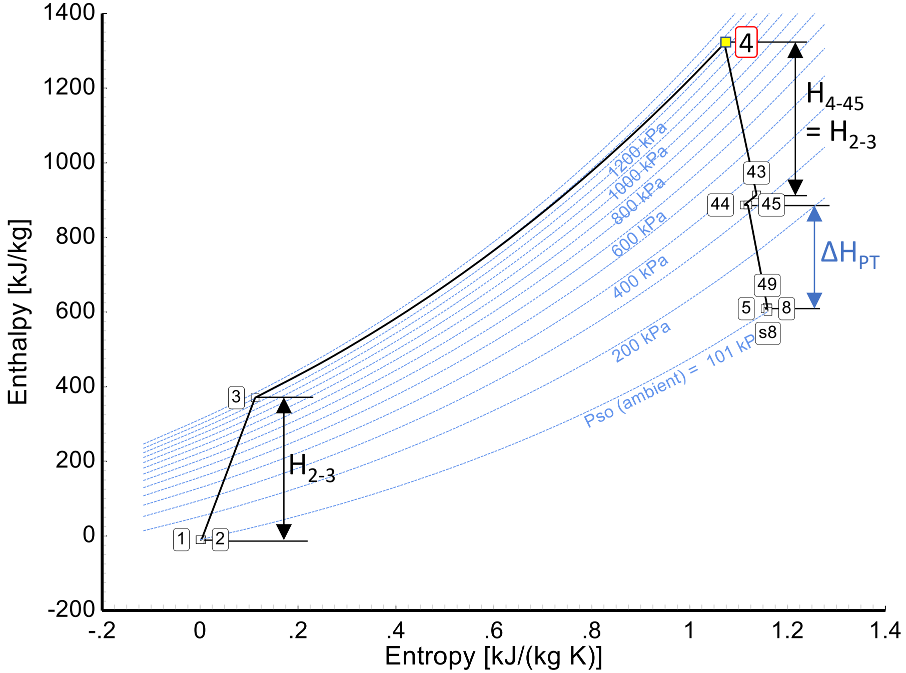




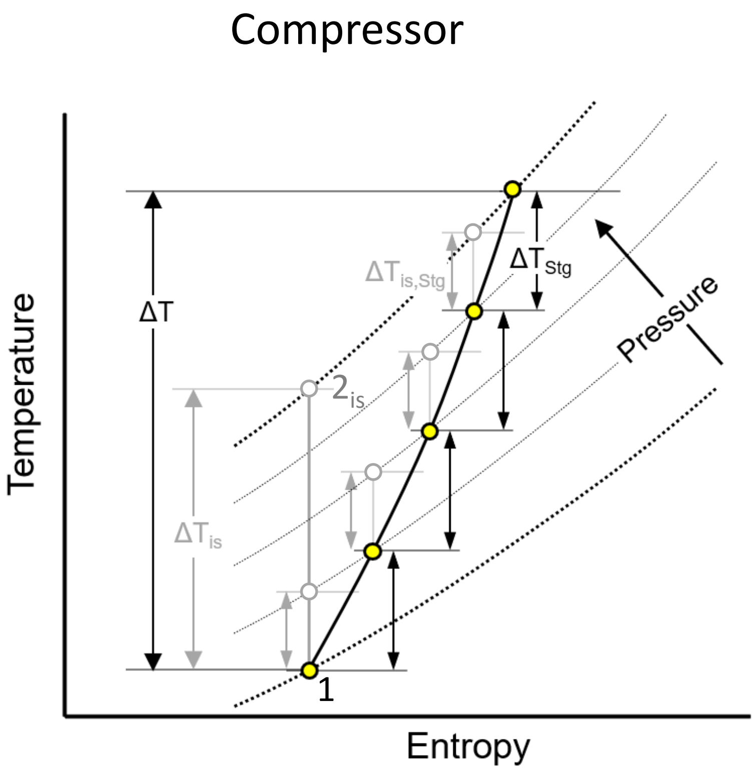
www.kurzke-consulting.de

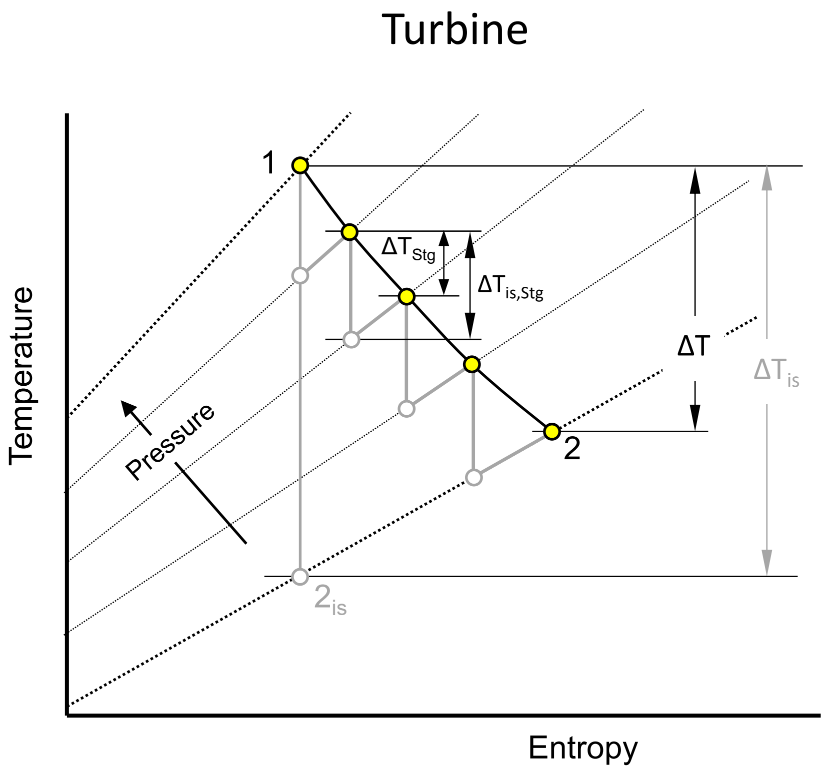
Ideal and Real Joule Process

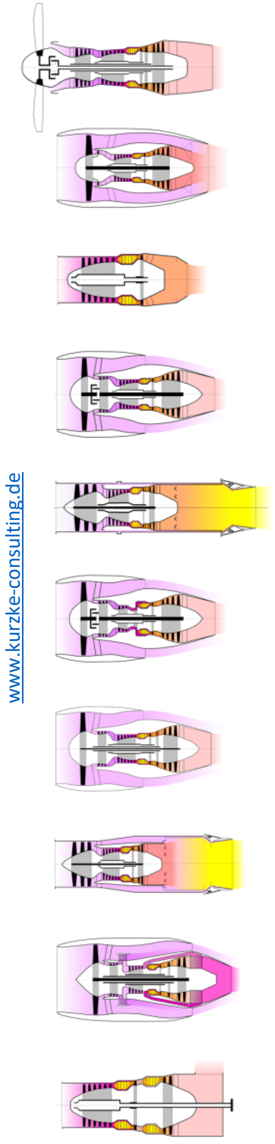




Polytropic Efficiency

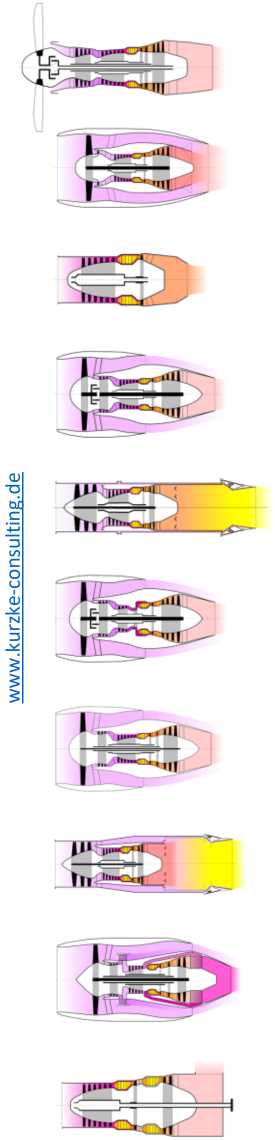


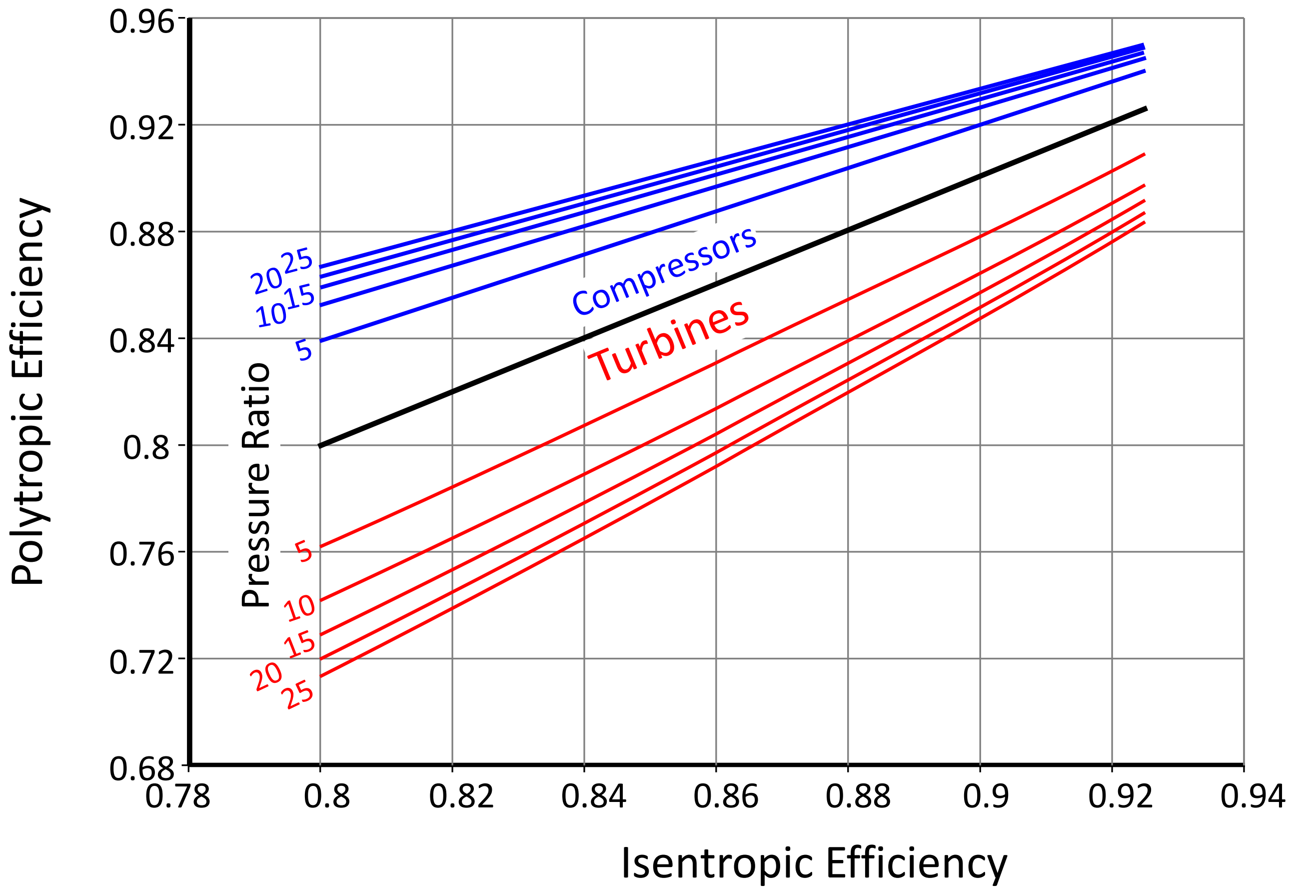




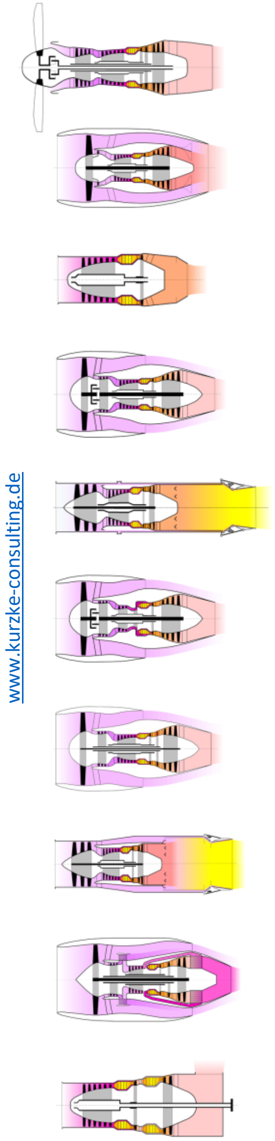
www.kurzke-consulting.de

Isentropic / Polytropic Efficiency

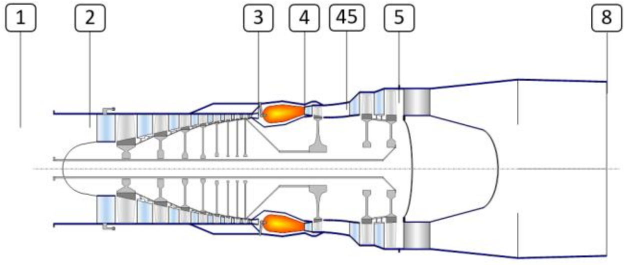


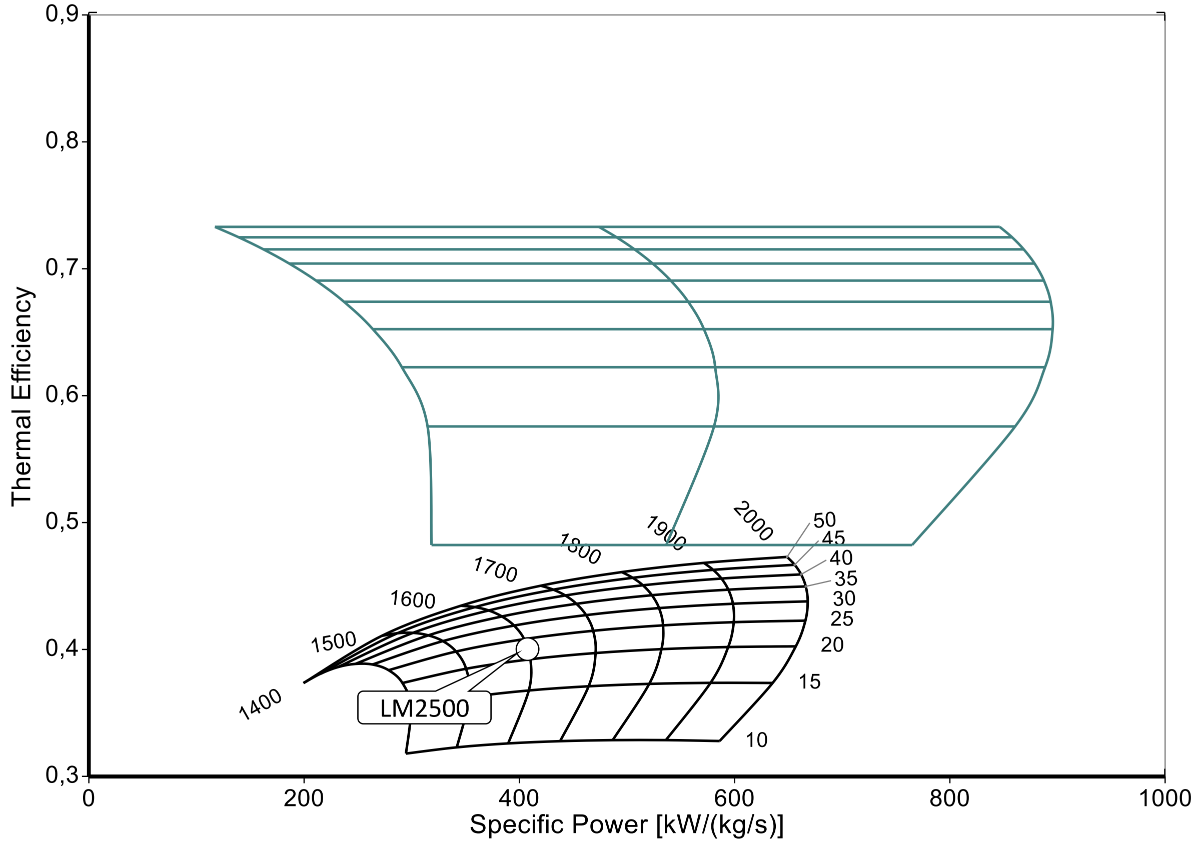


Efficiency of a Real Joule Process

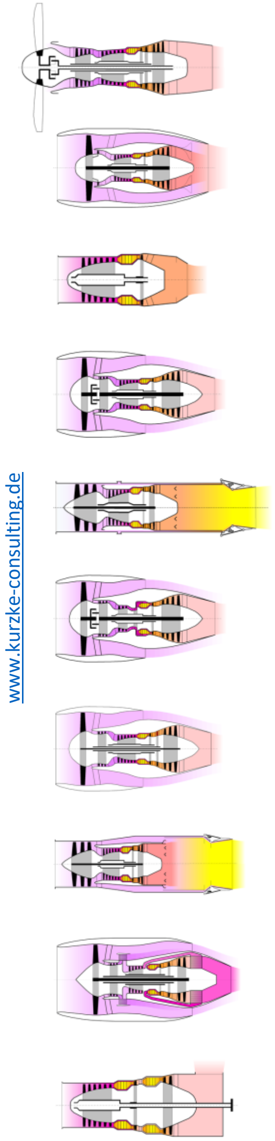


www.kurzke-consulting.de



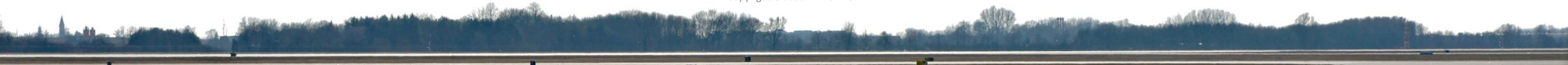


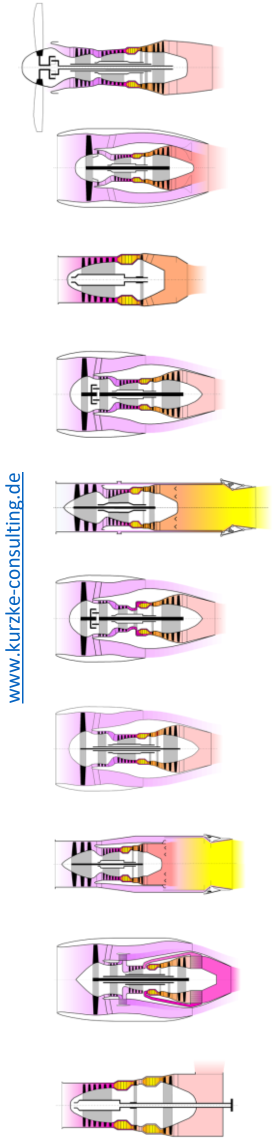
Outline



www.kurzke-consulting.de

- Fundamentals
- Ideal Cycles
- Thermal Efficiency
- Power Generation
- Aircraft Propulsion
- Fundamental Design Decisions
- Non-Dimensionals
- Turbojet Off-Design



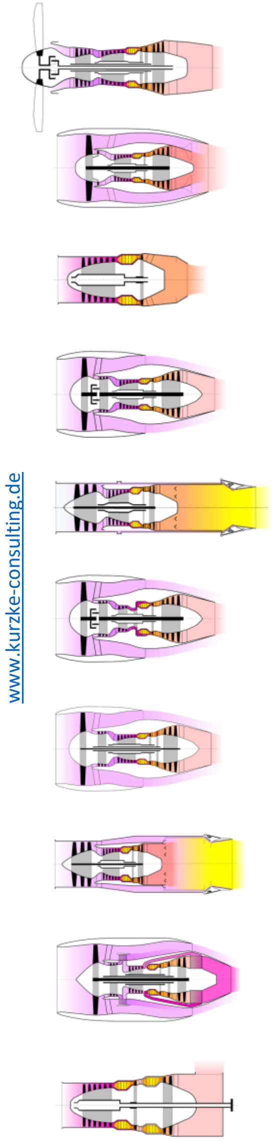


www.kurzke-consulting.de

Widespread View:

“Thermal efficiency of gas turbines is critically dependent on temperature at the turbine inlet; the higher this temperature, the higher the efficiency.”

This is incorrect !



www.kurzke-consulting.de

Schoolbook Wisdom

Simple definition of thermal efficiency:

$$\eta_{th} = \frac{H_T - H_C}{H_B} = \frac{T_4 - T_5 - T_3 + T_2}{T_4 - T_3} = 1 - \frac{T_5 - T_2}{T_4 - T_3}$$

T_2 Compressor Inlet

T_3 Compressor Exit

T_4 Burner Exit

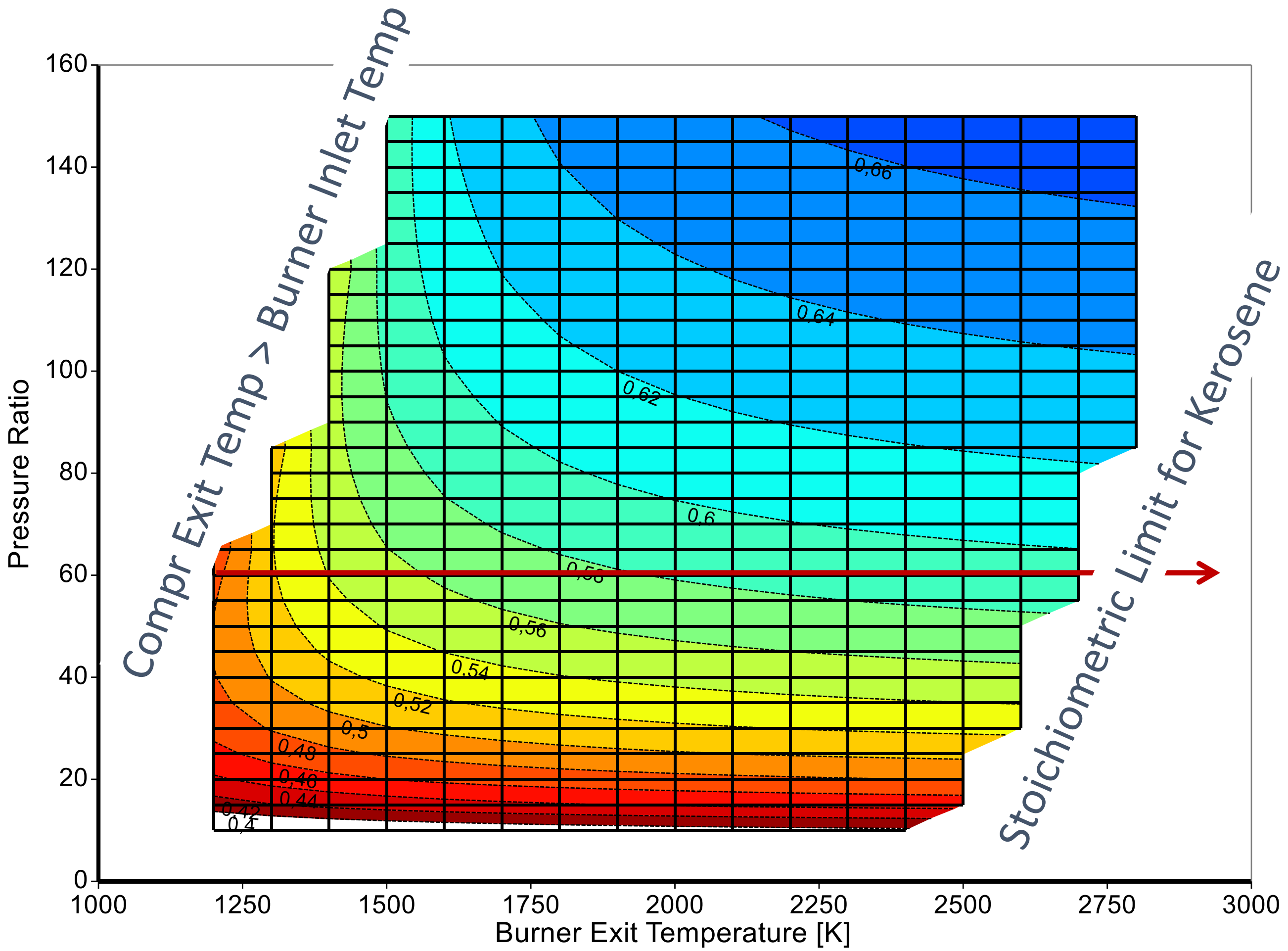
T_5 Turbine Exit

Different gas properties for compressor and turbine:

$$\eta_{th} = \frac{\frac{\gamma_T}{\gamma_T - 1} * R_T * \frac{T_4}{T_2} * \left[1 - \left(\frac{P_2}{P_3}\right)^{\frac{\gamma_T - 1}{\gamma_T}}\right] * \eta_T - \frac{\gamma_C}{\gamma_C - 1} * R_C * \left[\left(\frac{P_3}{P_2}\right)^{\frac{\gamma_c - 1}{\gamma_c}} - 1\right] \Big/ \eta_C}{\left(\frac{T_4}{T_2} - \frac{T_3}{T_2}\right) * \left(\frac{\gamma_C}{\gamma_C - 1} * R_C + \frac{\gamma_T}{\gamma_T - 1} * R_T\right) \Big/ 2}$$

Thermal Efficiency

Schoolbook Equation



$\gamma_C = 1.4$

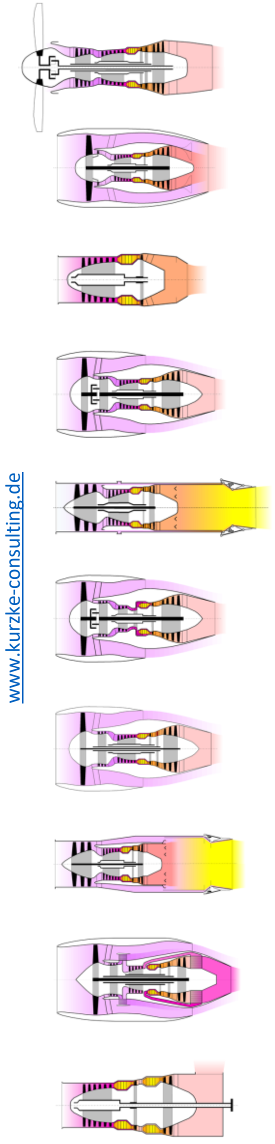
$\gamma_T = 1.3$

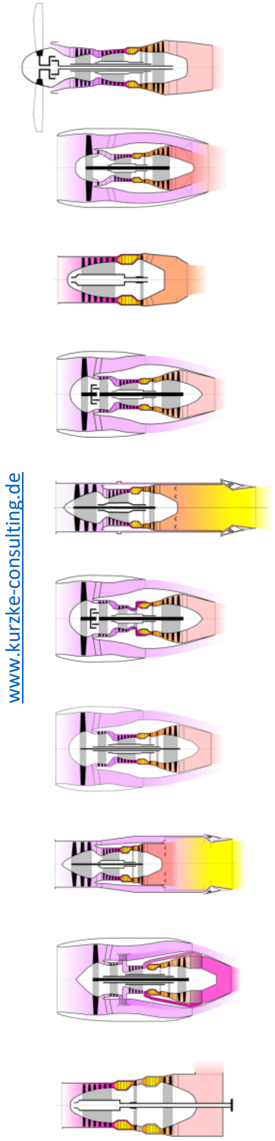
$\eta_C = 0.9$

$\eta_T = 0.9$

Schoolbook:

η increases with T_4





Definition of Thermal Efficiency

Definition as ratio of enthalpies:

$$\eta_{th} = \frac{H_T - H_C}{H_B}$$

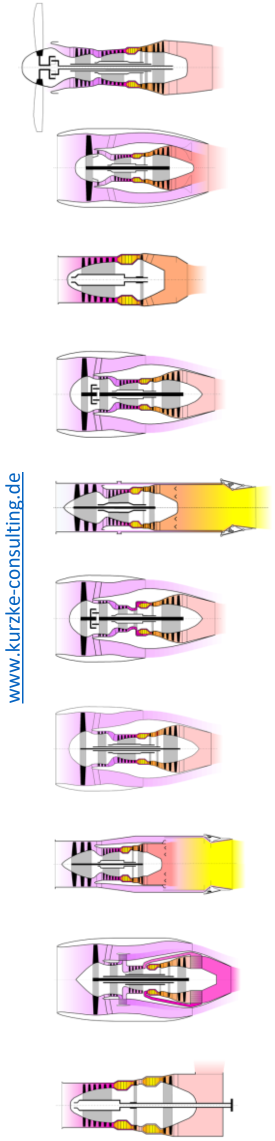
H_T	Turbine Spec. Work
H_C	Compressor Spec. Work
W_F	Fuel flow
FHV	Fuel Heating Value

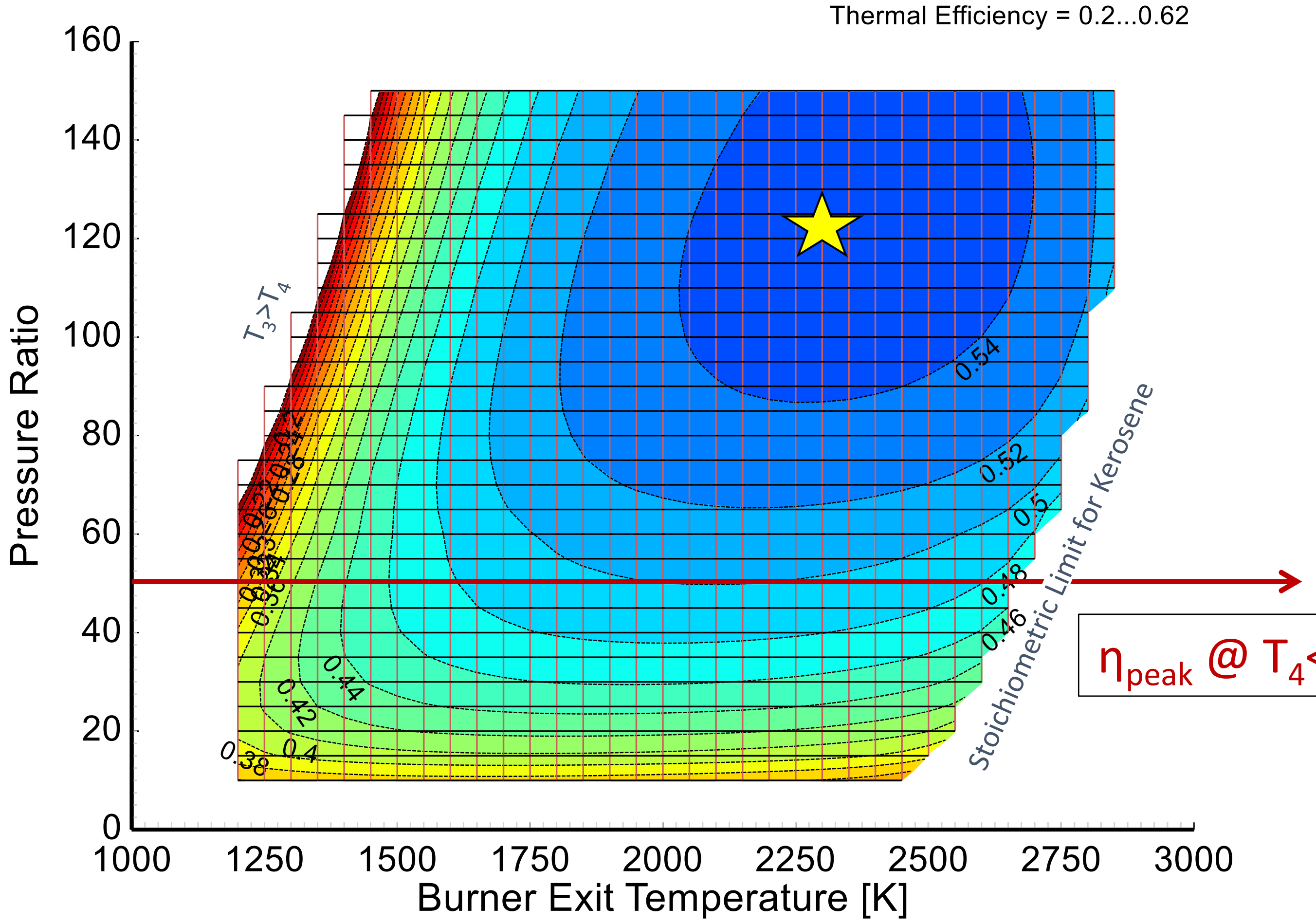
Definition with fuel mass flow:

$$\eta_{th} = \frac{PW_{SD}}{W_F * FHV}$$

Thermal Efficiency

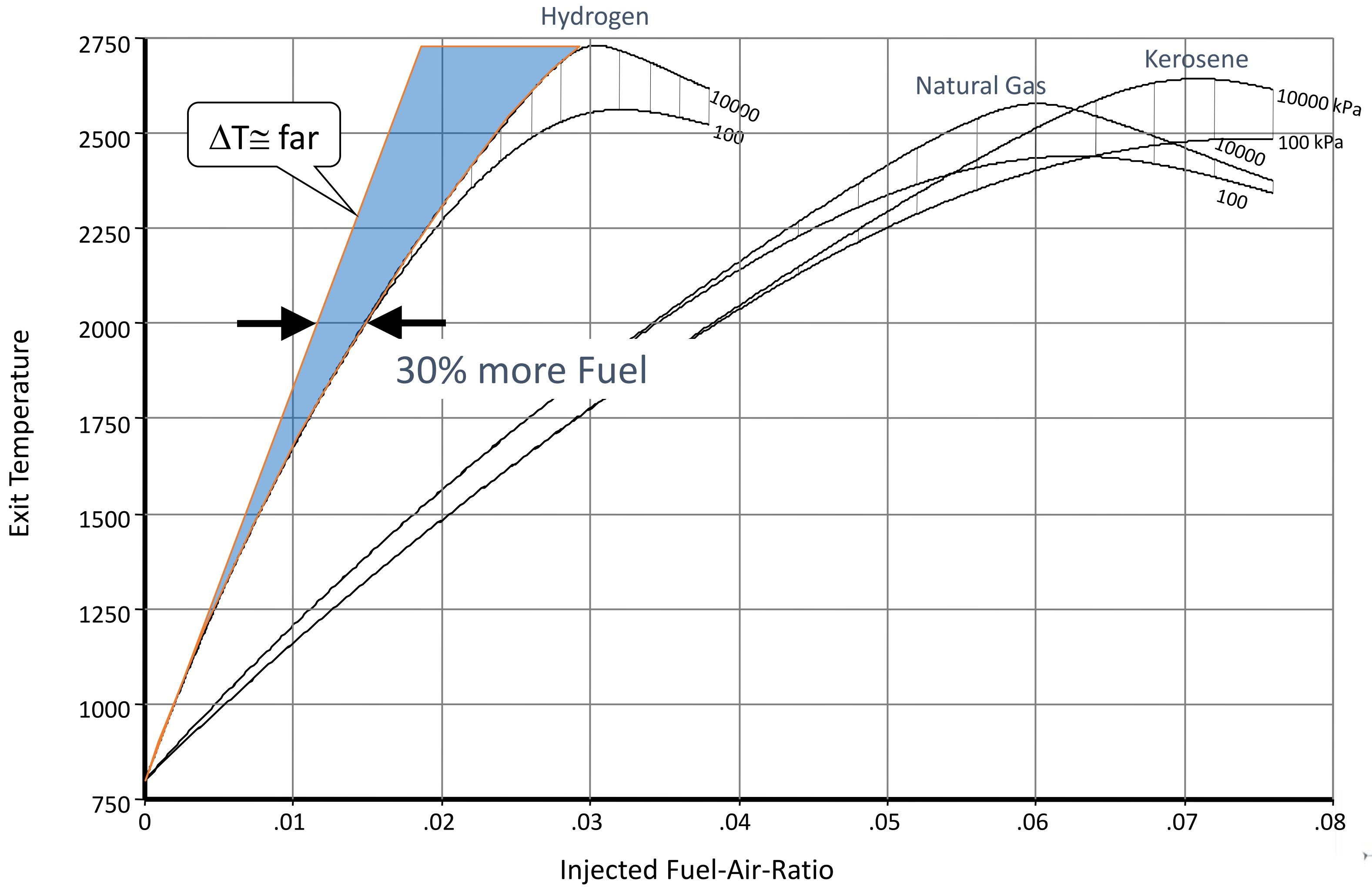
Compressors and Turbines η_{pol}=0.9, no Cooling Air

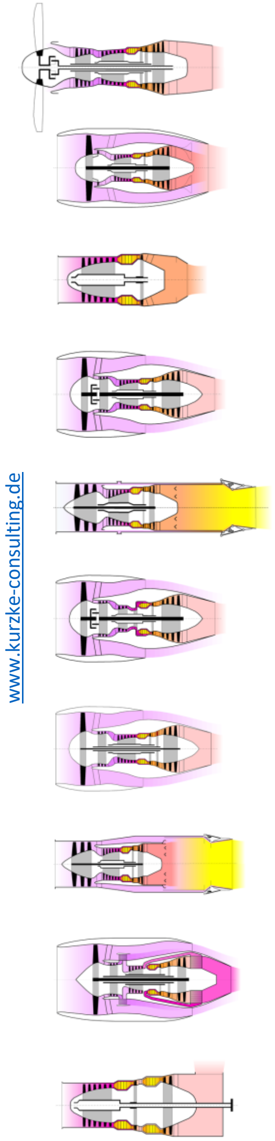




η_{peak} @ $T_4<T_{4max}$

Temperature Increase in the Burner
Chemical Equilibrium

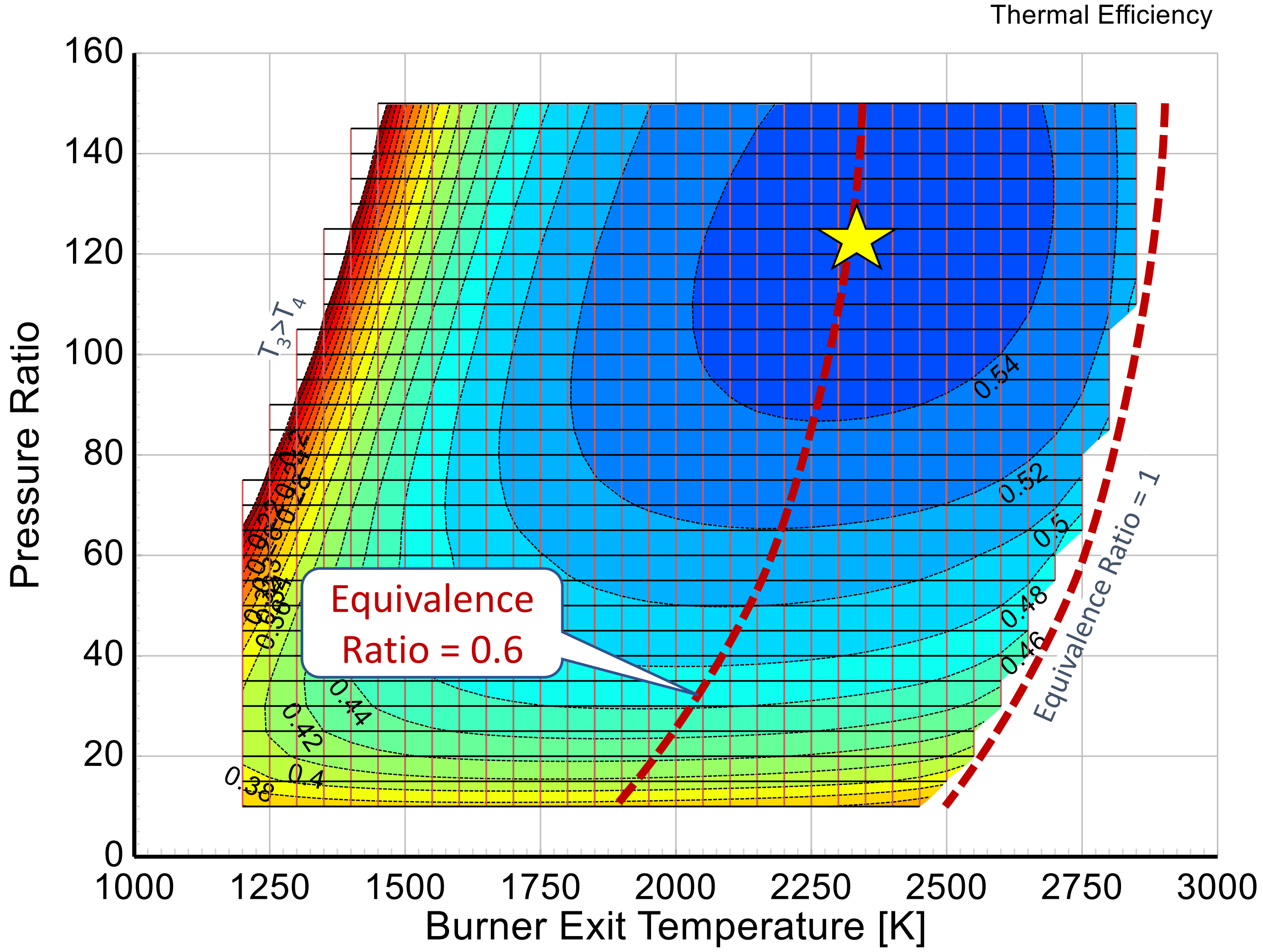




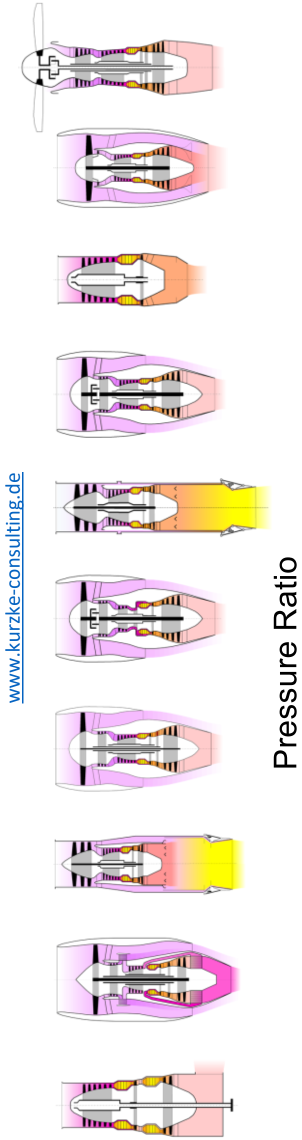
www.kurzke-consulting.de

Compressors and Turbines η_{pol}=0.9, No Cooling Air

Thermal Efficiency

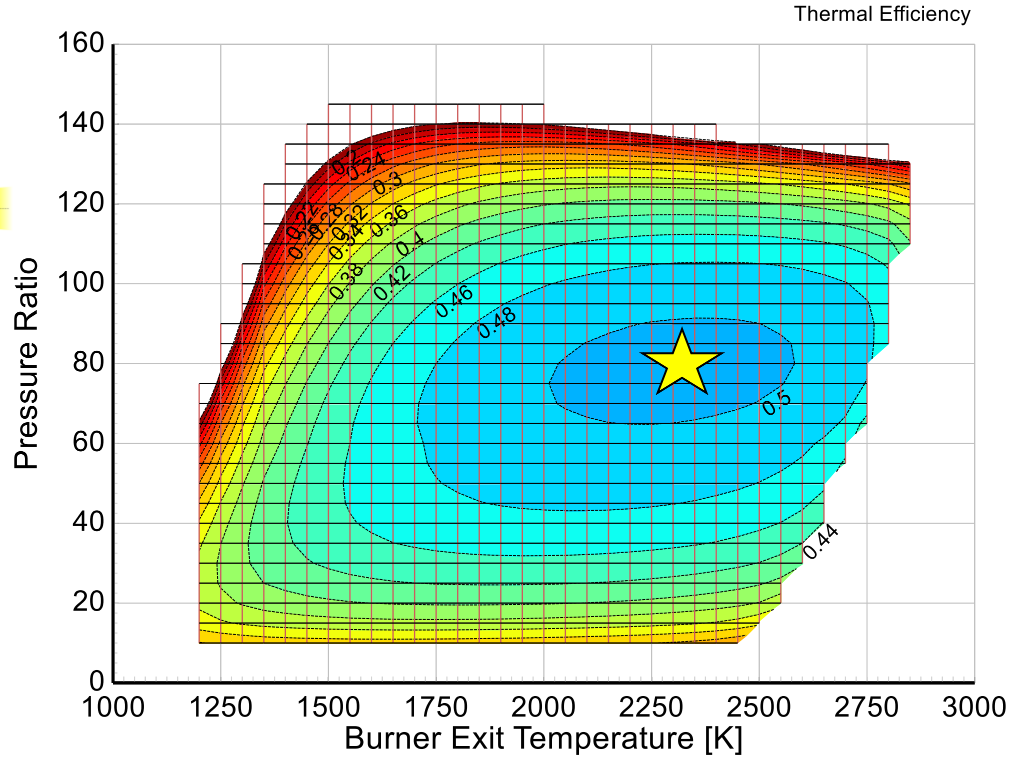


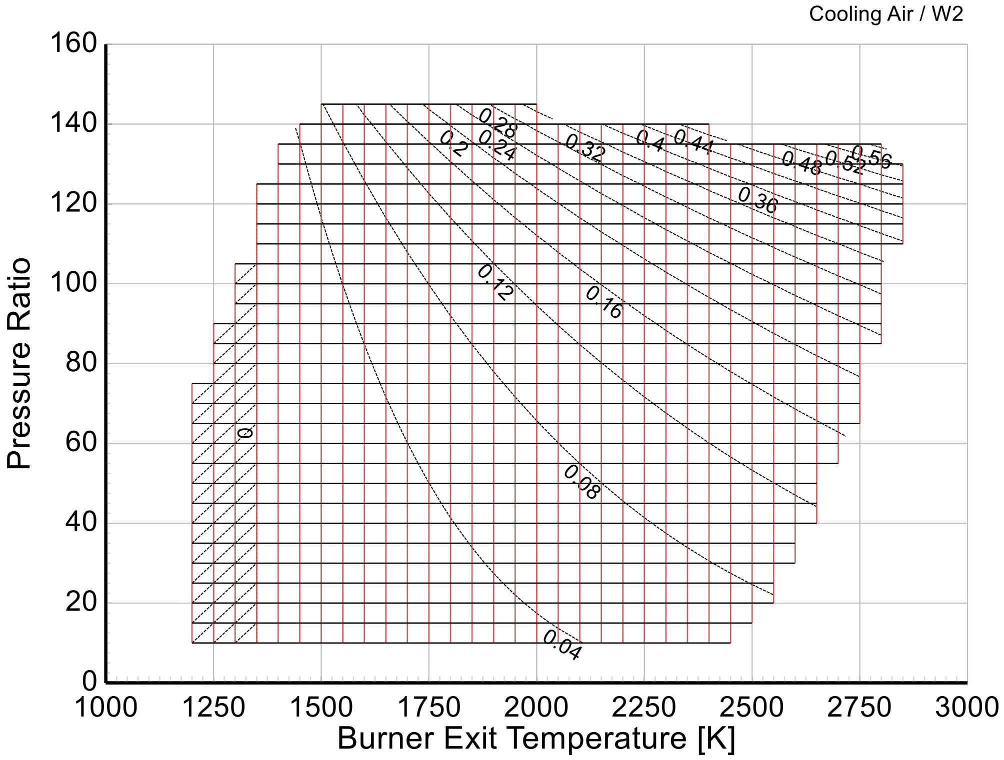
$$\eta_{th} = \frac{PW_{SD}}{W_F * FHV}$$

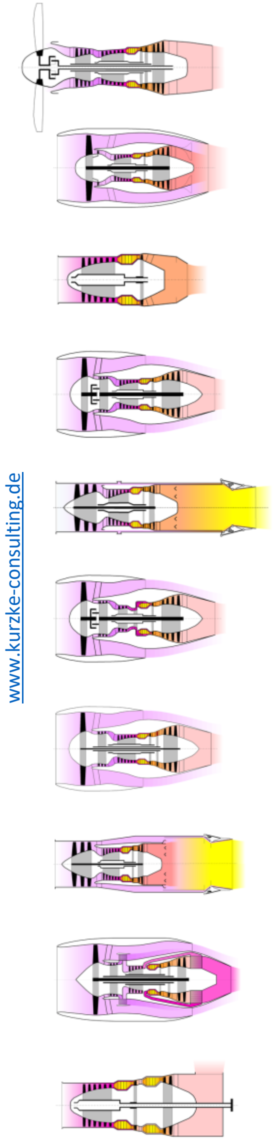


Compressors and Turbines η_{pol}=0.9, With Cooling Air

Thermal Efficiency

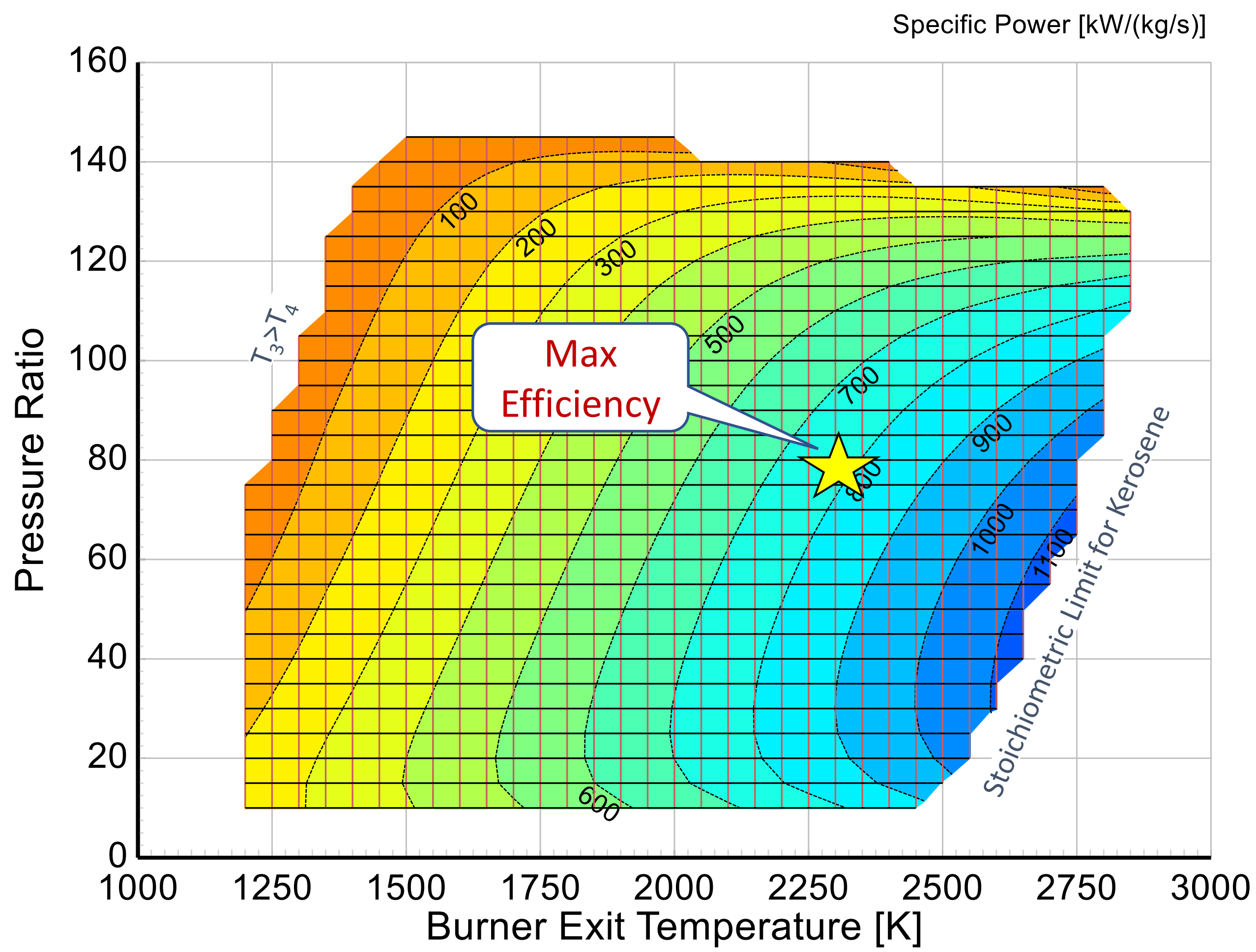






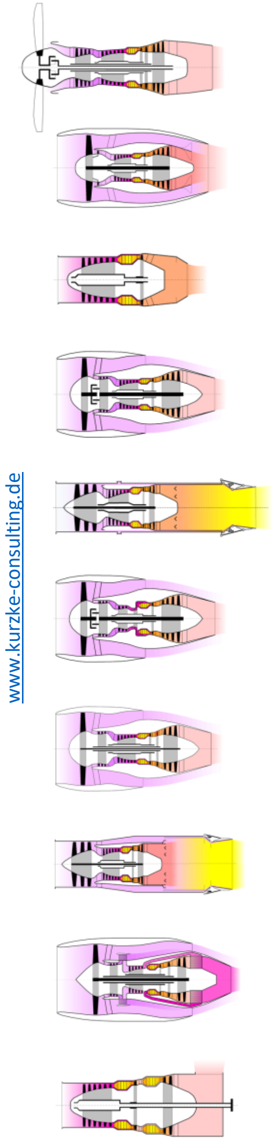
www.kurzke-consulting.de

Compressors and Turbines η_{pol}=0.9, With Cooling Air
Specific Power

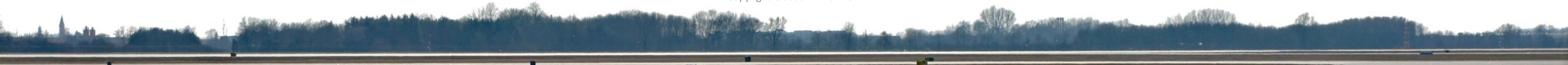


Outline

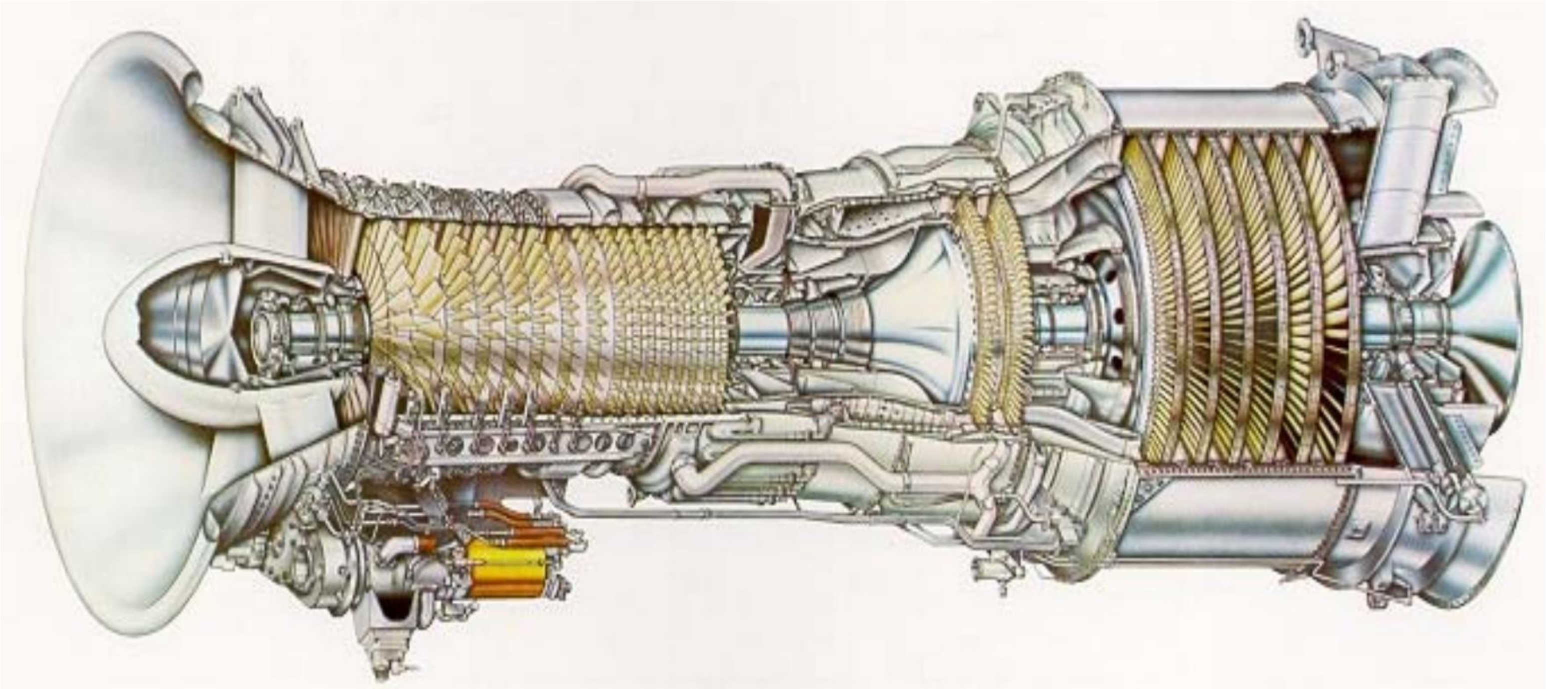
- Fundamentals
- Ideal Cycles
- Thermal Efficiency
- **Power Generation**
- Aircraft Propulsion
- Fundamental Design Decisions
- Non-Dimensionals
- Turbojet Off-Design

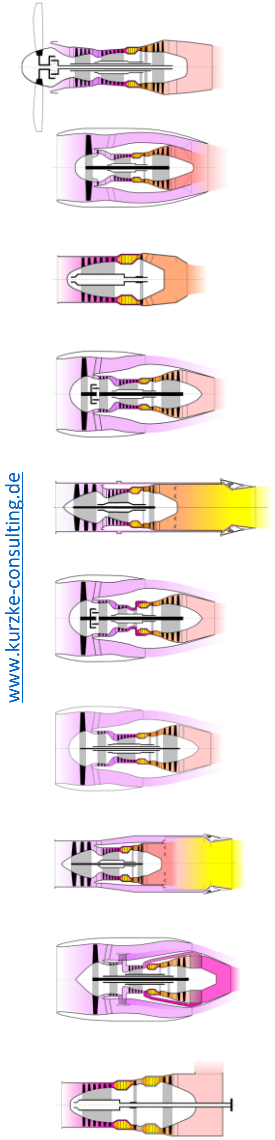


www.kurzke-consulting.de

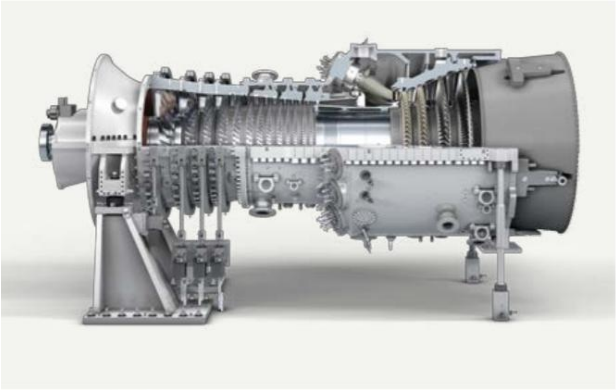


Aero-Derivative
LM2500





Simple Cycle
SGT-8000H Gas Turbine

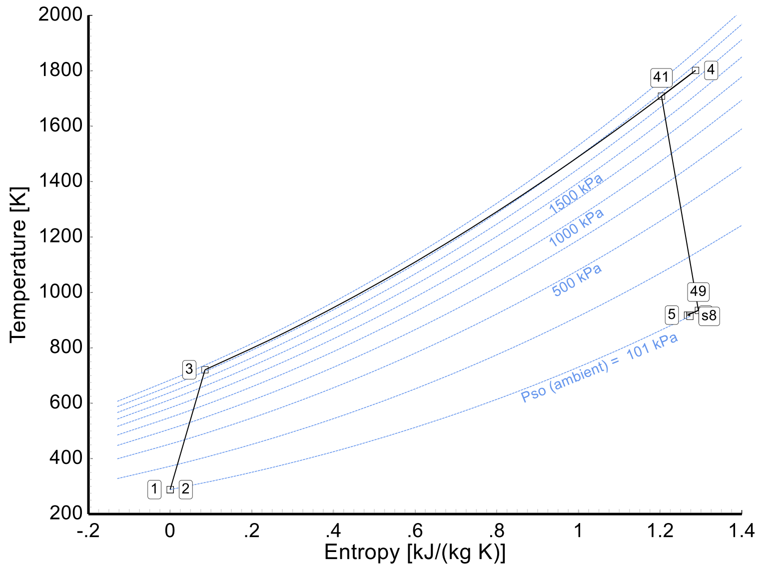


SGT5-8000H

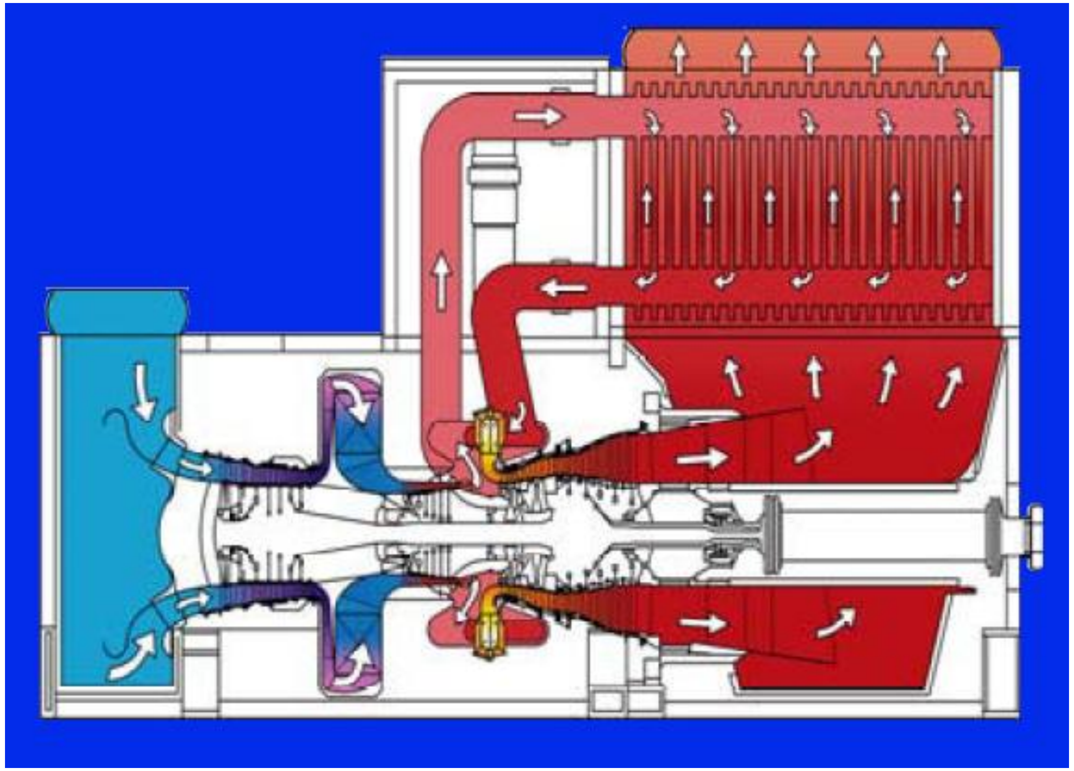
SGT6-8000H

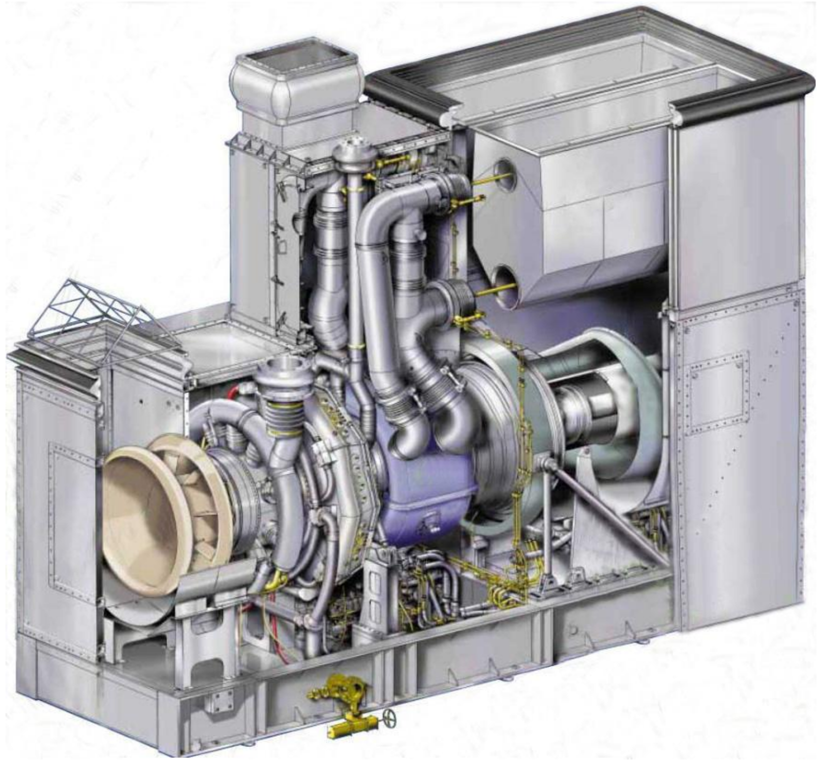
SGT5-8000H gas turbine	
Frequency	50 Hz
ISO base power output	400 MW
Efficiency	40 %
Exhaust mass flow	869 kg/s / 1,915 lb/s
Exhaust temperature	627 °C / 1,161 °F
Physical dimensions	
Weight	445 t
Length x Height x Width	12.6 m x 5.5 m x 5.5 m 41 ft x 18 ft x 18 ft
Combined cycle plant (single-shaft, 1S)	
Net power output	600 MW
Net efficiency	> 60 %
Combined cycle plant (multi-shaft, 2 x 1)	
Net power output	1,200 MW
Net efficiency	> 60 %

SGT6-8000H gas turbine	
Frequency	60 Hz
ISO base power output	296 MW
Efficiency	40 %
Exhaust mass flow	640 kg/s / 1,410 lb/s
Exhaust temperature	630 °C / 1,166 °F
Physical dimensions	
Weight	289 t
Length x Height x Width	10.5 m x 4.3 m x 4.3 m 34 ft x 14 ft x 14 ft
Combined cycle plant (single-shaft, 1S)	
Net power output	440 MW
Net efficiency	> 60 %
Combined cycle plant (multi-shaft, 2 x 1)	
Net power output	880 MW
Net efficiency	> 60 %



Intercooled Recuperated Cycle
RR WR-21

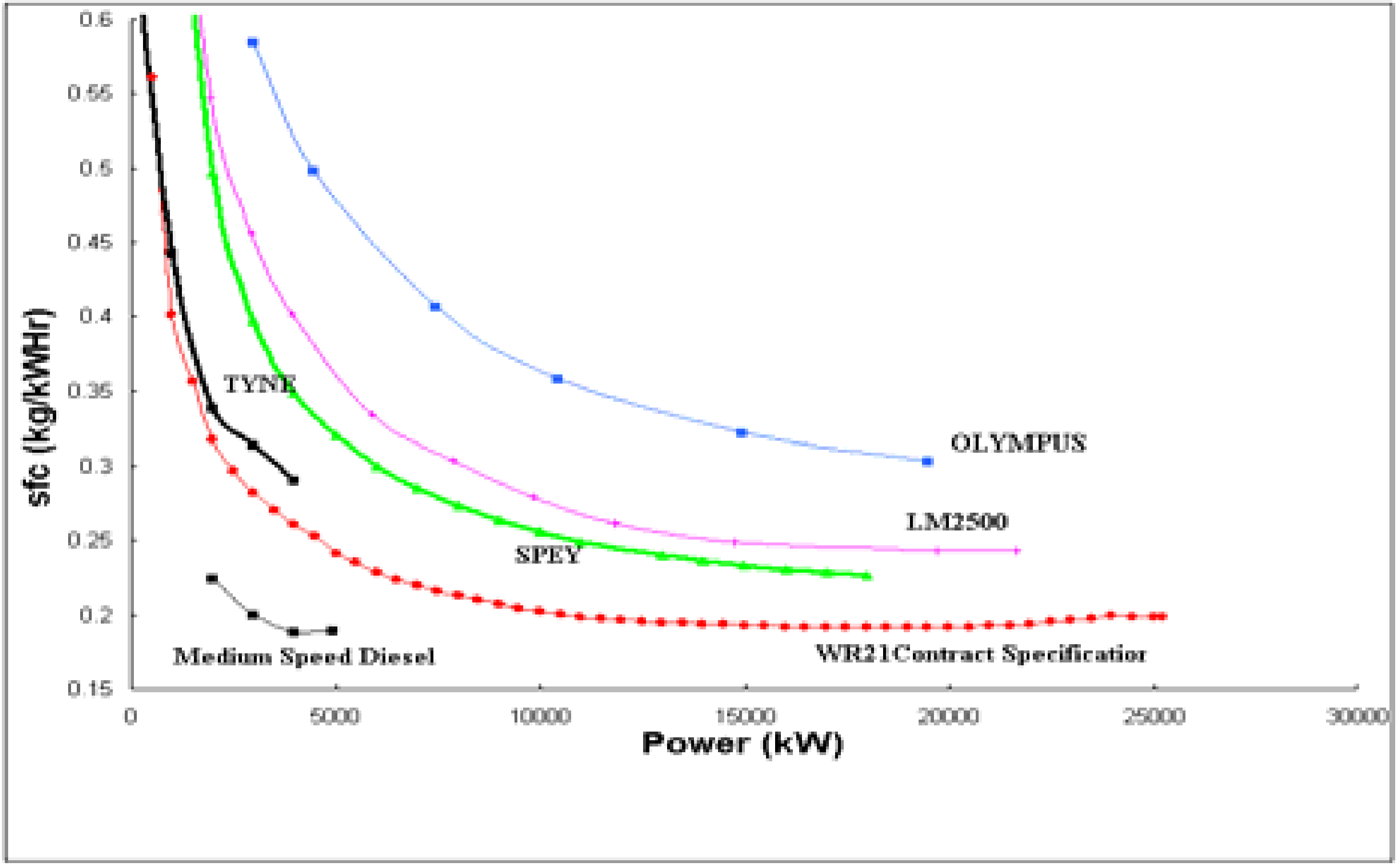




Ref. IGTC2003Tokyo OS-203

RR WR-21

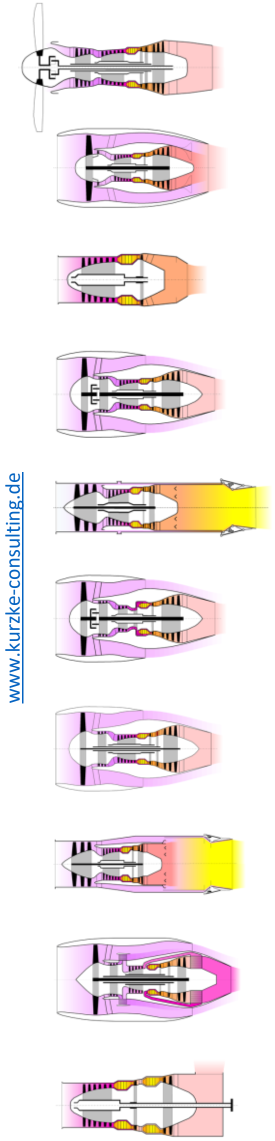
Specific Fuel Consumption SFC

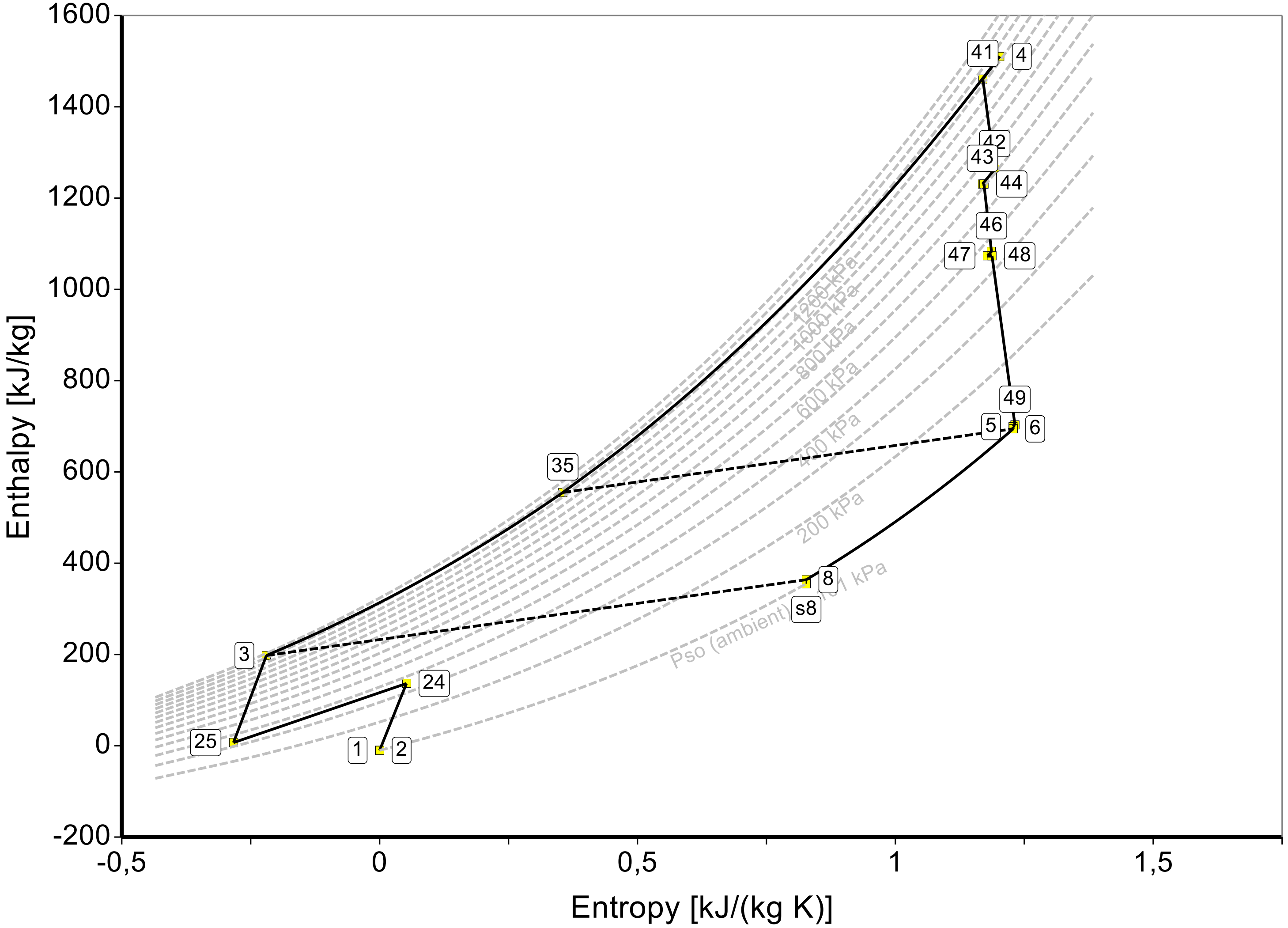


Ref. IGTC2003Tokyo OS-203

RR WR21

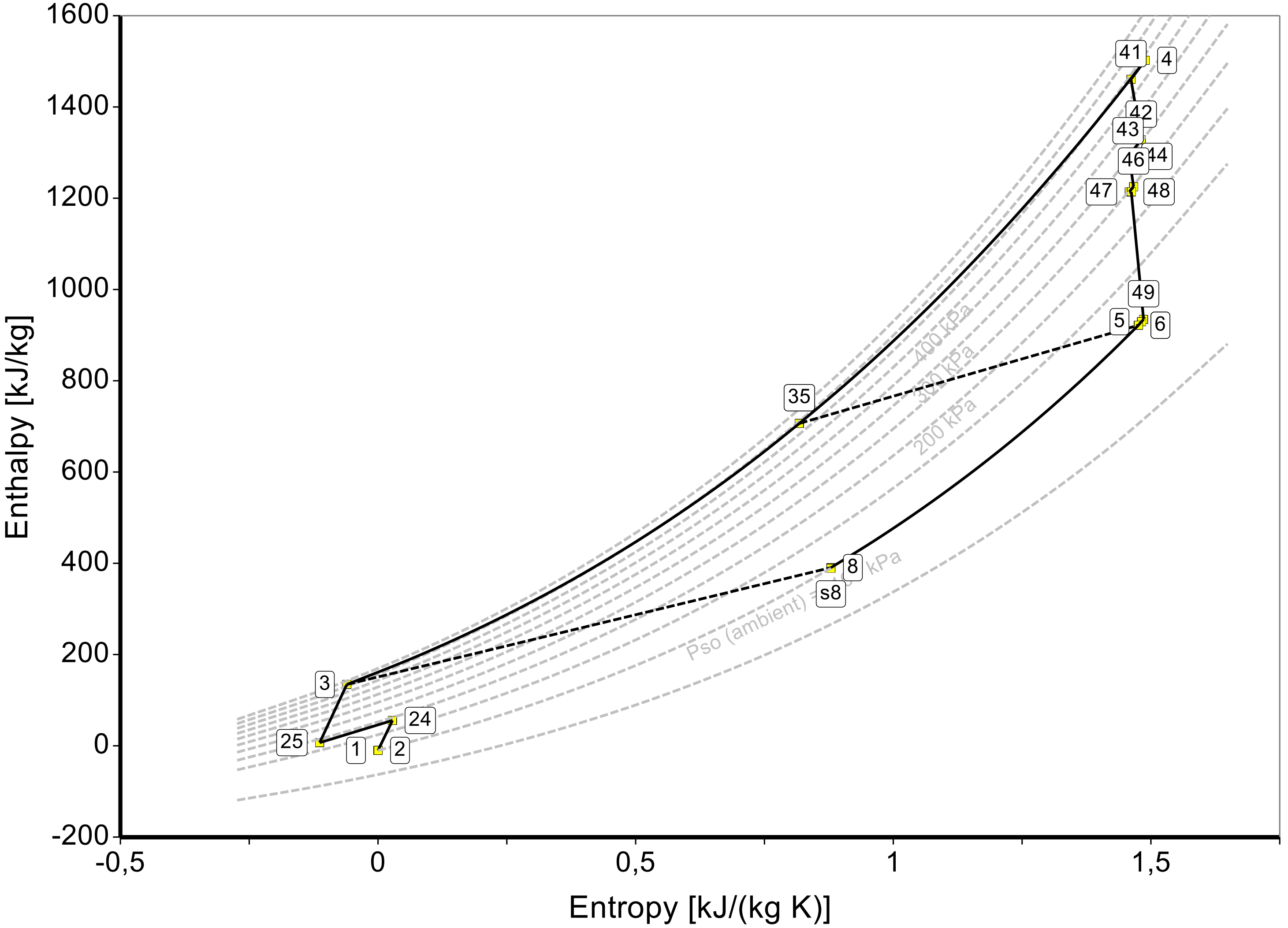
Full Power



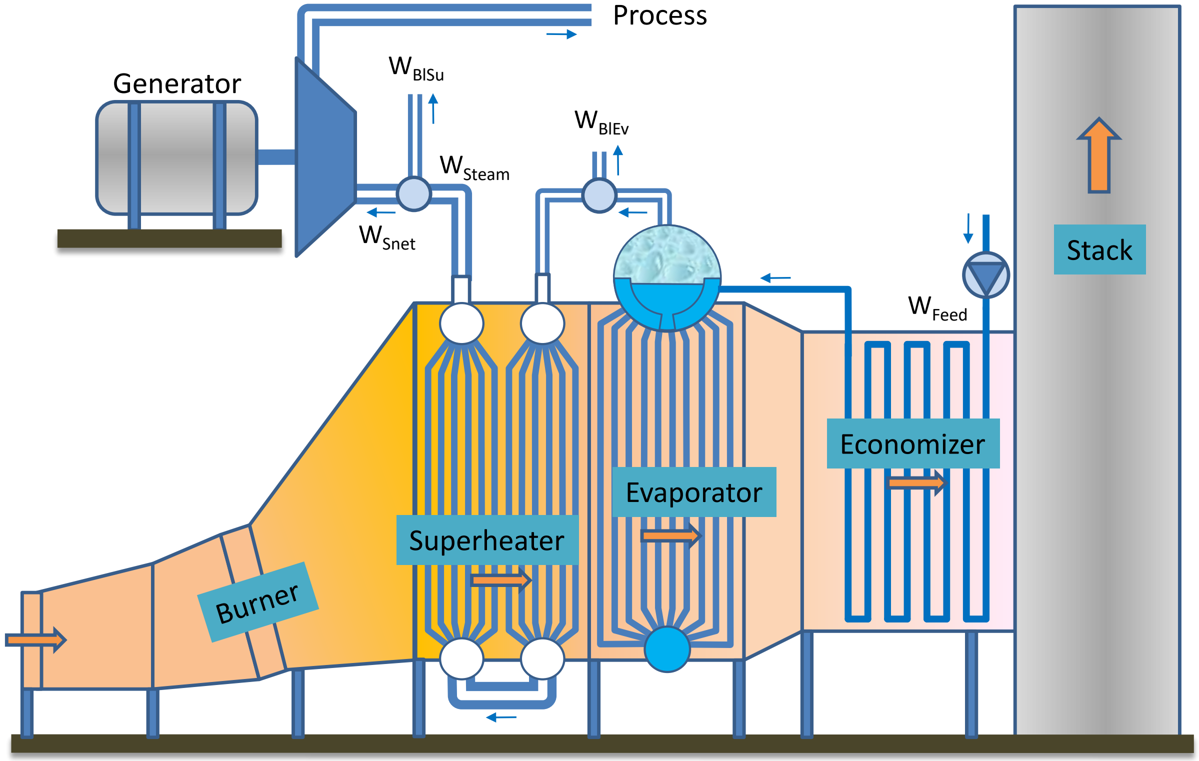


RR WR21

27% Power



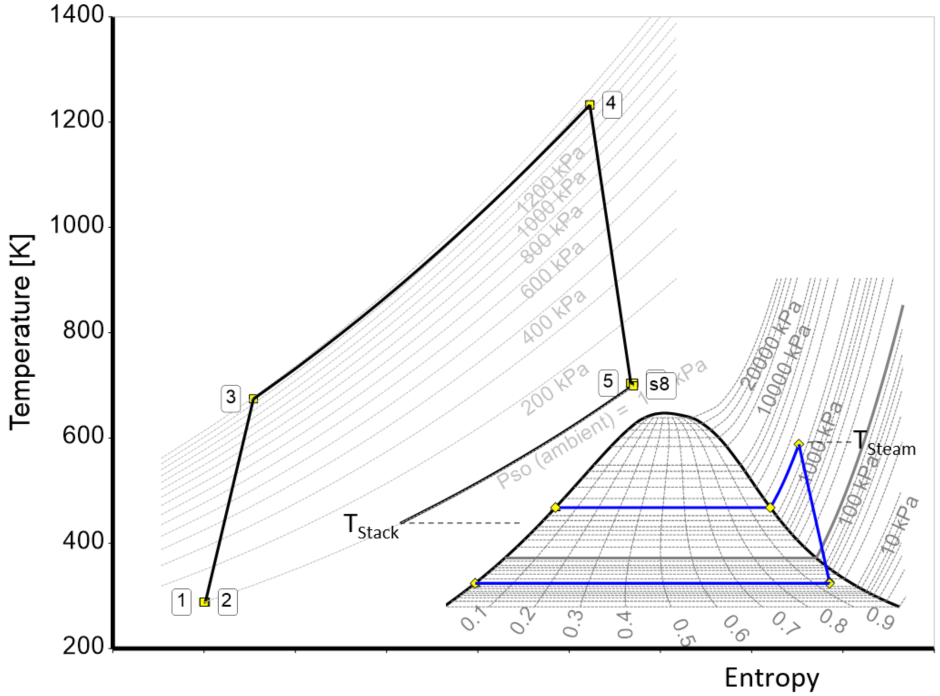
Combined Cycle
Heat Recovery Steam Generator (HRSG)

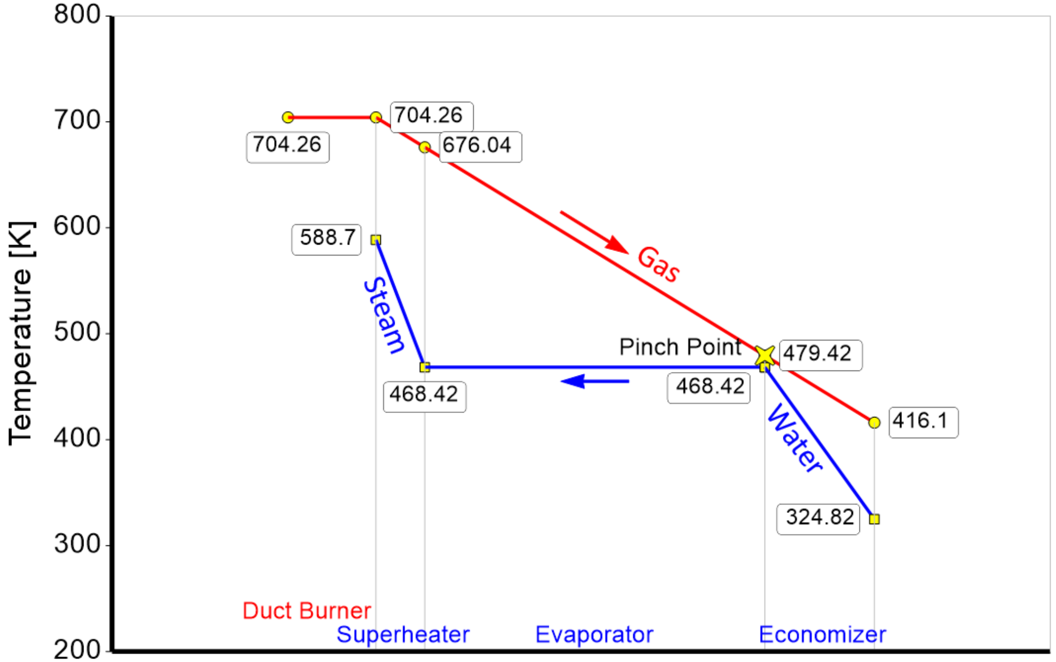


HRSGSinglePressTurb.emf

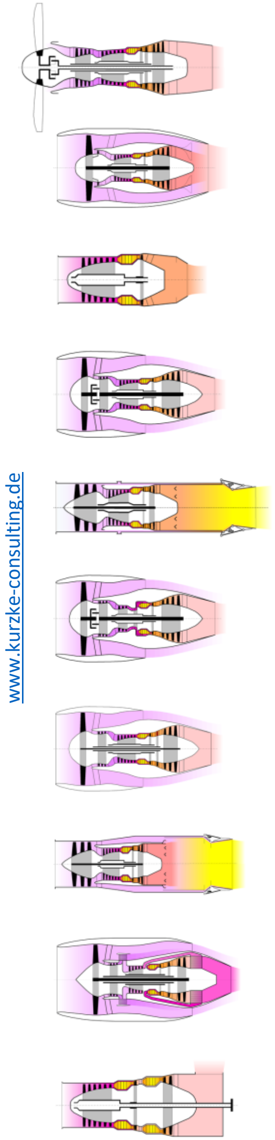
GasTurb

Combined Cycle
Joule and Rankine Cycle

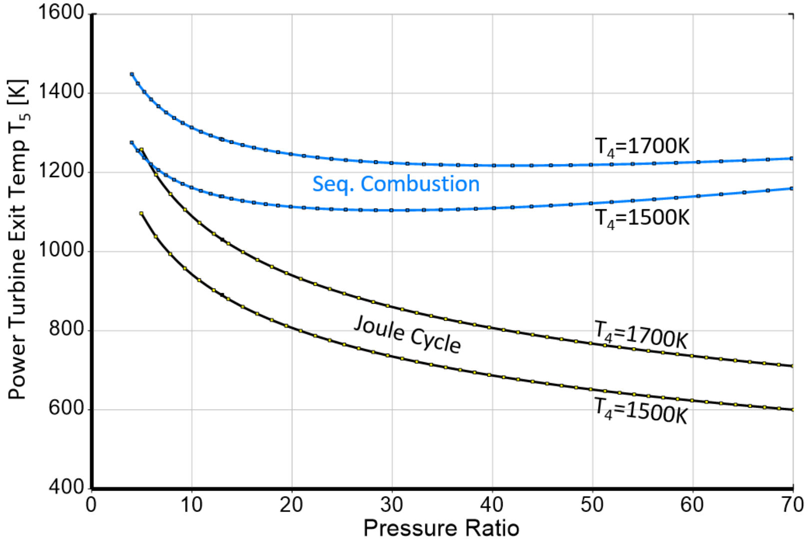




Pinch Point Diagram



Sequential Combustion
Alstom GT24/GT26

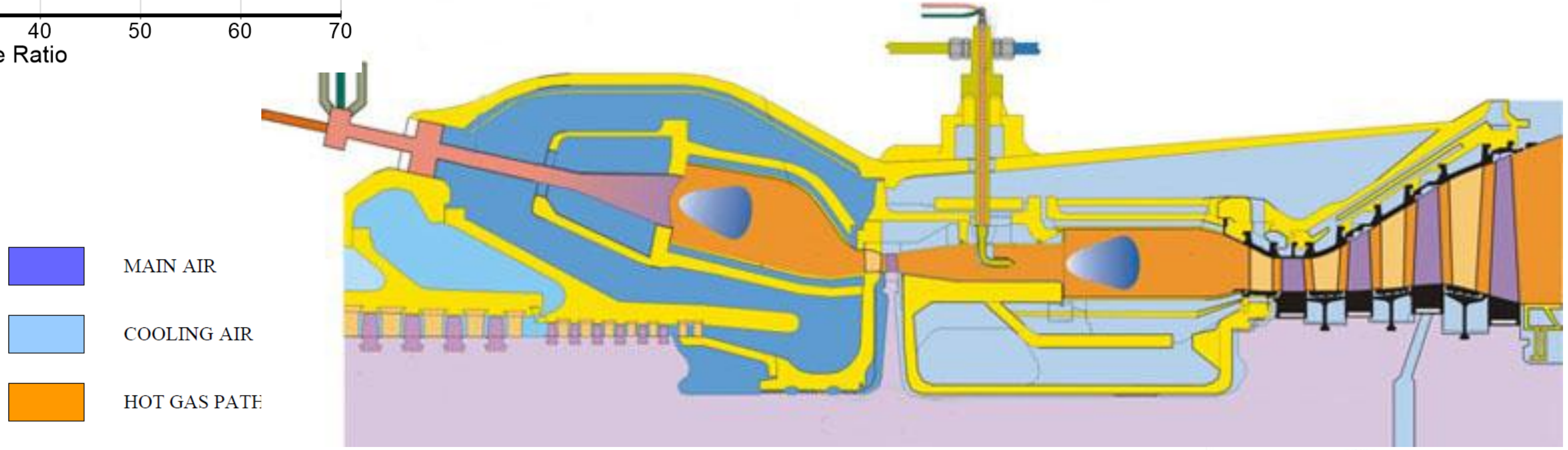


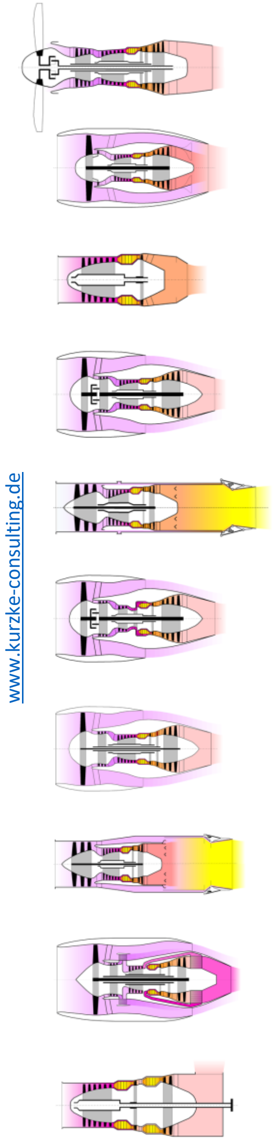
GT24

Fuel		Natural Gas
Frequency	Hz	60
Electrical output	MW	179
Electrical efficiency	%	37.5
Heat rate	Btu/kWh	9,098
Turbine speed	rpm	3,600
Compressor pressure ratio		30.0 : 1
Exhaust gas flow	kg/s	391
Exhaust gas temperature	°C	630
NOx emissions (corr. to 15% O_2, dry)	vppm	<25

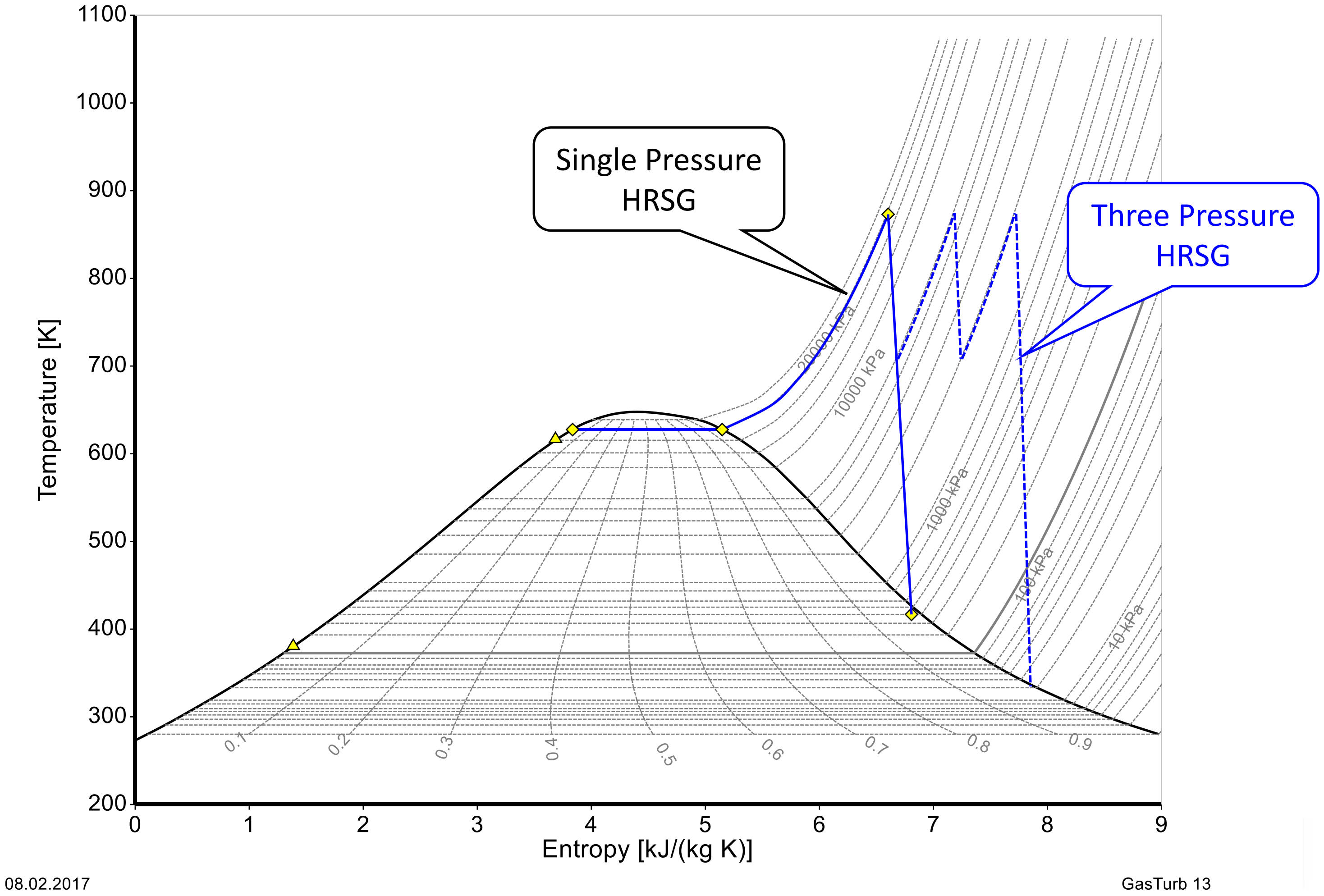
GT26

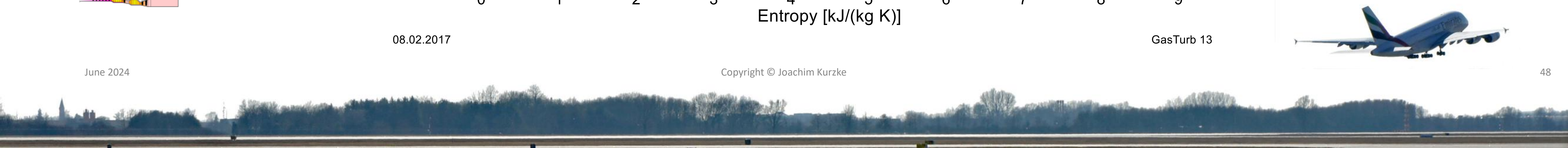
Fuel		Natural Gas
Frequency	Hz	50
Electrical output	MW	262
Electrical efficiency	%	38.2
Heat rate	Btu/kWh	8,932
Turbine speed	rpm	3,000
Compressor pressure ratio		30.0:1
Exhaust gas flow	kg/s	562
Exhaust gas temperature	°C	630
NOx emissions (corr. to 15% O_2, dry)	vppm	<25



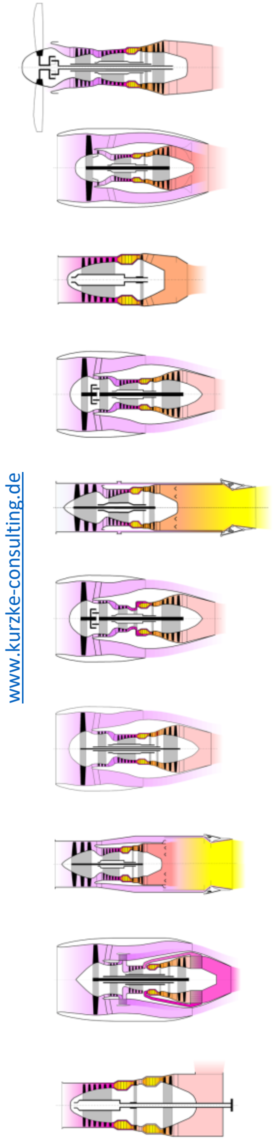


Combined Cycle
Steam Cycle





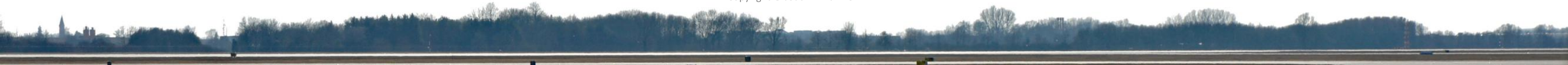
www.kurzke-consulting.de



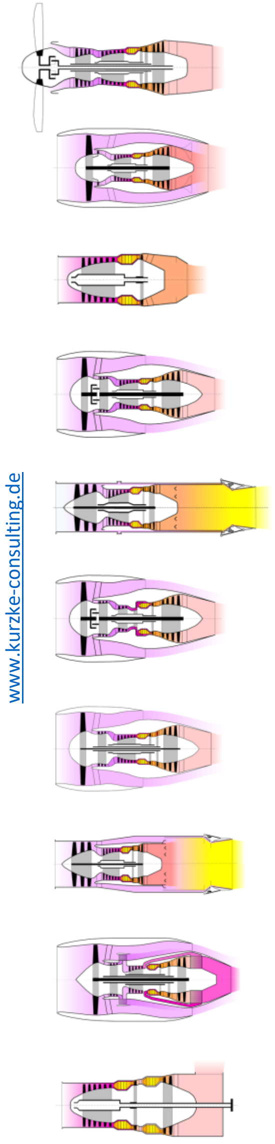
www.kurzke-consulting.de

Outline

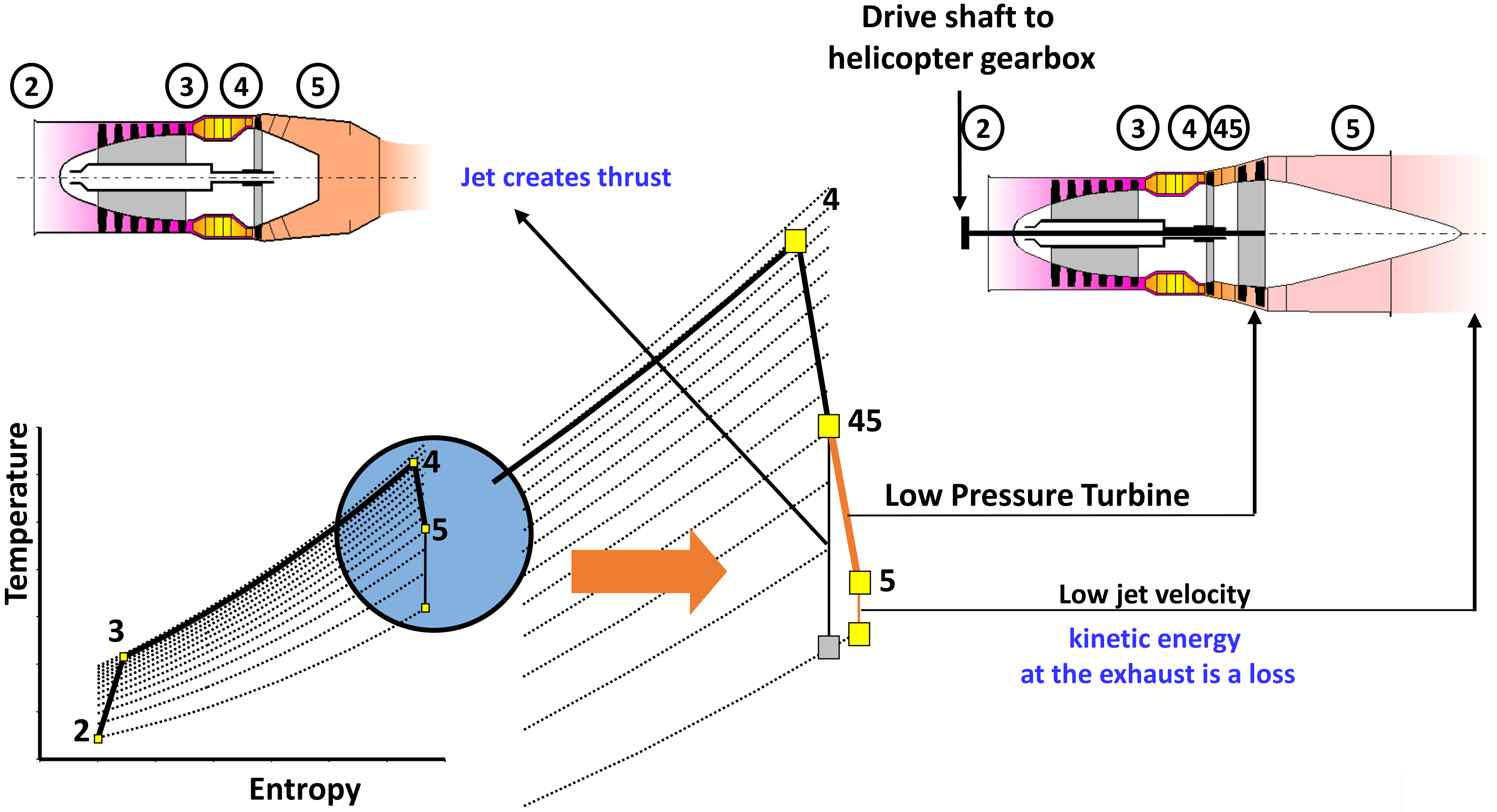
- Fundamentals
- Ideal Cycles
- Thermal Efficiency
- Power Generation
- **Aircraft Propulsion**
- Fundamental Design Decisions
- Non-Dimensionals
- Turbojet Off-Design

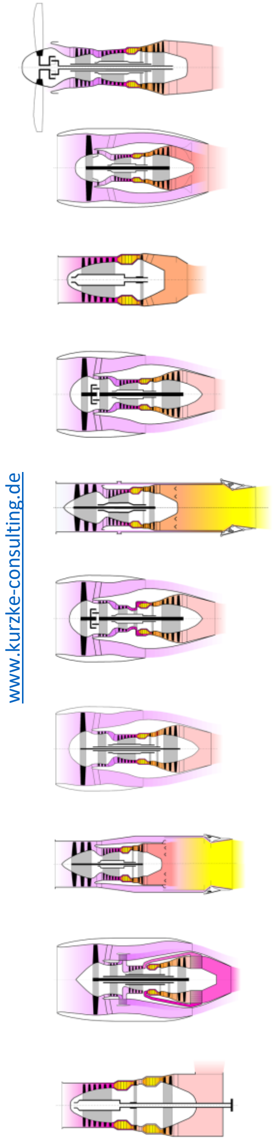


From Turboshaft to Turbojet



www.kurzke-consulting.de





Thermal Efficiency @ SLS

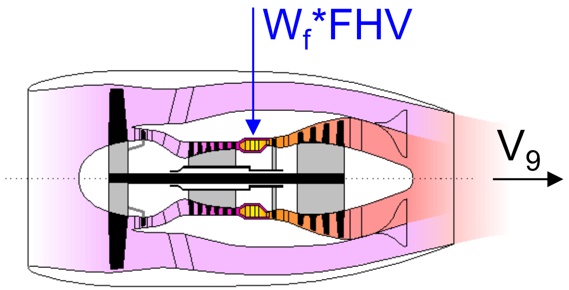
Thermal efficiency is defined as

increase of the kinetic energy of the gas stream

over

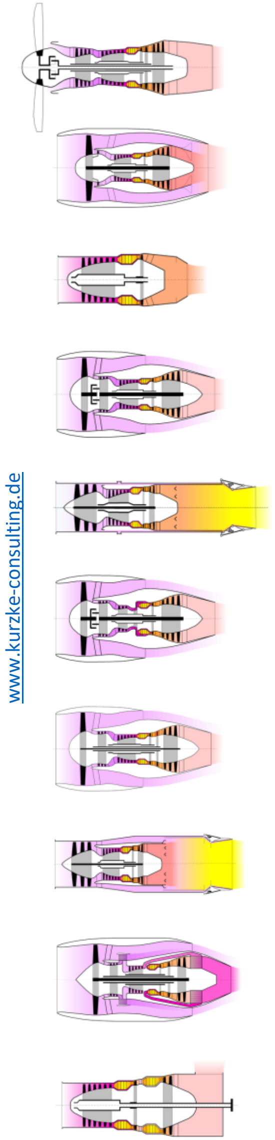
the amount of heat employed

the product of fuel mass flow W_f and fuel heating value FHV

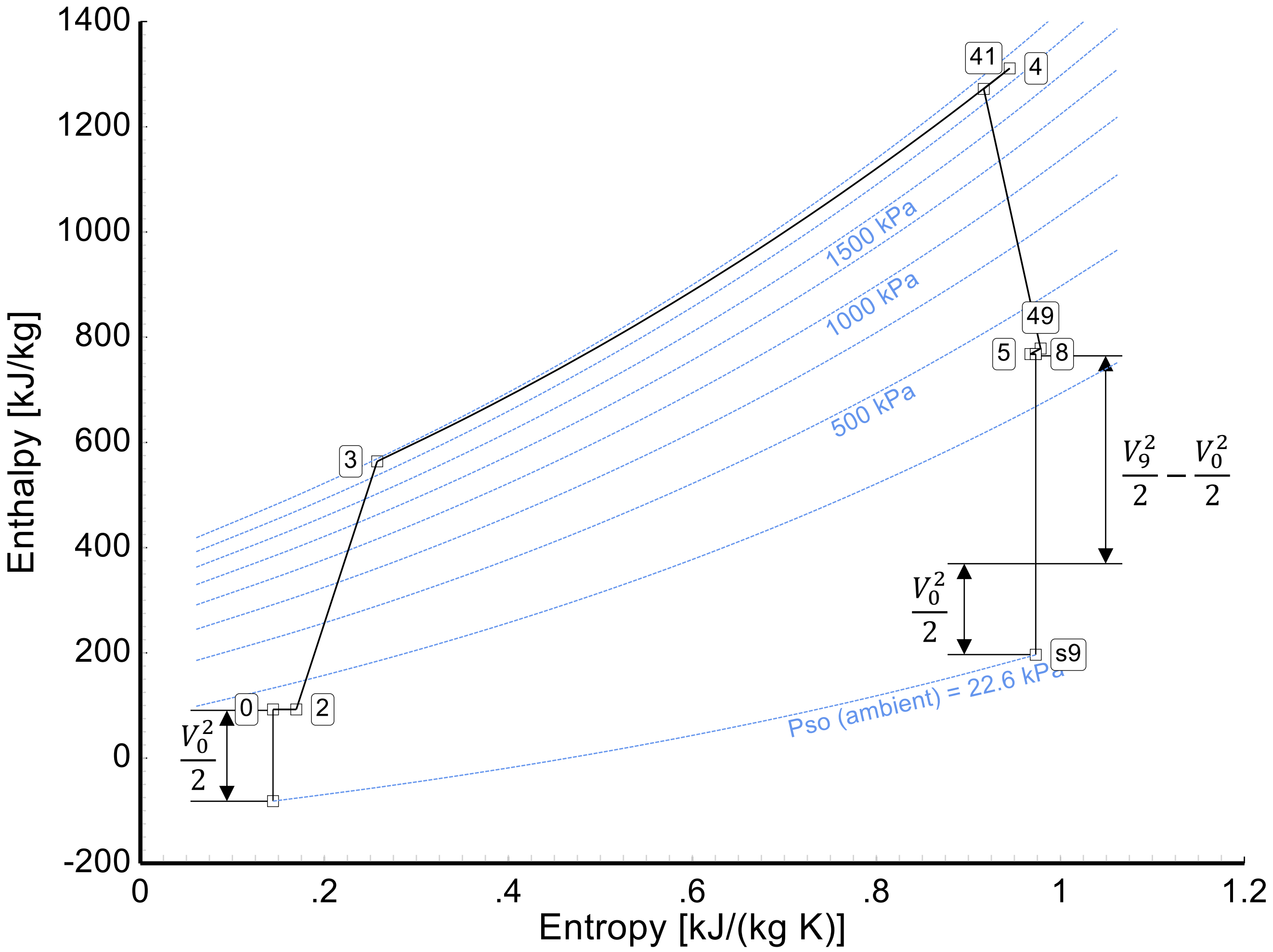


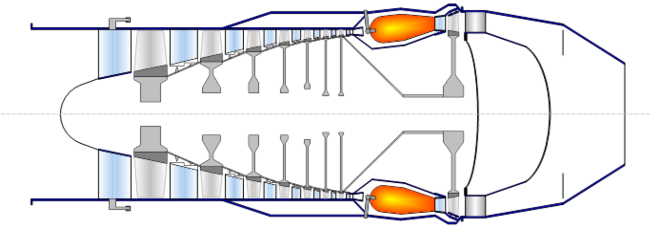
$$\eta_{th} = \frac{W_9 * \frac{V_9^2}{2}}{W_f * FHV}$$

Thermal Efficiency in Flight

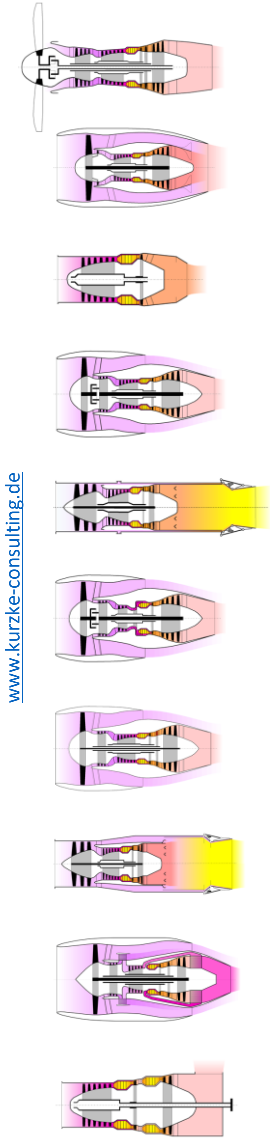


www.kurzke-consulting.de





$$\eta_{th} = \frac{\frac{1}{2} W_9 * V_9^2 - \frac{1}{2} W_0 * V_0^2}{W_f * FHV}$$



www.kurzke-consulting.de

Propulsive Efficiency

Propulsive efficiency is the ratio of

useful propulsive energy

– the product of thrust and flight velocity –

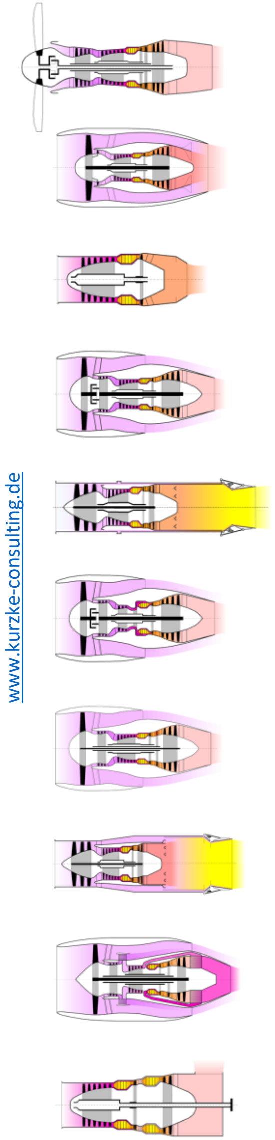
compared to

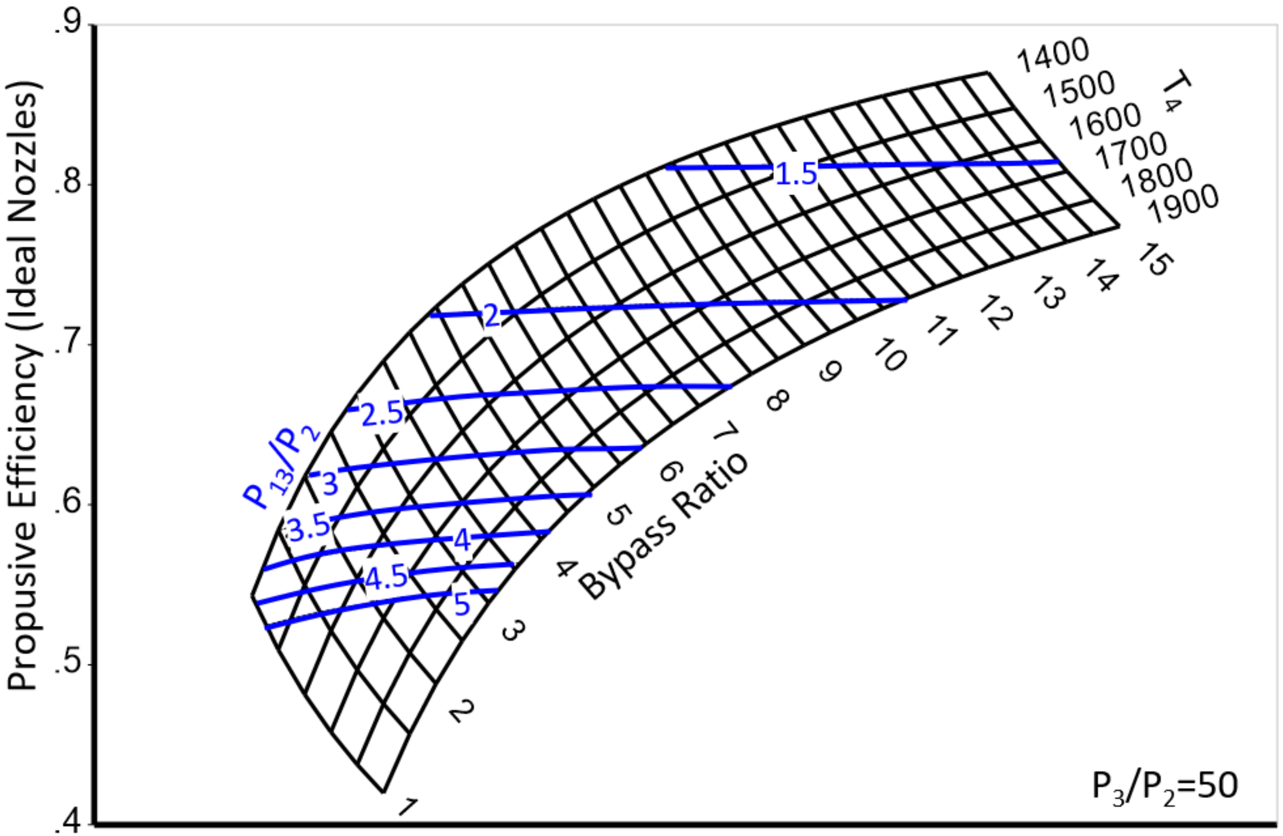
the wasted kinetic energy of the jet:

$$\eta_P = \frac{F * V_0}{W_9 \frac{V_9^2 - V_0^2}{2}}$$

$$\eta_P = \frac{2 * V_0}{V_0 + V_9}$$

Propulsive Efficiency of Turbofans

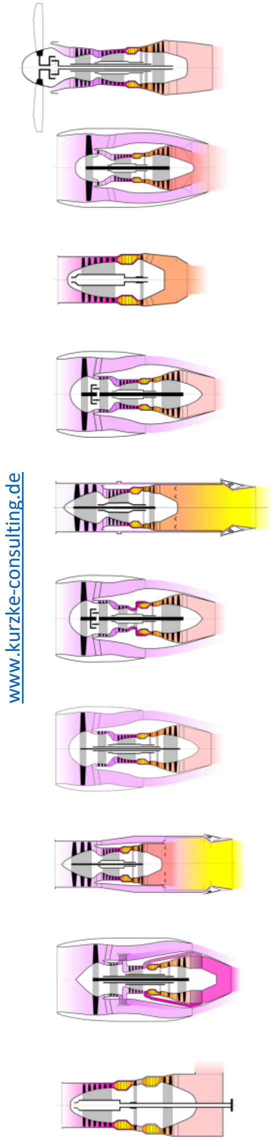




- Higher bypass ratio means higher propulsive efficiency
  that's the popular opinion.

- However, this is only true for constant T_4.

Overall Efficiency

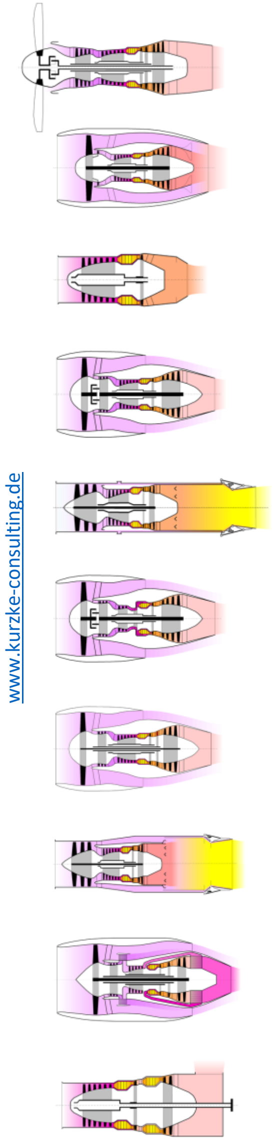


The overall efficiency is the ratio of useful work done in overcoming the drag of the airplane to the energy content of the fuel:

$$\eta_o = \frac{F * V_0}{W_f * FHV}$$

Simplified:

overall efficiency is equal to
the product of thermal efficiency and propulsive efficiency.



Specific Fuel Consumption

Overall efficiency of an aircraft engine is inseparably linked with the flight velocity.

$$\eta_o = \frac{F * V_0}{W_f * FHV}$$

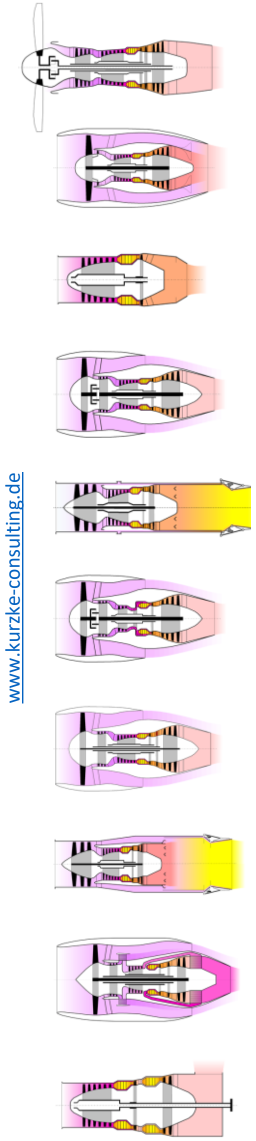
With SFC=W_f / F, overall efficiency becomes

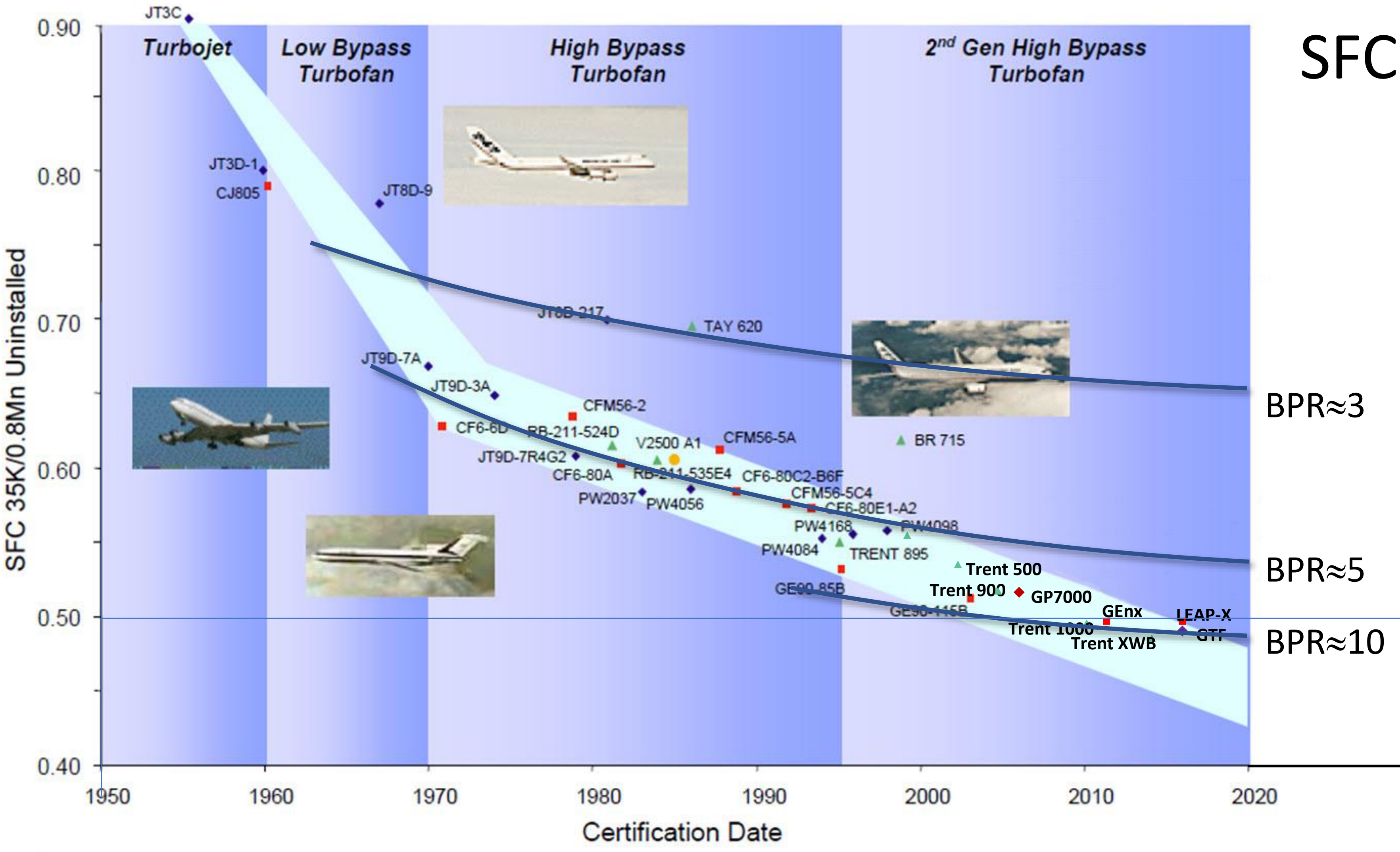
$$\eta_o = \frac{V_0}{SFC * FHV}$$

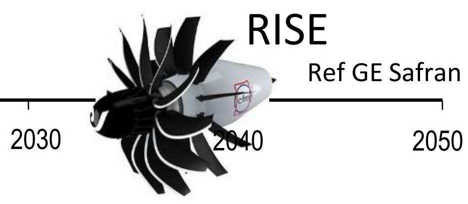
Rewritten:

$$SFC = \frac{V_0}{\eta_o * FHV} = \frac{V_0}{\eta_{th} * \eta_P * FHV}$$

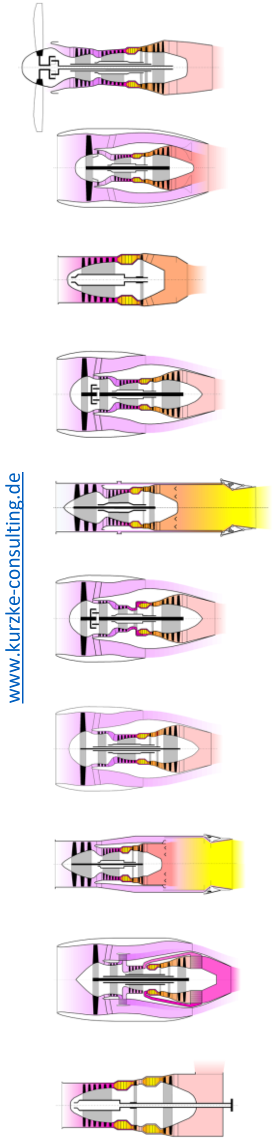
SFC History



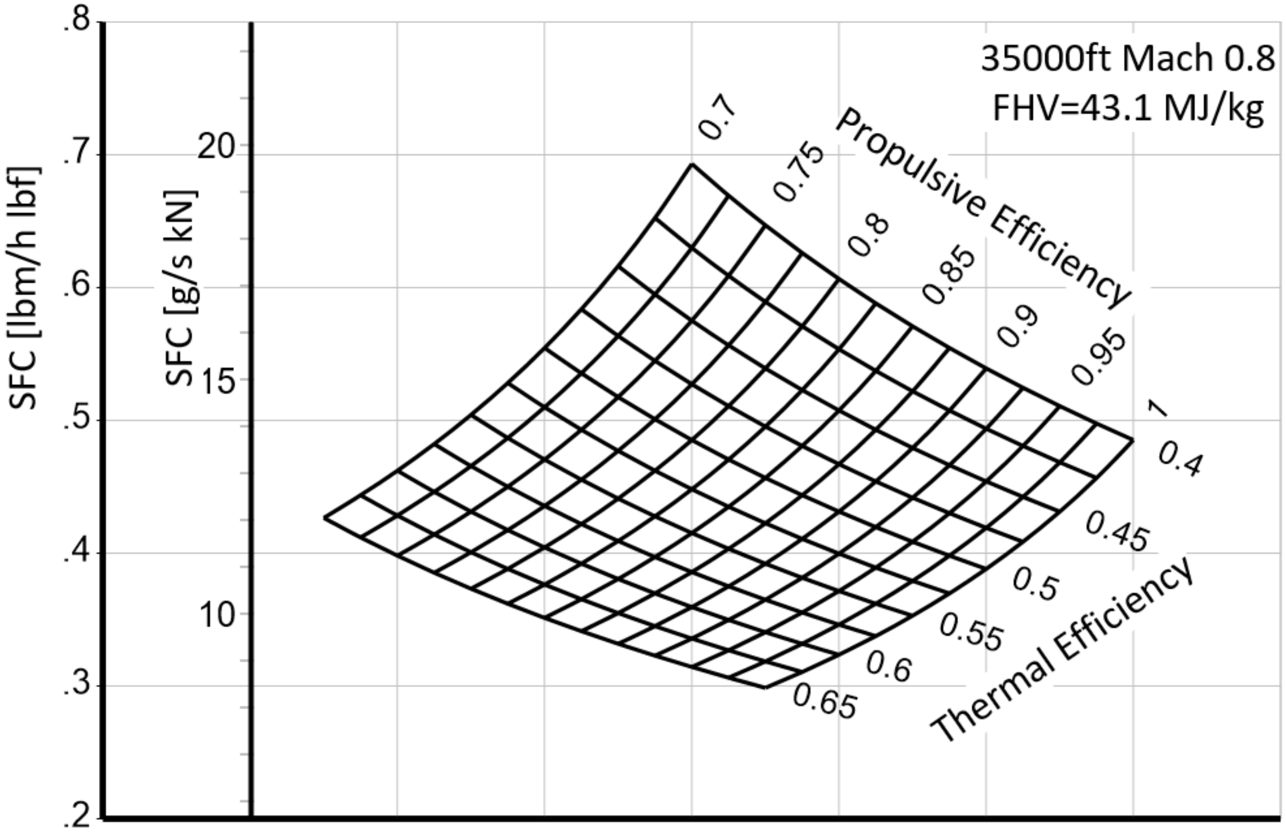




www.kurzke-consulting.de



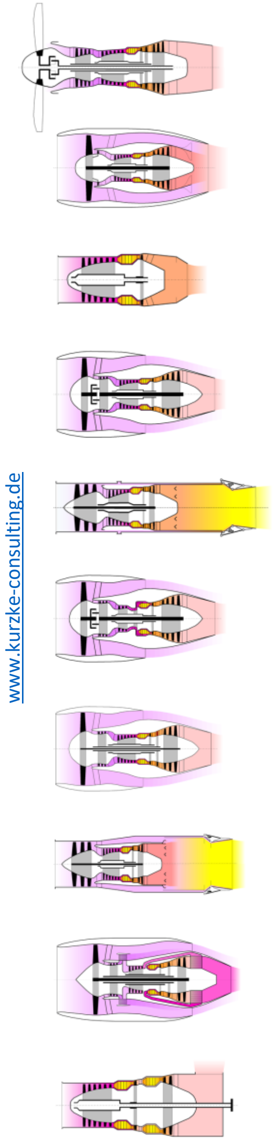
$SFC = f(\eta_{therm}, \eta_{prop})$



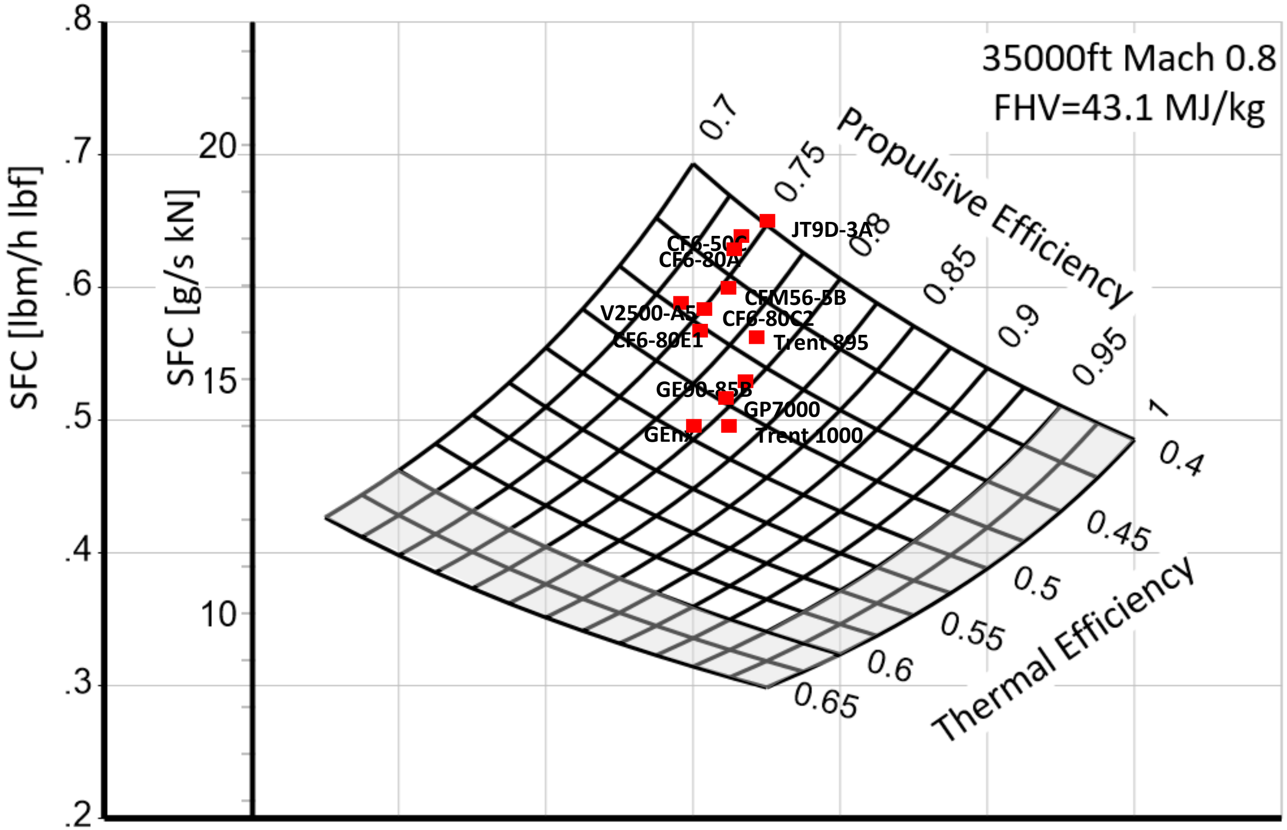
$$SFC = \frac{V_0}{\eta_{therm} * \eta_{prop} * FHV}$$

35000ft Mn 0.8 → V_0=237m/s

FHV=43.1 MJ/kg



$SFC = f(\eta_{therm}, \eta_{prop})$

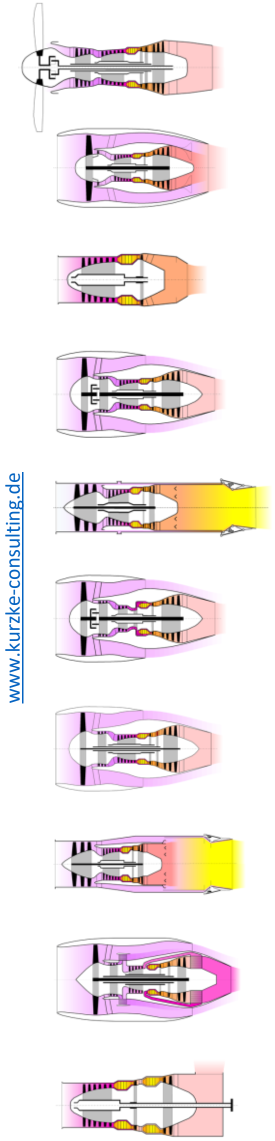


$$SFC = \frac{V_0}{\eta_{therm} * \eta_{prop} * FHV}$$

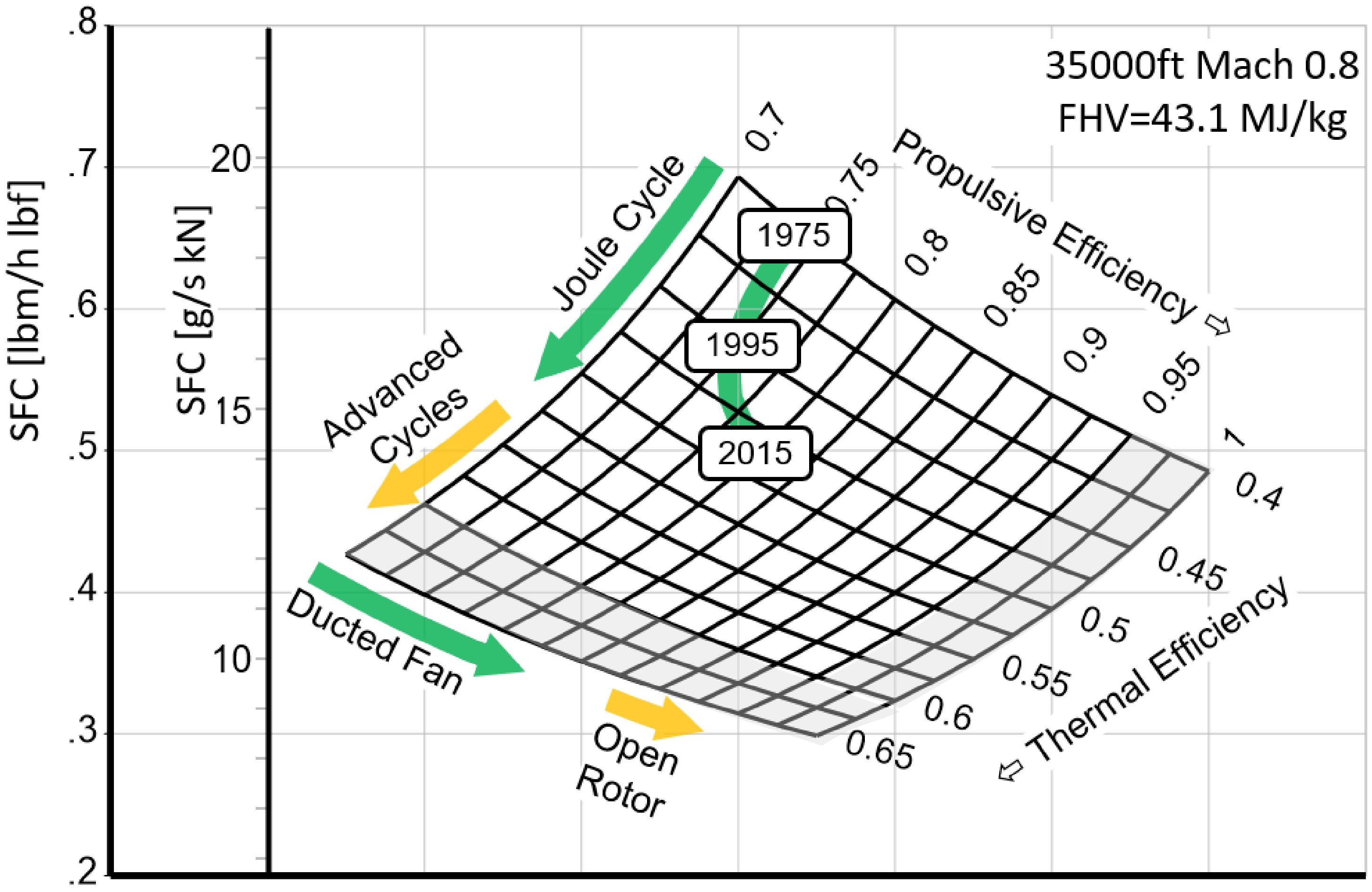
35000ft Mn 0.8 → V_0=237m/s

FHV=43.1 MJ/kg

A Personal View

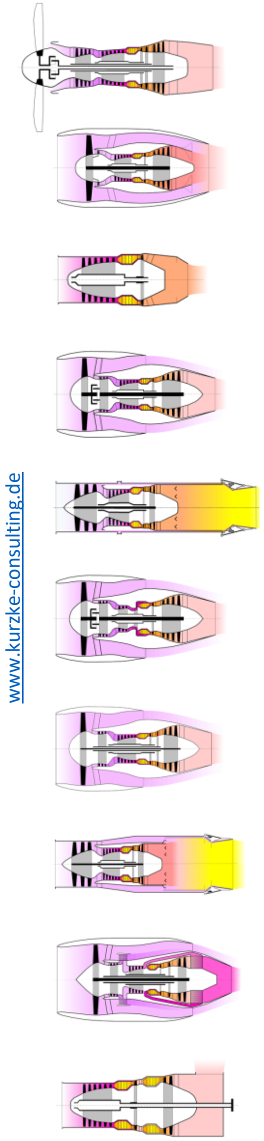


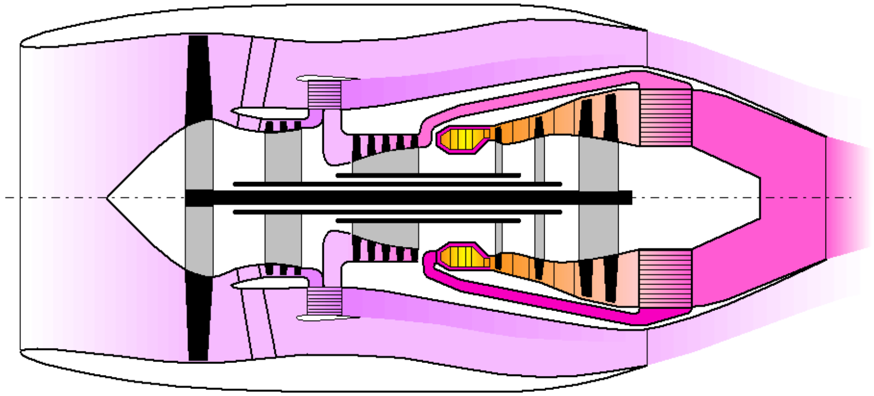
www.kurzke-consulting.de

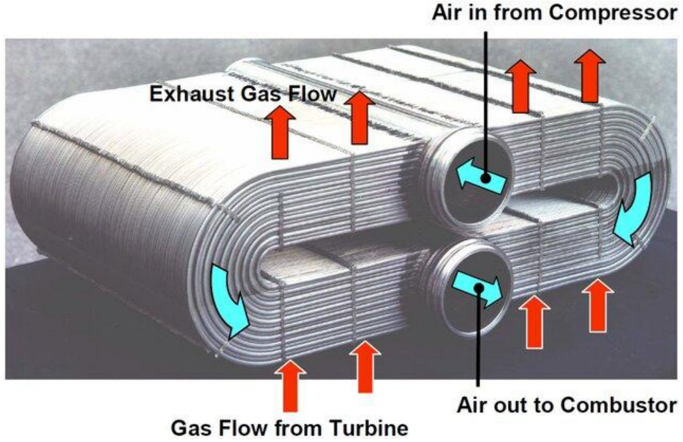


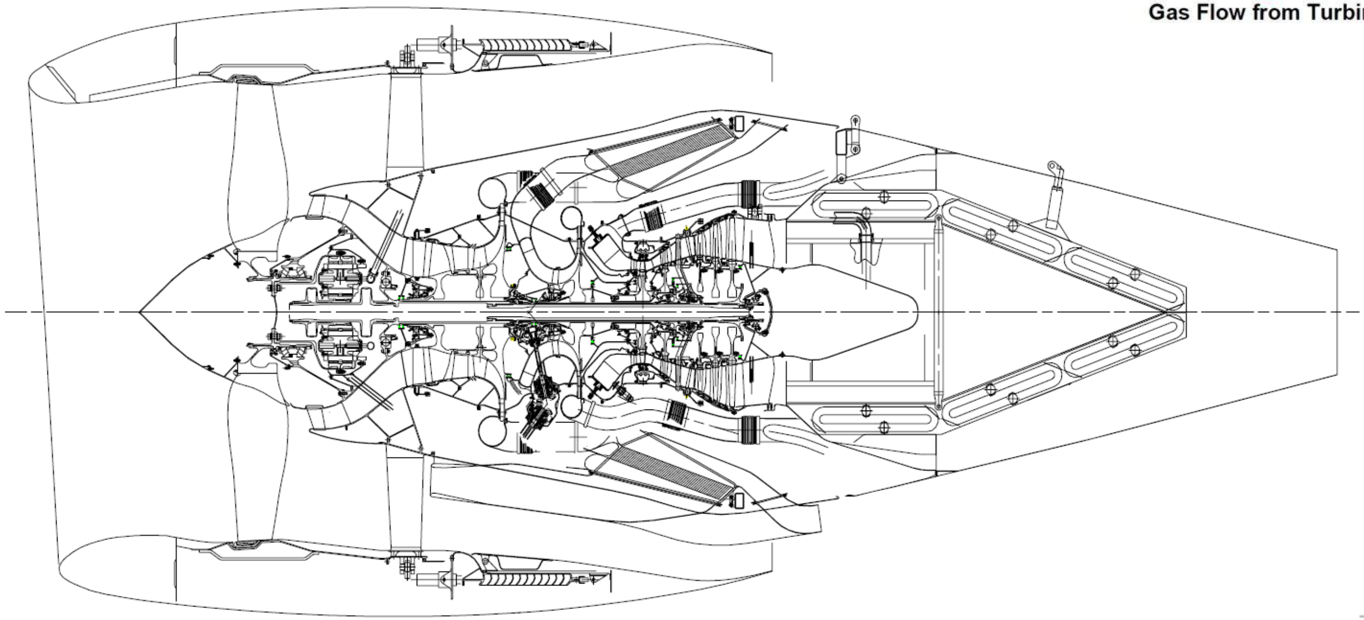
Intercooled Recuperated Turbofan

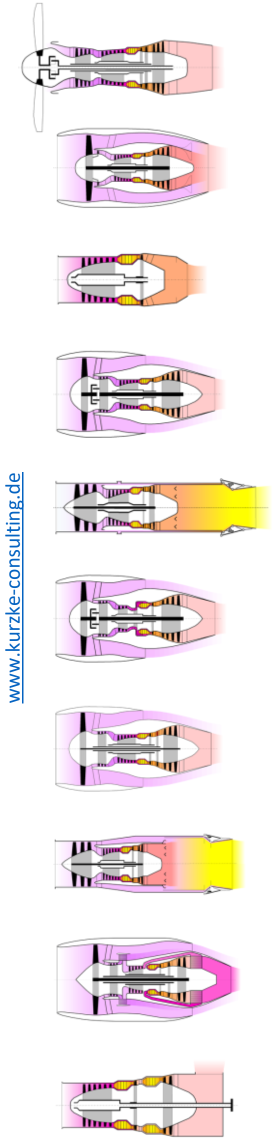
www.kurzke-consulting.de







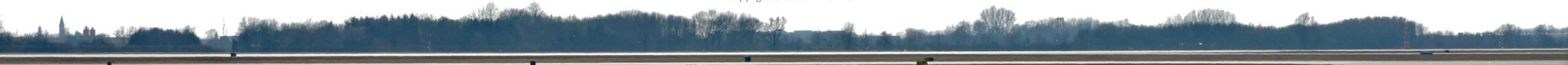




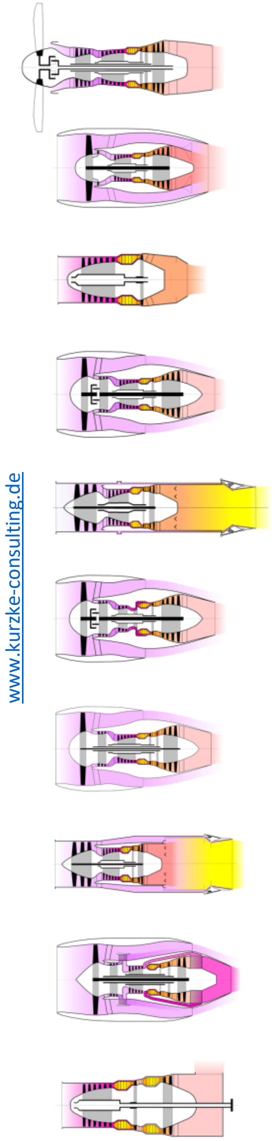
www.kurzke-consulting.de

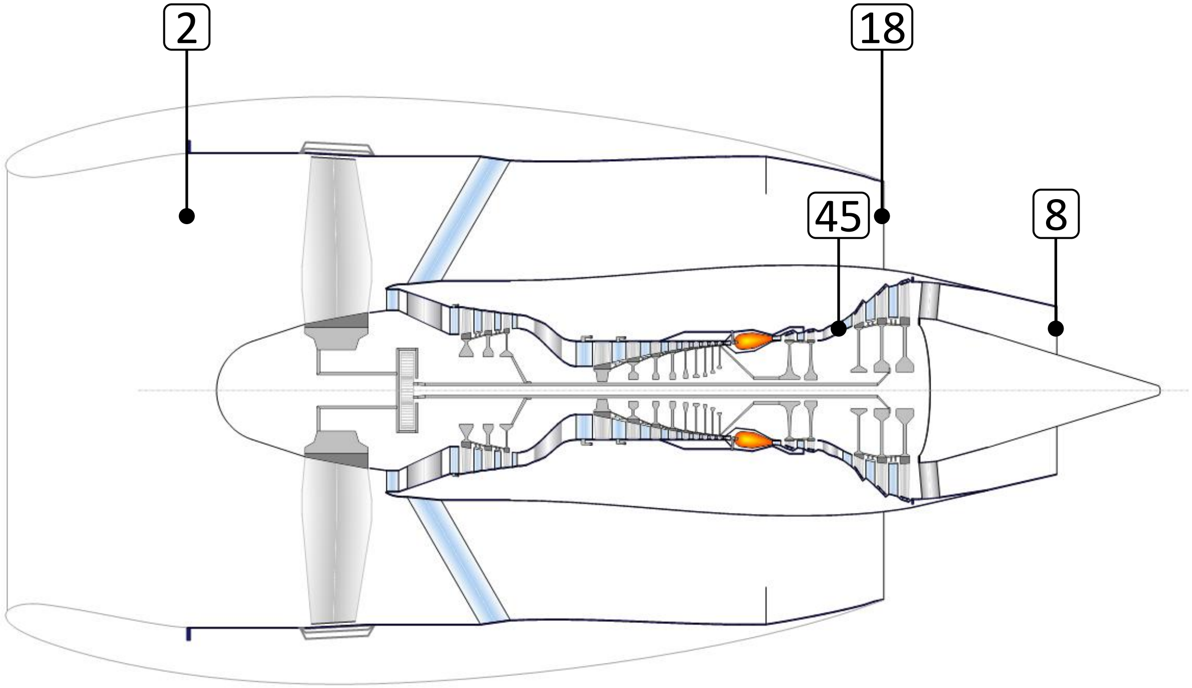
Outline

- Fundamentals
- Ideal Cycles
- Thermal Efficiency
- Power Generation
- Aircraft Propulsion
- **Fundamental Design Decisions**
- Non-Dimensionals
- Turbojet Off-Design



Turbofan: Mixed Flow or Separate Flow?

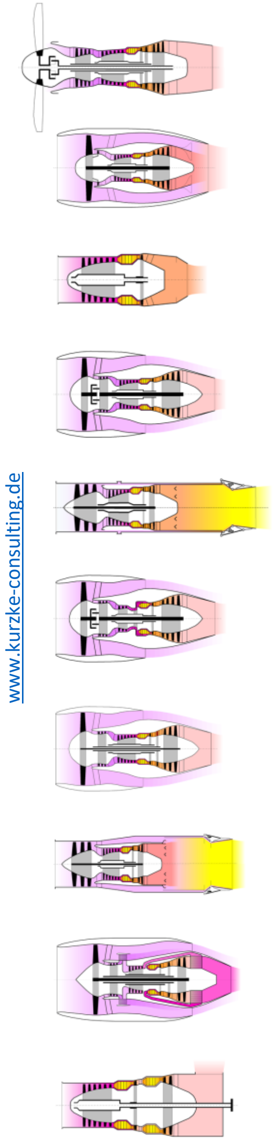


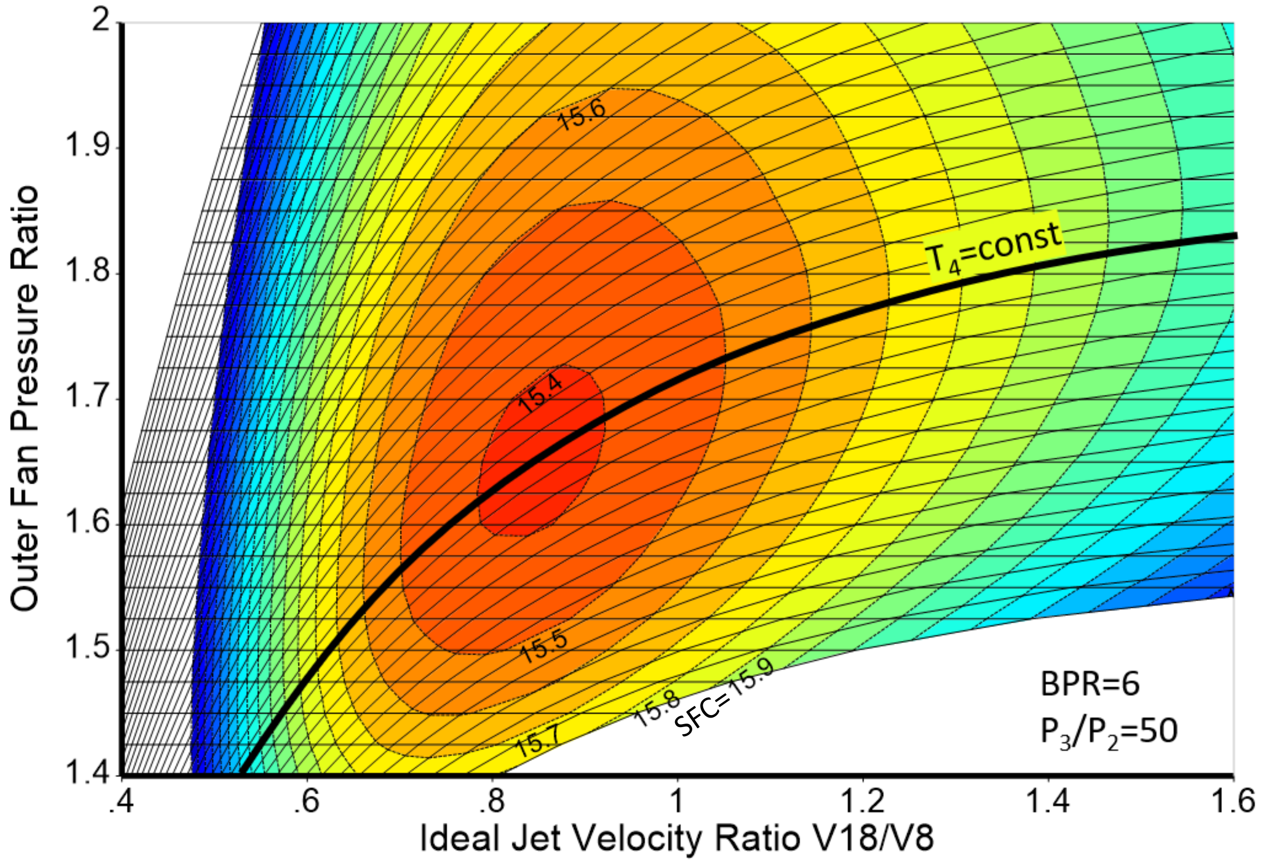


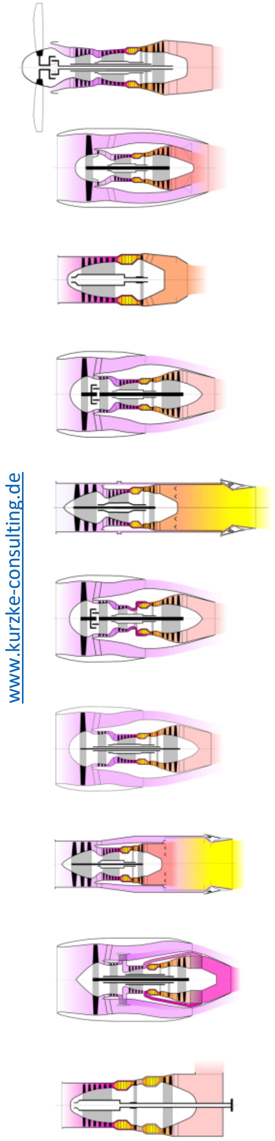
$$\left(\frac{V_{18}}{V_8}\right)_{id} = \eta_{2-18}\,\eta_{45-8}$$

Turbofan: Mixed Flow or Separate Flow?

Jet Velocity Ratio



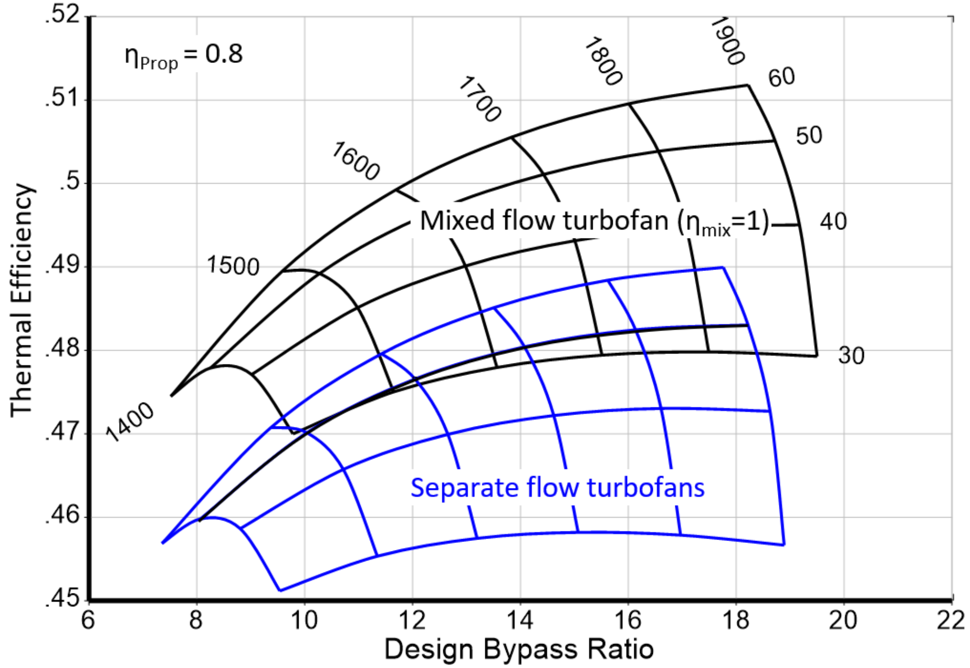


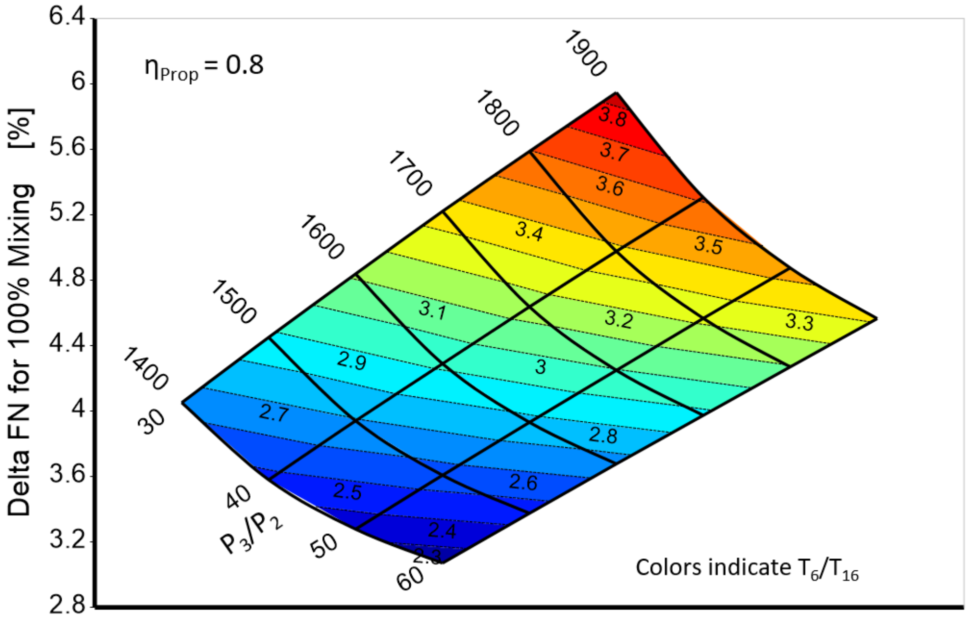


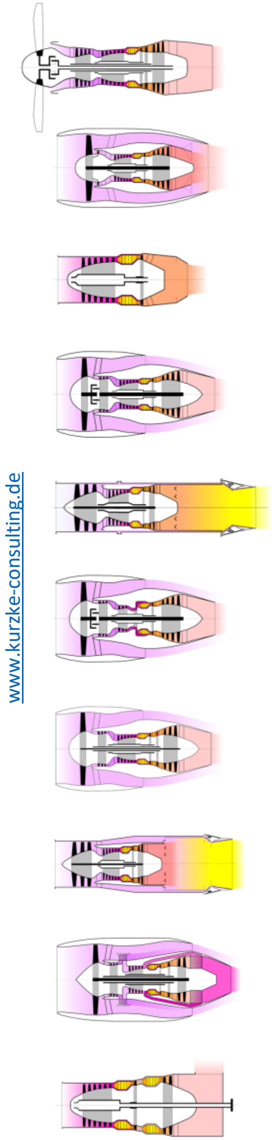
www.kurzke-consulting.de

Turbofan: Mixed Flow or Separate Flow?

Thermal Efficiency

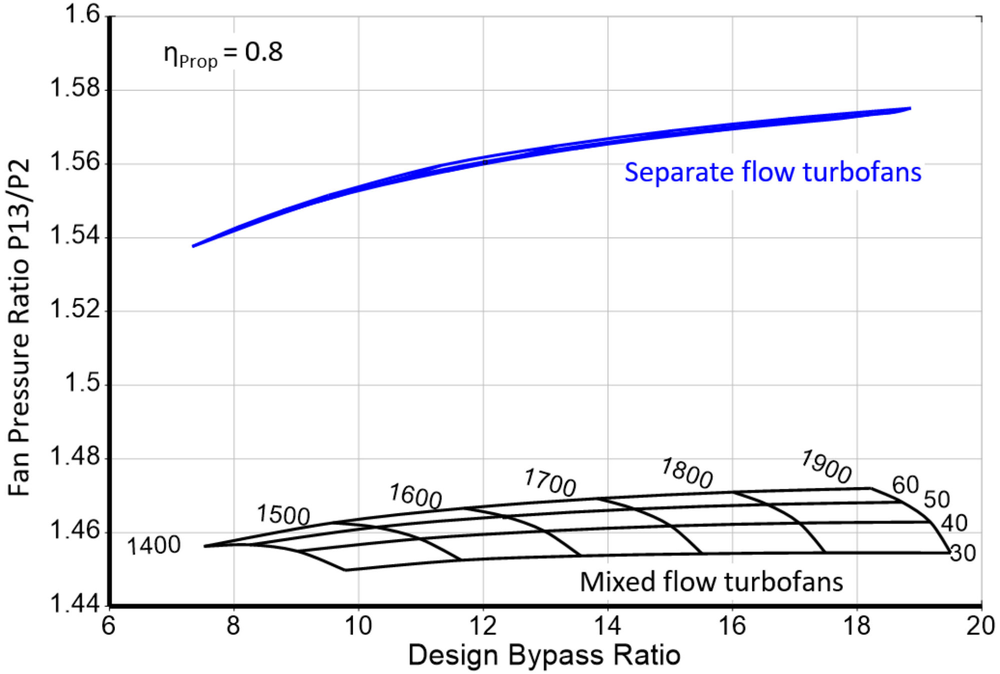


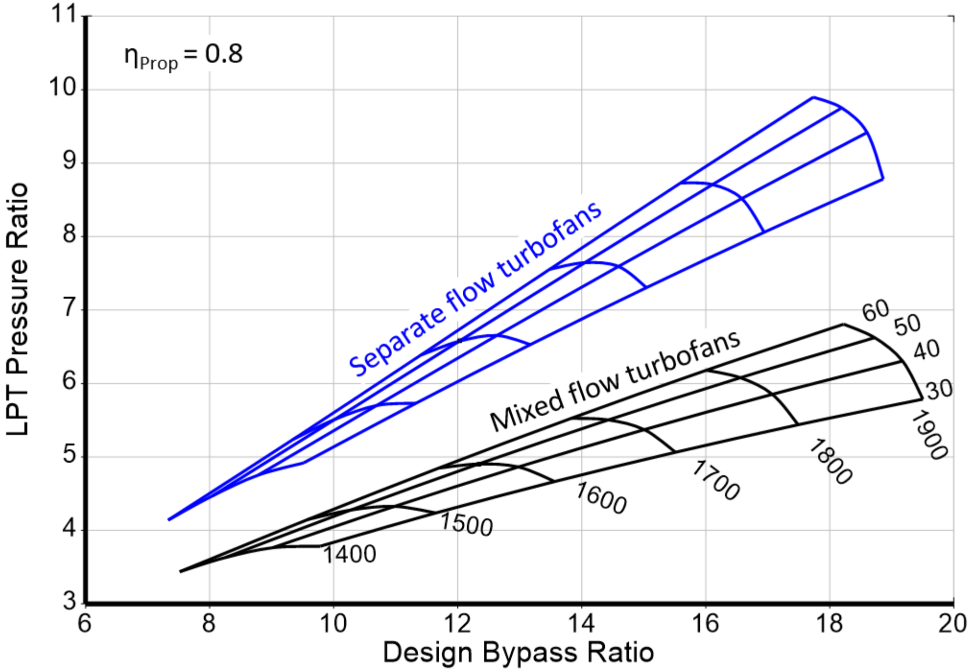




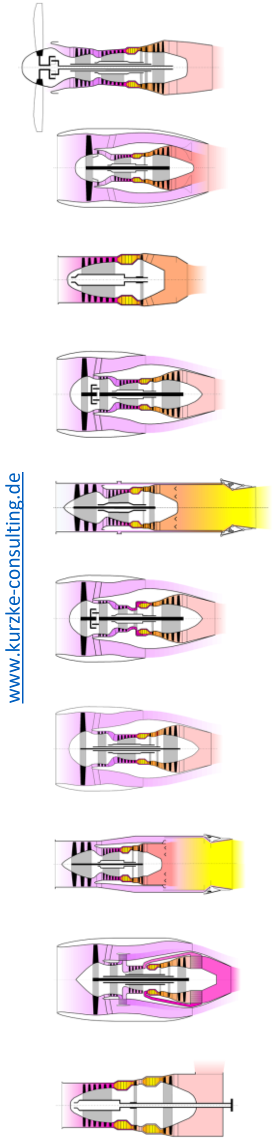
www.kurzke-consulting.de

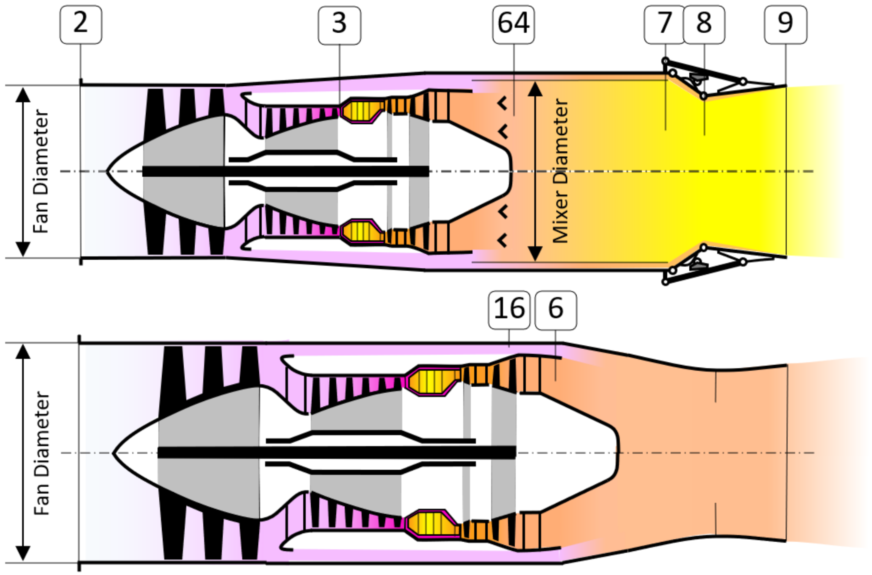
Turbofan: Mixed Flow or Separate Flow?
Fan and LPT Pressure Ratio

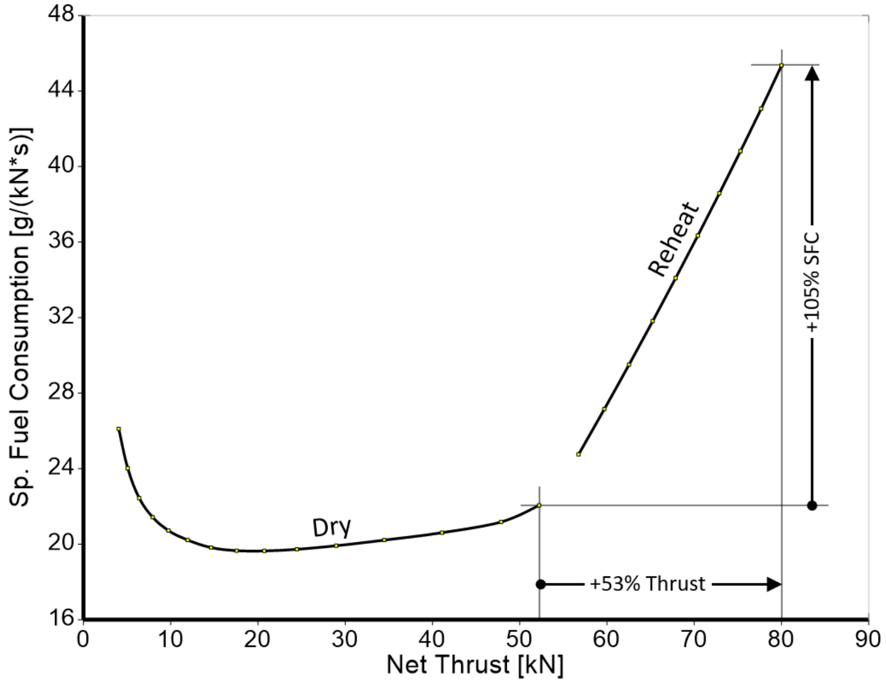




With or Without Afterburner (Reheat)?

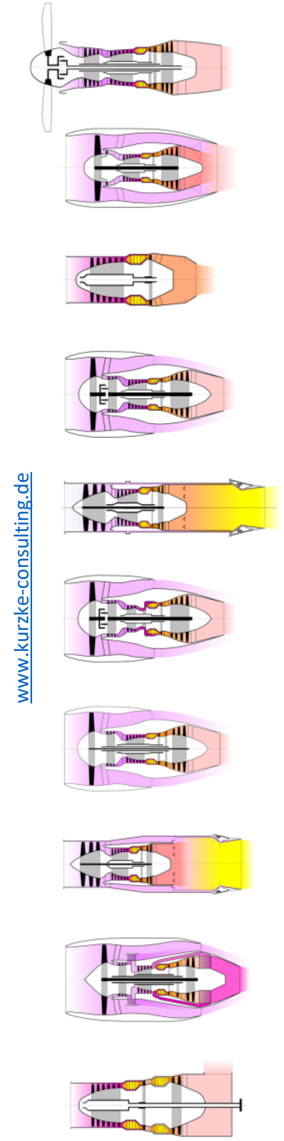


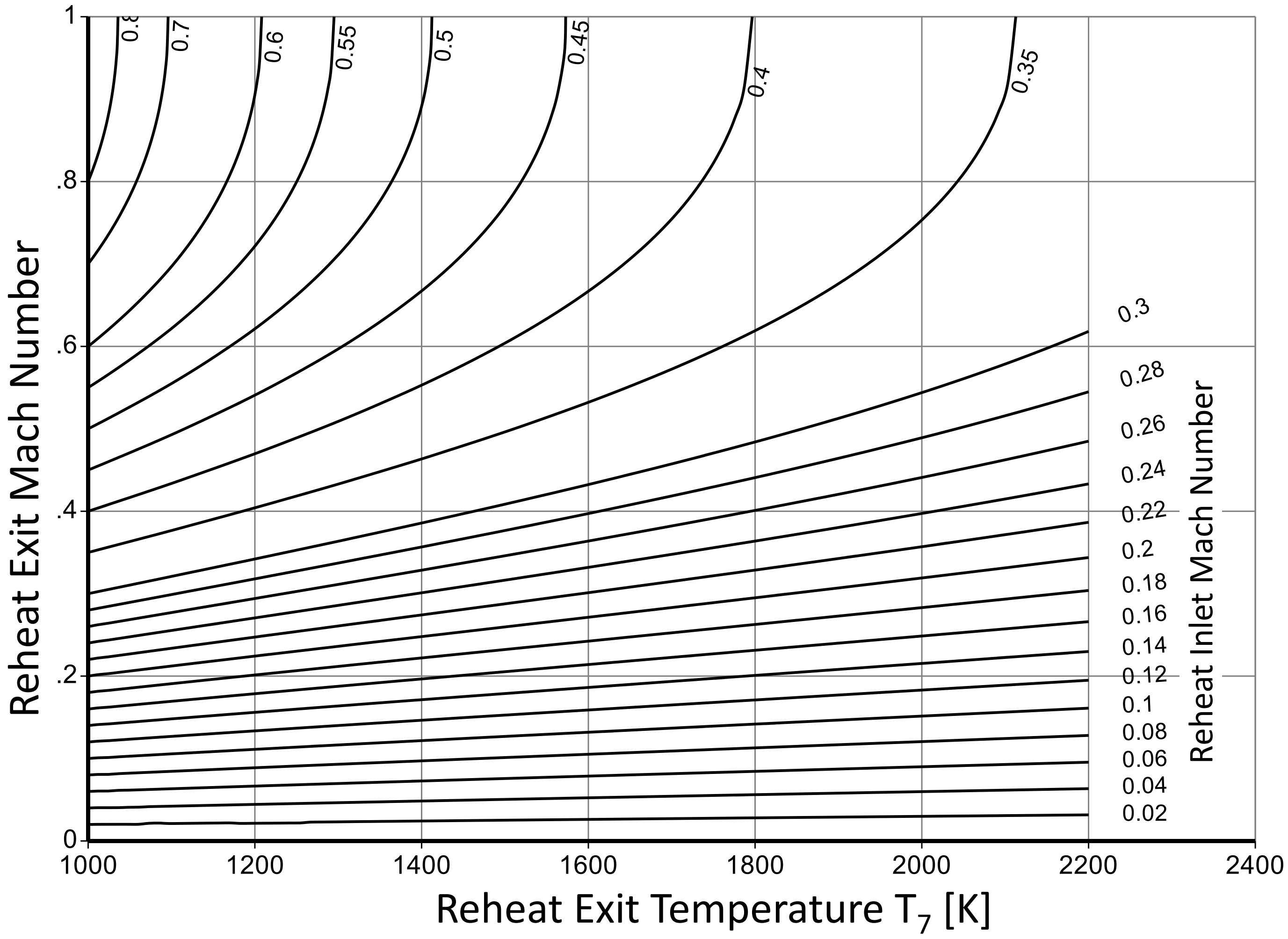




Rayleigh Line

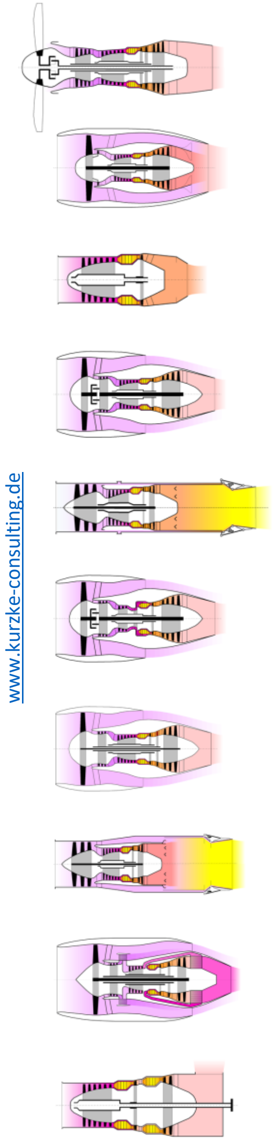
Heat Addition in a Constant Area Duct

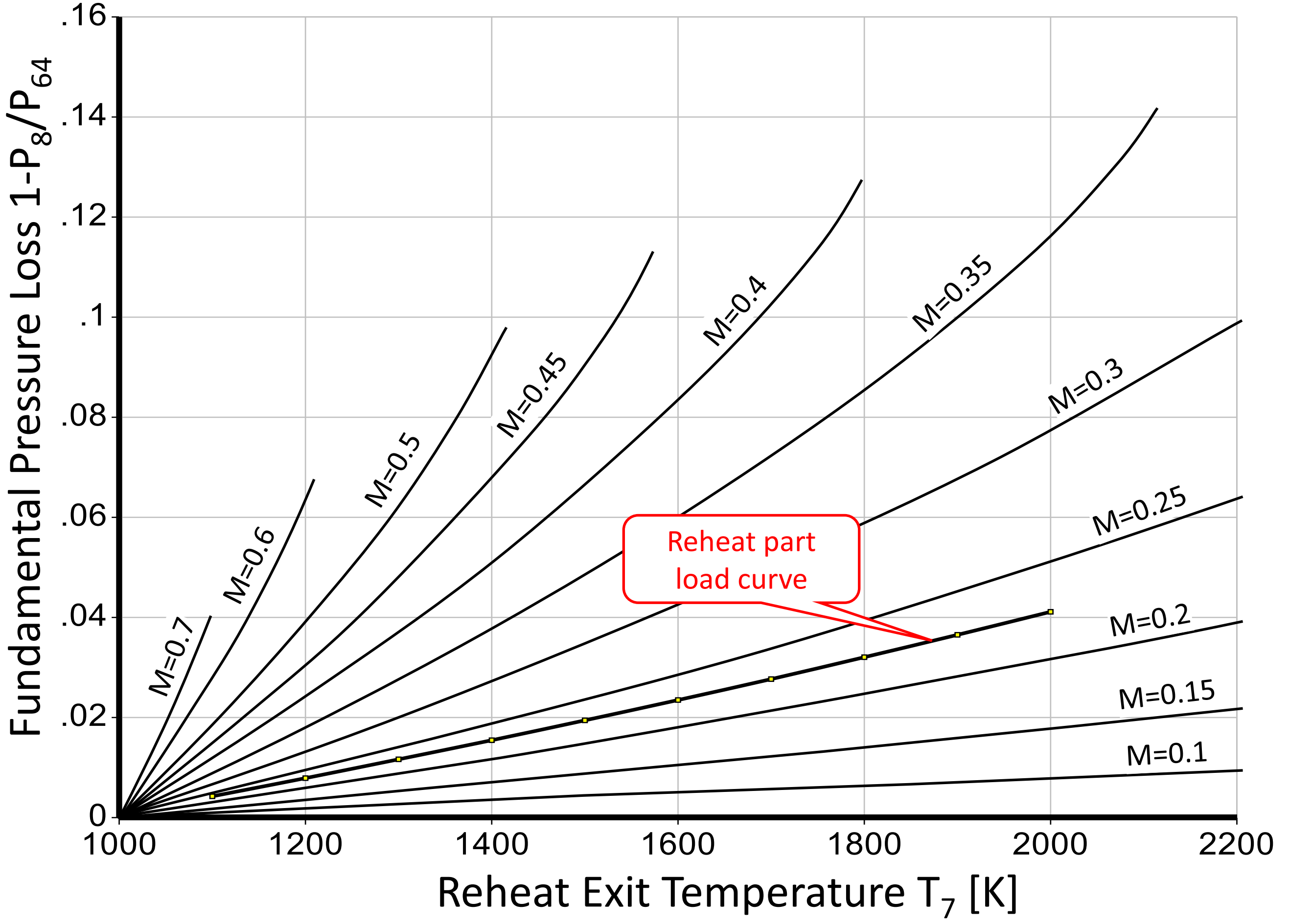


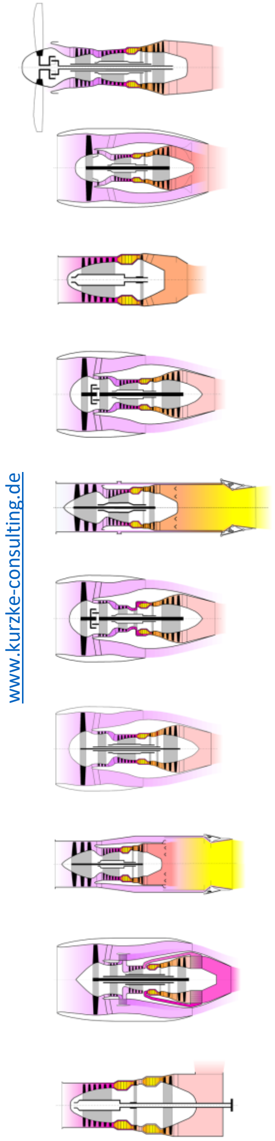


Rayleigh Line

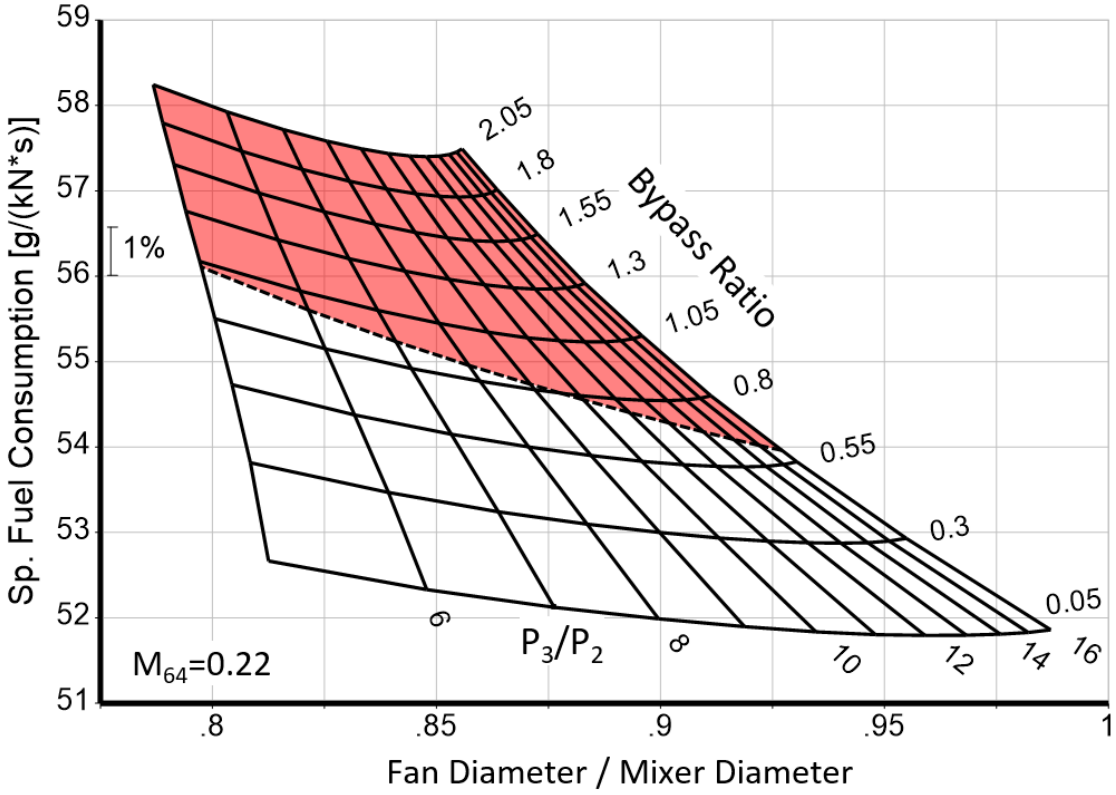
Fundamental Pressure Loss

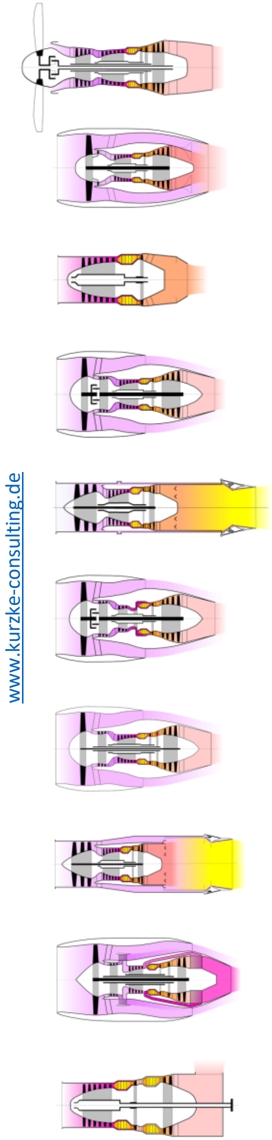






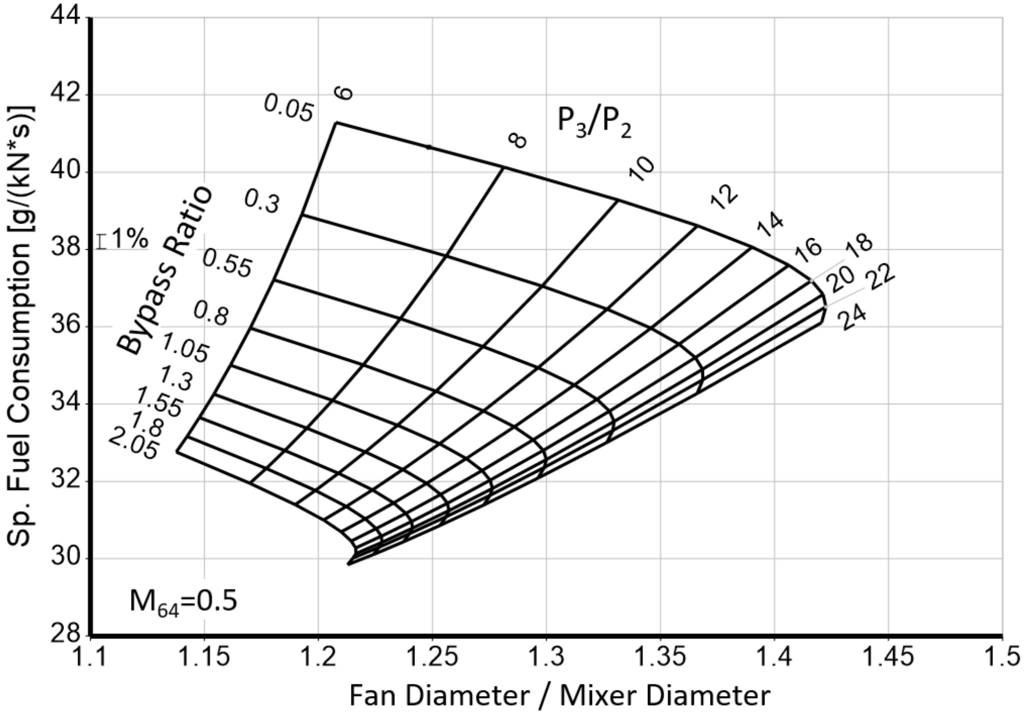
With Afterburner
Engine Size

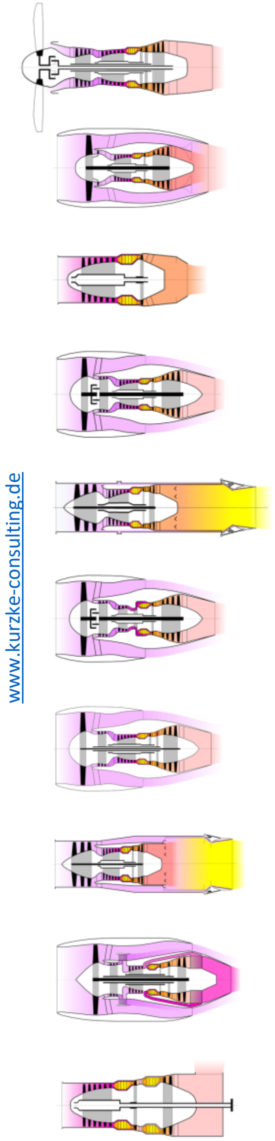




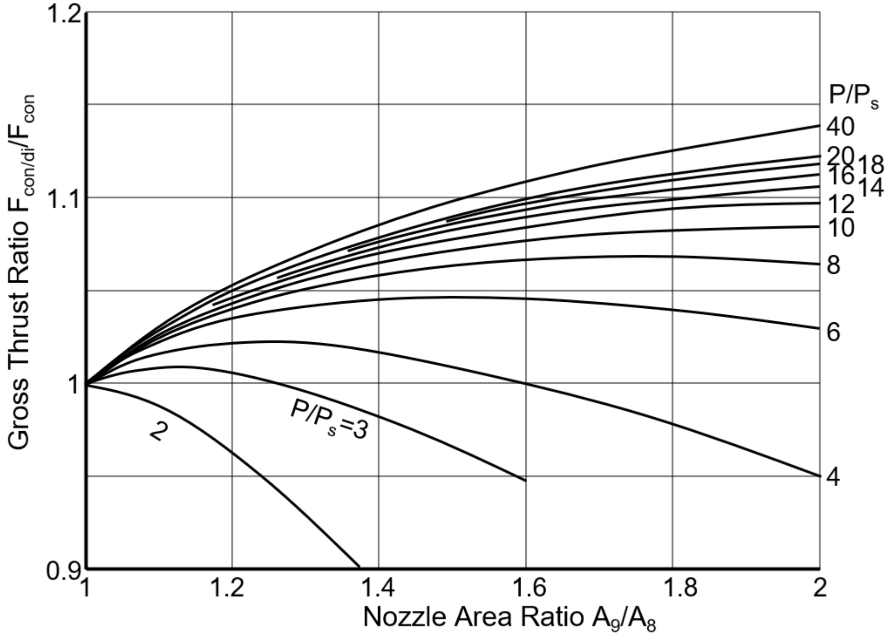
Without Afterburner

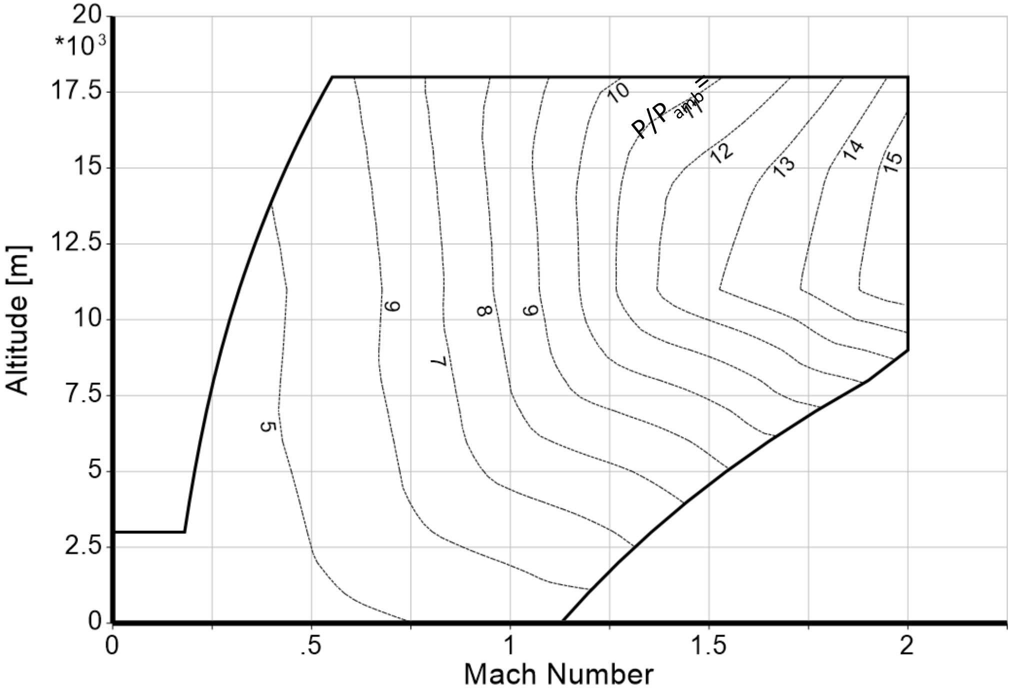
Engine Size



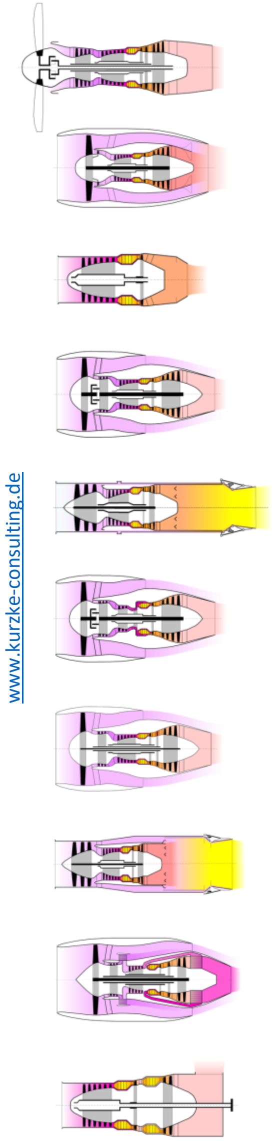


Fundamental Design Decisions
Convergent – Divergent Nozzle





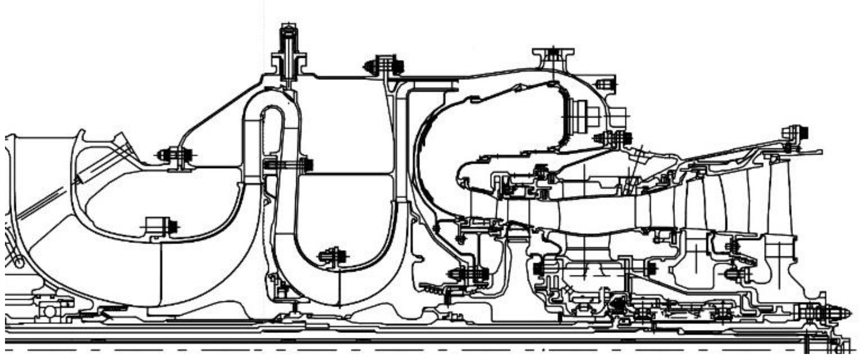
www.kurzke-consulting.de



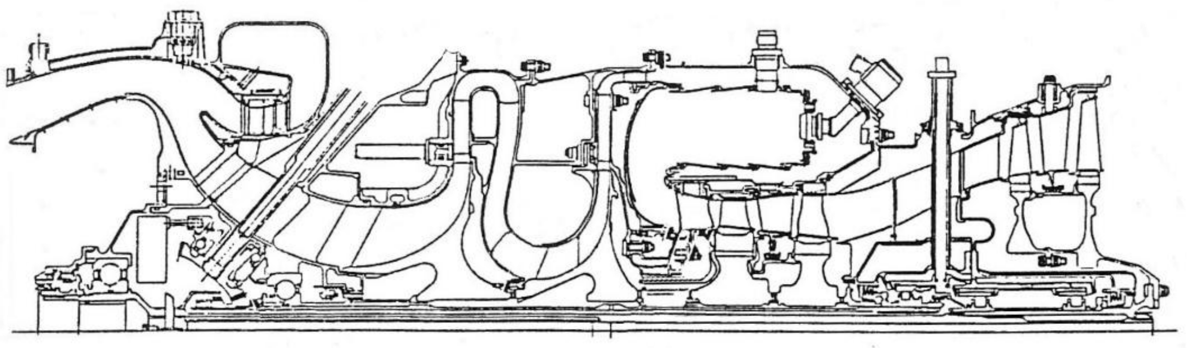
www.kurzke-consulting.de

Fundamental Design Decisions

Single or Two-Stage HP Turbine?

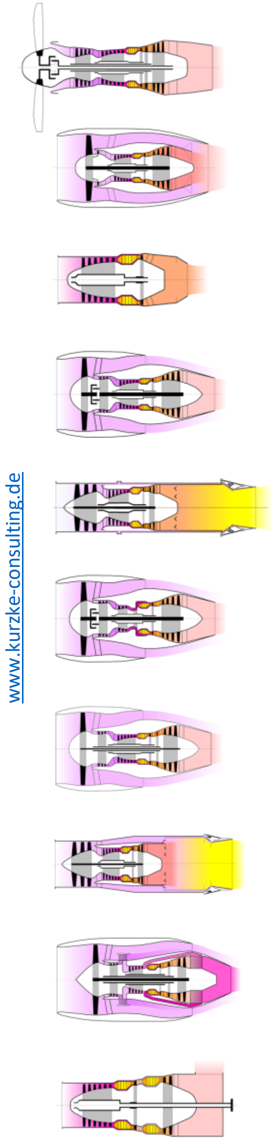


MTR 390

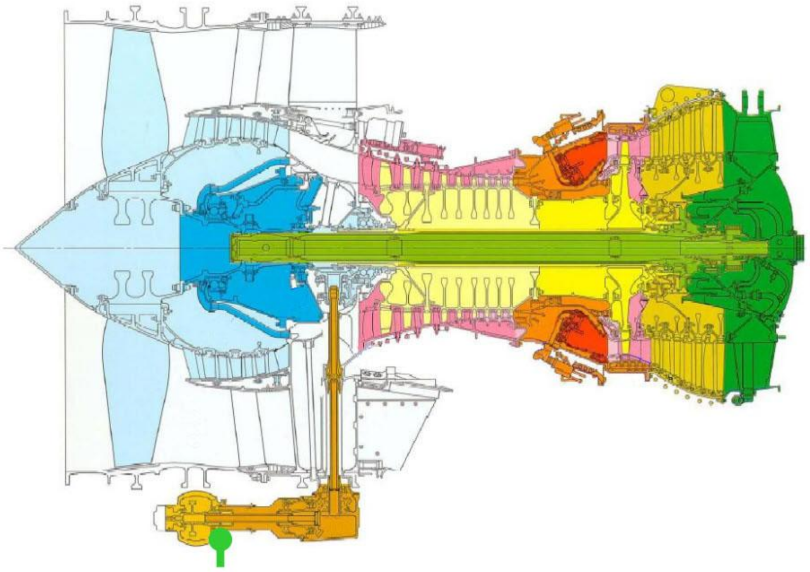


T800

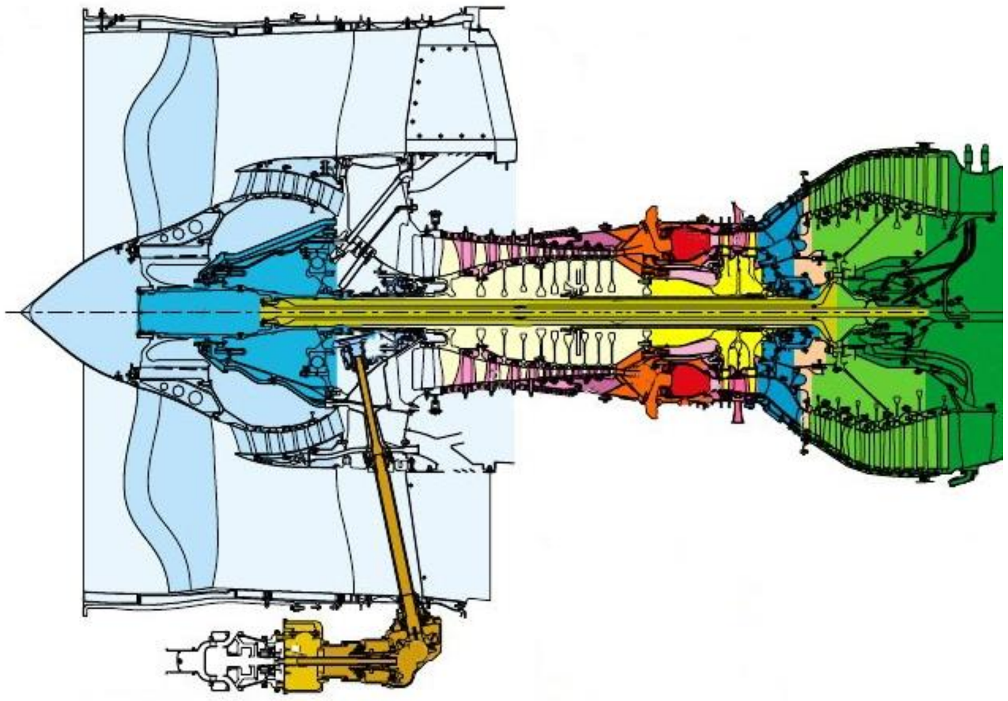
Single or Two-Stage HP Turbine?



www.kurzke-consulting.de



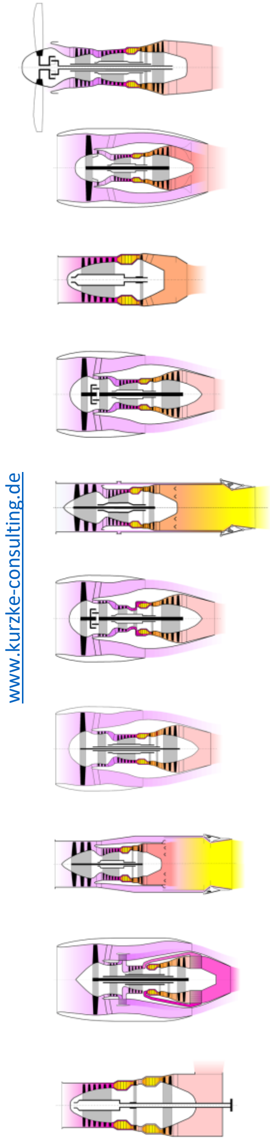
CFM56-7



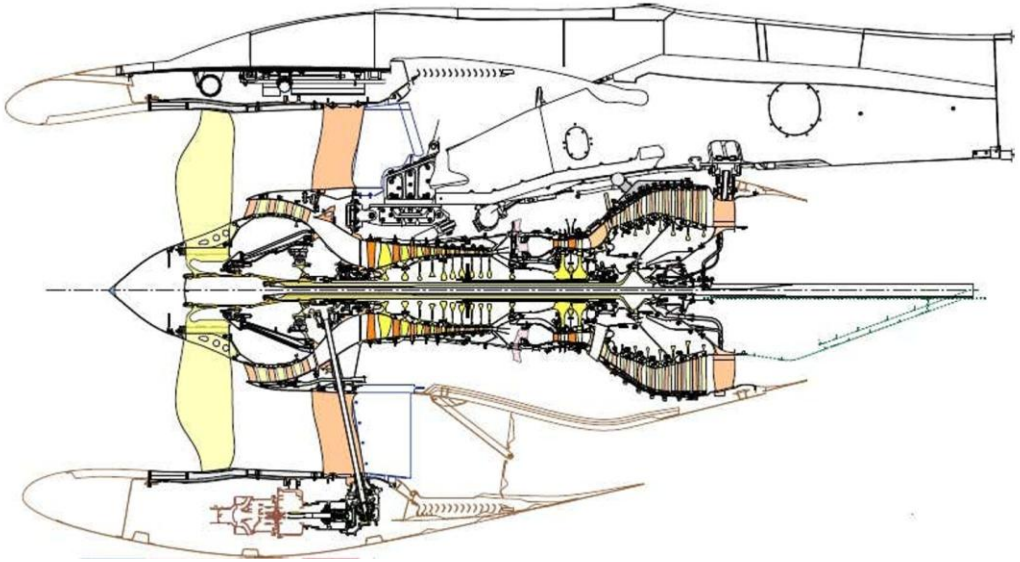
Leap 1A

Fundamental Design Decisions

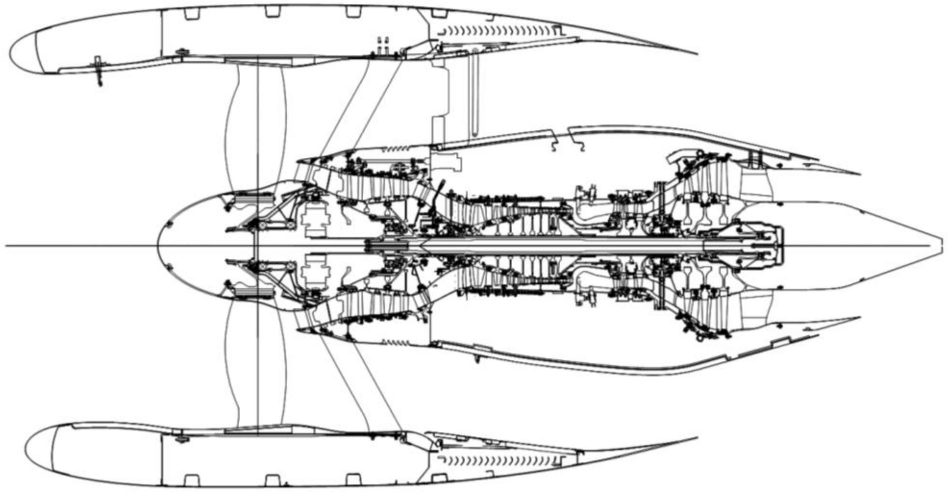
Conventional or Geared Turbofan?



www.kurzke-consulting.de

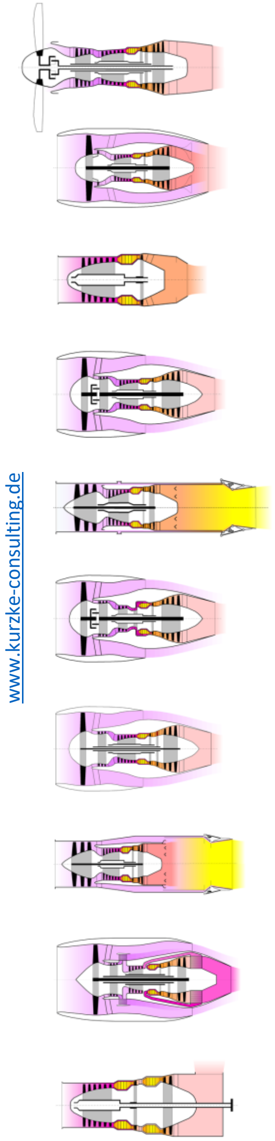


CFM Leap 1A



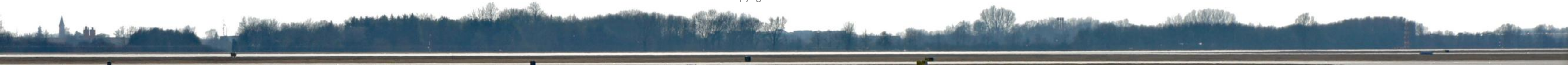
Pratt & Whitney Geared Turbofan

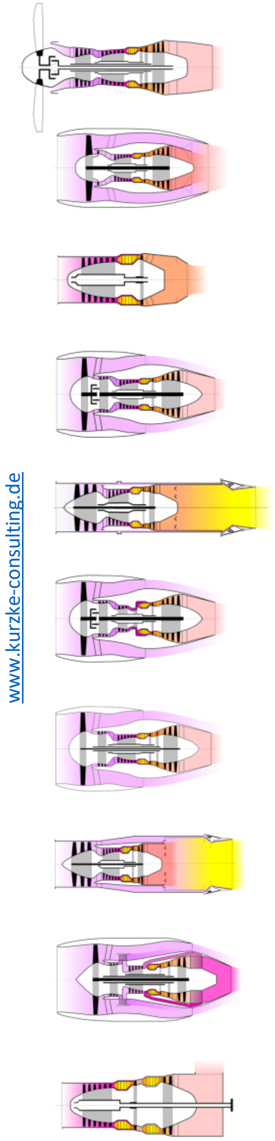
Airbus A320neo



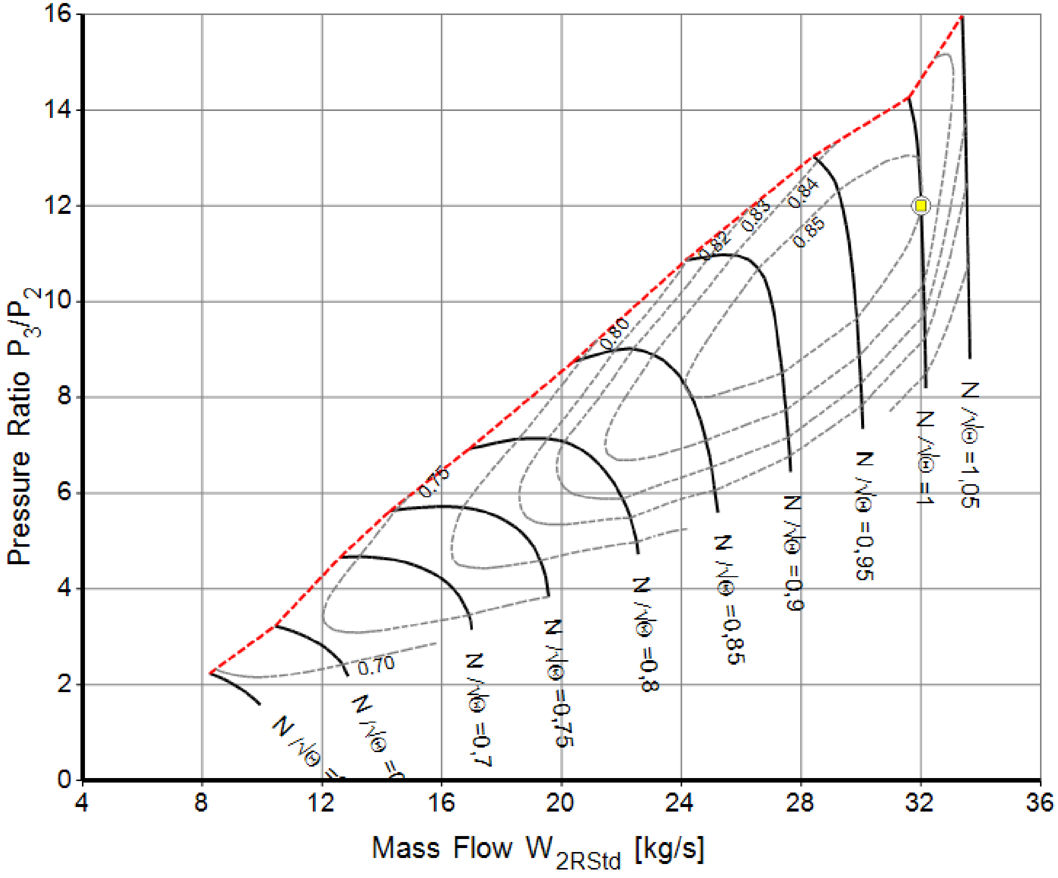
Outline

- Fundamentals
- Ideal Cycles
- Thermal Efficiency
- Power Generation
- Aircraft Propulsion
- Fundamental Design Decisions
- **Non-Dimensionals**
- Turbojet Off-Design

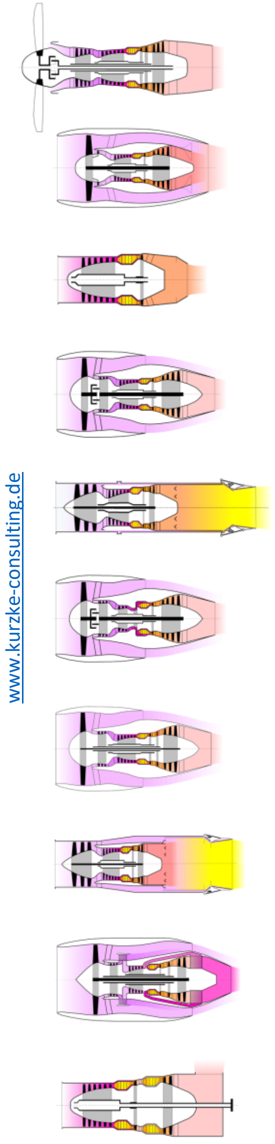




Compressor Map



www.kurzke-consulting.de



Parameters in a Compressor Map
Mach Numbers

$$Mn_{ax} = \frac{V_{ax}}{a} = \frac{W}{A * \rho * \sqrt{\gamma * R * T_s}}$$

$$= \frac{W * R * T_s}{A * P_s * \sqrt{\gamma * R * T_s}}$$

$$= \frac{W * \sqrt{\frac{R}{\gamma} T} * \sqrt{\frac{T_s}{T}}}{A * P * \frac{P_s}{P}}$$

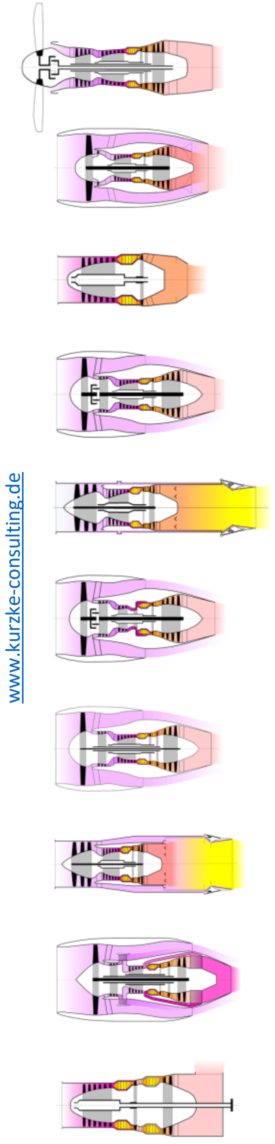
$$\frac{W * \sqrt{R * T}}{A * P} = f(\gamma, Mn_{ax})$$

$$W_{2R,std} = \frac{W * \sqrt{\Theta}}{\delta} = \frac{W * \sqrt{\frac{T_2}{288.15K}}}{\frac{P_2}{101.325kPa}}$$

$$Mn_u = \frac{u}{a} = \frac{const * N}{\sqrt{\gamma * R * T_s}} = \frac{const * N}{\sqrt{\gamma * R * T} * \sqrt{\frac{T_s}{T}}}$$

$$\frac{N}{\sqrt{T}} = f(\gamma, Mn_u)$$

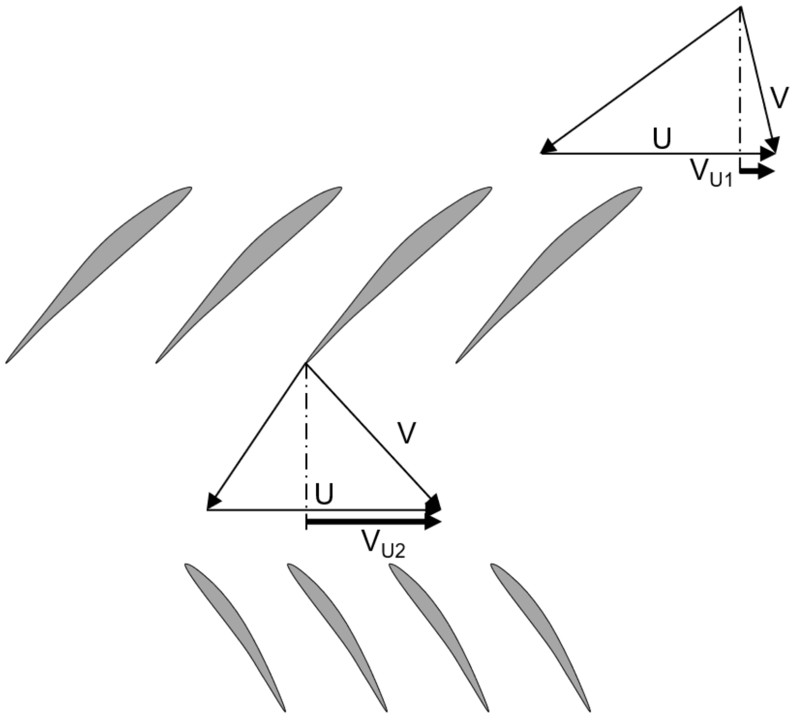
$$\frac{N}{\sqrt{\Theta}} = \frac{N}{\sqrt{\frac{T}{288.15K}}}$$



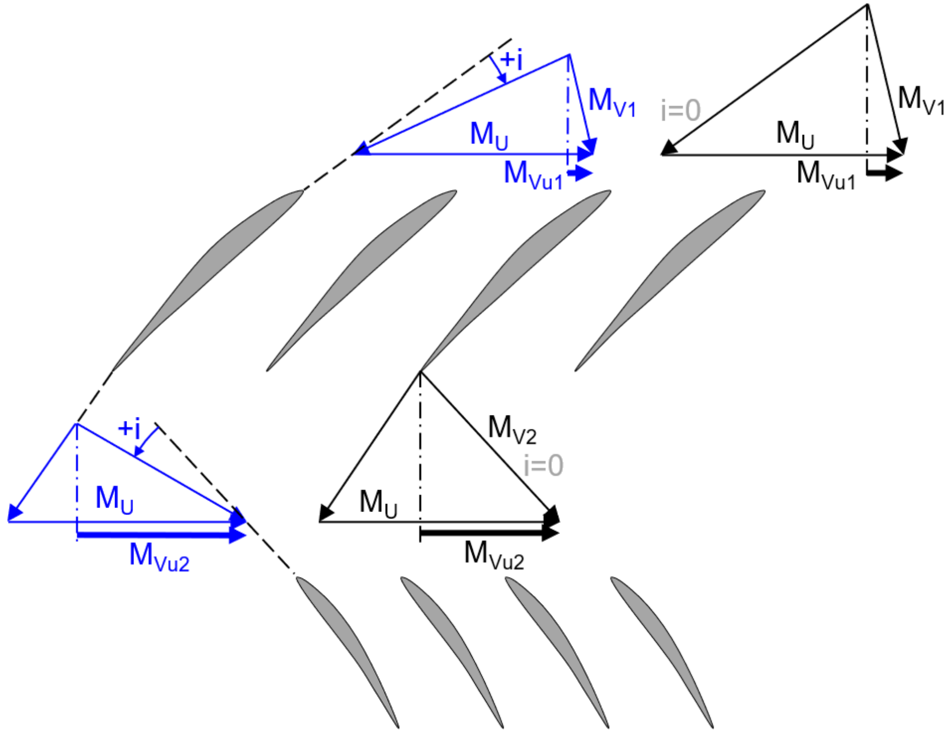
www.kurzke-consulting.de

Non-Dimensionals

Velocity Triangles of a Compressor Stage



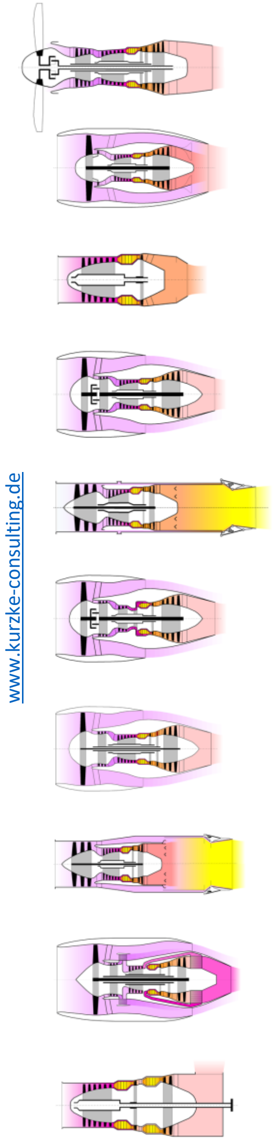
True velocities



Mach numbers

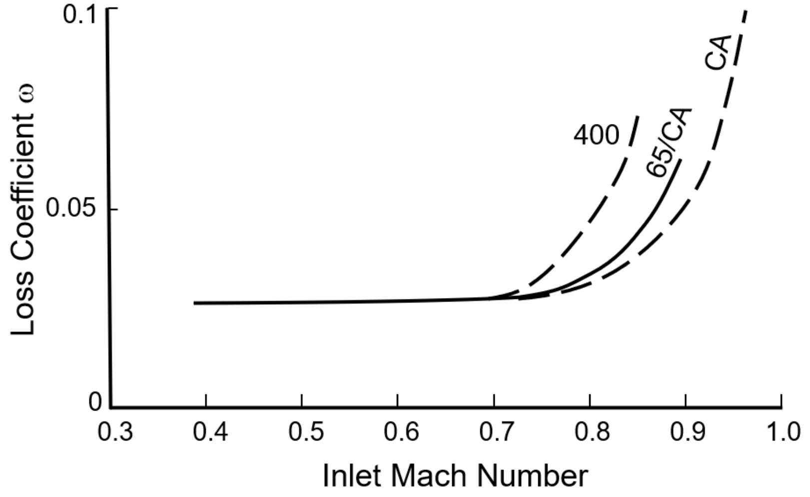
Work done:

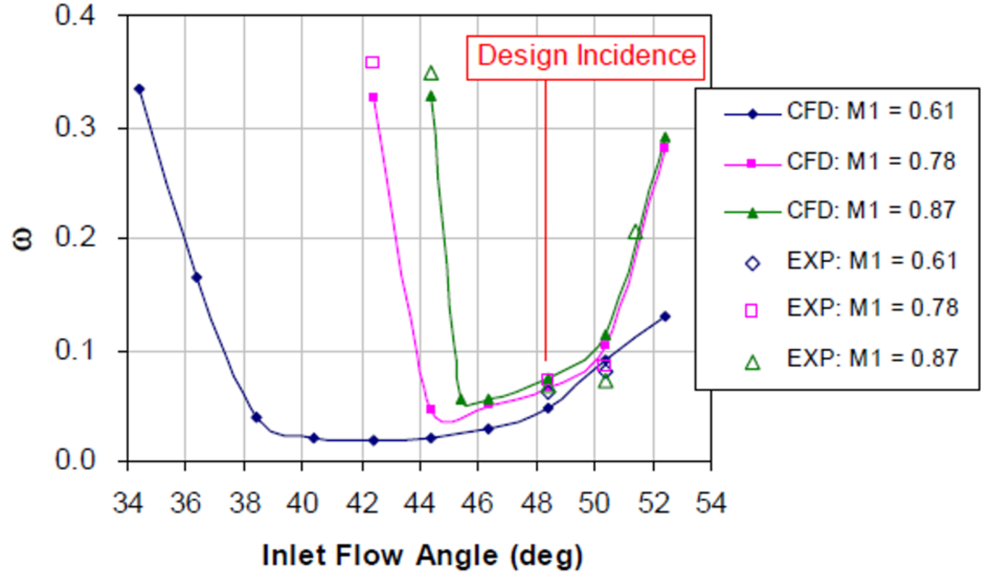
$$\Delta H = U \times (V_{u2} - V_{u1})$$



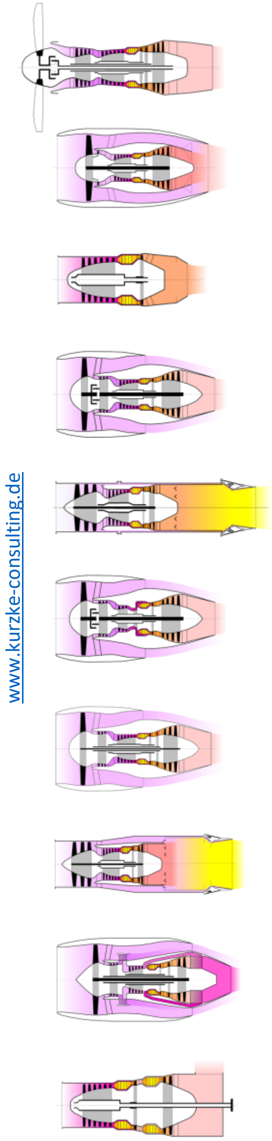
Non-Dimensionals

Cascade Losses





Engine Parameters



www.kurzke-consulting.de

- Spool Speed

$$N_{corr} = \frac{N}{\sqrt{T}} \qquad N_{corr} = \frac{N}{\sqrt{\Theta}}$$

- Mass Flow

$$W_{corr} = \frac{W * \sqrt{T}}{P} \qquad W_{corr} = \frac{W * \sqrt{\Theta}}{\delta}$$

- Power

$$PW_{corr} = \frac{PW}{\sqrt{T} * P} \qquad PW_{corr} = \frac{PW}{\sqrt{\Theta} * \delta}$$

- Fuel Flow

$$WF_{corr} = \frac{WF}{\sqrt{T} * P} \qquad WF_{corr} = \frac{WF}{\sqrt{\Theta} * \delta}$$

- Thrust

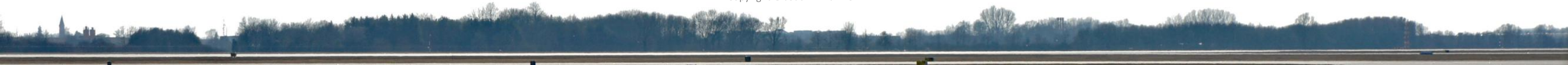
$$F_{corr} = \frac{F}{P} \qquad F_{corr} = \frac{F}{\delta}$$

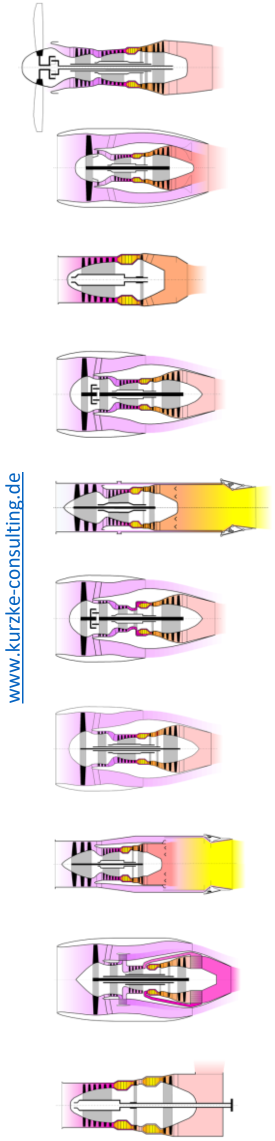
- SFC

$$SFC_{corr} = \frac{SFC}{\sqrt{T}} \qquad SFC_{corr} = \frac{SFC}{\sqrt{\Theta}}$$

$\Theta = T/288.15K$

$\delta = P/101.325\ kPa$

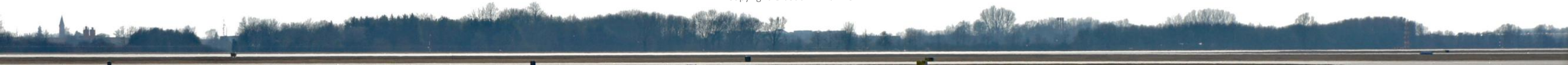




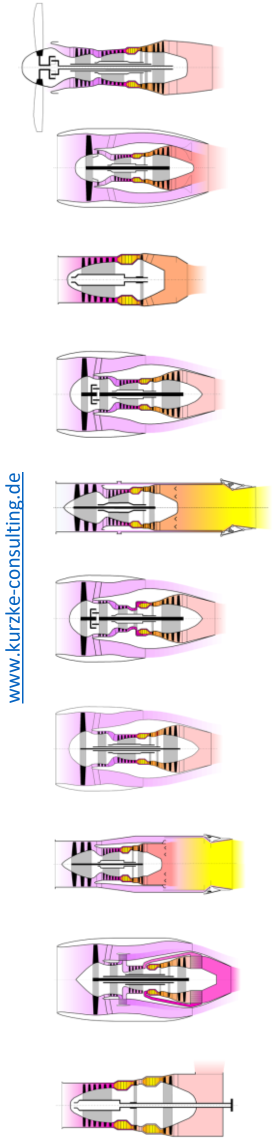
www.kurzke-consulting.de

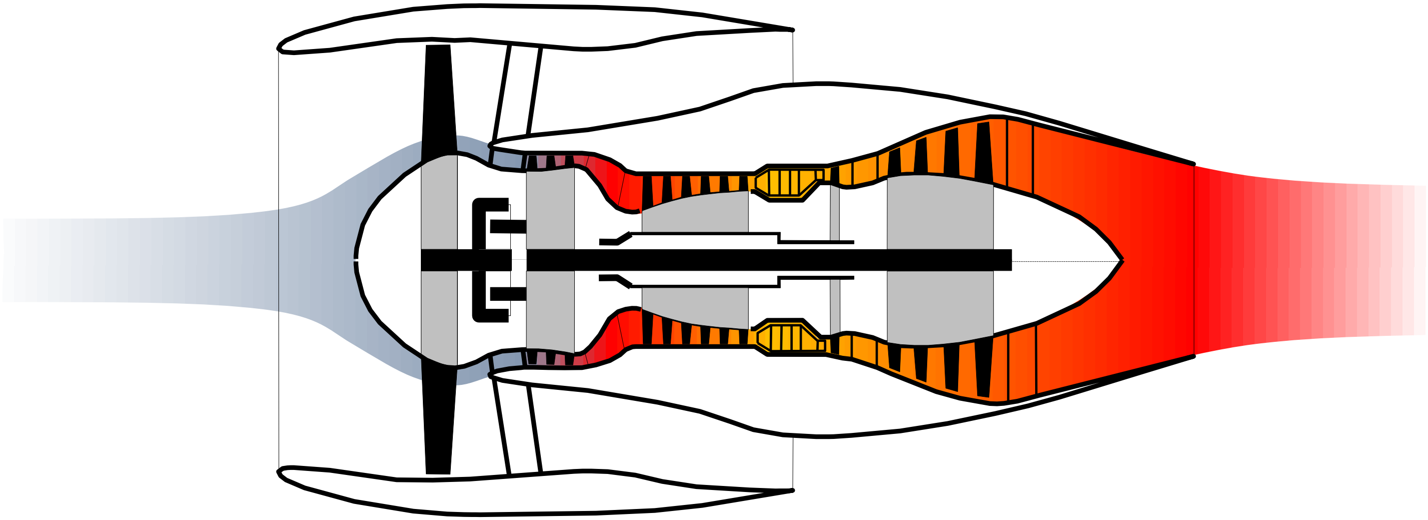
Outline

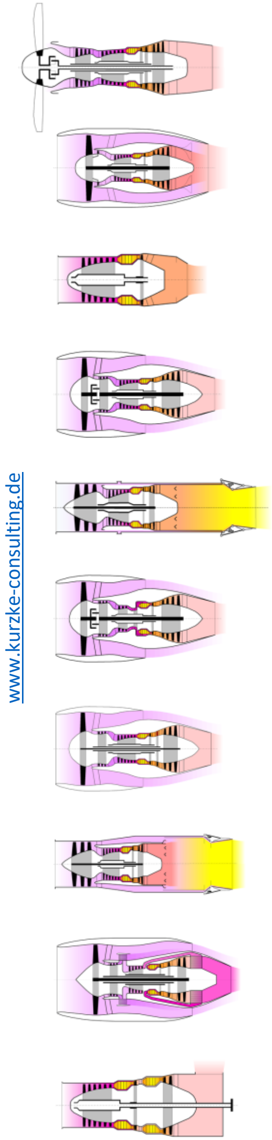
- Fundamentals
- Ideal Cycles
- Thermal Efficiency
- Power Generation
- Aircraft Propulsion
- Fundamental Design Decisions
- Non-Dimensionals
- **Turbojet Off-Design**



A Simple Gas Turbine Cycle is the Heart of Any Turbofan

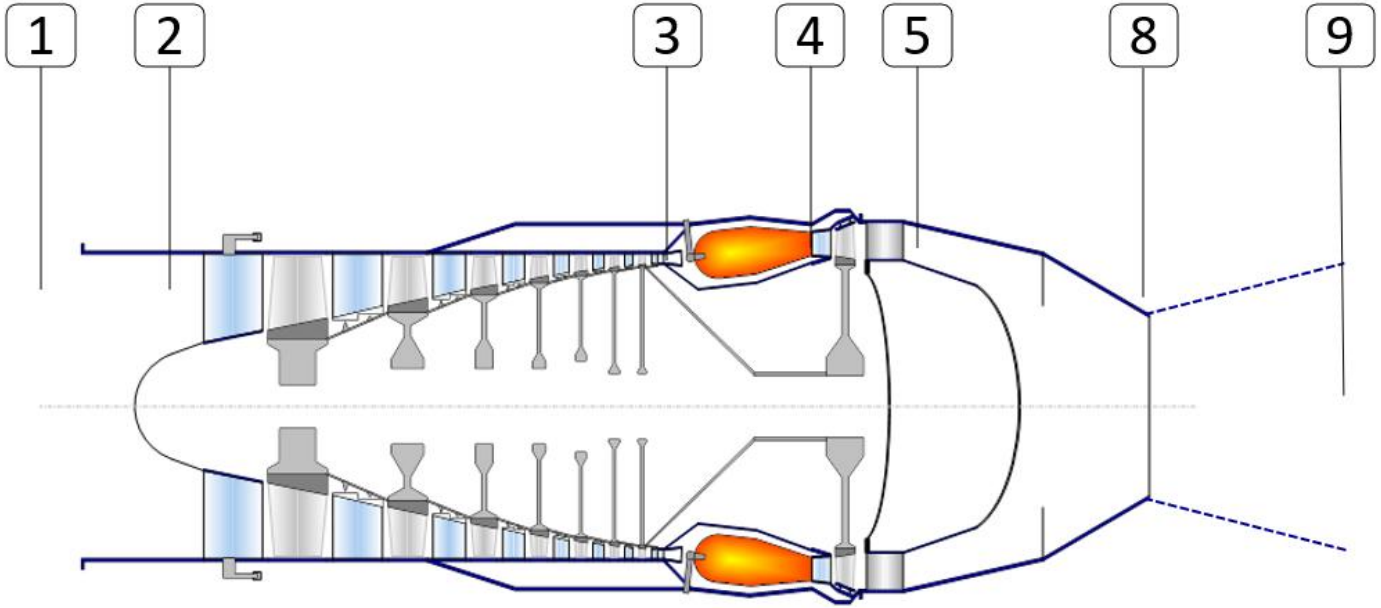




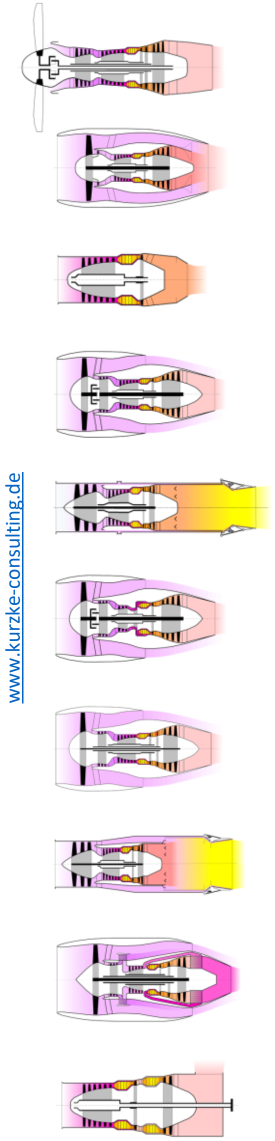


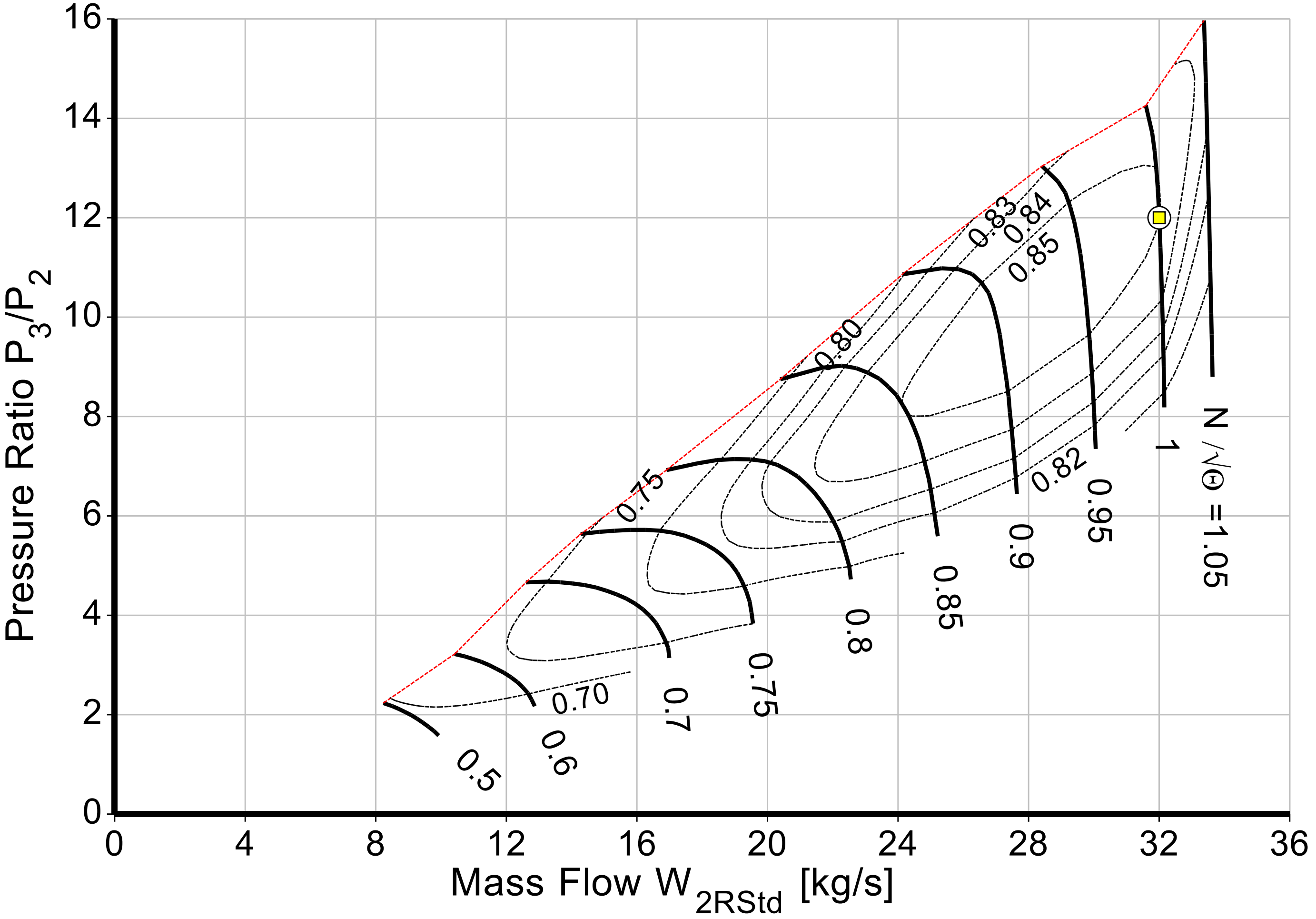
www.kurzke-consulting.de

Turbojet Off-Design
Nomenclature

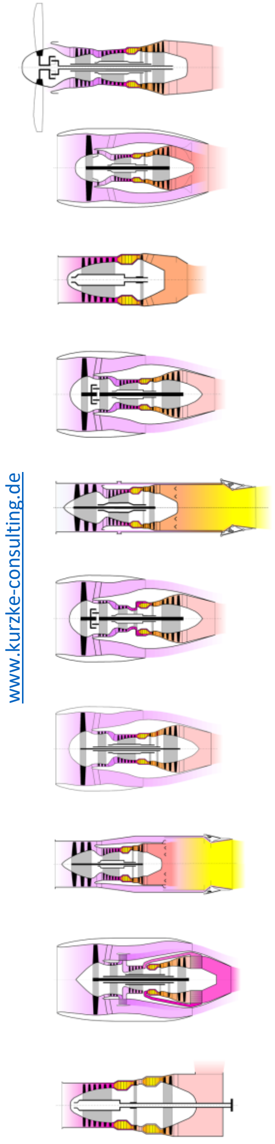


Turbojet Off-Design
Compressor Map

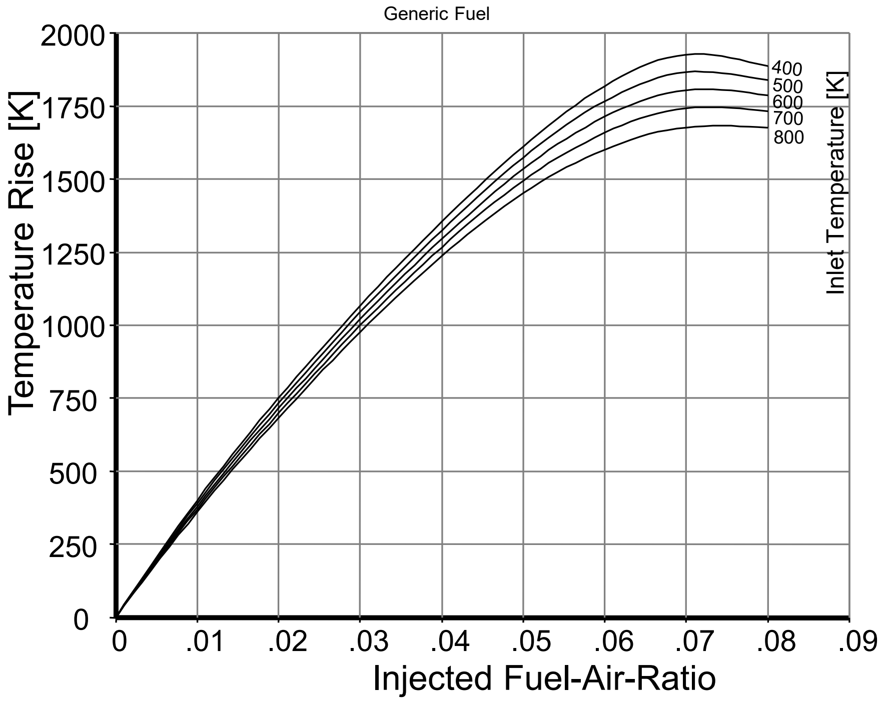


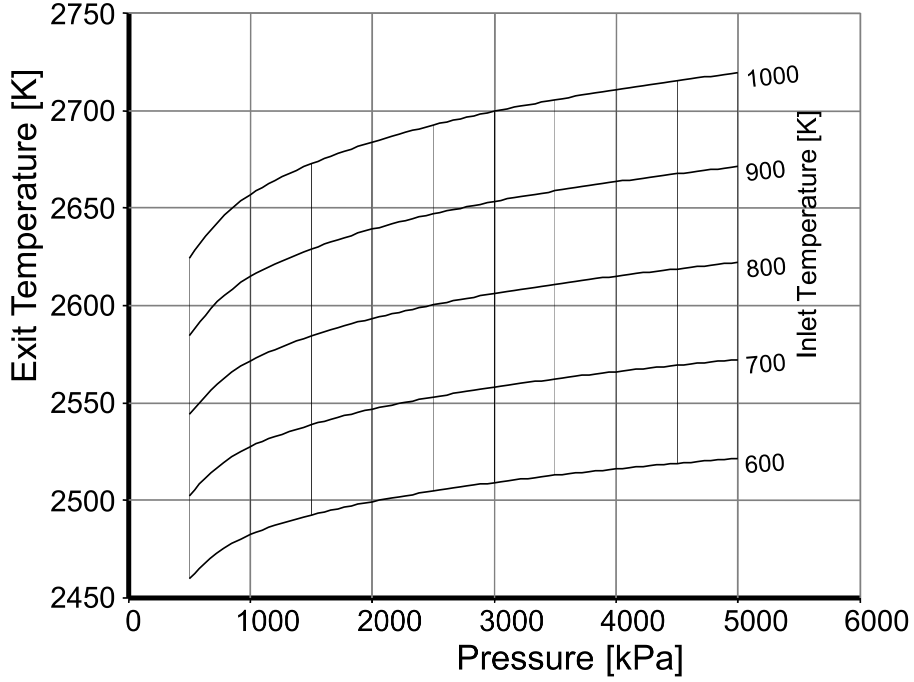


www.kurzke-consulting.de



Turbojet Off-Design
Combustor

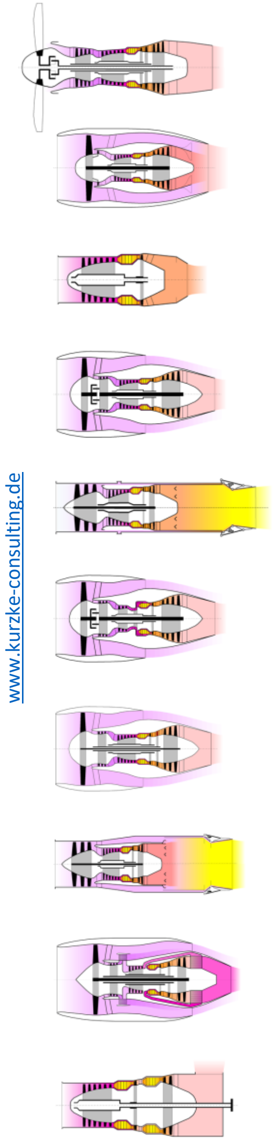


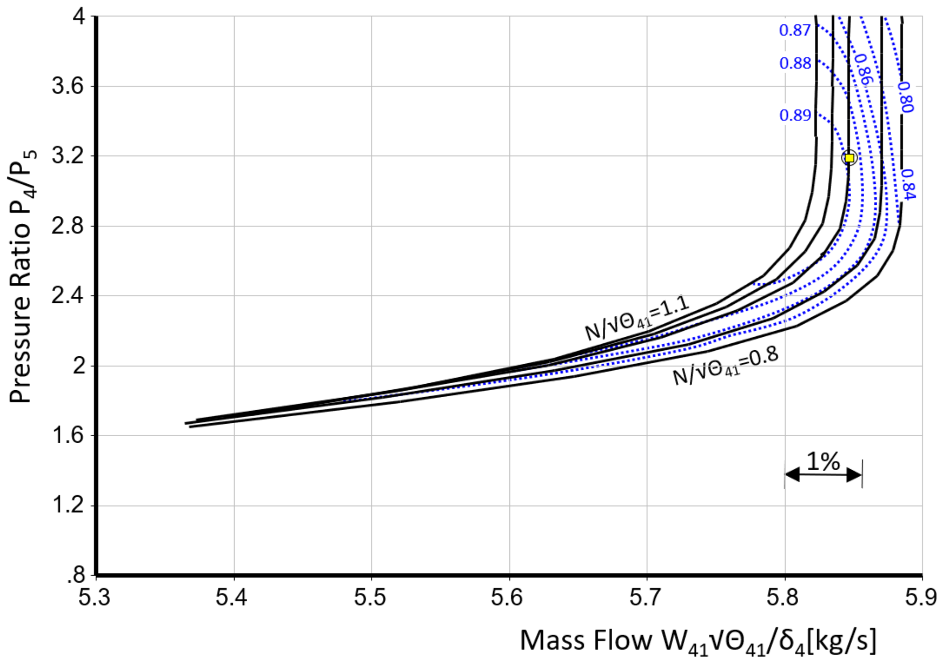


Chemical equilibrium - ideal temperature rise for a generic hydrocarbon fuel

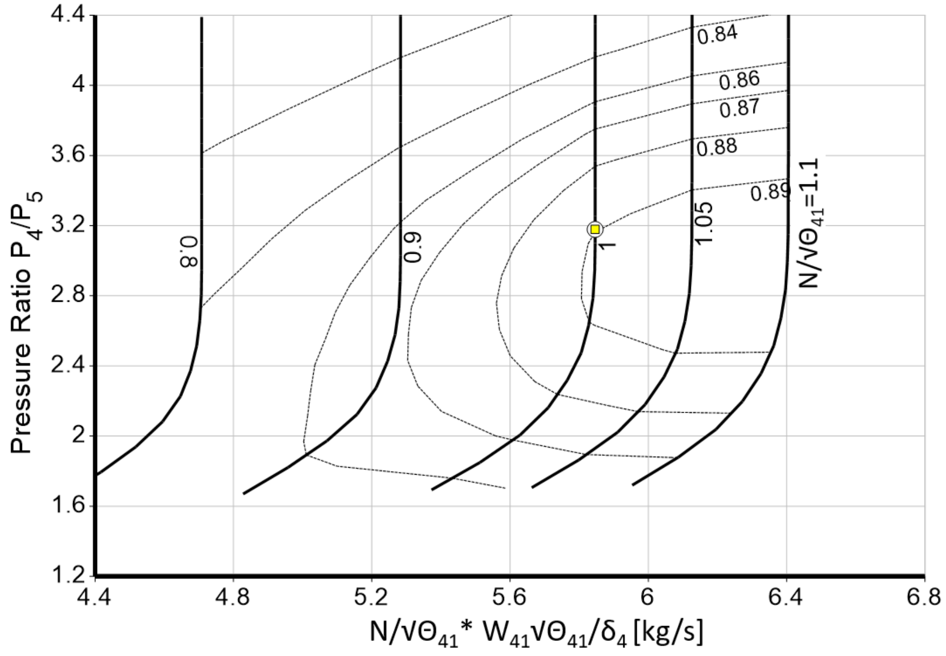
Turbojet Off-Design

Turbine Map





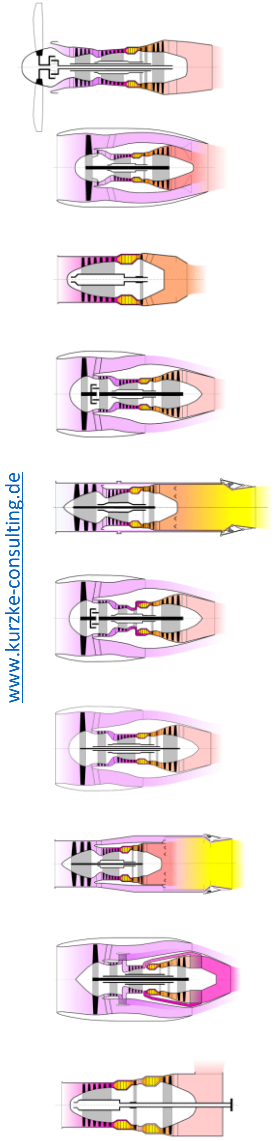
Compressor Map Format

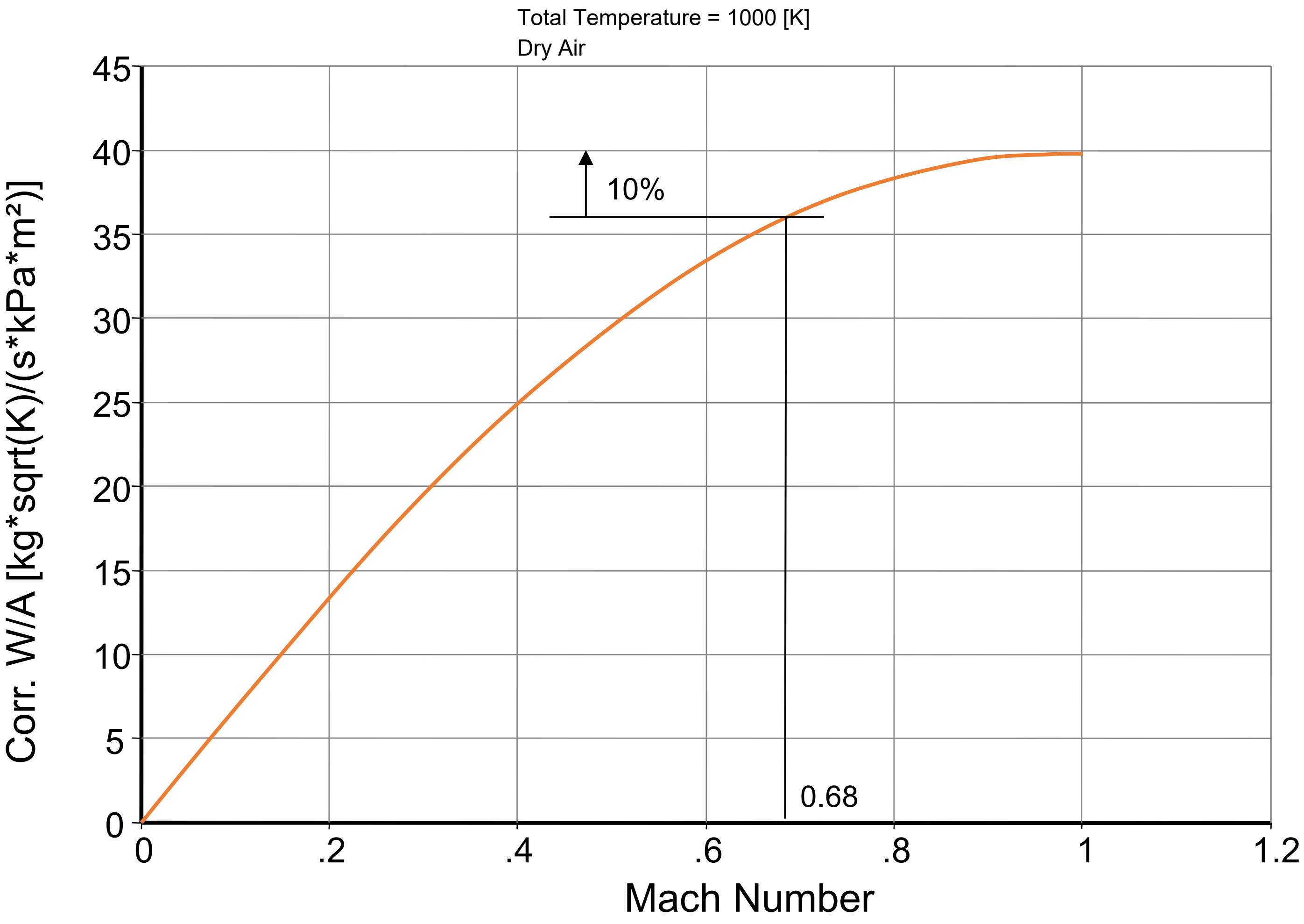


Turbine Map Format

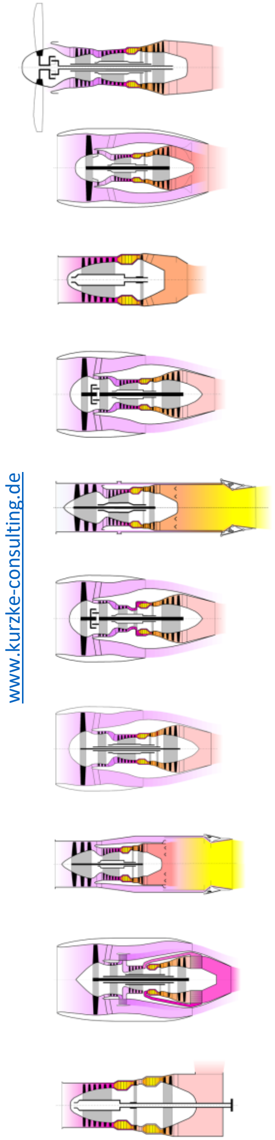
Turbojet Off-Design

Corrected Flow Through a Nozzle





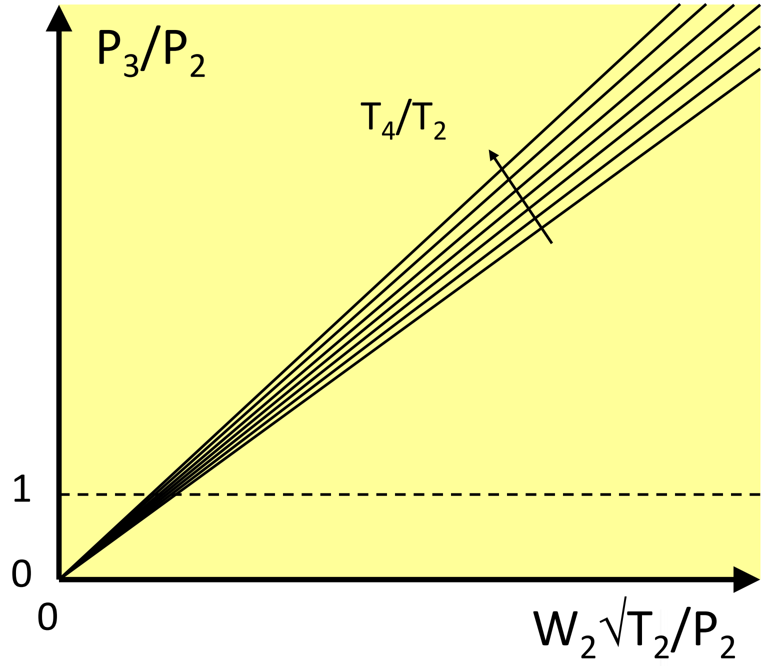
Flow Conservation Between Compressor and Turbine



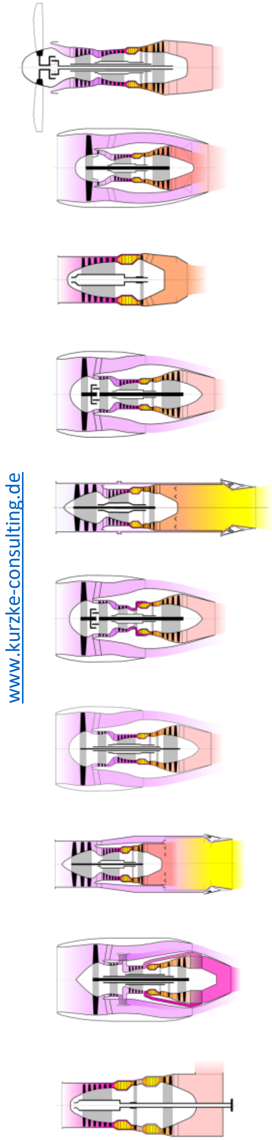
$$\frac{W_2 * \sqrt{T_2}}{P_2} = \boxed{\frac{W_4 * \sqrt{T_4}}{A_4 * P_4} * A_4} * \boxed{\frac{P_4}{P_3}} * \boxed{\frac{W_2}{W_4}} * \frac{P_3}{P_2} * \sqrt{\frac{T_2}{T_4}}$$

$$\frac{P_3}{P_2} = \boxed{const_A} * \frac{W_2 * \sqrt{T_2}}{P_2} * \sqrt{\frac{T_4}{T_2}}$$

Lines with constant T_4/T_2 in the compressor map



Flow Conservation Between Turbine and Nozzle



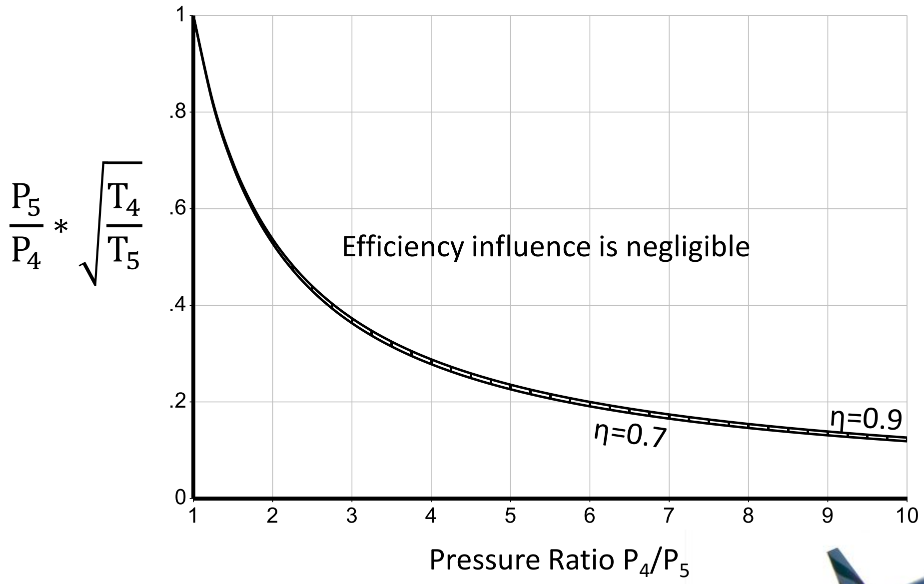
$$\frac{W_4 * \sqrt{T_4}}{A_4 * P_4} = \frac{W_8 * \sqrt{T_8}}{A_8 * P_8} * \frac{W_4}{W_8} * \frac{A_8}{A_4} * \frac{P_8}{P_5} * \sqrt{\frac{T_5}{T_8}} * \frac{P_5}{P_4} * \sqrt{\frac{T_4}{T_5}}$$

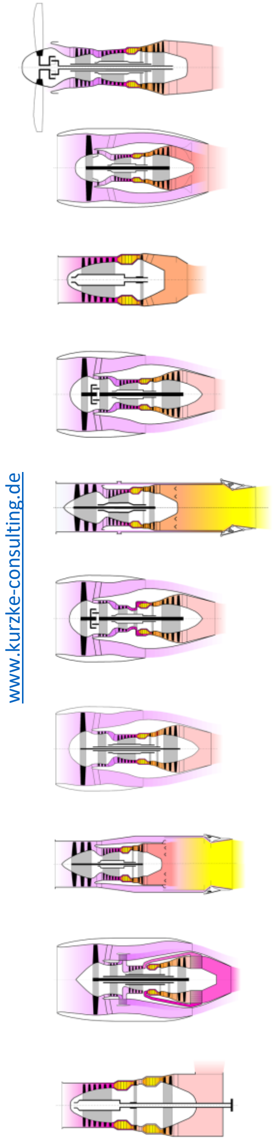
← $f(P_4/P_5,\eta)$

$const_C$

Turbine pressure ratio P_4/P_5 = const

Not affected by power offtake PW_x





www.kurzke-consulting.de

Turbojet Off-Design

Power Balance Between Compressor and Turbine

$$PW_T = PW_C \qquad + PW_{Loss} + PW_{Offtake}$$

$$W_2 * H_C = W_4 * H_T$$

with PW_{Loss} =0 and $PW_{Offtake}$ = 0

$$H_{is,C}/\eta_C = H_{is,T} * \eta_T$$

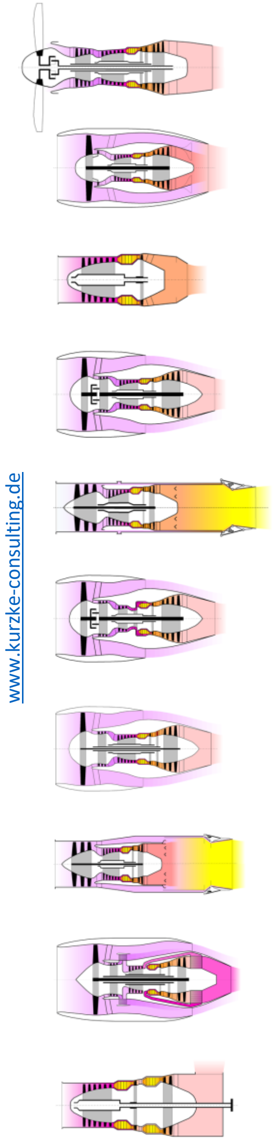
Simplified: $W_4 = W_2$

Mass flow continuity between turbine and nozzle yields constant P_4/P_5

$$H_{is,C} = c_{p,C} * T_2 * \left[\left(\frac{P_3}{P_2}\right)^{R/c_{p,C}} - 1\right]$$

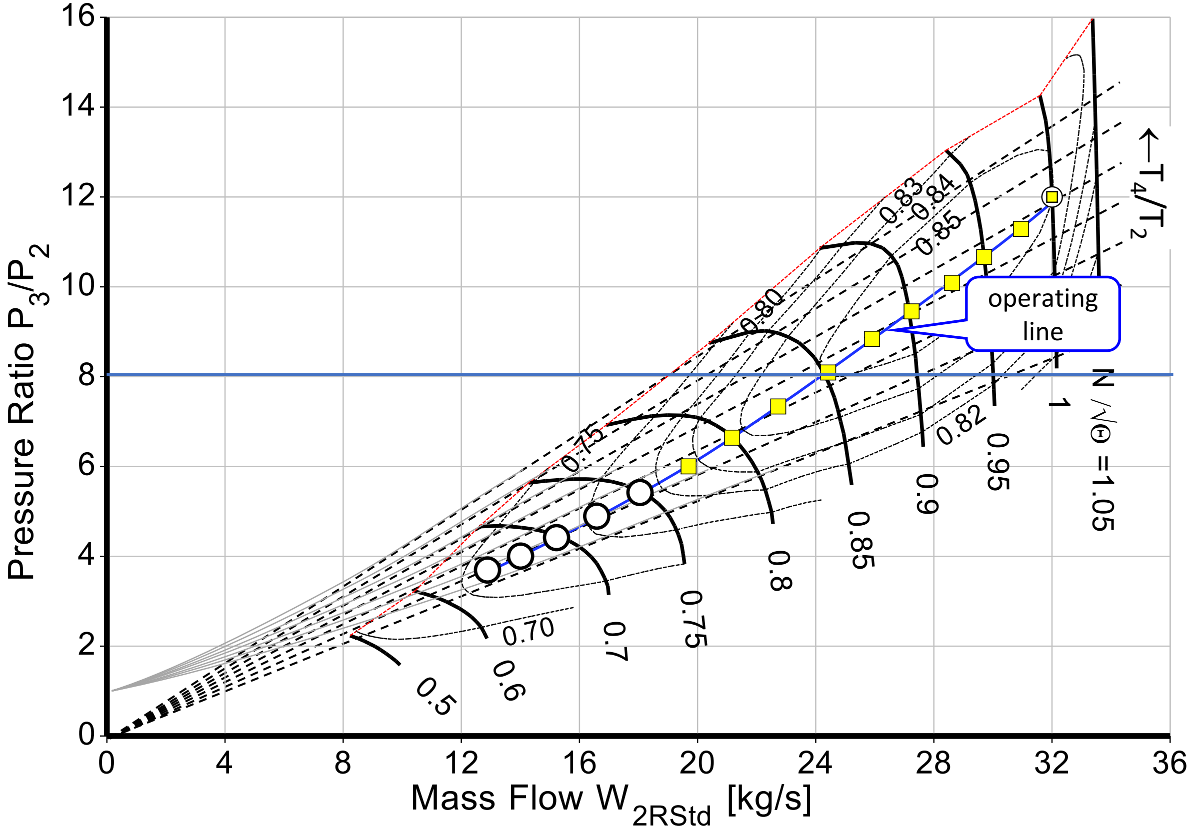
$$H_{is,T} = c_{p,T} * T_4 * \left[1 - \left(\frac{P_5}{P_4}\right)^{R/c_{p,T}}\right]$$

$$\frac{H_{is,C}}{T_2} = c_{p,C} * \left[\left(\frac{P_3}{P_2}\right)^{R/c_{p,C}} - 1\right] = \frac{T_4}{T_2} * \eta_C * \eta_T * const_{P_4/P_5}$$



Turbojet Off-Design

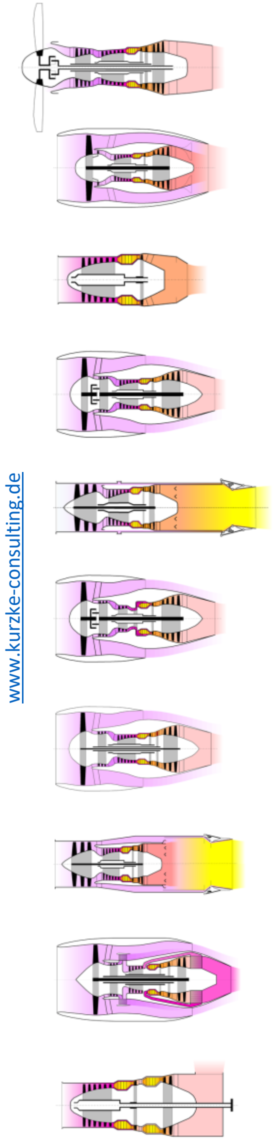
Compressor Operating Line



From previous slide:

$$c_{p,C} * \left[\left(\frac{P_3}{P_2}\right)^{\frac{R}{c_{p,C}}} - 1\right] =$$

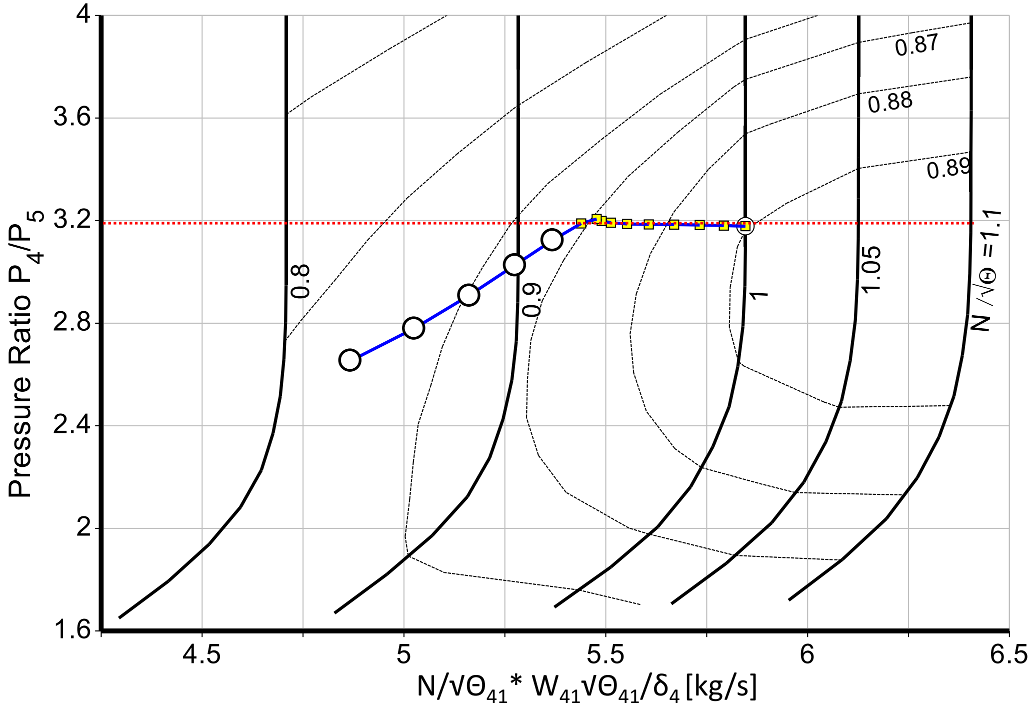
$$\frac{T_4}{T_2} * \eta_C * \eta_T * const_{P_4/P_5}$$

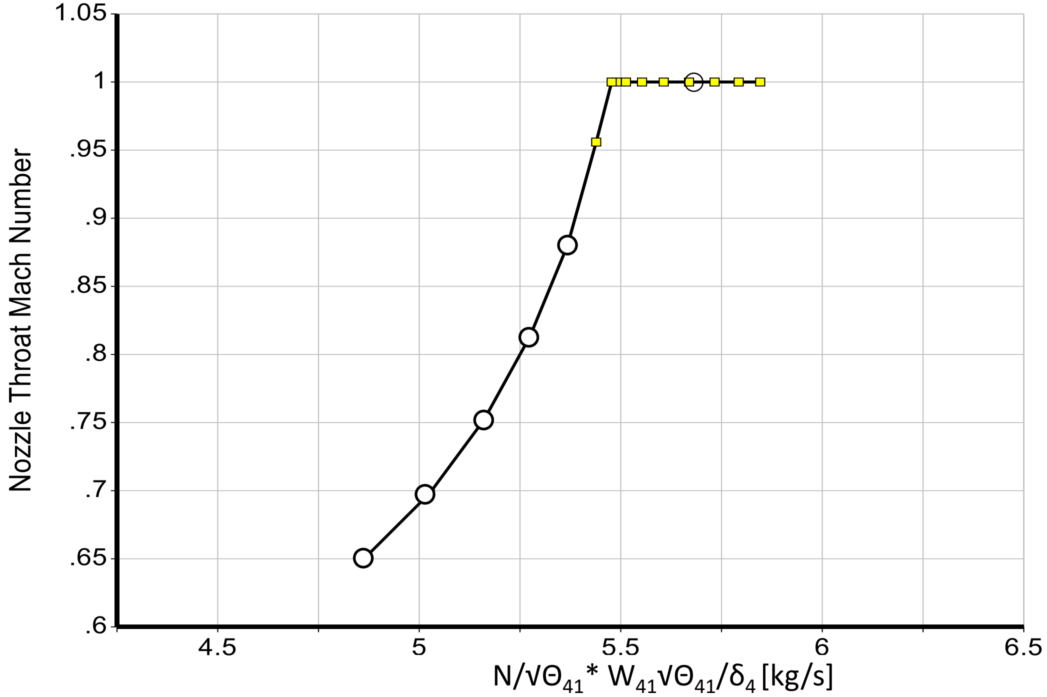


www.kurzke-consulting.de

Turbojet Off-Design

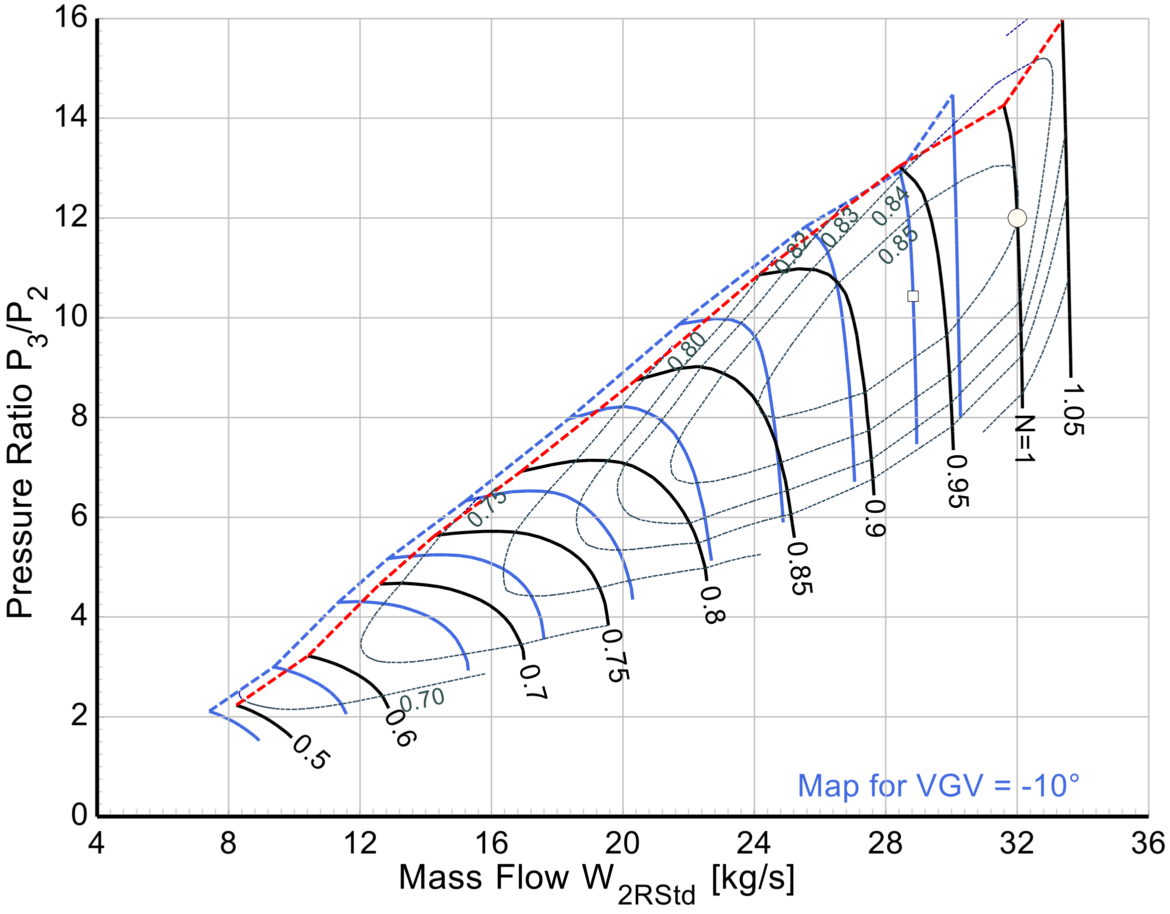
Turbine Operating Line and Nozzle Mach Number





Turbojet Off-Design

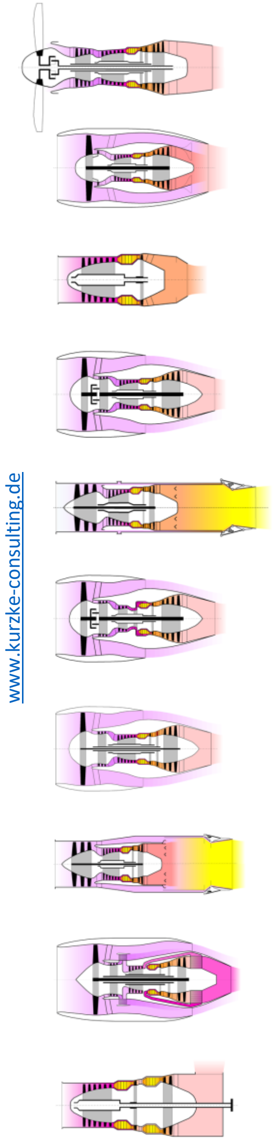
Effect of -10°VGV Setting

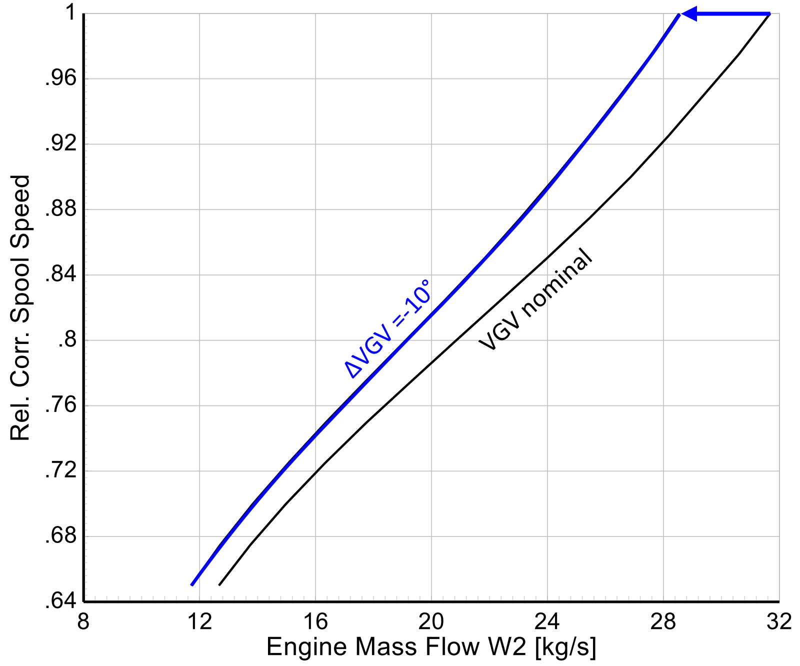


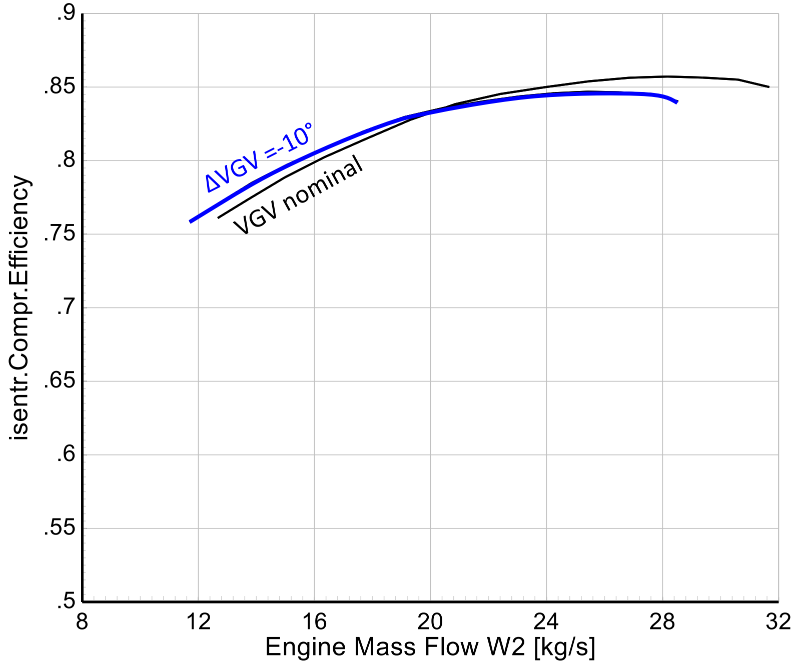
www.kurzke-consulting.de

Turbojet Off-Design

Effect of -10°VGV Setting on Flow and Efficiency

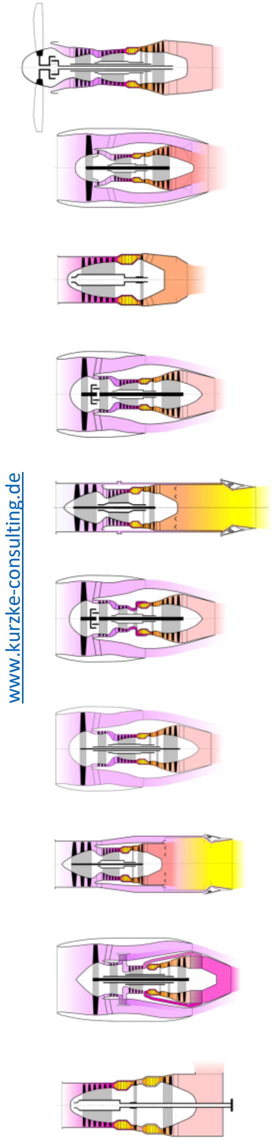


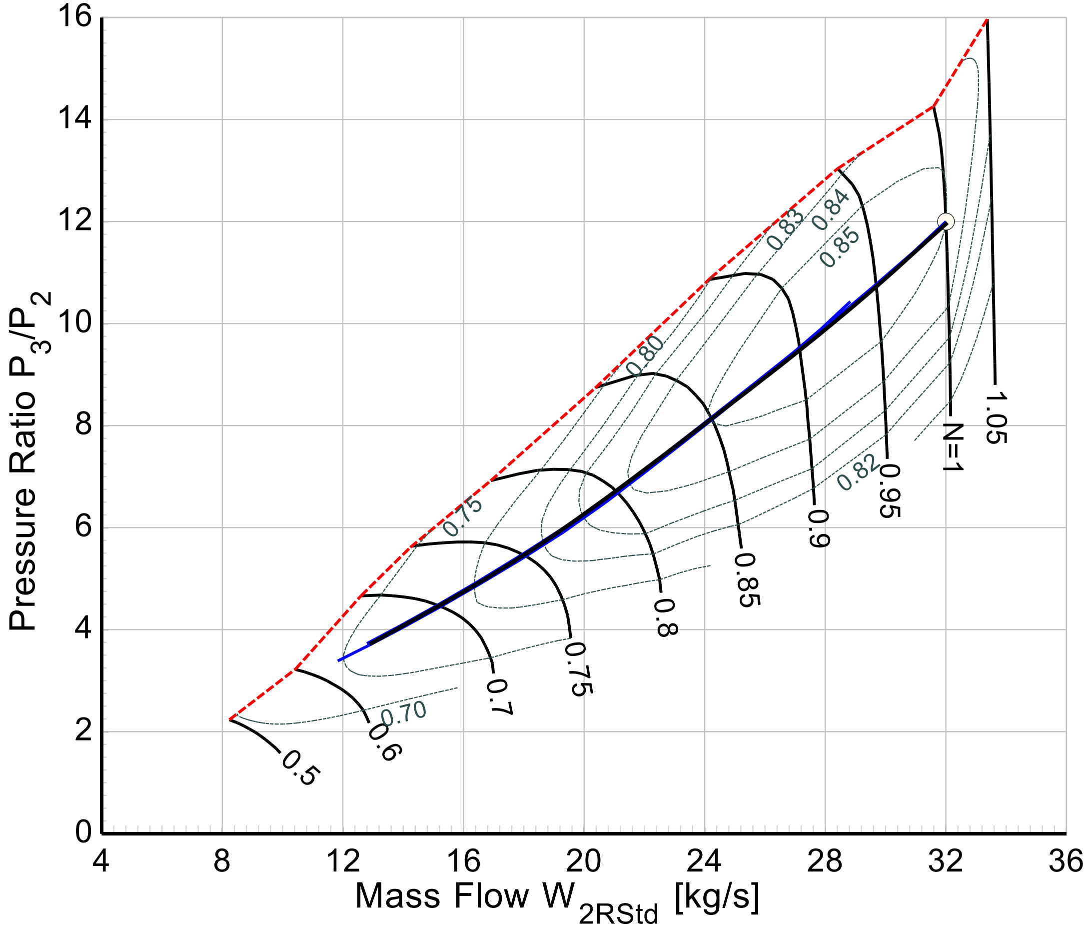


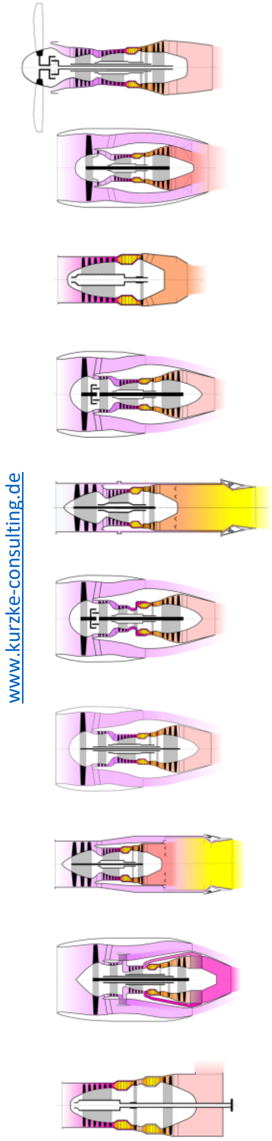


www.kurzke-consulting.de

Effect of -10°VGV Setting on Operating Line







Question

Station	W kg/s	T K	P kPa	WRstd kg/s
amb		288,15	101,325	
1	31,680	288,15	101,325	
2	31,680	288,15	100,312	32,000
3	31,680	630,42	1203,741	3,944
31	28,195	630,42	1203,741	
4	28,857	1450,00	1167,629	5,617
41	30,441	1411,20	1167,629	5,846
49	30,441	1113,50	367,374	
5	32,025	1091,37	367,374	17,190
6	32,025	1091,37	360,027	
8	32,025	1091,37	360,027	17,541
Bleed	0,317	630,42	1203,738	

P2/P1 = 0,9900 P4/P3 = 0,9700 P6/P5 0,9800

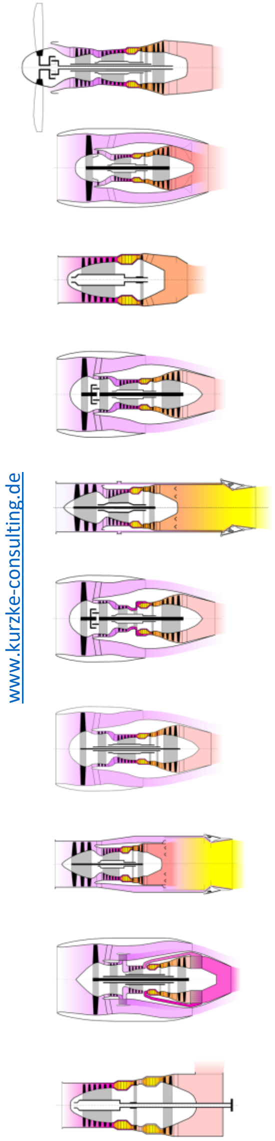
Efficiencies:	isentr	polytr	RNI	P/P
Compressor	0,8500	0,8913	0,990	12,000
Burner	0,9999			0,970
Turbine	0,8900	0,8757	1,798	3,178

Spool mech Eff 0,9999 Nom Spd 14284 rpm

FN	=	26,37 kN
TSFC	=	25,0985 g/(kN*s)
FN/W2	=	832,50 m/s
Prop Eff	=	0,0000
eta core	=	0,3884
WF	=	0,66194 kg/s
s NOx	=	0,28659
XM8	=	1,0000
A8	=	0,0773 m²
P8/Pamb	=	3,5532
WBld/W2	=	0,01000
Ang8	=	20,00 °
CD8	=	0,9600
W_NGV/W2	=	0,05000
WCL/W2	=	0,05000
Loading	=	100,00 %
e45 th	=	0,87139
far7	=	0,02111
PWX	=	0,00 kW

This turbojet has a thrust of FN=26,37 kN
How many kilowatt is that?

Answer



www.kurzke-consulting.de

Station	W kg/s	T K	P kPa	WRstd kg/s
amb		288,15	101,325	
1	31,680	288,15	101,325	
2	31,680	288,15	100,312	32,000
3	31,680	630,42	1203,741	3,944
31	28,195	630,42	1203,741	
4	28,857	1450,00	1167,629	5,617
41	30,441	1411,20	1167,629	5,846
49	30,441	858,96	103,499	
5	32,025	848,26	103,499	53,793
6	32,025	848,26	101,429	
8	32,025	848,26	101,429	54,891
Bleed	0,317	630,42	1203,738	

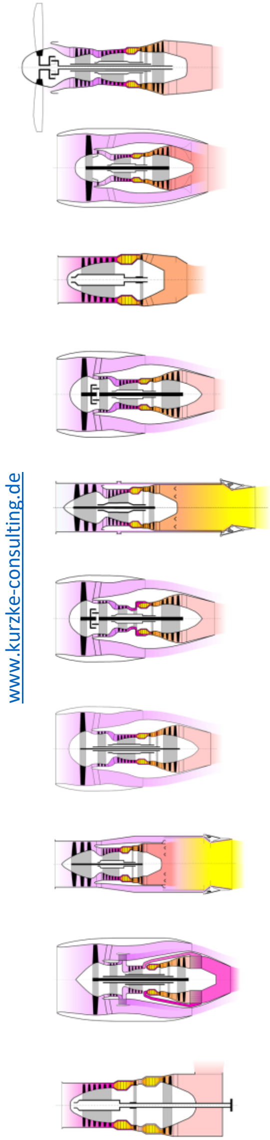
P2/P1 = 0,9900 P4/P3 = 0,9700 P6/P5 0,9800

Efficiencies:	isentr	polytr	RNI	P/P
Compressor	0,8500	0,8913	0,990	12,000
Burner	0,9999			0,970
Turbine	0,8900	0,8563	1,798	11,282

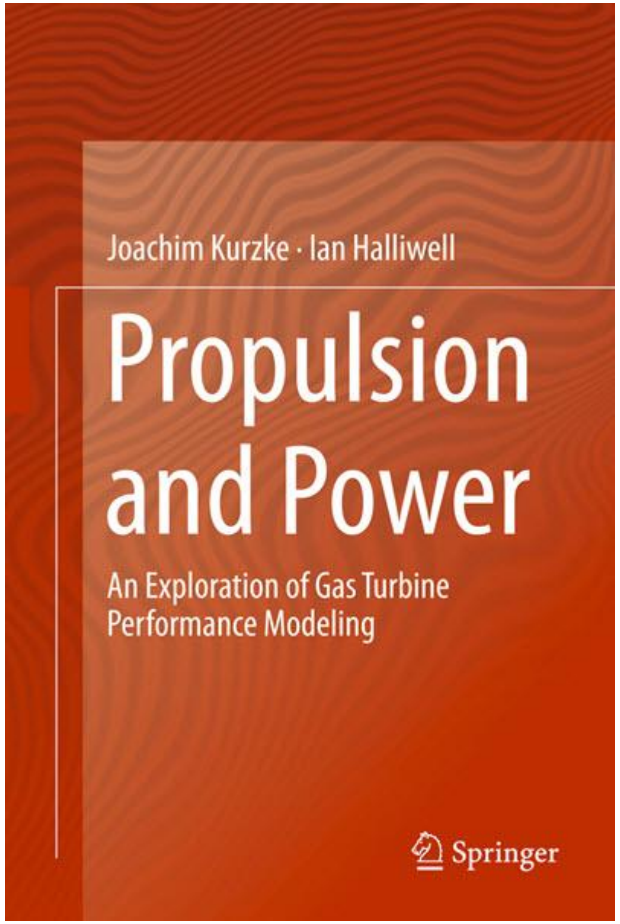
Spool mech Eff 0,9999 Nom Spd 14284 rpm

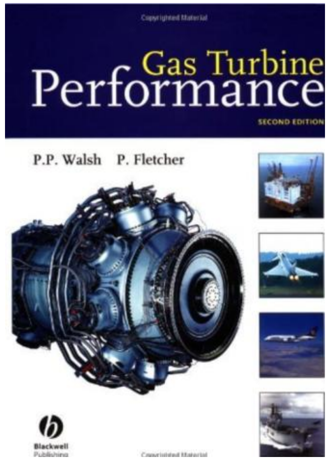
FN	=	0,72	kN
TSFC	=	299,0000	g/(kN*s)
FN/W2	=	22,57	m/s
Prop Eff	=	0,0000	
eta core	=	0,0058	
WF	=	0,66194	kg/s
s NOx	=	0,28659	
XM8	=	0,0392	
A8	=	4,0055	m²
P8/Pamb	=	1,0010	
WBld/W2	=	0,01000	
Ang8	=	20,00	°
CD8	=	0,8602	
W_NGV/W2	=	0,05000	
WCL/W2	=	0,05000	
Loading	=	100,00	%
e45 th	=	0,87201	
far7	=	0,02111	
PWX	=	9114,99	kW

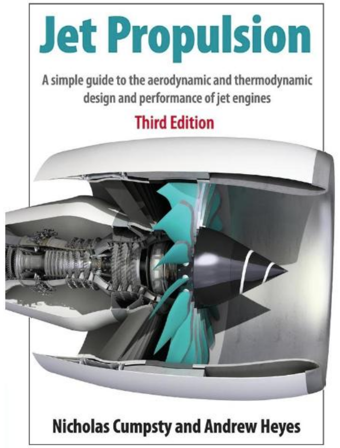
Books on my Bookshelf

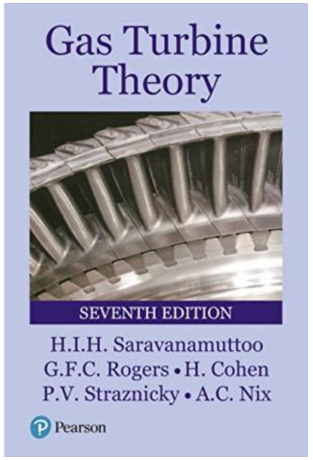


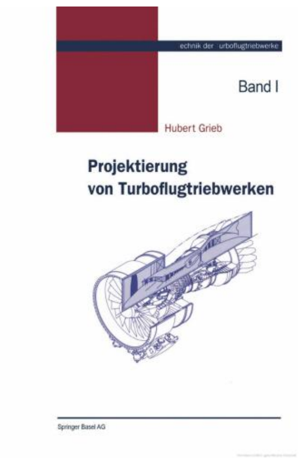
www.kurzke-consulting.de

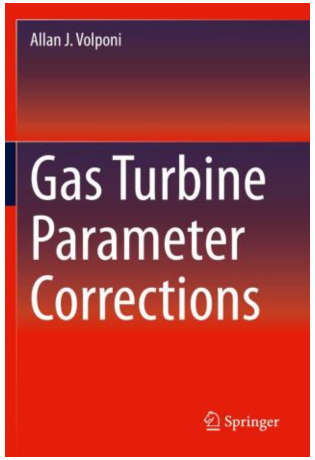




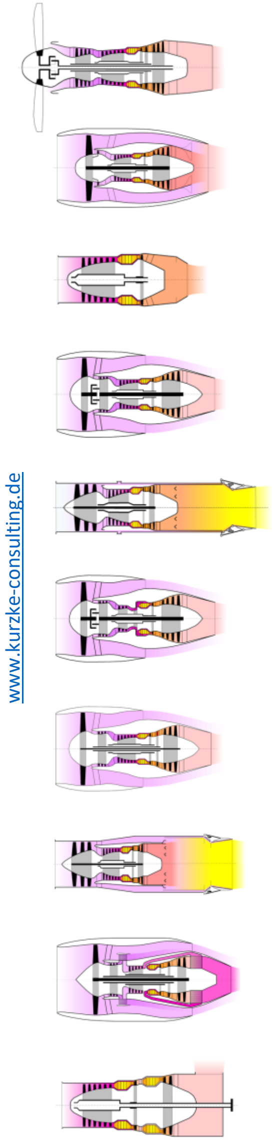




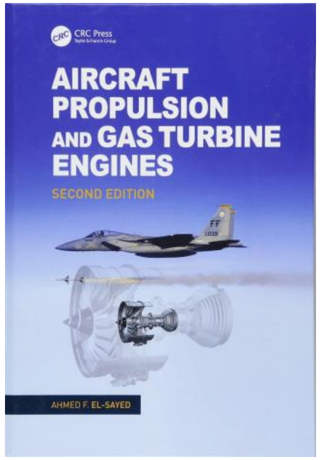


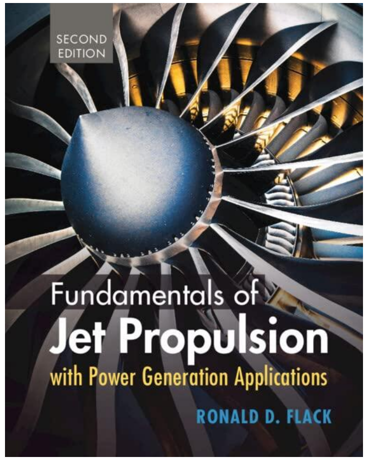


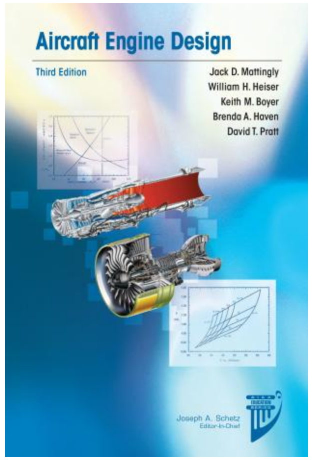
More …

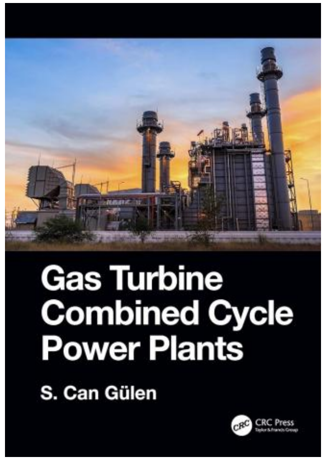


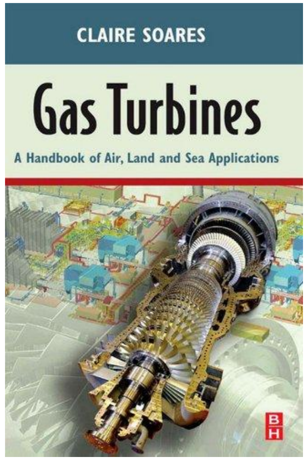
www.kurzke-consulting.de

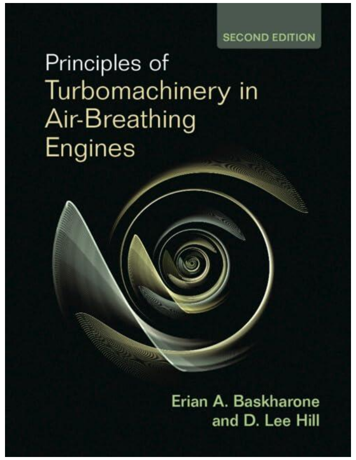


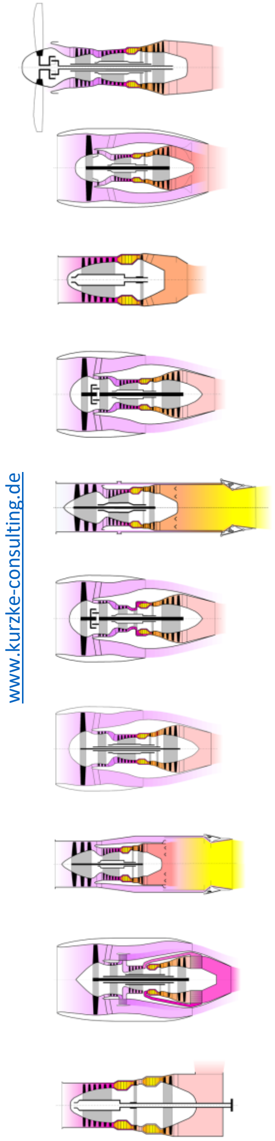






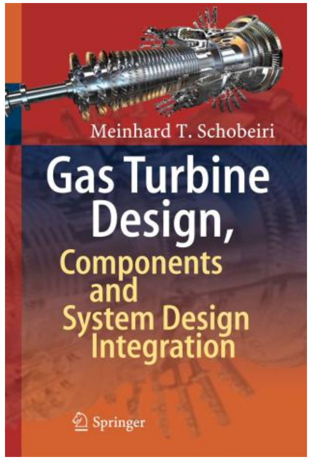


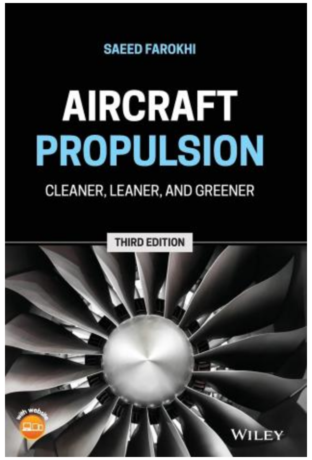


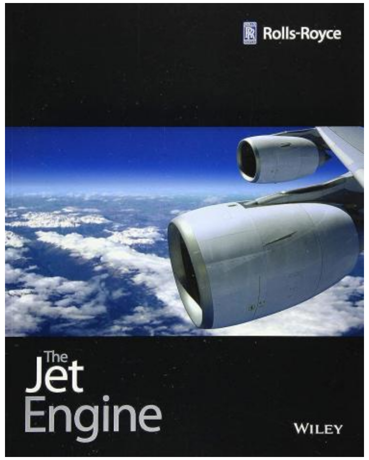


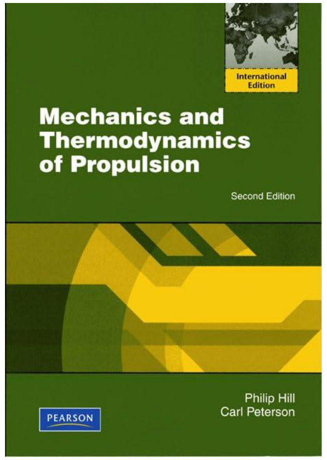
www.kurzke-consulting.de

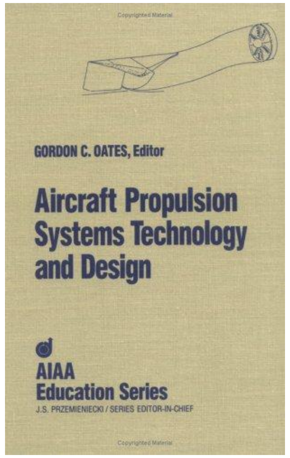
More …











And More …

www.kurzke-consulting.de