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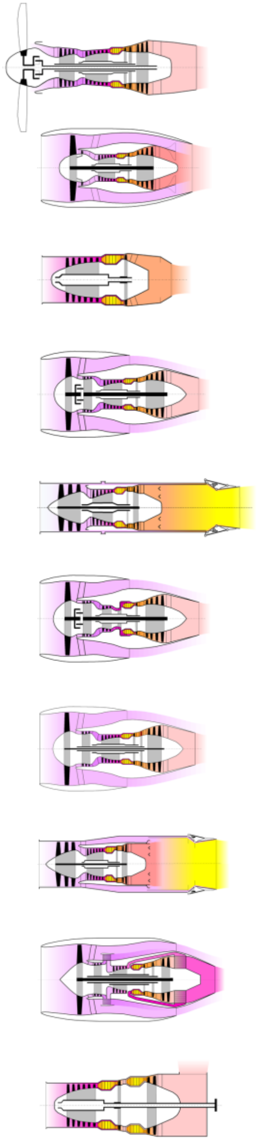

Basics of Gas Turbine Performance

Joachim Kurzke – the inventor of GasTurb
www.kurzke-consulting.de

Sustainable Aviation

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

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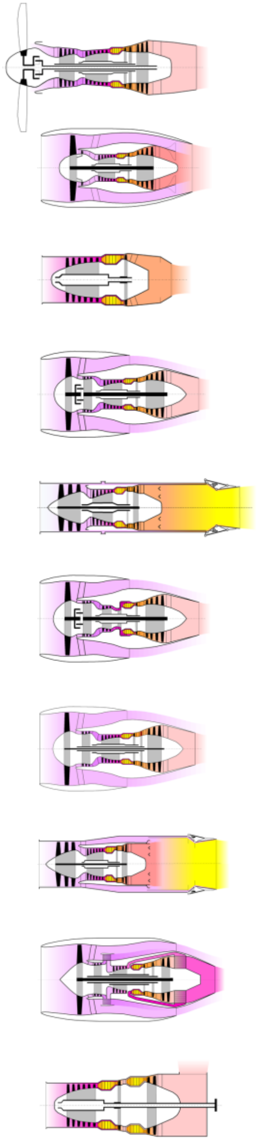

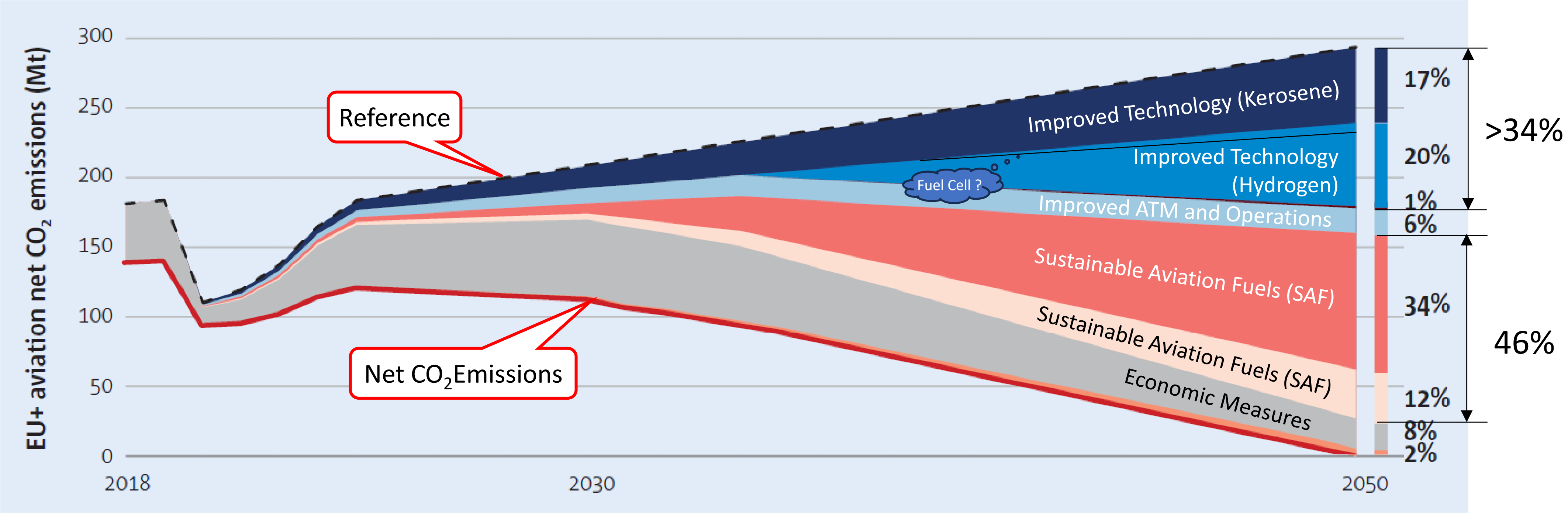

Gas Turbine Related → Σ= >80%

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

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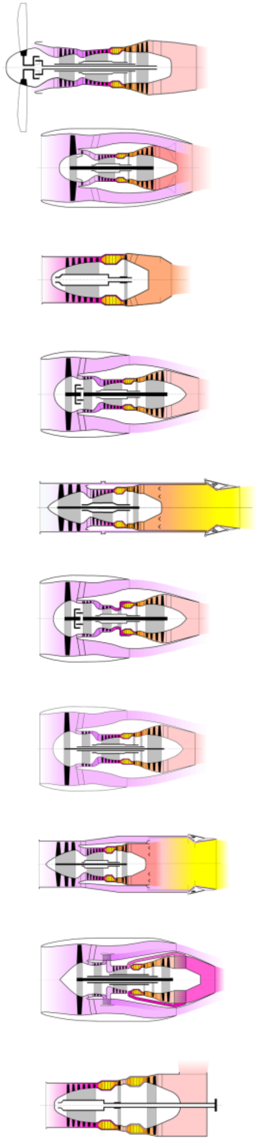
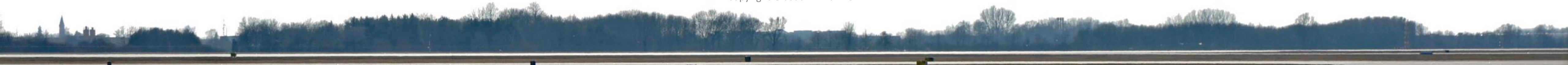


Outline

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



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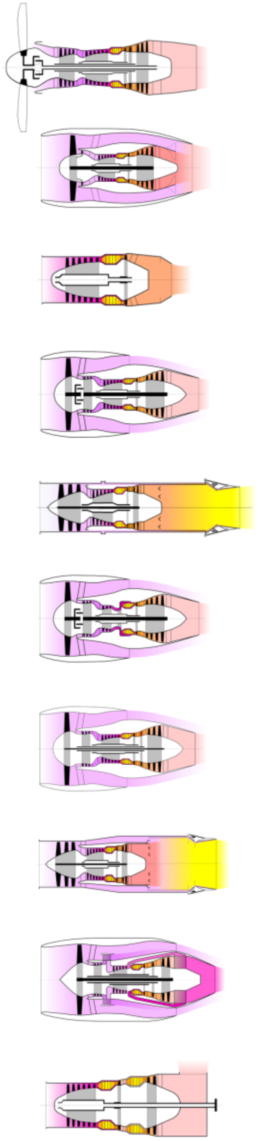
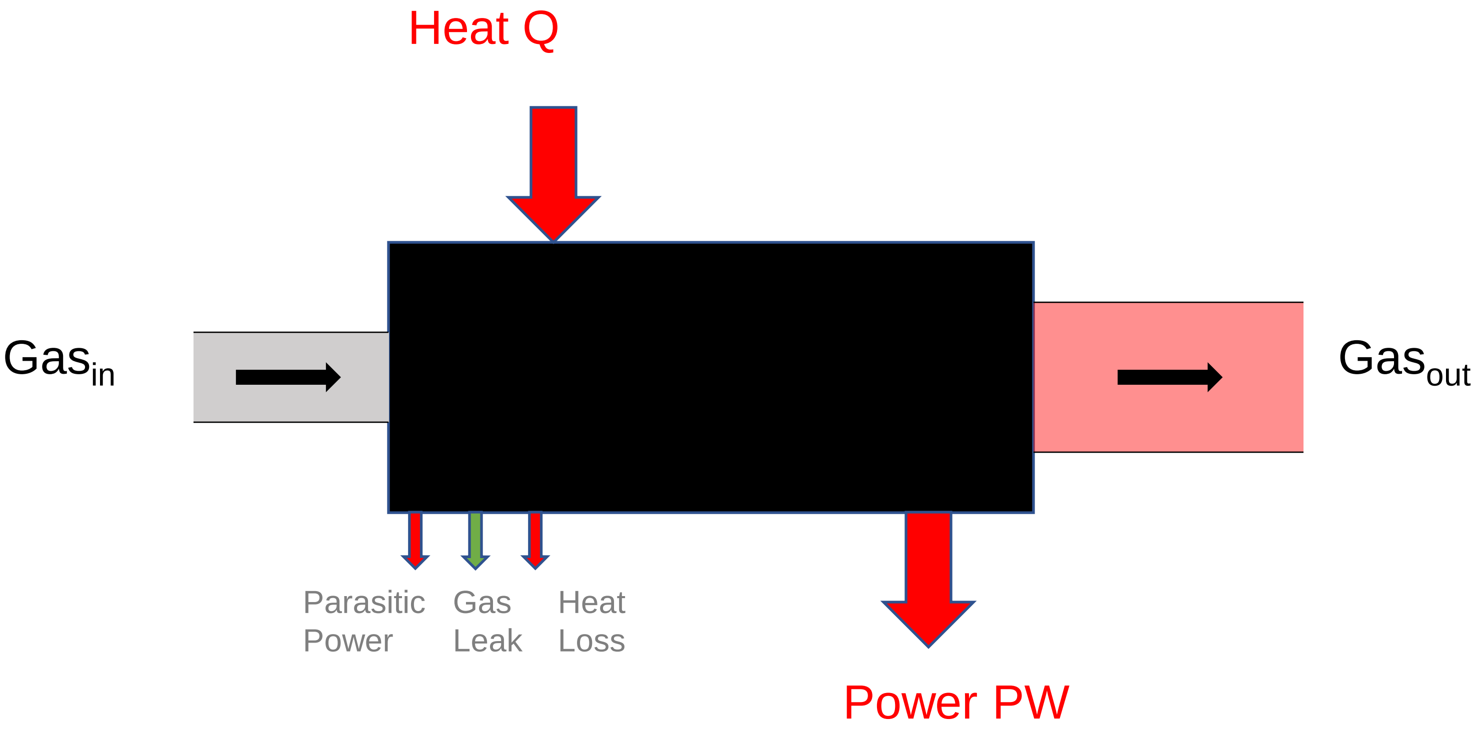


Thermodynamics of a Continuous Through Flow Machine



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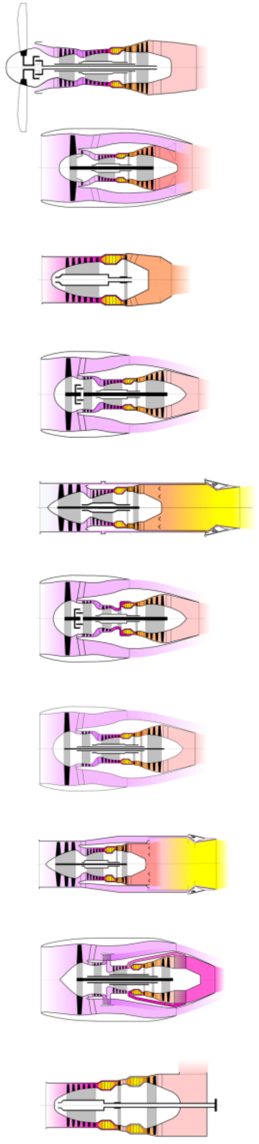
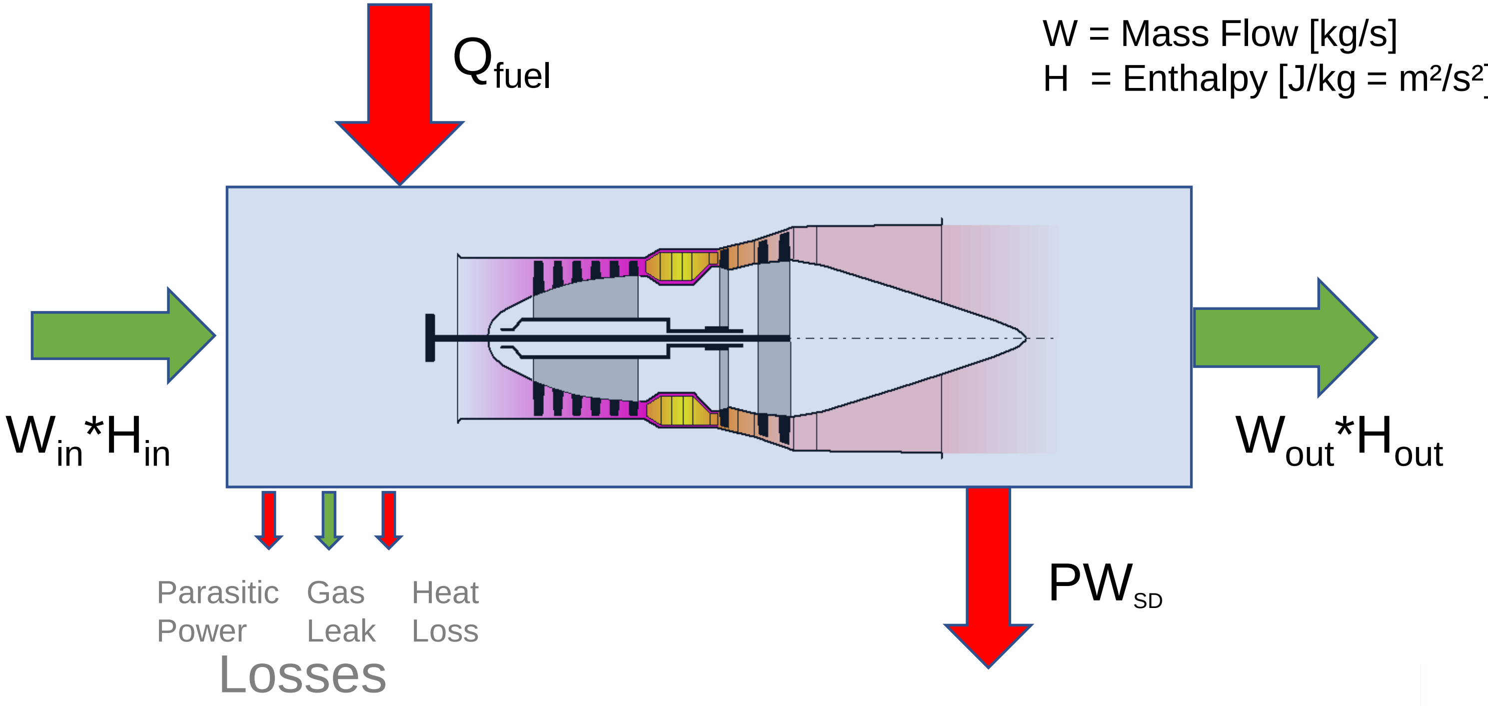


First Law of Thermodynamics

Energy in = Energy out

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

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



Flow in a Duct, no Heat Losses

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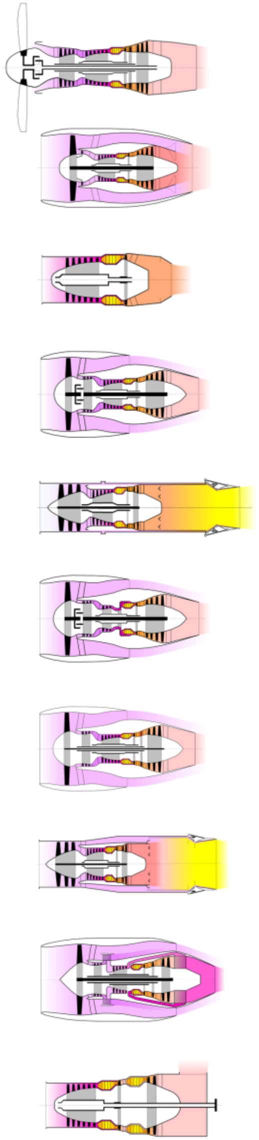
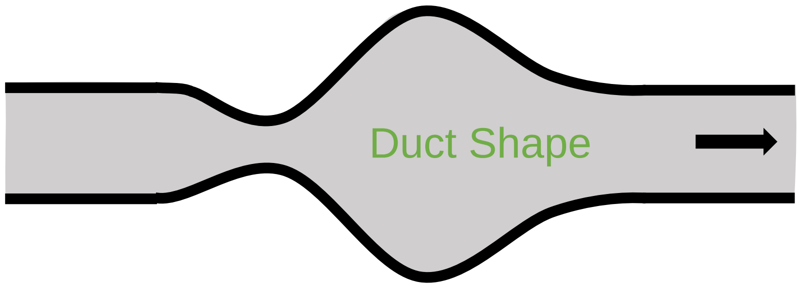




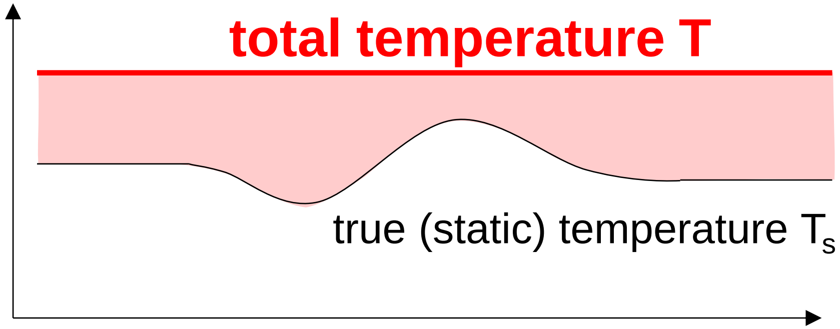
Total Energy = W*H = const

Mass Flow W = const

Total Enthalpy H = const

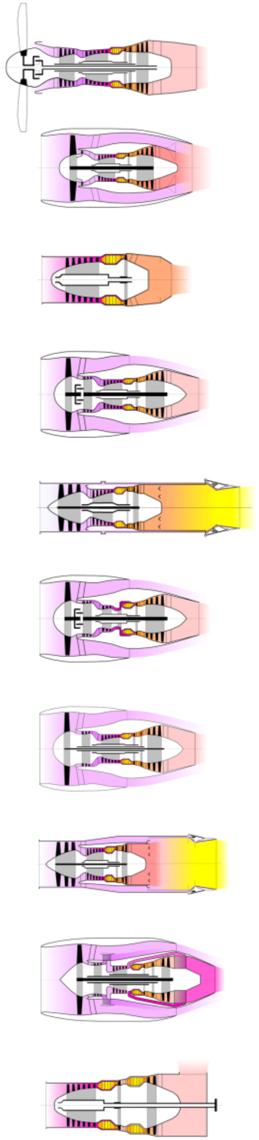
$H = c_P * \mathbf{T}$ = const

Total Temperature T = const



Static Temperature T_s varies:

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



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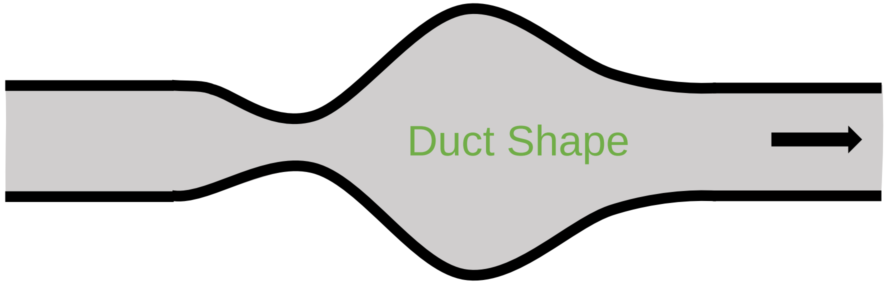
Static and Total Pressure

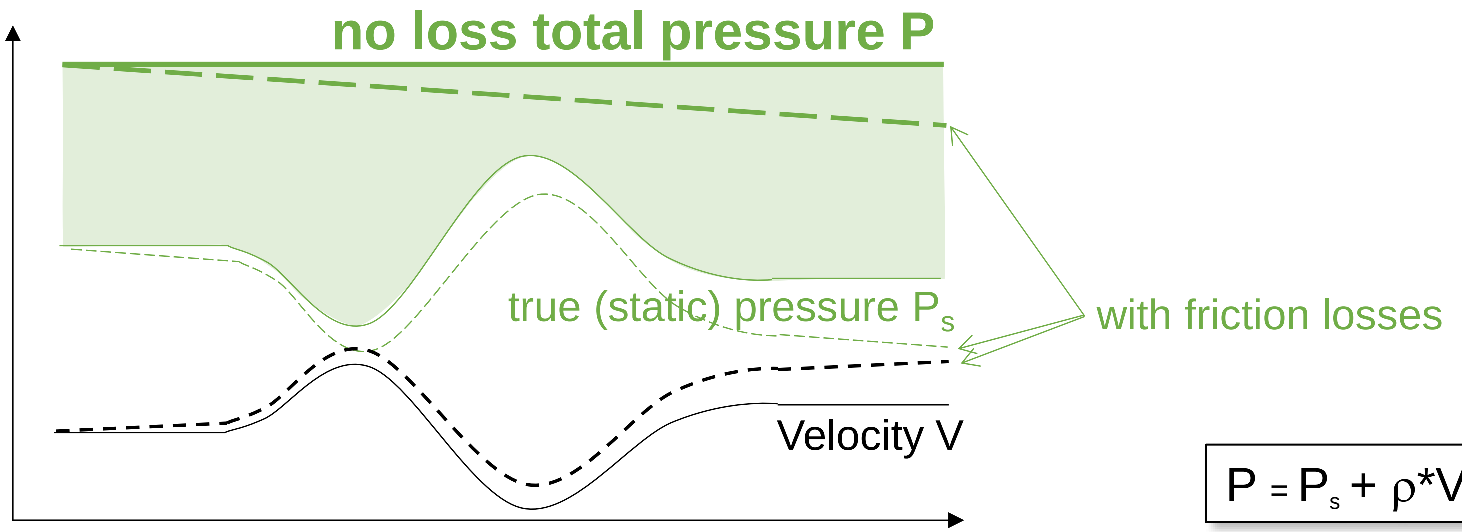
Flow in a Duct, no Heat Losses

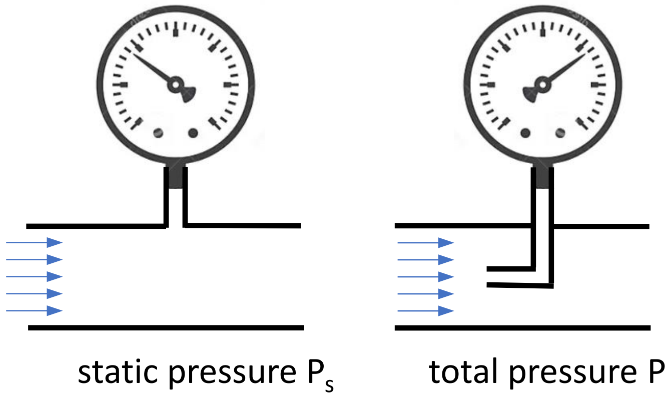


Energy = W*H = constant

$H = c_P{*}T$

T = constant





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

dynamic pressure

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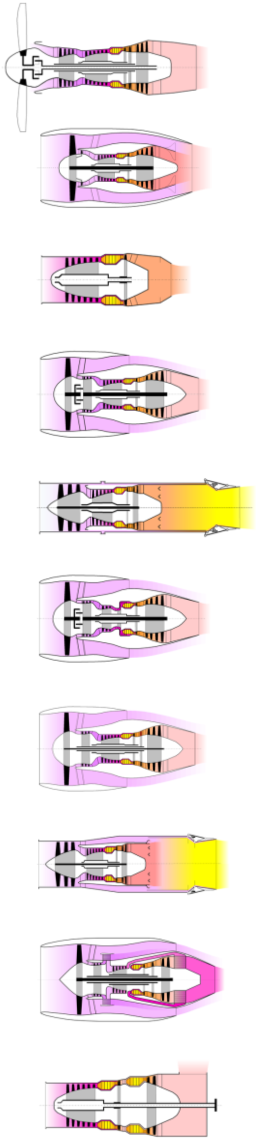


Correlations Between Static and Total Quantities

Constant Gas Properties:

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

Mach Number:

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

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

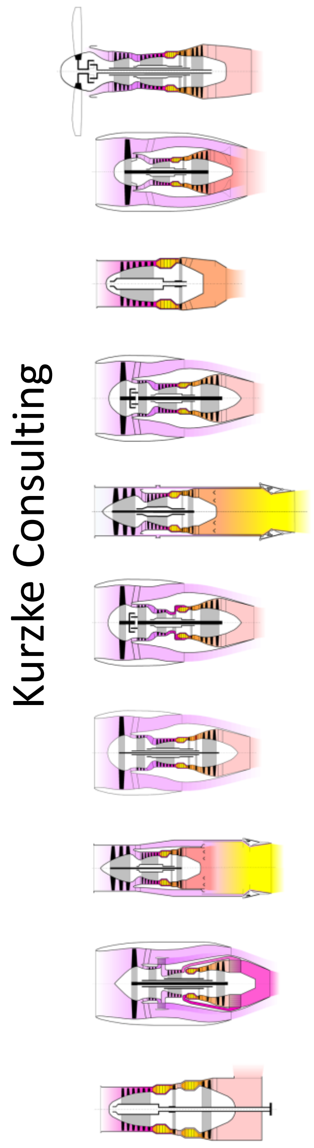
$$\frac{P}{P_s} = \left(\frac{T}{T_s}\right)^{\frac{\gamma}{\gamma-1}} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}$$

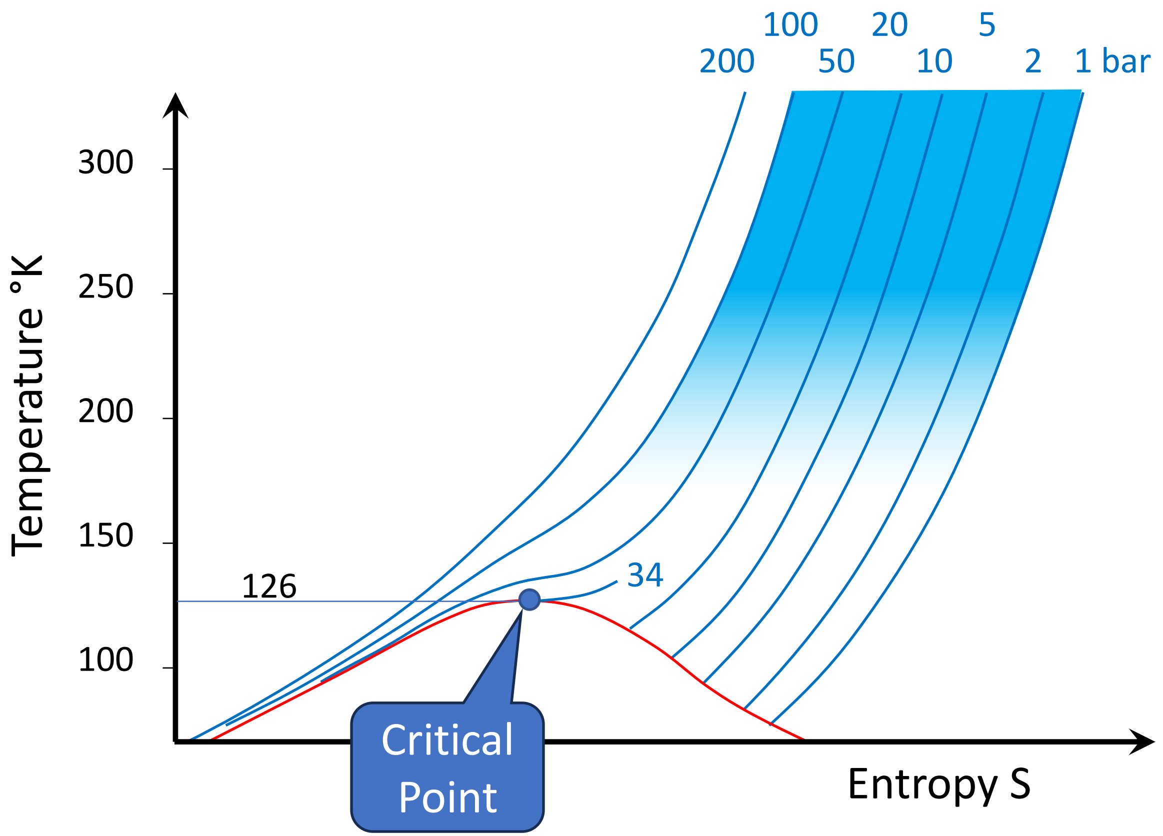
Isentropic Exponent:

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

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

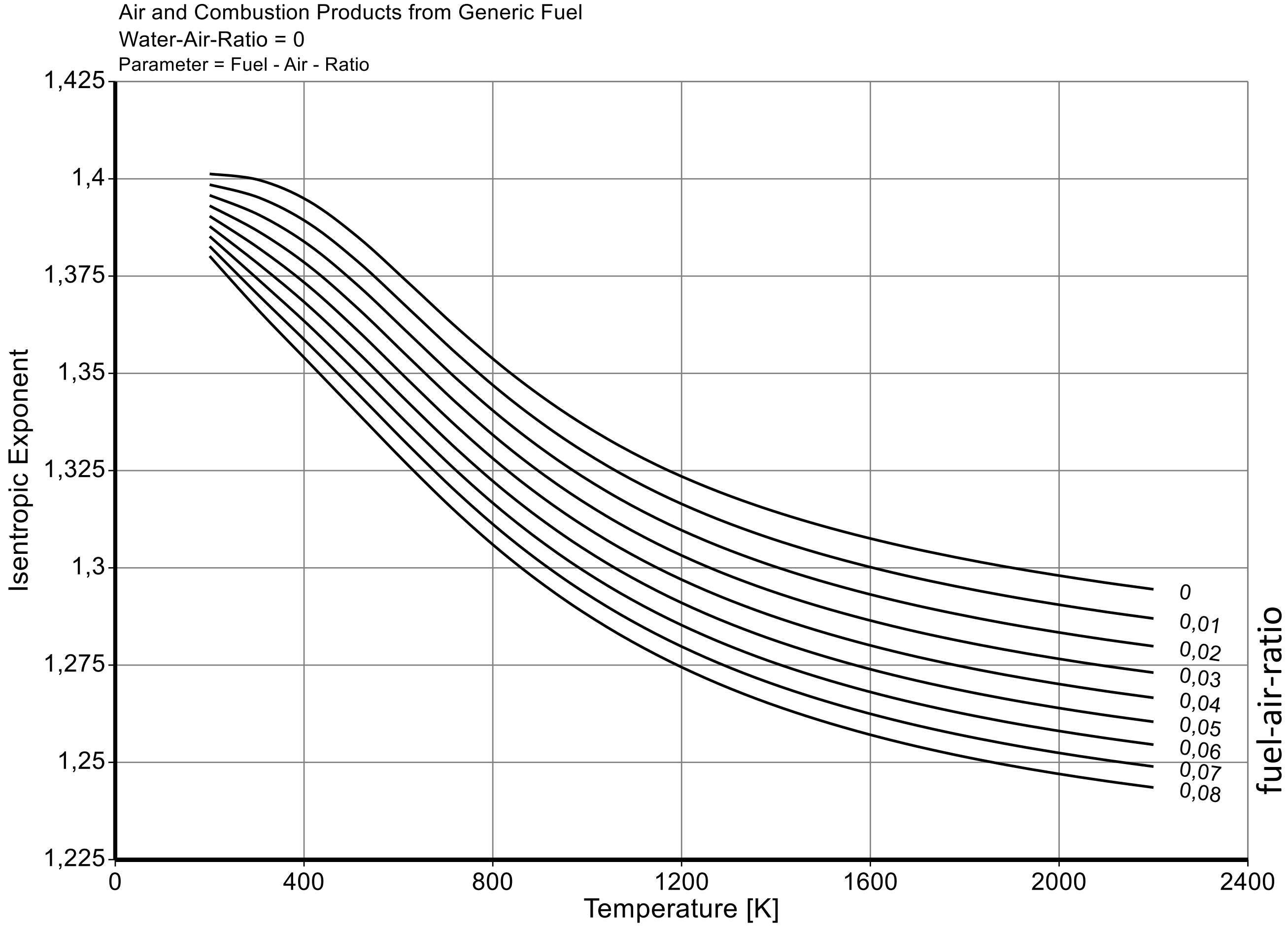




Gas	Critical Temp	Critical Pressure
Air	133K	37.7 bar
Nitrogen	126	34
CO_2	304	73.8
H_2O	647	221.2

True Gas Properties

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



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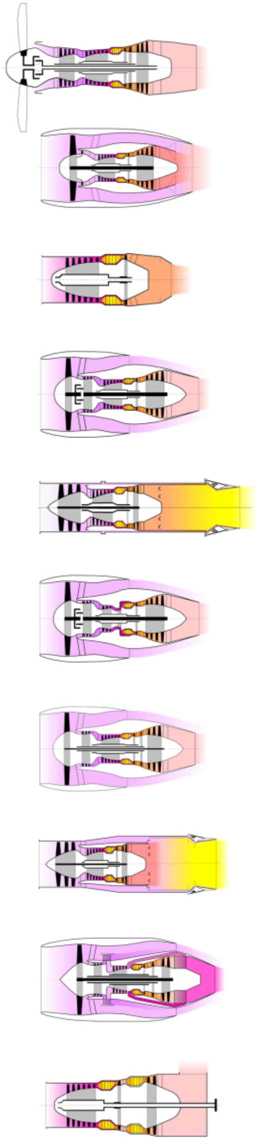
Specific Heat c_p



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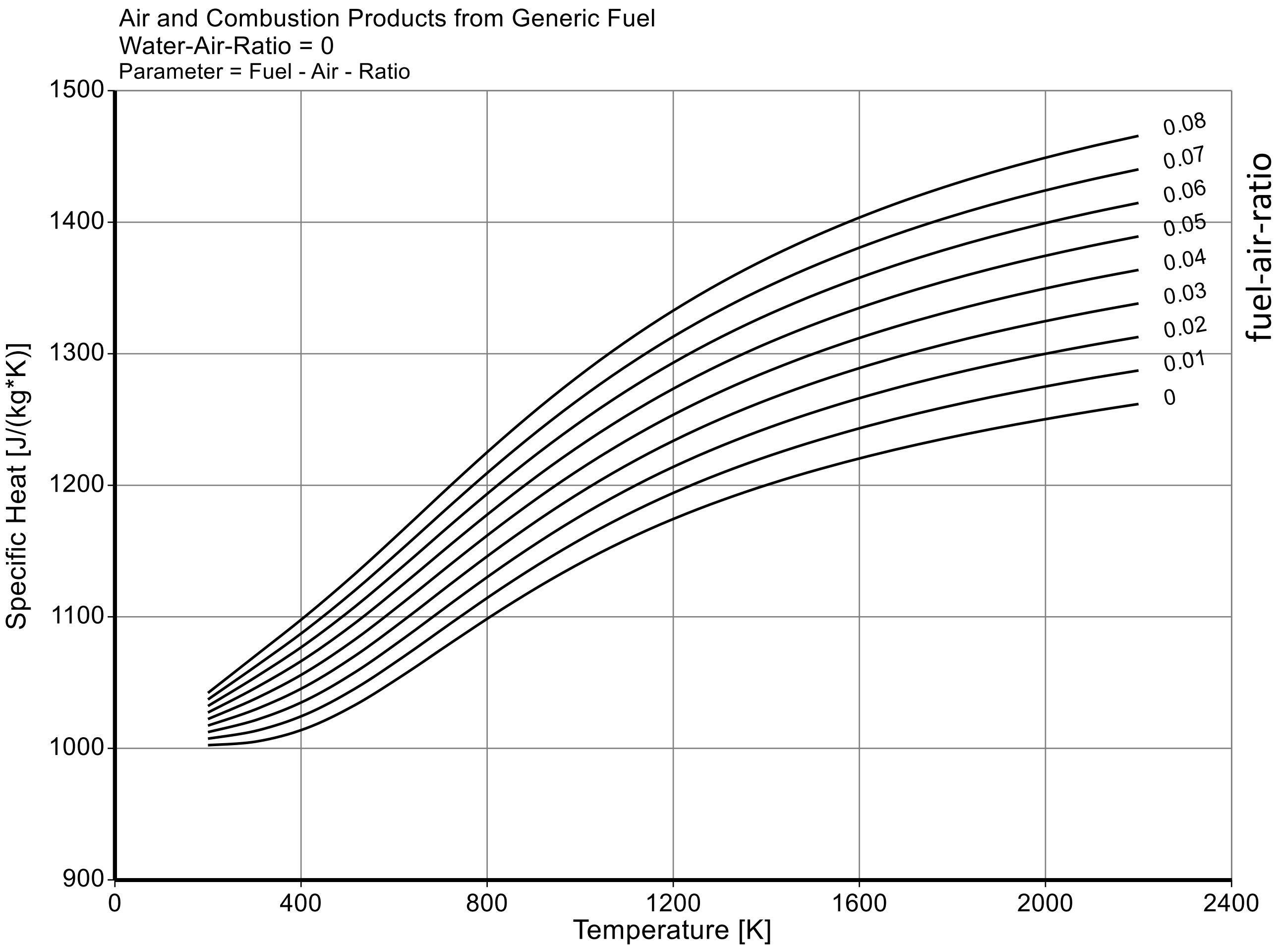

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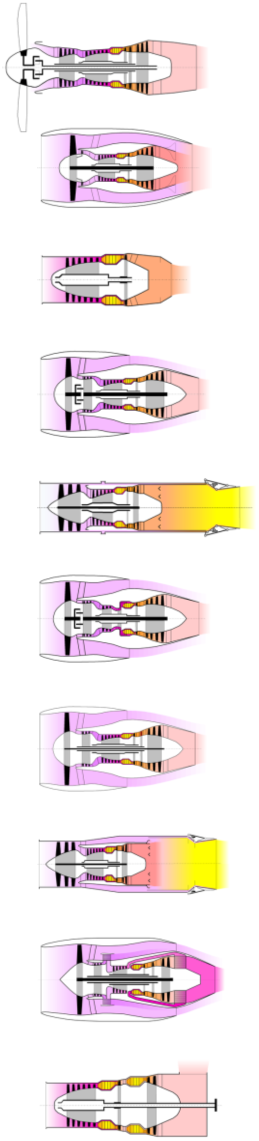

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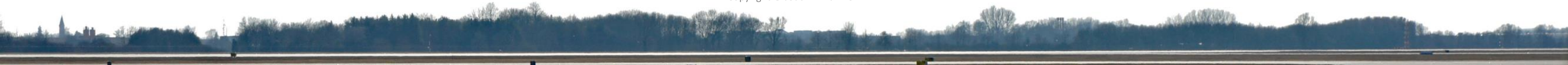

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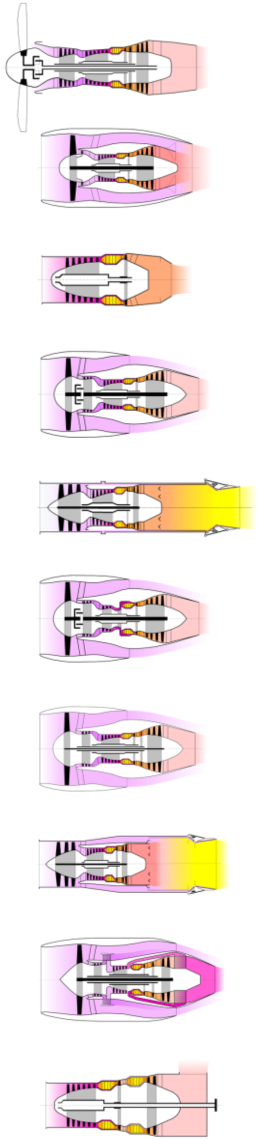
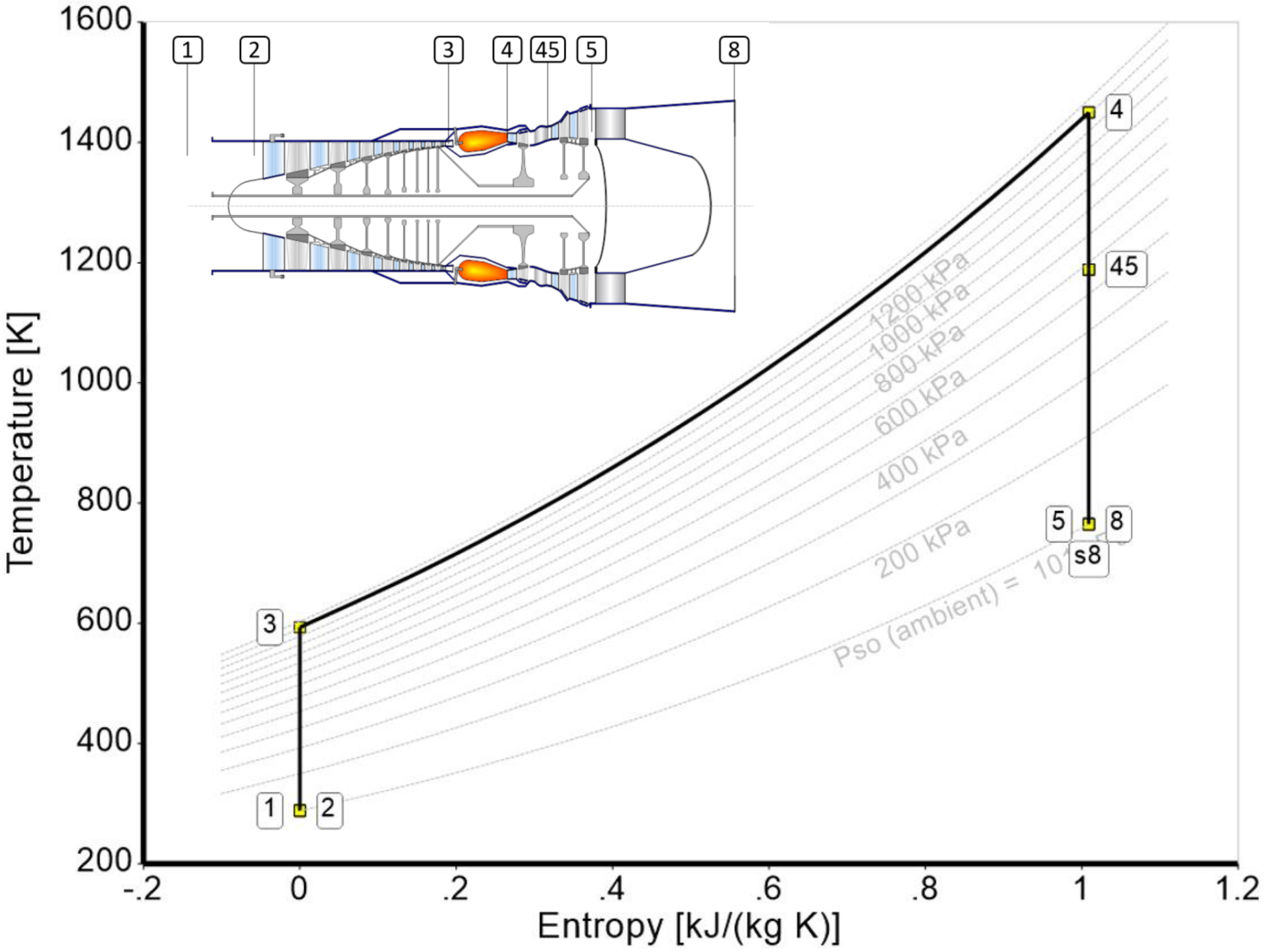
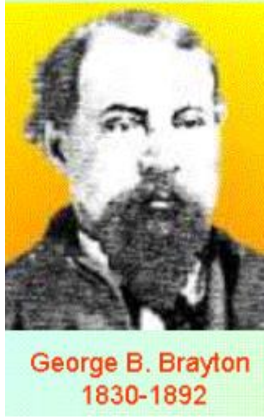


Temperature - Entropy Diagram

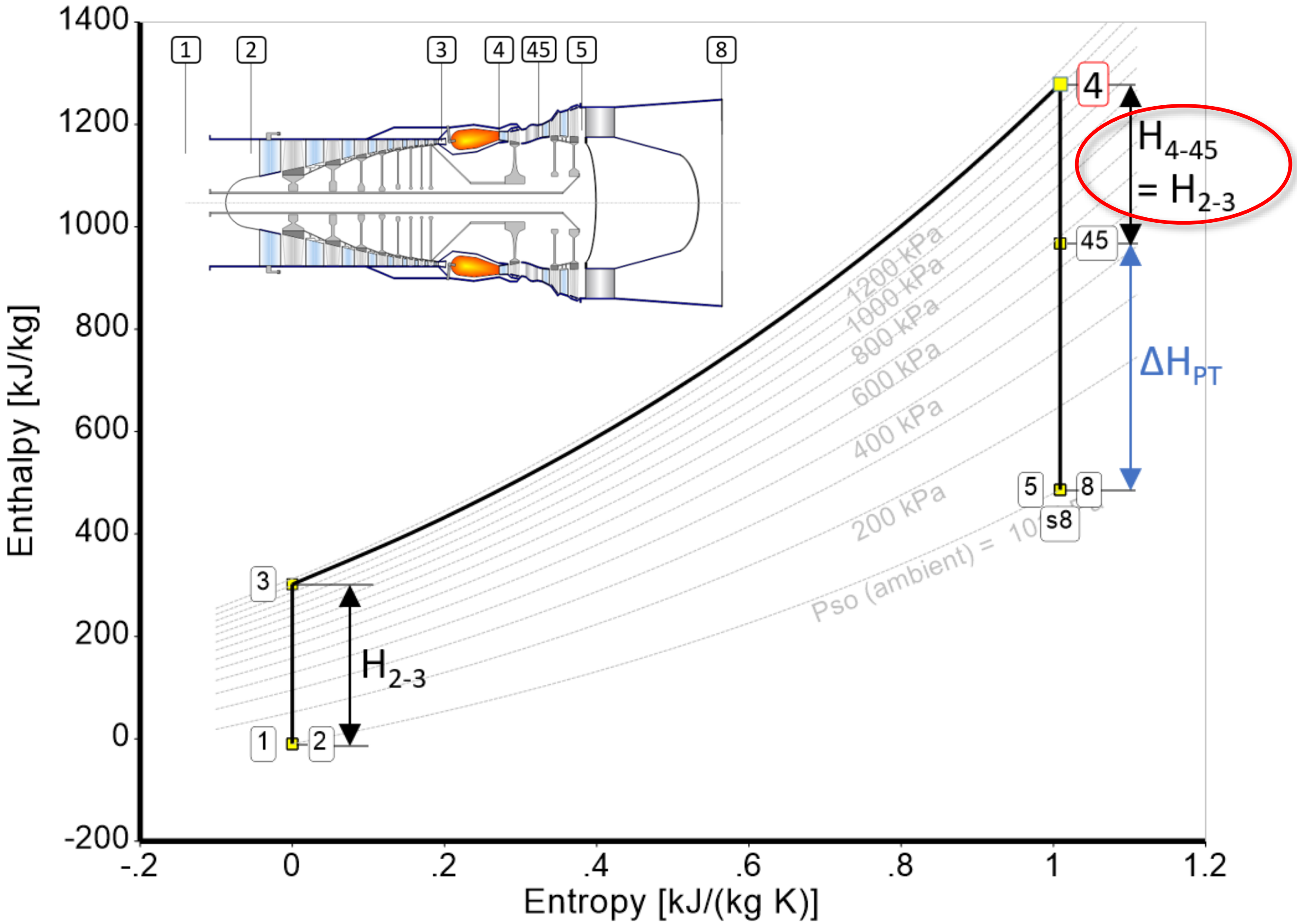
Ideal Joule (Brayton) Process



James P. Joule
1818-1889



Ideal Joule (Brayton) Process



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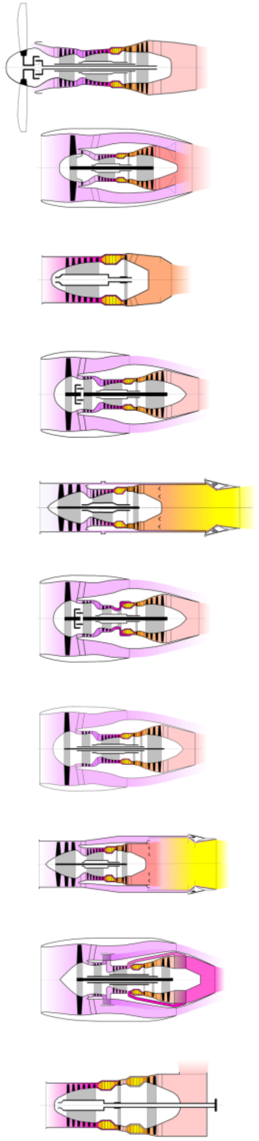
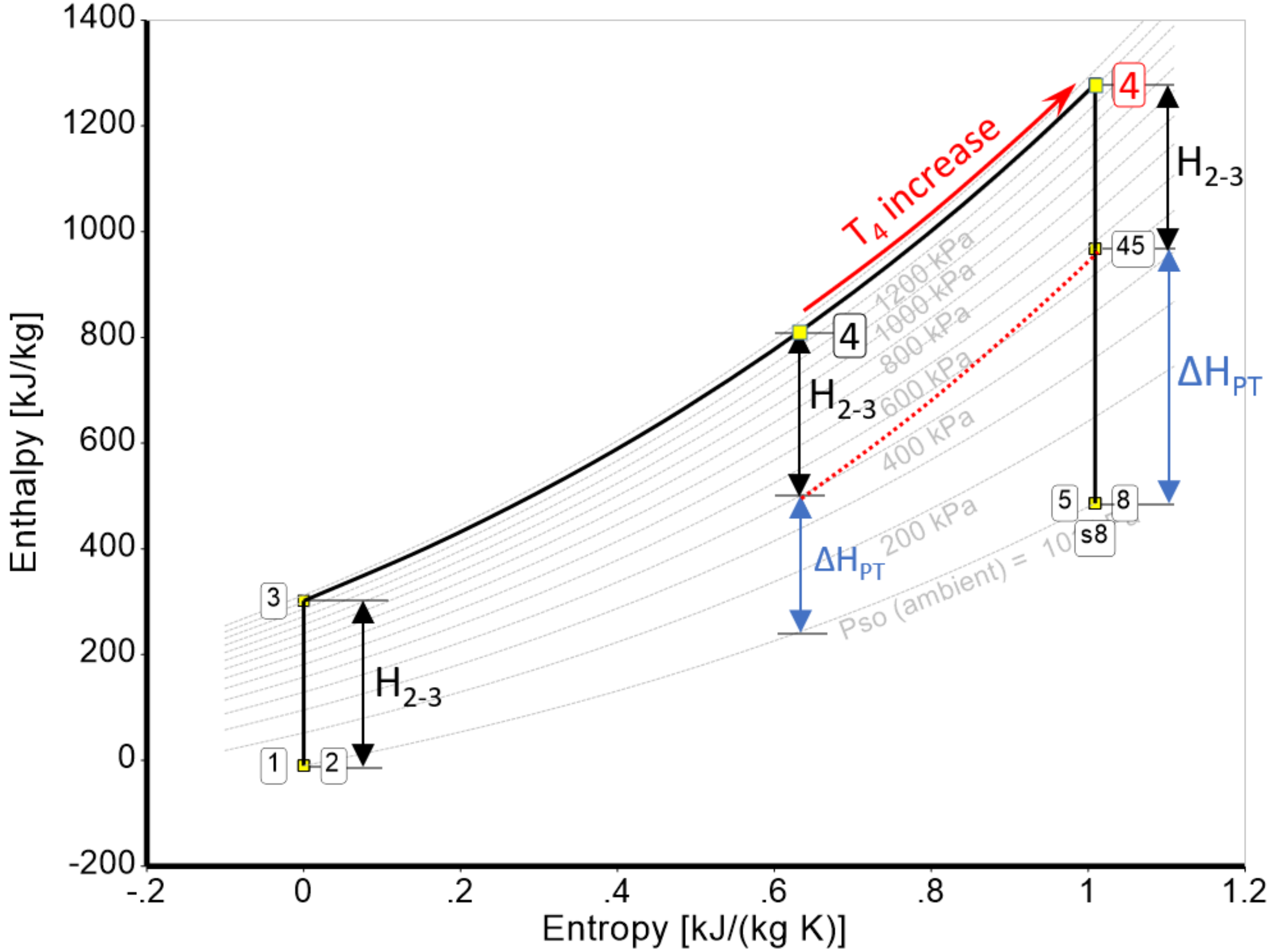
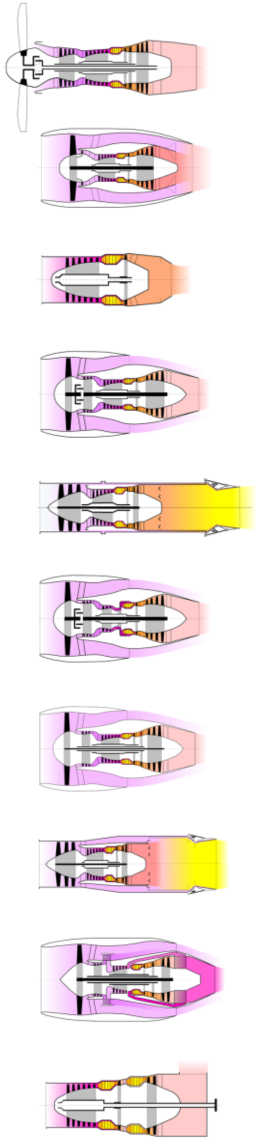
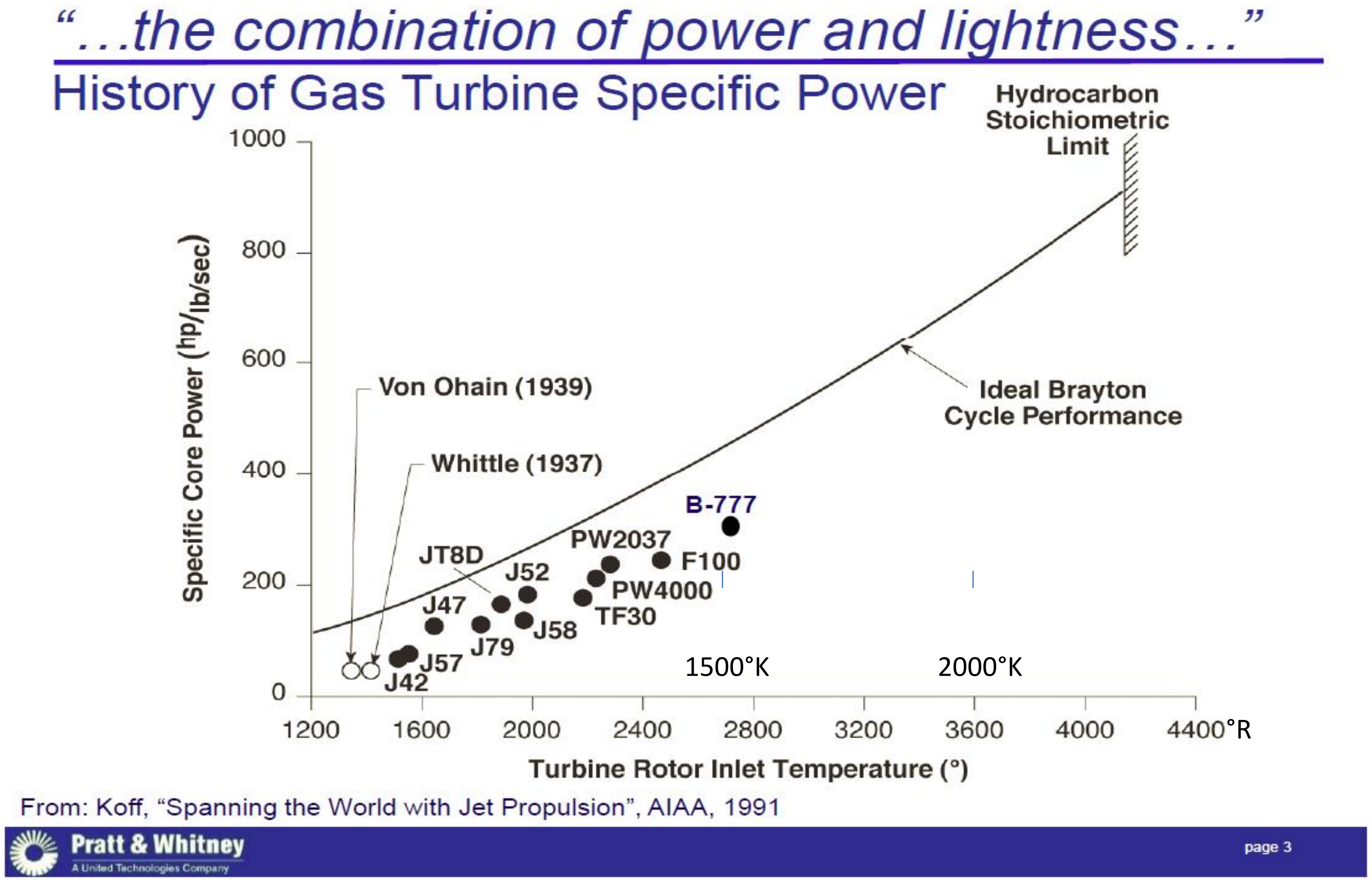


Ideal Joule Process
Influence of T_4



History





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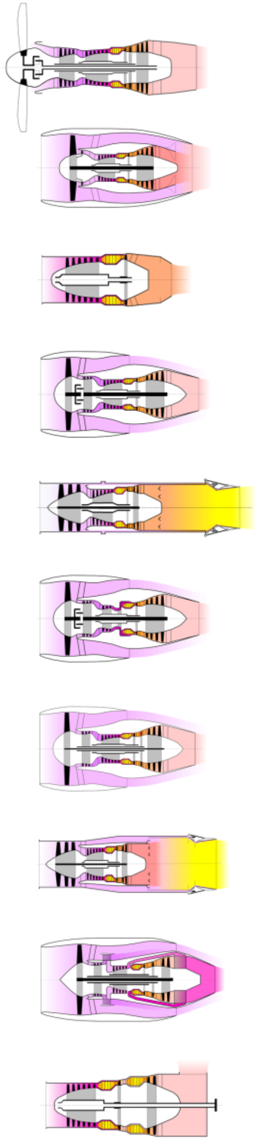
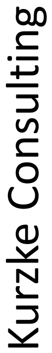
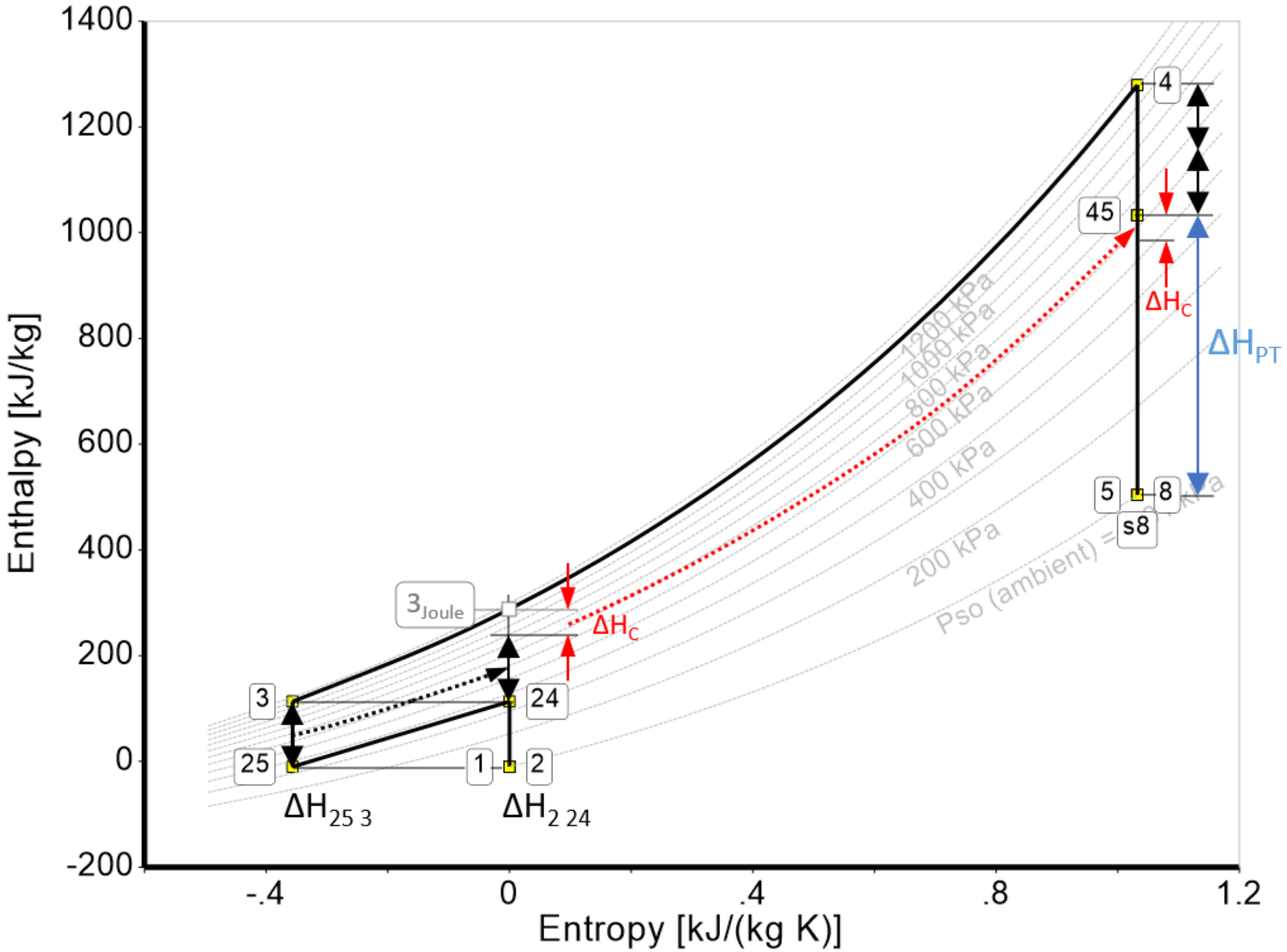
Increasing Power Output
Intercooling







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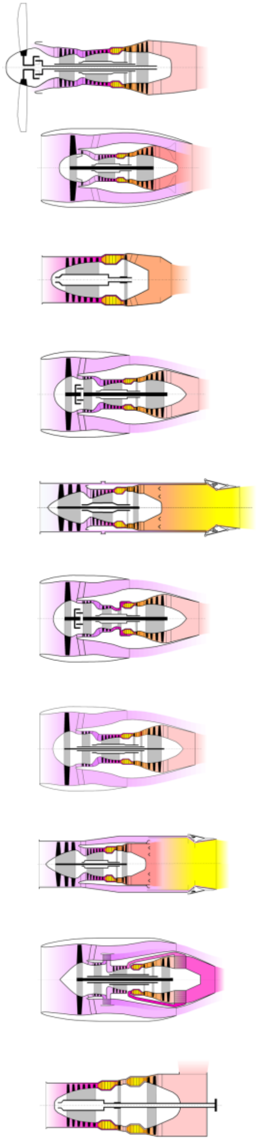
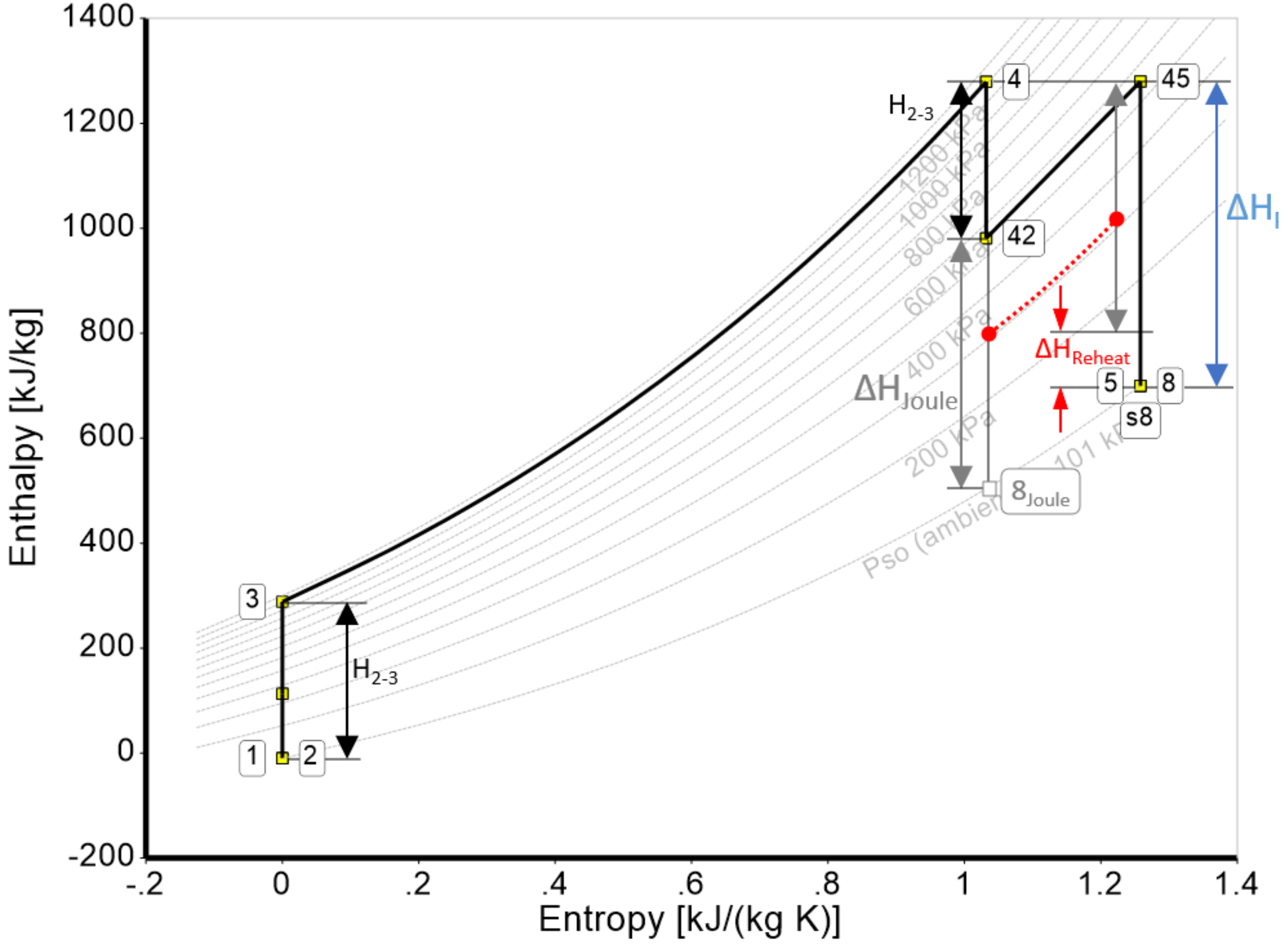


Increasing Power Output
Sequential Combustion



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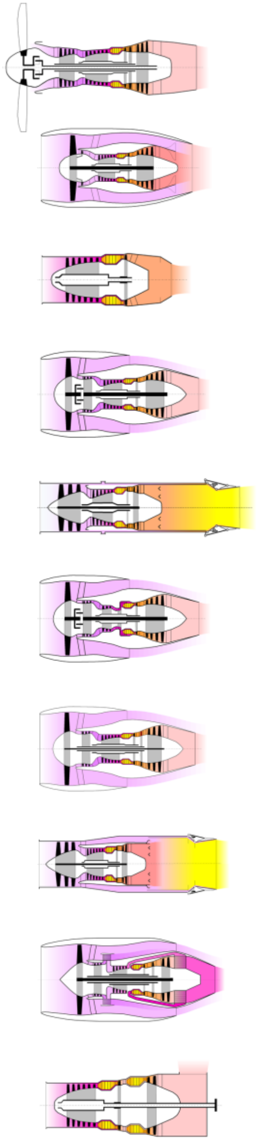
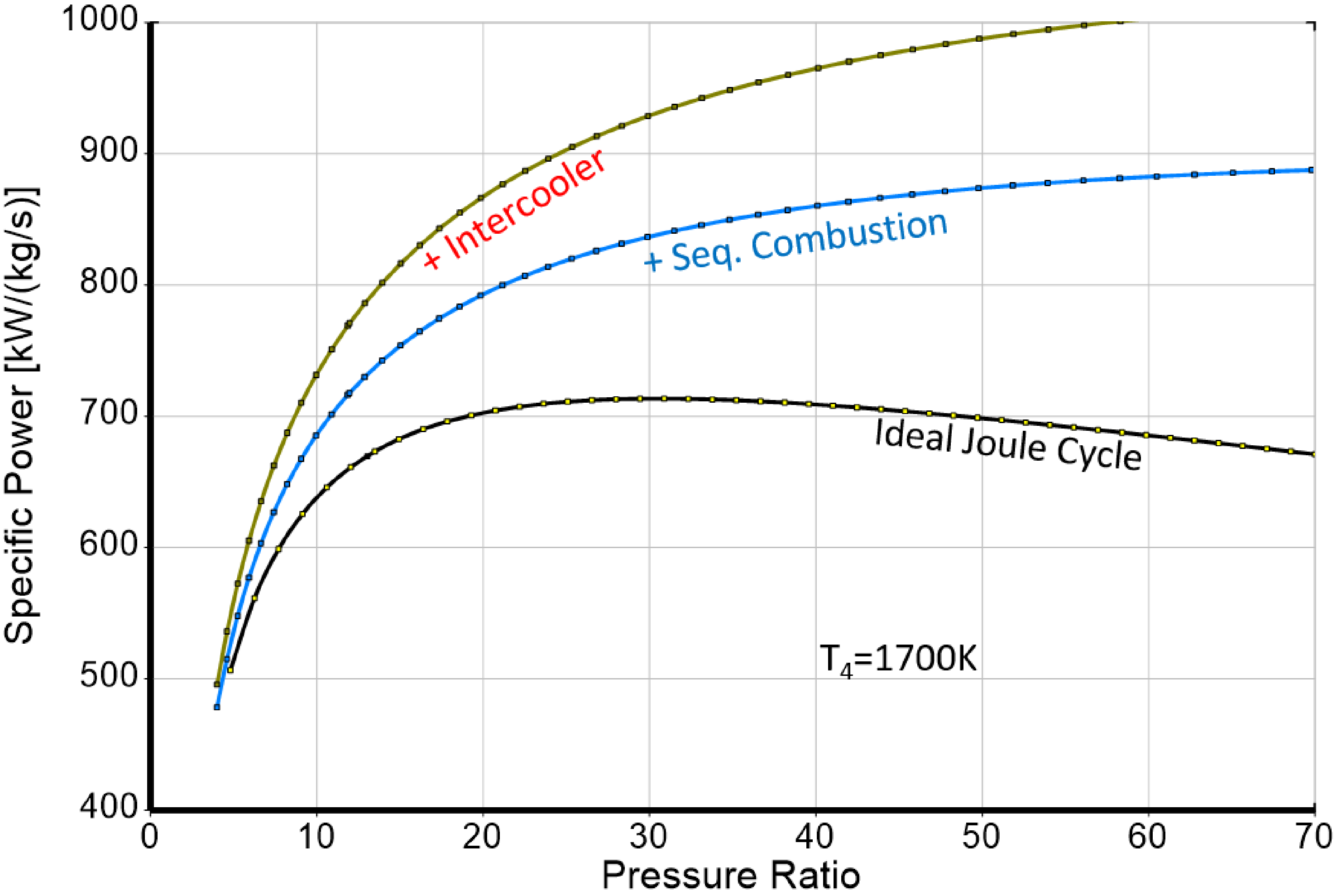
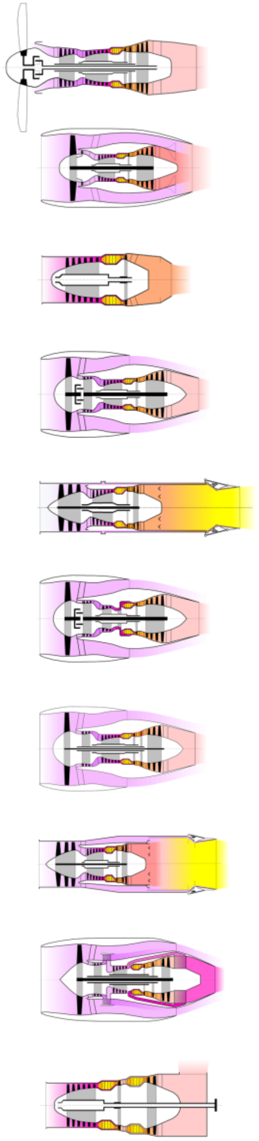


Increasing Power Output
Overview





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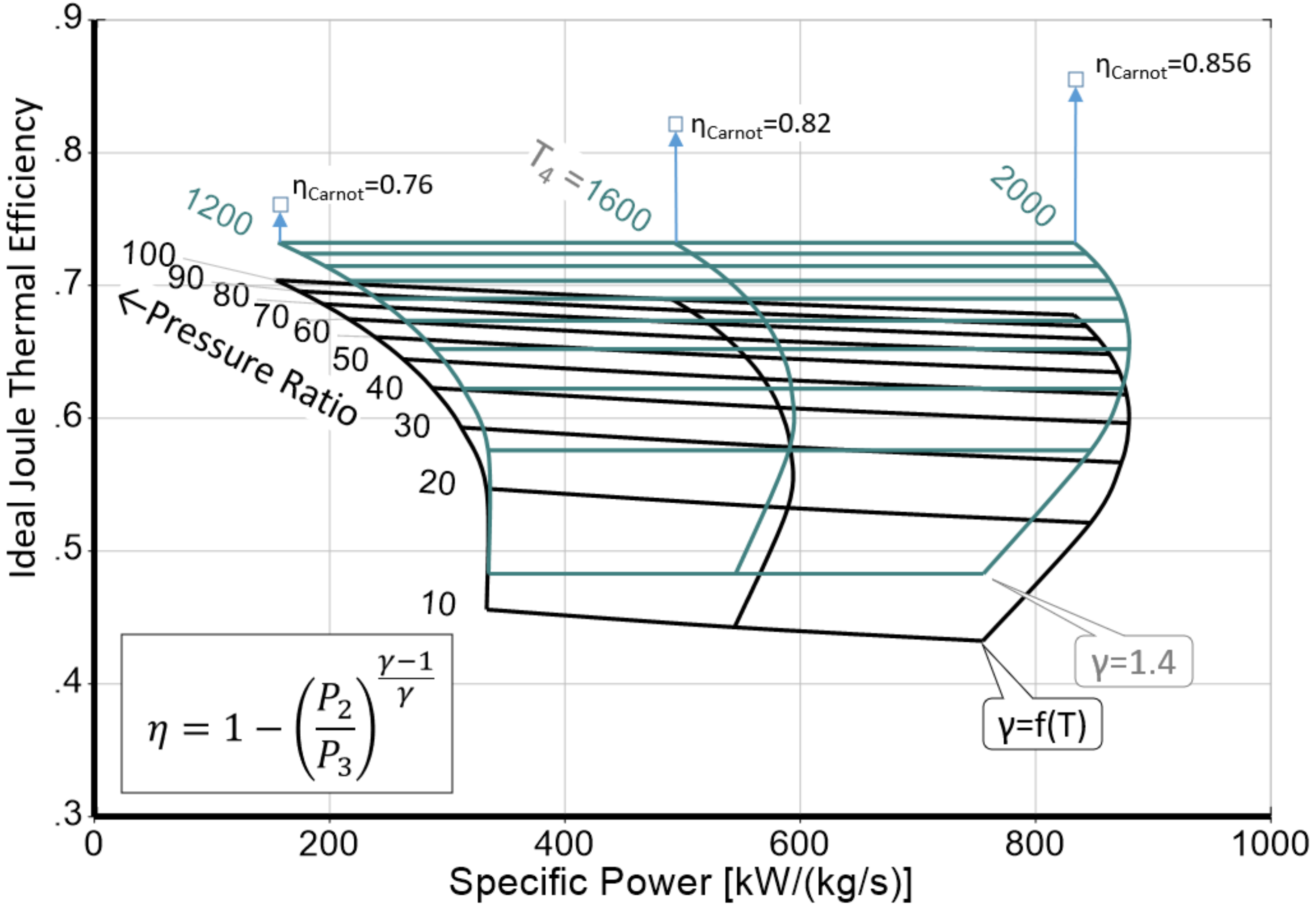
Ideal Joule Process
Thermal Efficiency



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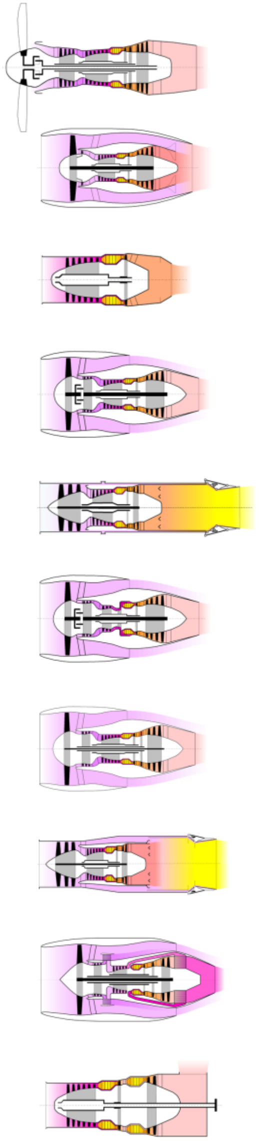
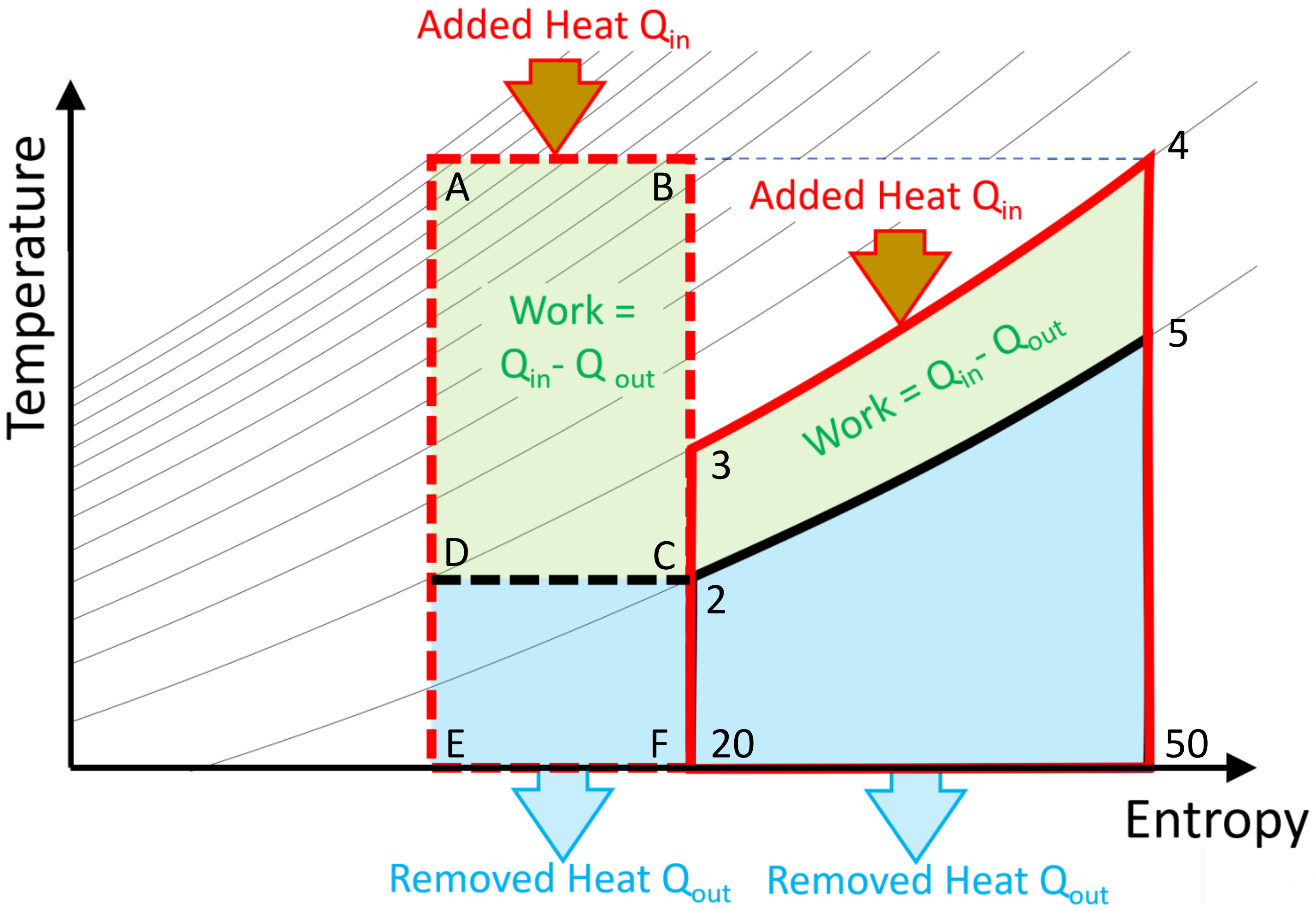


Carnot and Joule Cycle

Thermal Efficiency



Carnot:

Added Heat = A-B-F-E

Removed Heat = C-D-E-F

Work = A-B-C-D

Joule:

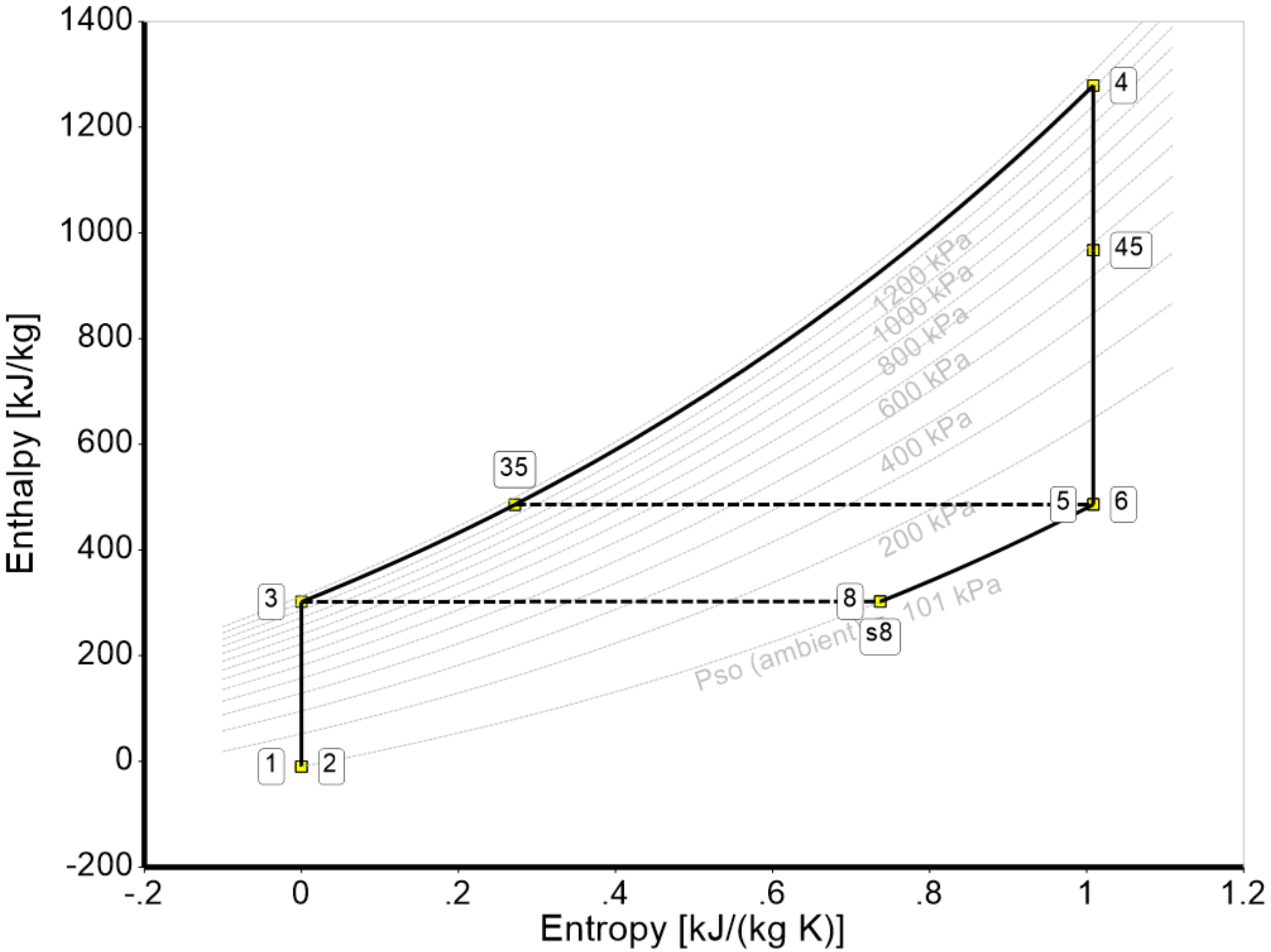
Added Heat = 3-4-50-20

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

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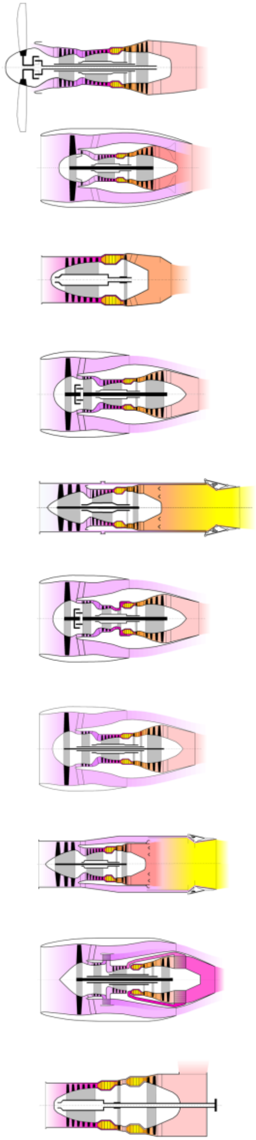
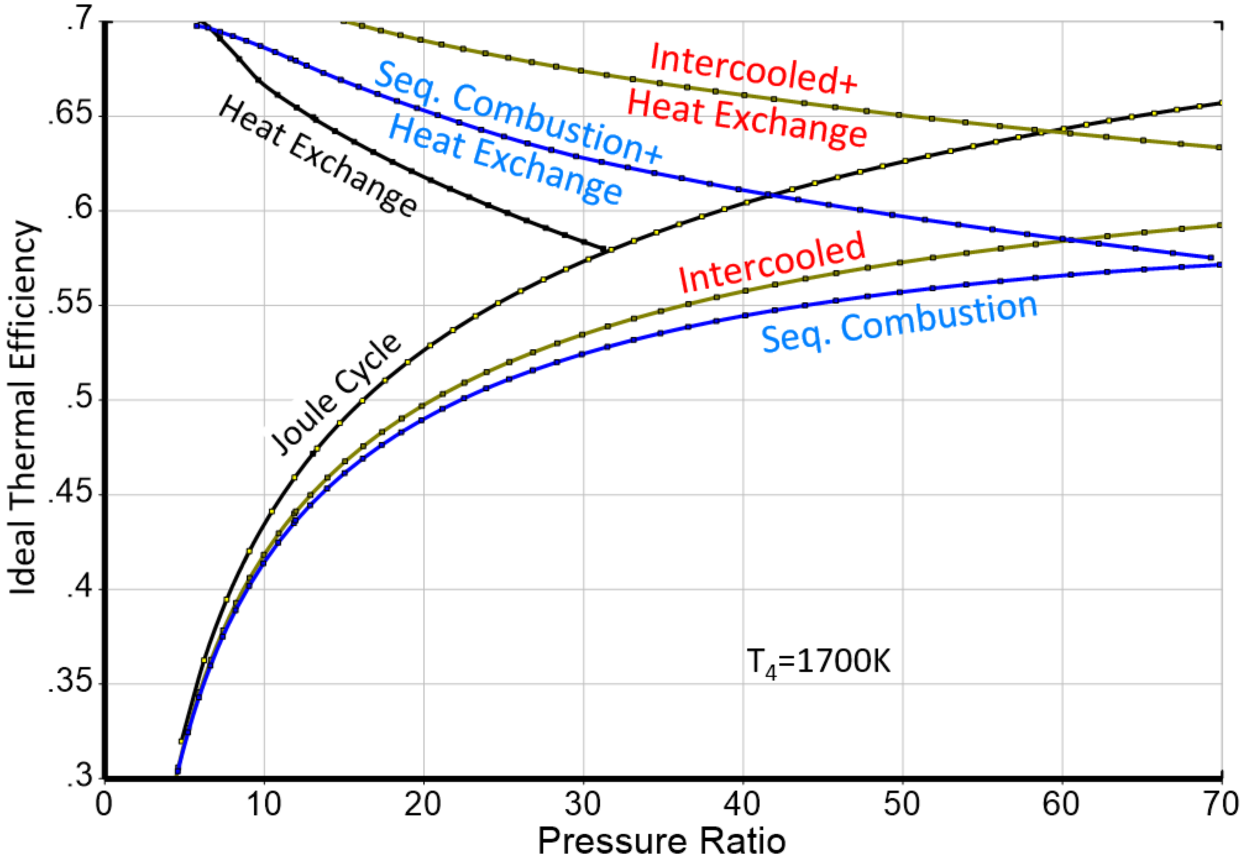
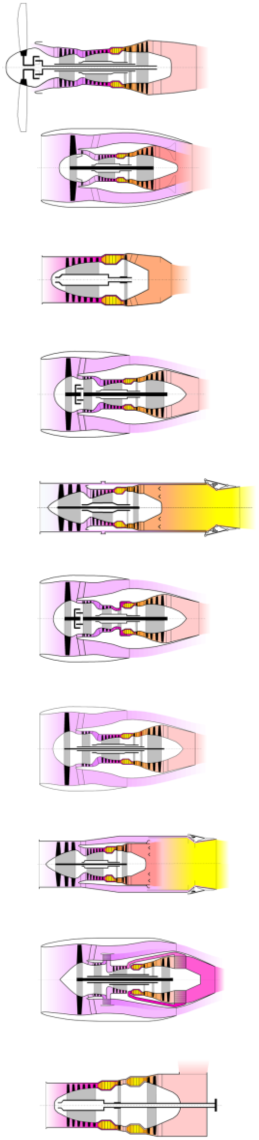
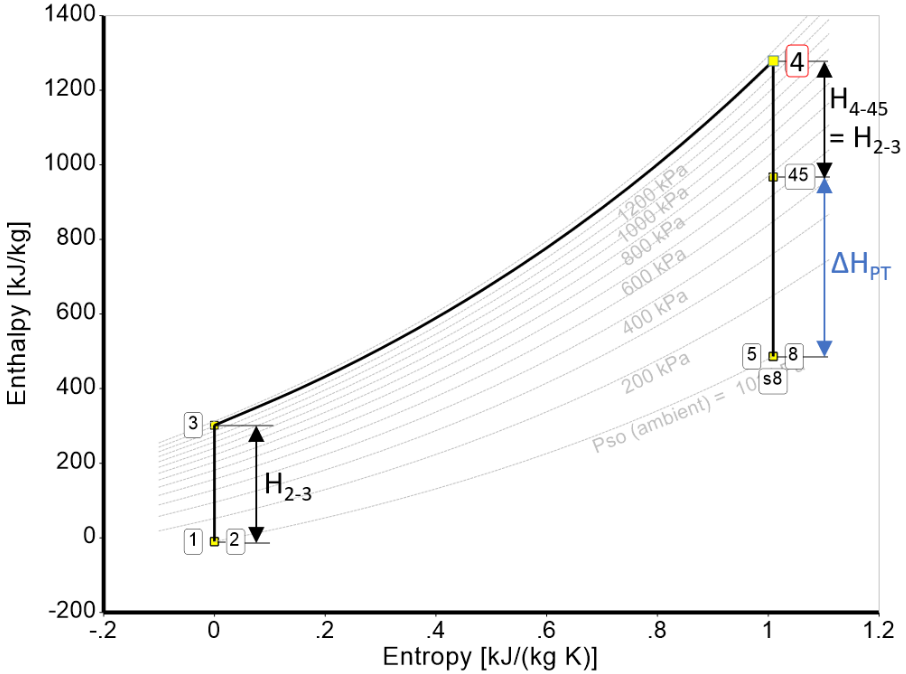
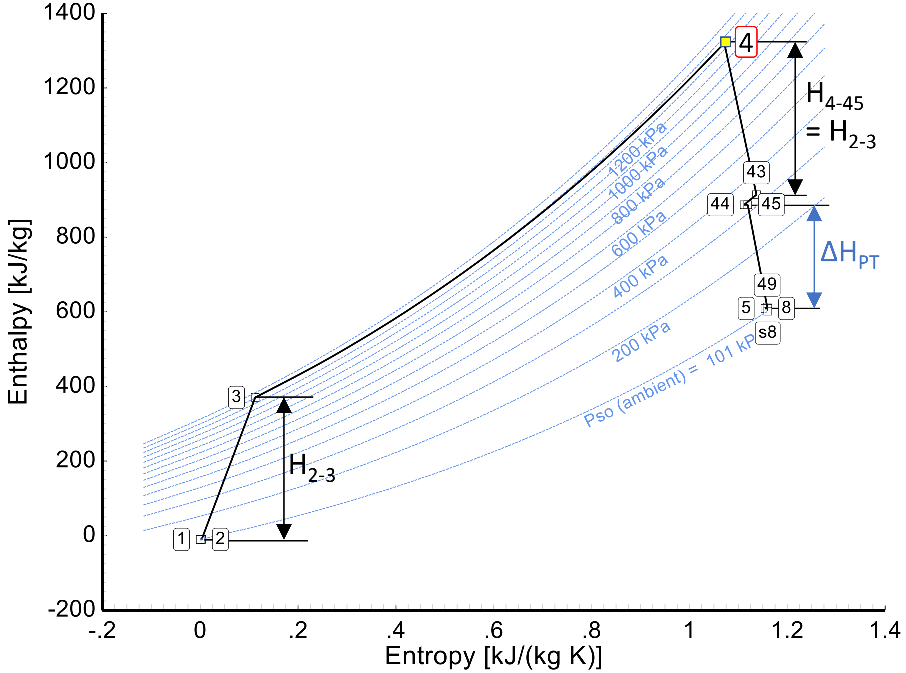


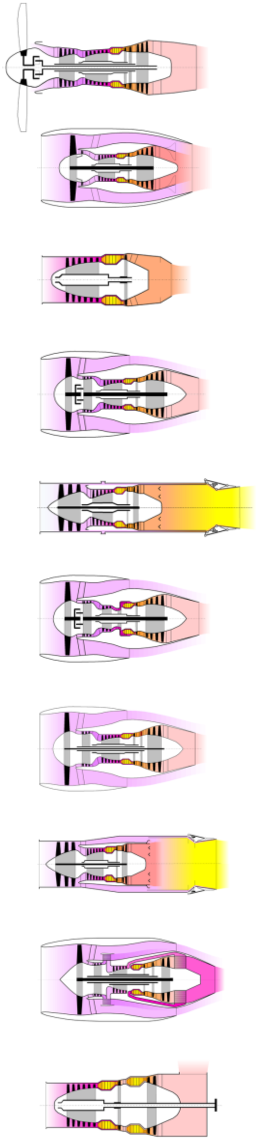


Ideal and Real Joule Process









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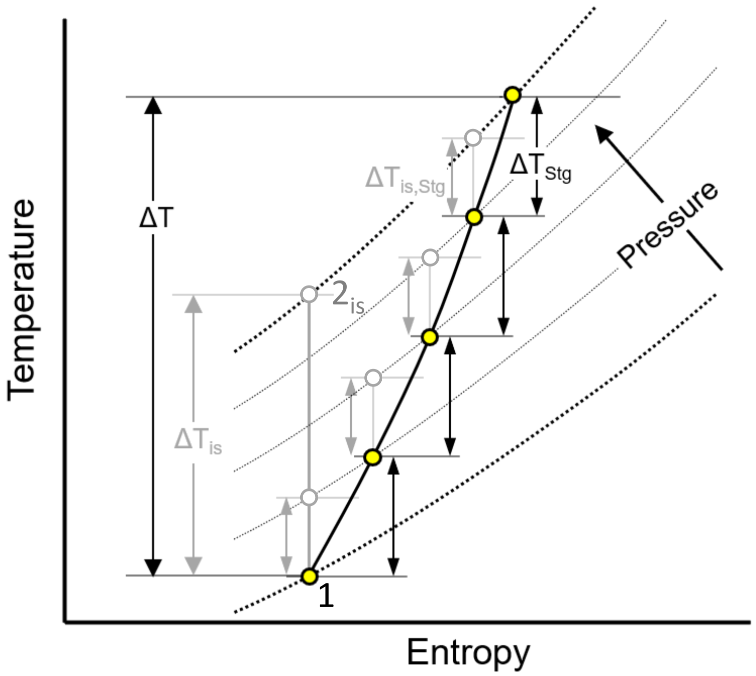
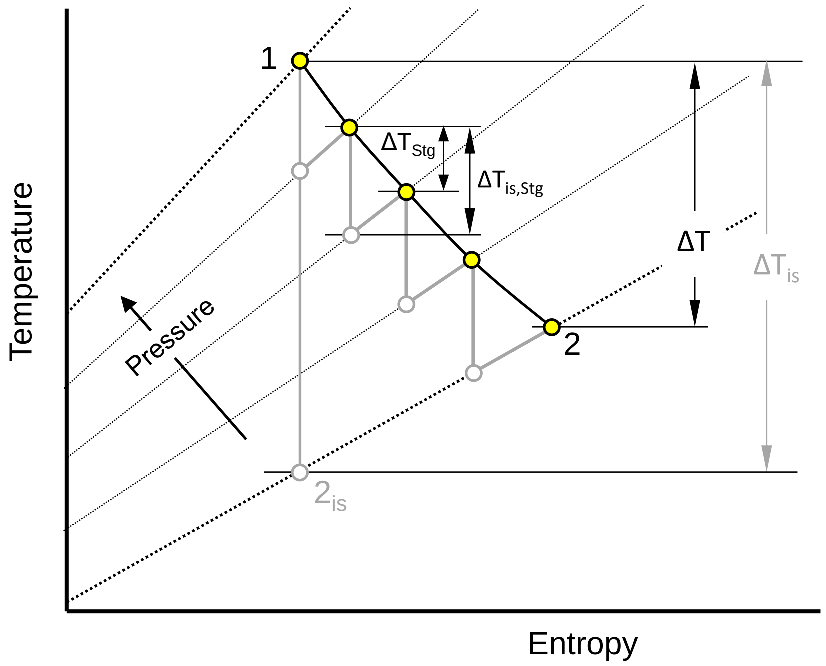
Polytropic Efficiency

Compressor



Turbine



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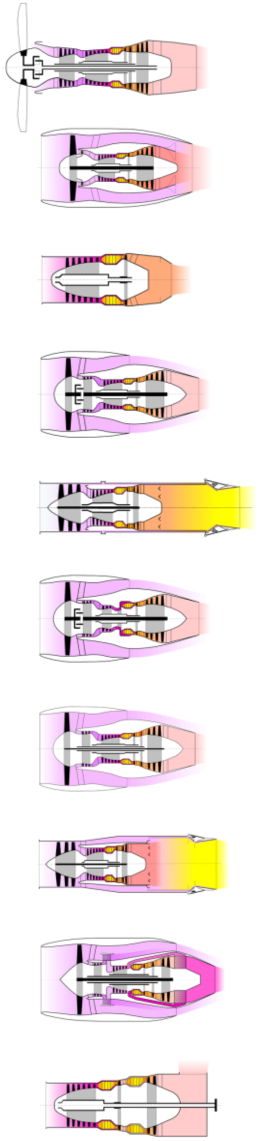
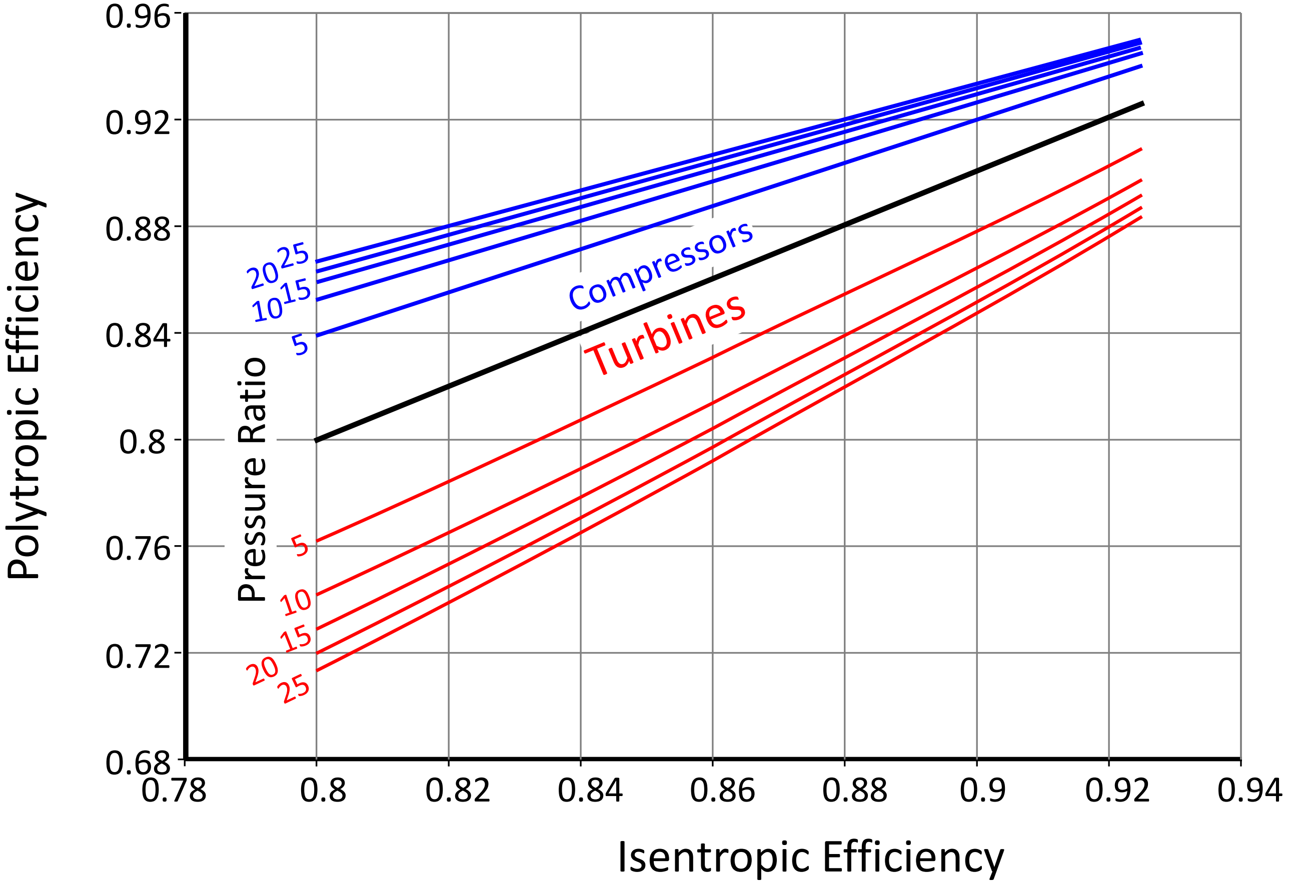


Isentropic / Polytropic Efficiency



Efficiency of a Real Joule Process

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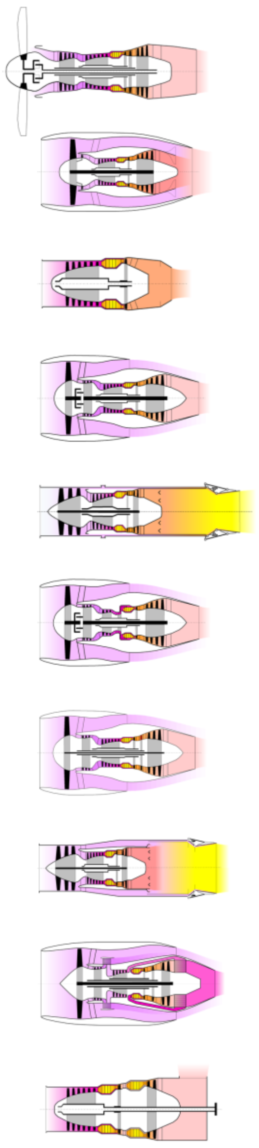

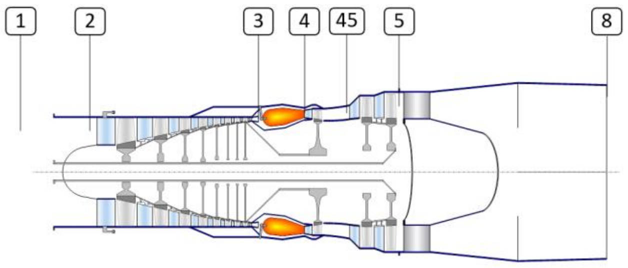

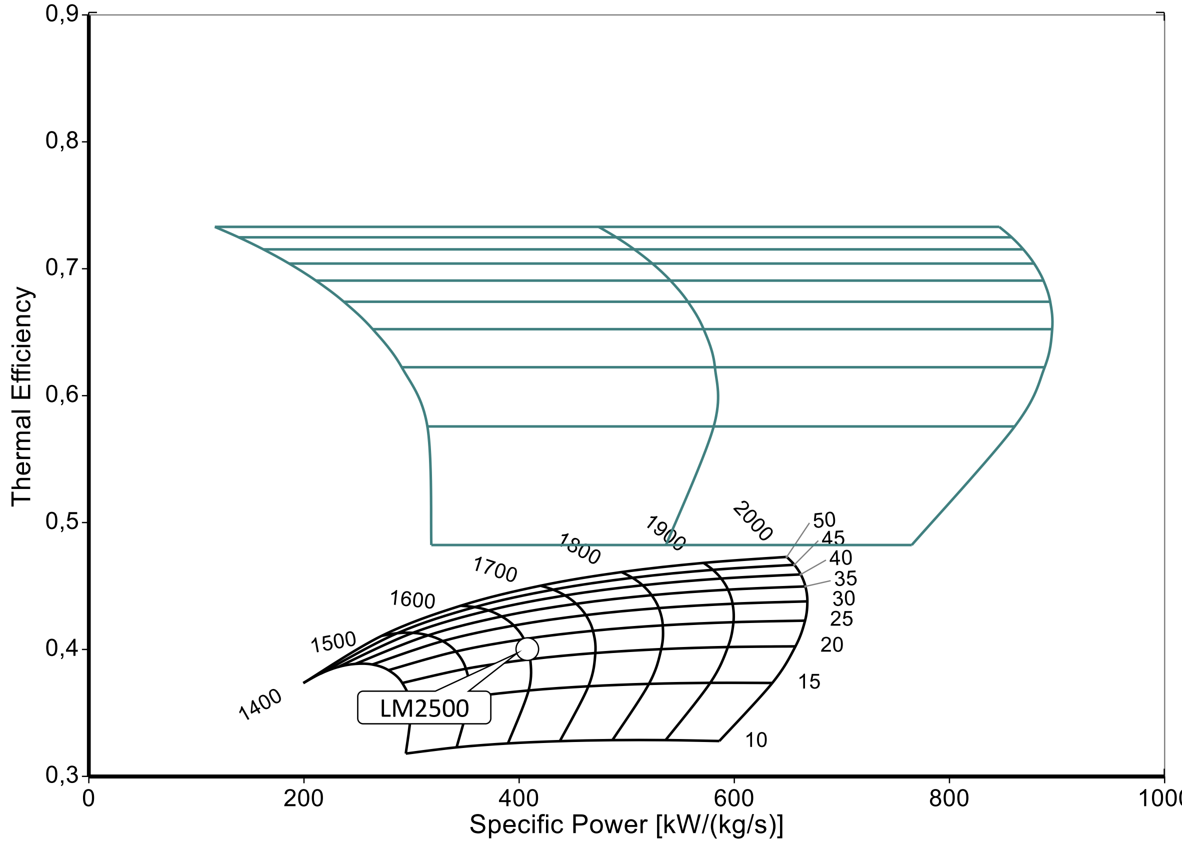

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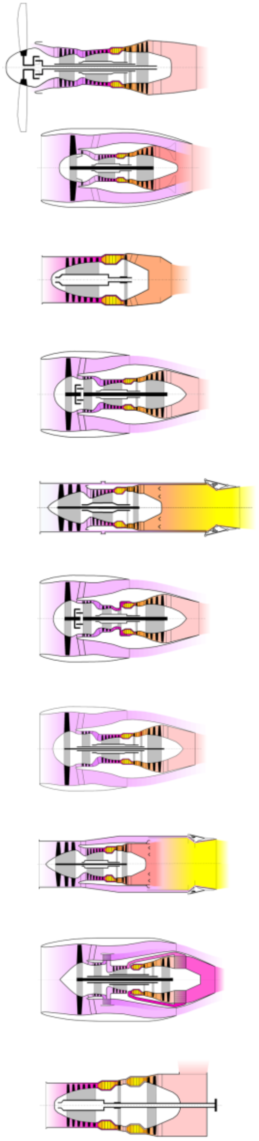

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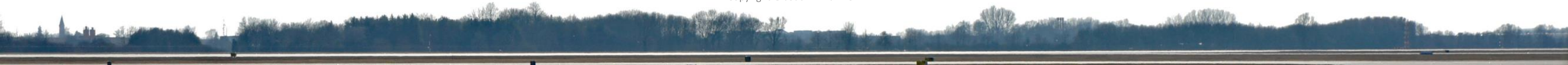

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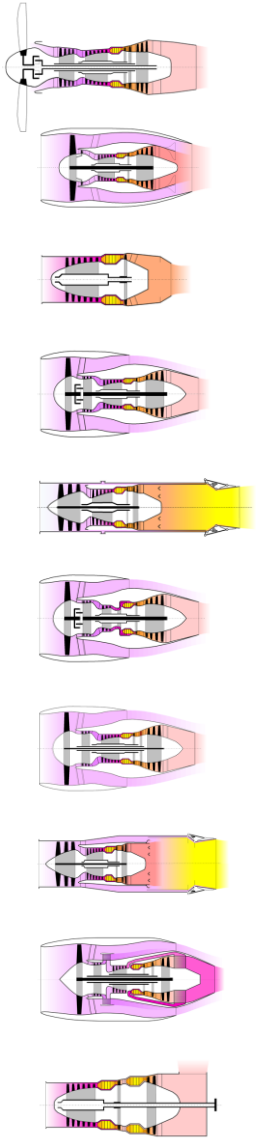
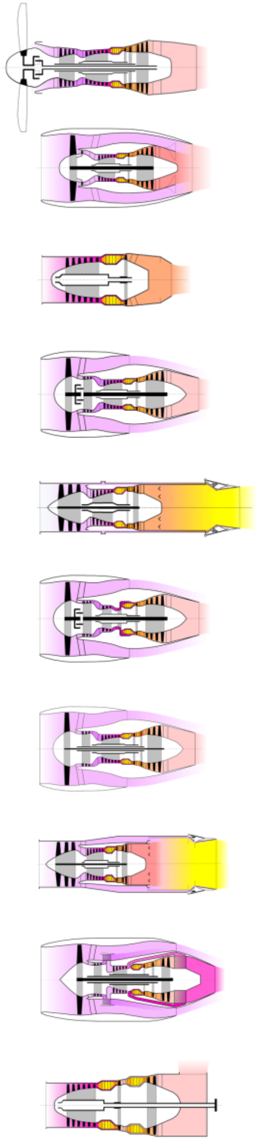


Widespread View:

"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 !



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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

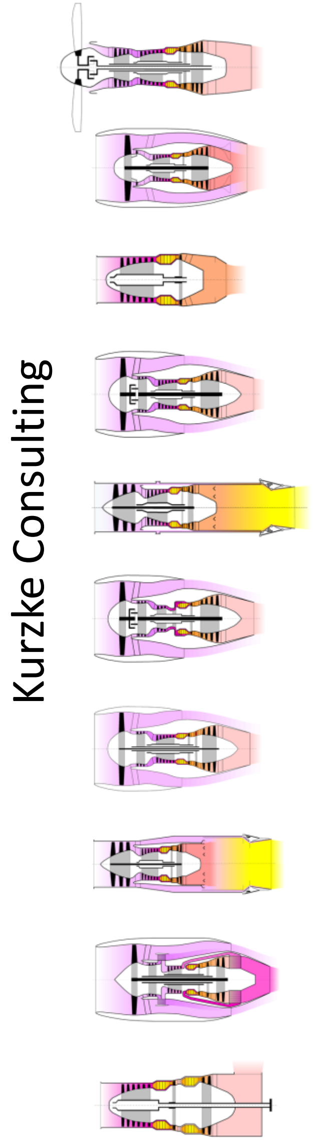
T_3 Compressor Exit

T_4 Burner Exit

T_5 Turbine Exit

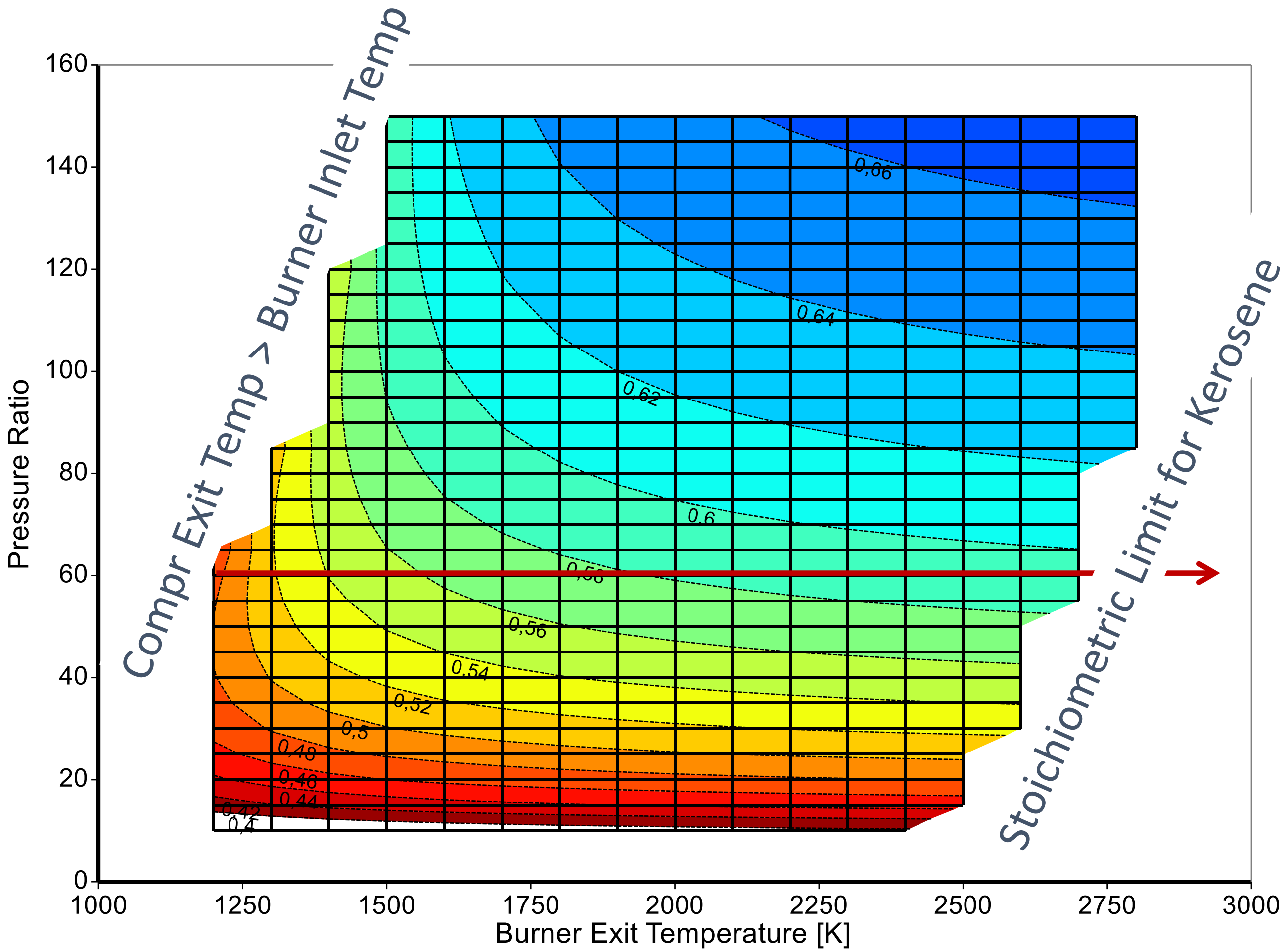
Different gas properties for compressor and turbine:

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



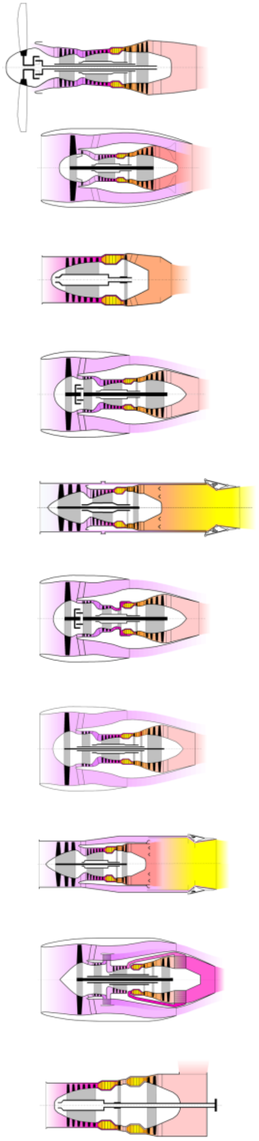
Thermal Efficiency

Schoolbook Equation



$\gamma_C = 1.4$
$\gamma_T = 1.3$
$\eta_C = 0.9$
$\eta_T = 0.9$

Schoolbook:
η increases with T_4



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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:

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

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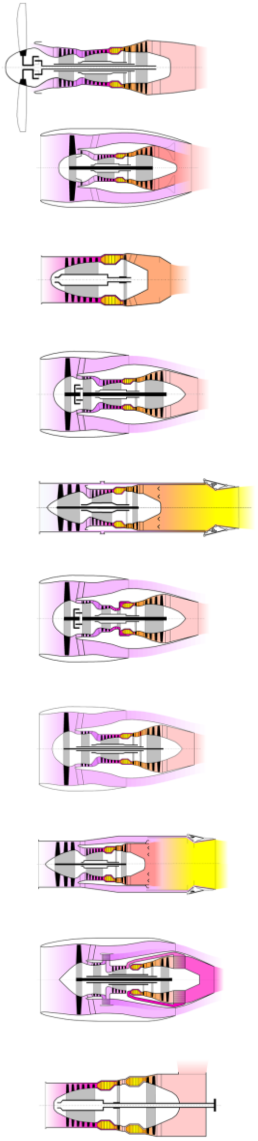
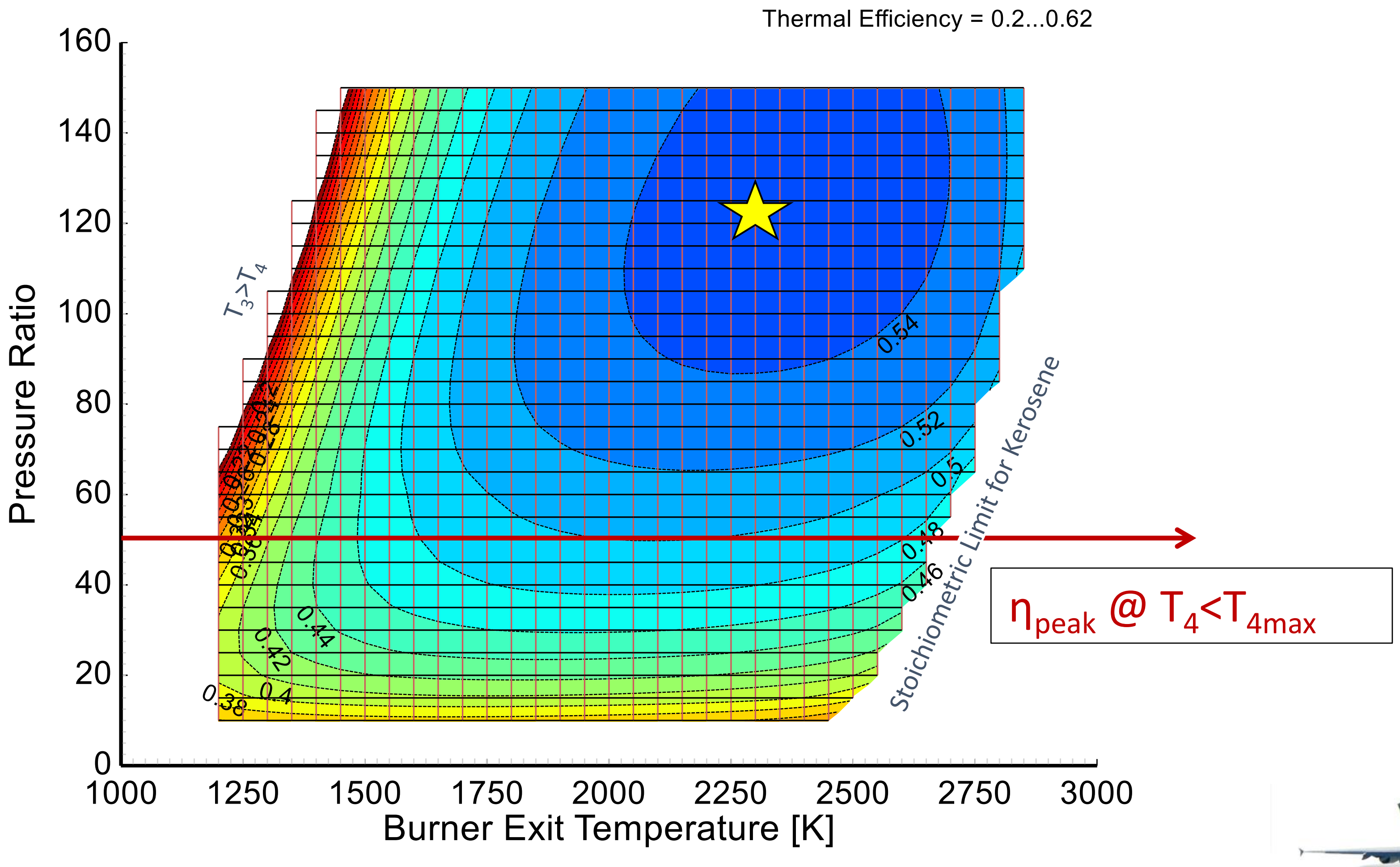


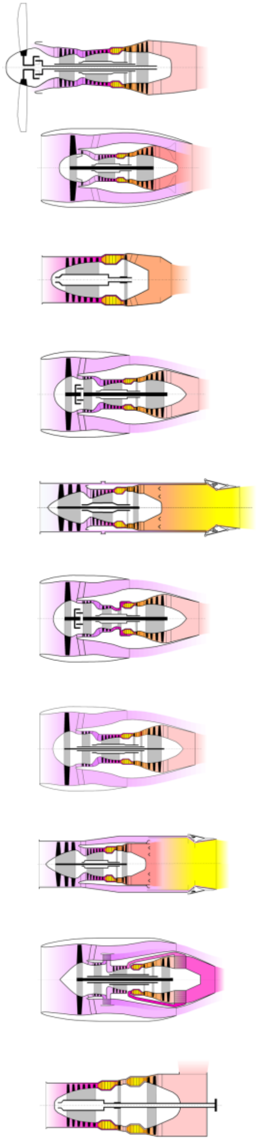
Thermal Efficiency

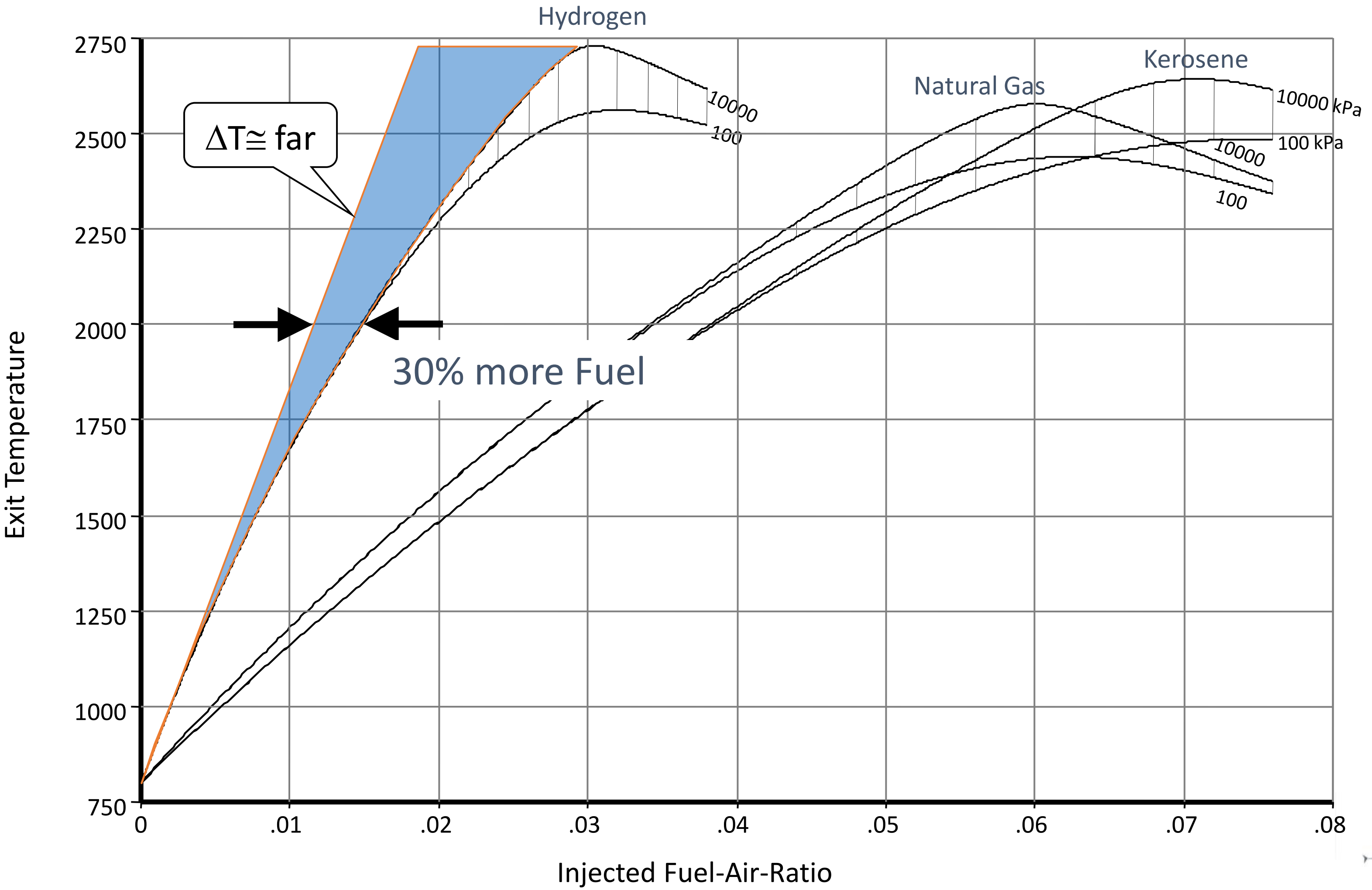
Compressors and Turbines η_{pol}=0.9, no Cooling Air



Temperature Increase in the Burner

Chemical Equilibrium





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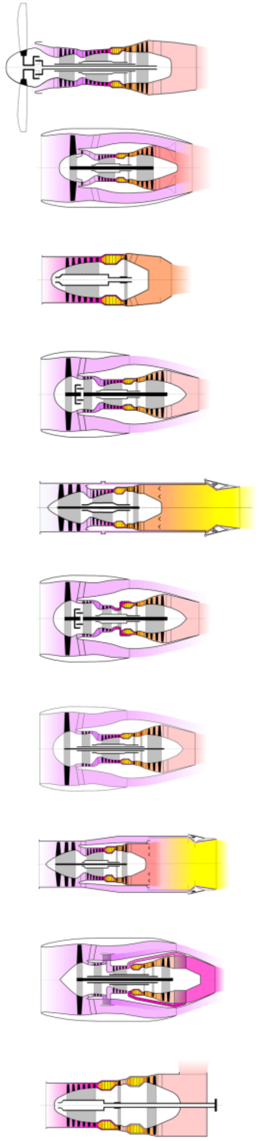
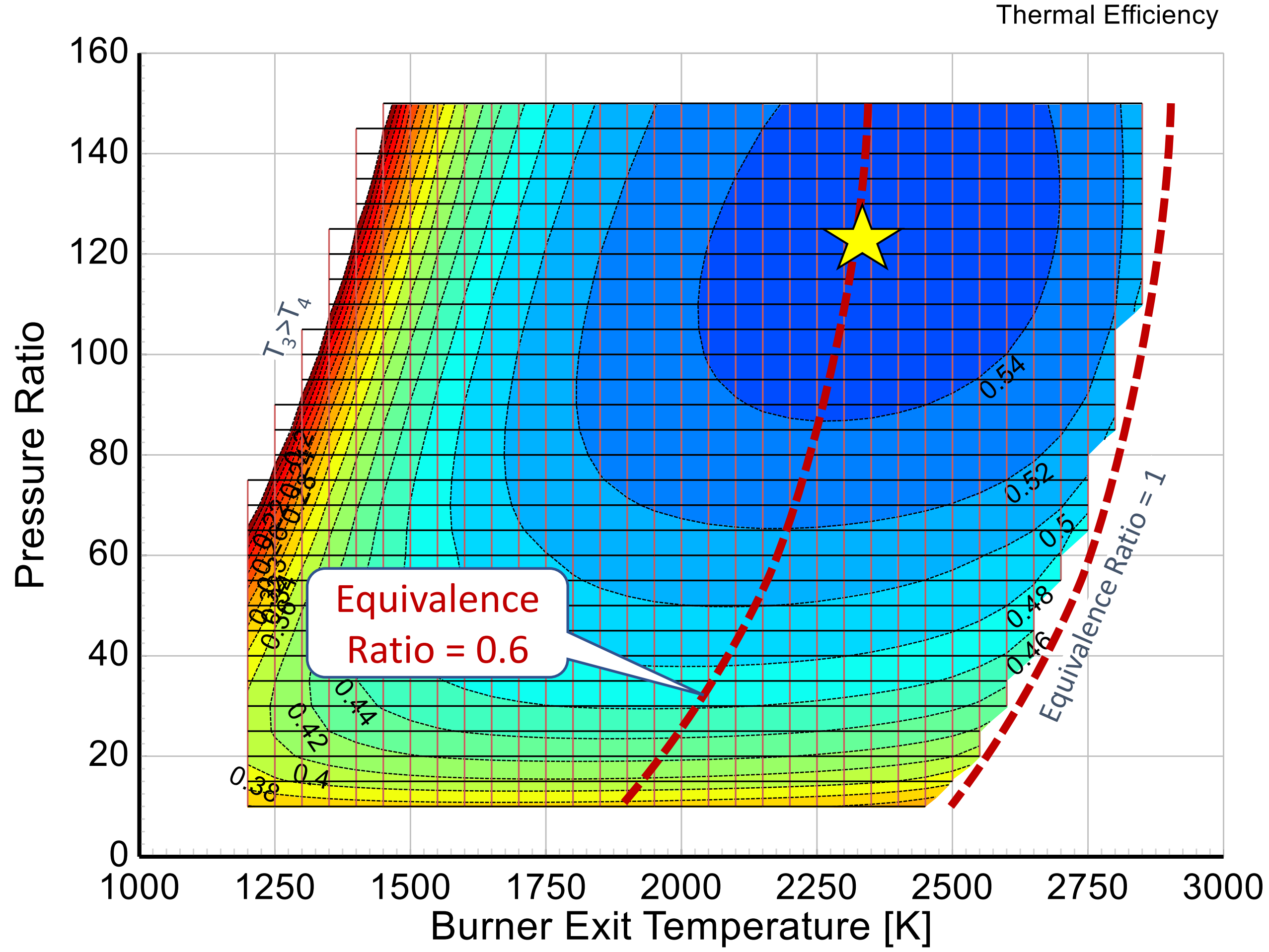


Compressors and Turbines η_{pol}=0.9, No Cooling Air

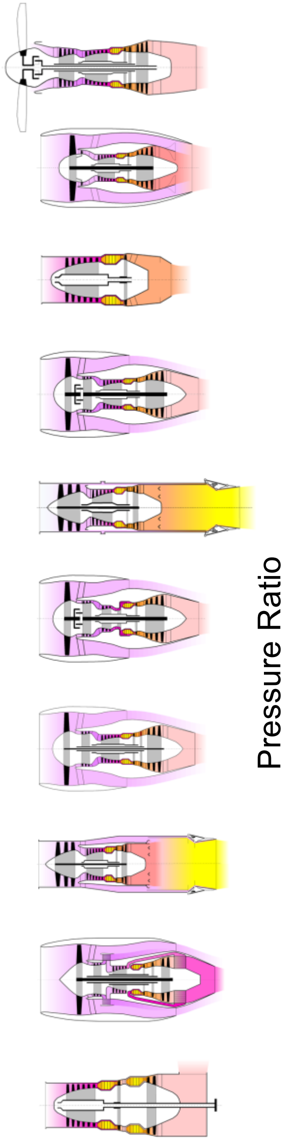
Thermal Efficiency



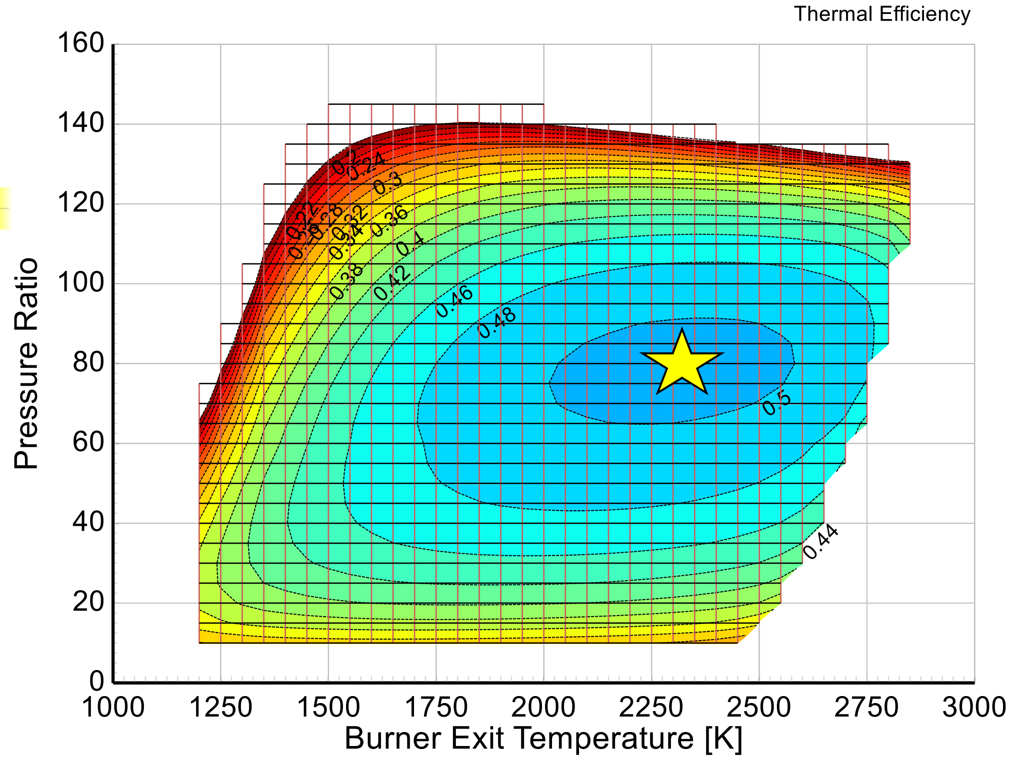
$$\eta_{th} = \frac{PW_{SD}}{W_F * FHV}$$

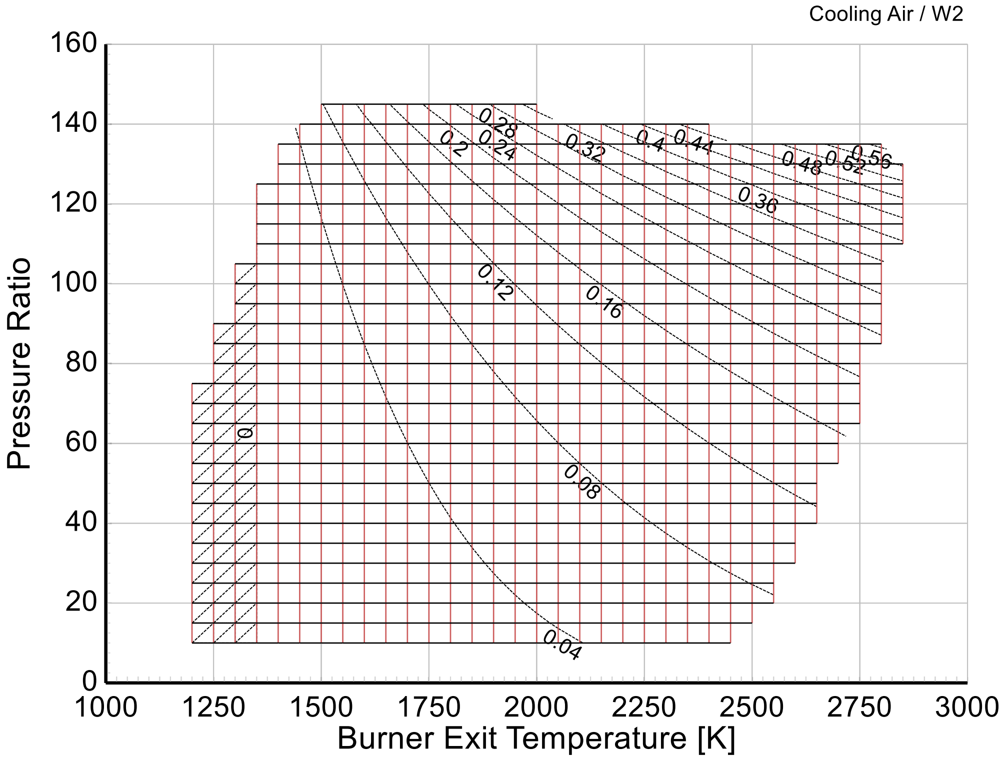
Compressors and Turbines η_{pol}=0.9, With Cooling Air

Thermal Efficiency



Kurzke Consulting





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

Specific Power

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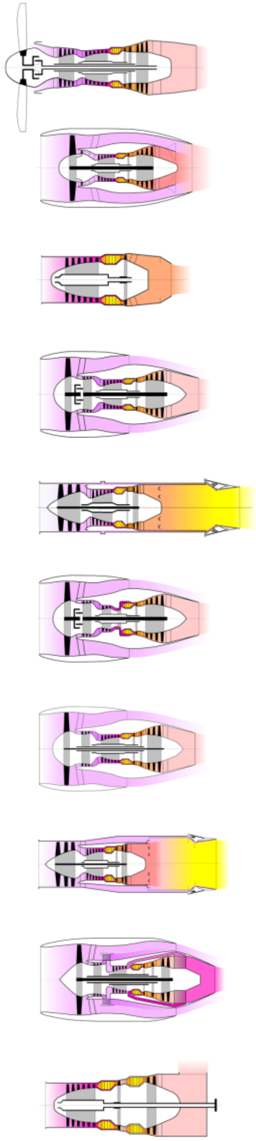
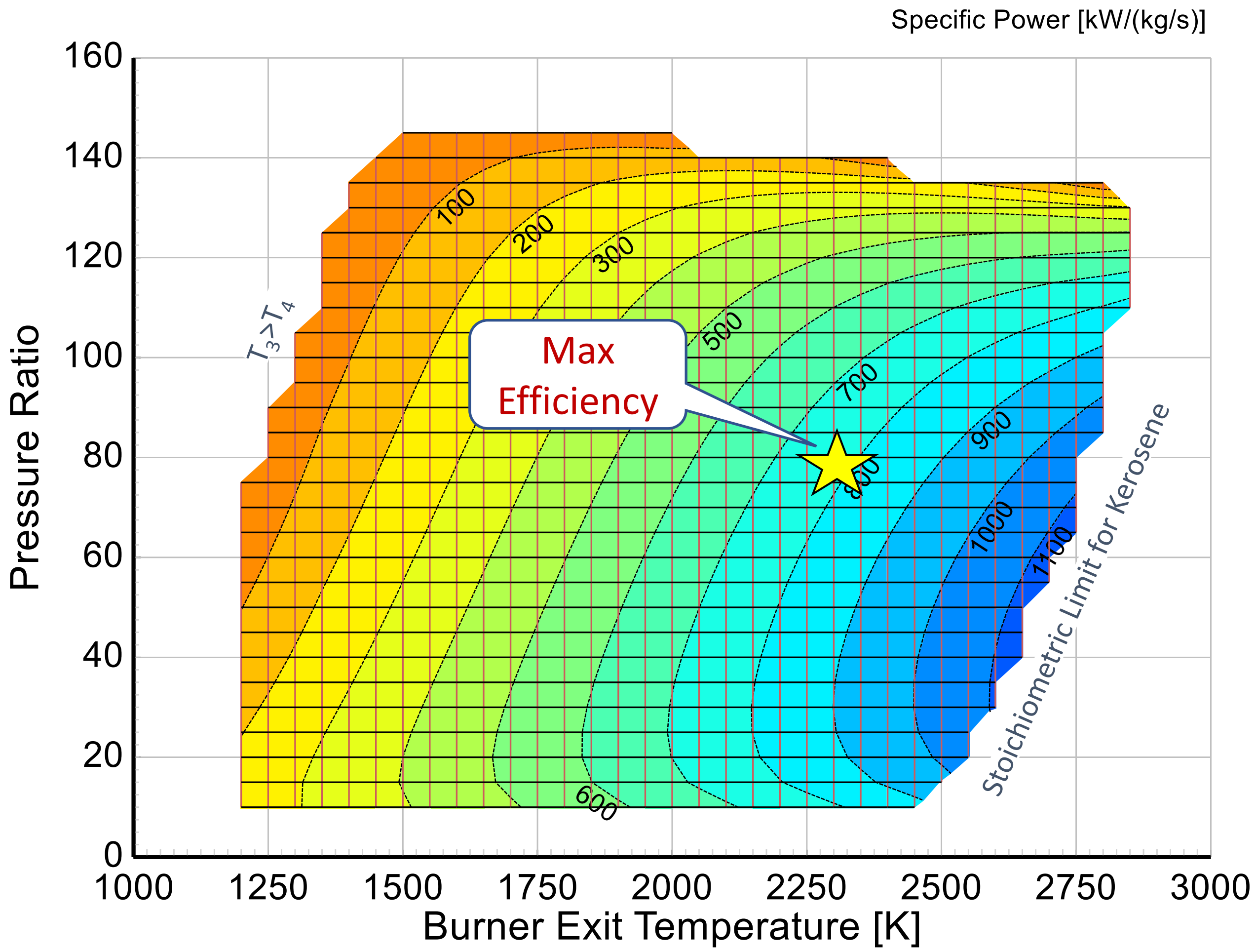
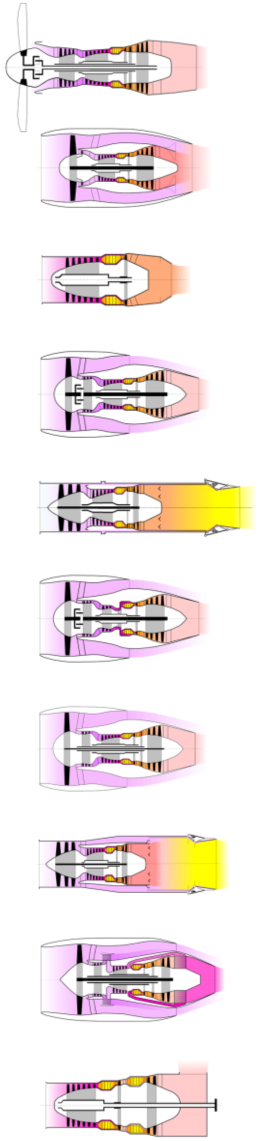




Kurzke Consulting



Outline

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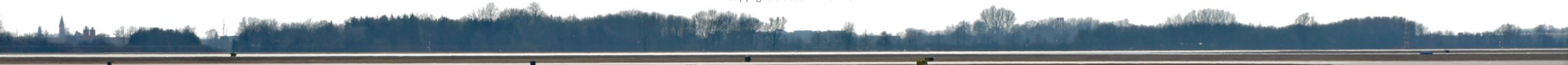
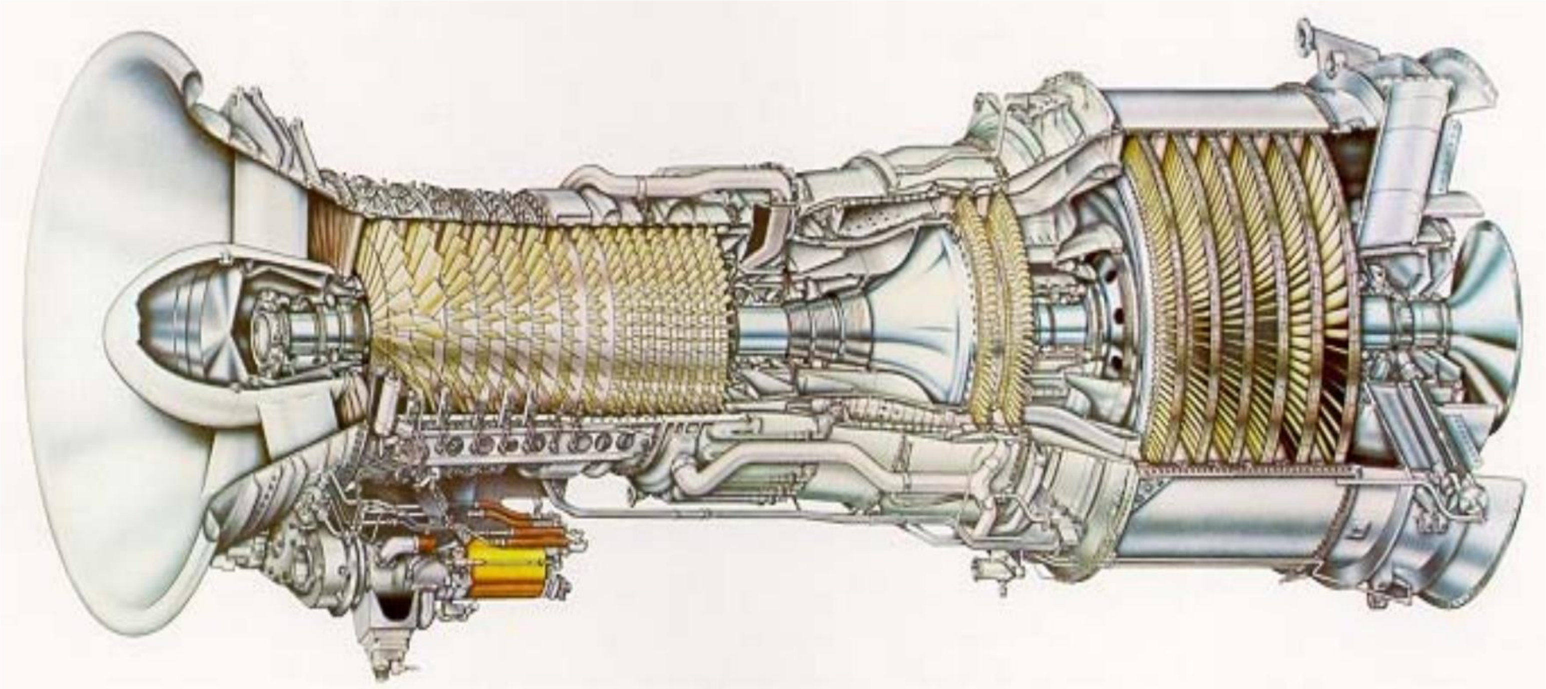
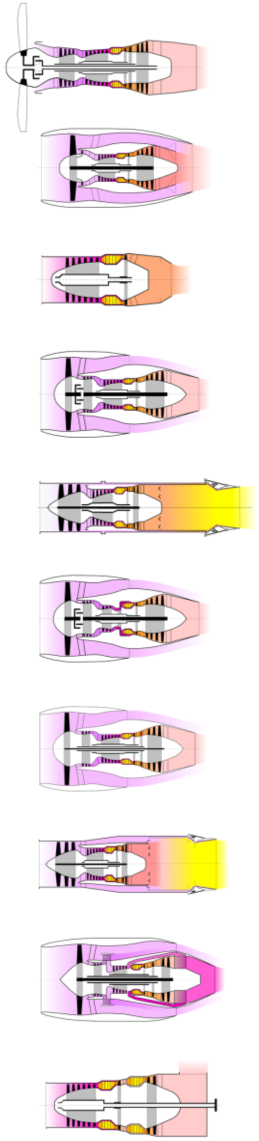
- Ideal Cycles
- Thermal Efficiency
- **Power Generation**
- Aircraft Propulsion
- Fundamental Design Decisions
- Non-Dimensionals
- Turbojet Off-Design



Aero-Derivative
LM2500





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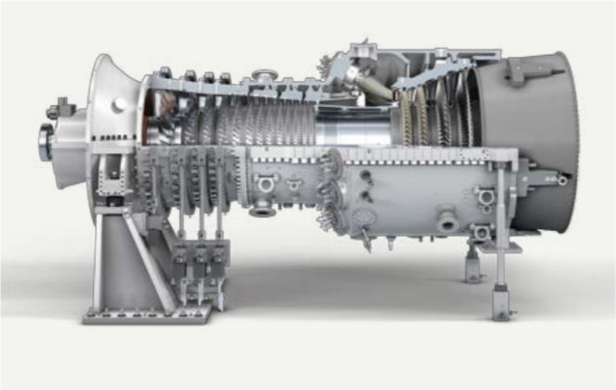
Simple Cycle

SGT-8000H Gas Turbine

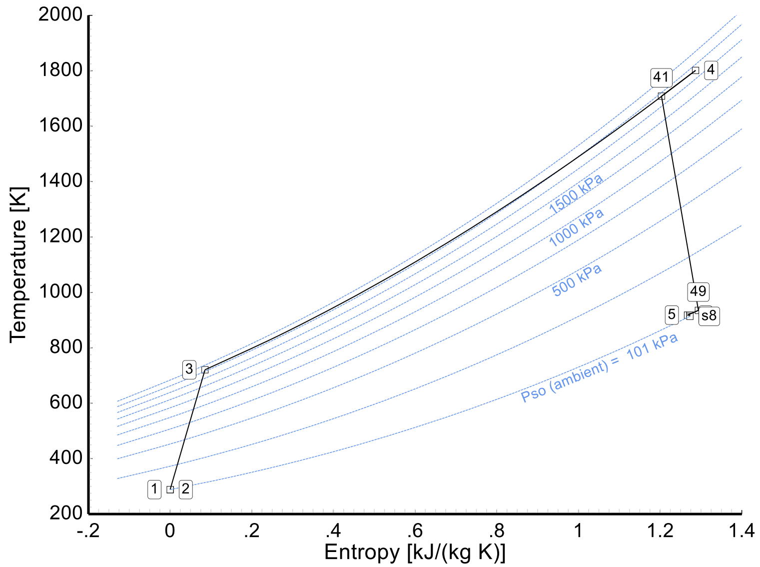


SGT5-8000H

SGT6-8000H

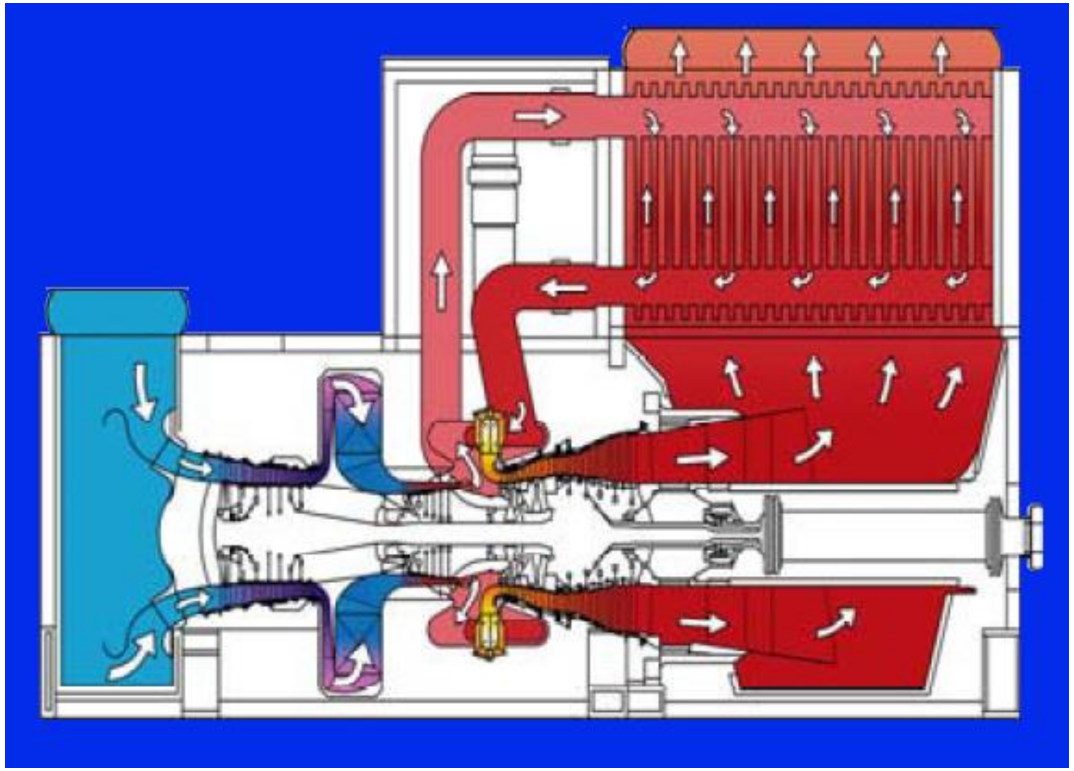
SGT5-8000H gas turbine	
Frequency	50 Hz
ISO base power output	400 MW
Efficiency	40 %
Exhaust mass flow	869 kg/s / 1,915 lb/s
Exhaust temperature	627 °C / 1,161 °F
Physical dimensions	
Weight	445 t
Length x Height x Width	12.6 m x 5.5 m x 5.5 m 41 ft x 18 ft x 18 ft
Combined cycle plant (single-shaft,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

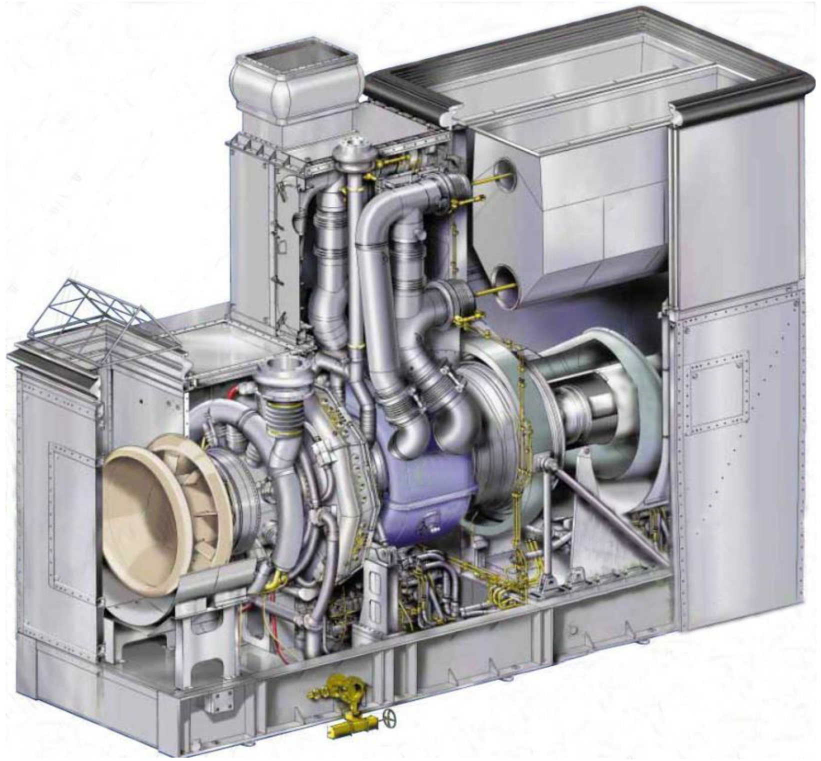
SGT6-8000H gas turbine	
Frequency	60 Hz
ISO base power output	296 MW
Efficiency	40 %
Exhaust mass flow	640 kg/s / 1,410 lb/s
Exhaust temperature	630 °C / 1,166 °F
Physical dimensions	
Weight	289 t
Length x Height x Width	10.5 m x 4.3 m x 4.3 m 34 ft x 14 ft x 14 ft
Combined cycle plant (single-shaft,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

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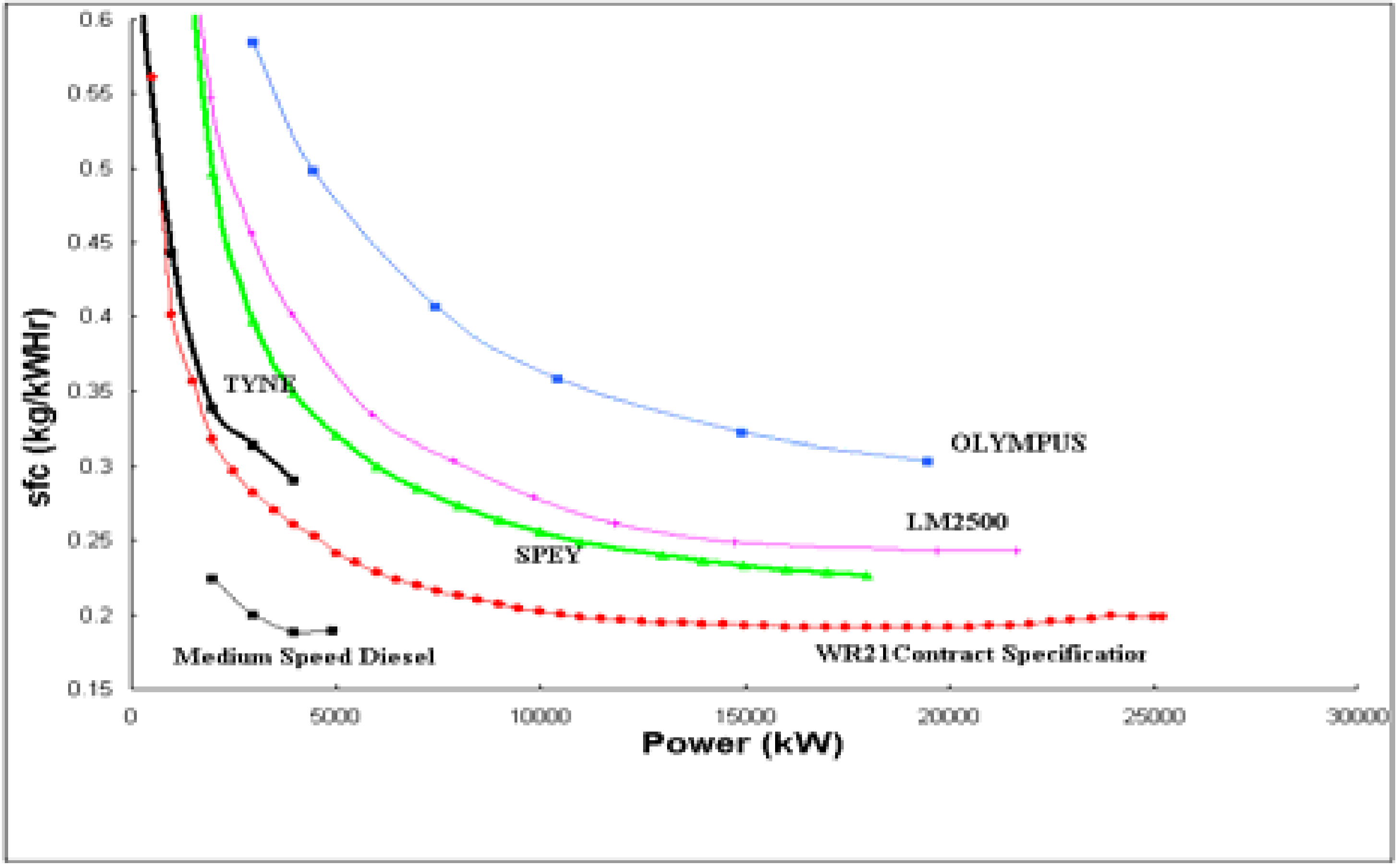
RR WR-21

Specific Fuel Consumption SFC



Ref. IGTC2003Tokyo OS-203

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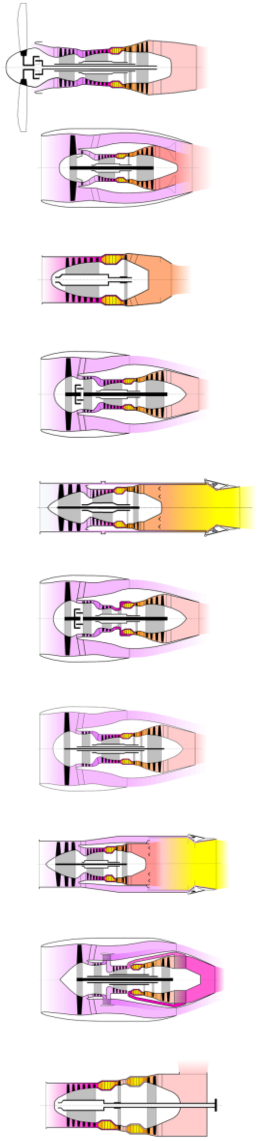
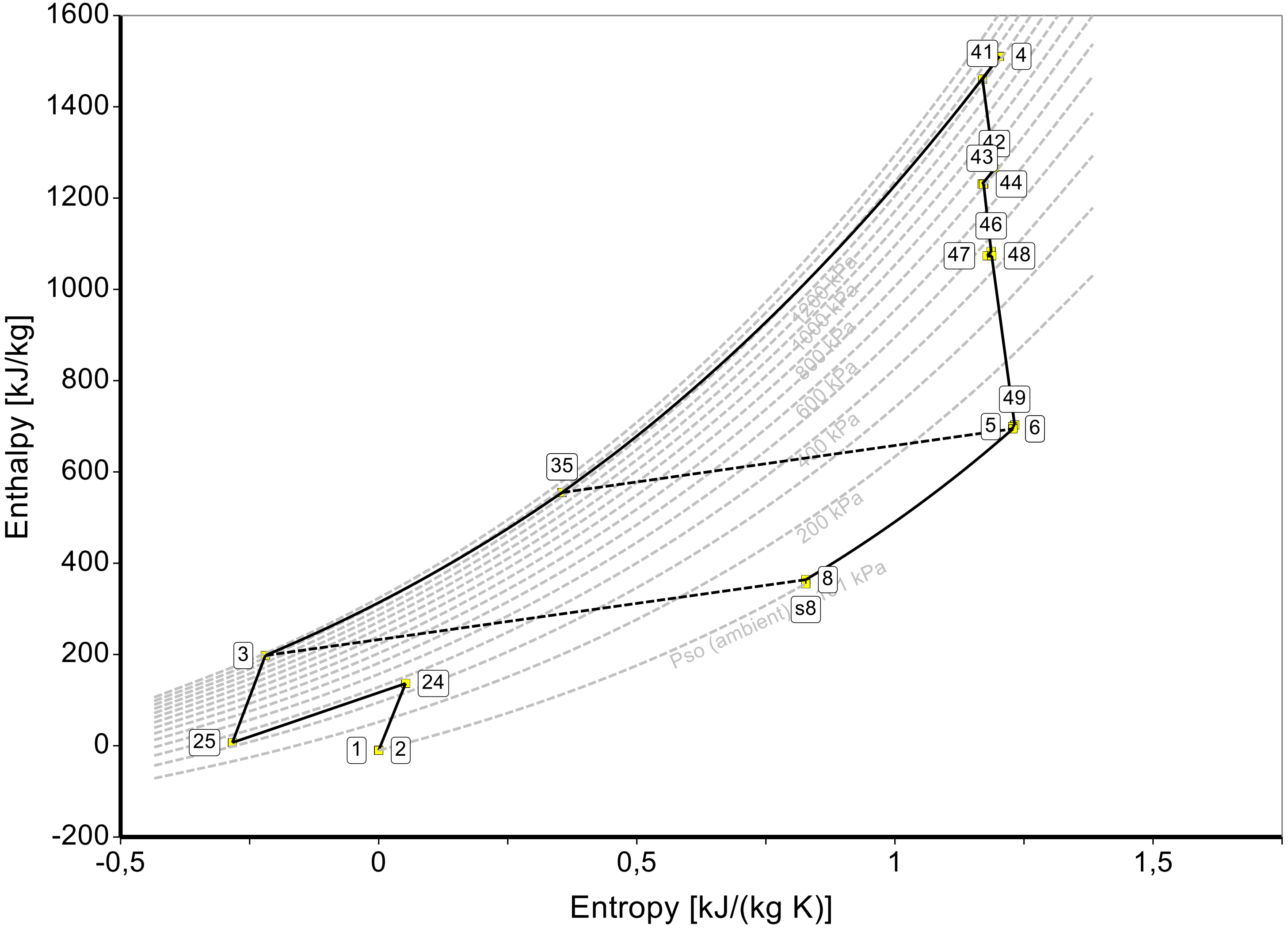


RR WR21
Full Power



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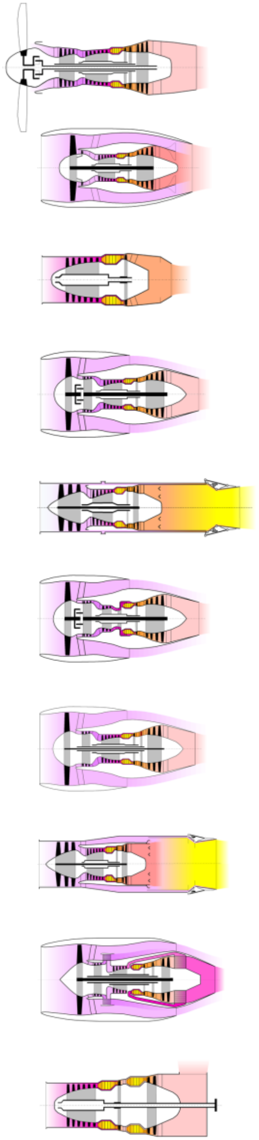
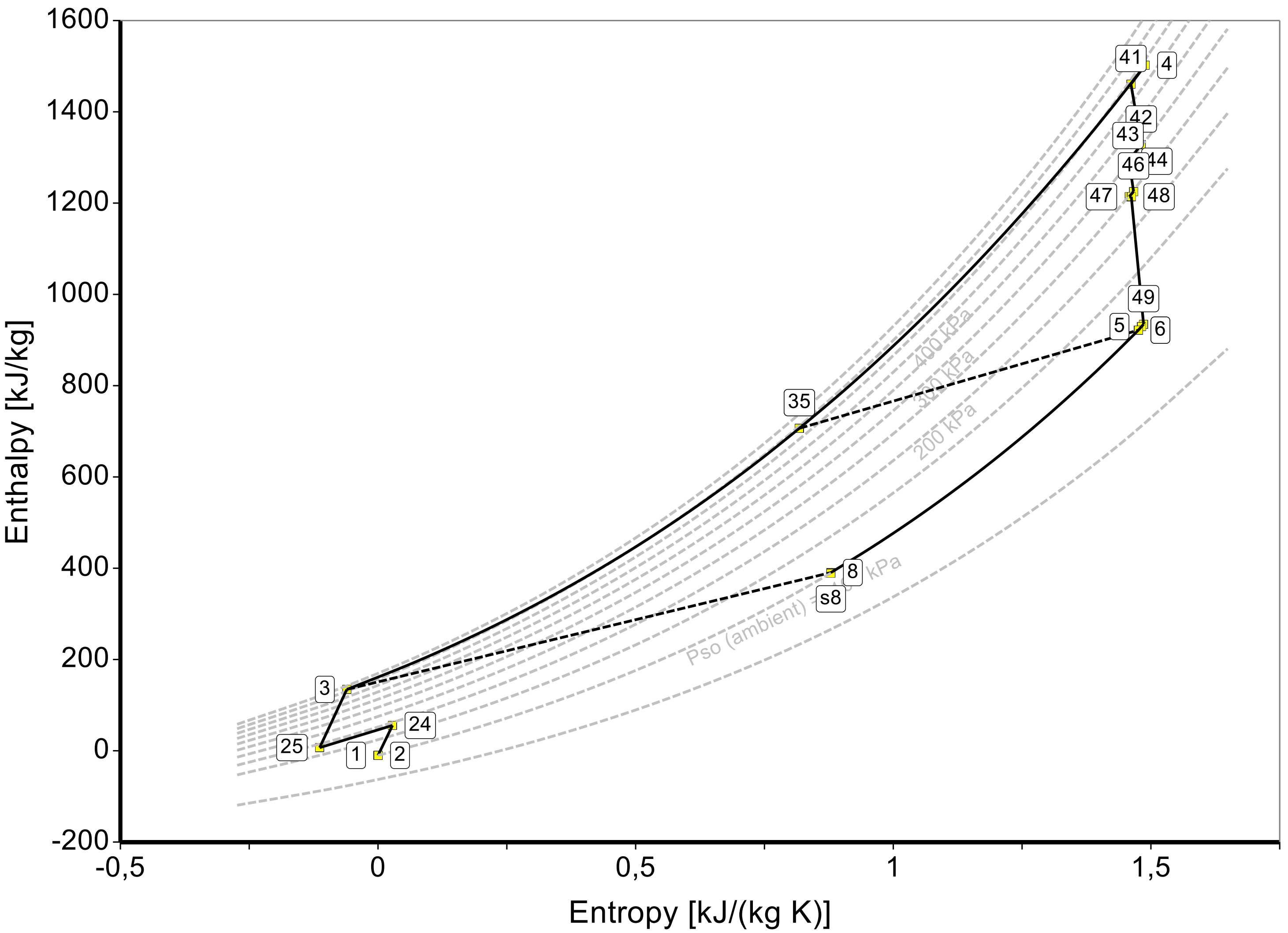
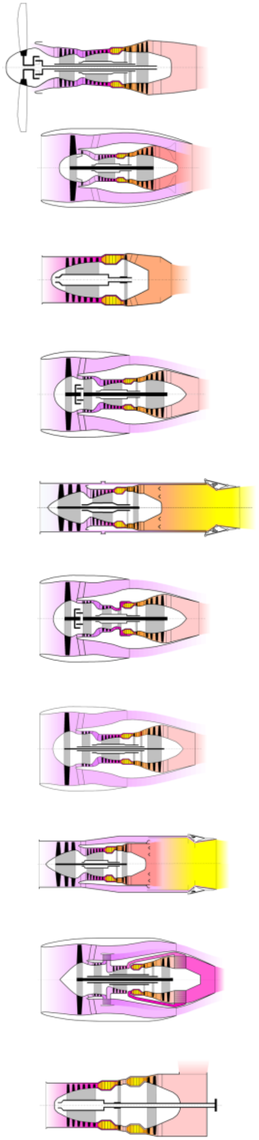


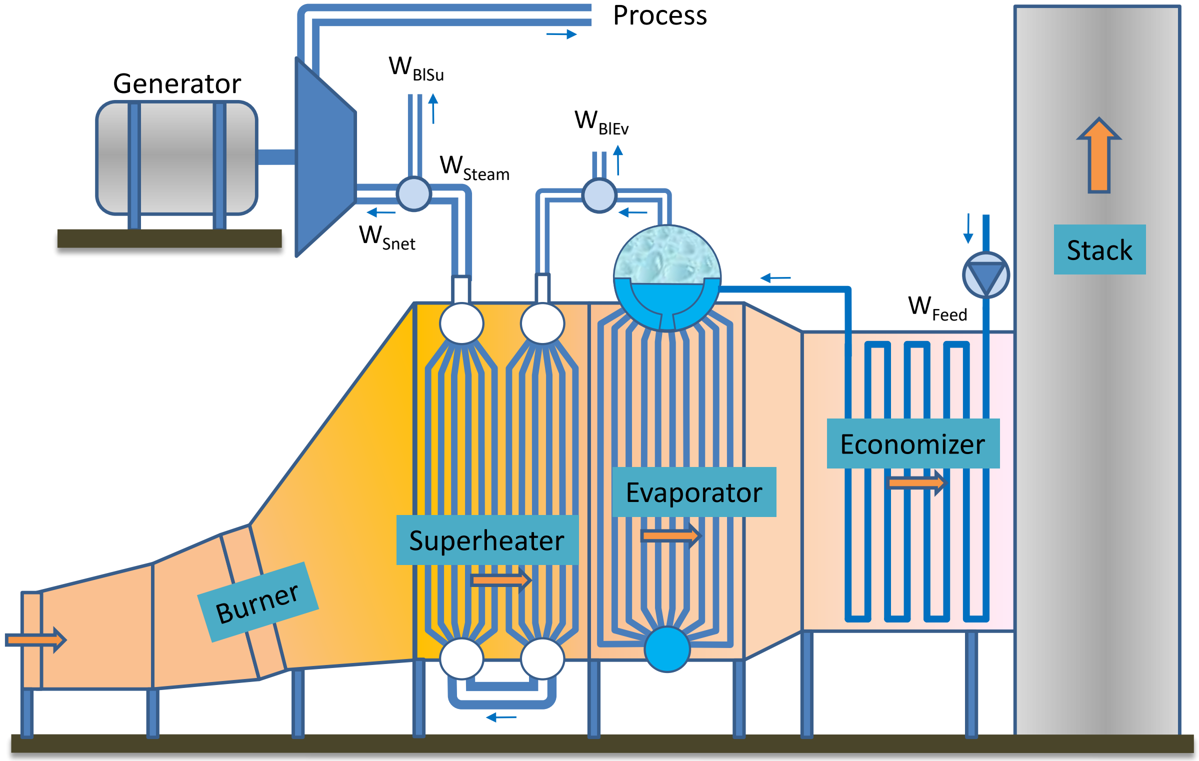
RR WR21
27% Power



Kurzke Consulting



Combined Cycle
Heat Recovery Steam Generator (HRSG)

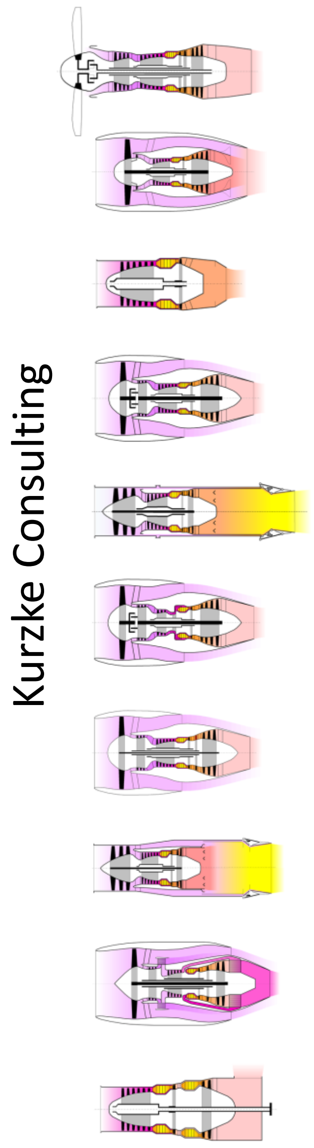


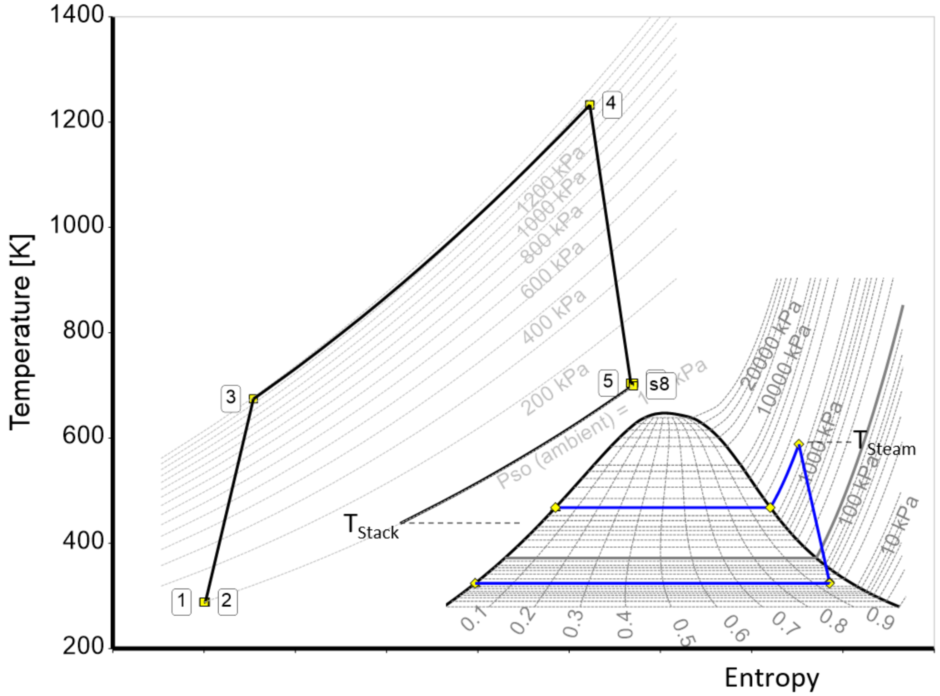
HRSGSinglePressTurb.emf

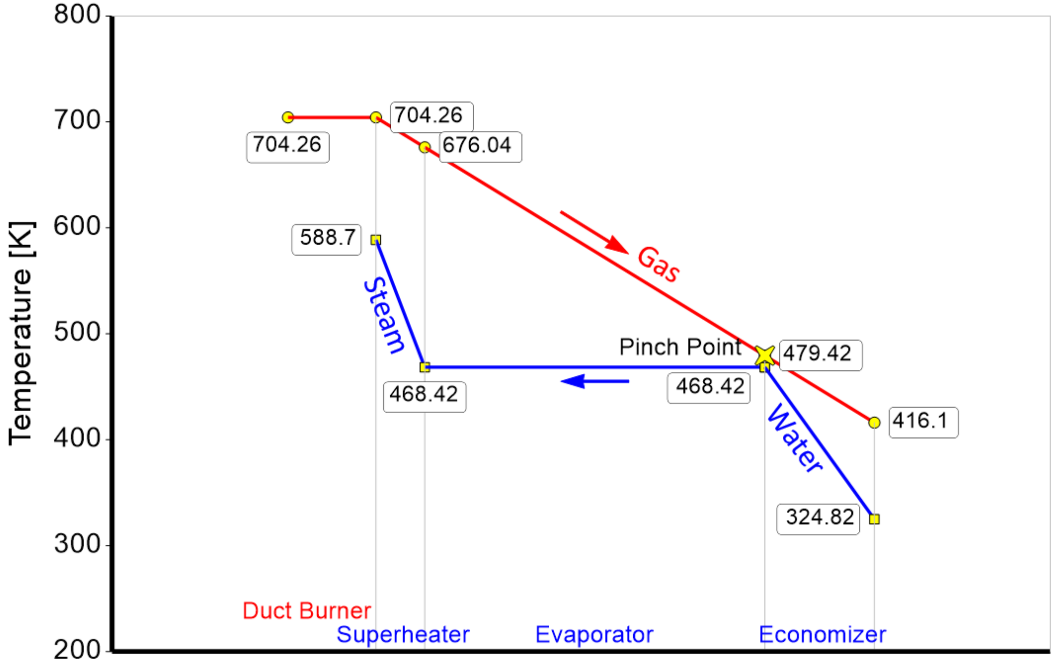
GasTurb

Combined Cycle

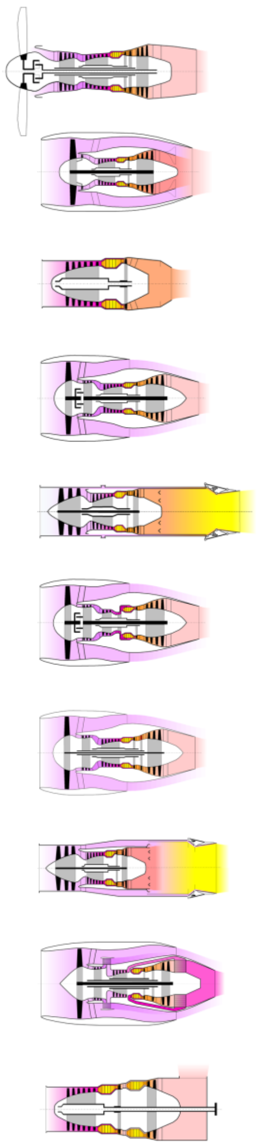
Joule and Rankine Cycle







Pinch Point Diagram



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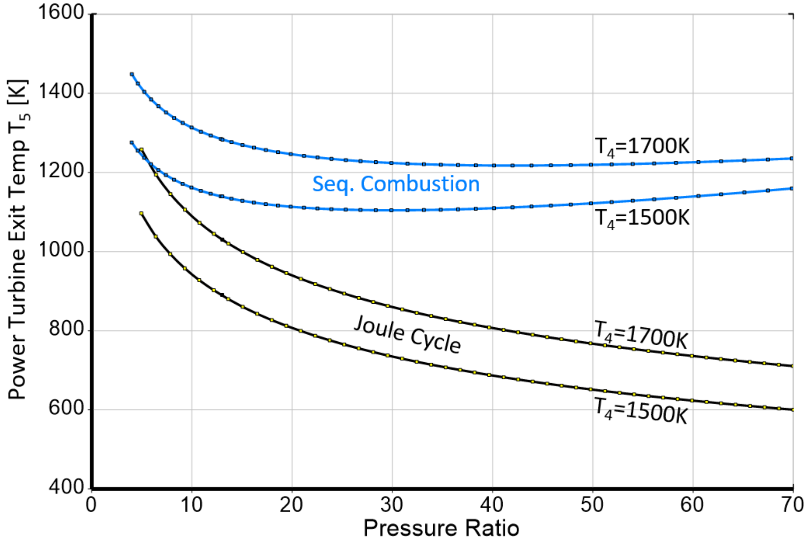
Sequential Combustion
Alstom GT24/GT26

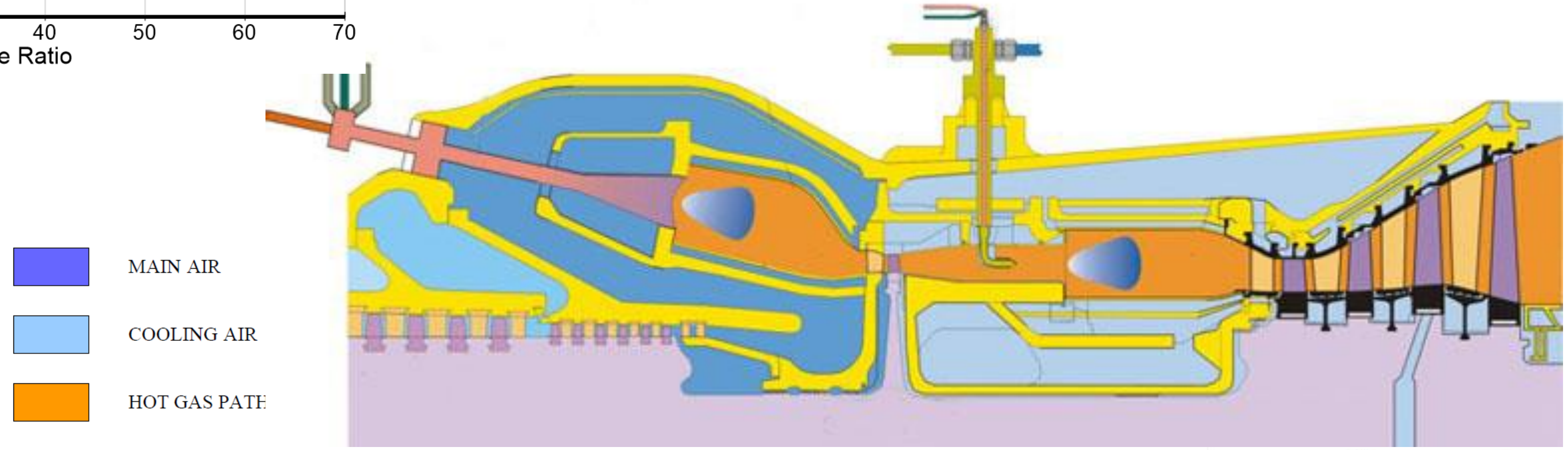


GT24

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



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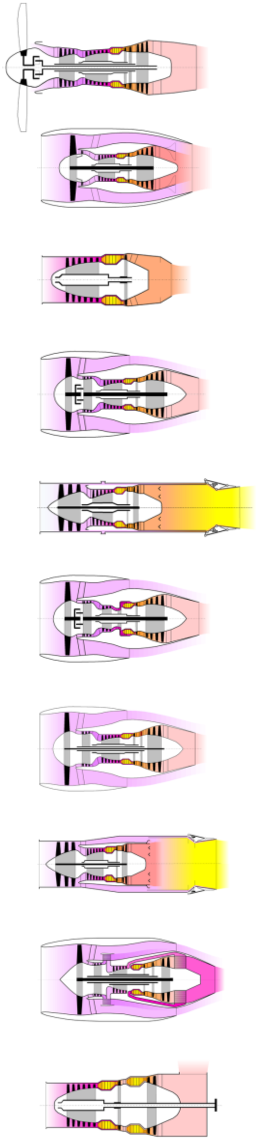
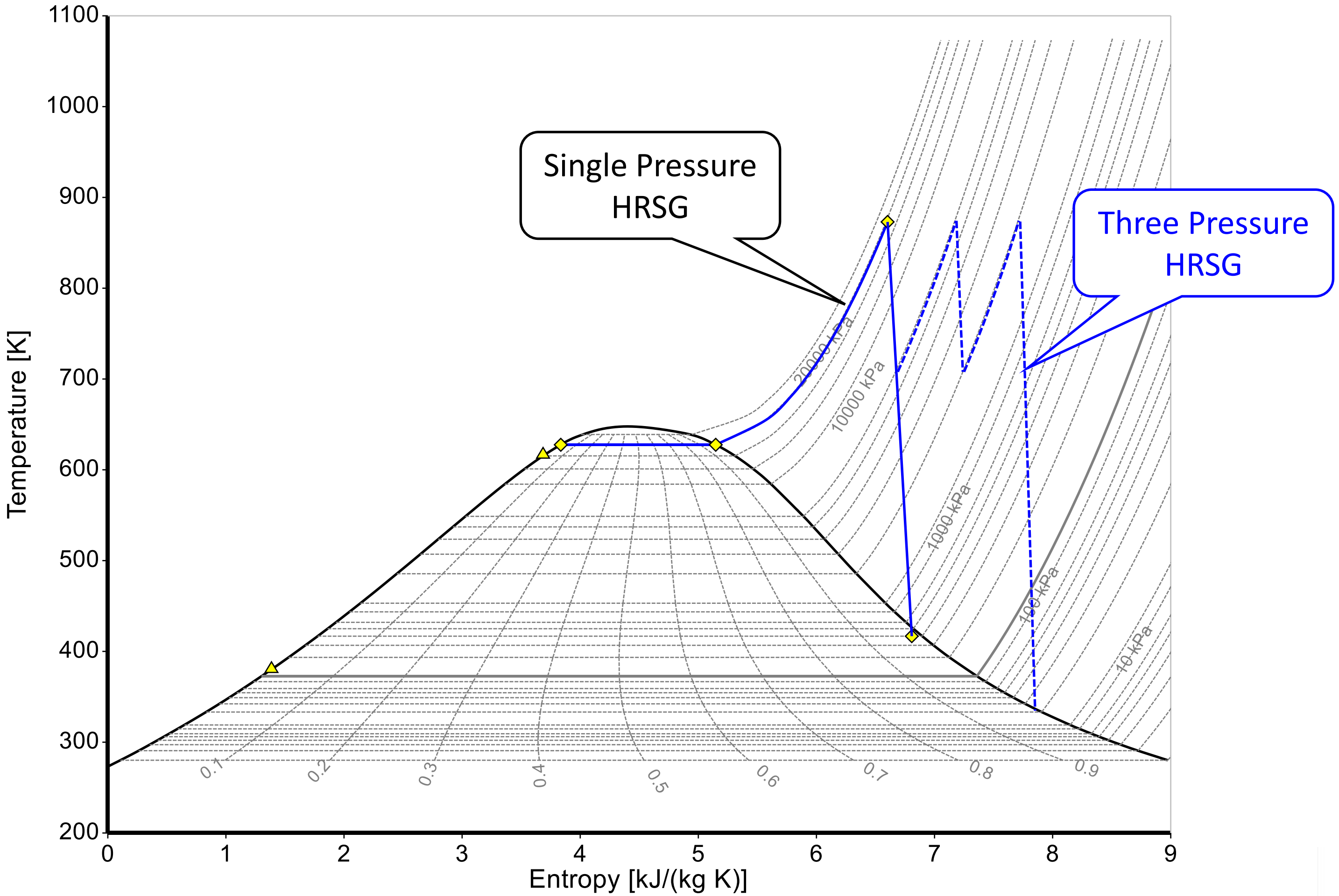


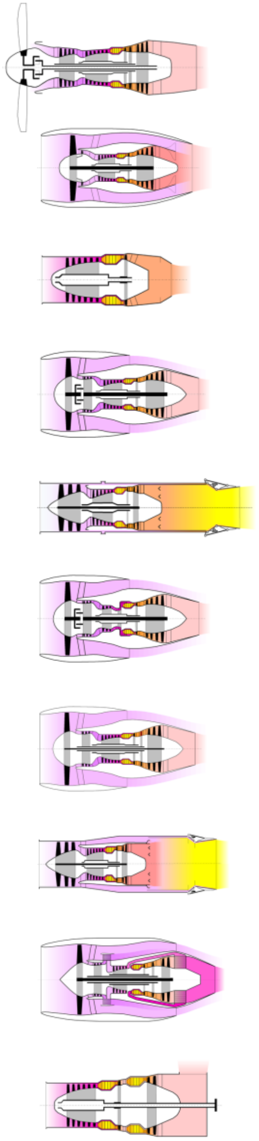
Combined Cycle
Steam Cycle



08.02.2017

GasTurb 13

Kurzke Consulting



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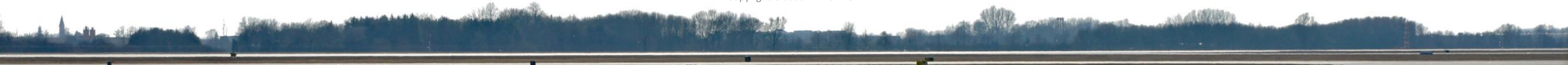

From Turboshaft to Turbojet

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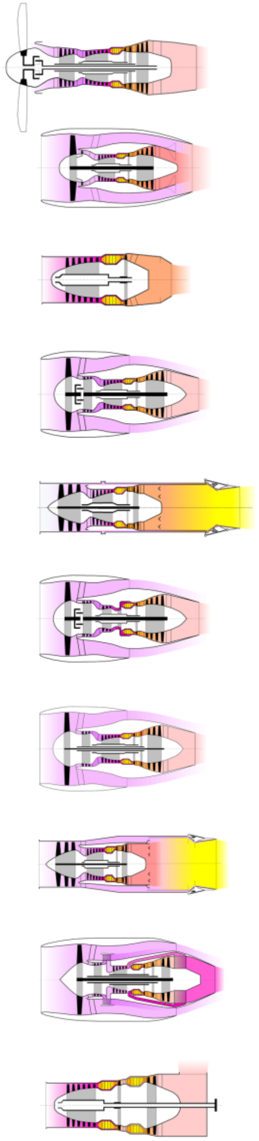

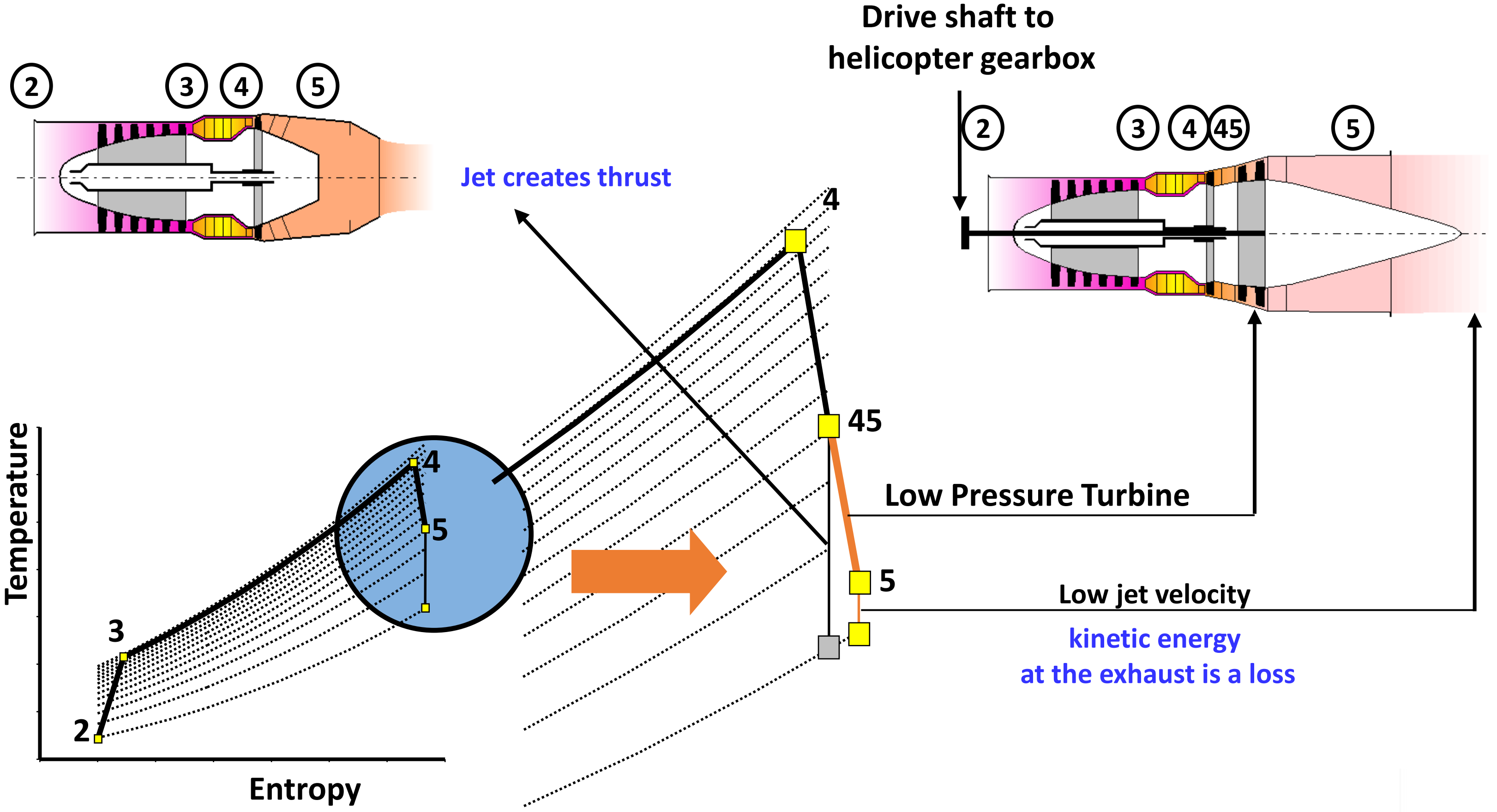

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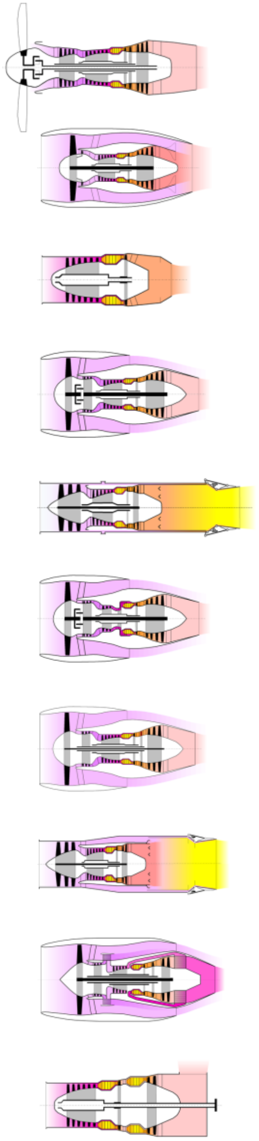


Thermal Efficiency @ SLS

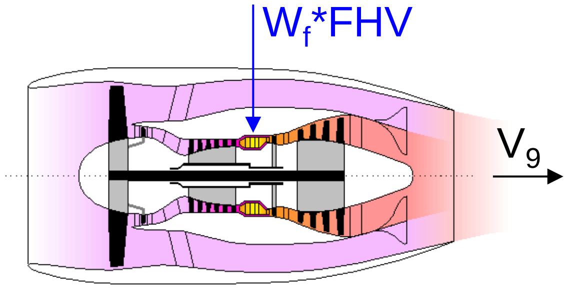
Thermal efficiency is defined as

increase of the kinetic energy of the gas stream

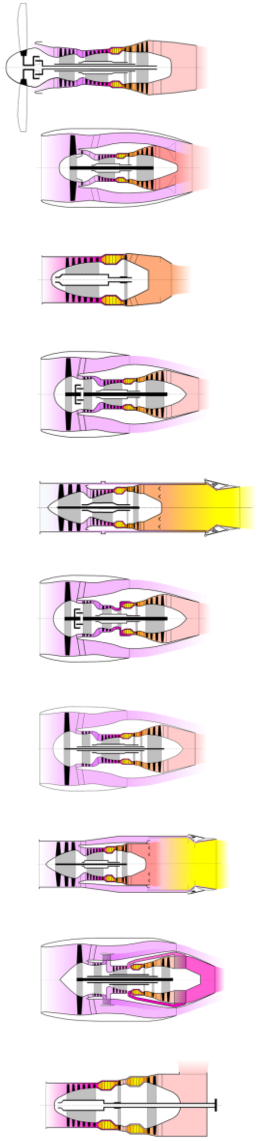
over

the amount of heat employed

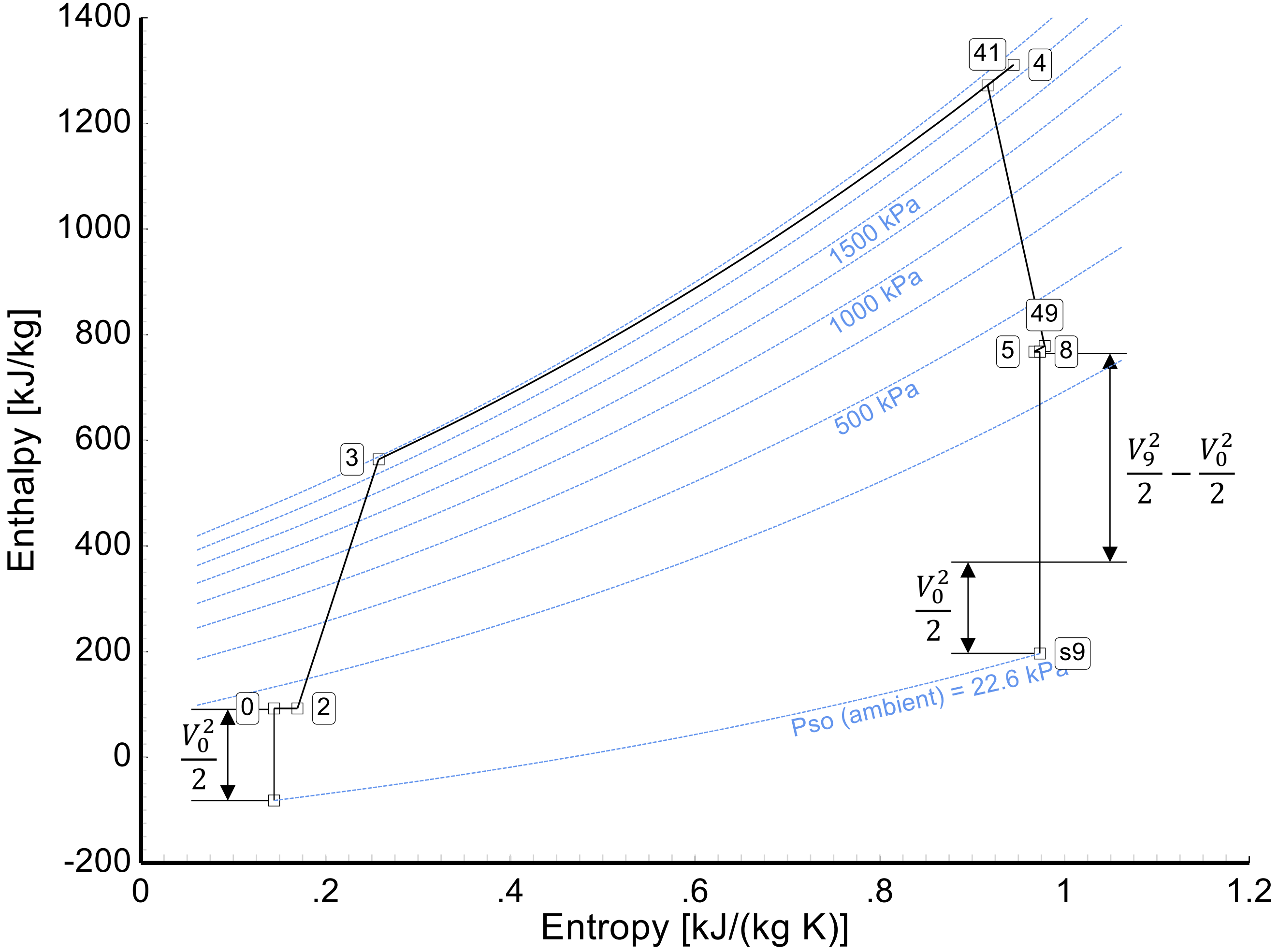
the product of fuel mass flow W_f and fuel heating value FHV

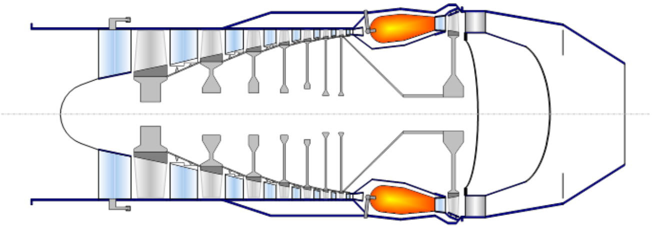


$$\eta_{th} = \frac{W_9 * \frac{V_9^2}{2}}{W_f * FHV}$$



Thermal Efficiency in Flight





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

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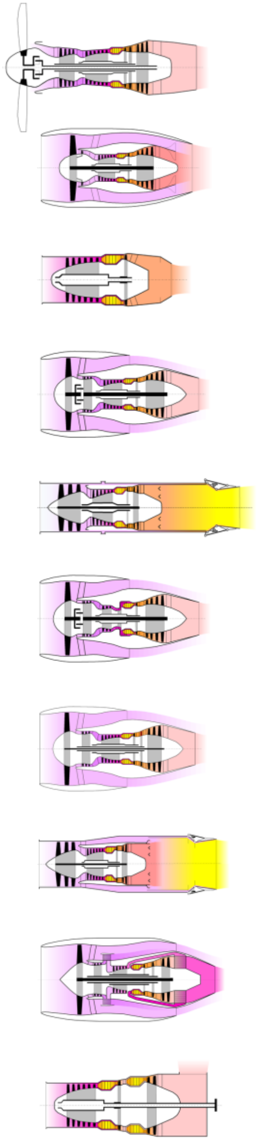


Propulsive Efficiency

Propulsive efficiency is the ratio of

useful propulsive energy

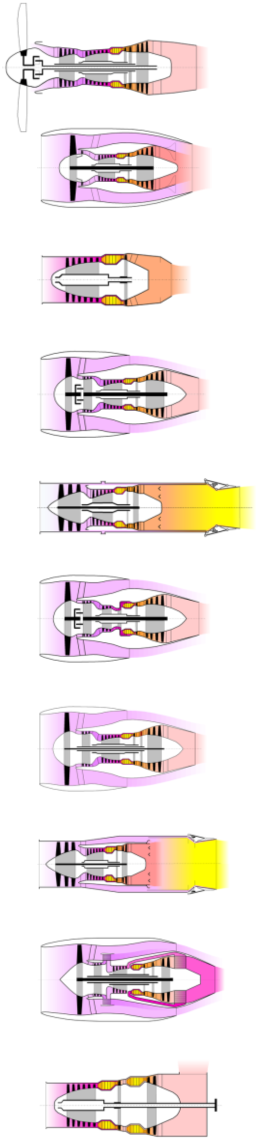
– the product of thrust and flight velocity –

compared to

the wasted kinetic energy of the jet:

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

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



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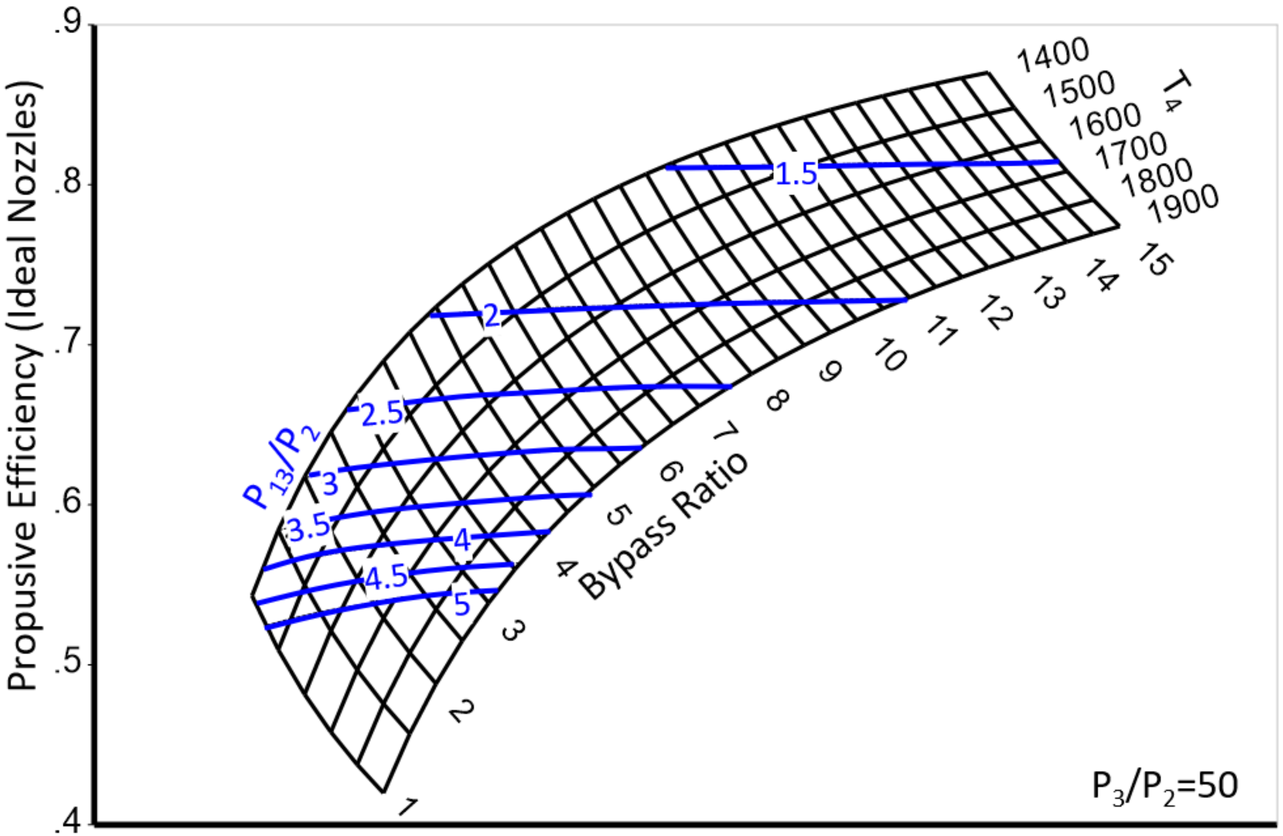
Propulsive Efficiency of Turbofans



- Higher bypass ratio means higher propulsive efficiency that's the popular opinion.
- However, this is only true for constant T_4.

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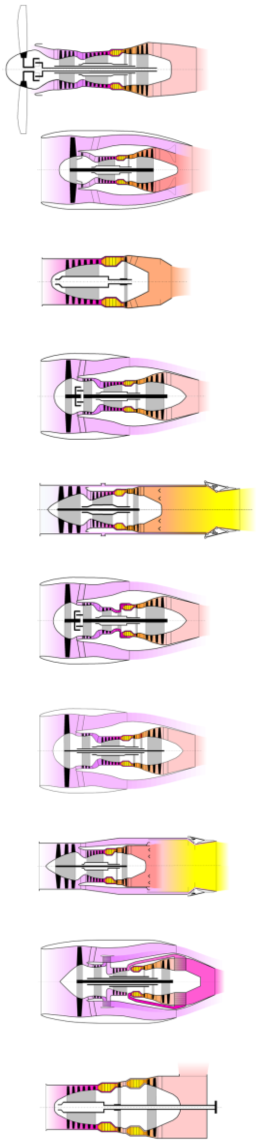

Overall Efficiency

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.

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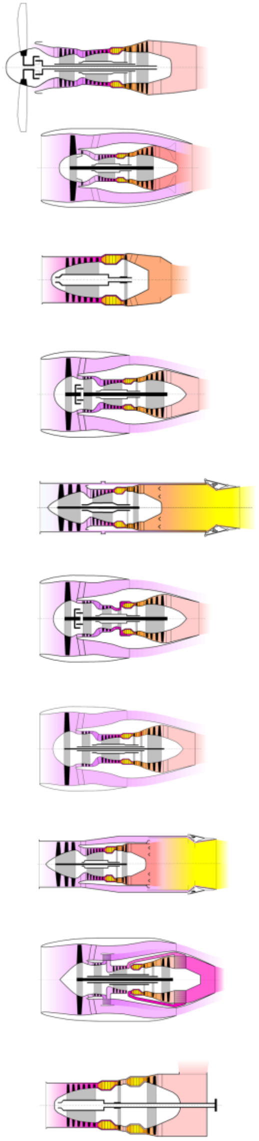

Specific Fuel Consumption

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

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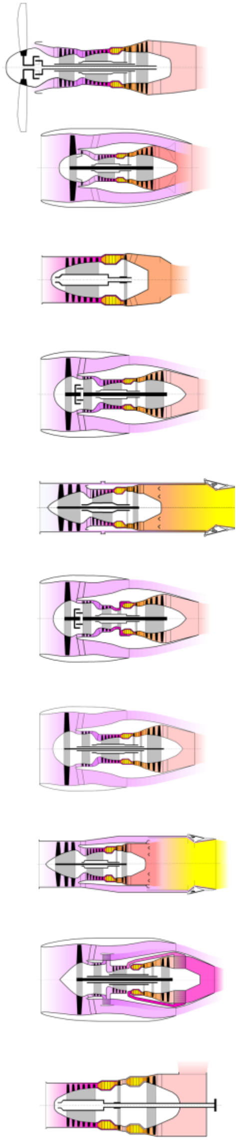

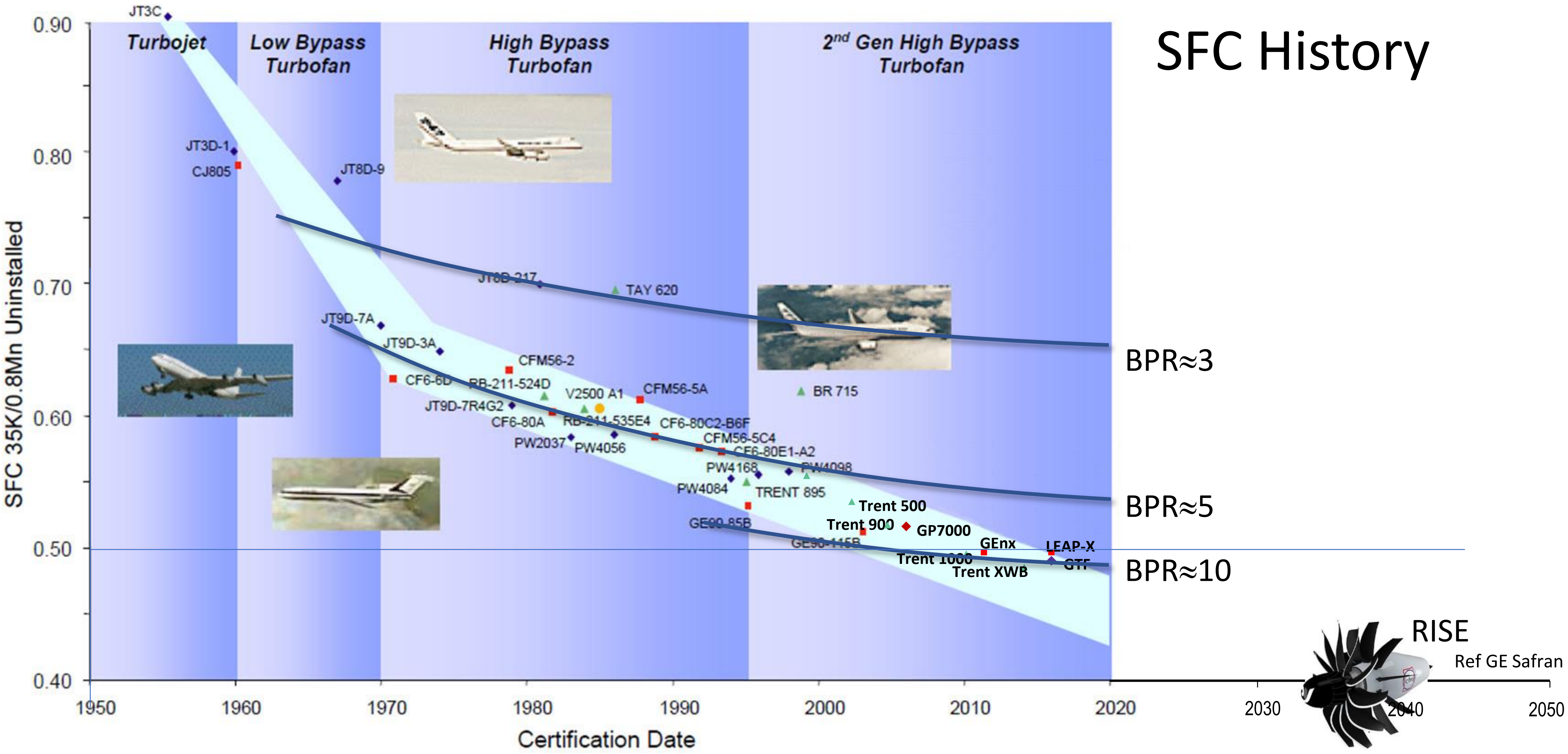
SFC 35K/0.8Mn Uninstalled
Certification Date
Turbojet
Low Bypass Turbofan
High Bypass Turbofan
2nd Gen High Bypass Turbofan
JT3C
JT3D-1
CJ805
JT8D-9
JT8D-217
TAY 620
JT9D-7A
JT9D-3A
CFM56-2
CF6-6D
RB-211-524D
V2500 A1
CFM56-5A
BR 715
JT9D-7R4G2
CF6-80A
RB-211-535E4
CF6-80C2-B6F
PW2037
PW4056
CFM56-5C4
CF6-80E1-A2
PW4168
PW4098
PW4084
TRENT 895
Trent 500
Trent 900
GP7000
GE90-85B
GE90-115B
GEnx
LEAP-X
Trent 1000
GTF
Trent XWB
BPR≈3
BPR≈5
BPR≈10
RISE
Ref GE Safran
0.90
0.80
0.70
0.60
0.50
0.40
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050

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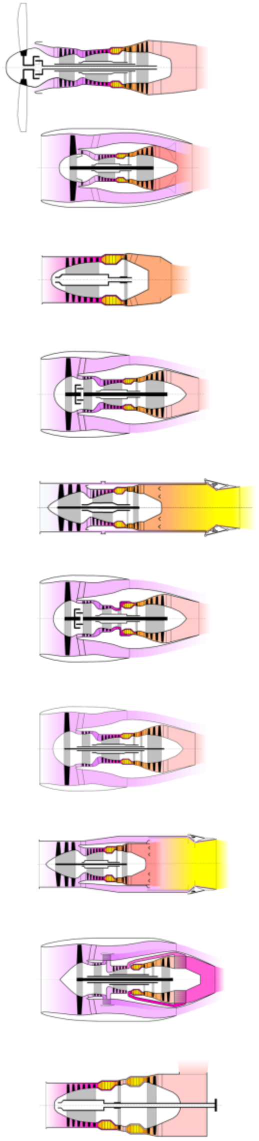
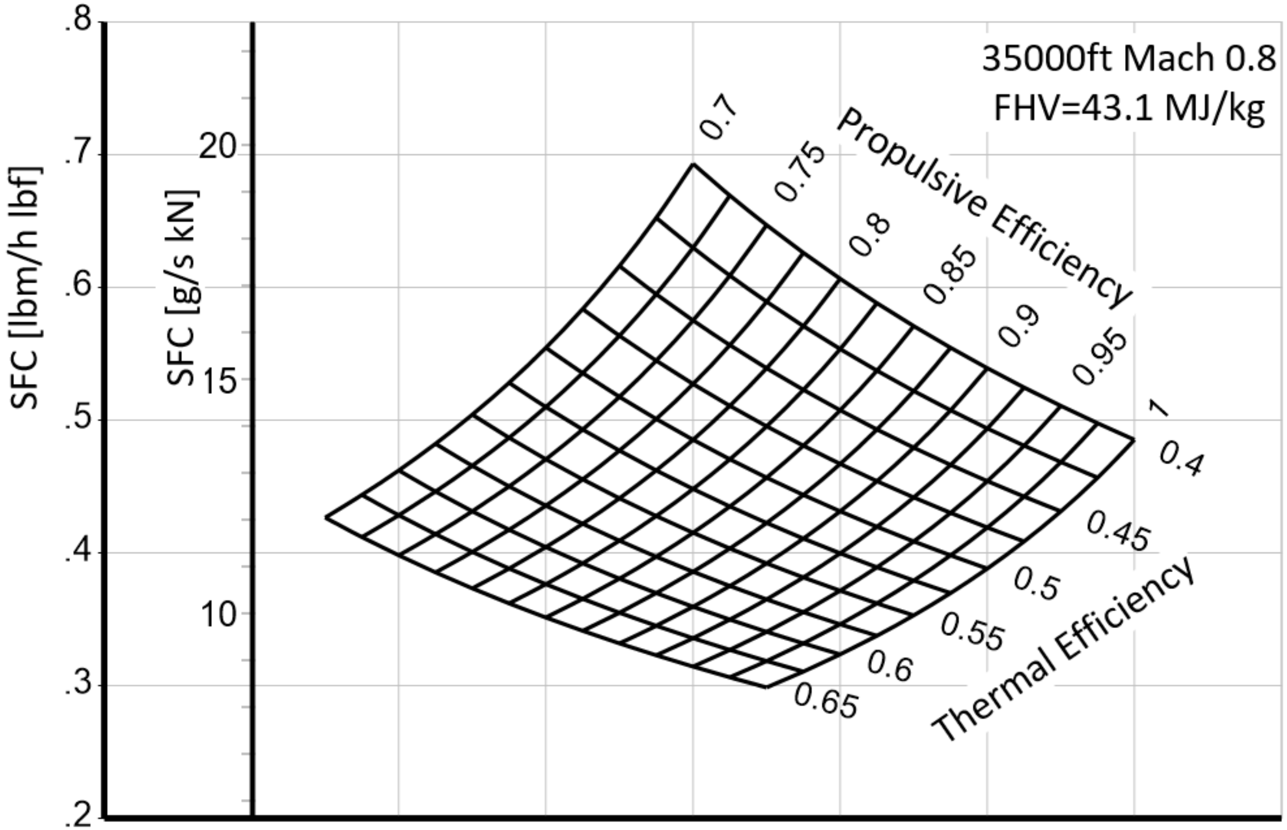


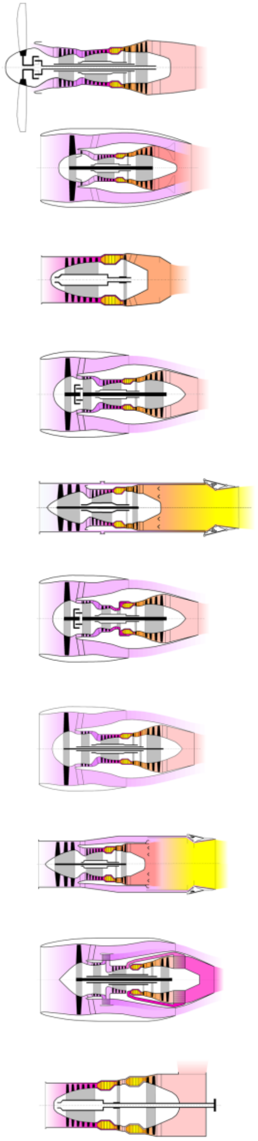
SFC = f(η_{therm}, η_{prop})



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

35000ft Mn 0.8 → V_0=237m/s

FHV=43.1 MJ/kg



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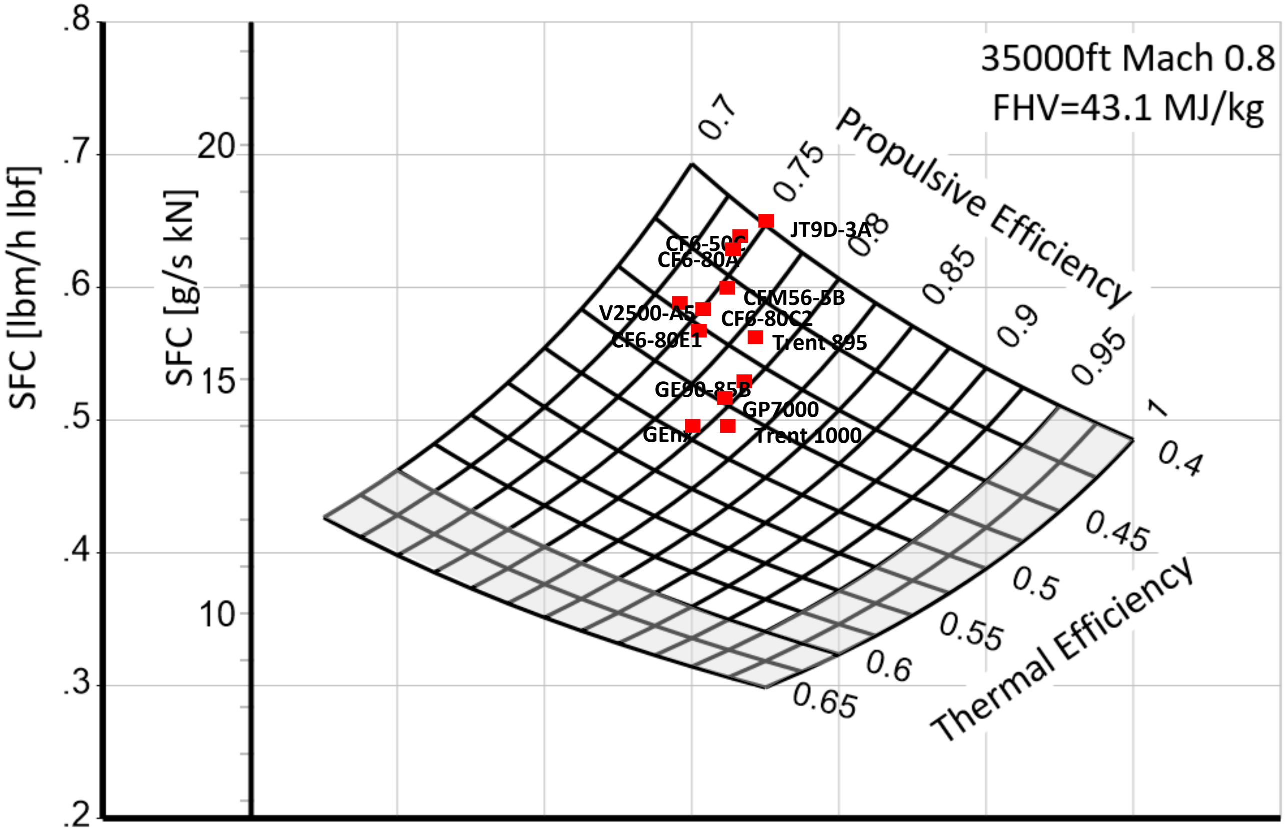
$SFC = f(\eta_{therm}, \eta_{prop})$



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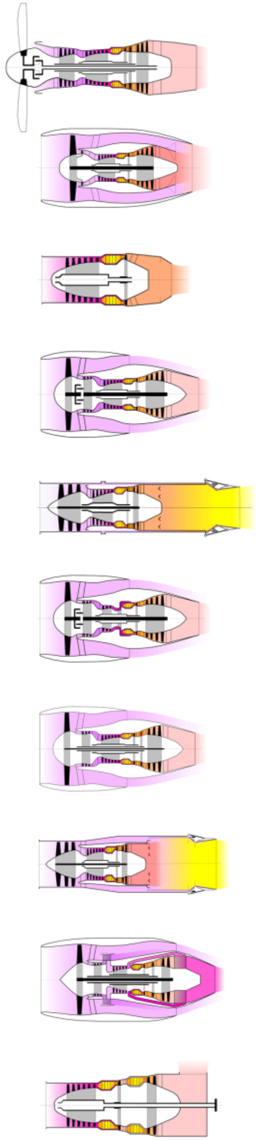
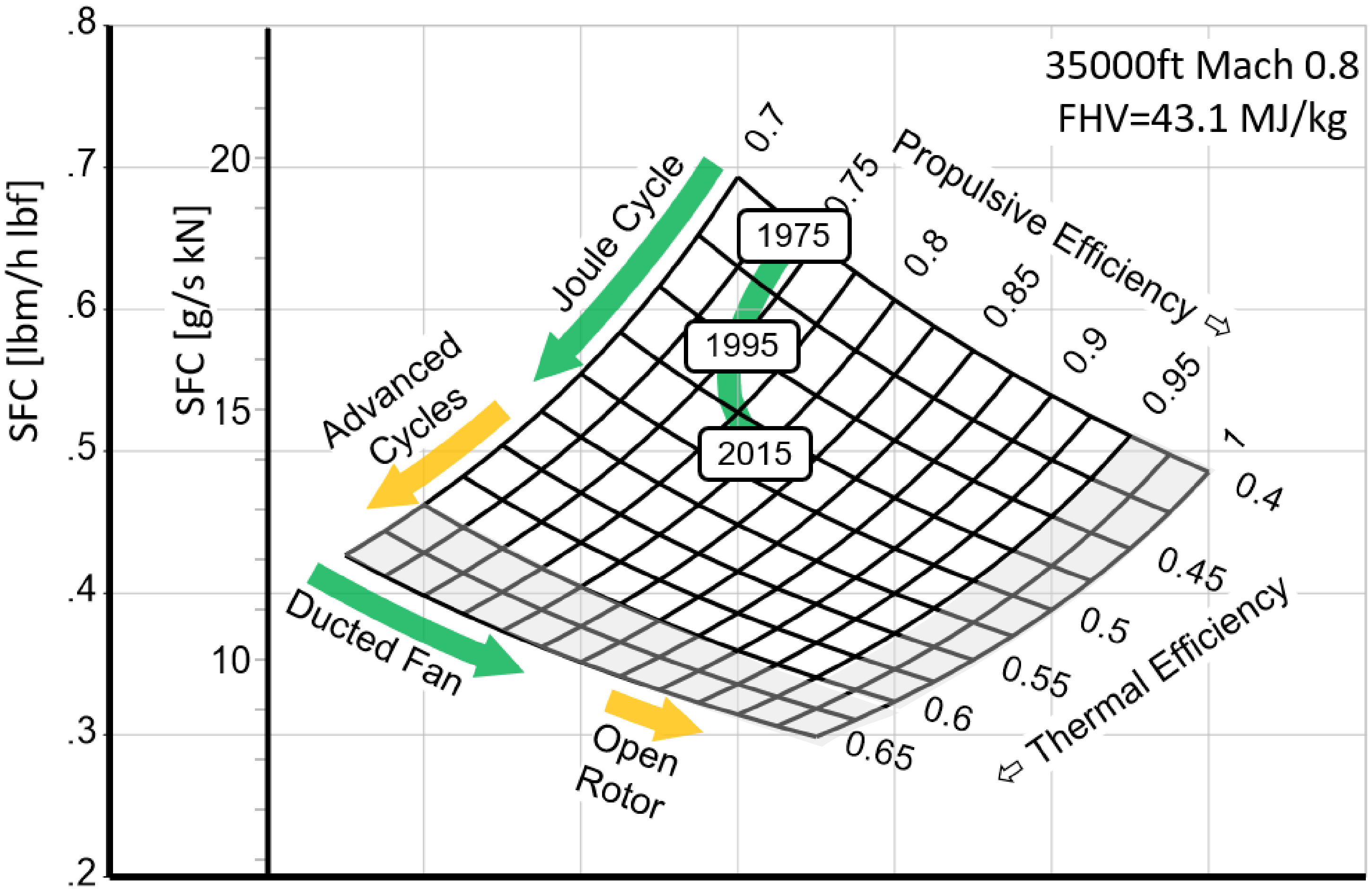
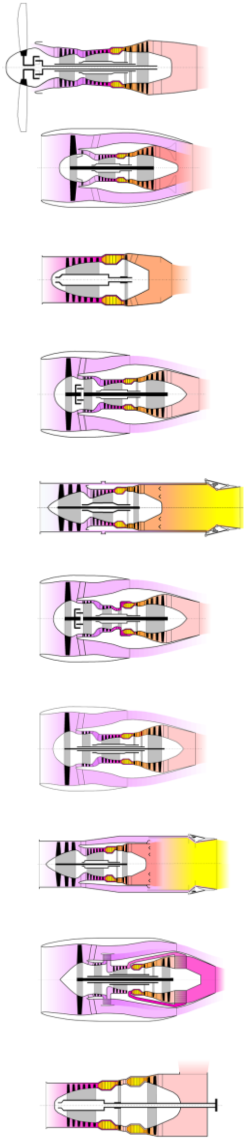
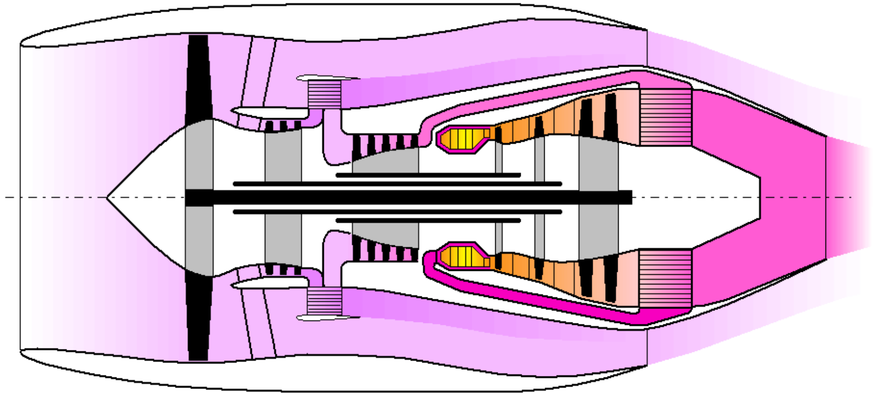


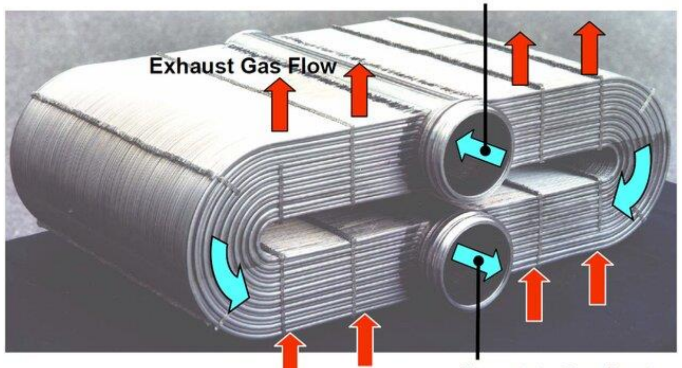
A Personal View

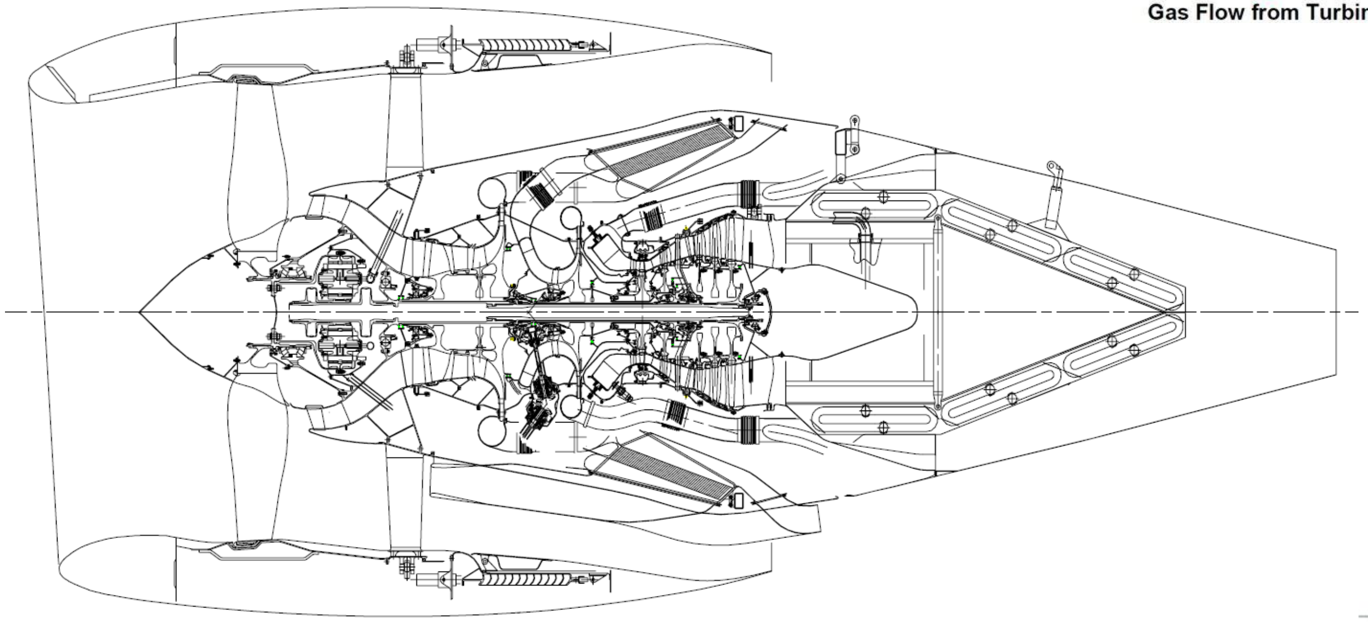


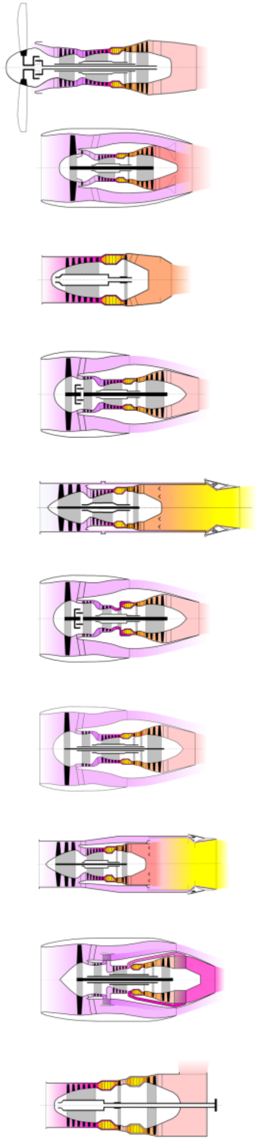


Intercooled Recuperated Turbofan





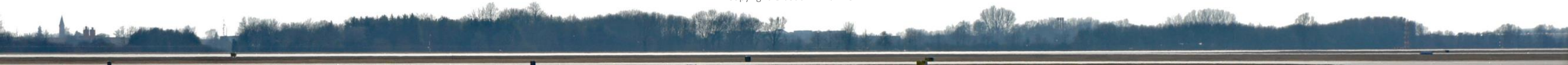


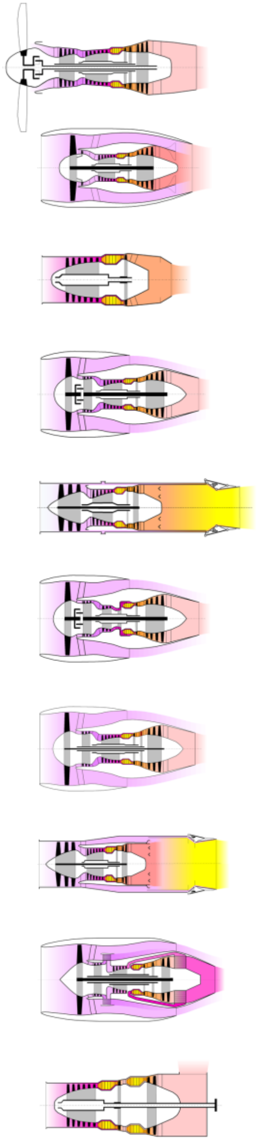


Kurzke Consulting

Outline

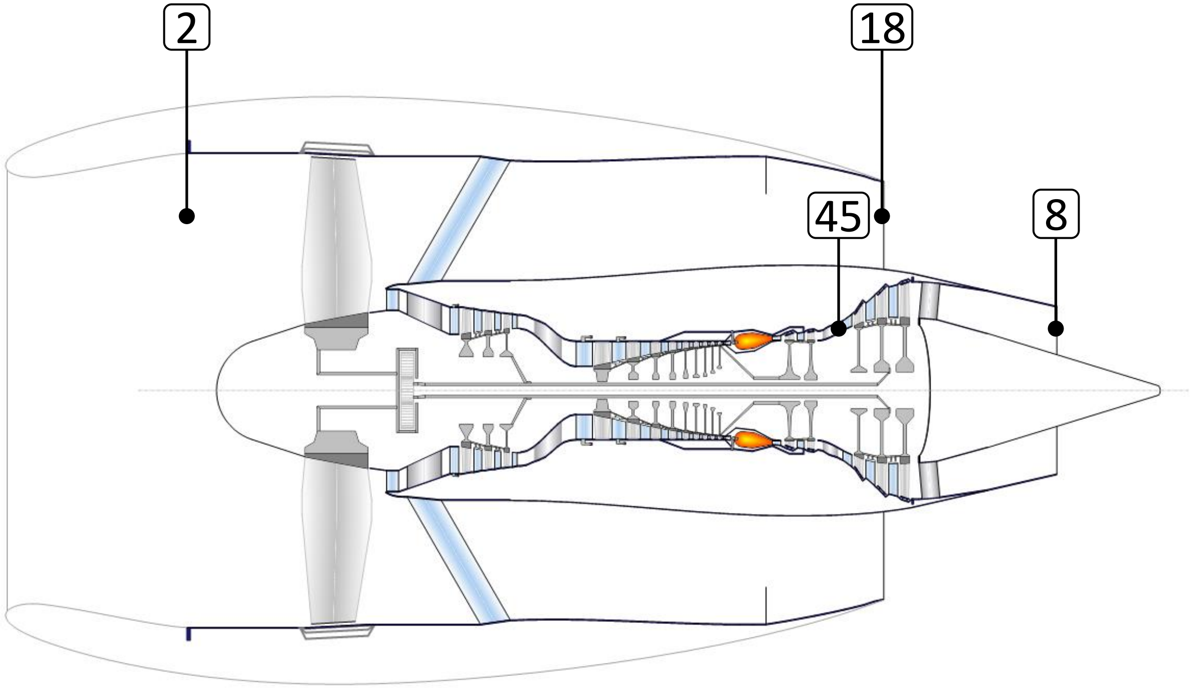
- Fundamentals
- Ideal Cycles
- Thermal Efficiency
- Power Generation
- Aircraft Propulsion
- **Fundamental Design Decisions**
- Non-Dimensionals
- Turbojet Off-Design



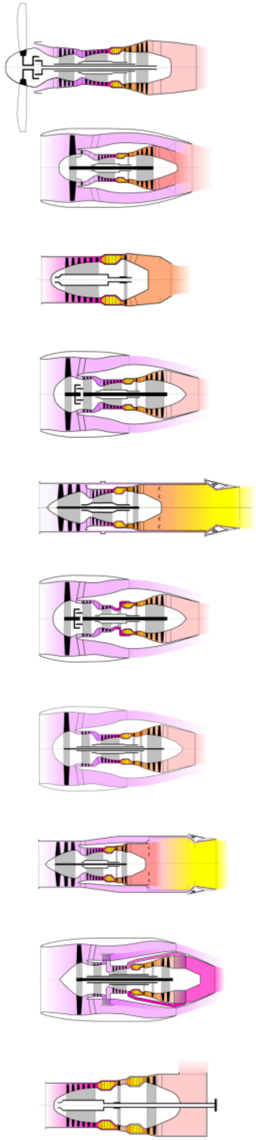


Fundamental Design Decisions

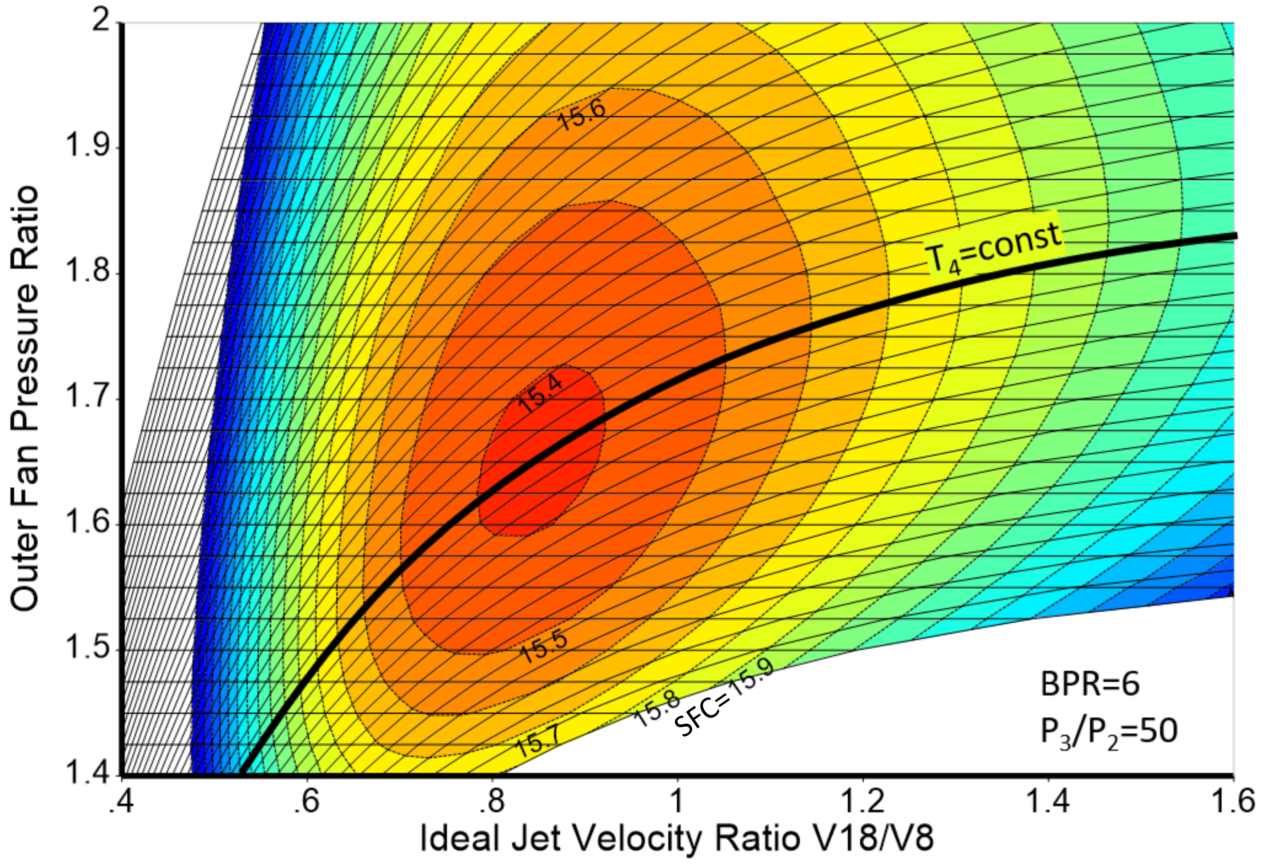
Turbofan: Mixed Flow or Separate Flow?



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



Turbofan: Mixed Flow or Separate Flow?
Jet Velocity Ratio



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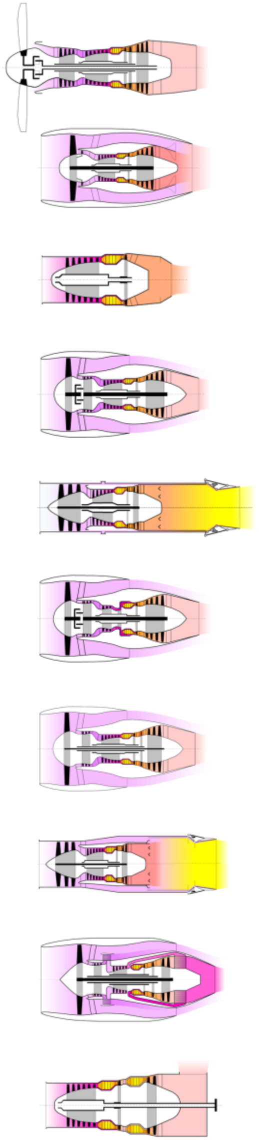
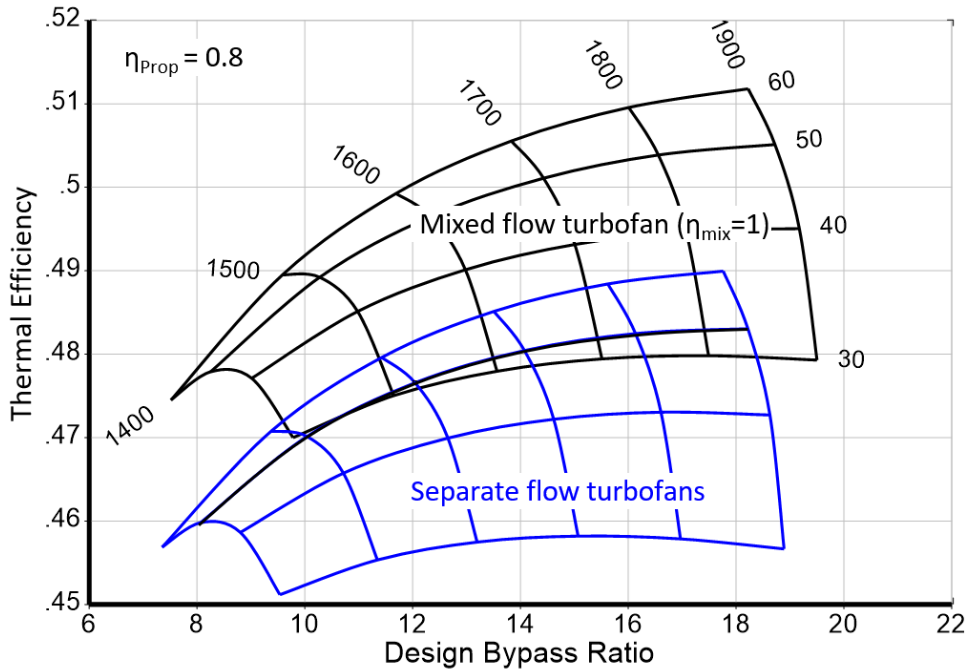
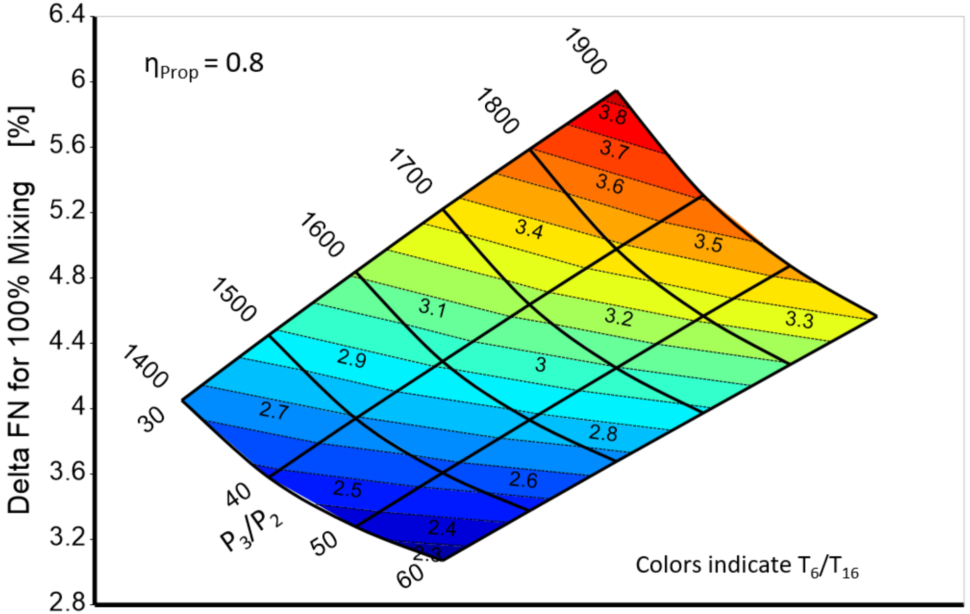


Turbofan: Mixed Flow or Separate Flow?
Thermal Efficiency





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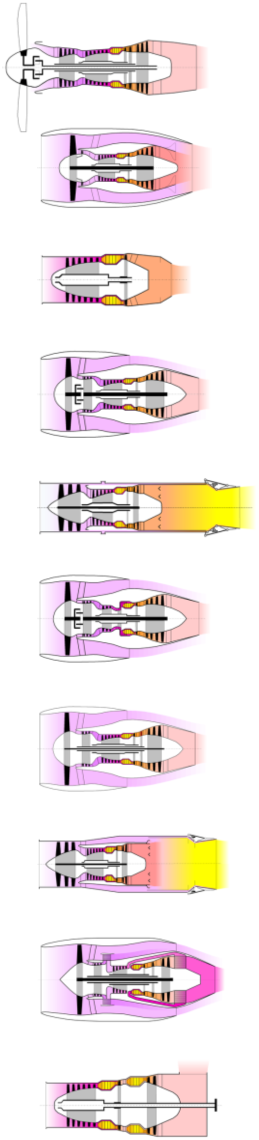
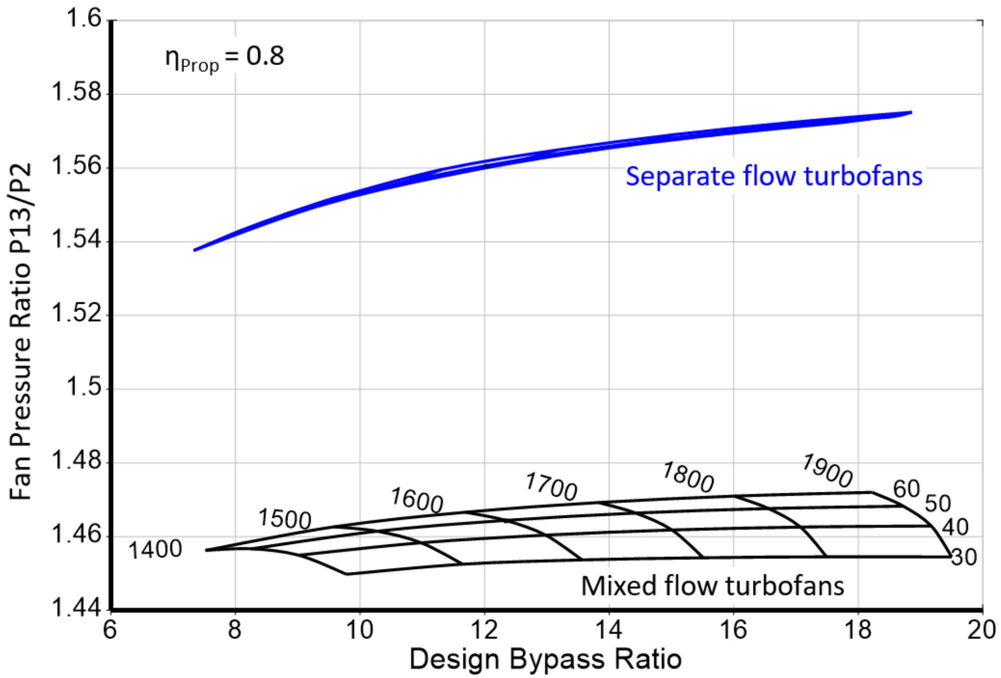
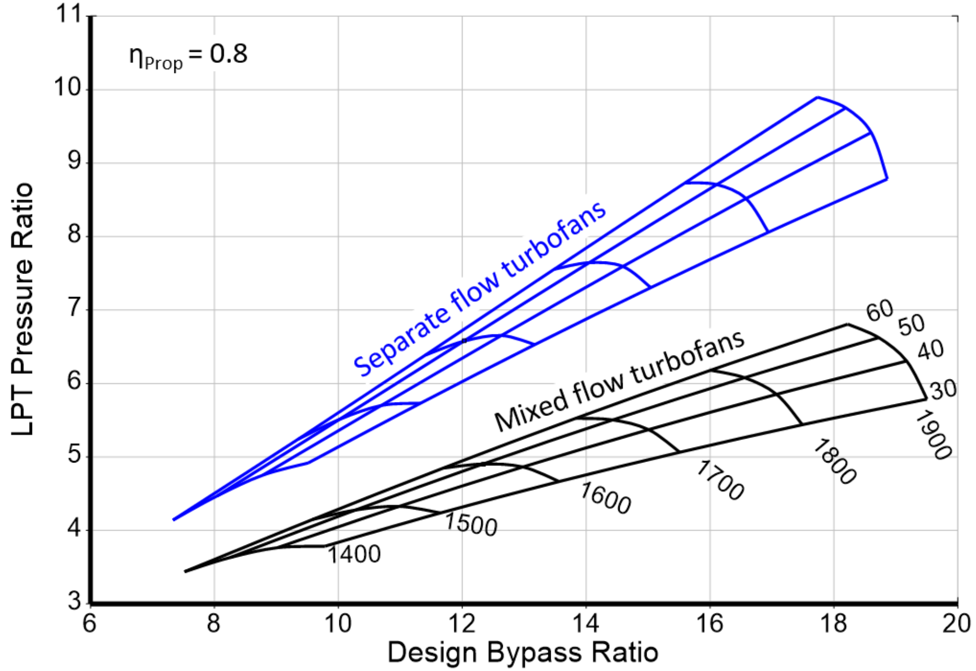


Turbofan: Mixed Flow or Separate Flow?

Fan and LPT Pressure Ratio





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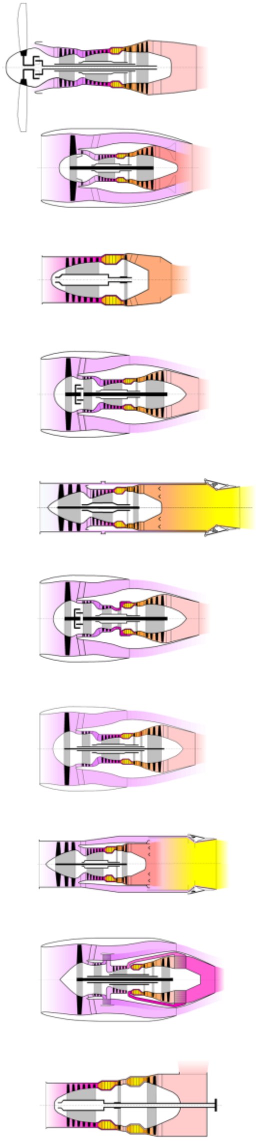
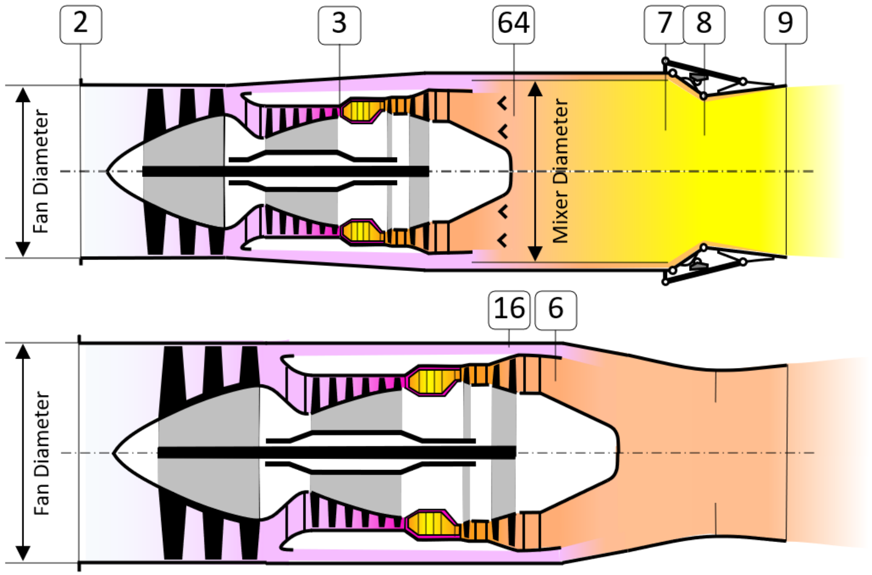
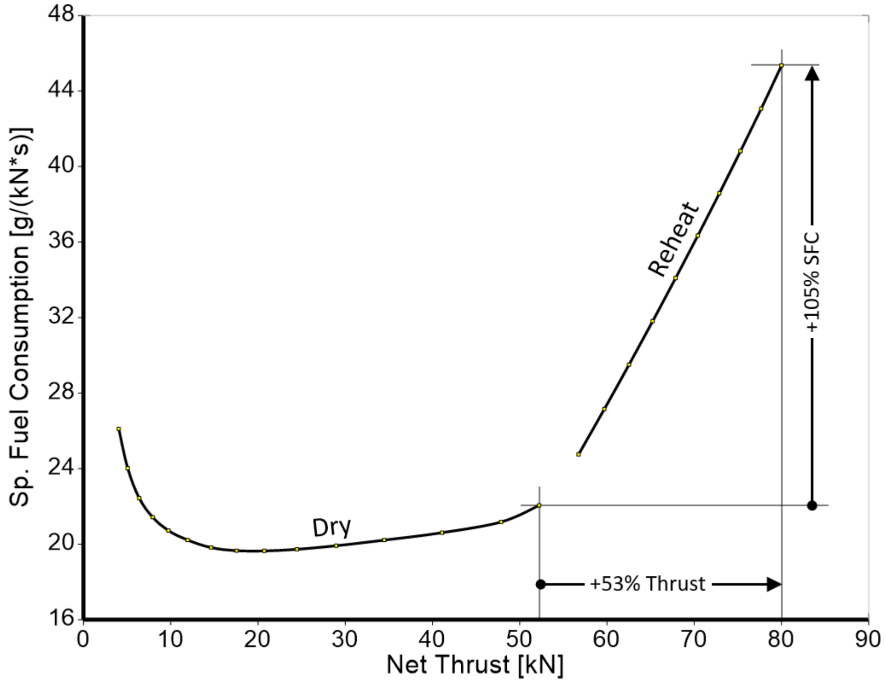
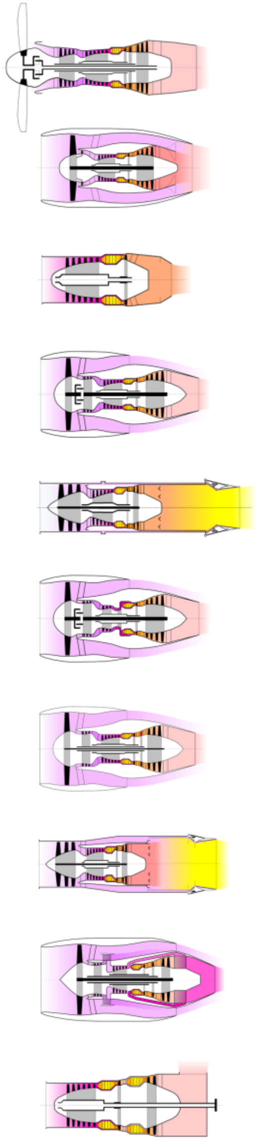


Fundamental Design Decisions
With or Without Afterburner (Reheat)?

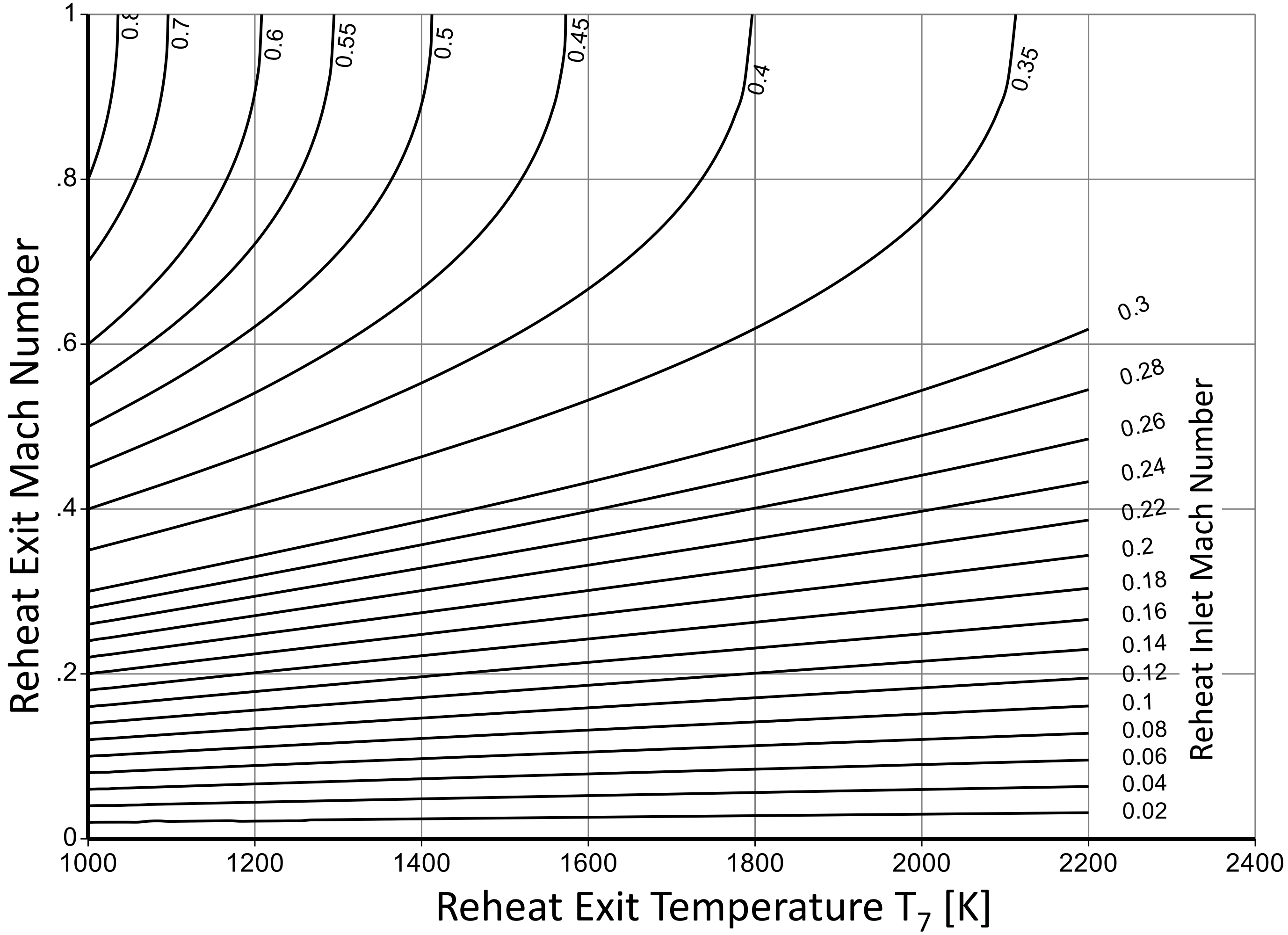


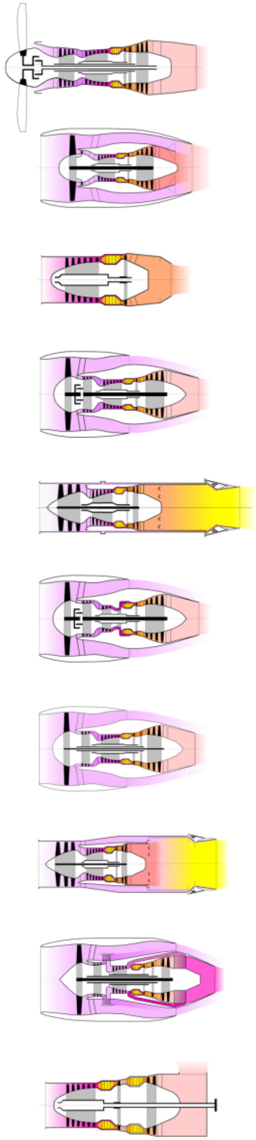


Kurzke Consulting

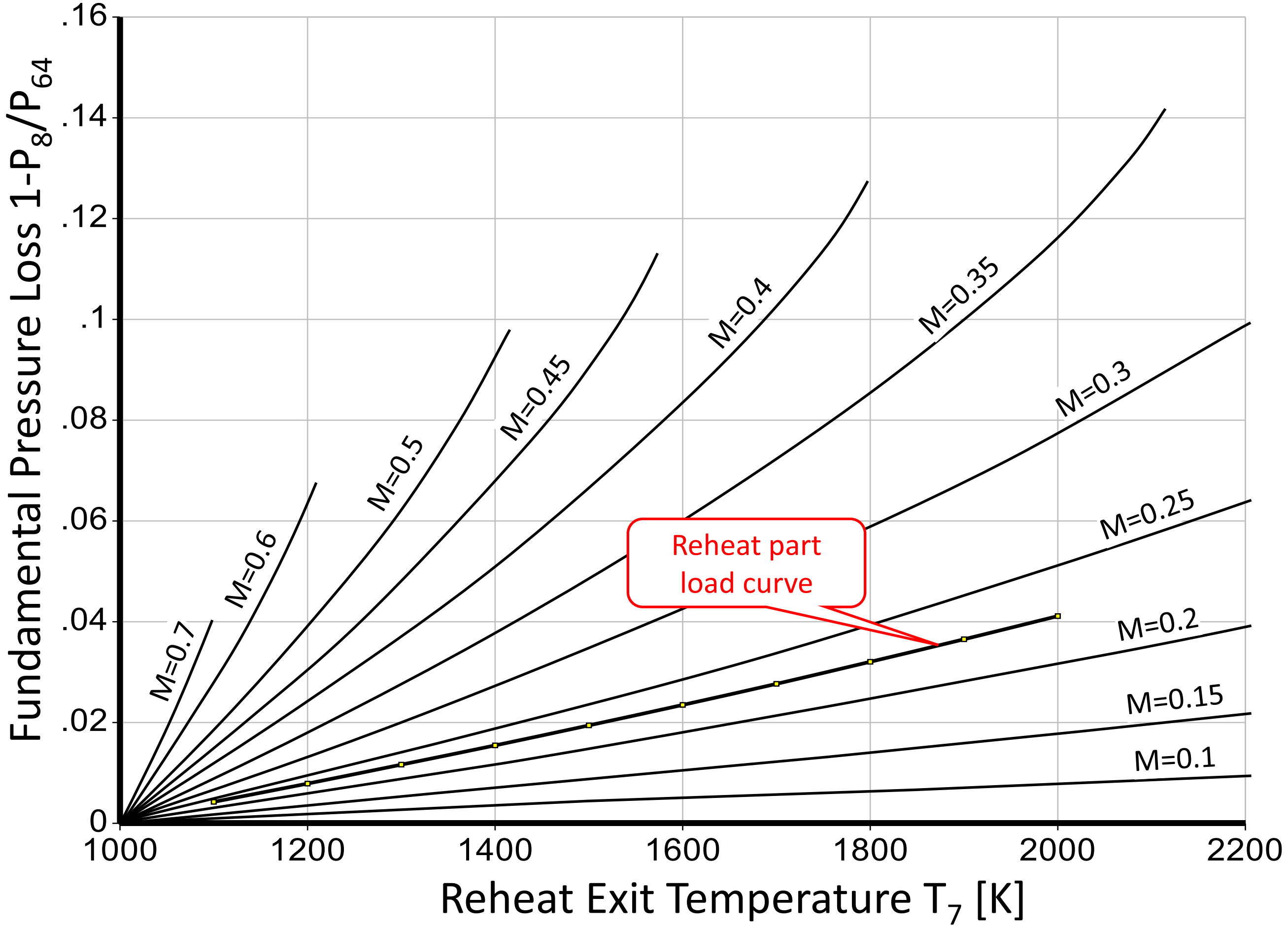


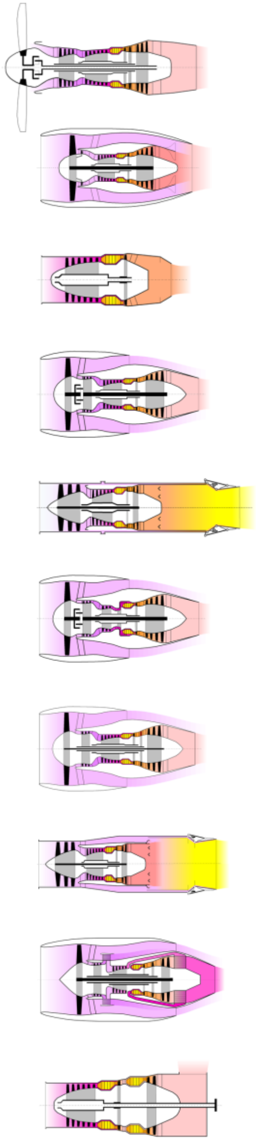
Rayleigh Line
Heat Addition in a Constant Area Duct



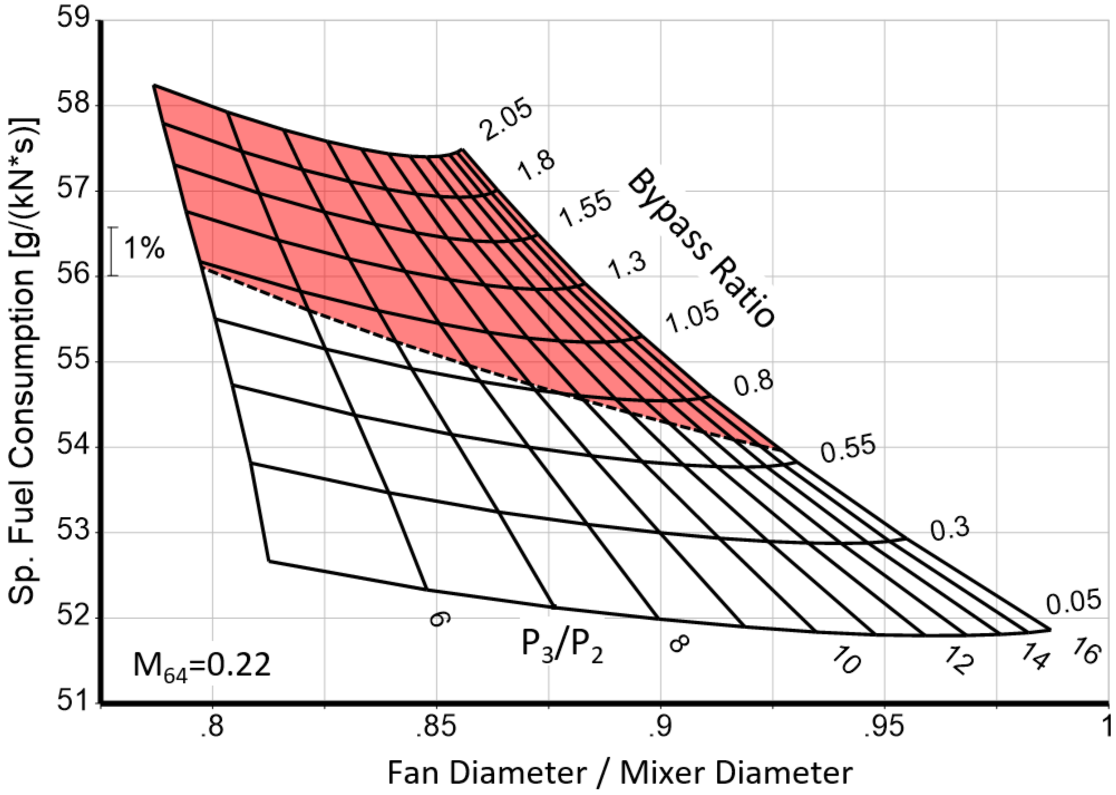


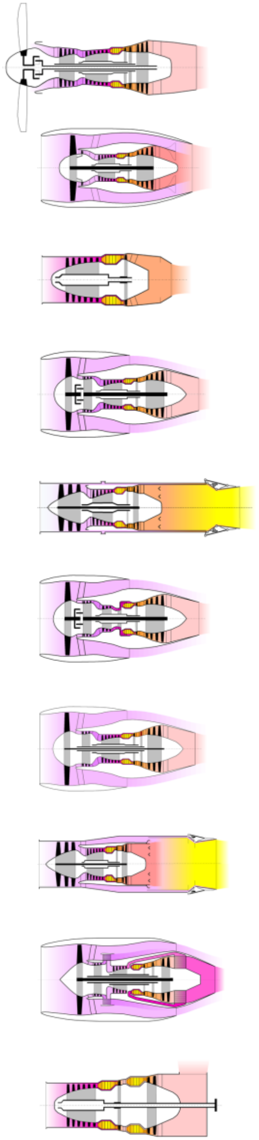
Rayleigh Line
Fundamental Pressure Loss





With Afterburner
Engine Size





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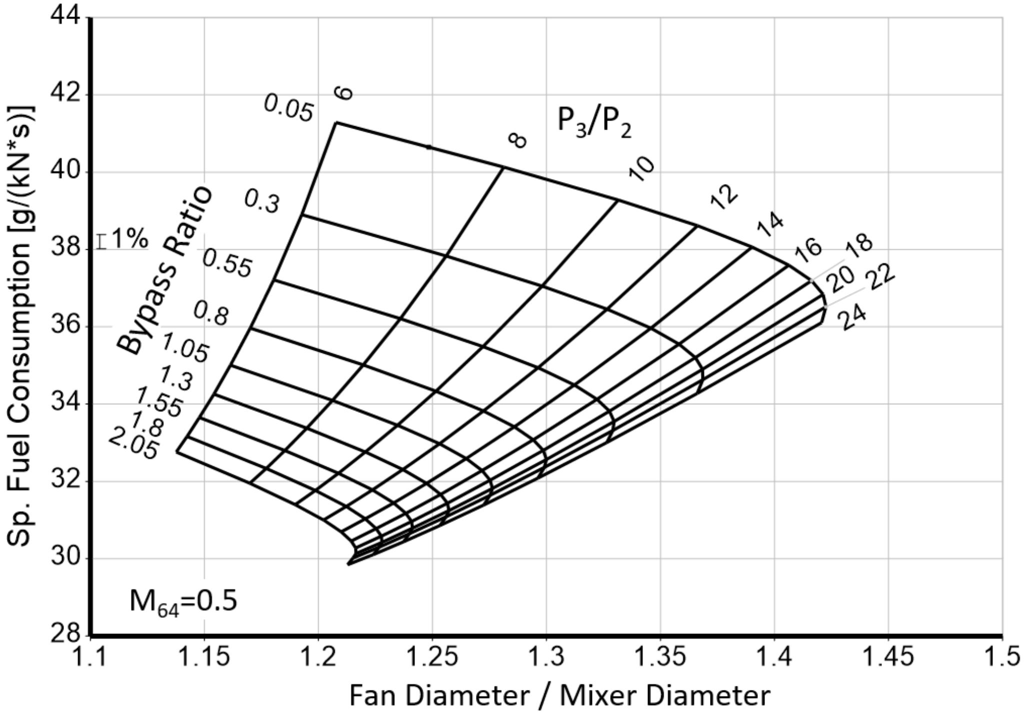
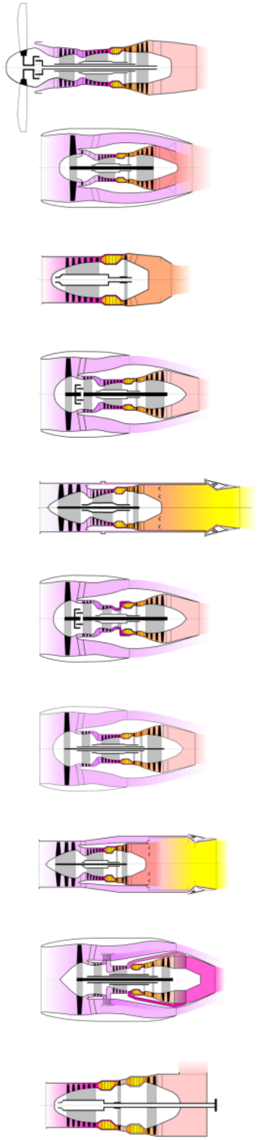
Without Afterburner
Engine Size





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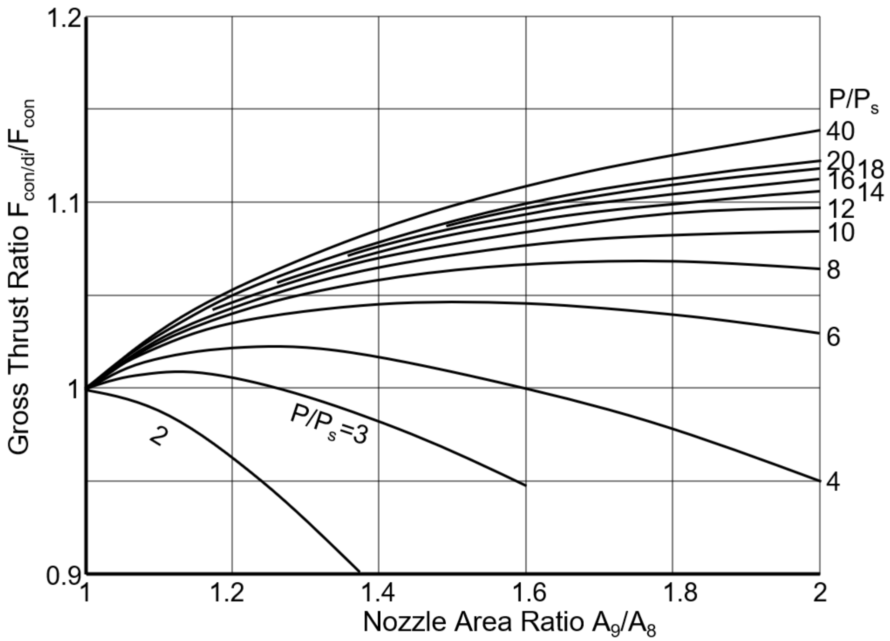
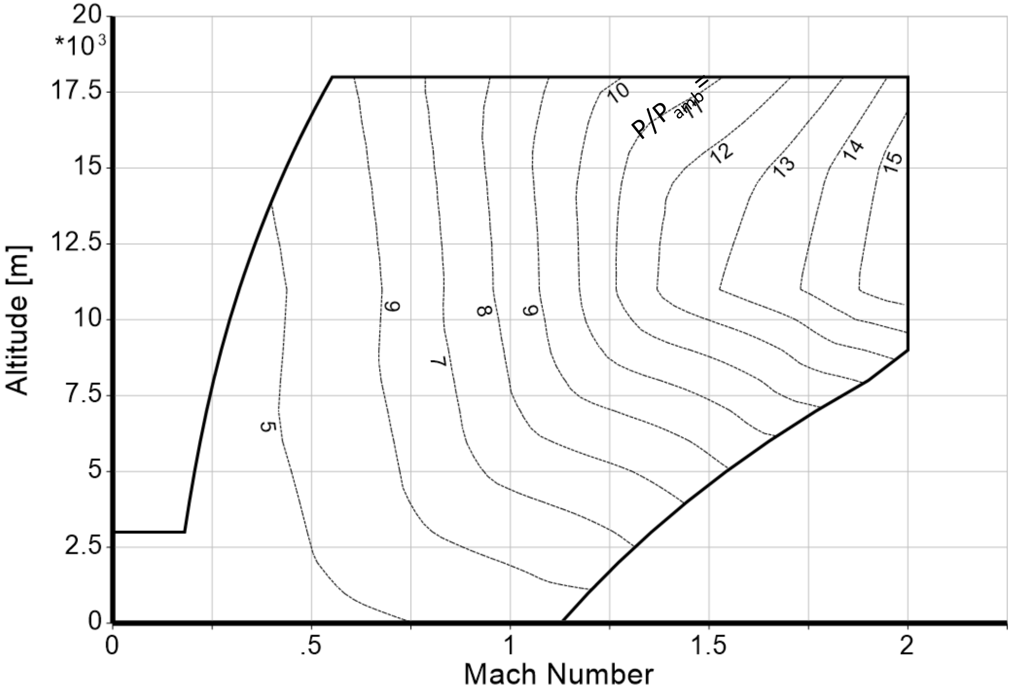
Fundamental Design Decisions

Convergent – Divergent Nozzle





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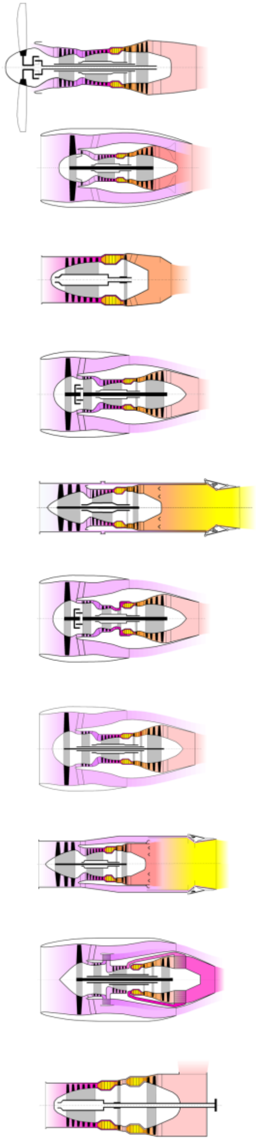
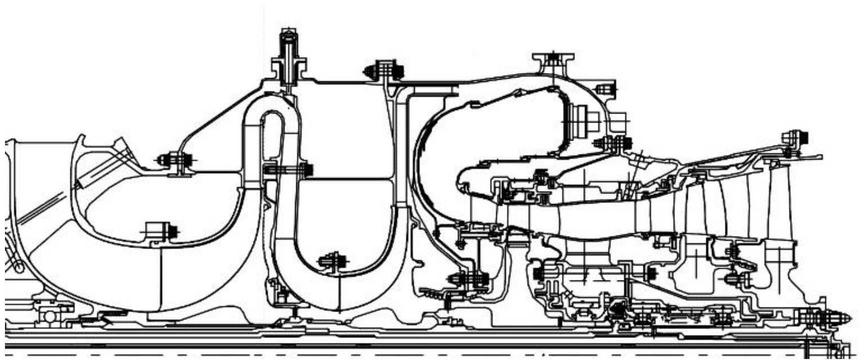
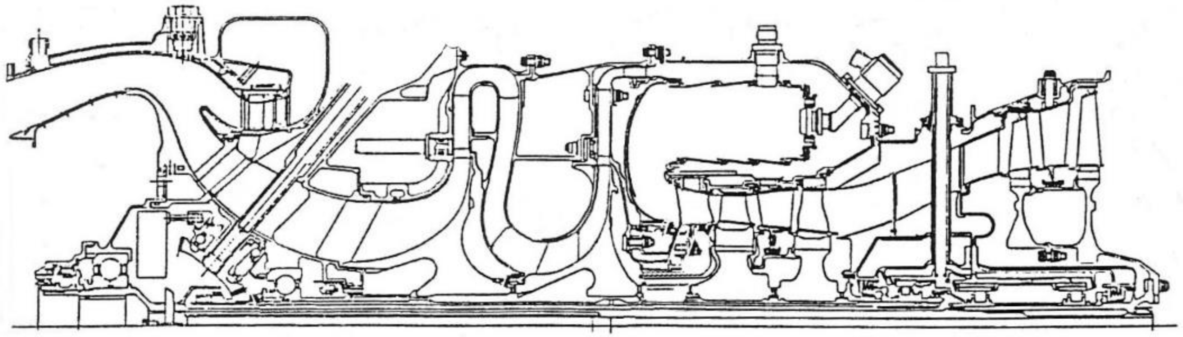


Fundamental Design Decisions

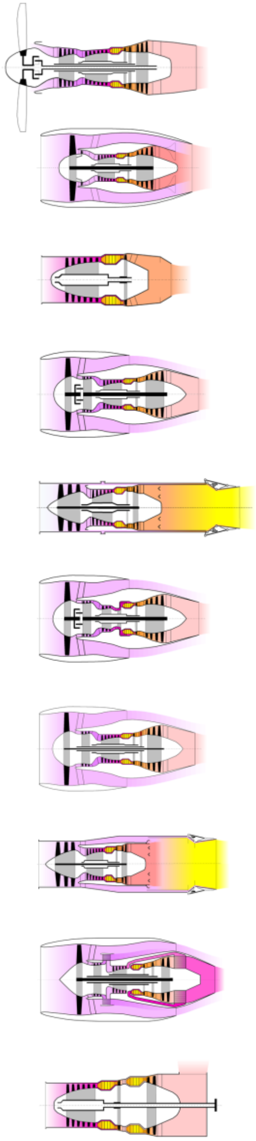
Single or Two-Stage HP Turbine?



MTR 390

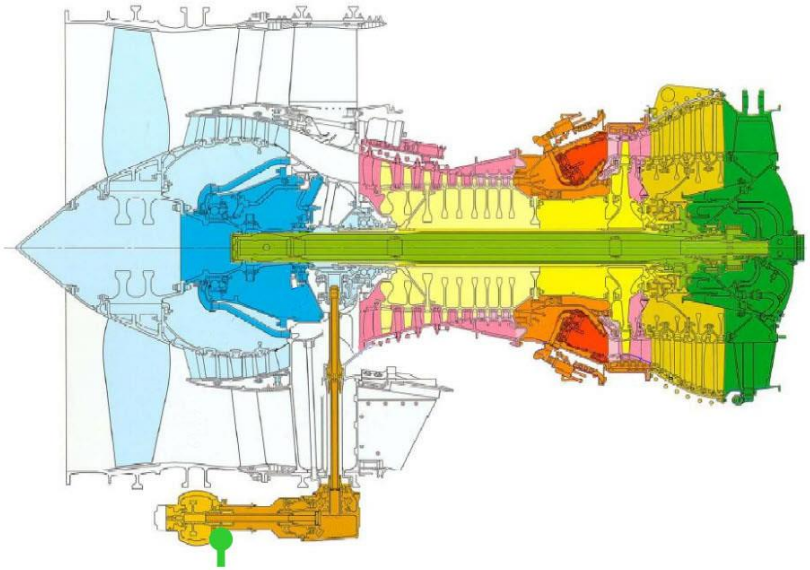


T800

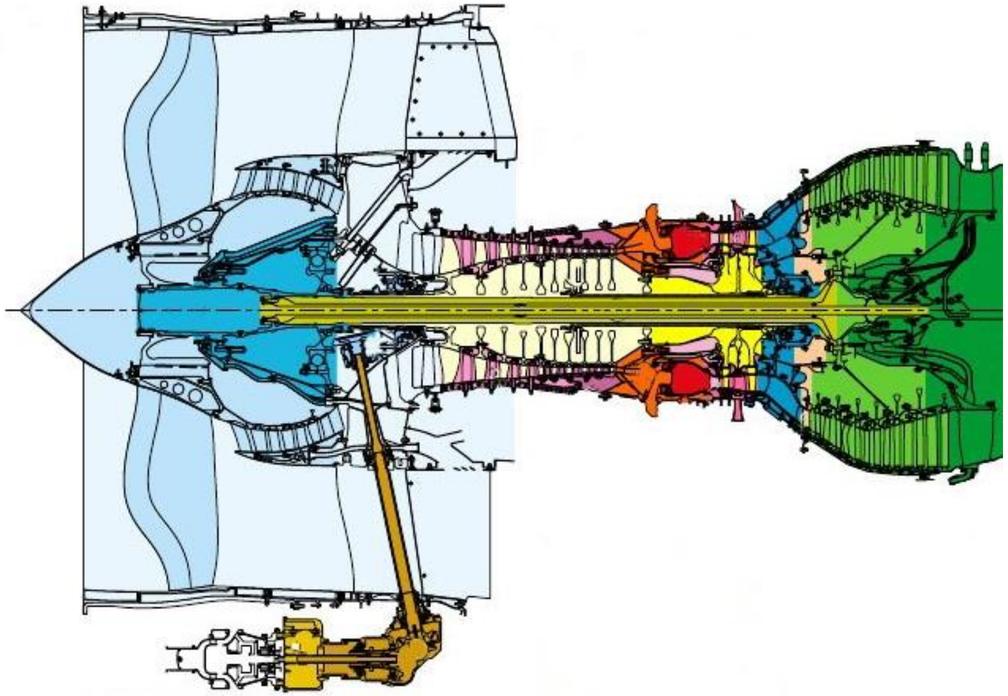


Fundamental Design Decisions

Single or Two-Stage HP Turbine?

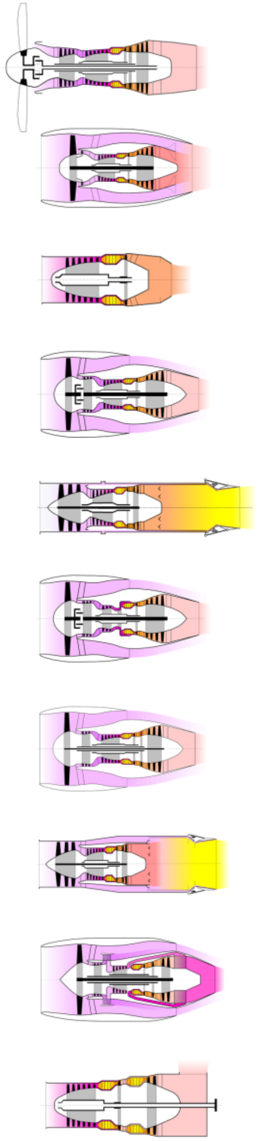


CFM56-7



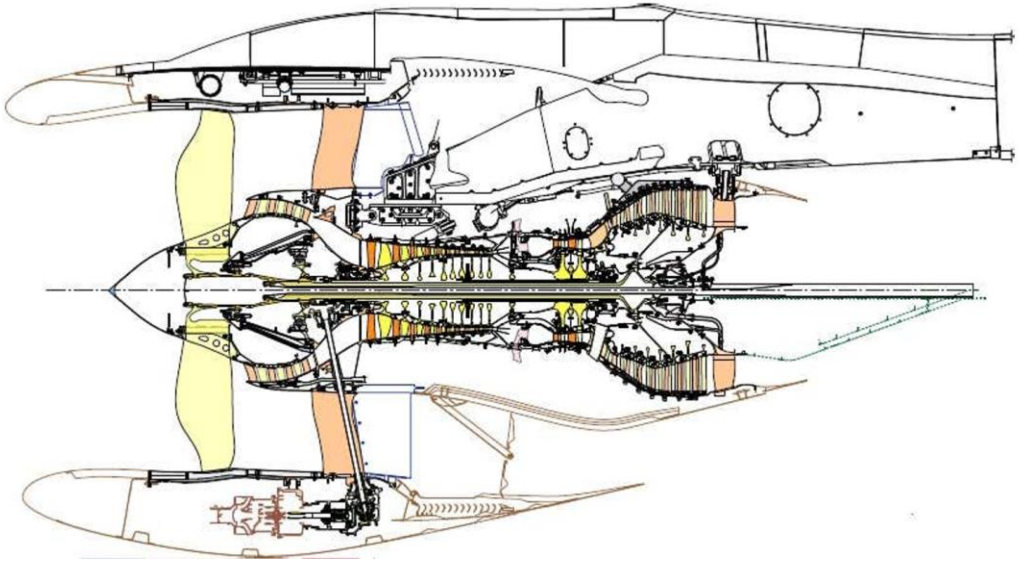
Leap 1A

Kurzke Consulting

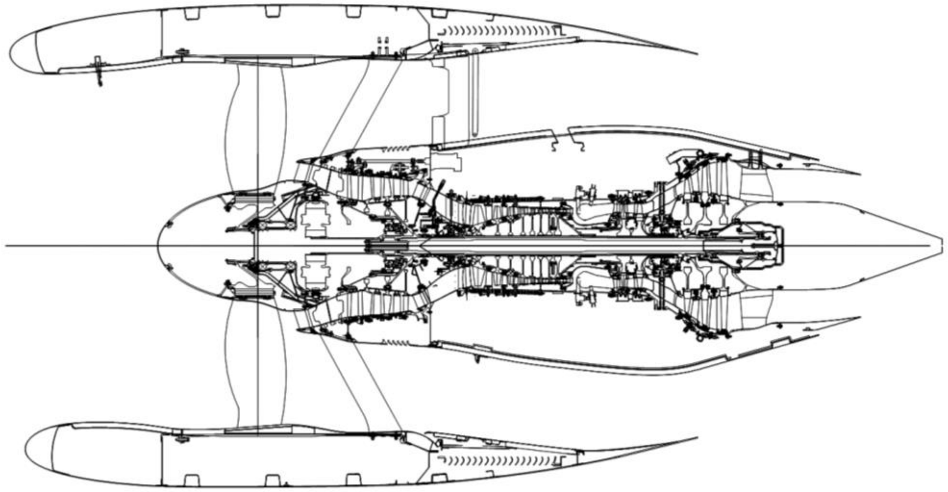


Fundamental Design Decisions

Conventional or Geared Turbofan?



CFM Leap 1A



Pratt & Whitney Geared Turbofan

Airbus A320neo

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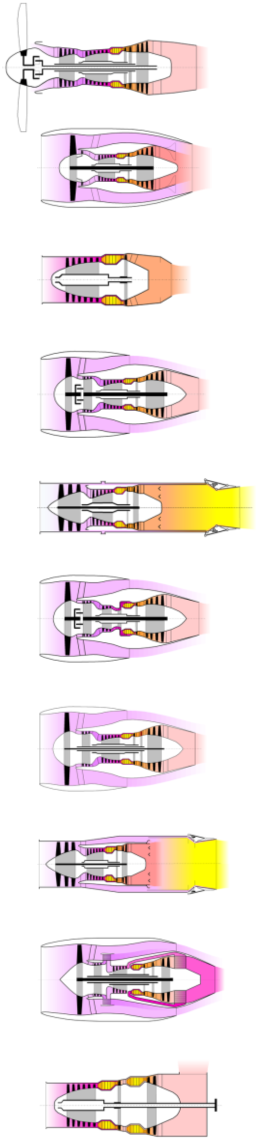

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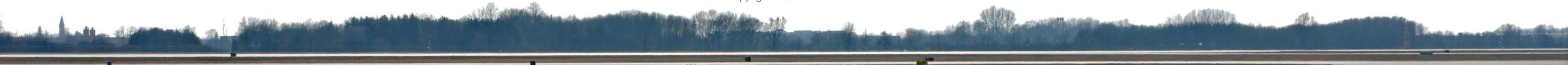

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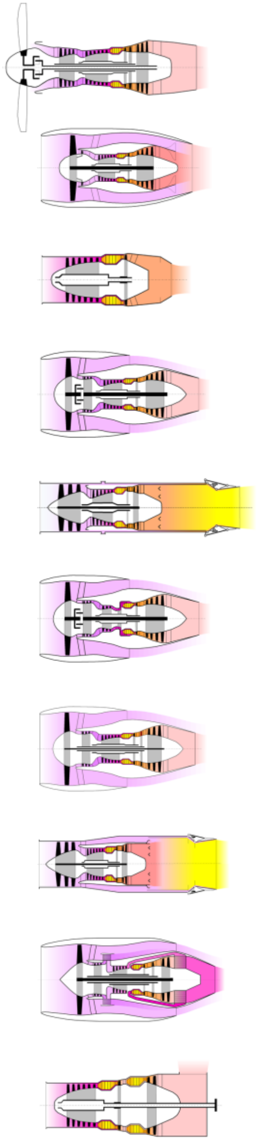
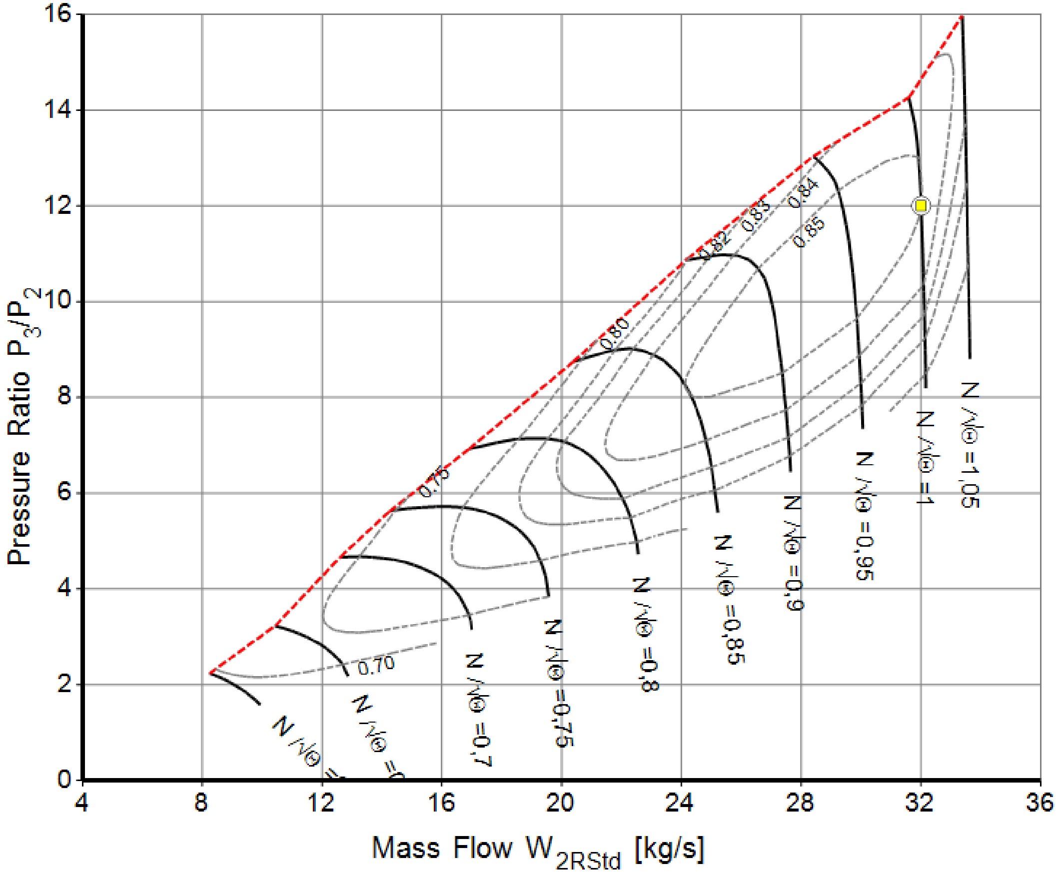
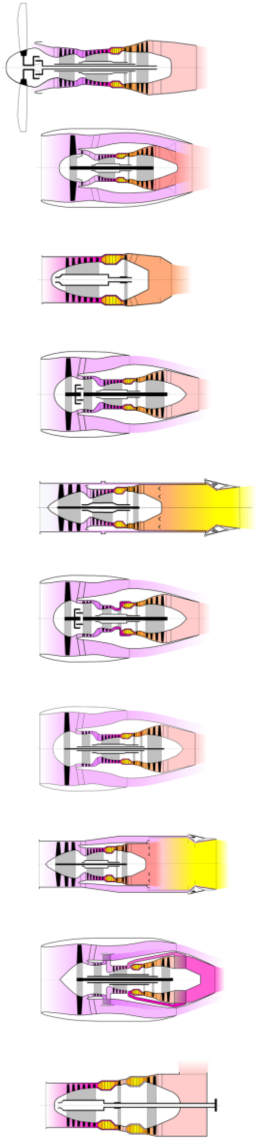


Non-Dimensionals
Compressor Map





Kurzke Consulting

Parameters in a Compressor Map
Mach Numbers

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

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

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

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

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

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

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

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

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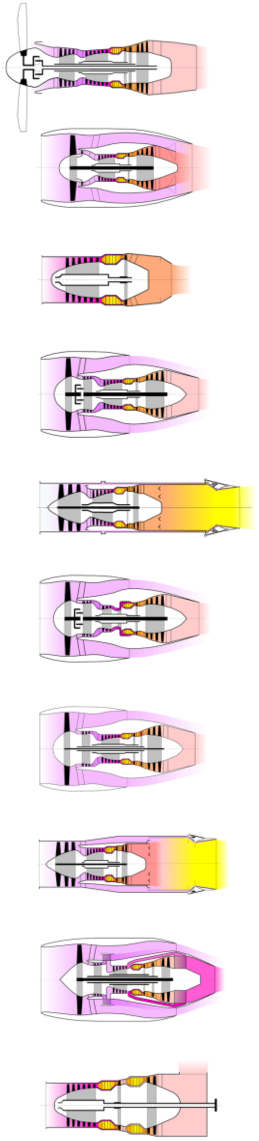
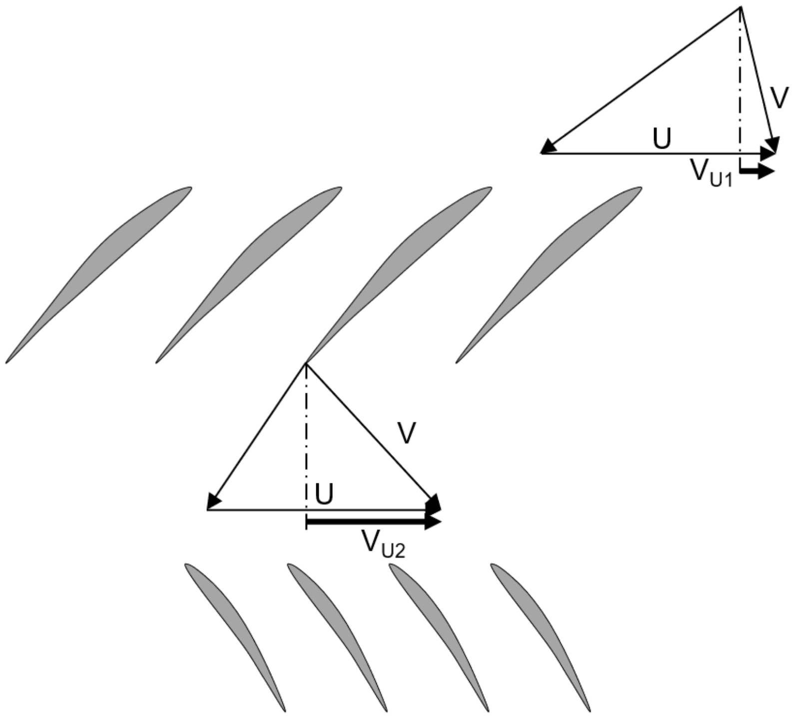
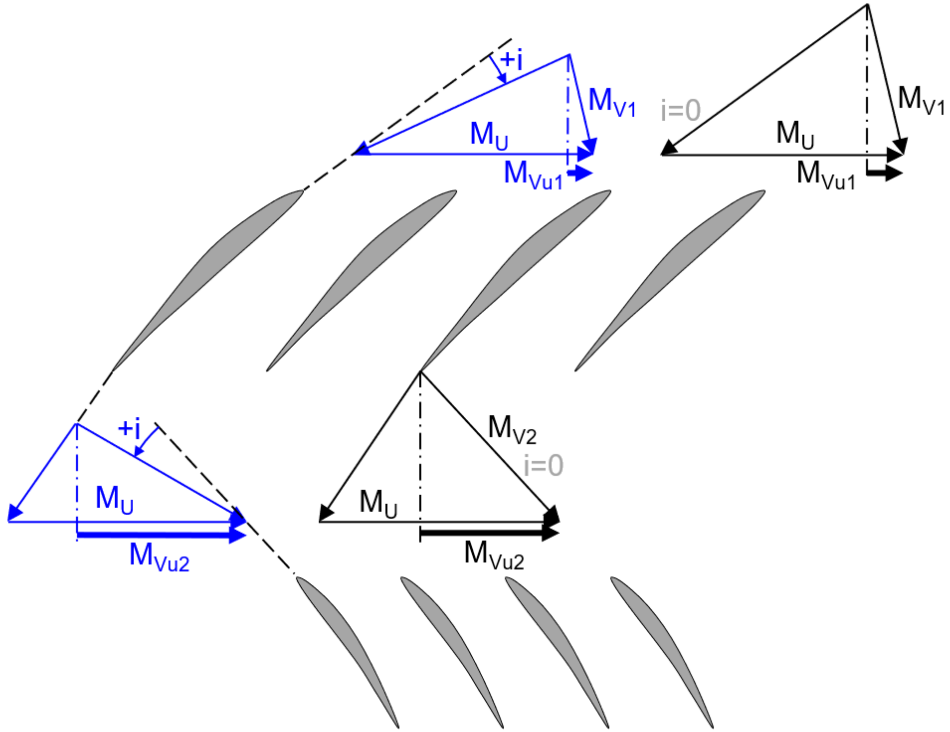


Non-Dimensionals

Velocity Triangles of a Compressor Stage



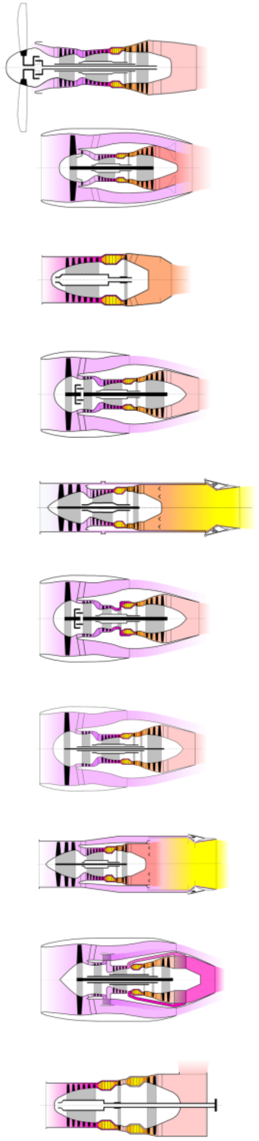


True velocities

Mach numbers

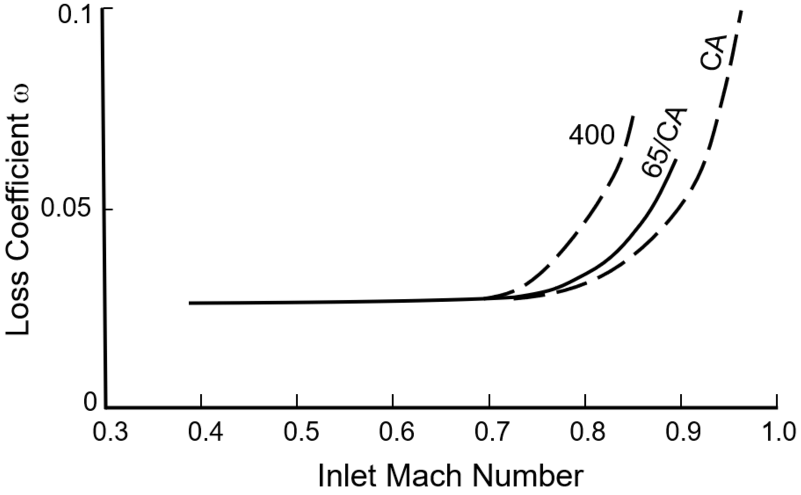
Work done:

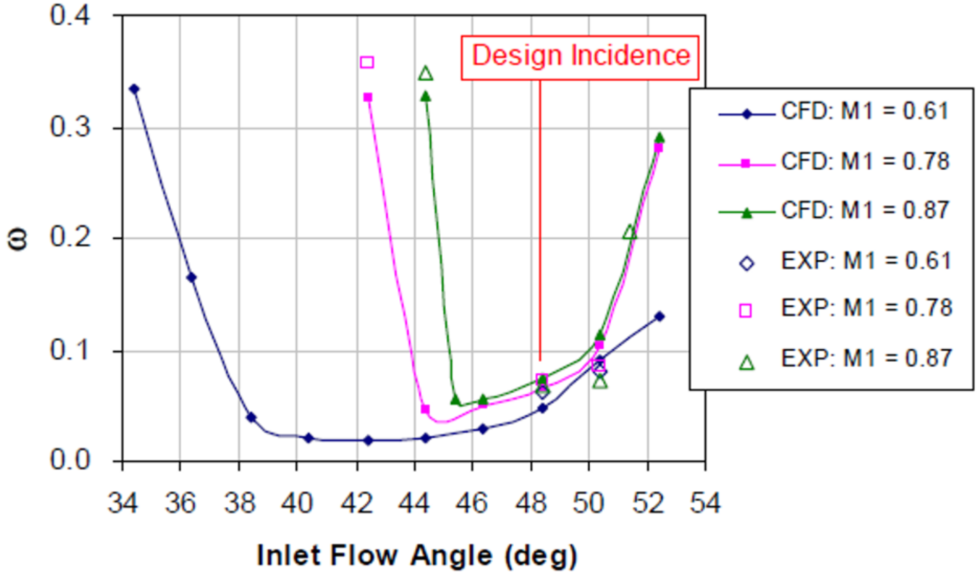
$$\Delta H = U \times (V_{u2} - V_{u1})$$



Non-Dimensionals

Cascade Losses





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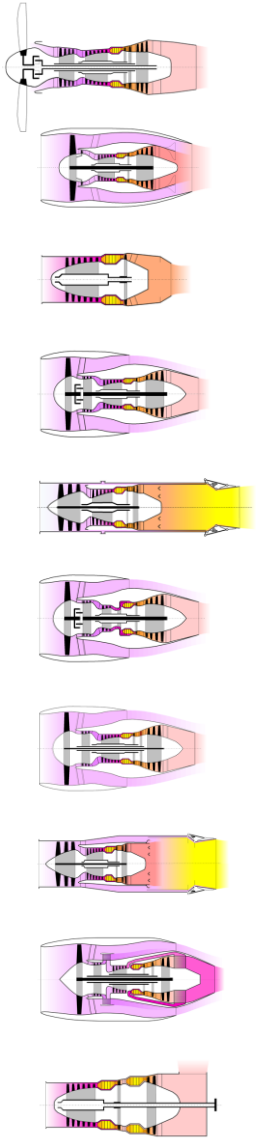


Non-Dimensionals – Mach Number Similarity

Engine Parameters

- 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

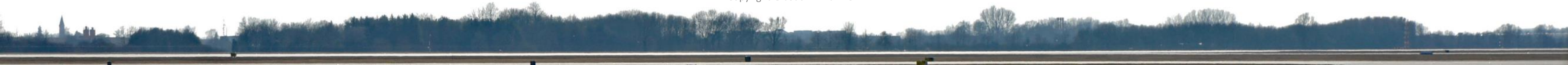
$$F_{corr} = \frac{F}{P} \qquad F_{corr} = \frac{F}{\delta}$$

- SFC

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

Θ = T/288.15K

δ = P/101.325 kPa



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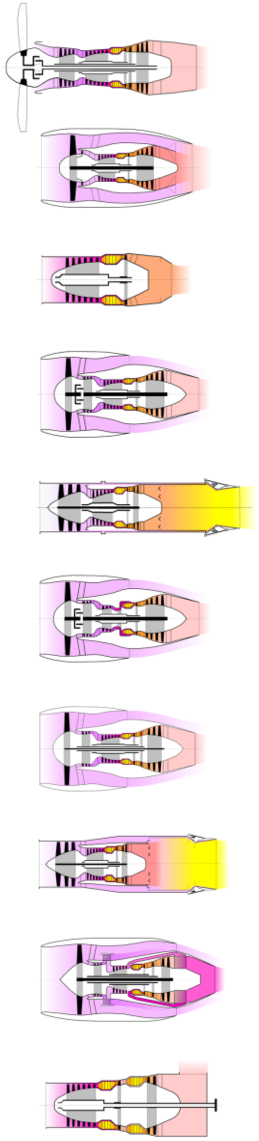

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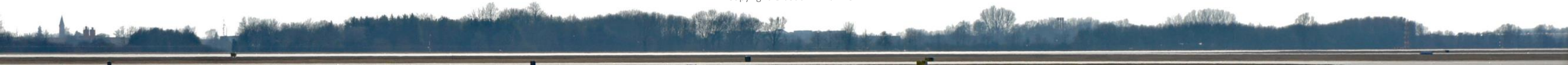
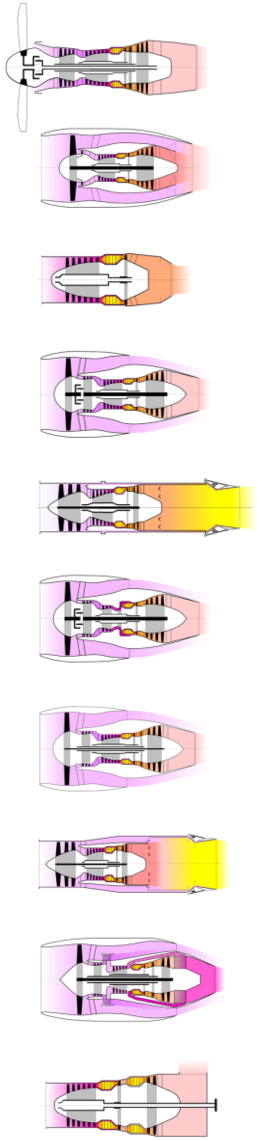
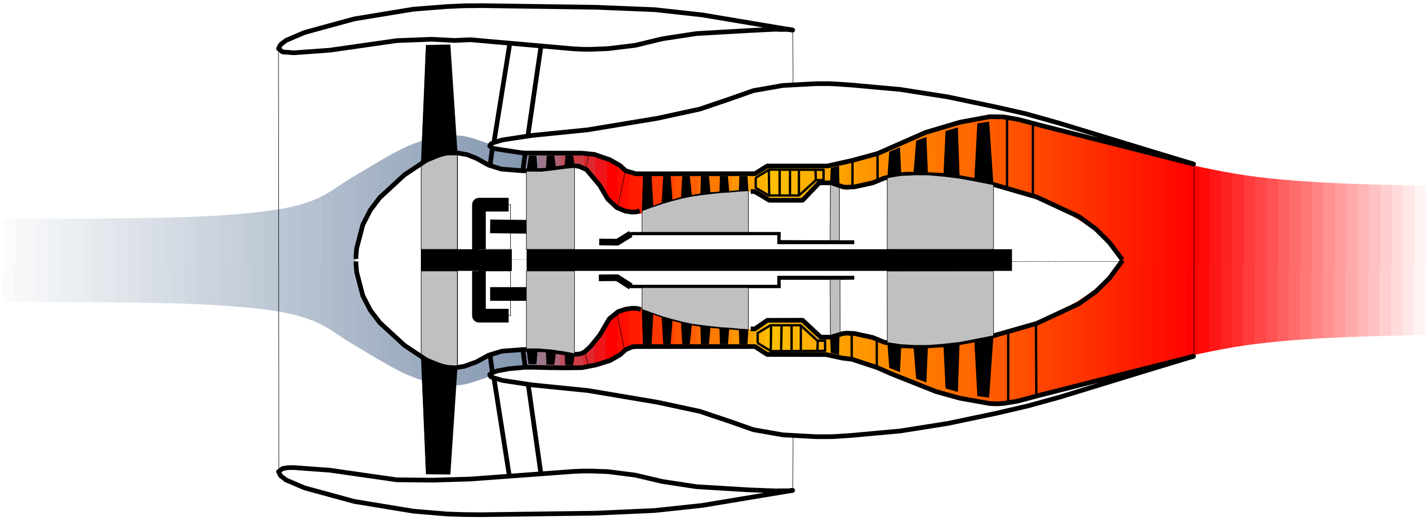


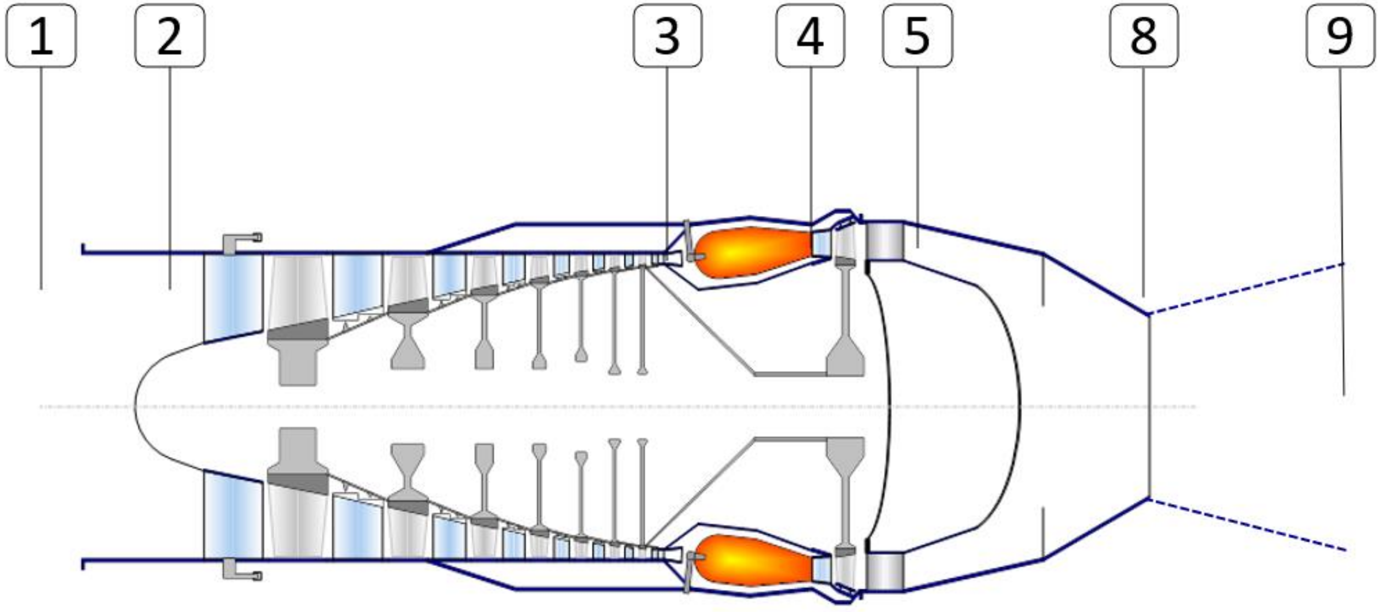
A Simple Gas Turbine Cycle is the Heart of Any Turbofan

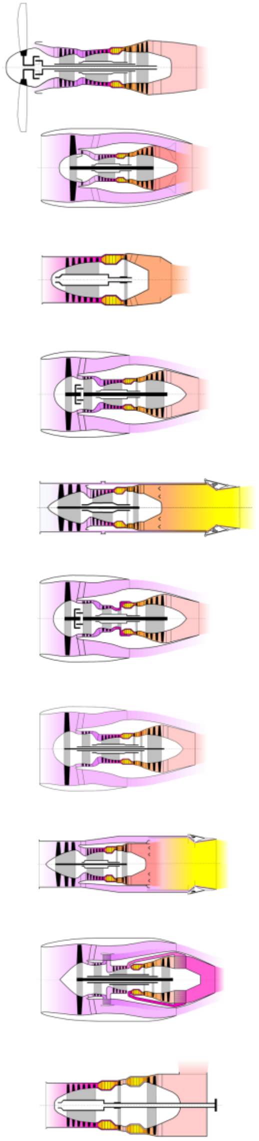




Turbojet Off-Design
Nomenclature

Kurzke Consulting





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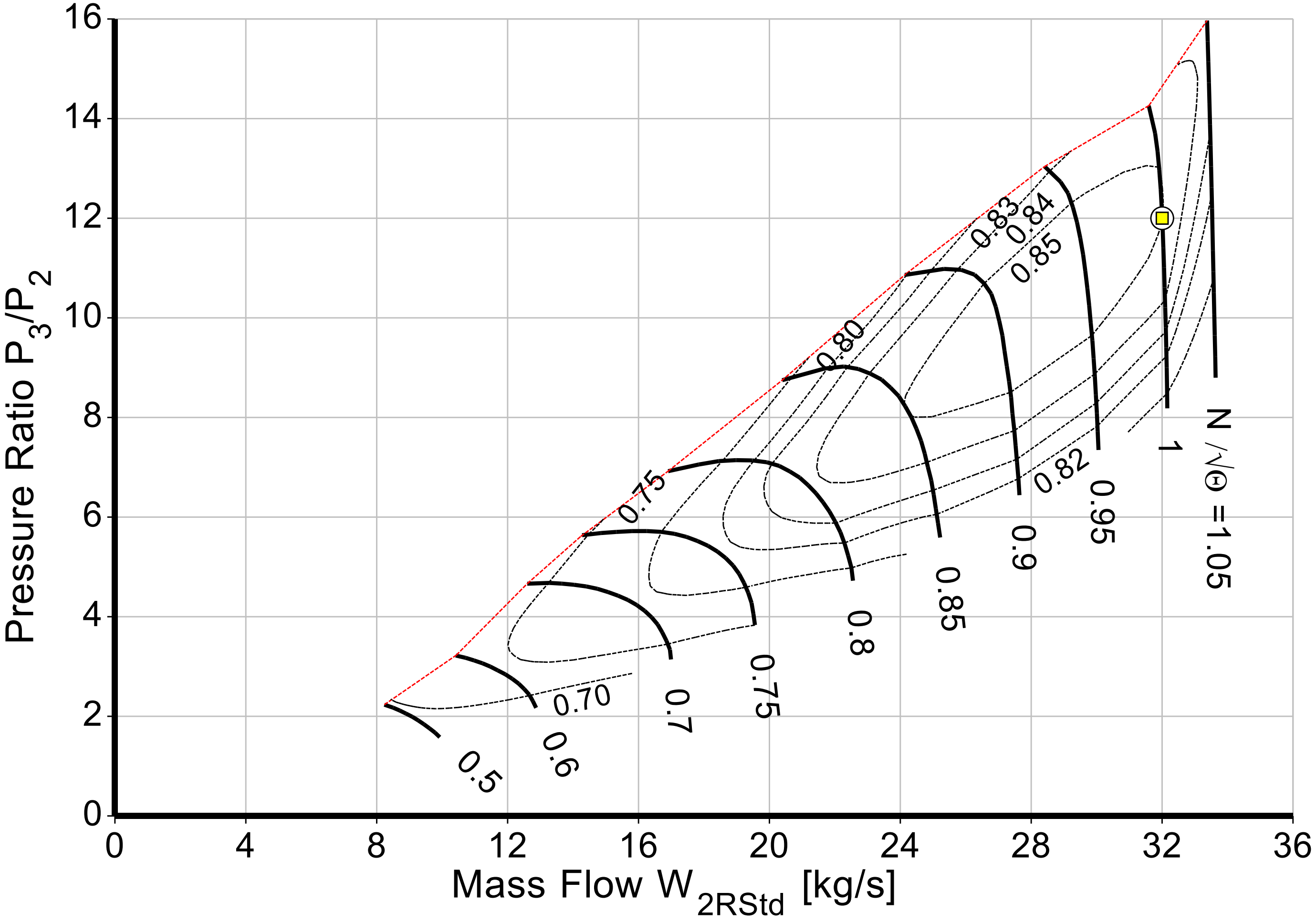
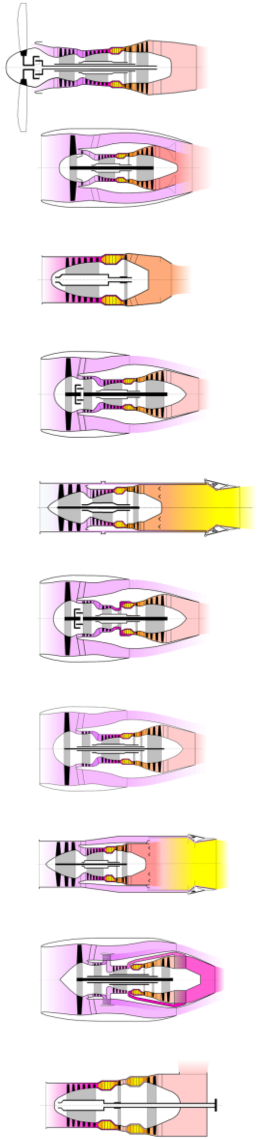
Turbojet Off-Design

Compressor Map





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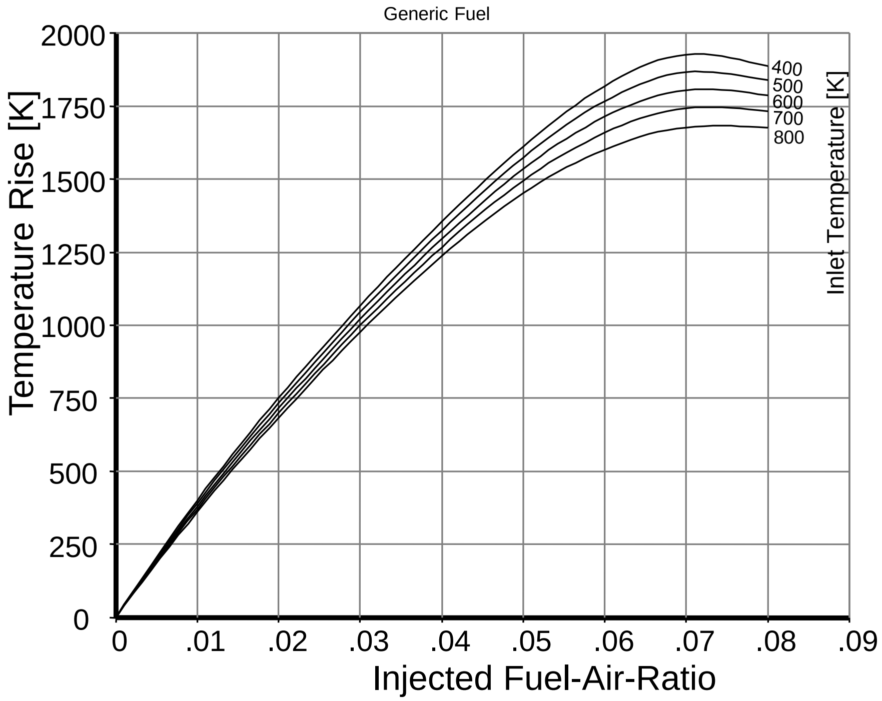
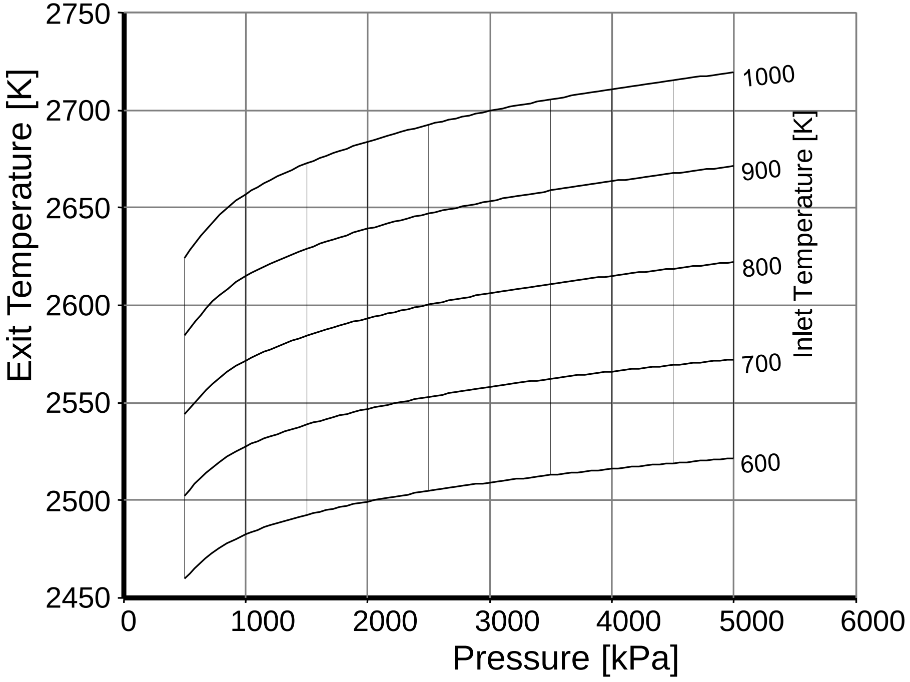
Turbojet Off-Design
Combustor





Chemical equilibrium - ideal temperature rise for a generic hydrocarbon fuel

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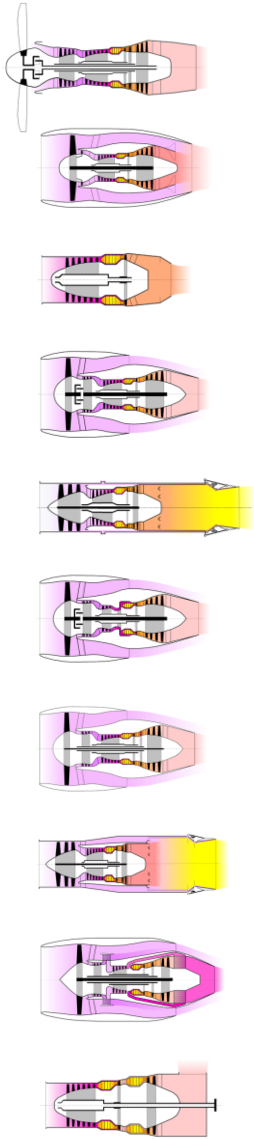
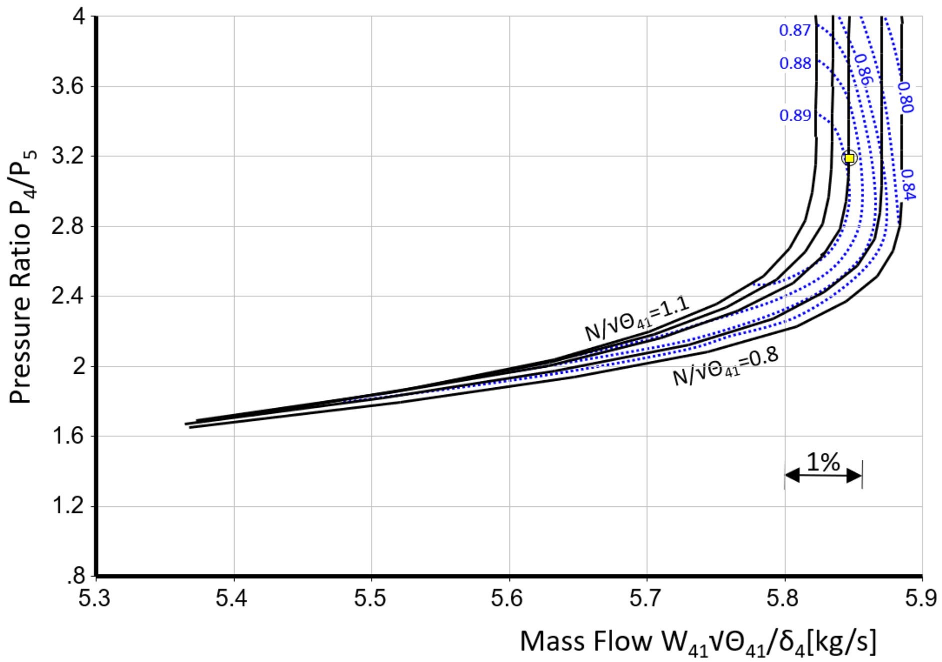
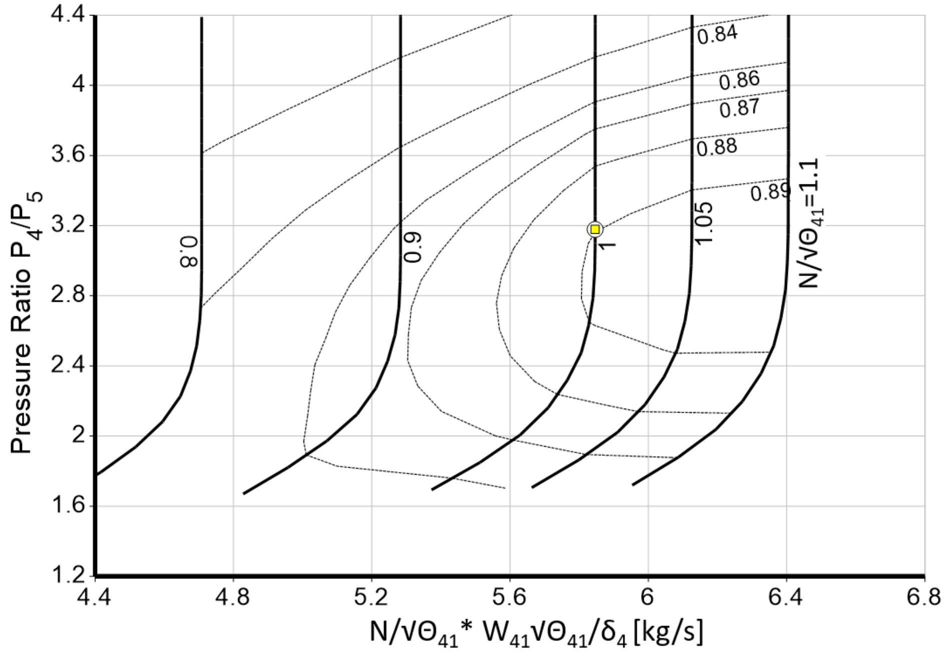


Turbojet Off-Design
Turbine Map

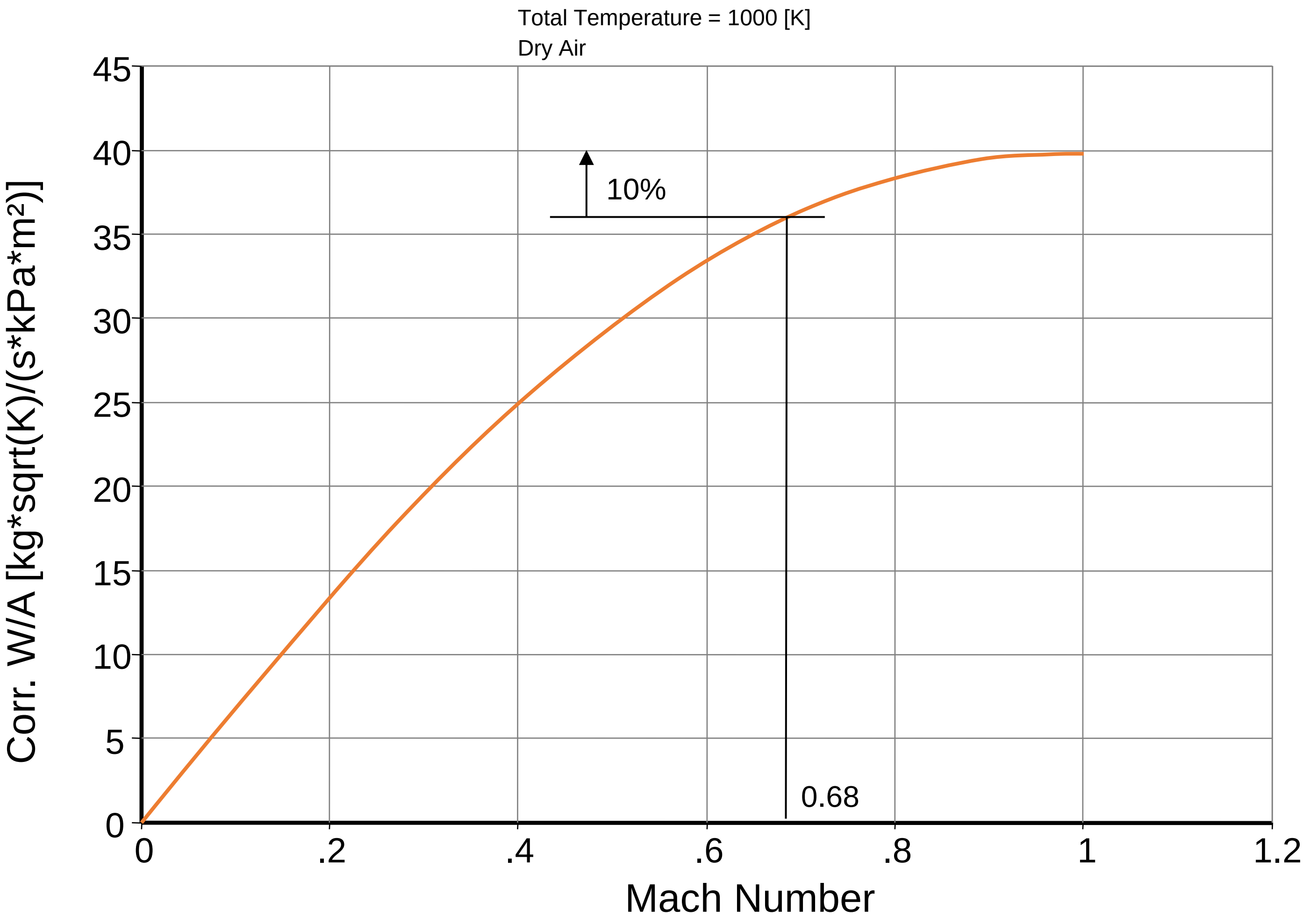


Compressor Map Format



Turbine Map Format

Turbojet Off-Design
Corrected Flow Through a Nozzle



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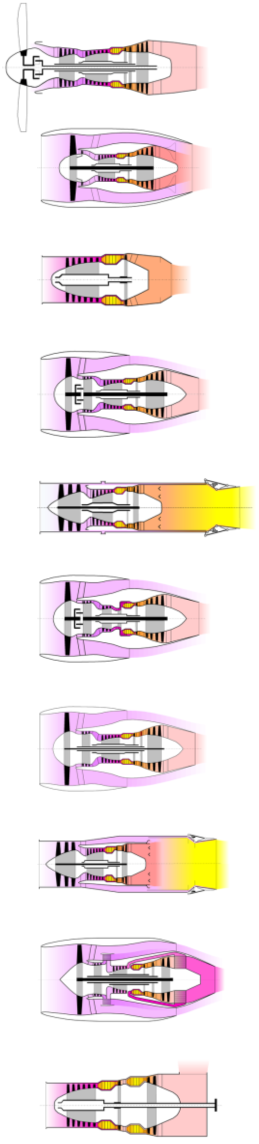

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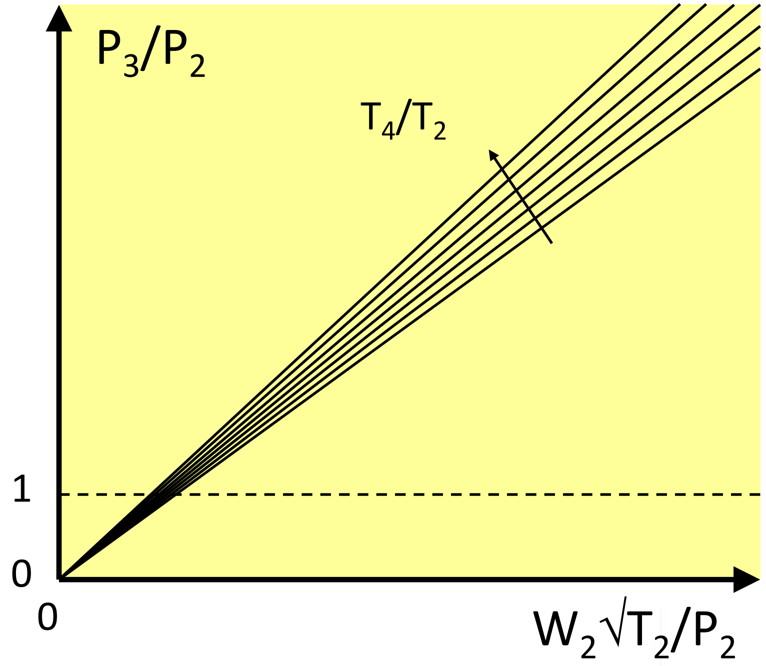
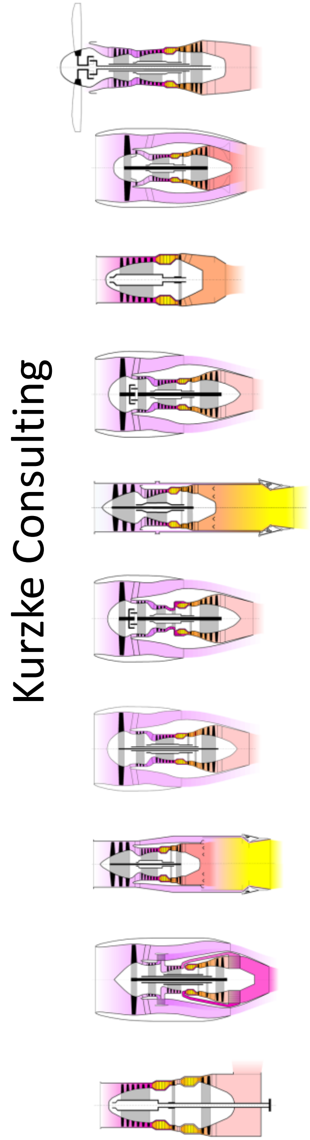
Flow Conservation Between Compressor and Turbine

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

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

Lines with constant T_4/T_2 in the compressor map



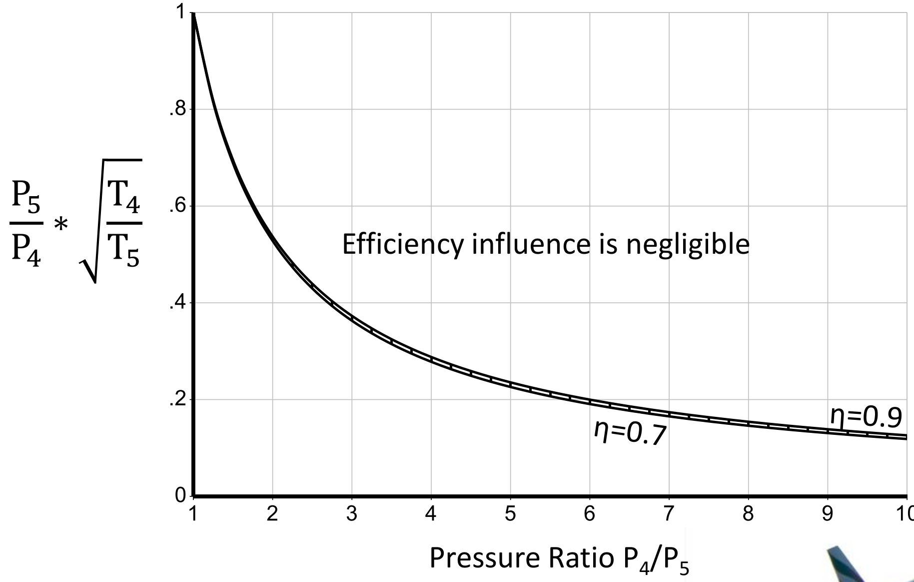


Turbojet Off-Design

Flow Conservation Between Turbine and Nozzle

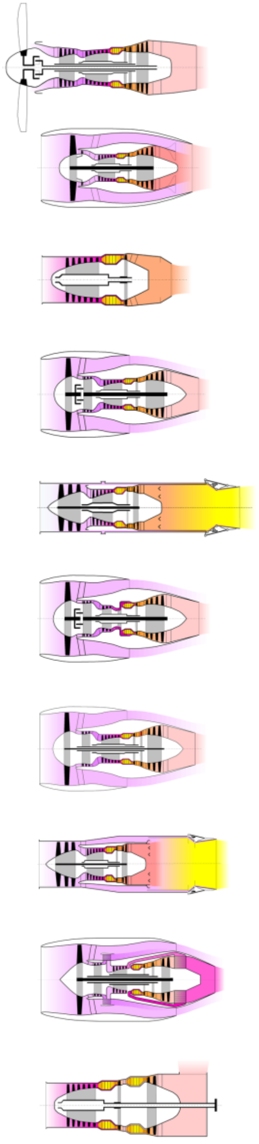
$$\frac{W_4 * \sqrt{T_4}}{A_4 * P_4} = \frac{W_8 * \sqrt{T_8}}{A_8 * P_8} * \frac{W_4}{W_8} * \frac{A_8}{A_4} * \frac{P_8}{P_5} * \sqrt{\frac{T_5}{T_8}} * \frac{P_5}{P_4} * \sqrt{\frac{T_4}{T_5}} \leftarrow f(P_4/P_5,\eta)$$

$const_C$



Turbine pressure ratio P_4/P_5 = const

Not affected by power offtake PW_x



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Turbojet Off-Design

Power Balance Between Compressor and Turbine

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

$$W_2 * H_C = W_4 * H_T$$

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

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

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

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

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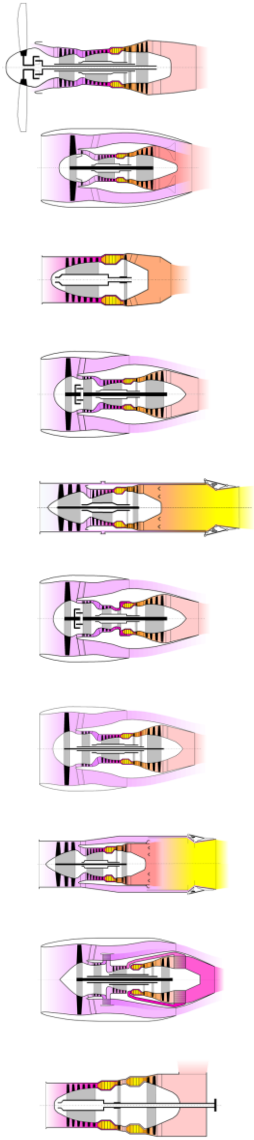
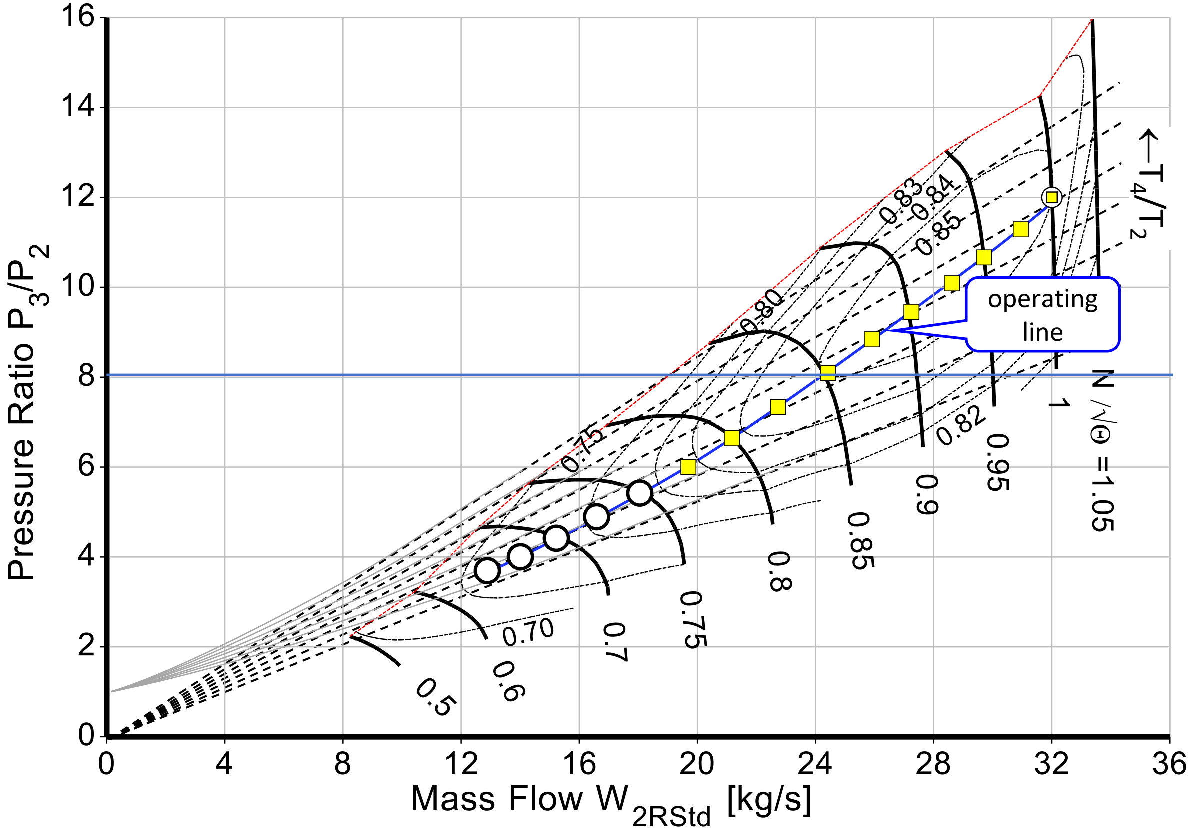


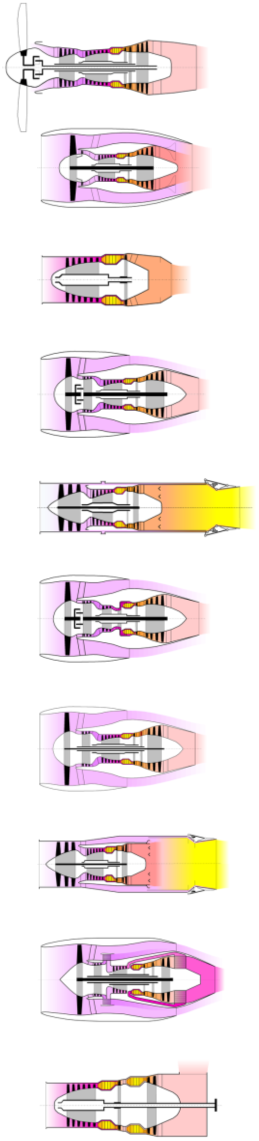
Turbojet Off-Design
Compressor Operating Line



From previous slide:

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

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



Turbojet Off-Design
Turbine Operating Line and Nozzle Mach Number

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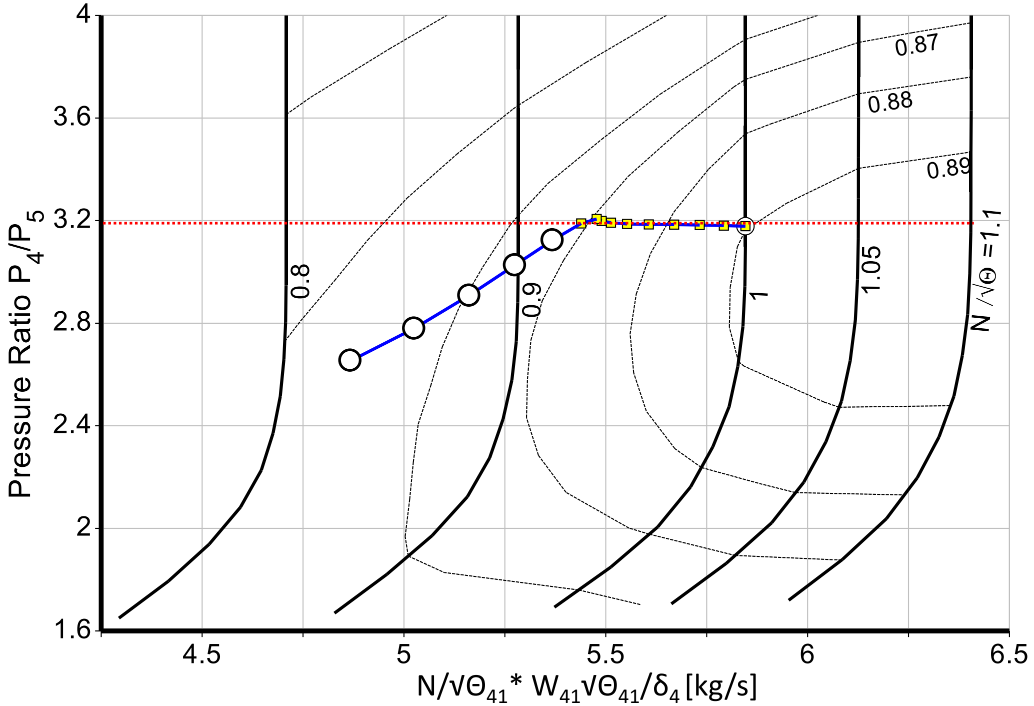
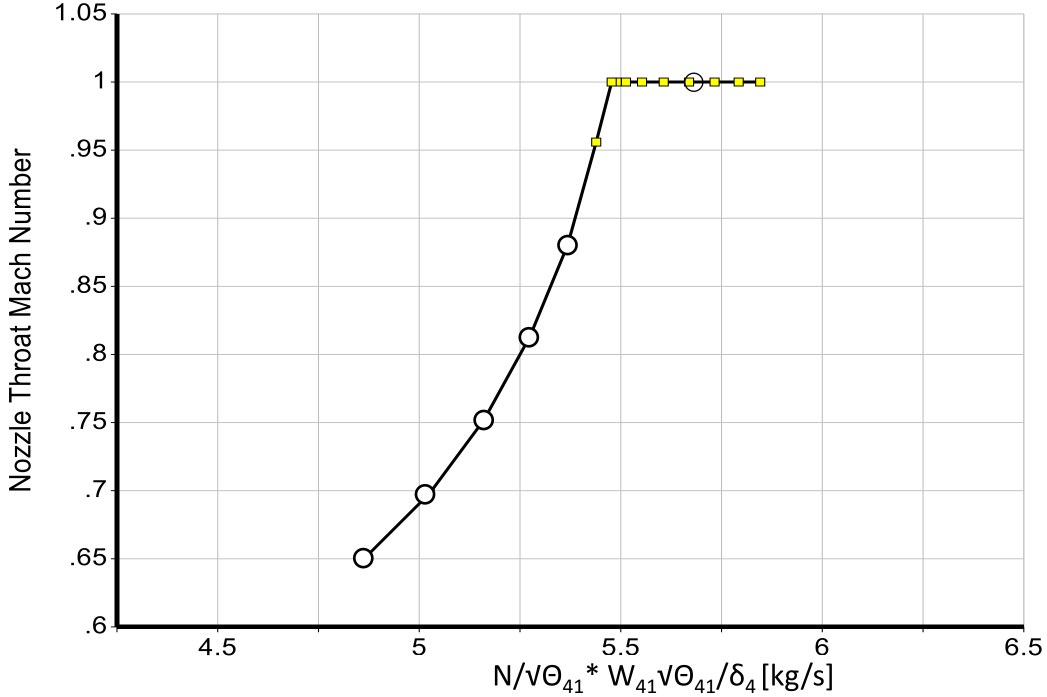
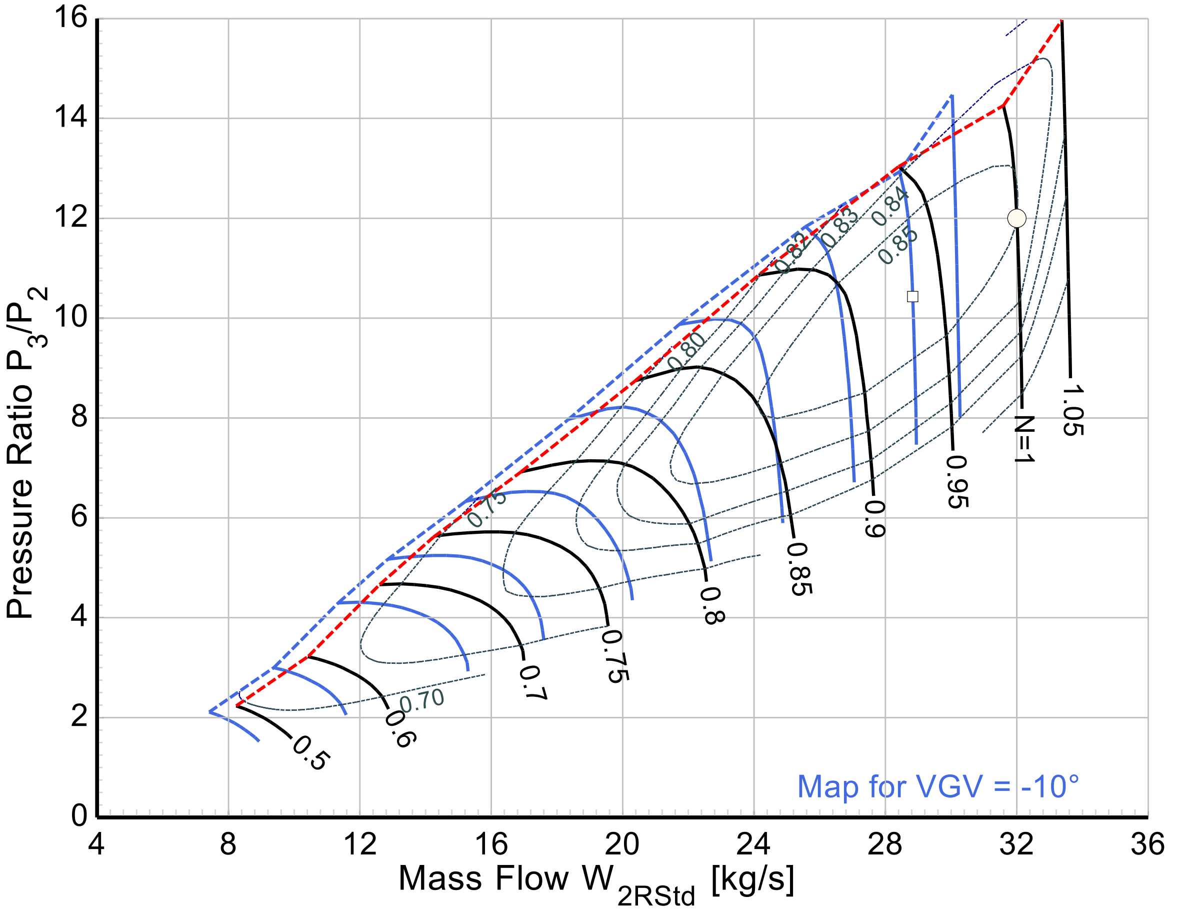
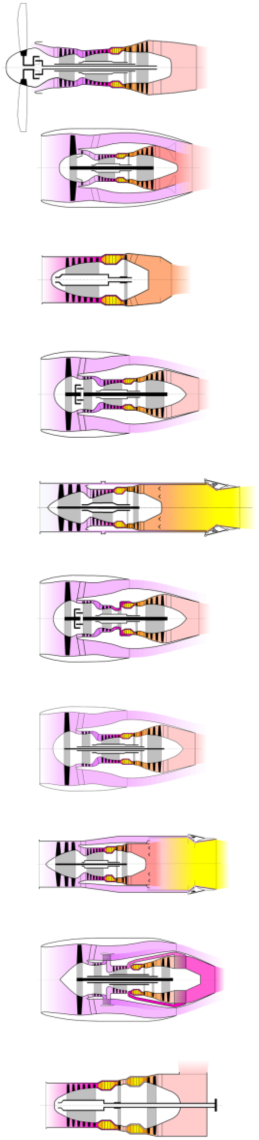


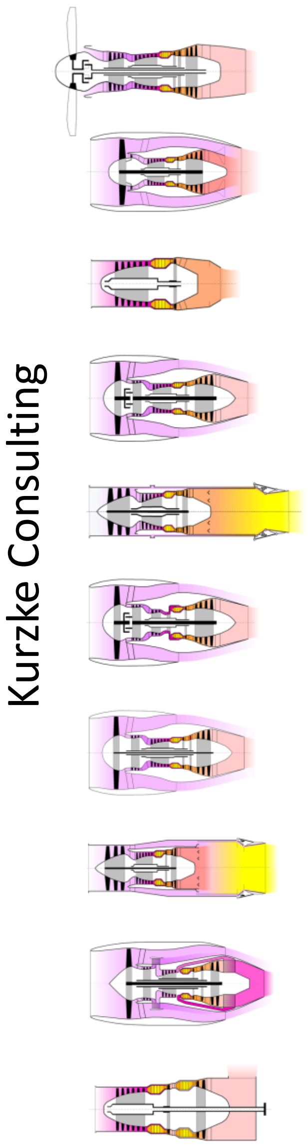


Turbojet Off-Design

Effect of -10°VGV Setting

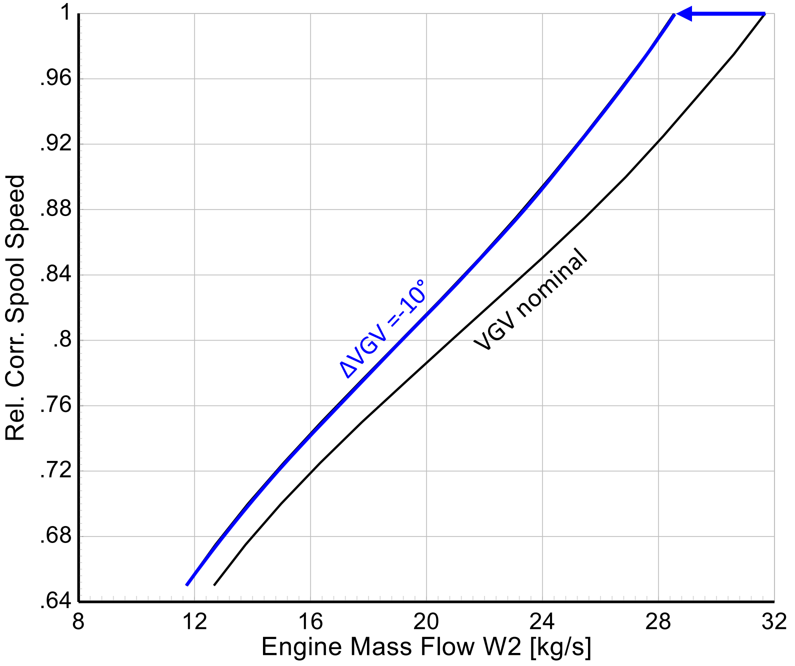


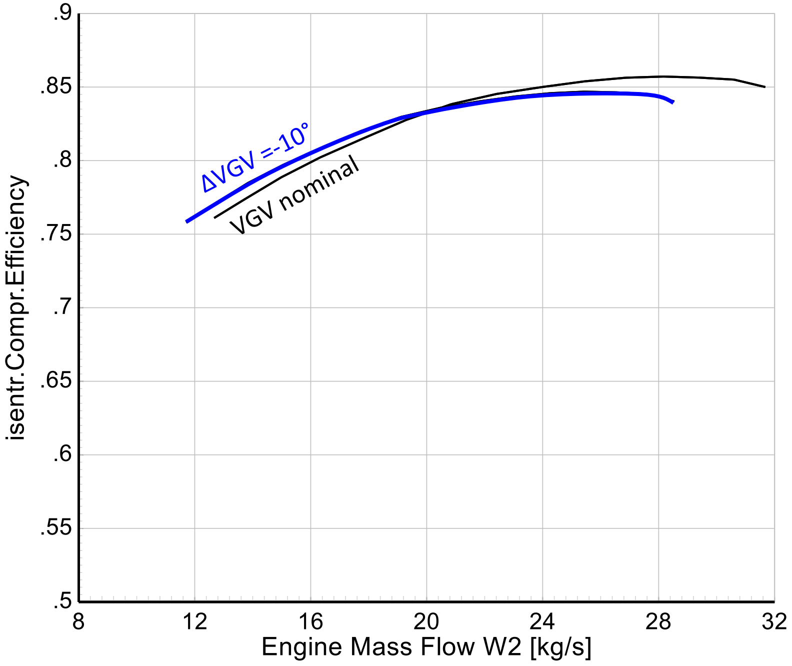




Turbojet Off-Design

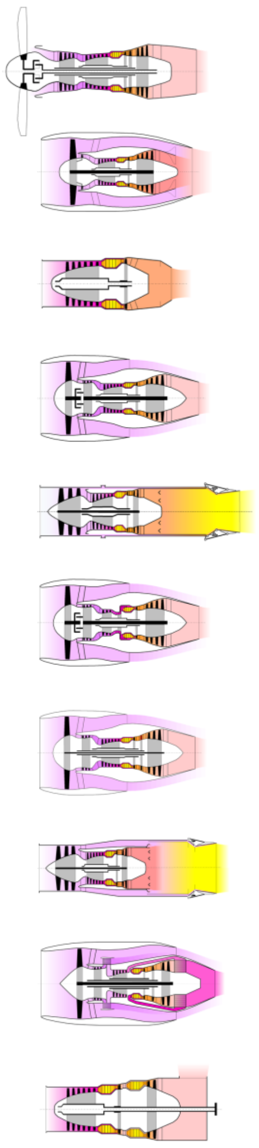
Effect of -10°VGV Setting on Flow and Efficiency

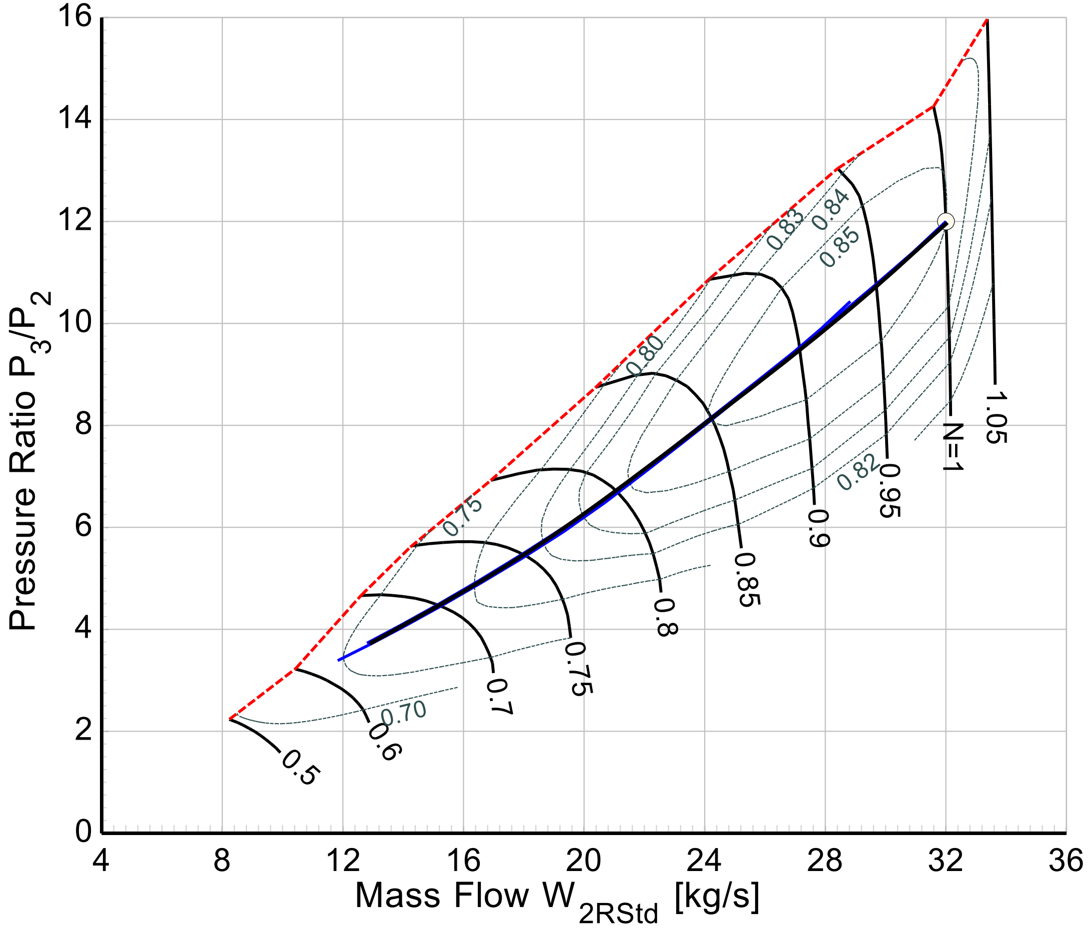




Turbojet Off-Design

Effect of -10°VGV Setting on Operating Line





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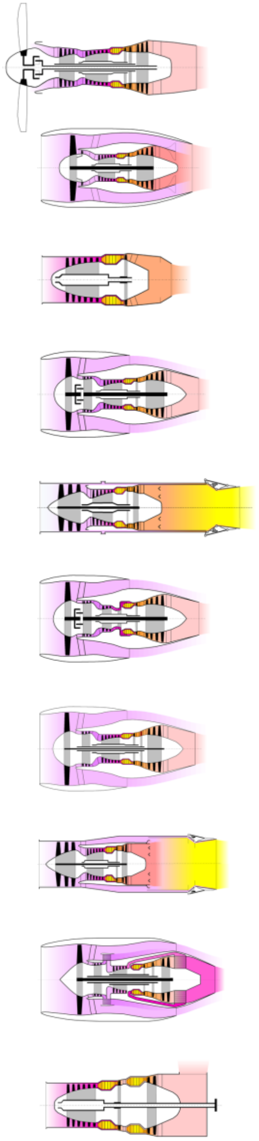


Question

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

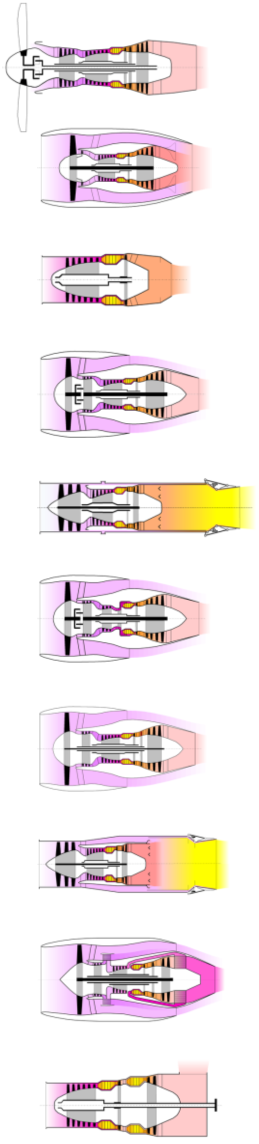
Efficiencies:	isentr	polytr	RNI	P/P
Compressor	0,8500	0,8913	0,990	12,000
Burner	0,9999			0,970
Turbine	0,8900	0,8757	1,798	3,178

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?



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Answer

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	

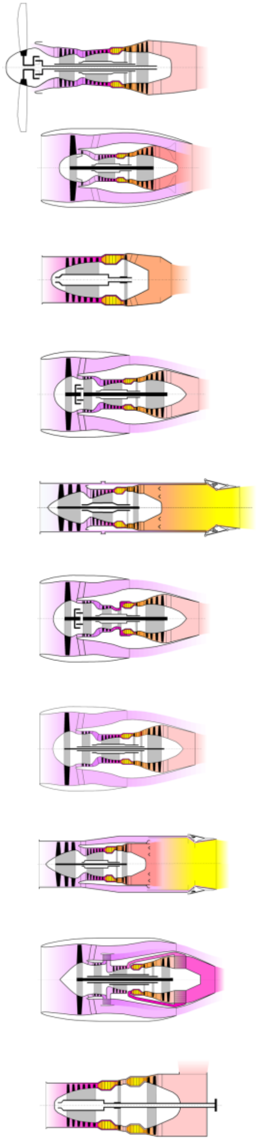
P2/P1 = 0,9900 P4/P3 = 0,9700 P6/P5 0,9800

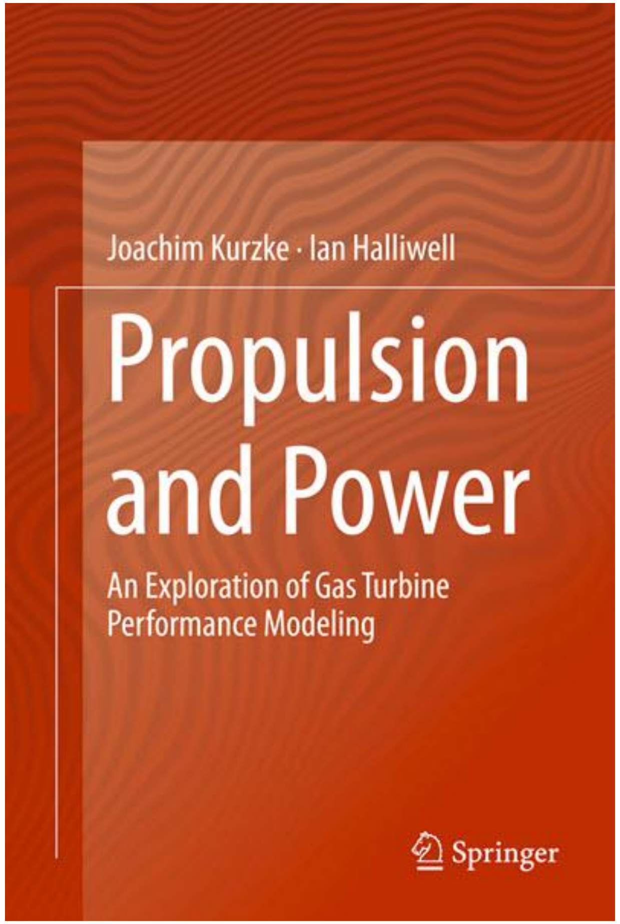
Efficiencies:	isentr	polytr	RNI	P/P
Compressor	0,8500	0,8913	0,990	12,000
Burner	0,9999			0,970
Turbine	0,8900	0,8563	1,798	11,282

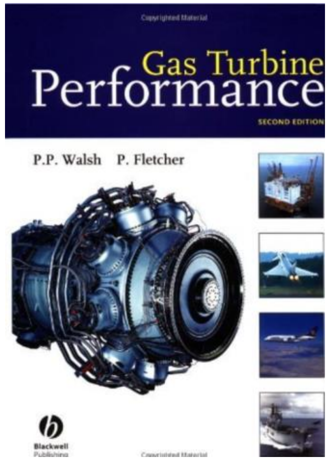
Spool mech Eff 0,9999 Nom Spd 14284 rpm

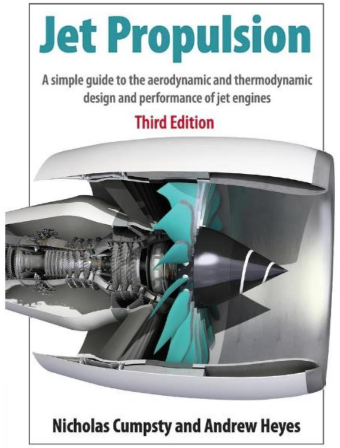
FN	=	0,72	kN
TSFC	=	299,0000	g/(kN*s)
FN/W2	=	22,57	m/s
Prop Eff	=	0,0000	
eta core	=	0,0058	
WF	=	0,66194	kg/s
s NOx	=	0,28659	
XM8	=	0,0392	
A8	=	4,0055	m²
P8/Pamb	=	1,0010	
WBld/W2	=	0,01000	
Ang8	=	20,00	°
CD8	=	0,8602	
W_NGV/W2	=	0,05000	
WCL/W2	=	0,05000	
Loading	=	100,00	%
e45 th	=	0,87201	
far7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

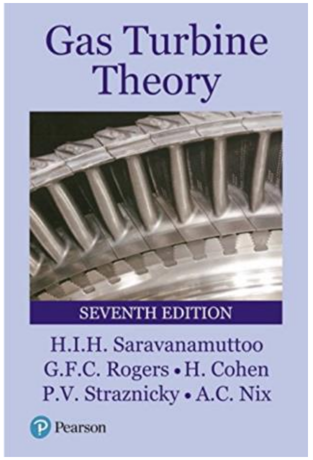
Books on my Bookshelf

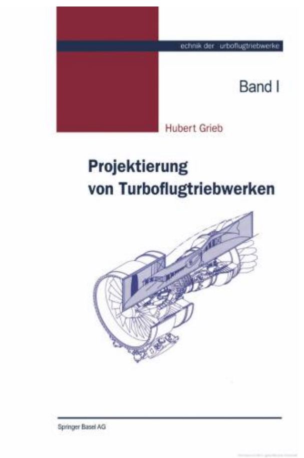


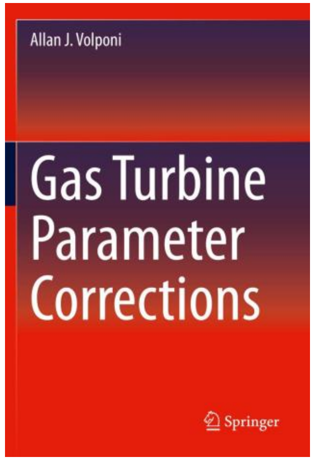












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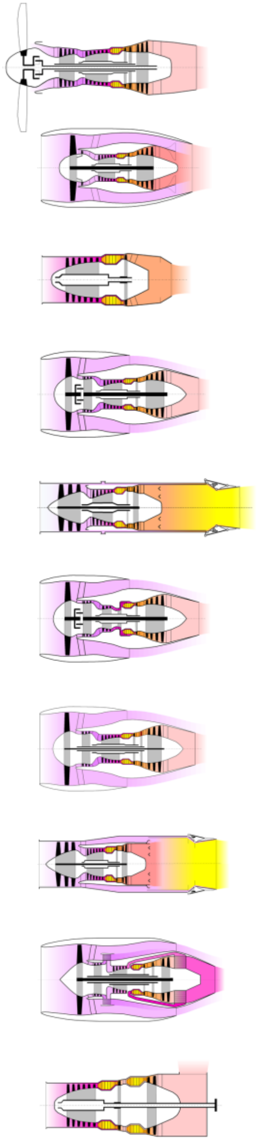
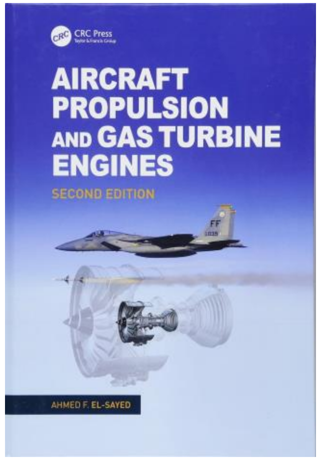
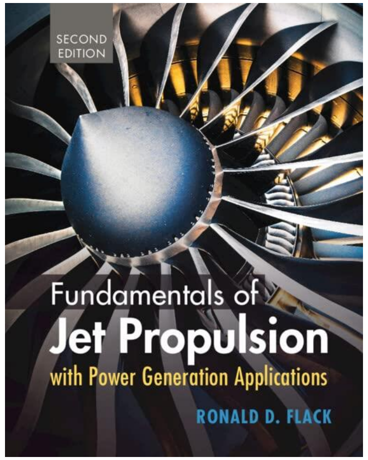
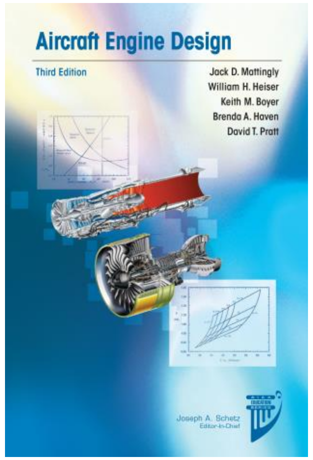
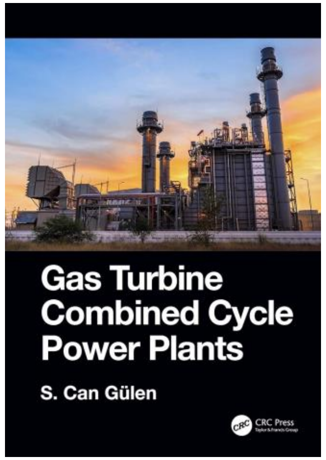


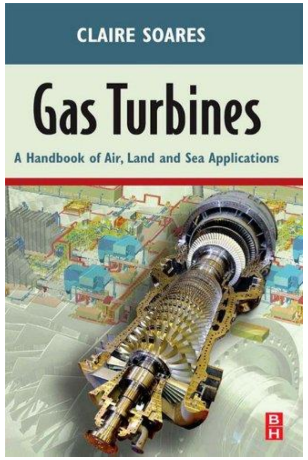
More …

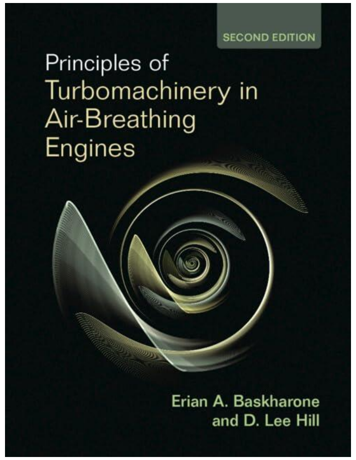


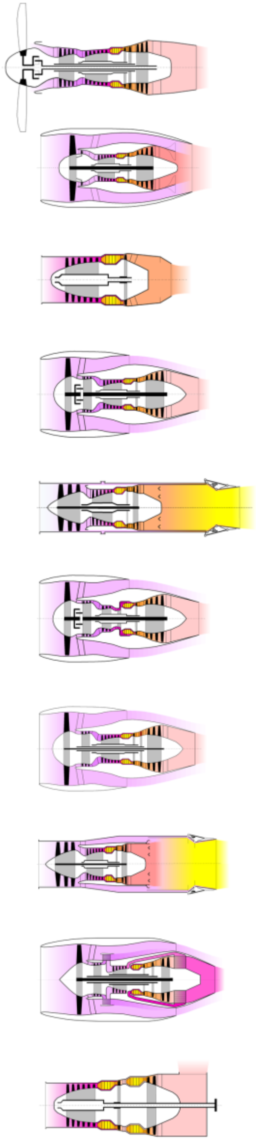












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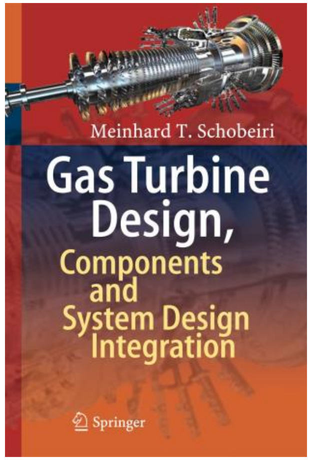
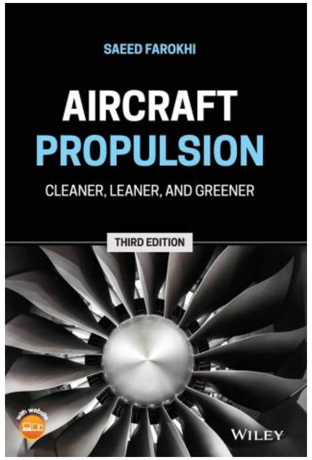
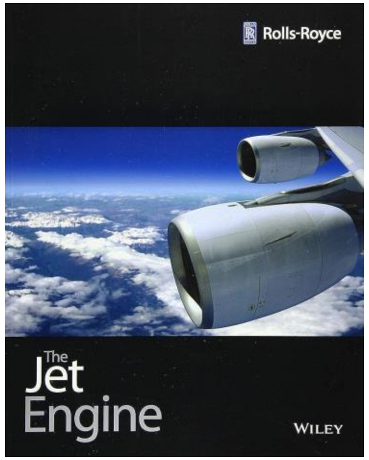
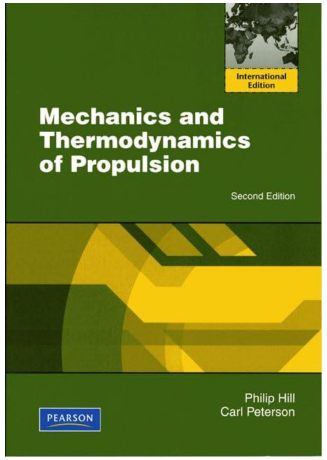
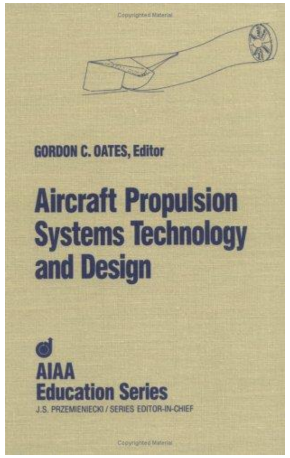
More …











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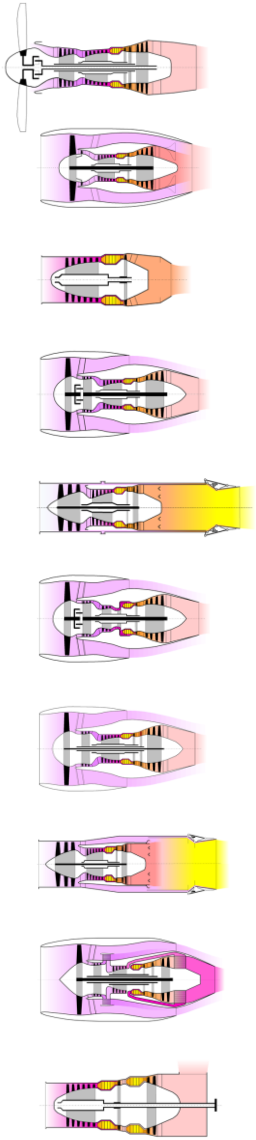
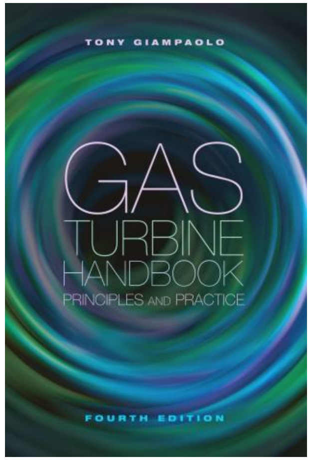
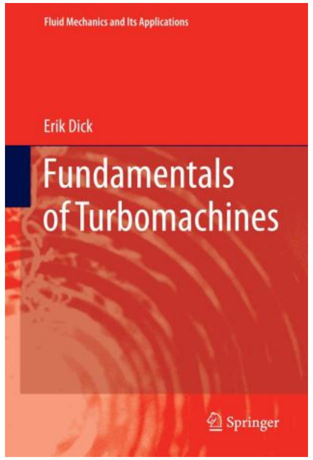
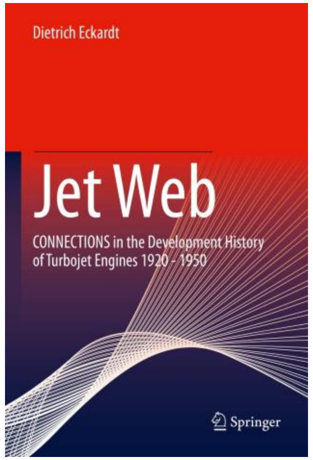


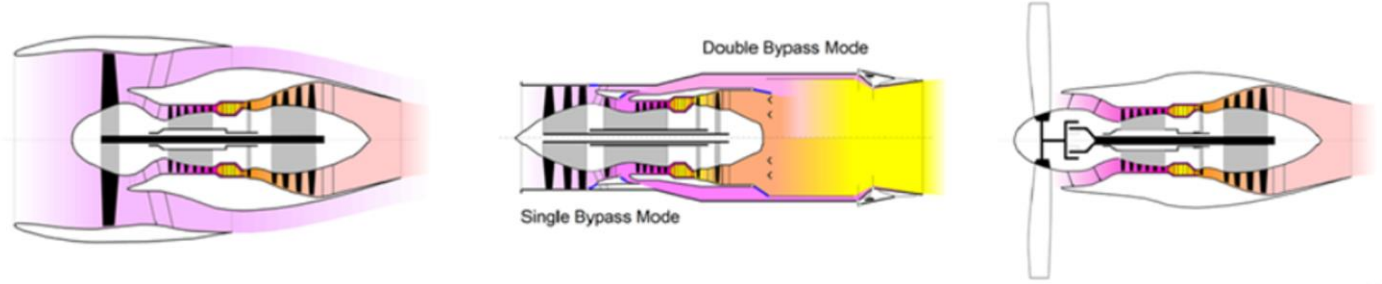
And More …



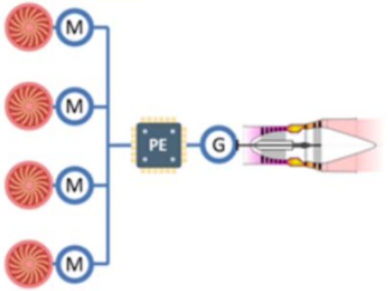




https://kurzke-consulting.de/



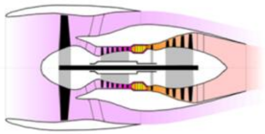
$$\mathrm{SFC} = \frac{V_0}{\eta_{therm} \times \eta_{prop}\,\mathrm{FHV}}$$



ADVANCED USER-FRIENDLY GAS TURBINE CALCULATIONS ON A PERSONAL COMPUTER

Joachim Kurzke

Paper 95-GT-147 presented at the International Gas Turbine and Aeroengine Congress and Exposition Houston, Texas – June 5-8, 1995



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