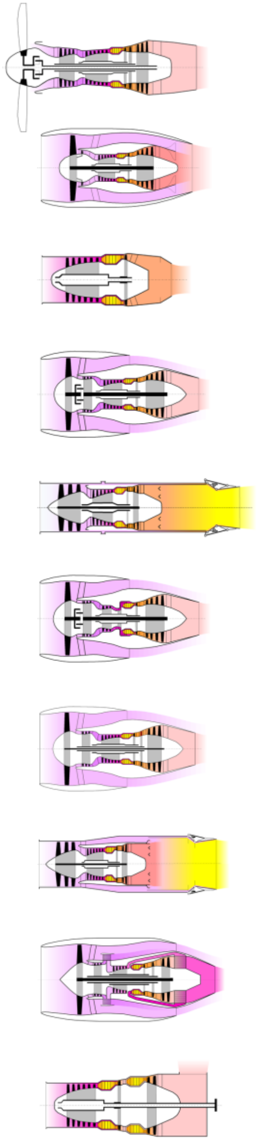
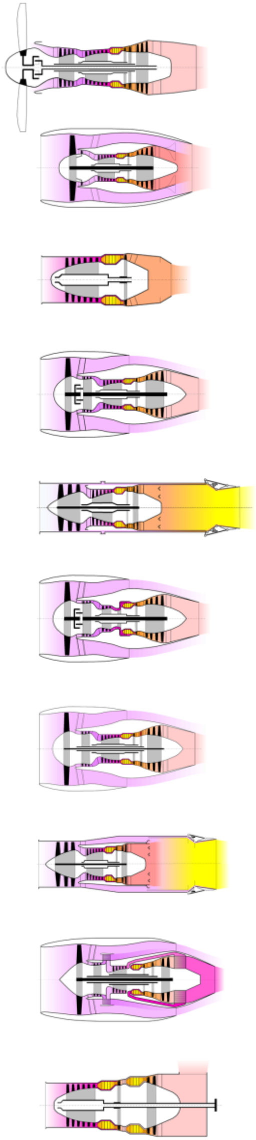


Practice-Relevant Teaching of Gas Turbine Performance

GPPS-TC-2025-0109 Presentation by Joachim Kurzke

Commercial Airliner 1958
JT3C Turbojet



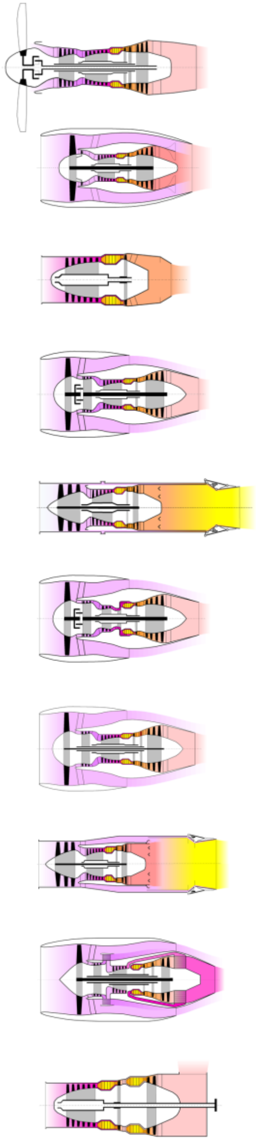
Should teaching gas turbine performance begin with the turbojet?

Turbojets are in 2025 not practice-relevant for commercial airliners

That’s what I said during the presentation

Commercial Airliner 2023

CFM Leap Turbofan



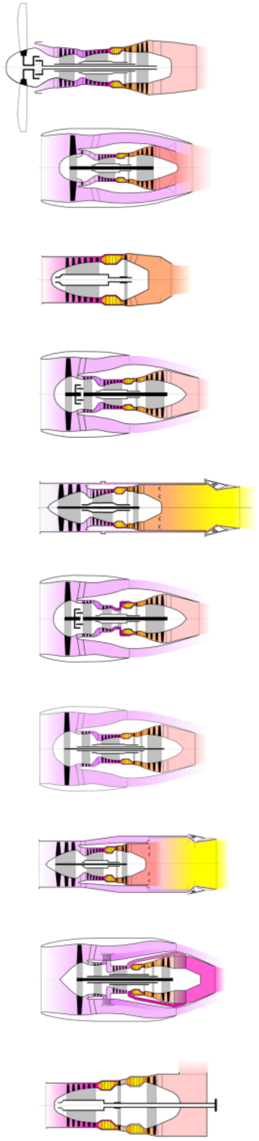
www.kurzke-consulting.de

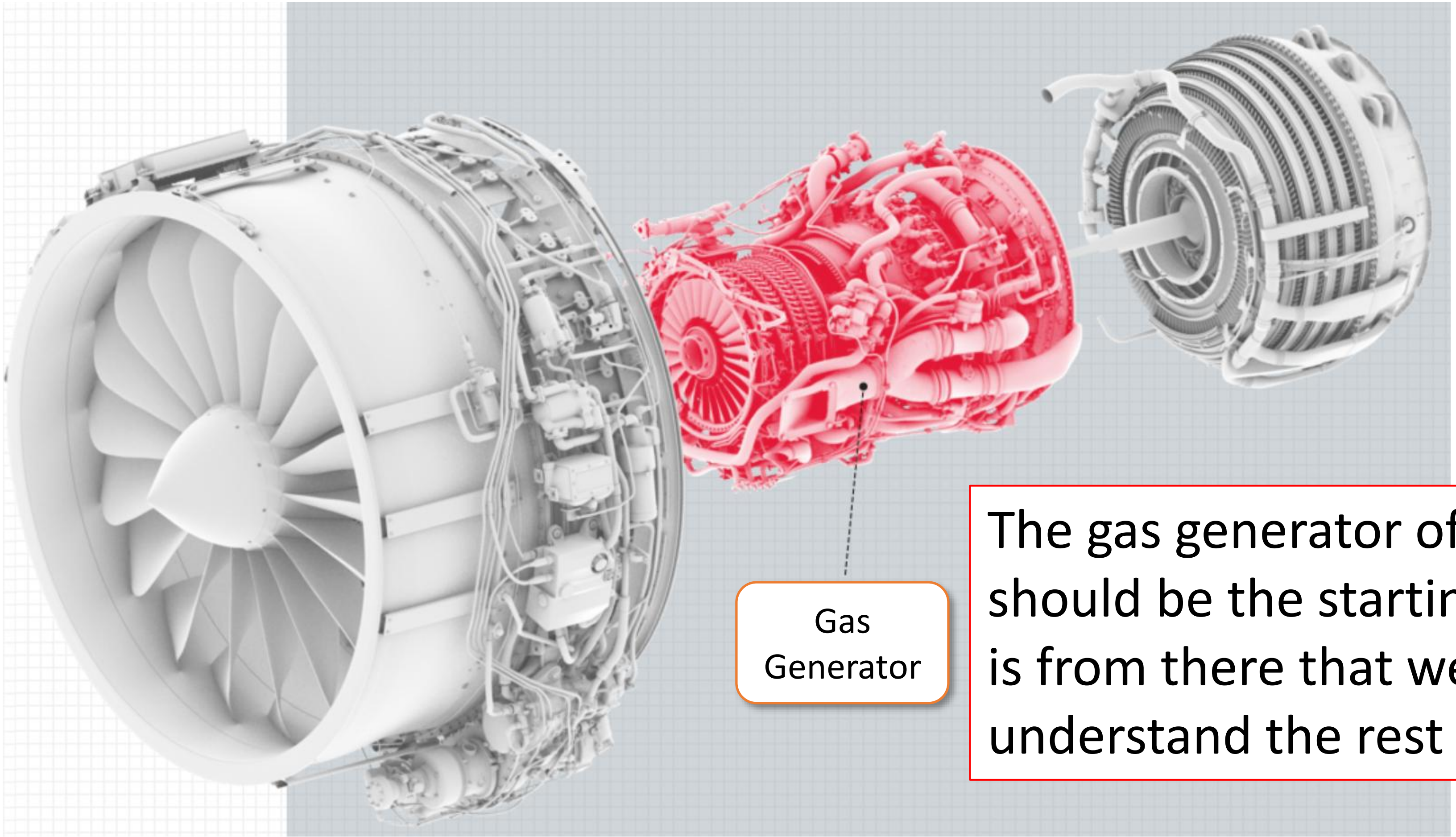
Turbofans are practice-relevant now!

Could teaching also begin with the turbofan?

Yes!

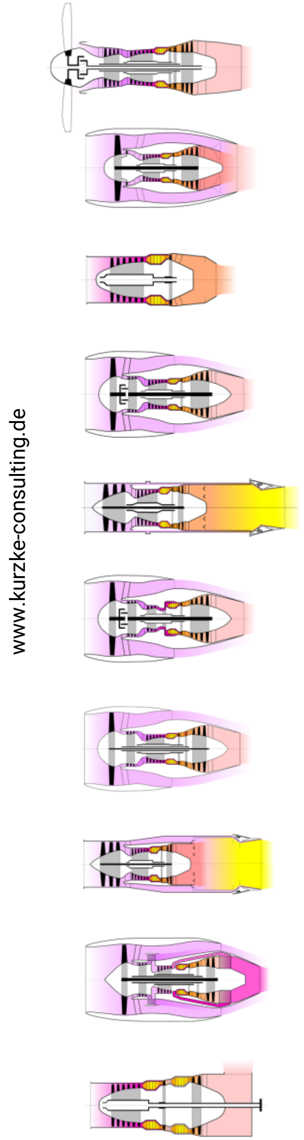
CFM56-3 Modular Design





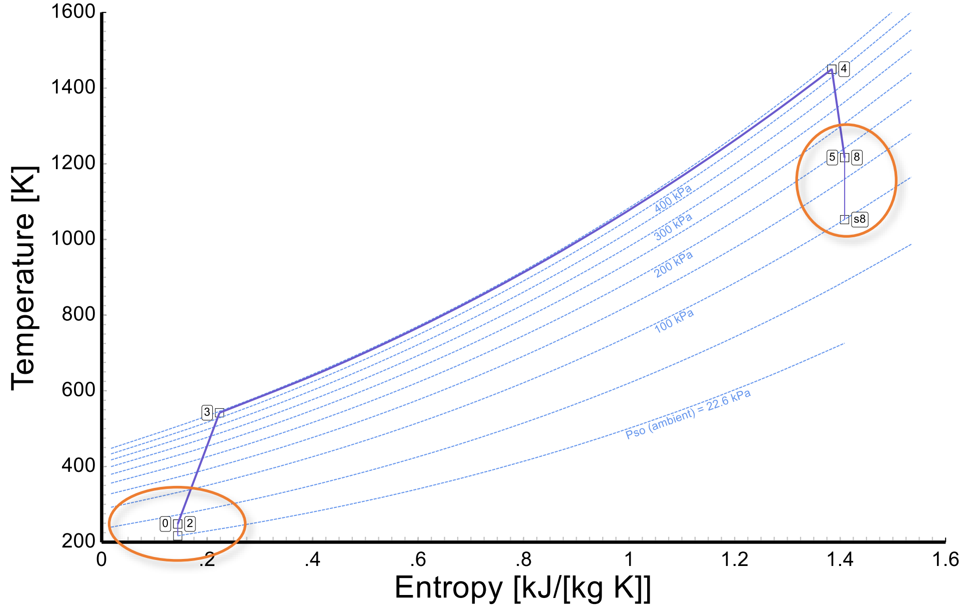
The heart of any aircraft gas turbine configuration is a gas generator!

The gas generator of the turbofan should be the starting point, and it is from there that we can begin to understand the rest of the system!



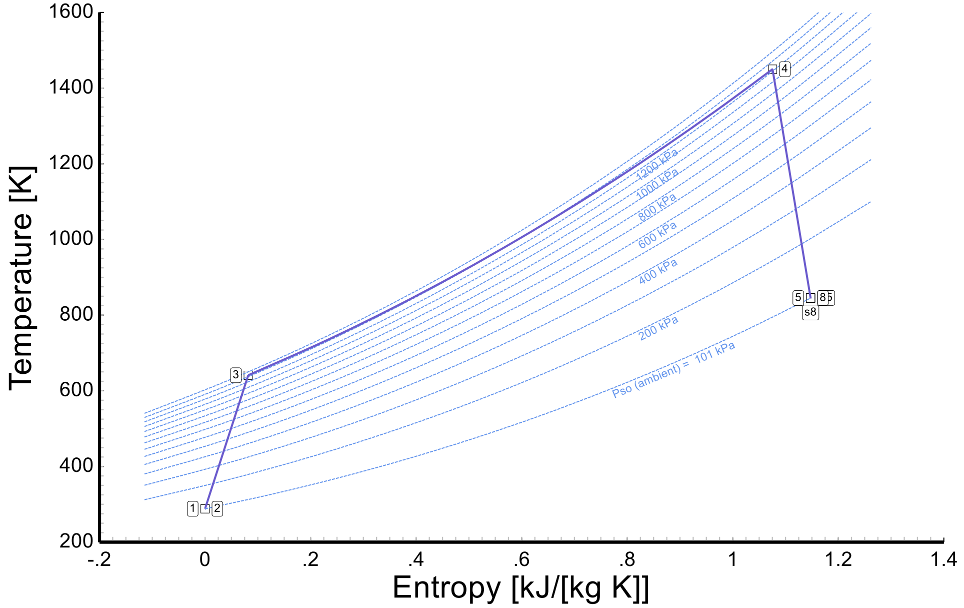
Introduction to the Thermodynamics of Gas Turbines

Turbojet @ 36000ft/0.85

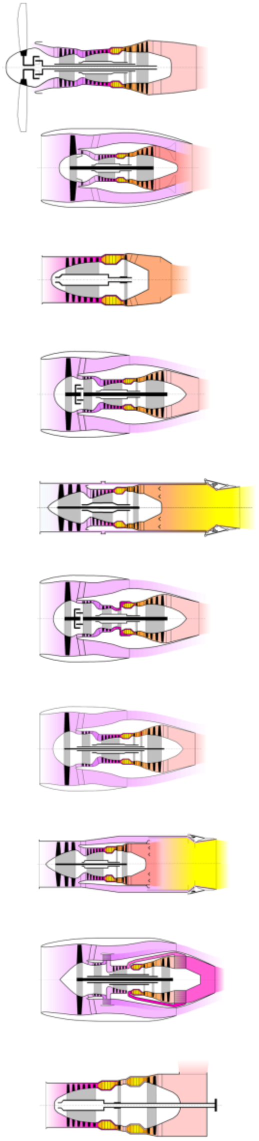


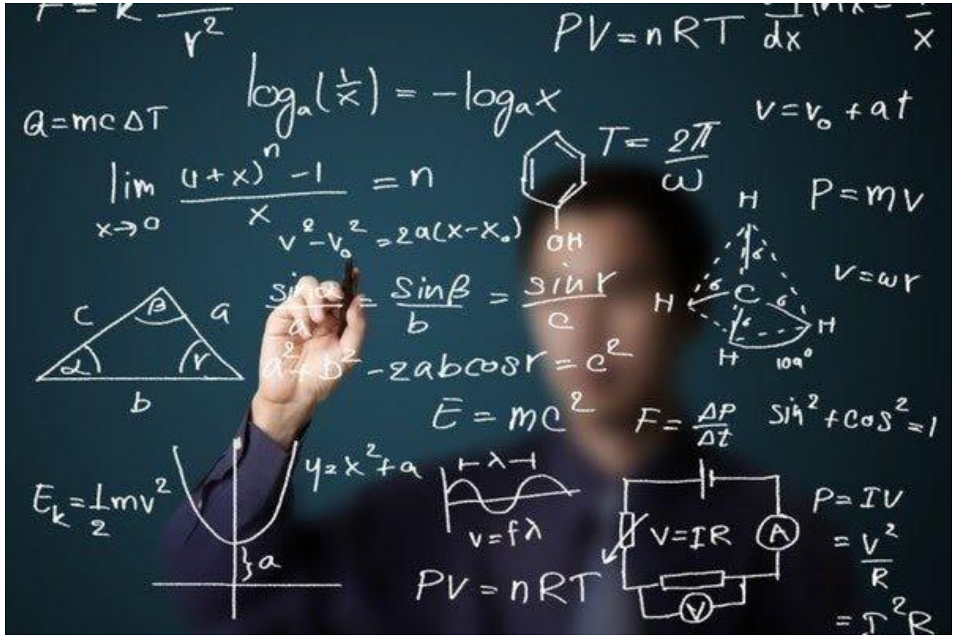
In fact, the operating cycle of a turbojet at 36,000 feet and Mach 0.85 is more complex than that of a gas generator!

Turboshaft SLS



The simplest way to introduce students to the field of gas turbine performance is to model the cycle of the gas generator as a turboshaft on a sea-level test bed!

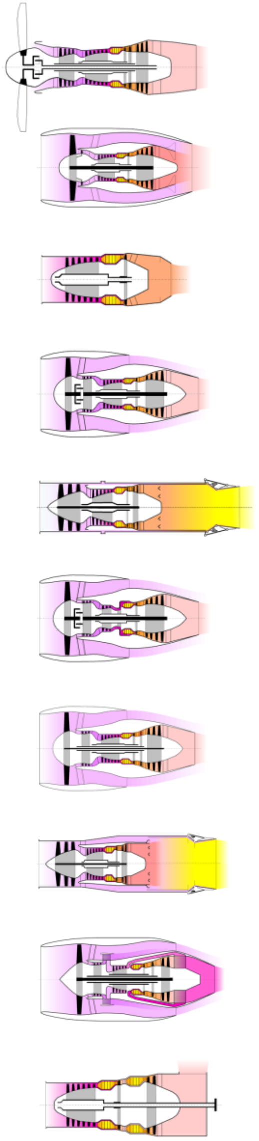




About Equations

… are they suited for realistic gas turbine performance calculations?

No one uses equations
in practice!



Thermal Efficiency
The Academic Definition

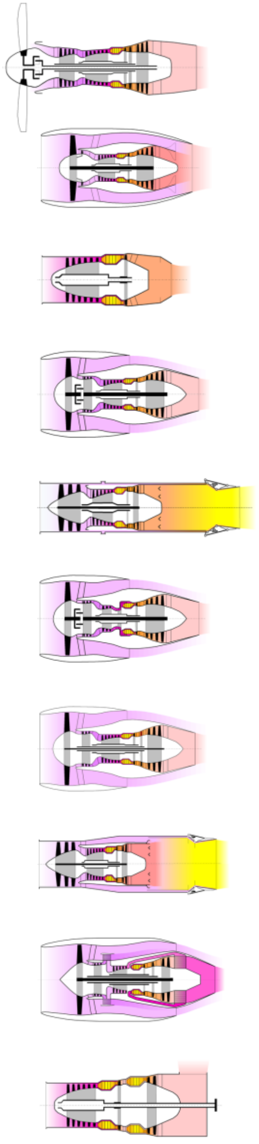
$$\eta_{th} = \frac{\Delta H_T - \Delta H_C}{\Delta H_B}$$

ΔH = specific work in kW per kg/s mass flow

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

This equation uses different isentropic exponents γ_C, γ_T and gas constants R_C, R_T for the compressor and turbine. Efficiencies η_C, η_T are isentropic.

www.kurzke-consulting.de

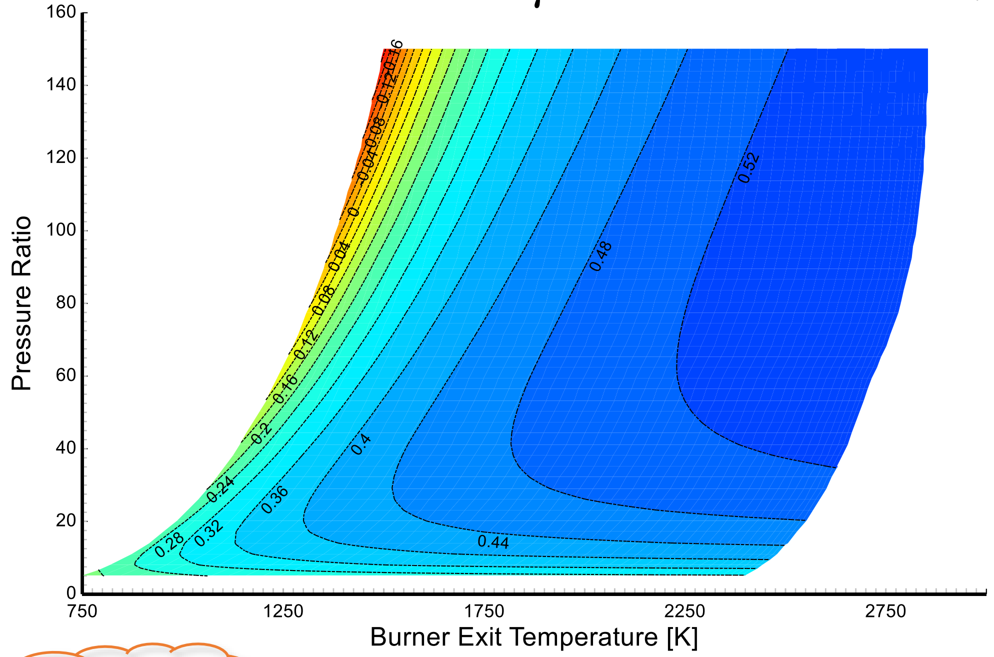


Thermal Efficiency – Academic Definition
Effect of Isentropic Exponent

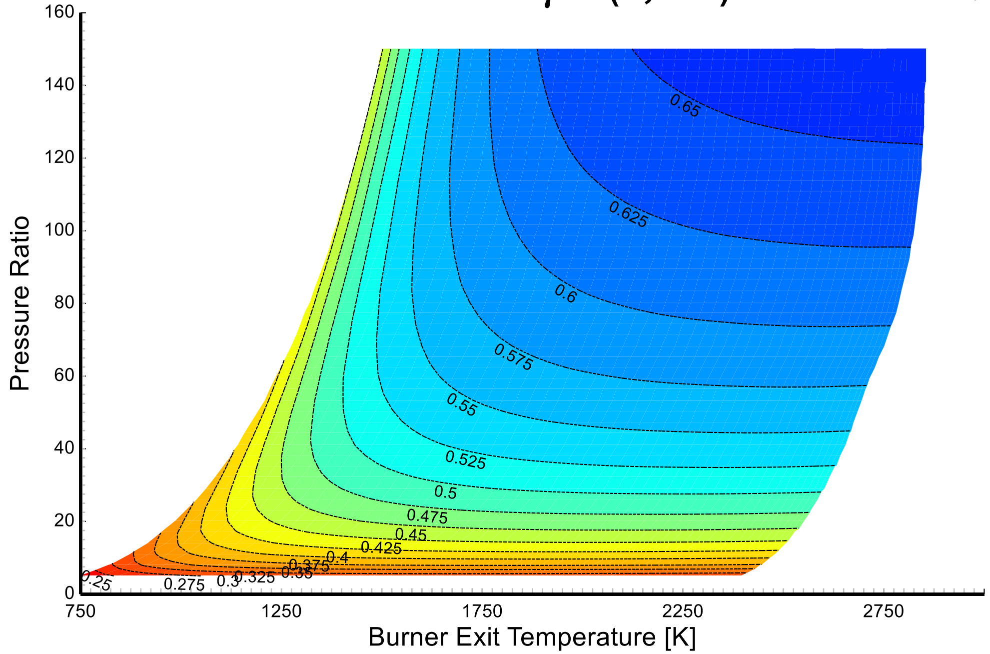
With constant isentropic exponent:
The higher the burner exit temperature, the greater the thermal efficiency.

With true gas properties:
The higher the pressure ratio, the greater the thermal efficiency.

$\gamma=1.4$



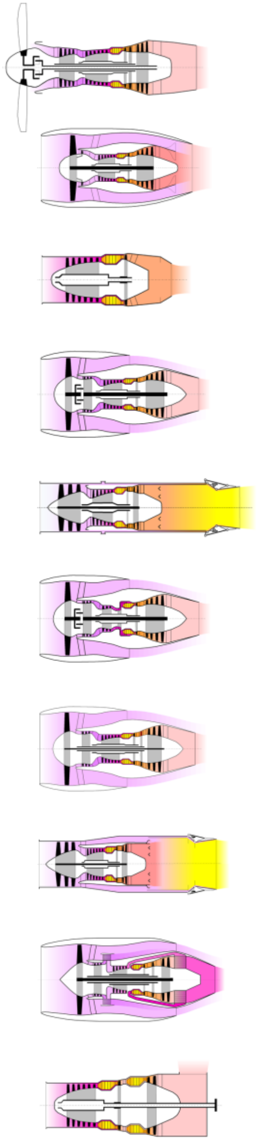
$\gamma=f(T,far)$



Color represents thermal efficiency

$\eta_{C,pol}=0.9$ $\eta_{T,pol}=0.9$

Two Definitions of Thermal Efficiency

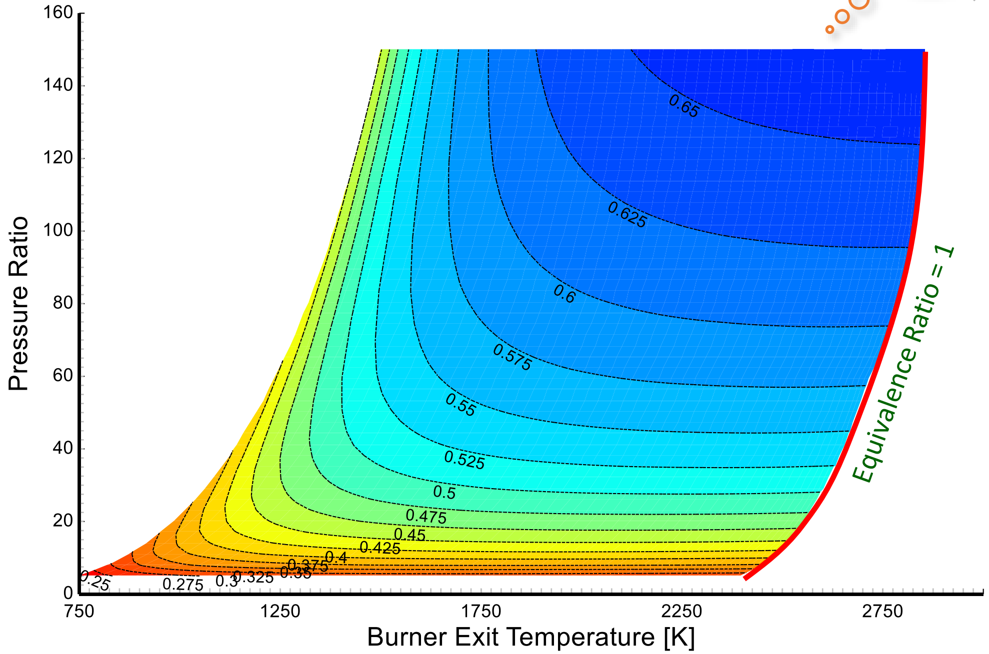


www.kurzke-consulting.de

Academic

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

No optimum exists!

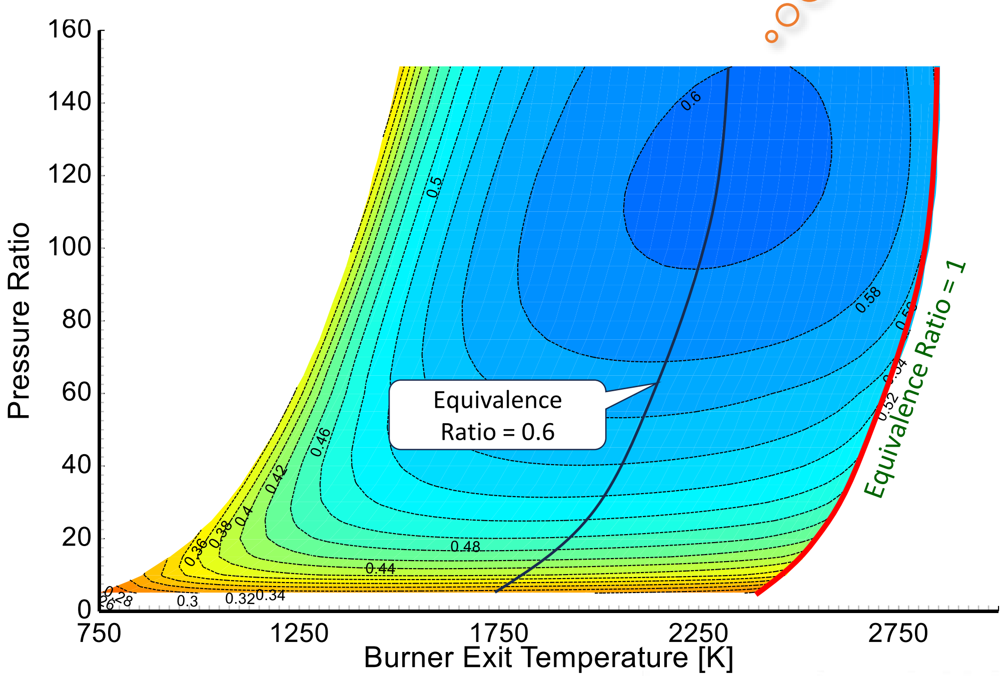


γ=f(T,far)

Practice

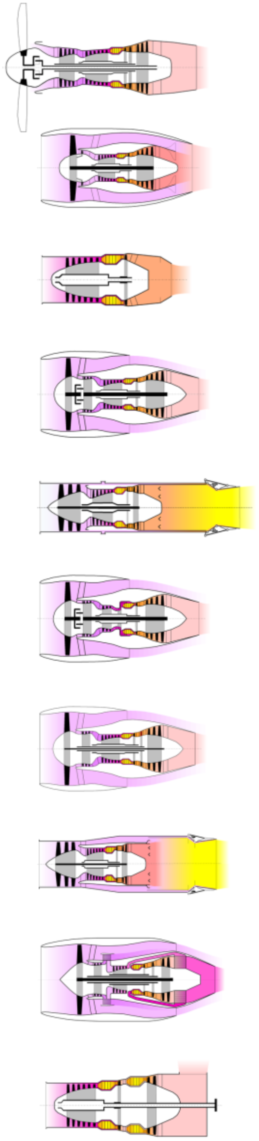
$$\eta_{th} = \frac{\Delta H_T - \Delta H_C}{W_F \times FHV}$$

There is an optimum along the line where the equivalence ratio is equal to 0.6.



$\eta_{C,pol}=0.9$ $\eta_{T,pol}=0.9$

$$Equivalence\ ratio = \frac{far}{far_{stoiciometric}}$$



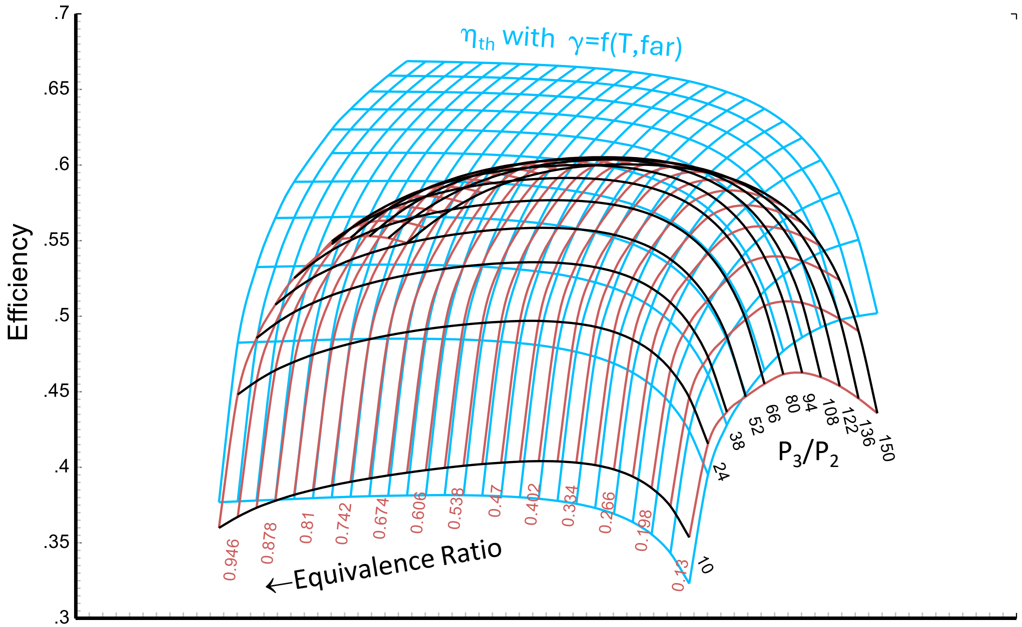
Thermal Efficiency – The Numbers

Academic

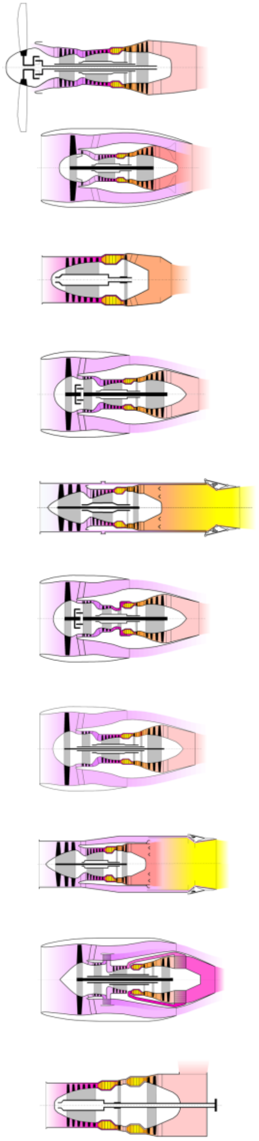
$$\eta_{th} = \frac{\Delta H_T - \Delta H_C}{\Delta H_B}$$

Practice

$$\eta_{th} = \frac{\Delta H_T - \Delta H_C}{W_F \times FHV}$$



The academic definition of thermal efficiency yields numbers that are not relevant in practice.



Observations

- The result for constant γ is misleading because it says that the highest burner exit temperature gives the highest thermal efficiency.

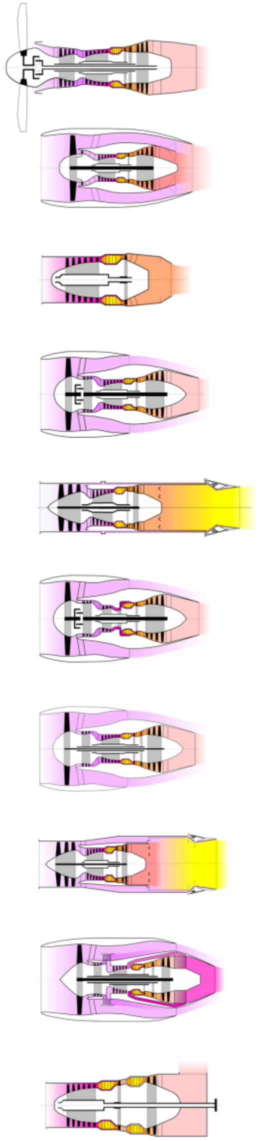
- The result for γ=f(T,far) is misleading also because it says that the highest pressure ratio gives the highest thermal efficiency.

- The pressure ratios of up to 150 considered have nothing in common with those of real gas turbines.

- The heat addition method is not included in the academic definition of thermal efficiency.

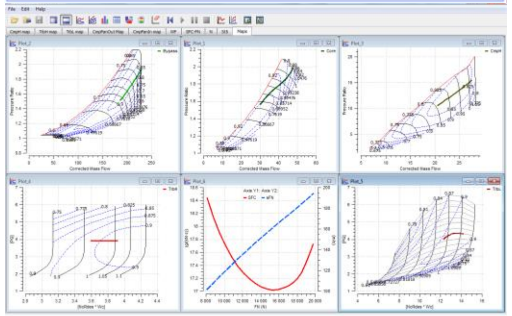
  - In practice, heat is added by burning fuel.
  - The achievable temperature is limited by stoichiometric combustion
  - The slope $\Delta T/\Delta W_f$ decreases with increasing fuel-air-ratio until $\Delta T/\Delta W_f = 0$ for stoichiometric combustion

www.kurzke-consulting.de



npss
NUMERICAL PROPULSION SYSTEM SIMULATION
A Consortium of SwRI

PROOSIS
Propulsion Object Oriented Simulation Software



Performance Software

The tool used in practice

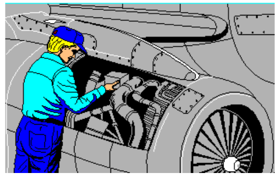
GasTurb 8 Professional

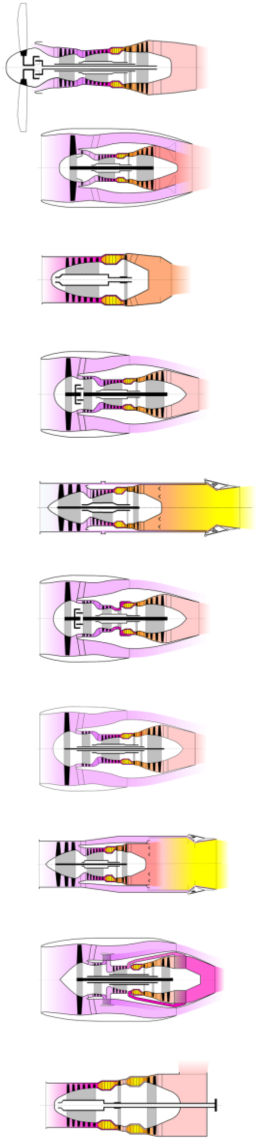
1998

GasTurb 8

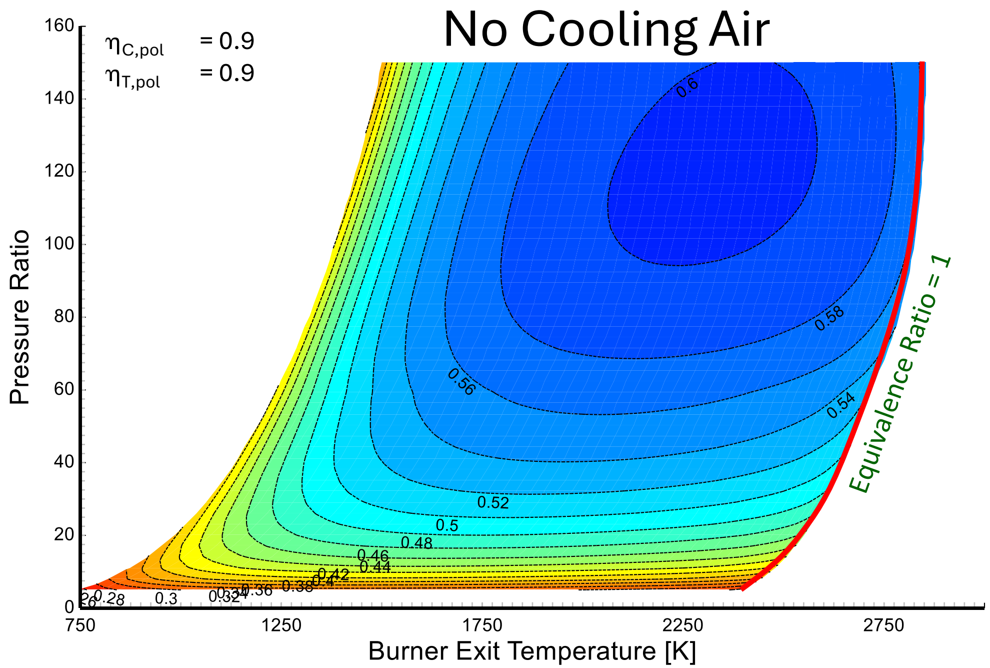
GasTurb Details

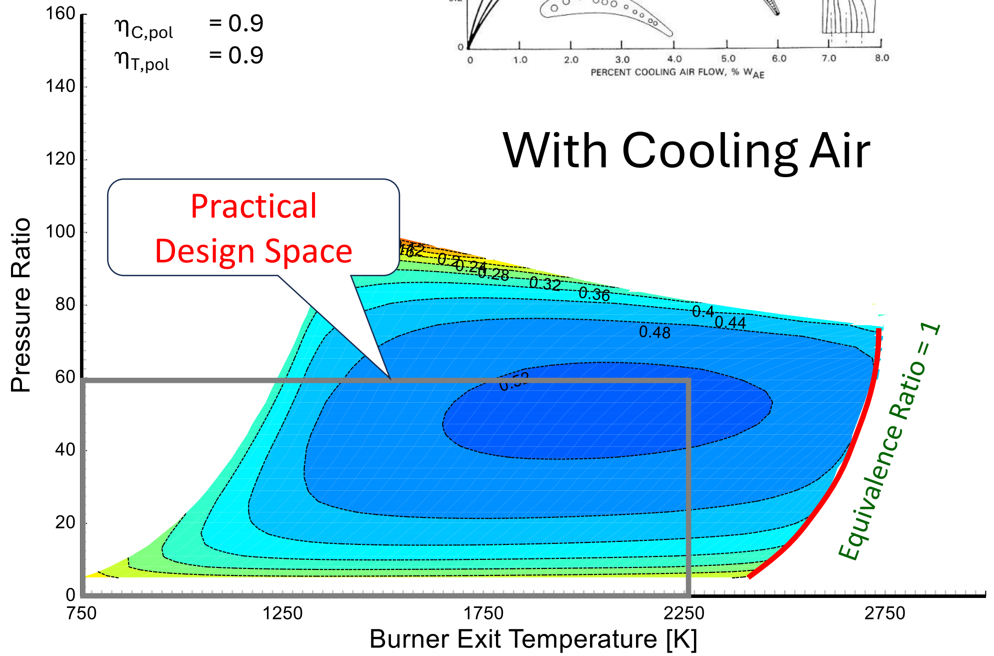
Smooth C Demo

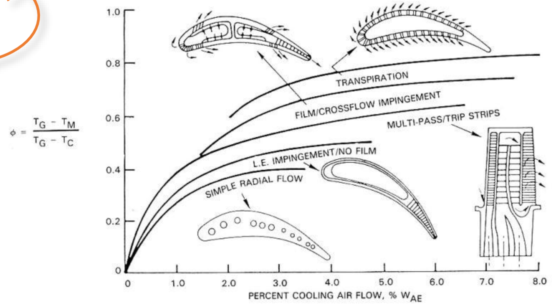




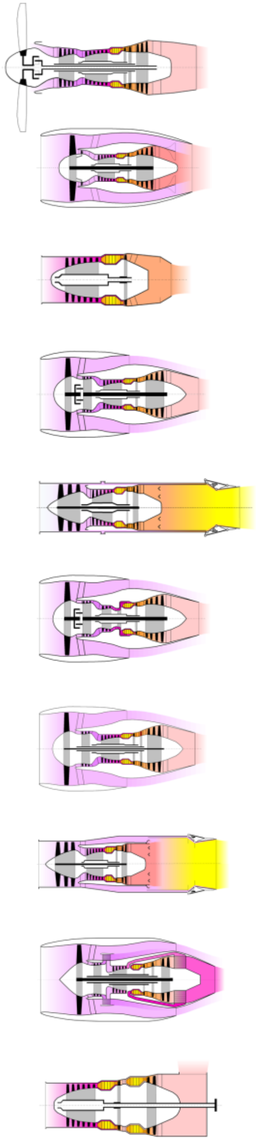
A More Realistic Efficiency Calculation



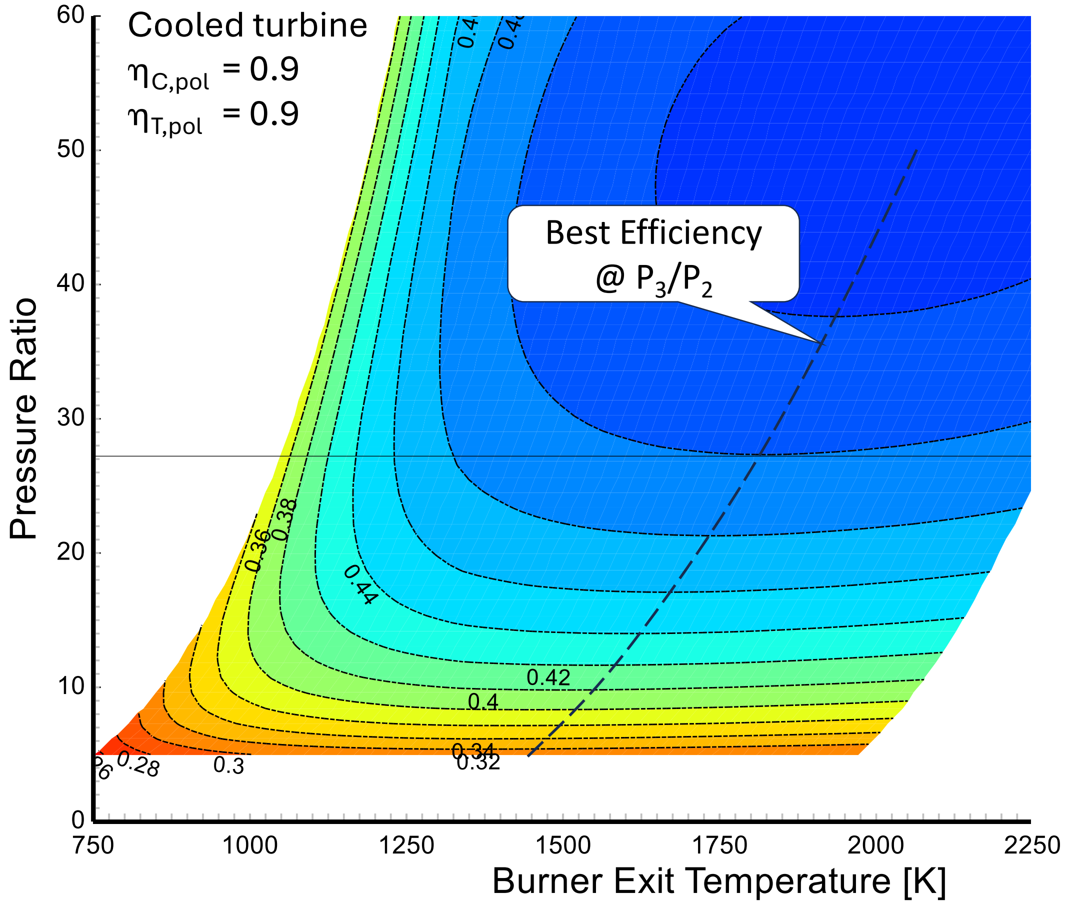




www.kurzke-consulting.de



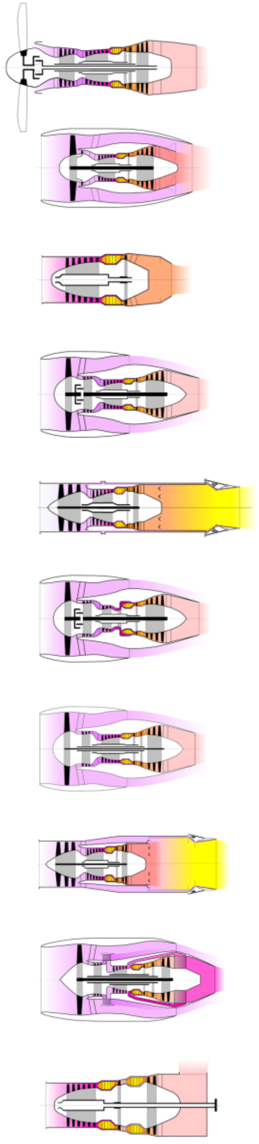
Practical Design Space
Thermal Efficiency

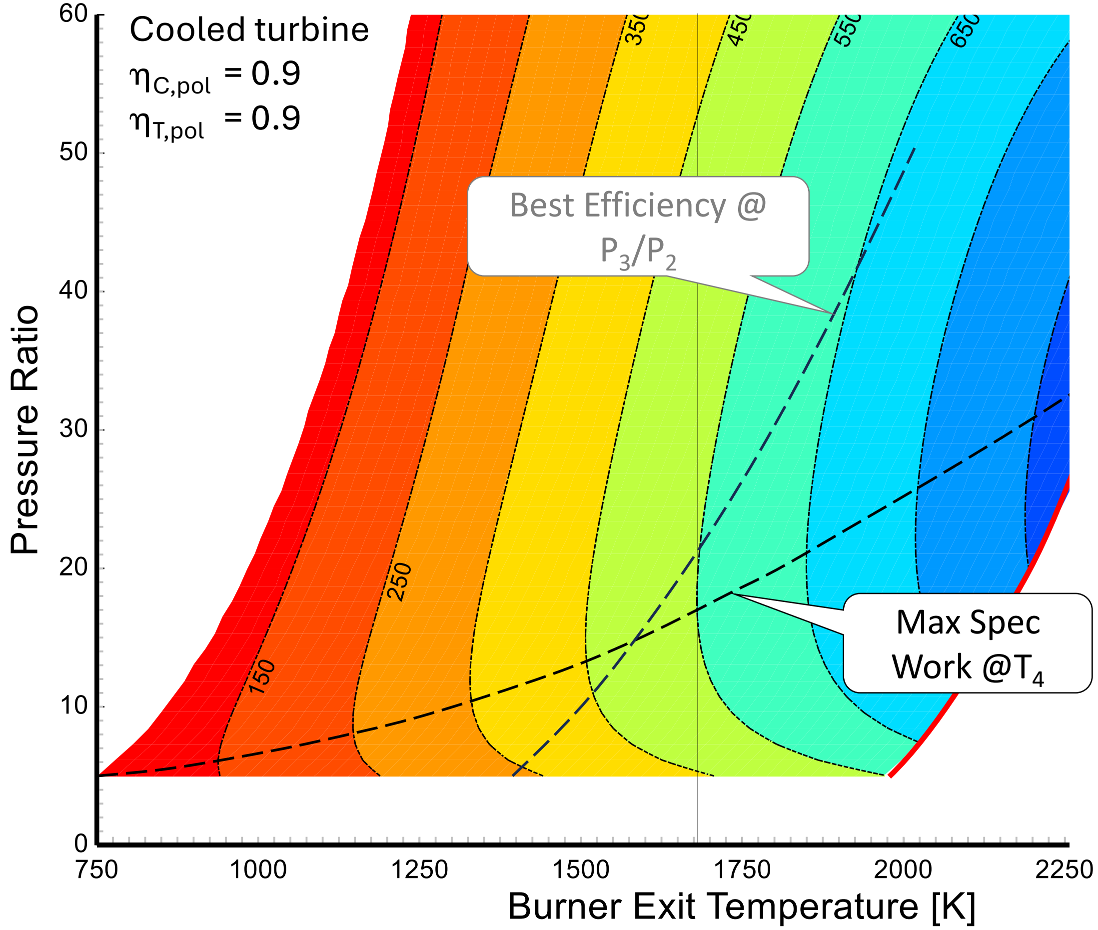


Stoichiometric combustion does not yield the ultimate thermal efficiency!

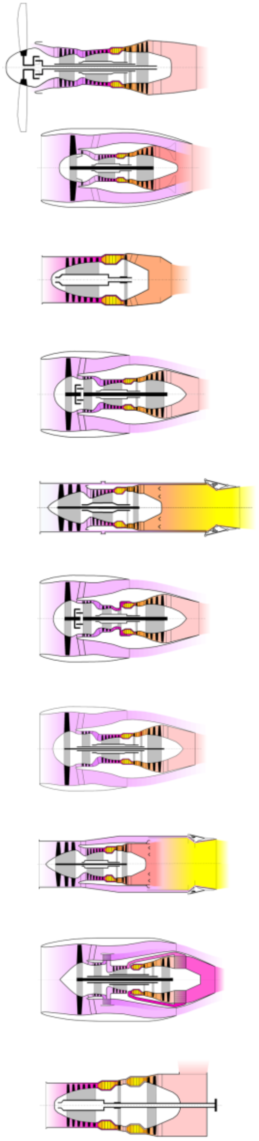
Practical Design Space
Specific Power

www.kurzke-consulting.de



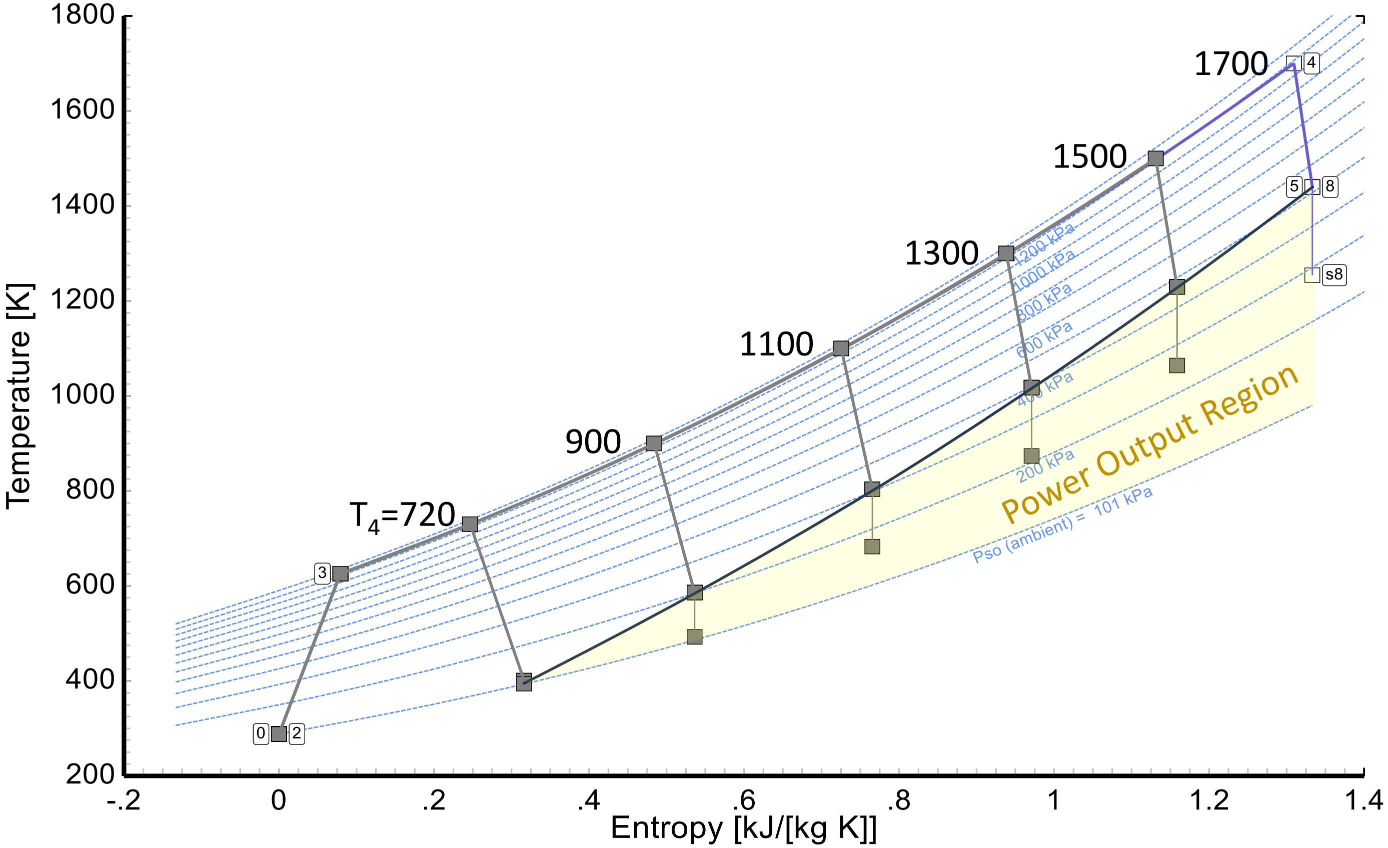


Specific power increases with burner exit temperature



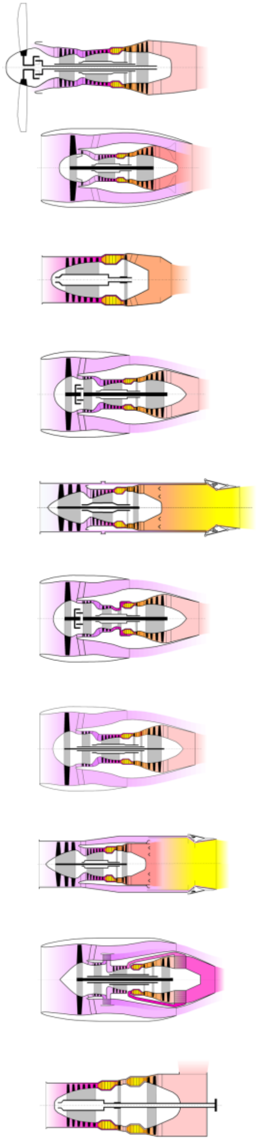
Why Increases Specific Power with T_4 ?

Pressure Ratio = 12



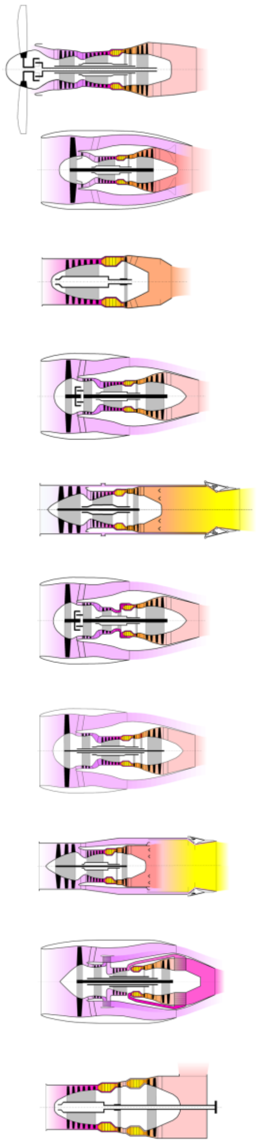
Because the isobar lines diverge. No equation is needed to explain why specific work increases with burner exit temperature!

www.kurzke-consulting.de



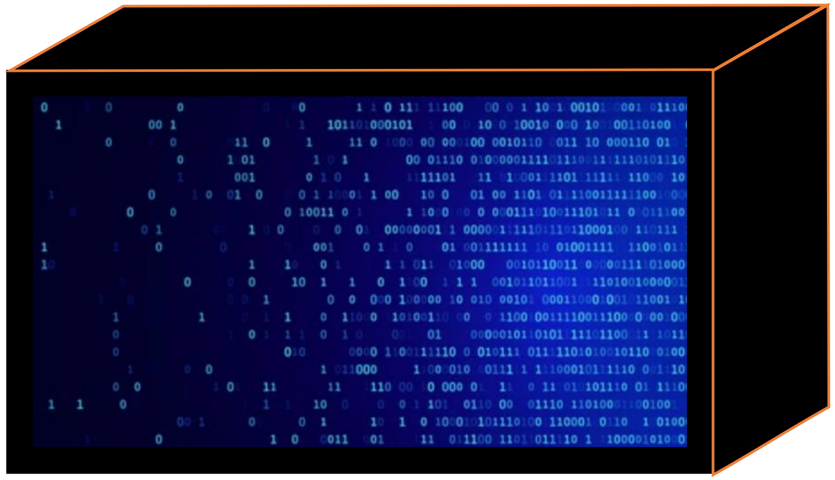
De-Mystify Your Performance Software

… by doing calculations manually



- Basic Data
- Secondary Air System
- ⊞ Ambient Conditions
- ⊞ Comp Efficiency
- ⊞ Comp Design
- ⊞ Turb Efficiency
- ⊞ Tip Clear.
- ⊞ Reheat
- ⊞ Nozzle Selection
- ⊞ Nozzle Calculation
- Stations

In



Is it Magic?

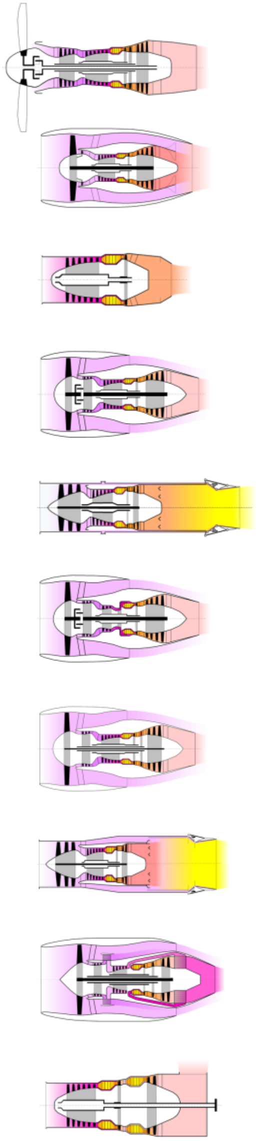
Out

```
             W          T          P        WRstd
Station   kg/s          K        kPa        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    12499 rpm
--------------------------------------------
```

```
FN        =    26.37 kN          Net Thrust
TSFC      =  25.0985 g/(kN*s)    Thrust Specific Fuel Consumption
FN/W2     =   832.50 m/s         Specific Thrust

Prop Eff  =   0.0000             Propulsion Efficiency
eta core  =   0.3884             Core Efficiency

WF        =  0.66194 kg/s        Fuel Flow
s NOx     =  0.28659             NOx Severity Parameter
XM8       =   1.0000             Nozzle Throat Mach No.
A8        =   0.0773 m²          Geometric Nozzle Throat Area
P8/Pamb   =   3.5532             Nozzle Pressure Ratio
WBld/W2   =  0.01000             Bleed Air Flow/Mass Flow W2
Ang8      =    20.00 deg         Nozzle Petal Angle
CD8       =   0.9600             Nozzle Discharge Coefficient
WClN/W2   =  0.05000             Turbine Nozzle Guide Vane Cooling Air / W2
WClR/W2   =  0.05000             Turbine Rotor Cooling Air/ W2
Loading   =   100.00 %           Burner Loading in % of the Cycle Design Point Value
e45 th    =  0.87139             Thermodynamic Turbine Efficiency
far8      =  0.02111             Nozzle Throat Fuel-Air-Ratio
PWX       =     0.00 kW          Power Offtake
```



www.kurzke-consulting.de

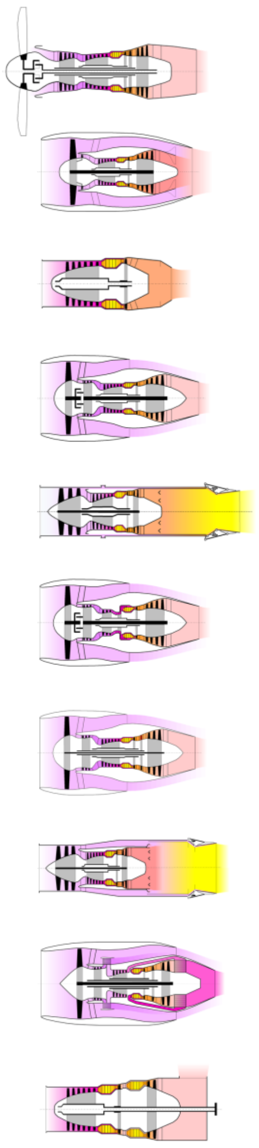
About Performance Software

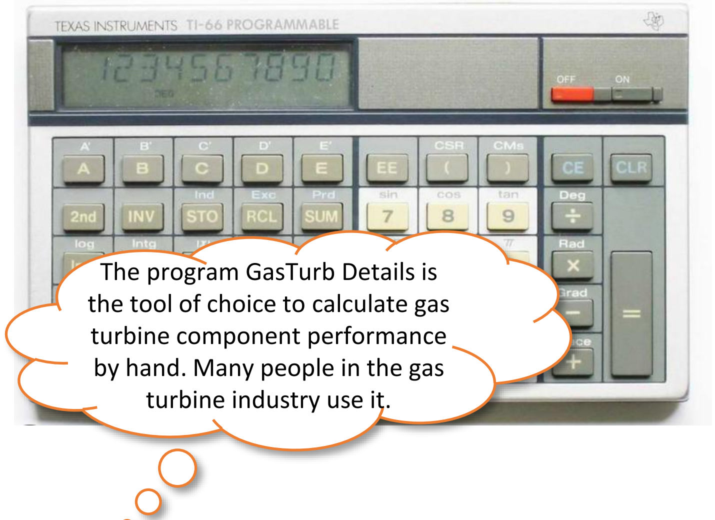
- Gas turbine performance calculation programs differ from those of computational fluid dynamics (CFD) and finite element analysis (FEA) in one important aspect:

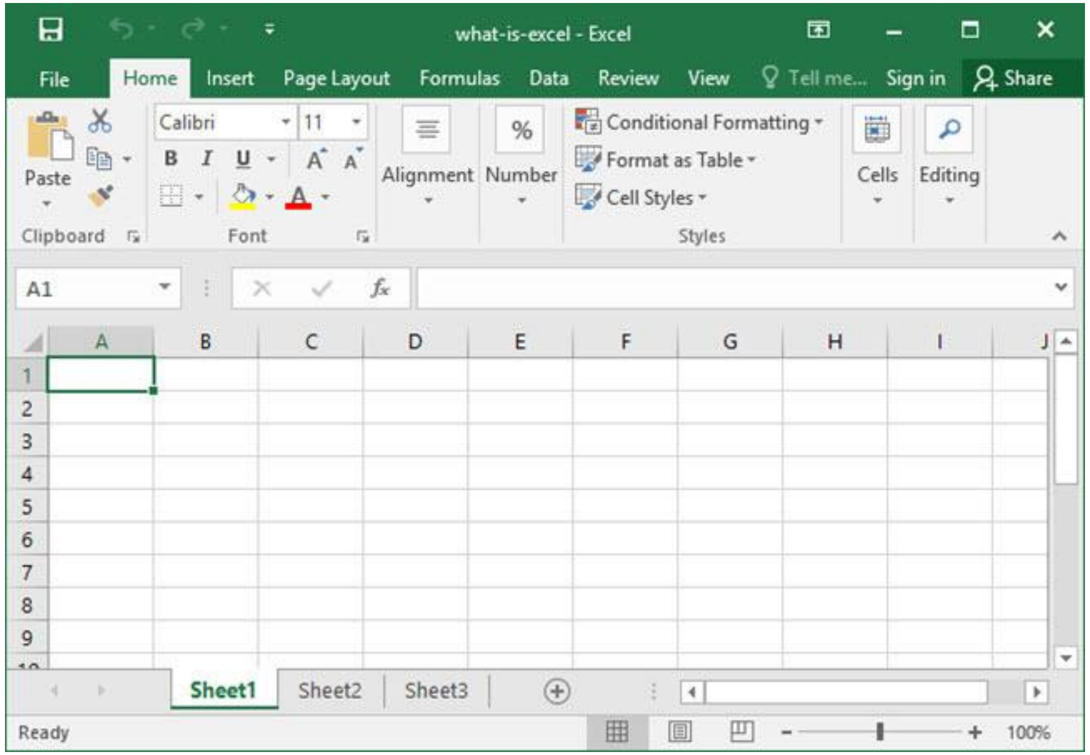
  Their output can be easily reproduced on a pocket computer or with Excel.

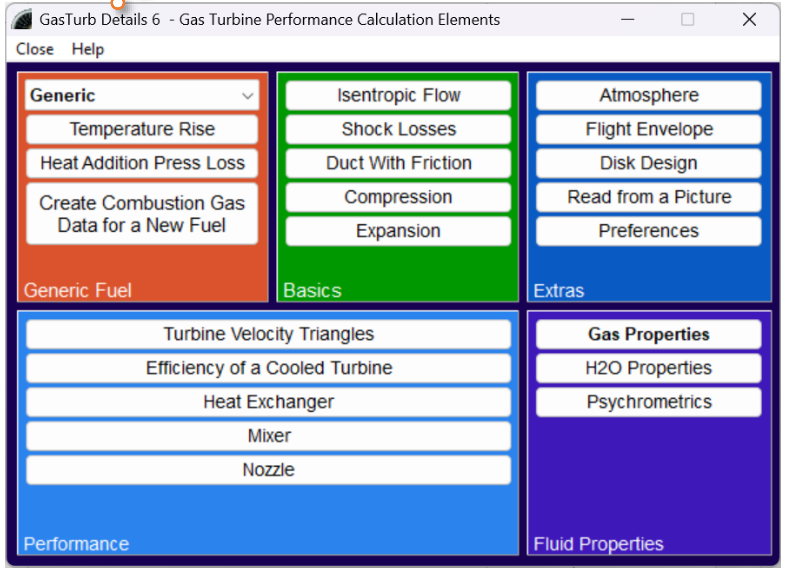
- Doing that is not just an academic exercise, but often necessary in practical engineering when partners in a collaborative project arrive at different results.

Calculation of the Cycle by Hand



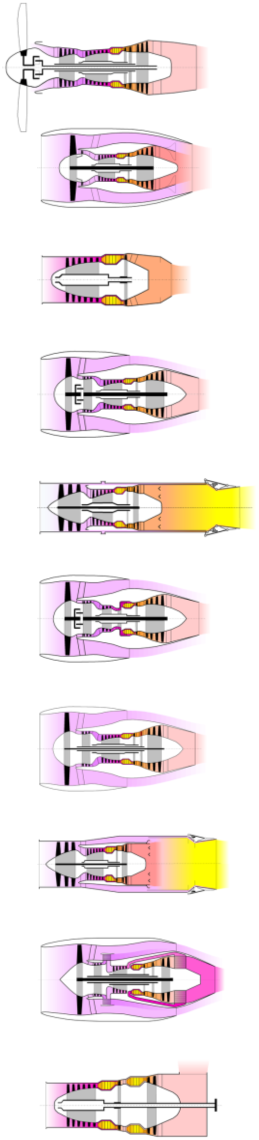






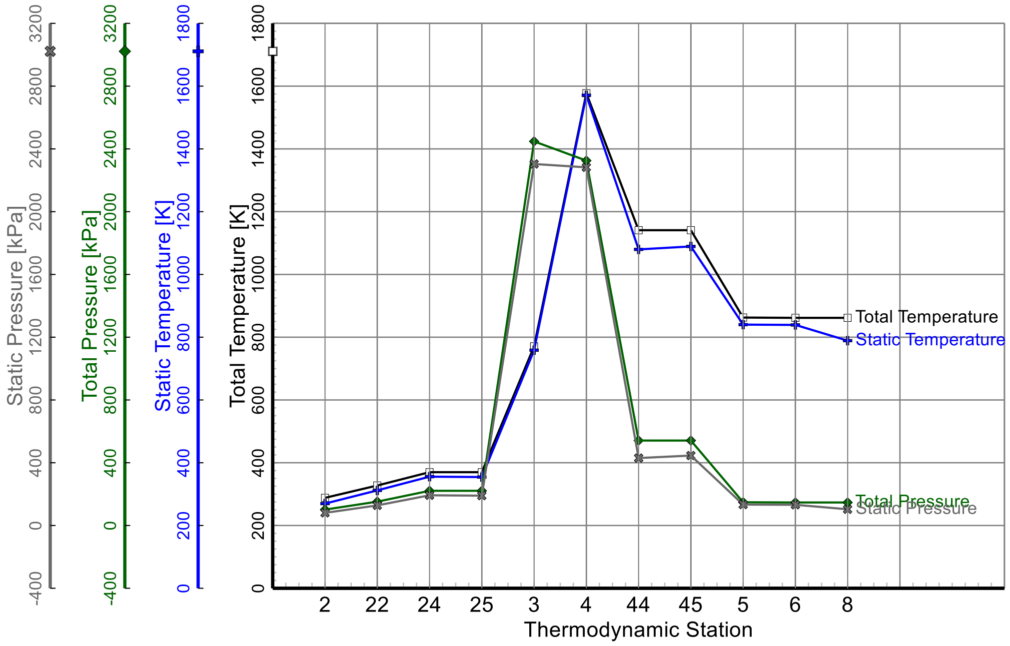
Cycle Data
CFM56-3 Take Off

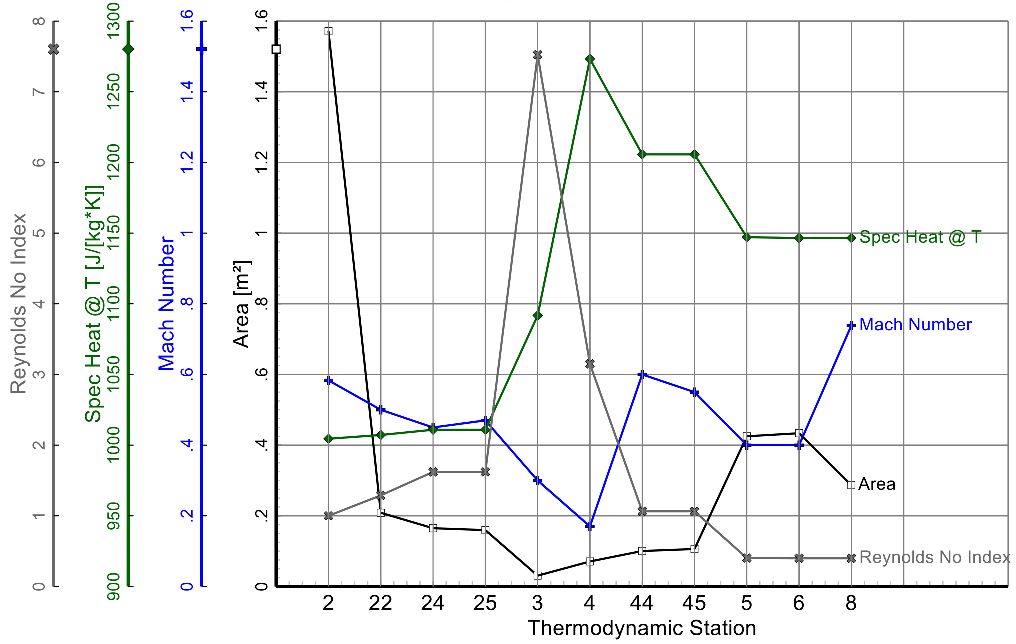
www.kurzke-consulting.de



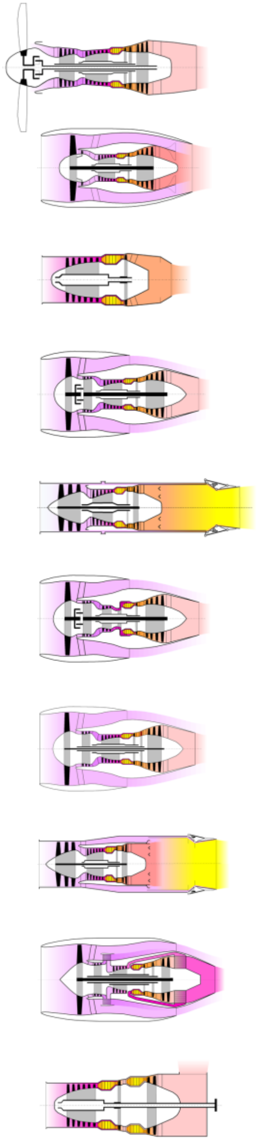
The cycle calculsation yields the total pressures and temperatures.

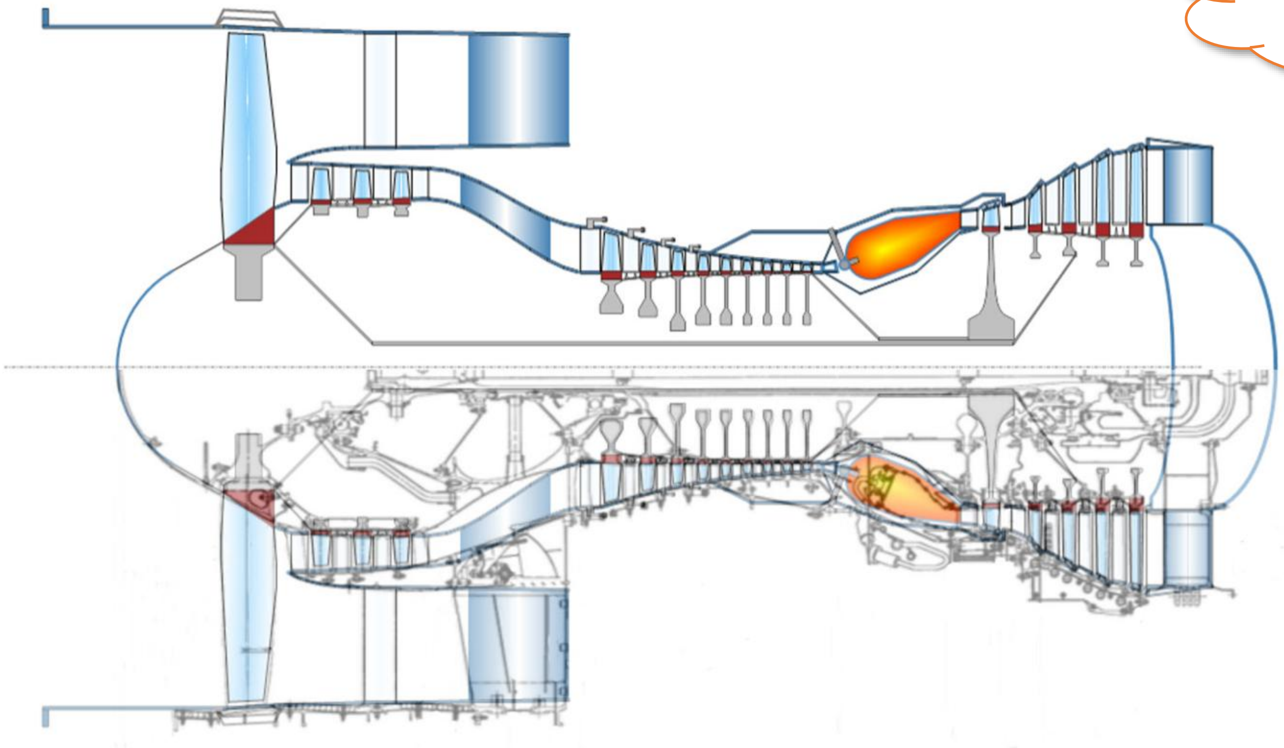
The engine geometry depends on the local Mach numbers.





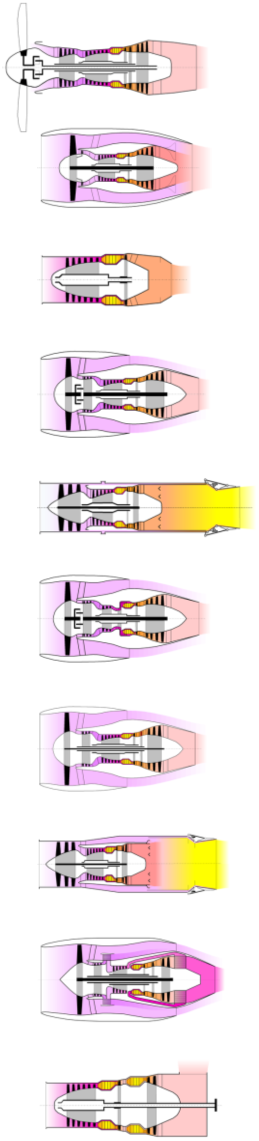
Geometry Model of the CFM56-3 Turbofan





Students will find it challenging and interesting to reproduce the geometry of an engine based on a given cross-cut and publicly available cycle data.

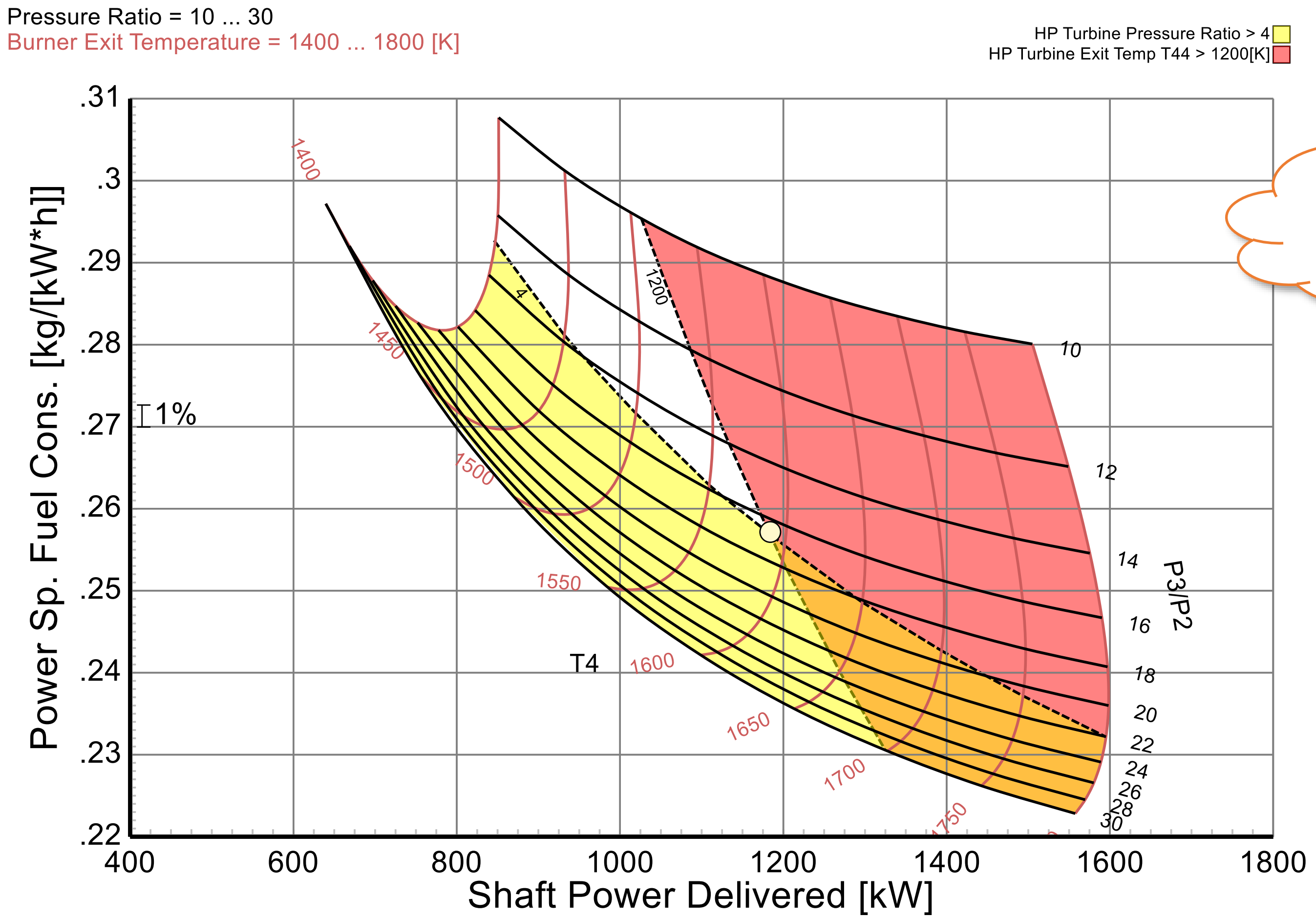
www.kurzke-consulting.de



Visualizing the Results

… a picture is worth a thousand words

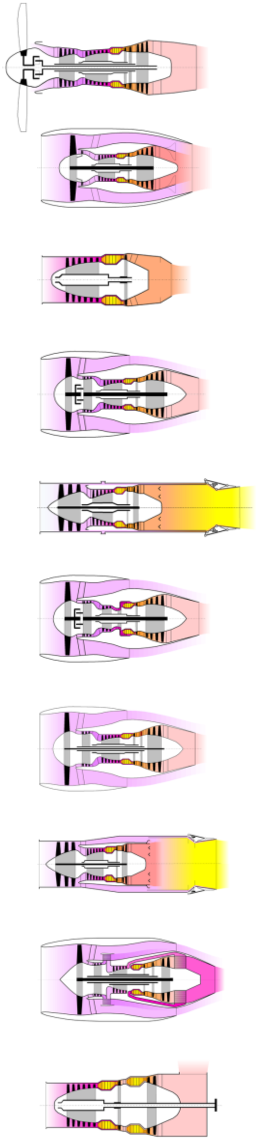
Parametric Study
Design Space

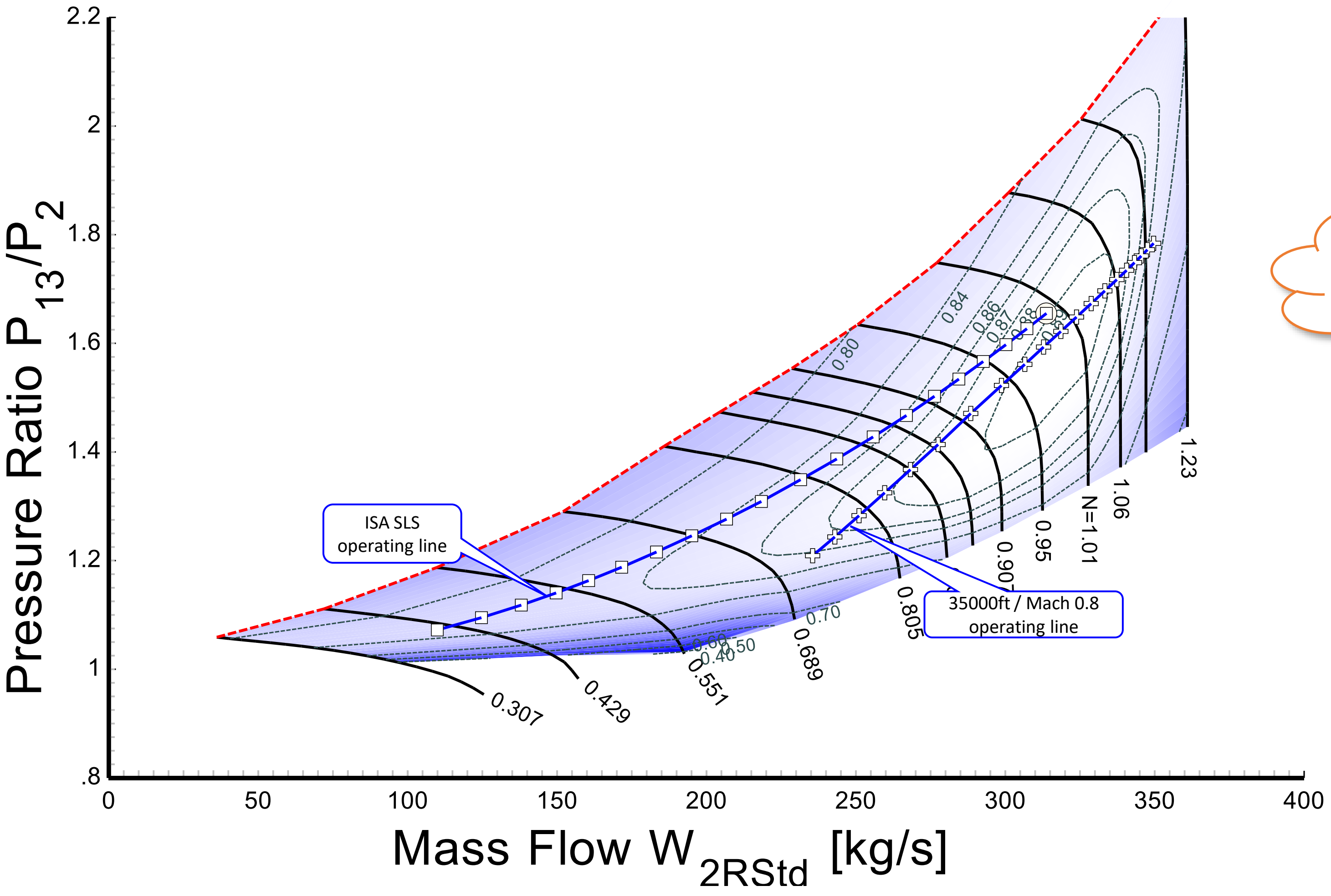


This is a conventional parametric study from which students can learn a lot.

www.kurzke-consulting.de

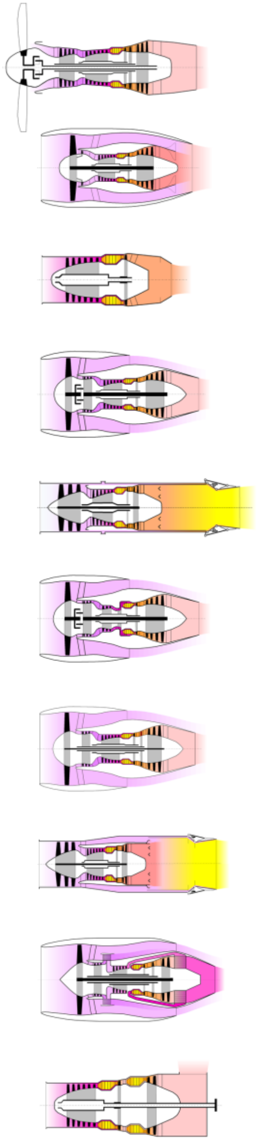
Operating Lines in the Fan Map

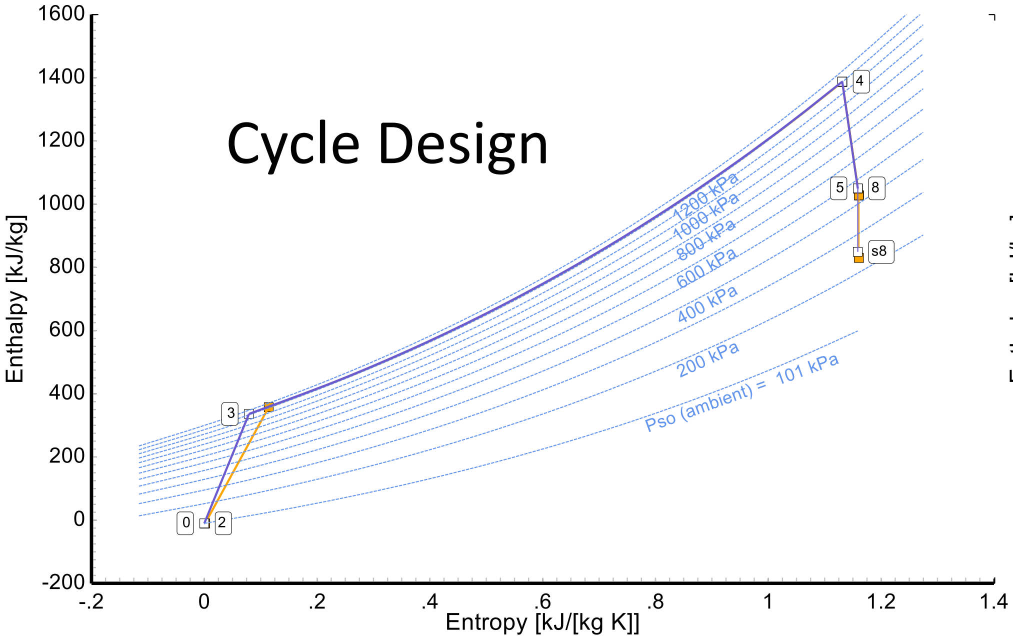


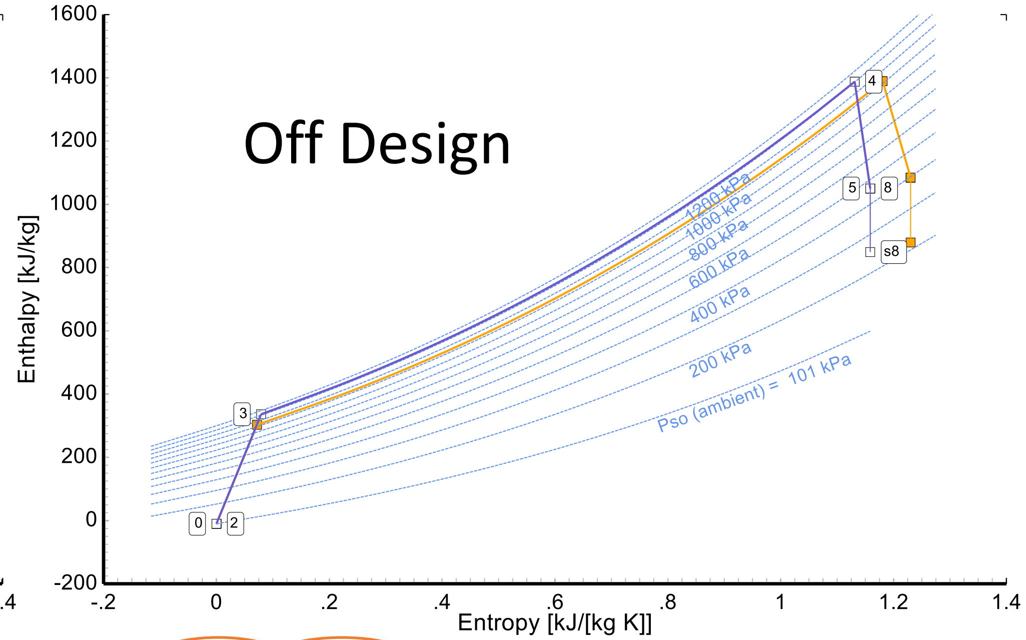


Using colors makes graphics easier to understand and remember.

Enthalpy-Entropy Diagram
Effect of -5% Compressor Efficiency





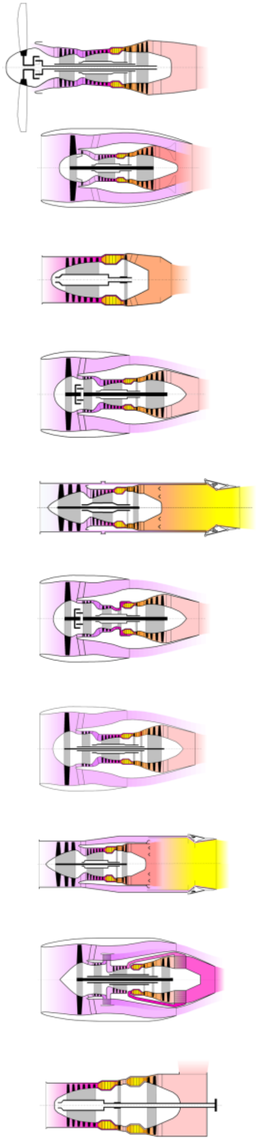


Drawing enthalpy-entropy diagrams to scale can be very helpful for understanding the effects of changes. It is much better than using complex equations!

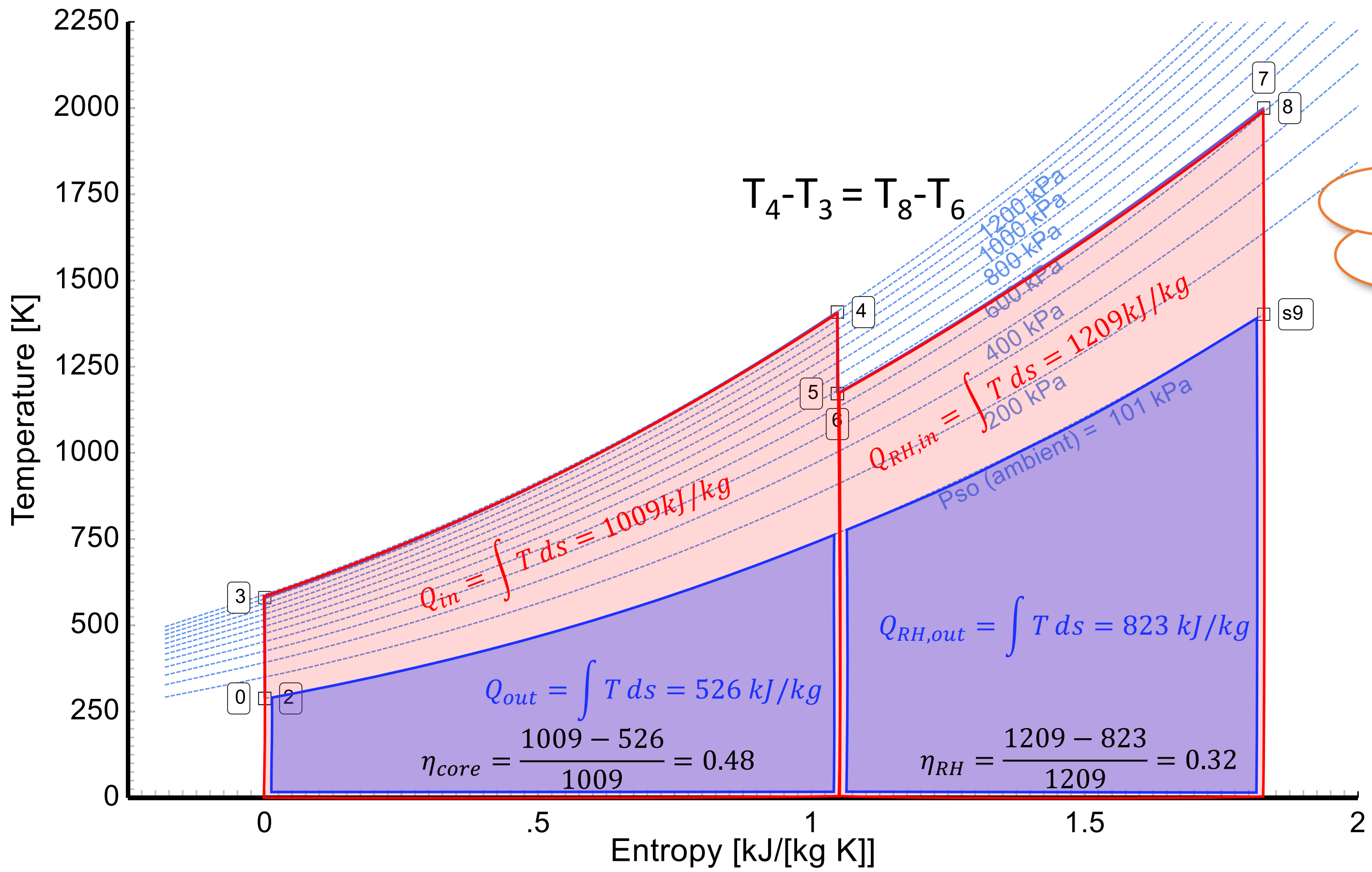
Temperature-Entropy Diagram

Visualize the Amount of Heat Transferred

www.kurzke-consulting.de



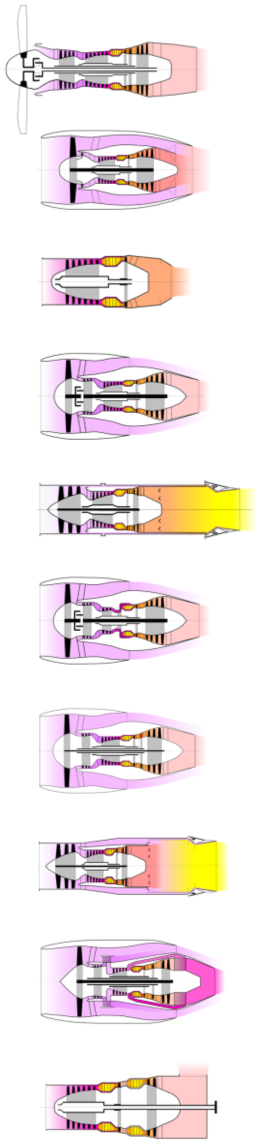
Why is afterburner SFC much larger than dry SFC ?



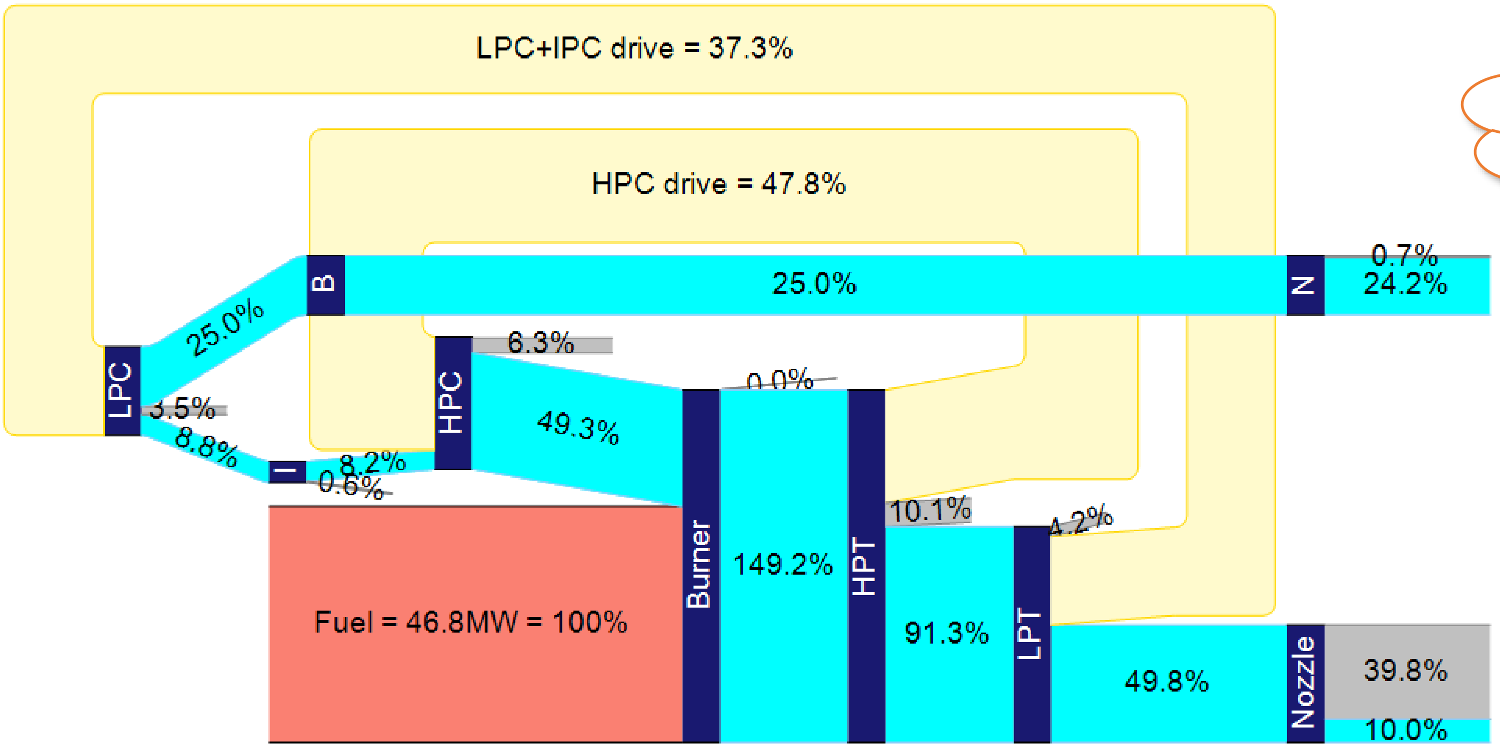
Drawing temperature-entropy diagrams to scale can help to improve understanding of thermodynamics. Presenting results in graphical form is much more effective than using complex equations!

Energy Flow - Sankey Diagram

CFM56-3 Take Off



www.kurzke-consulting.de

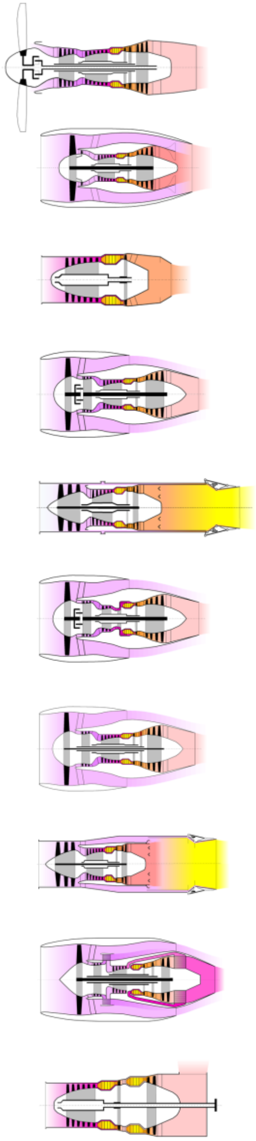


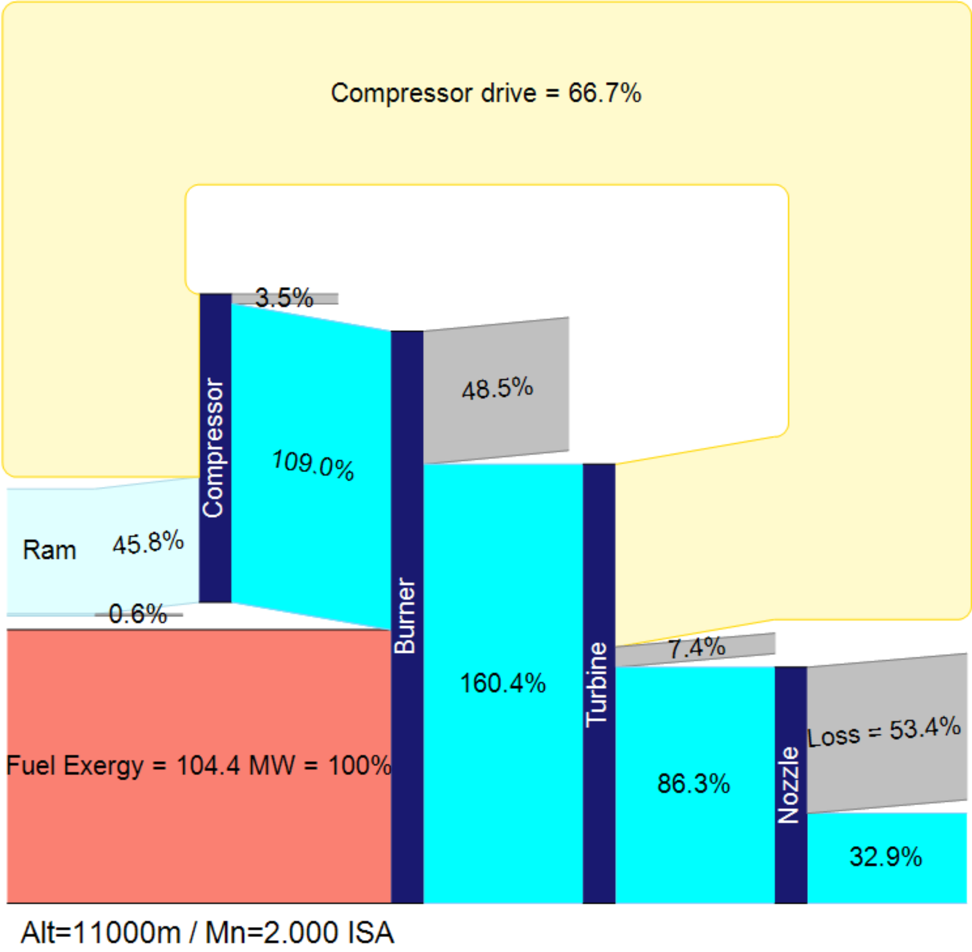
SL static, ISA

The Sankey diagram clearly shows that the small gas generator dominates the energy flows in a turbofan.

Work Potential - Exergy Diagram

Turbojet, Mach 2, 11km



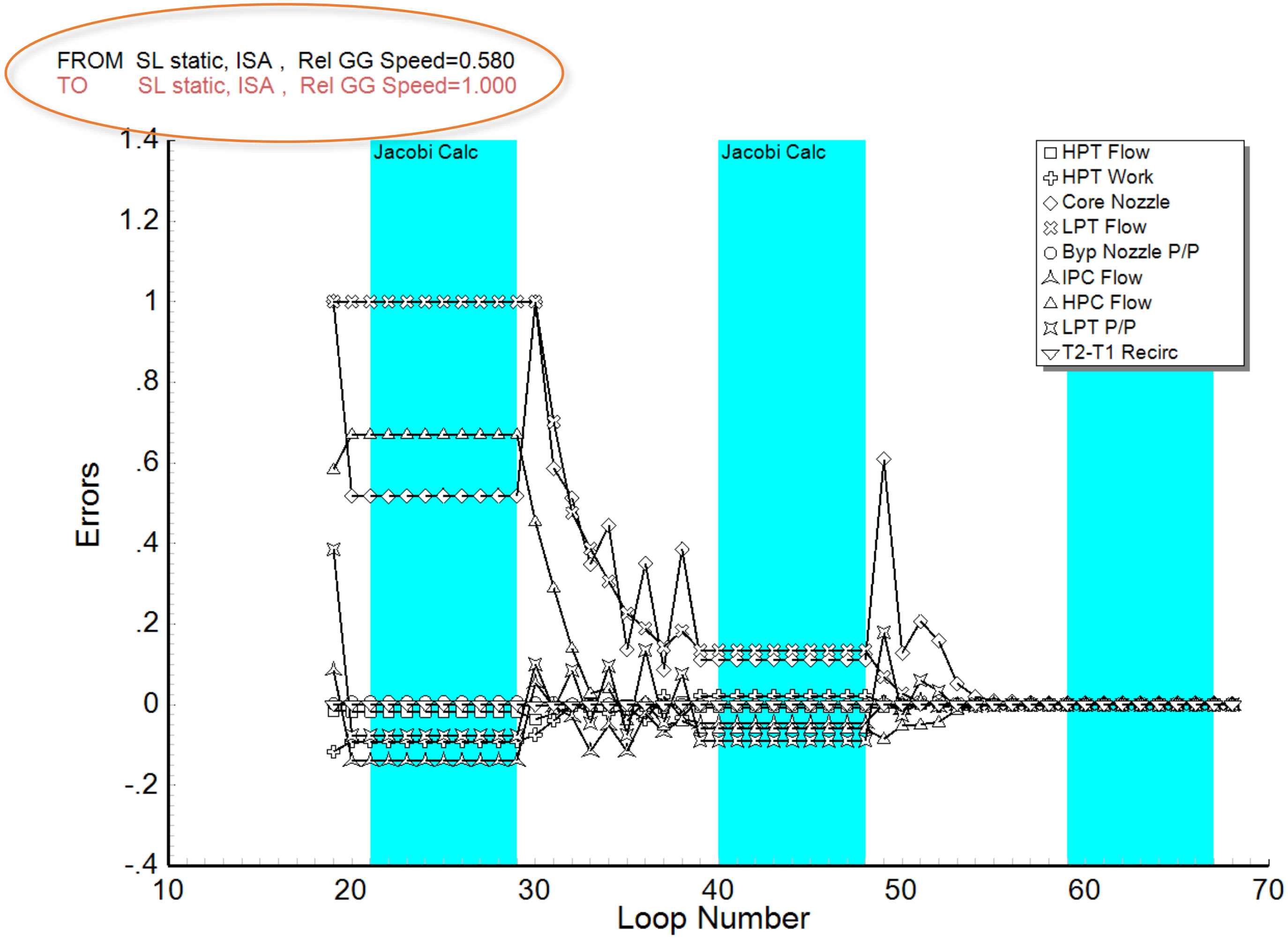


A turbojet could be an attractive option for the propulsion system of a supersonic fighter aircraft.

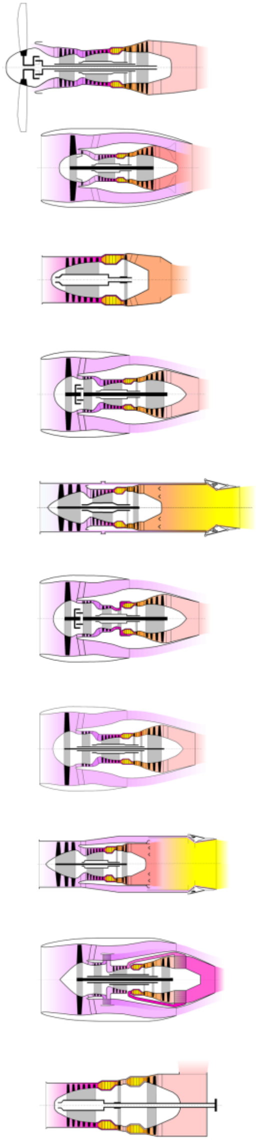
An exergy diagram shows where losses in terms of work potential occur, which is important to consider when analysing the system.

www.kurzke-consulting.de

The Iteration Progress



Off-design calculations require multidimensional, iterative algorithms. Sometimes, convergence problems are encountered. Solving these problems is very important in practice. Graphics can be helpful.



Is It Magic?

De-Mystify your Performance Program !

That's what a lecturer's really for – not teaching complex equations that don't actually apply to the day-to-day work of a performance engineer.

A good bedtime read …