Gas Turbine Technology

Aerodynamic design

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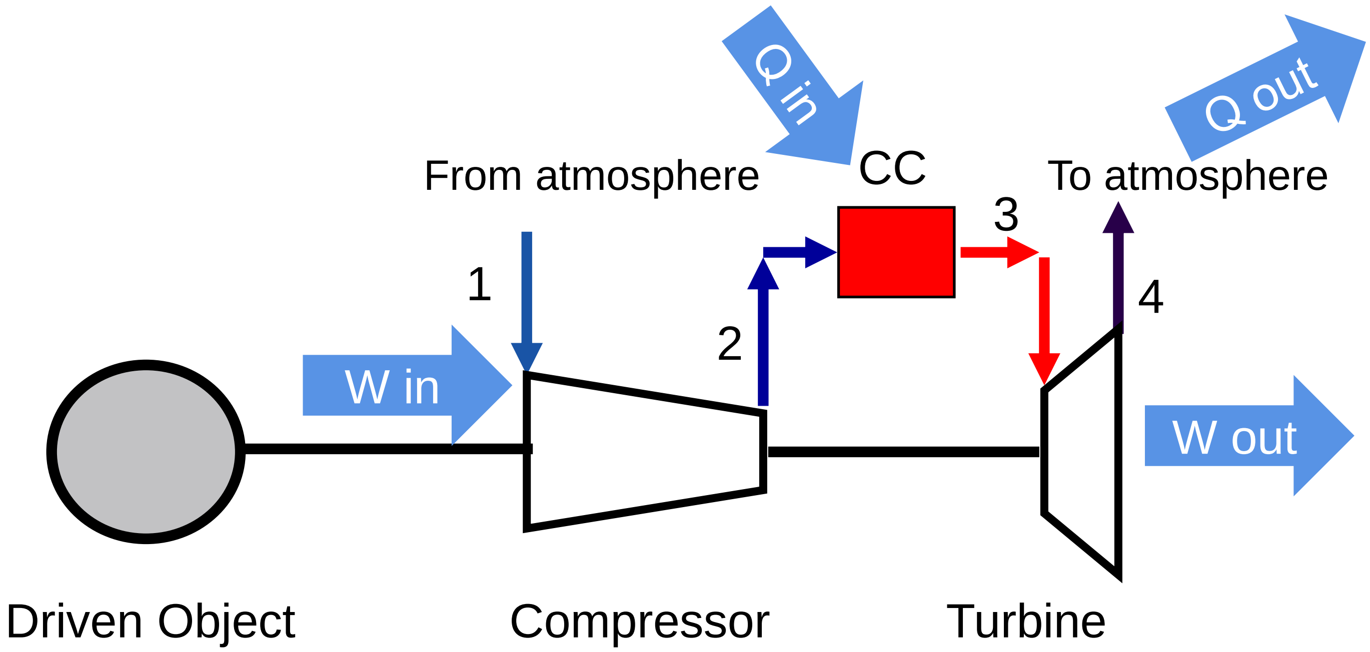
Based on: LARS HEDLUND, Siemens Industrial Turbomachinery

Brayton Cycle (a.k.a Gas Turbine)



1-2 Isentropic compression in a compression

2-3 Isobaric heat addition in a combustion chamber (CC)

3-4 Isentropic expansion in a **turbine**

4-1 Heat rejection /Exhaust gasses

The Gas Turbine – in the T-s diagram

Inlet: (p0-p1)

Pressure drop in filter, silencer and duct. etc.

Normally 0.3 to 1 kPa.

Compressor: (T1-T2)

Isentropic efficiency, depending on design, fouling, clearances etc. Efficiency 85-90%.

Extraction for cooling.

Combustion chamber: (T2-T3)

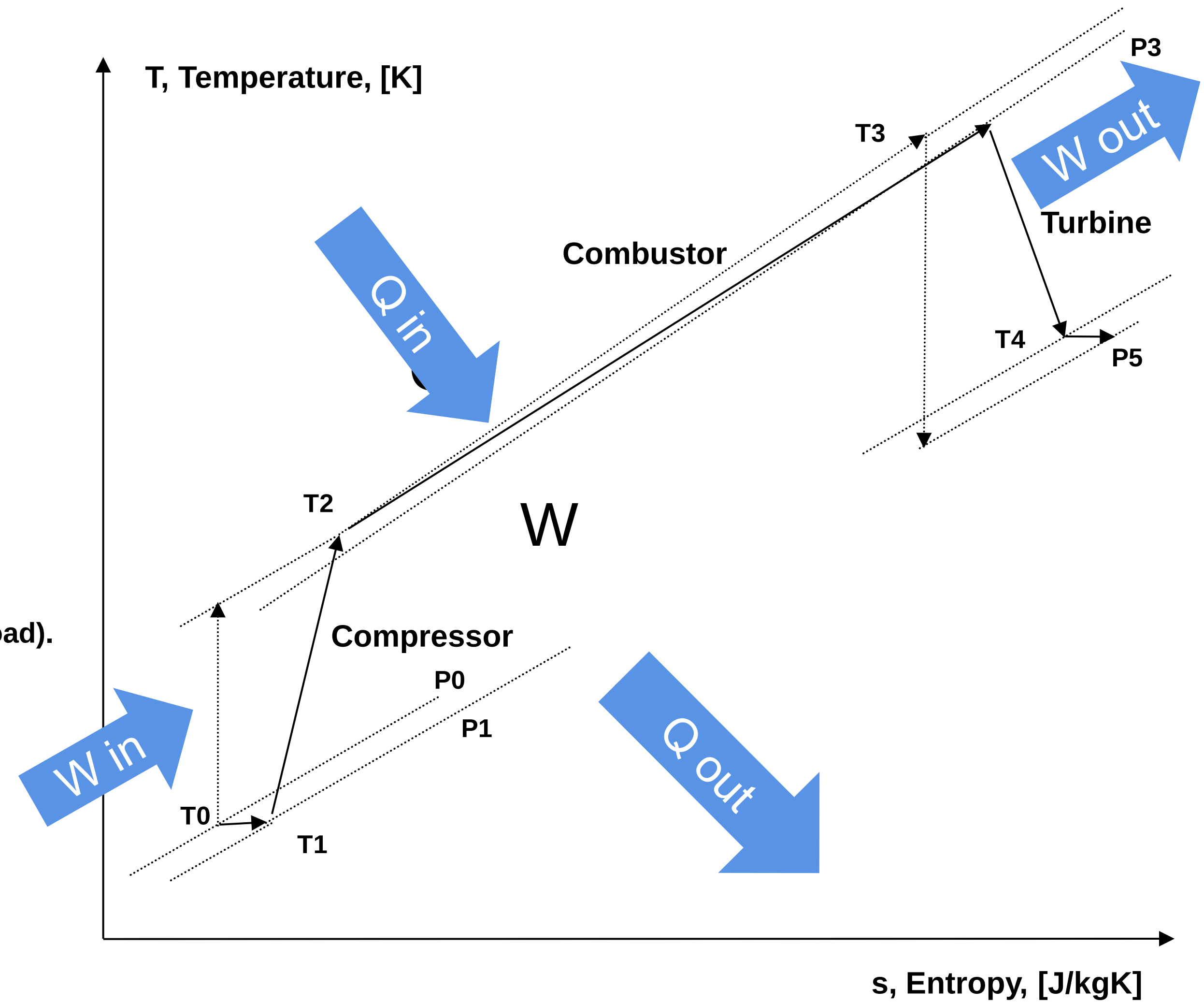
Pressure drop and combustion efficiency (in practice 100 % at full load). 2- 5 % of the pressure after the compressor is lost over the CC.

Turbine: (T3-T4)

Isentropic efficiency, depending on design, fouling, clearances etc. Efficiency 86-94%.

Outlet pressure drop (p4-p5)

0.5 to + 3 kPa.



Simple Cycle Definitions

Compressor: (T1-T2)

Isentropic efficiency:

$$\eta_{is} = \frac{\text{Ideal work}}{\text{Actual work}}$$

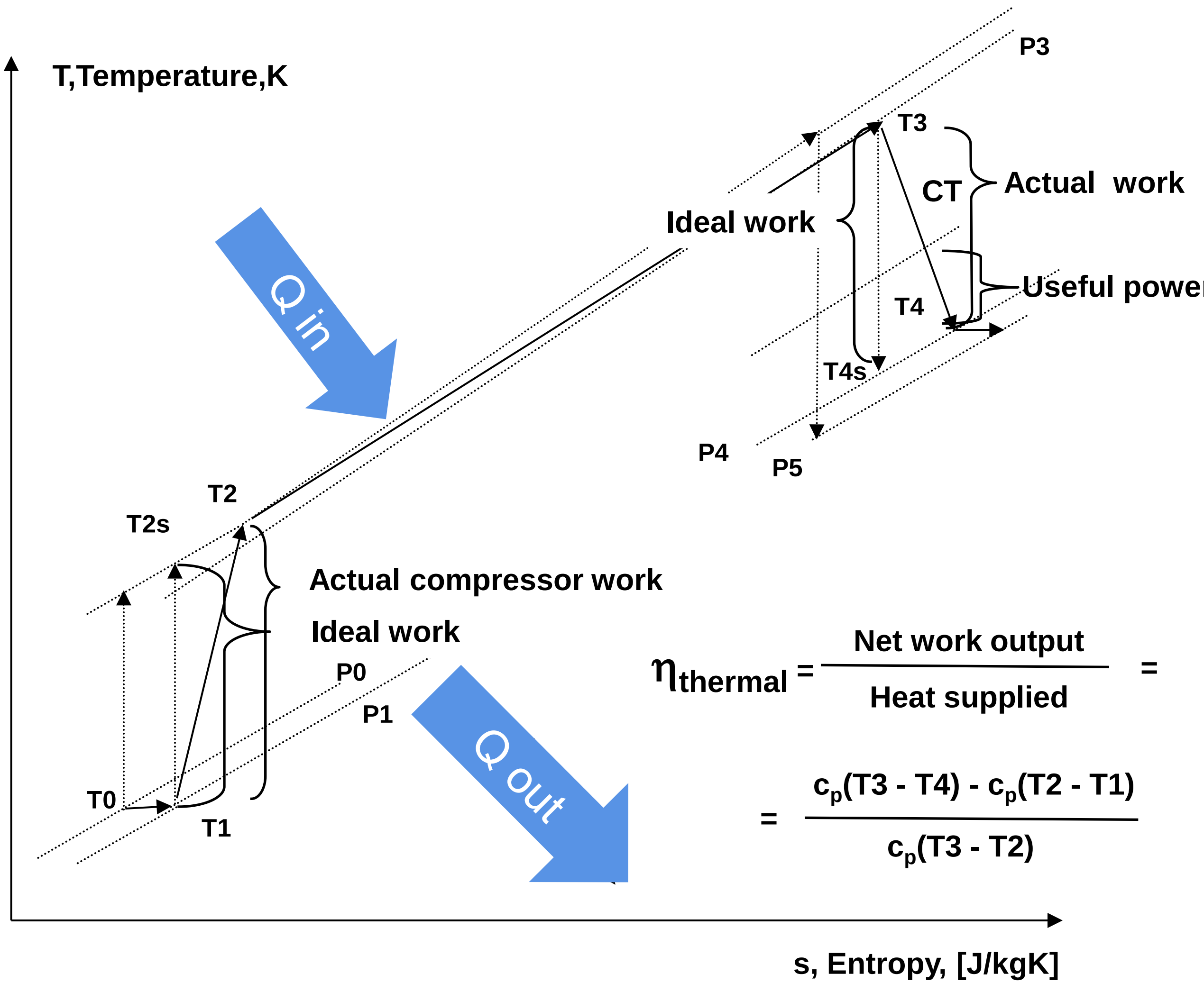
$$\eta_{is} = \frac{T2s - T1}{T2 - T1}$$

Turbine: (T3-T4)

Isentropic efficiency:

$$\eta_{is} = \frac{\text{Actual work}}{\text{Ideal work}}$$

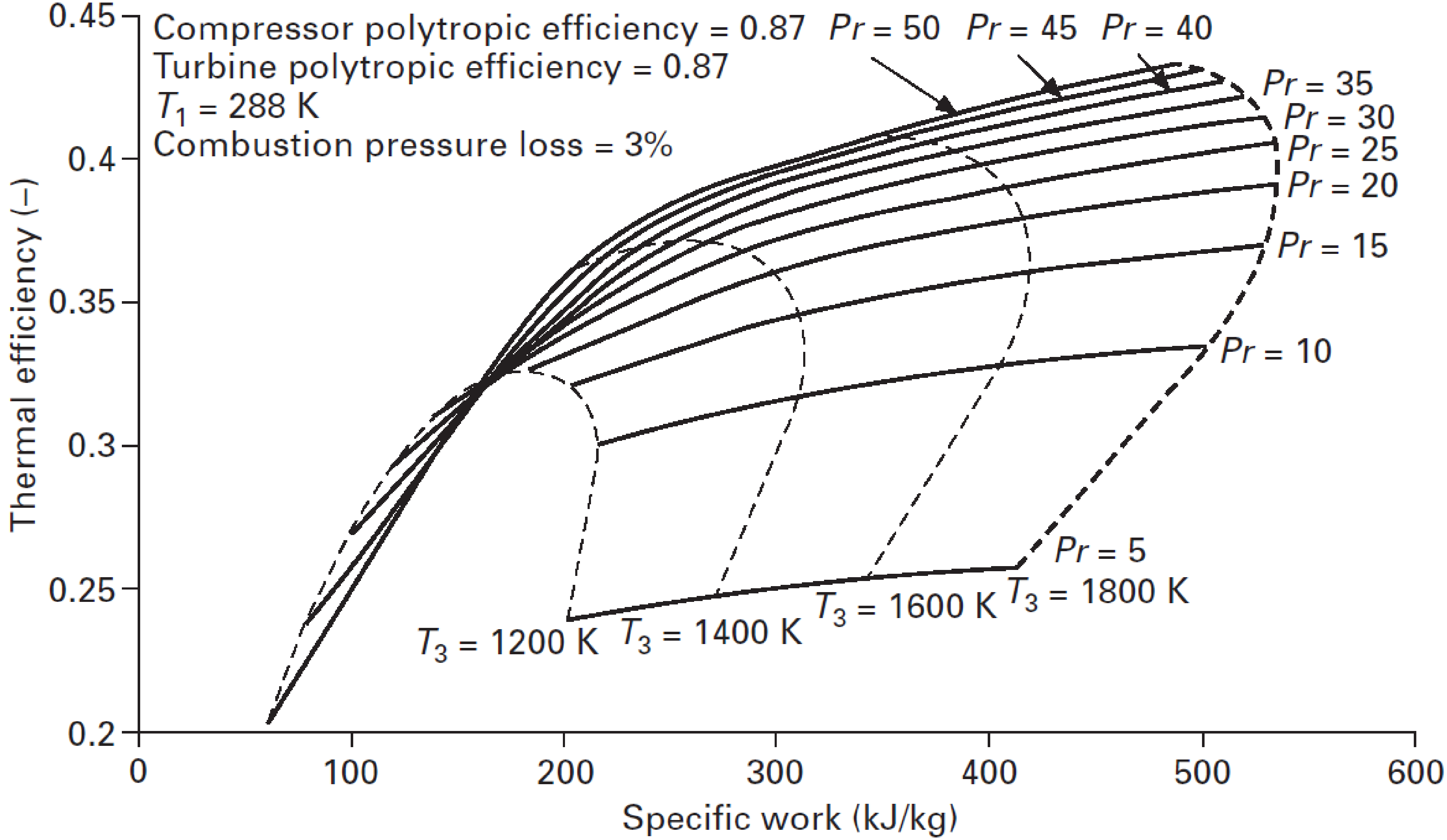
$$\eta_{is} = \frac{T3 - T4}{T3 - T4s}$$



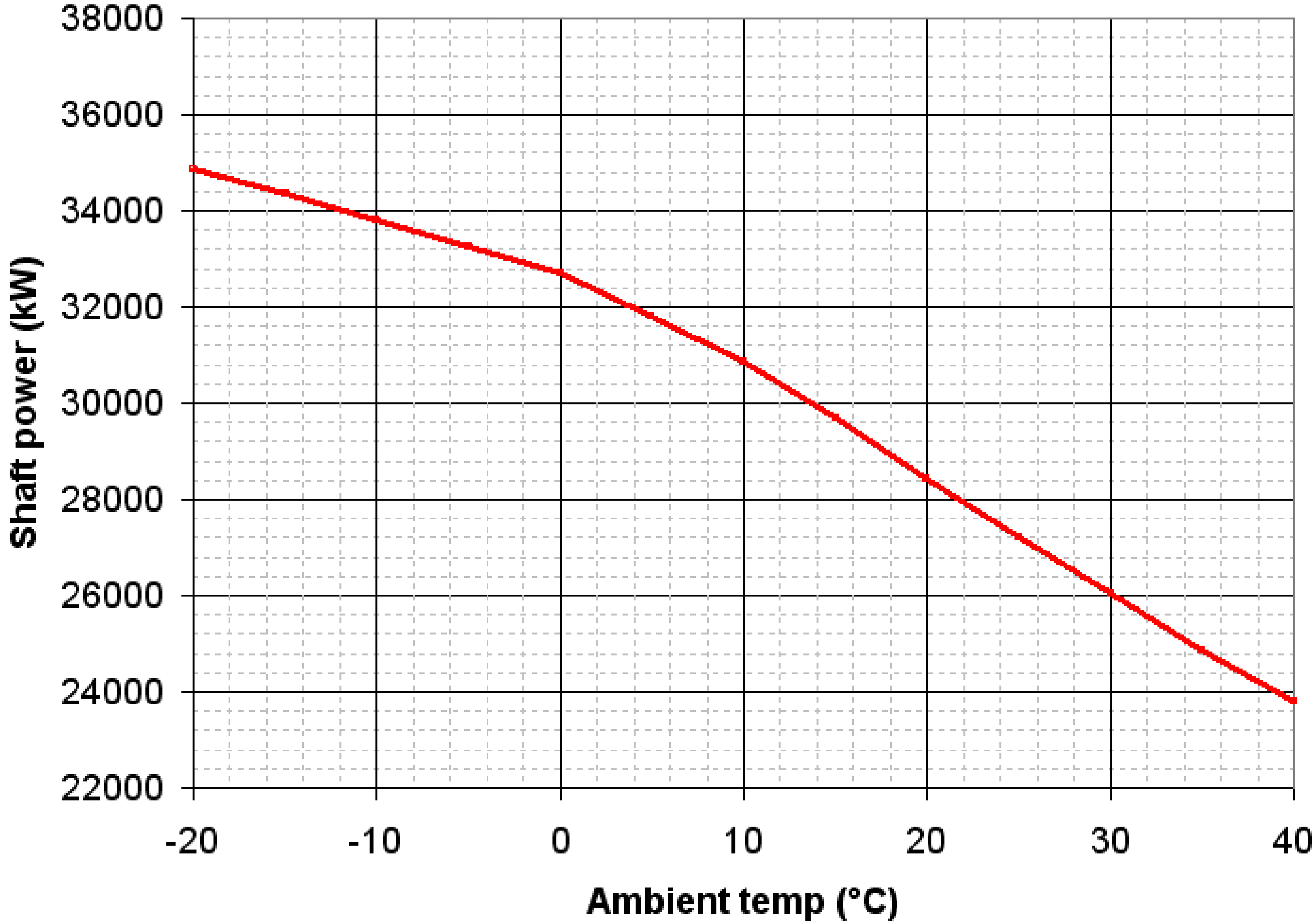
$$\eta_{thermal} = \frac{\text{Net work output}}{\text{Heat supplied}} = $$

$$= \frac{c_p(T3 - T4) - c_p(T2 - T1)}{c_p(T3 - T2)}$$

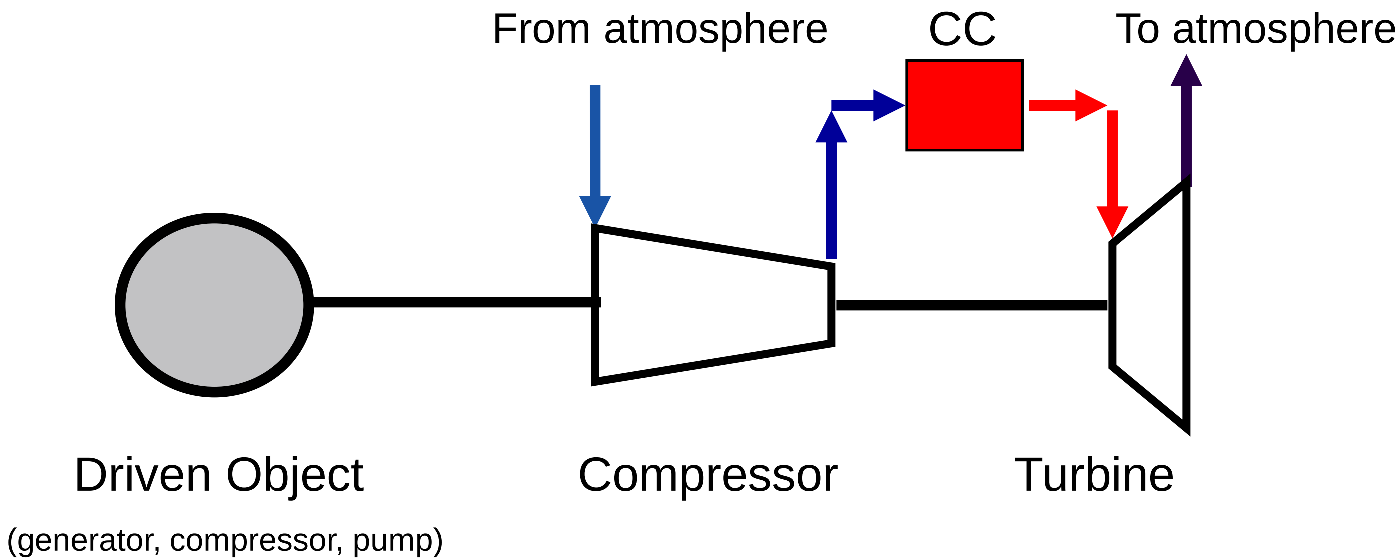
Influence of Pressure Ratio and Turbine Inlet Temperature on Efficiency



The Effect of Ambient Temperature on Power Output



Single Shaft



- Requires bleed valves on compressor

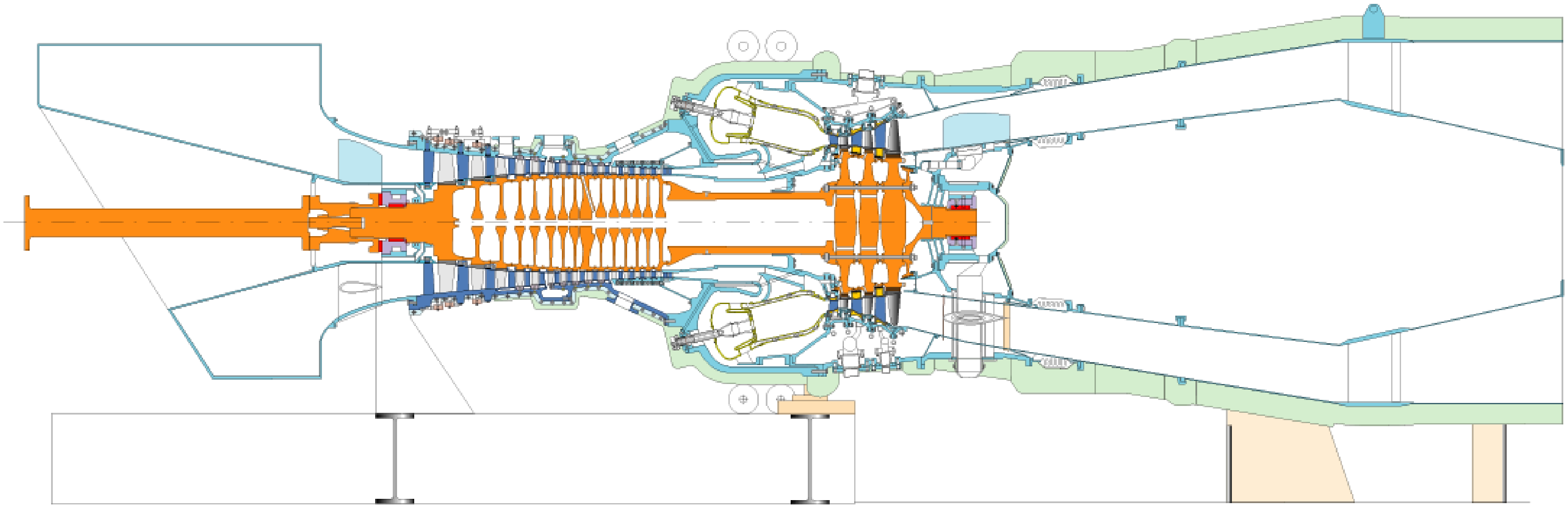
- Requires variable guide vanes in compressor

- Part load efficiency low or medium

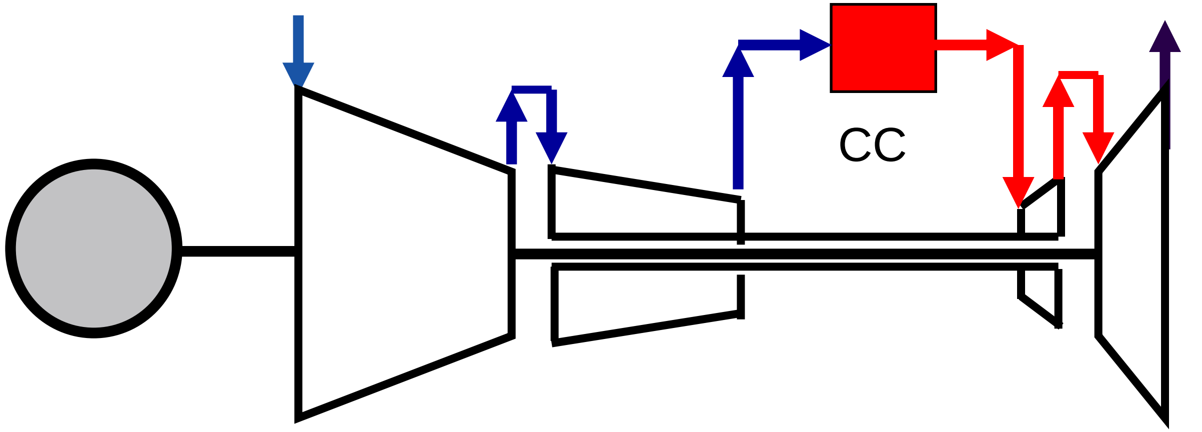
- Relatively high starting power

CC = Combustion Chamber

SGT-800, 47 MWe
Single Shaft Gas Turbine



Twin Shaft



(generator, compressor, pump)

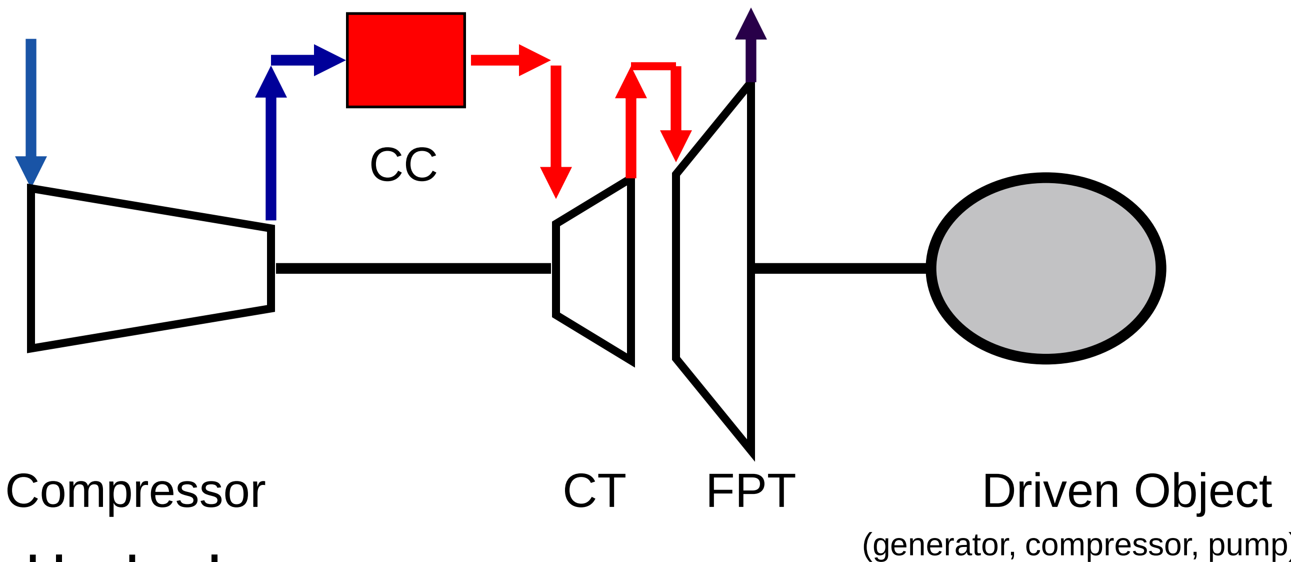
- Requires bleed valves on compressor

- Requires variable guide vanes in compressor

- Relatively good part load efficiency

LPC = Low Pressure Compressor
HPC = High Pressure Compressor
CC = Combustion Chamber
HPT = High pressure Turbine
LPT = Low Pressure turbine

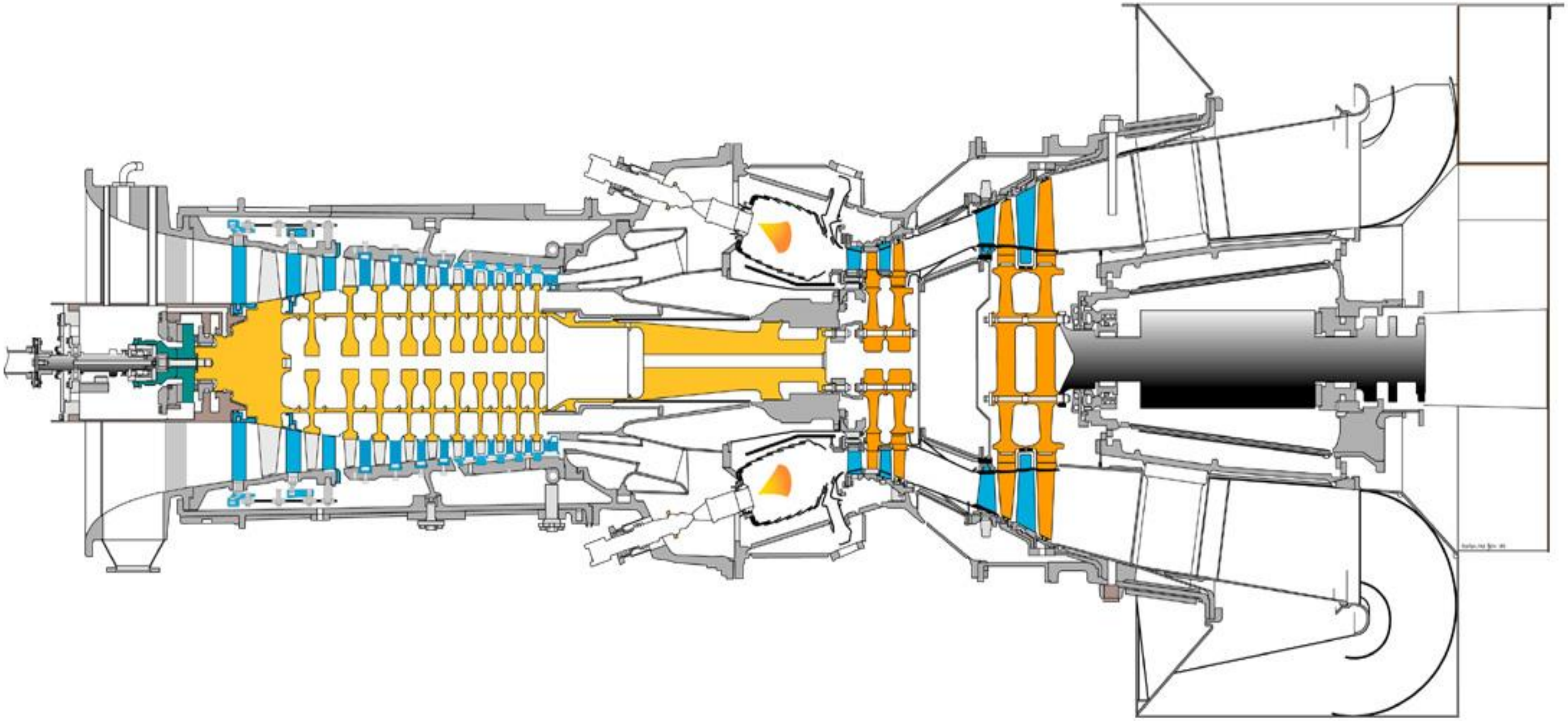
Single Shaft Gas Generator with Free Power Turbine



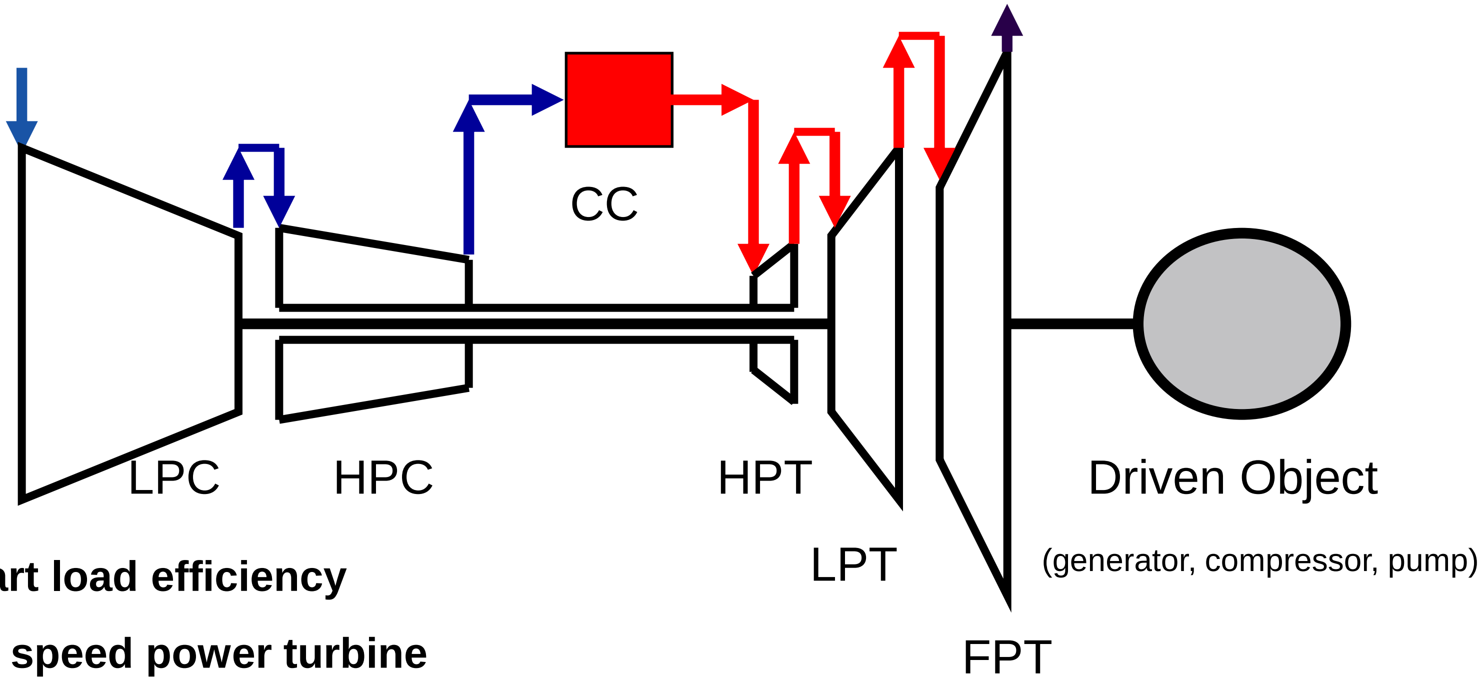
- **Requires bleed valves on compressor**
- **Requires variable guide vanes in compressor**
- **Relatively good part load efficiency**
- **Variable speed power turbine**

CT = Compressor Turbine
FPT = Free Power Turbine

SGT-700, 31 MWe
Single Shaft Gas Generator with Free Power Turbine



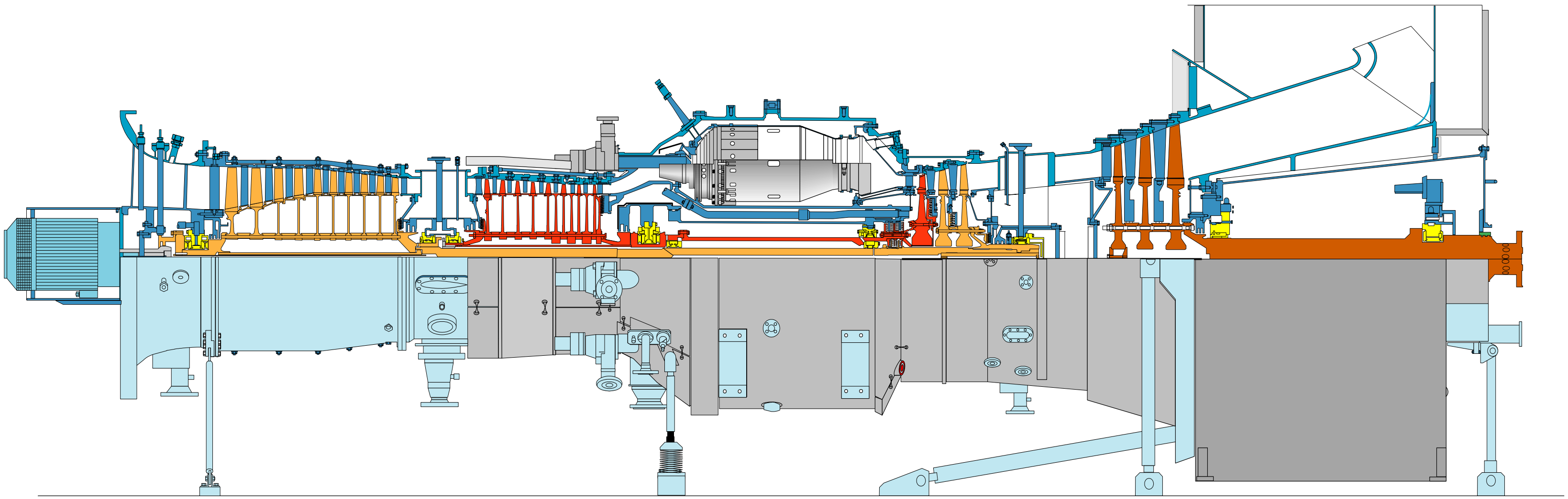
Twin Shaft Gas Generator with Free Power Turbine



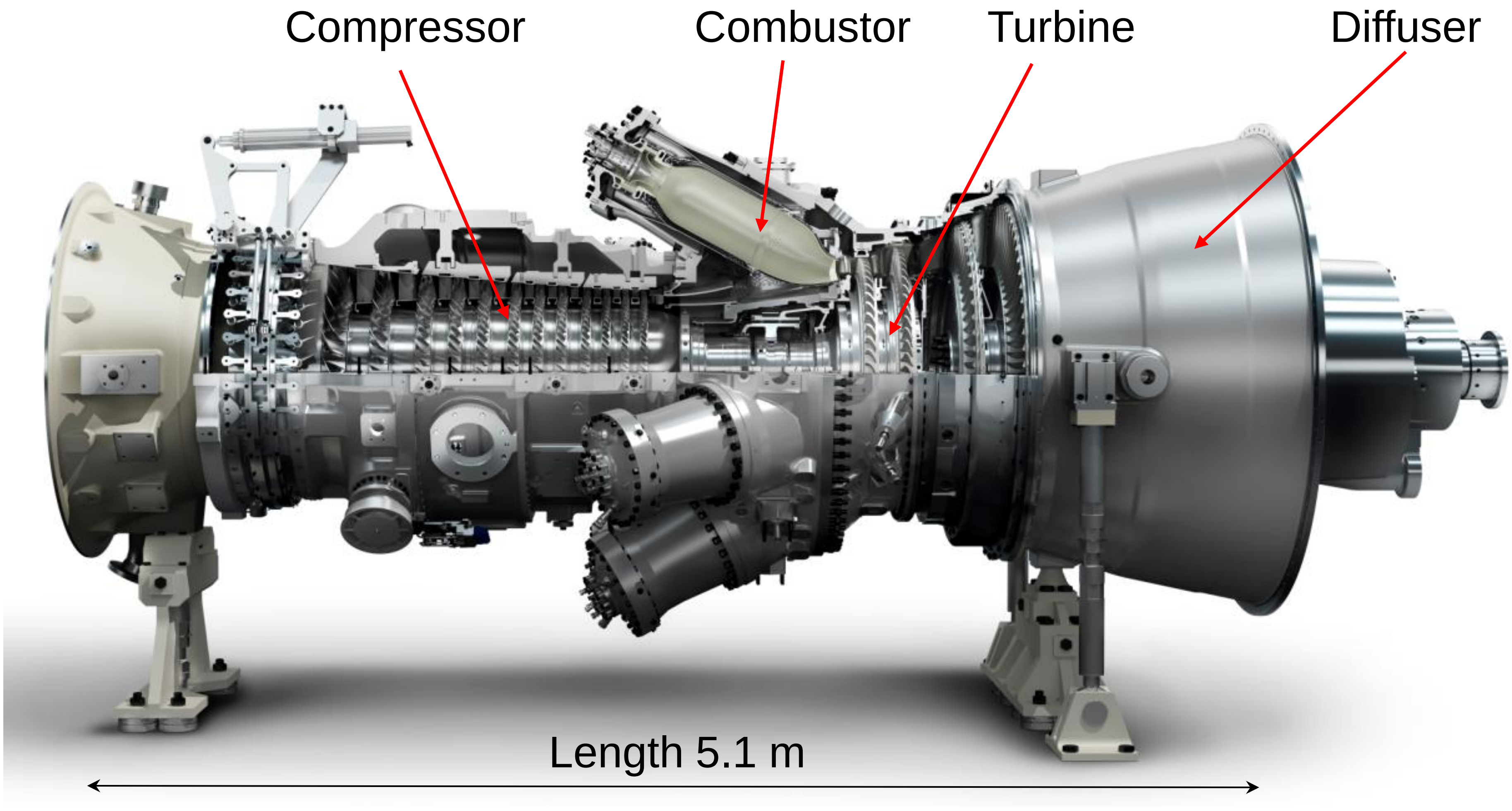
- **Good part load efficiency**
- **Variable speed power turbine**
- **No mandatory requirement for bleed valves on compressor**
- **No mandatory requirement for variable guide vanes in compressor**

LPC = Low Pressure Compressor
HPC = High Pressure Compressor
CC = Combustion Chamber
HPT = High pressure Turbine
LPT = Low Pressure turbine
FPT = Free Power Turbine

SGT-500, 19 MWe
Twin Shaft Gas Generator with Free Power Turbine

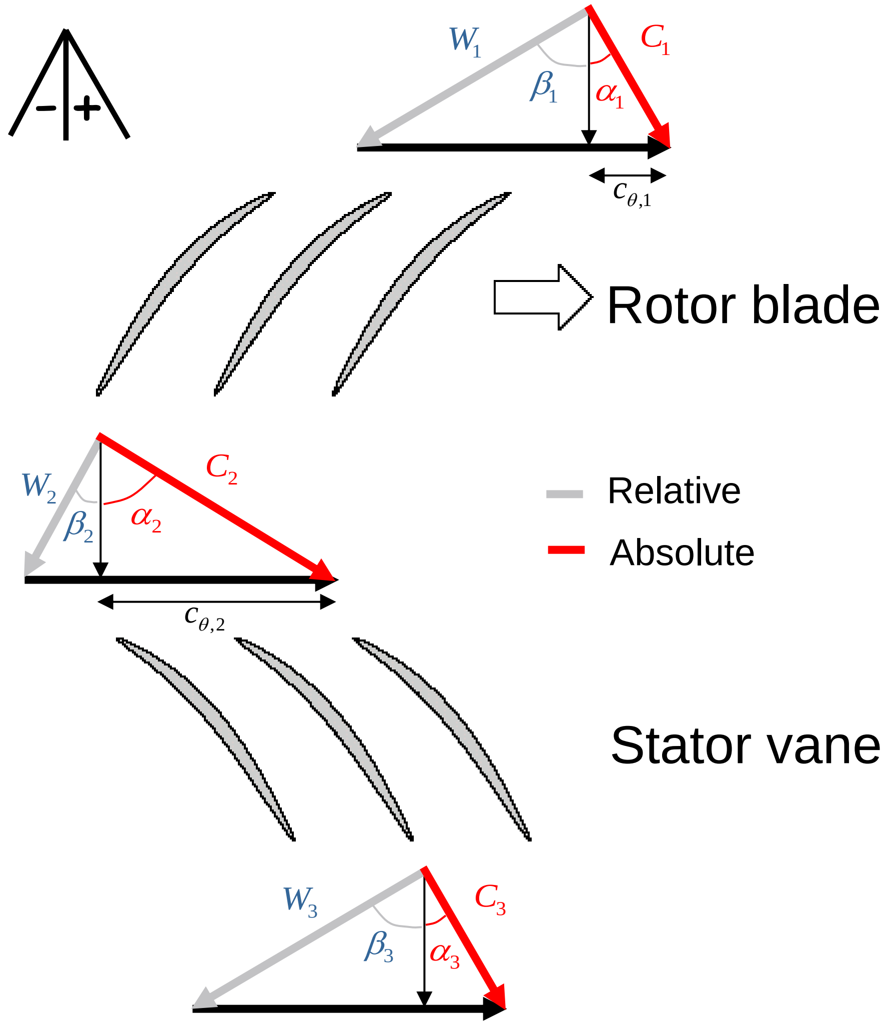


The SGT-750 Gas Turbine
Shaft Power 37 MW, Shaft Efficiency 40%



Compressor

Basic Compressor Velocity Triangles



Specific work according to Euler:

$\Delta h_0 = U(C_{\theta,2} - C_{\theta,3})$ [W/(kg/s)]

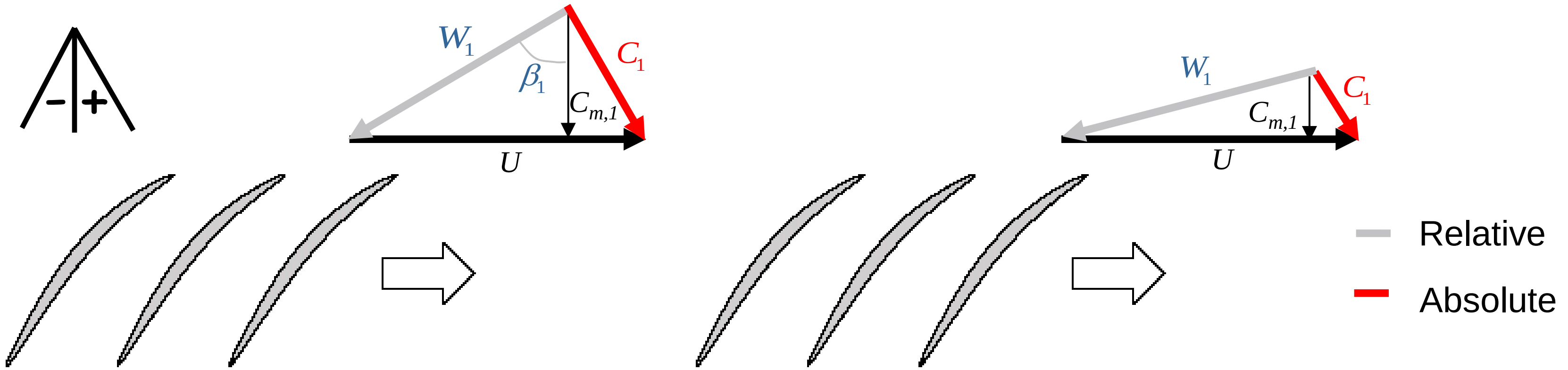
Pressure ratio:

$$\frac{p_{03}}{p_{01}} = \left[1 + \frac{\eta_s \cdot \Delta T_{0_{stage}}}{T_{01}}\right]^{\frac{\kappa}{\kappa - 1}}$$

Reaction:

$$\Lambda = -\frac{C_m}{2U}\left(\tan\beta_2 - \tan\beta_1\right)$$

Compressor Stall

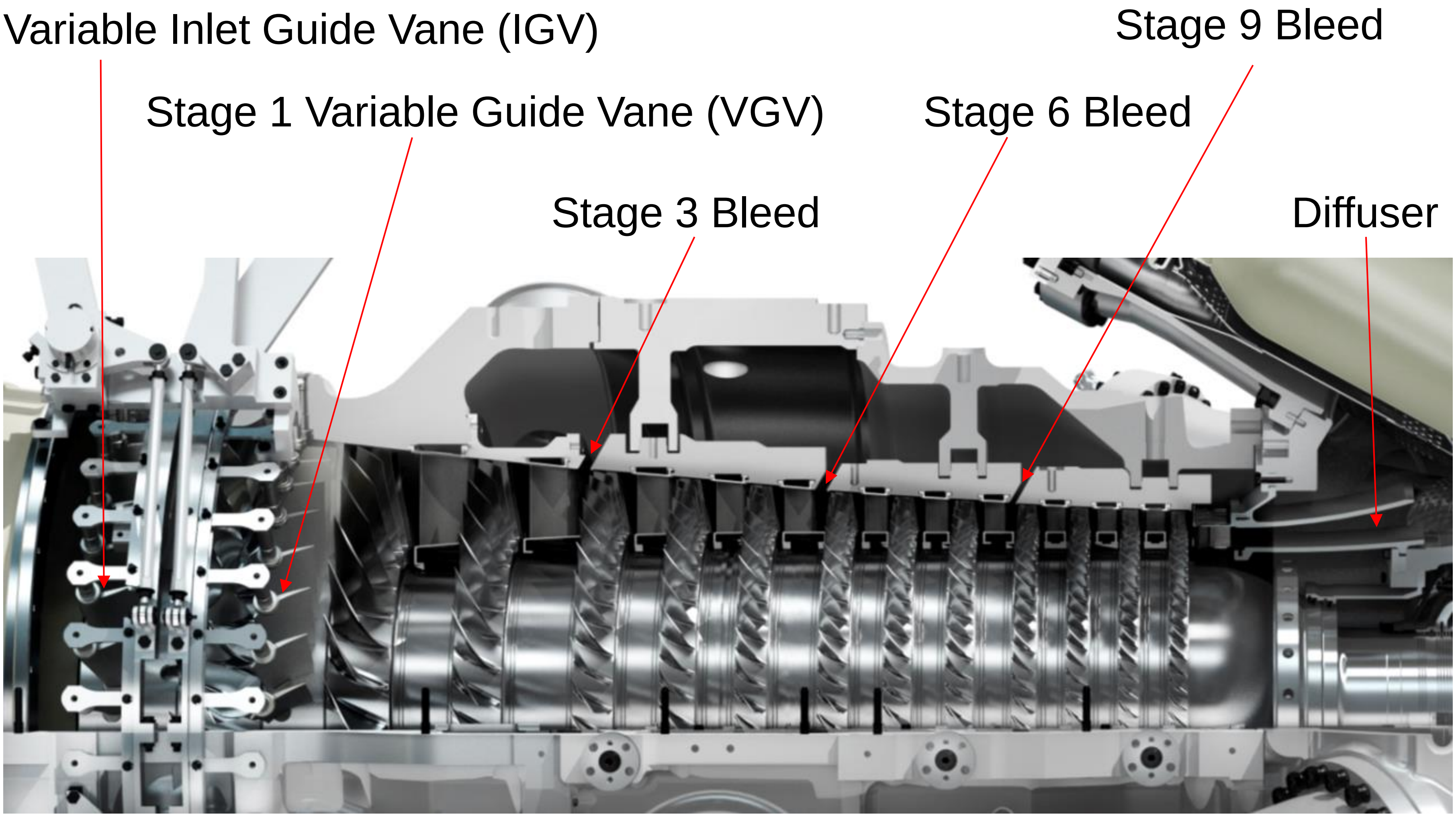


- When the meridional velocity decreases at constant blade speed, the relative inlet angle increases, so that the flow is directed more towards the pressure side.

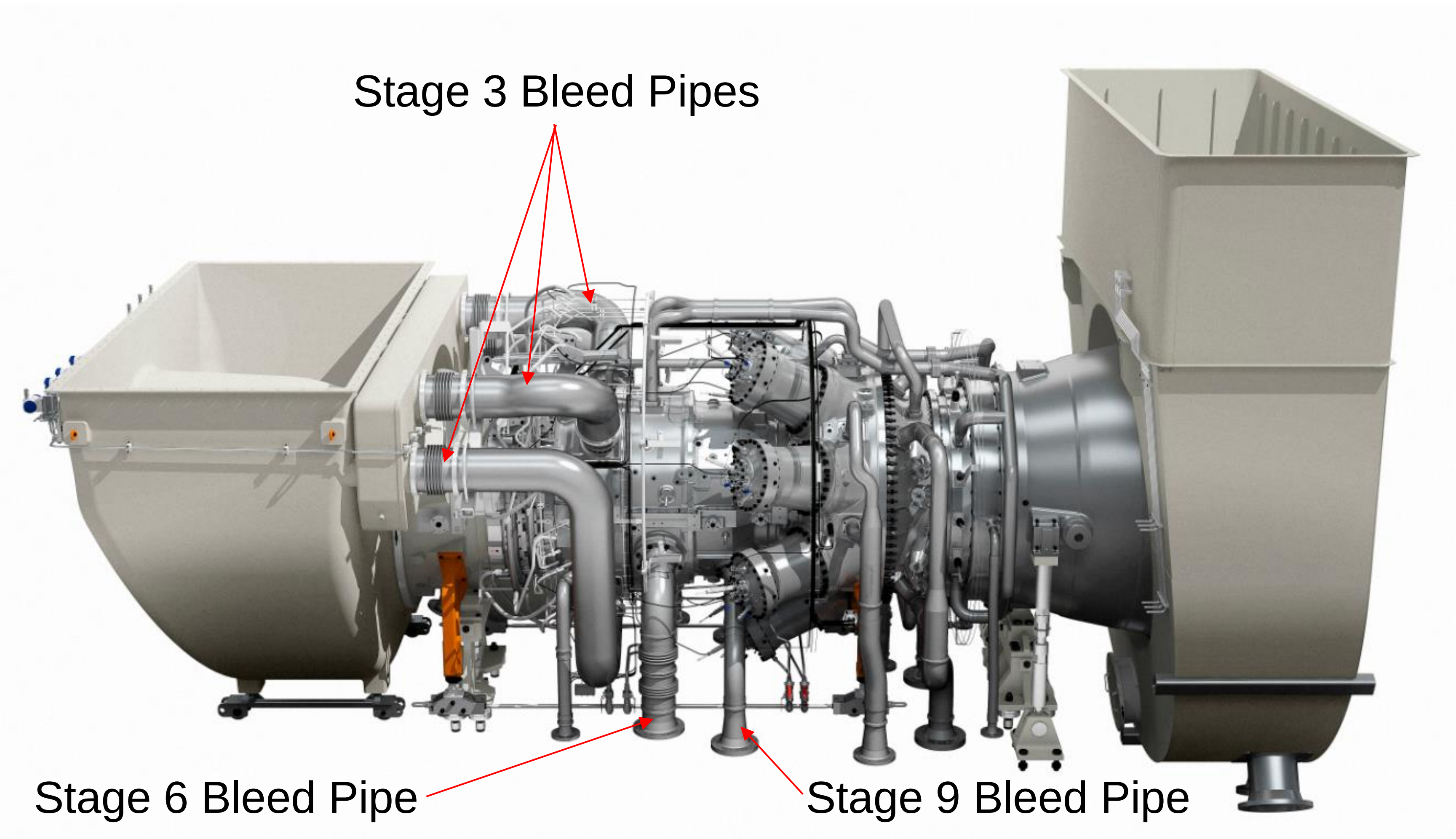
- If the inlet flow angle deviates too much from the blade metal angle, the flow separates on the suction side. Stall occurs.

- In severe cases many blade rows stall simultaneously and complete loss of compression takes place, so called surge, which might damage the engine.

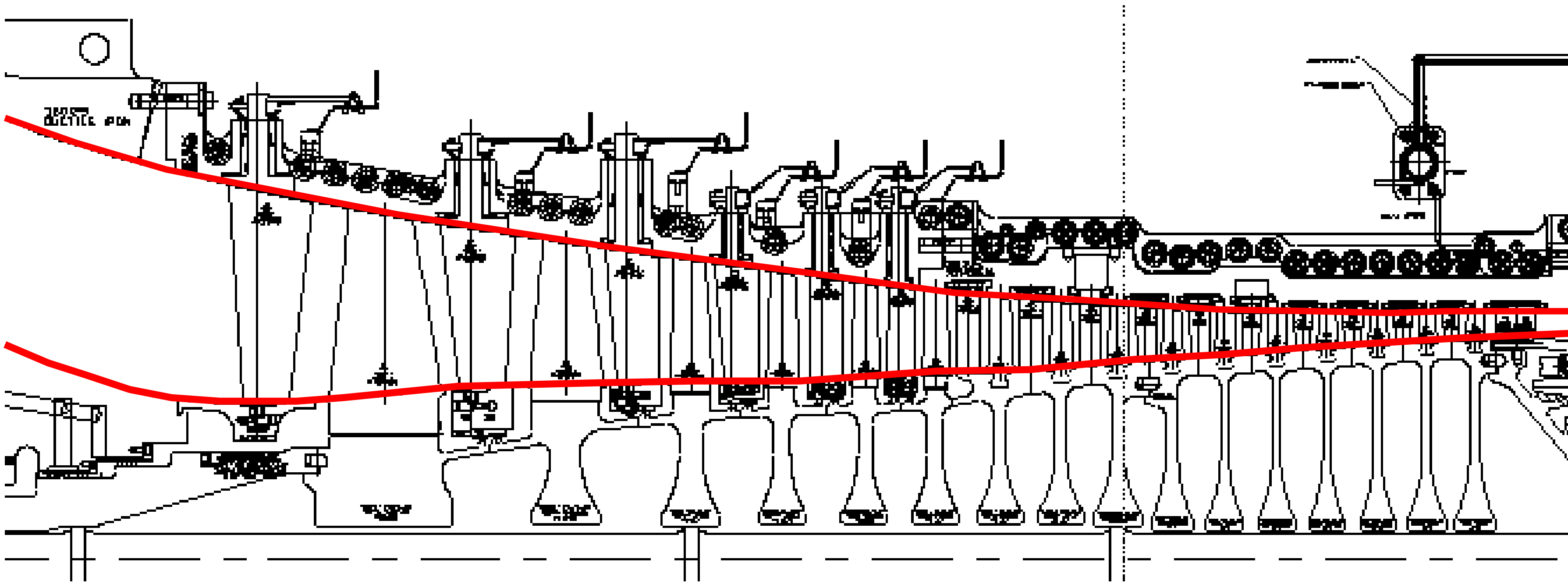
The SGT-750 Compressor



The SGT-750 Bleed Piping



Compressor Operation



The annular area distribution along the compressor is chosen to match the density distribution of the air at design load

Compressor Operation

- At low speed the pressure and thereby the density of the air is lower in the downstream stages than at design speed, so the air ”takes too much space” there and the last stages choke.

- This can lead to stall in the front stages as the meridional velocity decreases.

- This can be avoided by bleeding off air and/or reducing the flow area of the front stages by closing variable guide vanes (VGV’s).

Combustion Chamber

Combustor Principles

- Two main principles of combustor design are used in gas turbines: annular and can type .

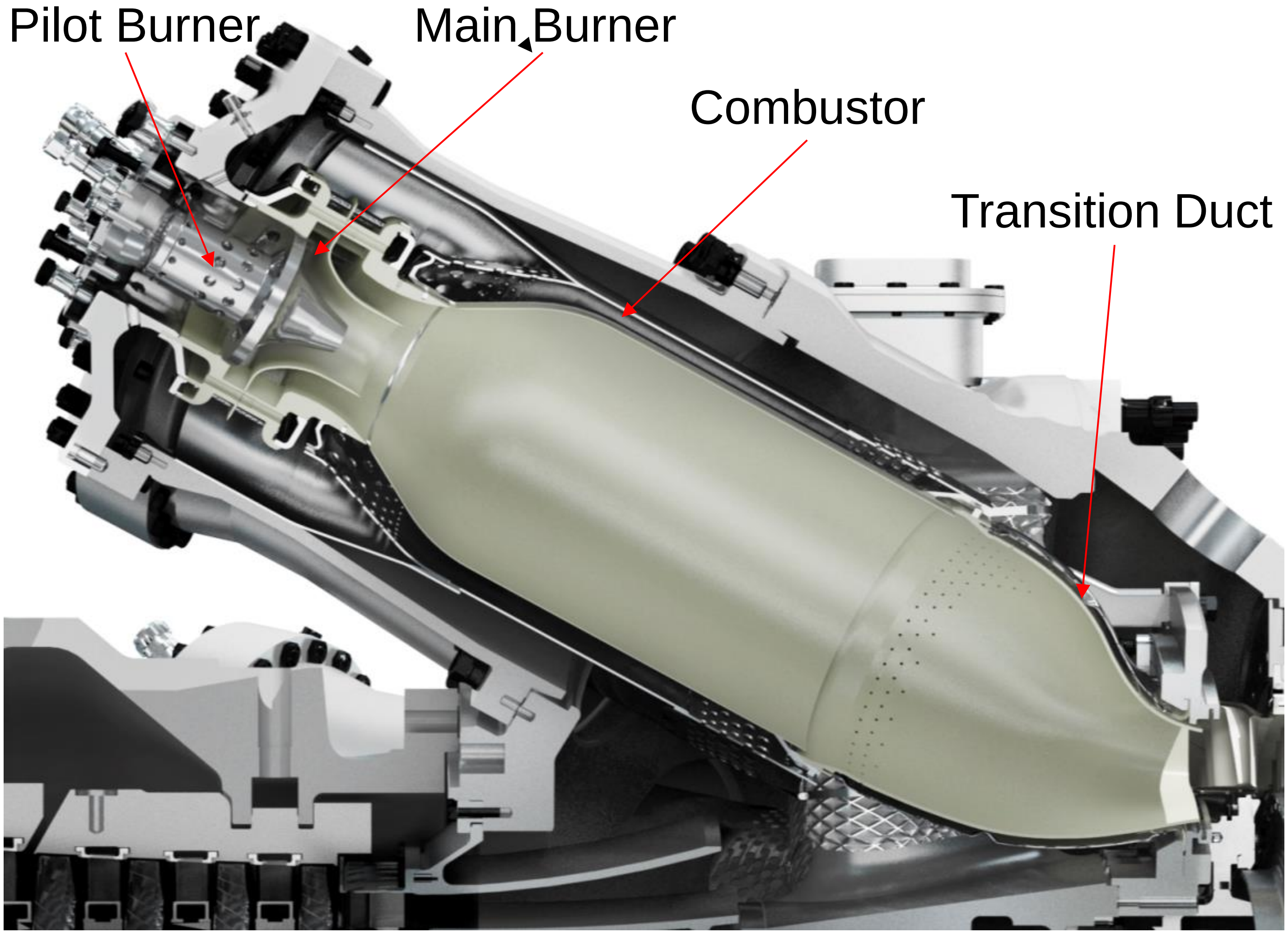
- The annular combustor gives a more uniform tangential temperature distribution which is advantageous from a turbine vane lifing point of view.

- The combustion in a can combustor is easier to adjust, since the burners do not influence their neighbours as in an annular combustor.

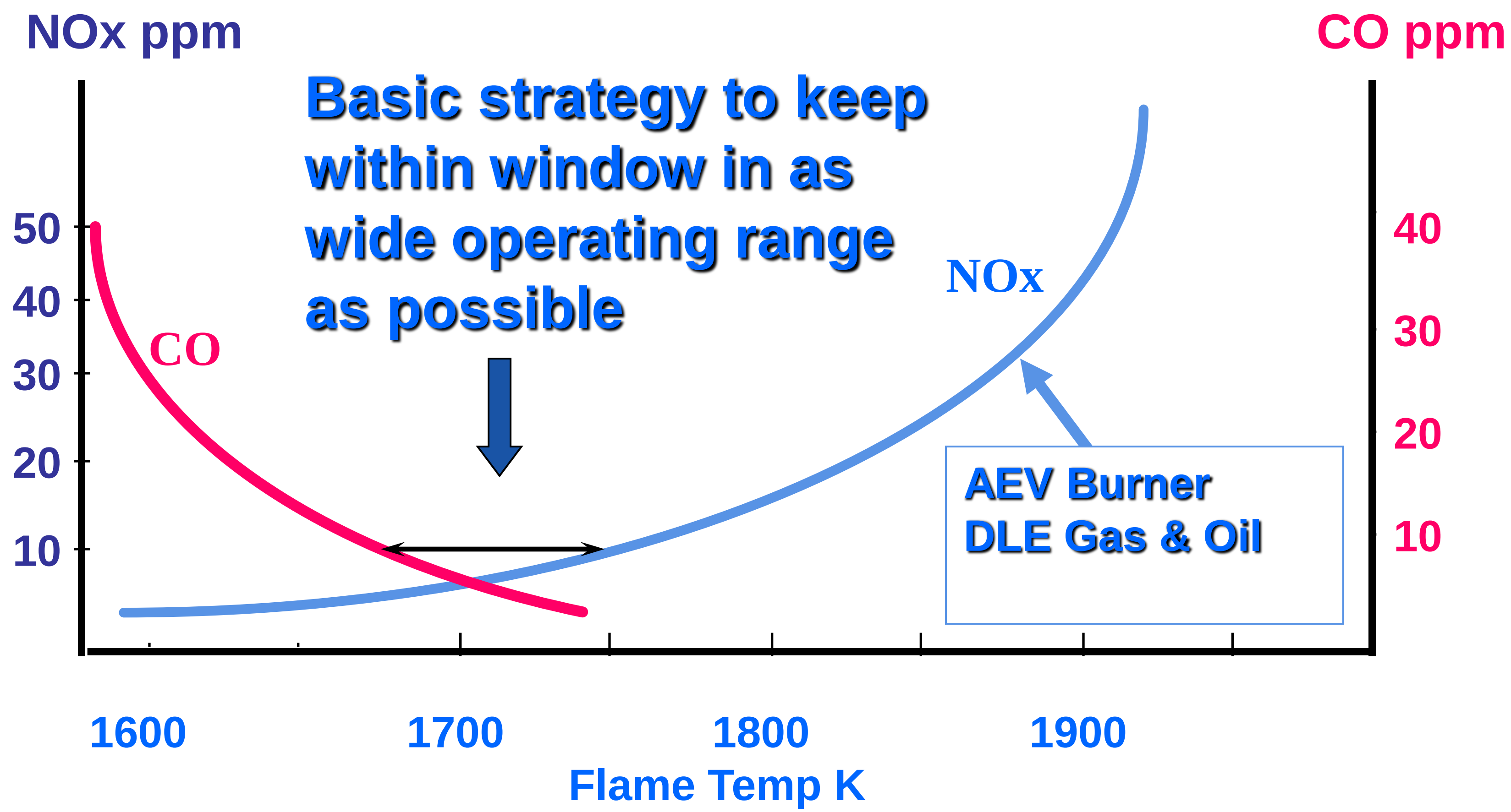
Flow Test Model of SGT-750 Can Combustor

SGT-600 Annular DLE Combustor

SGT-750 Can Combustor

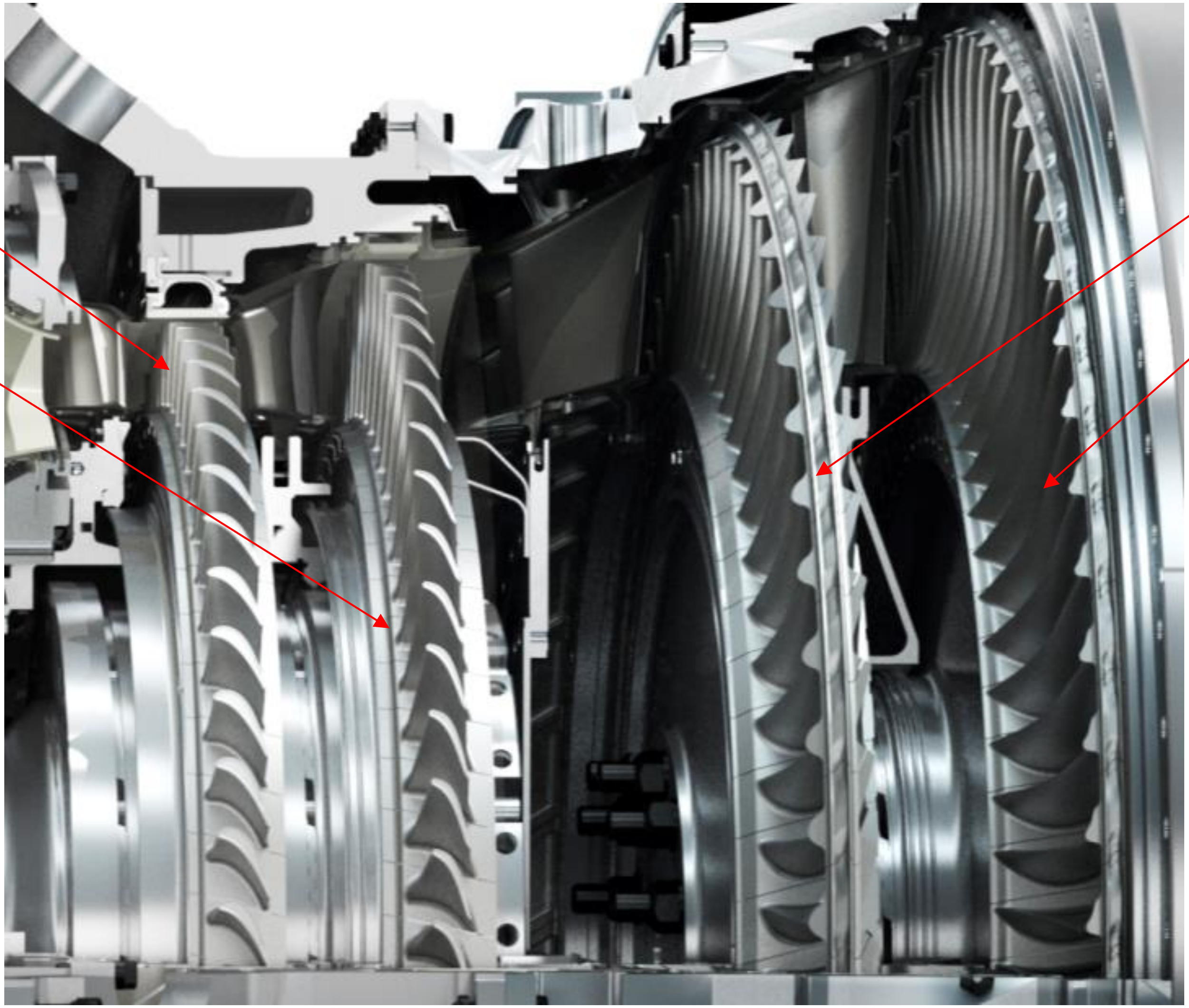


Combustion Control

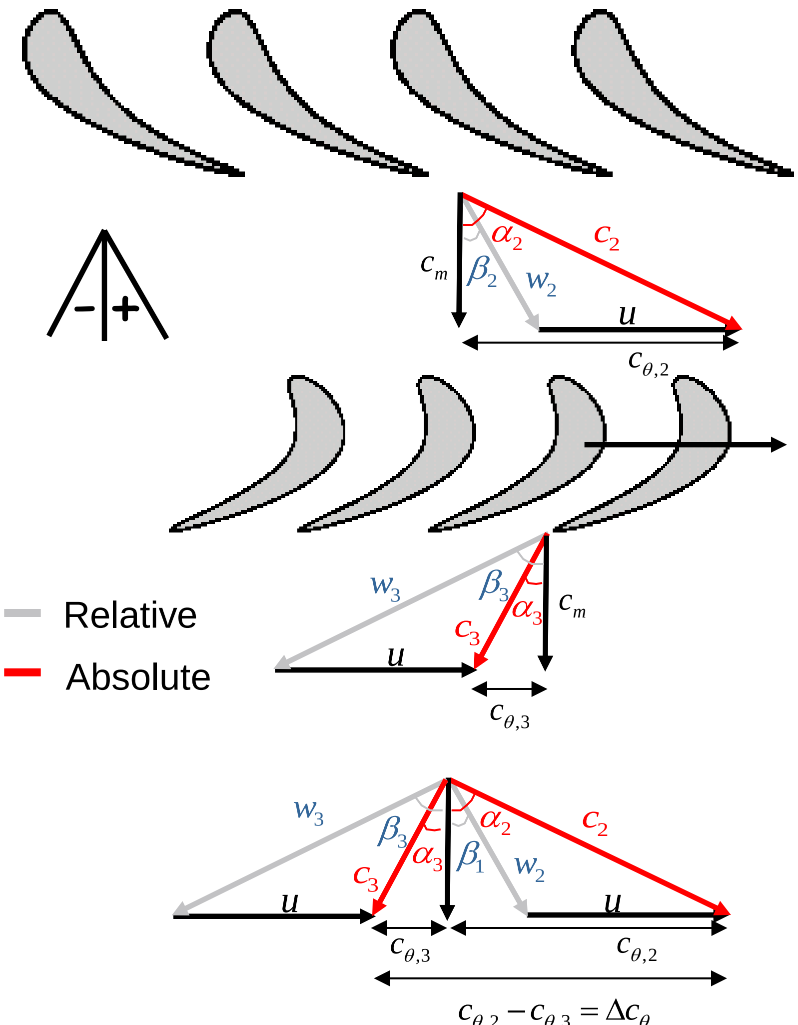


Turbine

SGT-750 Turbine



The Euler Turbomachine Equation



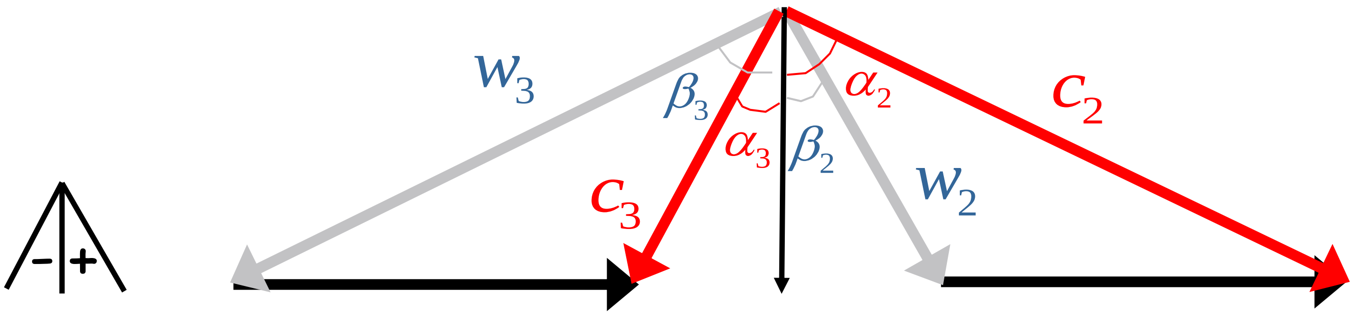
Stator vane

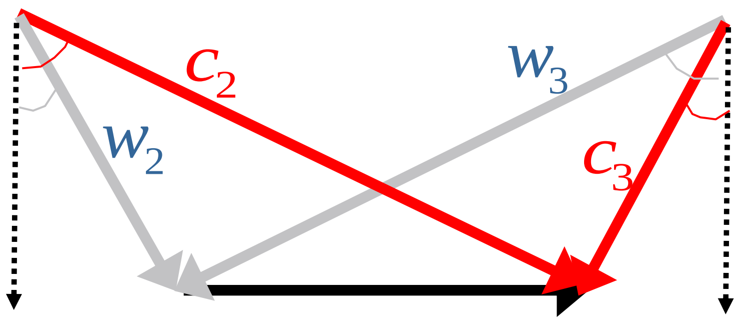
Rotor blade

Specific work according to Euler:

$\Delta h_0 = U(C_{\theta,2} - C_{\theta,3})$ [W/(kg/s)]

Basic Turbine Velocity Triangles





Relative

Absolute

Stage parameters

Stage loading coefficient

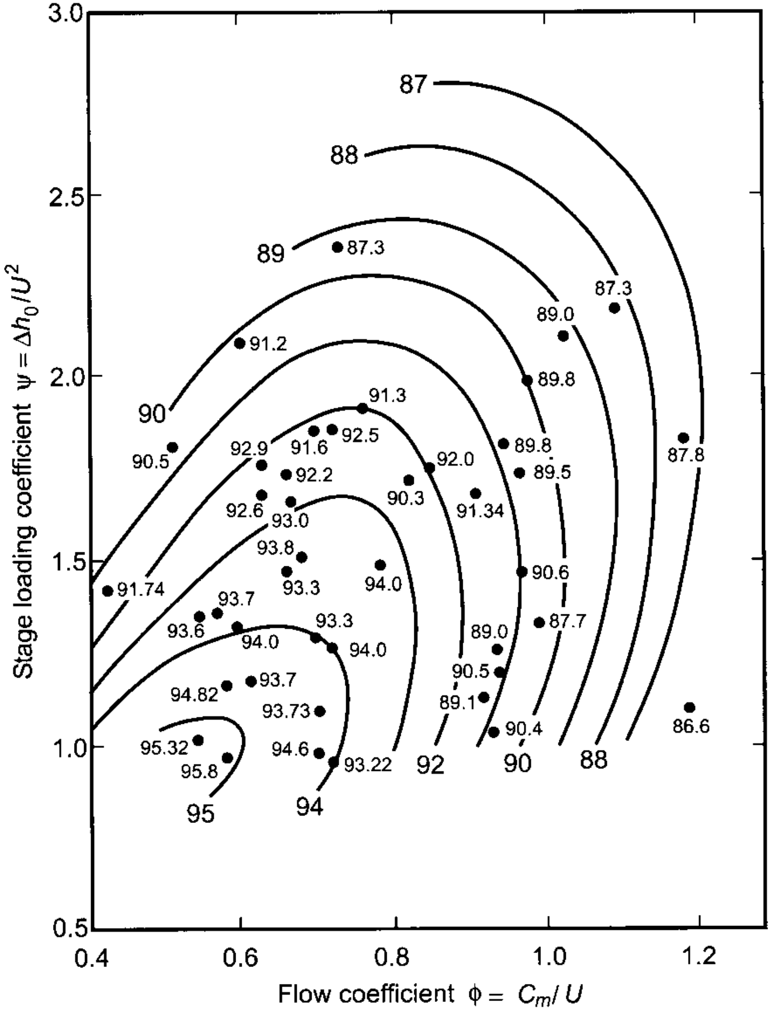
$\Psi = \Delta h_0 / U^2$

Flow coefficient

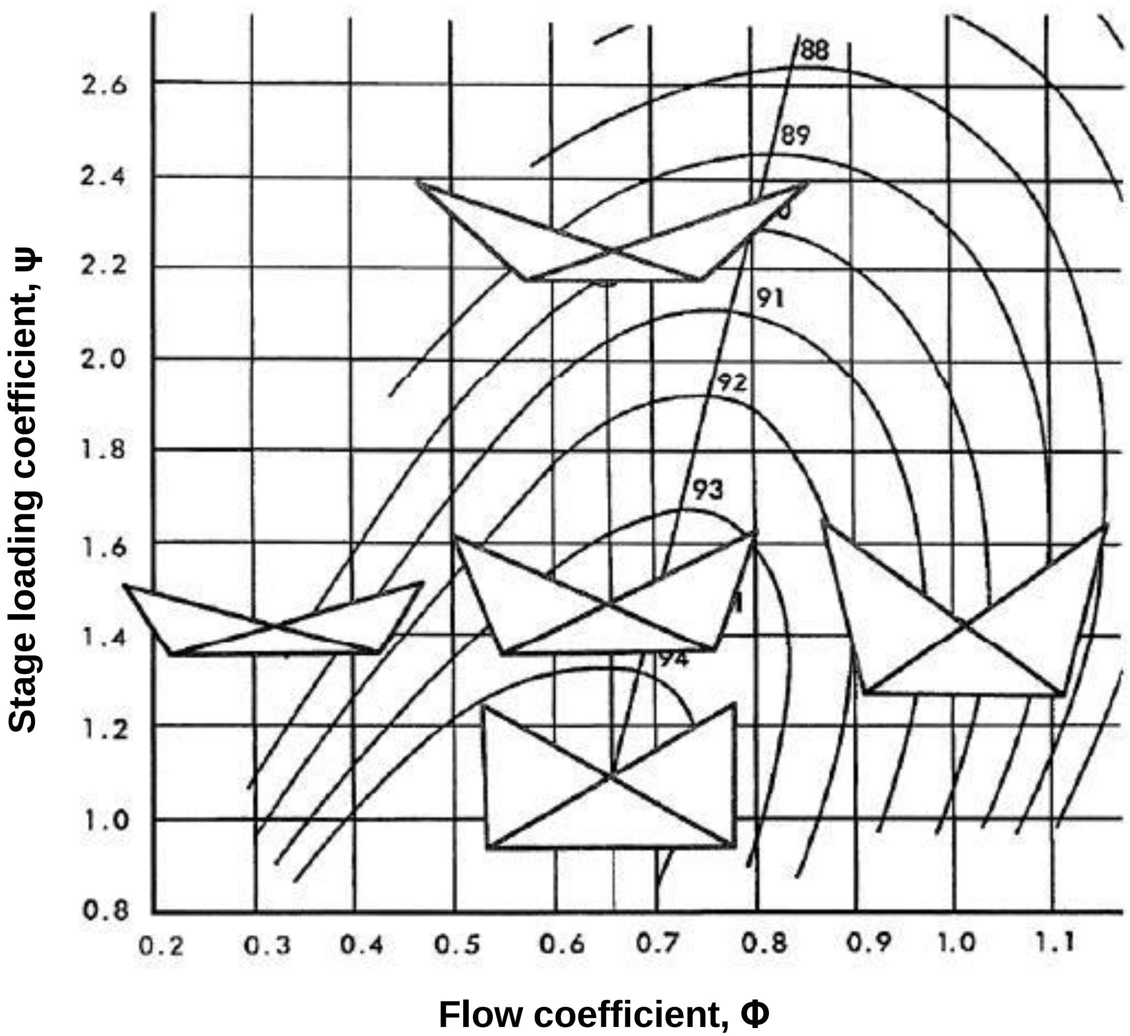
$\Phi = C_m / U$

Reaction

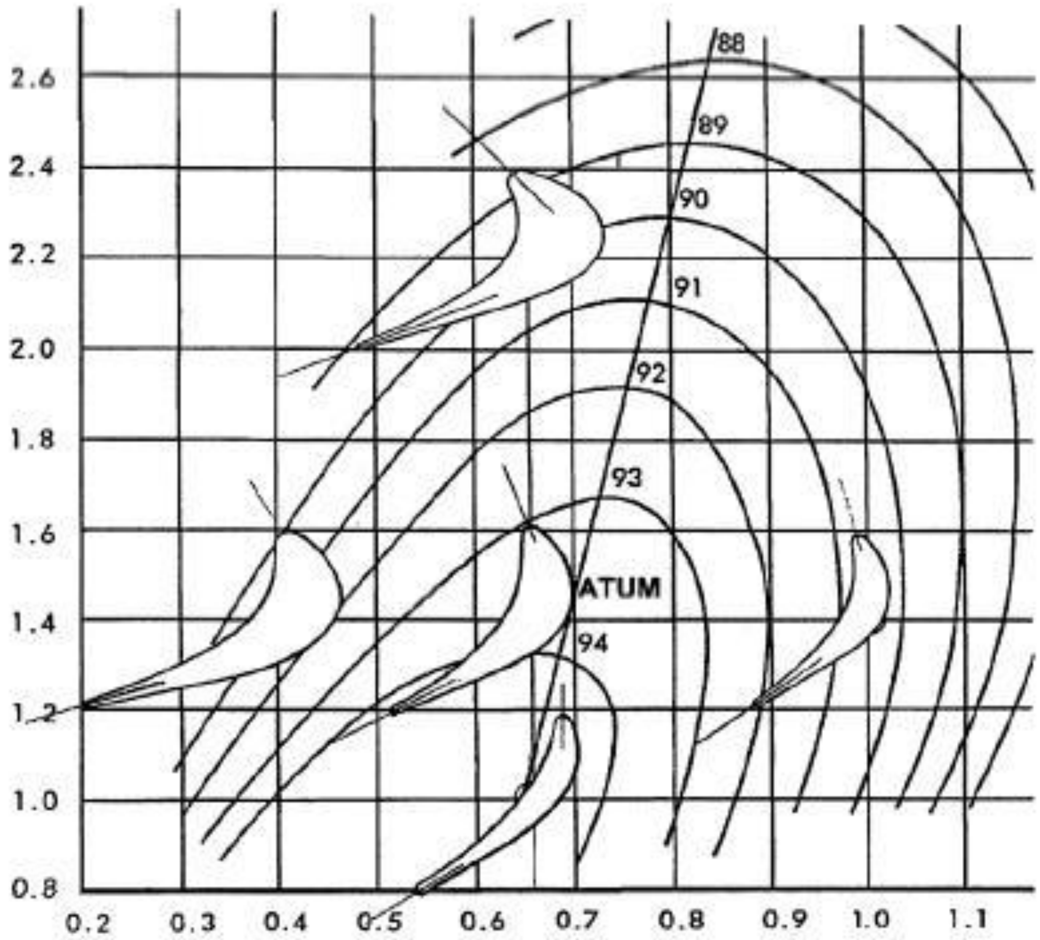
$\Delta h_{rotor} / \Delta h_{stage}$



Velocity Triangles in Smith Chart



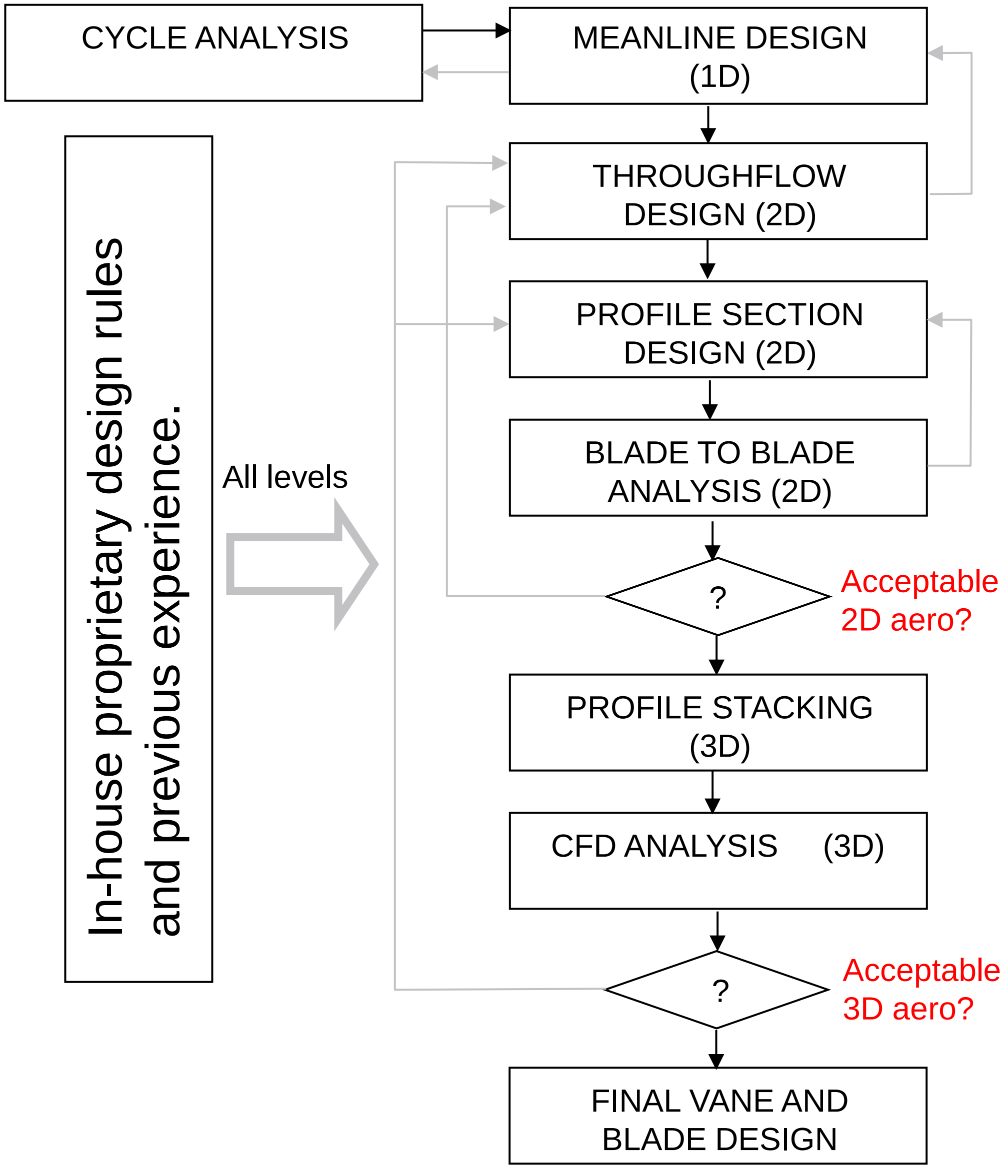
Rotor Blade Shape in Smith Chart



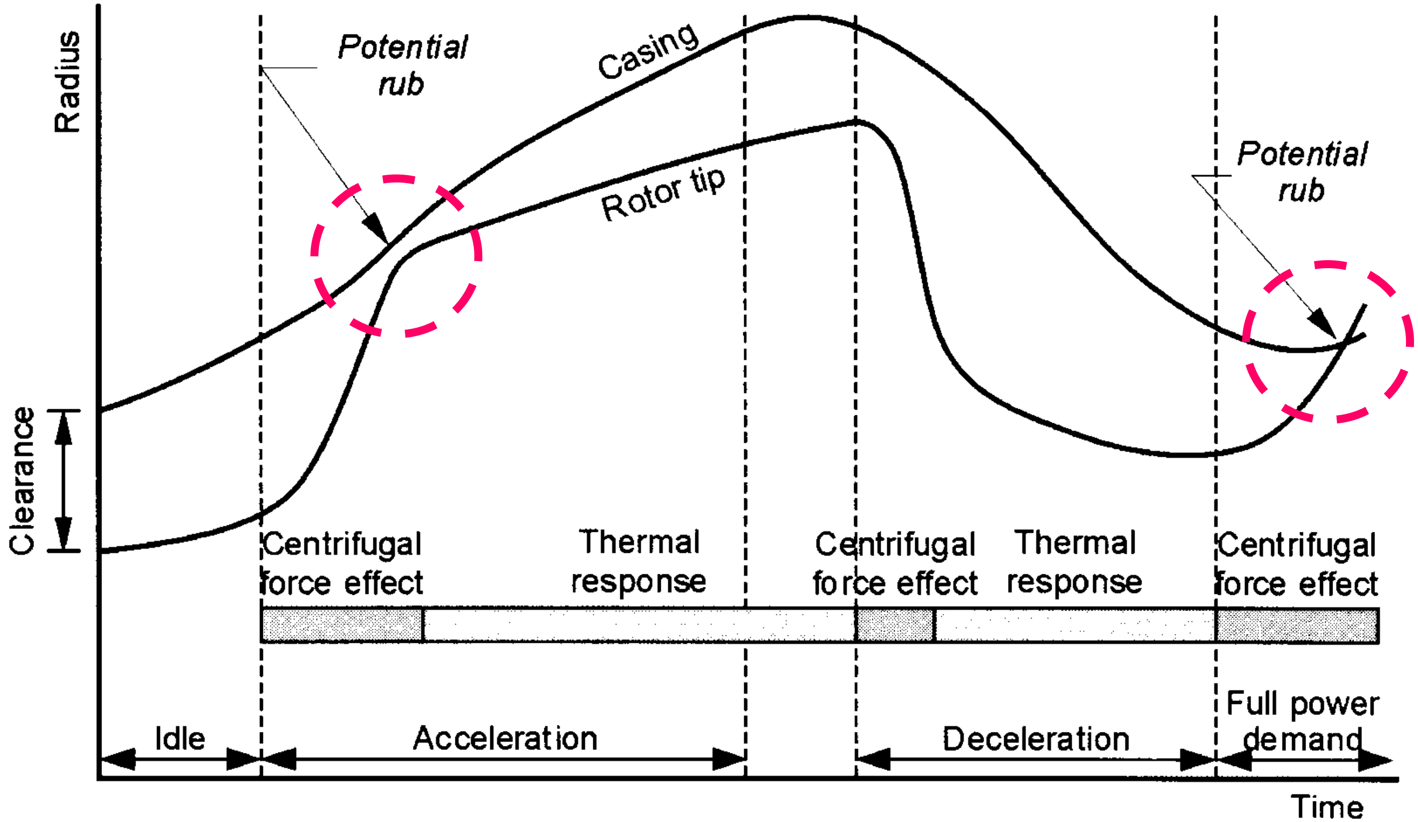
Stage loading coefficient, ψ

Flow coefficient, Φ

Aerodynamic design process



Tip clearance



Axial and Radial Turbines, Moustapha et. al.

Unshrouded:

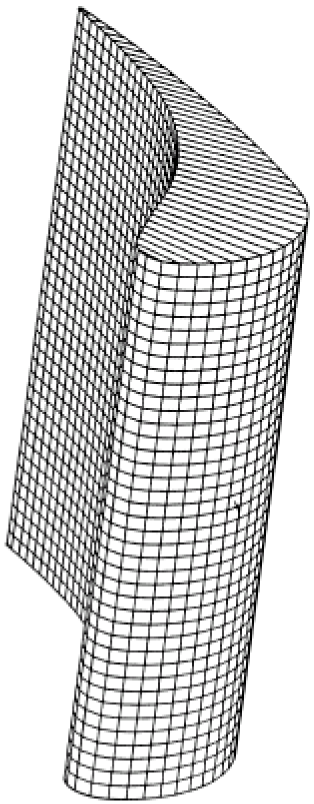
$$\frac{\Delta\eta}{\eta} \approx 0.6 \frac{\text{tip clearance}}{\text{span}} \frac{\text{chord}}{\text{throat}}$$

Shrouded:

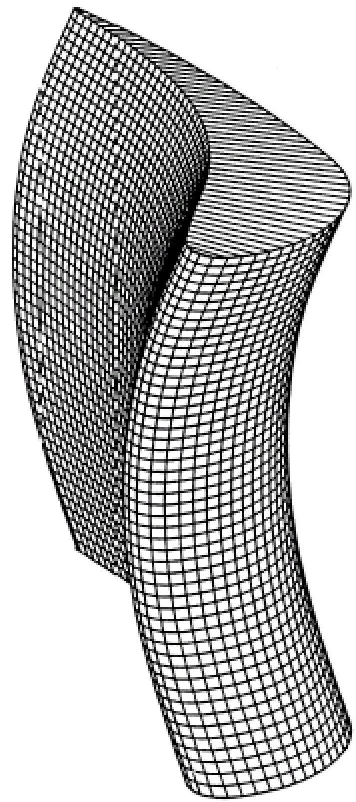
$$\frac{\Delta\eta}{\eta} \approx 0.6 \frac{\text{tip clearance}}{\text{span}} \frac{\text{pitch}}{\text{throat}} \frac{1}{\sqrt{N_{seals}}}$$

Different stacking philosophies

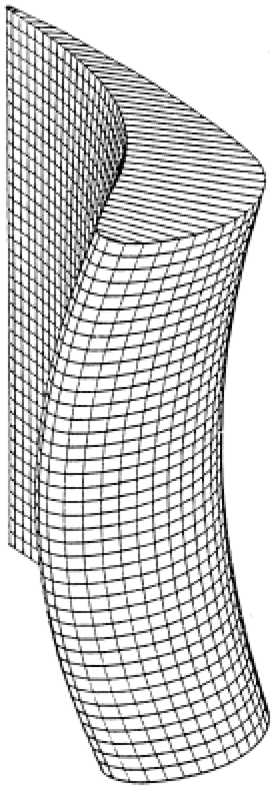
Negative lean



Compound lean

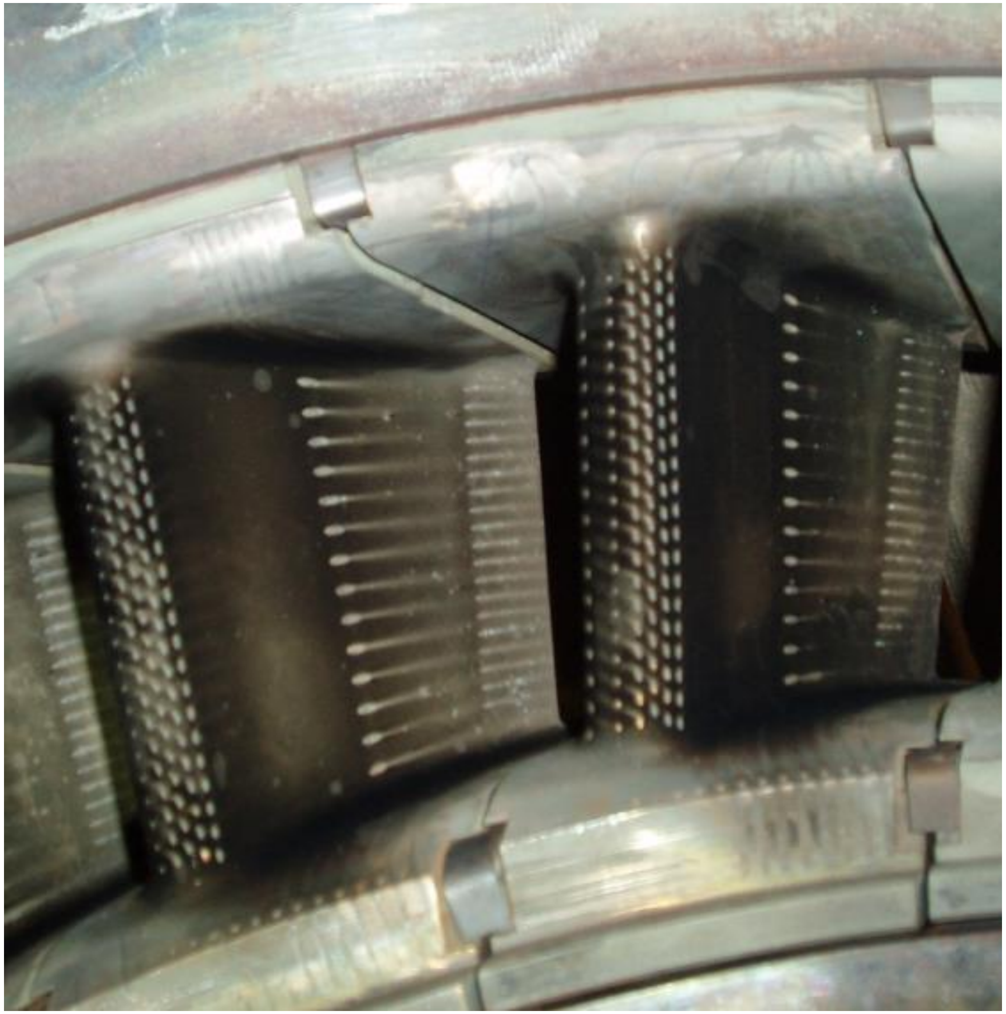


Controlled flow



Ref: Dr Brian Haller: Full 3D Blade Design

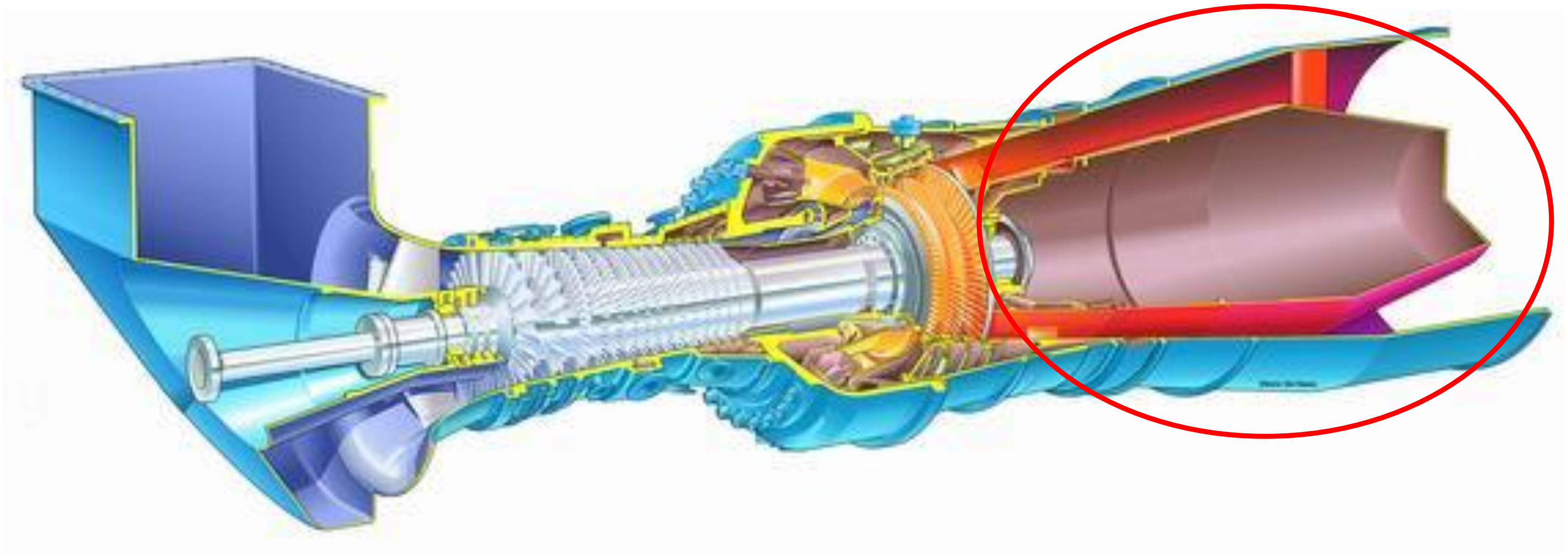
Vane Film Cooling



Film cooling holes on Vane 1 of SGT-700

Diffuser

The Diffuser



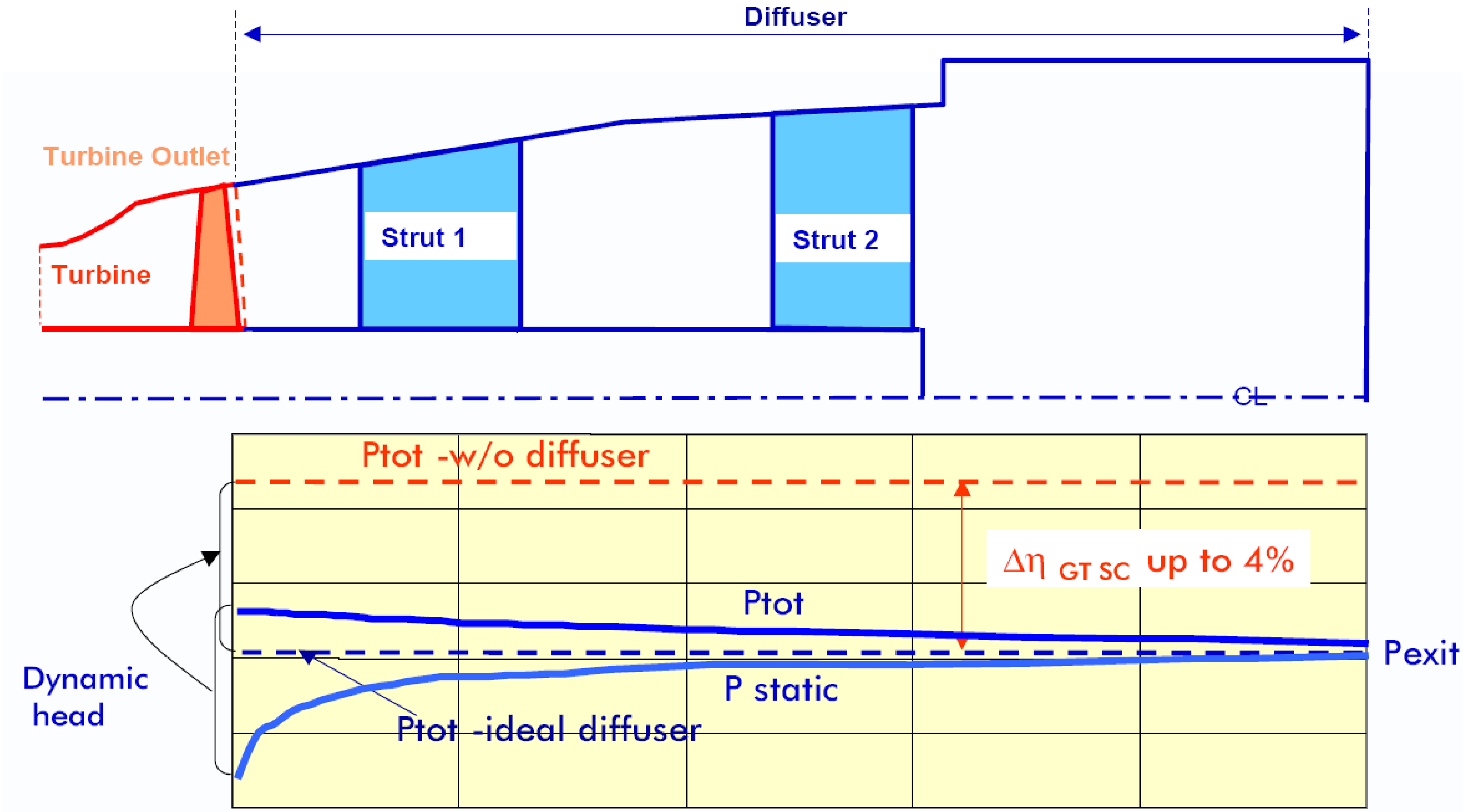
The Diffuser

- The gas leaving the last stage blade has a high velocity, typically around 250 m/s, representing a lot of kinetic energy.
- By applying a diffuser downstream of the last blade, thereby smoothly reducing the velocity of the gas before it is exhausted into the ambient atmosphere, much of this dynamic pressure can be converted into static pressure.
- This results in an increase in static pressure along the diffuser.
- Since the ambient atmospheric pressure at the diffuser exit is constant, the static pressure at the outlet of the last blade is reduced.
- This gives a higher available pressure ratio, which enables more power to be extracted from the gas.

Example of Exhaust Loss

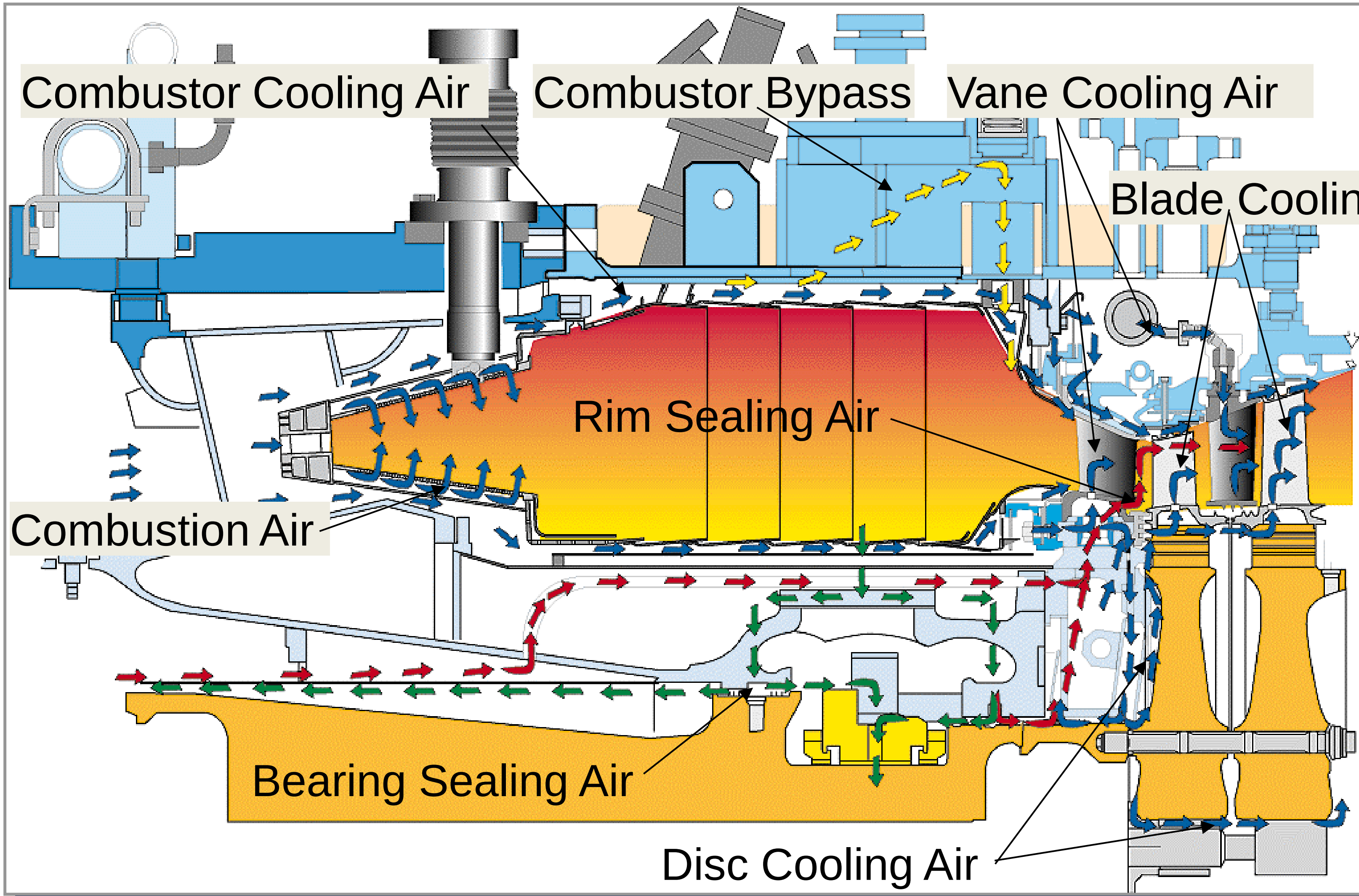
- $\Delta h_{exh}=c^2/2$
- $c=245$ m/s gives $\Delta h_{exh}=30$ kJ/kg
- With a mass flow of 135 kg/s this corresponds to more than 4MW which in this example is 8.5% of the power output
- More than 70 % of this can be recovered in a good diffuser.

Diffuser pressure recovery

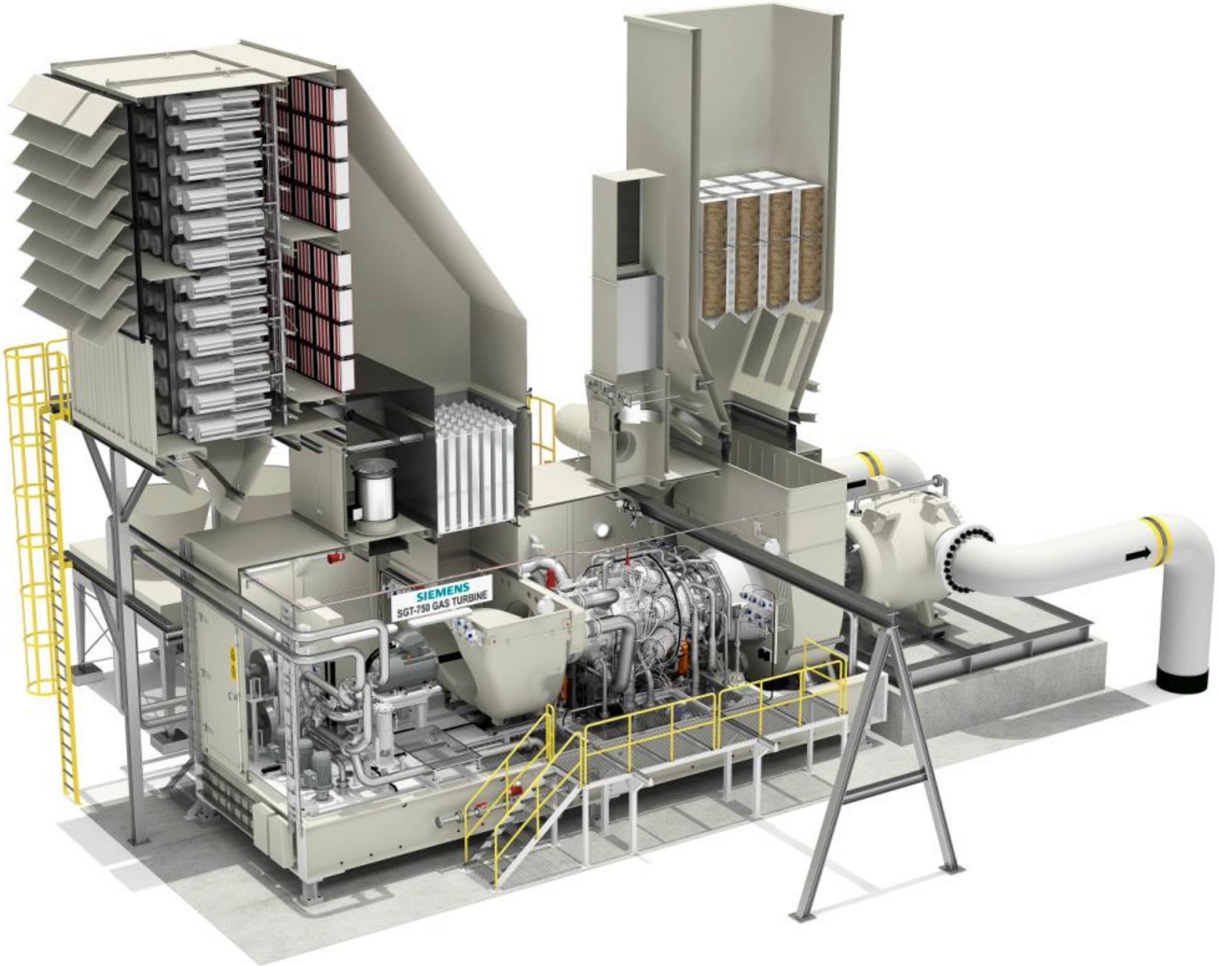


Secondary Air System

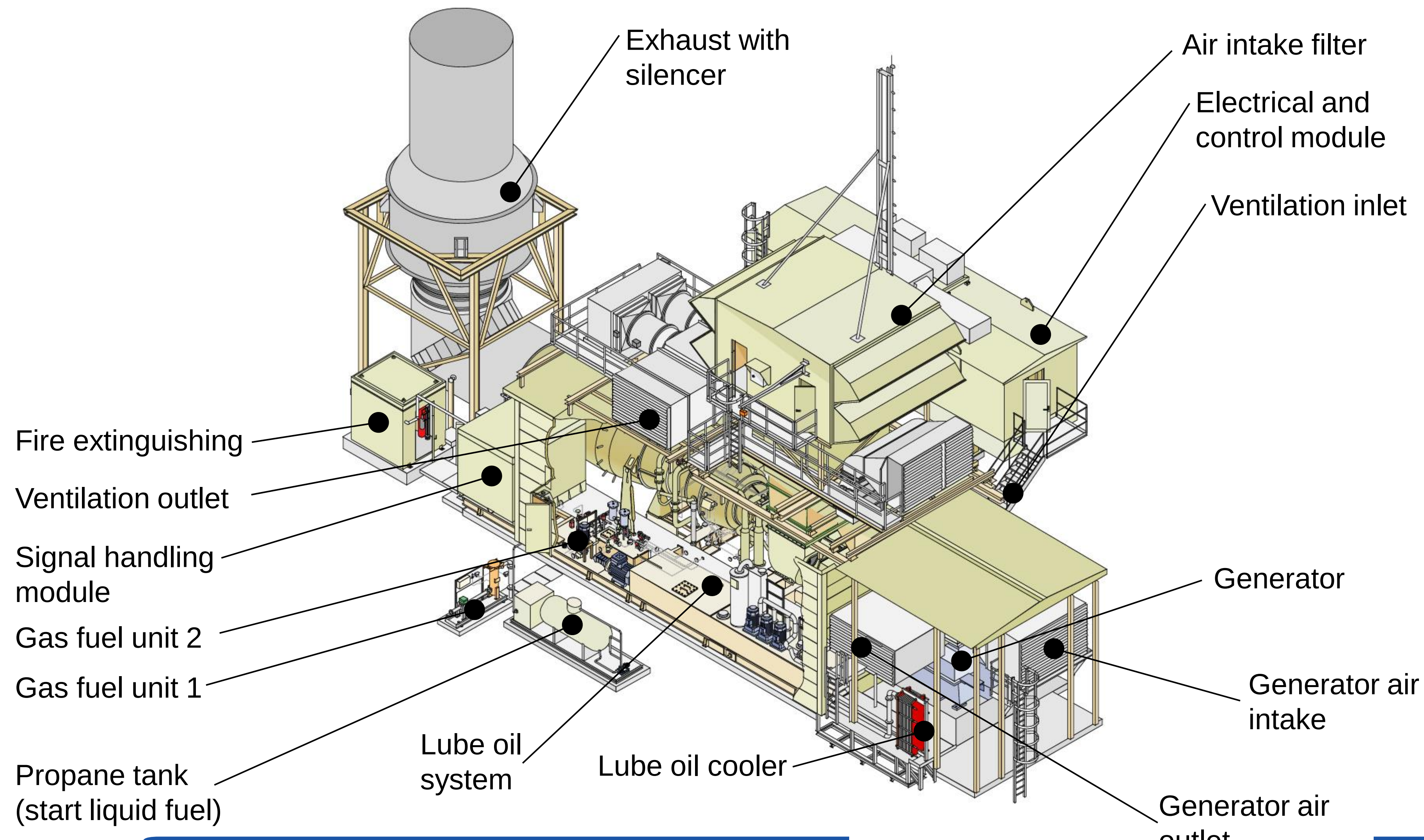
SGT-600 Combustor and Secondary Air Flows



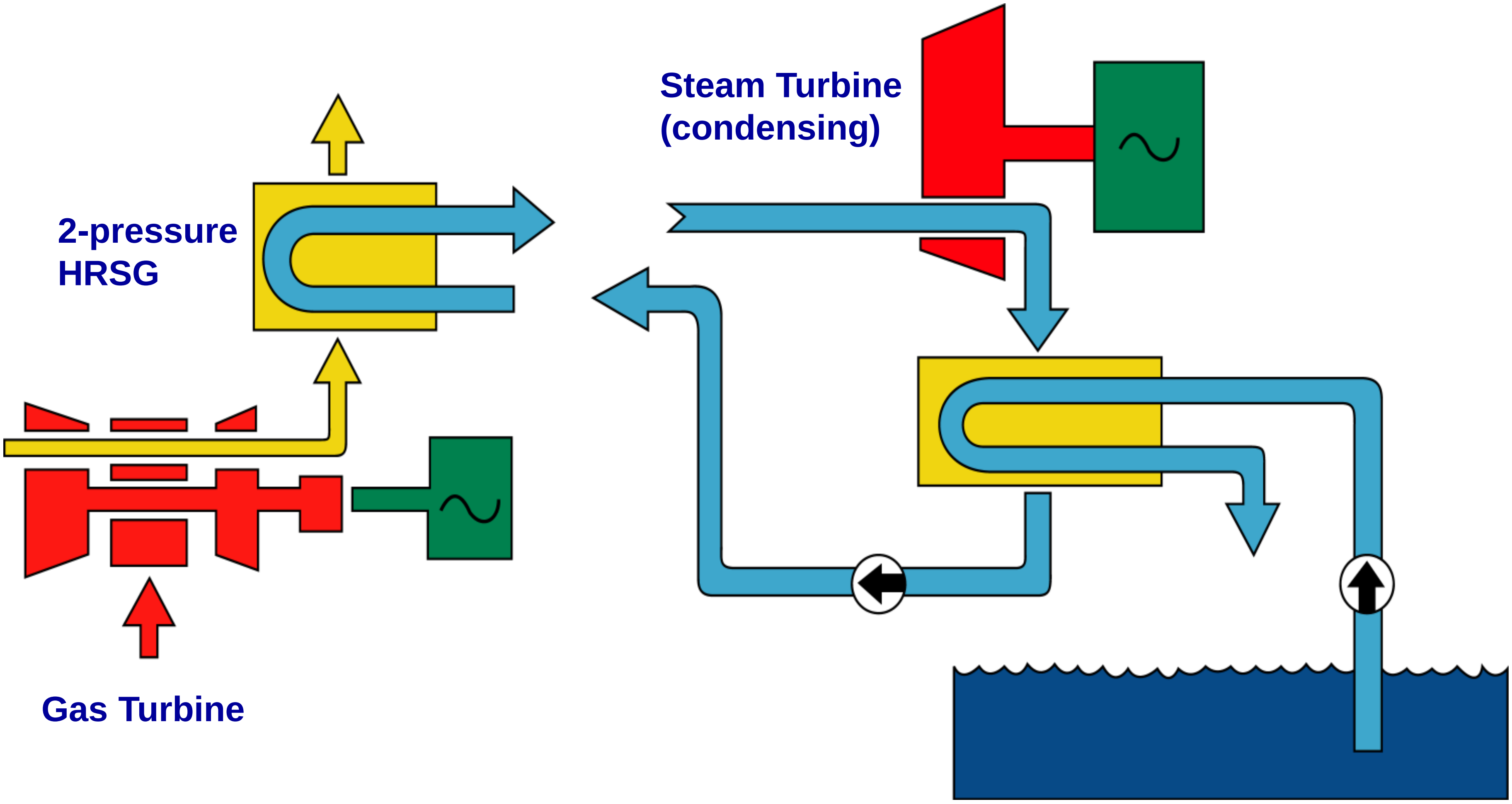
Complete SGT-750 Package



SGT-800 Auxiliary Equipment



Gas Turbine in Combined Cycle



Industrial vs. Aeroderivative Gas Turbines

Industrial gas turbines are designed for land based operation.

- Often better in combined cycle operation due to higher exhaust temperature.
- Often slower performance deterioration with time due to more robust design.

Aeroderivative gas turbines have the same main components as aero engines.

- Often higher pressure ratio and therefore higher simple cycle efficiency
- Shorter start up time due to light weight.

End of Presentation

Gas Turbine Technology

THANK YOU!