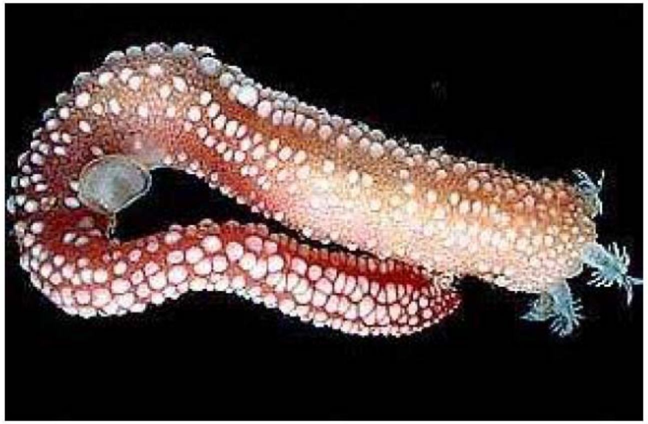
Gas Turbine Seminar -17

Lund University

Farligaste djuret?

Farligaste djuret?

Biological Origin of Heavy Metals in Crude Petroleum



Sea Cucumber

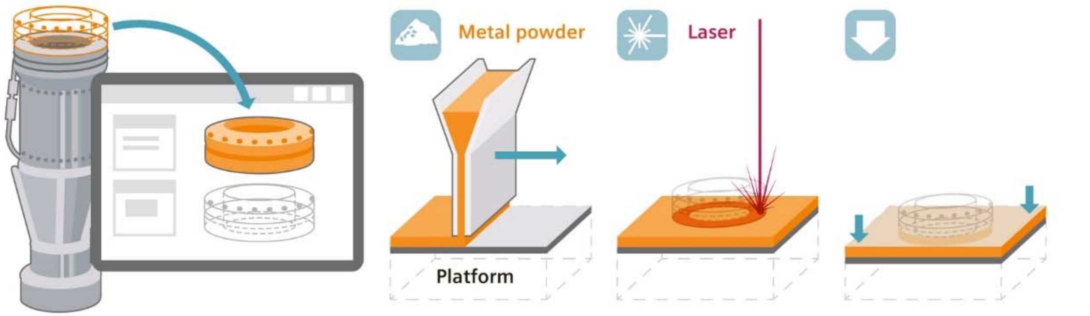
Sea Squirt

The Sea Cucumber contains about 6,500 ppm vanadium in its body. These type organisms are believed to be a biological source of heavy metals in crude petroleum.

Additive Manufacturing - AM

Additive Manufacturing

How burner tips are made: Using additive manufacturing, spare parts for smaller gas turbines are already being produced today.

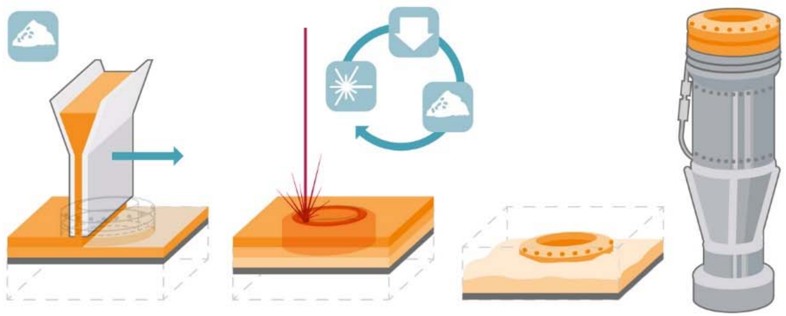


The gas turbine burner needs a new tip. A digital production plan is created on a computer.

A thin layer of stainless steel powder is applied.

A laser beam fuses the powder, thereby creating the first layer of metal.

The platform lowers by a few micrometers, lowering the component being produced.

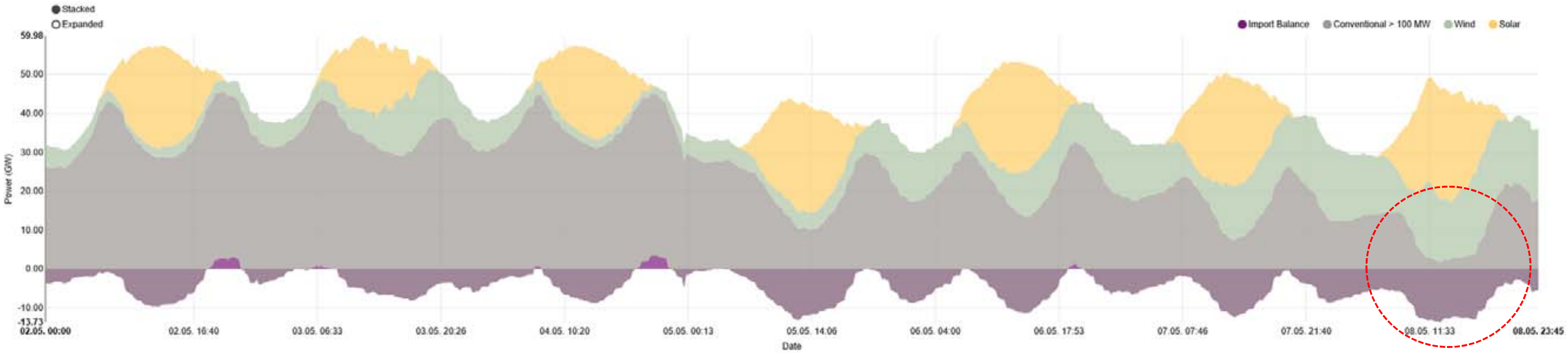


A new layer of metal powder is applied.

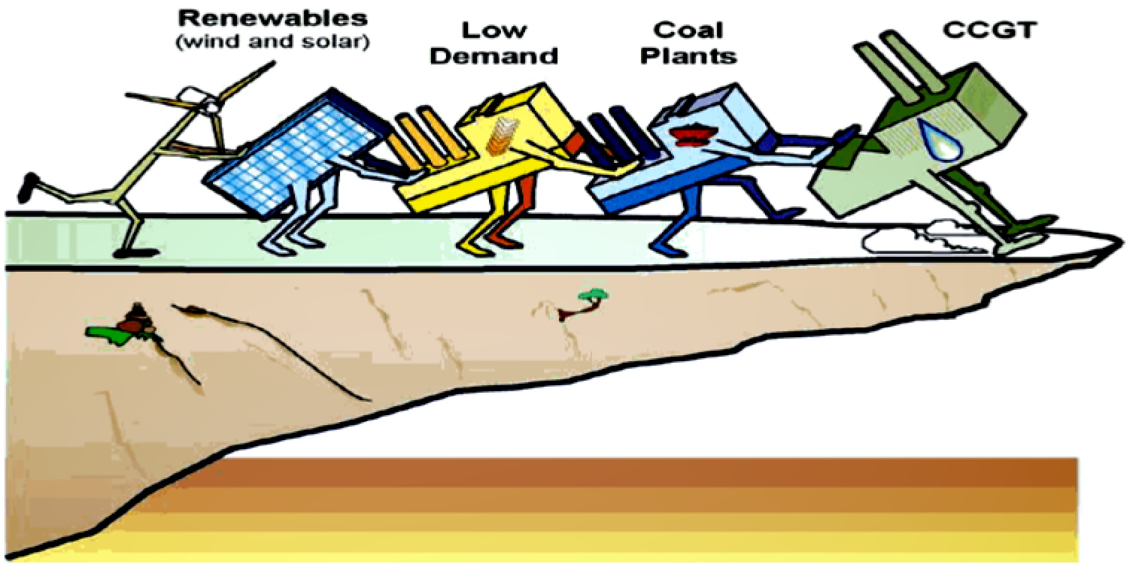
The laser again traces the outline of the piece being produced.

Layer by layer, a new burner tip is fused onto the component.

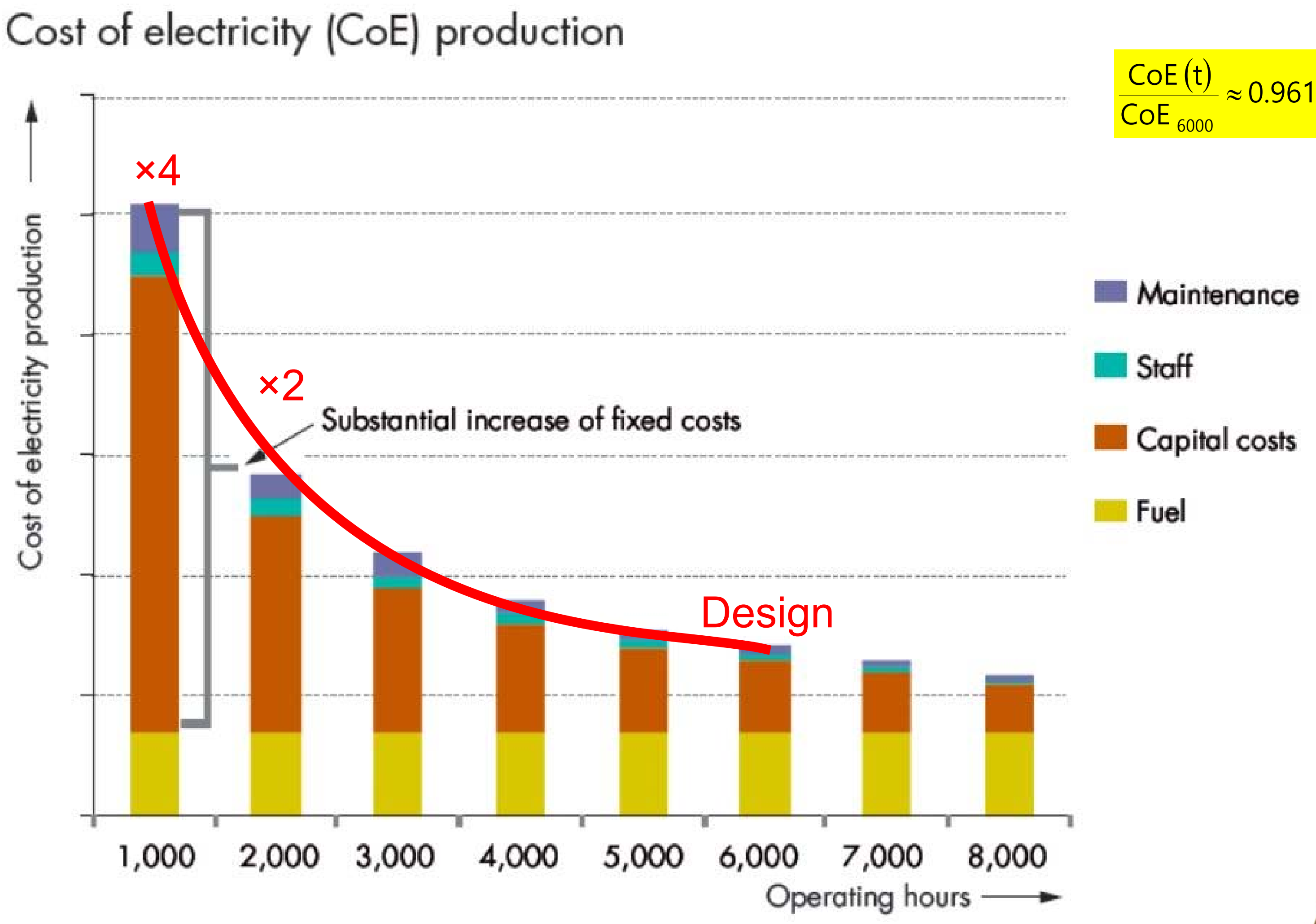
Almost 100% renewable in Germany W616



The European issue…



Cost of Electricity (CoE) vs. OH



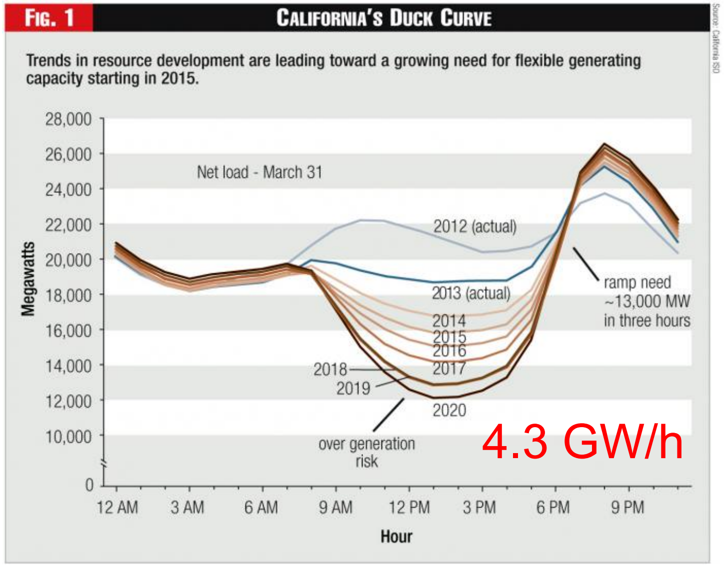
$$\frac{CoE(t)}{CoE_{6000}} \approx 0.961 \times \left(\frac{t}{6000}\right)^{-0.761}$$

Courtesy of VGB Powertech

The ”Duck-Curve”…

Sweden

California

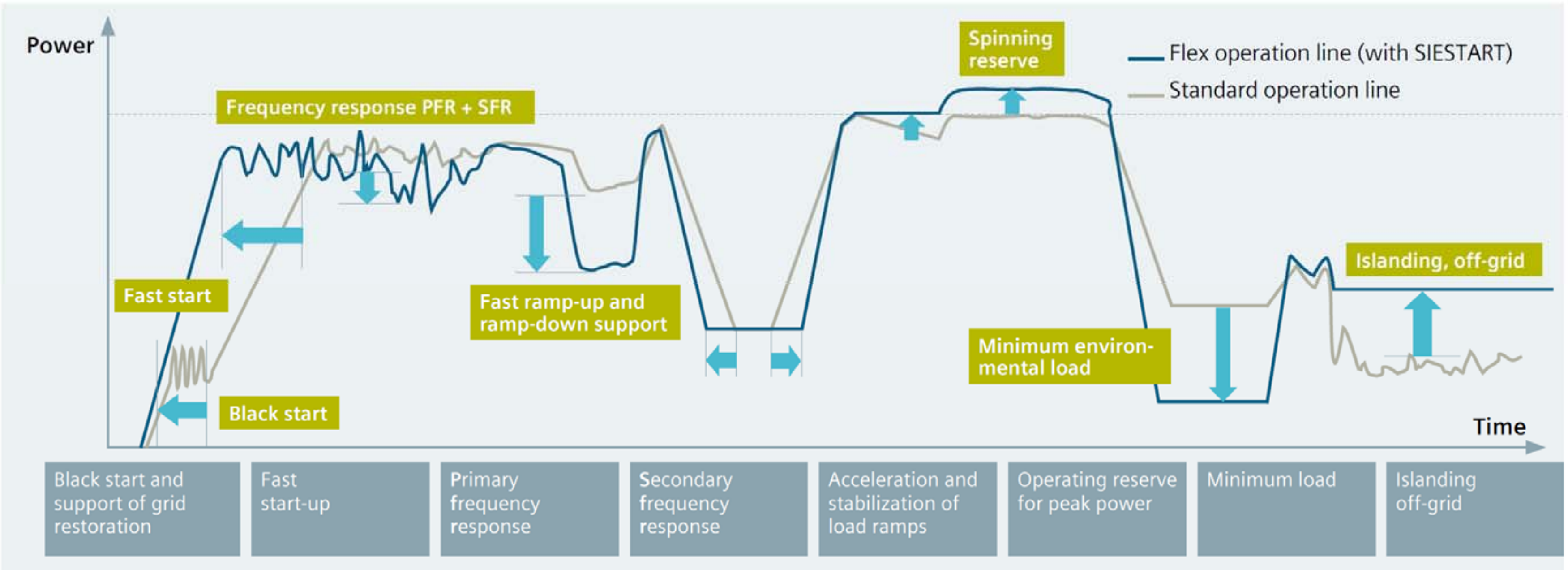


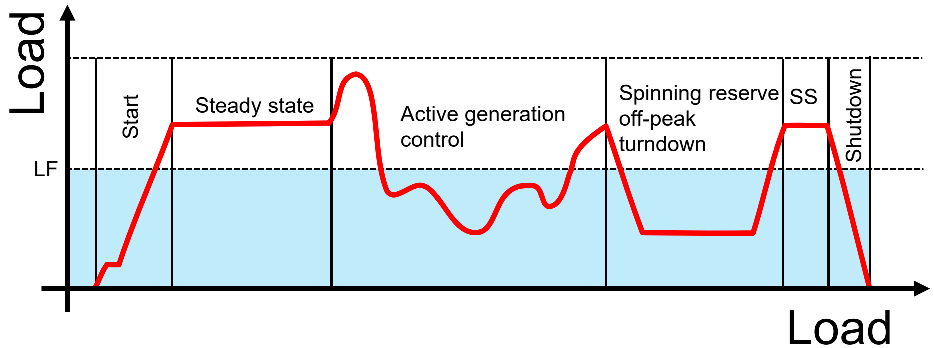
Grid codes

		Germany	United Kingdom	Japan	
		VDN	National grid	Japan Electric Association	
		Transmission code	Grid code	System interconnection regulations	
		2007	2012	2013	
FRT	Renewable energy	0 V—0.15 s 85% V—15 s	0 V—0.14 s 15% V–0.14 s 80% V—1.2 s 85% V—2.5 s 90% V—3 min	Wind power 0 V — 0.15 s 90% V — 15 s (2-cycle GB is permitted)	PV 20% V—0.3 s or less Continuous operation (2-cycle GB is permitted)
	Thermal power	0 V–0.15 s (brownout period undefined)		–	
	Reactive current supply	2% I/%ΔV, Max 100%	Max 100%	–	
	Output recovery rate	20% P/min	0.5 s after voltage recovery 90% P	1 s after voltage recovery 80% P	0.1 s after voltage recovery 80%P (> 20%V) 1 s after voltage recovery 80% P (<20% V)
Frequency fluctuation	Renewable energy	>+0.2 Hz droop gain 5% (MW decrease)	<−0.5 Hz 10% UP in 10 s and keep 30 min (some excluded)	Step change in 3 cycle ±0.8 Hz (50 Hz), ±1.0 Hz (60 Hz) Ramp change ±2 Hz/s 47.5–51.5 Hz, 57–61.8 Hz −> continuous operation	
	Thermal power	Droop control Control width ±2%		–	

Flexibility

Courtesy of Siemens

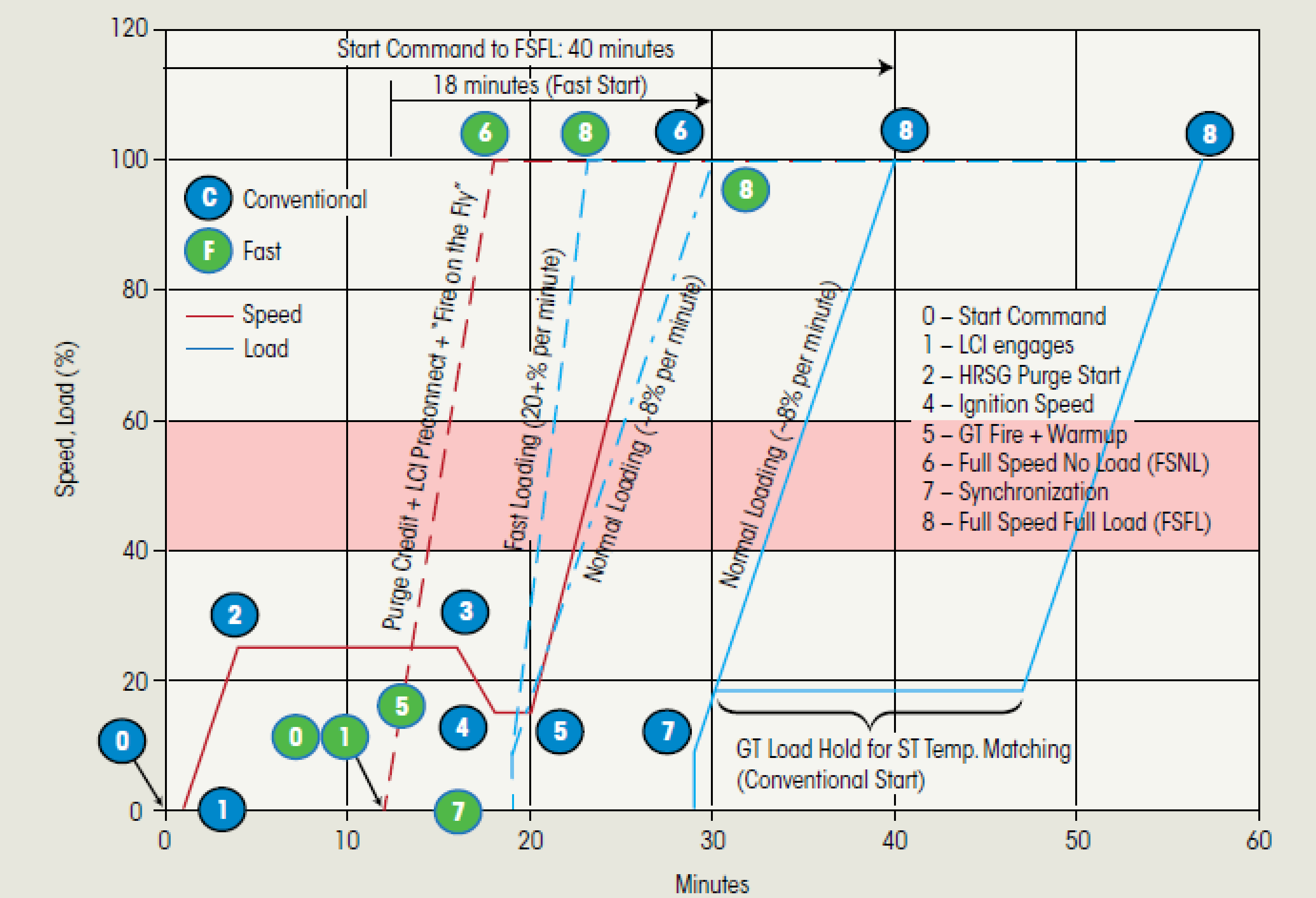




Flexibility

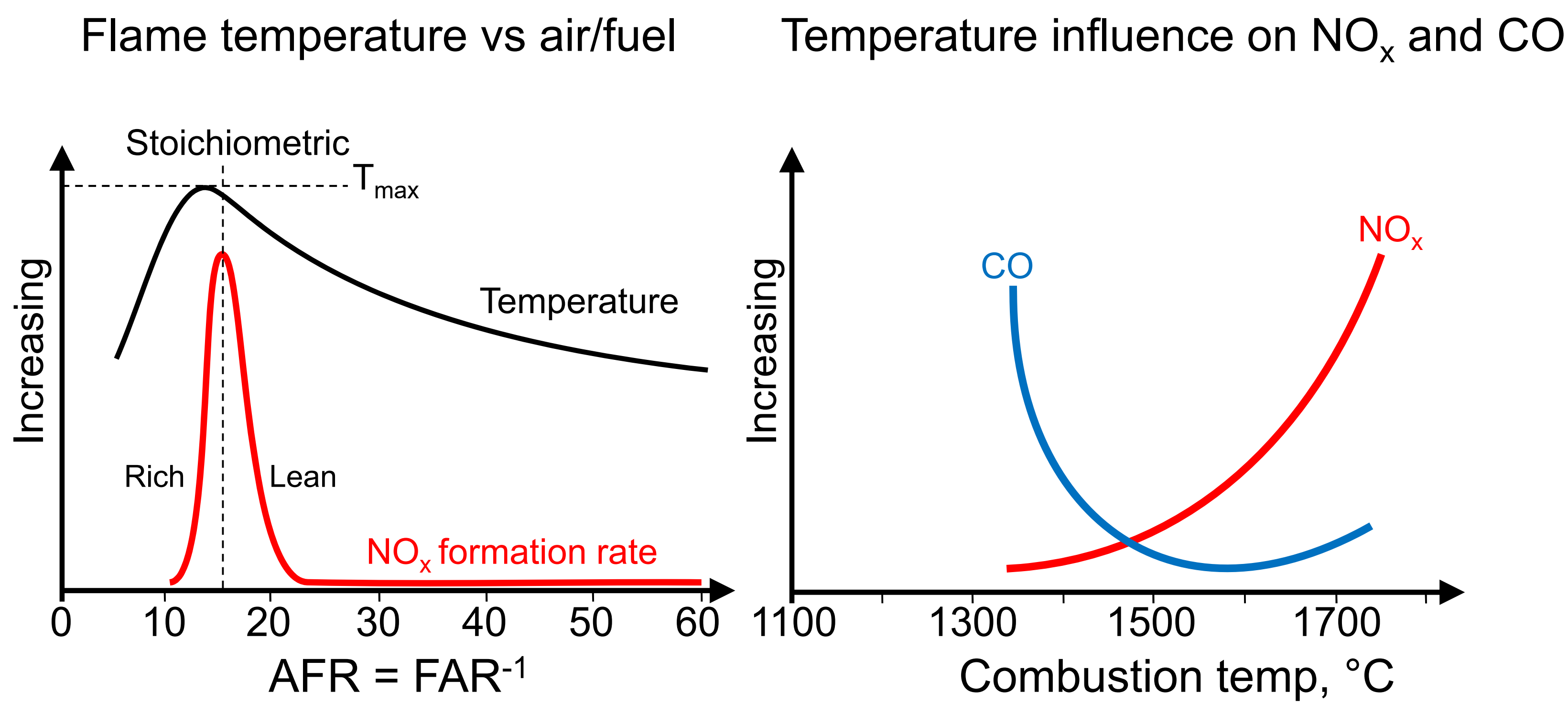
- Start-up
  - Air attemperation
  - Sky venting
  - Cascaded steam bypass with attemperation
- Ramping
- Turn-down
  - MECL
- Lock-out

GT start-up



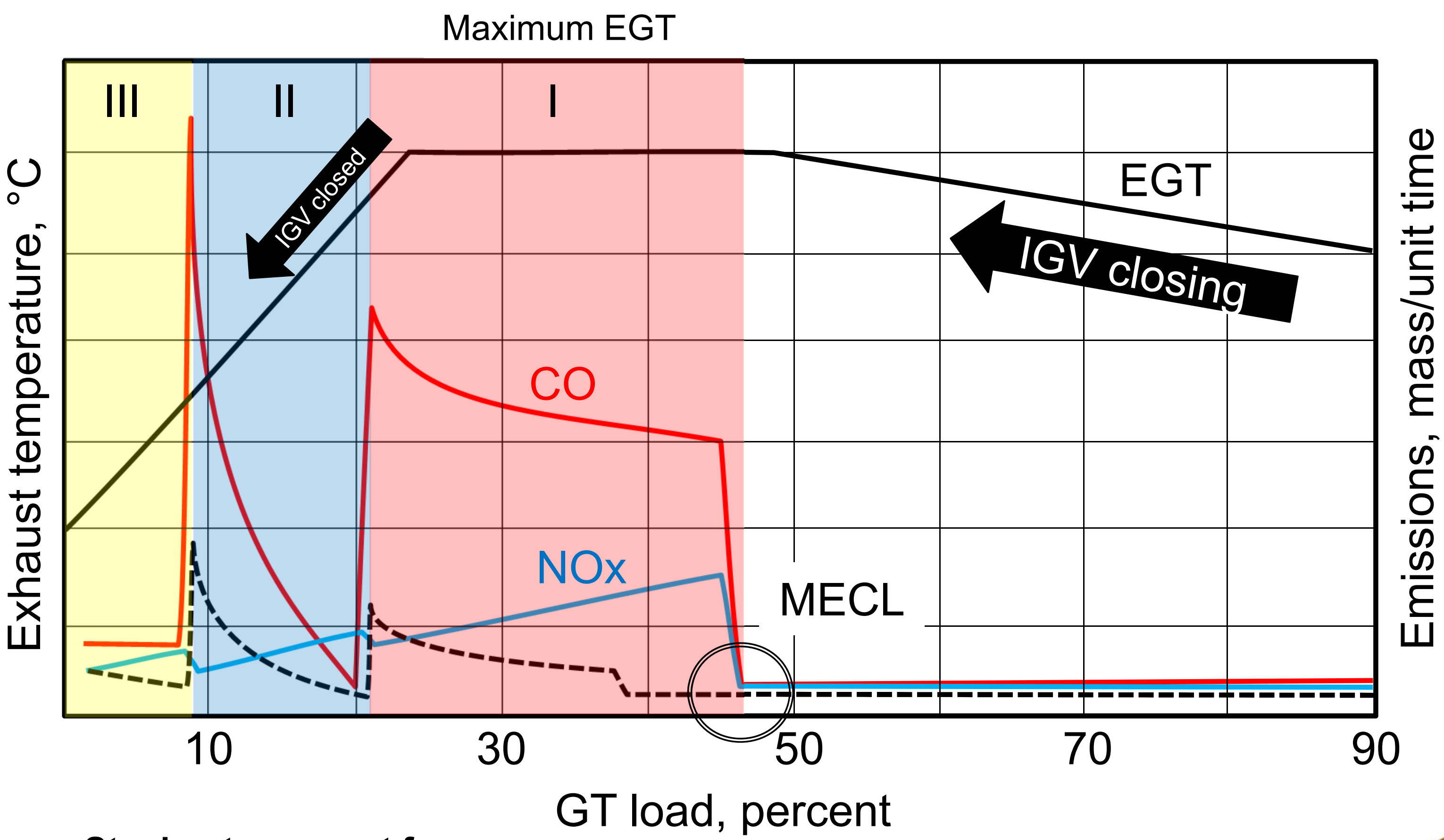
Typical gas turbine startup diagram (conventional and fast versions). Conventional start with GT hold can take up to 50 minutes to reach MECL. Purge credit shaves off 12 minutes of that time. Eliminating GT hold saves another 15+ minutes. With fast start feature MECL point is passed in less than 10 minutes.

Emissions vs. firing level



Typical optimum for design at AFR ≈ 30 (i.e. $\lambda \approx 2$)

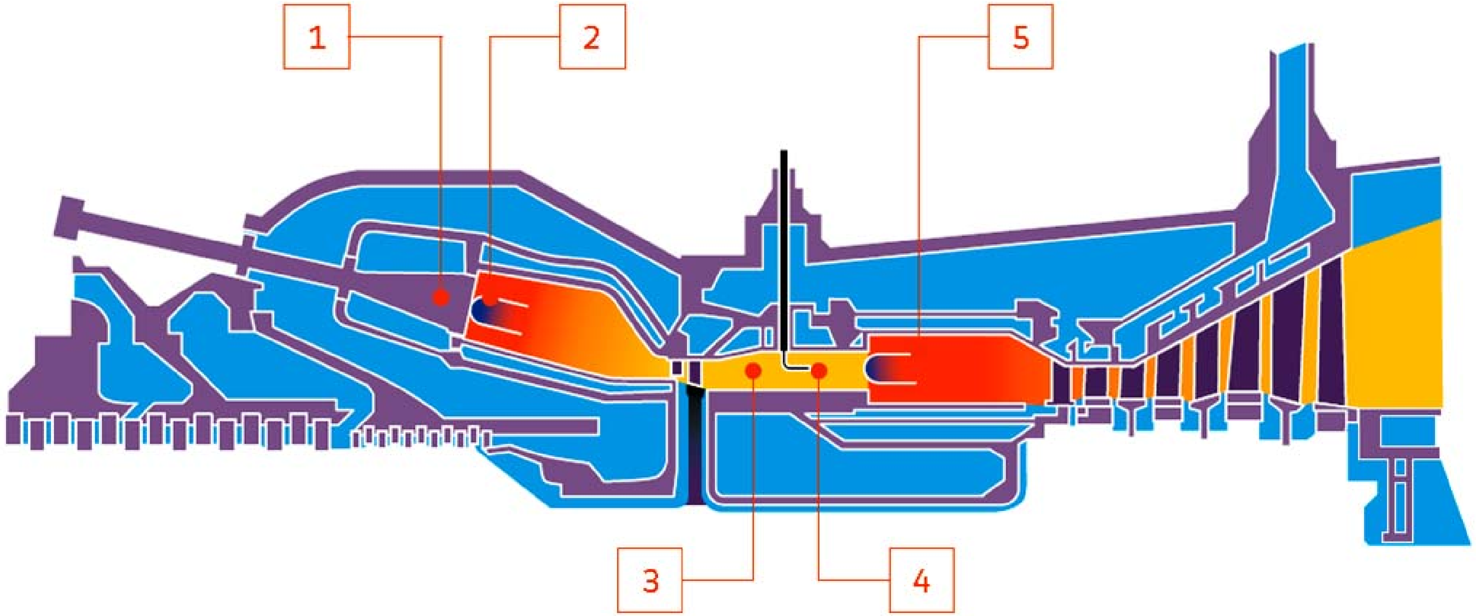
Min Emission Compliance Load – MECL



Staging to prevent from:

- Lean blow out (LBO)
- Combustion dynamics

Ansaldo sequential (SEV)



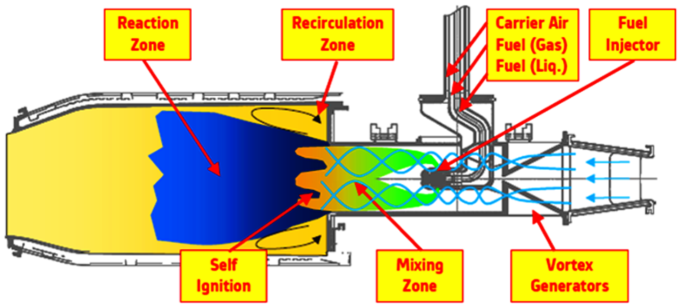
[1] COMPRESSED AIR
is fed into the EV burner, creating a homogeneous, lean fuel/air mixture. The vortex flow, induced by the shape of the burner, breaks down at the EV burner exit into the combustion zone, forming a central recirculation zone.

[2] THE MIXTURE
ignites to form a single, low-temperature flame ring. The inner recirculation zone stabilises the flame in the free space within the combustion zone, avoiding contact with the burner wall.

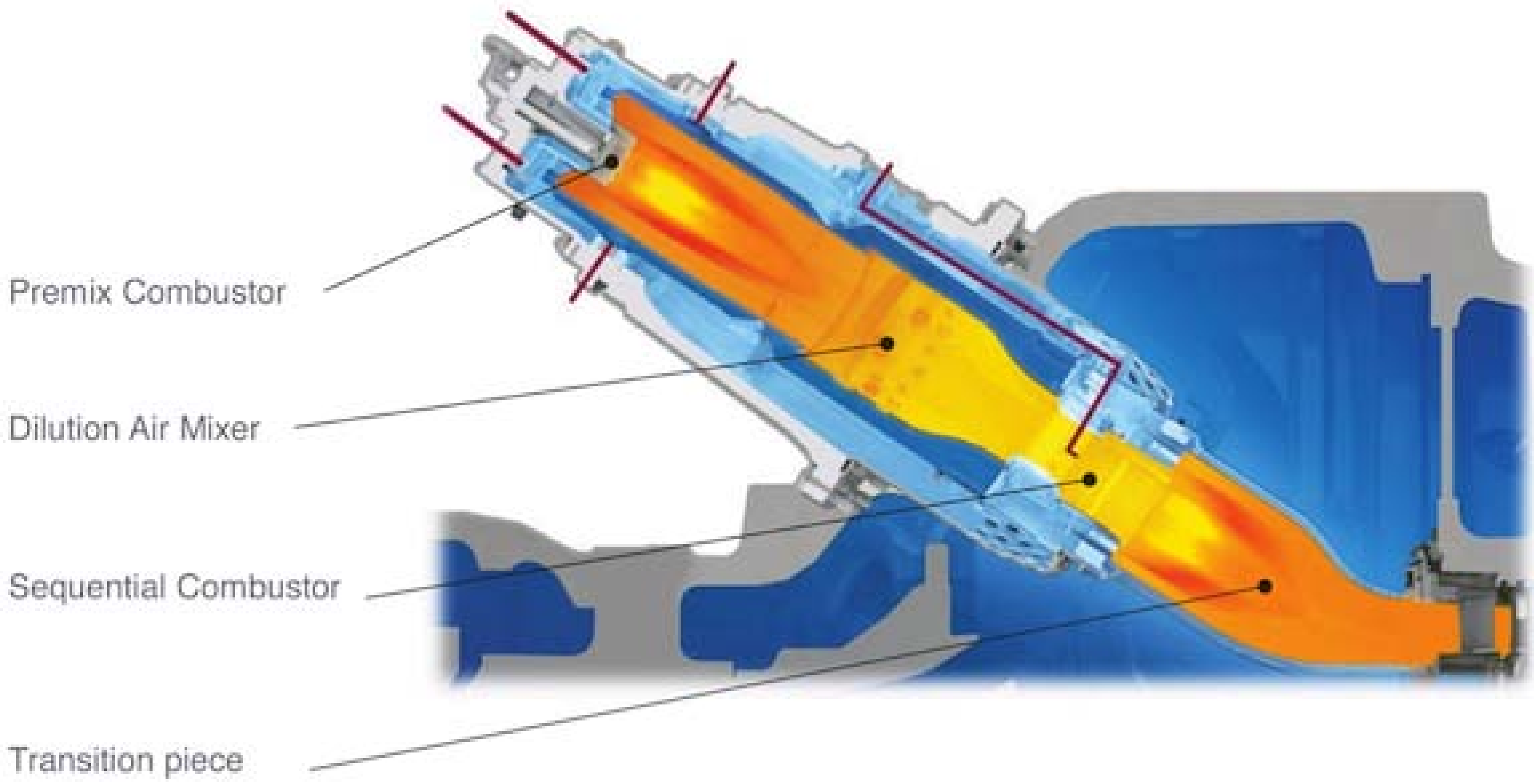
[3] THE HOT EXHAUST GAS,
low in oxygen content, exits the first combustor and moves through the high-pressure turbine stage before entering the SEV burner.

[4] VORTEX GENERATORS
in the SEV burner enhance the mixing process, while carrier air, injected with the fuel at the SEV fuel lance, delays spontaneous ignition until the mixture enters the annular SEV combustion chamber.

[5] IGNITION OCCURS
when the fuel reaches self-ignition temperature in the free space of the SEV combustor. The hot gas then continues its path into the low-pressure turbine.



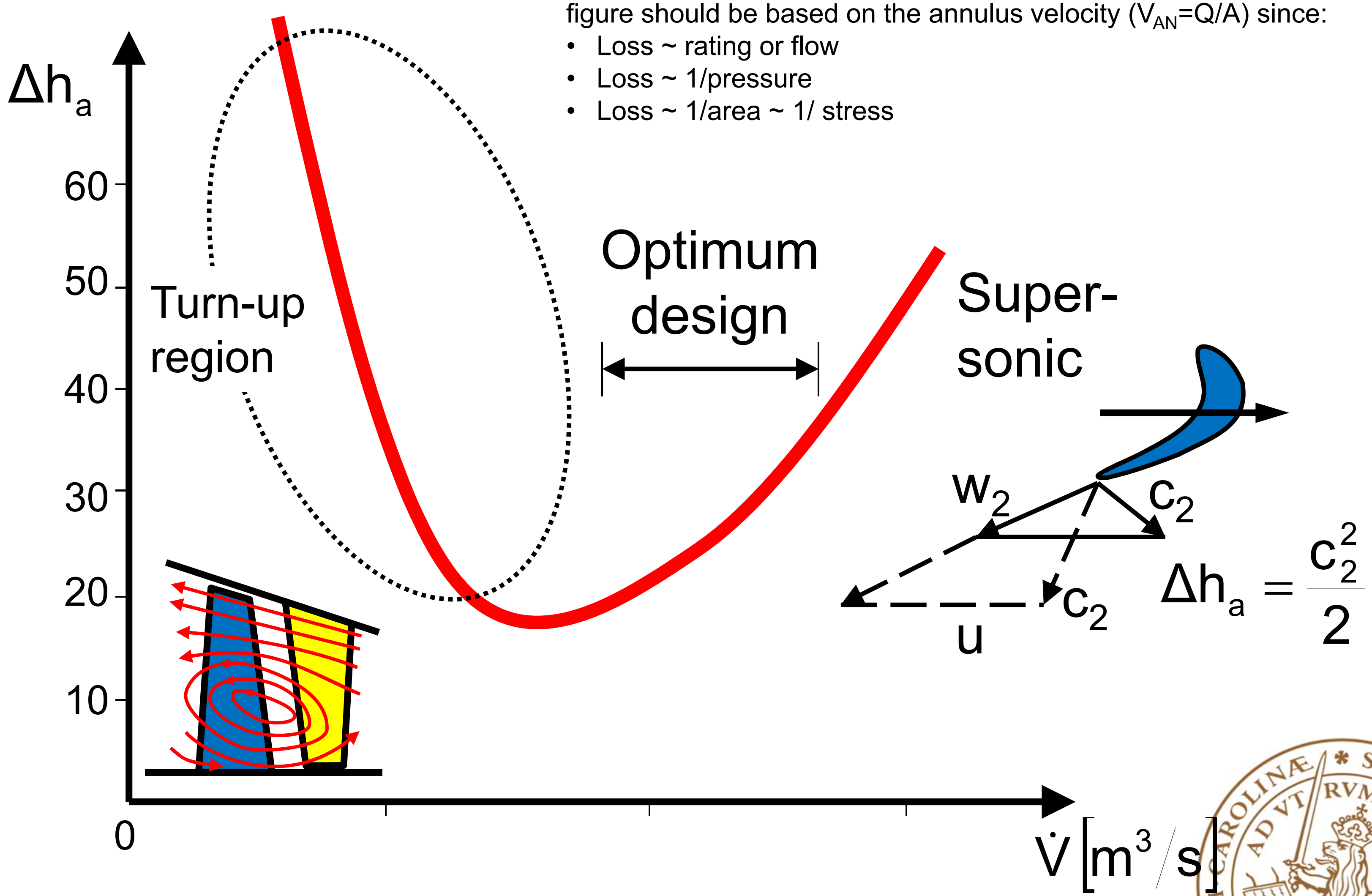
Ansaldo (Alstom) GT36



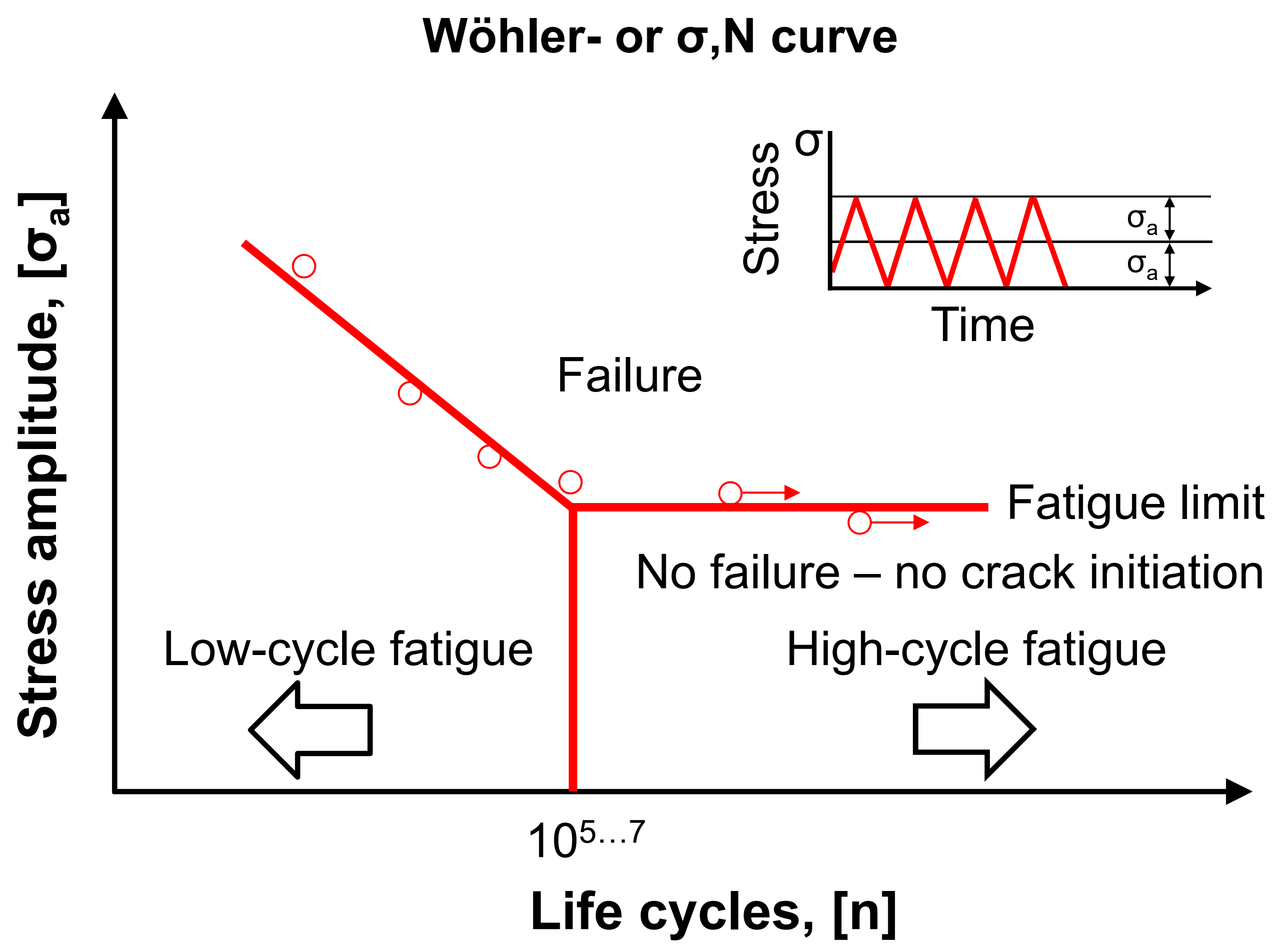
Exhaust loss

N.B. The figure is based on a certain exhaust size – a general figure should be based on the annulus velocity (V_{AN}=Q/A) since:

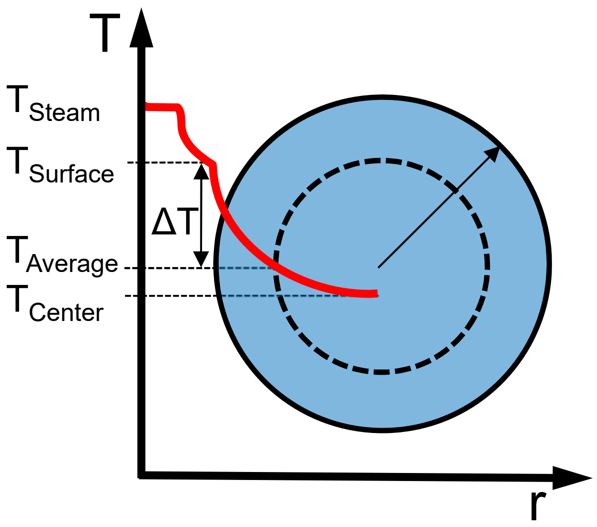
- Loss ~ rating or flow
- Loss ~ 1/pressure
- Loss ~ 1/area ~ 1/ stress



Fatigue – low or high?



Rotor stress – temperature gradients



Temperature induced stresses (radial and hoop):

$$\sigma_r(r) = \frac{\alpha E}{(1-\mu) r^2} \left\{ \frac{r^2 - r_i^2}{r_y^2 - r_i^2} \int_{r_i}^{r_y} T\, r\, dr - \int_{r_i}^{r} T\, r\, dr \right\}$$

$$\sigma_\theta(r) = \frac{\alpha E}{(1-\mu) r^2} \left\{ \frac{r^2 + r_i^2}{r_y^2 - r_i^2} \int_{r_i}^{r_y} T\, r\, dr + \int_{r_i}^{r} T\, r\, dr - T r^2 \right\}$$

Simplified equations for a case **without** a bore:

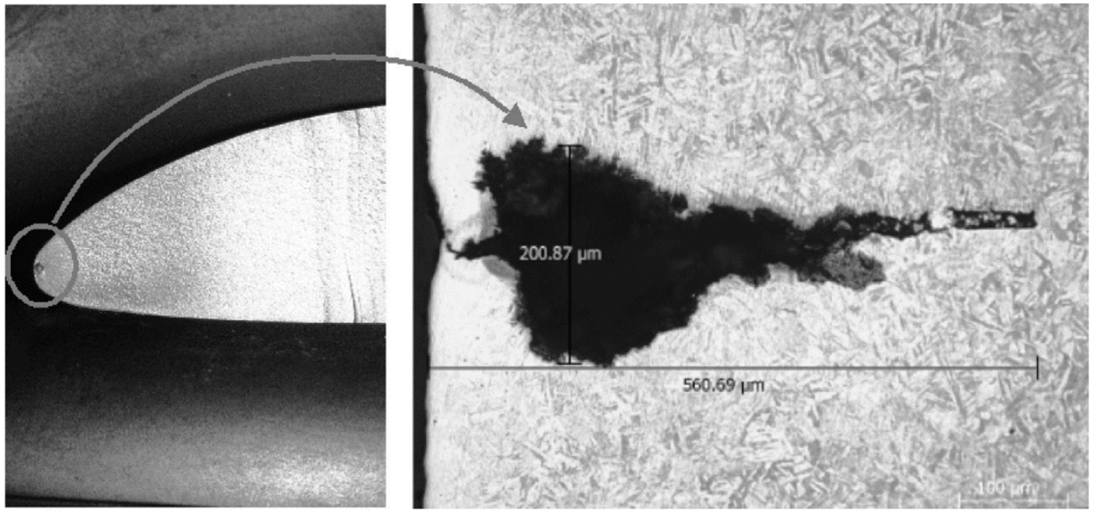
$$\sigma_r(r) = \alpha E \left\{ \frac{1}{r_{rim}^2} \int_0^{r_{rim}} T(r) dr - \frac{1}{r^2} \int_0^{r} T(r) dr \right\} \approx \frac{\alpha E \Delta T}{3} \left(1 - \frac{r}{r_{rim}} \right)$$

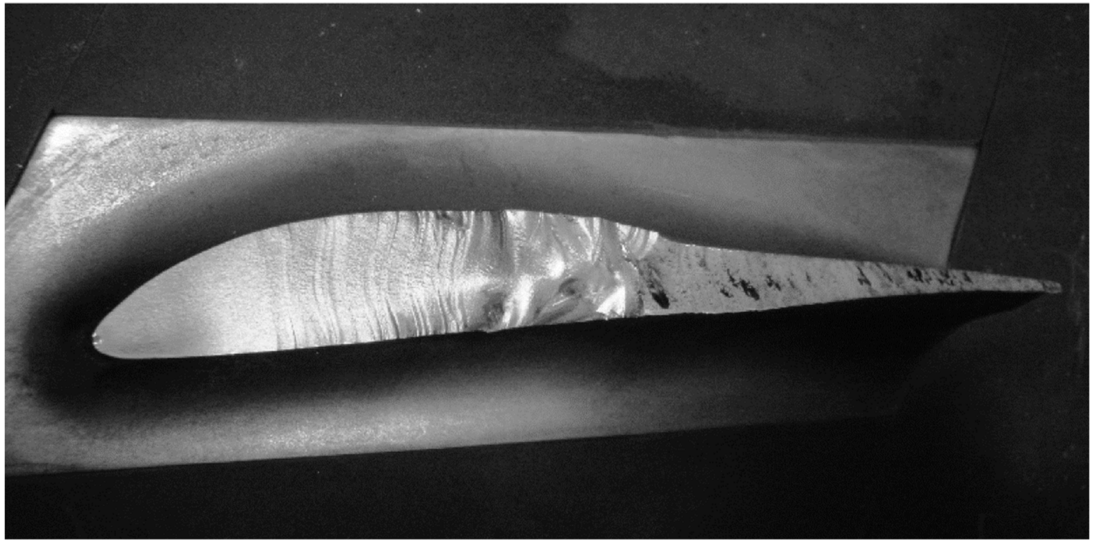
$$\sigma_\theta(r) = \alpha E \left\{ \frac{1}{r_{rim}^2} \int_0^{r_{rim}} T(r) dr + \frac{1}{r^2} \int_0^{r} T(r) dr - T \right\} \approx \frac{\alpha E \Delta T}{3} \left(1 - 2 \frac{r}{r_{rim}} \right)$$

Example

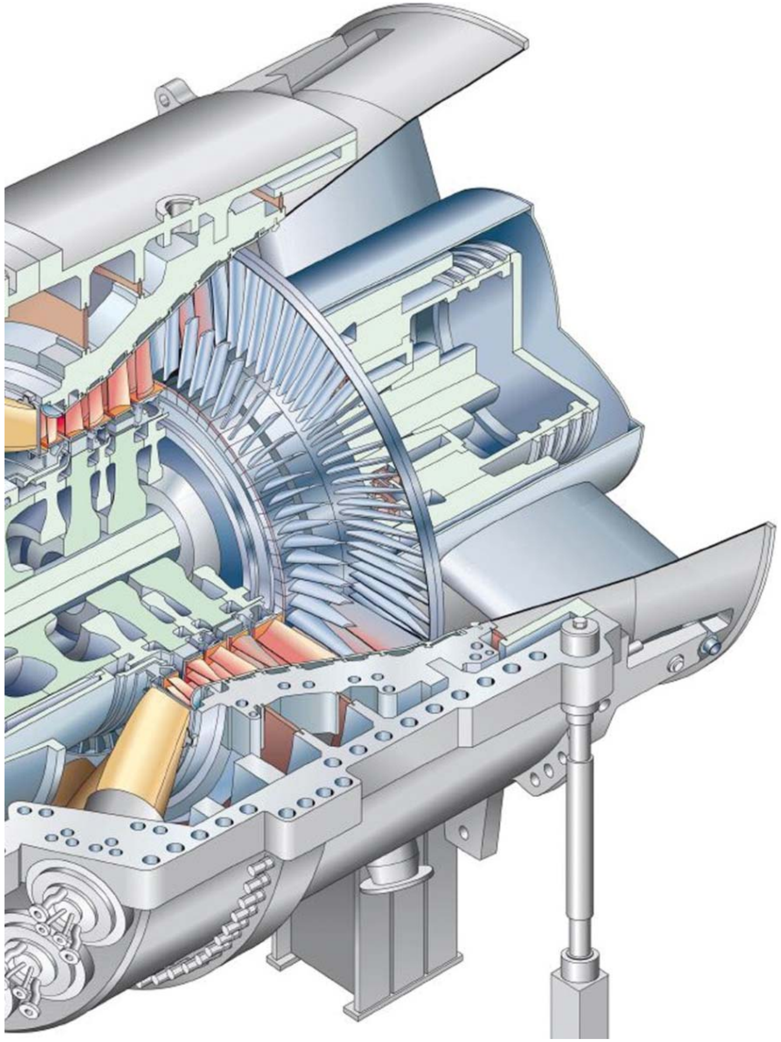
$\alpha = 1.8 \cdot 10^{5}$ °C^{-1}
$E = 6.9 \cdot 10^{4}$ MPa
$\Delta T = 55$ °C
$\sigma_{@r=0}$ = 46 MPa

Compressor blade failure

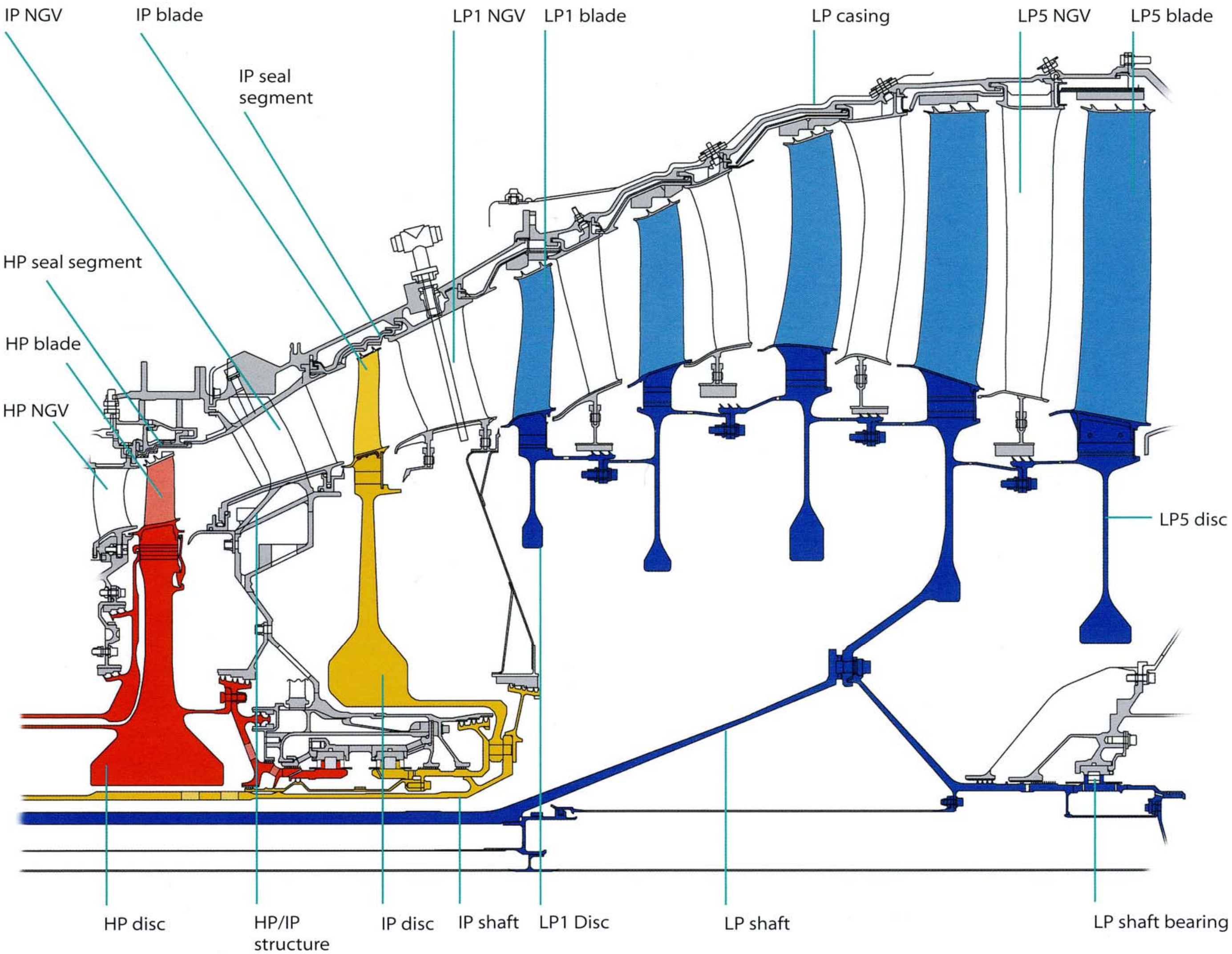


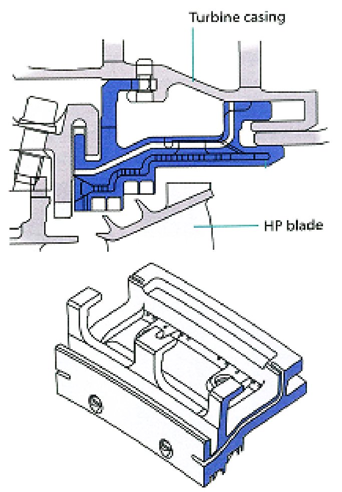


Siemens SGT5-8000H



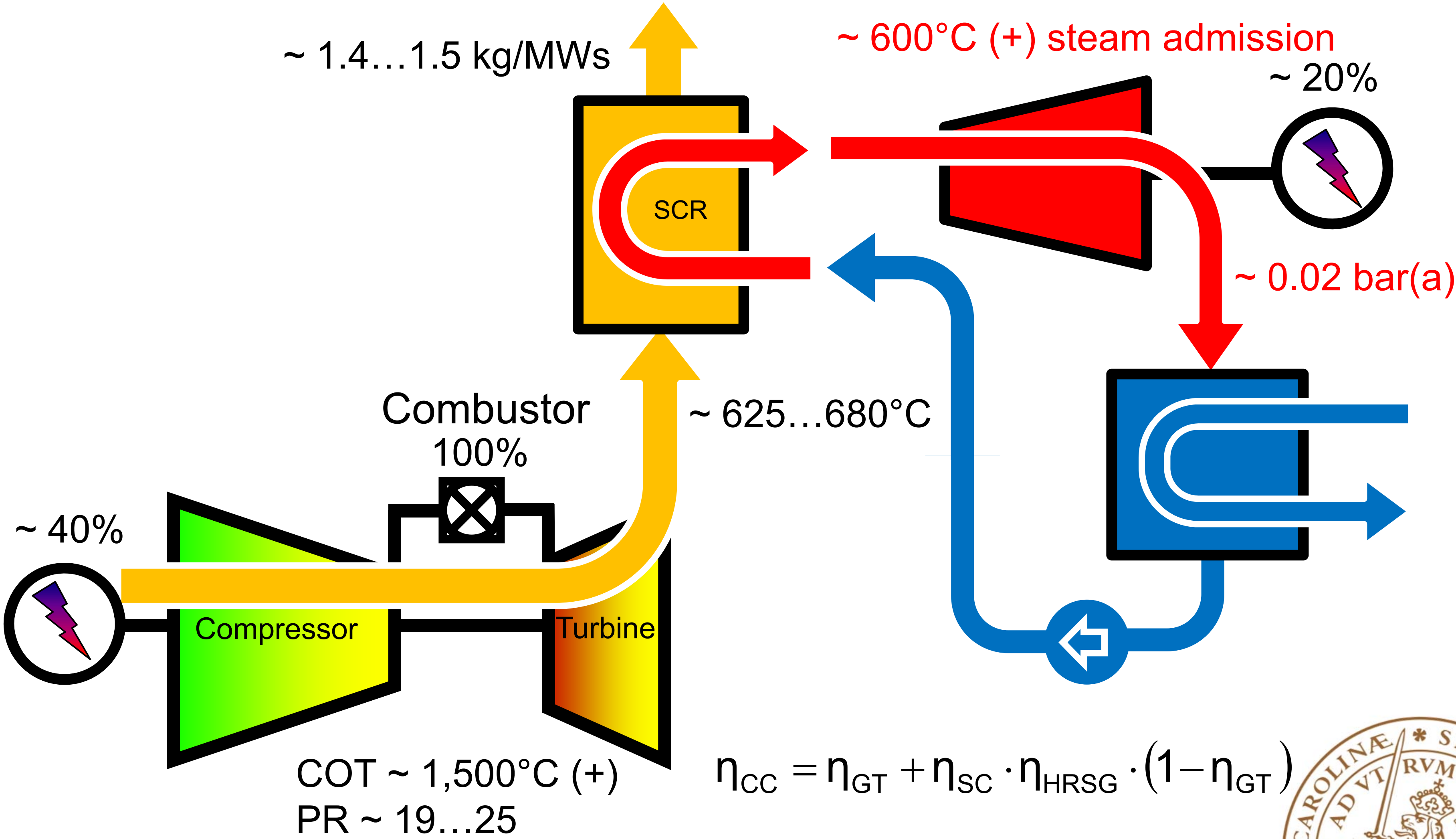
Turbine flow path – typical 3-spool aero





Rolls-Royce: The Jet Engine

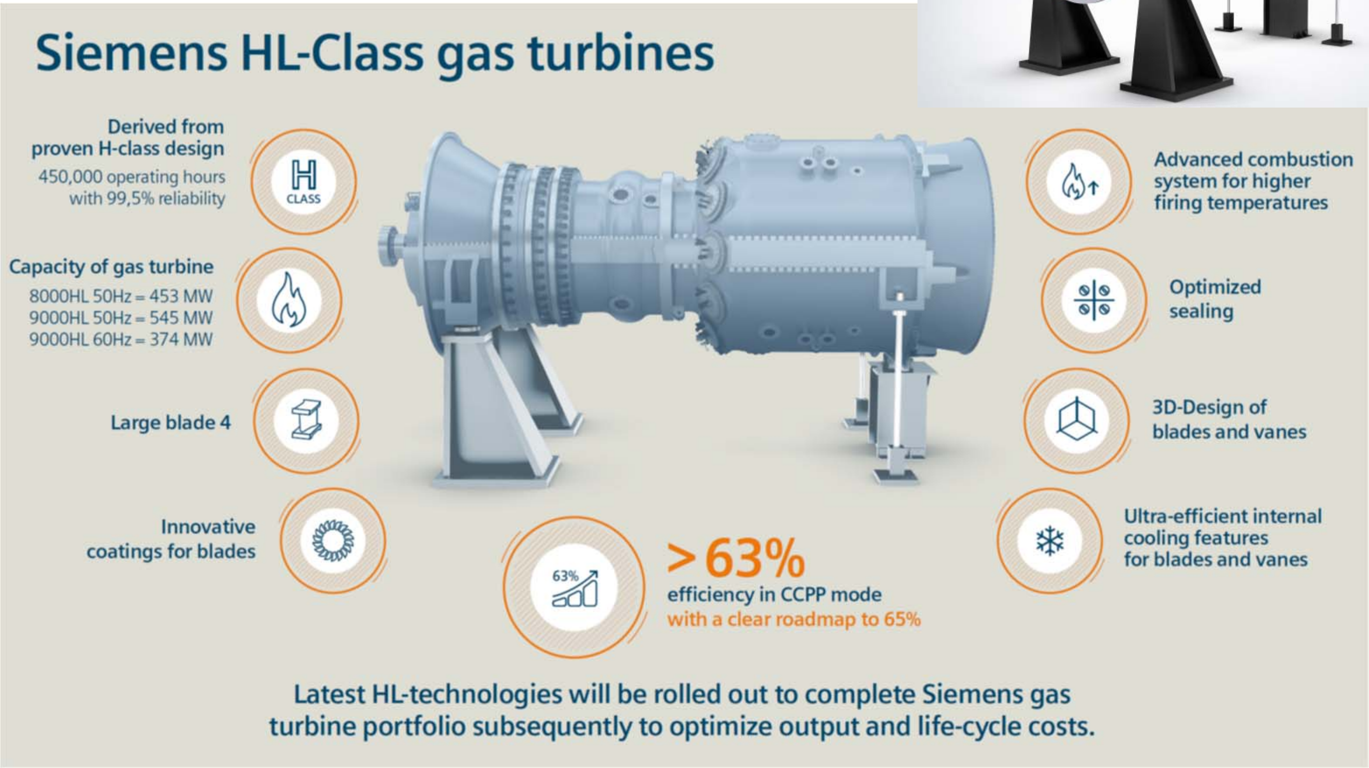
State-of-the-art combined cycle – GTCC



$$\eta_{CC} = \eta_{GT} + \eta_{SC} \cdot \eta_{HRSG} \cdot (1 - \eta_{GT})$$

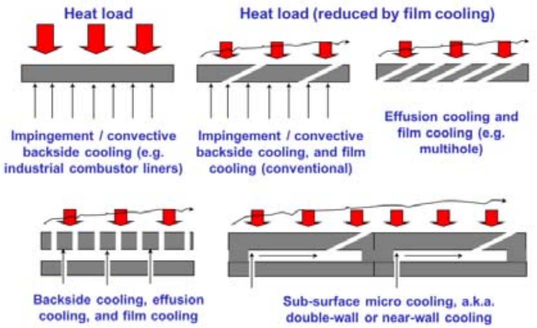
Siemens HL-class

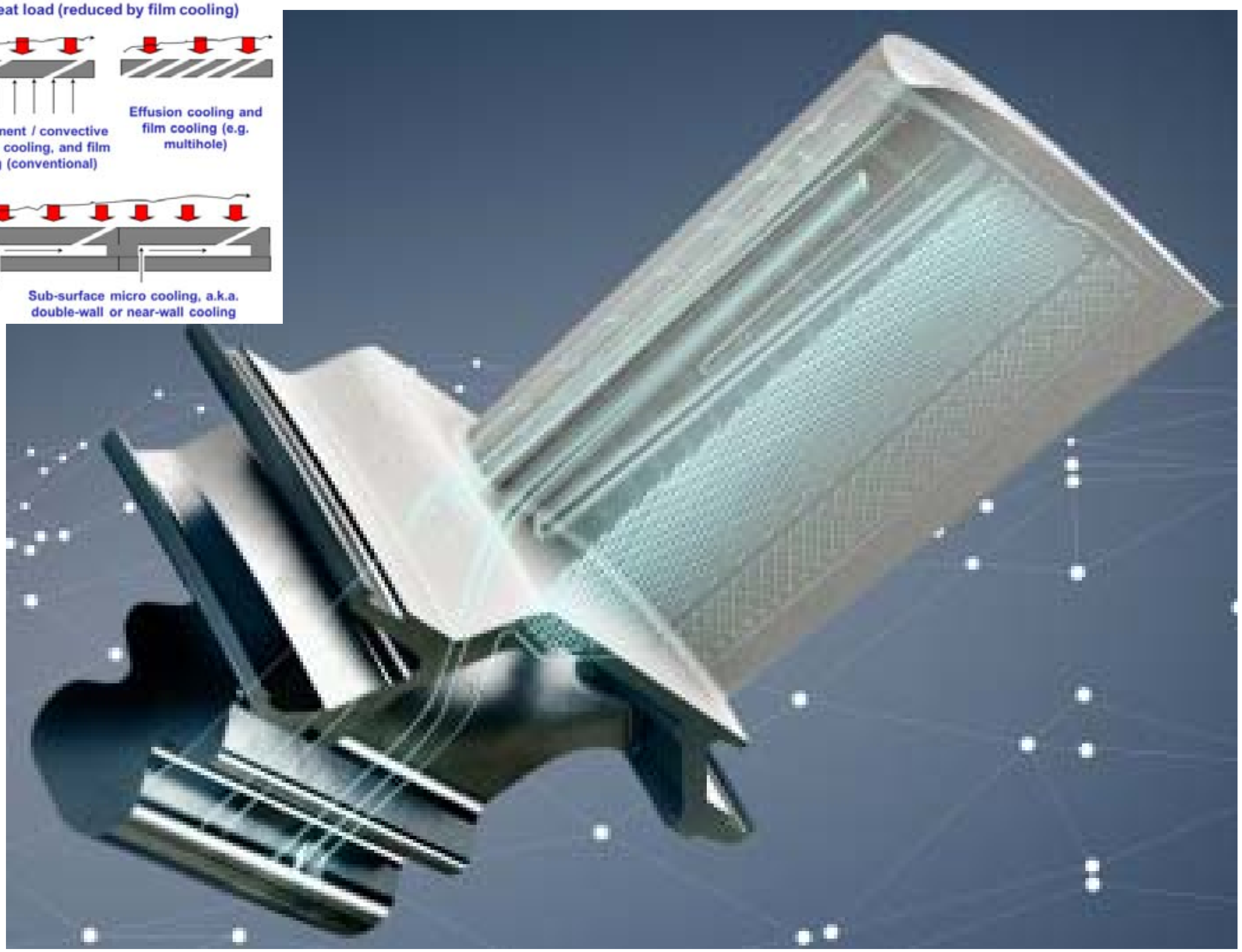
- 42% efficiency
- 85 MW/min
- 1000 kg/s
- 680 °C EGT



Courtesy of Siemens

Siemens HL-class rotor #1

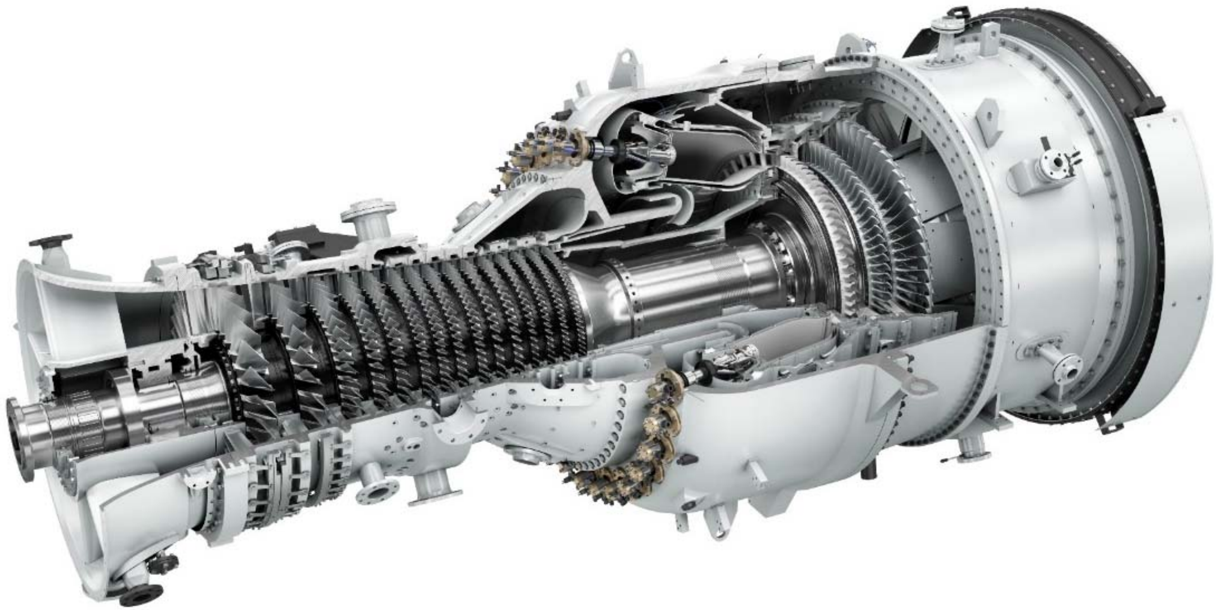




$$Nu = \frac{\mathit{Convective\ heat\ transfer}}{\mathit{Conductive\ heat\ transfer}} = \frac{hL}{k} = f(Re, Pr, \ldots) \qquad \because h \sim \left.\frac{1}{L}\right|_{Nu}$$

Courtesy of Siemens

Siemens SGT-800



GE LM9000

Simple Cycle CC & CHP Mechanical Drive

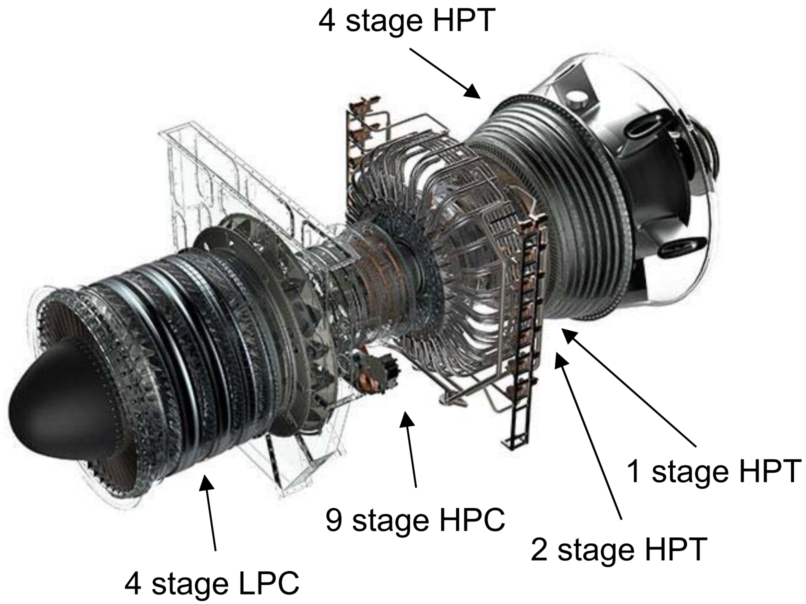
- Free power turbine (2400…3780 rpm)

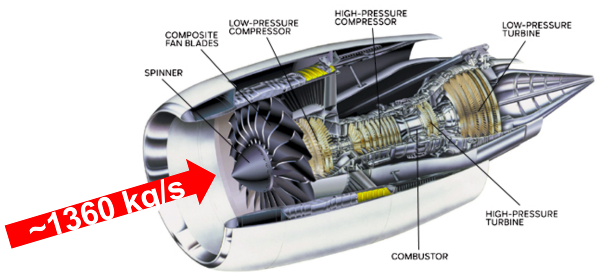
ISO Performance Maintenance Emissions

- **65 MW** power output
- **43%** simple-cycle efficiency
- 99% availability
- >80% cogeneration efficiency
- 33:1 pressure ratio
- 12,000 hours: inspections
- 36,000 hours: hot section replacement
- 72,000 hours: overhaul
- Package design allows engine swap in 24 hours
- 15 ppm DLE NOx & 25 ppm CO
- DLE 1.5 dual fuel (natural gas and liquid fuel)

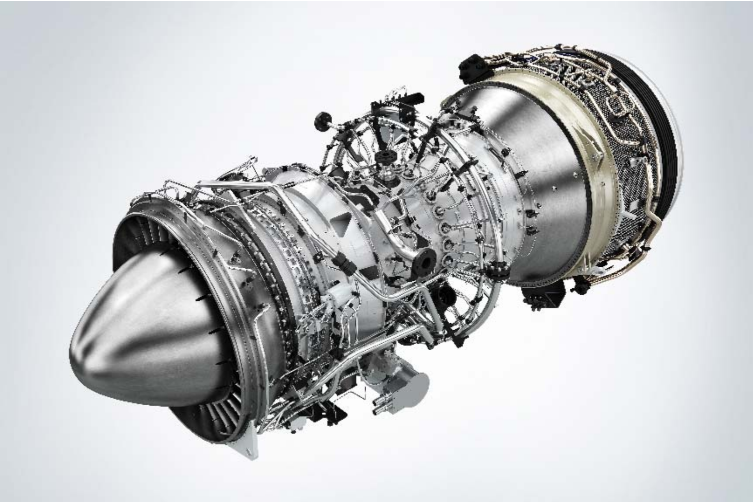
Fuel flex

- 30…54 MWl gas

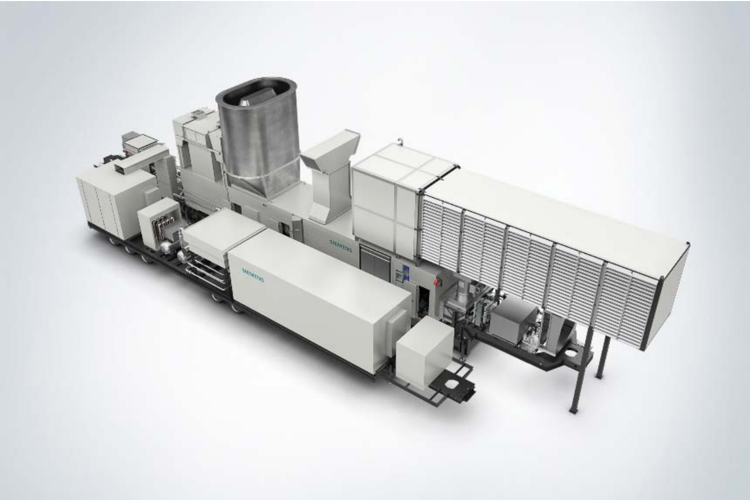




SGT-A45 TR



Specification	50 Hz		60 Hz	
	15° C	30° C	15° C	30° C
Electrical power (ISO, dry)	41.0 MW(e)	39.3 MW(e)	44.0 MW(e)	39.6 MW(e)
Electrical efficiency (ISO, dry)	39.0%	38.4%	40.4%	39.5%
Fuel type	Dual (gas & liquid)			
Low emissions option	Water injection			
Low emissions – gas fuel	25 vppm NO_x			
Low emissions – liquid fuel	42 vppm NO_x			
Turbine speed	3,000 rpm		3,600 rpm	
Pressure ratio	27.7 : 1	26.7 : 1	27.9 : 1	25.8 : 1
Exhaust gas flow	127 kg/s	120 kg/s	126 kg/s	116 kg/s
Exhaust gas temperature	477° C	501° C	483° C	498° C



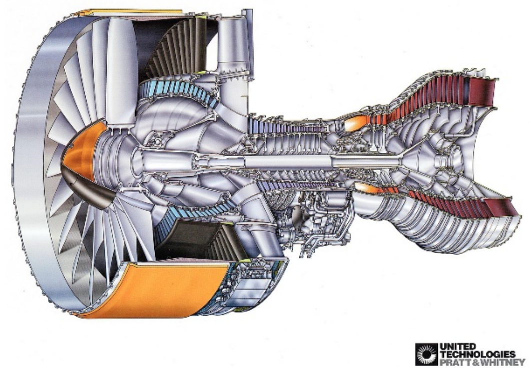
P&W FT4000

Performance
- 140 MW nominal output in twin-engine configuration
- Wet compression for improved performance above ISO conditions
- Single or dual engine operation (common alternator)
- 50 or 60 Hz performance with no penalty
- 41% (+) thermal efficiency without external cooling

Operational
- Less than 10 minutes start-up time
- 30 MW/min ramp rate
- Synchronous condensation with spinning PT, a FT has a windage loss of 500…1,000 kW
- NO maintenance penalty for start/stop!
- Fleet has 17,500 OH's and 1400 cycles

P&W has substantial experience in synchronous condensation without SSS-clutch!

PW4000 112-INCH FAN ENGINE



>900 engines
>20 years
>40 MOH

Ventilation work – spinning PT

- The spinning power turbine will feed work into the ”entrapped” air by increasing the angular momentum
- It is “standard” to assess the work with the equation from the book by Traupel:

$$P_V = \pi \cdot C \cdot (1-\varepsilon) \cdot \rho \cdot D_2 \cdot l_2 \cdot u_2^3$$

$$\because \frac{P_{V@500}}{P_{V@250}} \sim 2^3 = 8\,!!!$$

- The preceding equation shows why only non-geared PTs can be operated at nominal speed in ventilation

Firing level

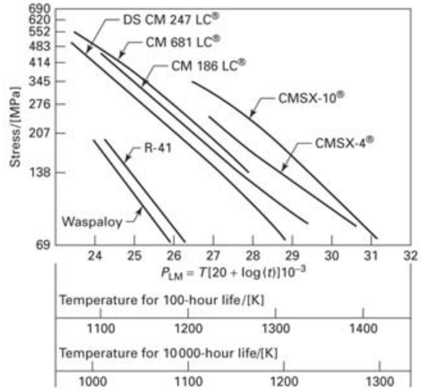
Firing temperature – the misery factor…

- Creep follows an Arrhenius type of expression…
  - The Larson-Miller parameter:

$$P_{L-M} = T_M\left[20 + \log(t)\right]10^{-3}$$

$$P_{L-M} = K_1 + K_2(\ln\sigma_c) + K_3(\ln\sigma_c)^2$$

$$\sigma_c = \rho K_{Taper}\left(AN^2/10^{10}\right)^{1.08} \sim AN^2$$

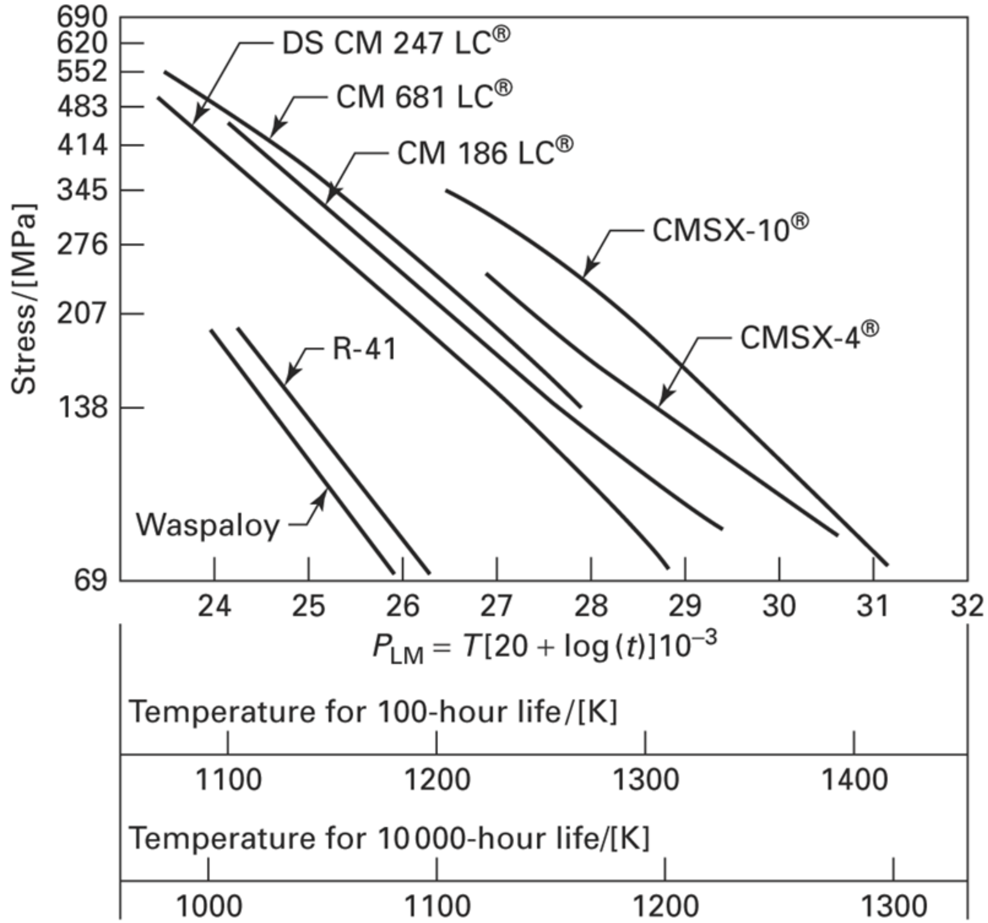


  - A more convenient and practical approach is to introduce a maintenance factor – MF (consumed life per hour of operation)

Firing	Lifing	MF
850	40000	1
860	20000	2
870	10000	4
880	5000	8

$$MF = e^{0.0693 \cdot \Delta COT}$$

Creep – Larson-Miller parameter



975 **1056** **1138** **1219** **@40000**

C.R.S

Lifing

- It may be argued that creep-induced damage will reduce the fatigue life of a metal, and that fatigue-induced damage will reduce the metals creep life…

- One approach is to use the linear damage summation (DS) model (also called the linear life fraction, or linear cumulative damage) for assessing creep-fatigue-life: $D_{fatigue} + D_{creep} = D_{total}$

- By combining the *Robinson* Rule (1952) for creep and *Miner* for fatigue, one gets the cumulative damage index (failure at unity):

$$\sum \frac{N}{N_f} + \sum \frac{t}{t_r} = D$$

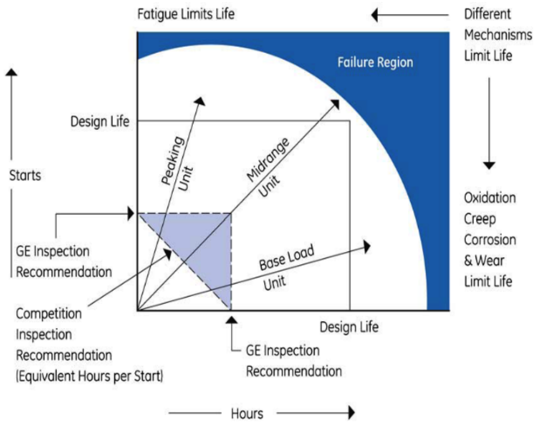
This is the rationale behind the concept of ”equivalent operating hours”

The expensive way – equivalent hours…

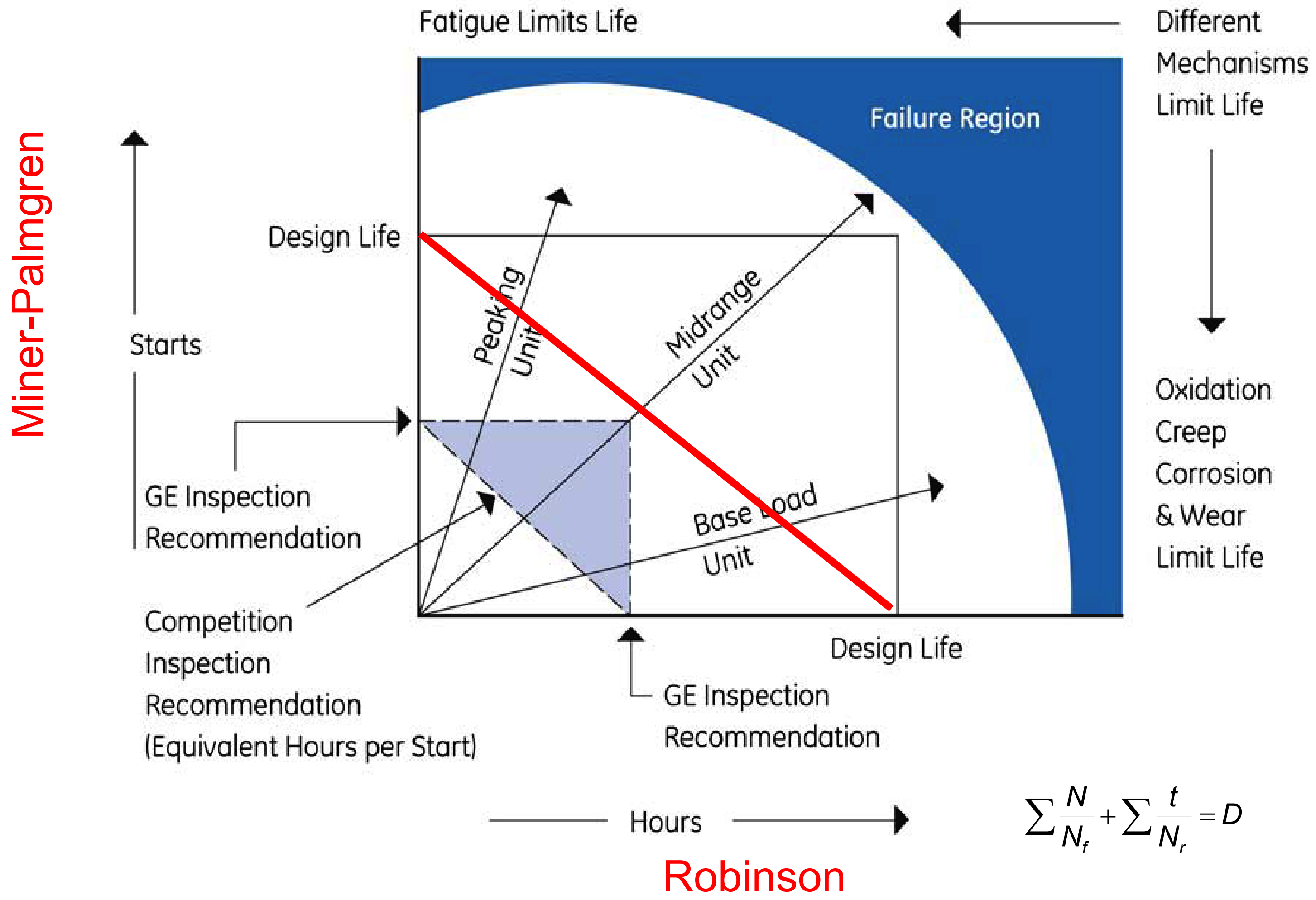
$$EOH = \underbrace{\sum_{1}^{OH} 1 \times F_{fuel} \times F_{firing}}_{creep\ and\ oxidation} + \underbrace{\sum_{1}^{n_{starts}} 1 \times F_{starts} \times F_{load\ rate} + \sum_{1}^{n_{trips}} 1 \times F_{Trips}}_{LCF}$$

Where:

EOH	equivalent operating hours
OH	actual operating hours
F_{fuel}	factor depending on fuel
F_{fuel}	factor depending on firing level
n_{starts}	number of “fired” starts
F_{starts}	number of hours per start
$F_{load\ rate}$	load rate factor



Lifing



$$\sum \frac{N}{N_f} + \sum \frac{t}{N_r} = D$$

Operational hours

$$\text{Maintenance interval} = \frac{24000}{\text{Factored Hours}/\text{Actual Hours}}\,[\text{hours}]$$

$$\text{Factored Hours} = (K + M \cdot I) \cdot (G + 1.5 \cdot D + A_f \cdot H + 10 \cdot P)$$

$$\text{Actual Hours} = (G + D + H + P)$$

G = Annual Base Load Operating hours on Gas Fuel

D = Annual Base Load Operating hours on Distillate Fuel

H = Annual Operating Hours on Heavy Fuel

A_f = Heavy Fuel Severity Factor (Residual = 3 to 4, Crude = 2 to 3)

P = Annual Peak Load Operating Hours

I = Percent Water/Steam Injection Referenced to Inlet Air Flow

M&K = Water/Steam Injection Constants (see GE documentation)

Noff cycles

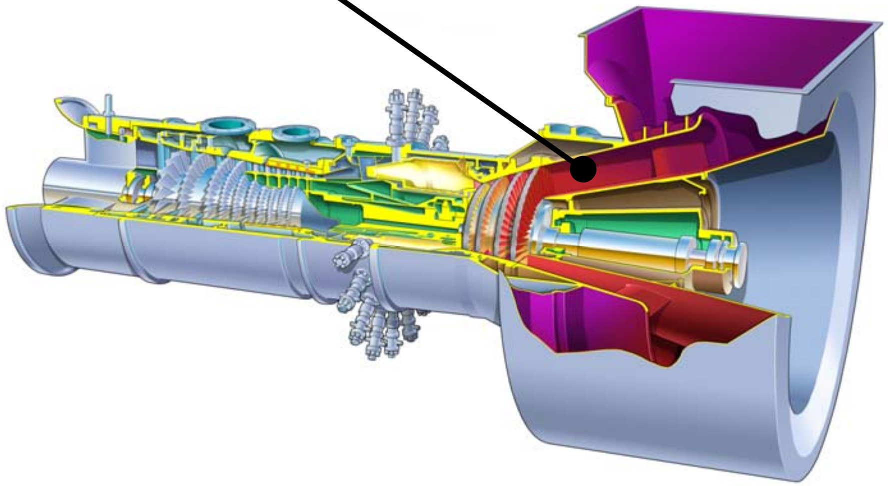
$$\text{Maintenance interval} = \frac{900}{\text{Factored Starts}/\text{Actual Starts}} [\text{Starts}]$$

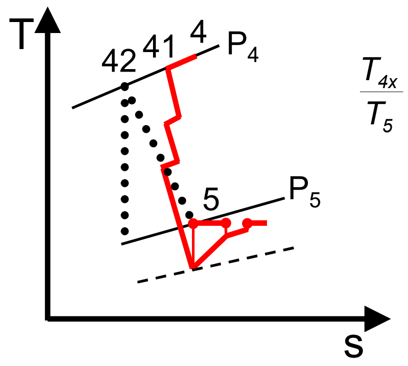
$$\text{Factored Starts} = 0.5 \cdot N_A + N_B + 1.6 \cdot N_P + 20 \cdot E + 2 \cdot F + \sum_{i=1}^{\eta} (a_{Ti} - 1) T_i$$

- Actual Starts = (N_A + N_B + N_P)
- S = Maximum Starts-Based Maintenance Interval (Model Size Dependent)
- N_A = Annual Number of Part Load Start/Stop Cycles (<60% Load)
- N_B = Annual Number of Base Load Start/Stop Cycles
- N_P = Annual Number of Peak Load Start/Stop Cycles (>100% Load)
- E = Annual Number of Emergency Starts
- F = Annual Number of Fast Load Starts
- T = Annual Number of Trips
- a_{Ti} = Trip Severity Factor = fcn(Load, Trip during accel. = 2, Peak = 10)
- η = Number of Trip Categories (i.e. Full Load, Part Load, etc.)

Turbine governor – twin-shaft

$$EGT_{control} = f\left(COT_{Nom}, PR, n, \ldots\right)$$

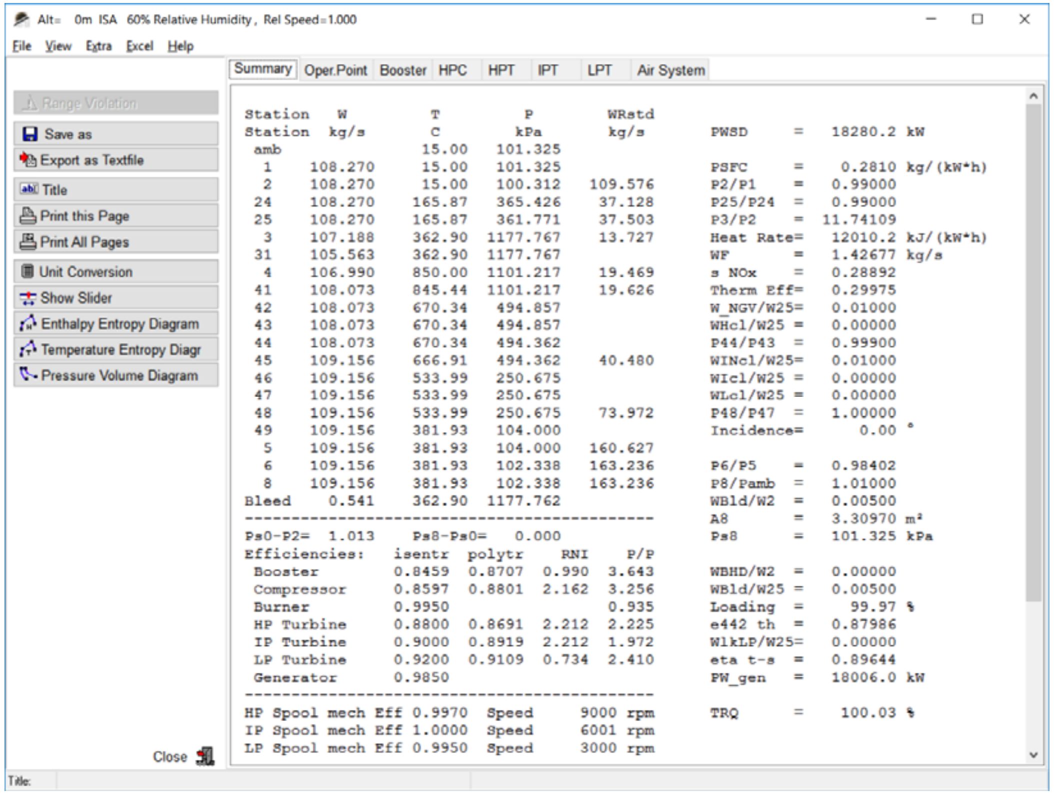


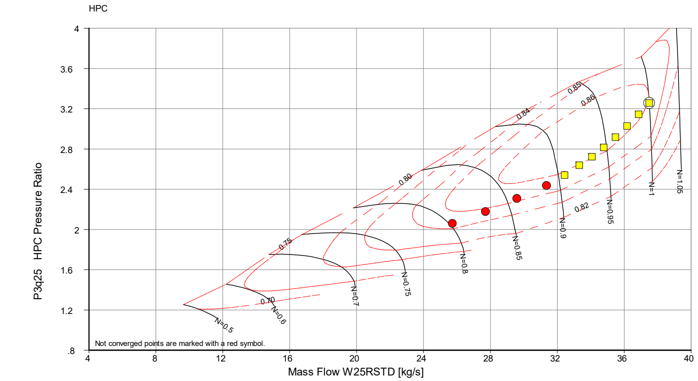


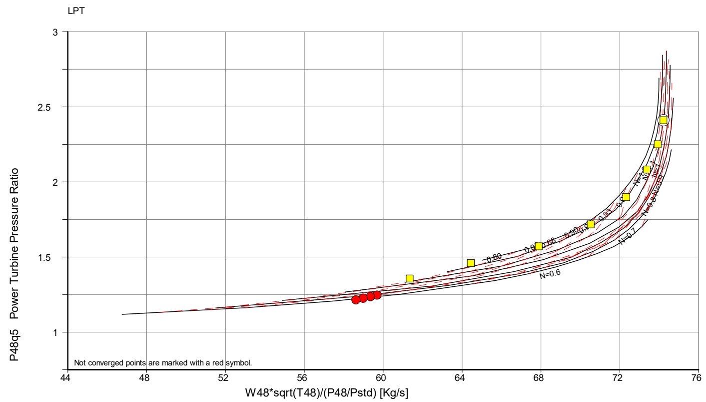
$$\frac{T_{4x}}{T_5} = \left(\frac{p_4}{p_5}\right)^{\frac{\eta_p(\gamma-1)}{\gamma}} = \left(\frac{p_4}{p_5}\right)^{\frac{n-1}{n}}$$

Courtesy of Siemens

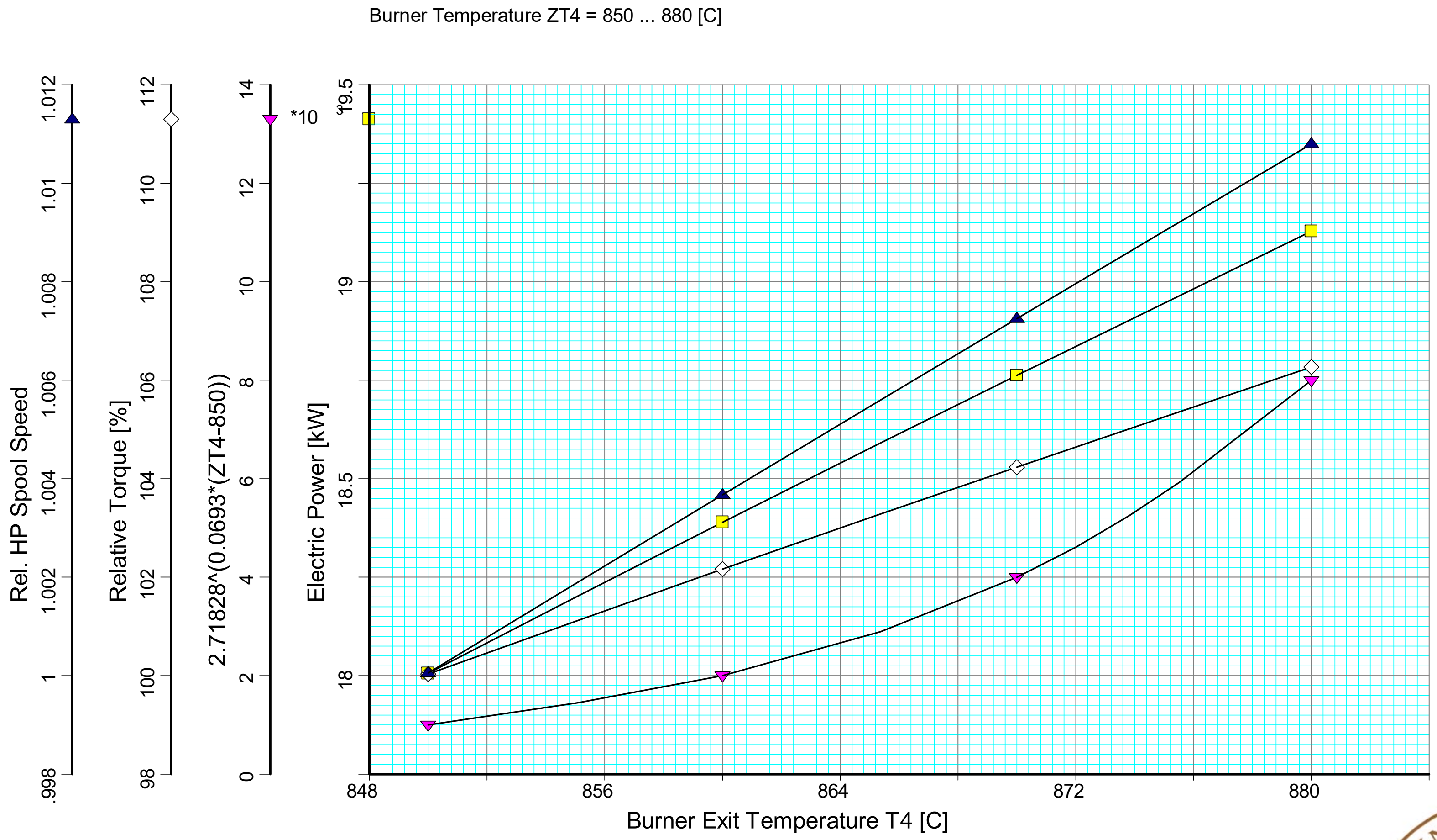
Performance modelling



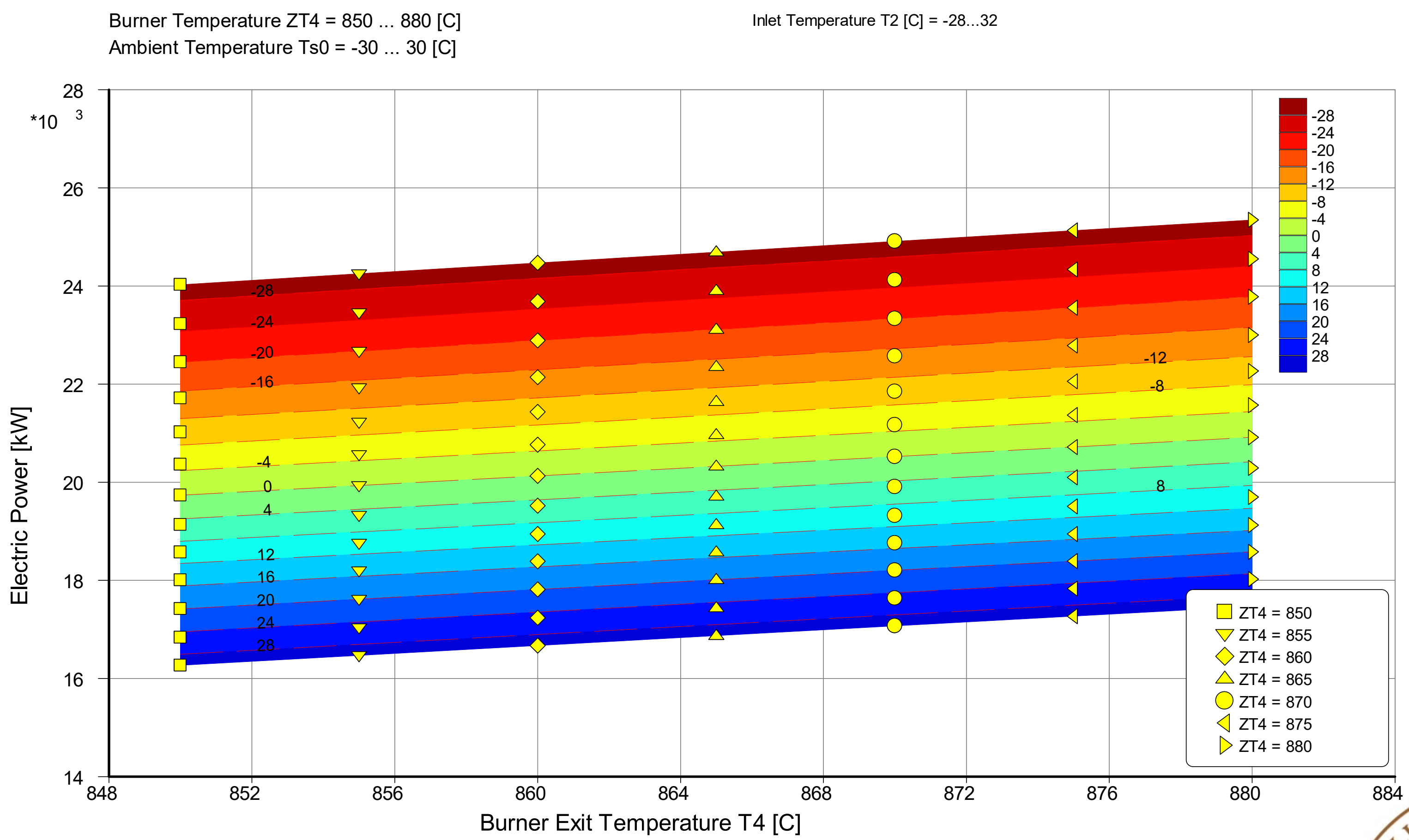




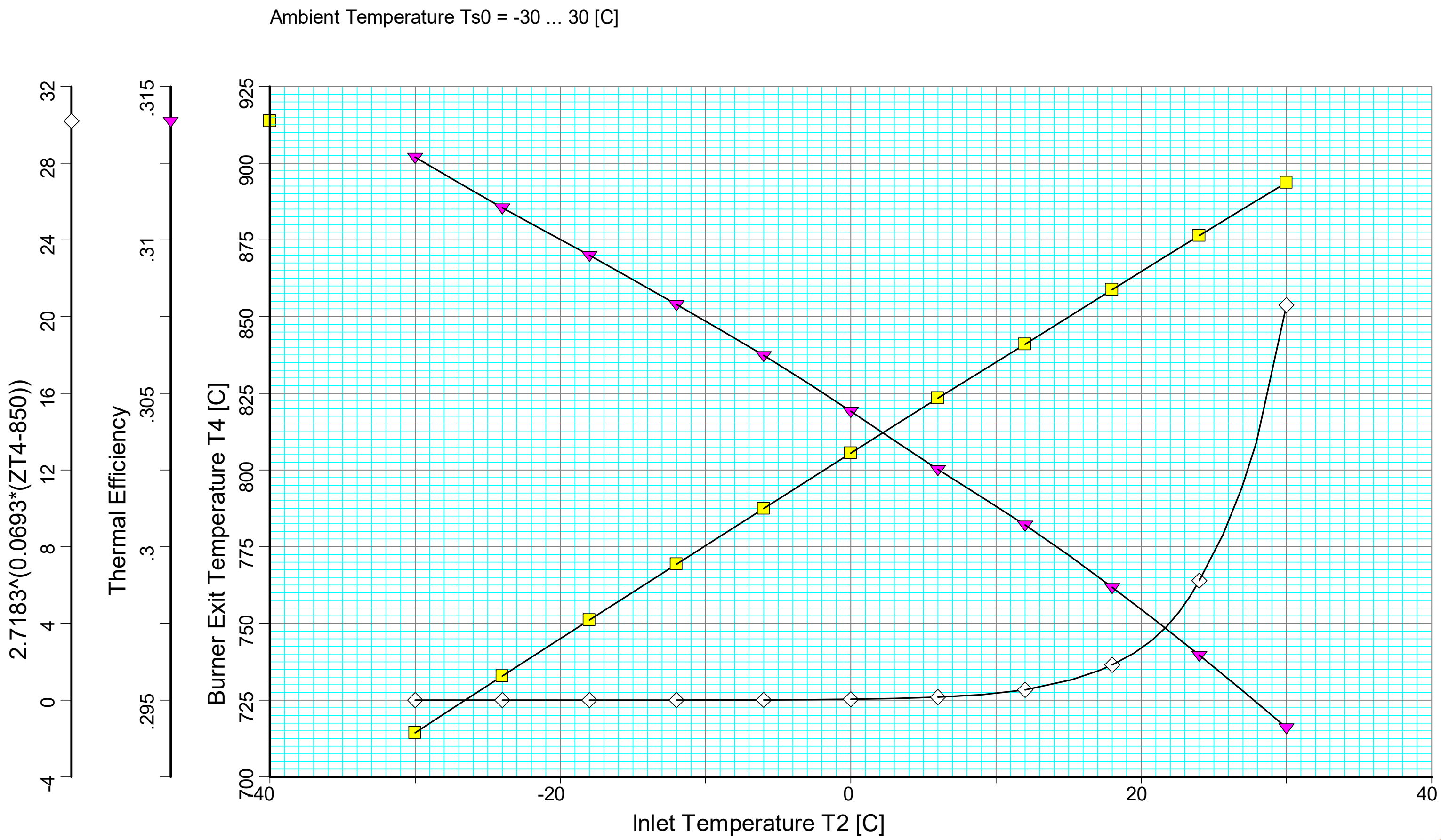
Some results…



Impact on output from firing and ambient



Flat rate @18 MW



Emulsionseldning