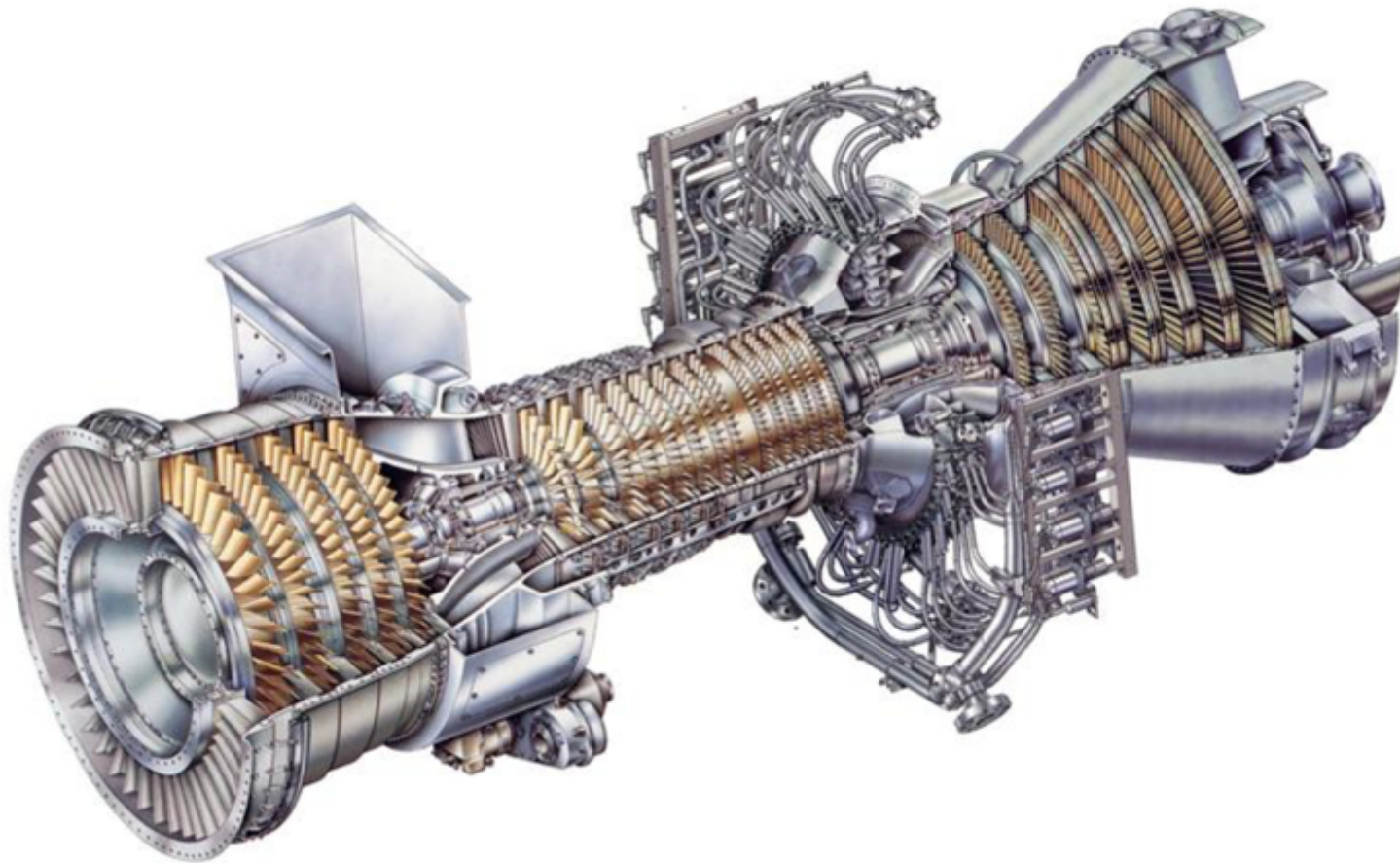


Thermodynamics of energy conversion

6) TURBINES



AE-3624 (3/98)

6. TURBINES

6.1. HISTORY OF TURBINES

6.2. NOZLE

6.2.1. VENTURI EFFECT

6.2.2. ADIABATIC EXPANSION

6.2.3. LAVAL EQUATION

6.2.4. PRESSURE AND VELOCITY IN LAVAL NOZLE

6.3. TURBINE TYPES

6.3.1. IMPULSE TURBINE

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6.3.3. EFFICIENCY REACTION TURBINE

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6.3.5. MODERN STEAM TURBINE

6.4. COAL FIRED POWER STATION

6.4.1. PHOTO OF COAL FIRED POWER STATION WITH COAL MINE

6.4.2. COAL FIRED POWER STATIONS IN 2020

6.4.3. EFFICIENCY COAL FIRED POWER STATION

6.5. COMBINED CYCLE POWER STATION (Natural Gas)

6.5.1. PRINCIPLE COMBINED CYCLE POWER STATION

6.5.2. COMBINED CYCLE POWER STATION PLANT

6.5.3. EFFICIENCY OF POWER STATION

6.5.4. EFFICIENCY OF ENGINES

6.5.5. COAL GASIFICATION

6.5.6. GAS TURBINE (Methane)

6.5.7. ECONOMICS OF ELECTRICITY GENERATION

6.6. JET ENGINE

6.6.1. JET ENGINE FILM

6.6.2. AIRPLANE JET ENGINE

6.6.3. TURBOPROP ENGINE

6.6.4. HIGH BYPASS JET ENGINE (TURBO FAN)

6.6.5. POWER AND FORCE

6.6.6. HIGH BYPASS JET ENGINE (TURBO FAN) FILM

6.6.7. p and T IN THE JET ENGINES

6.6.8. JET ENGINES TRUST & EFFICIENCY

6.6.9. JET ENGINE IDEAL EFFICIENCY

6.6.10. JET ENGINE PROPULSIVE EFFICIENCY

6.6.11. PROPULSION EFFICIENCY

6.6.12. JET ENGINE SPECIFICATIONS

6.6.13. BOEING 777 JET ENGINES

6.6.14. F/A-18 HORNET JET ENGINES

6.6.15. FIRST PROPULSION ENGINES

6.6.16. PULSE PROPULSION ENGINES

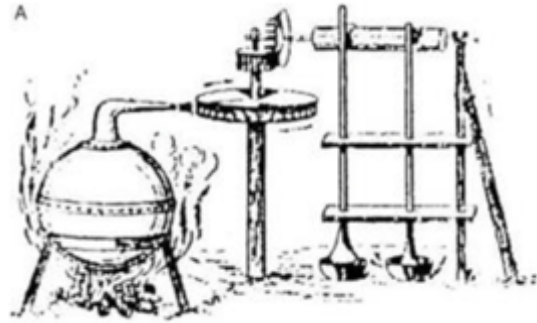
6.6.17. V1 ROCKET FILM

6. 1. HISTORY OF TURBINES

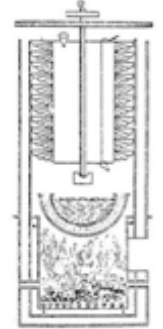


Aeolipile

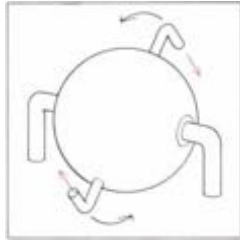
Hero of Alexandria
1st century CE



1629 in Italy



1784 James Watt patented
reaction and impulse turbines

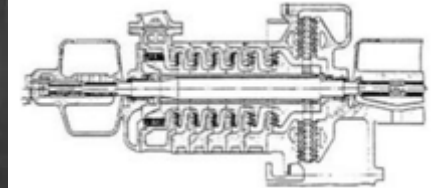


1837 William Avery (1793-1840)
USA



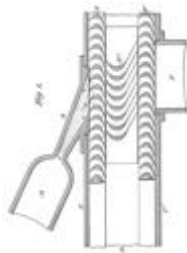
Laval Nozzle

1880s Carl G.P. de Laval
(1845 – 1913) of Sweden

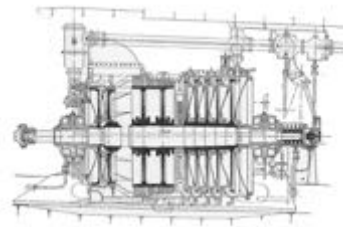


multi stage

1884 Sir Charles Algernon Parsons
(1854-1931), England

Laval nozzle &
multi stage

1890 Charles G. Curtis (1860 – 1953)
USA



1905 Allgemeine Elektrizitäts-Gesellschaft
AG (AEG) marine steam turbine, Germany



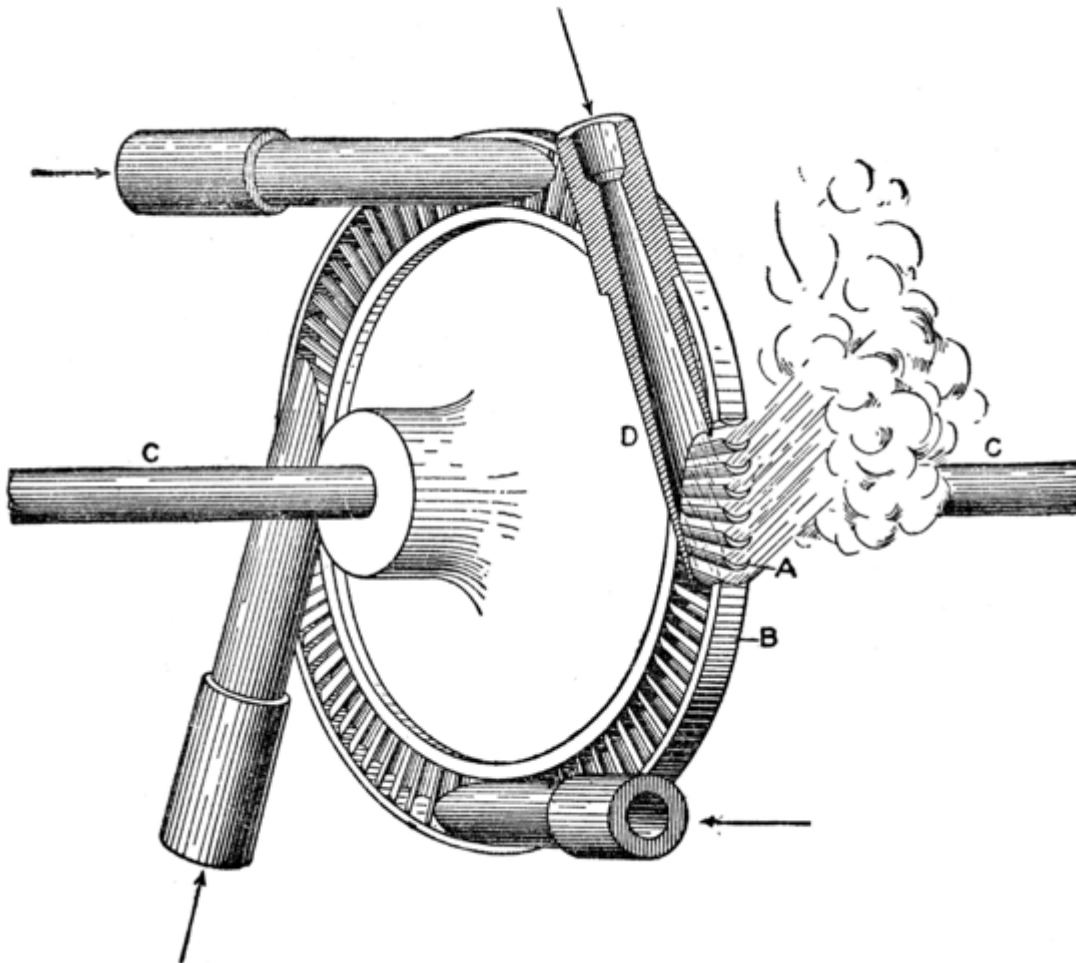
1922 Aurel Boleslav Stodola
(1859-1942) ETHZ, CH

6.2. NOZLE

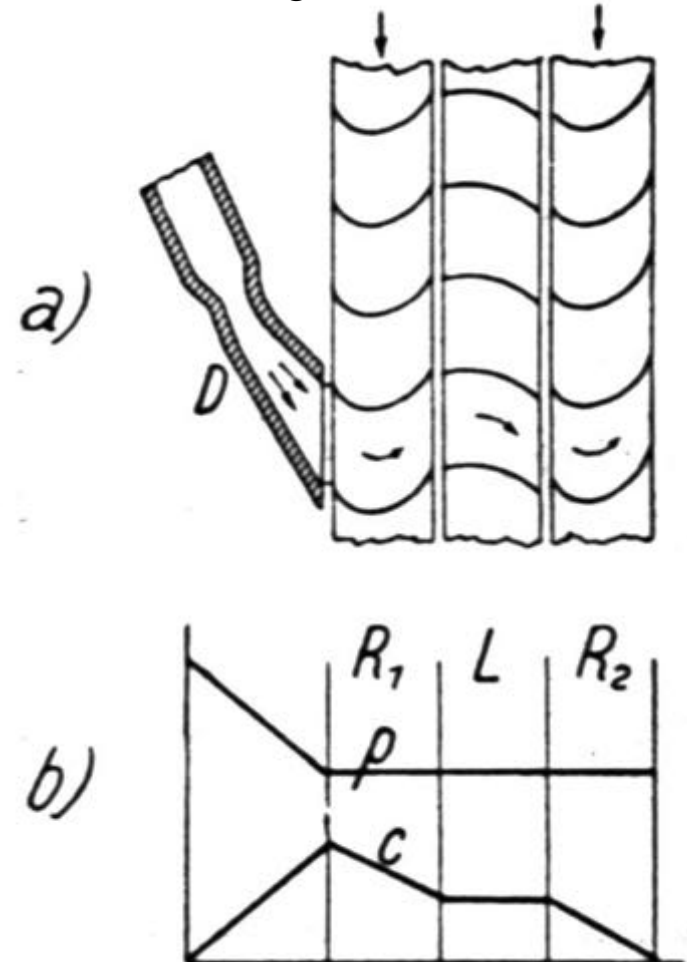


Carl Gustaf Patrik de Laval
1845 – 1913
Schweden

Single stage LAVAL-Steam turbine

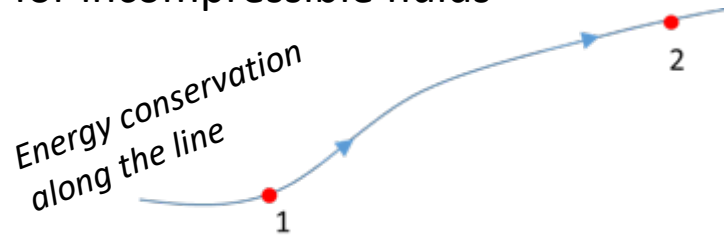


Multi Stage CURTIS-turbine



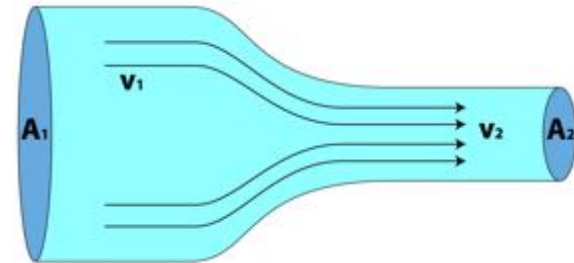
6.2.1. VENTURI EFFECT

Bernoulli Equation
for incompressible fluids

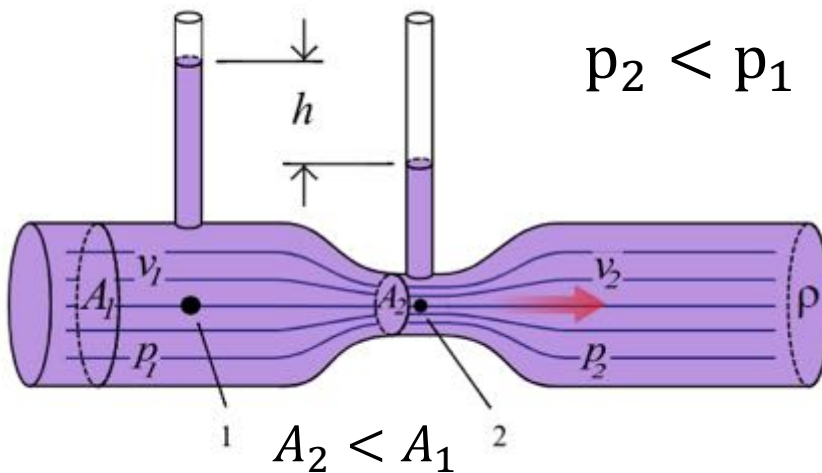


$$p_1 + \rho g h_1 + \frac{1}{2} \rho v_1^2 = p_2 + \rho g h_2 + \frac{1}{2} \rho v_2^2$$

Equation of continuity



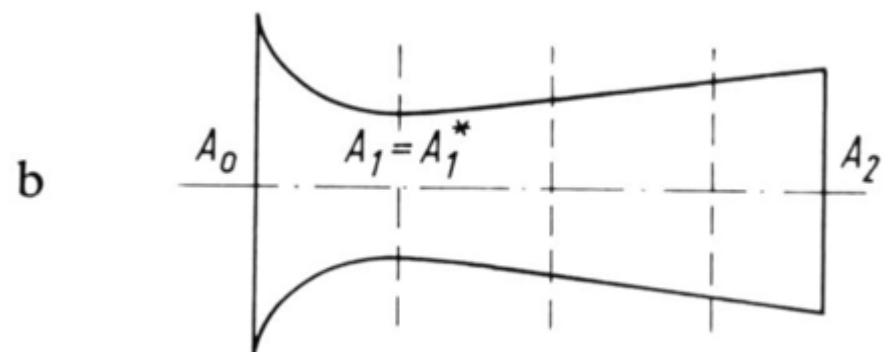
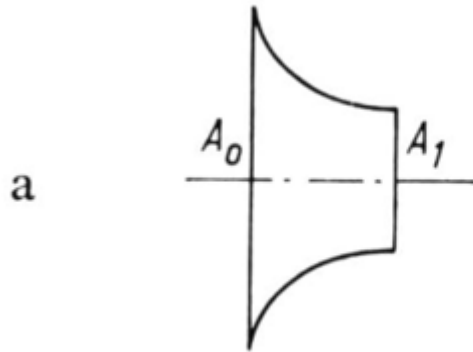
$$\rho_1 A_1 v_1 = \rho_2 A_2 v_2$$



$$p_2 = p_1 + \frac{1}{2} \rho v_1^2 \left(1 - \left(\frac{A_1}{A_2} \right)^2 \right)$$

$$\left(\frac{A_1}{A_2} \right)^2 > 1$$

6.2.2. ADIABATIC EXPANSION



Bernoulli eq. $\frac{1}{2} \cdot \rho \cdot v^2 + p = 0 \rightarrow \frac{1}{2} \cdot v^2 + \int_{p_0}^p \frac{dp}{\rho} = 0$

Continuity eq. $\int_A \rho \cdot v \cdot dA = \frac{dm}{dt} = \frac{m}{t} \rightarrow \rho \cdot v \cdot A = \frac{m}{t}$

6.2.3. LAVAL EQUATION

$$C_p = C_v + R$$

$$\kappa = \frac{C_p}{C_v} \quad \frac{\rho}{\rho_0} = \left(\frac{p}{p_0} \right)^{\frac{1}{\kappa}} = \left(\frac{T}{T_0} \right)^{\frac{1}{\kappa-1}}$$

$$v^2 = -2 \frac{1}{\rho_0} \int_{p_0}^p \left(\frac{p}{p_0} \right)^{-\frac{1}{\kappa}} dp \rightarrow v^2 = 2 \frac{\kappa}{\kappa-1} \frac{p_0}{\rho_0} \left[1 - \left(\frac{p}{p_0} \right)^{\frac{\kappa-1}{\kappa}} \right]$$

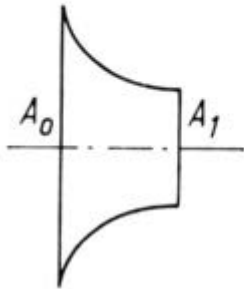
$$\rho \cdot v \cdot A = \frac{m}{t} \rightarrow \frac{m}{t} = A_1 \cdot \sqrt{2 \cdot \rho_0 \cdot p_0 \cdot \frac{\kappa}{\kappa-1} \left[\left(\frac{p}{p_0} \right)^{\frac{2}{\kappa}} - \left(\frac{p}{p_0} \right)^{\frac{\kappa+1}{\kappa}} \right]}$$

massflow max. for $p^* = p_0 \cdot \left(\frac{2}{\kappa+1} \right)^{\frac{\kappa}{\kappa-1}}$ LAVAL pressure $v^* = \sqrt{\kappa \cdot \frac{p_1}{\rho_1}}$

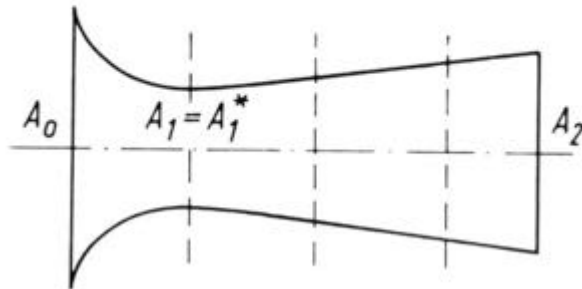
6.2.4. PRESSURE AND VELOCITY IN LAVAL NOZLE

$$\rho \cdot v = f(p) = \sqrt{2 \cdot \rho_0 \cdot p_0 \cdot \frac{\kappa}{\kappa - 1} \left[\left(\frac{p}{p_0} \right)^{\frac{2}{\kappa}} - \left(\frac{p}{p_0} \right)^{\frac{\kappa - 1}{\kappa}} \right]}$$

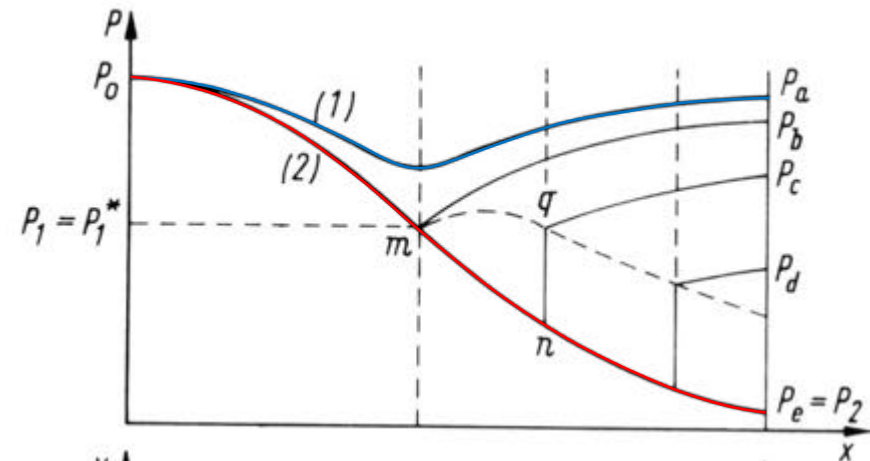
(1)



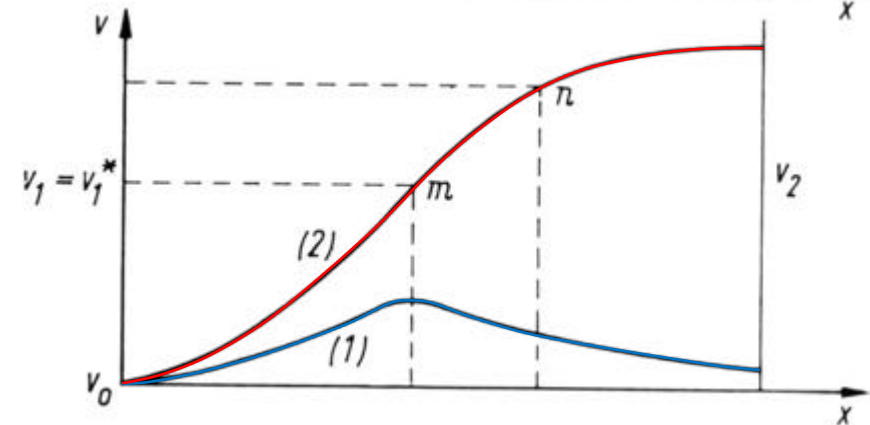
(2)



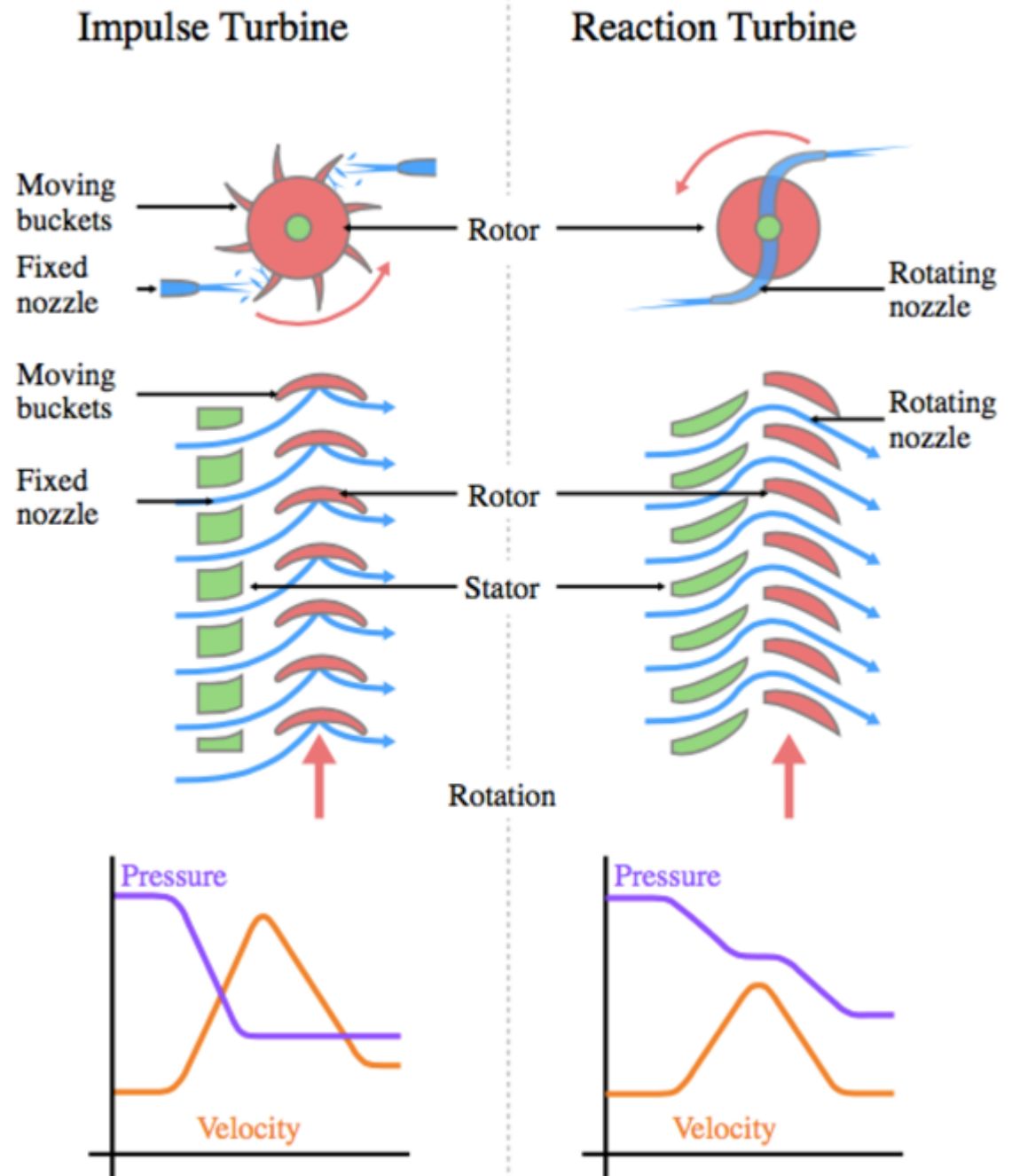
c



d



6.3. TURBINE TYPES



6.3.1. IMPULSE TURBINE

v_1 and v_2 are the absolute velocities at the inlet and outlet respectively.

v_{f1} and v_{f2} are the flow velocities at the inlet and outlet respectively.

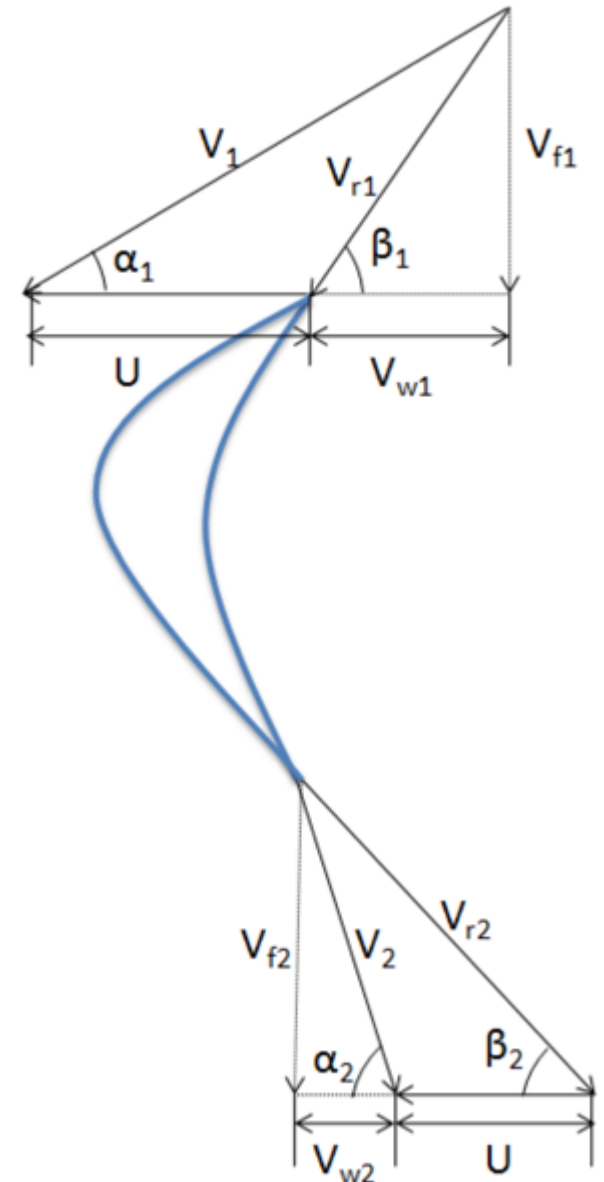
$v_{w1} + U$ and v_{w2} are the swirl velocities at the inlet and outlet respectively.

v_{r1} and v_{r2} are the relative velocities at the inlet and outlet respectively.

u_1 and u_2 are the velocities of the blade at the inlet and outlet respectively.

α is the guide vane angle and β is the blade angle.

$$\cos(\alpha_1) = (u + v_{w1})/v_1$$



6.3.2. EFFICIENCY IMPULSE TURBINE

Blade efficiency:

η_{blade} = Work done on the blades / kinetic energy supplied to the fluid

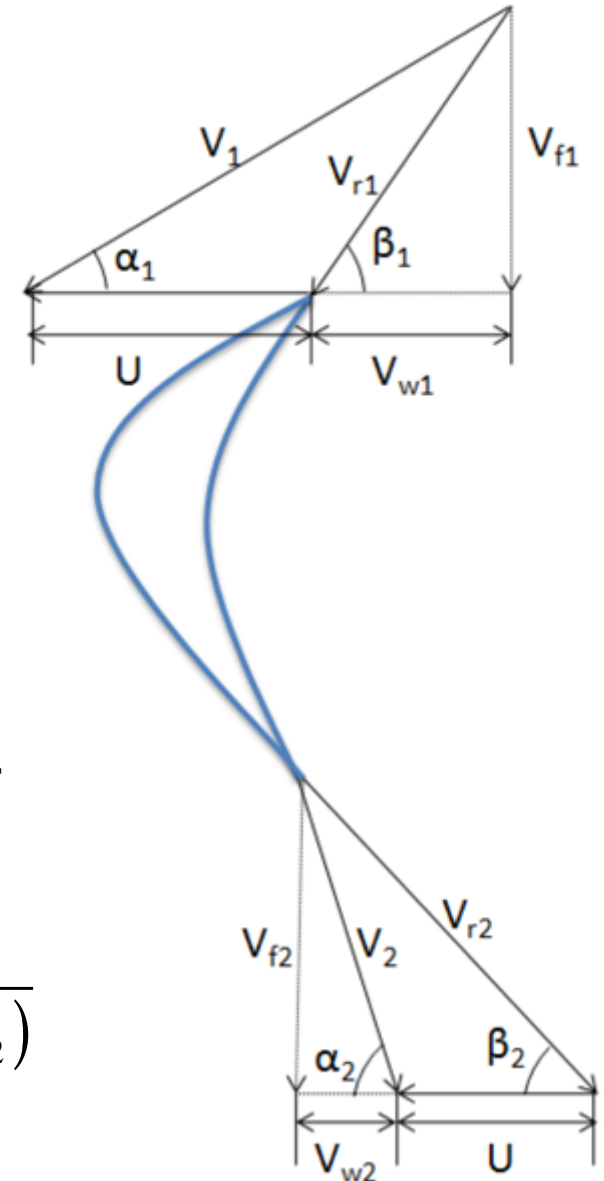
$$\eta_{blade} = \frac{\overset{\text{blade velocity}}{2 \cdot u} \cdot \overset{\Delta \text{ velocity}}{\Delta v_w}}{\underset{\text{inlet velocity}}{v_1^2}} = \frac{2 \cdot u \cdot \left(\cos \alpha_1 - \frac{u}{v_1} \right) (1 + k \cdot c)}{v_1}$$

Stage efficiency:

η_{stage} = Work done on the blades / energy supplied per stage

$$\eta_{stage} = \frac{\overset{\text{blade velocity}}{u} \cdot \overset{\Delta \text{ velocity}}{\Delta v_w}}{\Delta h} = \eta_{blade} \cdot \eta_{nozzle} = \eta_{blade} \cdot \frac{\overset{\text{outlet velocity}}{v_2^2}}{2(h_1 - h_2)}$$

Δh : difference in specific enthalpy

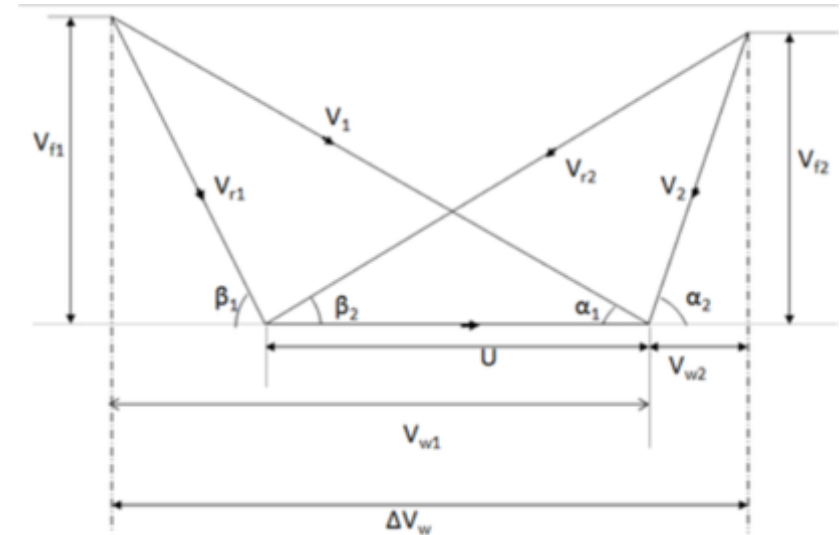


6.3.3. EFFICIENCY REACTION TURBINE

Blade efficiency:

$\eta_{blade} = \text{Work done on the blades} / \text{kinetic energy supplied to the fluid}$

$$\eta_{blade} = \frac{2 \cdot u \cdot (2v_1 \cdot \cos \alpha_1 - u)}{v_1^2 - u^2 + 2 \cdot v_1 \cdot u \cdot \cos \alpha_1}$$

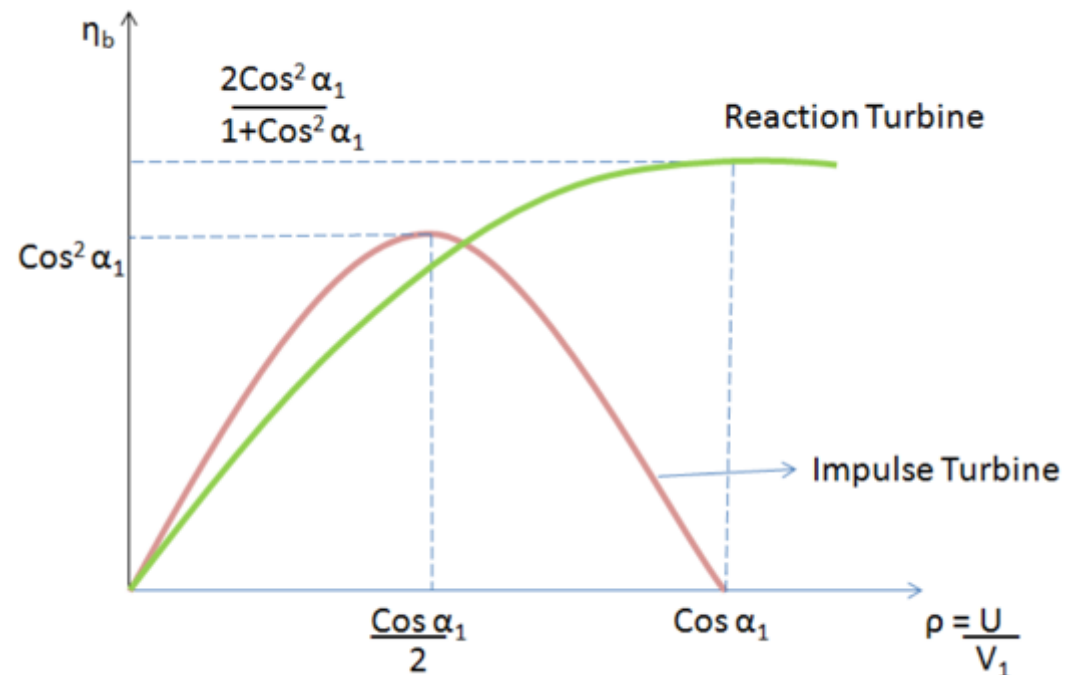


reaction:

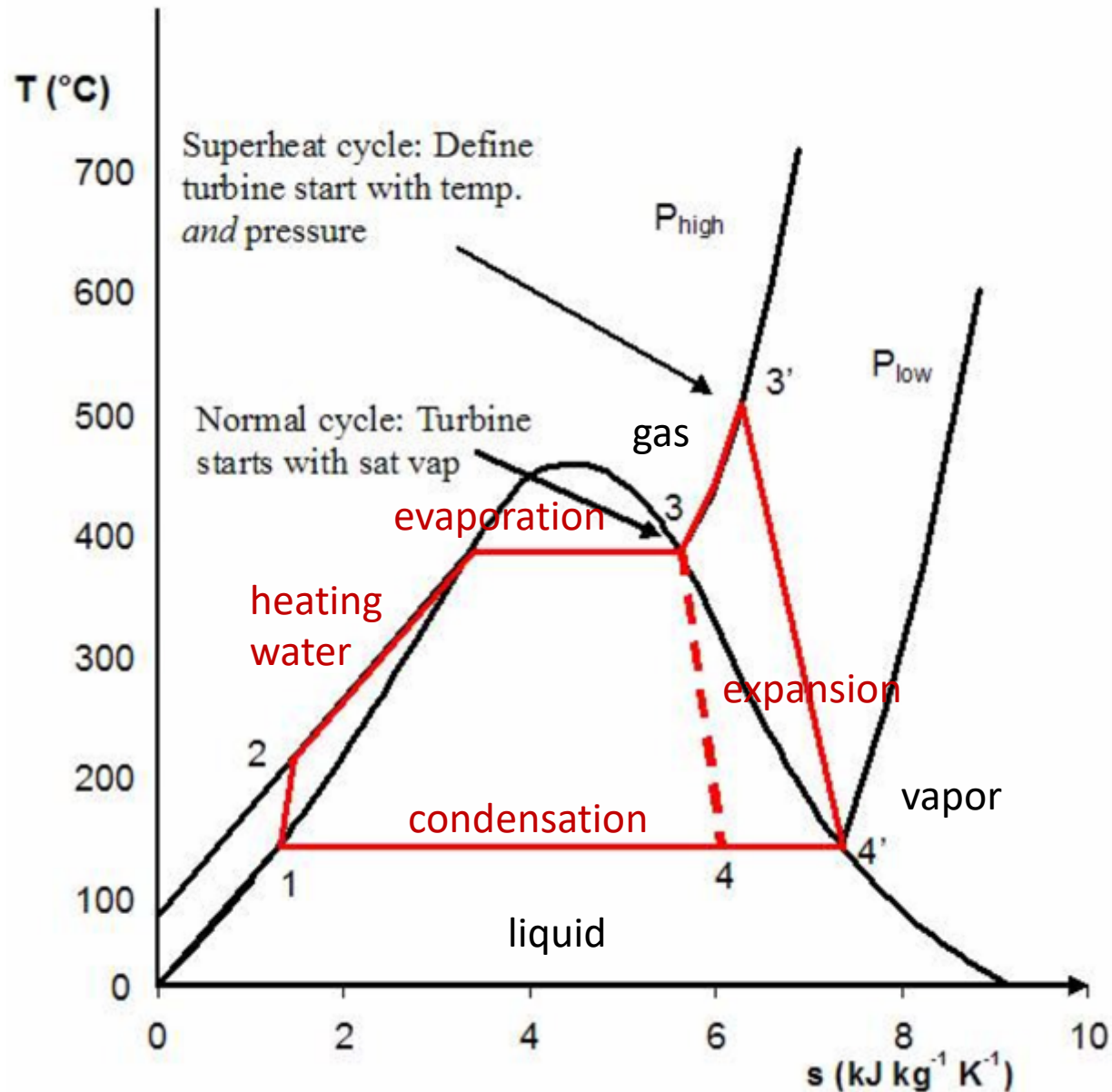
$$\eta_{blade} = \frac{2 \cdot \cos^2 \alpha_1}{1 + \cos^2 \alpha_1}$$

impulse:

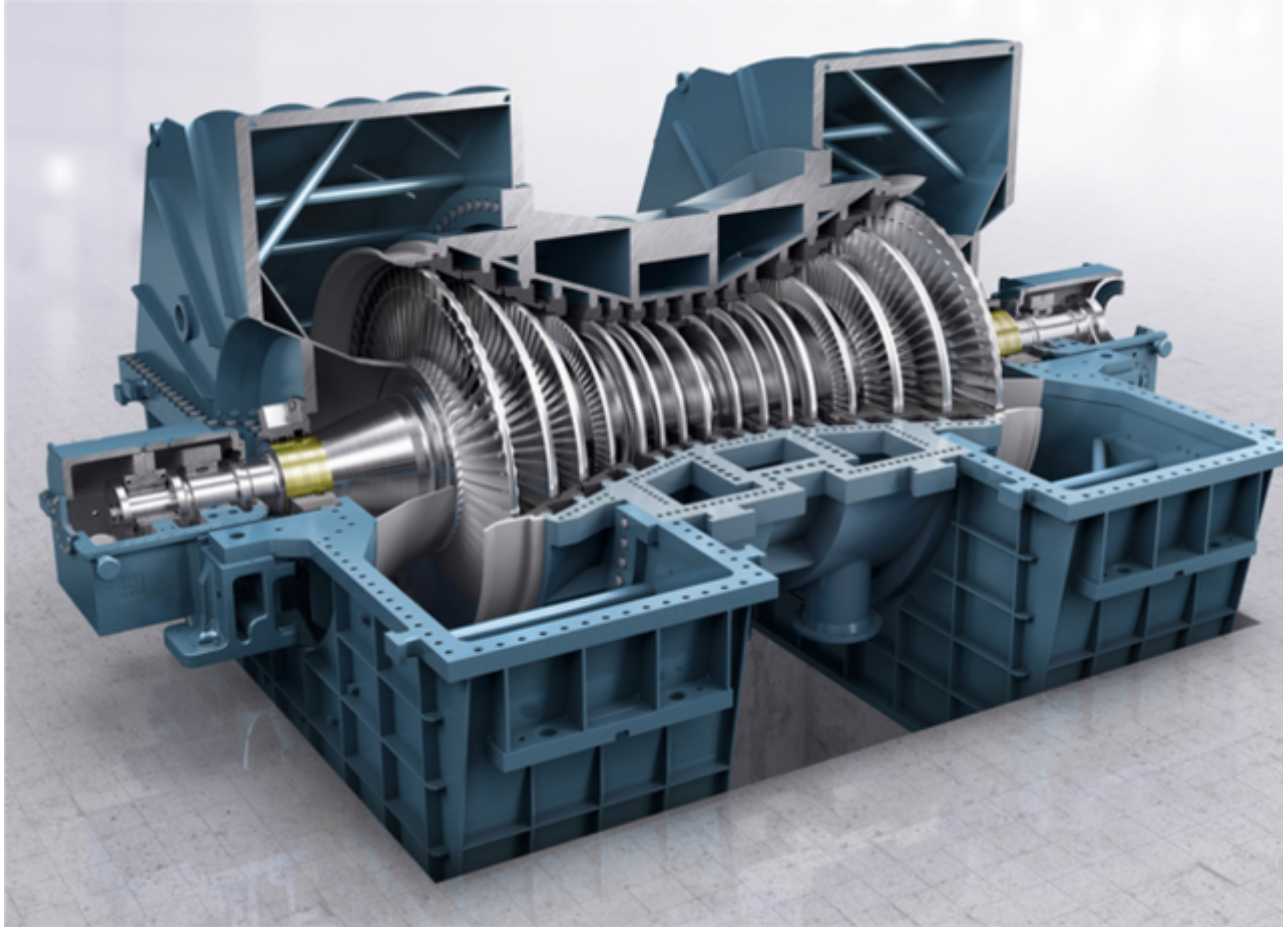
$$\eta_{blade} = \cos^2 \alpha_1$$



6.3.4. T-S DIAGRAM FOR STEAM



6.3.5. MODERN STEAM TURBINE

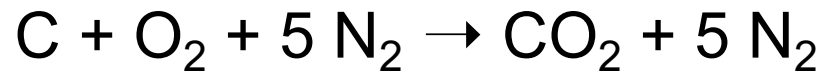


$P = 10 \text{ kW} - 1.9 \text{ GW}$

$p = 10 - 250 \text{ bar}$

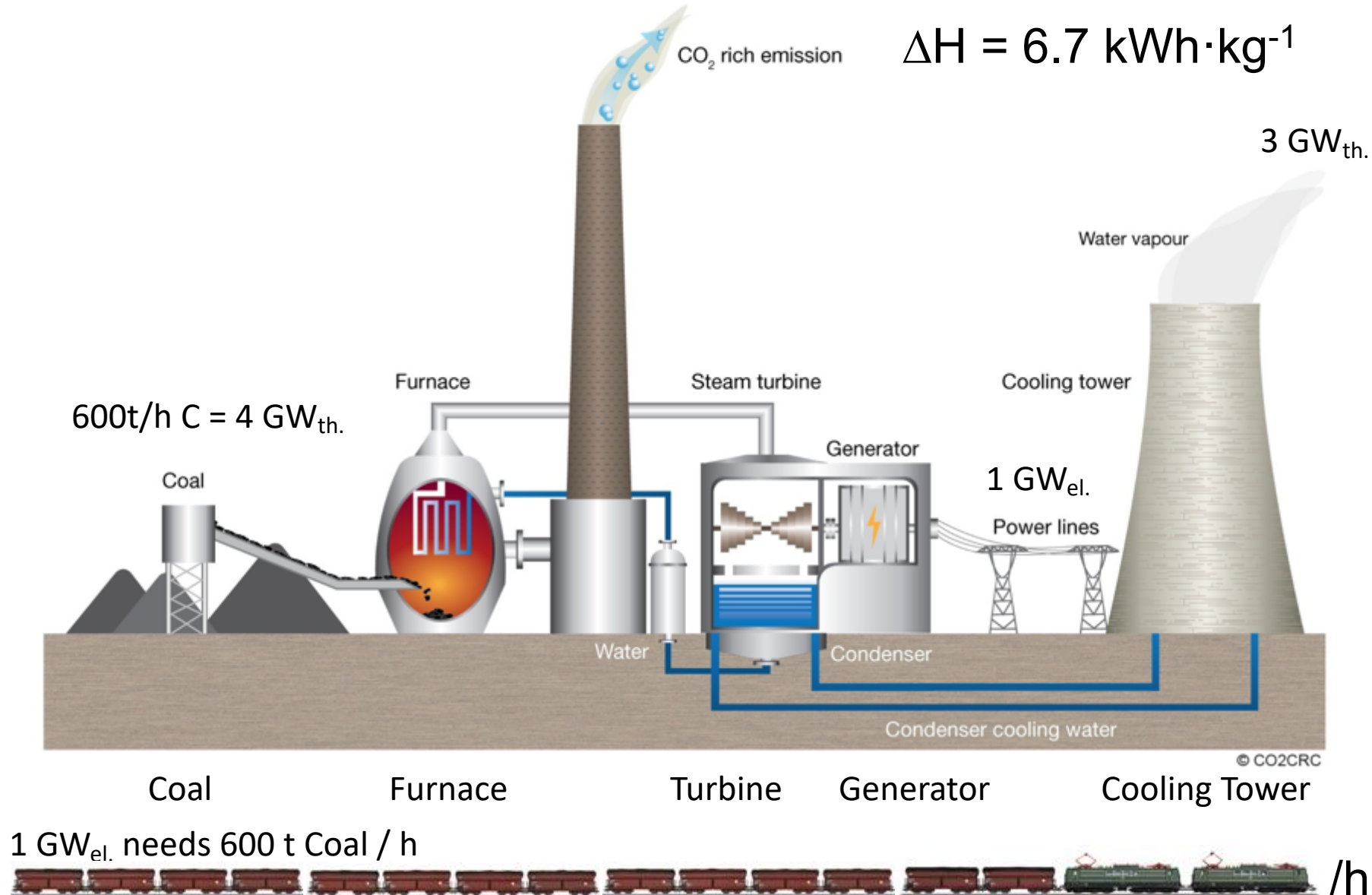
$T = 300^{\circ}\text{C} - 600^{\circ}\text{C}$

6.4. COAL FIRED POWER STATION



$$\Delta H = 288 \text{ kJ} \cdot \text{mol}^{-1}$$

$$\Delta H = 6.7 \text{ kWh} \cdot \text{kg}^{-1}$$

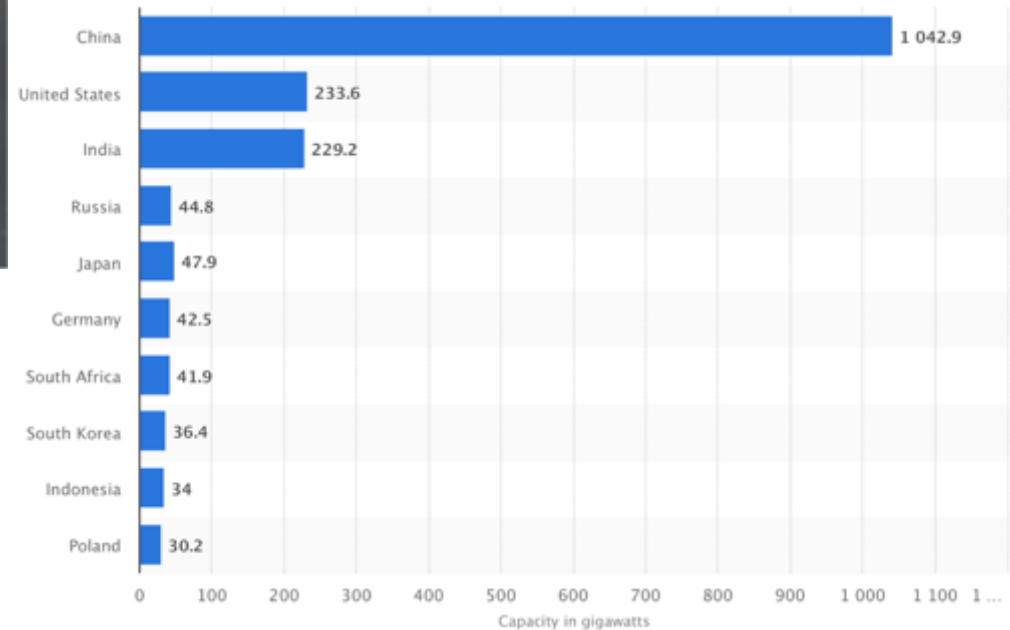
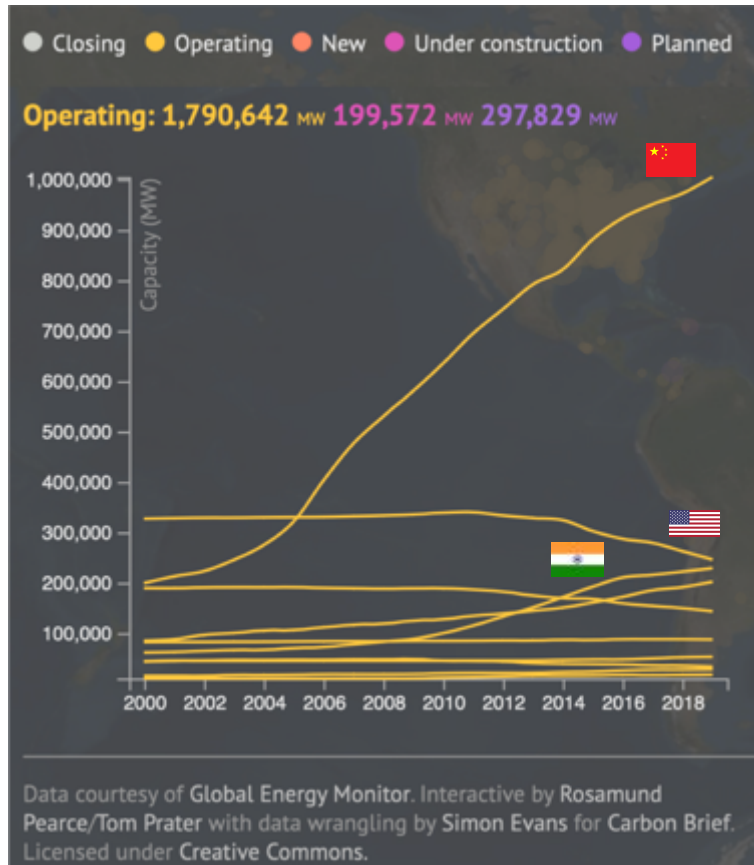


6.4.1. PHOTO OF COAL FIRED POWER STATION WITH COAL MINE



The Garzweiler coal mine and power plant near the city of Grevenbroich in western Germany. Plans to expand an open-pit brown coal mine in the eastern German village of Pödelwitz have prompted protests.

6.4.2. COAL FIRED POWER STATIONS IN 2020

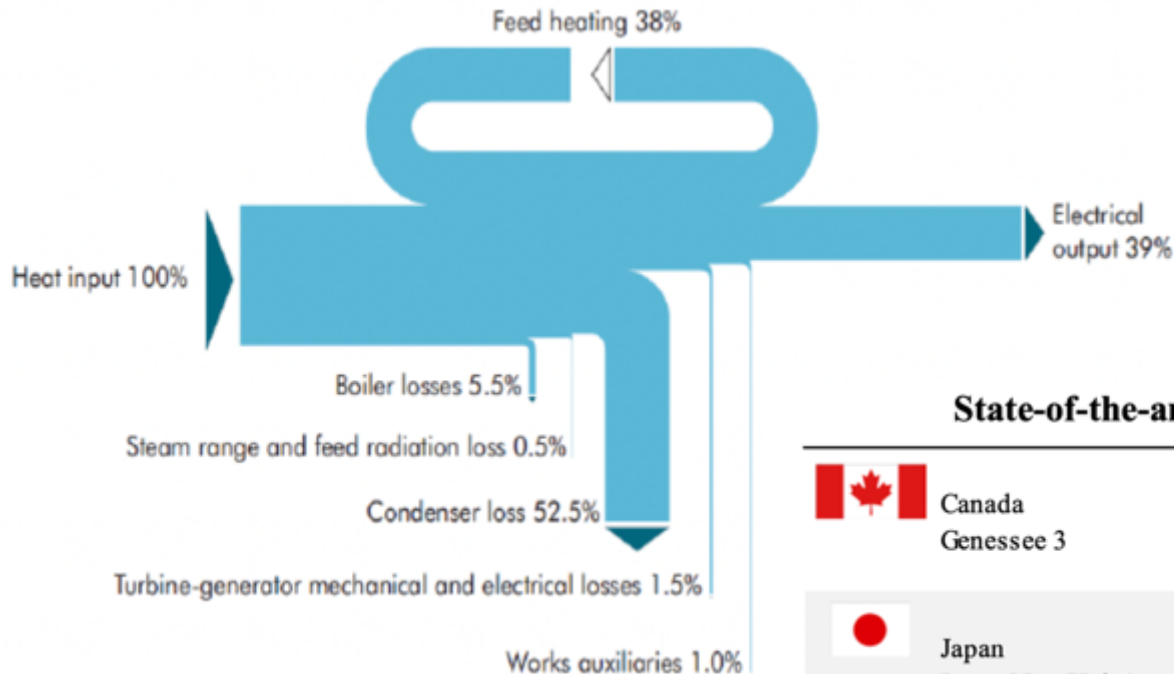


Total operating: 1'791 GW
 China: 1'005 GW
 Closing: 300 GW
 Under construction: 300 GW
 Planned: 298 GW

Ref.: <https://www.carbonbrief.org/mapped-worlds-coal-power-plants>

6.4.3. EFFICIENCY COAL FIRED POWER STATION

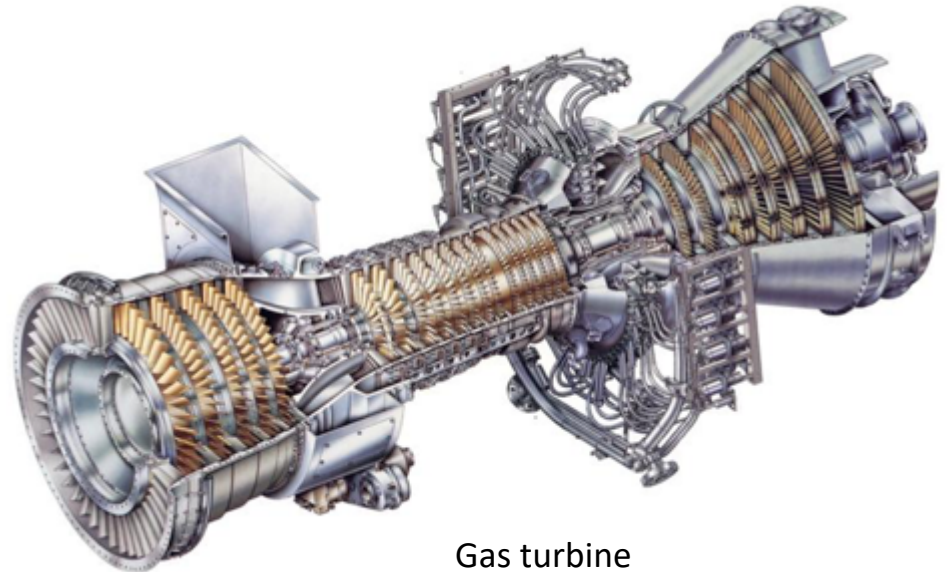
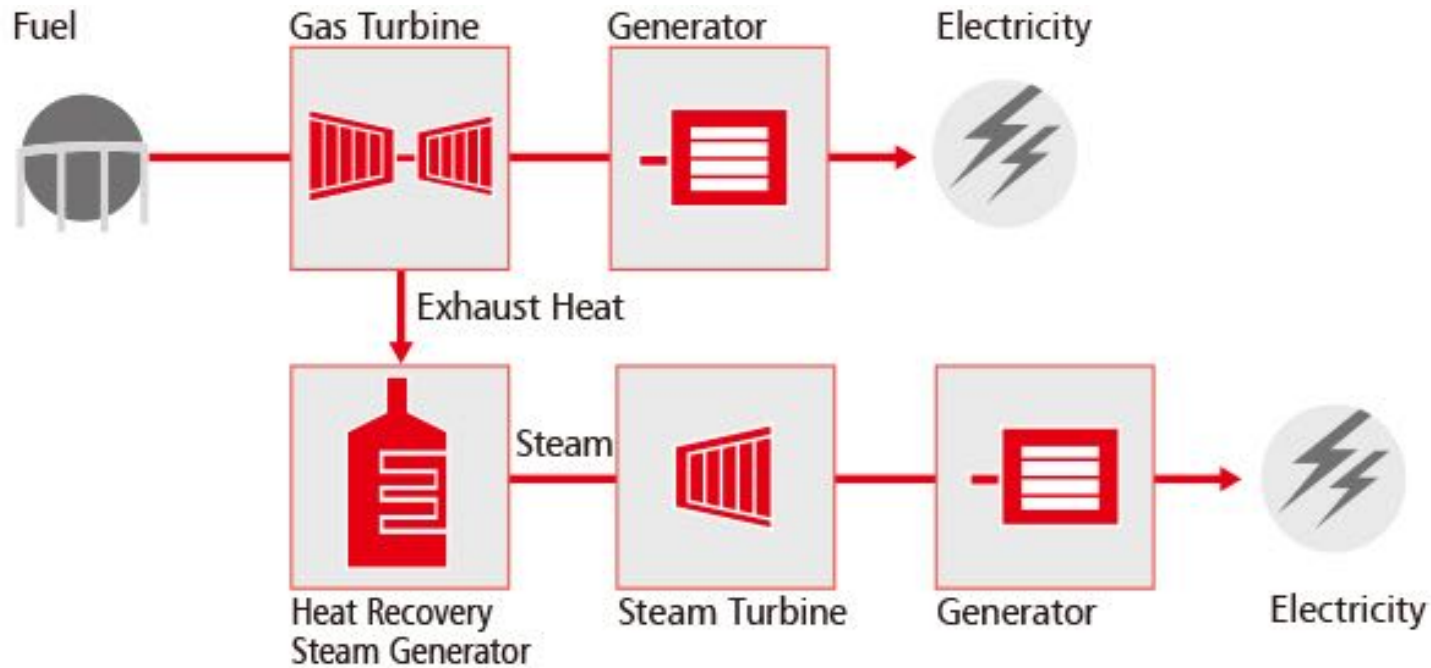
Energy flows in a typical 500 MW subcritical pulverized coal-fired boiler



State-of-the-art coal-fired power plants

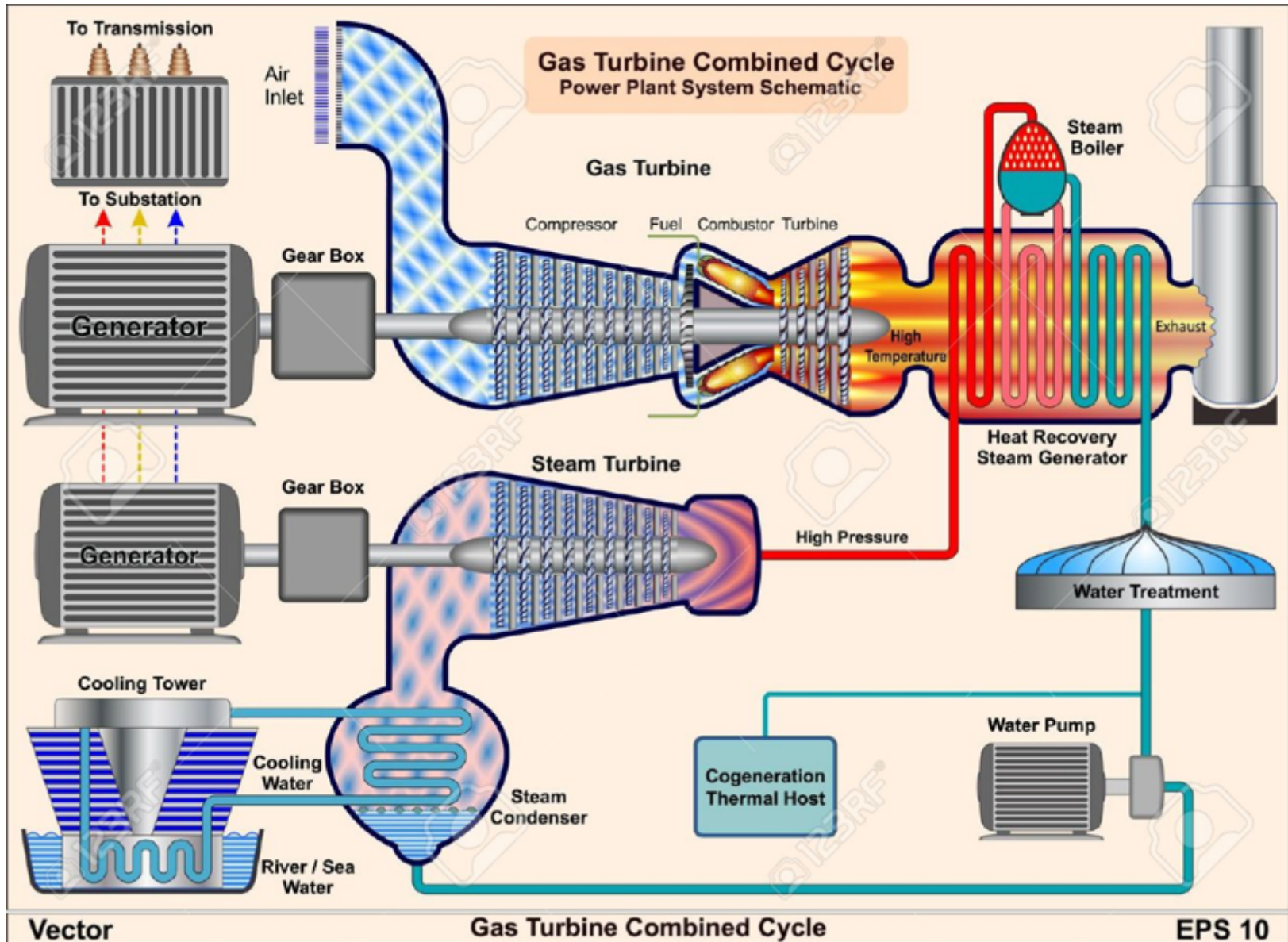
	Canada Genessee 3	sub-bituminous coal	Genessee 3 supercritical once-through Benson type, two-pass, sliding pressure	41.4%
	Japan Isogo New Unit 1	bituminous coal	Isogo New Unit 1 supercritical once-through, tower type, sliding pressure	42.0%
	Germany Niederaussem K	lignite	Niederaussem K once-through supercritical tower type	43.7%
	Denmark Nordjyllandsværket 3	international steam coals	Nordjyllandsværket 3 supercritical, Benson, tower type, tangential firing	47.0%
	South Korea Younghung	international bituminous	Younghung supercritical once-through, tower type, sliding pressure	43.3%

6.5. COMBINED CYCLE POWER STATION (Natural Gas)



Gas turbine

6.5.1. PRINCIPLE COMBINED CYCLE POWER STATION



6.5.2. COMBINED CYCLE POWER STATION PLANT

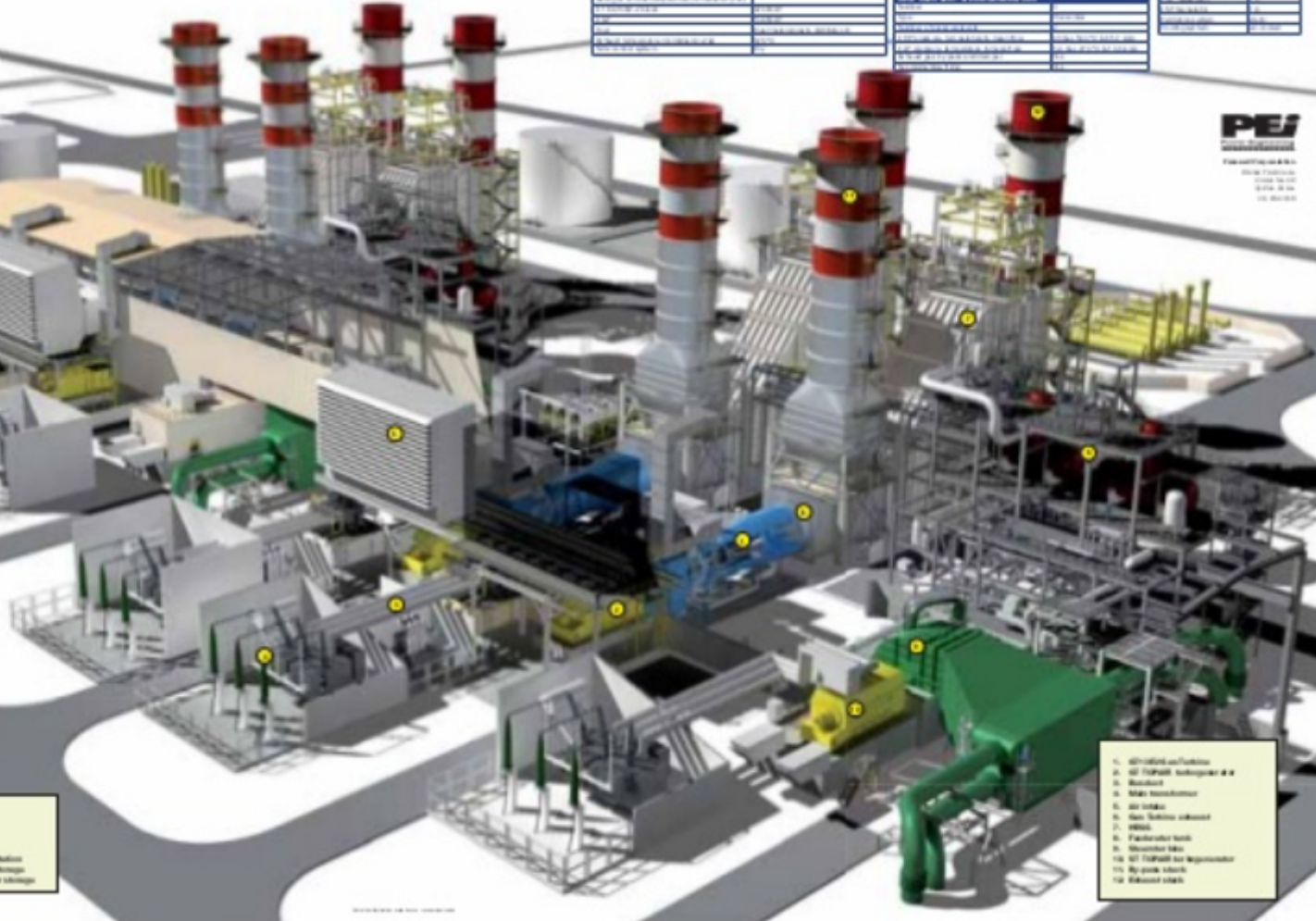
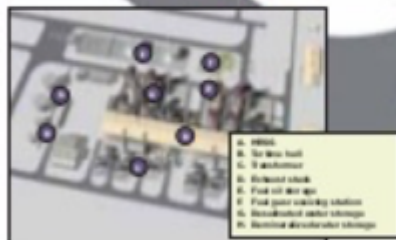
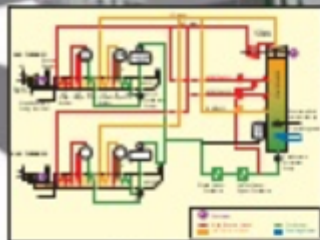
SOHAR – 1000 MW Combined-Cycle Power Plant:

Flexibility and availability for industrial applications

The 1000 MW combined-cycle power plant Sohar is an innovative gas turbine power plant, which is under initial operation in the Sultanate of Oman, an oil-rich country. It is built by Alstom on a turnkey EPC and construction basis. The power plant is based on Alstom's gas turbine combined-cycle technology, which has a very low emissions operating level. It is also the benefit of not only providing high plant efficiency (54.0%), but also no emission of operational pollutants and the ability. The Sohar CCPP was initially planned as a power plant for the Sultanate of Oman, but is now operated by the Sohar Aluminium Company LLC and used to generate electricity for the aluminium industry.

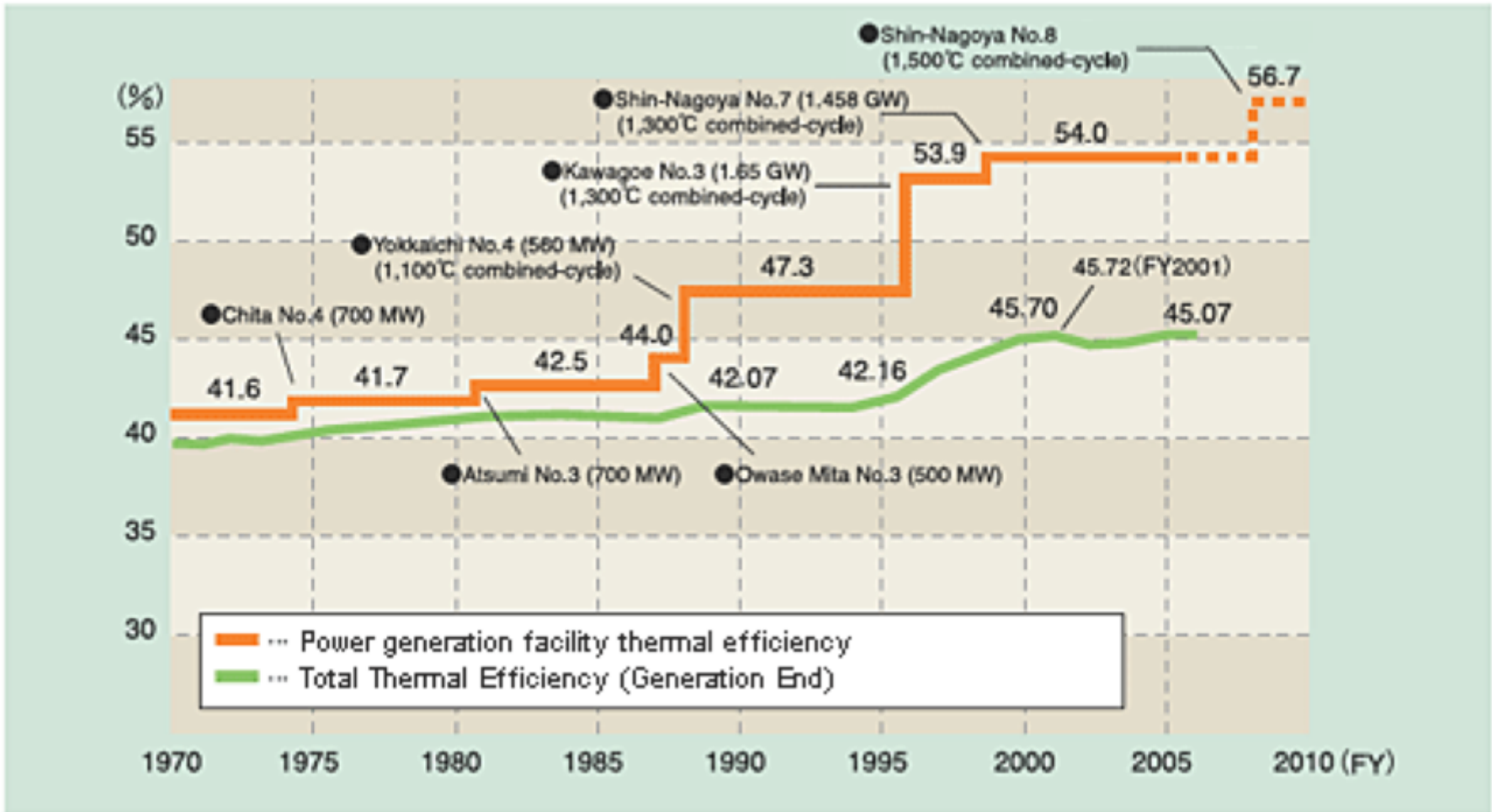


GENERAL DATA		TECHNICAL DATA		ENVIRONMENTAL DATA	
Plant name	SOHAR CCPP	Capacity	1000 MW	CO ₂ emissions	100 g/kWh
Location	Sohar, Oman	Efficiency	54.0%	NO _x emissions	10 ppm
Owner	SOHAR Aluminium Company LLC	Availability	95%	SO ₂ emissions	0 ppm
Operator	Alstom	Start-up time	15 min	PM ₁₀ emissions	0 mg/m ³
Construction start	2003	Commissioning	2005	Water consumption	100 m ³ /h
Construction end	2005	Warranty	5 years	Land use	100,000 m ²
Plant area	100,000 m ²	Water treatment	Reverse osmosis	Waste management	Recycling
Water supply	Desalination plant	Water consumption	100 m ³ /h	Waste management	Recycling
Water treatment	Reverse osmosis	Water consumption	100 m ³ /h	Waste management	Recycling
Water consumption	100 m ³ /h	Water consumption	100 m ³ /h	Waste management	Recycling
Water consumption	100 m ³ /h	Water consumption	100 m ³ /h	Waste management	Recycling

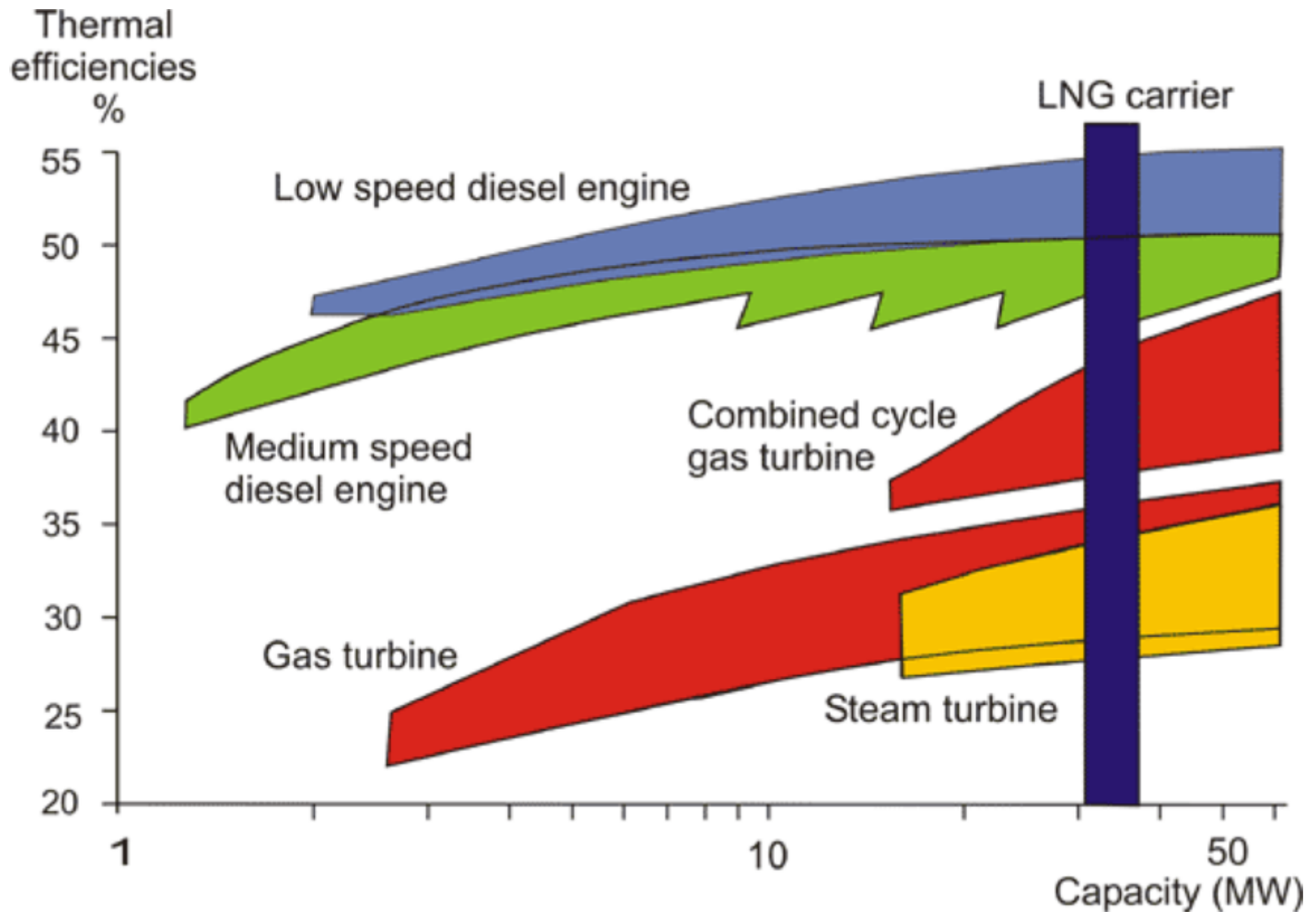


1. Air intake
2. Air filter
3. Air compressor
4. Compressor outlet
5. Compressor outlet
6. Compressor outlet
7. Compressor outlet
8. Compressor outlet
9. Compressor outlet
10. Compressor outlet
11. Compressor outlet
12. Compressor outlet
13. Compressor outlet
14. Compressor outlet
15. Compressor outlet
16. Compressor outlet
17. Compressor outlet
18. Compressor outlet
19. Compressor outlet
20. Compressor outlet

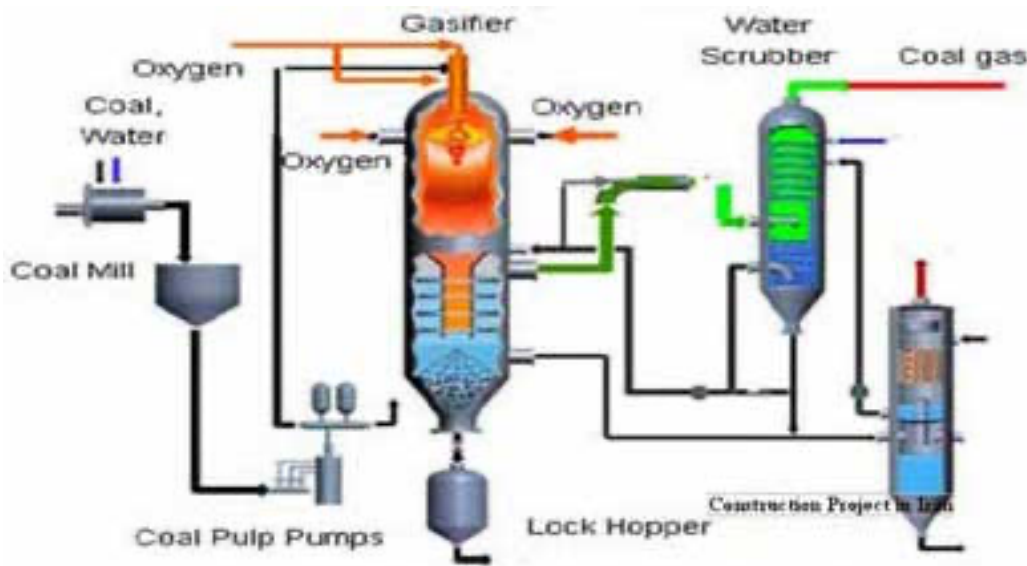
6.5.3. EFFICIENCY OF POWER STATION



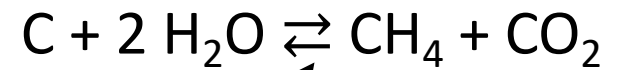
6.5.4. EFFICIENCY OF ENGINES



6.5.5. COAL GASIFICATION

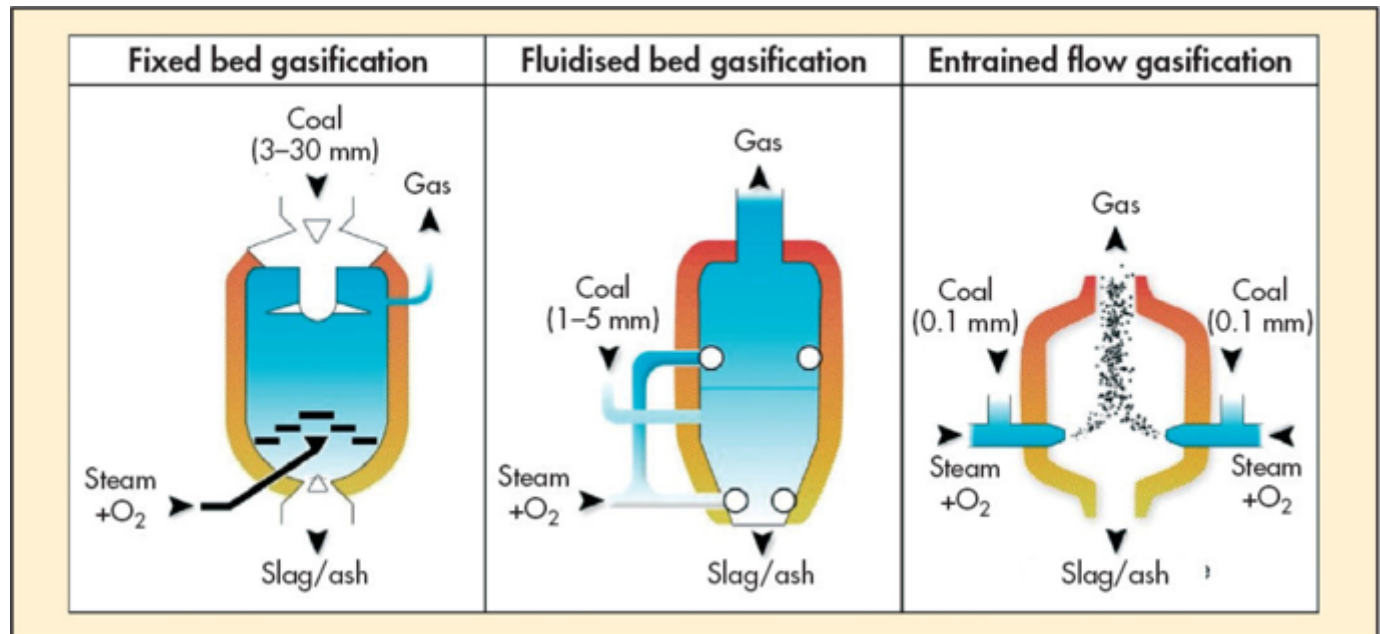


$$\Delta H_{\text{HHV}} = 6.6 \text{ Wh/kg C} \quad \Delta H_{\text{HHV}} = 15.4 \text{ kWh/kg C}$$

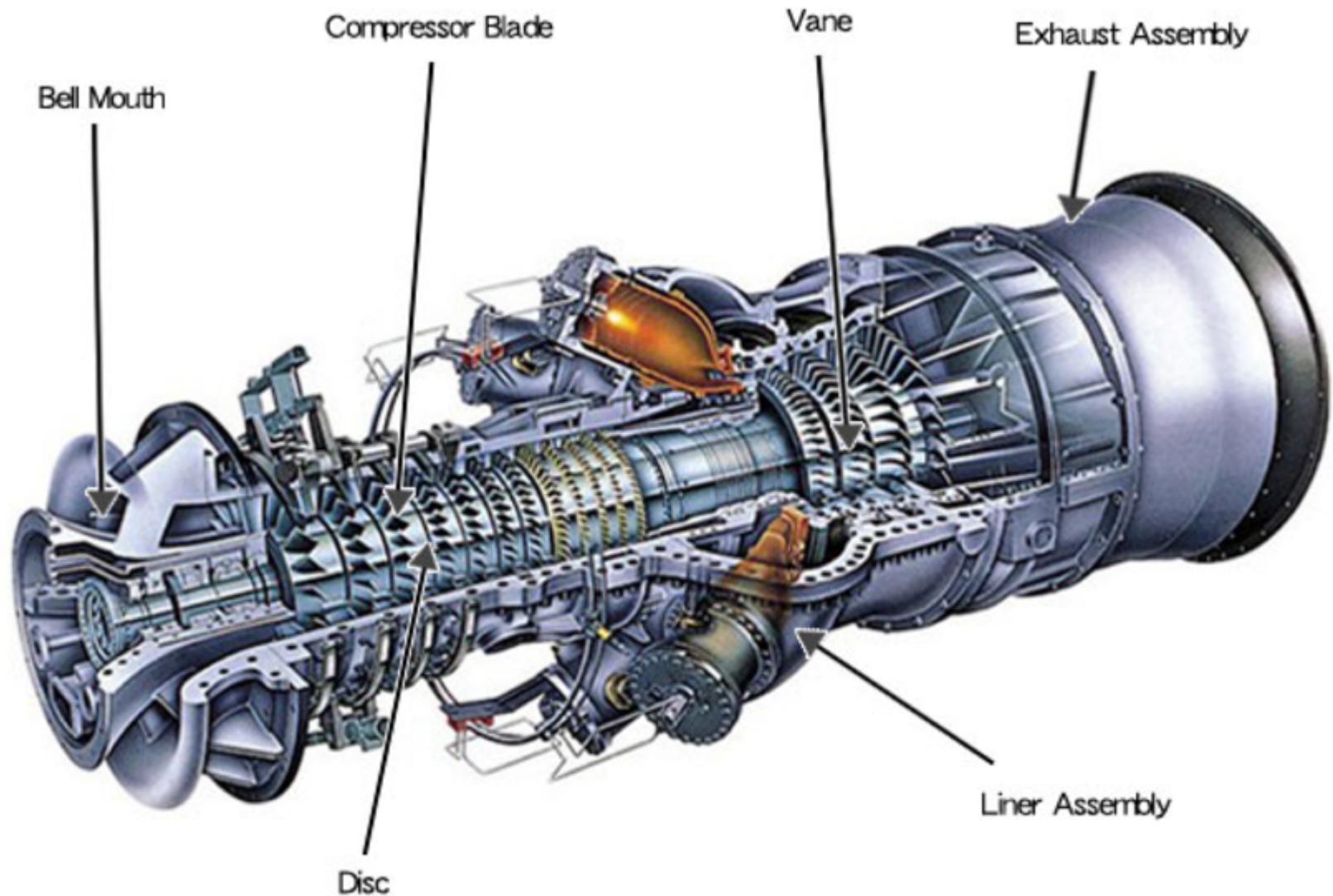


$$\Delta H = 102 \text{ kJ} \cdot \text{mol}^{-1}$$

$$\Delta H = 2.36 \text{ kWh} \cdot \text{kg}^{-1} \text{ C}$$

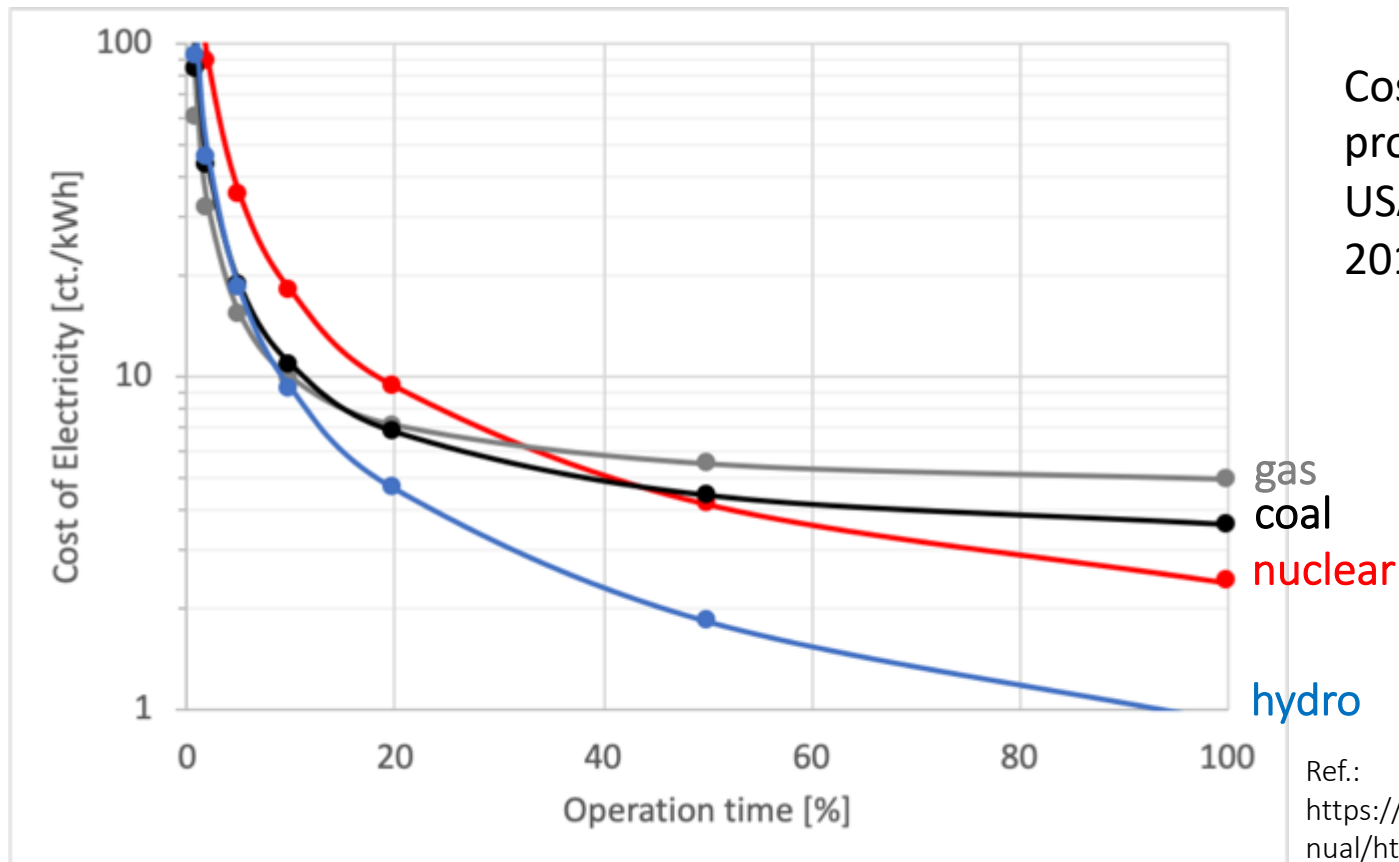


6.5.6. GAS TURBINE (Methane)



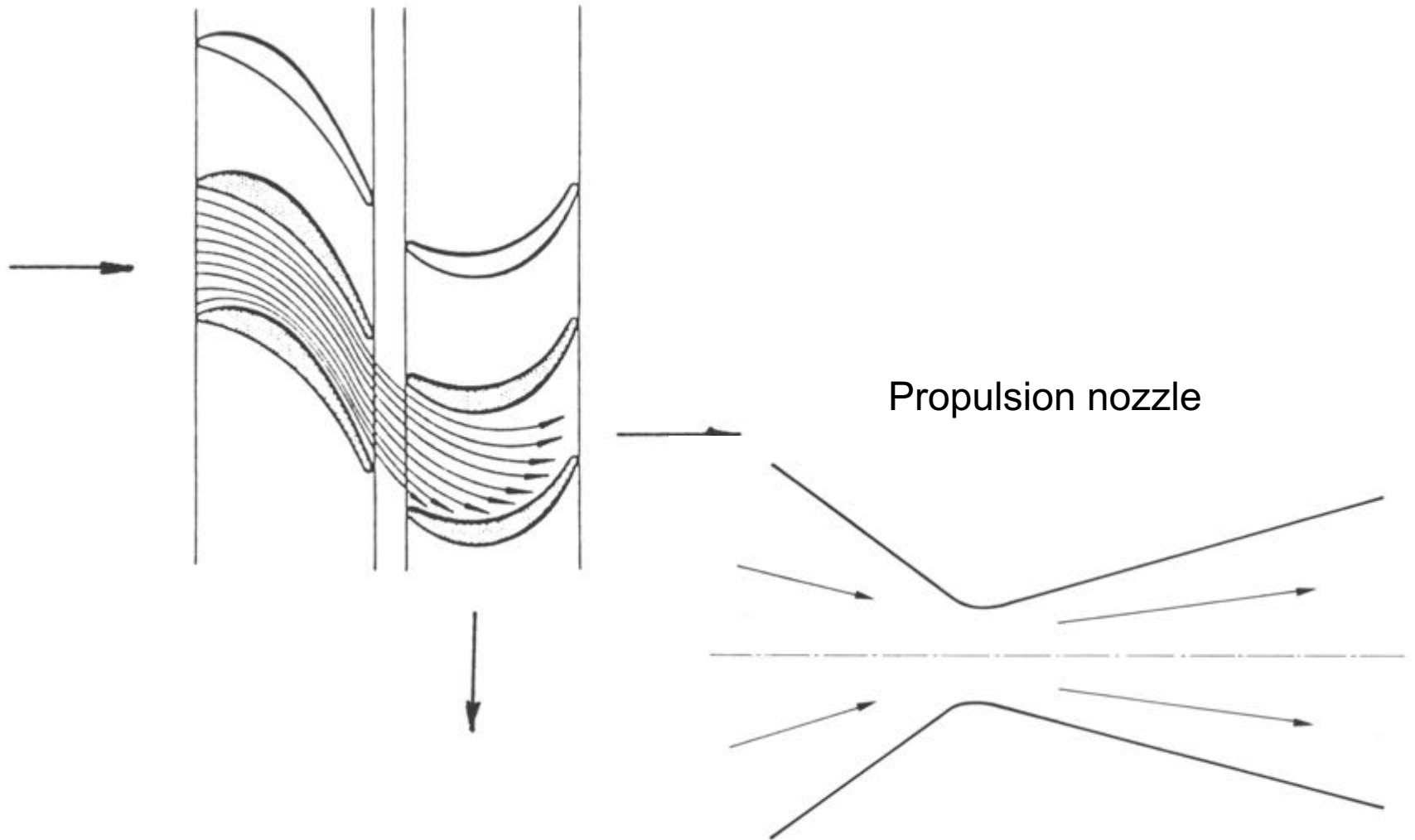
6.5.7. ECONOMICS OF ELECTRICITY GENERATION

in US cts/kWh	OPEX	Maintenance	Fuel	Total
Nuclear Power	1.05	0.68	0.668	2.398
Gas power plant	0.279	0.273	4.321	4.874
Coal power plant	0.404	0.399	2.773	3.576
Hydroelectric power plant	0.533	0.381	0	0.915



6.6. JET ENGINE

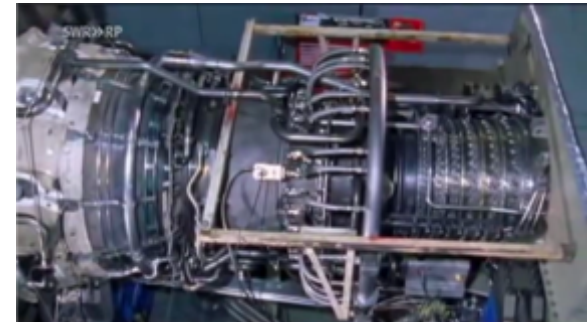
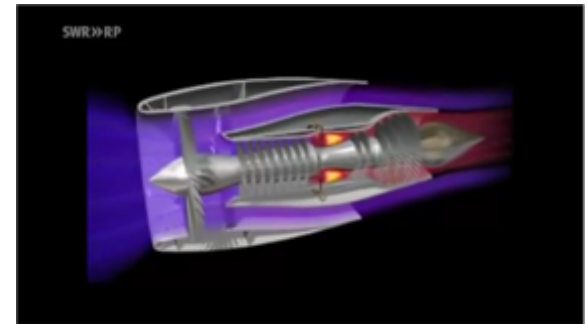
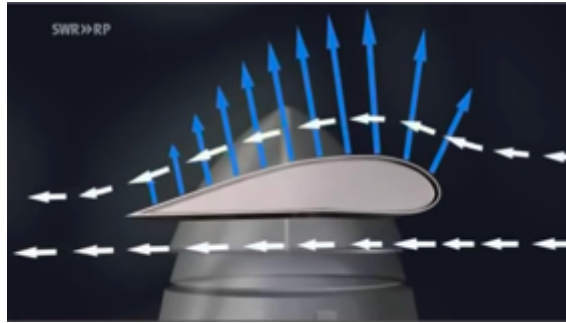
Turbine



6.6.1. JET ENGINE FILM

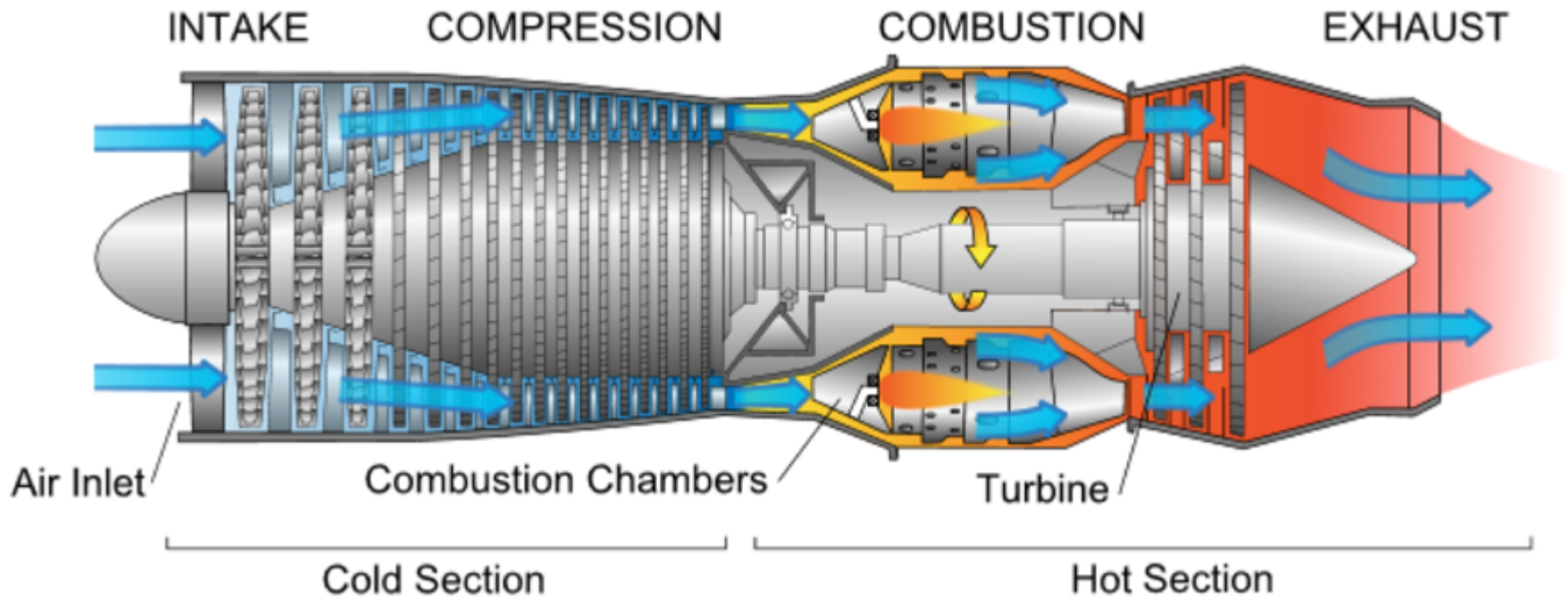


6.6.1. JET ENGINE FILM

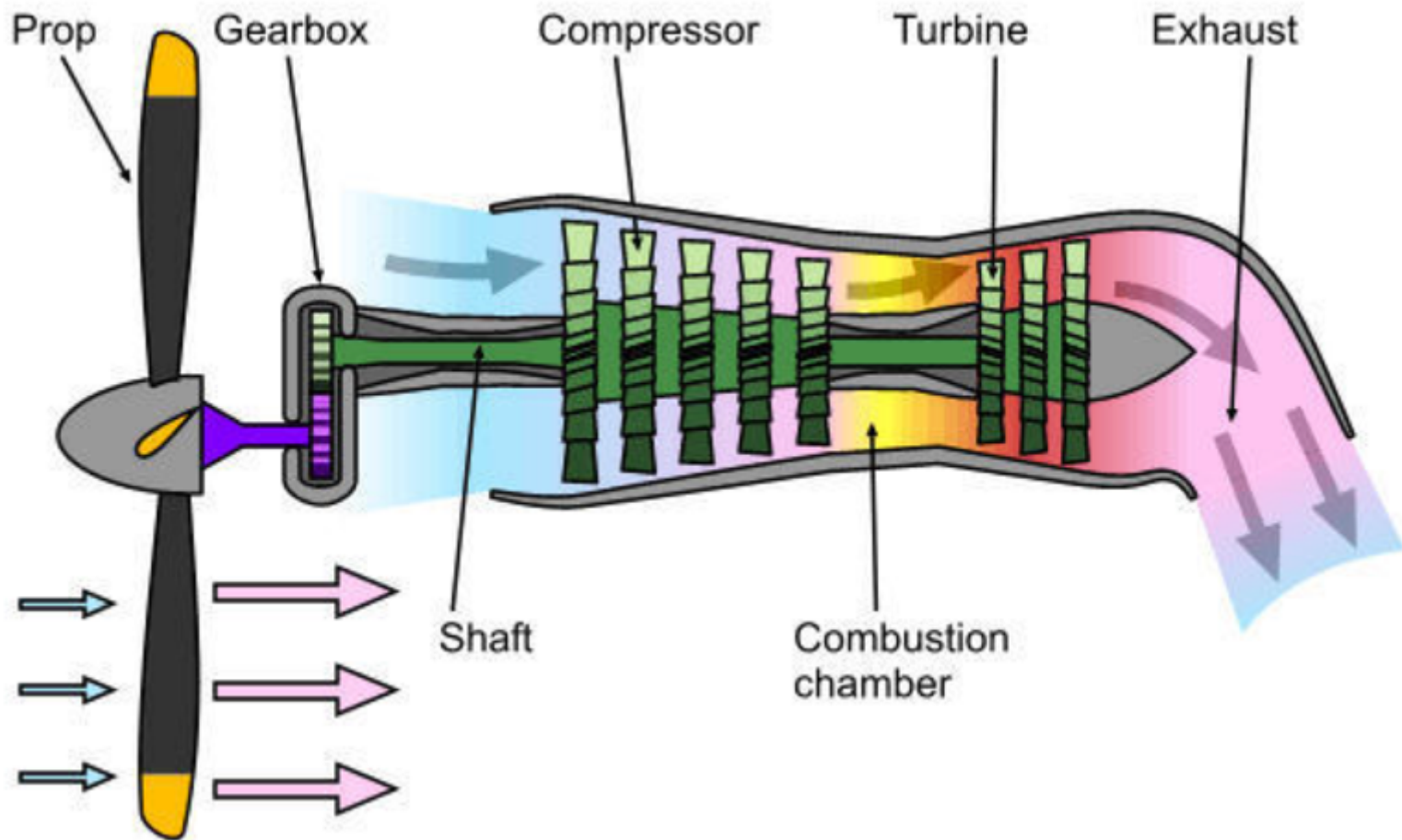


6.6.2. AIRPLANE JET ENGINE

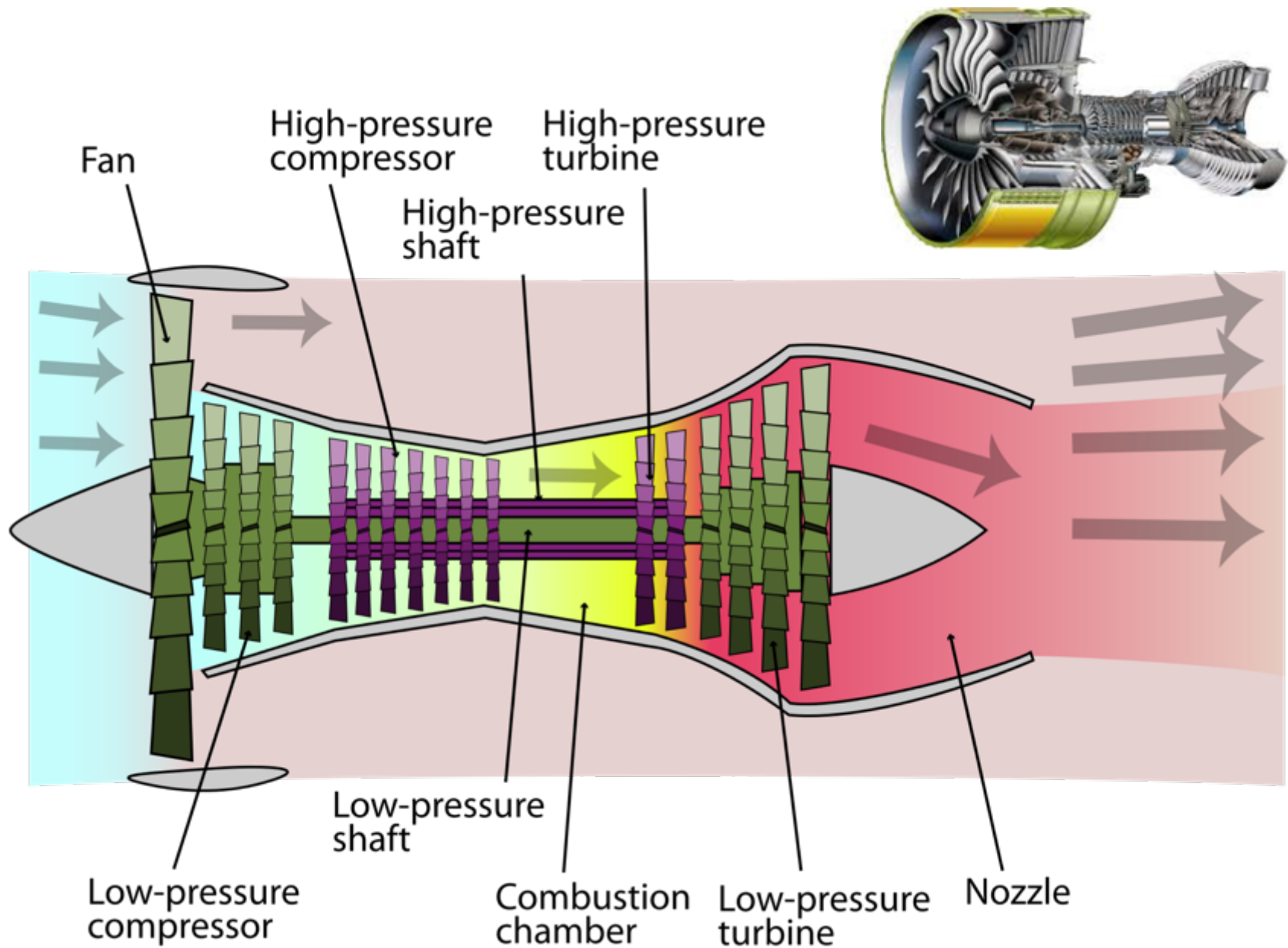
Hans Joachim Pabst von Ohain
(* 14. Dezember 1911 in Dessau;
† 13. März 1998 in Melbourne, Florida)



6.6.3. TURBOPROP ENGINE



6.6.4. HIGH BYPASS JET ENGINE (TURBO FAN)



6.6.5. POWER AND FORCE

The acceleration of an airplane is a function of the speed based on the energy contents and the momentum of the fuel.

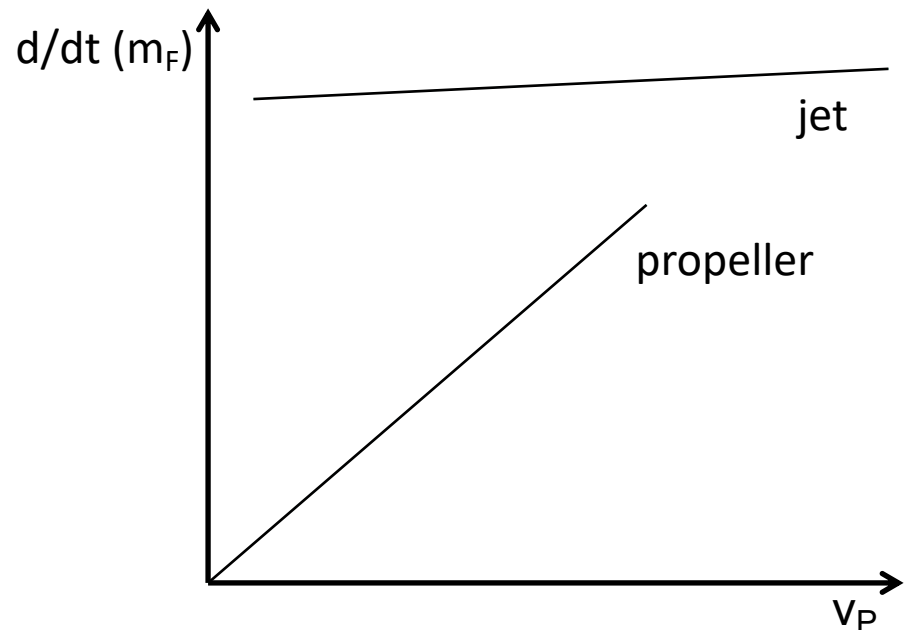
Energy content of Kerosene is $\gamma = 45 \text{ MJ/kg}$

Power (Energy change):
$$\frac{d}{dt}(F \cdot s) = F \cdot \frac{ds}{dt} = m_p \cdot a_p \cdot v_p = \frac{d}{dt}(m_F \cdot \gamma_F)$$

Force (Momentum change):
$$m_p \cdot a_p = \frac{d}{dt}(m_F) \cdot v = \frac{d}{dt}(m_F) \cdot \sqrt{2 \cdot \gamma_F}$$

because:

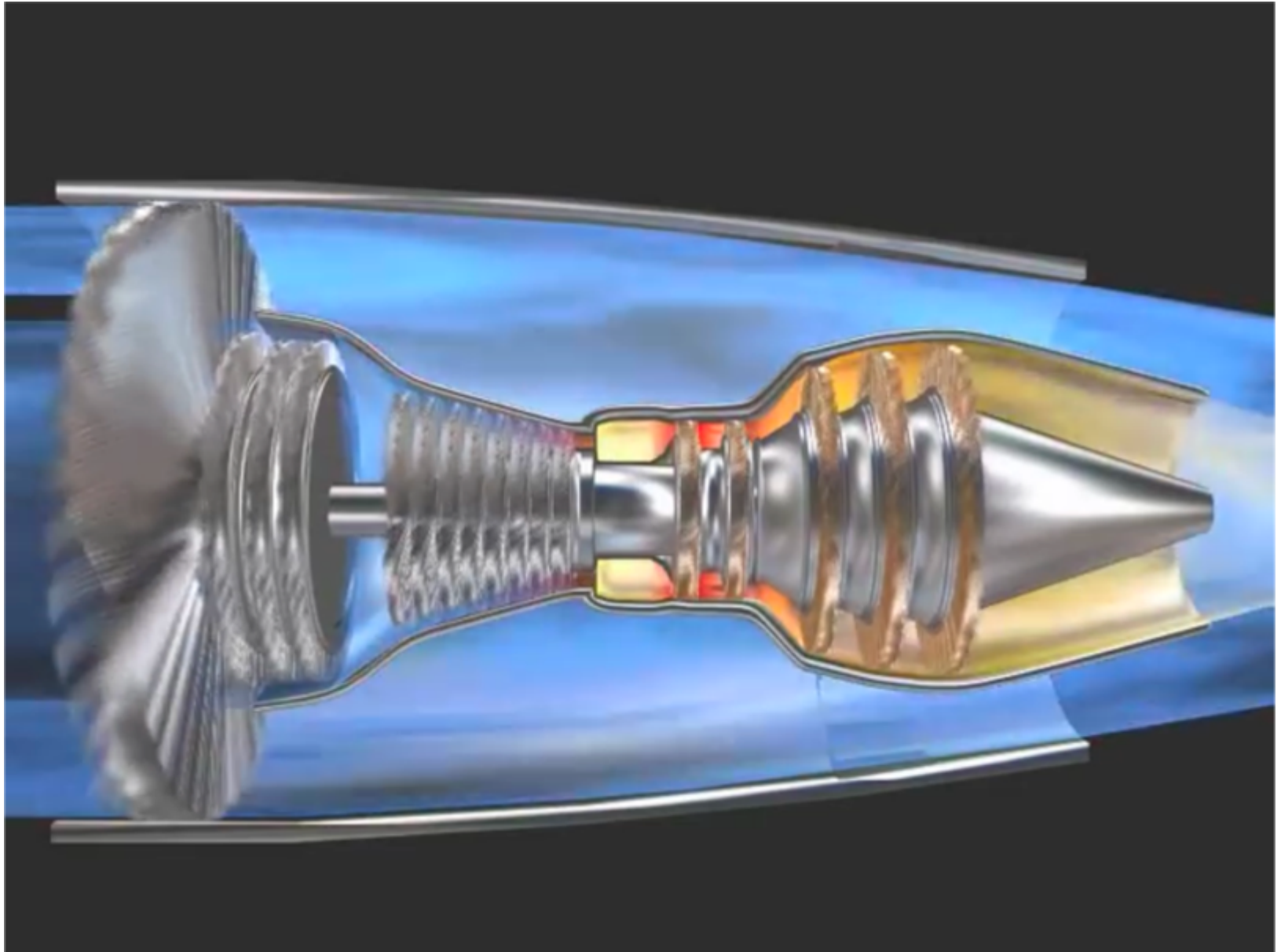
$$\frac{1}{2} \cdot m \cdot v^2 = m \cdot \gamma_F$$



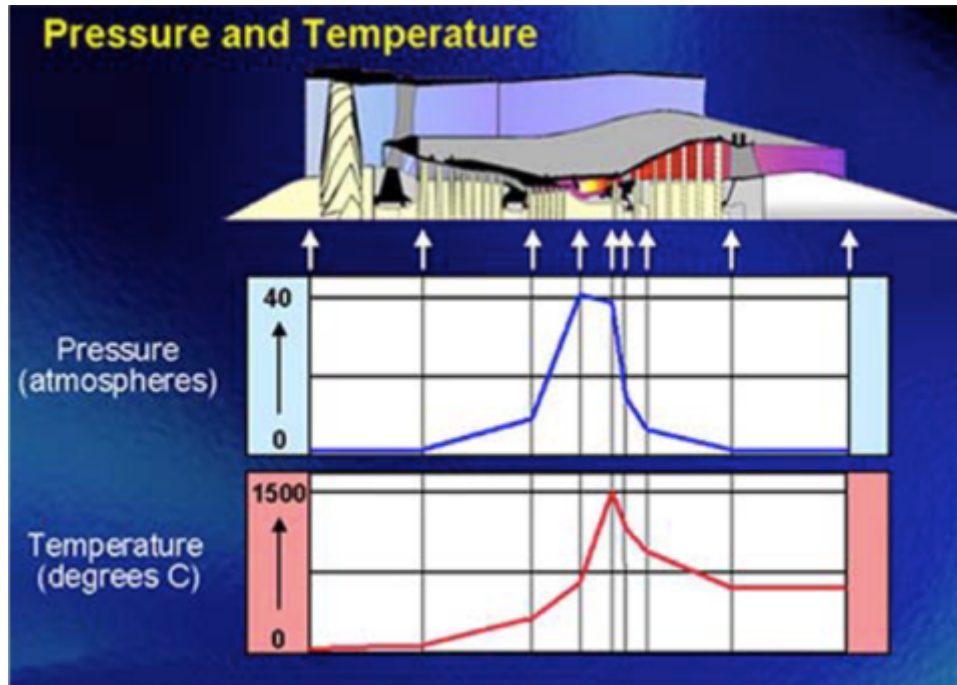
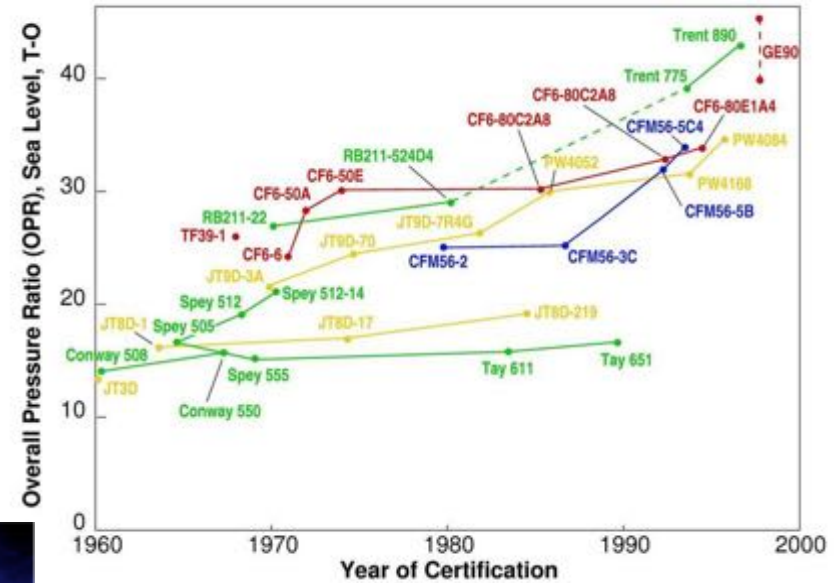
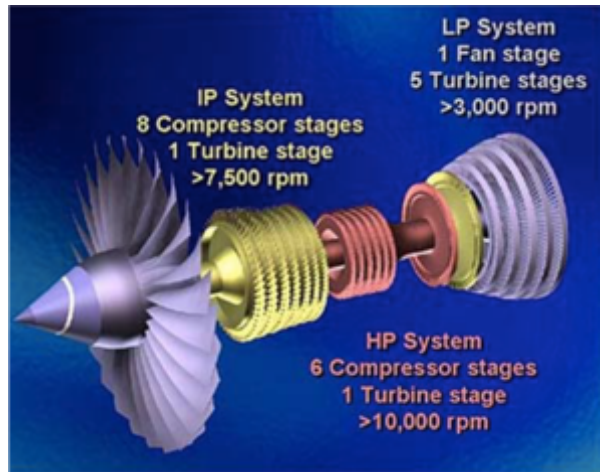
6.6.6. HIGH BYPASS JET ENGINE (TURBO FAN) FILM



6.6.6. HIGH BYPASS JET ENGINE (TURBO FAN) FILM

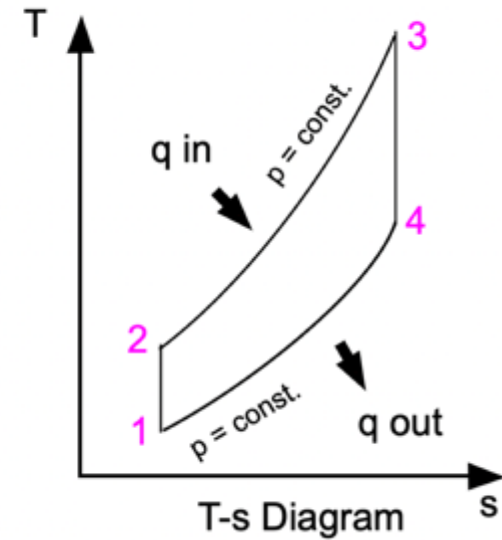
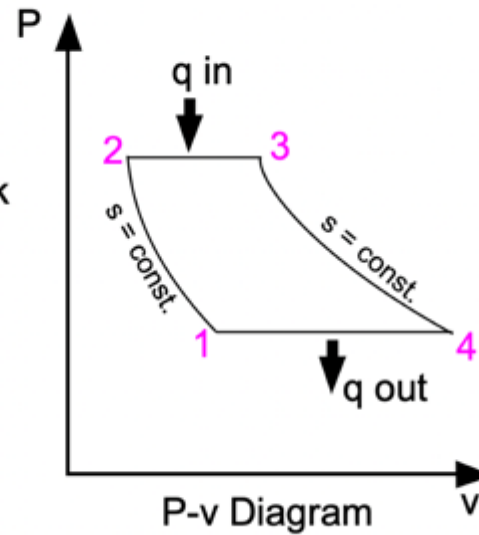
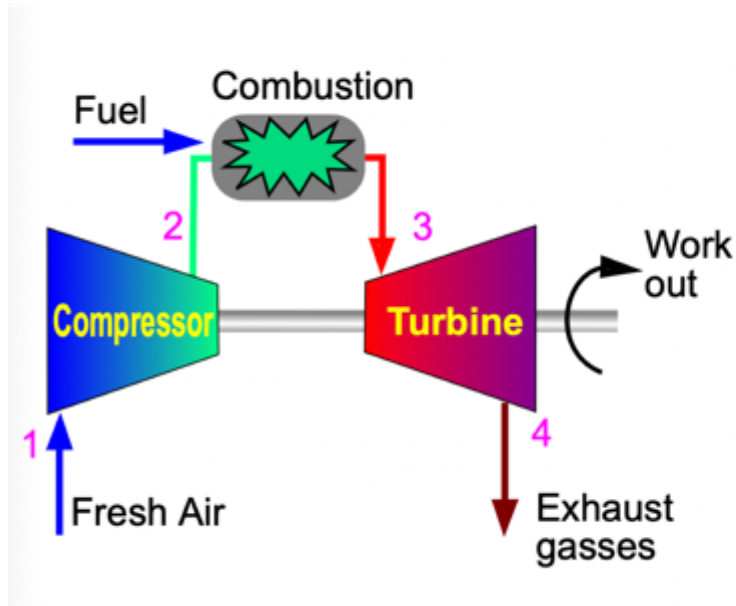


6.6.7. p and T IN THE JET ENGINES

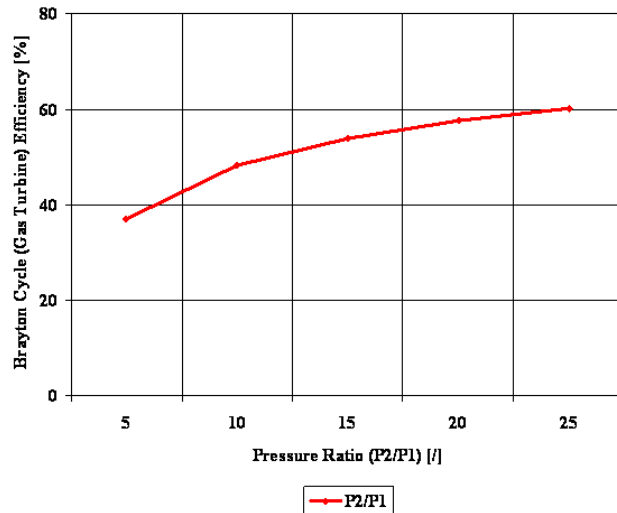


6.6.8. JET ENGINE IDEAL EFFICIENCY

Brayton Cycle



Brayton Cycle (Gas Turbine) Efficiency



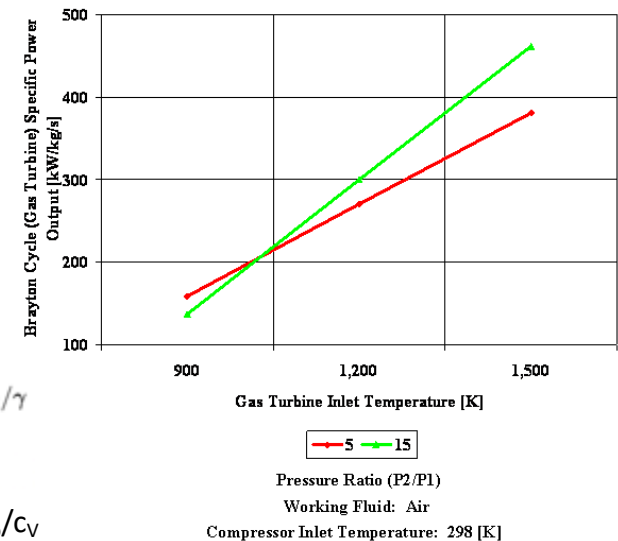
Compressor Inlet Temperature: 298 [K] -- Gas Turbine Inlet Temperature: 1,500 [K]

Efficiency:

$$\eta = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{P_1}{P_2} \right)^{(\gamma-1)/\gamma}$$

$$\gamma = c_p/c_v$$

Brayton Cycle (Gas Turbine) Specific Power Output



6.6.9. JET ENGINES TRUST & EFFICIENCY

Thrust:

$$F_N = \left(\dot{m}_{air} + \dot{m}_{fuel} \right) \cdot v_e - \dot{m}_{air} \cdot v$$

$\dot{m}_{air}$ = the mass rate of air flow through the engine

$\dot{m}_{fuel}$ = the mass rate of fuel flow entering the engine

v_e = the velocity of the jet (the exhaust plume) and is assumed to be less than sonic velocity

v = the velocity of the air intake = the true airspeed of the aircraft

$(\dot{m}_{air} + \dot{m}_{fuel})v_e$ = the nozzle gross thrust (F_G)

$\dot{m}_{air} v$ = the ram drag of the intake air

for an air-breathing engine (not rocket engine, thrust is independent of the velocity)

Efficiency:

$$\eta_0 = \eta_p \cdot \eta_{th} \cdot \eta_T \quad \text{after Bennett}$$

η_0 = energy efficiency

η_p = *propulsive efficiency*

η_{th} = *cycle efficiency*

η_T = transfer, efficiency (≈ 1)

Ref.: Aero engine development for the future, Bennett, Proc Instn Mech Engrs Vol 197A, IMechE July 1983, p.150

6.6.10. JET ENGINE PROPULSIVE EFFICIENCY

Efficiency:

Change of kinetic energy of the air entering the engine and the gas leaving the engine:

$$\Delta E_{kin} = \frac{1}{2} \left[\left(\dot{m}_{air} + \dot{m}_{fuel} \right) \cdot v_e^2 - \dot{m}_{air} \cdot v^2 \right] = F_N \cdot v$$

The propulsive efficiency is the ratio of the power supplied to aircraft divided by the energy of the jet:

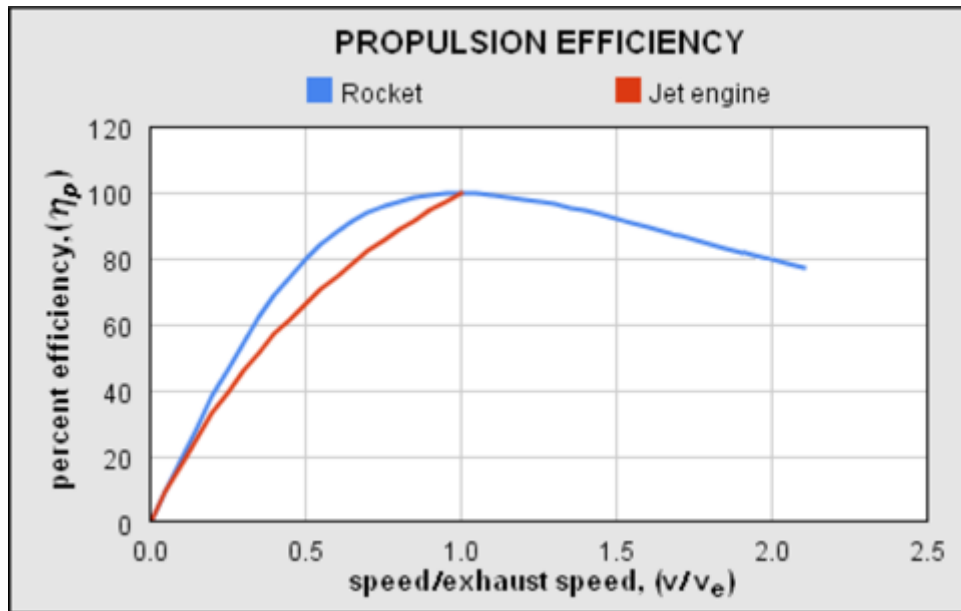
$$\eta_P = \frac{v \left[\left(\dot{m}_{air} + \dot{m}_{fuel} \right) \cdot v_e - \dot{m}_{air} \cdot v \right]}{\frac{1}{2} \left[\left(\dot{m}_{air} + \dot{m}_{fuel} \right) \cdot v_e^2 - \dot{m}_{air} \cdot v^2 \right]}$$

The mass flow of fuel is much smaller, as compared to the mass flow of air:

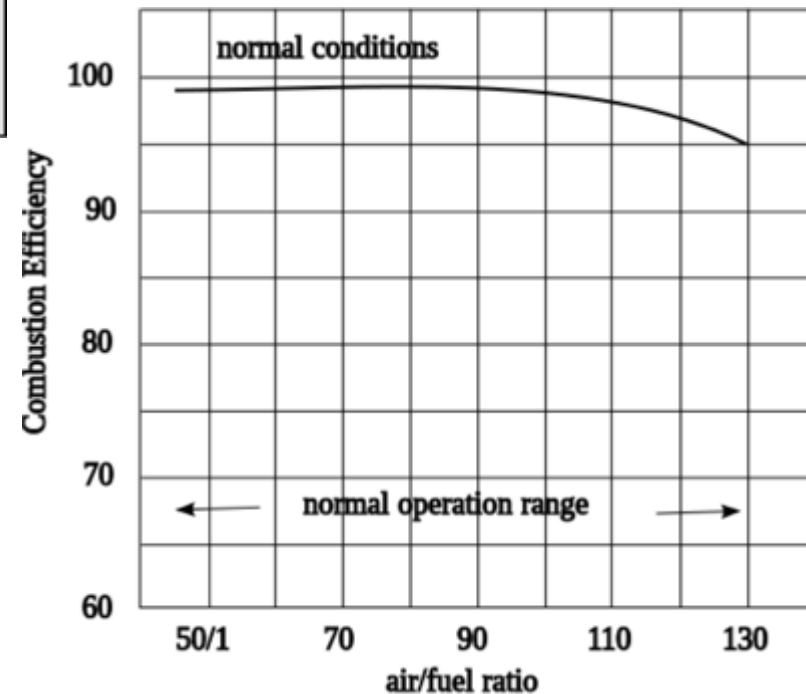
$$\eta_P = \frac{\dot{m}_{air} \cdot v \cdot [v_e - v]}{\frac{1}{2} \cdot \dot{m}_{air} [v_e^2 - v^2]} = \frac{2 \cdot v}{v + v_e}$$

Ref.: "Jet Propulsion" Nicholas Cumpsty ISBN 0 521 59674 2 p24

6.6.11. PROPULSION EFFICIENCY



Cycle efficiency (η_{th}) is highest in rocket engines (~60+%), as they can achieve extremely high combustion temperatures. Cycle efficiency in turbojet and similar is nearer to 40%, due to much lower peak cycle temperatures.



Ref.: "Jet Propulsion" Nicholas Cumpsty ISBN 0 521 59674 2 p24

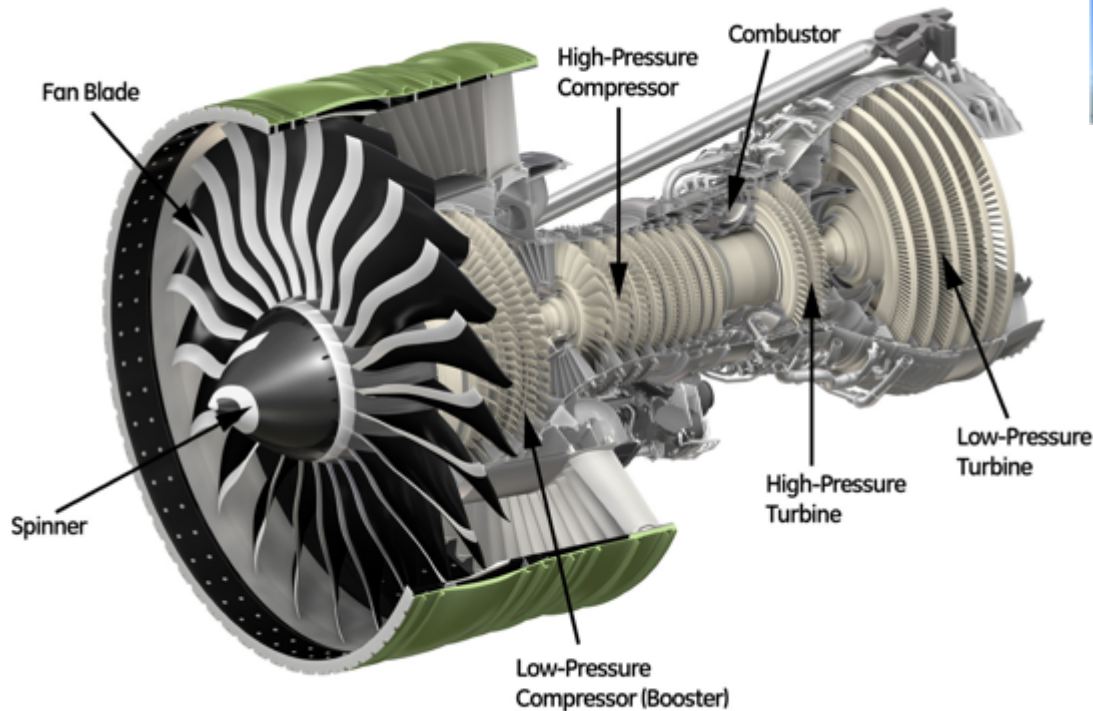
6.6.12. JET ENGINE SPECIFICATIONS

Specific fuel consumption (SFC), specific impulse, and effective exhaust velocity numbers for various rocket and jet engines.

Engine type	Scenario	SFC in lb/(lbf·h)	SFC in g/(kN·s)	Specific impulse (s)	Effective exhaust velocity (m/s)
NK-33 rocket engine	Vacuum	10.9	308	331 ^[71]	3250
SSME rocket engine	Space shuttle vacuum	7.95	225	453 ^[72]	4440
Ramjet ^[verification needed]	Mach 1	4.5	130	800	7800
J-58 turbojet	SR-71 at Mach 3.2 (Wet)	1.9 ^[73]	54	1900	19000
Eurojet EJ200	Reheat	1.66–1.73	47–49 ^[74]	2080–2170	20400–21300
Rolls-Royce/Snecma Olympus 593 turbojet	Concorde Mach 2 cruise (Dry)	1.195 ^[75]	33.8	3010	29500
Eurojet EJ200	Dry	0.74–0.81	21–23 ^[74]	4400–4900	44000–48000
CF6-80C2B1F turbofan	Boeing 747-400 cruise	0.605 ^[75]	17.1	5950	58400
General Electric CF6 turbofan	Sea level	0.307 ^[75]	8.7	11700	115000

Ref.: "Jet Propulsion" Nicholas Cumpsty ISBN 0 521 59674 2 p24

6.6.13. BOEING 777 JET ENGINES



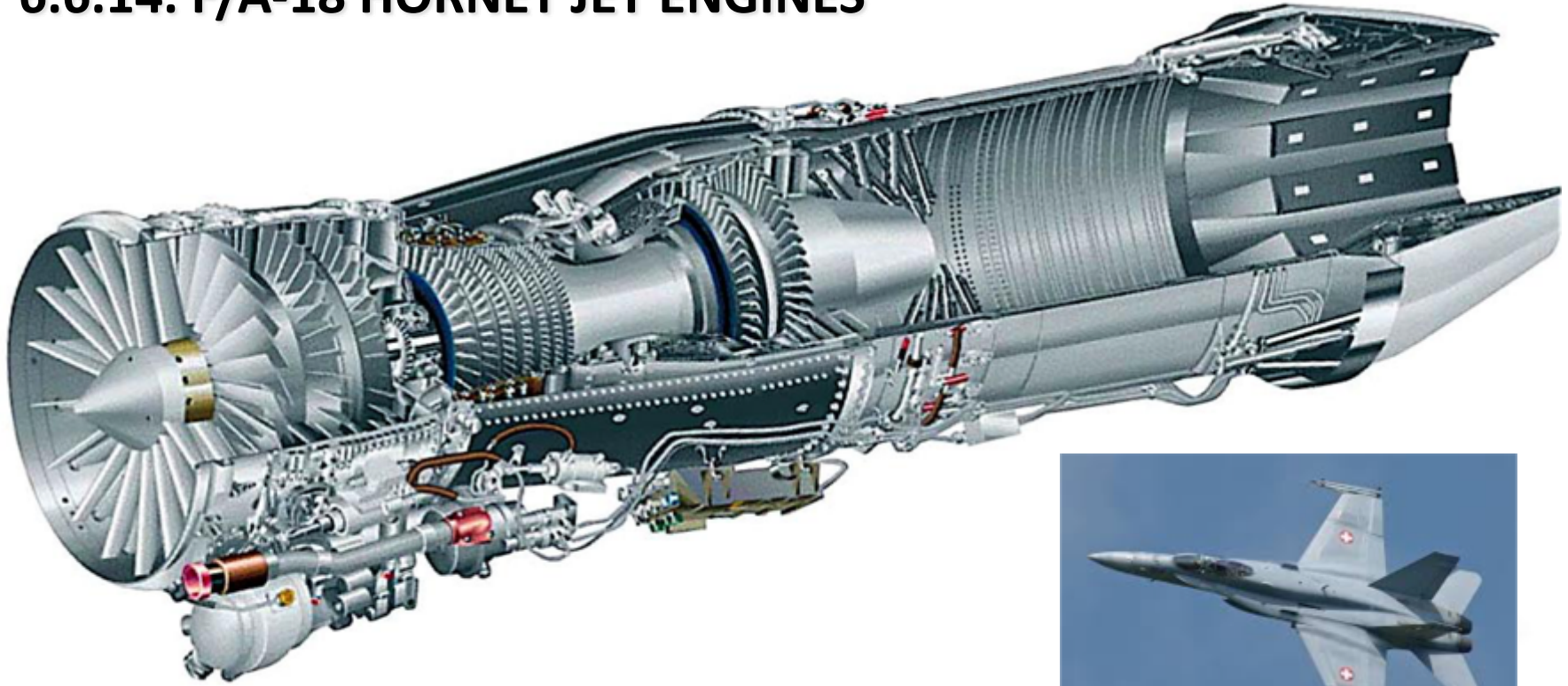
Boeing 777, 350 t

Boeing 777

Engines: 2 * 489 kN General Electric 90-115B turbofans
 2 * 519 kN for take off

145'000 kg Kerosene in 16 h $P_{th} = 90$ MW thermal

6.6.14. F/A-18 HORNET JET ENGINES



F/A-18 Hornet, 25 t

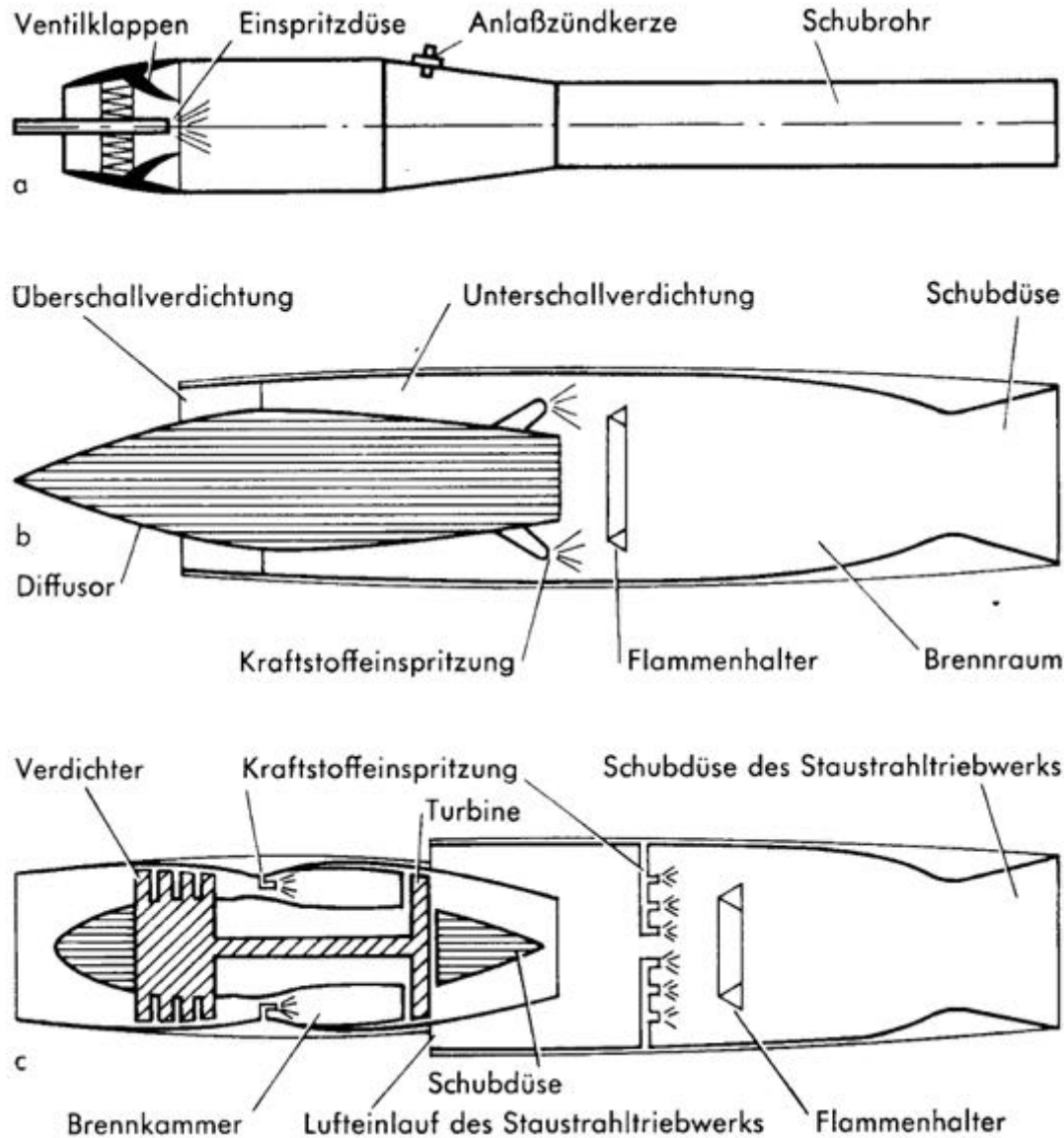
F/A-18 Hornet, McDonnell-Douglas

Engines: 2 * 79 kN General Electric F404-GE-402 turbofans
 2 * 53 kN without after burner

5126 kg Kerosen in 105 min. wo after burner, 8 min w. ab

$P_{th} = 30 \text{ MW}$ wo. after burner, 384 MW w. ab.

6.6.15. FIRST PROPULSION ENGINES



6.6.16. PULSE PROPULSION ENGINES

ANIMATION OF A PULSE JET ENGINE



6.6.17. V1 ROCKET FILM



FZG in Karlshagen, June 1944

6.6.17. V1 ROCKET FILM



FZG in Karlshagen, June 1944

EXERCISE

- 1) Calculate the Carnot efficiency and “real” efficiency of the steam turbine if the dry steam enters with 500°C and leaves the turbine with 120°C . How much coal does a power station with 1 GW_{el} use per day?
- 2) Calculate the minimum adiabatic compression from 20°C and 1 bar in order to reach the auto ignition temperature of Methane (632°C).
- 3) Calculate the temperature and volume increase due to the combustion in the gas turbine.
- 4) Calculate the acceleration of an airplane at take off, when it reaches 280 km/h in 30 sec. What is the consumption of fuel ($m = 550\text{ t}$) for take off.
- 5) Calculate the energy consumption of an airplane per passenger and 100 km. (A380, 10'000 km, 550 passenger, 130'000 kg kerosene)