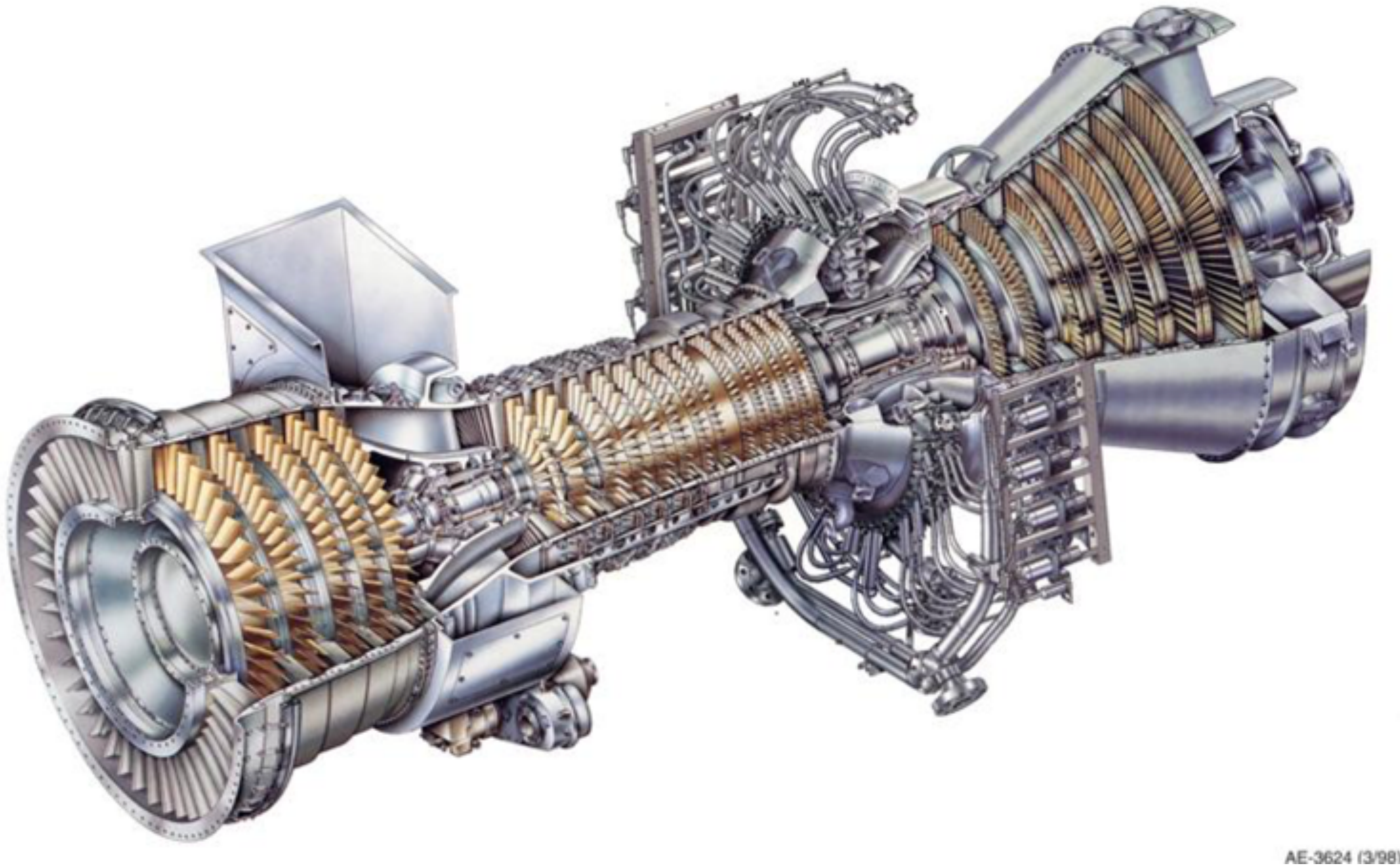
Thermodynamics of energy conversion

6) TURBINES

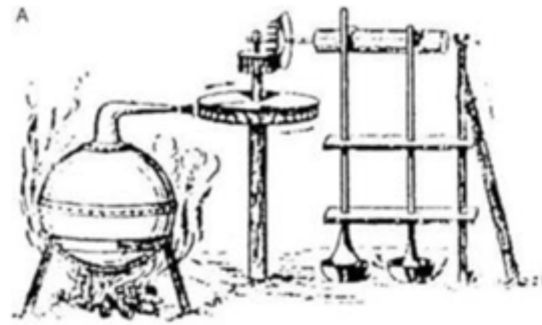


6. TURBINES

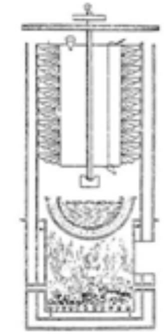
6. 1. HISTORY OF TURBINES

Aeolipile

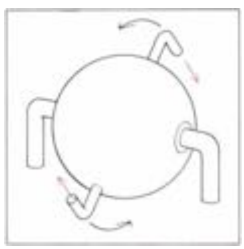
Hero of Alexandria
1st century CE



1629 in Italy



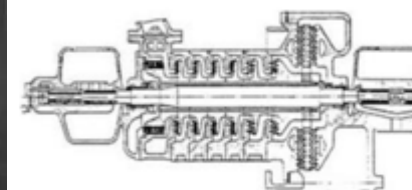
1784 James Watt patented
reaction and impulse turbines



1837 William Avery (1793-1840)
USA

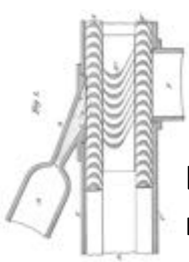
Laval Nozle

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



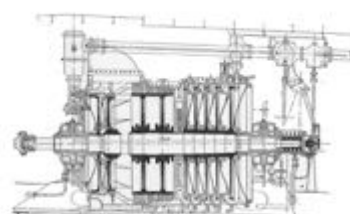
multi stage

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



Laval nozle &
multi stage

1890 Charles G. Curtis (1860 – 1953)
USA



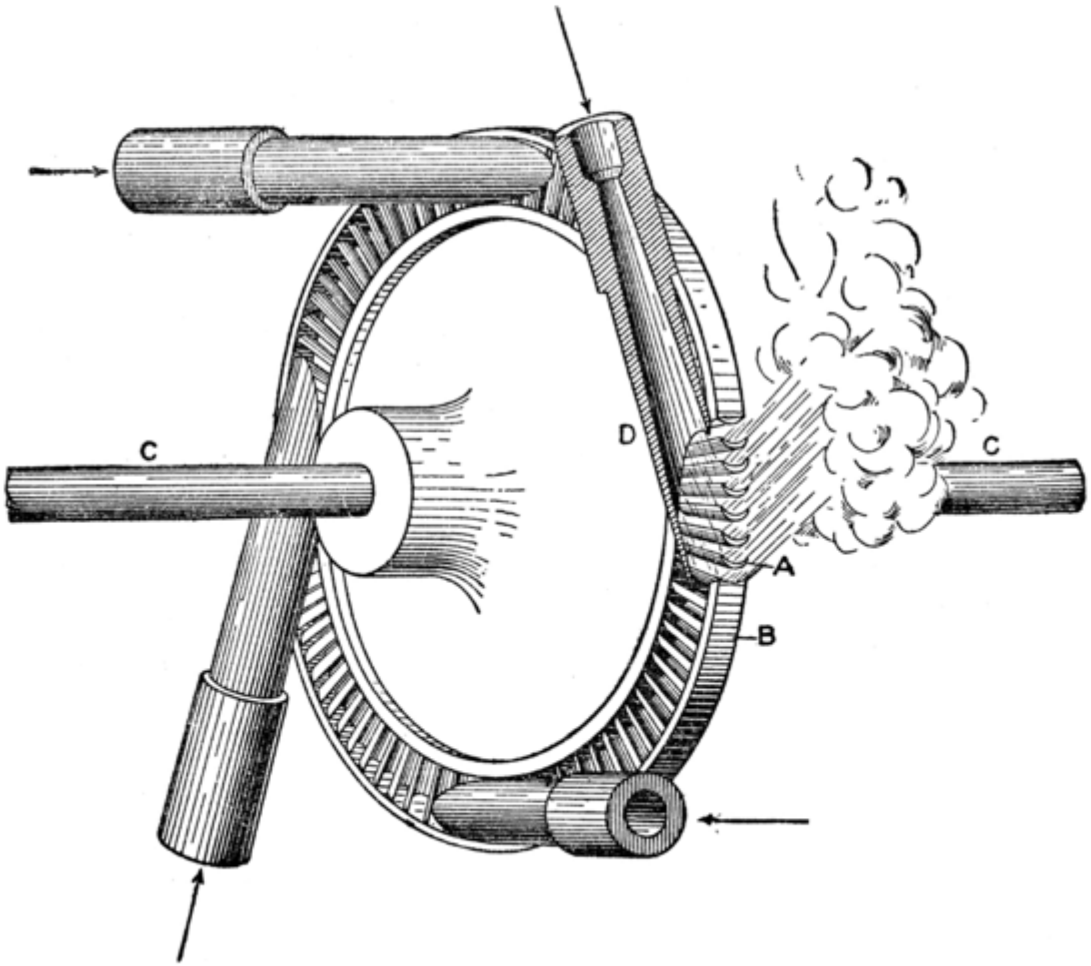
1905 Allgemeine Elektrizitäts-Gesellschaft
AG (AEG) marine steam turbine, Germany

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

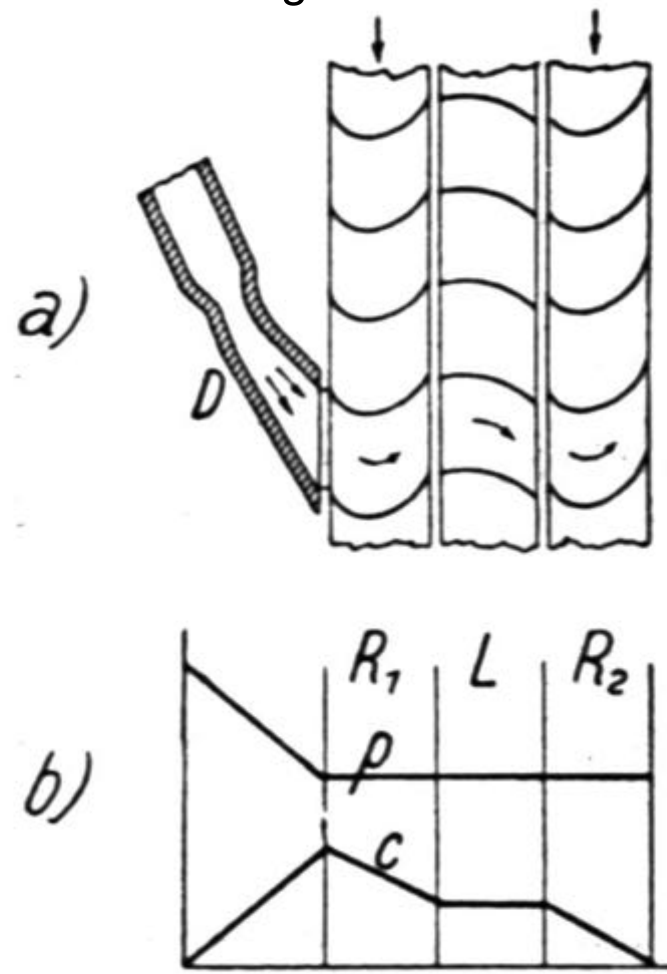
6.2. NOZLE

Carl Gustaf Patrik de Laval
1845 – 1913
Schweden

Single stage LAVAL-Steam turbine

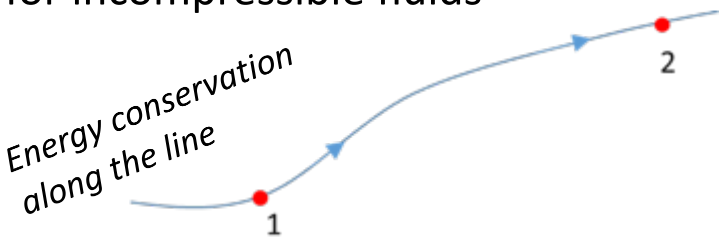


Multi Stage CURTIS-turbine



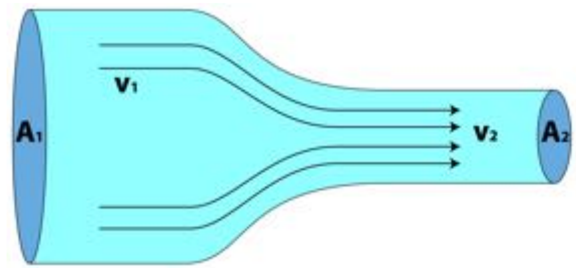
6.2.1. VENTURI EFFECT

Bernoulli Equation
for incompressible fluids

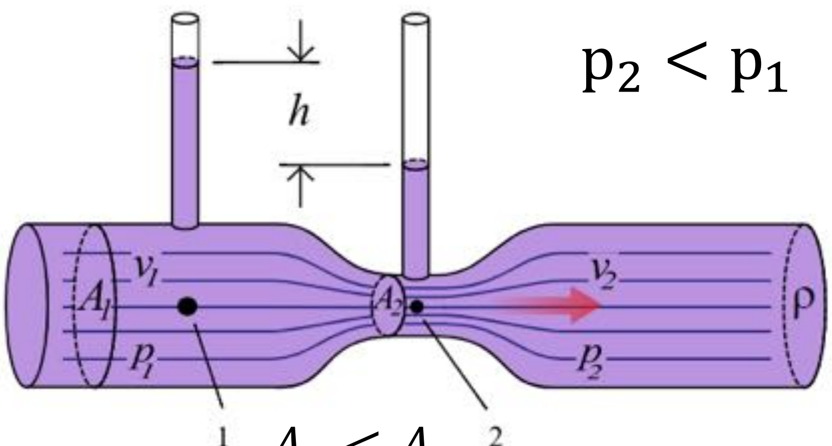


$$p_1 + \rho g\, h_1 + \frac{1}{2}\rho v_1^2 = p_2 + \rho g\, h_2 + \frac{1}{2}\rho v_2^2$$

Equation of continuity



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



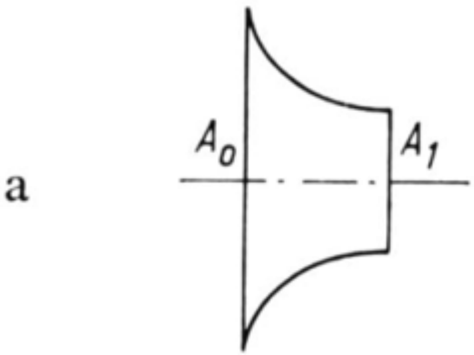
$A_2 < A_1$

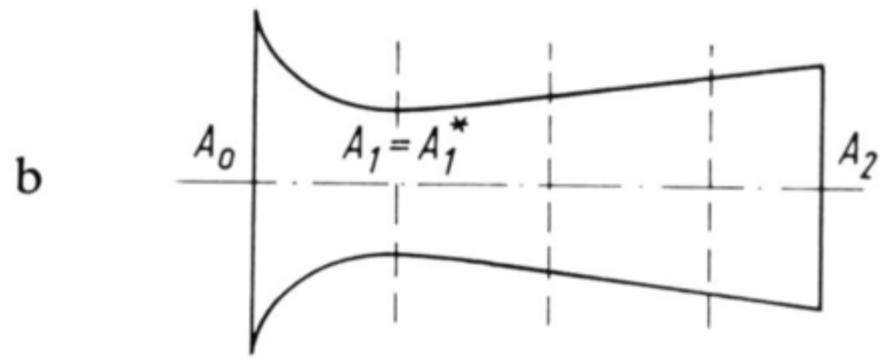
$p_2 < p_1$

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

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

6.2.2. ADIABATIC EXPANSION





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

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

6.2.3. LAVAL EQUATION

$$C_p = C_V + R$$

$$\kappa = \frac{c_p}{c_V} \qquad \frac{\rho}{\rho_0} = \left(\frac{p}{p_0}\right)^{\frac{1}{\kappa}} = \left(\frac{T}{T_0}\right)^{\frac{1}{\kappa-1}}$$

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

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

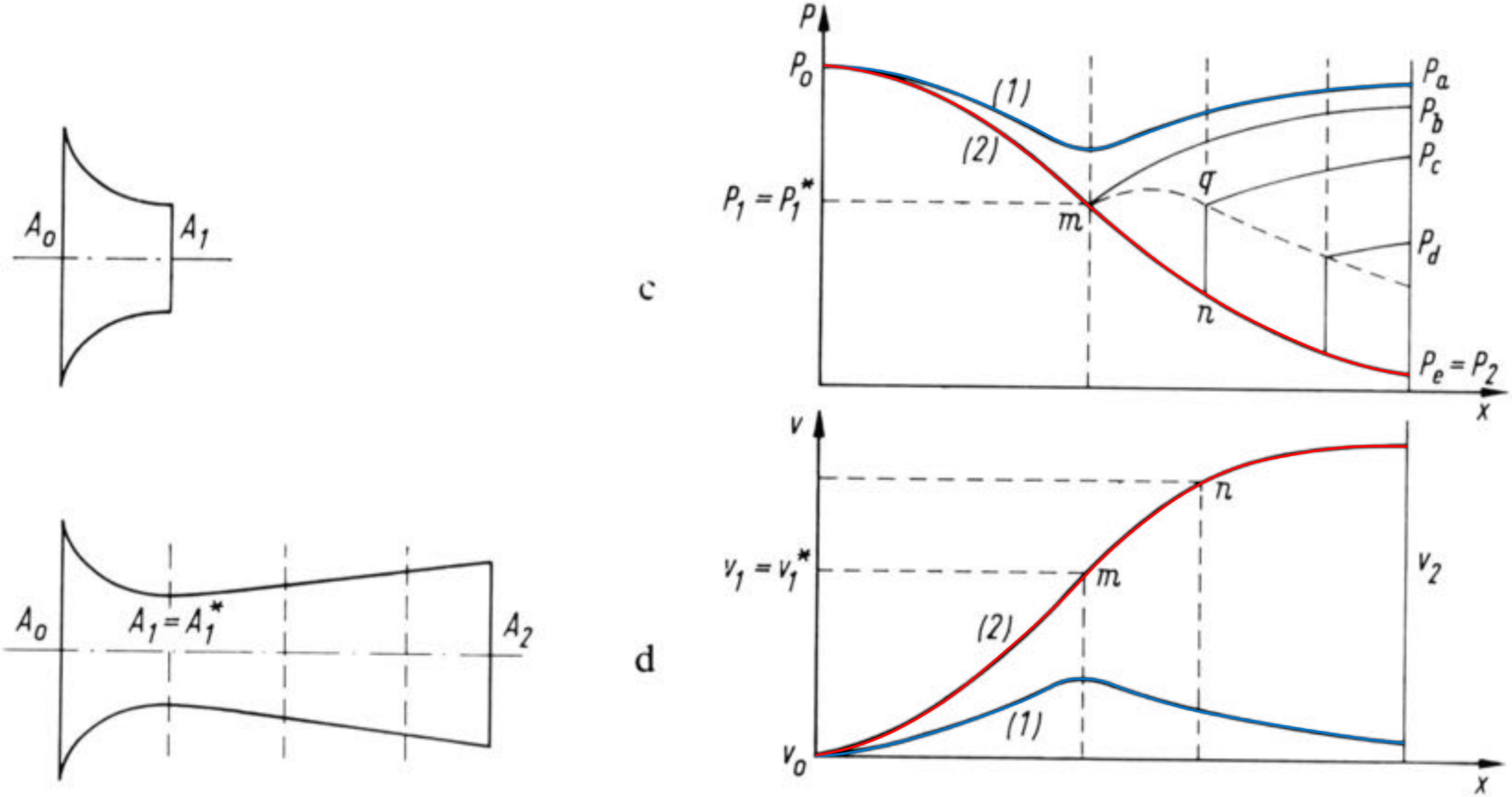
massflow max. for $p^* = p_0\cdot\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}}$ LAVAL pressure $v^* = \sqrt{\kappa\cdot\frac{p_1}{\rho_1}}$

6.2.4. PRESSURE AND VELOCITY IN LAVAL NOZLE

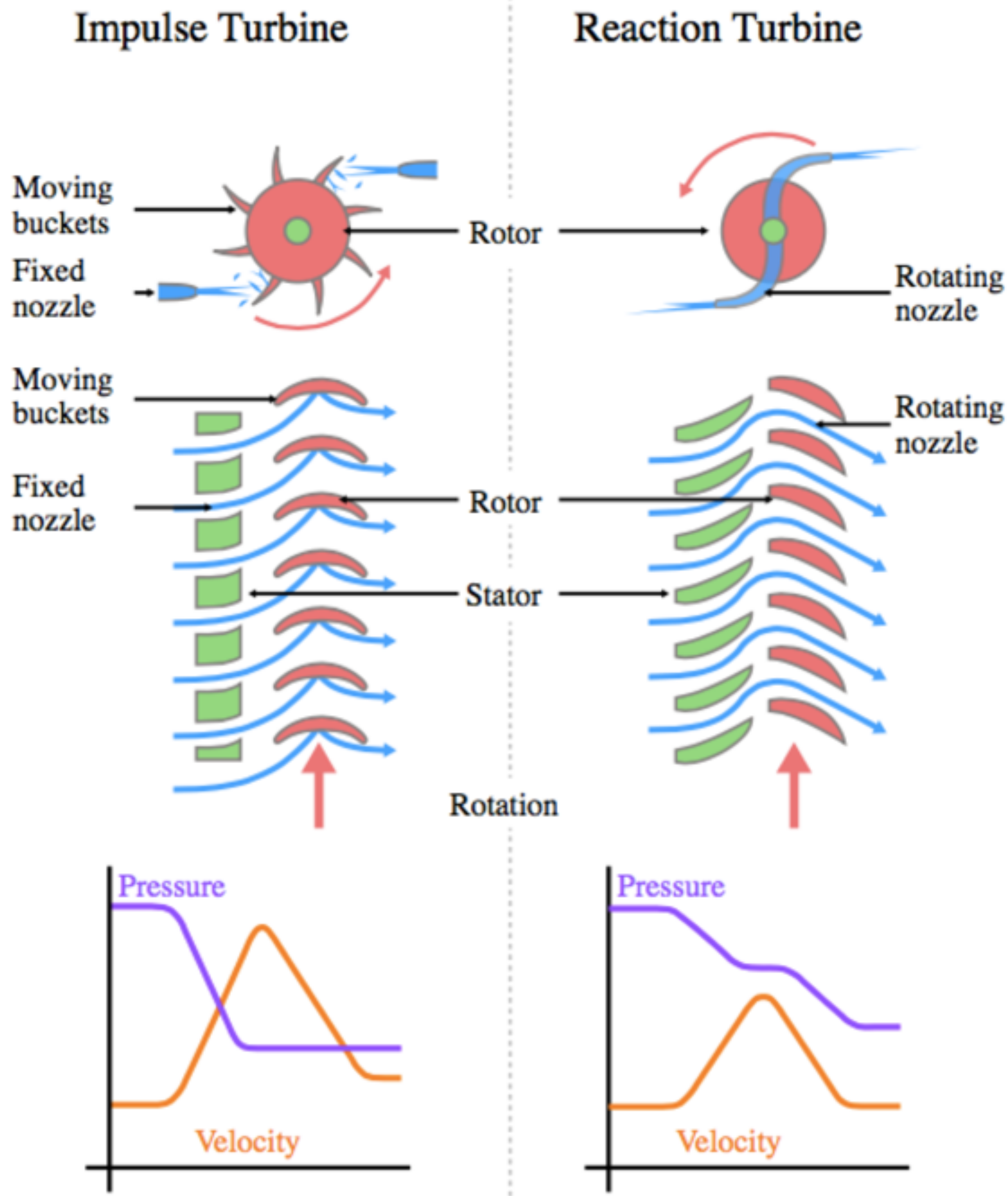
$$\rho \cdot v = f(p) = \sqrt{2 \cdot \rho_0 \cdot p_0 \cdot \frac{\kappa}{\kappa - 1}\left[\left(\frac{p}{p_0}\right)^{\frac{2}{\kappa}} - \left(\frac{p}{p_0}\right)^{\frac{\kappa-1}{\kappa}}\right]}$$

(1)

(2)



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.

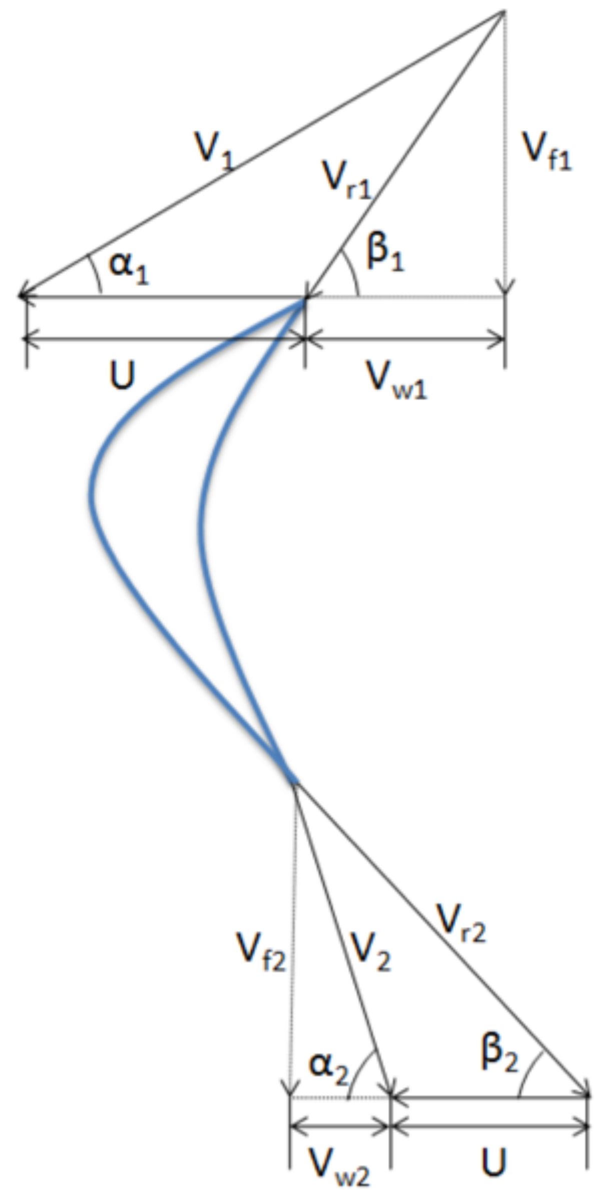
v_{w1} + U and v_{w2} are the swirl velocities at the inlet and outlet respectively.

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

blade velocity → u; Δ velocity → Δv_w; inlet velocity → v_1^2

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

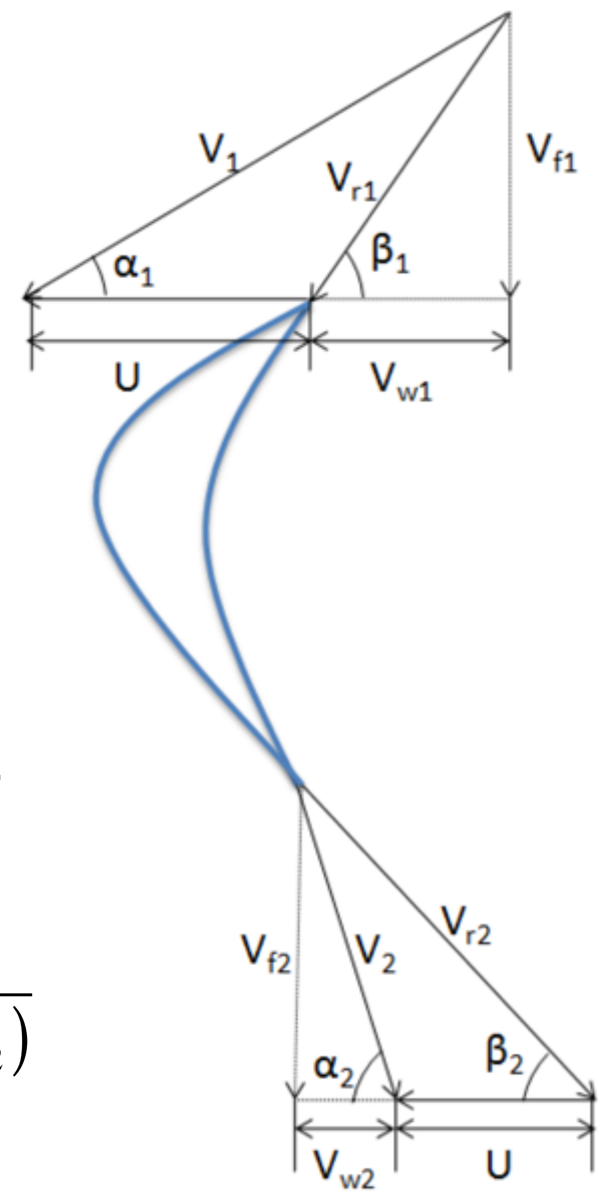
Stage efficiency:

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

blade velocity → u; Δ velocity → Δv_w; outlet velocity → v_2^2

$$\eta_{stage} = \frac{u \cdot \Delta v_w}{\Delta h} = \eta_{blade} \cdot \eta_{nozzle} = \eta_{blade} \cdot \frac{v_2^2}{2 \left(h_1 - h_2 \right)}$$

Δh: difference in specific enthalpy

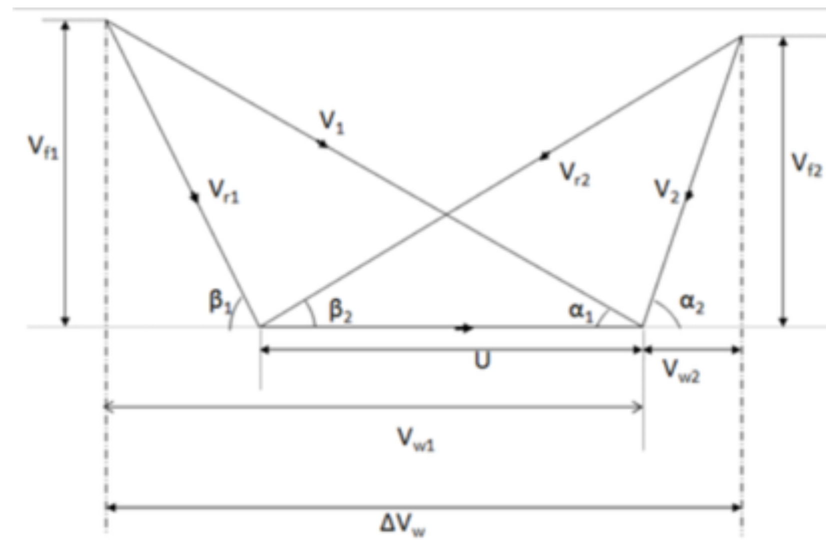


6.3.3. EFFICIENCY REACTION TURBINE

Blade efficiency:

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

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

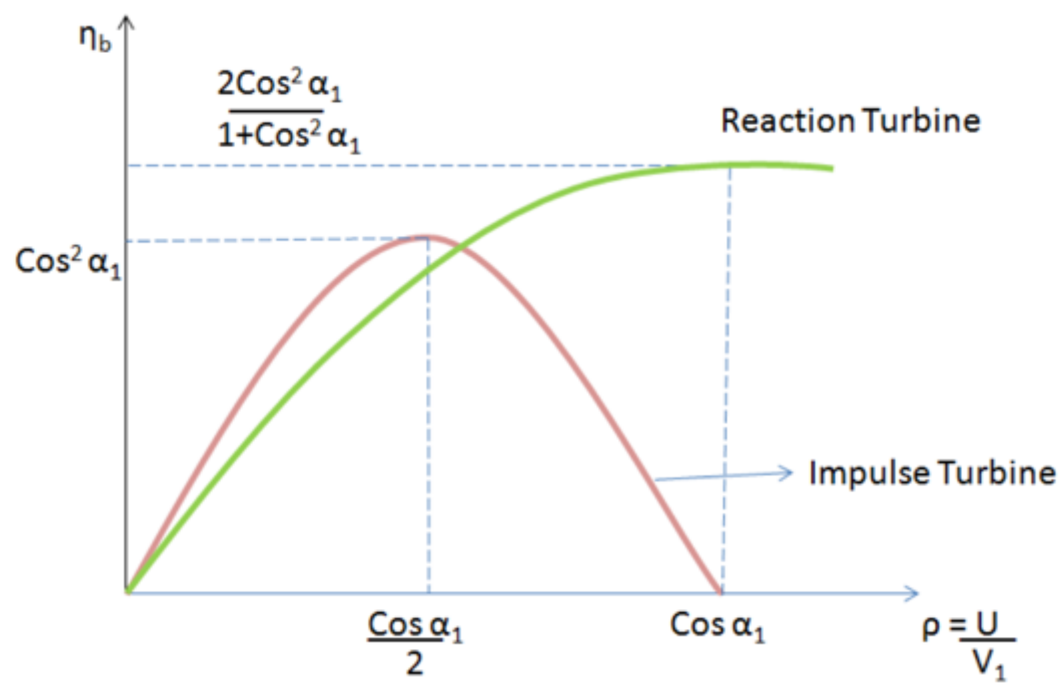


reaction:

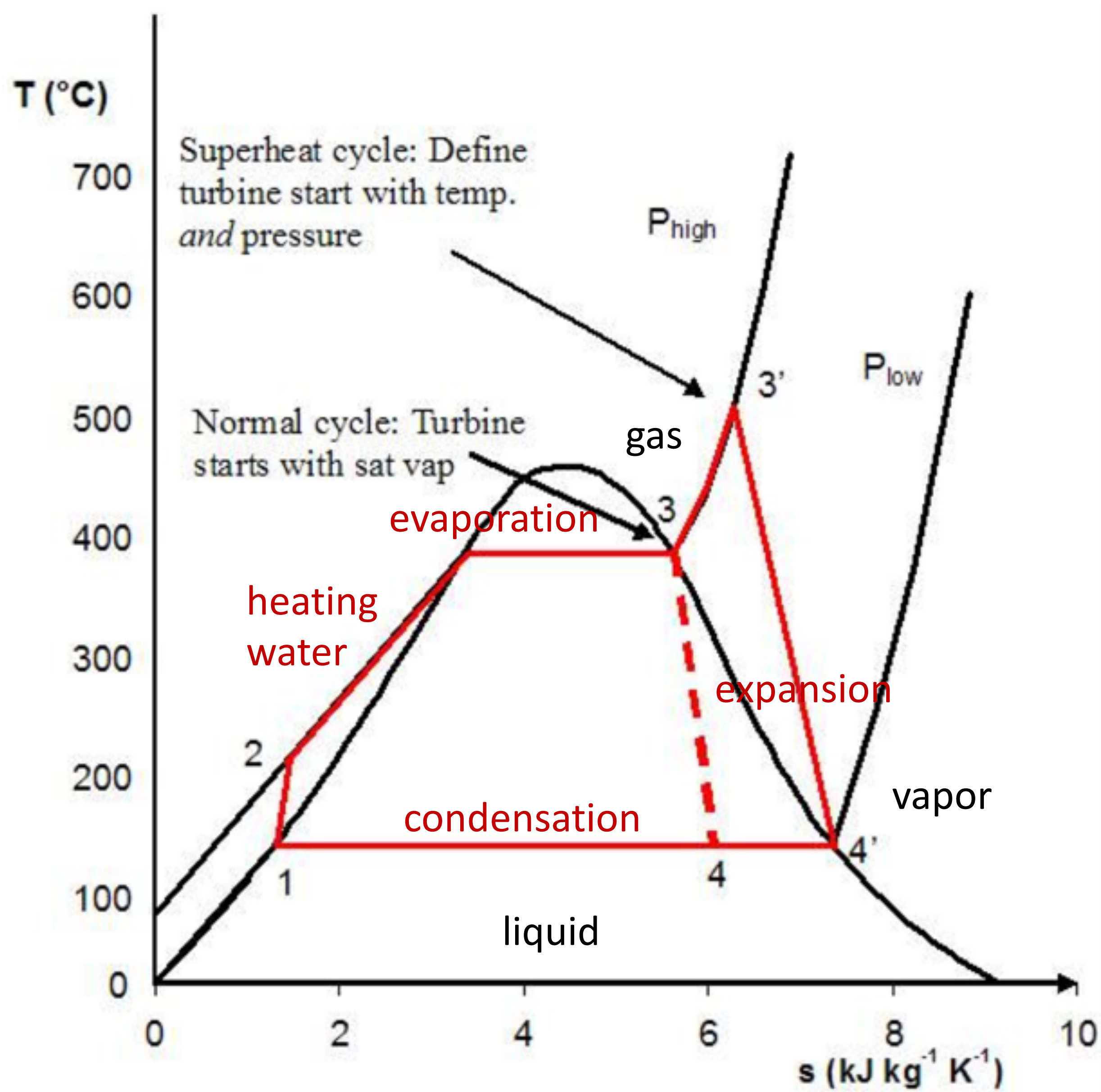
$$\eta_{blade} = \frac{2 \cdot \cos^2\alpha_1}{1 + \cos^2\alpha_1}$$

impulse:

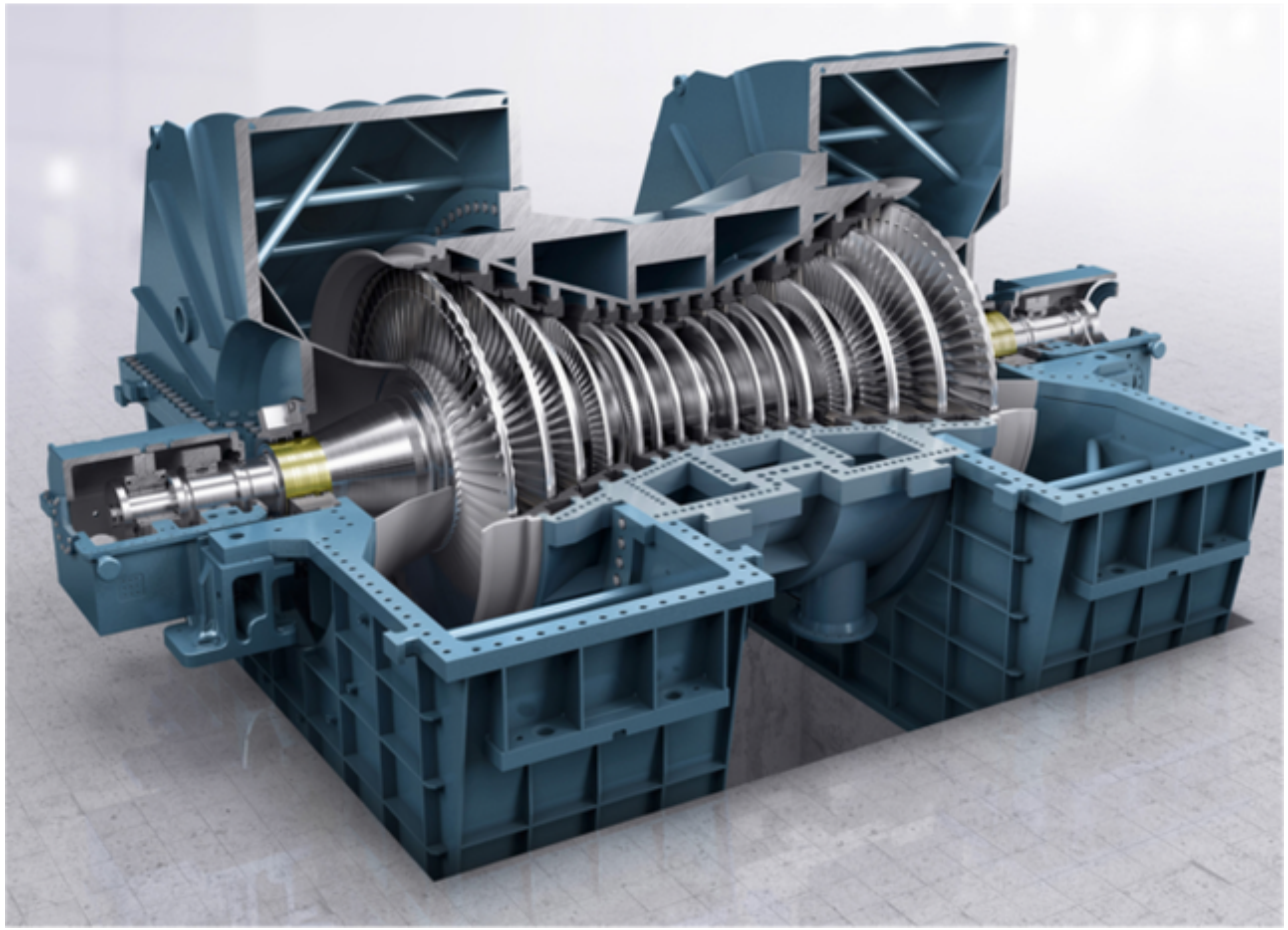
$$\eta_{blade} = \cos^2\alpha_1$$



6.3.4. T-S DIAGRAM FOR STEAM



6.3.5. MODERN STEAM TURBINE



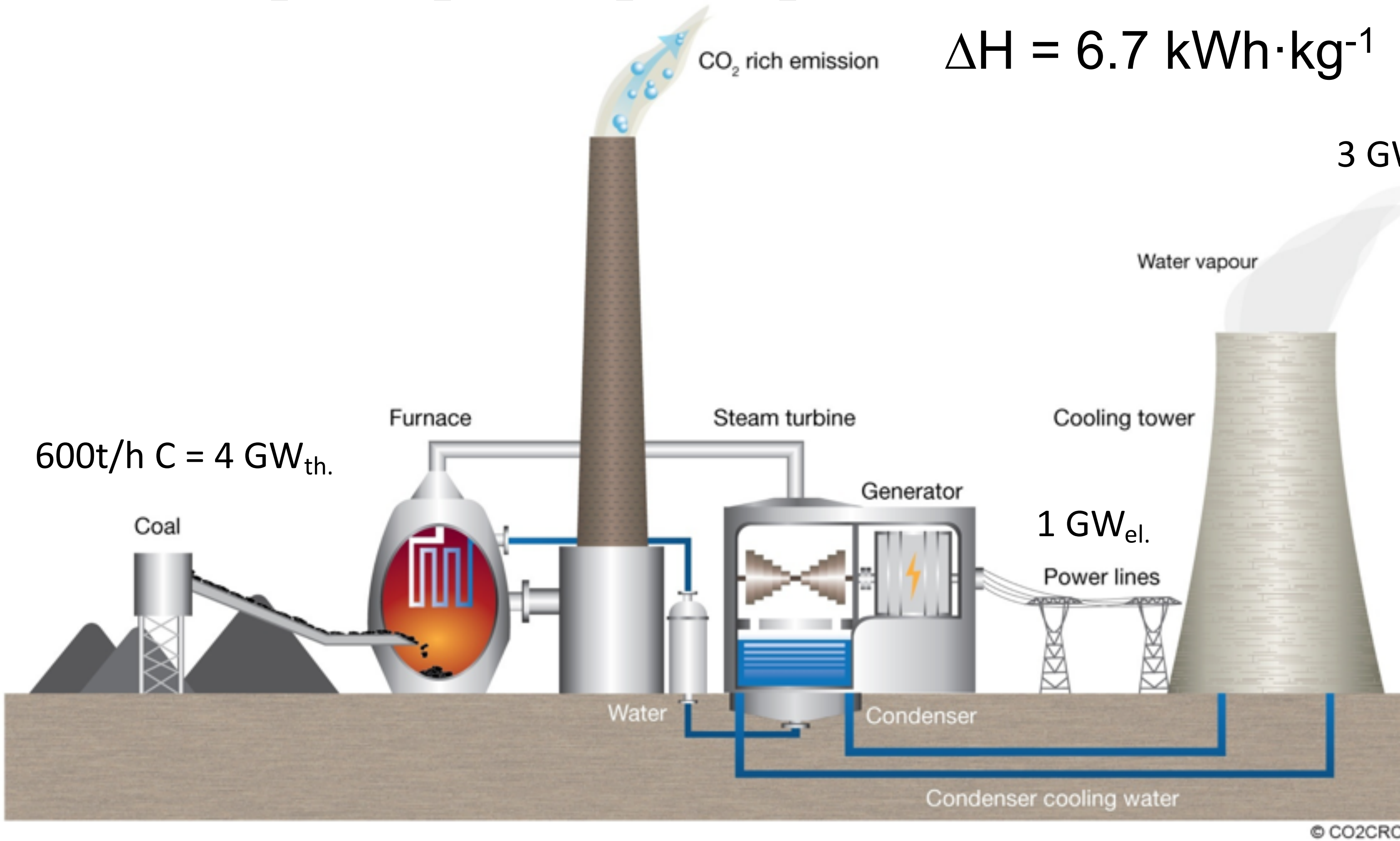
P = 10 kW – 1.9 GW
p = 10 – 250 bar
T = 300°C – 600°C

6.4. COAL FIRED POWER STATION

$$C + O_2 + 5\,N_2 \rightarrow CO_2 + 5\,N_2$$

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

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



Coal Furnace Turbine Generator Cooling Tower

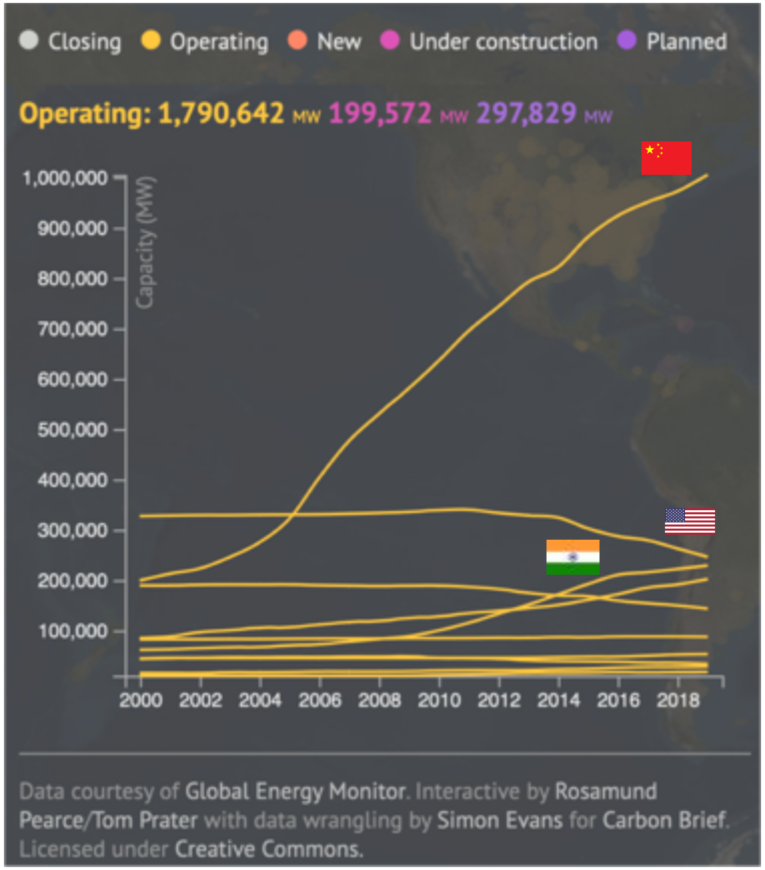
1 $GW_{el.}$ needs 600 t Coal / h

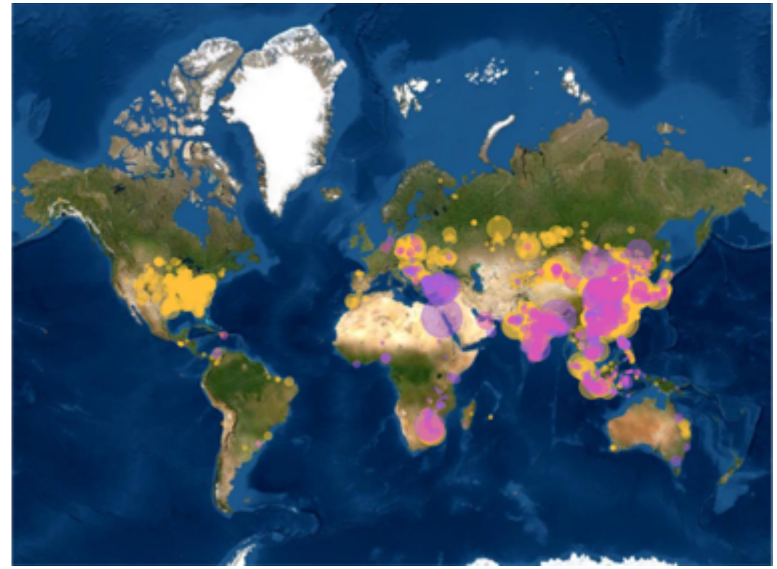
/h

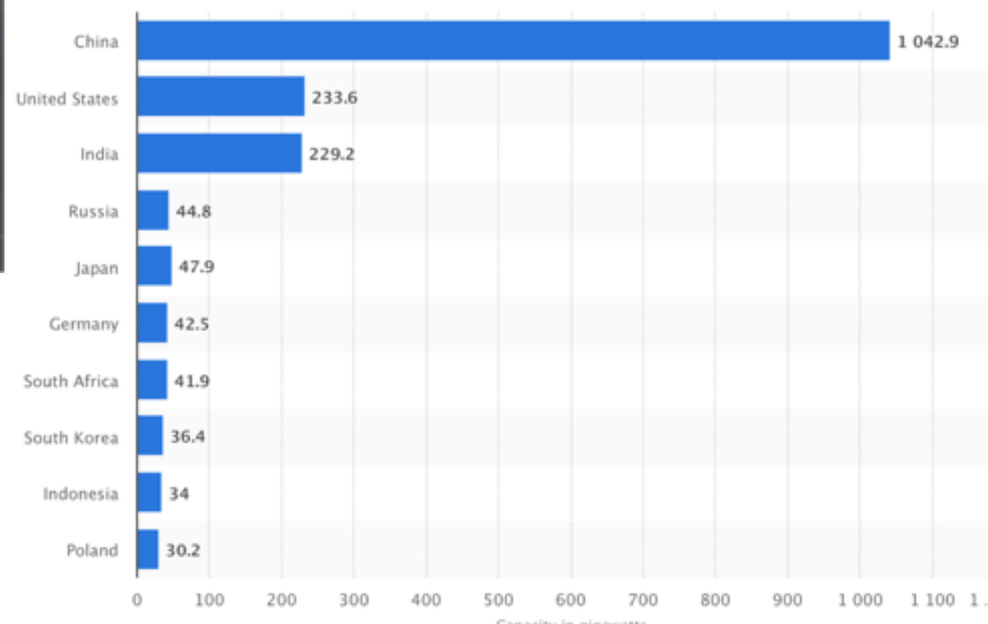
6.4.1. PHOTO OF COAL FIRED POWER STATION WITH COAL MINE

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





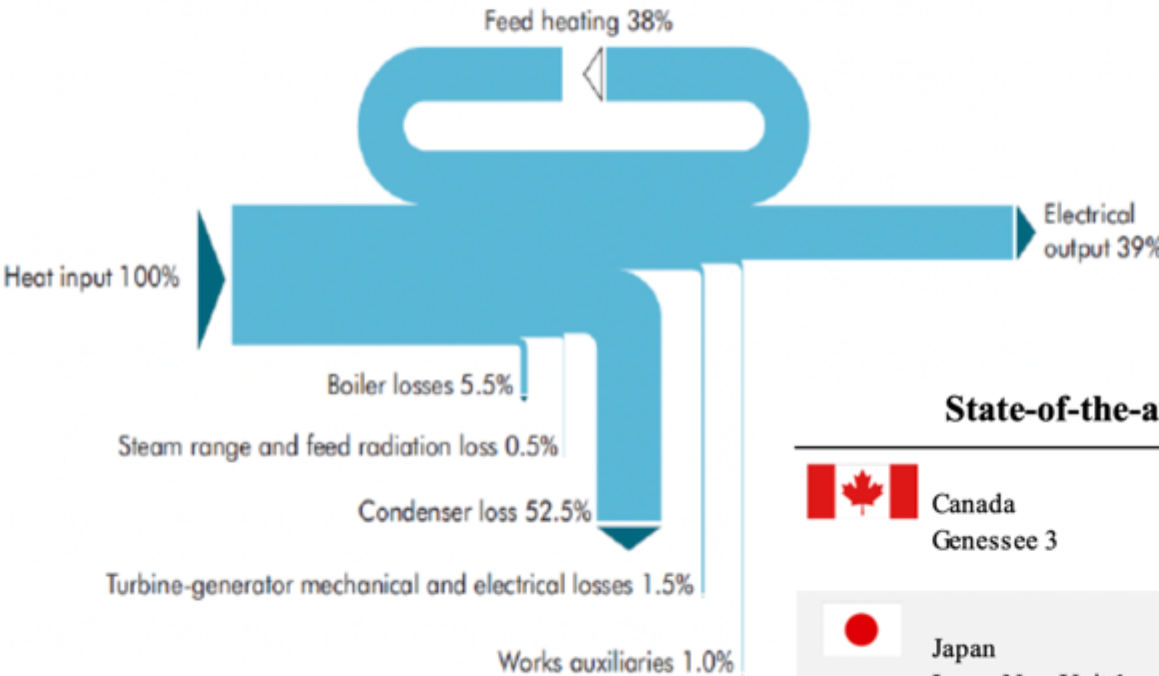


Total operating:	1’791 GW
China:	1’005 GW
Closing:	300 GW
Under construction:	300 GW
Planned:	298 GW

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

6.4.3. EFFICIENCY COAL FIRED POWER STATION

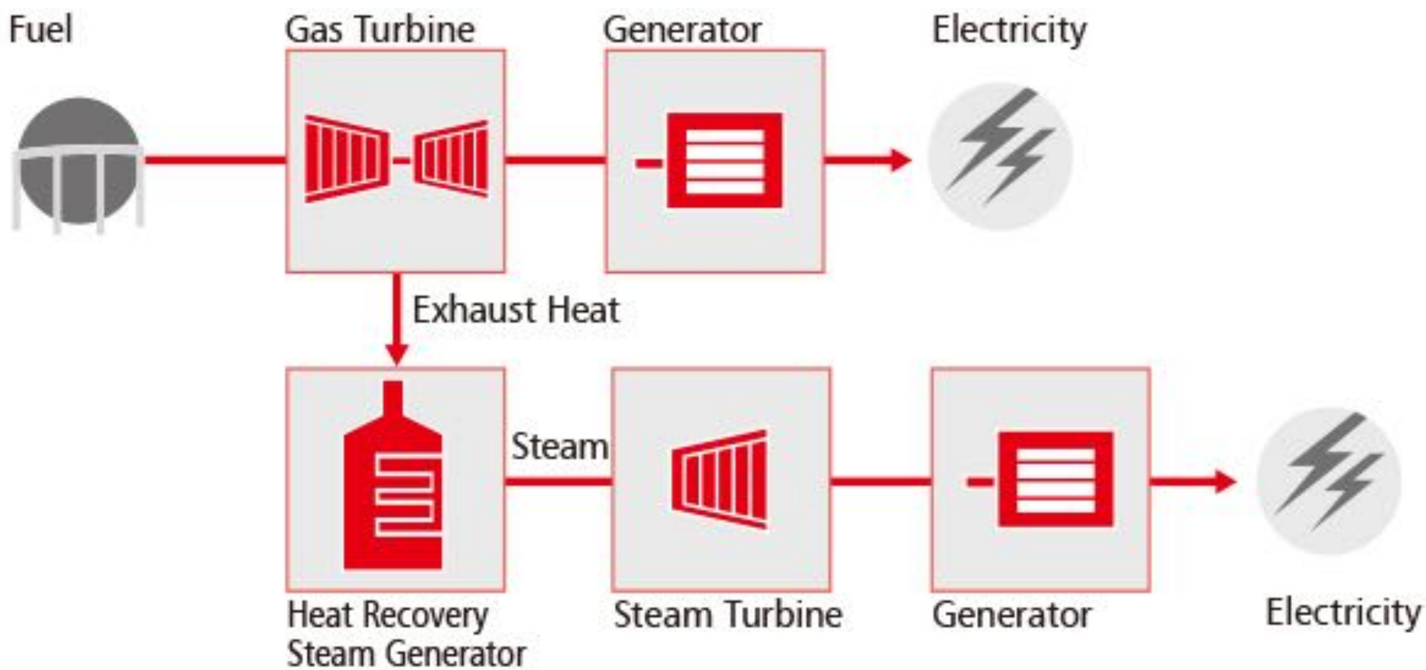
Energy flows in a typical 500 MW subcritical pulverized coal-fired boiler

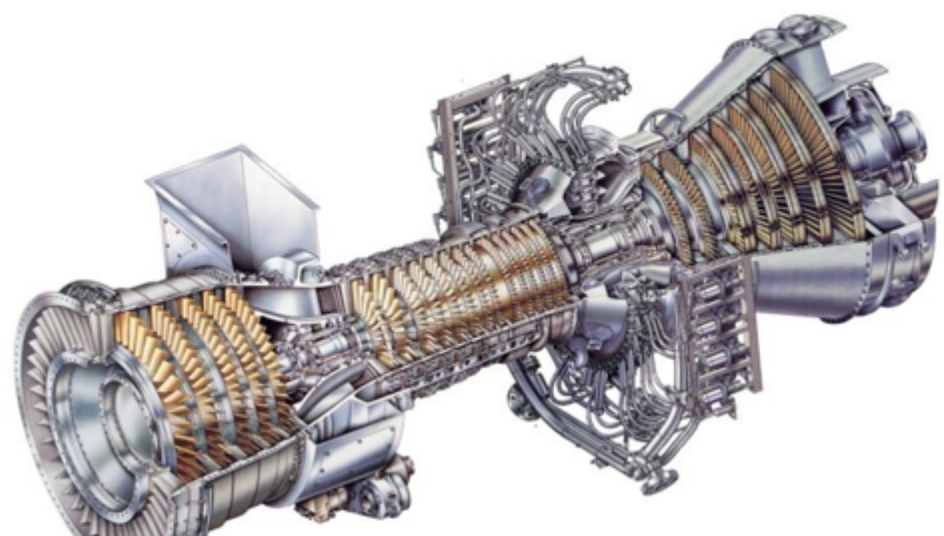


State-of-the-art coal-fired power plants

	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%

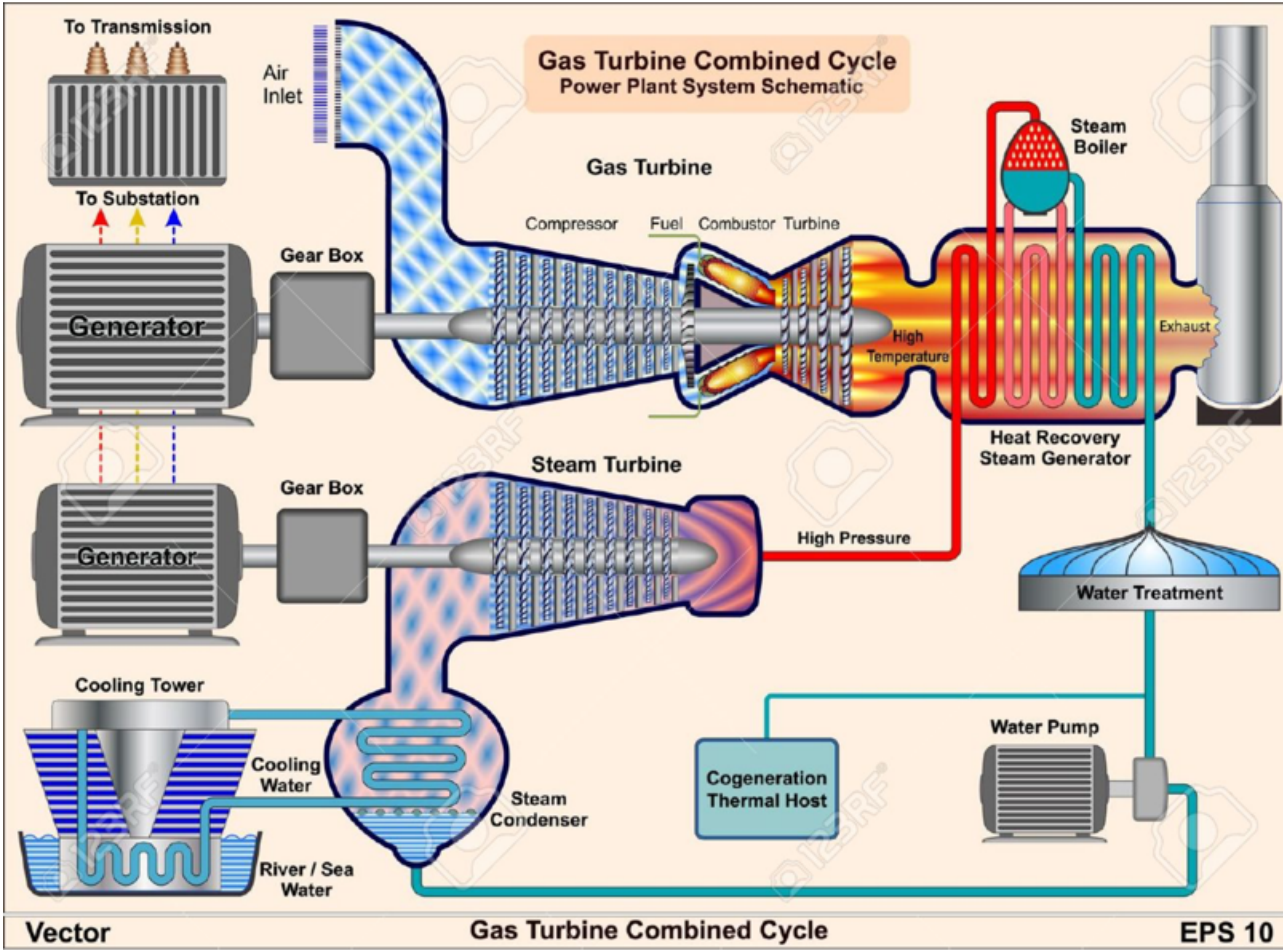
6.5. COMBINED CYCLE POWER STATION (Natural Gas)



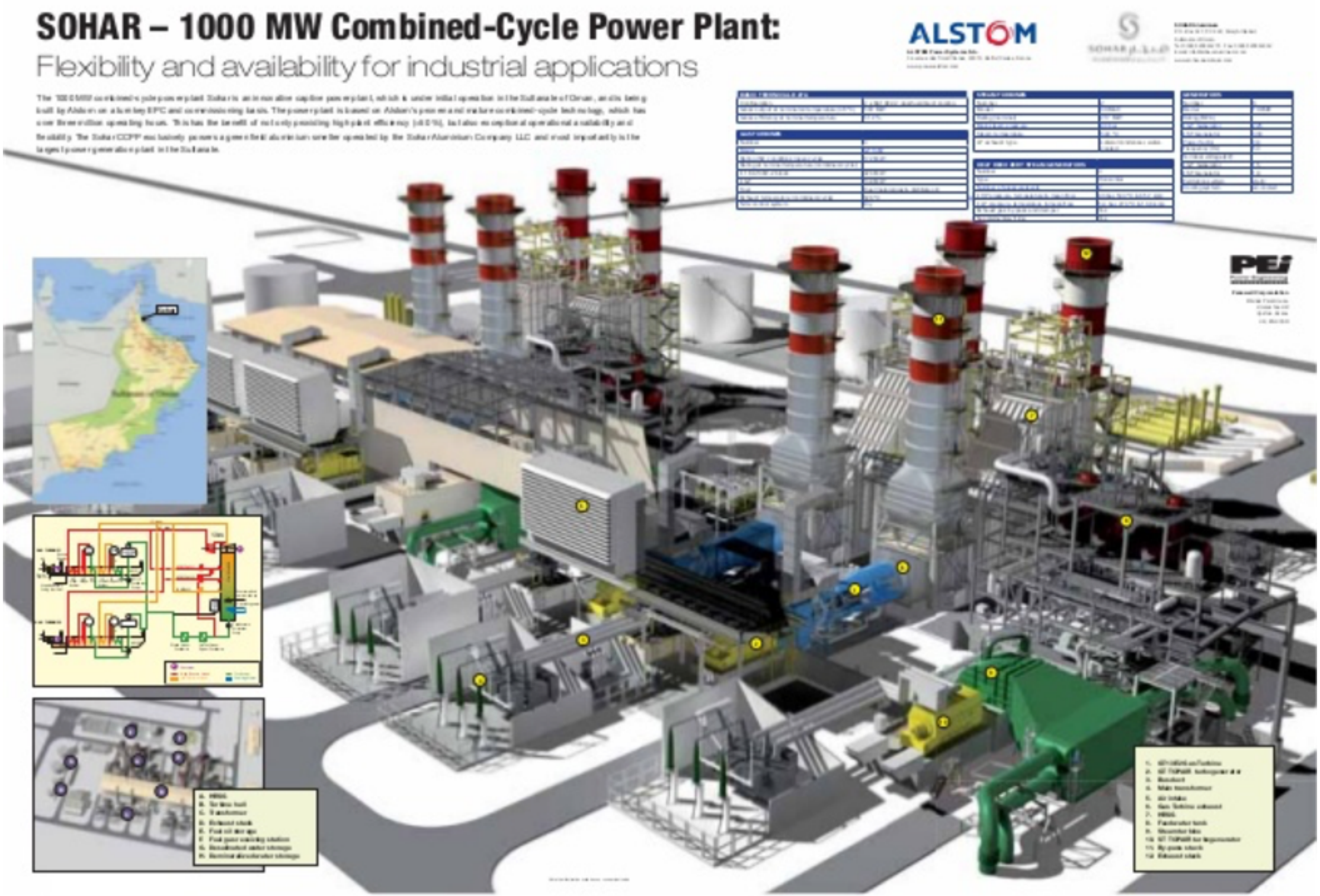


Gas turbine

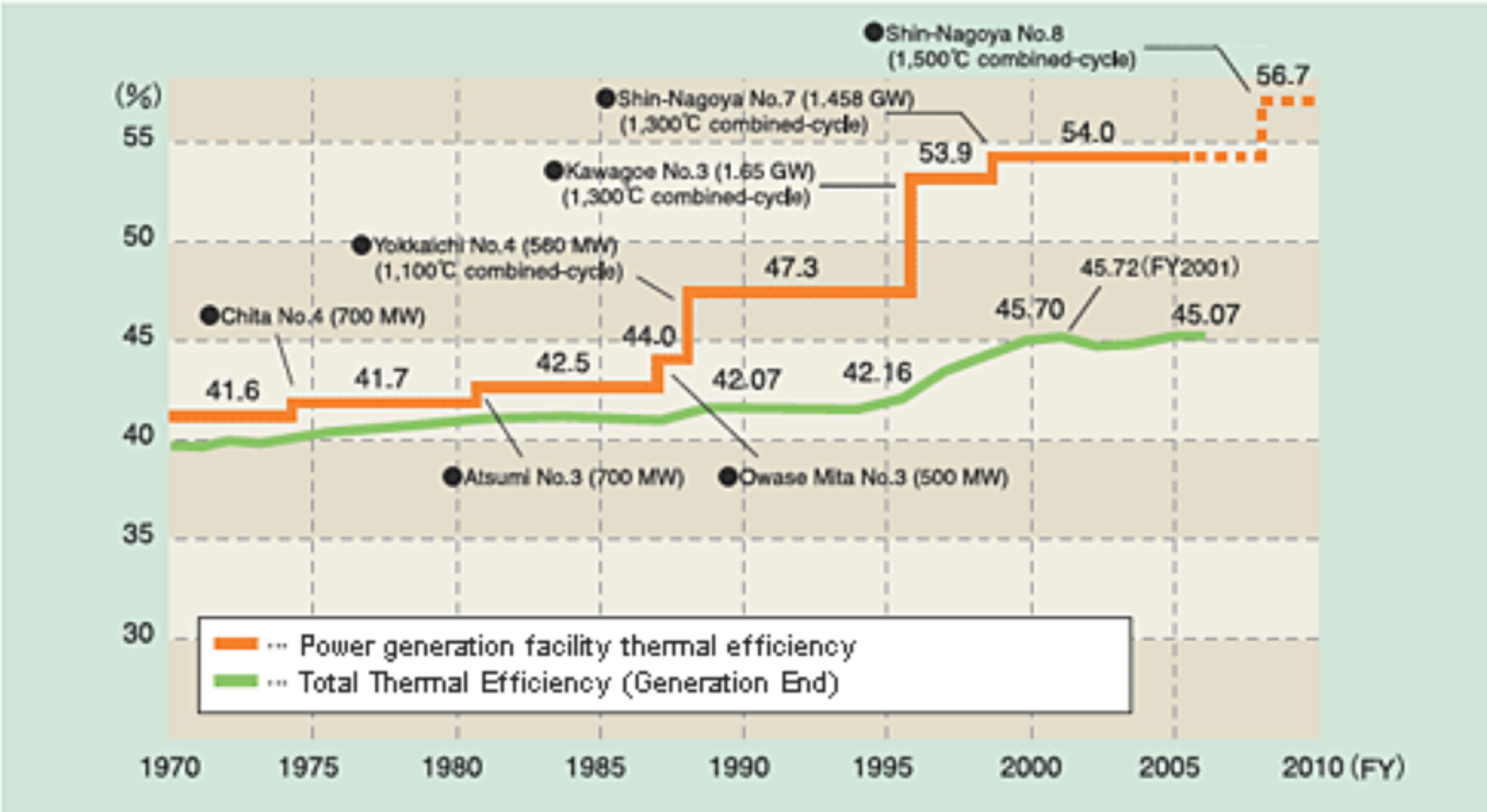
6.5.1. PRINCIPLE COMBINED CYCLE POWER STATION



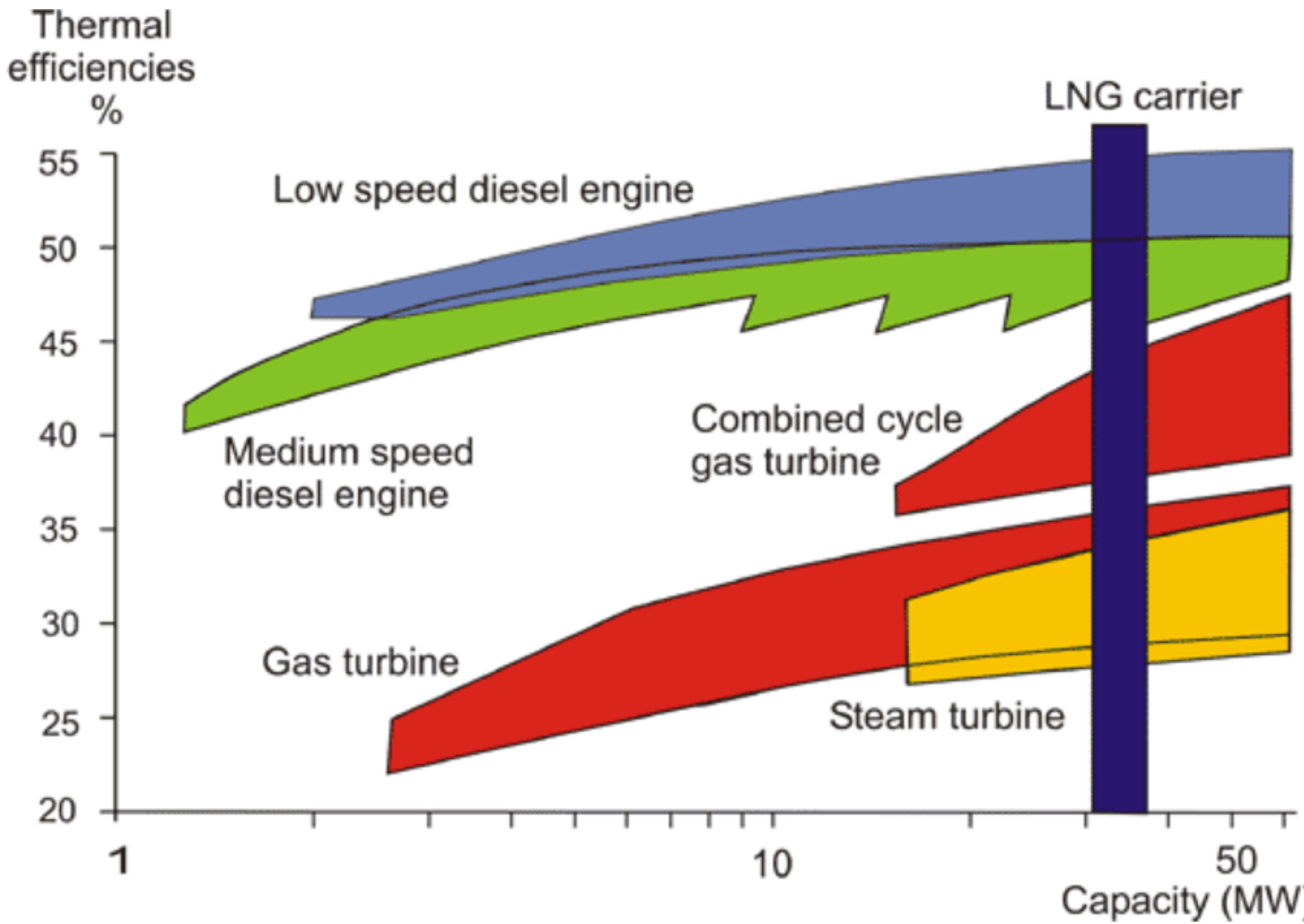
6.5.2. COMBINED CYCLE POWER STATION PLANT



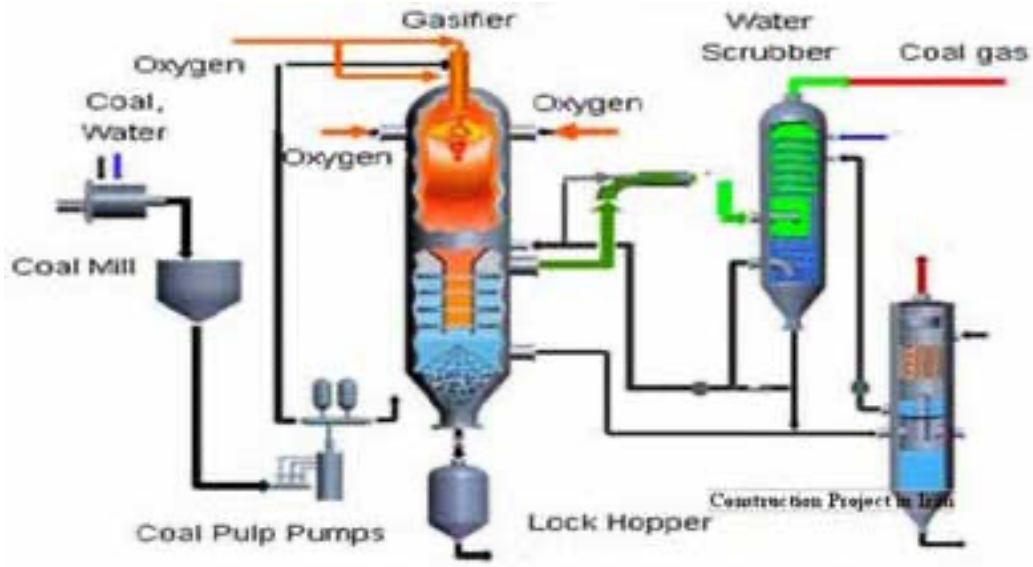
6.5.3. EFFICIENCY OF POWER STATION



6.5.4. EFFICIENCY OF ENGINES



6.5.5. COAL GASIFICATION

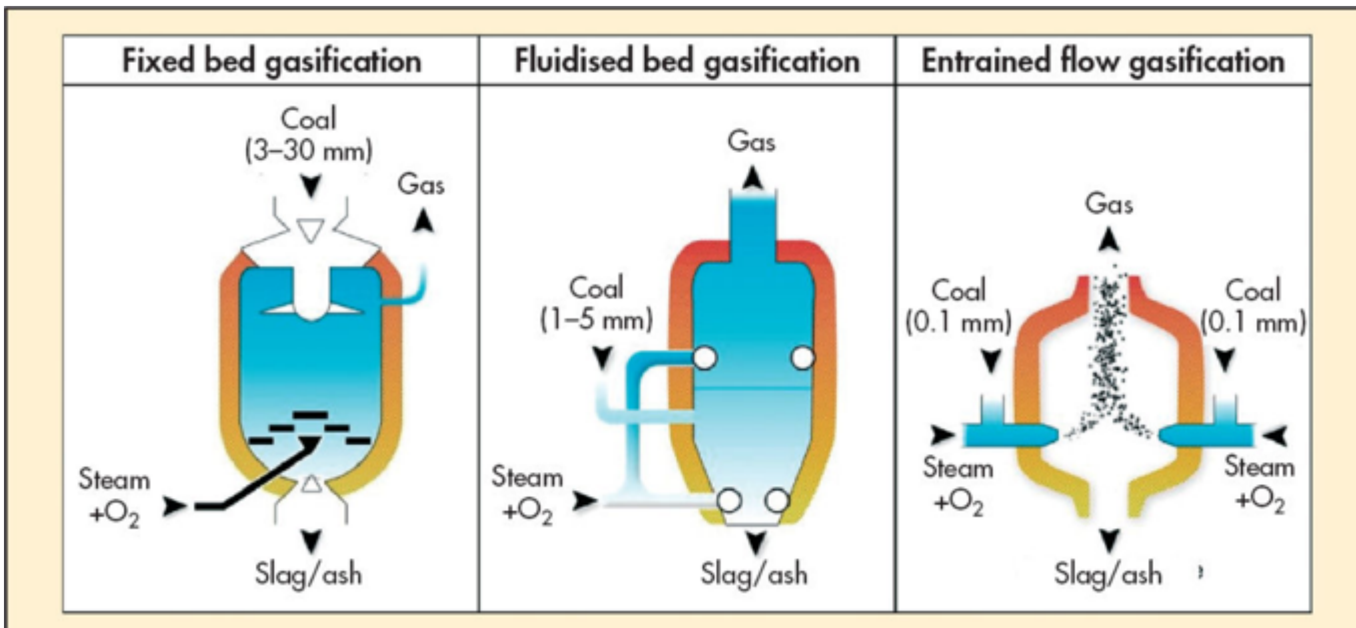


ΔH_{HHV} = 6.6 Wh/kg C

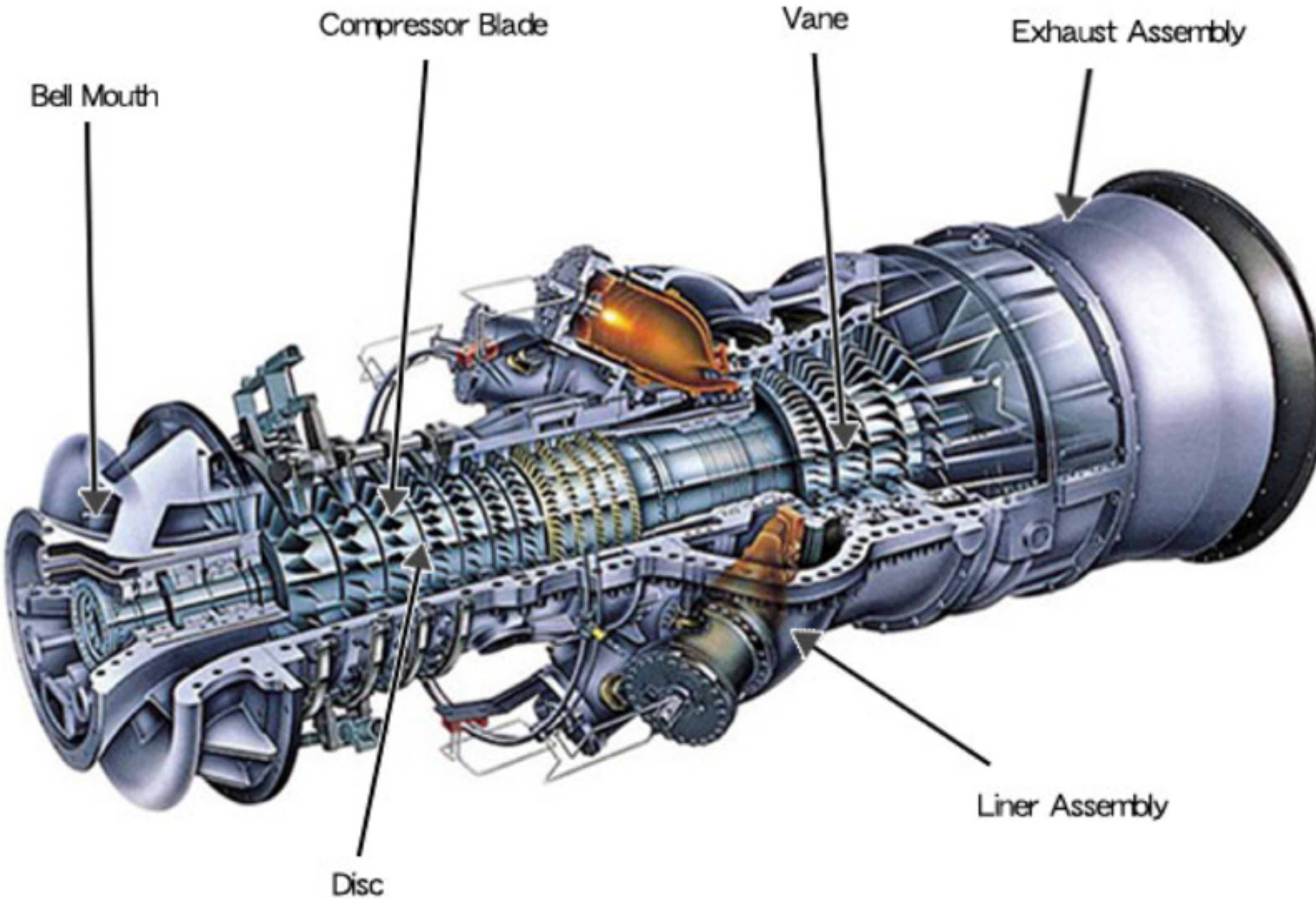
ΔH_{HHV} = 15.4 kWh/kg C

$$C + 2\,H_2O \rightleftarrows CH_4 + CO_2$$

ΔH = 102 kJ·mol^{-1}
ΔH = 2.36 kWh·kg^{-1} C

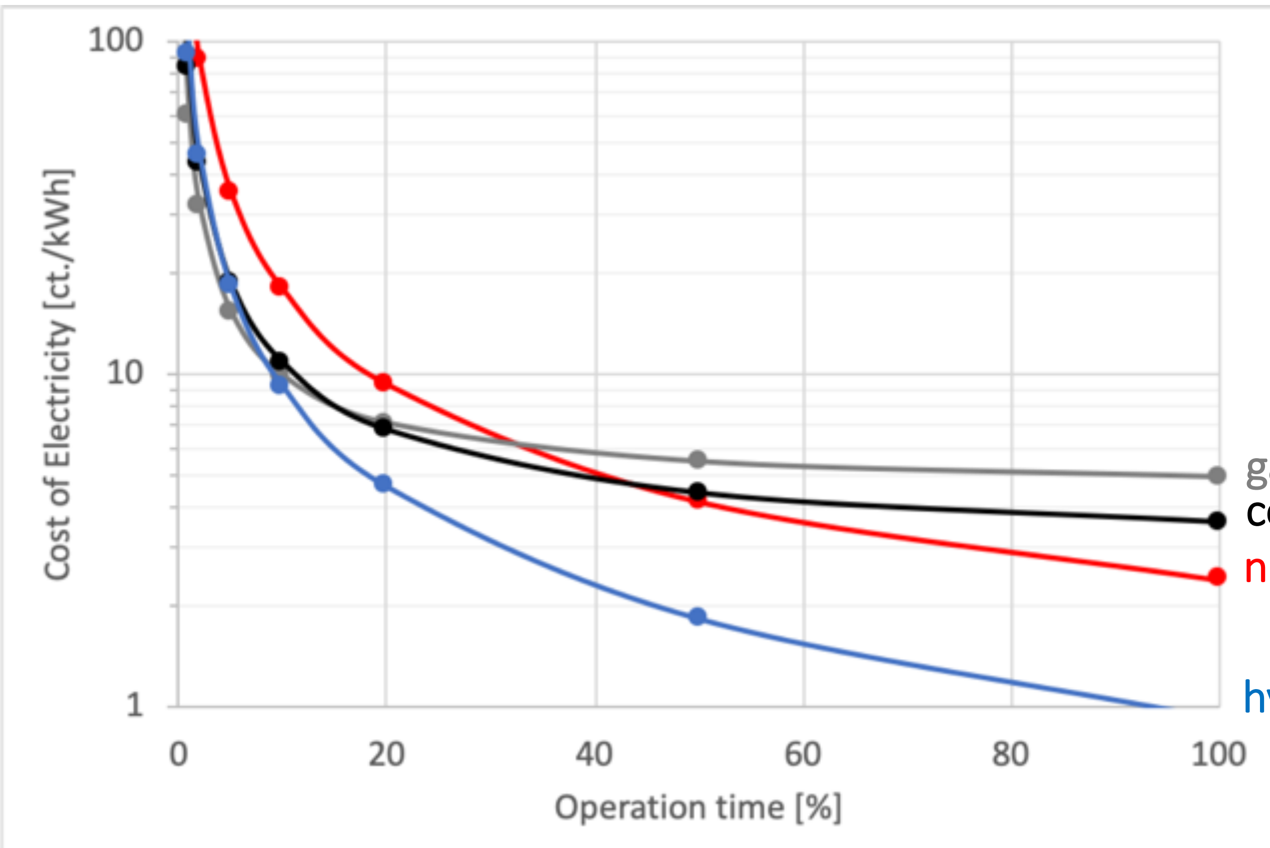


6.5.6. GAS TURBINE (Methane)



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

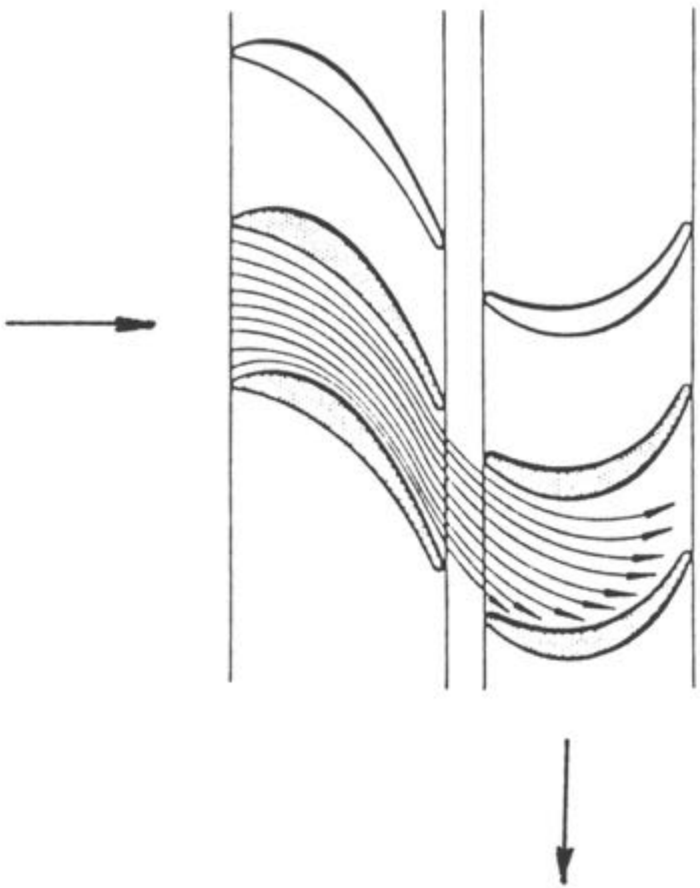


Cost of electricity production in the USA in the year 2010

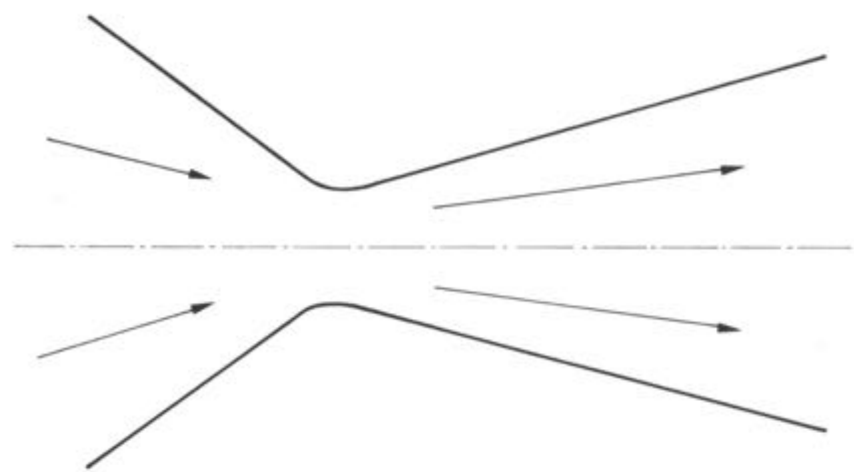
Ref.: https://www.eia.gov/electricity/annual/html/epa_08_04.html

6.6. JET ENGINE

Turbine

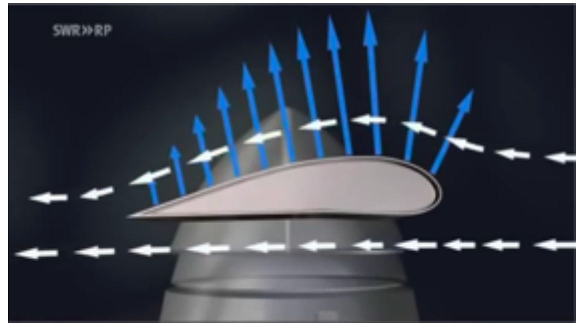


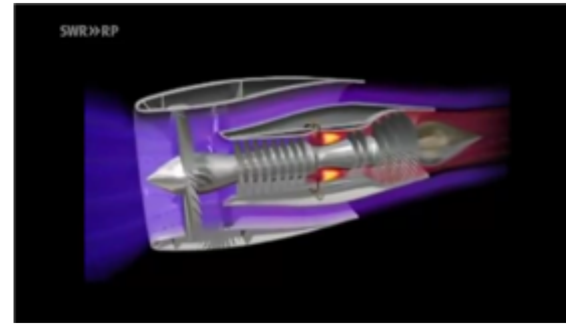
Propulsion nozzle

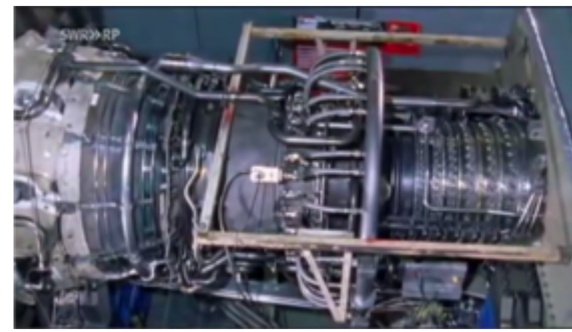


6.6.1. JET ENGINE FILM

6.6.1. JET ENGINE FILM

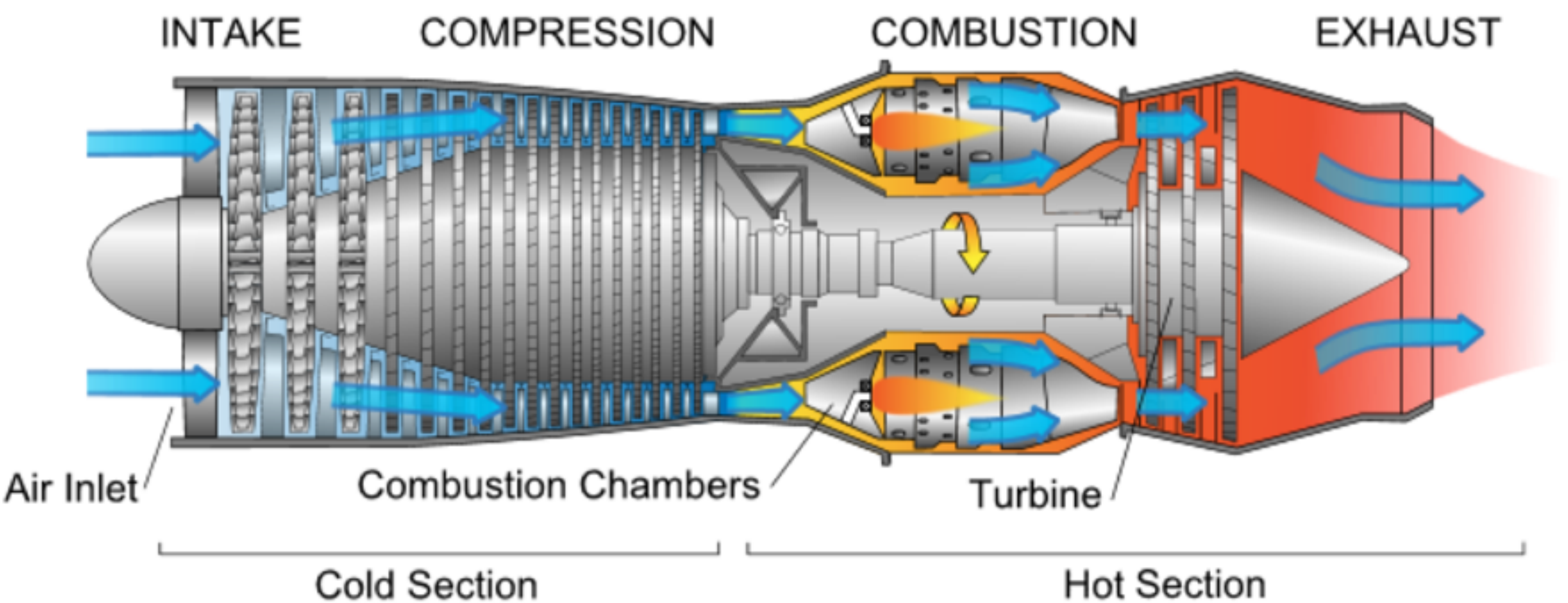




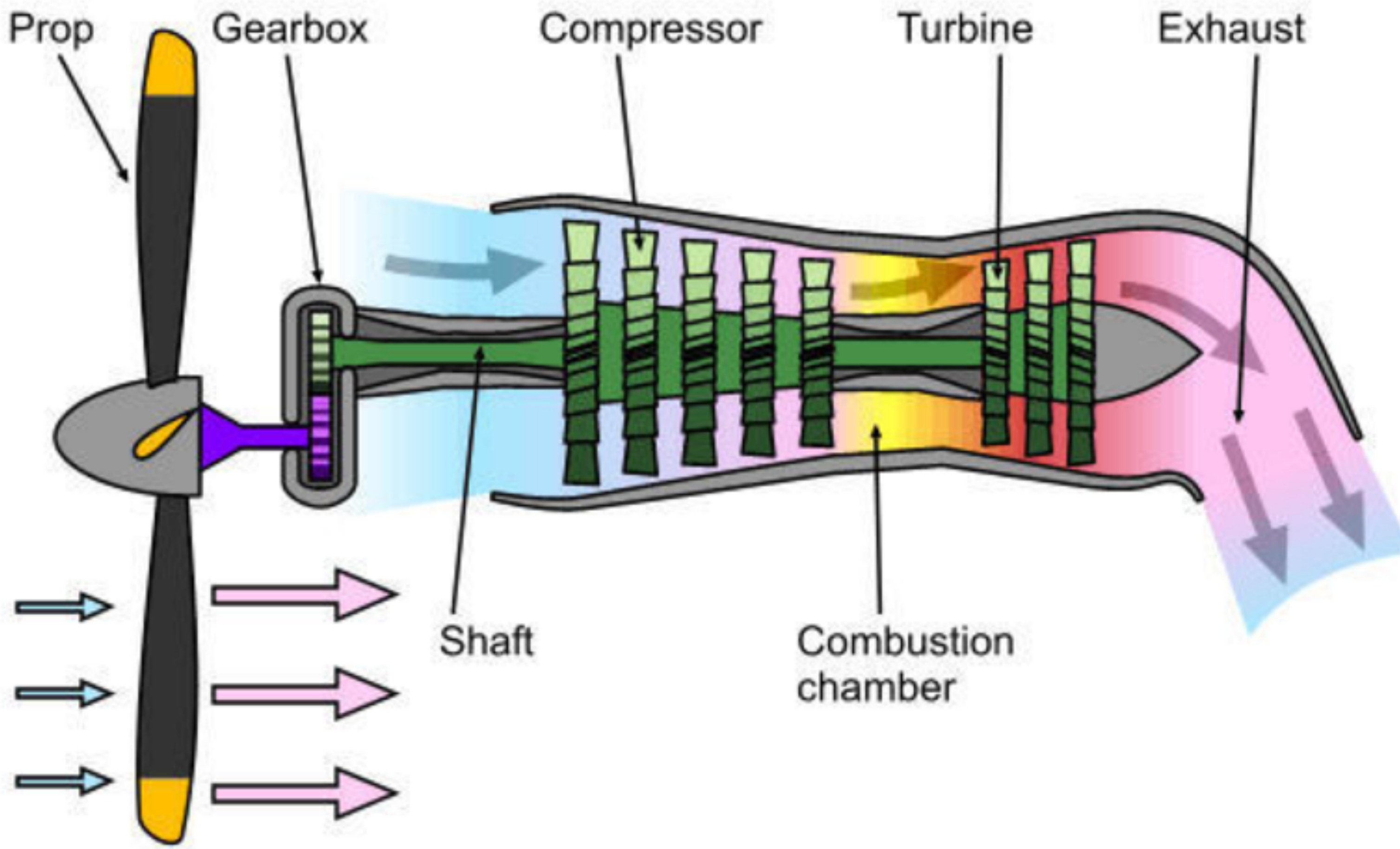


6.6.2. AIRPLANE JET ENGINE

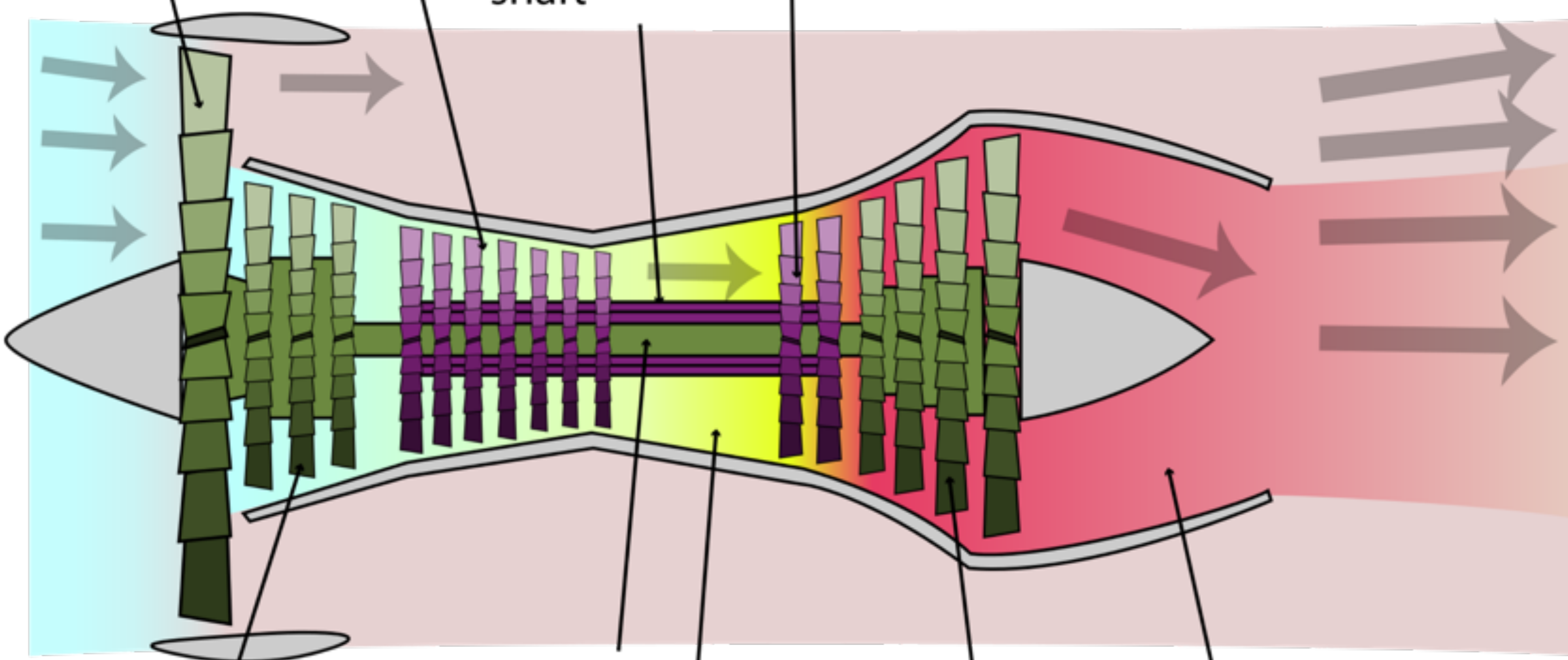
Hans Joachim Pabst von Ohain
(* 14. Dezember 1911 in Dessau;
† 13. März 1998 in Melbourne, Florida)



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.

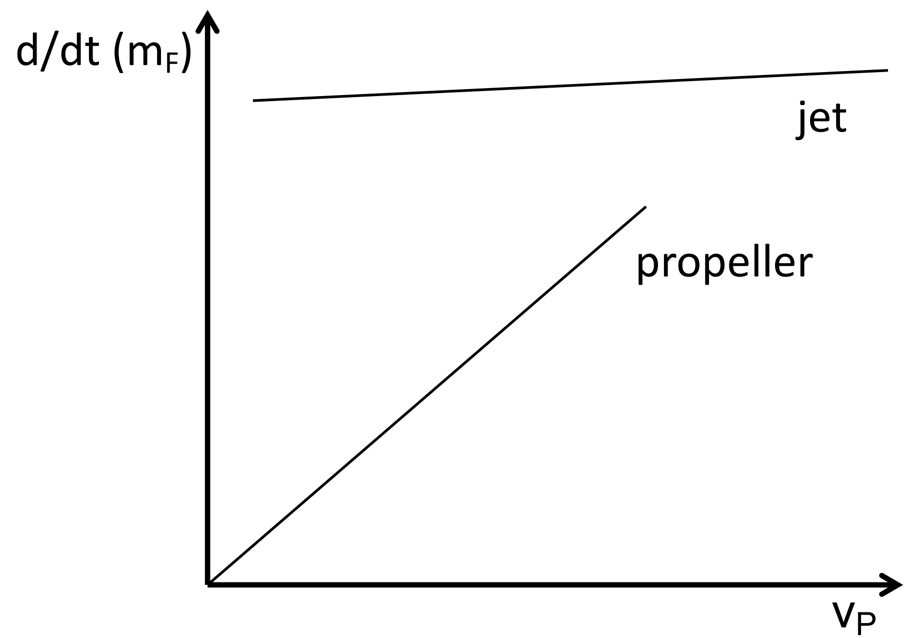
Energy content of Kerosene is γ = 45 MJ/kg

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

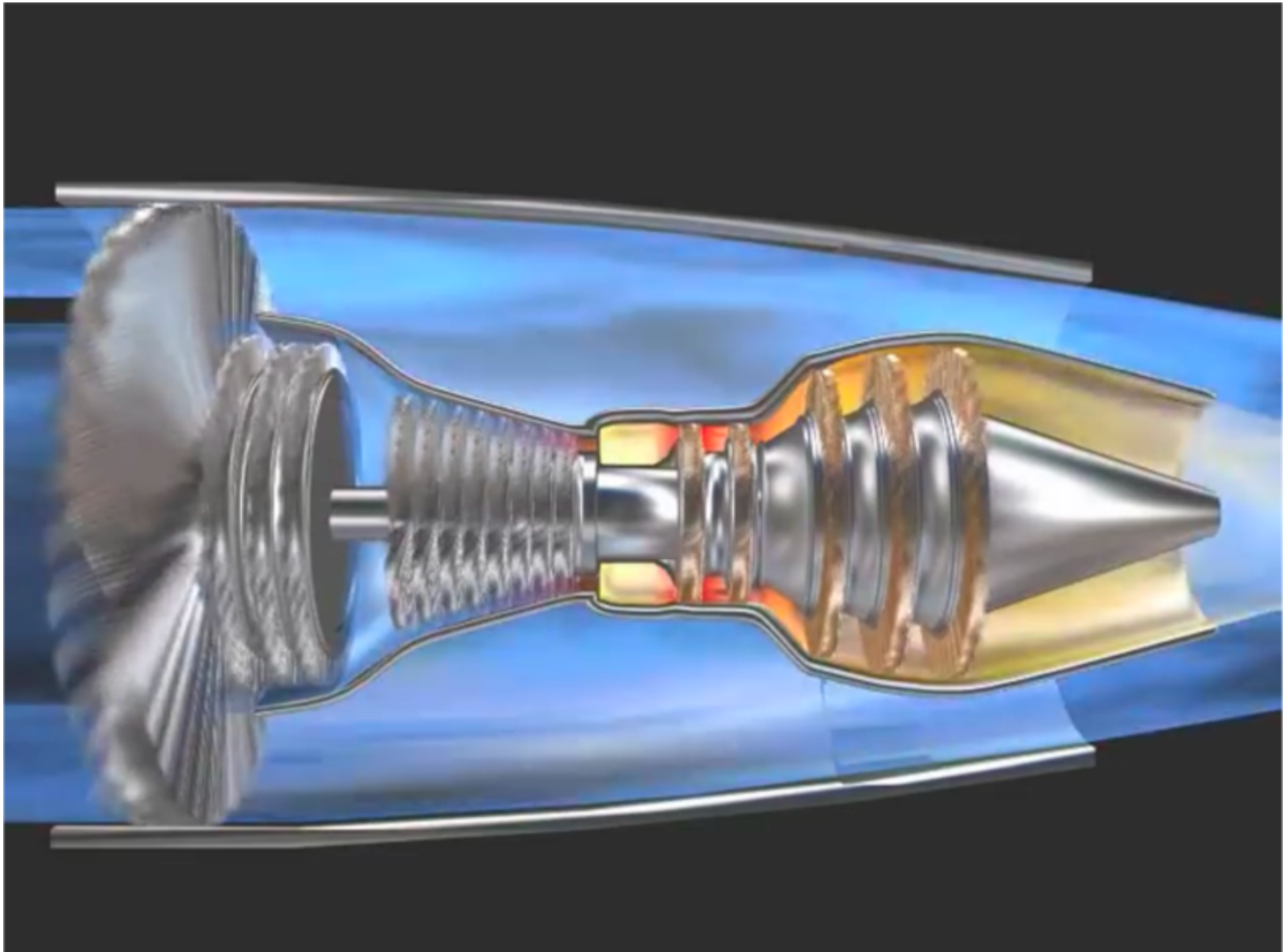
because:

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

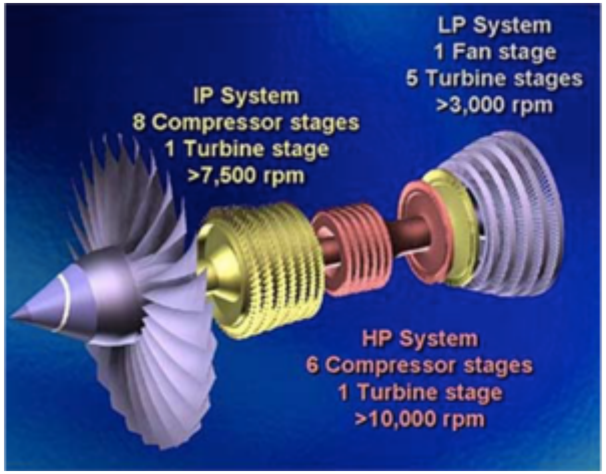


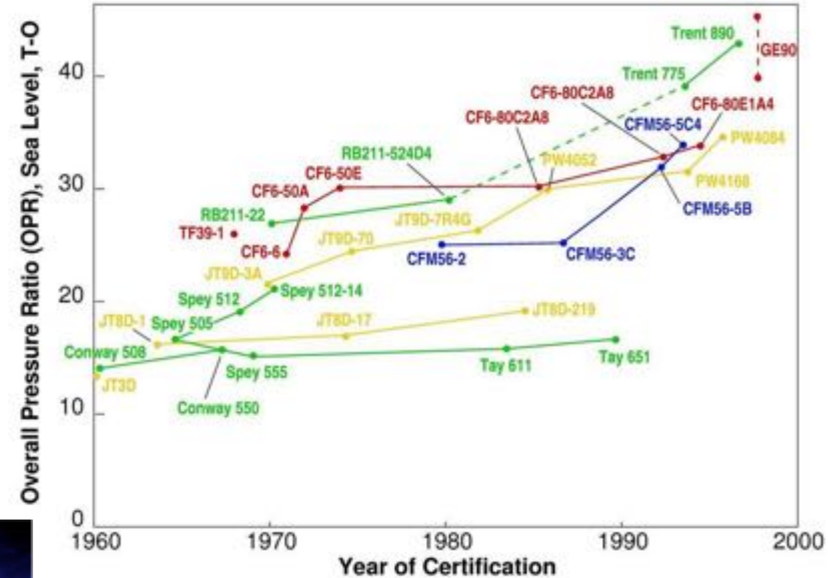
6.6.6. HIGH BYPASS JET ENGINE (TURBO FAN) FILM

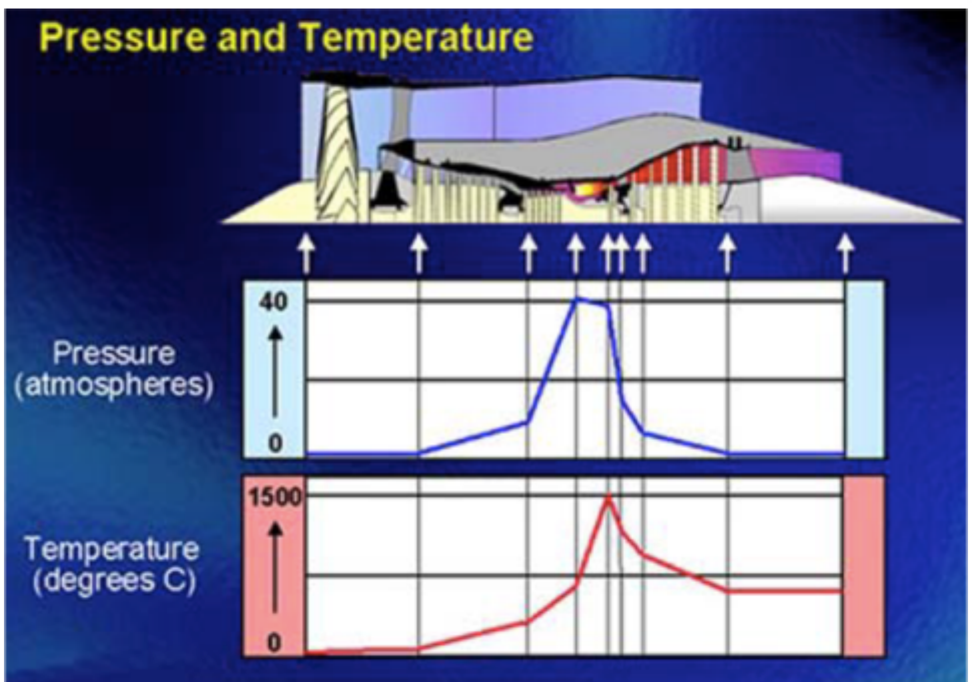
6.6.6. HIGH BYPASS JET ENGINE (TURBO FAN) FILM



6.6.7. p and T IN THE JET ENGINES

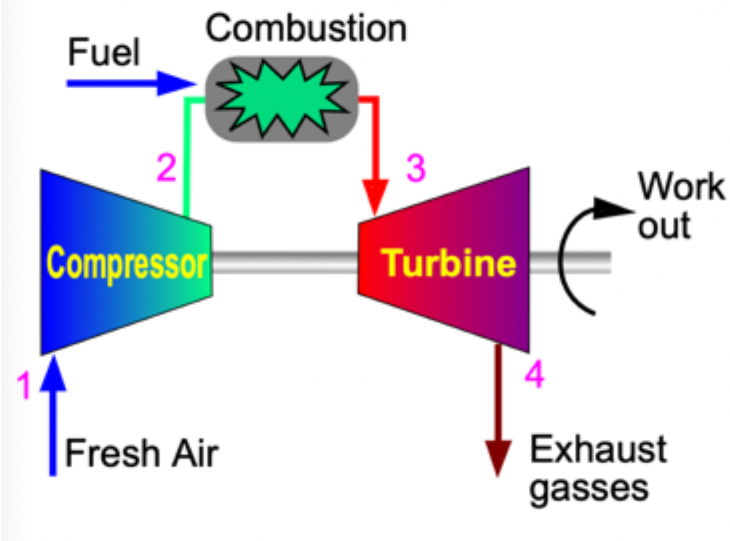


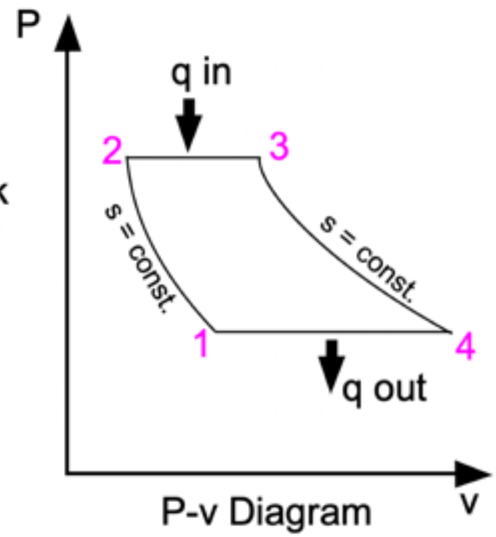


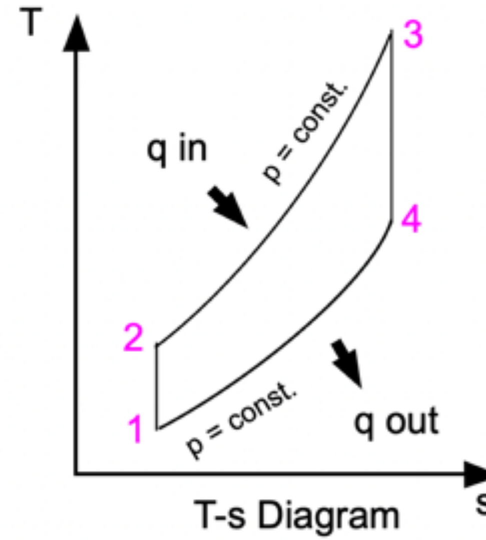


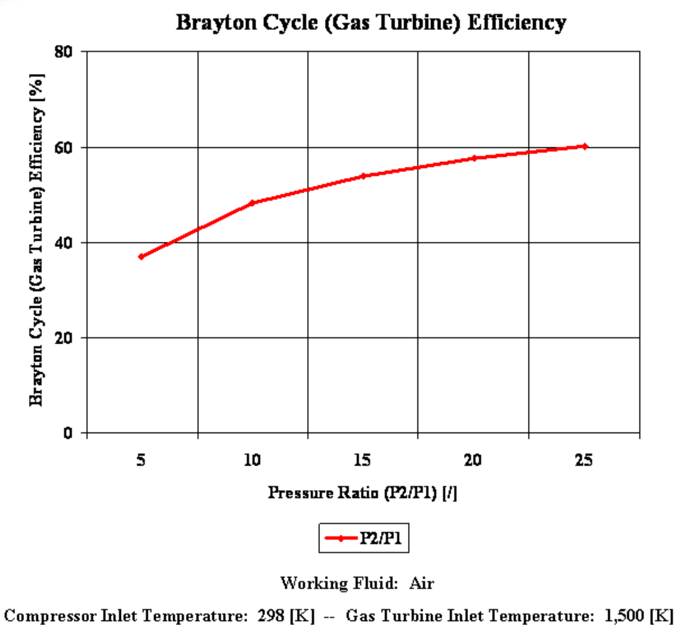
6.6.8. JET ENGINE IDEAL EFFICIENCY

Brayton Cycle





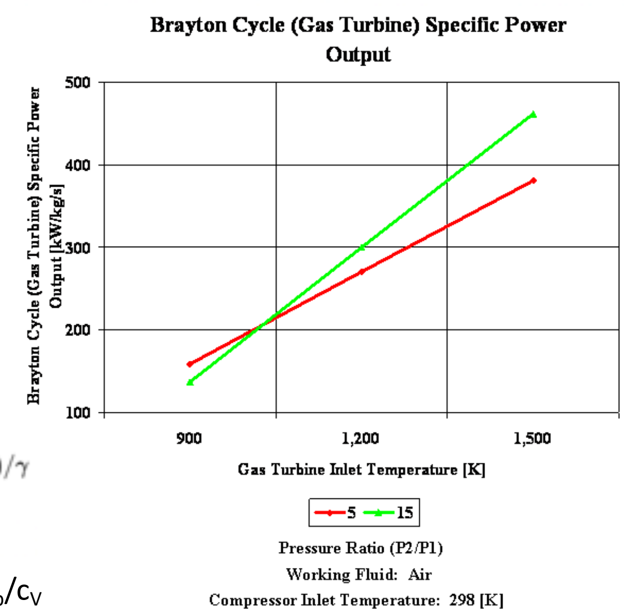




Efficiency:

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

$\gamma = c_p/c_V$



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:

$$\eta_0 = \eta_p \cdot \eta_{th} \cdot \eta_T$$

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:

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

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

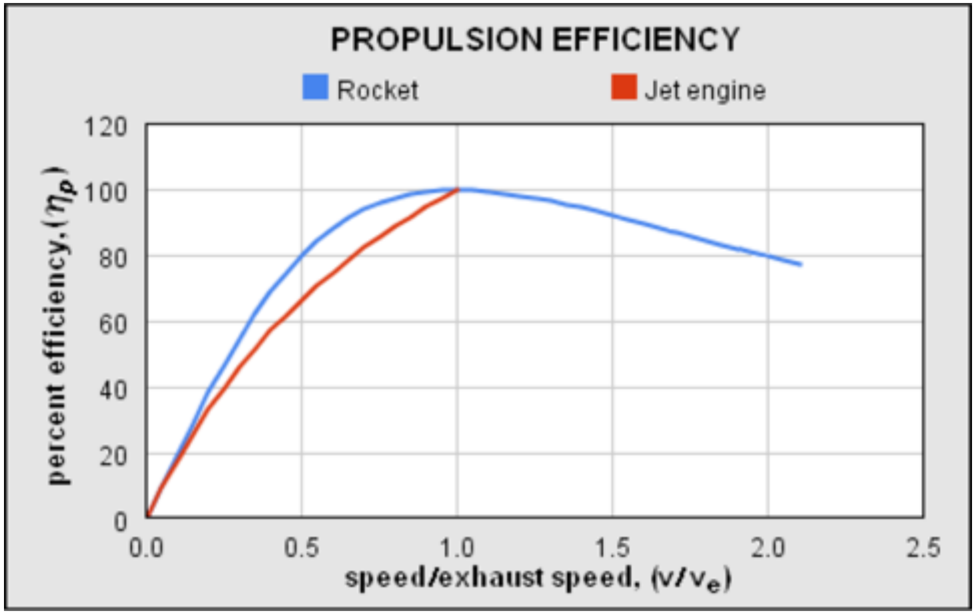
$$\eta_P = \frac{v\left[\left(\dot{m}_{air} + \dot{m}_{fuel}\right)\cdot v_e - \dot{m}_{air}\cdot v\right]}{\tfrac{1}{2}\left[\left(\dot{m}_{air} + \dot{m}_{fuel}\right)\cdot v_e^2 - \dot{m}_{air}\cdot v^2\right]}$$

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

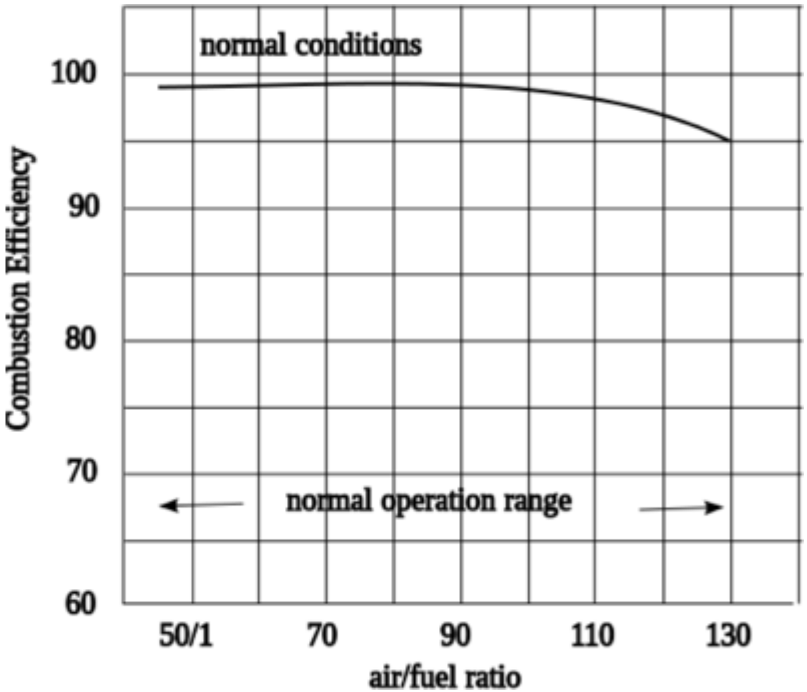
$$\eta_P = \frac{\dot{m}_{air}\cdot v \cdot \left[v_e - v\right]}{\tfrac{1}{2}\cdot \dot{m}_{air}\left[v_e^2 - v^2\right]} = \frac{2\cdot v}{v + v_e}$$

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

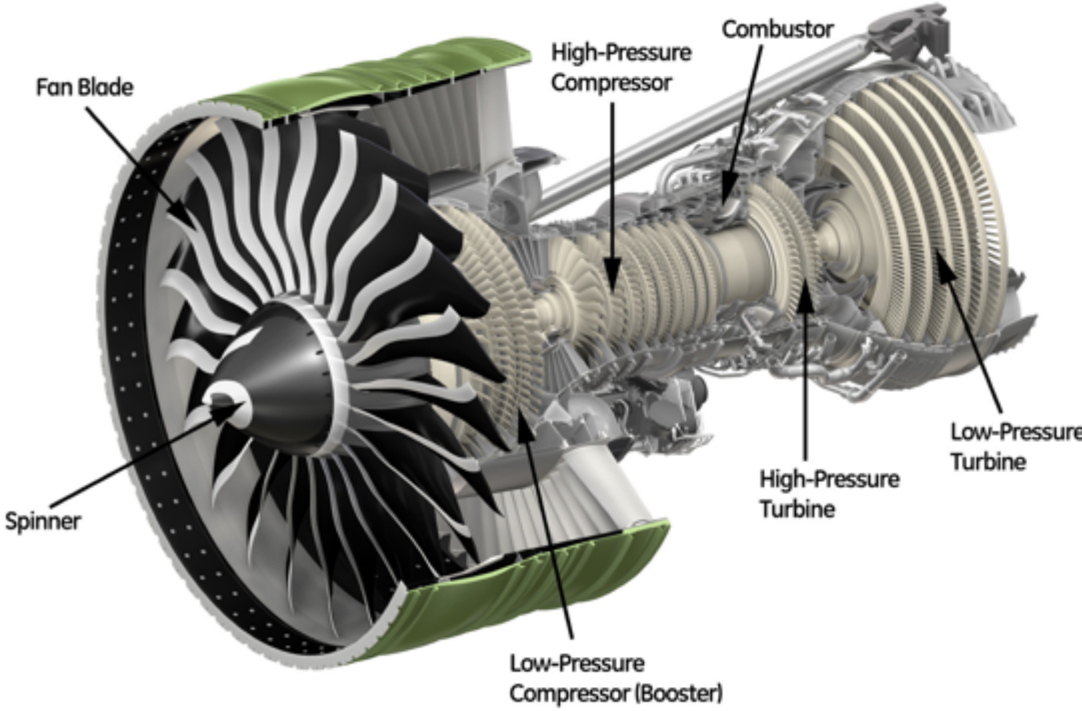
6.6.12. JET ENGINE SPECIFICATIONS

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

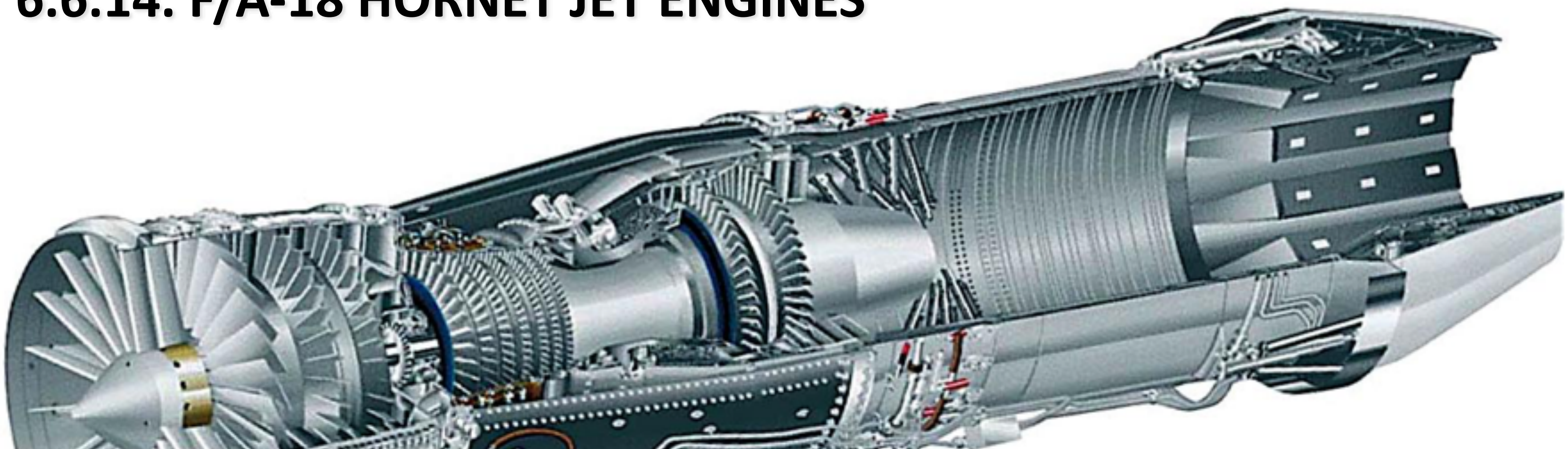
Boeing 777

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

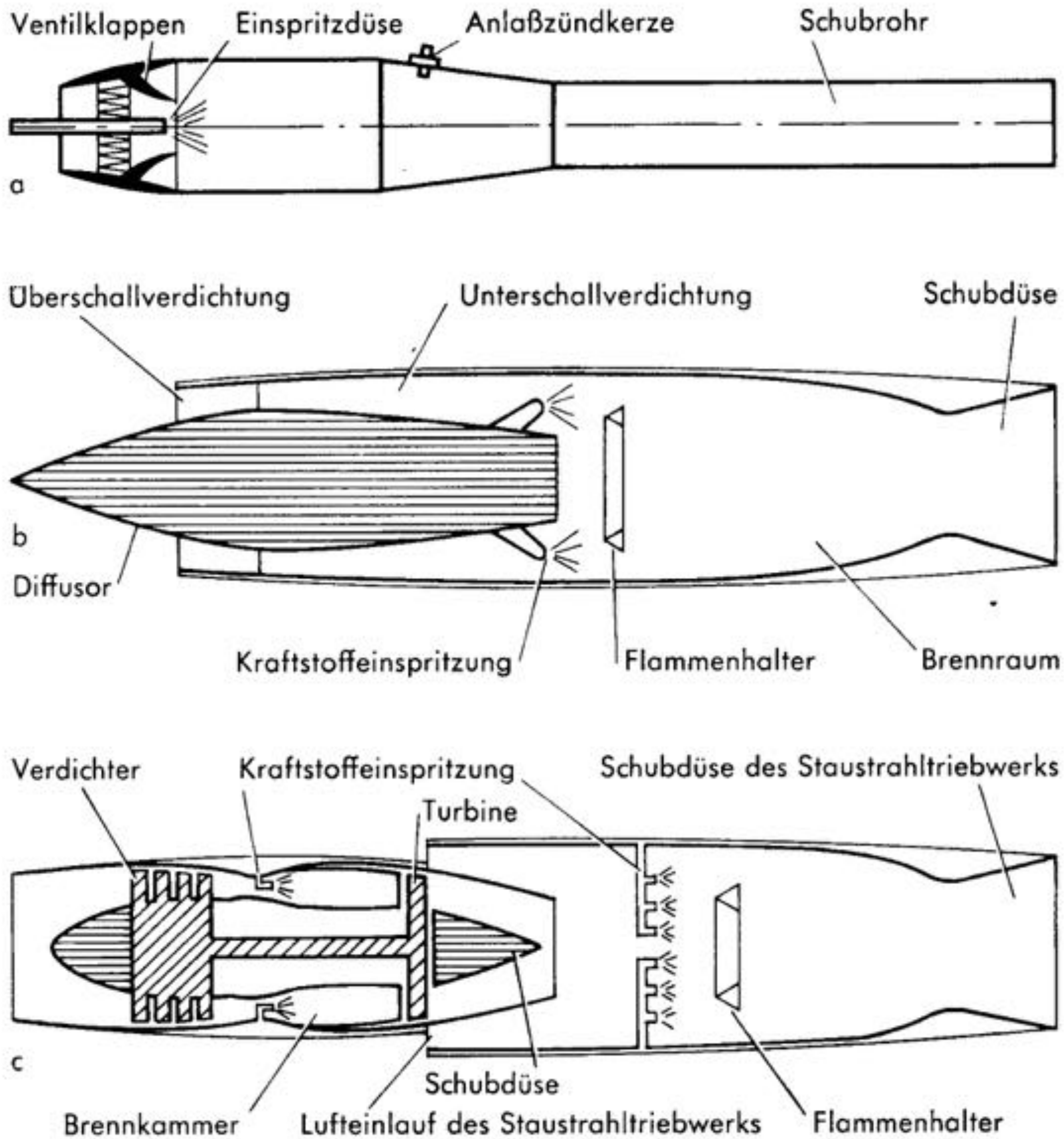
F/A-18 Hornet, McDonnell-Douglas

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

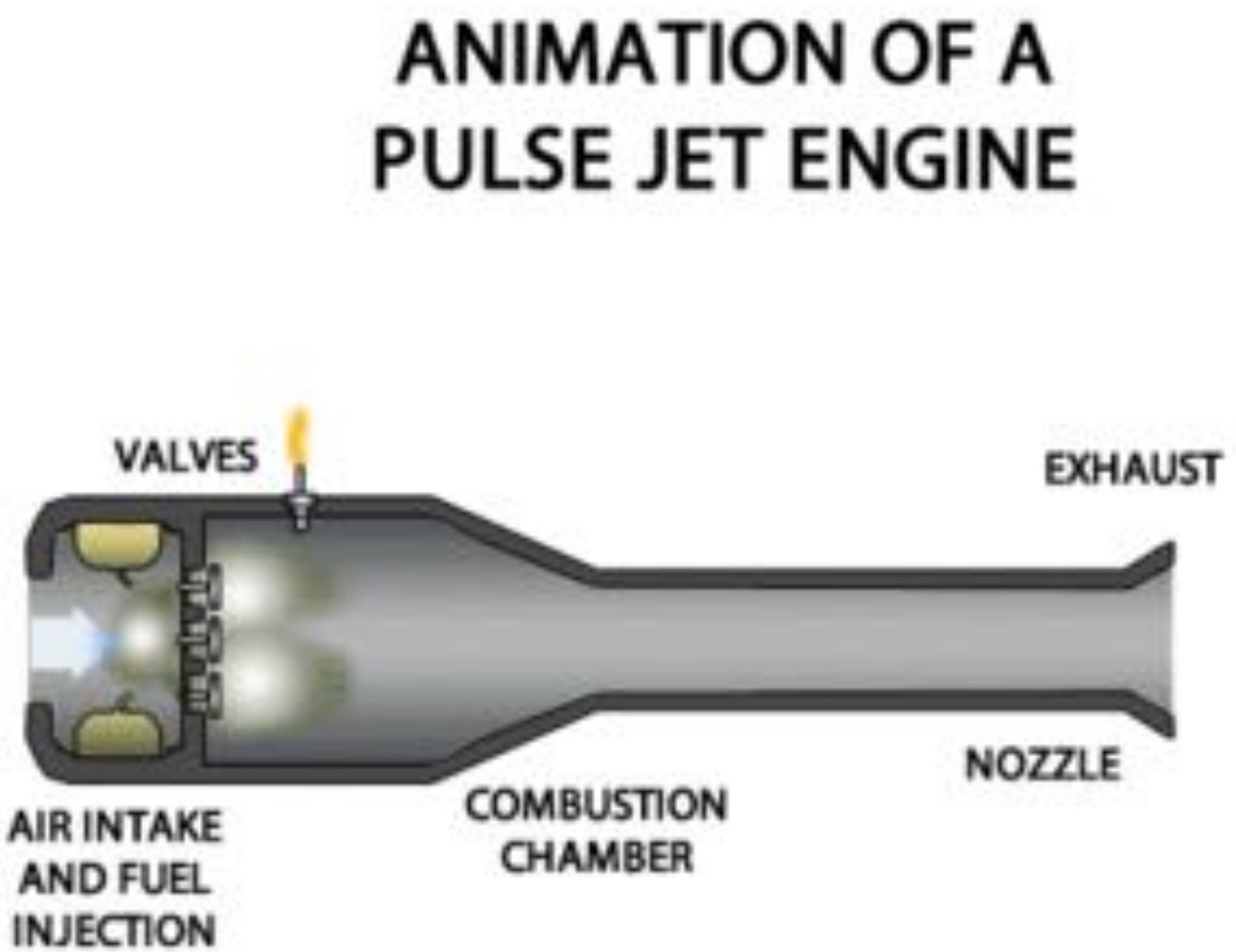
5126 kg Kerosen in 105 min. wo after burner, 8 min w. ab

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

6.6.15. FIRST PROPULSION ENGINES



6.6.16. PULSE PROPULSION ENGINES



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 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)