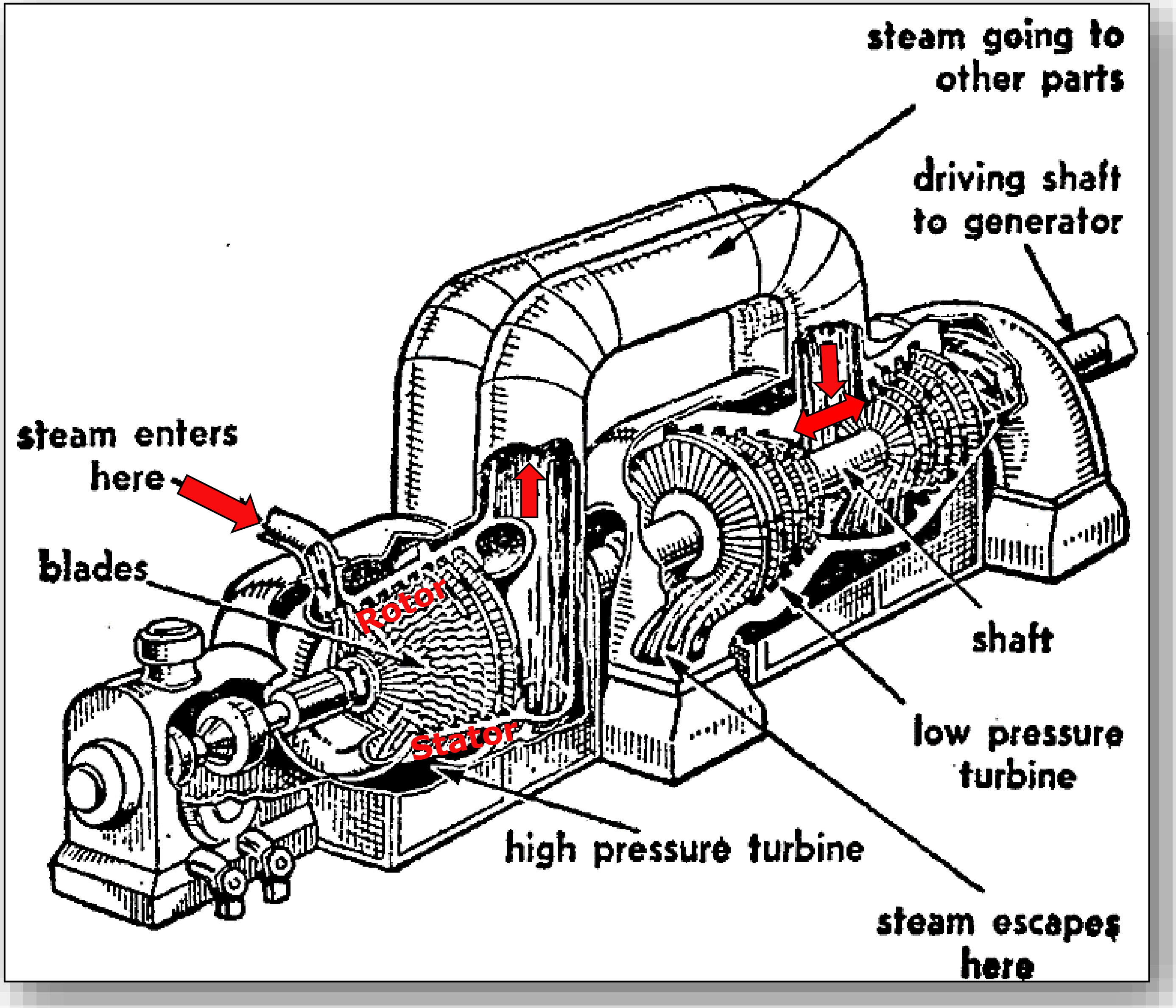
Thermal Power Plants

Agenda: Thermal Power Plants

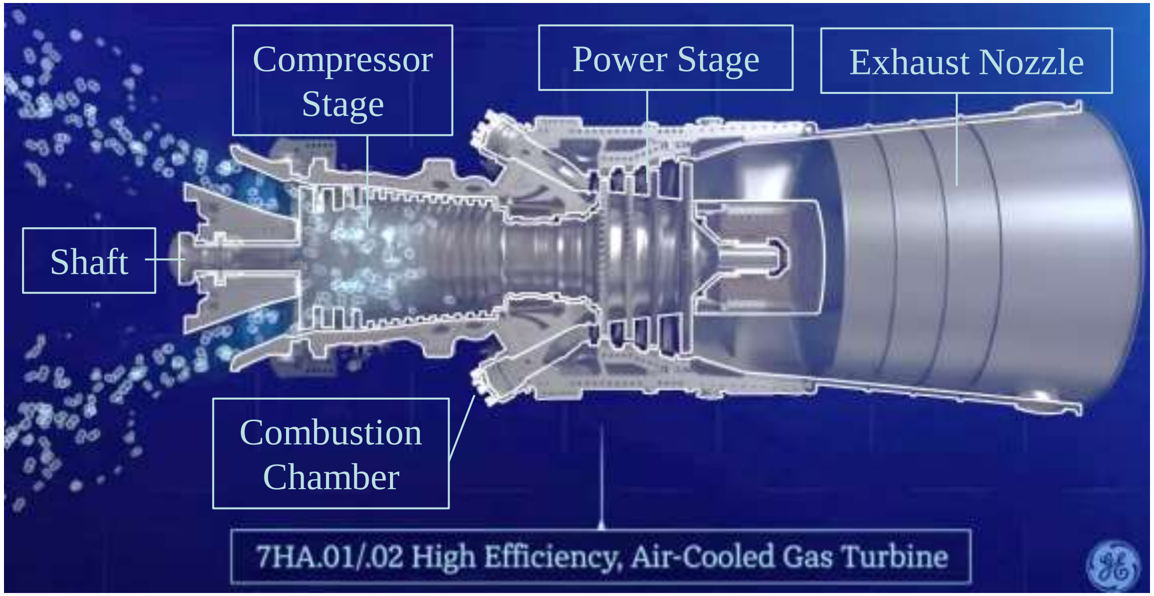
- Operational principle of cyclic thermodynamic engines
    - Entropy, heat, and work in Carnot cycle
- Reciprocating (piston) engines
    - Steam cylinder
    - Otto internal combustion cycle
    - Stirling engine
- Steam power plants
    - Isotherms of real gases
    - Steam and air as working media
    - S-T cycles for Carnot, Rankine, and Brayton cycles
- Steam & Gas turbine power plants
    - Combined-cycle
- Chemistry of complete & incomplete combustion
    - Examples
- Carbon (CO_2) capture processes

Next: Power from nuclear transmutation
Andrew & Jelley Chs. 9 & 10

Low/Medium Pressure Steam Turbines



Gas Power Turbine: Parts & Operation (GE)



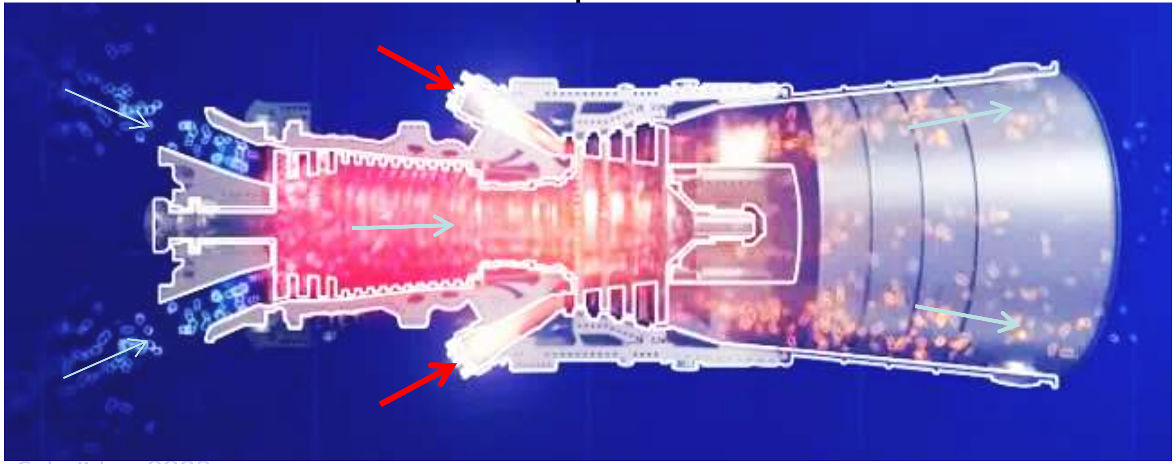
→ Combustion gases-working fluid

Air intake at turbo compressor stage. Fuel/air mix injected in annular combustion chambers. Combustion gas drives turbine directly: power stage.

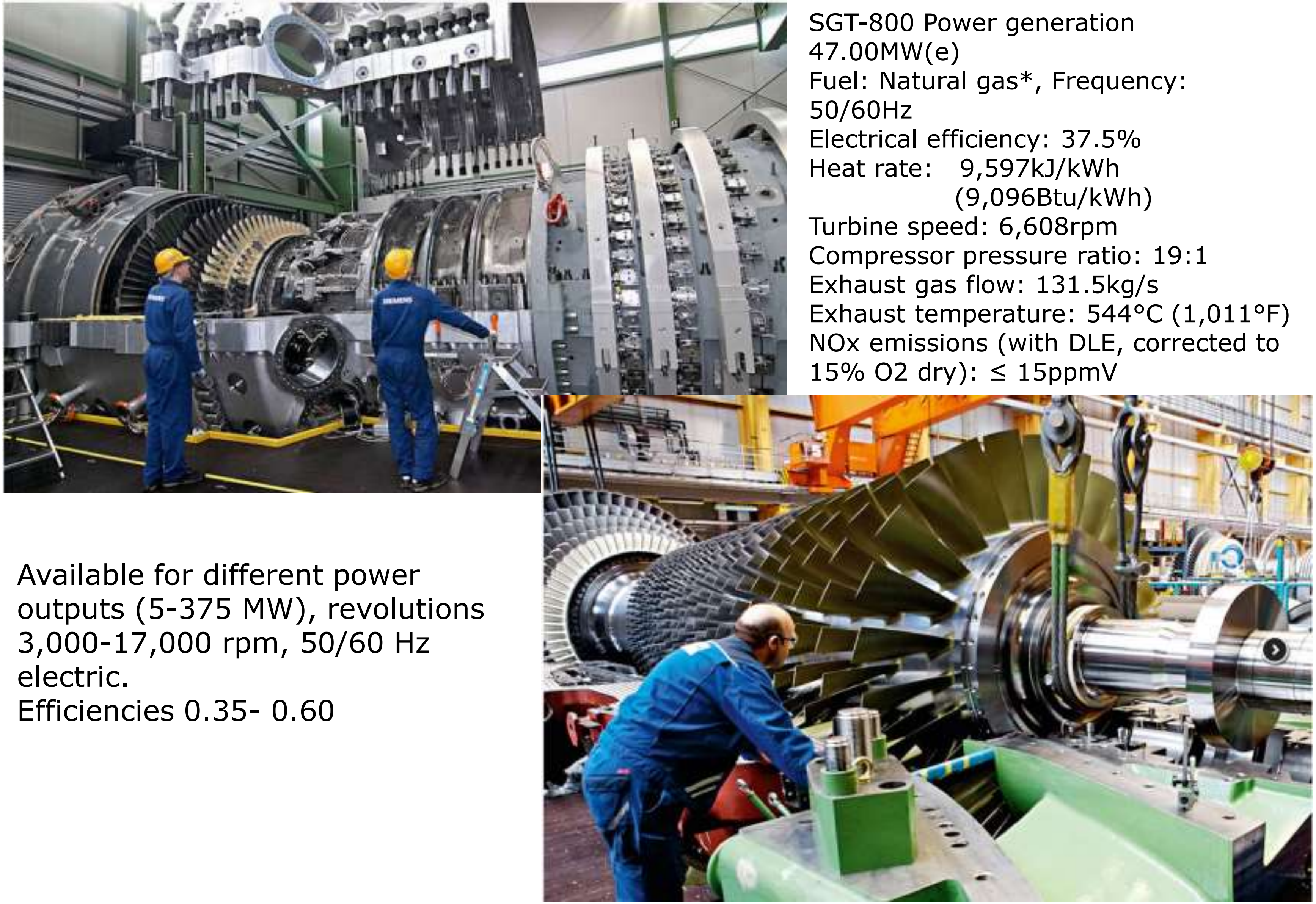
Turbo compressor raises air pressure (x20) & temperature.

Fuel/air mix is ignited in combustion chambers.
→ Super heated compressed fuel/air mix drives power rotors. Exhaust gas is still hot.

In Operation



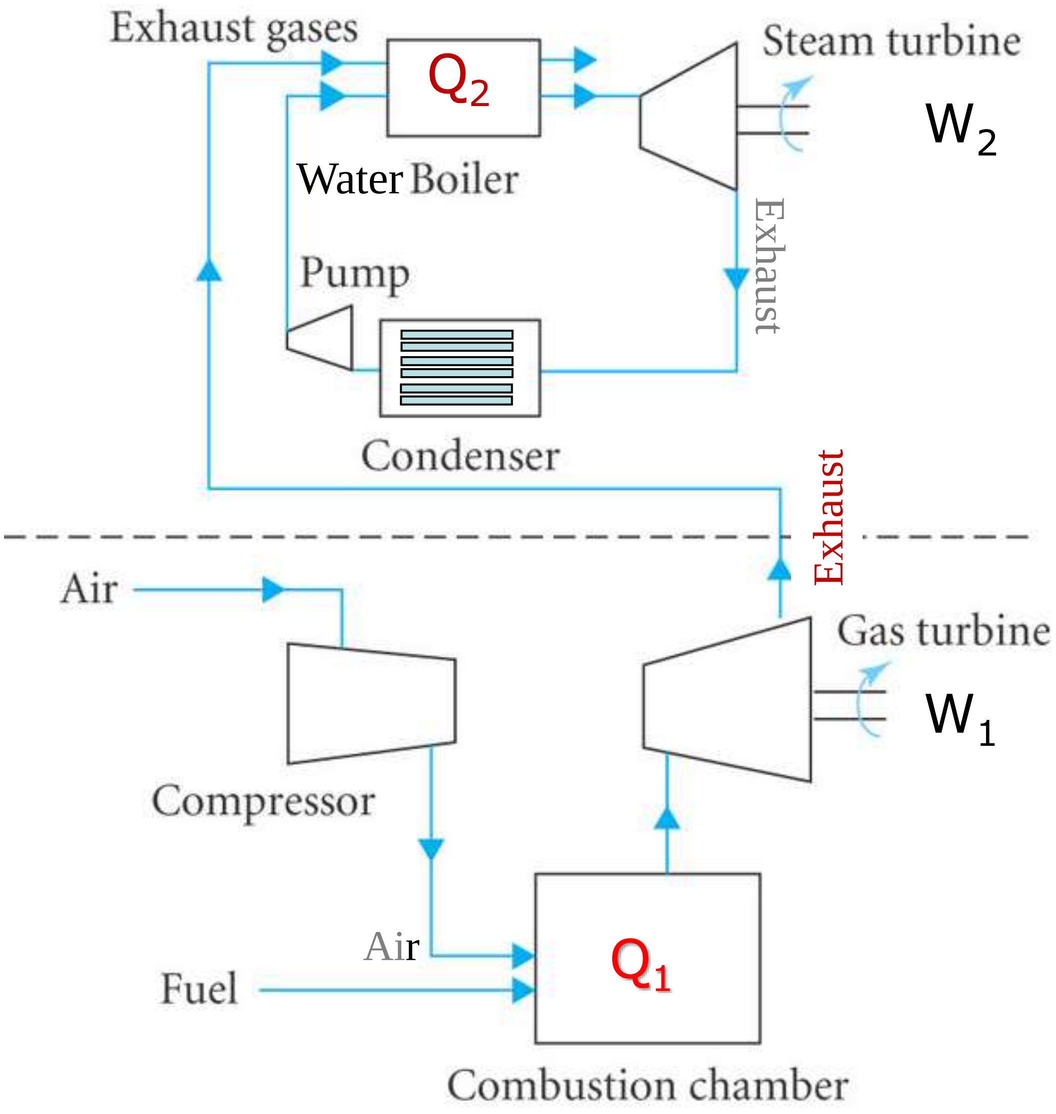
Turbine for Gas Power Plants

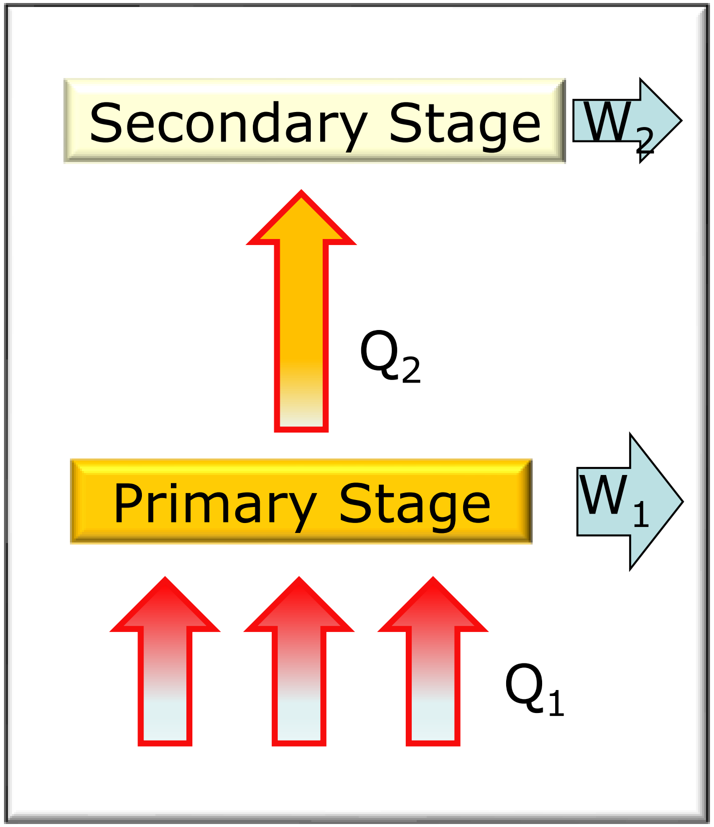


SGT-800 Power generation
47.00MW(e)
Fuel: Natural gas*, Frequency: 50/60Hz
Electrical efficiency: 37.5%
Heat rate: 9,597kJ/kWh
(9,096Btu/kWh)
Turbine speed: 6,608rpm
Compressor pressure ratio: 19:1
Exhaust gas flow: 131.5kg/s
Exhaust temperature: 544°C (1,011°F)
NOx emissions (with DLE, corrected to 15% O2 dry): ≤ 15ppmV

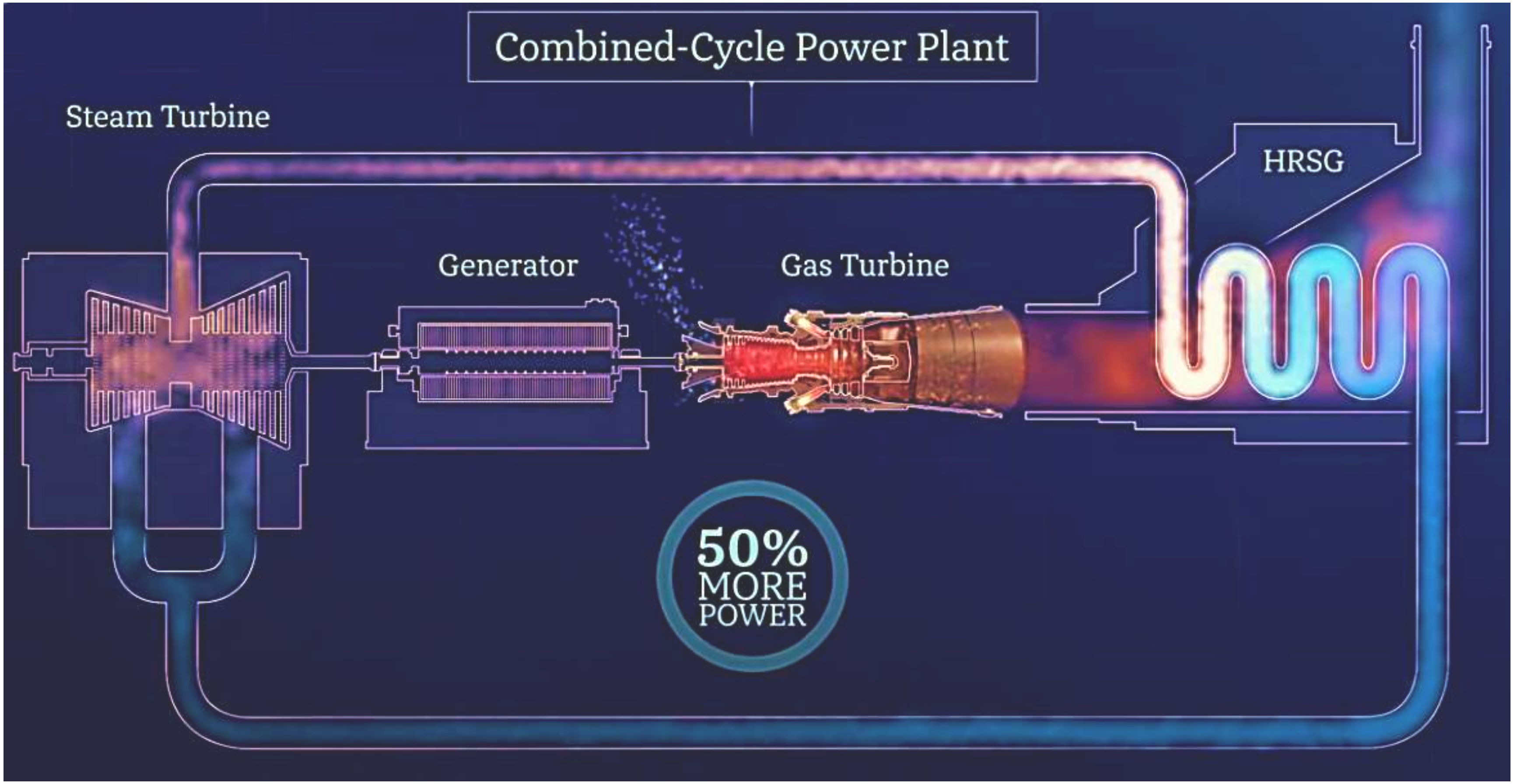
Available for different power outputs (5-375 MW), revolutions 3,000-17,000 rpm, 50/60 Hz electric.
Efficiencies 0.35- 0.60

Combined Cycle Power Plants (CCGT)

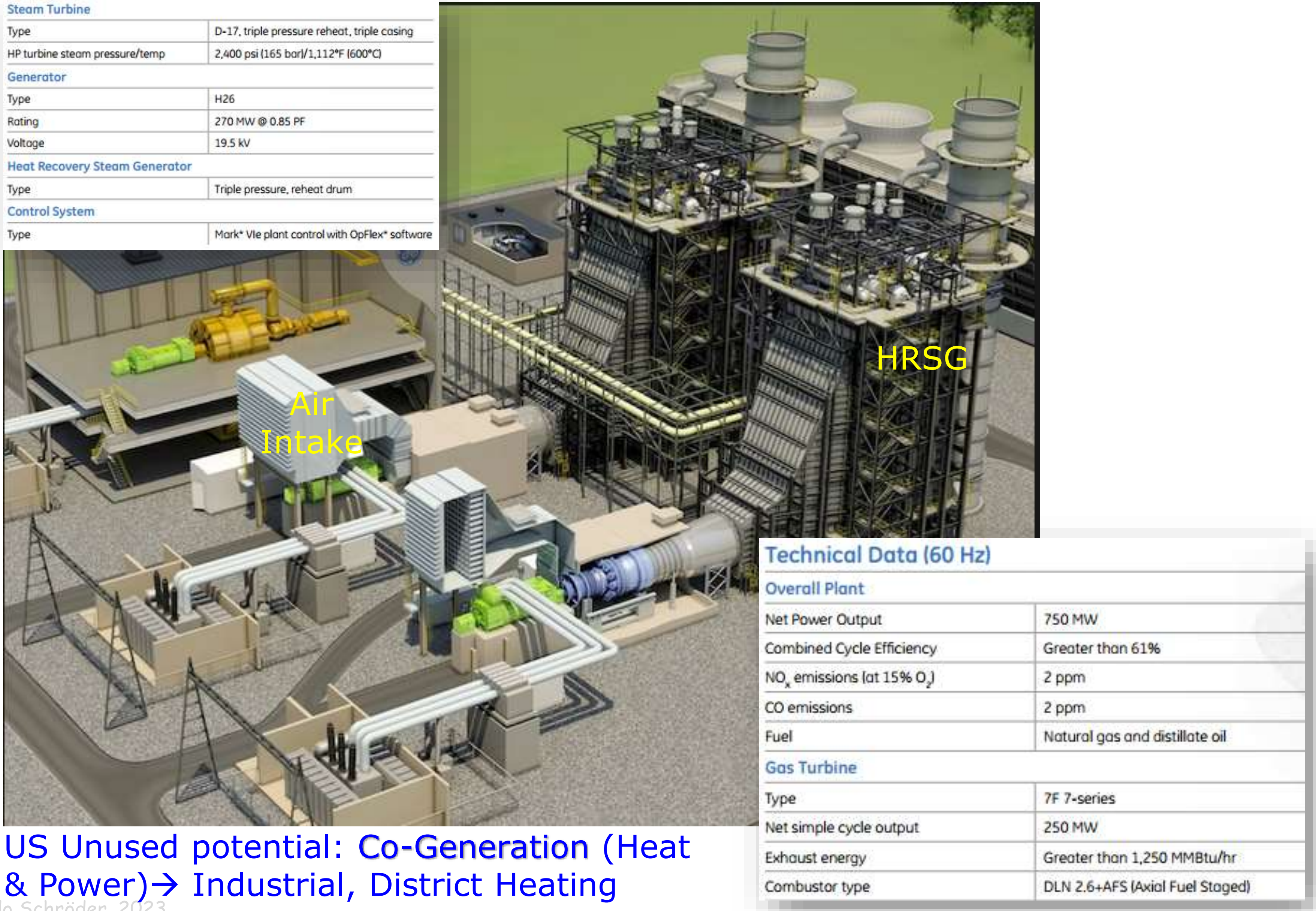




Combined Cycle Power Plants (CCGT)



Combined-Cycle Gas Power Plant (General Electric)



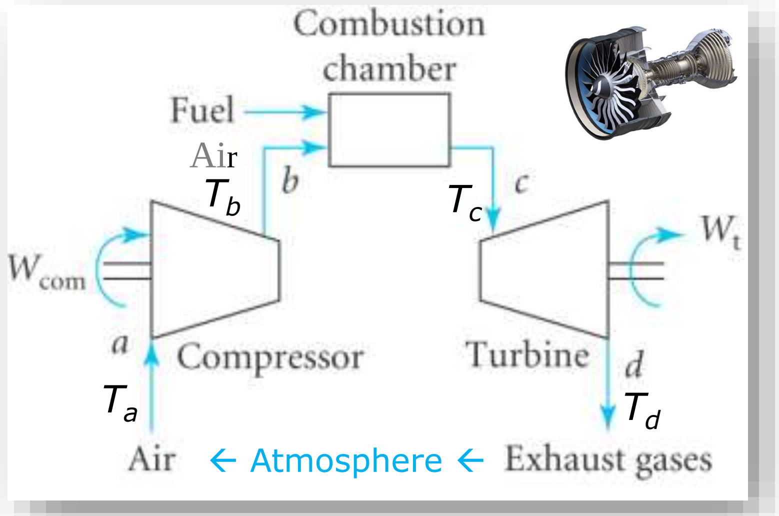
Steam Turbine	
Type	D-17, triple pressure reheat, triple casing
HP turbine steam pressure/temp	2,400 psi (165 bar)/1,112°F (600°C)
Generator	
Type	H26
Rating	270 MW @ 0.85 PF
Voltage	19.5 kV
Heat Recovery Steam Generator	
Type	Triple pressure, reheat drum
Control System	
Type	Mark* VIe plant control with OpFlex* software

Technical Data (60 Hz)

Overall Plant	
Net Power Output	750 MW
Combined Cycle Efficiency	Greater than 61%
NO_x emissions (at 15% O_2)	2 ppm
CO emissions	2 ppm
Fuel	Natural gas and distillate oil
Gas Turbine	
Type	7F 7-series
Net simple cycle output	250 MW
Exhaust energy	Greater than 1,250 MMBtu/hr
Combustor type	DLN 2.6+AFS (Axial Fuel Staged)

US Unused potential: **Co-Generation** (Heat & Power)→ Industrial, District Heating

Brayton/Joule Open Turbine Cycle



Open cycle (Jet engine):
a-b Compression (x 10-30), adiabatic → ***q***=0
b-c Combustion (***p***=const.)
c-d Turbine, adiabatic (***q***=0), $\boldsymbol{w_t} \neq 0$
d-a Exhaust waste energy (***p***=const.)

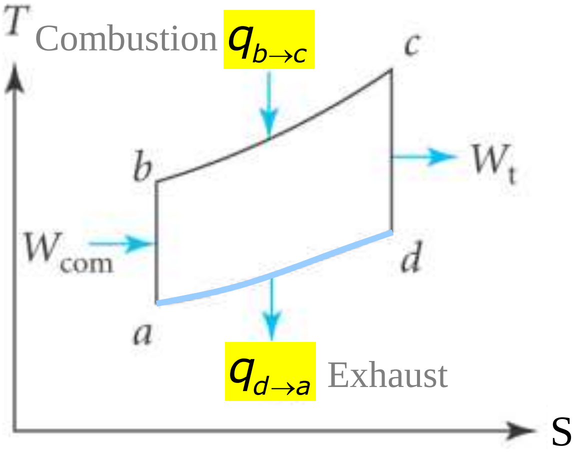
$$q_{b\to c} = h_c - h_b = c_p \cdot (T_c - T_b) > 0 \quad absorbed\ @\, p = const$$
$$q_{d\to a} = h_a - h_d = c_p \cdot (T_a - T_d) < 0 \quad emitted\ @\, p = const$$

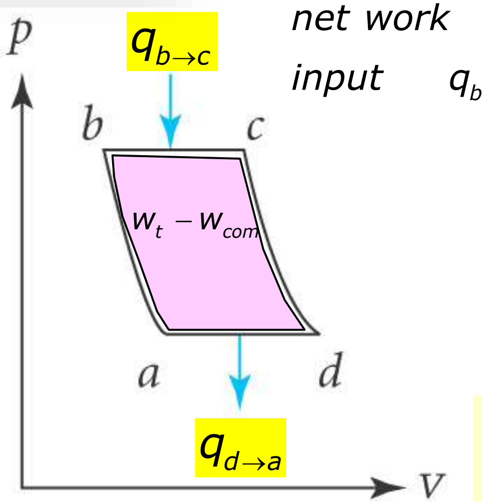
$$w_{com} = h_b - h_a = c_p \cdot (T_b - T_a) > 0 \quad absorbed\ @\, q = 0$$
$$w_t = h_c - h_d = c_p \cdot (T_c - T_d) < 0 \quad emitted\ @\, q = 0$$

$$net\ work \quad w = w_t - w_{com} = (h_c - h_d) - (h_b - h_a)$$
$$input \quad q_{b\to c} = h_c - h_b$$

$$\varepsilon = \frac{w}{q_{b\to c}} = \frac{(h_c - h_d) - (h_b - h_a)}{h_c - h_b}$$

$$\varepsilon = 1 - \frac{(h_d - h_a)}{(h_c - h_b)}$$





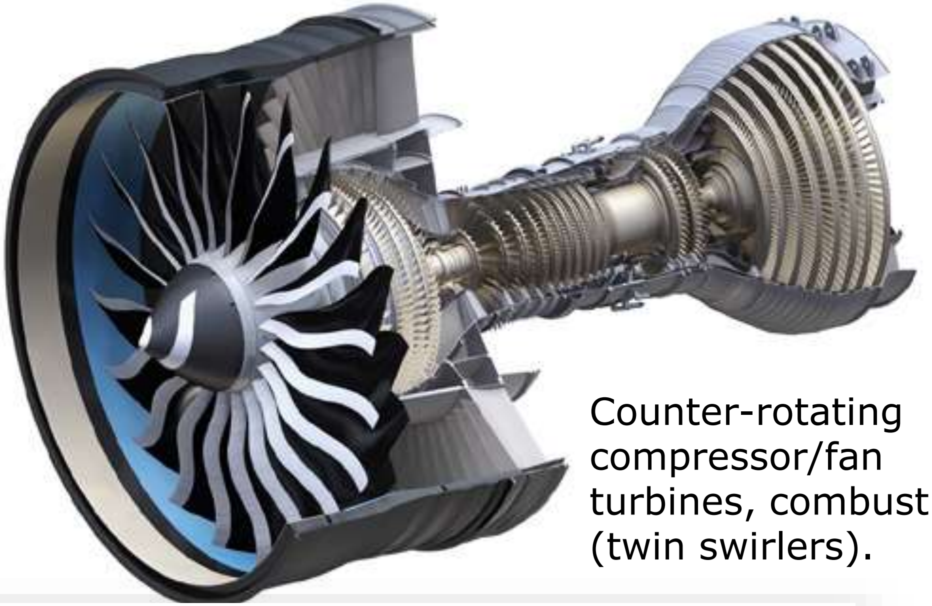
Compression $p_b/p_a=10$, $c_p/c_v=1.3$ → $\varepsilon=0.41$

$$Adiabatic\ EOS: \boxed{\varepsilon = 1 - \left(\frac{p_b}{p_a}\right)^{-\frac{R}{c_p}}}$$

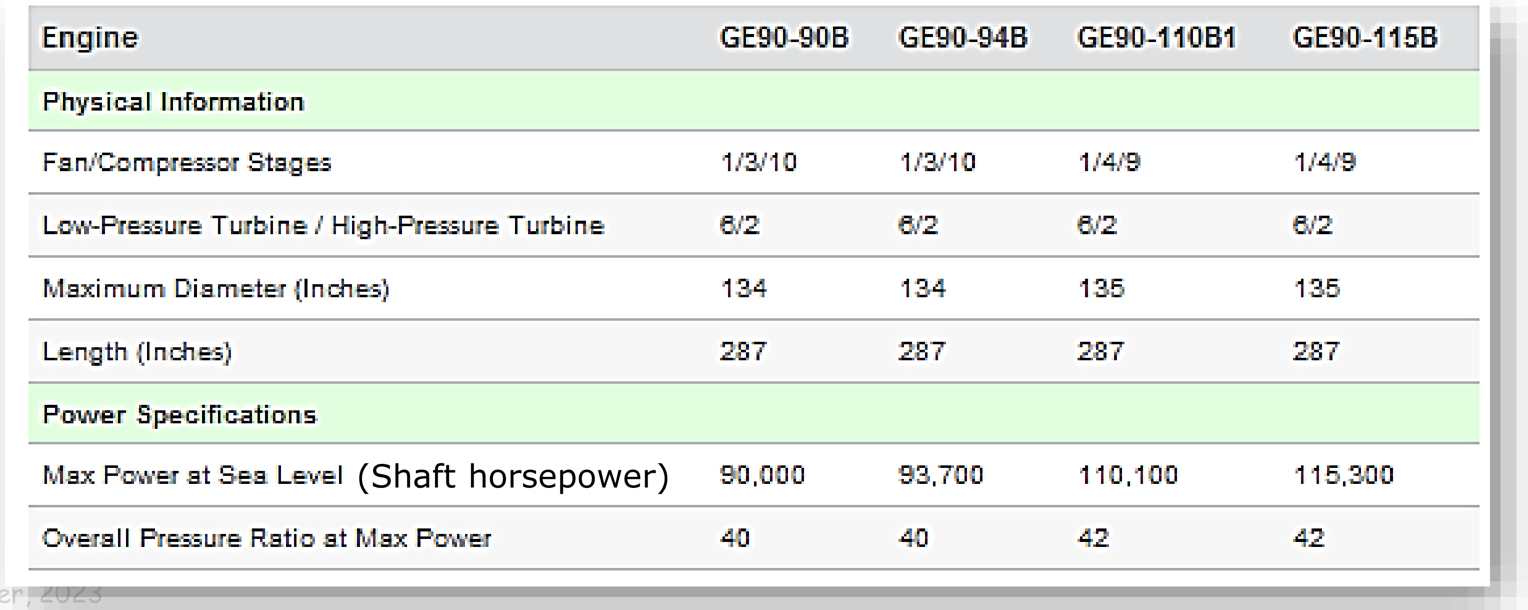
Turbine exhaust still very hot → use again

Aircraft Turbo Fan Engine

Advanced materials, titanium-aluminide on turbine blades, composites + Ti on fan blades, By-pass ratio 9.6:1.
Thrust up to 75,000 lbf (330 ***kN***)



Counter-rotating compressor/fan turbines, combustion (twin swirlers).



Engine	GE90-90B	GE90-94B	GE90-110B1	GE90-115B
Physical Information				
Fan/Compressor Stages	1/3/10	1/3/10	1/4/9	1/4/9
Low-Pressure Turbine / High-Pressure Turbine	6/2	6/2	6/2	6/2
Maximum Diameter (Inches)	134	134	135	135
Length (Inches)	287	287	287	287
Power Specifications				
Max Power at Sea Level (Shaft horsepower)	90,000	93,700	110,100	115,300
Overall Pressure Ratio at Max Power	40	40	42	42

Fin
Steam & Gas Turbines

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Combustion of Hydrocarbons

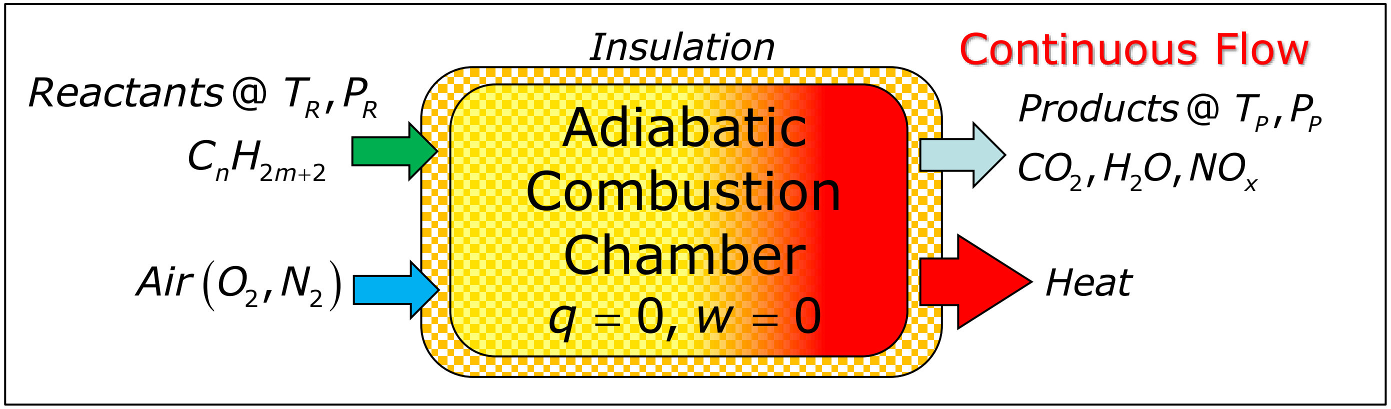
Currently, in most thermal power plants: Combustion of hydrocarbons
→ Heat → Mechanical Energy→ Electrical Energy

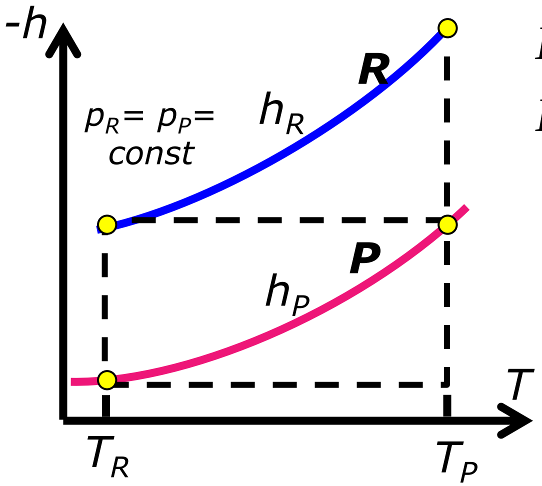
Combustion = reversible chemical rxn oxidizes fuel & releases heat energy.

reversible

$$C_nH_m + \underbrace{(n+m/4)}_{\text{stoichiometric ratio}} O_2 \leftrightarrow nCO_2 + (m/2)H_2O + \Delta H$$

$$\boxed{CH_4 \rightarrow \Delta H(-55\,MJ/kg)}$$





Excess enthalpy in rxn products → kinetic energy gas particles

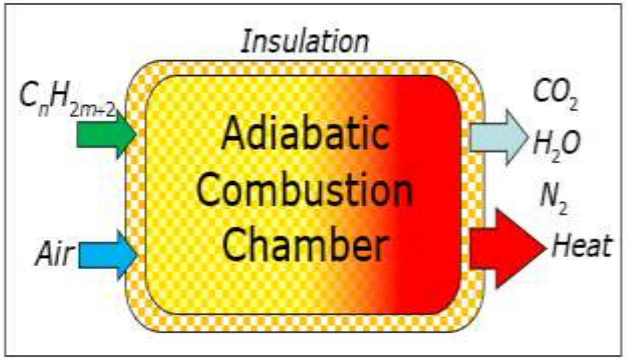
Plus heat → external, potentially useful

$$q = h_R(T_R, p_R) - h_P(T_R, p_R) < 0$$
$$= h_P(T_P, p_R) - h_P(T_R, p_R)$$

Adiabatic combustion temperature T_P → Reversible process.

Fossil Fuel Combustion in Power Plants

Complete combustion in oxygen



Hydrocarbons:

$$C_nH_m + \underbrace{(n+m/4)}_{\text{stoichiometric ratio}}\ O_2 \rightarrow nCO_2 + (m/2)H_2O\,(+\Delta H)$$

Octane (*complete combustion*):

$$C_8H_{18} + 12.5\,O_2 \rightarrow 8CO_2 + 9H_2O$$

Complete combustion in theoretical air **a_{th}** ≈ 21%O_2+79%N_2

Ratio N_2/O_2 = 79/21=3.76

Octane (*complete combustion in air*):

$$C_8H_{18} + 12.5\cdot(O_2 + 3.76\ N_2) \rightarrow 8\,CO_2 + 9H_2O + 47N_2$$

$$\boxed{a_{th} = (O_2 + 3.76\ N_2)}$$

Theoretical (balanced) air/fuel for C_8H_{18} →

$$AF_{th} := \frac{\#\,moles\ air}{\#\,moles\ fuel} = \frac{12.5(1+3.76)}{1} = 59.5$$

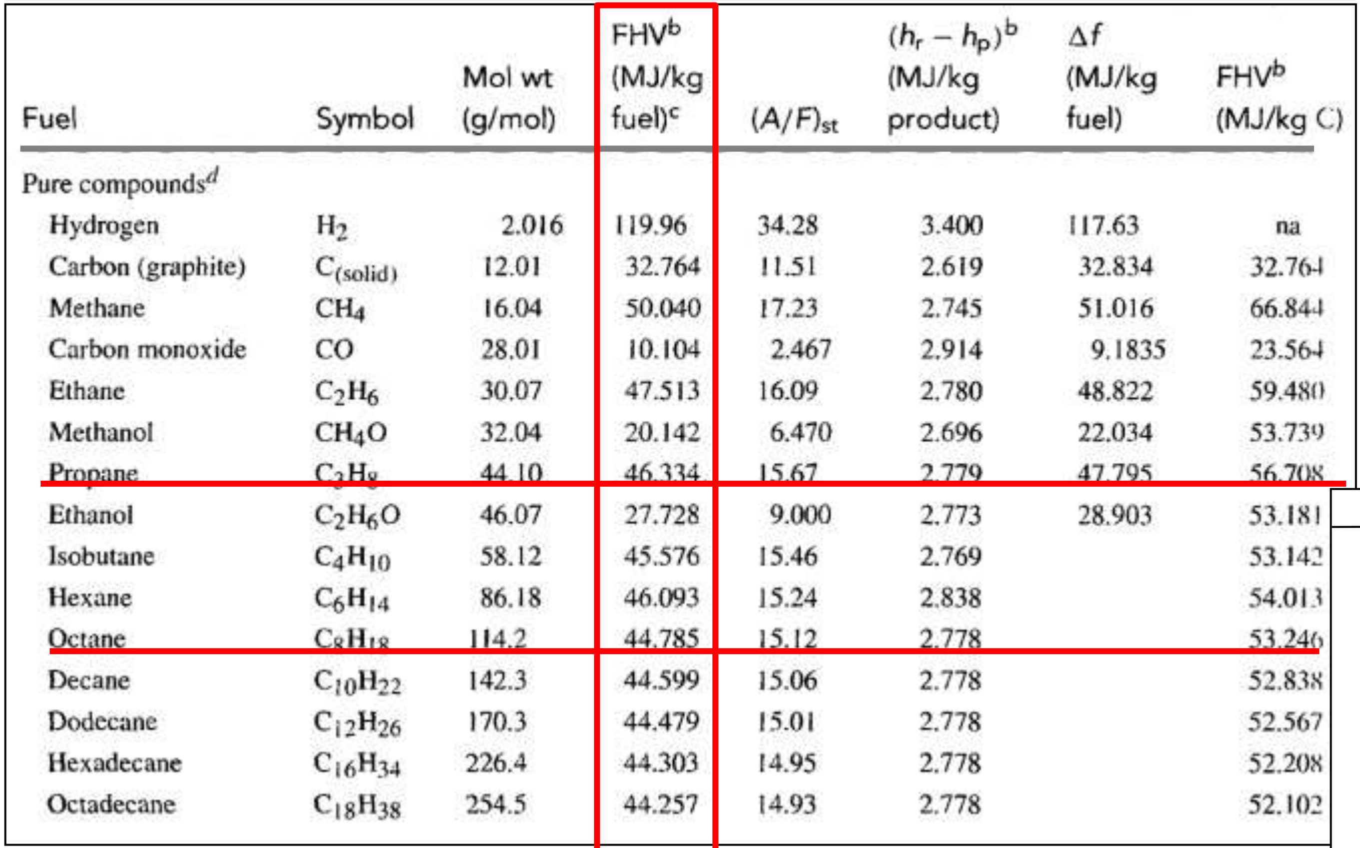
Theoretical air/fuel mass ratio for C_8H_{18}

$$AF_{m,th} := \frac{g/mole\ air}{g/mole\ fuel} = 59.5\cdot\frac{28.97g}{(8\cdot 12 + 18\cdot 1)g} = 15.12$$

In practical applications (ICE, or power plants), air amount available for combustion is mostly $\boxed{a \neq a_{th}}$

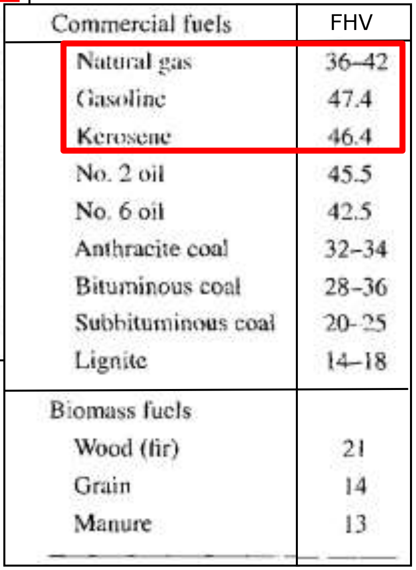
Heating Values for Fossil Fuels

Thermodynamic Properties of Fuel Combustion in Air (1atm, 25⁰C)



Fuel	Symbol	Mol wt (g/mol)	FHV[b] (MJ/kg fuel)[c]	$(A/F)_{st}$	$(h_r - h_p)^b$ (MJ/kg product)	Δf (MJ/kg fuel)	FHV[b] (MJ/kg C)
Pure compounds[d]							
Hydrogen	H_2	2.016	119.96	34.28	3.400	117.63	na
Carbon (graphite)	$C_{(solid)}$	12.01	32.764	11.51	2.619	32.834	32.764
Methane	CH_4	16.04	50.040	17.23	2.745	51.016	66.844
Carbon monoxide	CO	28.01	10.104	2.467	2.914	9.1835	23.564
Ethane	C_2H_6	30.07	47.513	16.09	2.780	48.822	59.480
Methanol	CH_4O	32.04	20.142	6.470	2.696	22.034	53.739
Propane	C_3H_8	44.10	46.334	15.67	2.779	47.795	56.708
Ethanol	C_2H_6O	46.07	27.728	9.000	2.773	28.903	53.181
Isobutane	C_4H_{10}	58.12	45.576	15.46	2.769		53.142
Hexane	C_6H_{14}	86.18	46.093	15.24	2.838		54.013
Octane	C_8H_{18}	114.2	44.785	15.12	2.778		53.246
Decane	$C_{10}H_{22}$	142.3	44.599	15.06	2.778		52.838
Dodecane	$C_{12}H_{26}$	170.3	44.479	15.01	2.778		52.567
Hexadecane	$C_{16}H_{34}$	226.4	44.303	14.95	2.778		52.208
Octadecane	$C_{18}H_{38}$	254.5	44.257	14.93	2.778		52.102

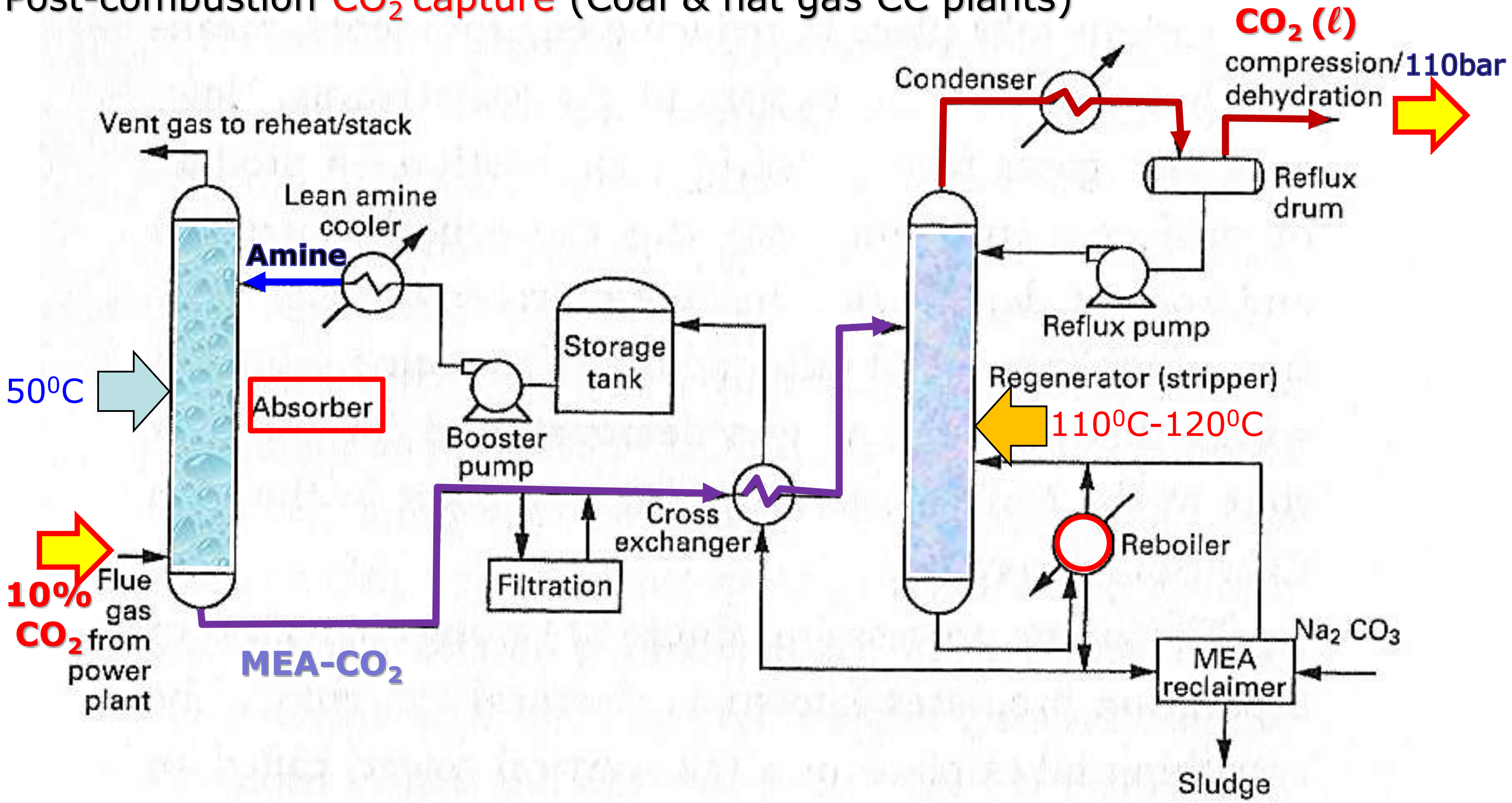
CRC Handbook of Chemical Properties



Commercial fuels	FHV
Natural gas	36–42
Gasoline	47.4
Kerosene	46.4
No. 2 oil	45.5
No. 6 oil	42.5
Anthracite coal	32–34
Bituminous coal	28–36
Subbituminous coal	20–25
Lignite	14–18
Biomass fuels	
Wood (fir)	21
Grain	14
Manure	13

Post-Combustion CO_2 Capture: Amine Scrubbing Process

Post-combustion CO_2 capture (Coal & nat gas CC plants)

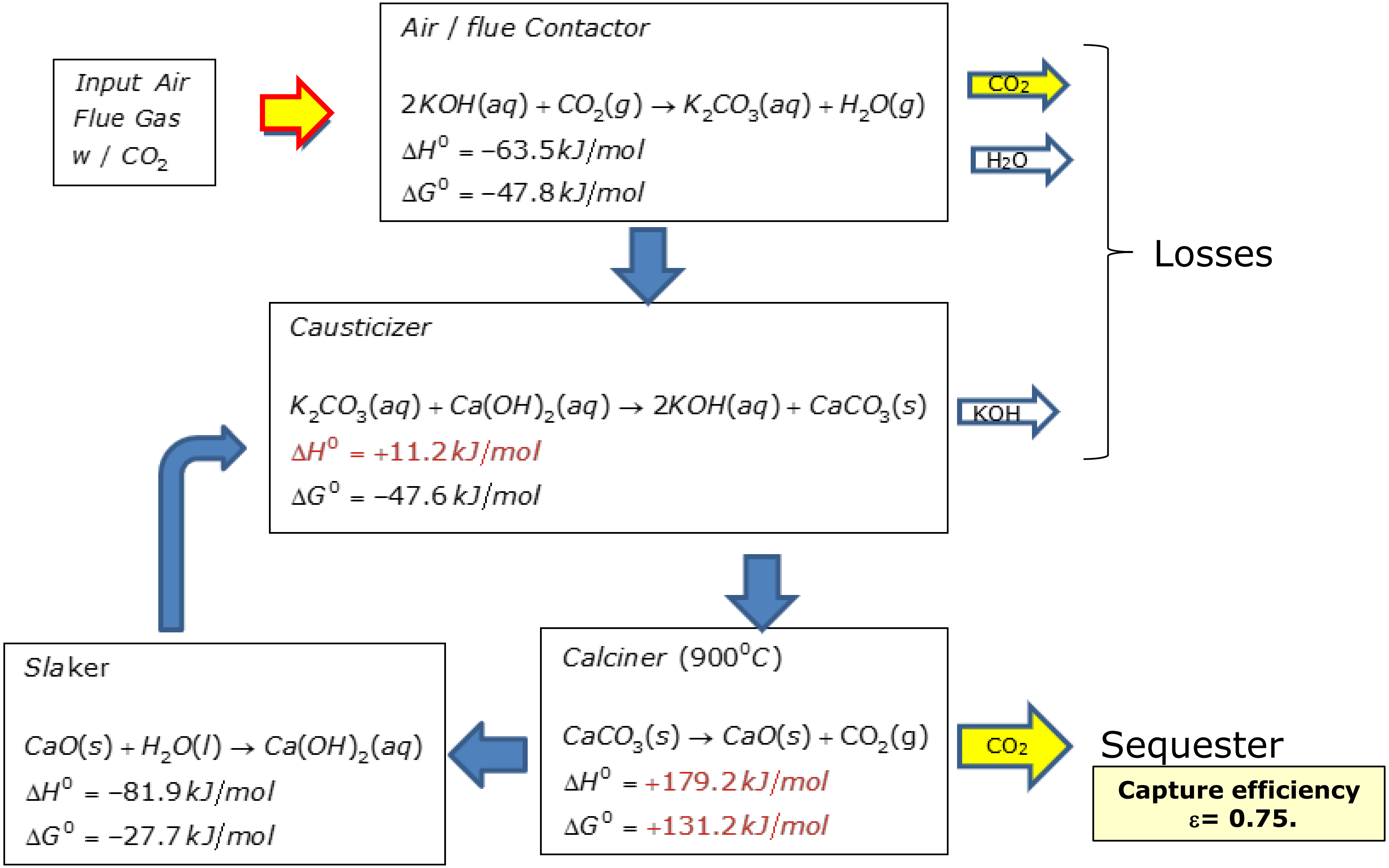


Efficiency of amine process: ≳90% of CO_2 in the flue gas,
energy intensive (steam: 2GJ/tCO_2), =30% of the plant power generation.
CO_2 product purity >99%

(CC Cost: E.S. Rubin et al., Int. Jour. Greenhouse Gas Control 40, 382 (2015))

Post-Combustion Carbon Capture (Air/Flue Stream)

Main components of a direct CO_2 capture process using a liquid solvent. Partial recycling of chemical. Energy intense process (calciner).



Input Air Flue Gas w / CO_2

Air / flue Contactor

$$2KOH(aq) + CO_2(g) \rightarrow K_2CO_3(aq) + H_2O(g)$$
$$\Delta H^0 = -63.5\,kJ/mol$$
$$\Delta G^0 = -47.8\,kJ/mol$$

CO_2

H_2O

Causticizer

$$K_2CO_3(aq) + Ca(OH)_2(aq) \rightarrow 2KOH(aq) + CaCO_3(s)$$
$$\Delta H^0 = +11.2\,kJ/mol$$
$$\Delta G^0 = -47.6\,kJ/mol$$

KOH

Losses

Slaker

$$CaO(s) + H_2O(l) \rightarrow Ca(OH)_2(aq)$$
$$\Delta H^0 = -81.9\,kJ/mol$$
$$\Delta G^0 = -27.7\,kJ/mol$$

Calciner (900^0C)

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$$
$$\Delta H^0 = +179.2\,kJ/mol$$
$$\Delta G^0 = +131.2\,kJ/mol$$

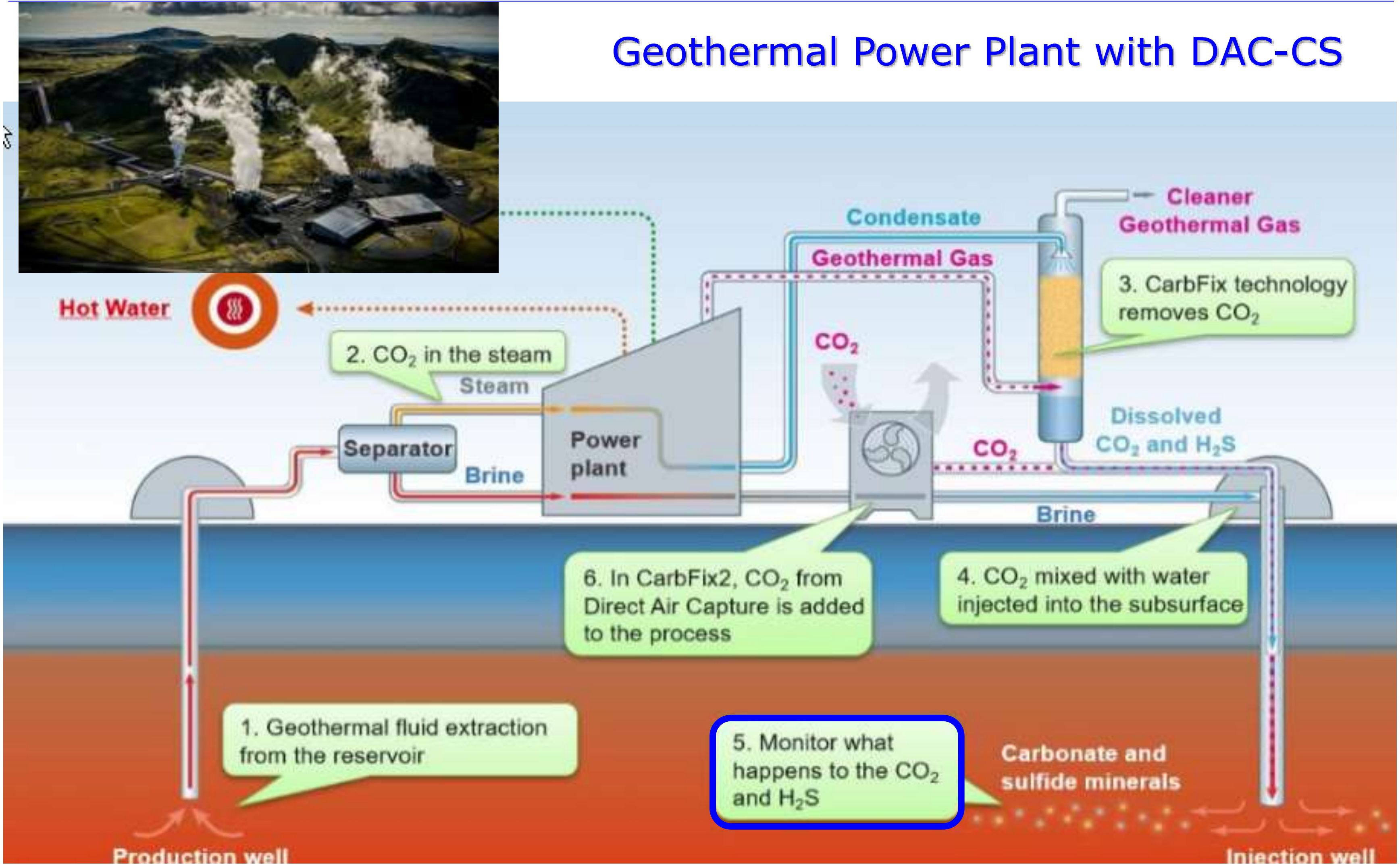
CO_2

Sequester

Capture efficiency
ε= 0.75.

Post-Combustion &DAC CO_2 (Hellisheidi CarbFix/Mammoth Plant)

Geothermal Power Plant with DAC-CS

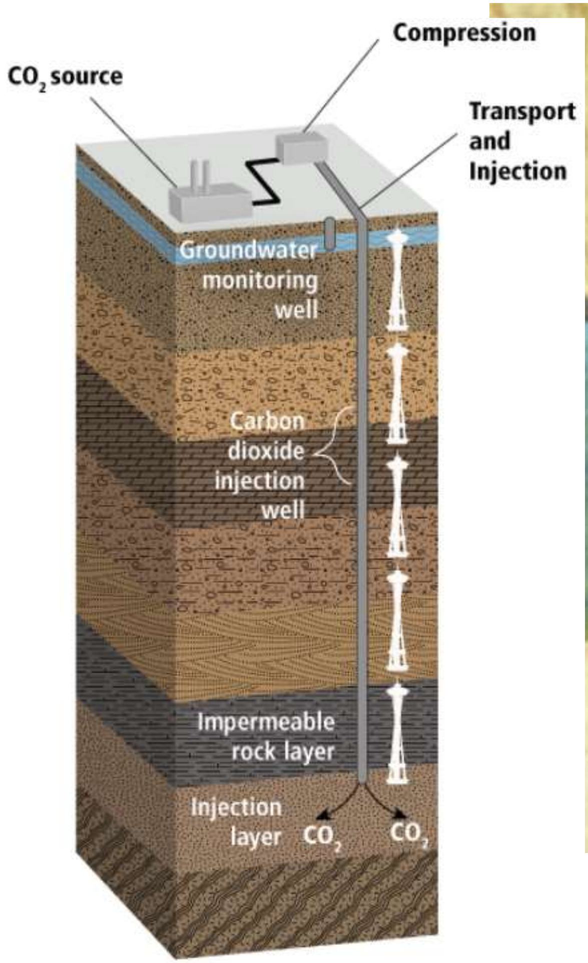


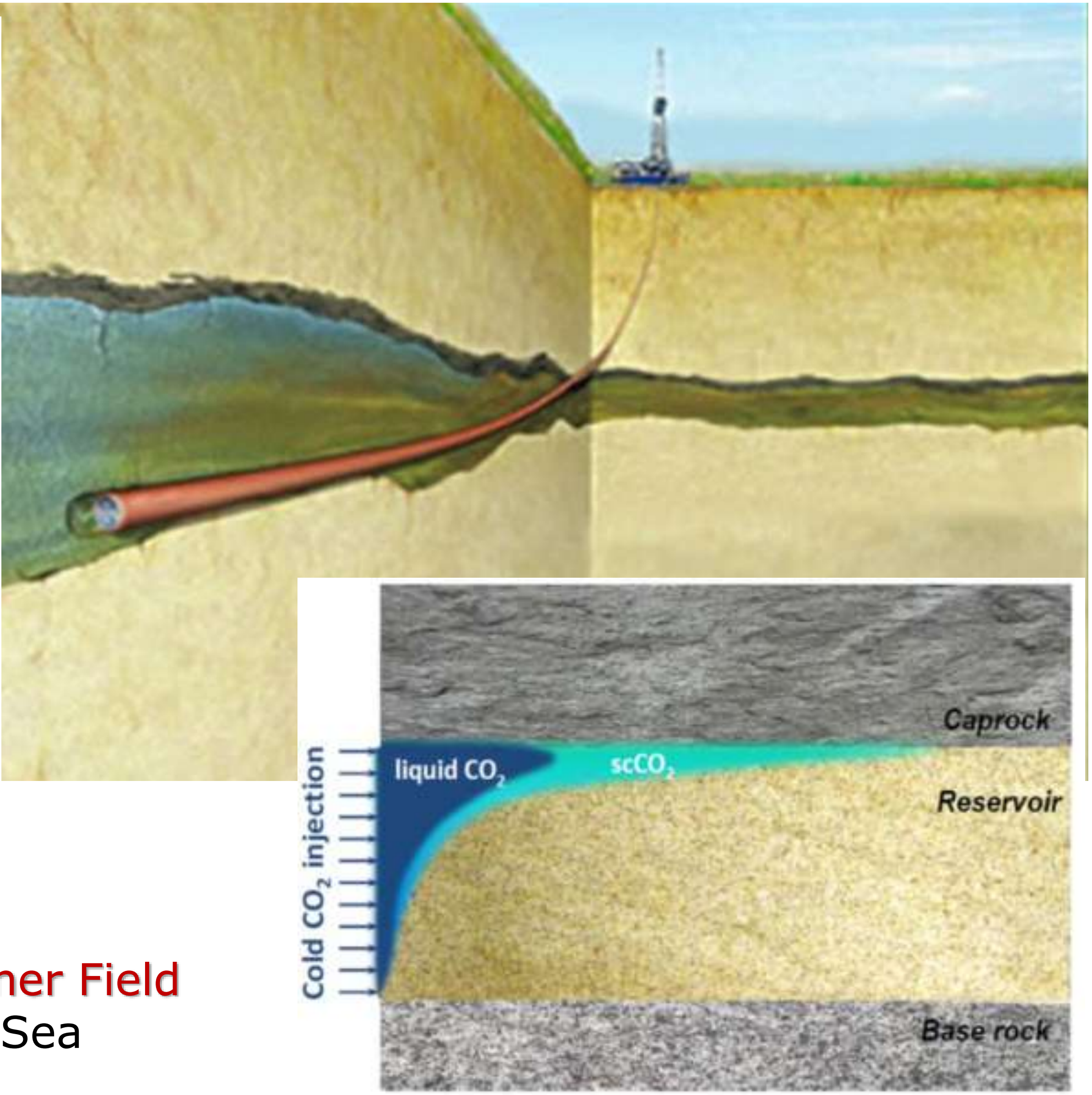
Island: Process disposes of CO_2 (permanently) as *carbonate minerals* in subsurface basaltic rocks. Experimental research: two years after injection, 95% of the CO_2 was mineralized, contradicting earlier expectations. UNESCO Science Report (2021)

CO_2 Direct Air Capture (Trials)

Climeworks, which operates the world's largest direct air capture plant in Iceland, is participating in the U.S. DAC hub program. (Climeworks)

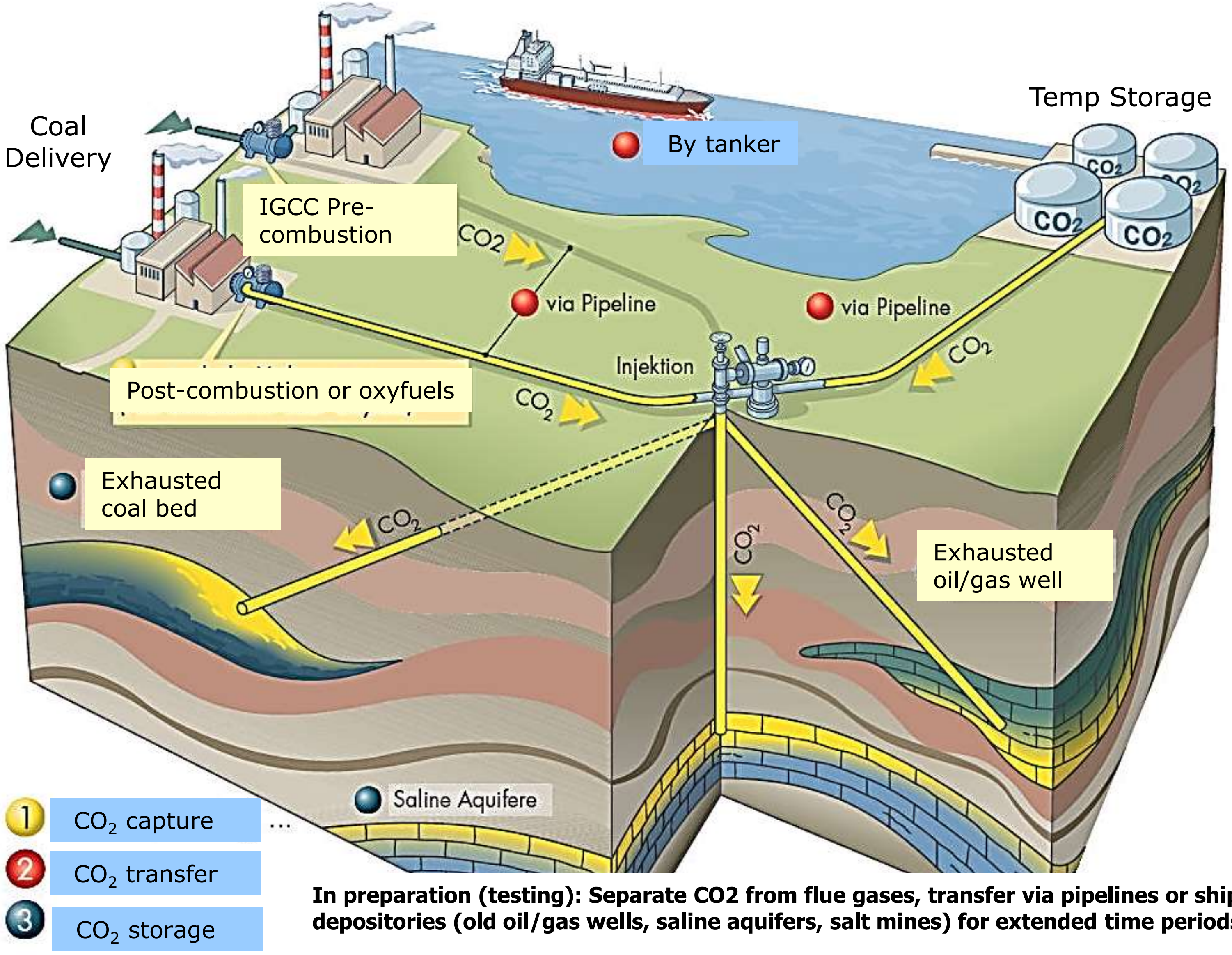
Proven CCS Technology





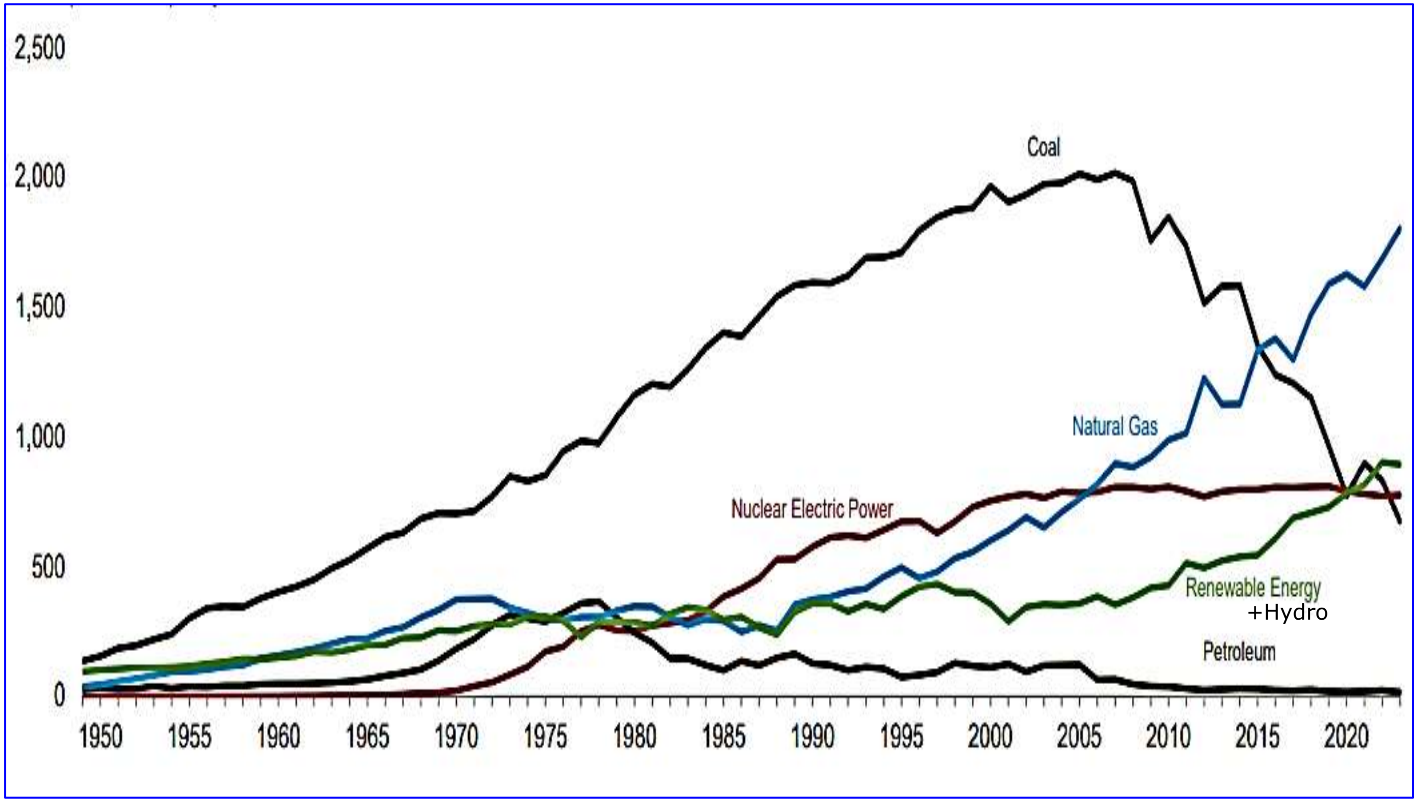
Since 1980s: **Sleipner Field**
NW Norway, North Sea
Oil/Gas fields

Other CO_2 Sequestration Concepts



In preparation (testing): Separate CO2 from flue gases, transfer via pipelines or ships to geological depositories (old oil/gas wells, saline aquifers, salt mines) for extended time periods ~ 10^3 a.

U.S. Electricity Production 1949-2023



US >2010 Steady increase of primary energy carriers for electricity natural gas and renewables (hydro+wind+solar).

>2030 Large contributions of coal and hydro should decrease.

Fin
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