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
- Gas turbine power plants
  - Combined-cycle plants
- Chemistry of complete & incomplete combustion
  - Examples
- Carbon (CO_2) capture processes

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

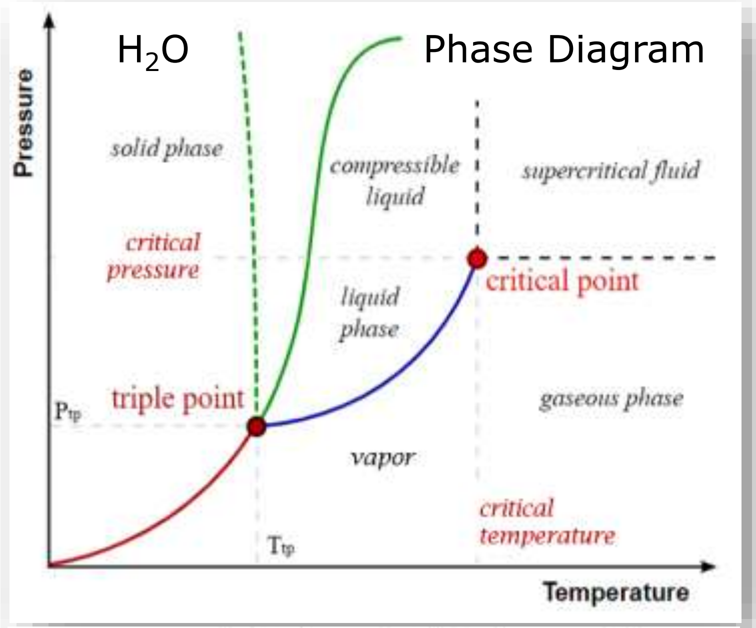
Real Substances (Different Phases: *s*, *ℓ*, *g*, *sc*)

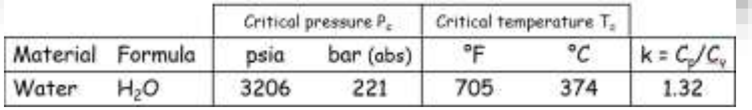
All real substances have distinct physical phases:

solid ($T<T_{\text{freeze}}$), liquid ($T_{\text{freeze}}<T< T_{\text{boil}}$) and gas ($T_{\text{boil}}<T$)

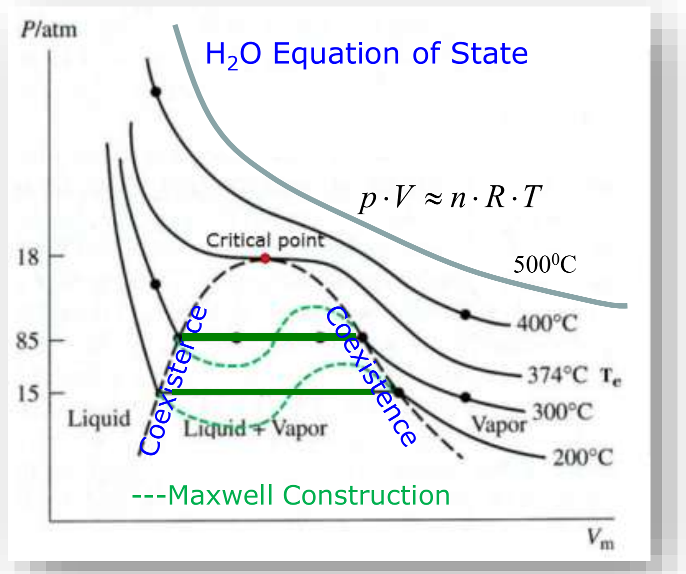
Phase transitions occur upon changes in internal energy by characteristic amounts: *latent heat* (*Δ-enthalpy*) *of fusion or* *latent heat of vaporization*

$$Enthalpy\ \boxed{H = U + p_{ext}\cdot V_{sys}} \qquad \underline{at\ P_{ext} = const.}: \boxed{q = \Delta H = C_p \Delta T}\ heat\ capacity\ C_p$$





		Critical pressure P_c		Critical temperature T_c		
Material	Formula	psia	bar (abs)	°F	°C	$k = C_p/C_v$
Water	H_2O	3206	221	705	374	1.32



- - - - van der Waals gas model

$$\left(p + a\cdot\left(\frac{n}{V}\right)^2\right)\cdot(V - n\cdot b) = n\cdot R\cdot T$$

Using Real Gases/Vapor Working Media

Since 18. century: thermal engines work fluid steam=water vapor, water droplets (wet steam). Real gas molecules interact → viscous motion depending on ρ, T. → **Several phases**.

$$\textit{Ideal – Gas EoS}\quad p\cdot V = R\cdot T\ (\textit{per mole}) \rightarrow$$

$$\textit{Virial expansion of}\ \textbf{compression factor}$$

$$\boxed{z = \frac{p\cdot V}{R\cdot T} = 1 + \frac{B(T)}{V} + \frac{C(T)}{V^2} + \ldots =: \sum_{n=0}^{\infty} \frac{c_n(T)}{V^n}}$$

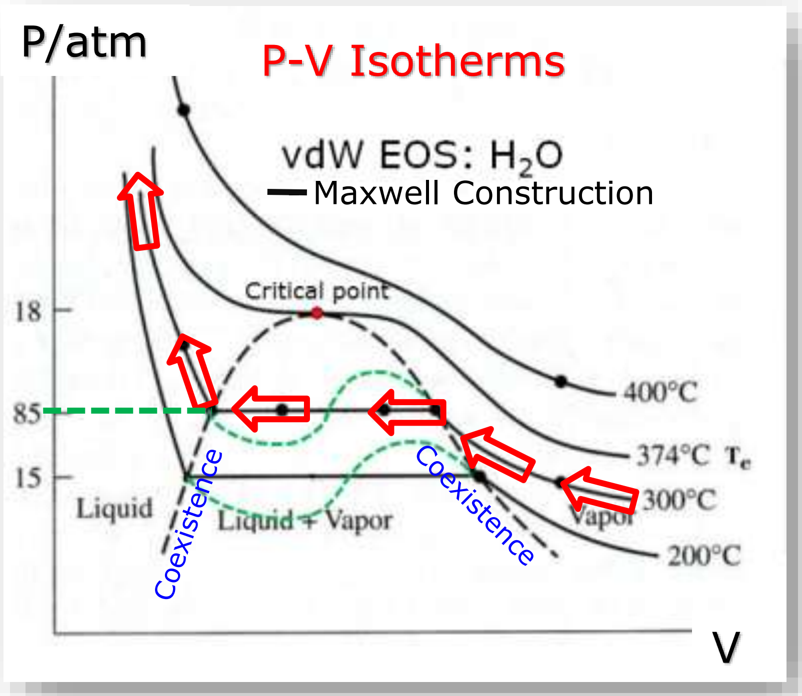
Useful Parameterizations

van der Waals EoS :

$$p = \frac{n\cdot R\cdot T}{(V - n\cdot b)} - a\frac{n^2}{V^2}$$

Redlich Kwong EoS :

$$p = \frac{n\cdot R\cdot T}{(V - nb)} - a\frac{n^2}{\sqrt{T}}\cdot\frac{1}{V(V+nb)}$$



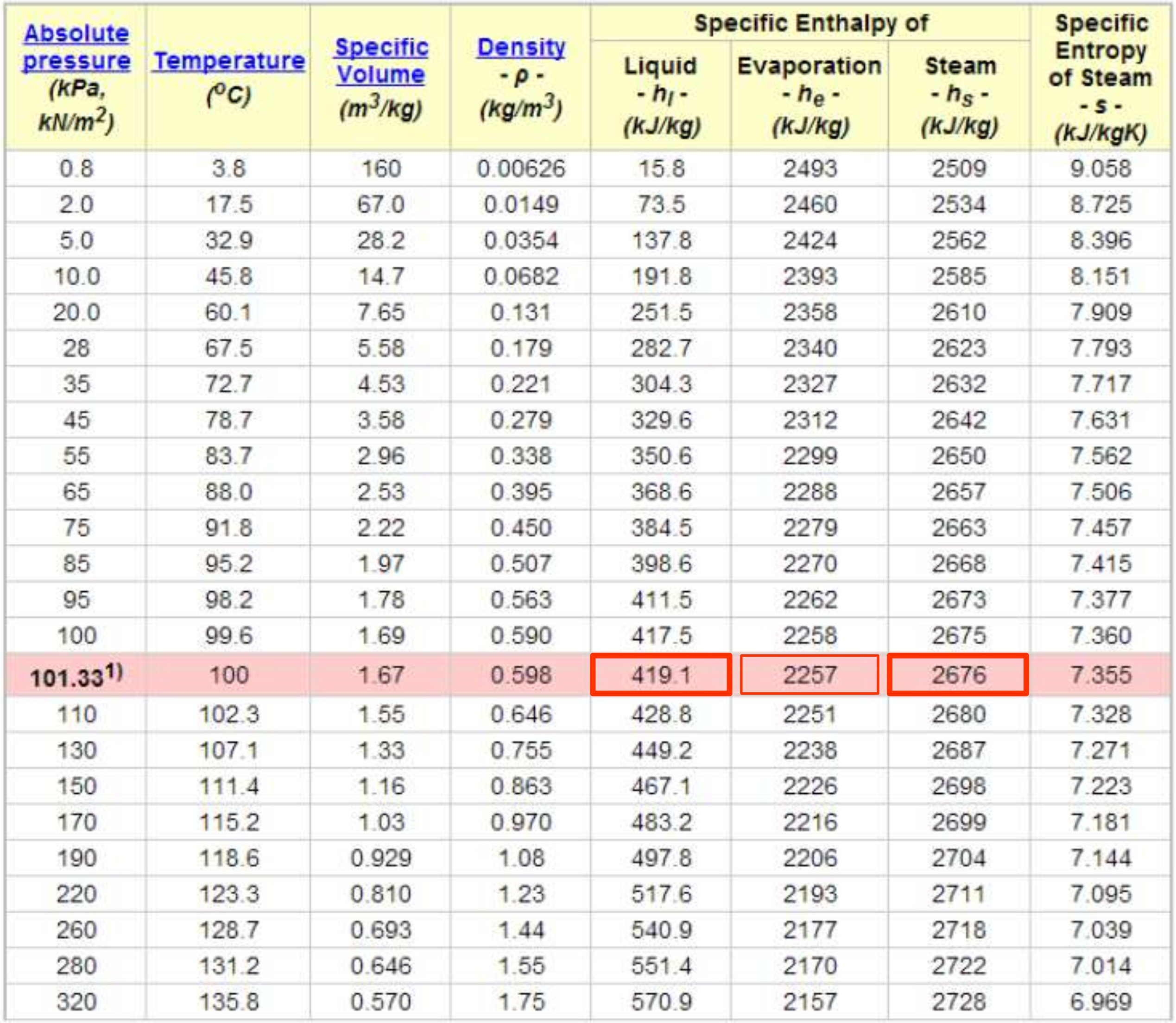
Van der Waals Parameters

Substance	a (L^2 atm/mol^2)	b (L/mol)
He	0.0341	0.0237
H_2	0.244	0.0266
O_2	1.36	0.0318
H_2O	5.46	0.0305
CCl_4	20.4	0.1383

Non-monotonic EoS → liquid-gas instability.
Increasing compression: vdW model gas temporarily collapses (p decreases with decreasing V) but reconstitutes again.
Real gases aggregate, form droplets → progressive liquefaction @ $\mu_{vapor} = \mu_{liquid}$ *per mol*

Combine vdW EoS with isobar in instability domain Maxwell Construction

Steam Tables



Absolute pressure (kPa, kN/m²)	Temperature (°C)	Specific Volume (m³/kg)	Density - ρ - (kg/m³)	Specific Enthalpy of			Specific Entropy of Steam - s - (kJ/kgK)
				Liquid - h_l - (kJ/kg)	Evaporation - h_e - (kJ/kg)	Steam - h_s - (kJ/kg)	
0.8	3.8	160	0.00626	15.8	2493	2509	9.058
2.0	17.5	67.0	0.0149	73.5	2460	2534	8.725
5.0	32.9	28.2	0.0354	137.8	2424	2562	8.396
10.0	45.8	14.7	0.0682	191.8	2393	2585	8.151
20.0	60.1	7.65	0.131	251.5	2358	2610	7.909
28	67.5	5.58	0.179	282.7	2340	2623	7.793
35	72.7	4.53	0.221	304.3	2327	2632	7.717
45	78.7	3.58	0.279	329.6	2312	2642	7.631
55	83.7	2.96	0.338	350.6	2299	2650	7.562
65	88.0	2.53	0.395	368.6	2288	2657	7.506
75	91.8	2.22	0.450	384.5	2279	2663	7.457
85	95.2	1.97	0.507	398.6	2270	2668	7.415
95	98.2	1.78	0.563	411.5	2262	2673	7.377
100	99.6	1.69	0.590	417.5	2258	2675	7.360
101.33 1)	100	1.67	0.598	419.1	2257	2676	7.355
110	102.3	1.55	0.646	428.8	2251	2680	7.328
130	107.1	1.33	0.755	449.2	2238	2687	7.271
150	111.4	1.16	0.863	467.1	2226	2698	7.223
170	115.2	1.03	0.970	483.2	2216	2699	7.181
190	118.6	0.929	1.08	497.8	2206	2704	7.144
220	123.3	0.810	1.23	517.6	2193	2711	7.095
260	128.7	0.693	1.44	540.9	2177	2718	7.039
280	131.2	0.646	1.55	551.4	2170	2722	7.014
320	135.8	0.570	1.75	570.9	2157	2728	6.969

Latent Heat

Heat required to initiate phase transition.
$\boldsymbol{T} \equiv$ const. until entire sample mass has transitioned.

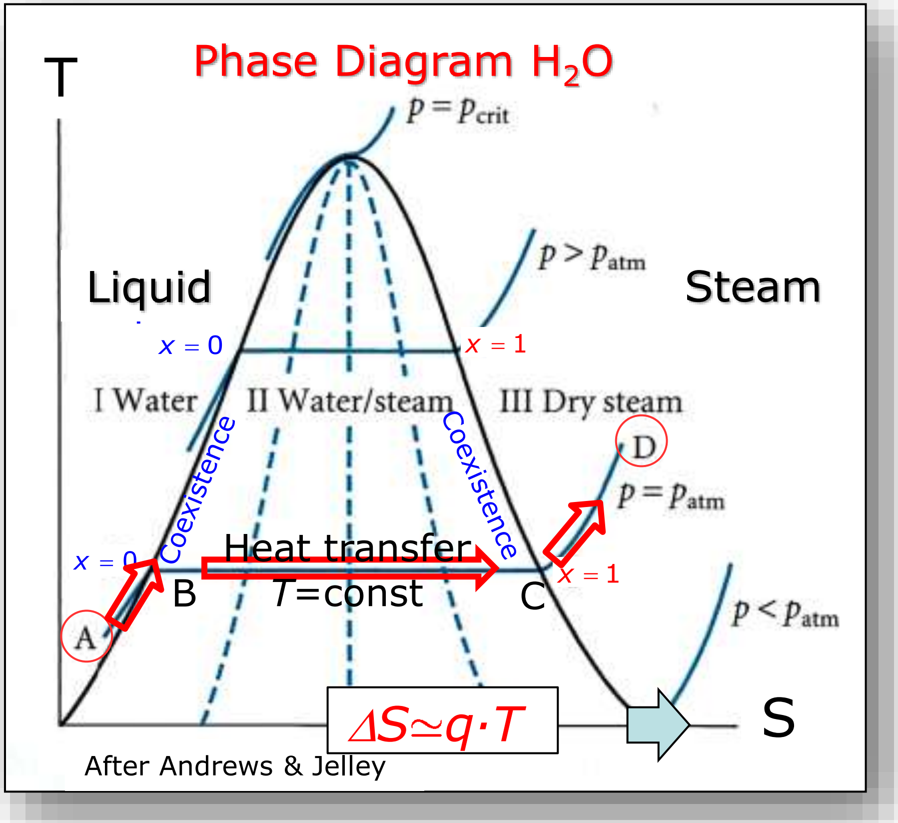
p = 1 bar= 101.33 kN/m²

1) *Water @ 0^0C → 100^0C.*
→ 419 kJ/kg
$\boldsymbol{h}_{water}(100^0C) = 419$ *kJ/kg*.

2) *Water @100^0C* → steam @100^0C. Specific enthalpy of evaporation (latent heat):
$\boldsymbol{h}_{evap}(100^0C) = 2{,}257$*kJ/kg*

3) *Water @0^0C* → steam @100^0C. Specific enthalpy
$\boldsymbol{h}_{steam}(100^0C) = 2.676$*MJ/kg*

Water as a Working Power Medium



After Andrews & Jelley

To use steam as driving gas for thermal engines, heat energy has to be transferred to water at T_l (e.g., 25^{0}C)

A) heat 1mol liquid H_2O to 100^{0}C
B-C) evaporate all H_2O (@ 100^{0}C)
D) heat vapor beyond 100^{0}C→T_h

p = 1 atm *(bar)= 101.33 kN/m²*
→ Water boils @ at *100⁰C*
→ Need *419 kJ/kg* H_2O to heat water from *0⁰C* to *T= 100⁰C*.

→ @ *p=101.33 kN/m²* and *100⁰C*
Specific enthalpy H_2O:
$\boldsymbol{h}_{water}(100^0C) = 419\ kJ/kg$.

Specific enthalpy of evaporation (latent heat): $\boldsymbol{h}_{evap}(100^0C) = 2{,}257\ kJ/kg$
(not applicable to ideal gas)

Total heat required at *p=const.* to convert H_2O to steam @*100⁰C* :

$$\boldsymbol{h}_{steam}(100^0C) = (419 + 2{,}257)kJ/kg = 2{,}676\ kJ/kg = 2.676\ (MJ/kg) = 0.74\ kWh/kg$$

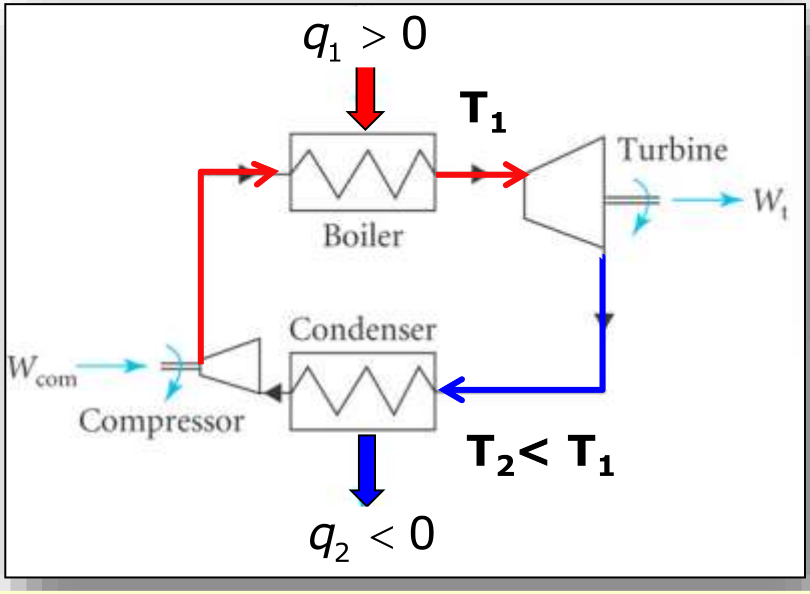
L-G mixture $\boldsymbol{h_s(x) = (1-x)\cdot h_{water} + x\cdot h_{steam}}$

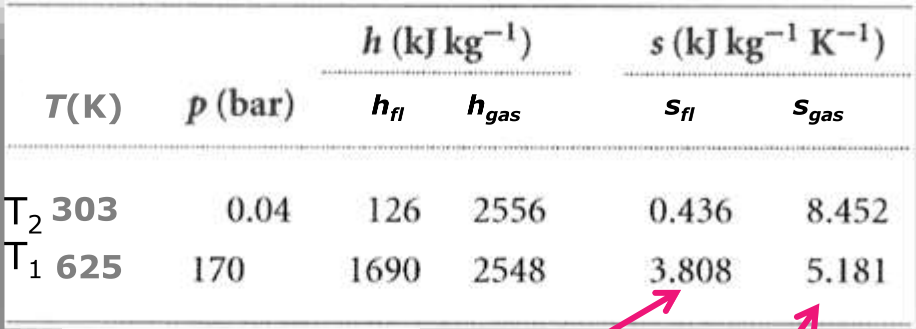
Similar: $\boldsymbol{u_s(x) = (1-x)\cdot u_{water} + x\cdot u_{steam}}$

Extensive variables

(U, H, S,..)

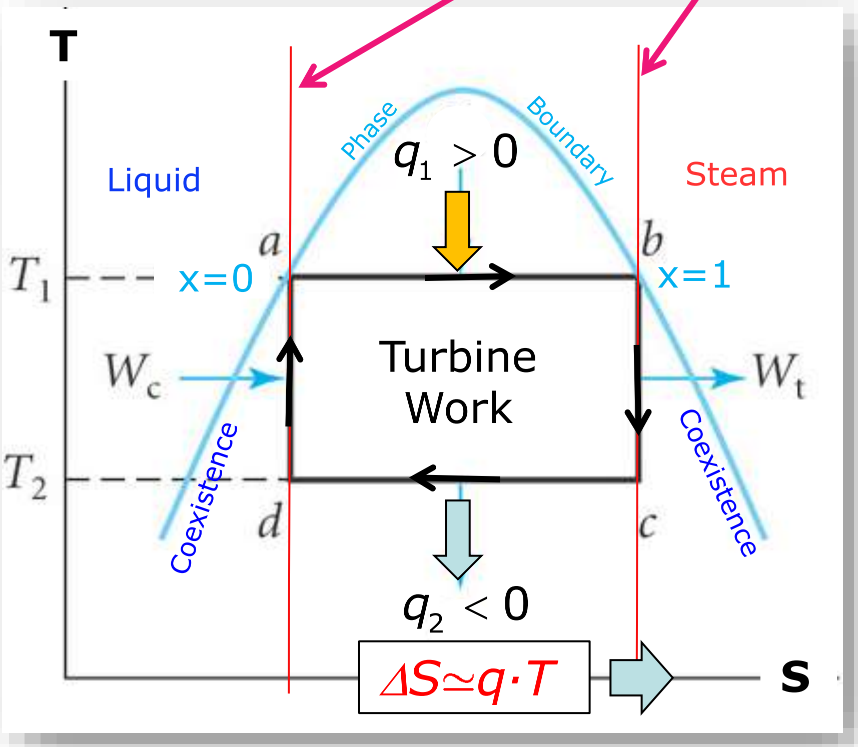
S-T Diagram for Steam Carnot Process





		h (kJ kg^{-1})		s (kJ kg^{-1} K^{-1})	
T(K)	p (bar)	h_{fl}	h_{gas}	s_{fl}	s_{gas}
T_2 303	0.04	126	2556	0.436	8.452
T_1 625	170	1690	2548	3.808	5.181

After Andrews & Jelley



Enthalpy, entropy extensive→ Scale w/ x

$$x = \text{steam quality} \ (\text{fraction } g/(g+fl))$$

$$h = (1-x)\cdot h_{fl} + x\cdot h_{gas} \qquad h = H/\text{unit mass}$$

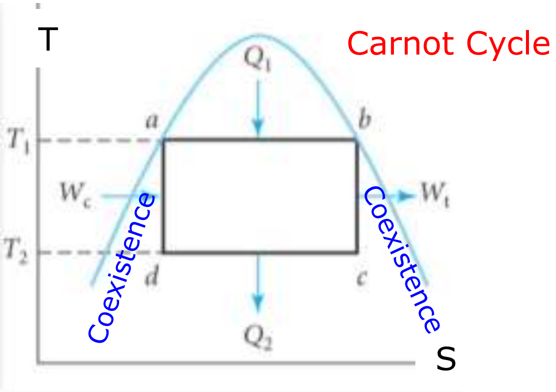
$$s = (1-x)\cdot s_{fl} + x\cdot s_{gas} \qquad s = S/\text{unit mass}$$

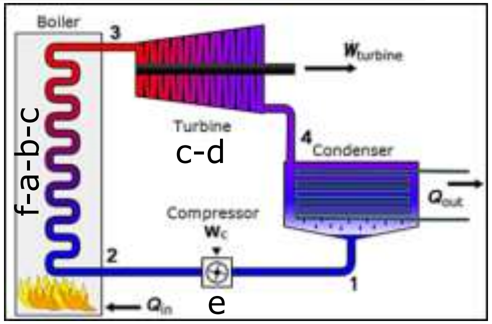
$$\text{Example}: s(d) = s(a) = 3.808\,\frac{kJ}{kg\cdot K}$$

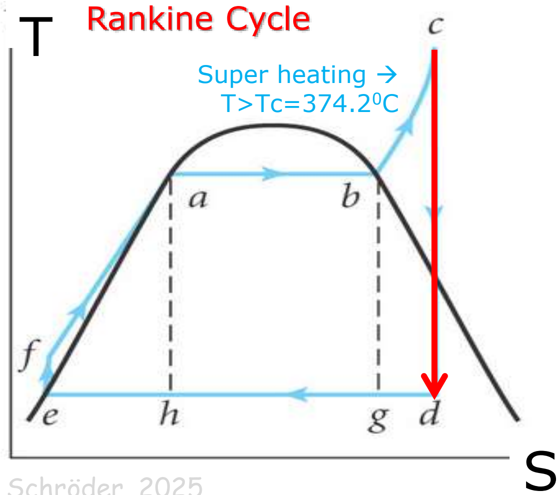
$$s(d) = (1-x_d)\cdot \underset{0.436}{s_{fl}} + x_d \cdot \underset{8.452}{s_{gas}} = 3.808 \ \ (@T_1)$$

$$\rightarrow x_d = 0.42 \ , \ \text{Solve for} \quad ....$$

Rankine Steam Cycle







Carnot cycle: highest possible work output per q for
→*T=const. processes.*
Works well for ideal gases (simple molecules, high *T*)

Disadvantage for real gases and moderate **T** because phase coexistence region limits gas $\boldsymbol{T_h}$ per $\boldsymbol{q}_{in}$
q= T·ΔS in Carnot process, i.e., T_h is limited → low ε

Rankine cycle*:* (Thermodynamically robust)

e→ *f* Compressor (pump) injects H_2O under *p*
f → *a* Economizer heats H_2O under pressure.
a→ *b* Evaporator boils H_2O under *p* = const.
b→ *c* Superheater heats steam @high *p* = const.
c→ *d* Turbine produces work, expands steam

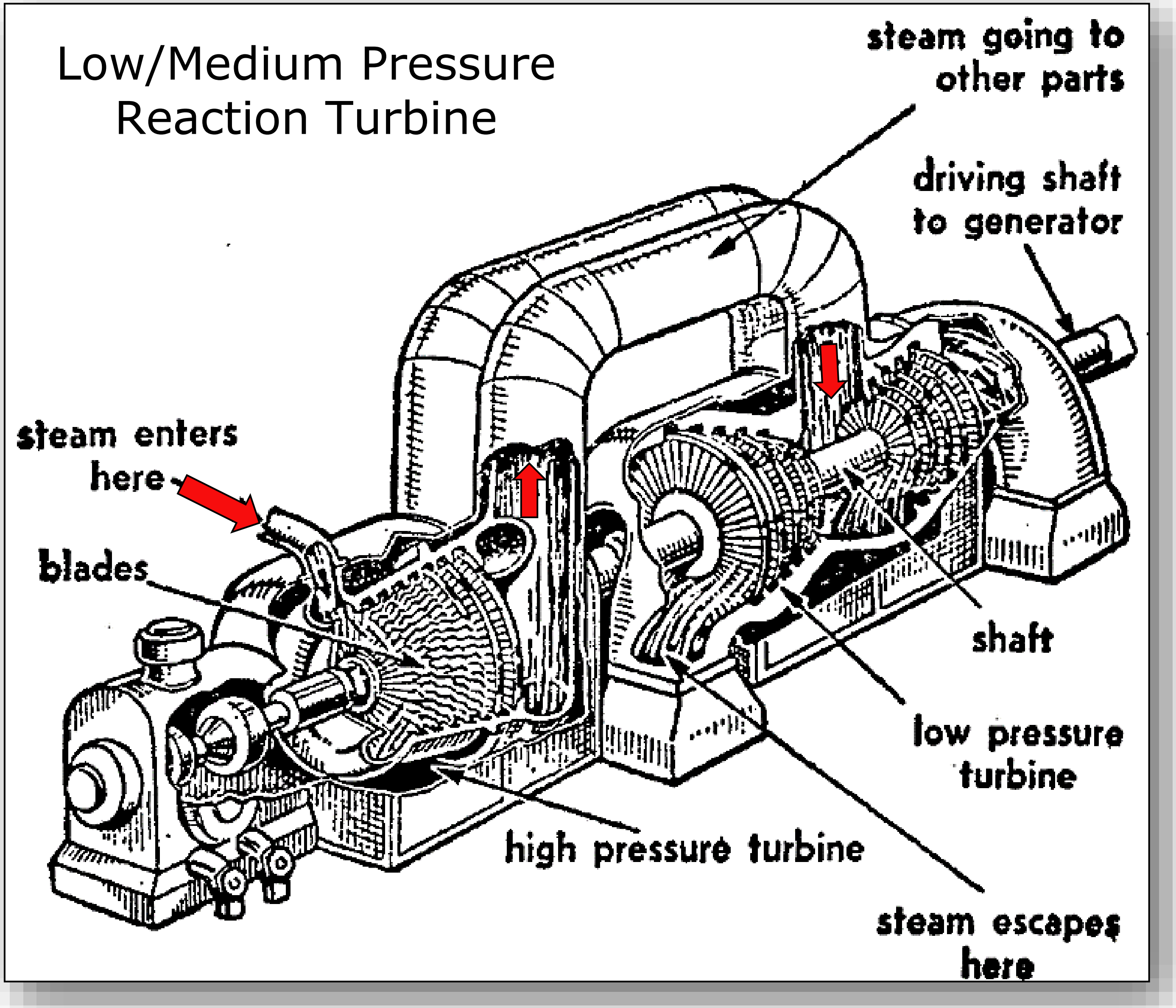
$$w_{Turbine} = H_c - H_d = \Delta\left(U + p \cdot V\right) = \int_c^d V \cdot dp \quad (S = const.)$$

d→ *e* condenser liquifies vapor @ *p* < p_{at}.
Heating and cooling occur at p=const.

Efficiency:

$$\varepsilon_{Rankine} = \frac{w_{Turbine} - w_{Compressor}}{Q_{in}} = 0.3 - 0.5$$

Steam Turbines

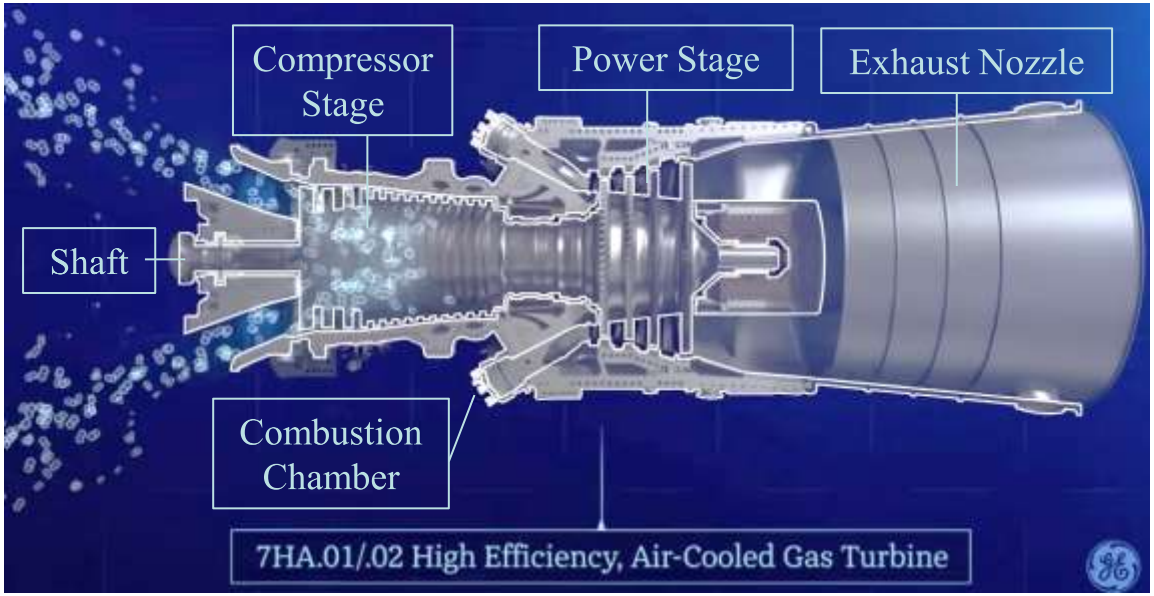

Low/Medium Pressure
Reaction Turbine

Agenda: Thermal Power Plants

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

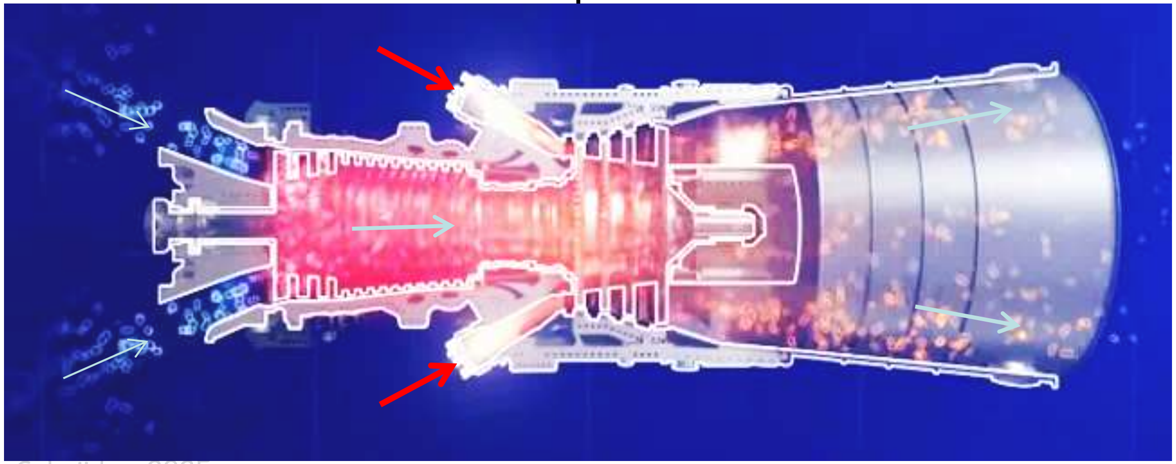
Next: Power from nuclear transmutation
Andrew & Jelley Chs. 9 & 10

Gas Power Turbine: Parts & Operation (GE)



Air intake at turbo compressor stage. Fuel/air mix injected in annular combustion chambers. Combustion gas drives turbine power stage (4).

In Operation



Turbo compressor raises air pressure (x20) & temperature.

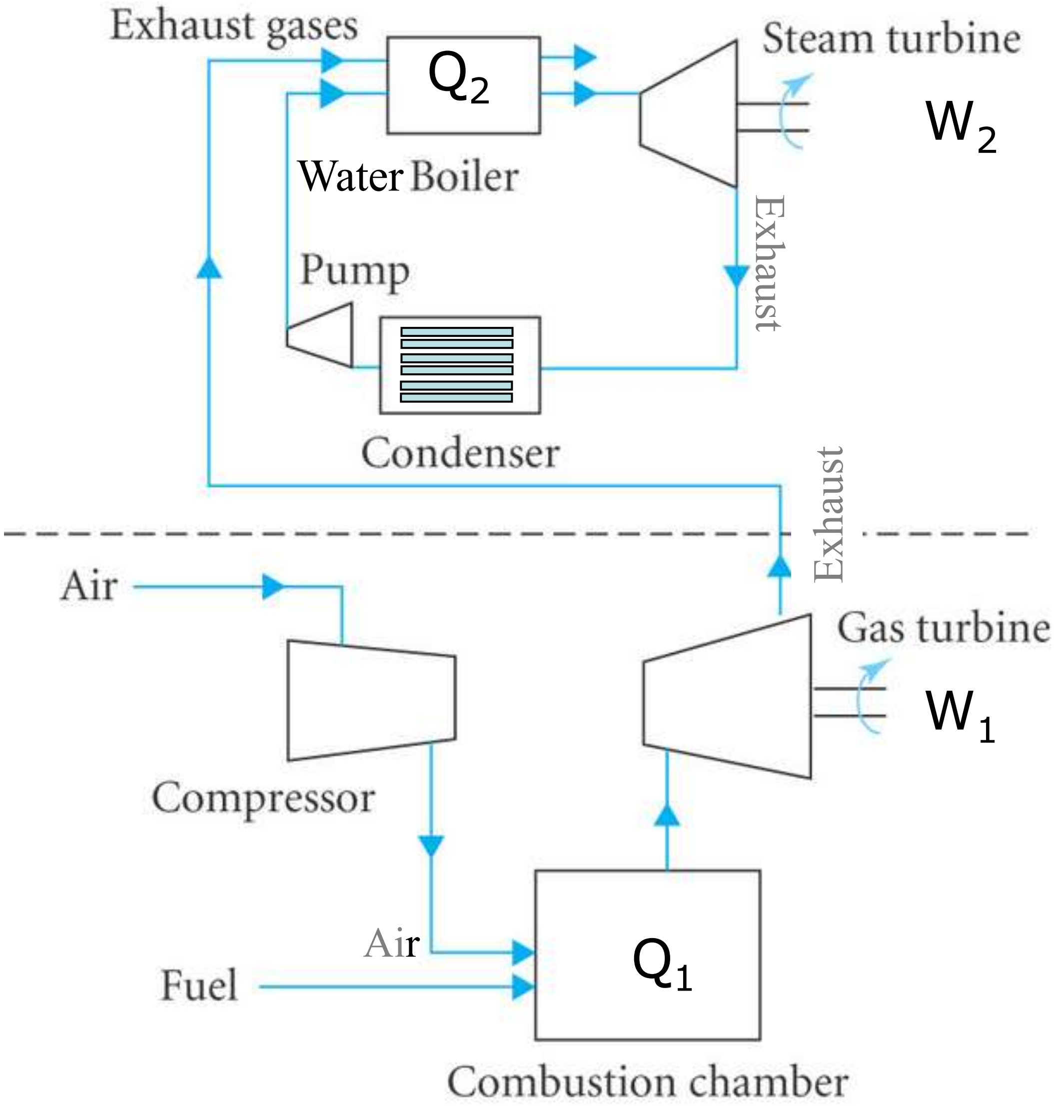
Fuel/air mix is ignited in combustion chambers. → Super heated compressed fuel/air mix drives power rotors. Hot gas exhaust.

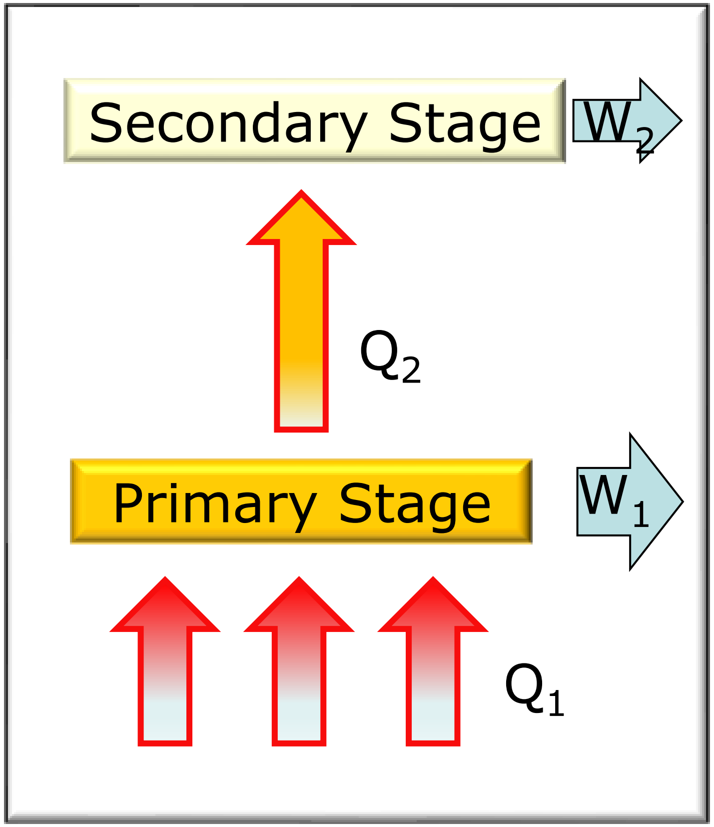
Turbine for Gas Power Plants

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

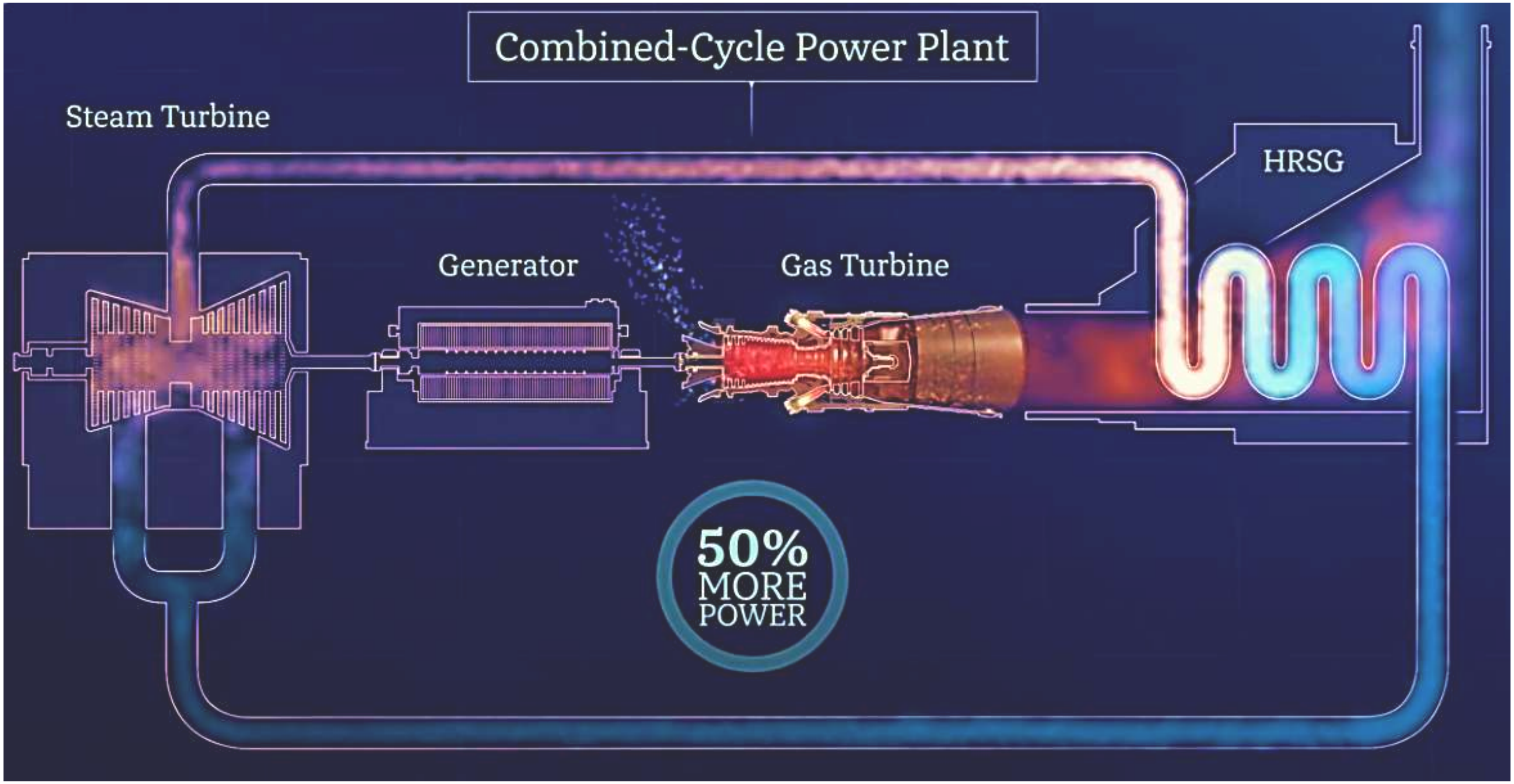
Available for different power outputs (5-375 MW), revolutions 3,000-17,000 rpm, 50/60 Hz electric.
Efficiencies 0.35- 0.60

Combined Cycle Power Plants (CCGT)





Combined Cycle Power Plants (CCGT)



[HRSG Boilers](#)

Heat Recovery Steam Generators Waste Heat Recovery Systems

General Electric Combined-Cycle Power Plant

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)

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 combustion (complete & incomplete)
    - Examples
- Carbon (CO_2) capture techniques

Combustion of Hydrocarbons

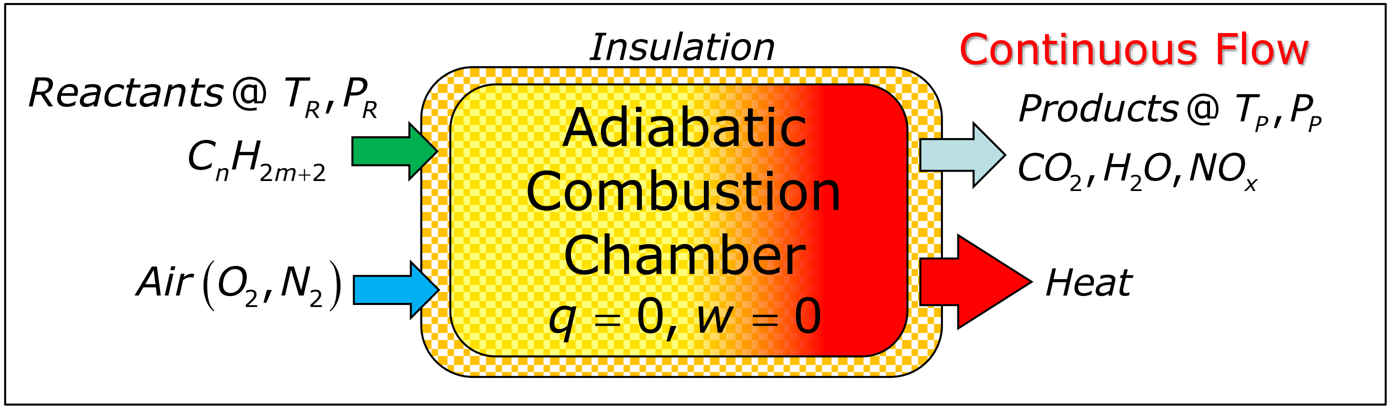
Currently, in most thermal power plants: Combustion of hydrocarbons
→ Heat → Mechanical Energy→ Electrical Energy

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

reversible

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

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



Insulation

Continuous Flow

Reactants @ T_R, P_R

C_nH_{2m+2}

Air (O_2, N_2)

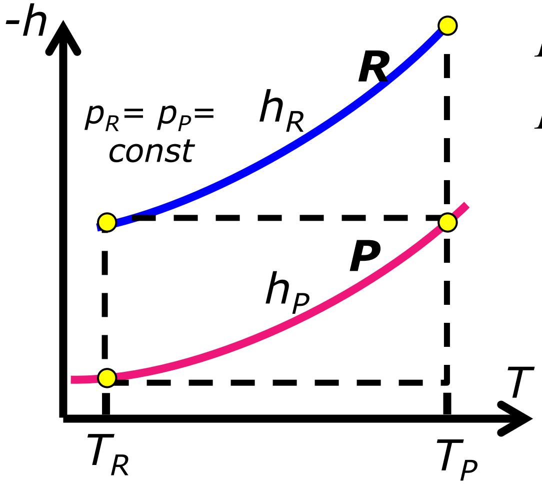
Adiabatic Combustion Chamber

$q = 0,\ w = 0$

Products @ T_P, P_P

CO_2, H_2O, NO_x

Heat



Excess enthalpy in rxn products → kinetic energy gas particles

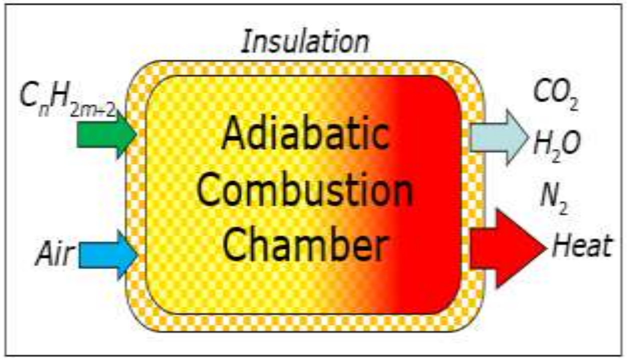
Plus heat → external, potentially useful

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

Adiabatic combustion temperature T_P → Reversible process.

Fossil Fuel Combustion in Power Plants

Complete combustion in oxygen



Hydrocarbons:

$$C_nH_m + \underbrace{(n+m/4)}_{\text{stoichiometric ratio}} O_2 \rightarrow n\,CO_2 + (m/2)H_2O(+\Delta H)$$

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* $C_8H_{18} \rightarrow$

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

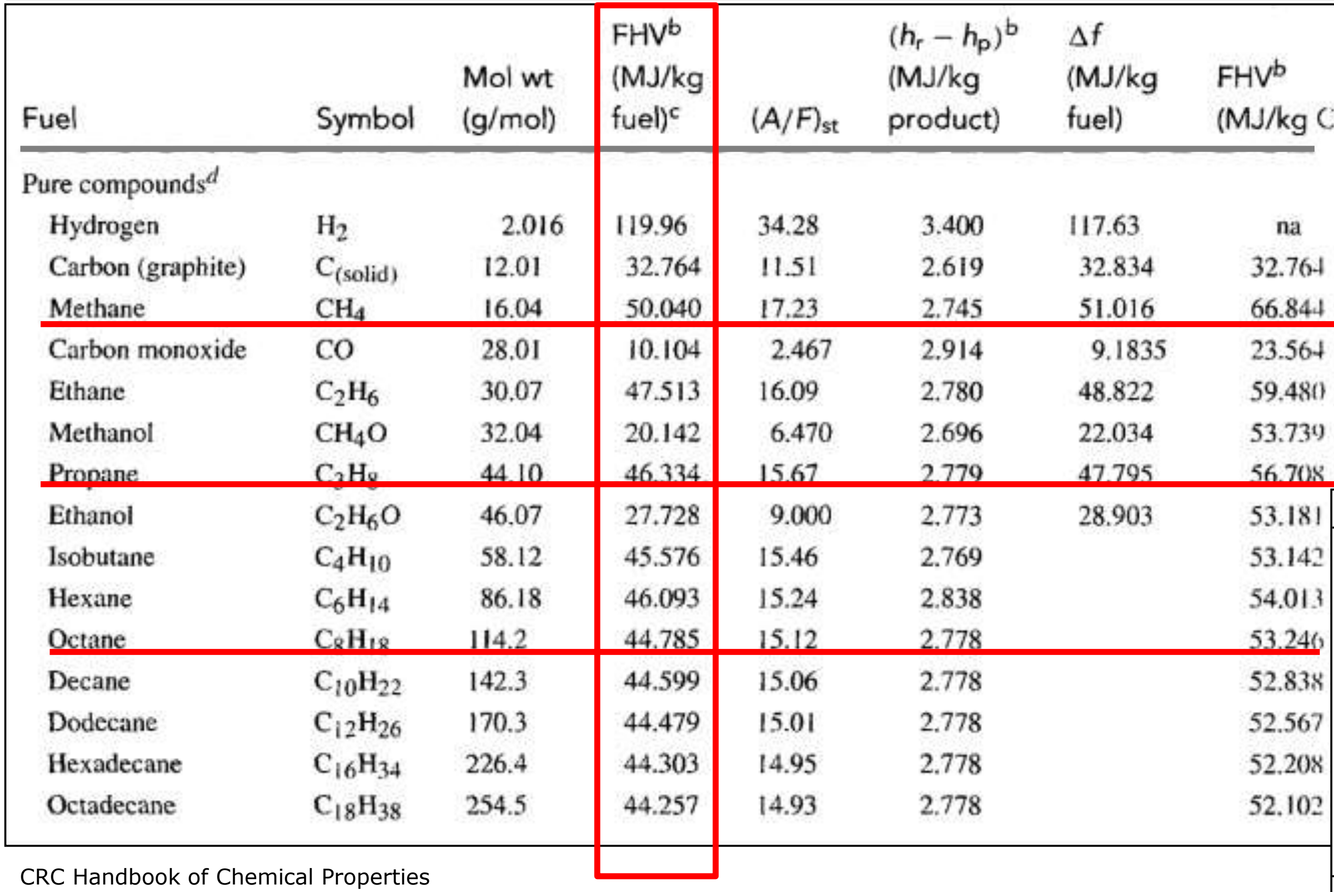
Theoretical *air/fuel mass ratio* *for* C_8H_{18}

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

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

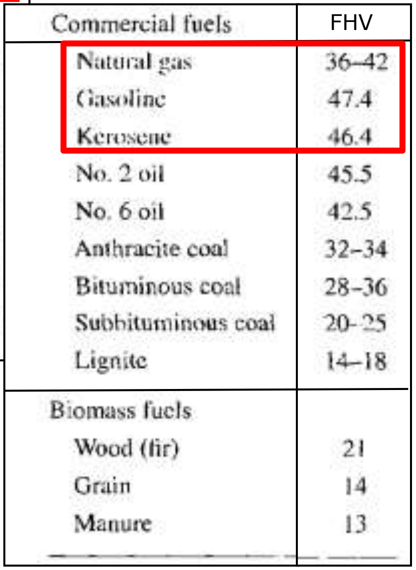
Heating Values for Fossil Fuels

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

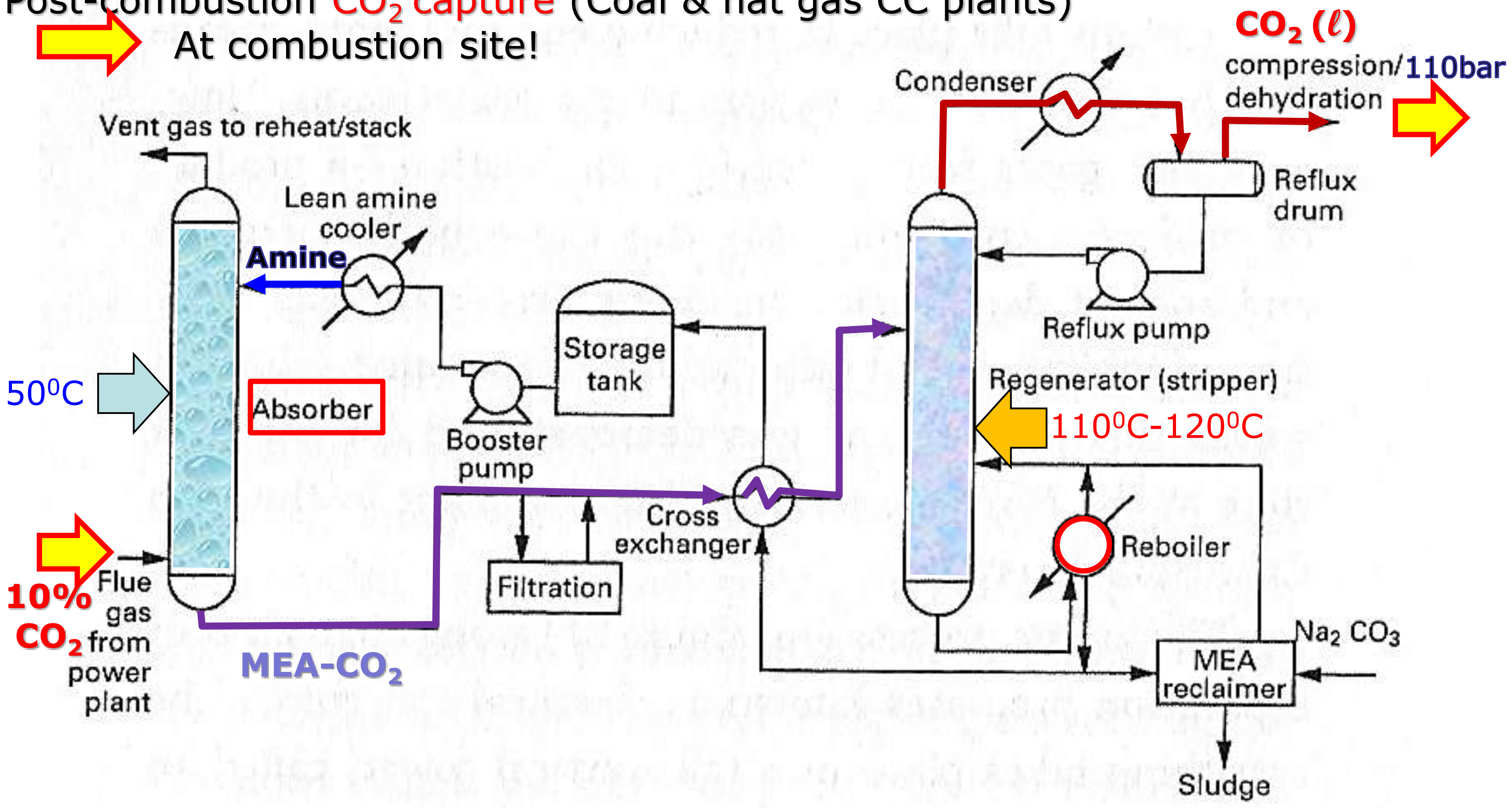


Commercial fuels	FHV
Natural gas	36–42
Gasoline	47.4
Kerosene	46.4
No. 2 oil	45.5
No. 6 oil	42.5
Anthracite coal	32–34
Bituminous coal	28–36
Subbituminous coal	20–25
Lignite	14–18
Biomass fuels	
Wood (fir)	21
Grain	14
Manure	13

Post-Combustion CO_2 Capture: Amine Scrubbing Process

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

At combustion site!



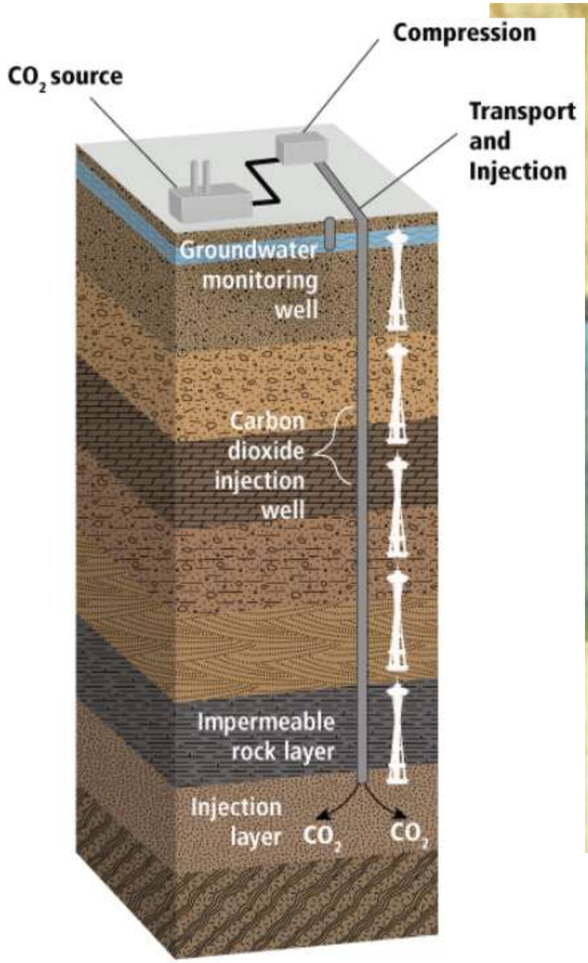
Efficiency of amine process: ≳90% of CO_2 in the flue gas,

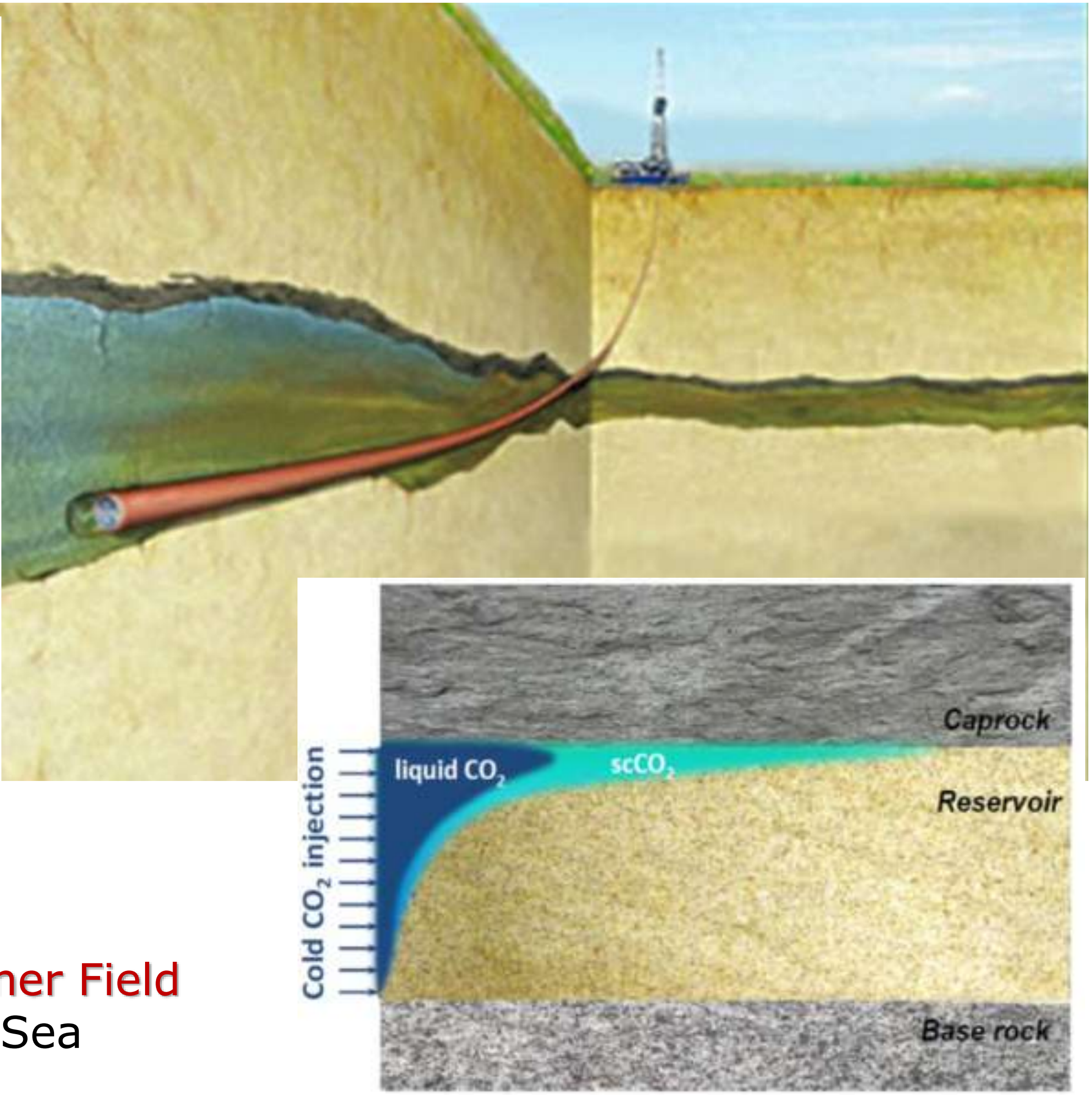
energy intensive (steam: 2GJ/tCO_2), =30% of the plant power generation.

CO_2 product purity >99%

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

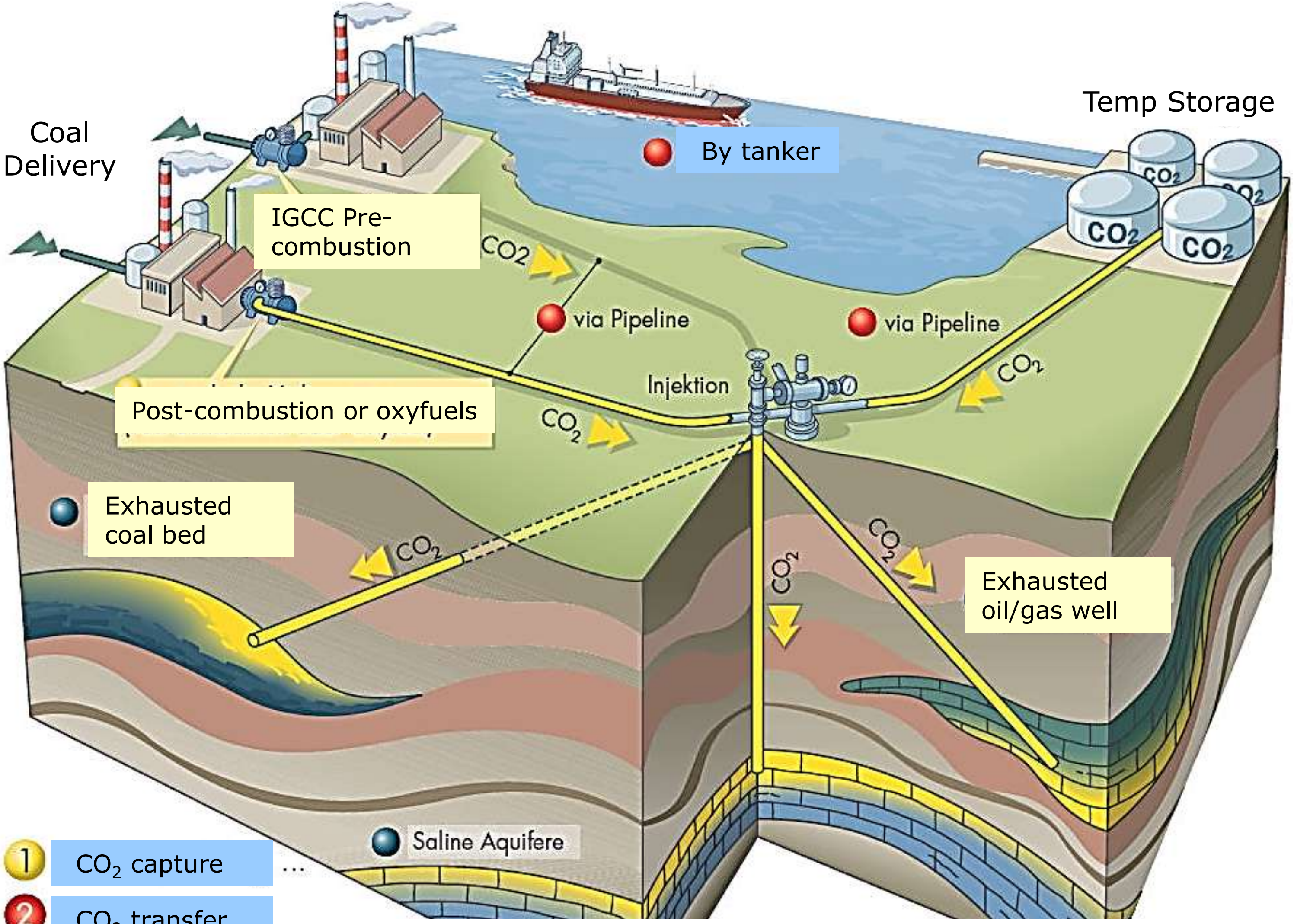
Proven CCS Technology





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

Other CO_2 Sequestration Concepts



Coal Delivery

Temp Storage

By tanker

IGCC Pre-combustion

Post-combustion or oxyfuels

Exhausted coal bed

Exhausted oil/gas well

① CO_2 capture …

② CO_2 transfer

③ CO_2 storage

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.

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)

Fin
Thermal Power Plants
Steam & Gas Turbines