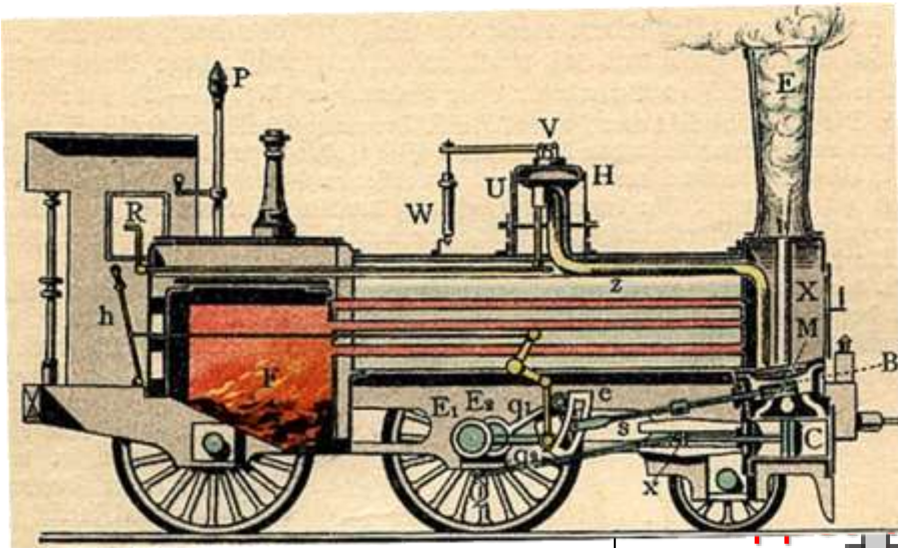

Thermal Power Plants

Agenda: Thermal Power Plants

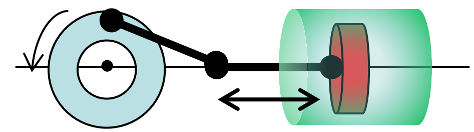
- Operational principle of cyclic thermodynamic engines
  - Entropy, heat, and work in Carnot cycle
- Reciprocating (piston) engines
  - Steam cylinder
  - Otto internal combustion cycle
  - Stirling engine
- Steam power plants
  - Isotherms of real gases
  - Steam and air as working media
  - S-T cycles 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

Uniflow Steam Cylinder

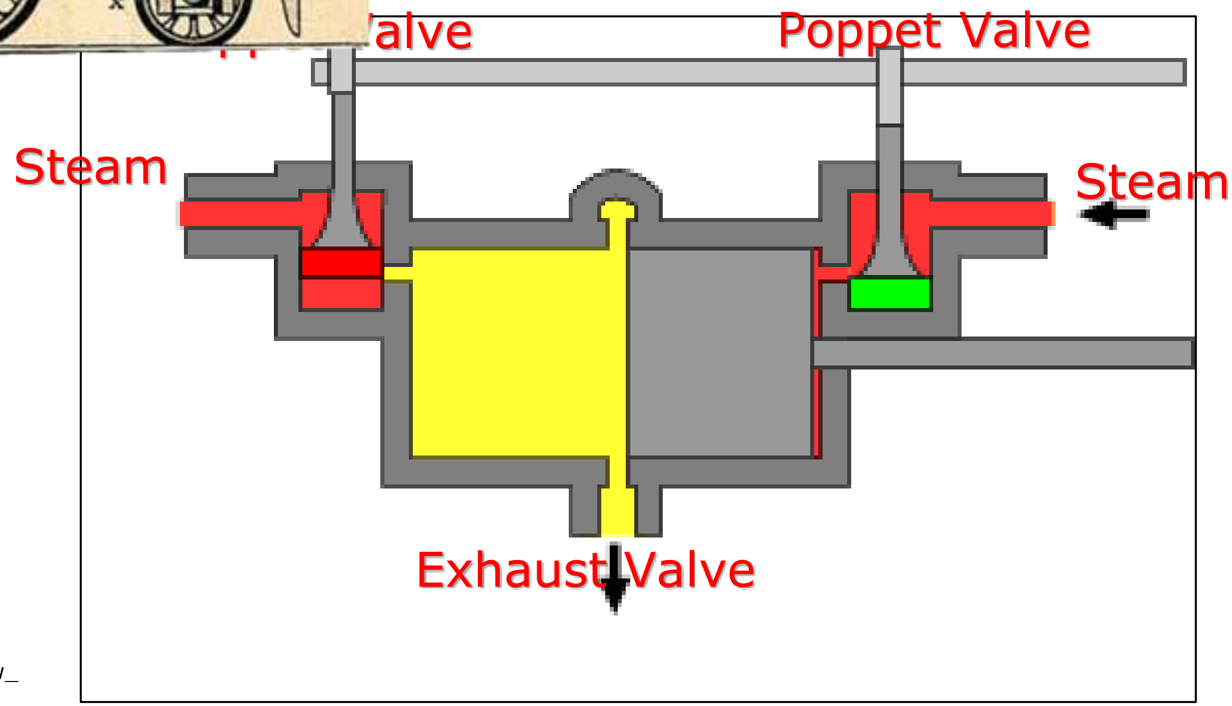


Linear motion is converted via excentric lever on crank wheel. produced by geared rotational motion, sustained by inertia.



Poppet valves connected to piston via levers or rotating crank shaft steer steam inlet and exhaust outlet.

Red = path closed
Green= path open



https://commons.wikimedia.org/wiki/File:Uniflow_steam_engine.gif

Early Steam Engines (America's Centennial Exposition 1876)

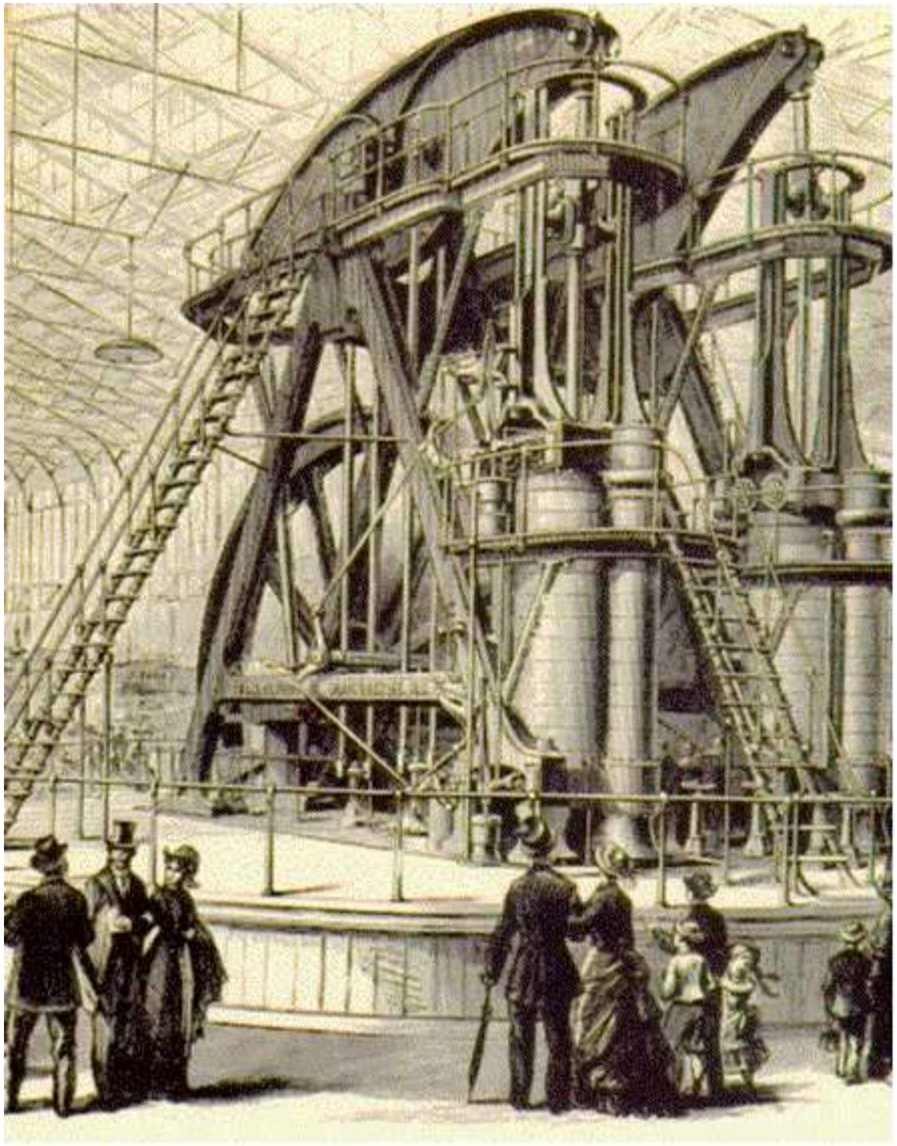
George H. Corliss.
Inventor, Providence, RI

American made Corliss steam engine at the Philadelphia exhibition.

Eye witness account:
"It stood in excess of forty-five feet above the floor and has cylinders of forty-four inches in diameter with a ten foot stroke. Another characteristic is the huge fifty-six ton, thirty feet in diameter, and twenty-four inch face, flywheel which made up to thirty-six revolutions per minute." (McCabe)

America's Centennial Exposition, →→→
held in Philadelphia in 1876

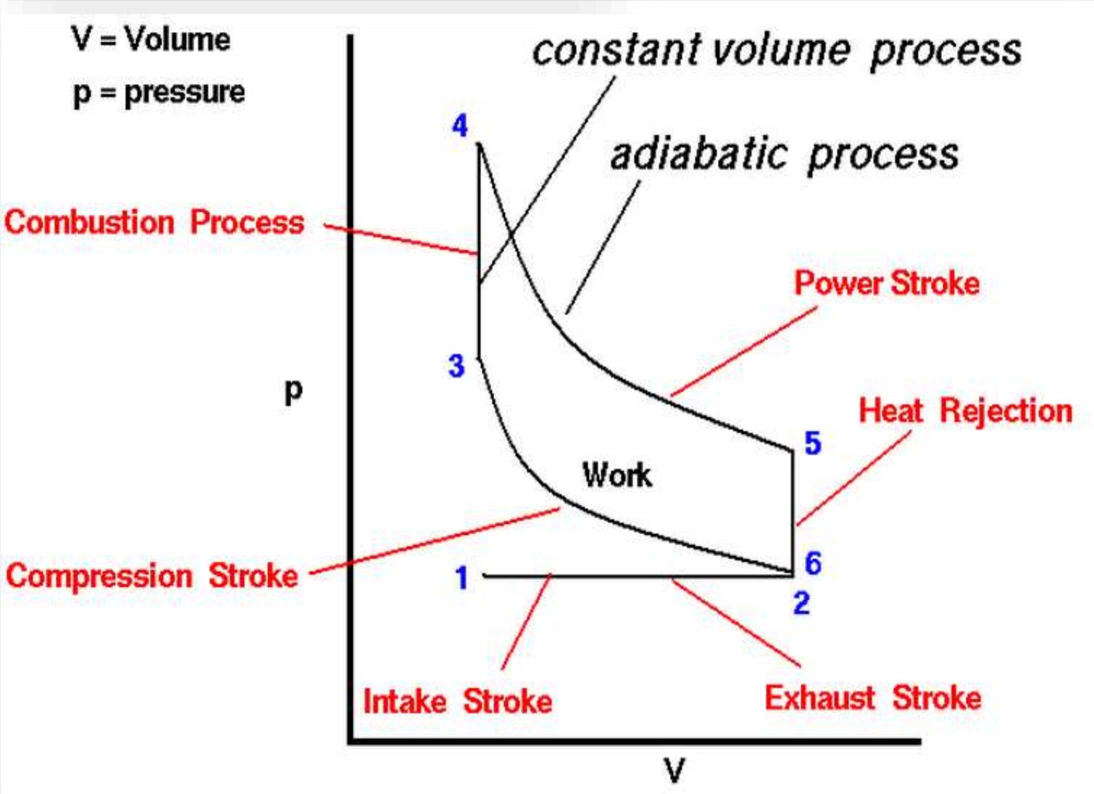
The pictured steam engine powered all machines and devices in the exhibition. It was operated by a single engineer. W=1,400 hp

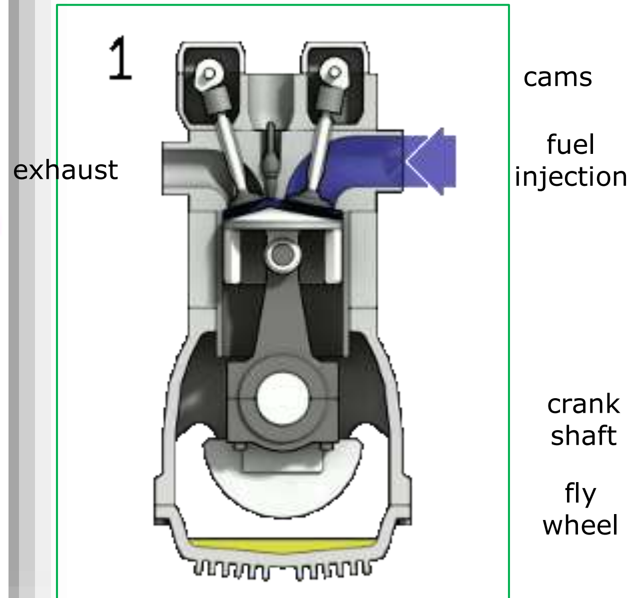


Ideal Otto Cycle

1) Intake stroke (1→2), gasoline vapor and air drawn into engine.
2) Compression stroke (2→3) . *p,T* increase.
3) Combustion (spark) (3→4), short time, *V*= constant. Heat absorbed from high-*T* “reservoir”.
4) Power stroke: expansion (4→5).
5) Valve exhaust: Valve opens, gas can escape.
6) Emission of heat (5→6) to *low-T reservoir.*
7) Exhaust stroke (2→1), piston evacuates cylinder.

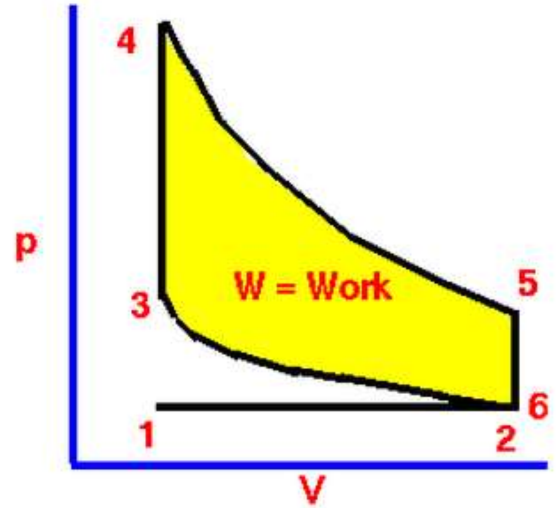
Needs engine starter !





Energetics of Otto Cycle

C_v = Specific Heat constant volume
γ = Specific Heat Ratio C_p/C_V
p = pressure
T = Temperature
V = Volume
f = fuel / air ratio
Q = Fuel heating value
c p s = cycles per second
P = Power
V_2 / V_3 = r = Compression Ratio



Compression Stroke:
$T_3/T_2 = r^{\gamma-1}$
$p_3/p_2 = r^{\gamma}$

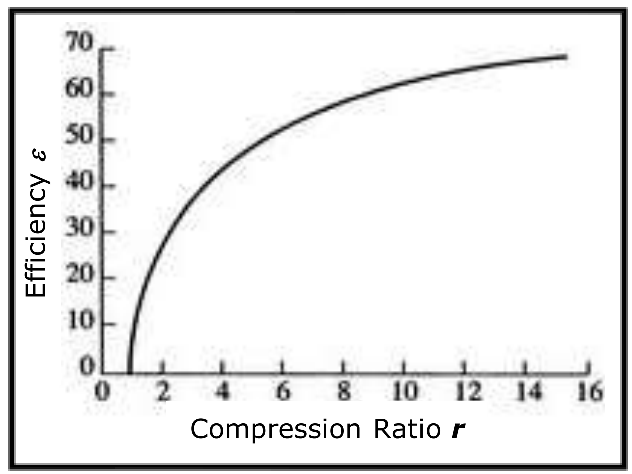
Combustion:
$T_4 = T_3 + fQ/c_V$
$p_4 = p_3(T_4/T_3)$

Power Stroke:
$T_5/T_4 = r^{1-\gamma}$
$p_5/p_4 = r^{-\gamma}$

$$Efficiency: \varepsilon = \frac{w}{q_{3\to4}} = \frac{q_{3\to4}+q_{5\to6}}{q_{3\to4}} = \frac{c_V\left(T_4-T_3\right)+c_V\left(T_6-T_5\right)}{c_V\left(T_4-T_3\right)}$$

$$\varepsilon = 1-\frac{\left(T_5-T_6\right)}{\left(T_4-T_3\right)}$$

$$Adiabatic\ EoS\ \left[T\cdot V^{R/c_V} = const.\right] \to \boxed{\varepsilon = 1-r^{-R/c_V}}$$



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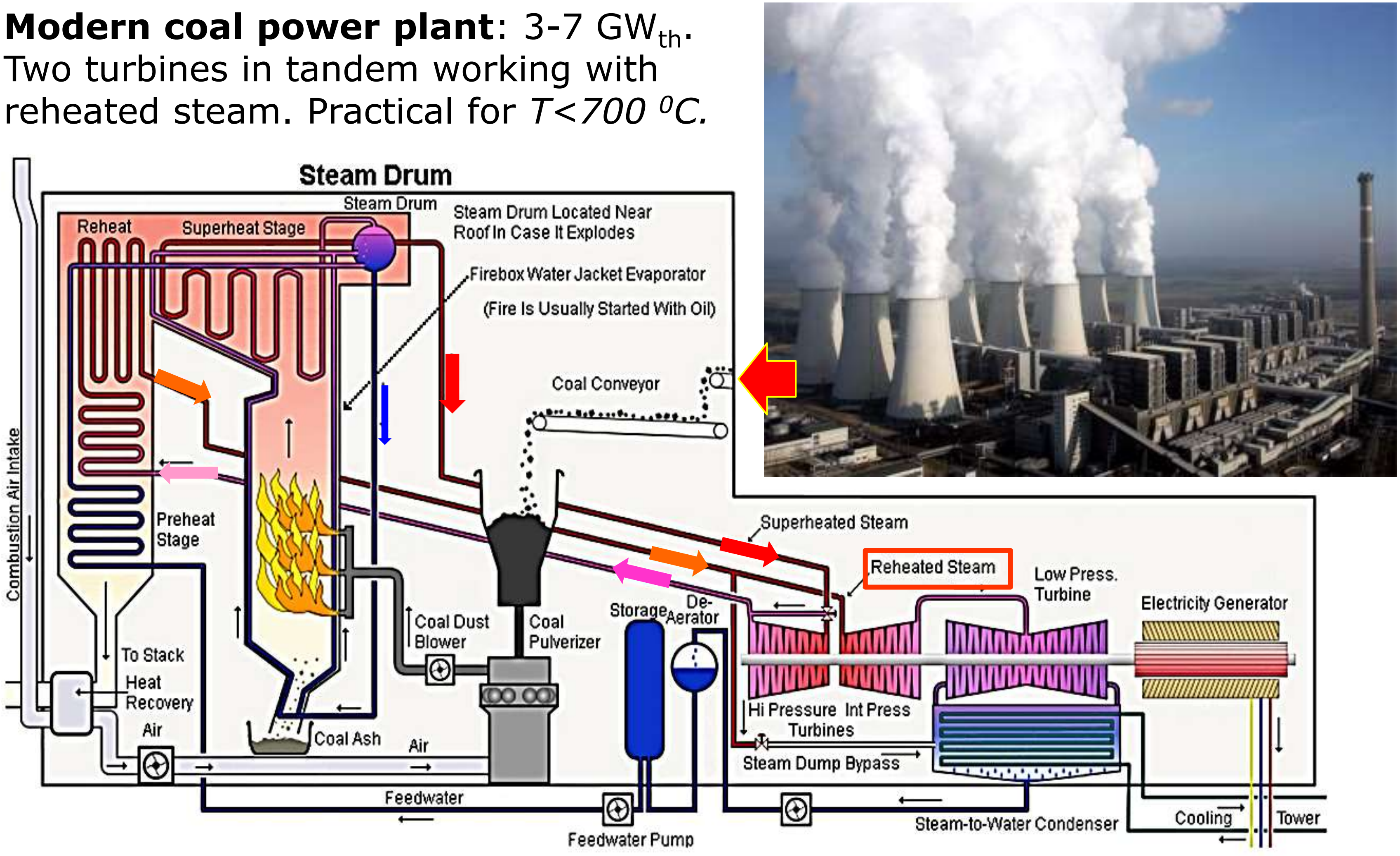
Coal Power Plant (Photo & Schematic)

Modern coal power plant: 3-7 GW_{th}. Two turbines in tandem working with reheated steam. Practical for *T<700* ^0C.



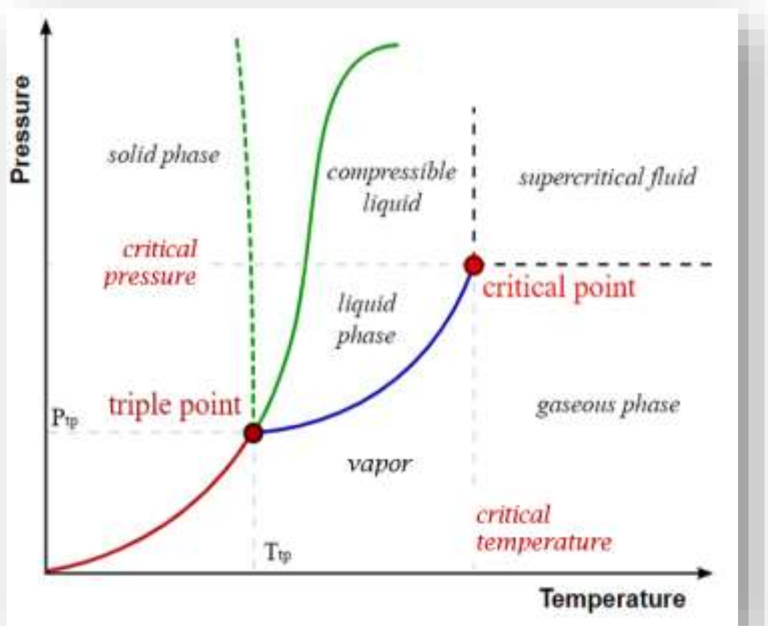
Real Substances (Different Phases: *s*, *ℓ*, *g*, *sc*)

All real substances have distinct physical phases:

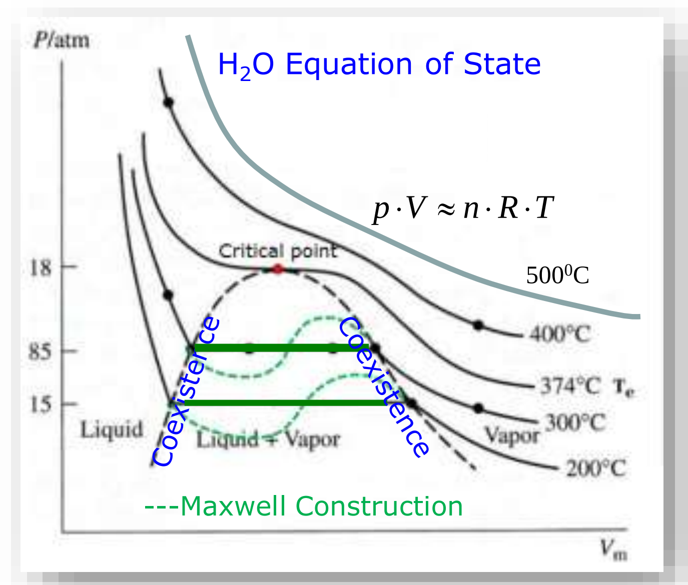
solid ($T<T_{freeze}$), liquid ($T_{freeze}<T< T_{boil}$) and gas ($T_{boil}<T$)

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

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



		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*

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

Using Real Gases/Vapor Working Media

Since 150 years practical use: steam = water vapor, water droplets (wet steam).
→ Real gas molecules interact more, motion is less free, depending on ρ, T.
→ Several phases.

Ideal – Gas EoS $p \cdot V = R \cdot T$ *(per mole)* →
Virial expansion of compression factor

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

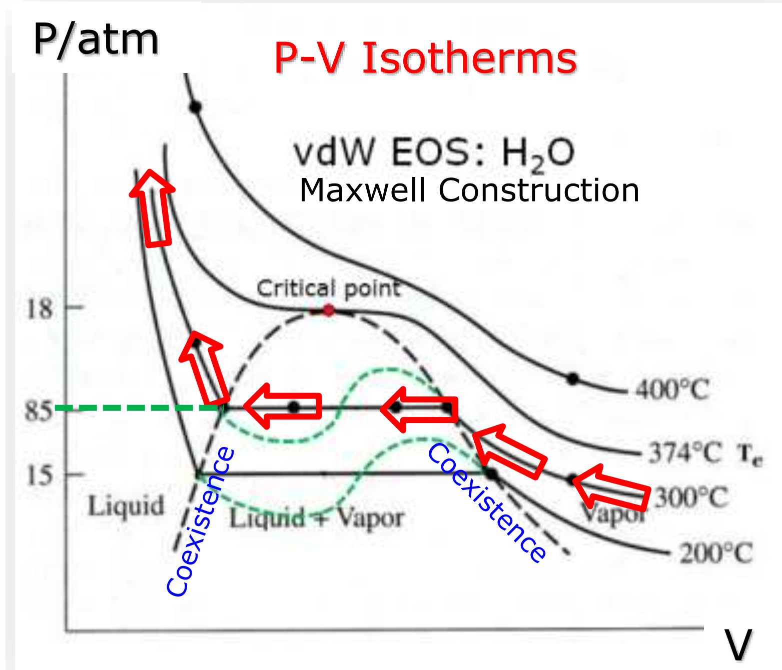
Useful Parameterizations

van der Waals EoS:

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

Redlich Kwong EoS:

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



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

EoS non-monotonic → liquid-gas instability.
High compression: real (vdW model) gases collapse (p decreases with decreasing V)
→ liquefaction

Correct EoS for unphysical instability:
Maxwell Construction

Steam Tables

Absolute pressure (kPa, kN/m^2)	Temperature (^oC)	Specific Volume (m^3/kg)	Density - ρ - (kg/m^3)	Specific Enthalpy of: Liquid - h_l - (kJ/kg)	Evaporation - h_e - (kJ/kg)	Steam - h_s - (kJ/kg)	Specific Entropy of Steam - s - (kJ/kgK)
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

p = 1 bar= 101.33 kN/m²

Water 0⁰C → 100⁰C.
→ 419 kJ/kg

→ Specific enthalpy H_2O:
$h_{water}(100^0C) = 419\ kJ/kg$.

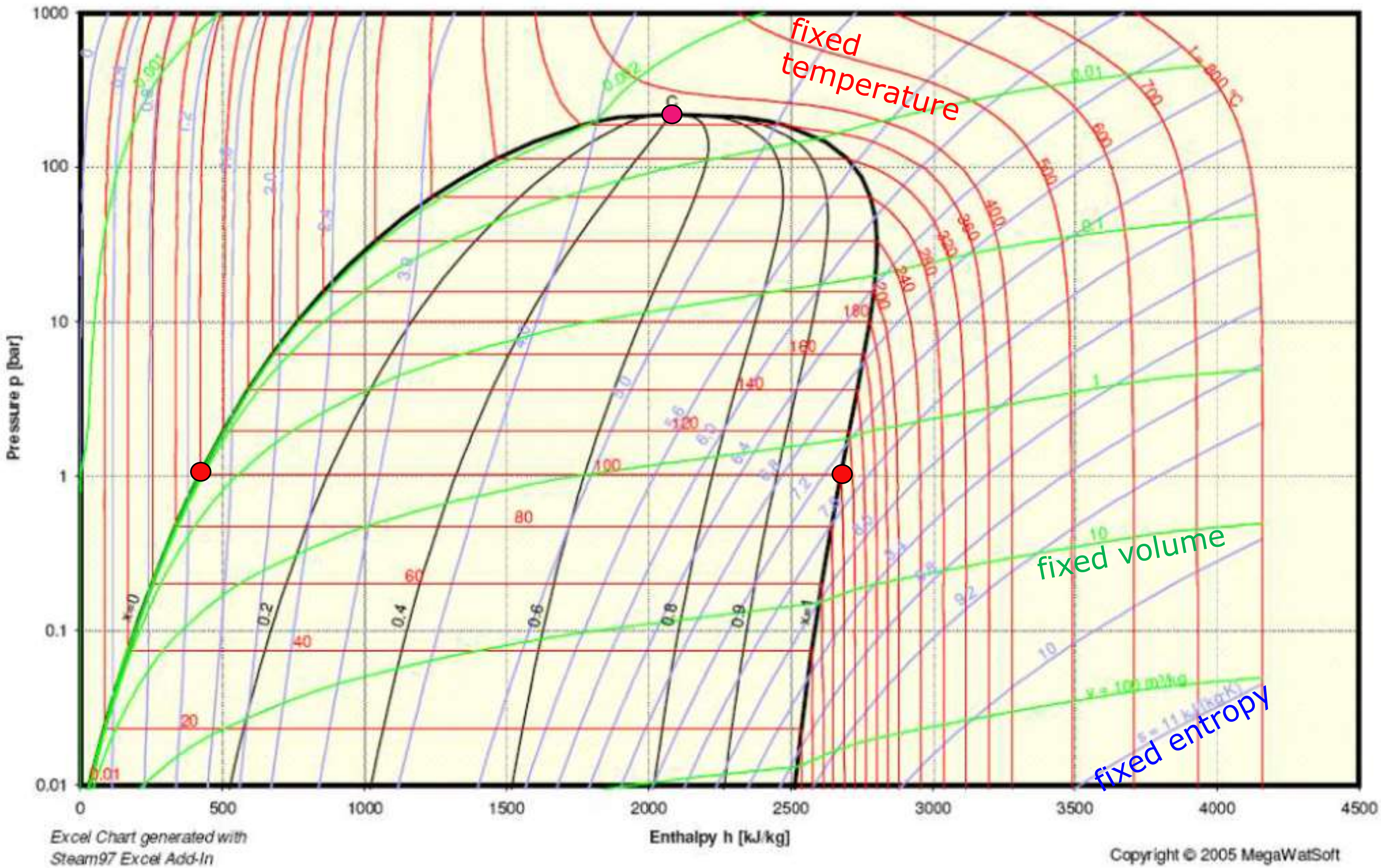
Specific enthalpy of evaporation (latent heat):
$h_{evap}(100^0C) = 2{,}257 kJ/kg$

$h_{steam}(100^0C) = 2.676 MJ/kg$

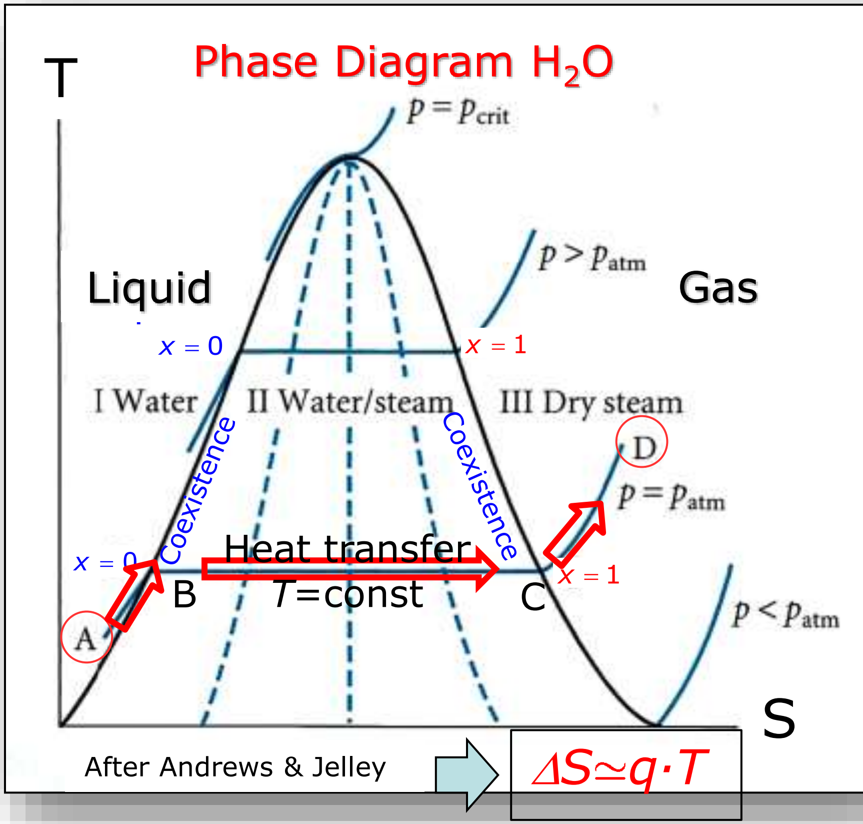
Latent Heat

Steam Tables/P-H Graphs

x=0 →100% water, x=1 → 100% steam



Water as a Working Power Medium



To use steam as driving gas for thermal engines, heat energy has to be transferred to water at T_l (e.g., 25⁰C)

A) heat 1mol liquid H_2O to 100⁰C
B-C) evaporate all H_2O (@ 100⁰C)
D) heat vapor beyond 100⁰C→T_h

p = 1 atm *(bar)= 101.33 kN/m²*
→ Water boils @ at *100⁰C*
→ Need *419 kJ/kg H₂O* to heat water from *0⁰C* to *T= 100⁰C*.

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

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

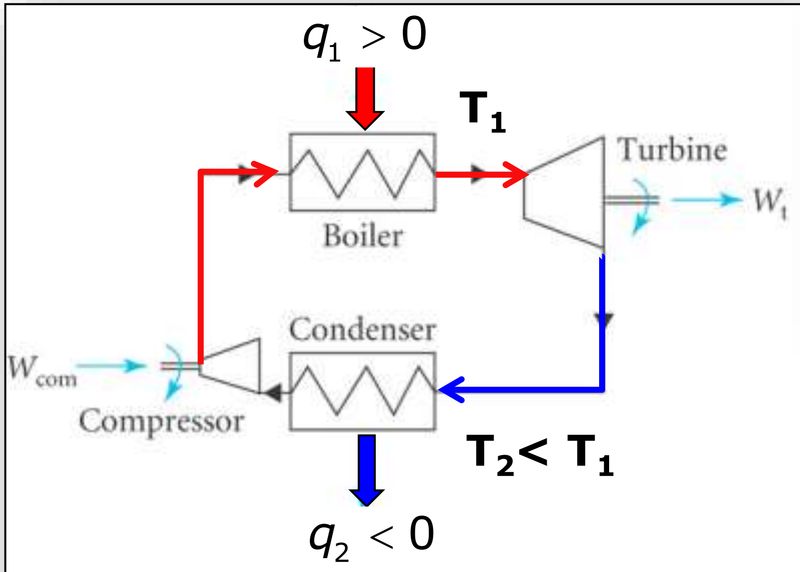
Total heat required at *p=const.* to convert H_2O to steam @*100⁰C* :

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

L-G mixture	$h_s(x) = (1-x)\cdot h_{water} + x\cdot h_{steam}$
Similar:	$u_s(x) = (1-x)\cdot u_{water} + x\cdot u_{steam}$

Extensive variables
(U, H, S,..)

S-T Diagram for Steam Carnot Process



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

Enthalpy, entropy extensive→ Scale w/ x

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

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

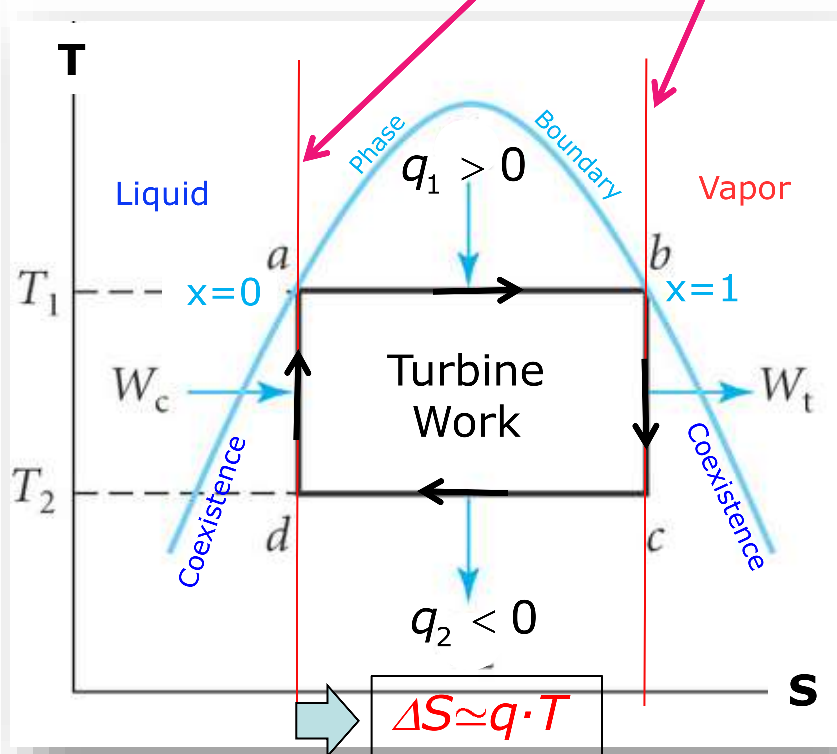
$s = (1-x)\cdot s_{fl} + x\cdot s_{gas}$ $\quad s = S/unit\ mass$

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

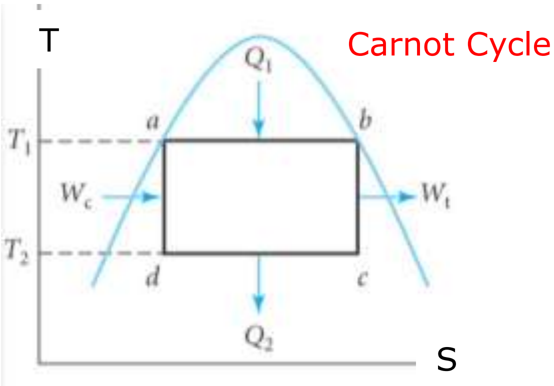
$$s(d) = (1-x_d)\cdot \underset{0.436}{s_{fl}} + x_d\cdot \underset{8.452}{s_{gas}} = 3.808$$

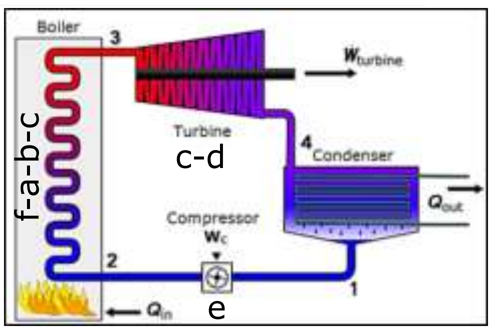
$\rightarrow Solve\ \ for\ \ x_d = 0.42,\ \ ....$

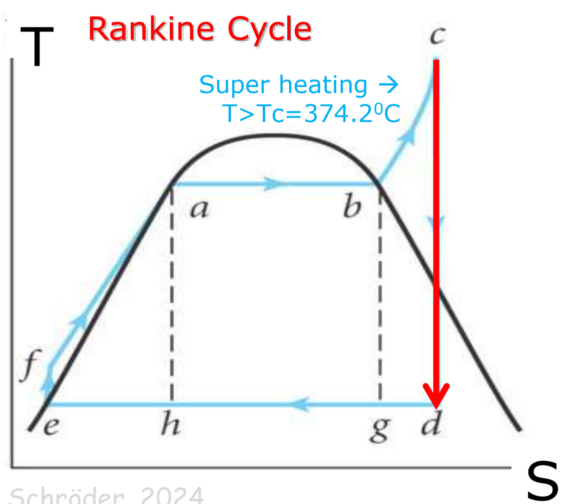
After Andrews & Jelley



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)

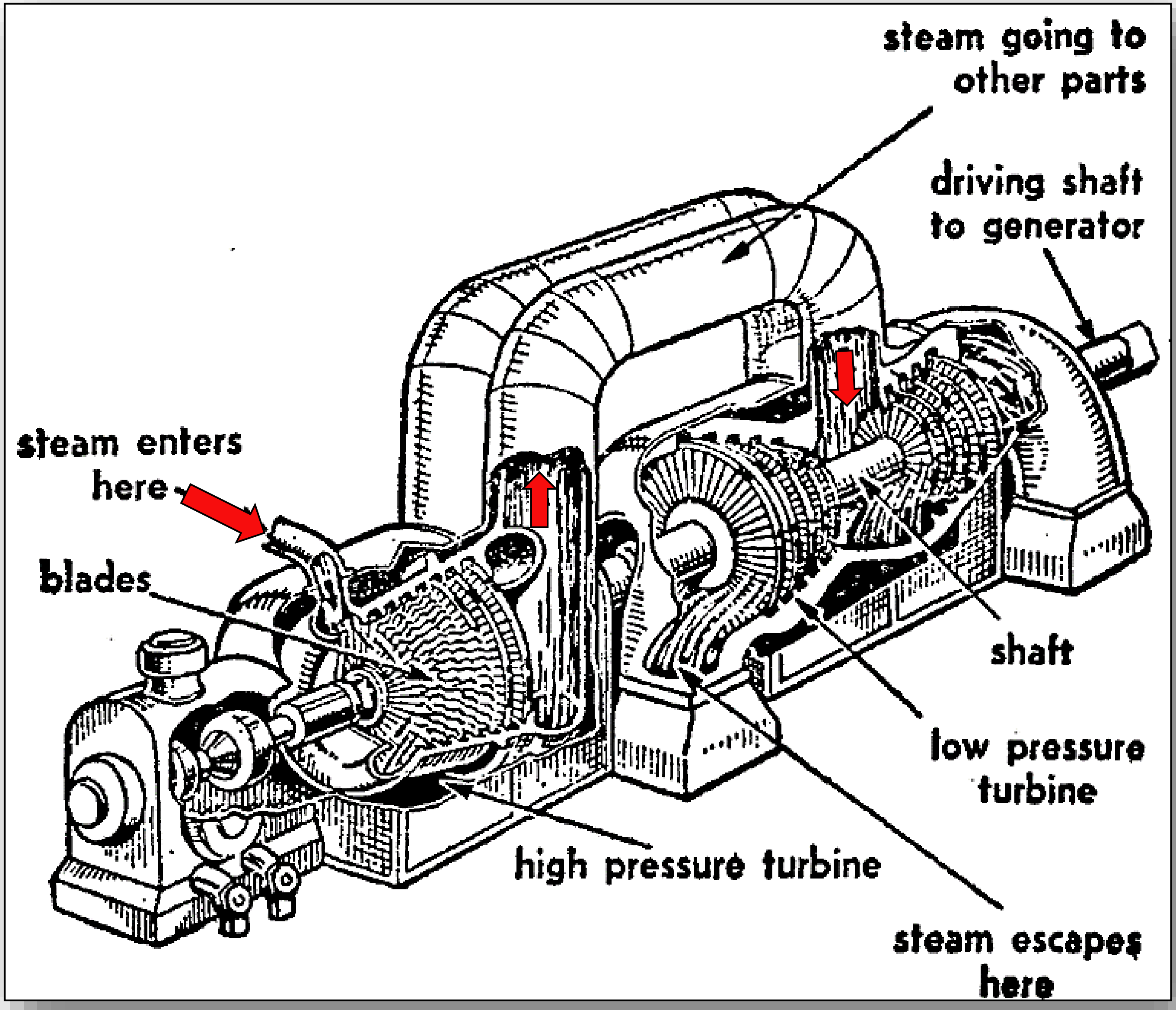
e→ *f* Compressor (pump) injects H_2O under *p*
f → *a* Economizer heats H_2O under pressure.
a→ *b* Evaporator boils H_2O under *p* = const.
b→ *c* Superheater heats steam @high *p* = const.
c→ *d* Turbine produces work, expands steam

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

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

Efficiency: $\varepsilon_{Rankine} = \dfrac{w_{Turbine} - w_{Compressor}}{Q_{in}} = 0.3 - 0.5$

Low/Medium Pressure Steam Turbines



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  - Gas turbine operation, enthalpy balance
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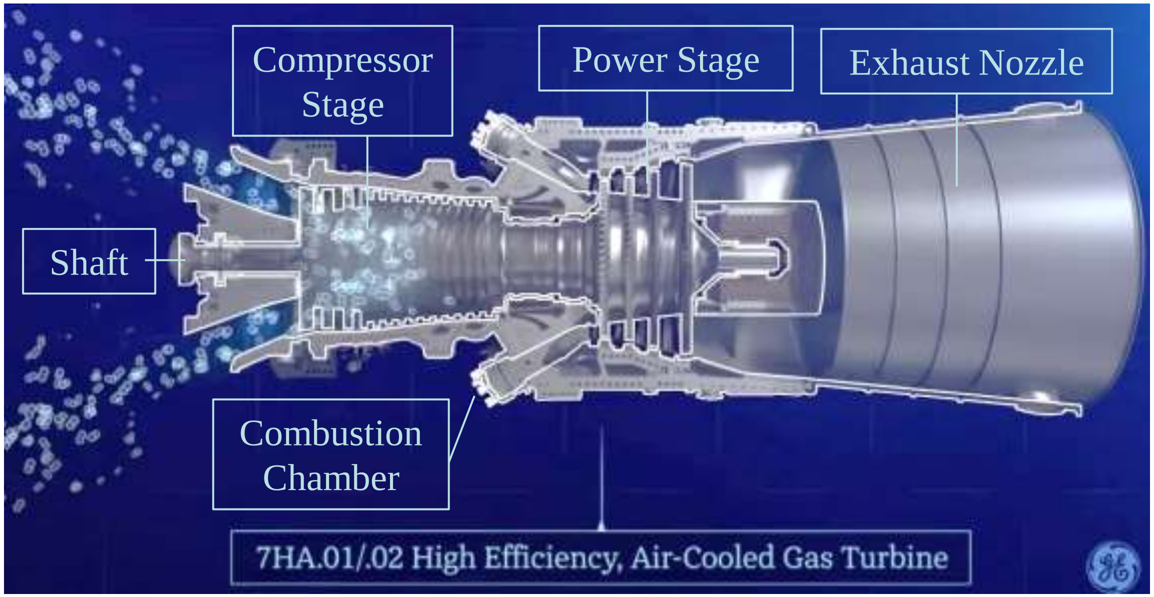
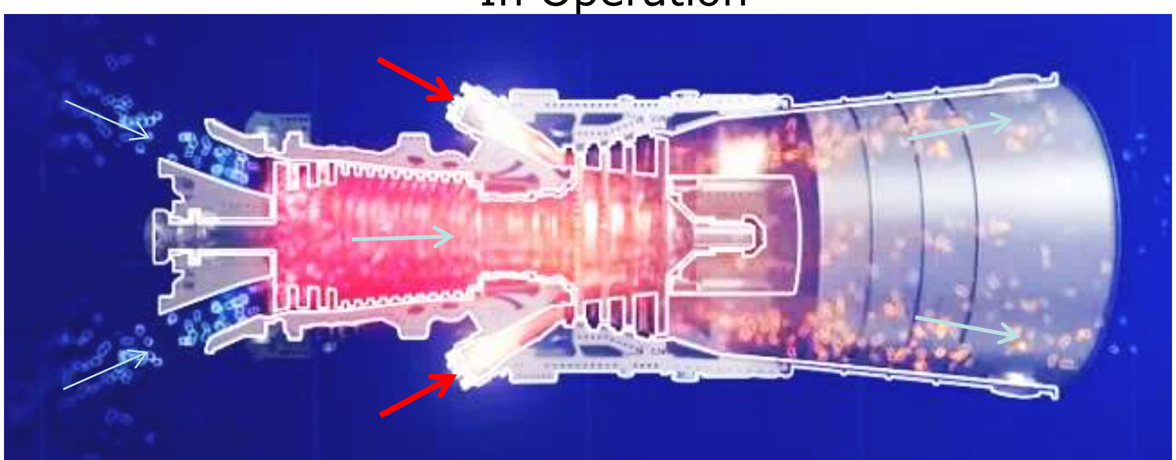
Gas Power Turbine: Parts & Operation (GE)



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

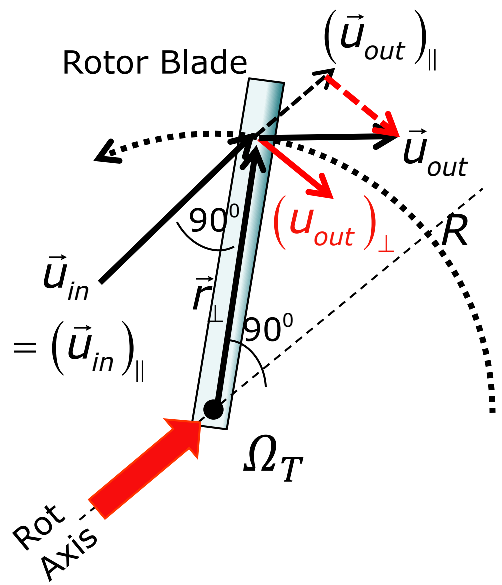
In Operation



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.

Angular Momentum Transfer in Turbines



Angular momentum to turbine (runner) by driving gas

$$\Delta\vec{L}_T = \vec{L}_{in} - \vec{L}_{out};\ Torque\ M = \Delta L_T/\Delta t;\ Power\ P = M \cdot \Omega_T$$

Turbine power depends on power blade geometry/angle of attack → Task: maximize angular momentum transfer $\Delta\vec{L}_T$!

$$P = \Omega_T \cdot \rho_m \cdot \dot{Q} \cdot \left[\left(\vec{r}_\perp \times \vec{u}_{in} \right) - \left(\vec{r}_\perp \times \vec{u}_{out} \right) \right]$$

Euler's Turbine Equation

Driving gas is injected coaxially → brings in zero torque about rot axis. Power is maximized if exhaust gas carries maximum momentum perpendicular to rot axis → coaxial inflow & radial outflow.

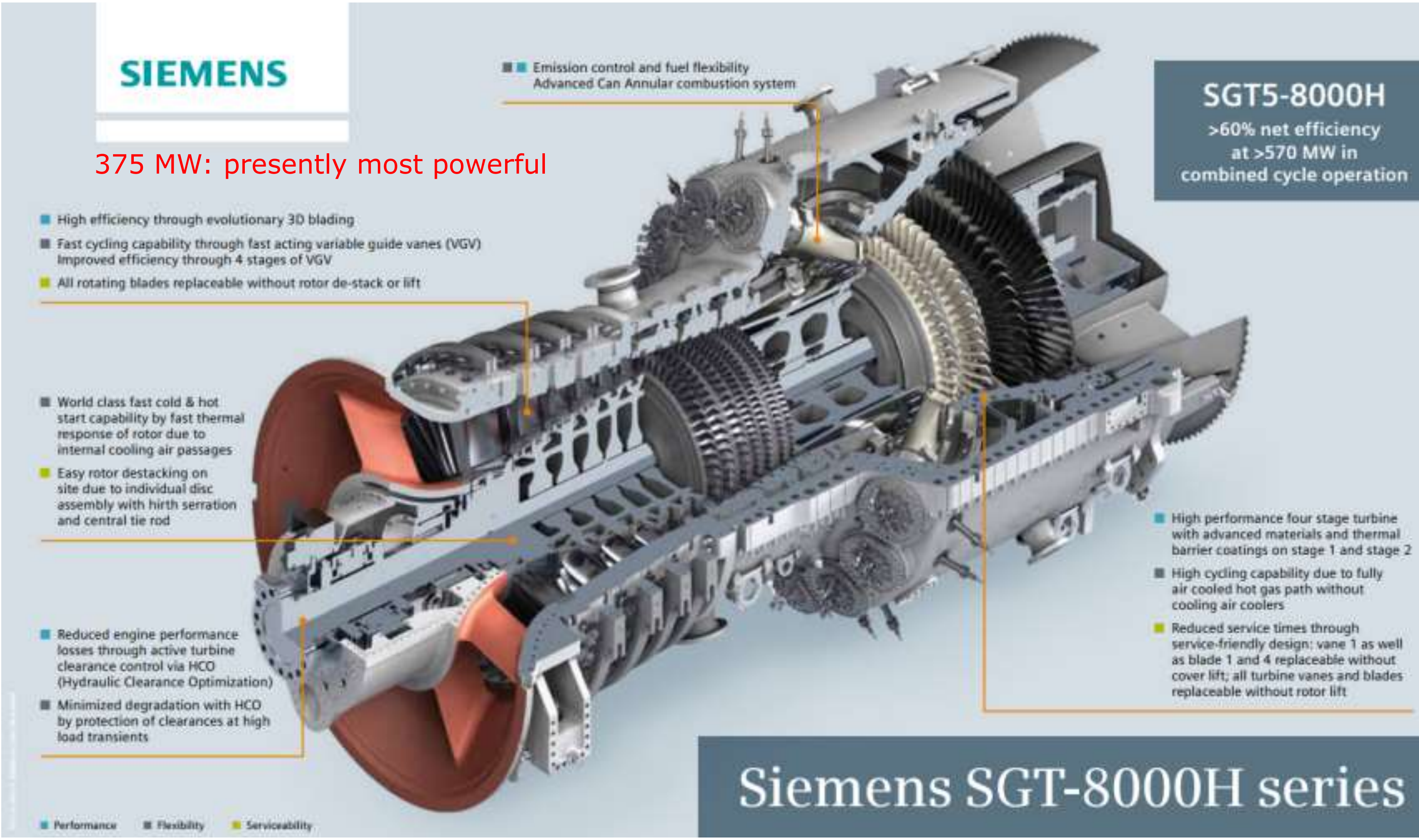
$$P_{max} = \dot{m} \cdot R \cdot \Omega_T \cdot \left(u_{out} \right)_\perp$$

$R =$ *injection radius for turbine*, $(u_{out})_\perp =$ *gas velocity perp to axis*

High power produced by large turbines: high coaxial gas injection + radial outflow.

Gas Power Turbine (Siemens)

375 MW: presently most powerful

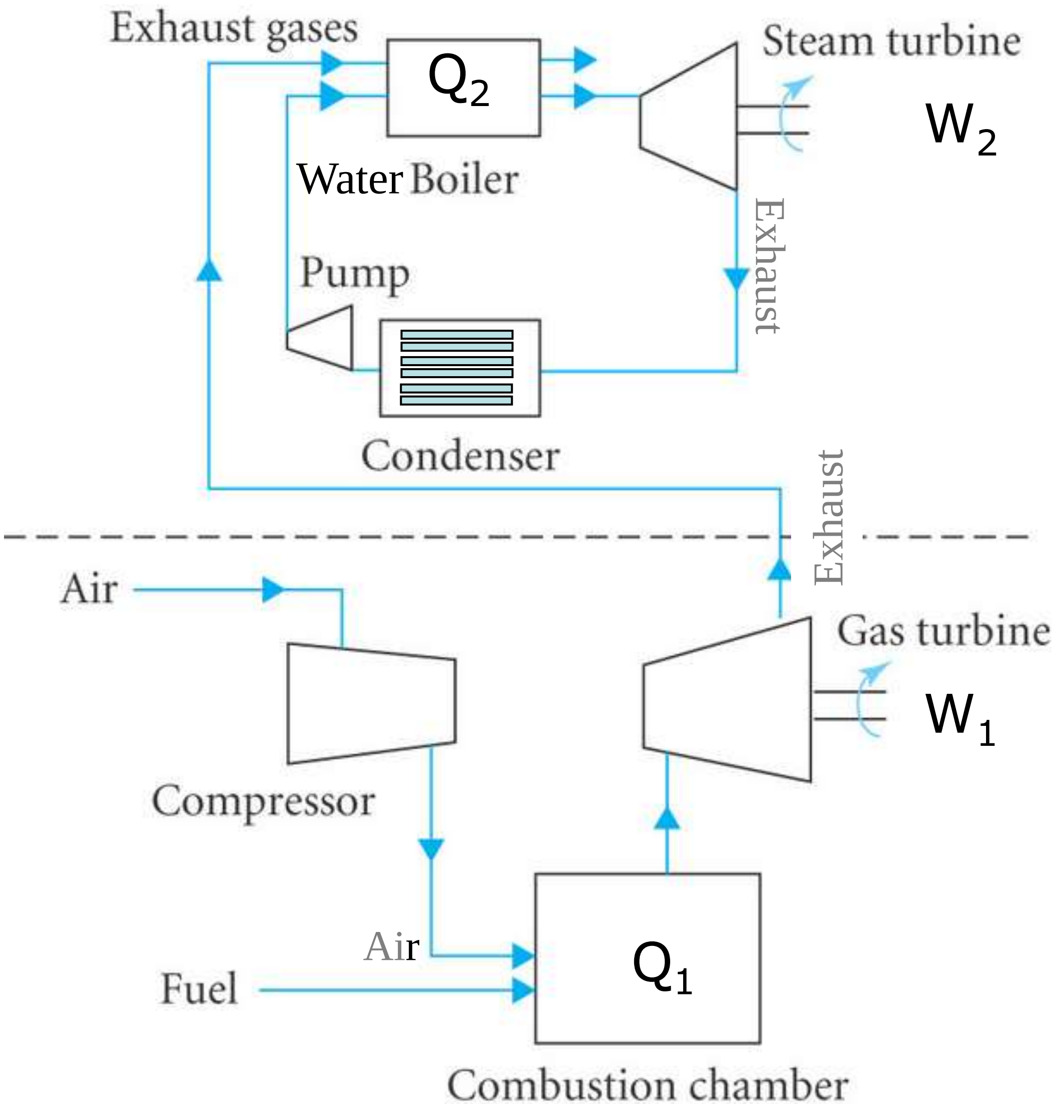


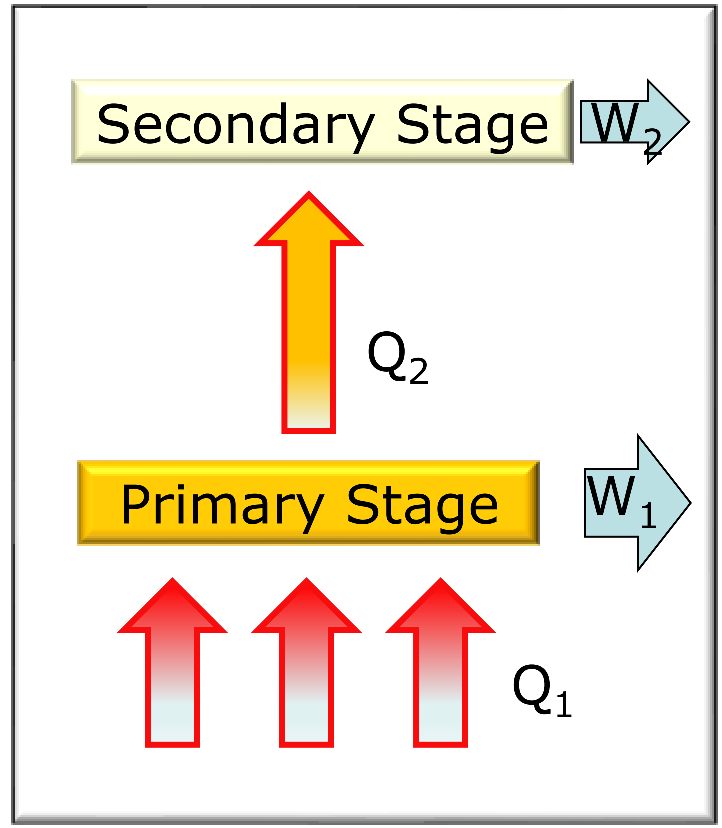
Turbine for Gas Power Plants

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)





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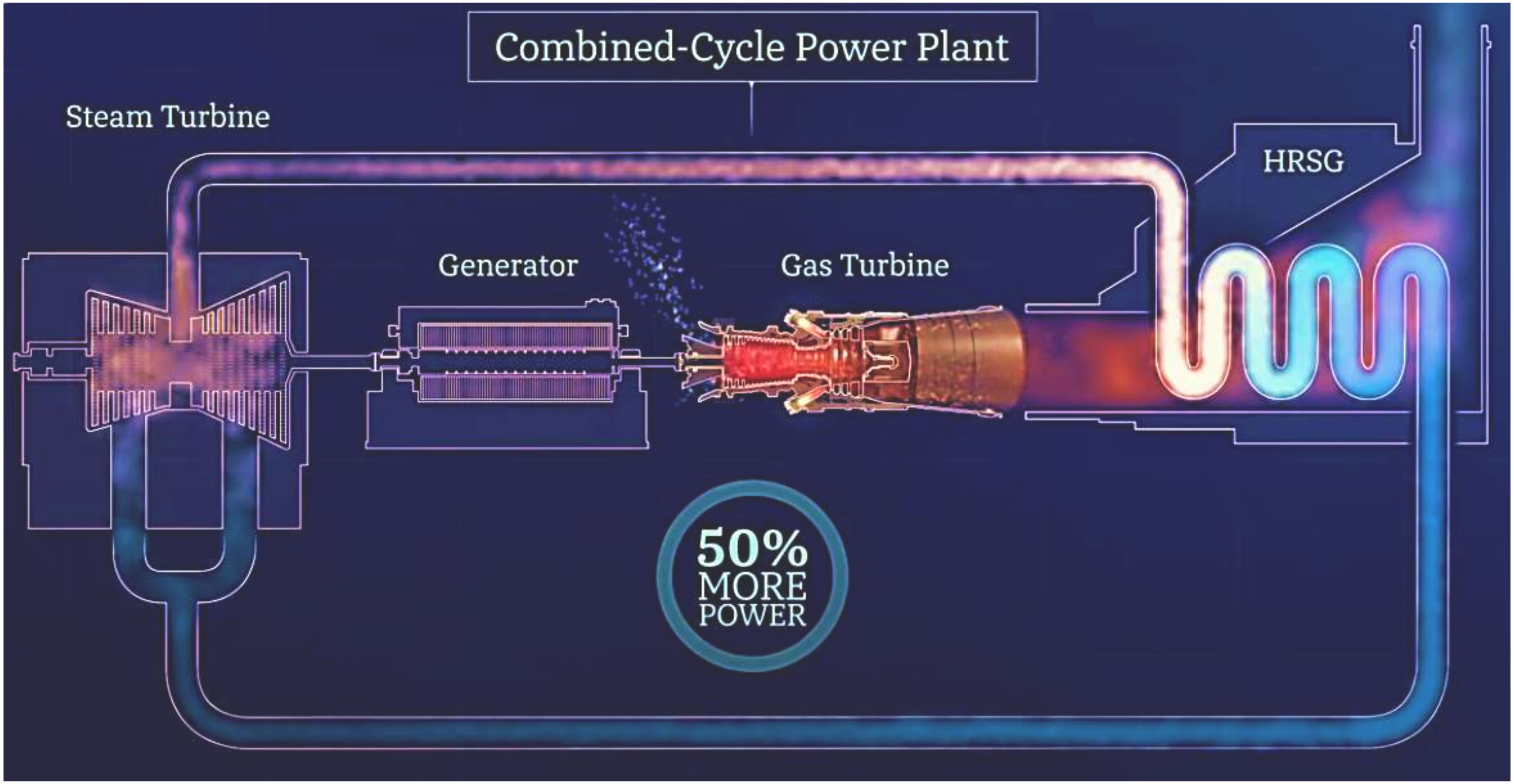


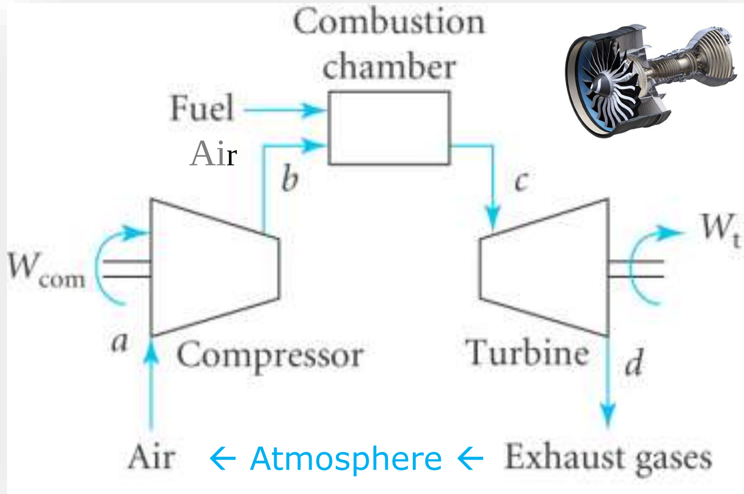
General Electric Combined-Cycle Power Plant

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)

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.)

$$q_{b\to c} = h_c - h_b = c_p \cdot (T_c - T_b) > 0 \quad absorbed\ @\ p = const$$

$$q_{d\to a} = h_a - h_d = c_p \cdot (T_a - T_d) < 0 \quad emitted\ @\ p = const$$

$$w_{com} = h_b - h_a = c_p \cdot (T_b - T_a) > 0 \quad absorbed\ @\ q = 0$$

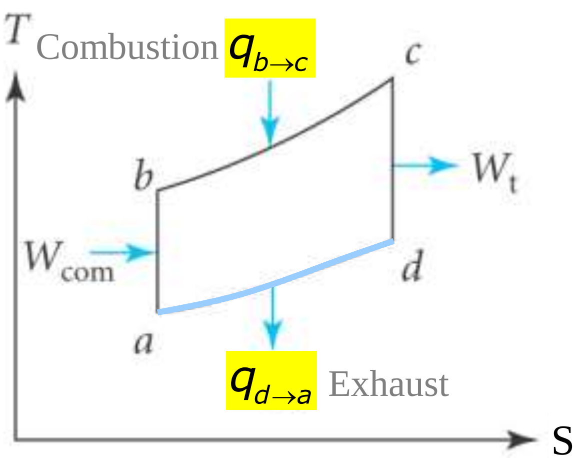
$$w_t = h_c - h_d = c_p \cdot (T_c - T_d) < 0 \quad emitted\ @\ q = 0$$

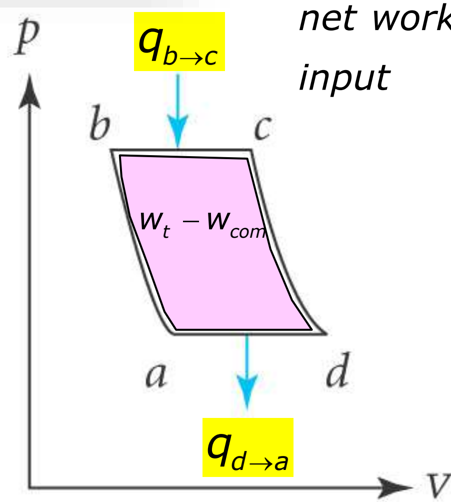
$$net\ work \quad w = w_t - w_{com} = (h_c - h_d) - (h_b - h_a)$$

$$input \quad q_{b\to c} = h_c - h_b$$

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

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





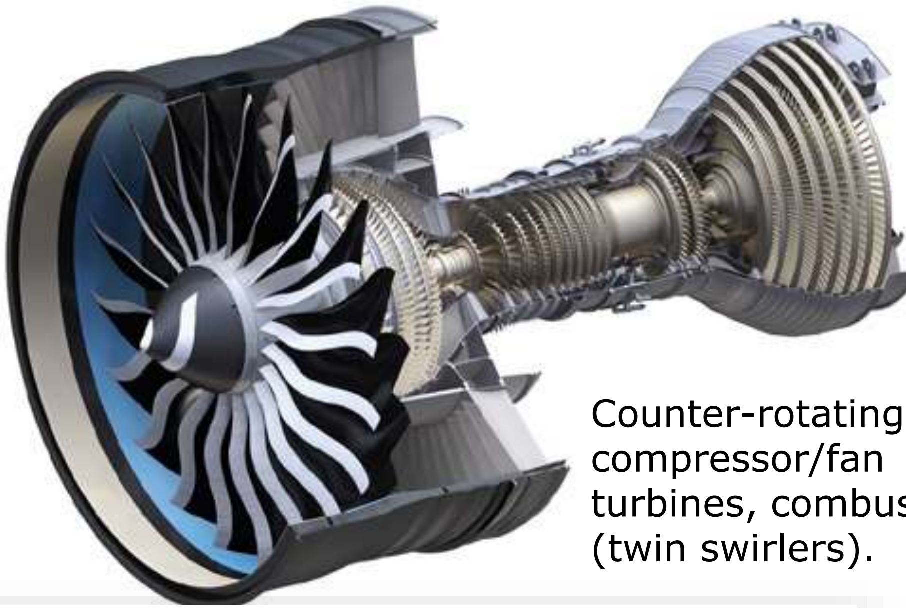
$$Adiabatic\ EOS: \quad \varepsilon = 1 - \left(\frac{p_b}{p_a}\right)^{-\frac{R}{c_p}}$$

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

Turbine exhaust still very hot → use again

Aircraft Turbo Fan Engine

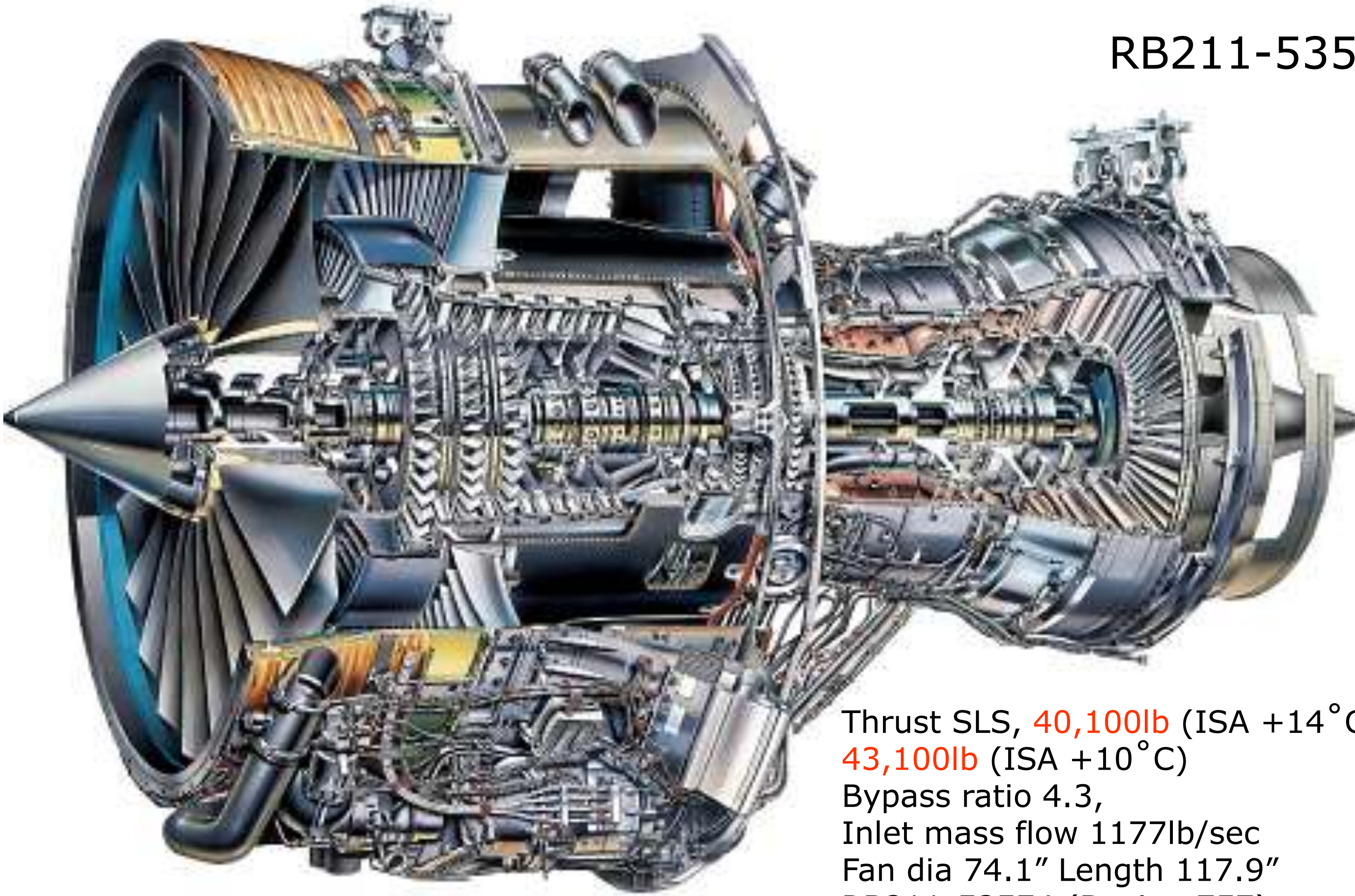
Advanced materials, titanium-aluminide on turbine blades, composites + Ti on fan blades, By-pass ratio 9.6:1.
Thrust up to 75,000 lbf (330 kN)



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	90,000	93,700	110,100	115,300
Overall Pressure Ratio at Max Power	40	40	42	42

Rolls Royce Aircraft Turbofan Engine



RB211-535E4

Thrust SLS, 40,100lb (ISA +14°C)
43,100lb (ISA +10°C)
Bypass ratio 4.3,
Inlet mass flow 1177lb/sec
Fan dia 74.1″ Length 117.9″
RB211-535E4 (Boeing 757)
Certification Nov 1983 EIS Oct 1984

Fin

Steam & Gas Turbines