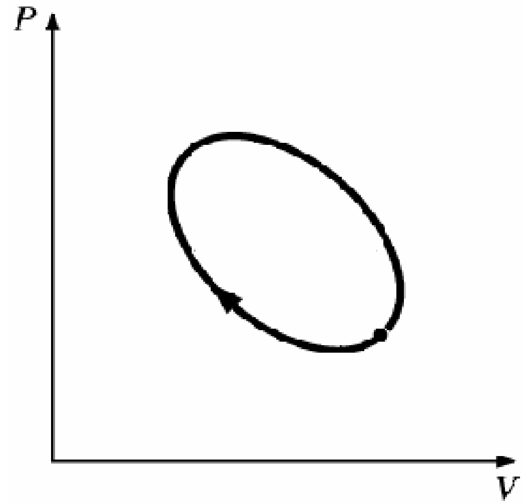
The First Law of Thermodynamics & Cyclic Processes

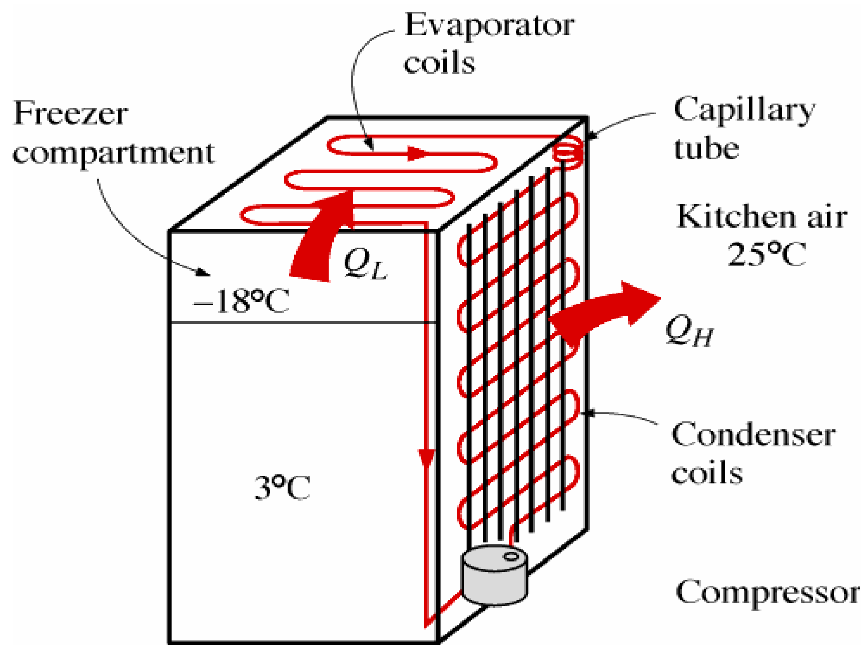
Meeting 7

Section 4-1

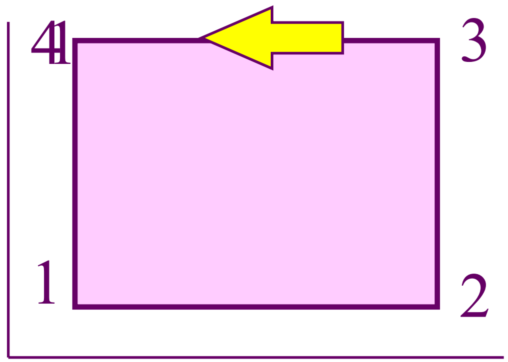
Thermodynamic Cycle

- **Is a series of processes which form a closed path.**
- **The initial and the final states are coincident.**
- **All thermal engines work in a cyclic process.**





1st Law for a Cycle



$$\cancelto{0}{\oint_{cycle} dE} = \oint_{cycle} \delta Q - \oint_{cycle} \delta W$$

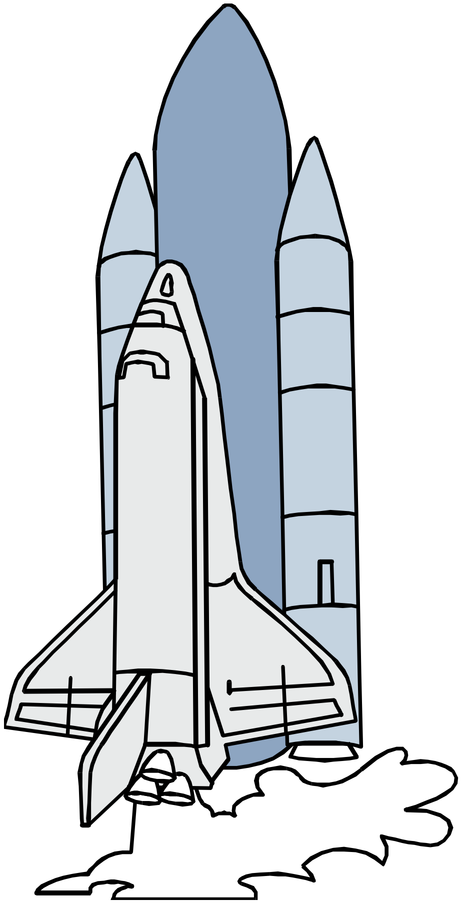
or $\Delta E_{cycle} = Q_{cycle} - W_{cycle} = 0$

- **The Energy change is zero due to the cyclic nature;**
- **But not heat and work, they are path dependent functions. That is, the net work in a cyclic process has to equal to the net heat.**

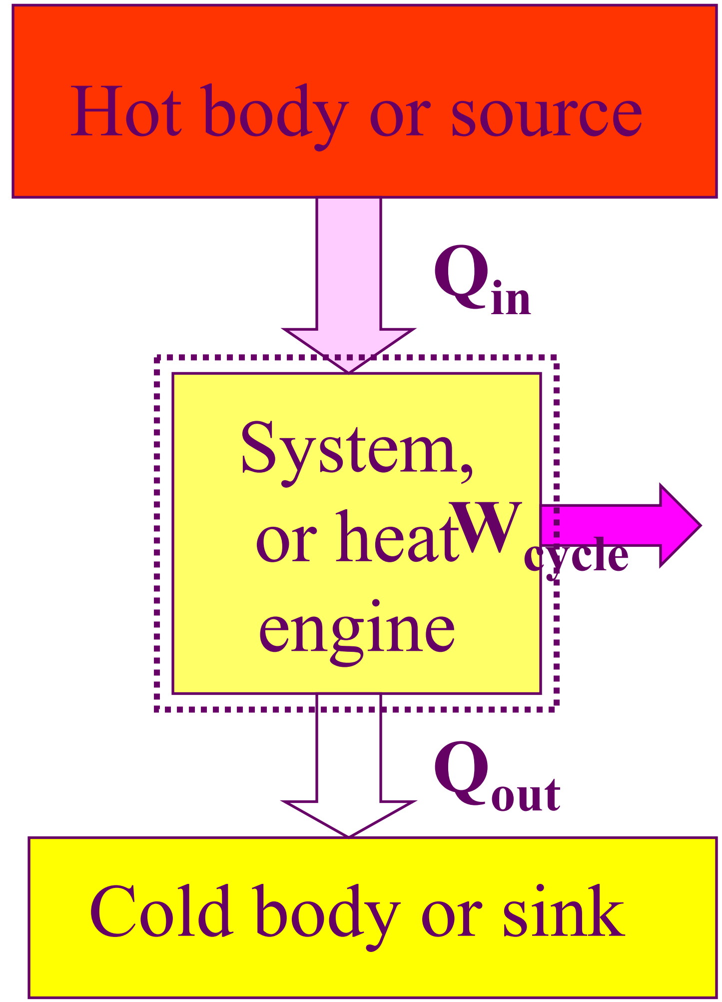
$$\boxed{\Delta E_{cycle} = 0} \qquad \boxed{Q_{cycle} = W_{cycle}}$$

- **Furthermore, the AREA inside the cycle represents the net Work or the net Heat**

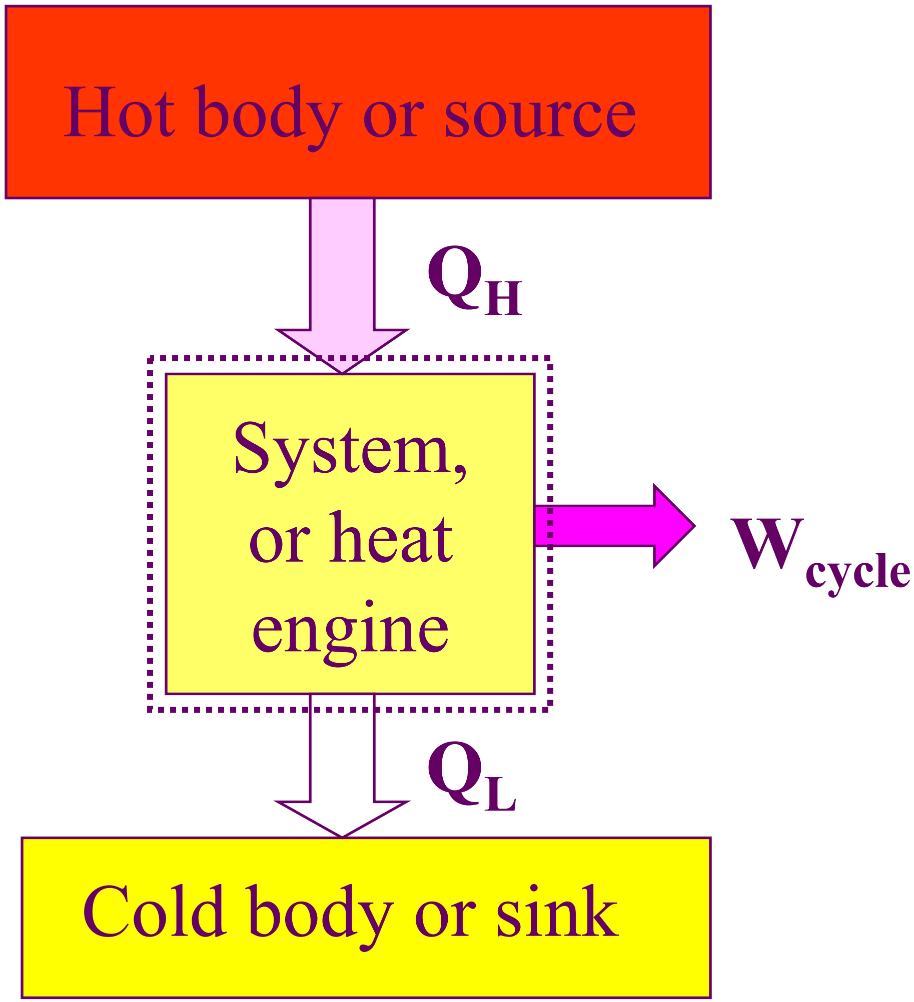
Heat Engine Power Cycles



A Thermal engines draws heat from a hot source and rejects heat to a cold source producing work

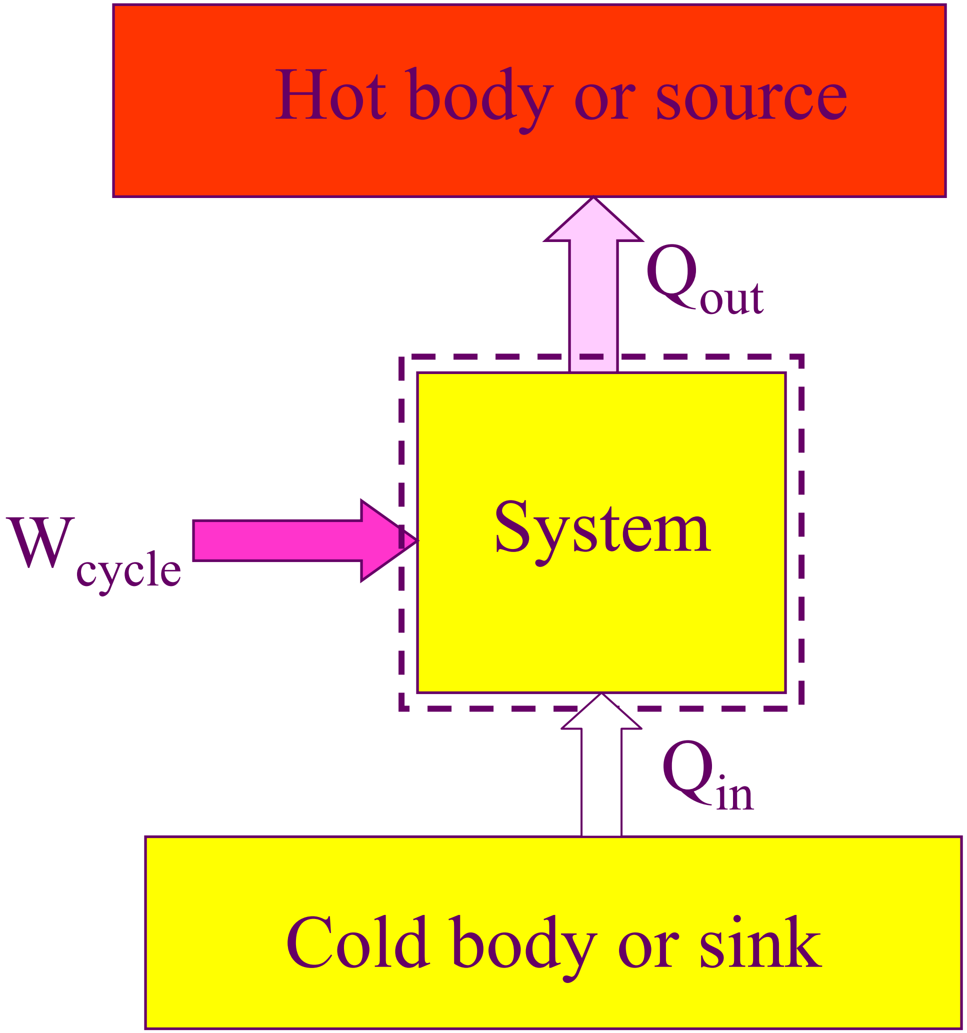


Heat Engine Efficiency: machines that produce work



$$\eta = \frac{W_{LIQ}}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

Refrigerators and heat pumps: machines that consume work



REFRIGERATOR

$$\eta = \frac{Q_L}{W_{IN}} = \frac{Q_L}{Q_H - Q_L}$$

HEAT PUMP

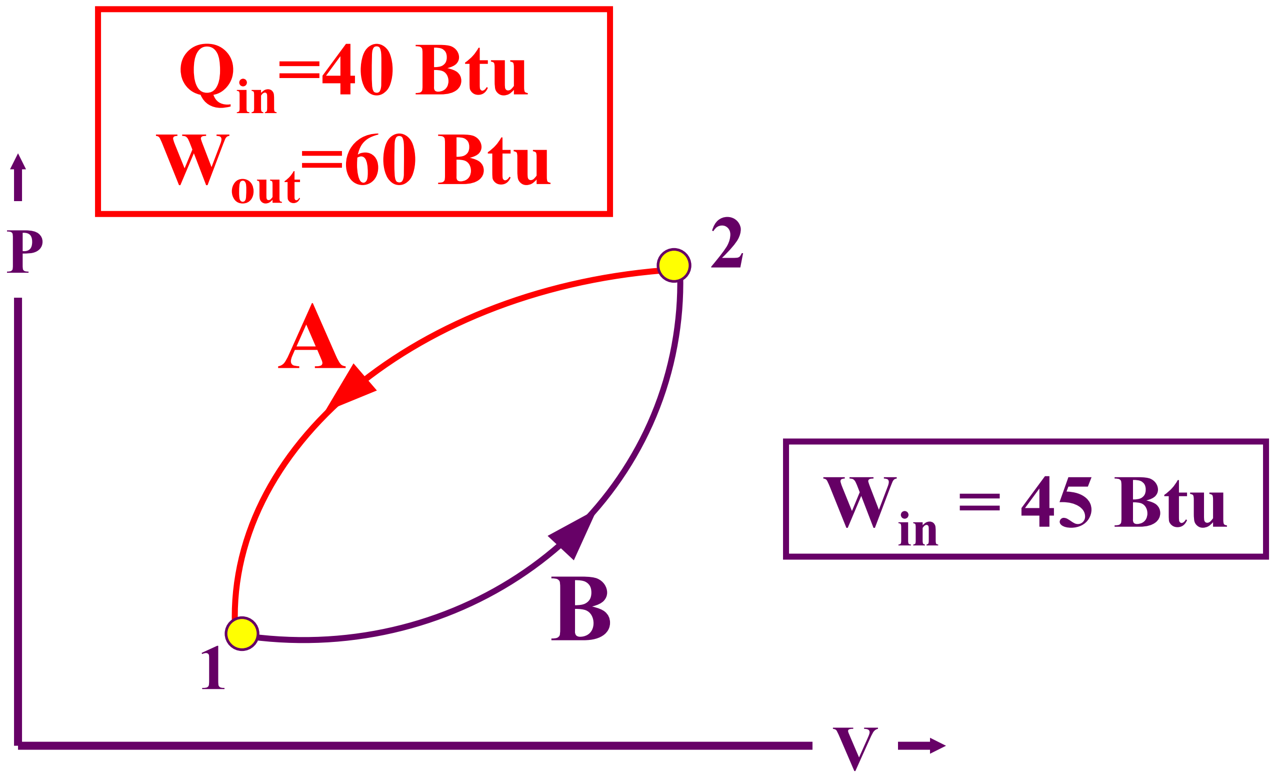
$$\eta = \frac{Q_H}{W_{IN}} = \frac{Q_H}{Q_H - Q_L}$$

TEAMPLAY

A closed system undergoes a cycle consisting of two processes. During the first process, 40 Btu of heat is transferred to the system while the system does 60 Btu of work. During the second process, 45 Btu of work is done on the system.

(a) Determine the heat transfer during the second process.

(b) Calculate the net work and net heat transfer of the cycle.



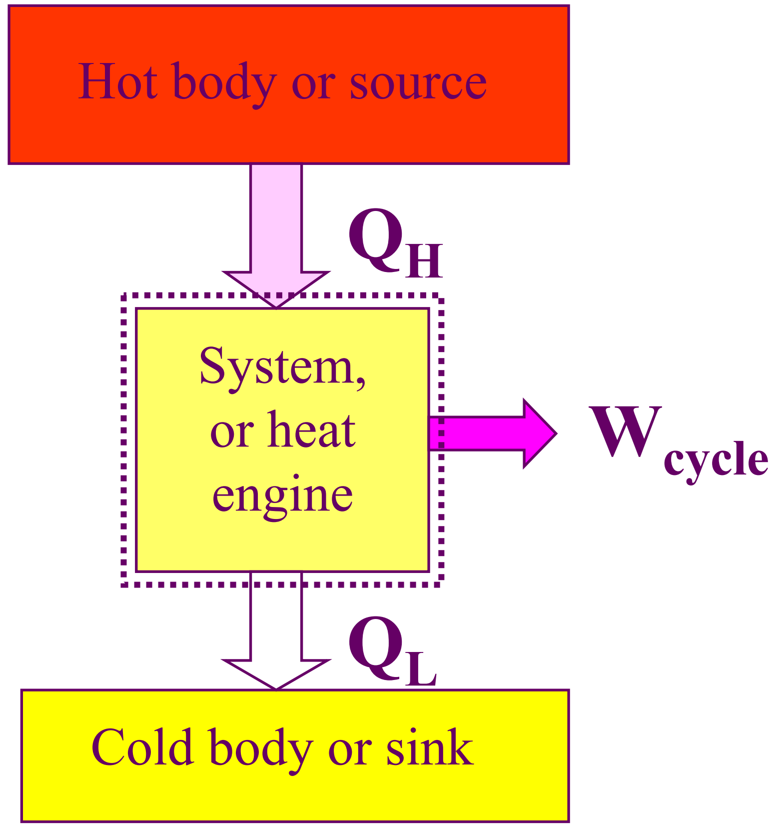
Ex4.14) **Uma grande central de potência produz 1000MW de potência elétrica com uma eficiência térmica do ciclo de 40%. Qual é a taxa com que o calor é rejeitado ao ambiente por esta central?**

$$\eta_T = 0{,}4 = \frac{\dot{W}}{\dot{Q}_h}$$

$$\dot{Q}_H = \frac{1000\text{MW}}{0{,}4} = 2500\text{MW}$$

$$\oint \dot{Q} = \oint \dot{W} \Rightarrow (\dot{Q}_H - \dot{Q}_L) = \dot{W}_{liq}$$

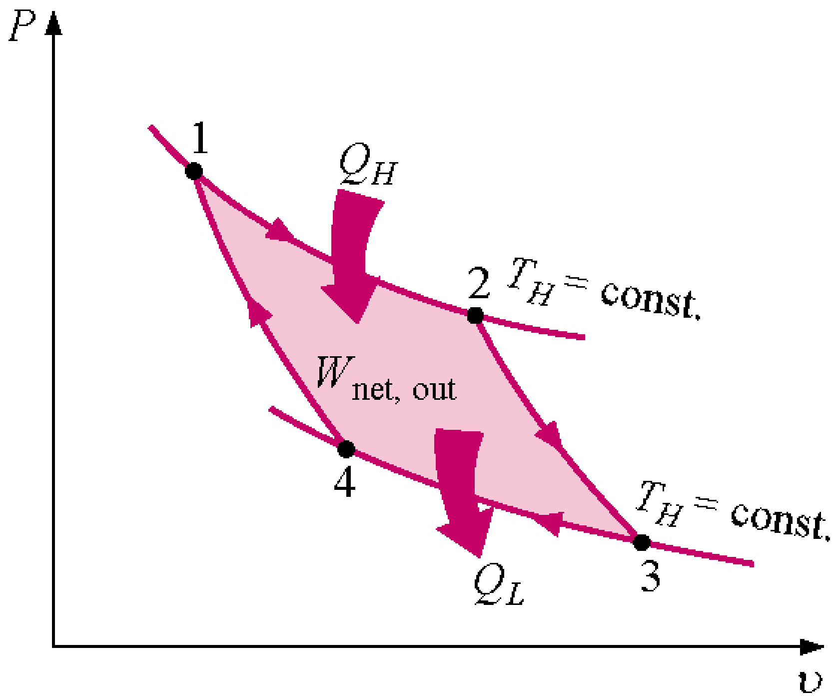
$$\therefore \dot{Q}_L = 1500\text{MW}$$



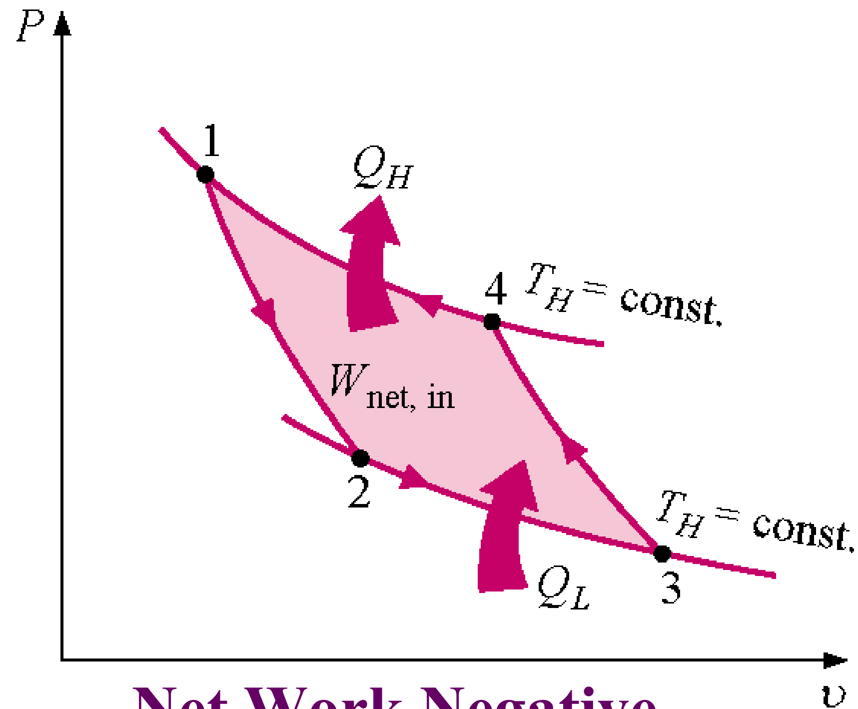
Carnot Cycle for Gas

- The *Carnot cycle* is a reversible cycle that is composed of four internally reversible processes.
  - Two isothermal processes
  - Two adiabatic processes

•*The area represents the net work or net heat.*

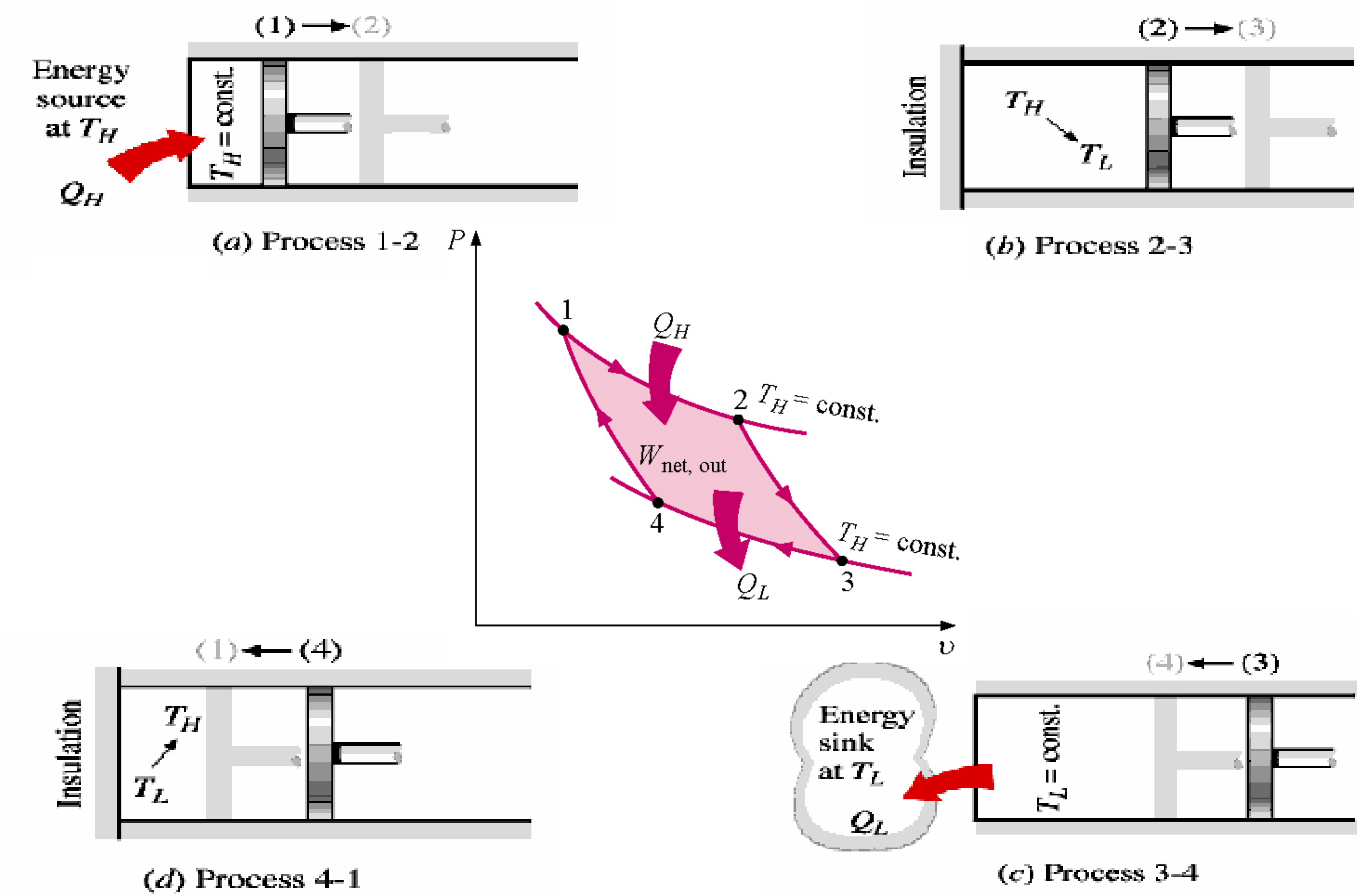


Net Work Positive

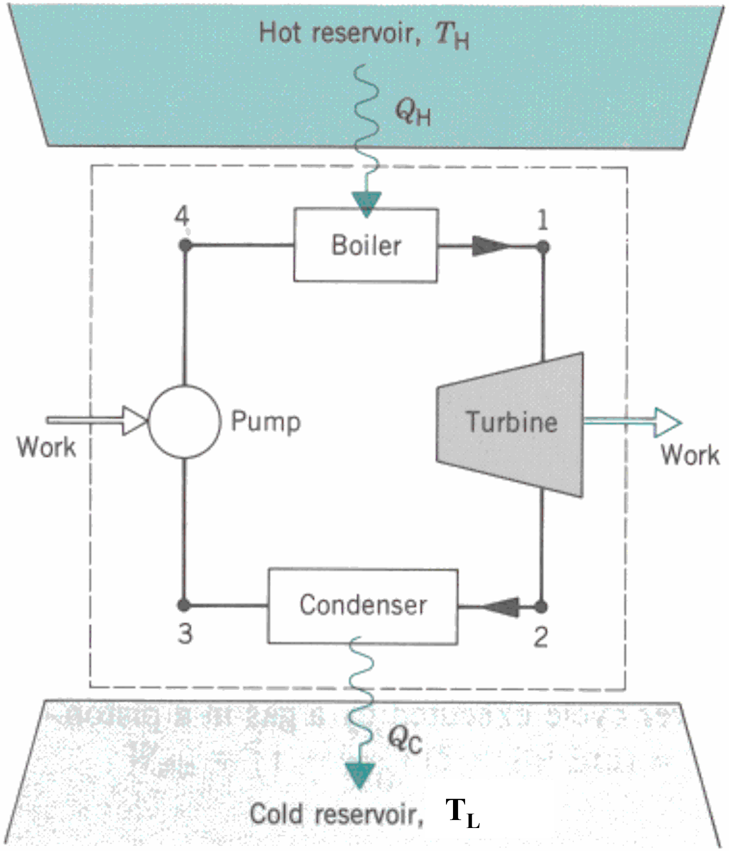


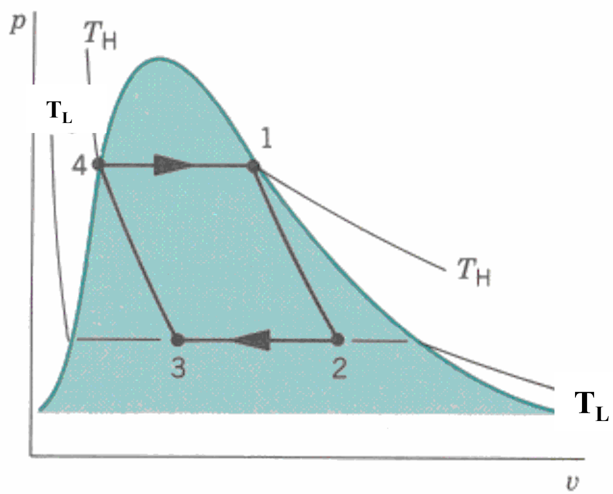
Net Work Negative, Reversed cycle.

Execution of the Carnot Cycle in a Closed System



Carnot Cycle for Vapor



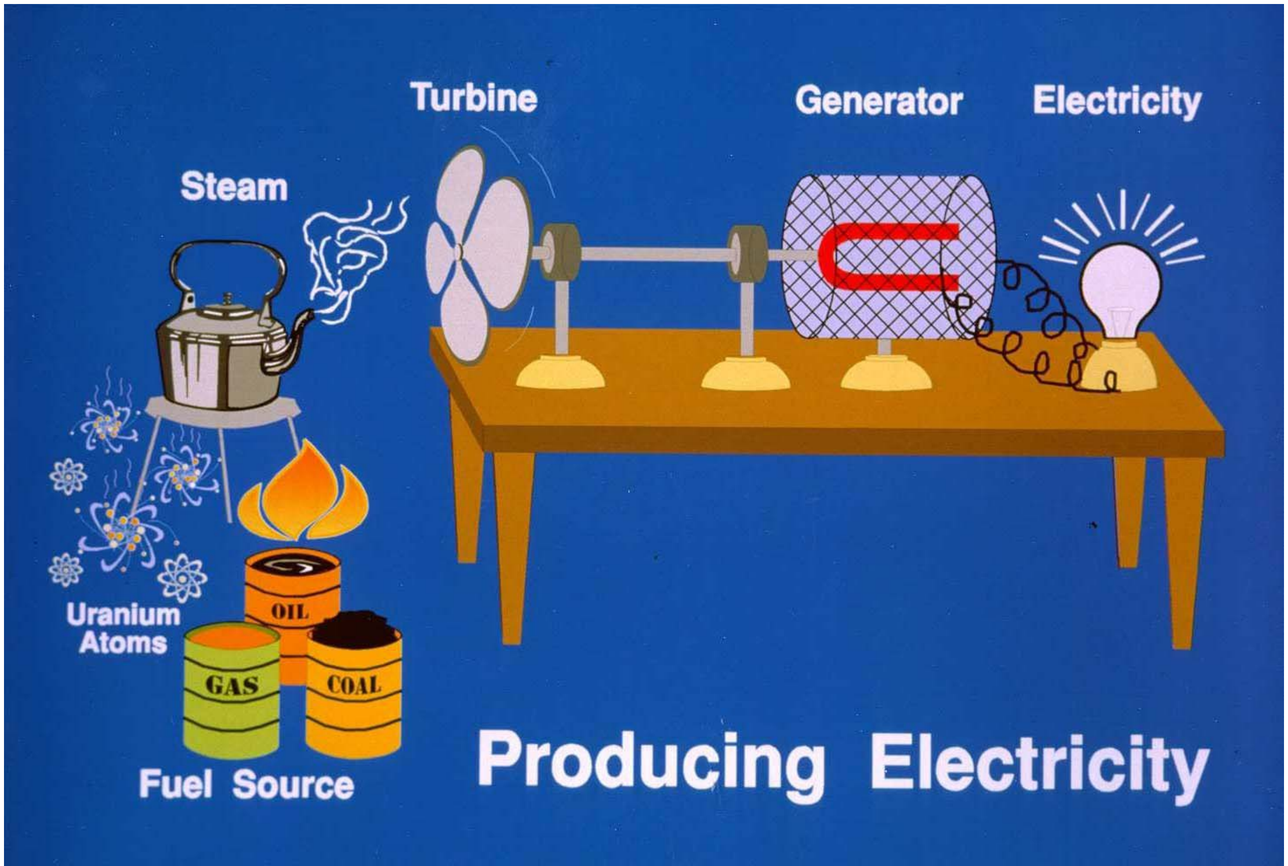


- Carnot cycle involving two phases -- it is still two adiabatic processes and two isothermal processes.

- It is always reversible -- a Carnot cycle is reversible by definition.

Vapor Power Cycles

- We'll look specifically at the Rankine cycle, which is a vapor power cycle.
- It is the primary electrical producing cycle in the world.
- The cycle can use a variety of fuels.



Basic view of how electricity is produced.
(Courtesy of Carolina Power and Light Company)

Overview of a coal fired steam power station.
(Courtesy of Carolina Power and Light Company)

HOW A COAL FIRED GENERATING PLANT PRODUCES ELECTRICITY...

Coal is delivered by road, rail or water to the generating station where it is stored in piles. ❶

Before use, the coal is crushed into small pieces and conveyed to bins ❷ where a 1 to 2 day supply is held.

The crushed coal goes through a pulverizer ❸ which reduces it to a fine powder. Mixed with hot air, the powder is blown through coal burners ❹ into the boiler furnace ❺ where the mixture is ignited and burned at high intensity.

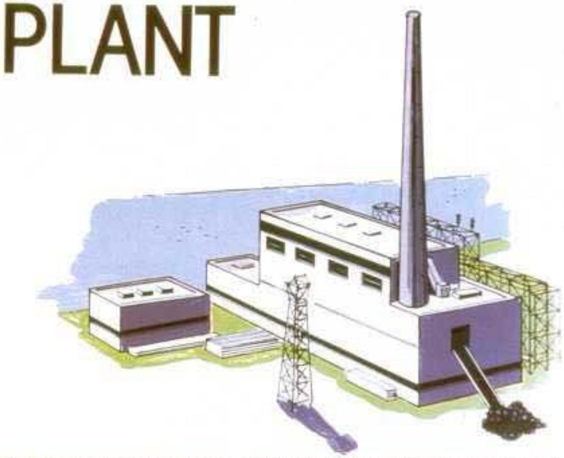
The heavy ash produced by burning, drops into an ash hopper ❻ for disposal while the light fly ash in the flue gases is removed by electric precipitators and mechanical dust collectors ❼ before the gases are discharged through the chimney.

Water flowing through thousands of tubes in the boiler furnace ❽, is converted into steam which collects in a "steam drum" ❾ at the top of the boiler. The steam then travels at high pressure through a steam line ❿ into the turbines.

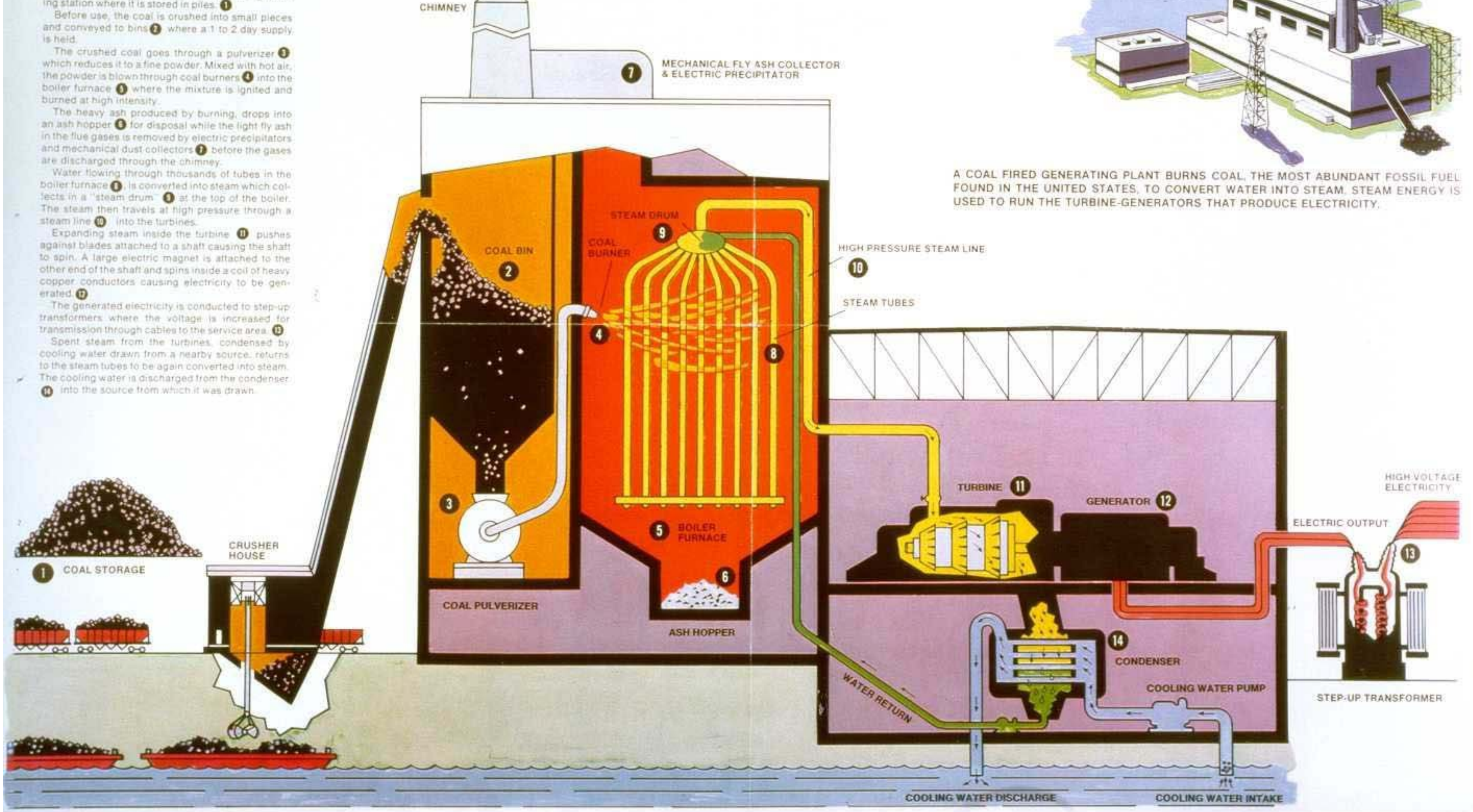
Expanding steam inside the turbine ⓫ pushes against blades attached to a shaft causing the shaft to spin. A large electric magnet is attached to the other end of the shaft and spins inside a coil of heavy copper conductors causing electricity to be generated. ⓬

The generated electricity is conducted to step-up transformers where the voltage is increased for transmission through cables to the service area. ⓭

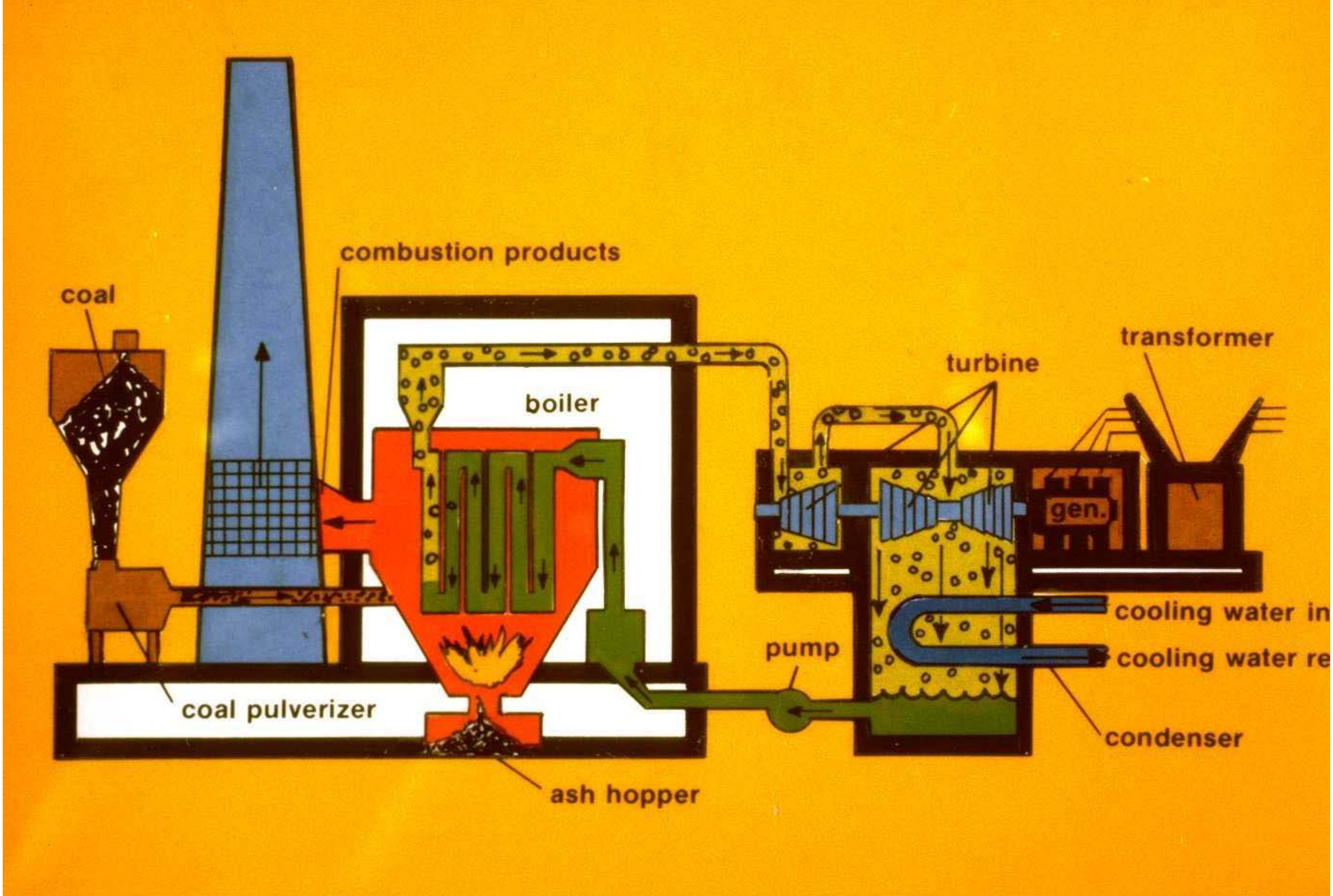
Spent steam from the turbines, condensed by cooling water drawn from a nearby source, returns to the steam tubes to be again converted into steam. The cooling water is discharged from the condenser ⓮ into the source from which it was drawn.



A COAL FIRED GENERATING PLANT BURNS COAL, THE MOST ABUNDANT FOSSIL FUEL FOUND IN THE UNITED STATES, TO CONVERT WATER INTO STEAM. STEAM ENERGY IS USED TO RUN THE TURBINE-GENERATORS THAT PRODUCE ELECTRICITY.



(Courtesy of Carolina Power and Light Company)

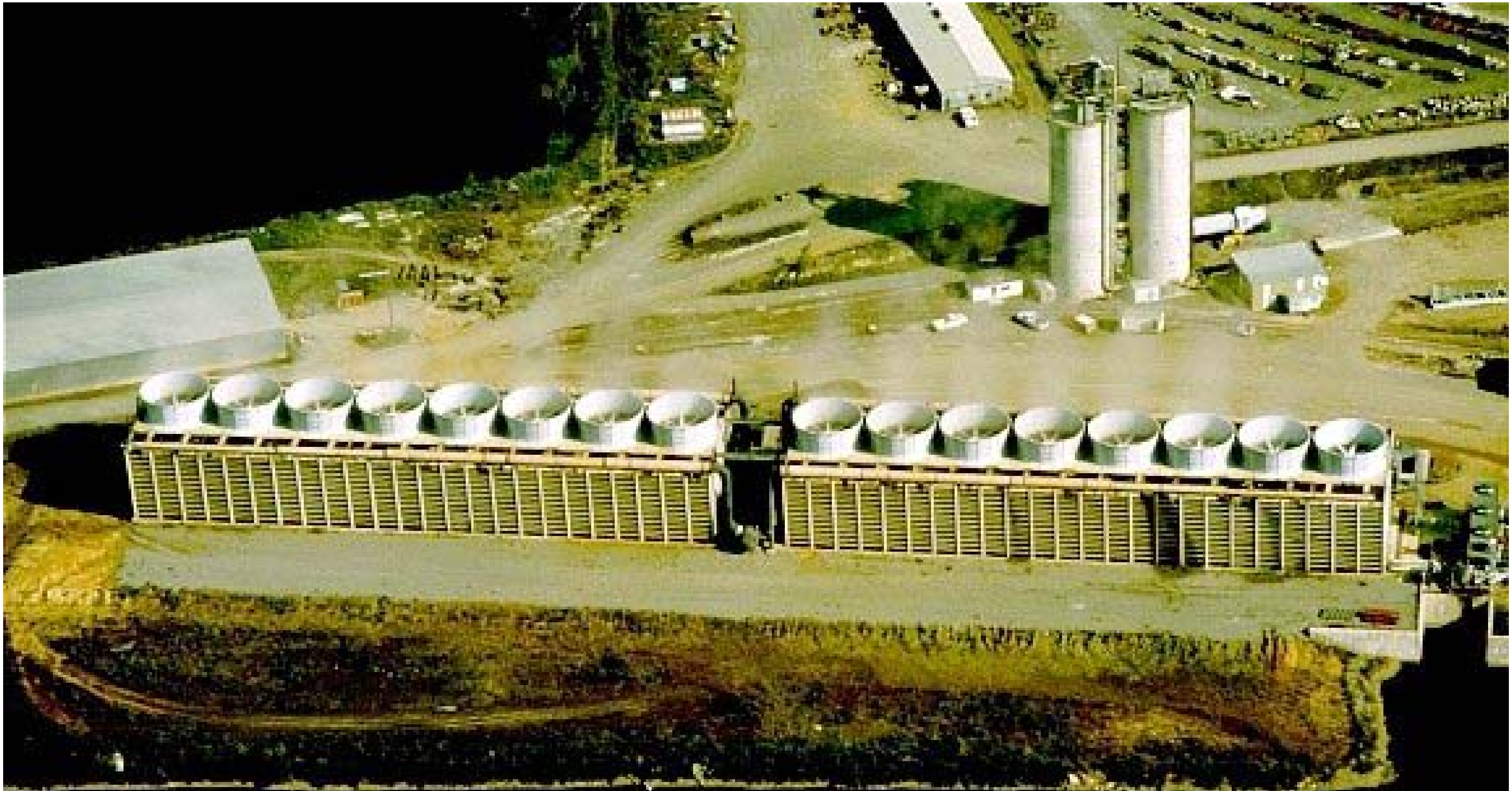


Overview of a coal fired generating plant.
(Courtesy of Carolina Power and Light Company)

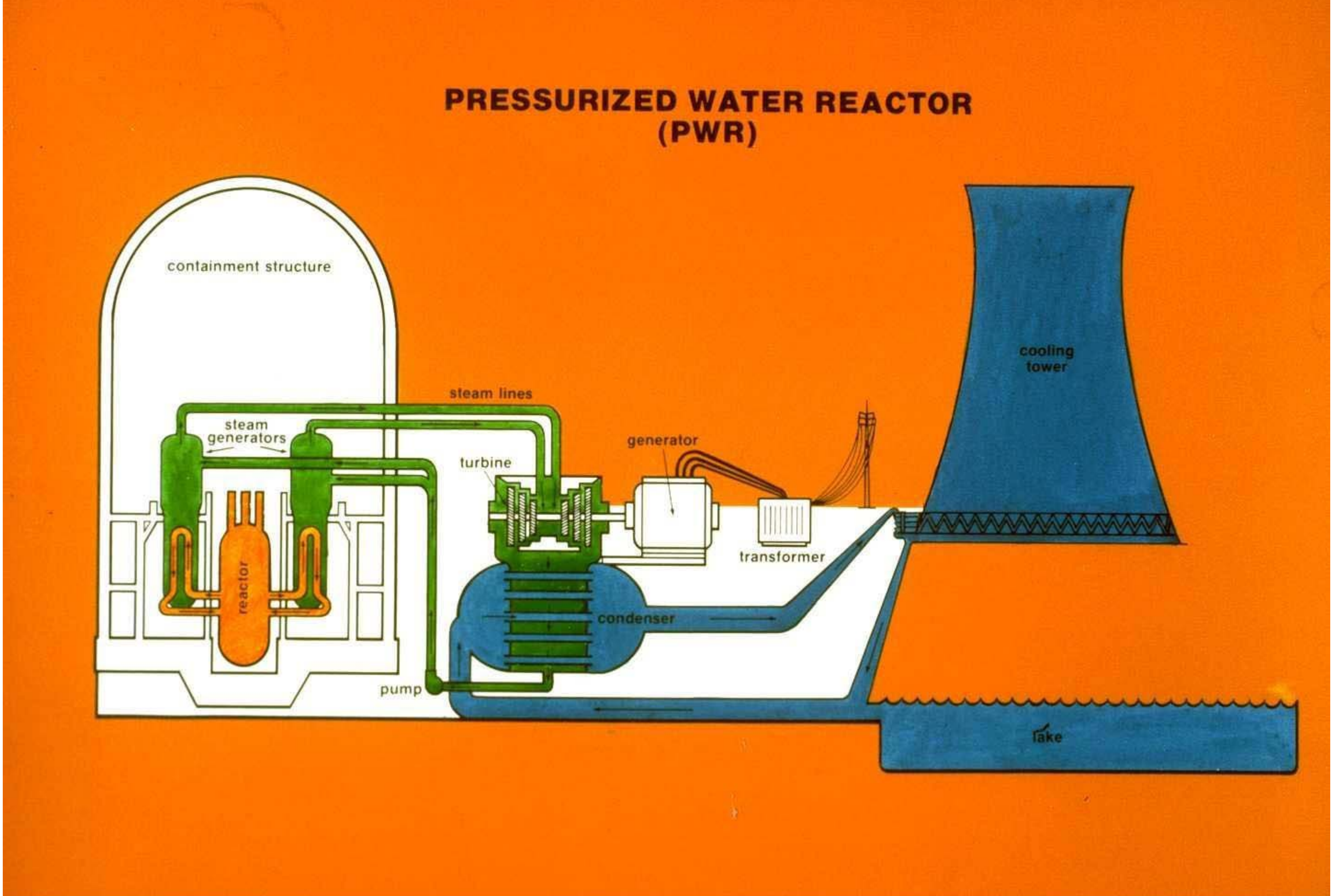
Steel structure of a steam generator at a coal fired steam power plant. (Courtesy of Carolina Power and Light Company)

Installation of steam drum for a steam generator at a coal fired steam power plant.

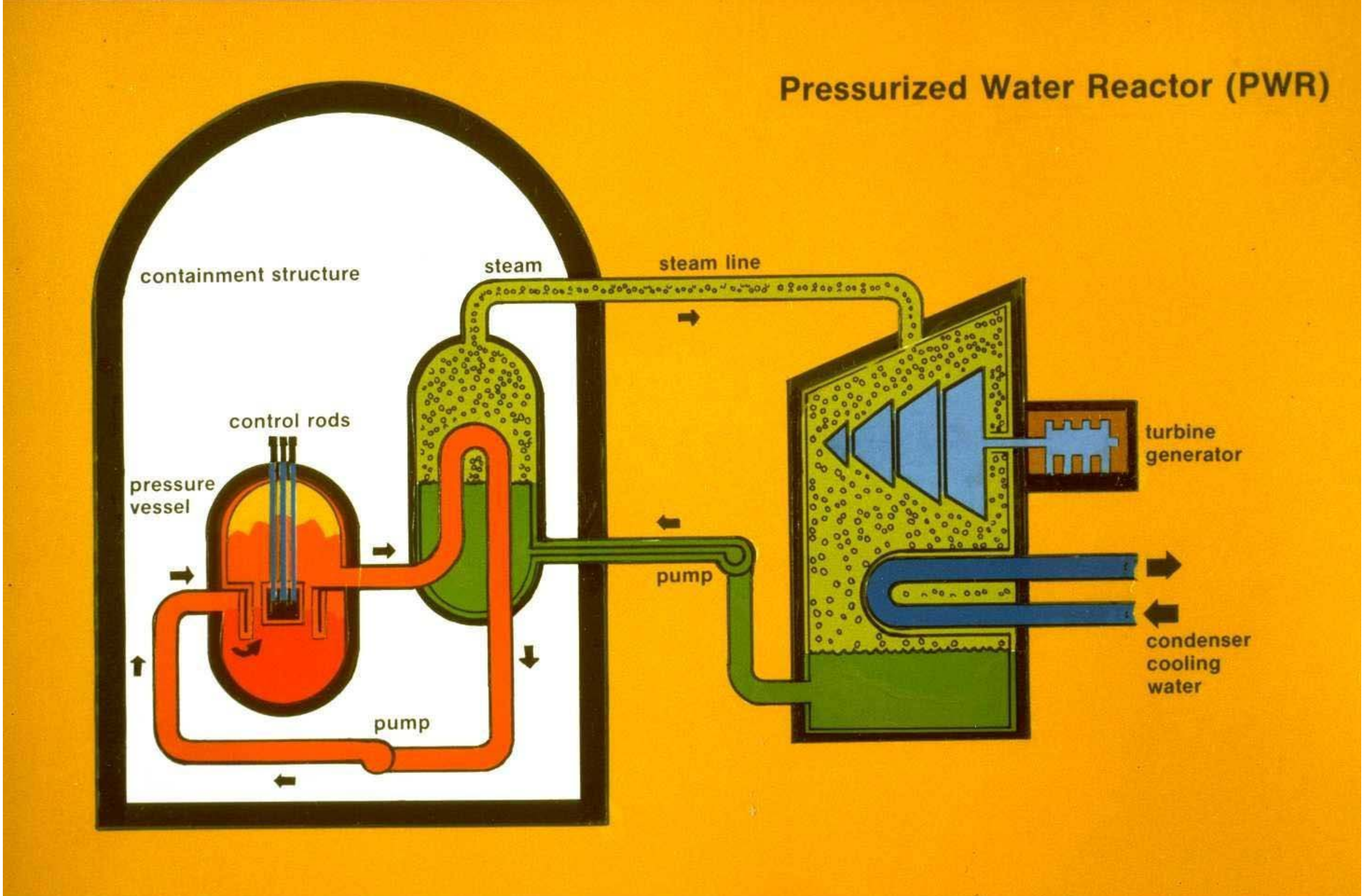
(Courtesy of Carolina Power and Light Company)



Auxiliary forced air cooling towers for a coal fired steam power station.
(Courtesy of Carolina Power and Light Company)



Pressurized water reactor power plant.
(Courtesy of Carolina Power and Light Company)



Pressurized water reactor steam generator.
(Courtesy of Carolina Power and Light Company)

Question .....

How much does it cost to operate a gas fired 1000 MW(output) power plant with a 35% efficiency for 24 hours/day for a full year if fuel cost are $2.00 per 10^6 Btu?

$467,952.27/day

$170,801,979/year

Question ....

If you could improve the efficiency of a 1000 MW power plant from 35% to 36%, what would be the savings?

$12,998/day

$4,744,499/year

Considering you did this job, what would be reasonable charge for your services?

Vapor-cycle Power Plants

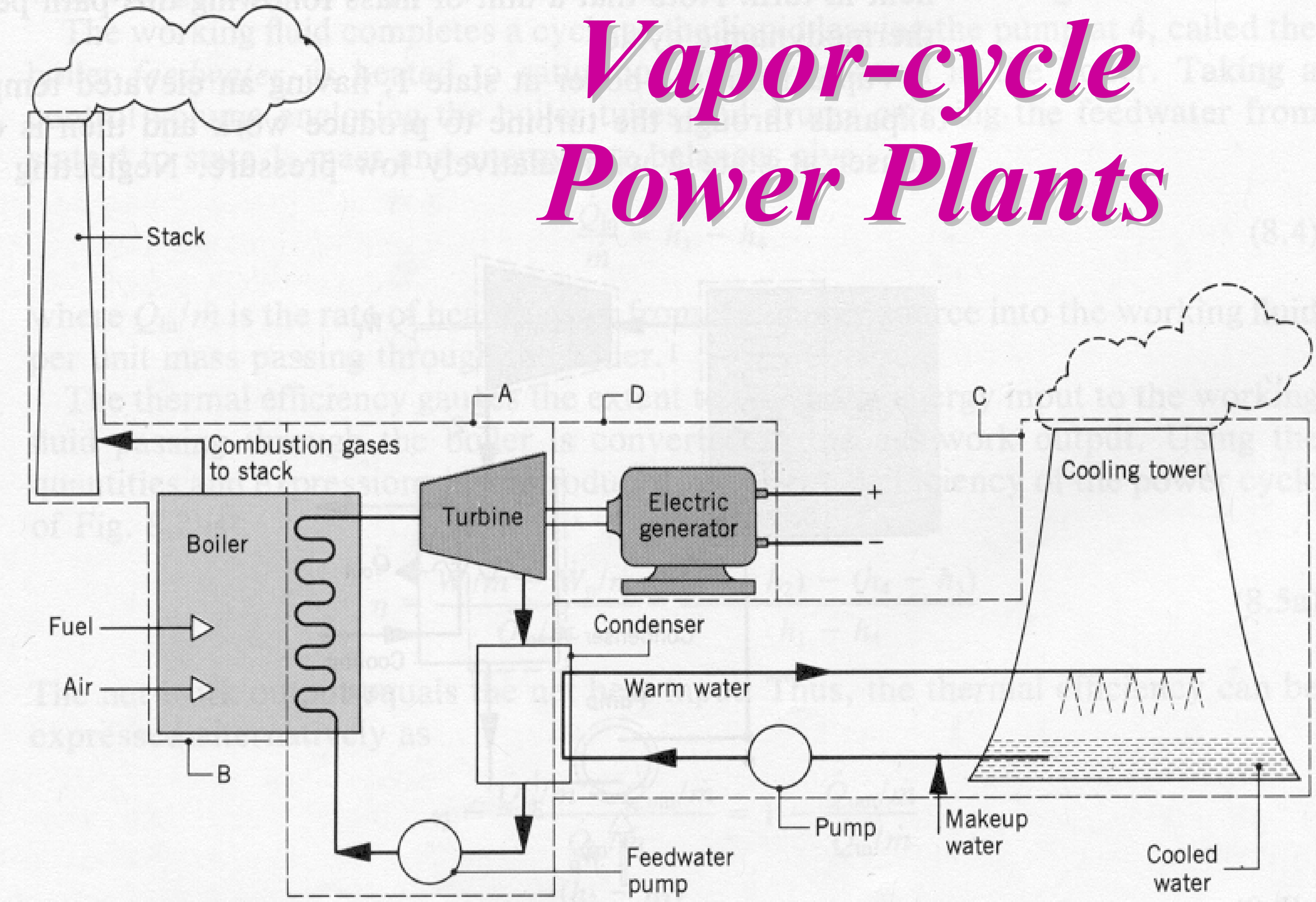
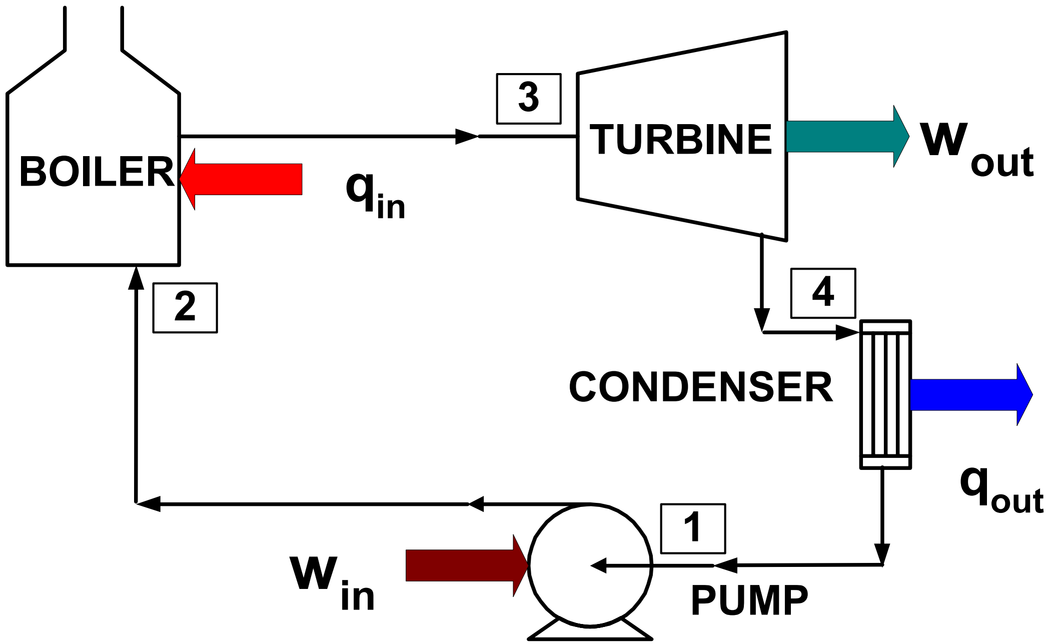
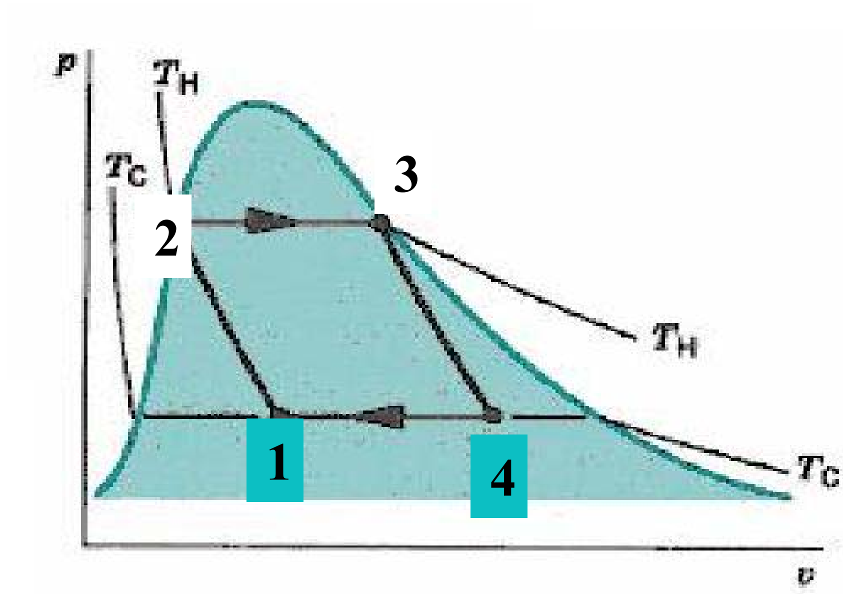


Figure 8.1 Components of a simple vapor power plant.

We'll simplify the power plant





- Low thermal efficiency
- Compressor and turbine must handle two phase flows
- The *Carnot cycle* is not a suitable model for vapor power cycles because it cannot be approximated in practice.

4-15 Uma central de potência térmica opera segundo o seguinte ciclo (veja Fig. P4.15). A água é bombeada para uma caldeira onde ela é convertida em vapor a alta pressão e temperatura através da adição do calor fornecido pela combustão de carvão. O vapor é expandido em uma turbina de vapor que aciona um gerador elétrico. Após passar pela turbina, o vapor é condensado em um condensador, rejeitando calor antes de ser bombeado de volta à caldeira.

(a) Identifique os sinais das interações de transferências de calor e de trabalho que ocorrem durante o ciclo, adotando a água/vapor como sistema.

(b) Se 5.000 MW de potência térmica é adicionada à água na caldeira, 3.500 MW é rejeitado no condensador, e as perdas de calor adicionais do ciclo são 500 MW, qual é a potência líquida do ciclo? Qual é a eficiência térmica da central de potência?

(c) Se a potência da bomba é de 1.000 kW, qual é a saída da turbina de potência?

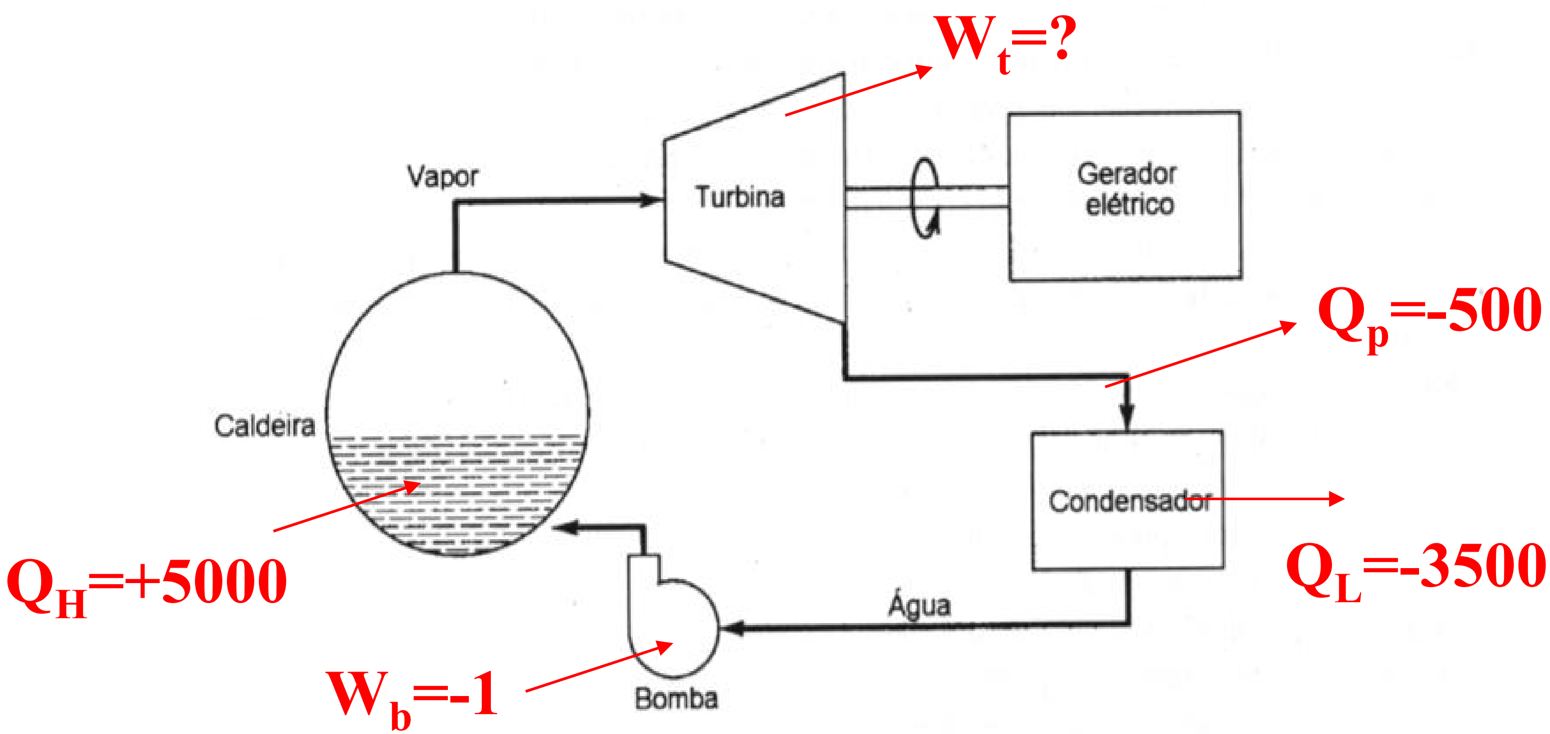
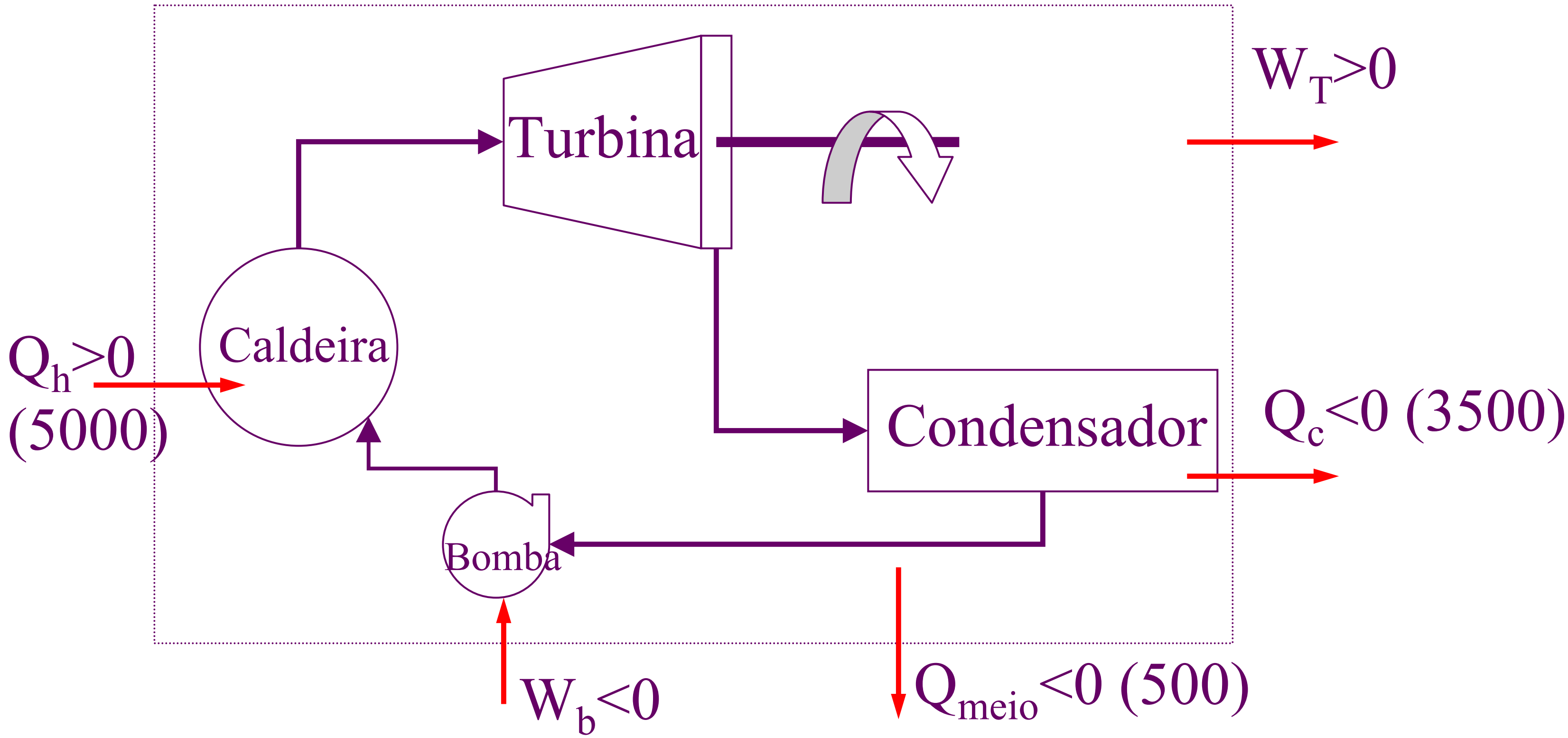


Figura P4-15 Ciclo de central de potência a vapor.

Ex4.15)



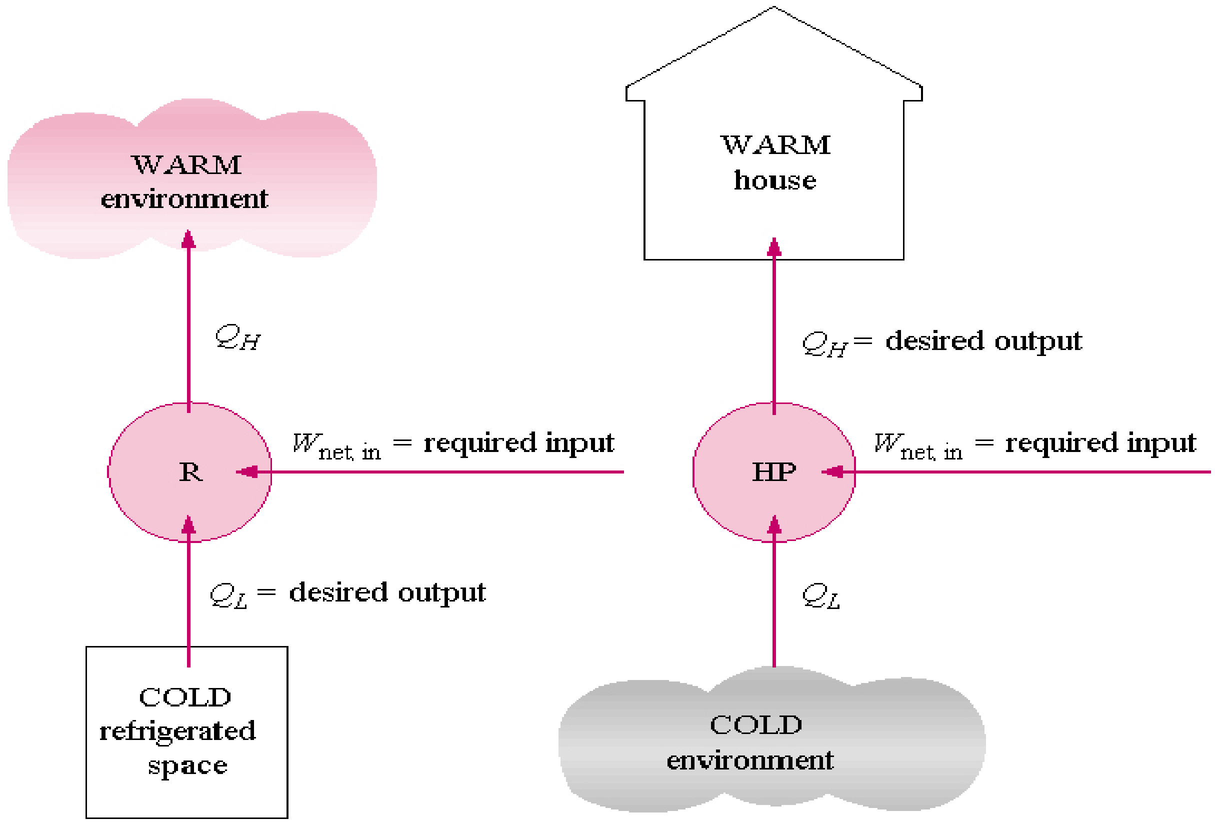
$$\oint \dot{Q} = \oint \dot{W} \rightarrow 5000 - 4000 = 1000\,\mathrm{MW}$$

$$\eta_T = \frac{W_{liq}}{Q_h} = \frac{1000}{5000} = 25\%$$

$$W_{liq} = W_T - W_b \rightarrow 1000 = W_T - 1 \rightarrow W_T = 1001\,\mathrm{MW}$$

Reversed Vapor Cycles:
Refrigerator and Heat Pump

The objective of a refrigerator is to remove heat (Q_L) from the cold medium; the objective of a heat pump is to supply heat (Q_H) to a warm medium

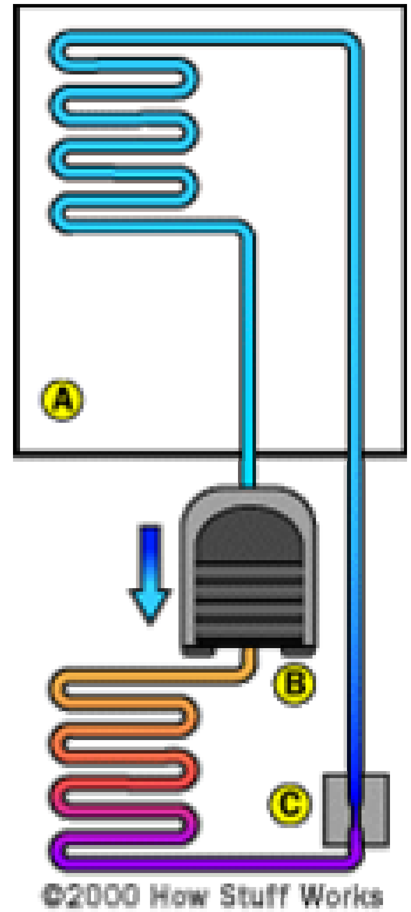


(*a*) Refrigerator (*b*) Heat pump

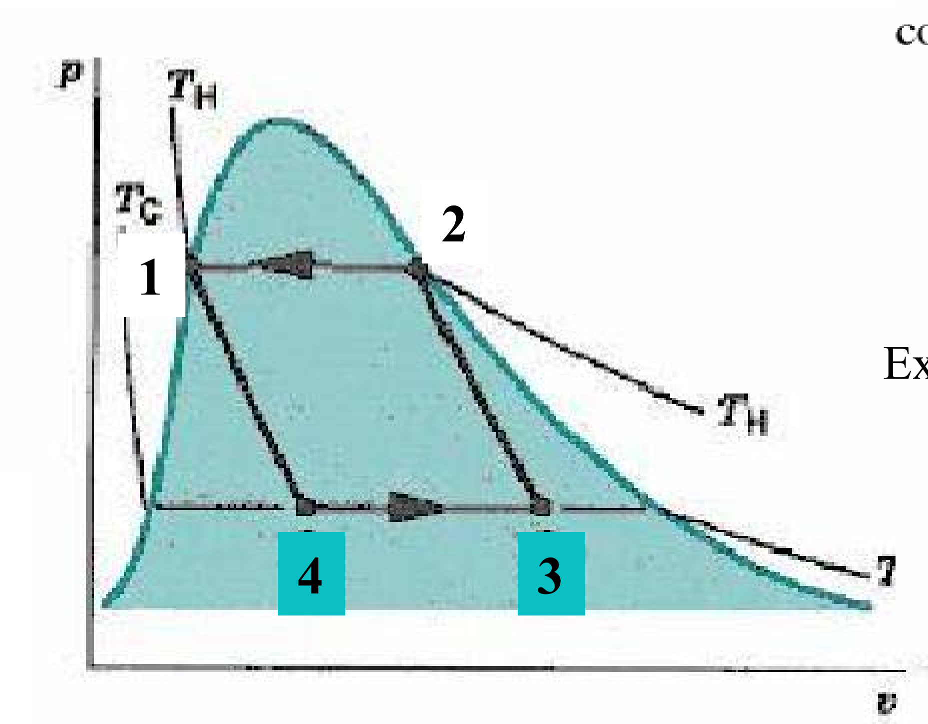
Inside The Household Refrigerator

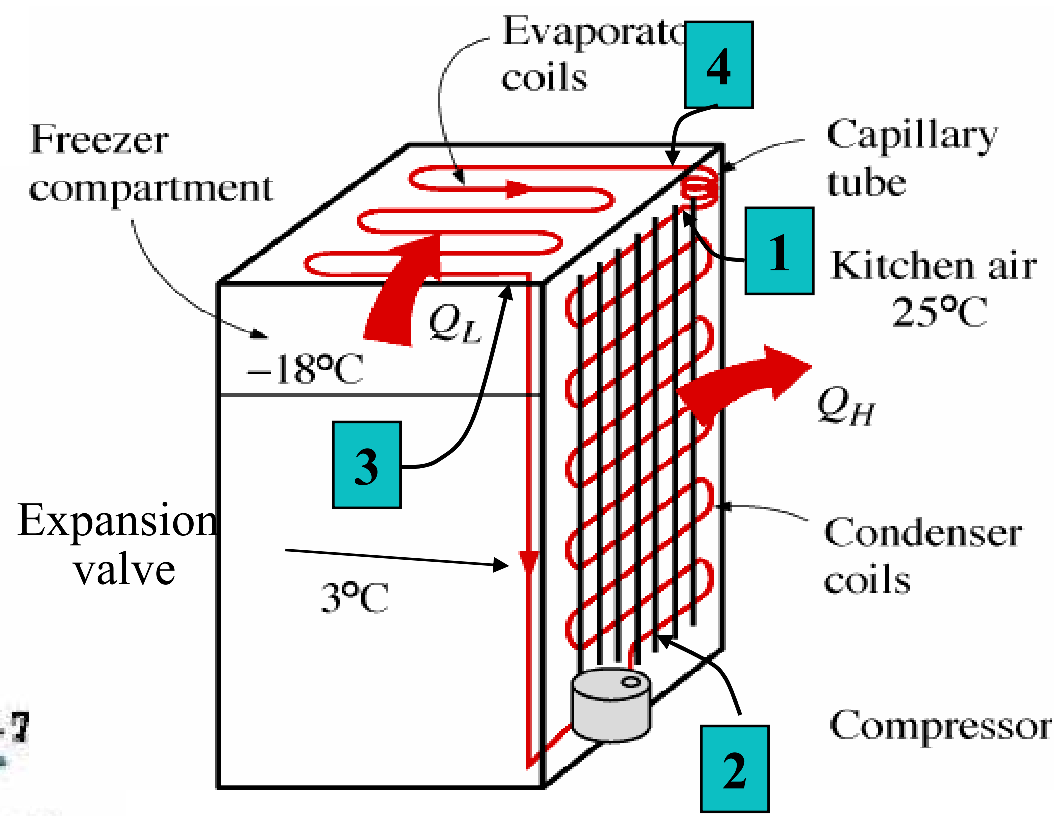
common view

engineering view



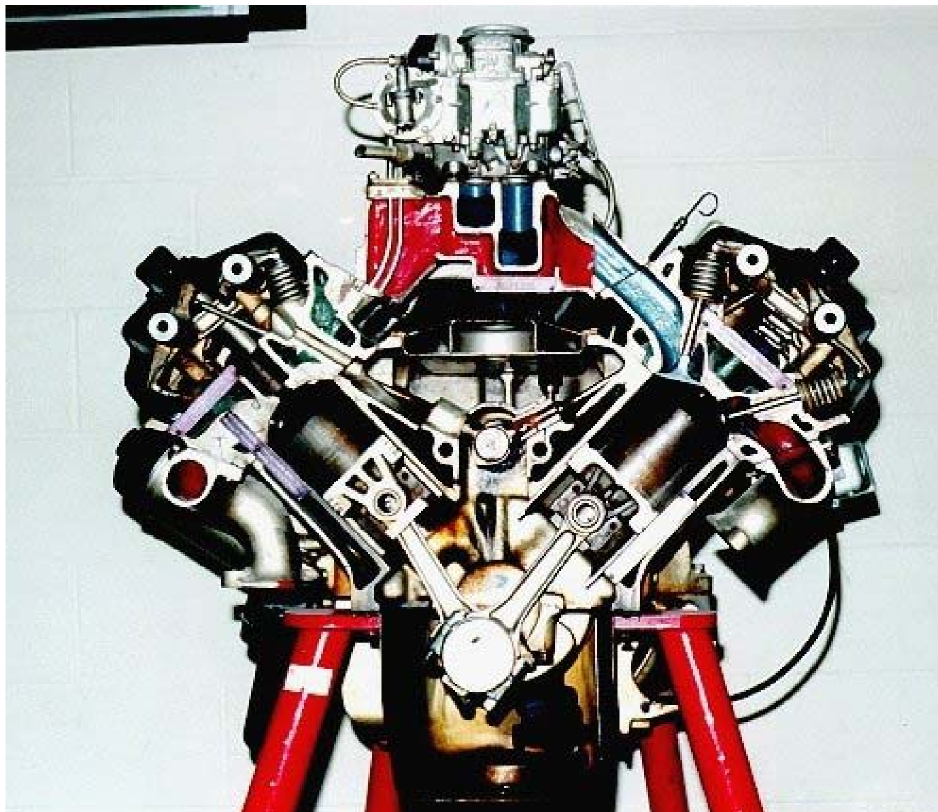
Reversed Carnot Vapor Cycle Refrigerator





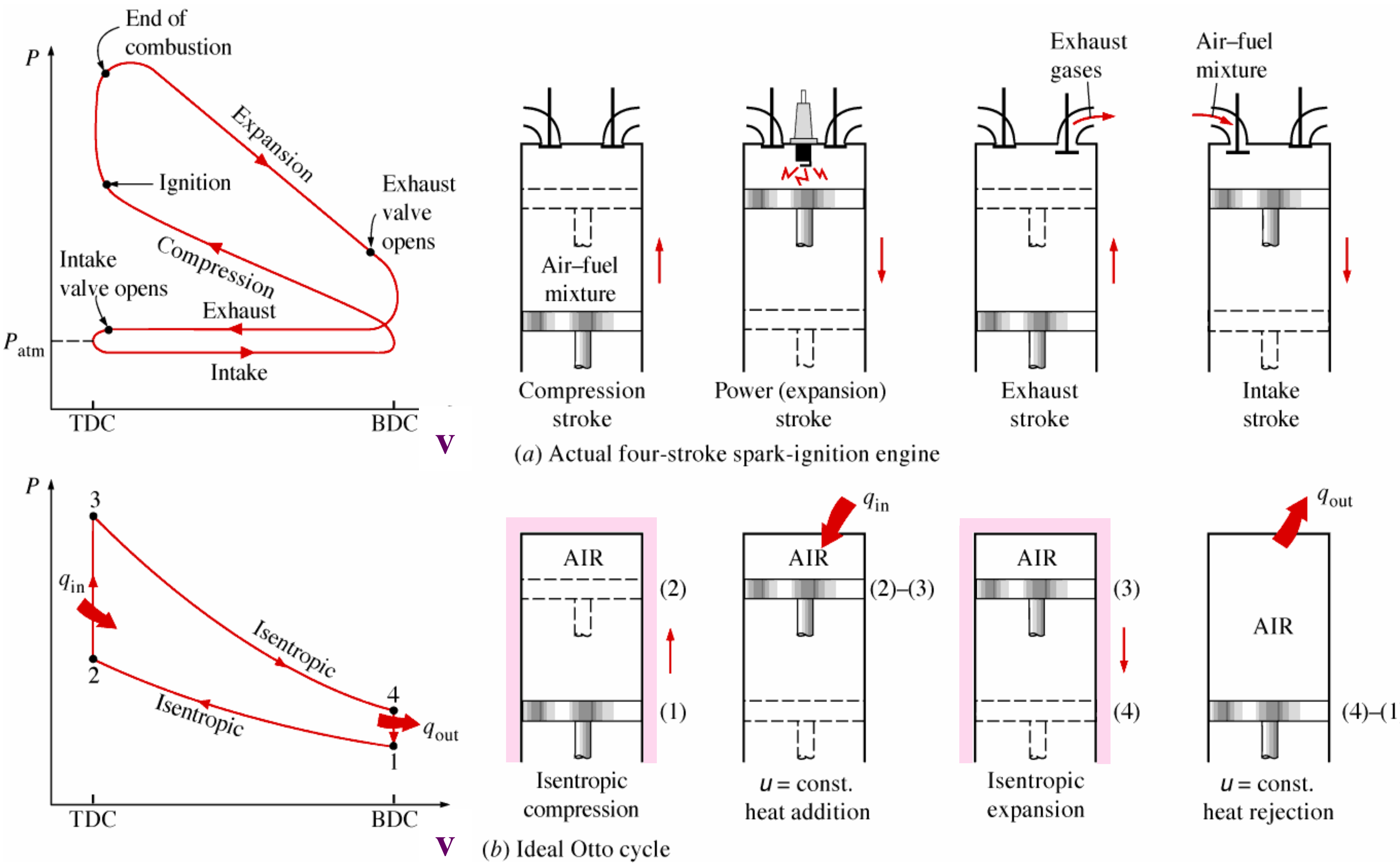
Gas Power Cycle

- **A cycle during which a net amount of work is produced is called a *power cycle*,**
- **and a power cycle during which the working fluid remains a gas throughout is called a *gas power cycle*.**



Inside view of a V-8 gasoline engine.

Actual and Ideal Cycles in Spark-Ignition Engines



(*a*) Actual four-stroke spark-ignition engine

(*b*) Ideal Otto cycle

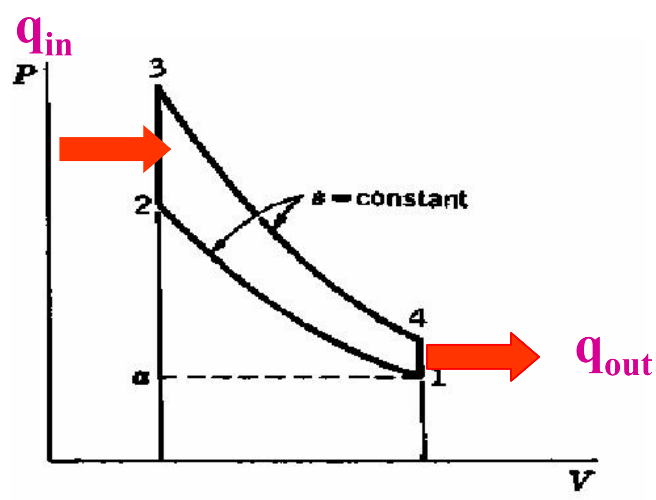
Otto Cycle

- **Heat addition 2-3** $Q_H = mC_V(T_3 - T_2)$
- **Heat rejection 4-1** $Q_L = mC_V(T_4 - T_1)$

$$\eta = 1 - \frac{Q_L}{Q_H} = 1 - \frac{mC_V\left(T_4 - T_1\right)}{mC_V\left(T_3 - T_2\right)}$$

- **or in terms of the temperature ratios**

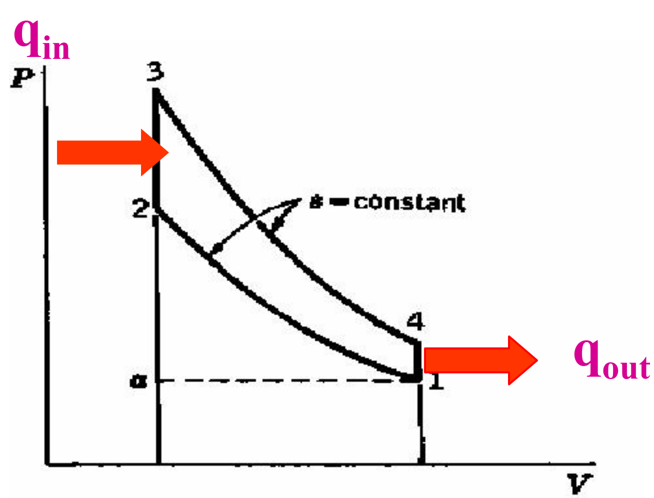
$$\eta = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_1\left(T_4/T_1 - 1\right)}{T_2\left(T_3/T_2 - 1\right)}$$



Otto Cycle

- 1-2 and 3-4 are adiabatic process, using the adiabatic relations between T and V

$$\frac{T_2}{T_1} = \underbrace{\left(\frac{V_1}{V_2}\right)^{\gamma-1} = \left(\frac{V_4}{V_3}\right)^{\gamma-1}}_{\text{SAME VOLUME RATIO}} = \frac{T_3}{T_4} \Rightarrow \frac{T_2}{T_1} \equiv \frac{T_3}{T_4}$$



$$\eta = 1 - \frac{T_1\left(T_4/T_1 - 1\right)}{T_2\left(T_3/T_2 - 1\right)} \equiv 1 - \frac{T_1}{T_2}$$

$$\eta = 1 - \frac{1}{\left(r_v\right)^{\gamma-1}} \quad \text{where} \quad r_v = \frac{V_1}{V_2}$$

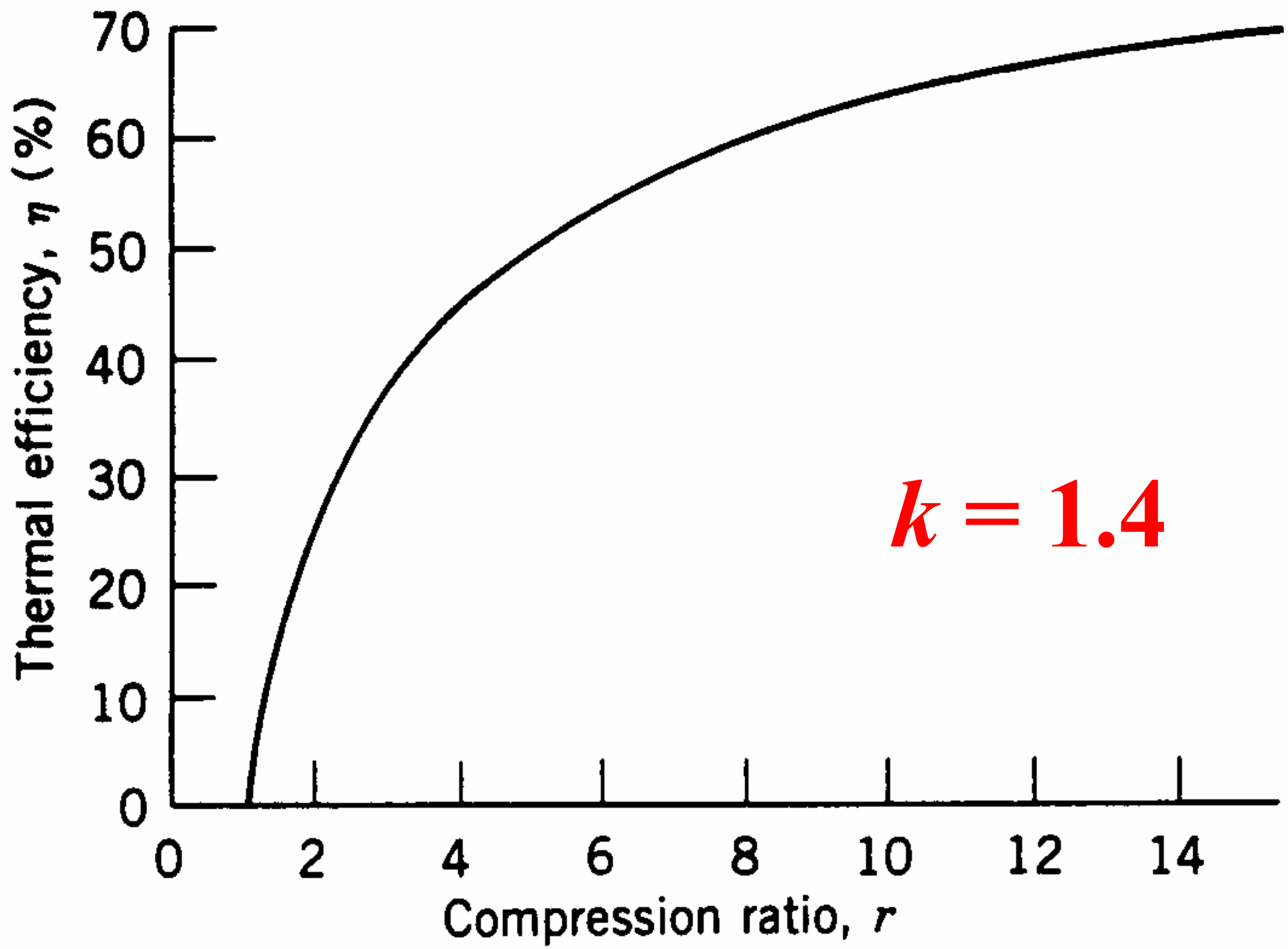
Thermal Efficiency of Ideal Otto Cycle

- Under cold-air-standard assumptions, the thermal efficiency of the ideal Otto cycle is

$$\eta_{th,\,Otto} = 1 - \frac{1}{r^{k-1}}$$

where r is the compression ratio and k is the specific heat ratio C_p / C_v.

Effect of compression ratio on Otto cycle efficiency



Brayton Cycle

- This is another air standard cycle and it models modern turbojet engines. Proposed by George Brayton in 1870!


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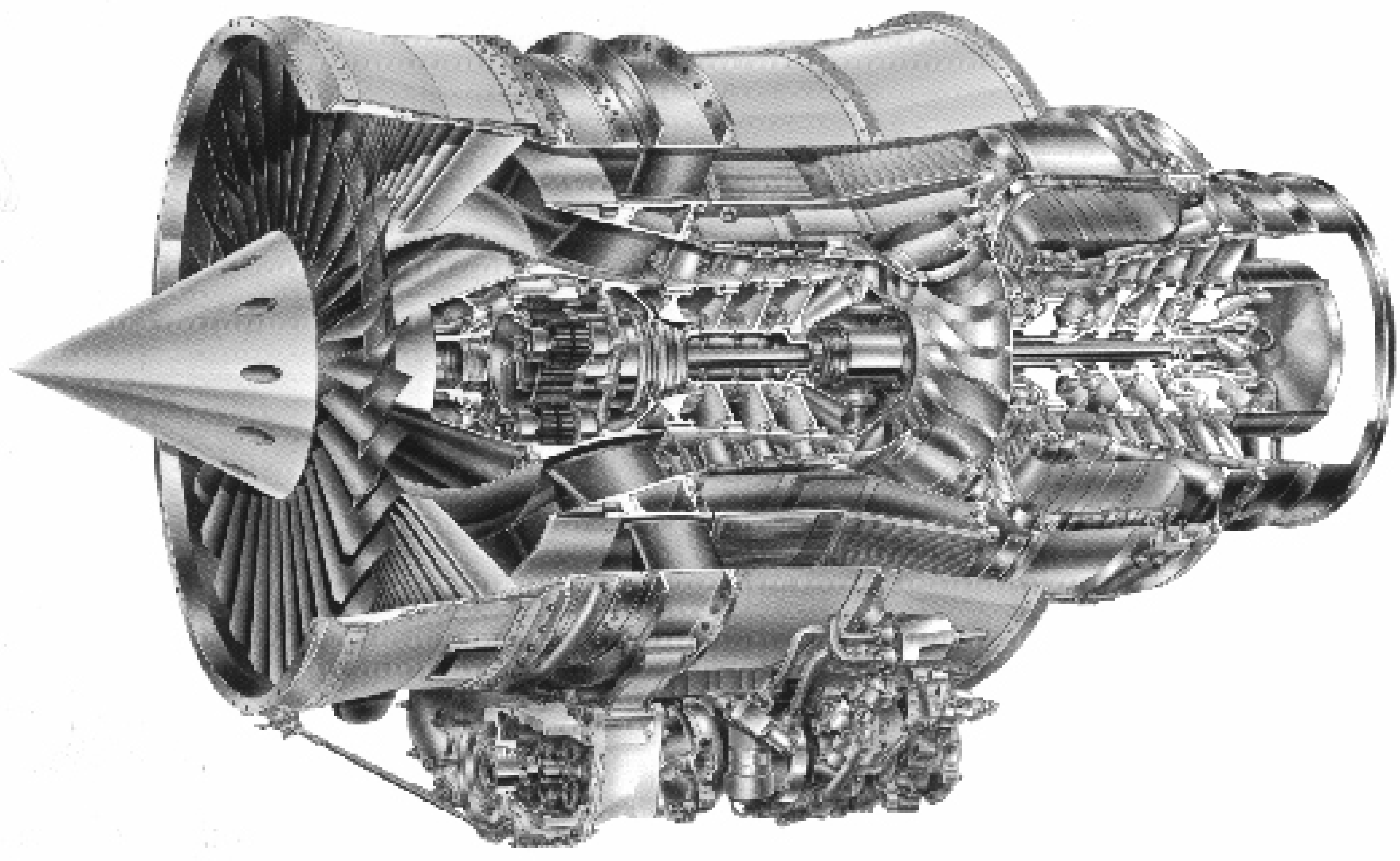
Illustration of A Turbofan Engine

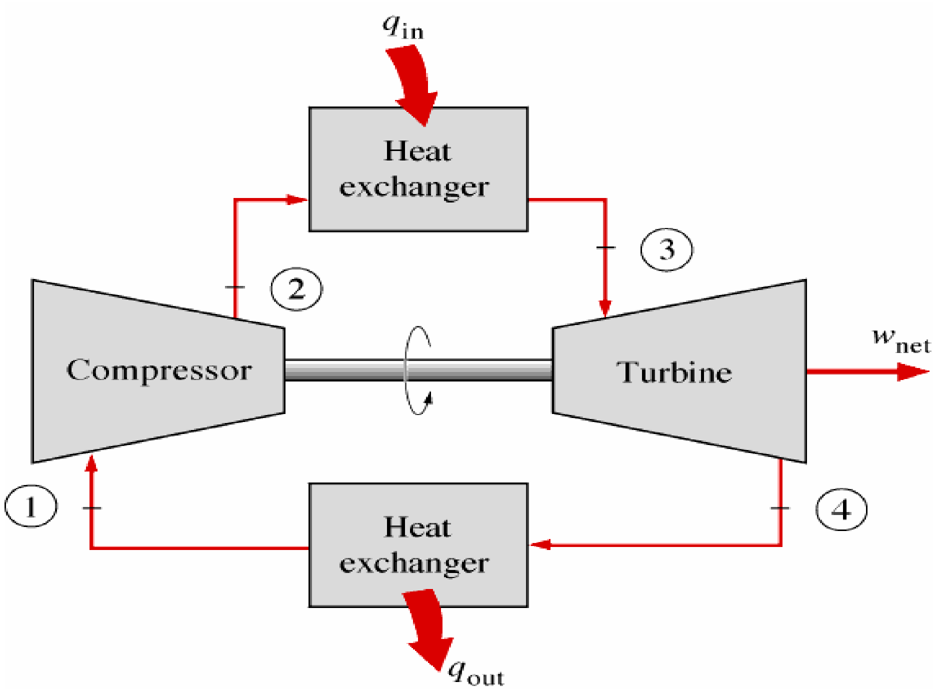


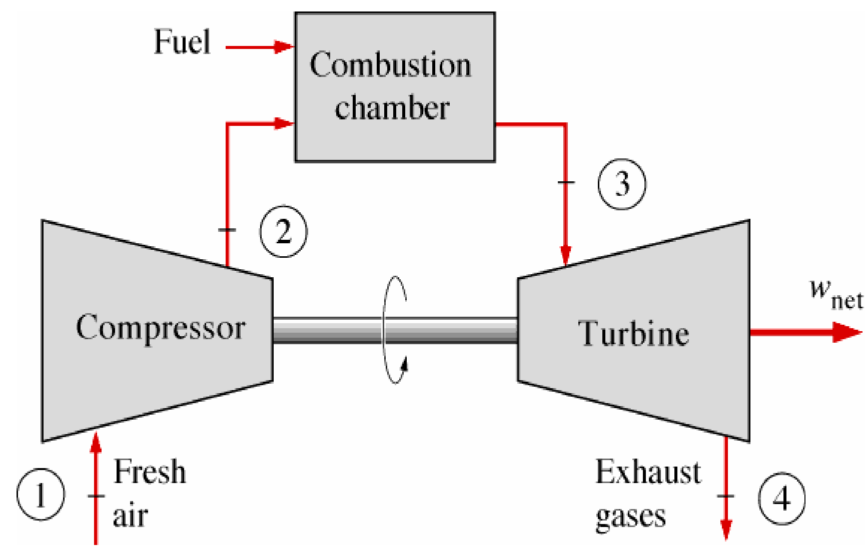
Other applications of Brayton cycle

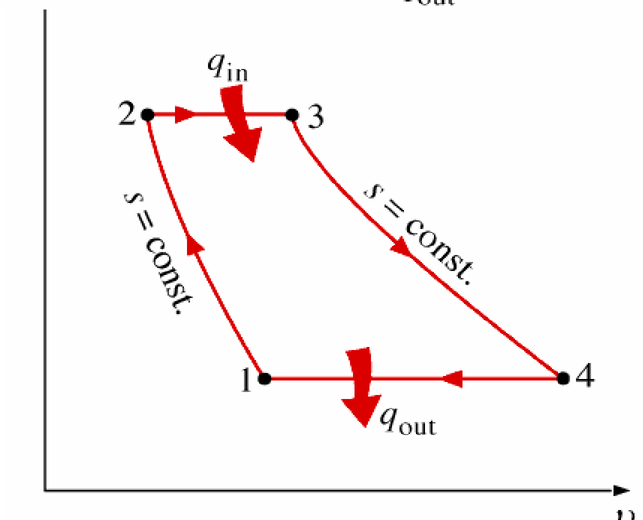
- Power generation - use gas turbines to generate electricity…very efficient

- Marine applications in large ships

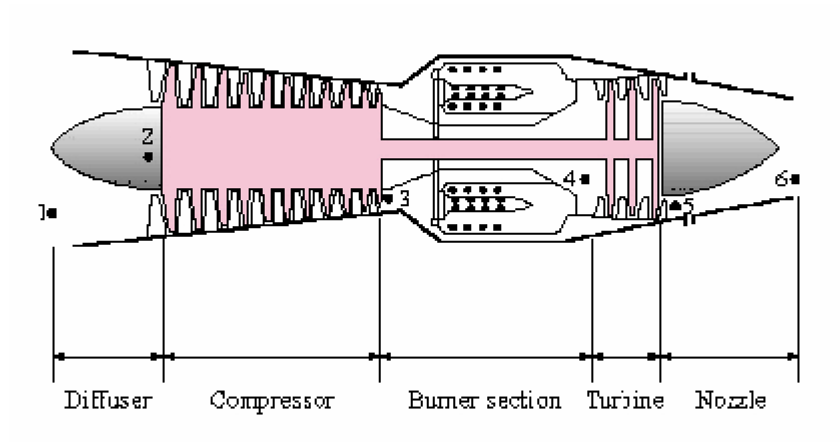
A Closed & Open-Cycles Gas-Turbine Engine







(b) *P*- υdiagram

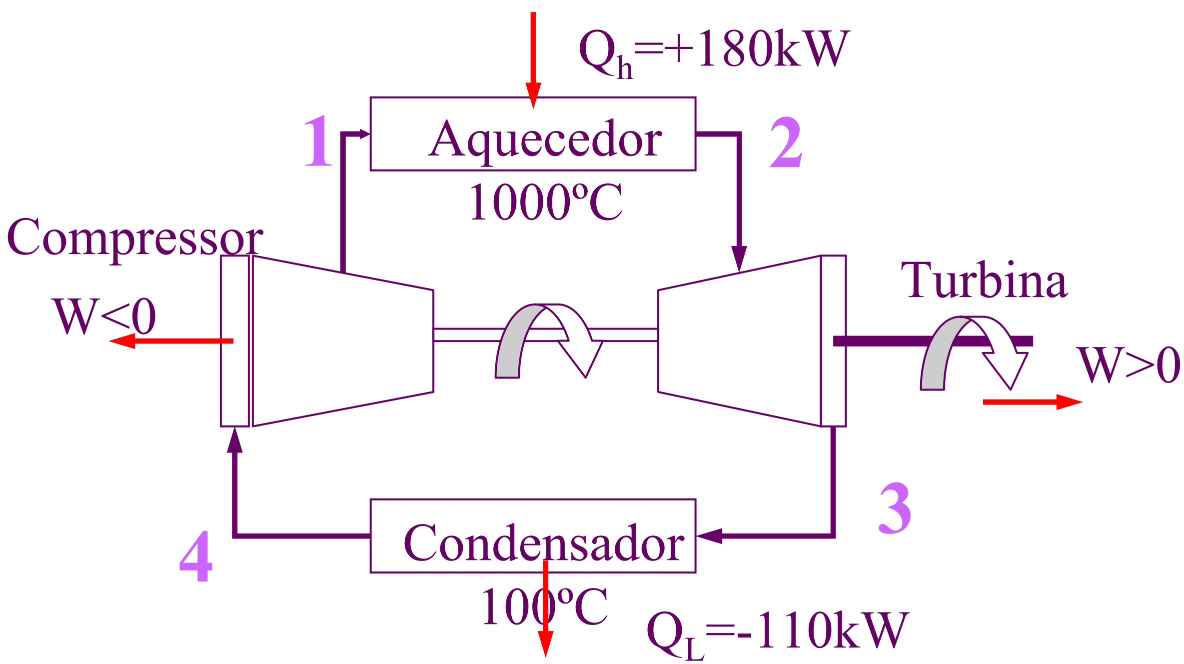


Ex4.17) **Uma central de potência com turbina a gás operando num ciclo fechado usa ar como fluido de trabalho, veja esquema da figura.**

(a) Identifique as interações das transf. de calor e trabalho considerando o ar como sistema.

(b) (b) se 180KW são fornecidos ao aquecedor e 110KW são rejeitados no condensador, determine a potência líquida e a eficiência da central.

parte (a)



parte (b)

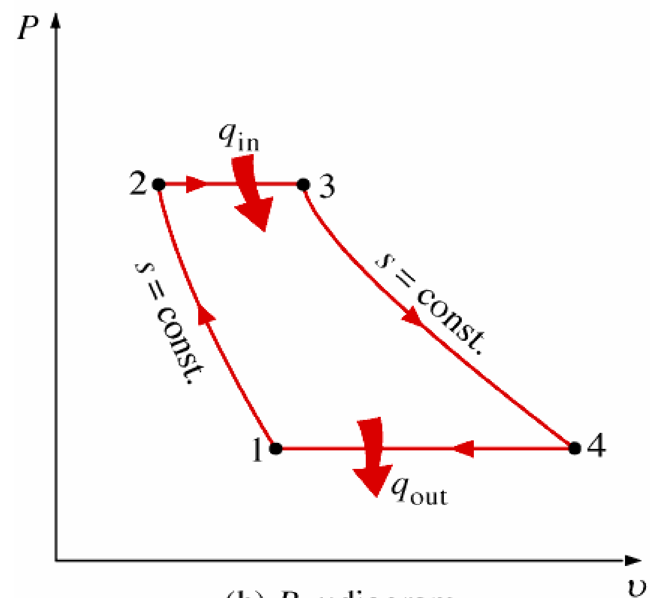
$$1^{o}\,\mathbf{Lei:}\oint Q = \oint W$$

$$W_{liq} = 180 - 110 = 70\,kW$$

$$\eta_T = \frac{W_{liq}}{Q_h} = \frac{70}{180} = 0{,}39\,\%$$

Brayton Cycle

- **1 to 2--adiabatic compression in the compressor**
- **2 to 3--constant pressure heat addition (replaces combustion process)**
- **3 to 4--adiabatic expansion in the turbine**
- **4 to 1--constant pressure heat rejection to return air to original state**



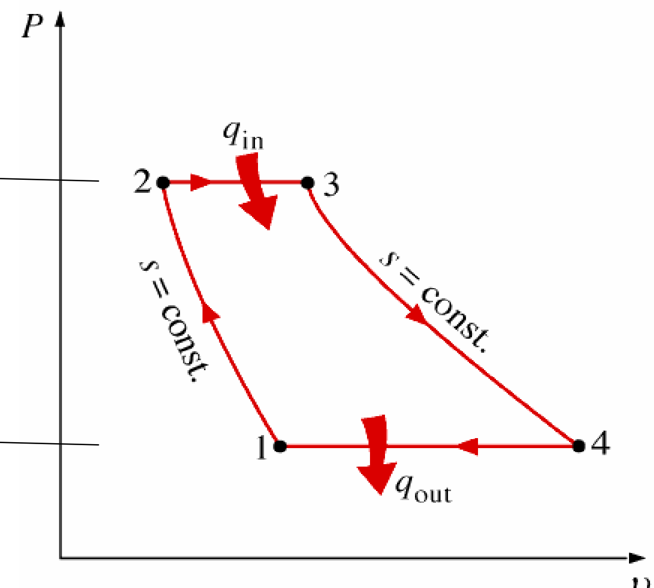
(b) P- υdiagram

Brayton Cycle

- **Because the Brayton cycle operates between two constant pressure lines, or isobars, the <u>pressure</u> ratio is important.**

- **The pressure ratio is <u>not</u> a compression ratio.**

Pressure Ratio $\frac{P_2}{P_1} = \frac{P_3}{P_4}$



(b) *P*- υdiagram

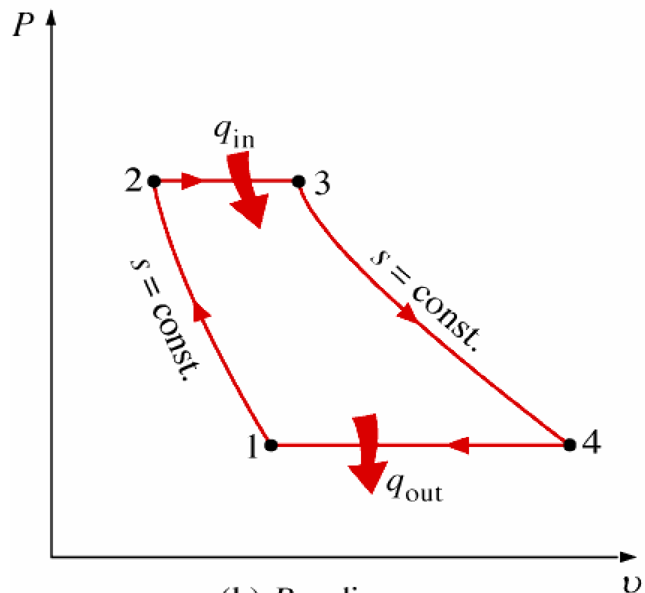
Brayton Cycle Analysis

Let's assume cold air conditions and manipulate the efficiency expression:

$$\eta = 1 - \frac{Q_L}{Q_H} = 1 - \frac{C_p(T_4 - T_1)}{C_p(T_3 - T_2)}$$

or

$$\eta = 1 - \frac{T_1}{T_2}\frac{\left(T_4/T_1 - 1\right)}{\left(T_3/T_2 - 1\right)}$$



(b) P- υdiagram

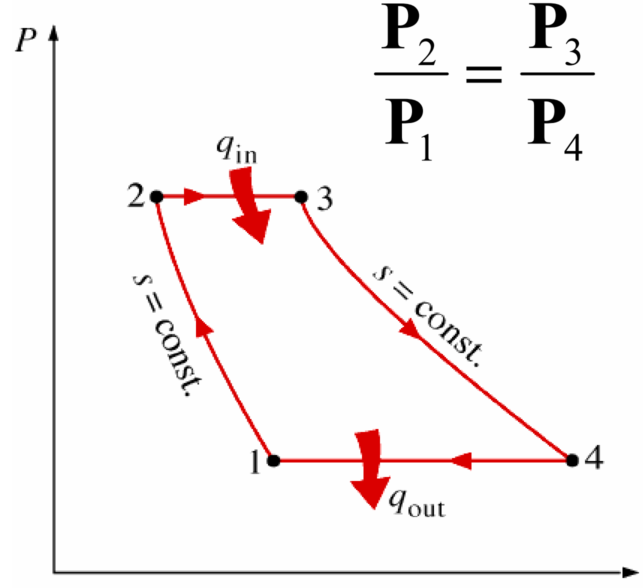
Brayton cycle analysis

Using the adiabatic relationships:

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

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\frac{P_2}{P_1} = \frac{P_3}{P_4}$$



(b) P- υdiagram

Pressure and temperature ratios

since $\left(\frac{P_3}{P_4}\right) = \left(\frac{P_2}{P_1}\right) \rightarrow \frac{T_3}{T_4} = \frac{T_2}{T_1}$ **or** $\frac{T_3}{T_2} = \frac{T_4}{T_1}$

Brayton Cycle Analysis

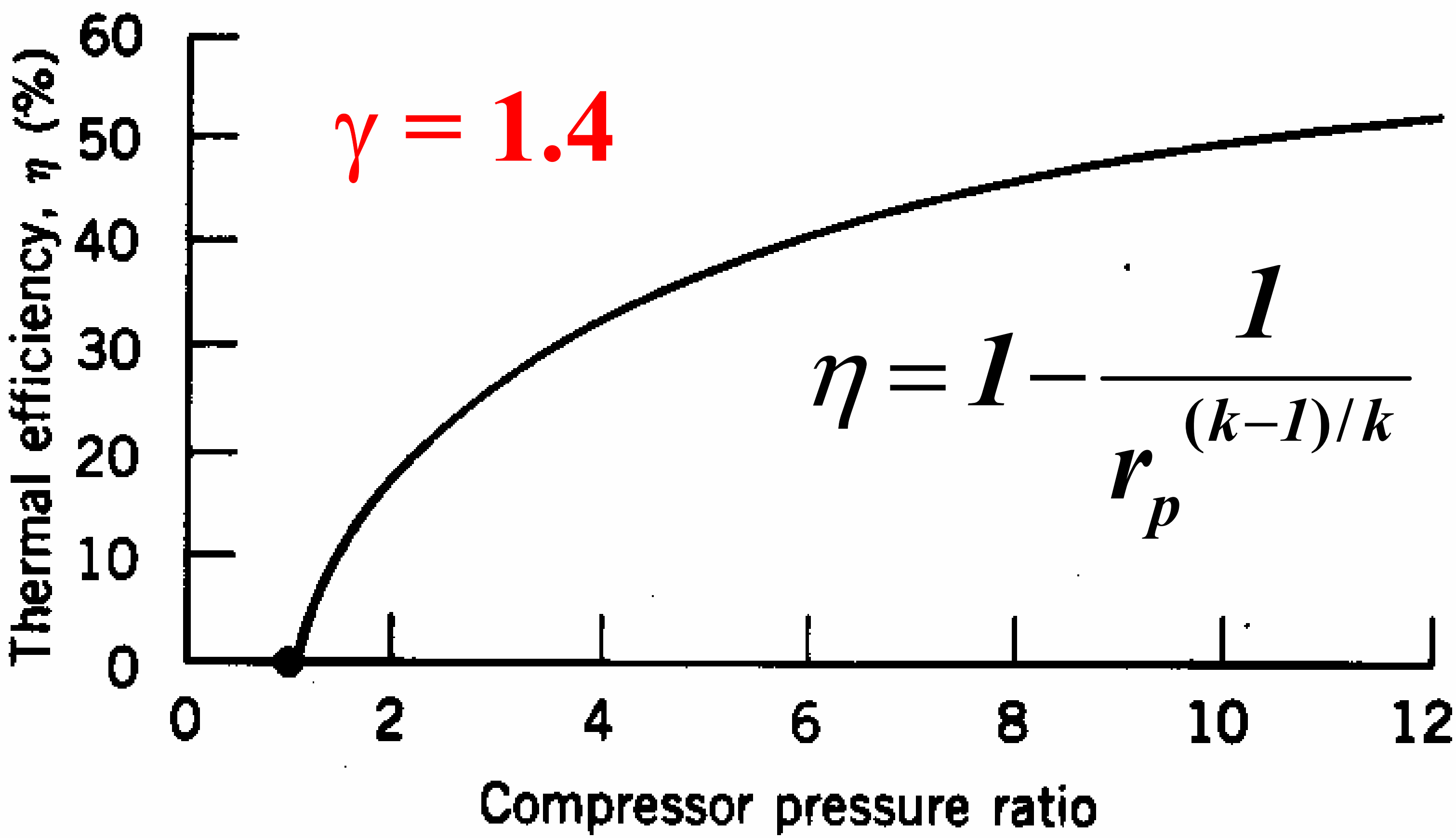
Then we can relate the temperature ratios to the pressure ratio:

$$\frac{T_2}{T_1} = r_p^{(\gamma-1)/\gamma} = \frac{T_3}{T_4}$$

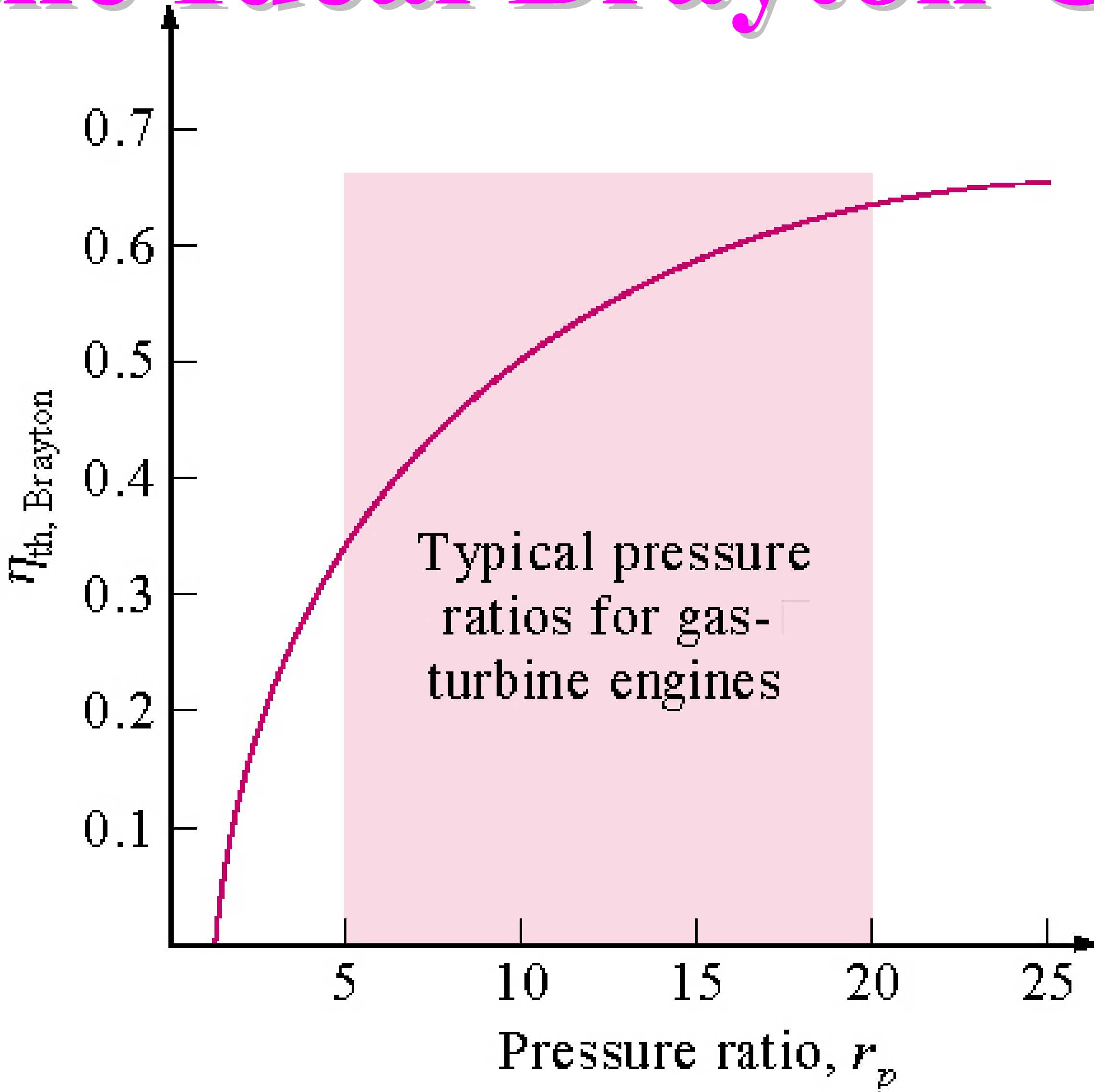
Plug back into the efficiency expression and simplify:

$$\eta_{th,Brayton} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}$$

Brayton Cycle



Thermal Efficiency of the Ideal Brayton Cycle



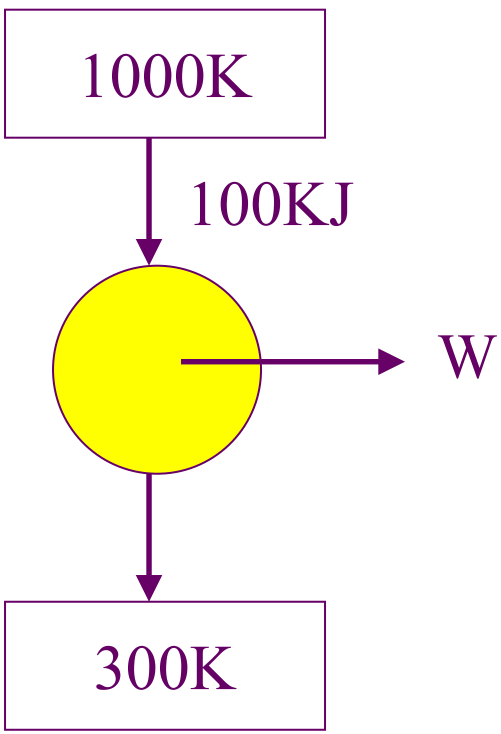
Solução de Exercícios
Cap 4

Ex4.13) **100 KJ de calor é adicionada a um ciclo de Carnot a 1000K. O ciclo rejeita calor a 300K. Quanto trabalho o ciclo produz e quanto calor ele rejeita?**

Ciclo de Carnot

$W=?$

$Q_c=?$



$$\eta_c = \frac{W}{Q_h} = 1 - \frac{T_c}{T_h} = 1 - \frac{3}{10}$$

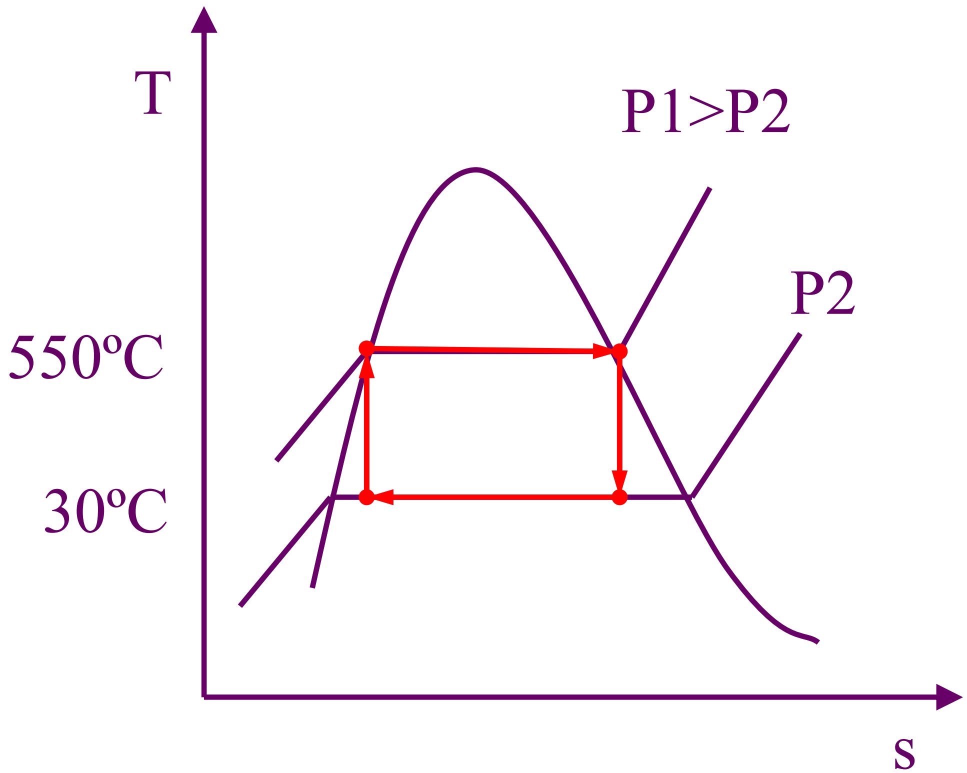
$$\eta_c = 0,7 \rightarrow W = 0,7 \times 100$$

$$W = 70KJ$$

$$\oint Q = \oint W \rightarrow (100 - Q_c) = 70$$

$$Q_c = 30KJ$$

Ex4.16)



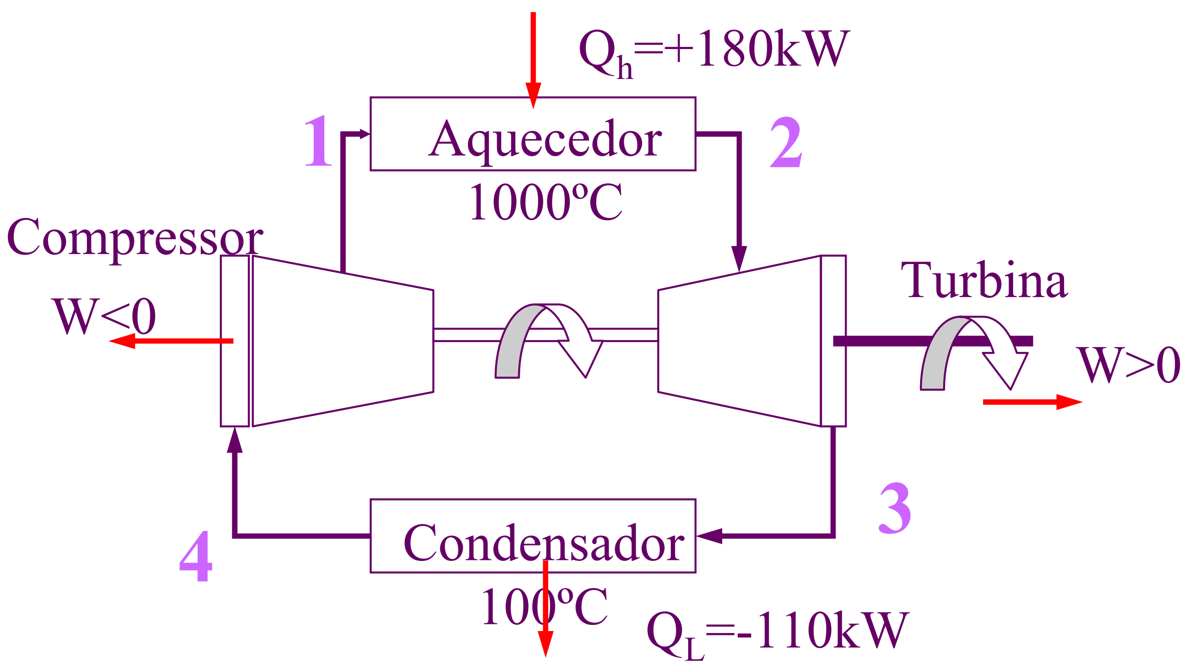
$$\eta_T = 1 - \frac{303}{823} = 0{,}63$$

Ex4.17) Uma central de potência com turbina a gás operando num ciclo fechado usa ar como fluido de trabalho, veja esquema da figura.

(a) Identifique as interações das transf. de calor e trabalho considerando o ar como sistema.

(b) (b) se 180KW são fornecidos ao aquecedor e 110KW são rejeitados no condensador, determine a potência líquida e a eficiência da central.

parte (a)



parte (b)

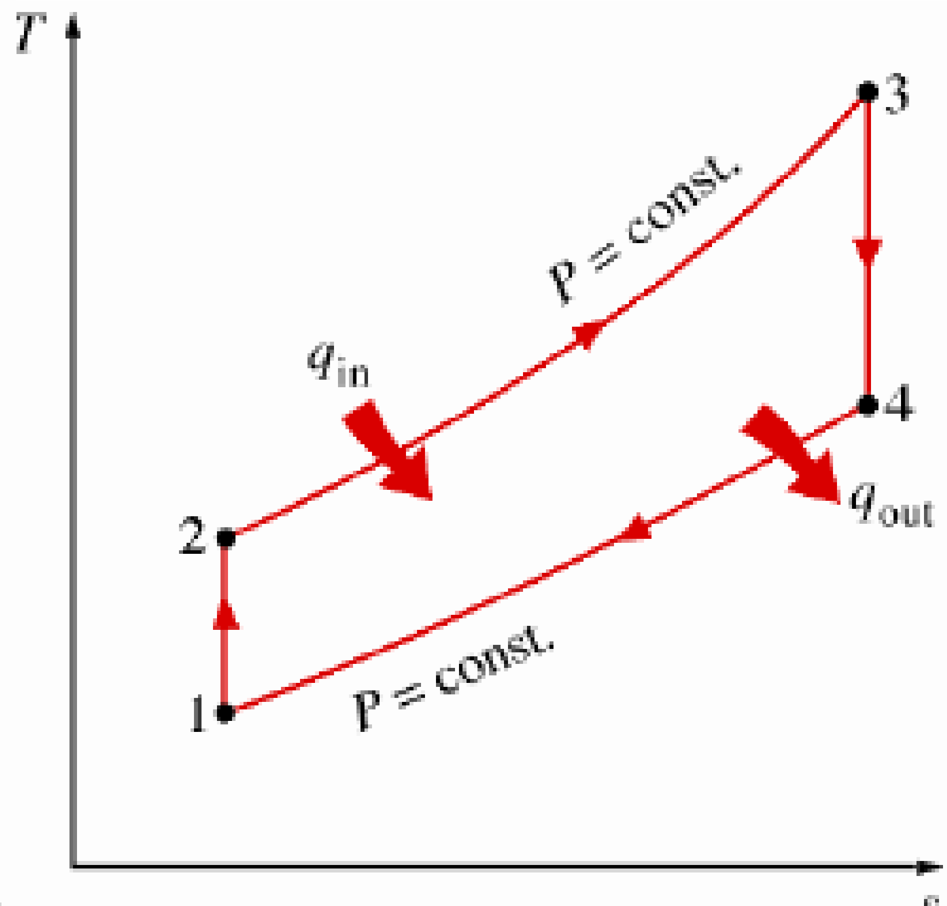
$$1^o \text{ Lei}: \oint Q = \oint W$$

$$W_{liq} = 180 - 110 = 70\text{kW}$$

$$\eta_T = \frac{W_{liq}}{Q_h} = \frac{70}{180} = 0{,}39\,\%$$

Rendimento Máximo -> Rendimento de Carnot

$$\eta_{máx} = \eta_{Carnot} = 1 - \frac{373}{1273} = 0{,}71$$



(a) T-s diagram

Ciclo Brayton

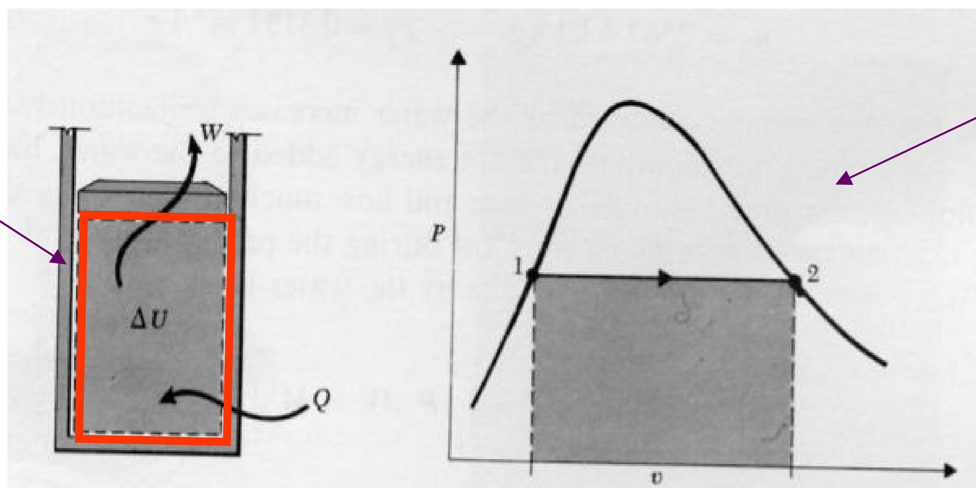
$$\eta = 1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

Conhecer Pressões

Evaporação a pressão constante

Um sistema pistão cilindro contêm, inicialmente, três kg de H_2O no estado de líquido saturado com 0.6 MPa.
Calor é adicionado, vagarosamente, a água fazendo com que o pistão se movimente de tal maneira que a pressão seja constante.
Quanto de trabalho é realizado pela água?
Quanta energia deve ser transferida para a água de tal maneira que ao final do processo ela esteja no estado de vapor saturado?

Fronteira do Sistema



Representação do processo

processo a pressão const.

Primeira Lei:

$_1Q_2 - {_1W_2} = U_2 - U_1$

mas o trabalho $_1W_2 = P_{atm}*(V_2-V_1)$,

Logo $_1Q_2 = (P_2V_2+U_2)-(P_1V_1+U_1) = H_2-H_1$

Onde h_2 é a entalpia do vapor saturado e h_1 é a entalpia do líquido. Na tabela 1-2 termodinâmico para 0.6MPa, tem-se que h_2 = 2756,8 KJ/kg e h_1 = 670,56 KJ/kg. Considerando 3kg de H_2O, então o calor transferido será de 3*(2756-670) = 6259 KJ.

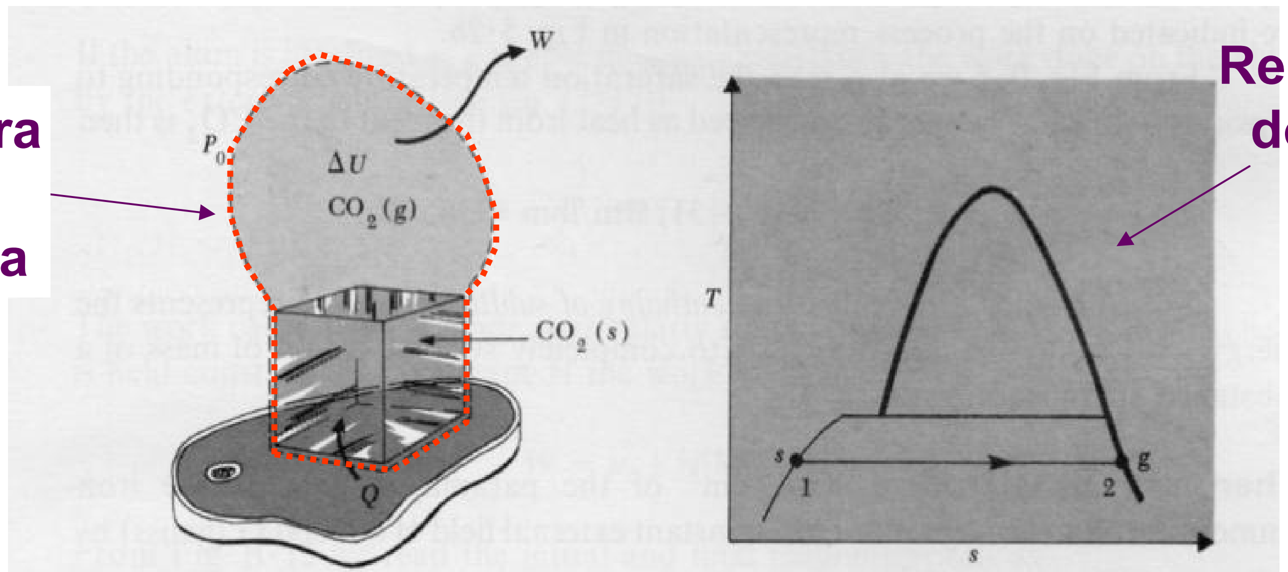
Resfriamento com Gelo Seco

0.5 kg de gelo seco (CO_2) a 1 atm é colocado em cima de uma fatia de picanha. O gelo seco sublima a pressão constante devido ao fluxo de calor transferido pela picanha. Ao final do processo todo CO2 está no estado de vapor (foi completamente sublimado).

Determine a temperatura do CO_2 e quanto de calor ele recebeu da picanha.

Fronteira do Sistema

Representação do processo



(a) *The control mass*   (b) *The process representation*

Figure 5·2.

Resfriamento com Gelo Seco – processo a pressão const.

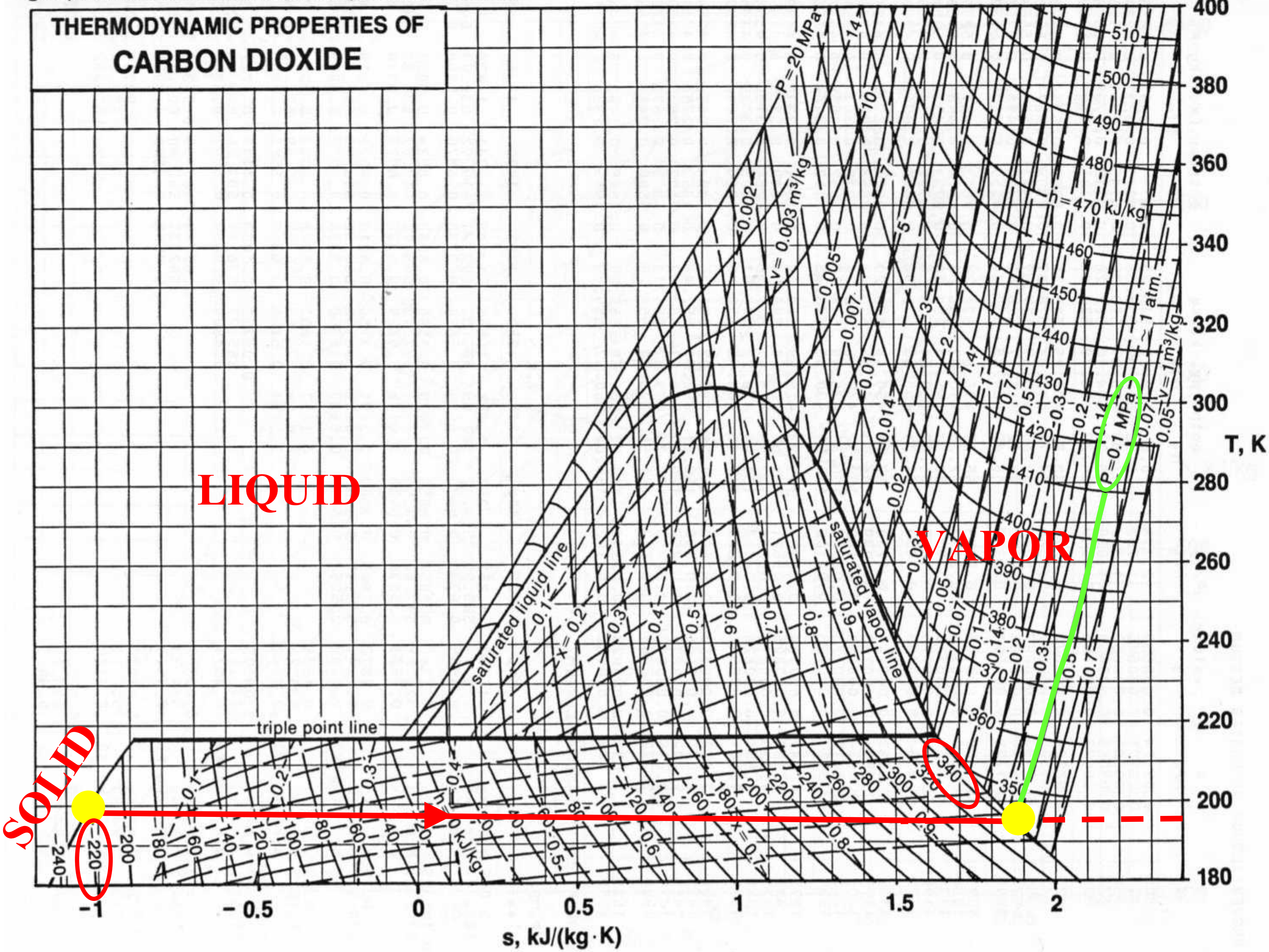
Primeira Lei:

$$ {}_1Q_2 - {}_1W_2 = U_2 - U_1 $$

mas o trabalho ${}_1W_2 = P_{atm}*(V_2-V_1)$,

Logo ${}_1Q_2 = (P_2V_2+U_2)-(P_1V_1+U_1) = H_2-H_1$

Onde h_2 é a entalpia do vapor saturado e h_1 é a entalpia do sólido. No diagrama termodinâmico para P_{atm}, tem-se que h_2 = 340 KJ/kg e h_1 = -220 KJ/kg. Considerando 0.5kg de CO_2, então o calor transferido será de 280 KJ. A temperatura de saturação do CO_2 será de 175K (-98 °C)


THERMODYNAMIC PROPERTIES OF
CARBON DIOXIDE
LIQUID
VAPOR
SOLID
triple point line
saturated liquid line
saturated vapor line
P=20 MPa
P=0.1 MPa
1 atm.
v = 0.003 m³/kg
v = 1 m³/kg
h = 470 kJ/kg
h = 0 kJ/kg
x = 0.2
x = 0.7
T, K
s, kJ/(kg·K)