Operational Reactor Safety

22.091/22.903

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Professor of the Practice

Lecture 8
Power Cycles for Nuclear Plants
Rankine and Brayton

Topics to be Covered

- Review of Rankine Cycle
  - Basic
  - Superheat
  - Multi-fluid cycles
- Brayton cycle
    - Pressure Ratios

Important Terms and Concepts

- Enthaply - h = Btu/lbm (heat content)
- Entropy - Btu/^{0}R
- Specific Heat - C_p Btu/lbm ^{0}R at constant pressure
- Mass Flow Rate = $\dot{m}$ - lbm/hr
- Pressure Ratio - P_2/P_1 (For gas systems)
- Power – Watts - Btu/hr
- Work - Btu
- Efficiency - $(W_t - W_p) / Q_{in}$ (Heat Added)

Governing Equations

- Heat Transfer
  - Mass flow, specific heat, temperature
  - Mass flow, specific enthalpy
  - Efficiency factors – heat loss
- Use of Steam Tables
- Quality

Rankine Cycle

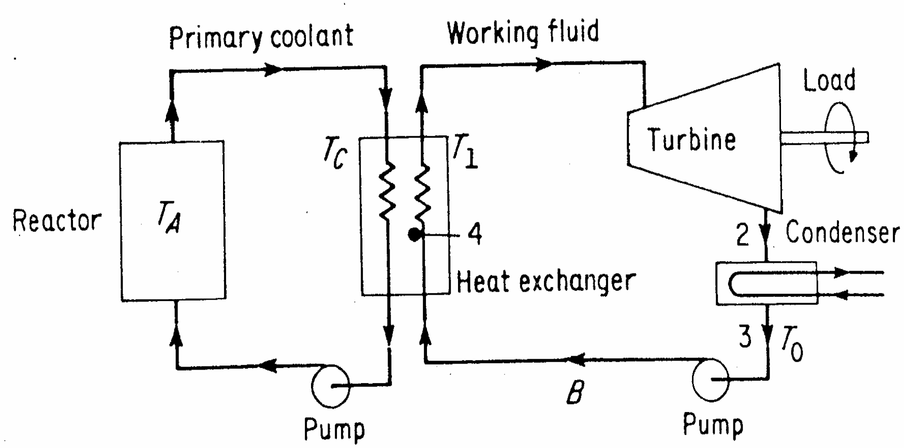


FIG. 2-5. Schematic of two-loop nuclear power plant.

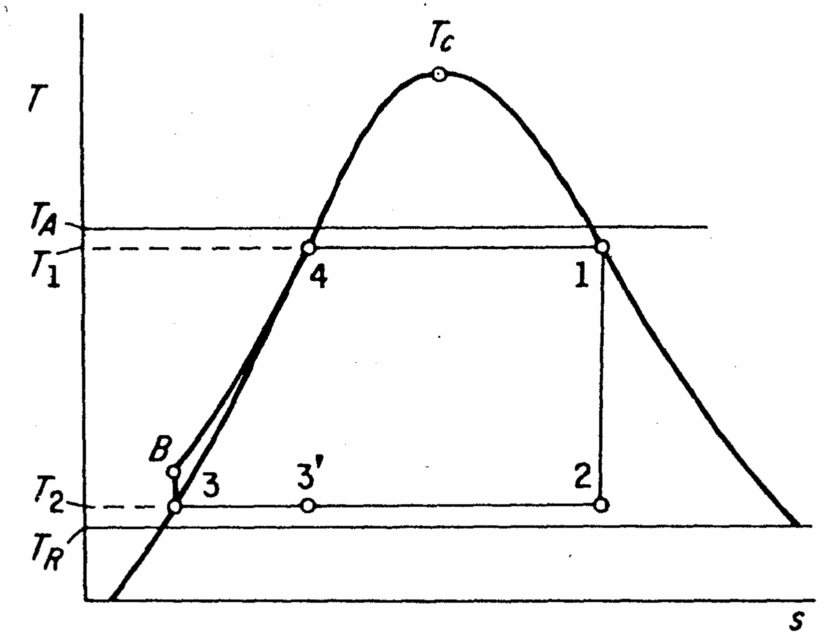


FIG. 2-4. Internally reversible Rankine cycle with saturated vapor.

$$\text{Thermal Efficiency} = \frac{\text{Heat Added - Heat Rejected}}{\text{Heat Added}}$$

Important Equations

$$Q_{in} = \dot{m}\,(h_1 - h_B)$$

$$W_t = \dot{m}\,(h_1 - h_2)$$

$$W_p = \dot{m}\,(h_B - h_3)$$

$$Q_{in} = C_p\,\dot{m}\,(T_{in} - T_{ou})$$

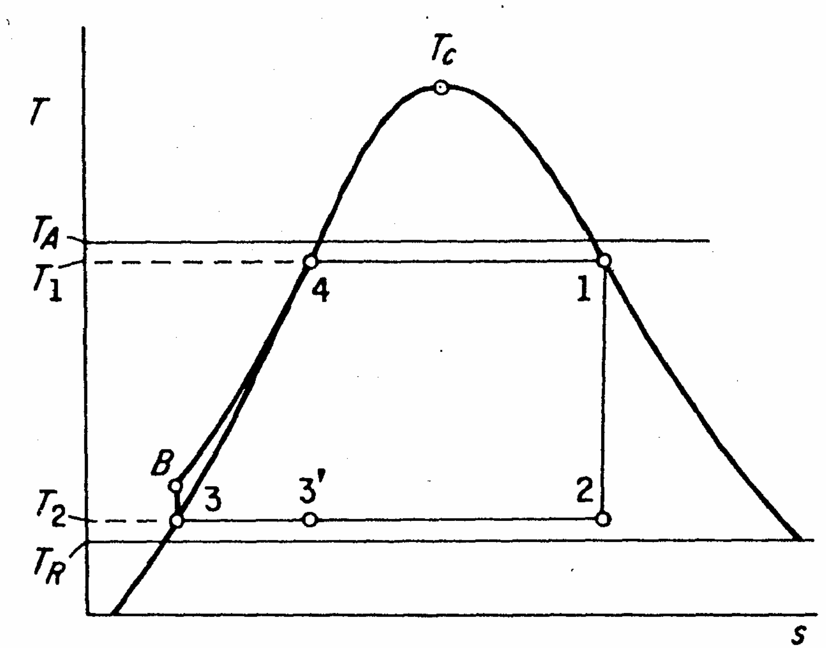


FIG. 2-4. Internally reversible Rankine cycle with saturated vapor.

Rankine Cycle with Feedwater Heaters

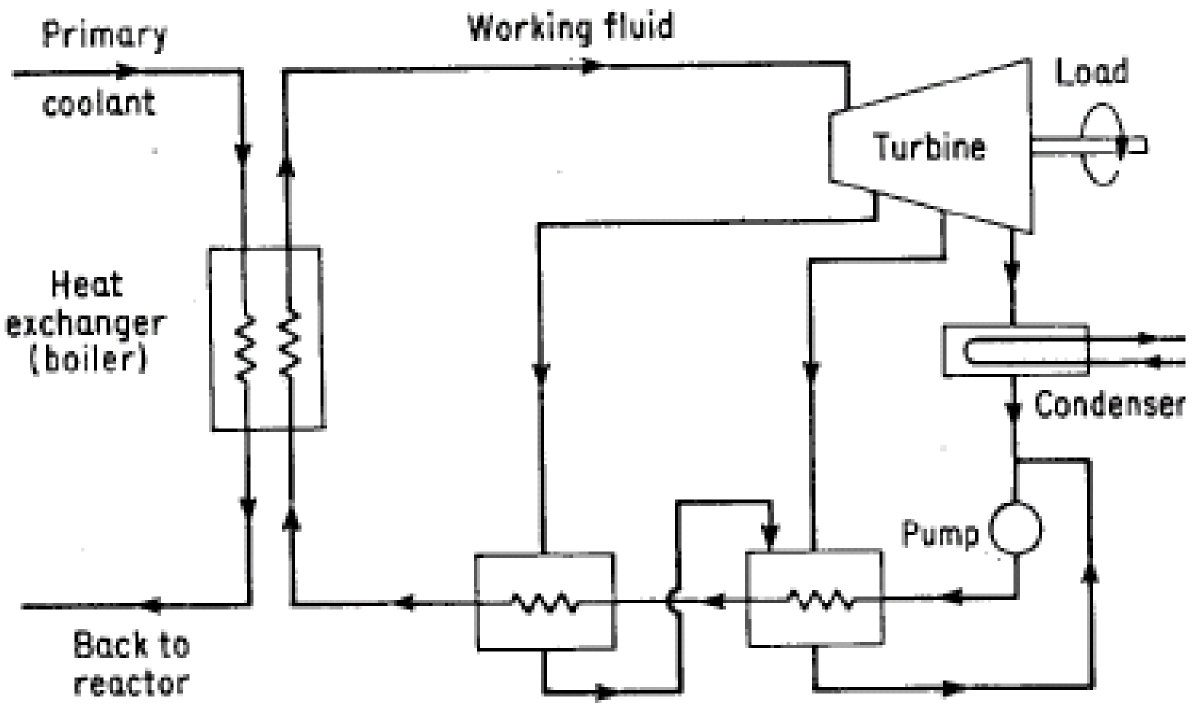
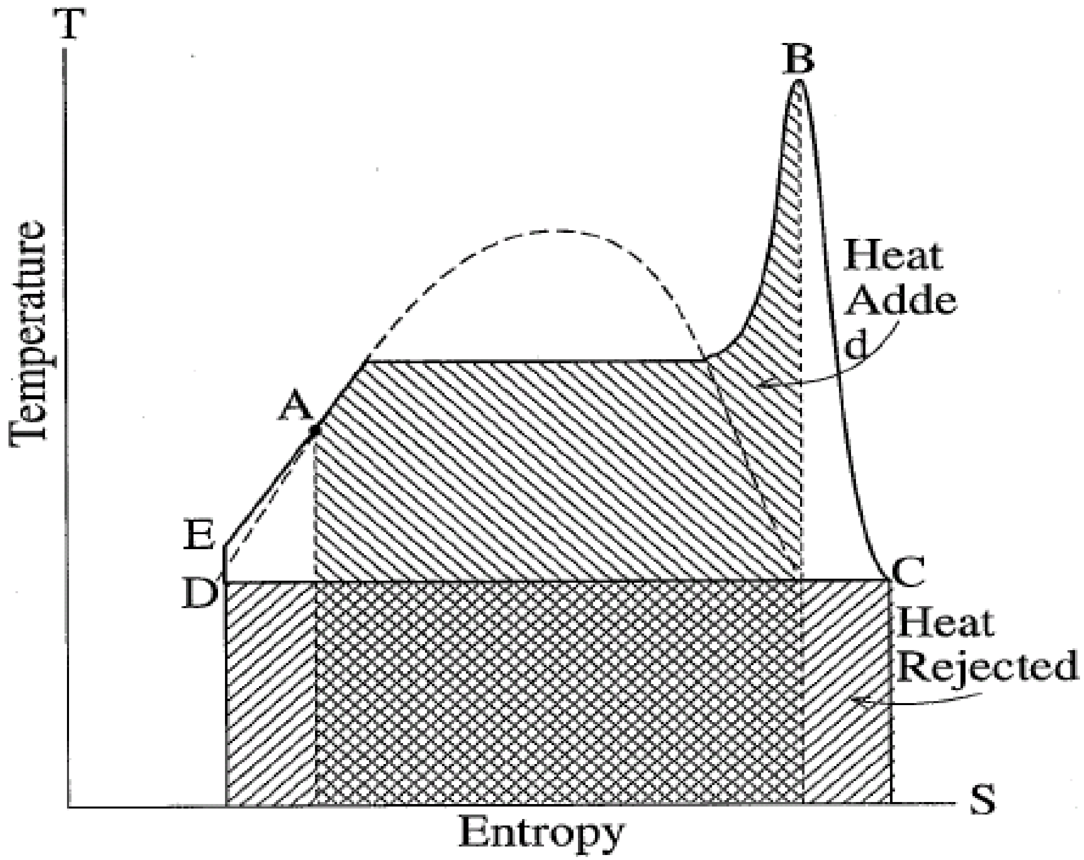


FIG. 2-9. Schematic of Rankine cycle with two closed-type feedwater heaters.

REFINED RANKINE CYCLE USING SUPERHEATING AND REGENERATIVE HEATING



Thermal Efficiency $= \frac{\text{(Heat Added - Heat Rejected)}}{\text{Heat Added}} \cong 0.42_{\text{ma}}$

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Power Cycles

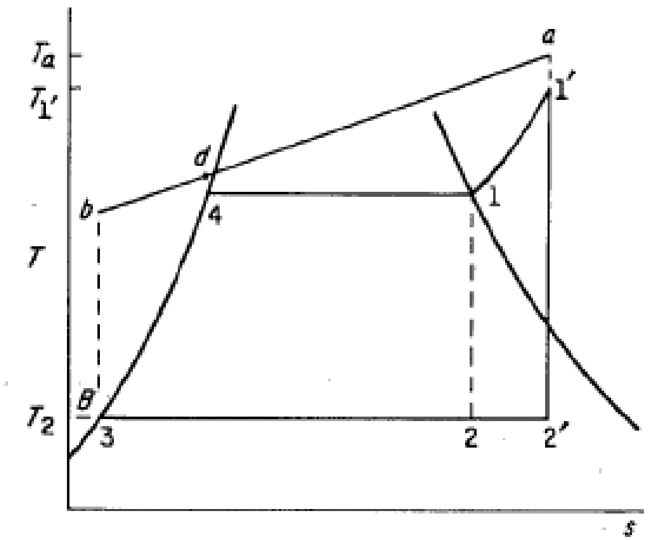

FIG. 2-12. Internally reversible Rankine cycle with superheat and a variable-temperature heat source.

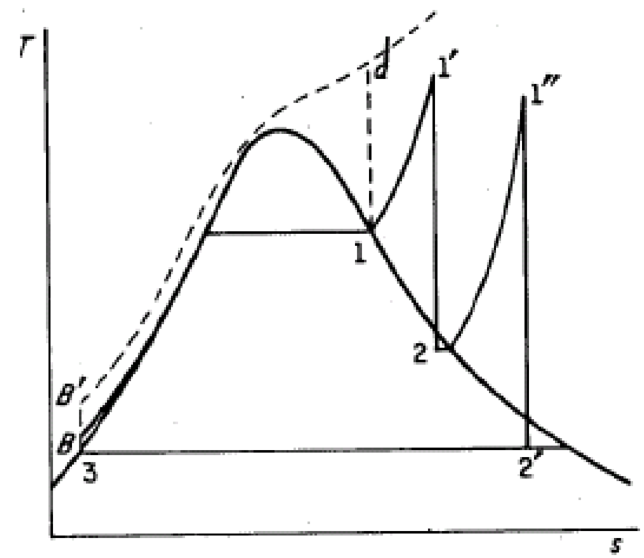

FIG. 2-13. *Ts* diagram of internally reversible supercritical and reheat cycles.

Binary Cycle Plants

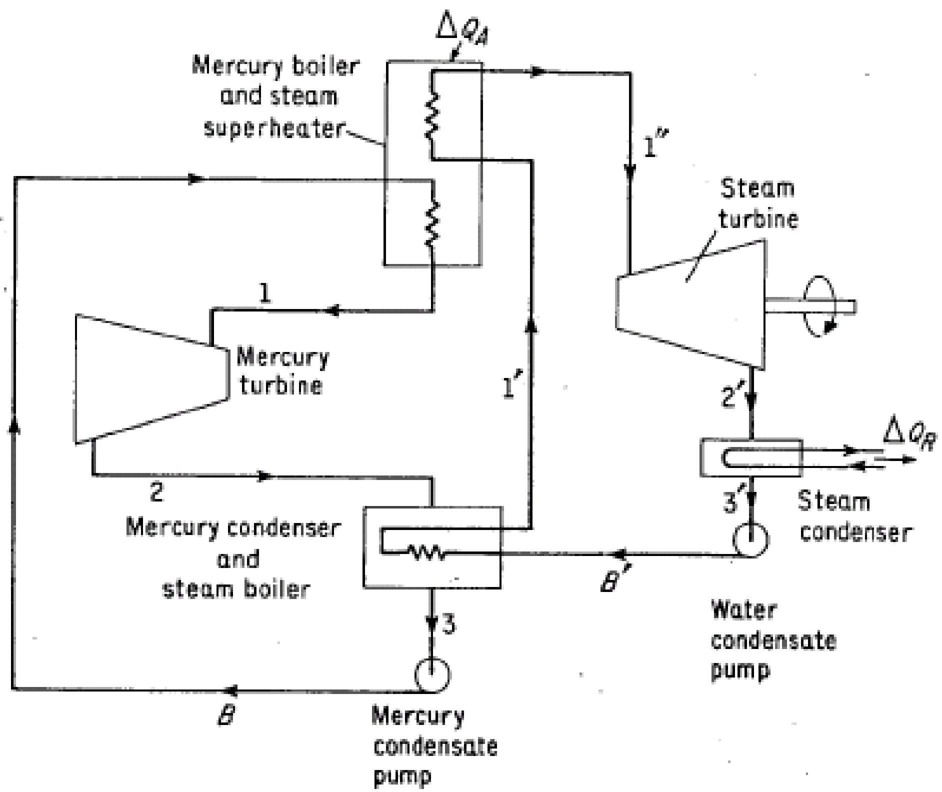

FIG. 2-16. Schematic of a mercury-steam binary-vapor power plant.

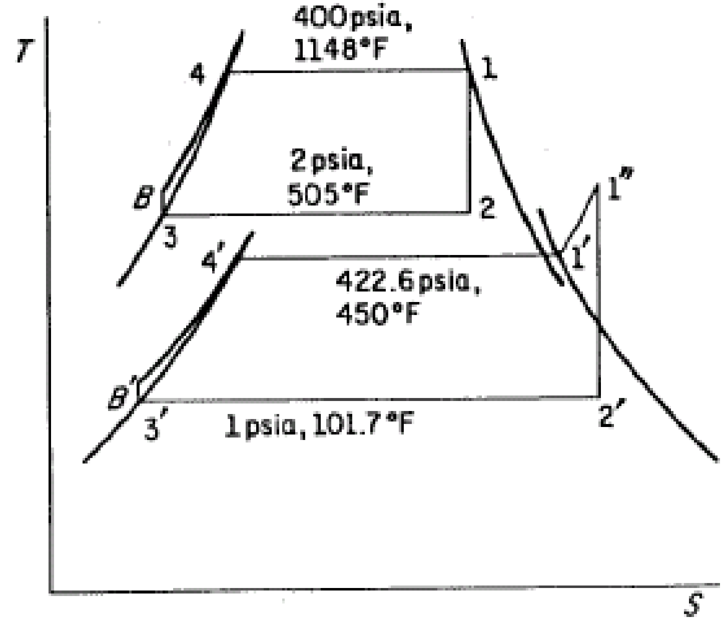

FIG. 2-17. *TS* diagram of internally reversible mercury-steam cycle.

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Gas Reactor Cycles

- Brayton Cycle
- Brayton-Rankine Dual Cycle
- Real Example – Pebble Bed
- Choices for Efficiency and Cost
  - *Materials*
  - *Costs*
  - *Efficiency Trade-offs*

Brayton Gas Cycle - Open

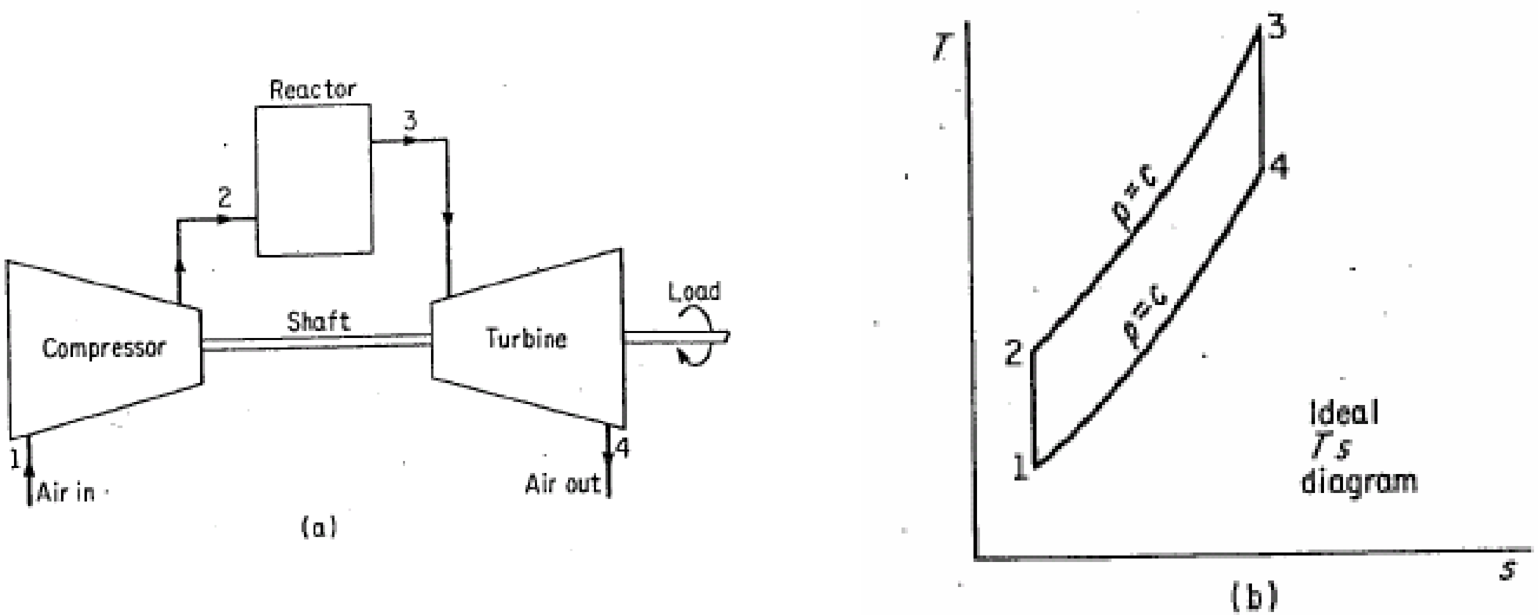

FIG. 7-1. The direct open cycle. (a) Cycle diagram; (b) *Ts* diagram.

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Perfect Gas Relationships

TABLE 2-1
Perfect-gas Relationships

Process	p, v, T relationships	$u_2 - u_1$	$h_2 - h_1$	$s_2 - s_1$	W (nonflow)	Q
Isothermal	$T =$ const $p_1/p_2 = v_2/v_1$	0	0	$(R/J) \ln (v_2/v_1)$	$(p_1 v_1/J) \ln (v_2/v_1)$	$(p_1 v_1/J) \ln (v_2/v_1)$
Constant pressure	$p =$ const $T_2/T_1 = v_2/v_1$	$c_v(T_2 - T_1)$	$c_p(T_2 - T_1)$	$c_p \ln (T_2/T_1)$	$p(v_2 - v_1)/J$	$c_p(T_2 - T_1)$
Constant volume	$v =$ const $T_2/T_1 = p_2/p_1$	$c_v(T_2 - T_1)$	$c_p(T_2 - T_1)$	$c_v \ln (T_2/T_1)$	0	$c_v(T_2 - T_1)$
Isentropic .... (adiabatic reversible)	$s =$ const $p_1 v_1^{\gamma} = p_2 v_2^{\gamma}$ $T_2/T_1 = (v_1/v_2)^{\gamma - 1}$ $T_2/T_1 = (p_2/p_1)^{\gamma - 1/\gamma}$	$c_v(T_2 - T_1)$	$c_p(T_2 - T_1)$	0	$\dfrac{p_2 v_2 - p_1 v_1}{J(1 - \gamma)}$	0
Throttling	$h =$ const $T =$ const $p_1/p_2 = v_2/v_1$	0	0	$(R/J) \ln (v_2/v_1)$	0	0
Polytropic	$p_1 v_1^n = p_2 v_2^n$ $T_2/T_1 = (v_1/v_2)^{n-1}$ $T_2/T_1 = (p_2/p_1)^{(n-1)/n}$	$c_v(T_2 - T_1)$	$c_p(T_2 - T_1)$	$c_v \ln (p_2/p_1)$ $+ c_p \ln (v_2/v_1)$	$\dfrac{p_2 v_2 - p_1 v_1}{J(1 - n)}$	$c_v \left(\dfrac{\gamma - n}{1 - n}\right) (T_2 - T_1)$

Indirect Brayton Open Cycle

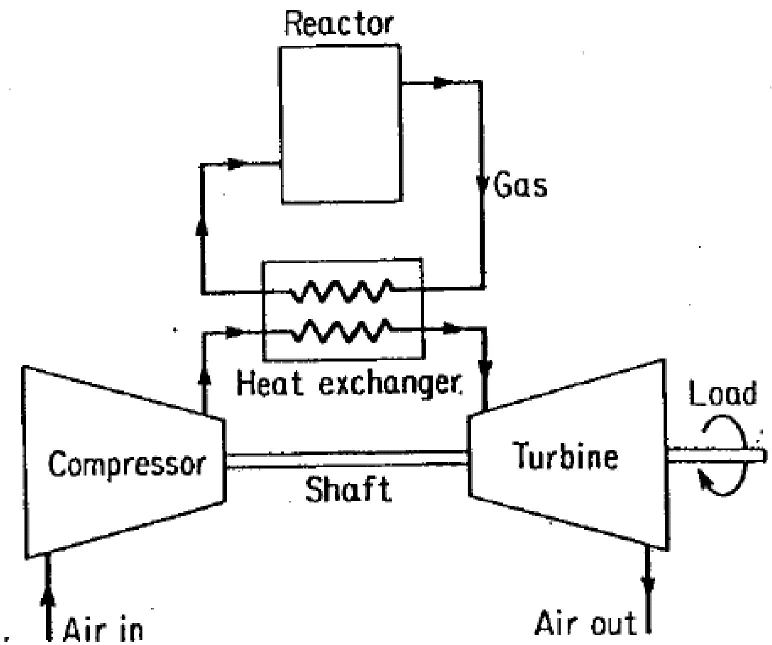


FIG. 7-2. The indirect open cycle.

Brayton Cycle – Direct Closed

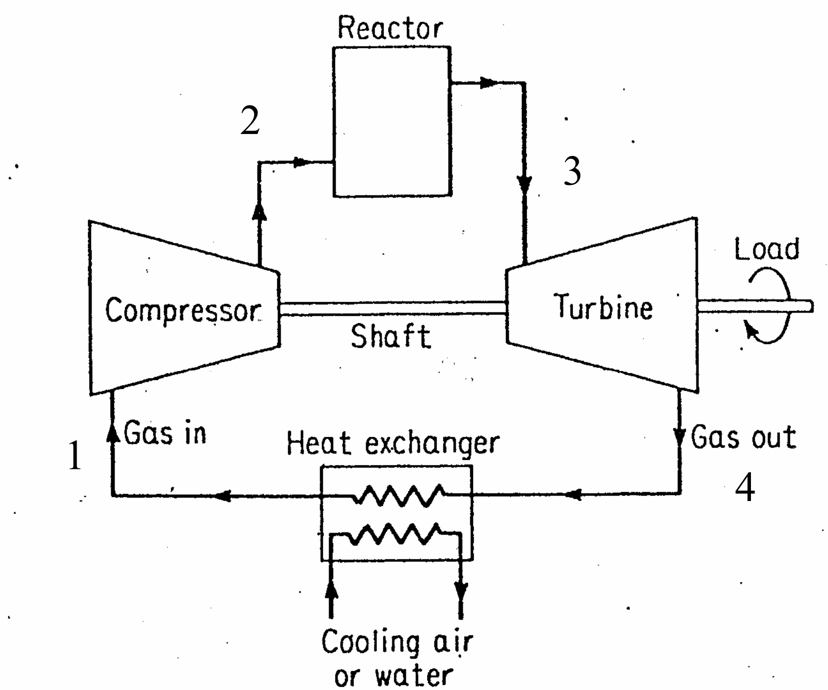
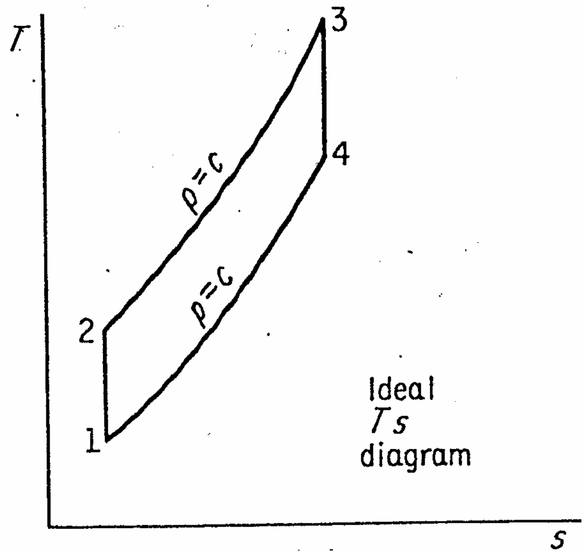


FIG. 7-3. The direct closed cycle.



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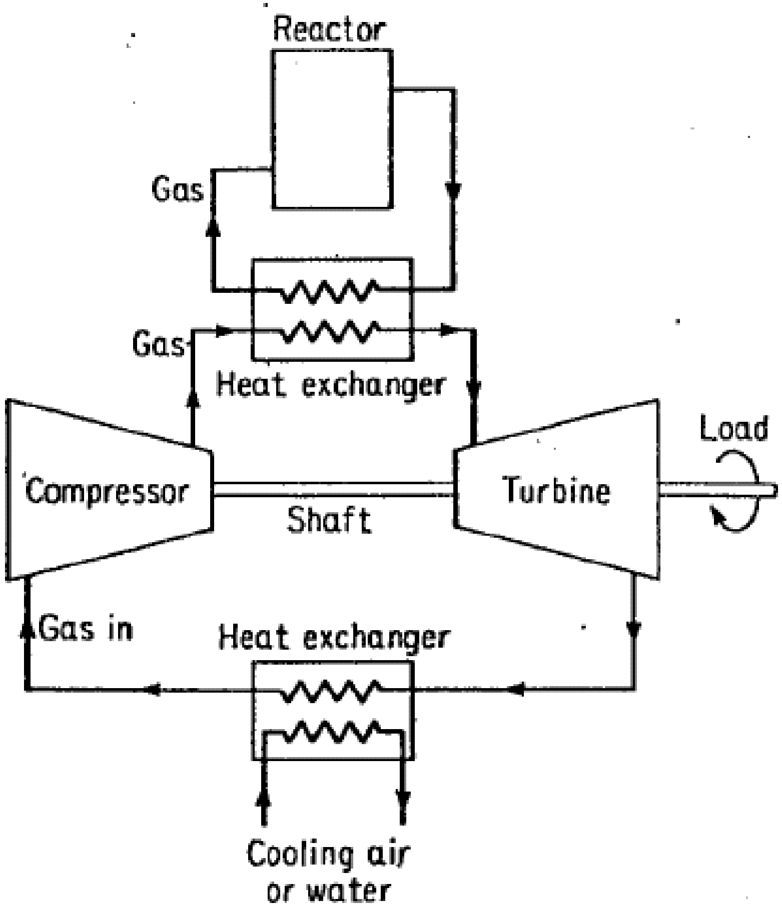
Indirect Closed Cycle – Gas to Gas



Indirect Gas to Steam Generator

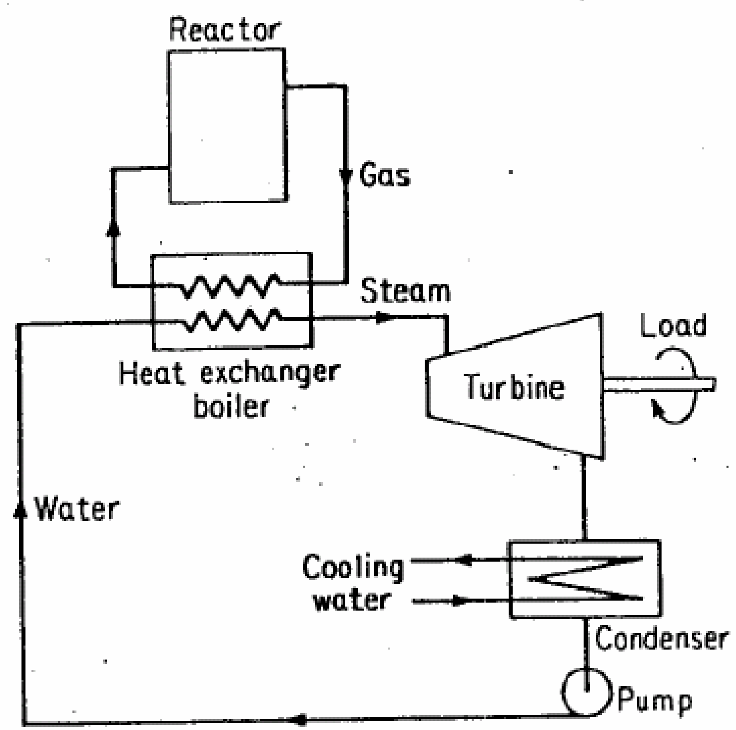


FIG. 7-5. The indirect closed cycle, gas to water.

Specific Heats of Gases

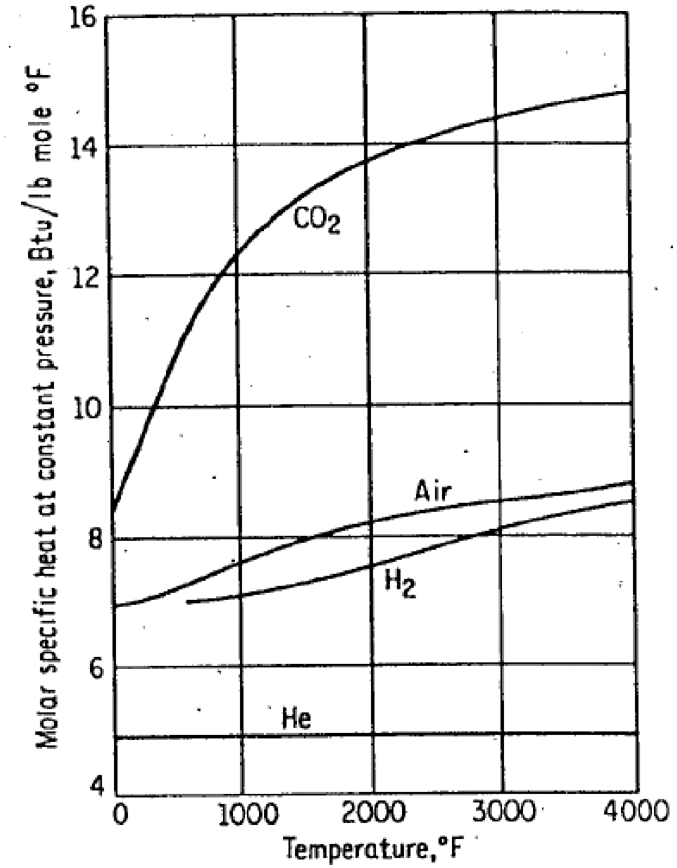


FIG. 7-6. Variation of molar c_p with temperature for various gases.

Ideal Brayton Cycle

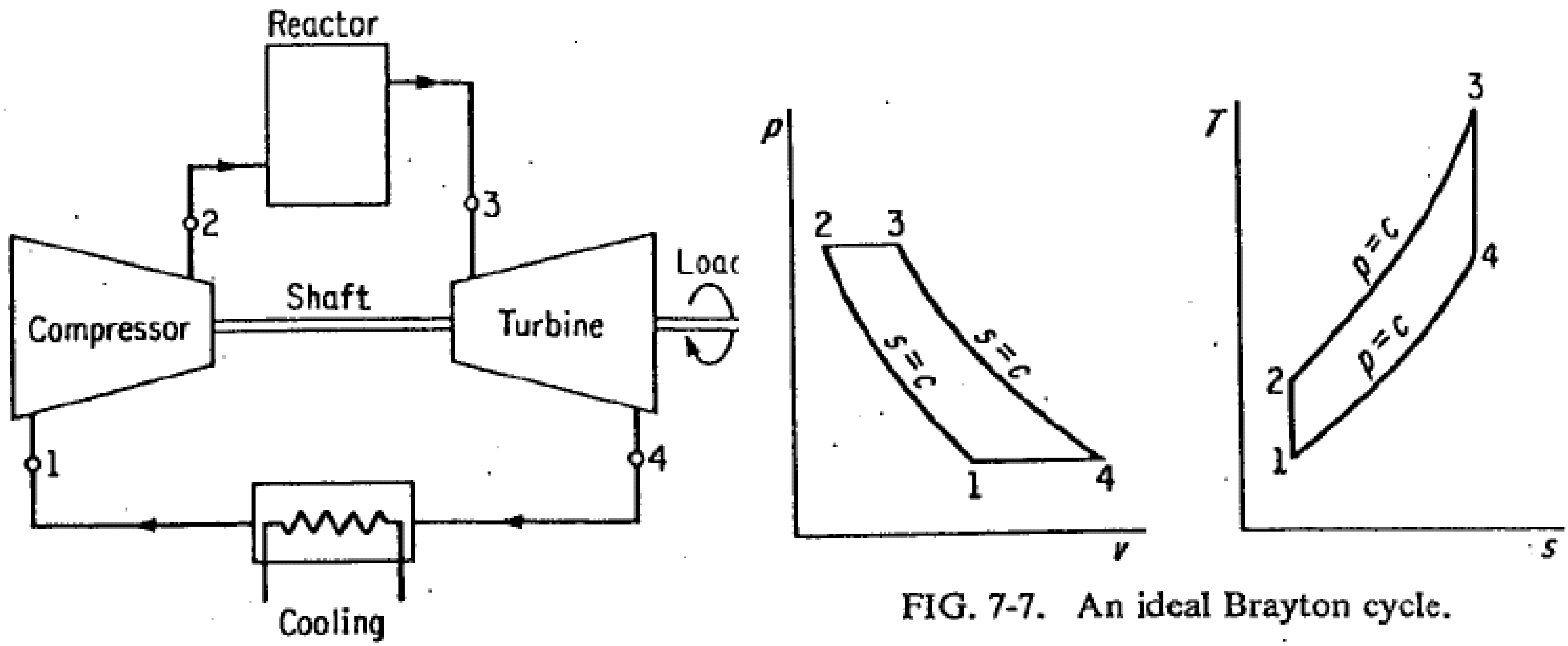
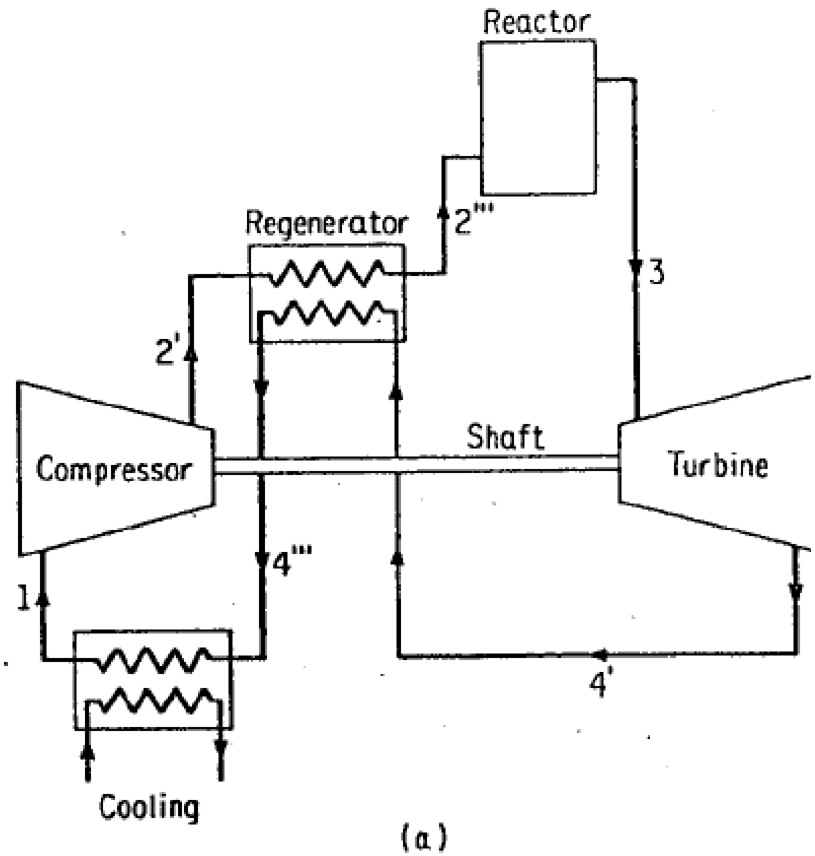


FIG. 7-7. An ideal Brayton cycle.

Non-Ideal Brayton Cycle



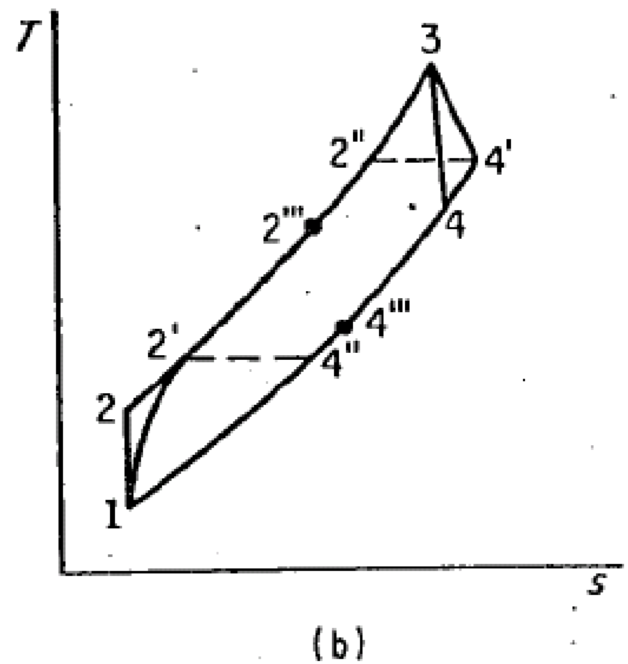
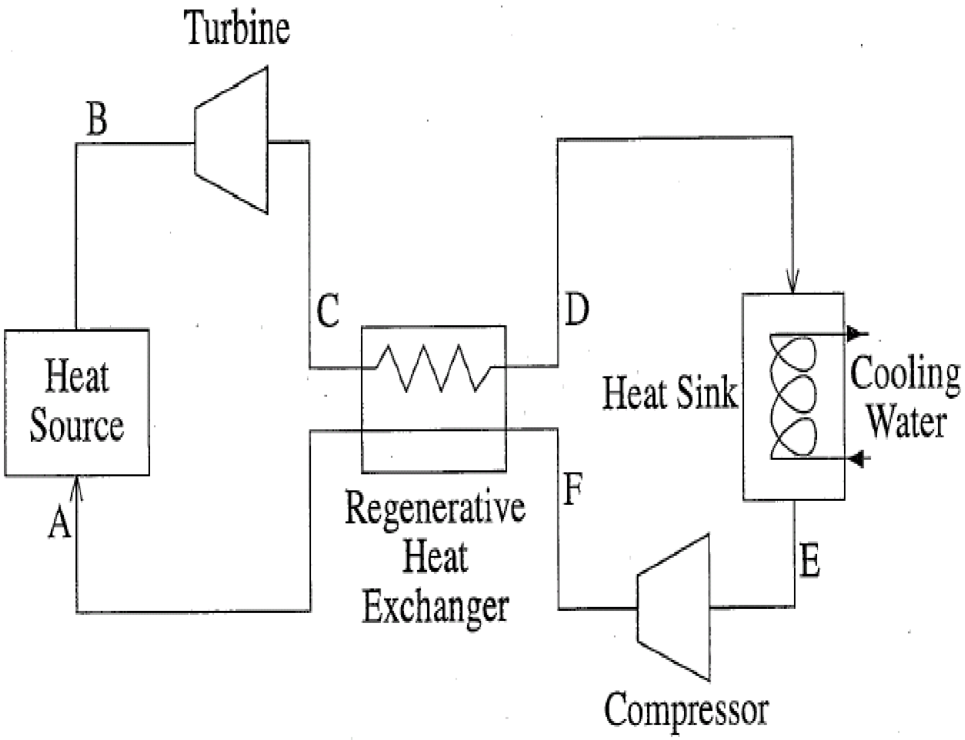
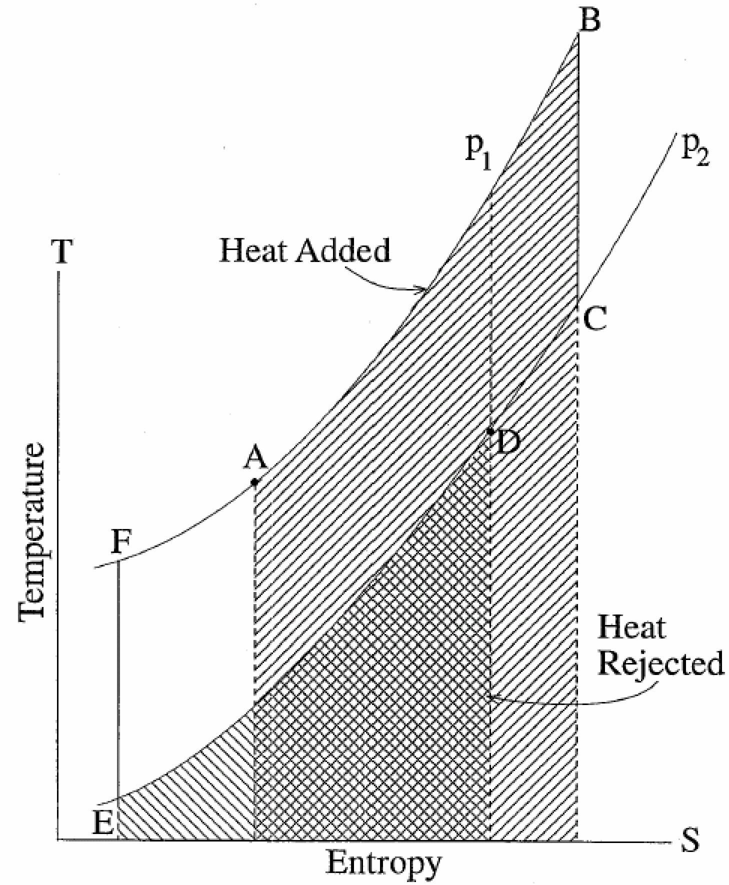


FIG. 7-12. Closed nonideal Brayton cycle with re-generation.



BRAYTON CYCLE WITH REGENERATIVE HEATING

BRAYTON CYCLE WITH REGENERATIVE HEATING



Gas-Steam Reactor Power Plant

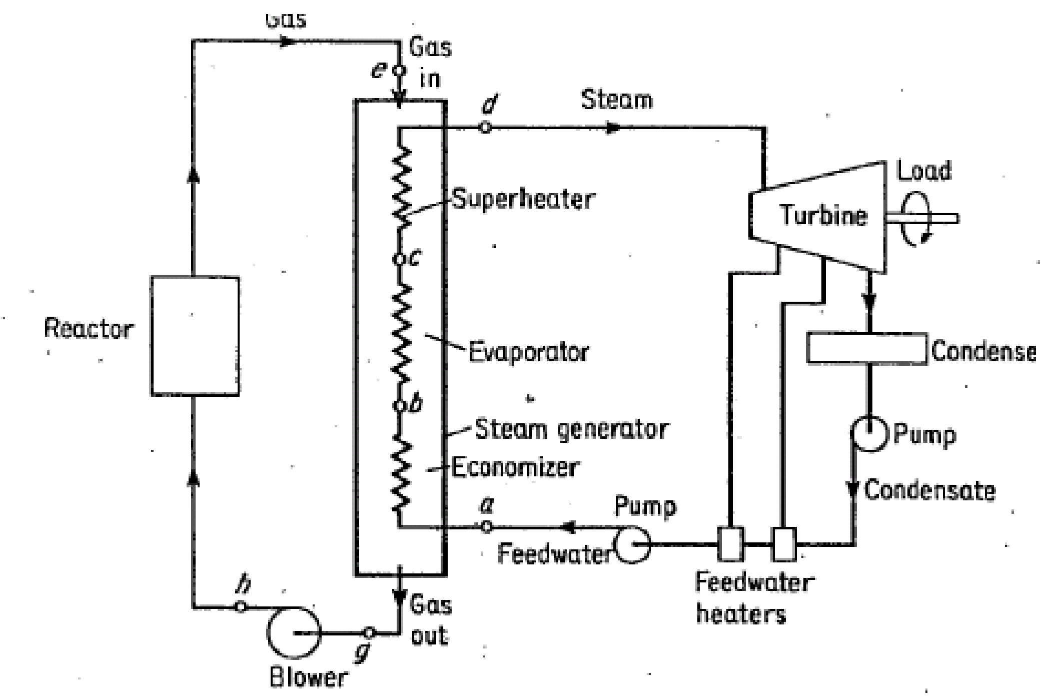


FIG. 8-1. Schematic of a simple-cycle gas-steam-reactor power plant.

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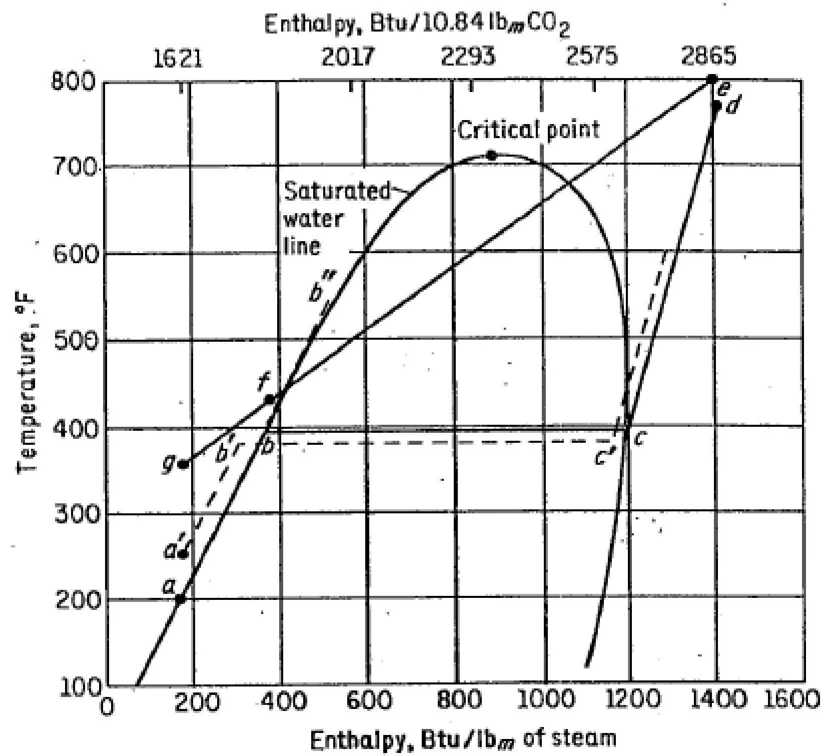
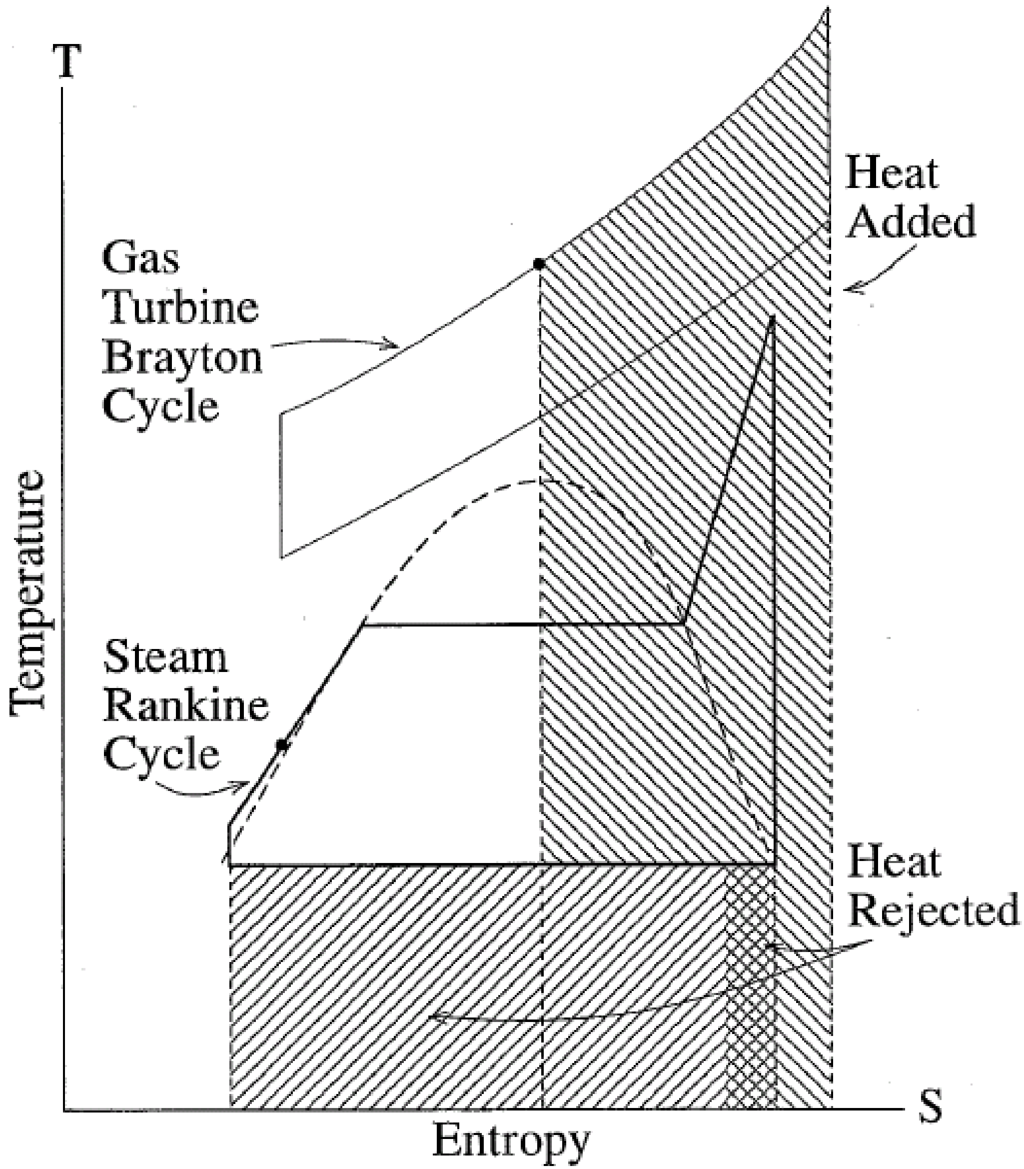
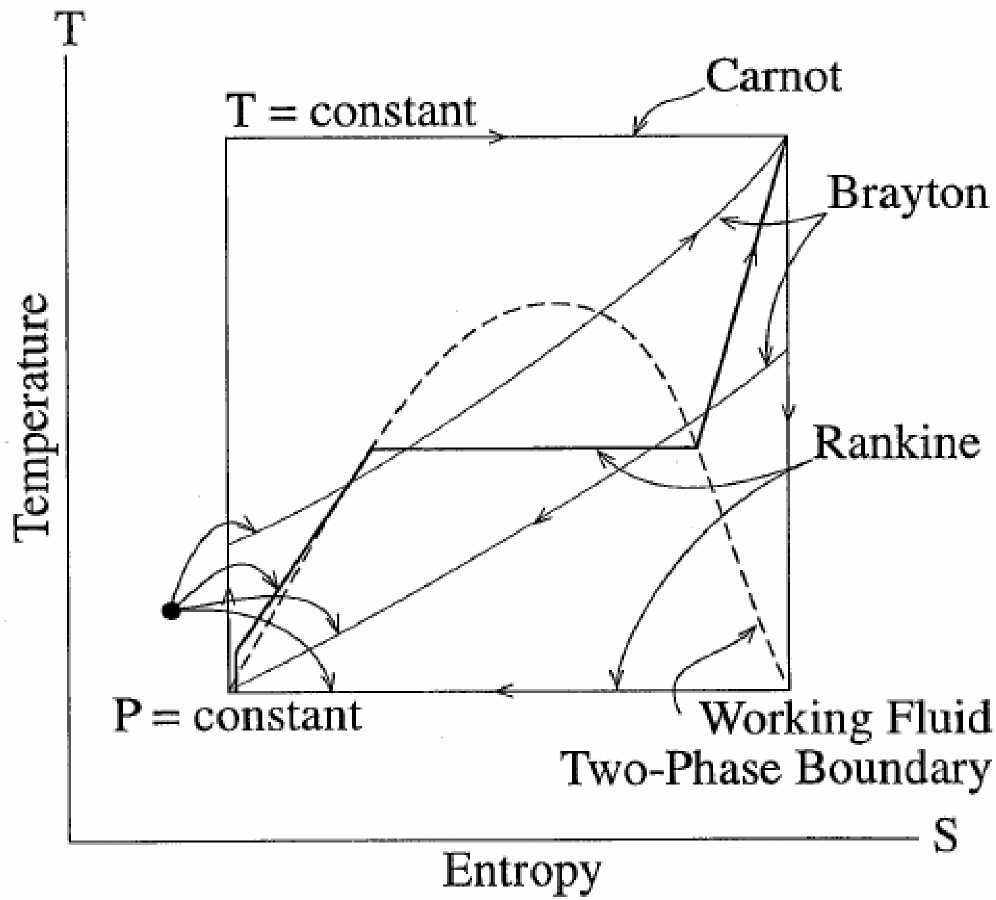


FIG. 8-2. Temperature-enthalpy diagram of a gas-steam heat exchanger in simple cycle.

COMBINED CYCLE BRAYTON (Topping), RANKINE (Bottoming)



VARIOUS VAPOR POWER CYCLES OPERATING BETWEEN THE SAME TEMPERATURE LIMITS



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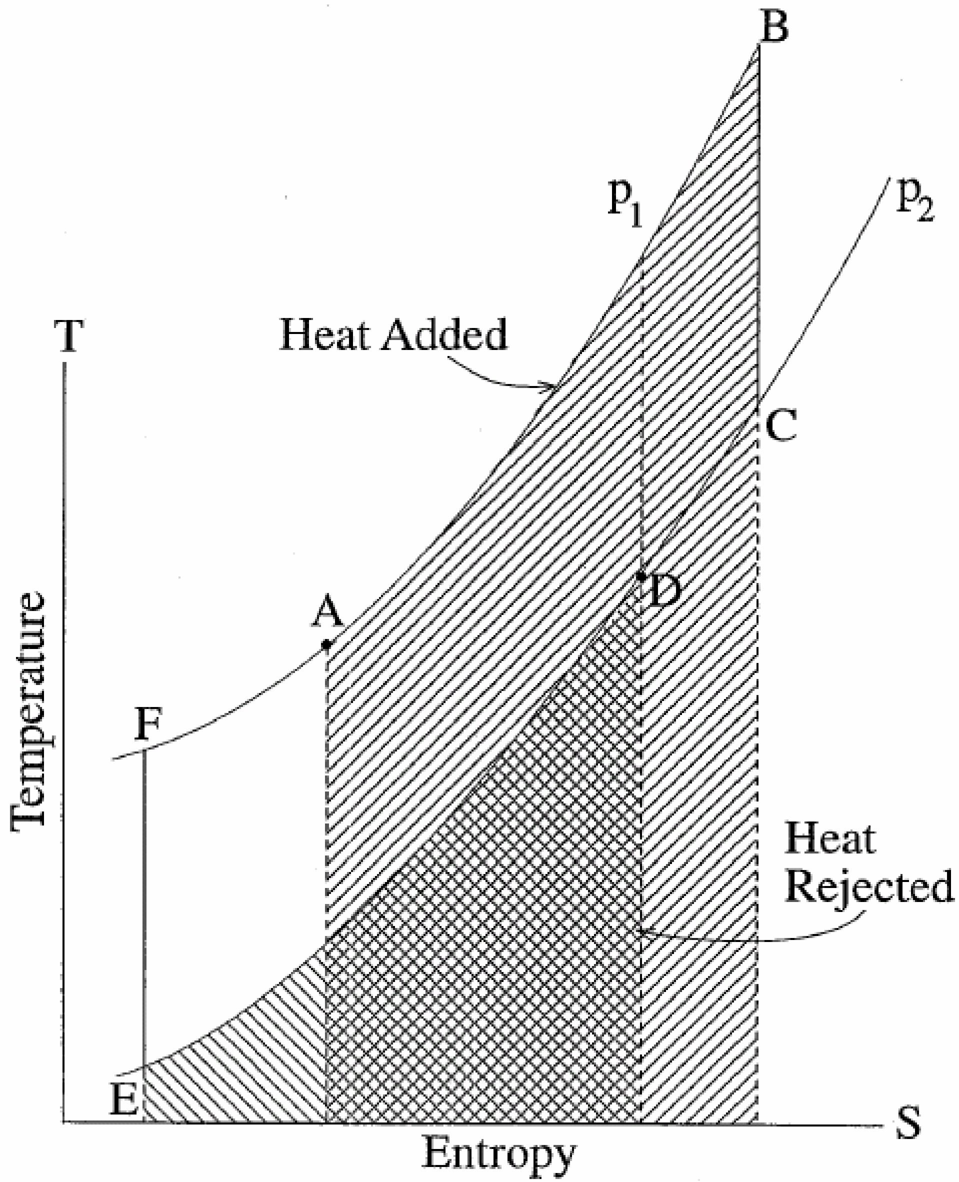
BRAYTON CYCLE WITH REGENERATIVE HEATING



Reading and Homework Assignment

1. Outside Reading El Wakil Chapters 7, 8
    1. Handout Problem

Handout Problem

Power Cycles and Heat Removal

1. An indirect closed cycle, gas to water reactor power plant generates 2×10^{-6} lbm/hr of steam at 1,000 psia and 800 F from feedwater at 200 F. Helium coolant at 200 psia leaves the reactor at 840 F and the boiler ate 540 F, is pumped with a polytropic exponent n=1.50, and undergoes a 60 psi pressure drop throughout the primary loop. (assume that 2/3 of the pressure drop occurs in the reactor vessel). Assuming no heat losses:

   a. Draw the T-S diagram for this cycle including the helium loop.
   b. Calculate the mass flow rate of the helium coolant
   c. Calculate the reactor power output in Mw thermal
   d. Calculate the thermal efficiency of the cycle

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