Operational Reactor Safety

22.091/22.903

Professor Andrew C. Kadak
Professor of the Practice

Lecture 7

Design Issues

Power Cycles for Nuclear Plants

Topics to be Covered

- Design Issues for nuclear plants Kneif (8,9 10)
- Rankine Cycle
  - Basic
  - Superheat
  - Multi-fluid cycles
  - Brayton cycle
    - Pressure Ratios

Reactor Design Interactions

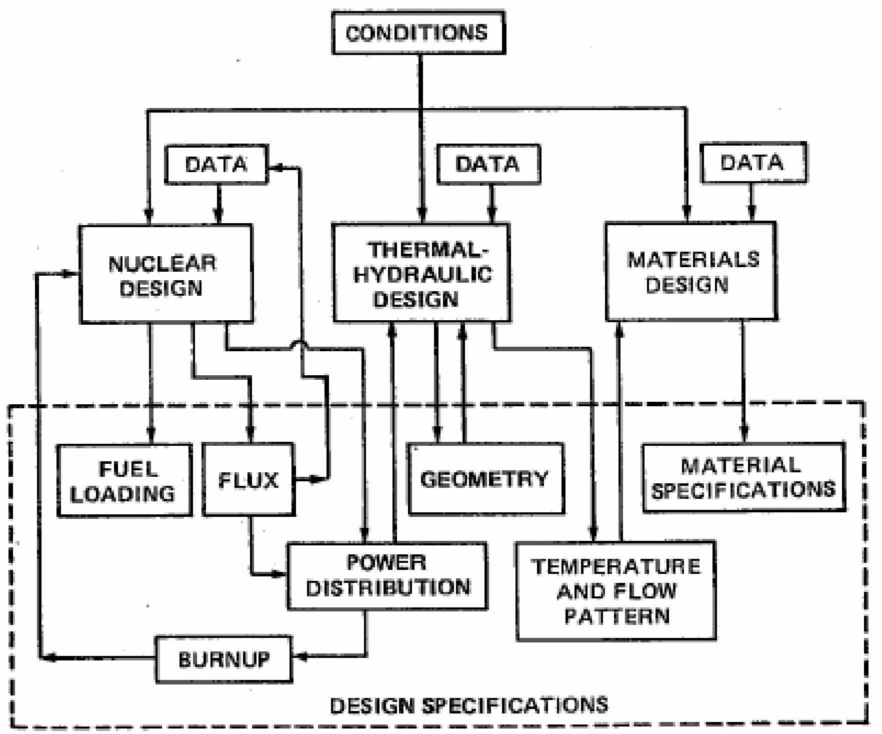


FIGURE 8-3
Reactor design interactions. (From A. Sesonske, *Nuclear Power Plant Design Analysis*, TID-26241, 1973.)

Reactor Core Design

- Thermal Analysis
  - Set inlet and outlet temperature
  - Assume radial peaking factor to calculate hot channel coolant temperature
  - Assume axial flux profile and engineering factors to calculate hot channel coolant temperature
  - Calculate clad surface temperature profile for hot channel assuming a clad surface heat flux and empirical heat transfer coefficient

Design Process (2)

  - Set clad and gap conductance materials and dimensions
  - Calculate fuel surface temperature profile
- Fuel Pin Composition and diameter selection
  - For a given fuel material use thermal conductivity and peak temperature to determine limiting heat rate for hot channel
  - Set pellet diameter based on fuel fabrication cost
  - Recalculate heat fuel and temperature

Reactor Design (3)

- Core sizing
  - Calculate number of fuel pins from core power and length
  - Chose geometry and spacing
  - Calculate physics parameters – axial and radial power profiles
  - Assess safety (reactivity coefficients) and power conversion factor (core lifetime)
  - Calculate required coolant velocity

Reactor Design (4)

- Fuel Cycle Economic Analysis
- Fuel Pin Structural Analysis
- Hydraulic Analysis
  - Pressure drops, flow distributions
  - Pumping power requirements
- Safety Analysis
  - Reactivity coefficients for accident analysis
- Fuel element reliability analysis – fuel stress etc.
- Post Irradiation handling considerations – cooling needs

Fuel Performance

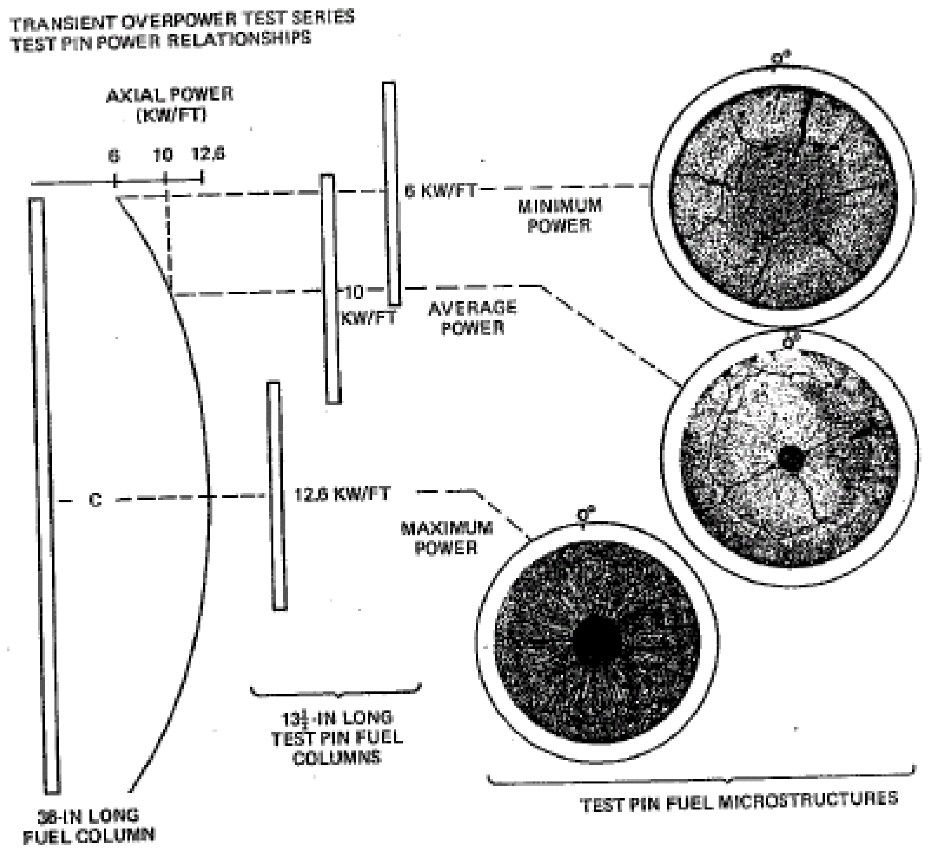


FIGURE 9-4
Mixed-oxide fuel restructuring versus linear heat rate. (Photograph courtesy of the Hanford Engineering Development Laboratory, operated by Westinghouse Hanford Company for the U.S. Department of Energy.)

Fuel Designs for LWRs

TABLE 9-1
Representative Fuel Design Parameters for Water-Cooled Reactor Systems

	PWR		BWR		CANDU		RBMK
Design parameter	15 × 15	17 × 17	7 × 7	8 × 8	28-pin	37-pin	18-pin
Rod diameter (mm)	10.7	9.50	14.3	12.5	15.2	13.1	13.6
Active fuel height (m)	3.66	3.66	3.66	3.66	0.495	0.495	3.43
Clad thickness (mm)	0.61	0.58	0.81	0.86	0.38	0.38	0.9
Pellet-clad diametrical gap (mm)	0.19	0.17	0.28	0.23	0.089	0.089	0.18–0.38
Average linear heat rate (kW/m)†	23.1	17.8	23.3	19.8	26.5	25.7	15.2
Average power density (kW/l)‡	106	105	51	56	85.2	109	54

†Calculated from core thermal power and total length of fuel.
‡Calculated from core thermal power and active core volume (for CANDU and RBMK, volume is that for pressure tubes only).

BWR Fuel Assembly

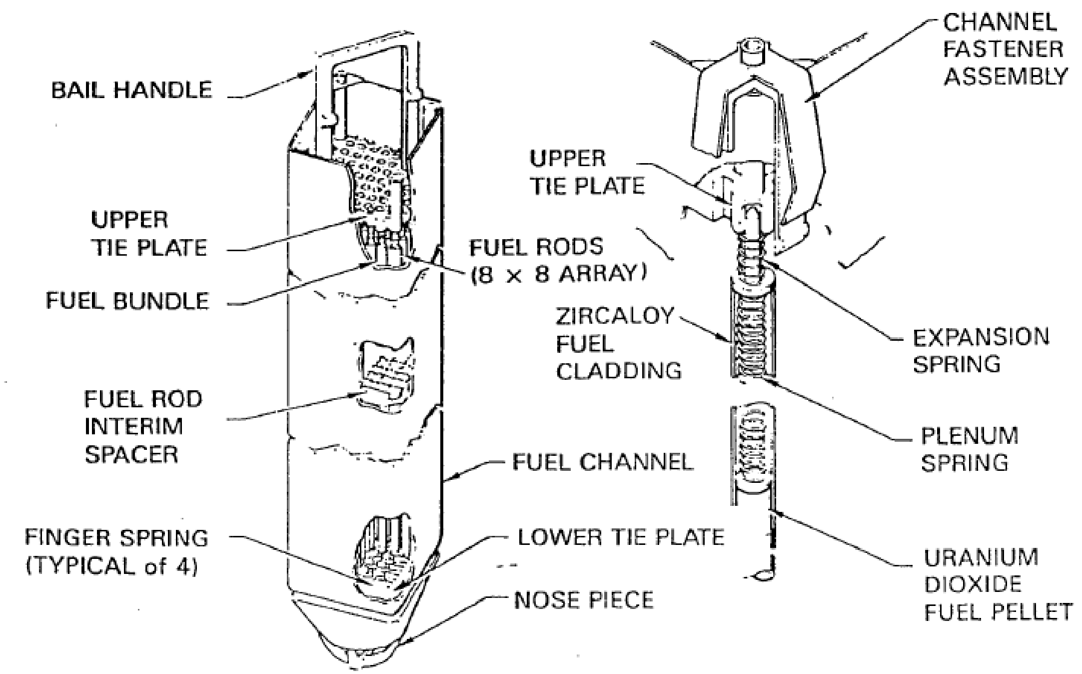
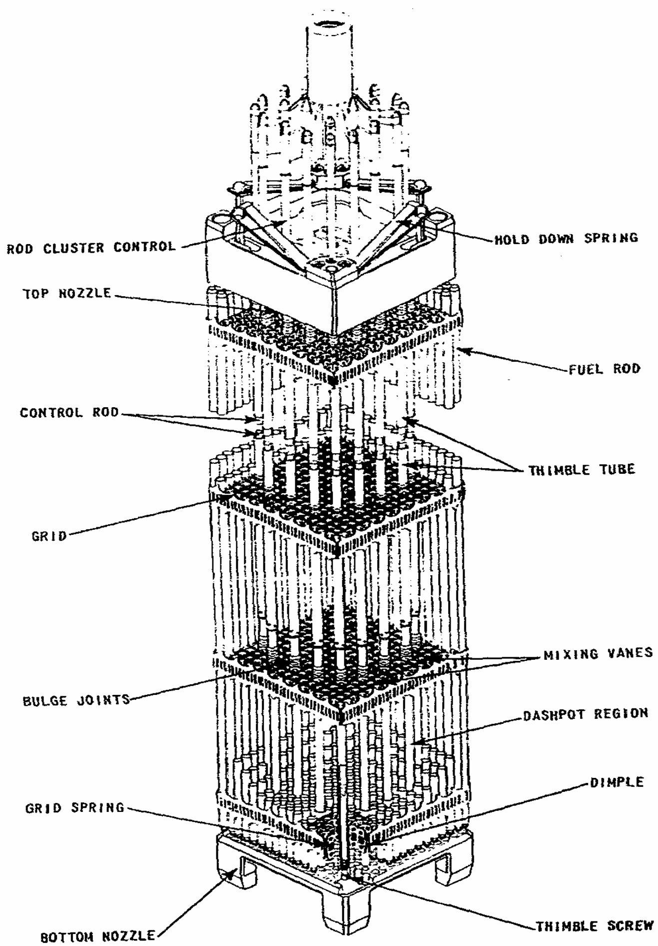
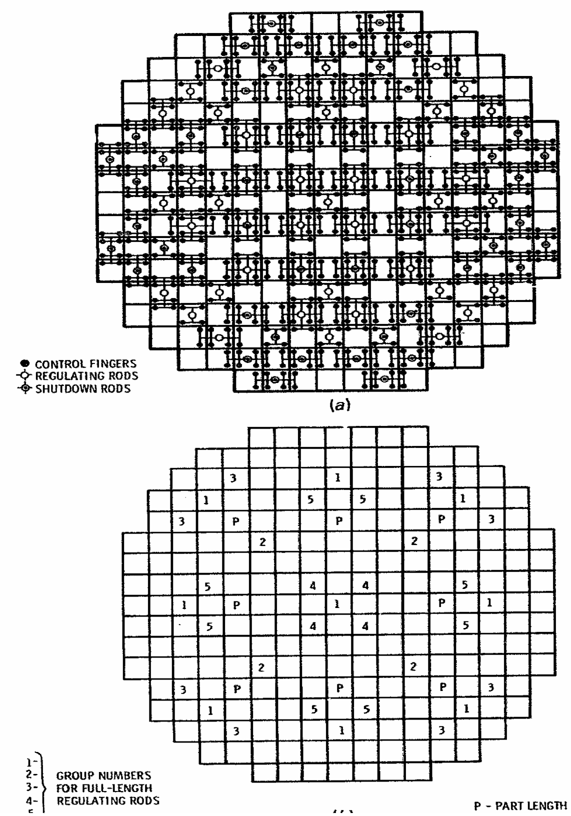


FIGURE 1-6
Fuel assembly for a representative boiling-water reactor. (Adapted courtesy of General Electric Company.)

PWR Fuel Assembly





Fuel Rod Design Interactions

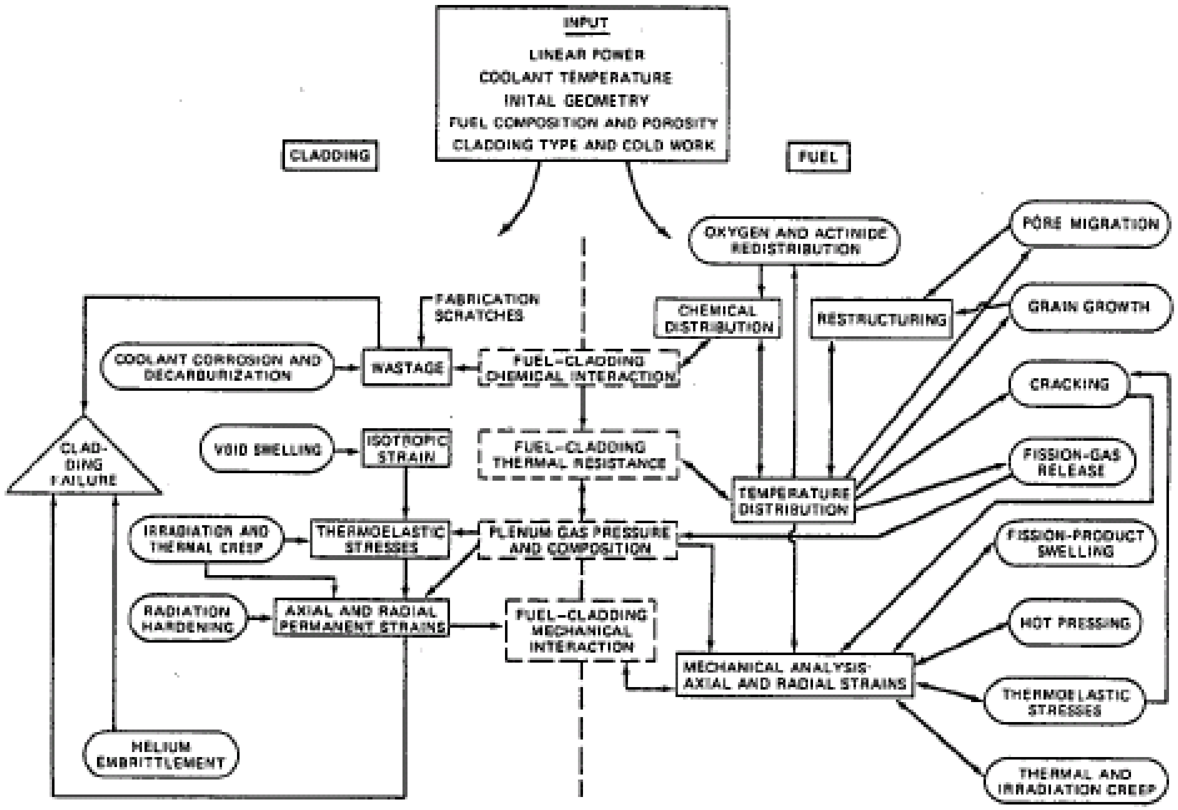


FIGURE 9-6
Flow chart for representative fuel-rod design interactions. (From D. R. Olander, *Fundamental Aspects of Nuclear Reactor Fuel Elements*, TID-26711-P1, 1976.)

Typical Protective System

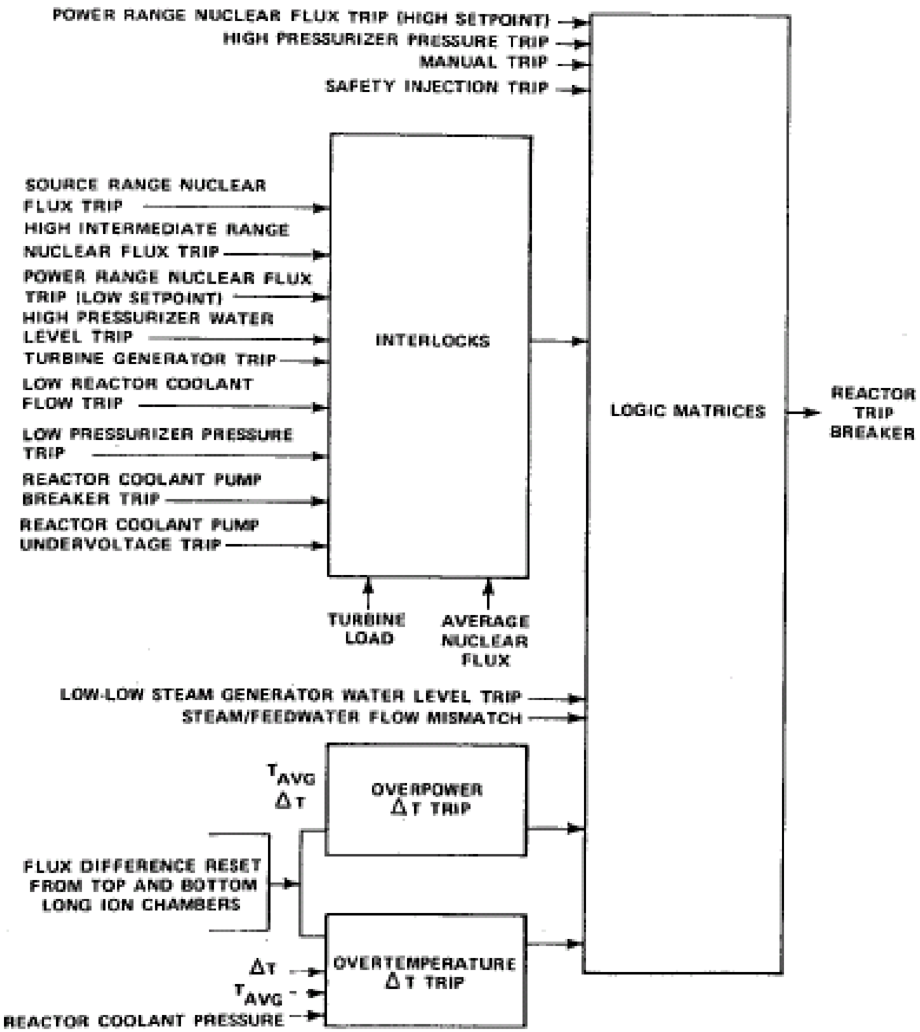


FIGURE 10-14
Typical protective system inputs for a pressurized water reactor. (Courtesy of Westinghouse Electric Corporation.)

Daya Bay PWR – French Design

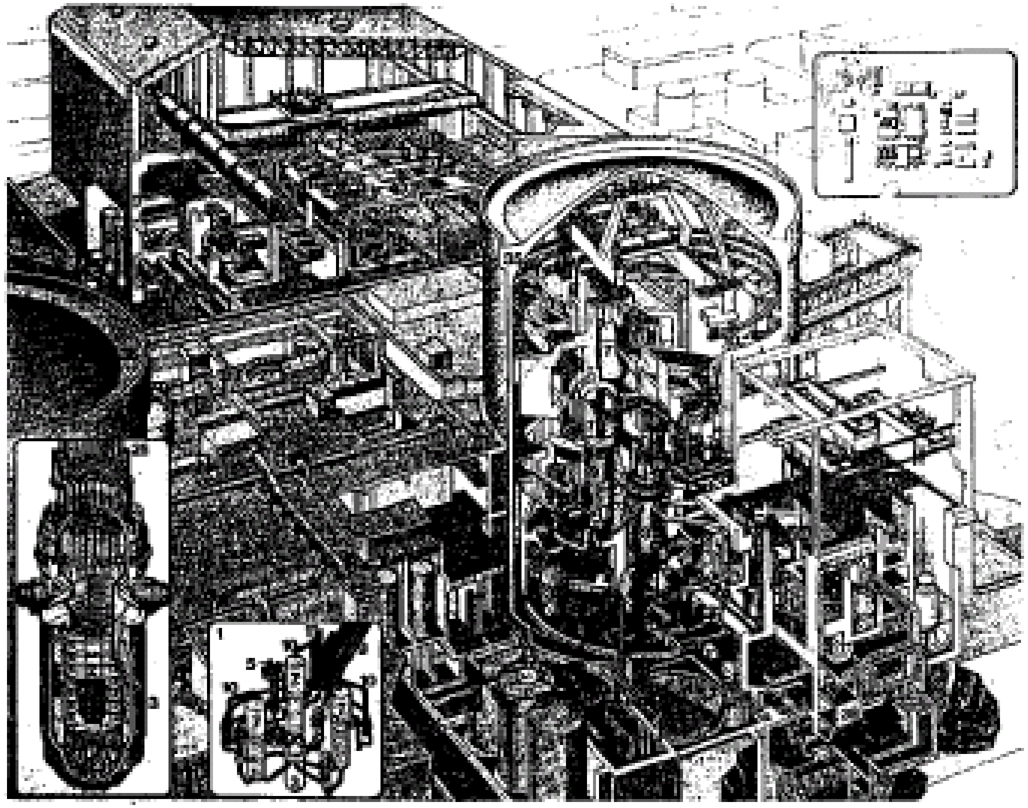


FIGURE 8-4
Cut-away drawing of the Guangdong pressurized water reactor [Courtesy of *Nuclear Engineering International* (Sept. 1987), with permission of the editor.]

Schematic of Plant Design

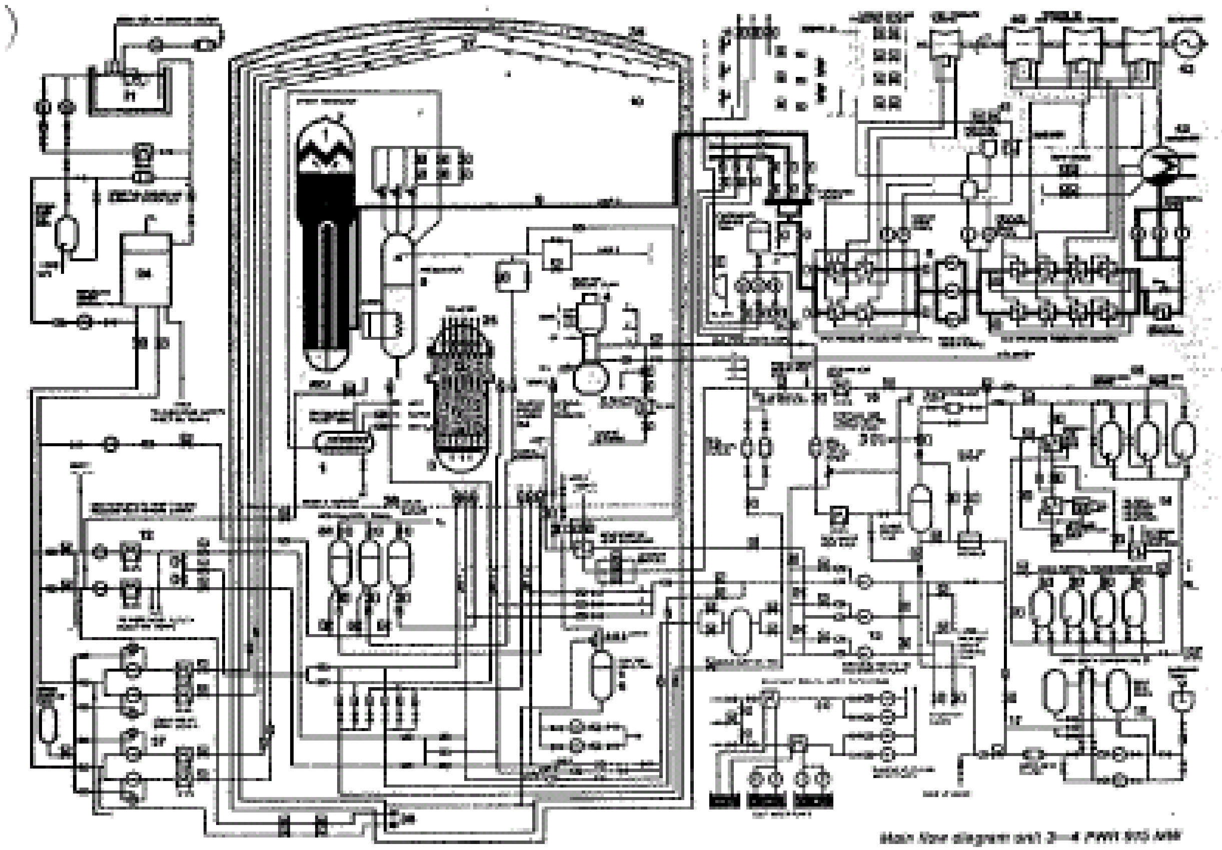


FIGURE 8-5
Schematic diagram of the fluid subsystems of the Ringhals, Units 3 and 4 pressurized water reactors [Courtesy of the Swedish State Power Board.]

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Key Reactor Systems

- Reactor Coolant System
- Heat Removal Systems
- Nuclear Support Systems
- Plant Service Systems
- Nuclear Safety Systems
- Balance of Plant

Power Conversion Systems

- Carnot Efficiency
- Rankine Cycle Fundamentals
- Superheat
- Muti-Fluid Cycles
- Choices for Efficiency and Cost

ENERGY IN THE FORMS OF HEAT AND WORK

Heat: Energy of a system associated with the unordered motion of the system's molecules (indicated by the system's temperature).

Work: Energy of a system associated with the ordered motion of the system's molecules (Work = Force * Displacement).

IDEAL HEAT ENGINE
VAPOR-POWER CYCLES

- Carnot Cycle (Ideal, Reversible Engine)
  - Heat addition and rejection at constant temperatures
  - System expansion and compression at constant entropies

- Rankine Cycle (Two-Phase Working Fluid)
  - Heat addition and rejection at constant temperatures
  - System expansion and compression at constant entropies

- Brayton Cycle (Single-Phase Working Fluid)
  - Heat addition and rejection at constant temperatures
  - System expansion and compression at constant entropies

REVERSIBILITY AND IRREVERSIBILITY

Reversible Process: A process involving the change from system State A to State B, such that the system can be restored to State A with no net change in the status of any other system in the universe.

Irreversibility: Net work that must be supplied by an external system in order to restore the system of interest from State B back to its initial state, A.

Sources of Irreversibility:

- Heat not converted to work in association with heat from a hot body to a colder body.
- Work that is transferred from one system to another without being preserved in the form of work (i.e., work that is converted to heat via friction during a process).

Temperature Entropy Diagrams

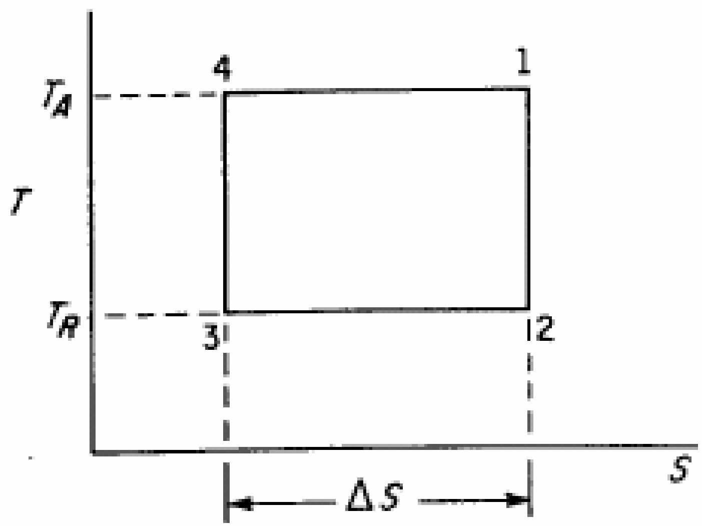


FIG. 2-1. *TS* diagram of Carnot cycle.

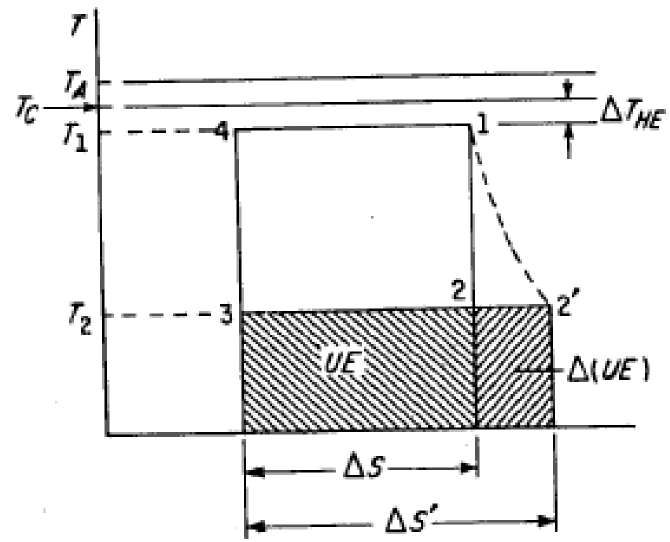
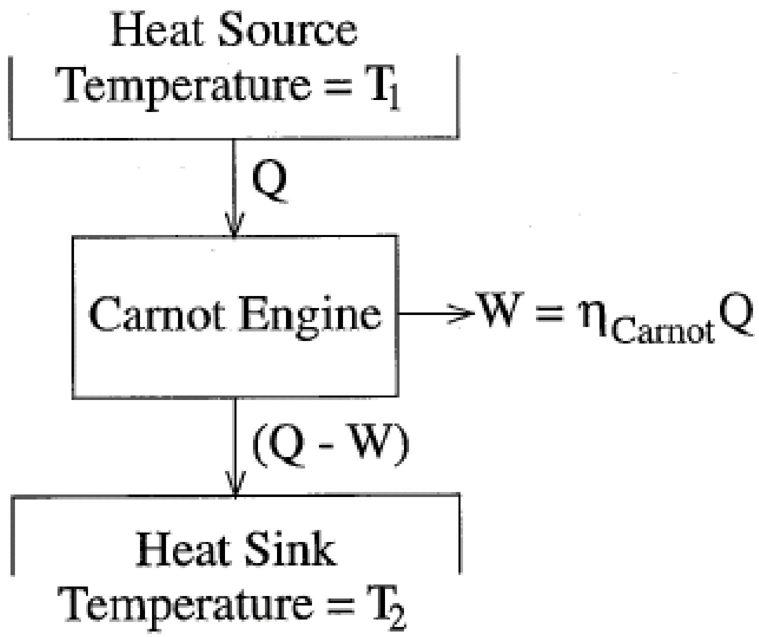


FIG. 2-6. *TS* diagram of cycle with irreversible expansion and irreversible constant-temperature heat addition.

IRREVERSIBILITY IN HEAT TRANSFER



$$\eta_{Carnot} = \frac{T_1 - T_2}{T_1}$$

Irreversibility, I, in transferring heat, Q, is the work not performed, $W = \eta_{Carnot} Q$, due to absence of a perfect heat engine.

Basic Rankine Cycle

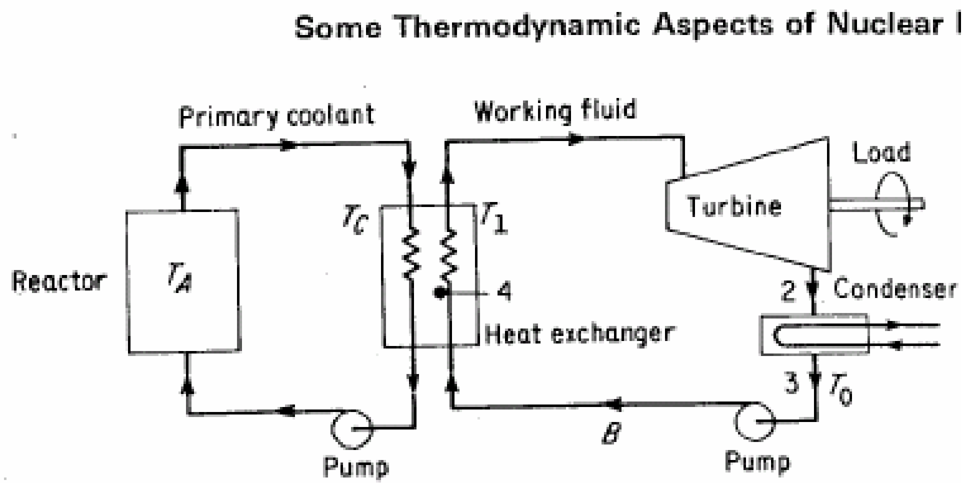


FIG. 2-5. Schematic of two-loop nuclear power plant.

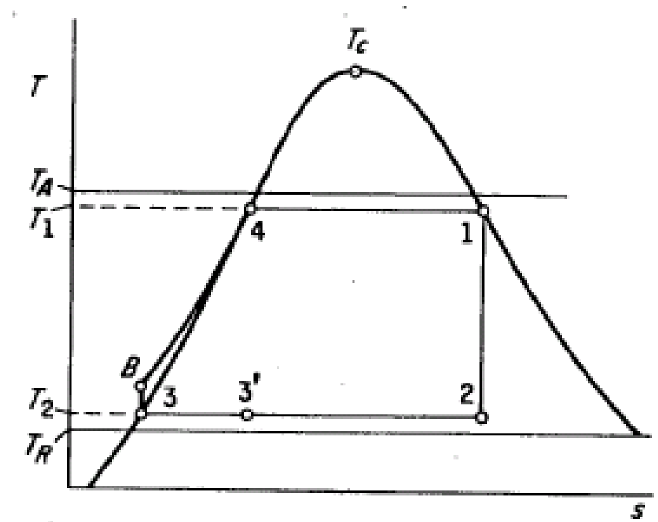


FIG. 2-4. Internally reversible Rankine cycle with saturated vapor.

Steam Generators

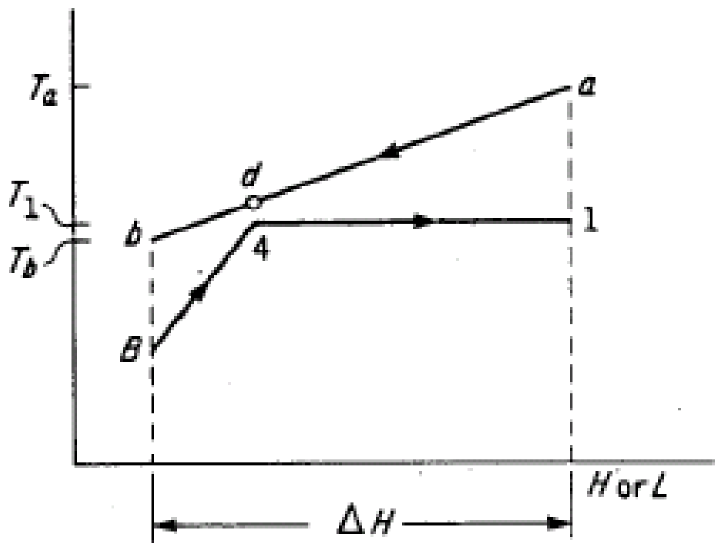


FIG. 2-10. Heat addition to vaporizing fluid with a variable-temperature source; counter-flow heat exchanger.

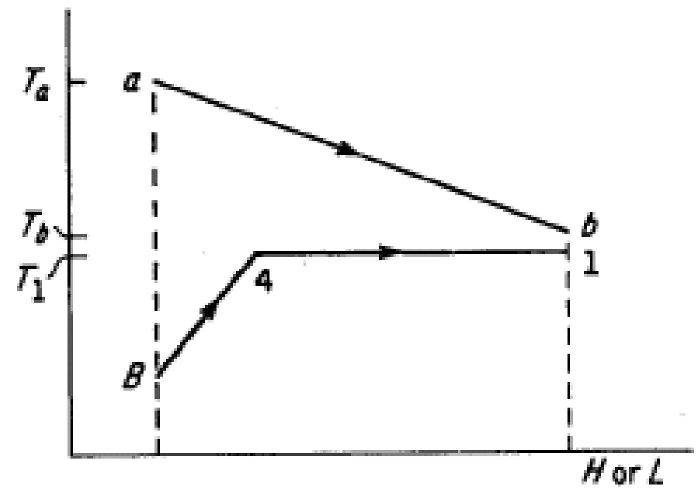


FIG. 2-11. Heat addition to vaporizing fluid with a variable-temperature source; parallel-flow heat exchanger.

Rankine Cycle with Feedwater Heaters

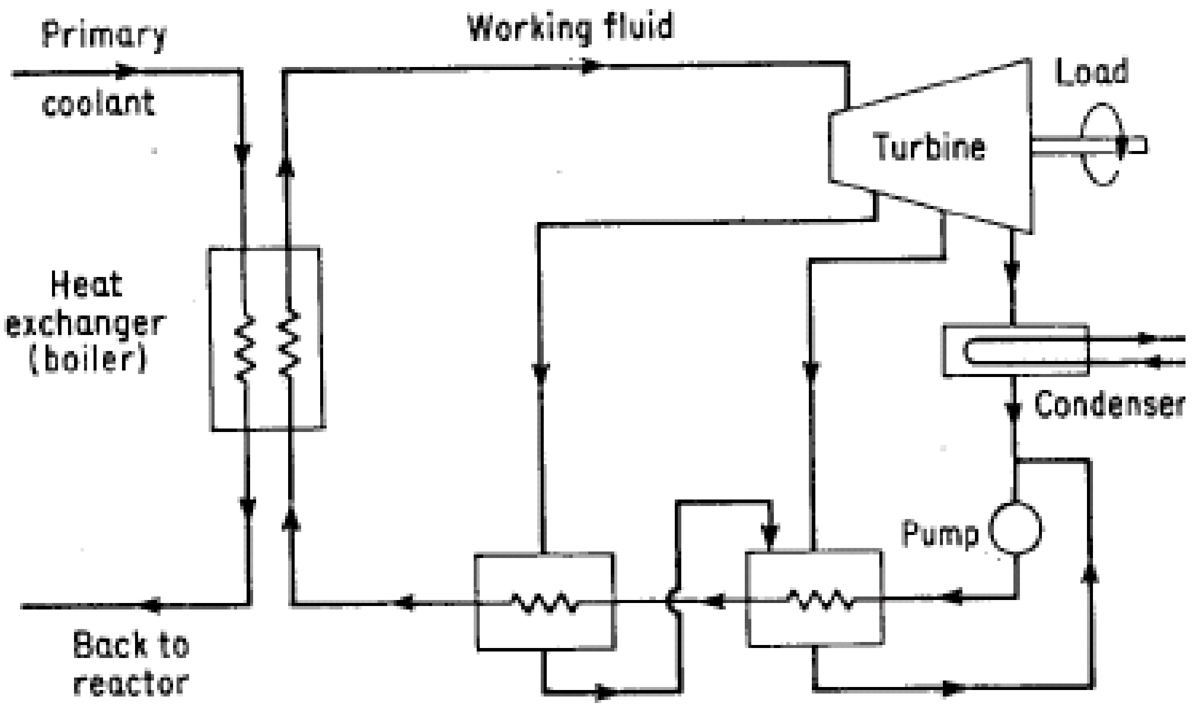
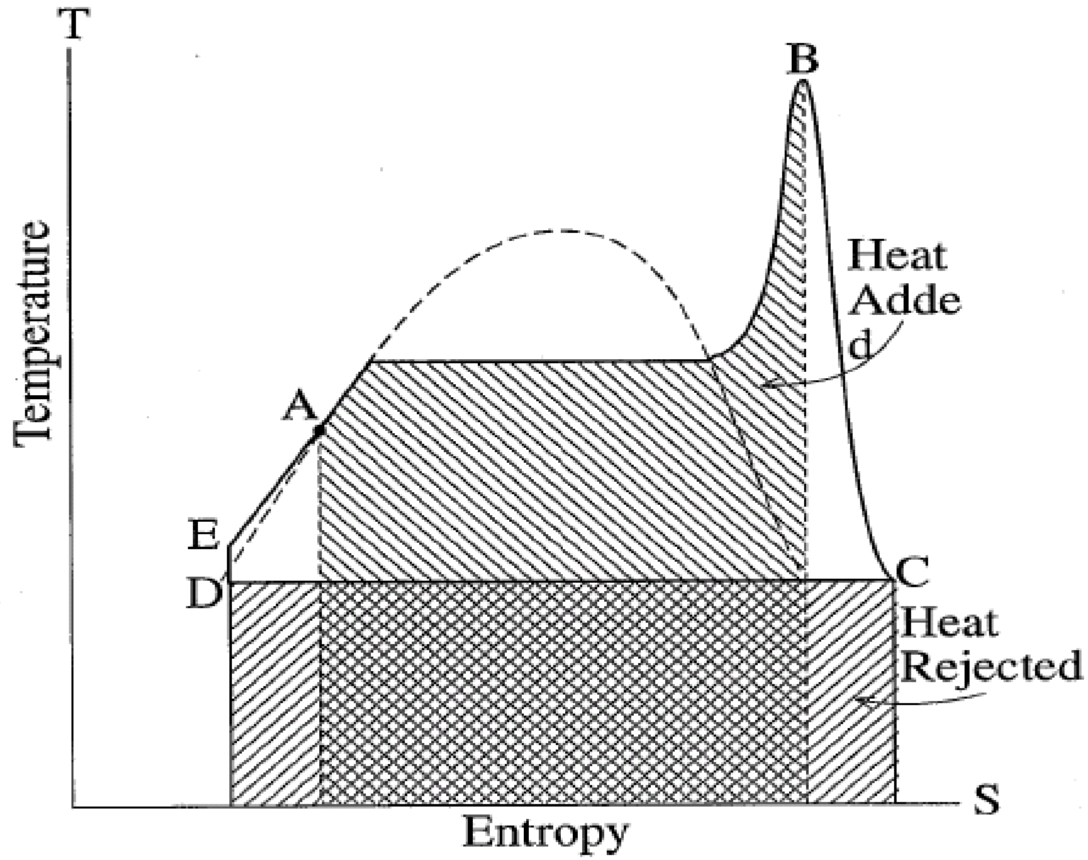


FIG. 2-9. Schematic of Rankine cycle with two closed-type feedwater heaters.

REFINED RANKINE CYCLE USING SUPERHEATING AND REGENERATIVE HEATING



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

Power Cycles

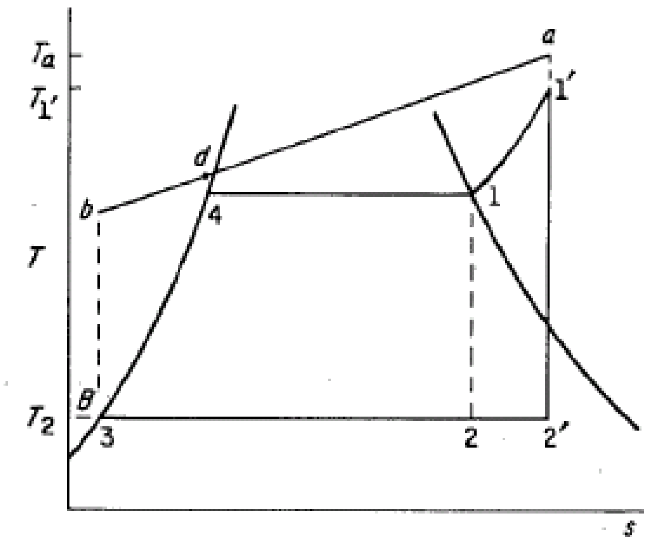

FIG. 2-12. Internally reversible Rankine cycle with superheat and a variable-temperature heat source.

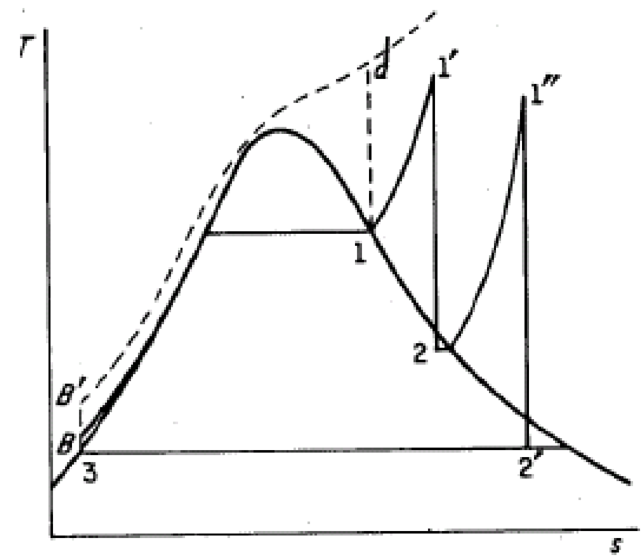

FIG. 2-13. *Ts* diagram of internally reversible supercritical and reheat cycles.

Binary Cycle Plants

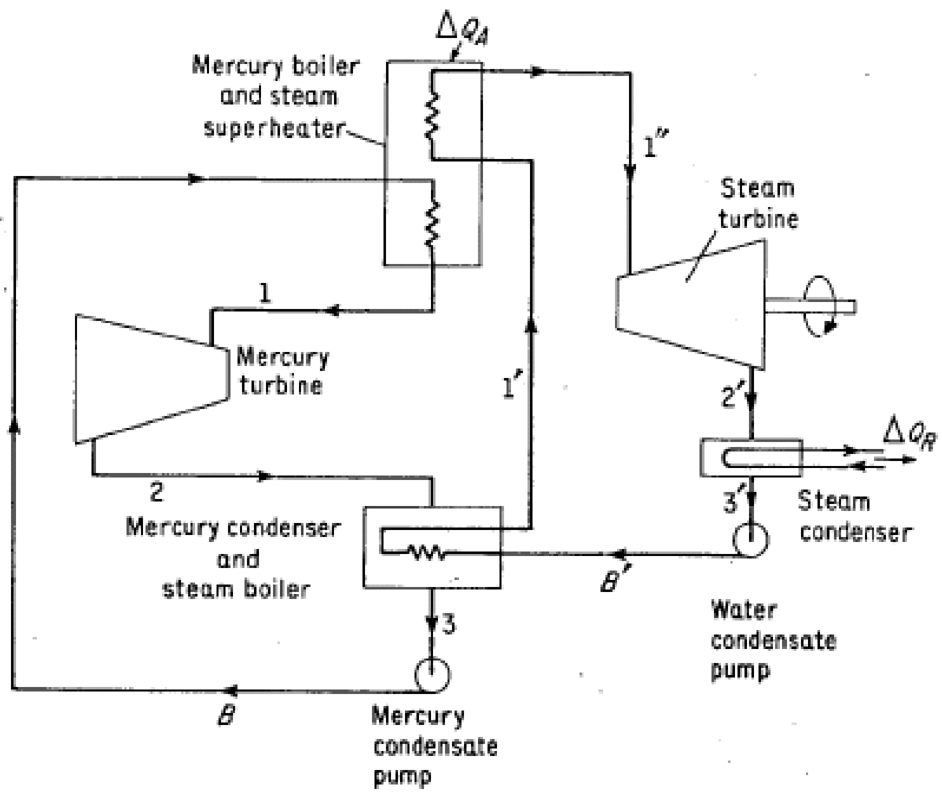

FIG. 2-16. Schematic of a mercury-steam binary-vapor power plant.

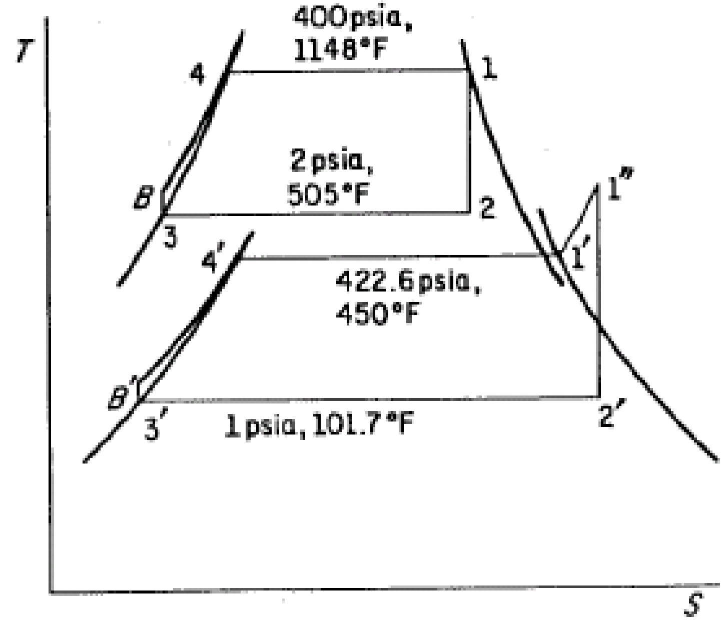

FIG. 2-17. TS diagram of internally reversible mercury-steam cycle.

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

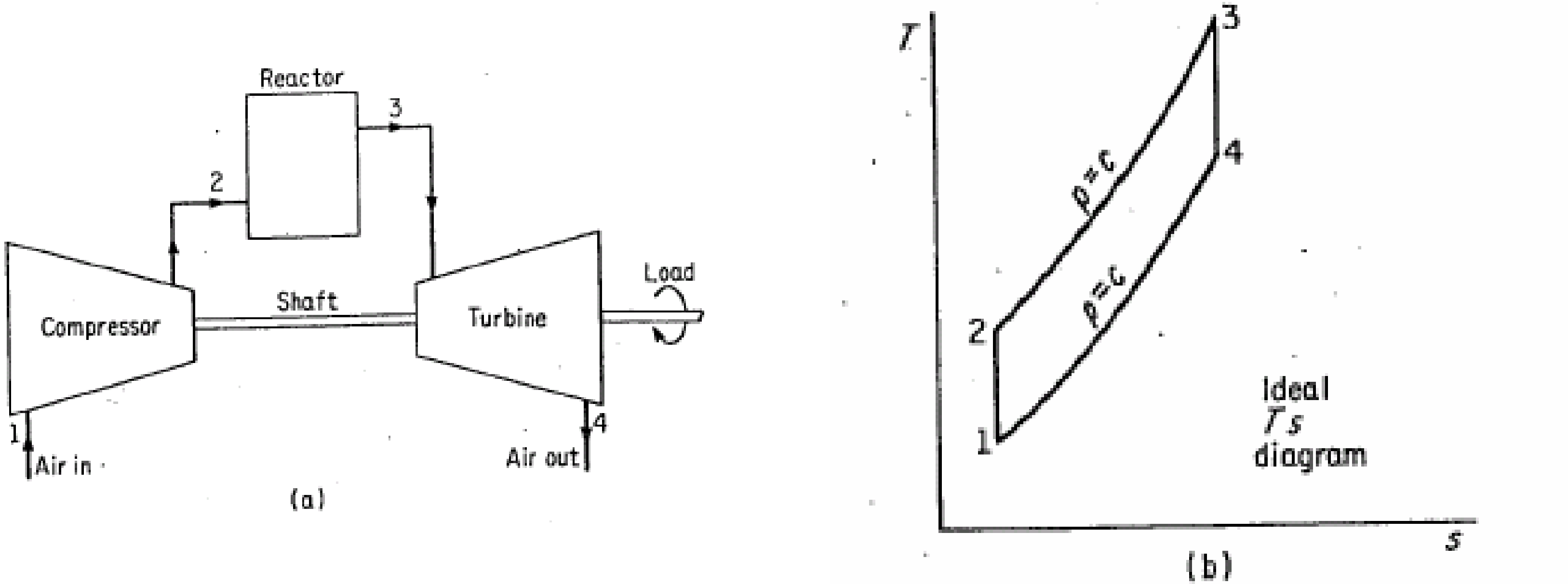

FIG. 7-1. The direct open cycle.
(a) Cycle diagram; (b) *Ts* diagram.

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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	$(R/J) \ln (v_2/v_1)$	$(p_1v_1/J) \ln (v_2/v_1)$	$(p_1v_1/J) \ln (v_2/v_1)$
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 $p_1v_1^\gamma = p_2v_2^\gamma$ $T_2/T_1 = (v_1/v_2)^{\gamma-1}$ $T_2/T_1 = (p_2/p_1)^{\gamma-1/\gamma}$	$c_v(T_2 - T_1)$	$c_p(T_2 - T_1)$	0	$\dfrac{p_2v_2 - p_1v_1}{J(1-\gamma)}$	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	$p_1v_1^n = p_2v_2^n$ $T_2/T_1 = (v_1/v_2)^{n-1}$ $T_2/T_1 = (p_2/p_1)^{(n-1)/n}$	$c_v(T_2 - T_1)$	$c_p(T_2 - T_1)$	$c_v \ln (p_2/p_1) + c_p \ln (v_2/v_1)$	$\dfrac{p_2v_2 - p_1v_1}{J(1-n)}$	$c_v\left(\dfrac{\gamma - n}{1 - n}\right)(T_2 - T_1)$

Indirect Brayton Open Cycle

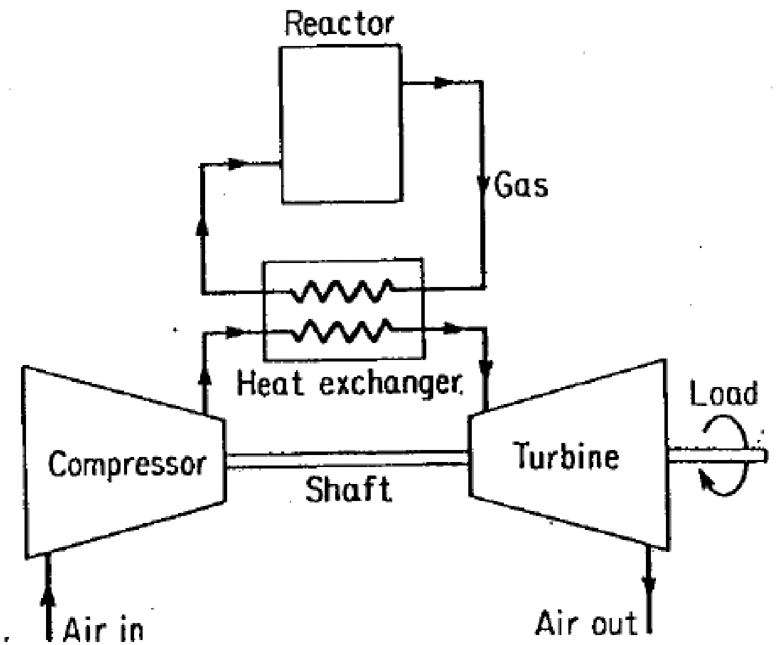


FIG. 7-2. The indirect open cycle.

Direct Closed Brayton Cycle

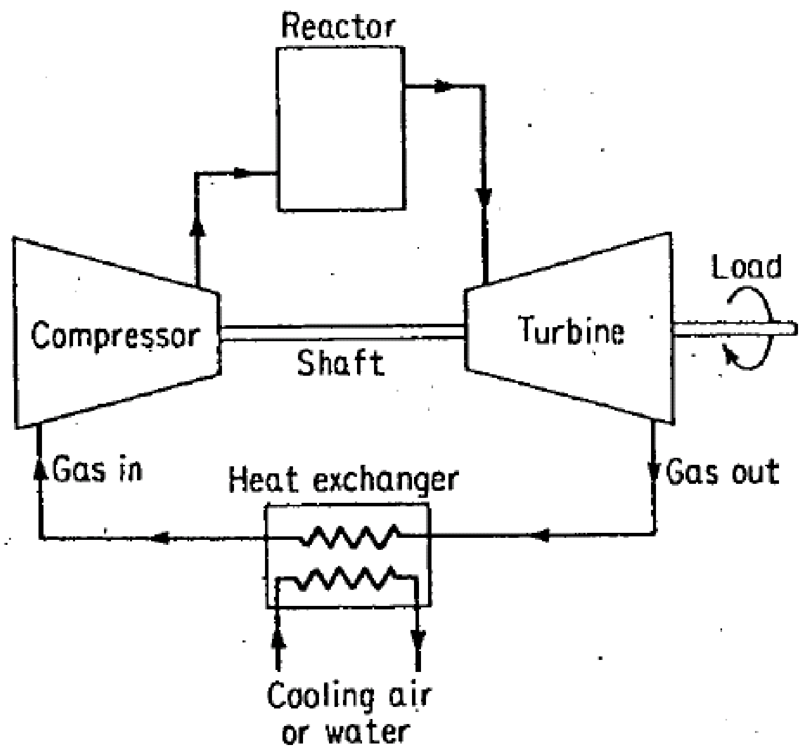
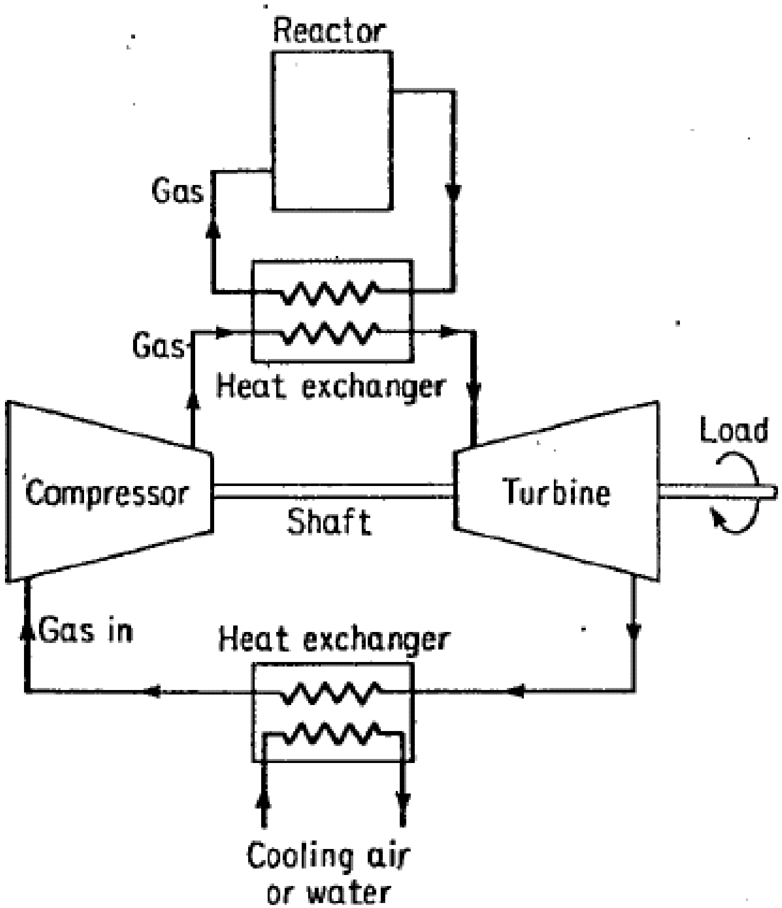


FIG. 7-3. The direct closed cycle.

Indirect Closed Cycle – Gas to Gas



Indirect Gas to Steam Generator

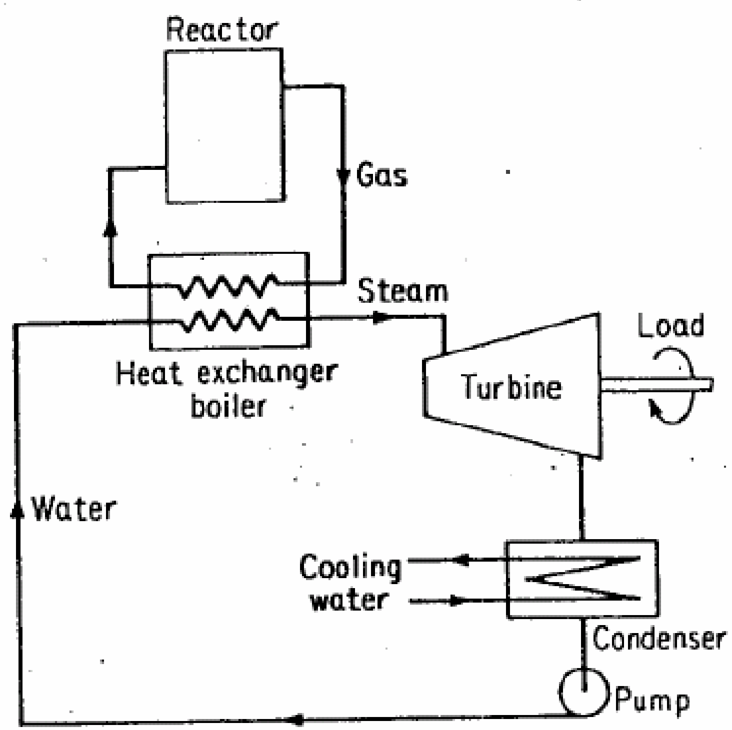


FIG. 7-5. The indirect closed cycle, gas to water.

Specific Heats of Gases

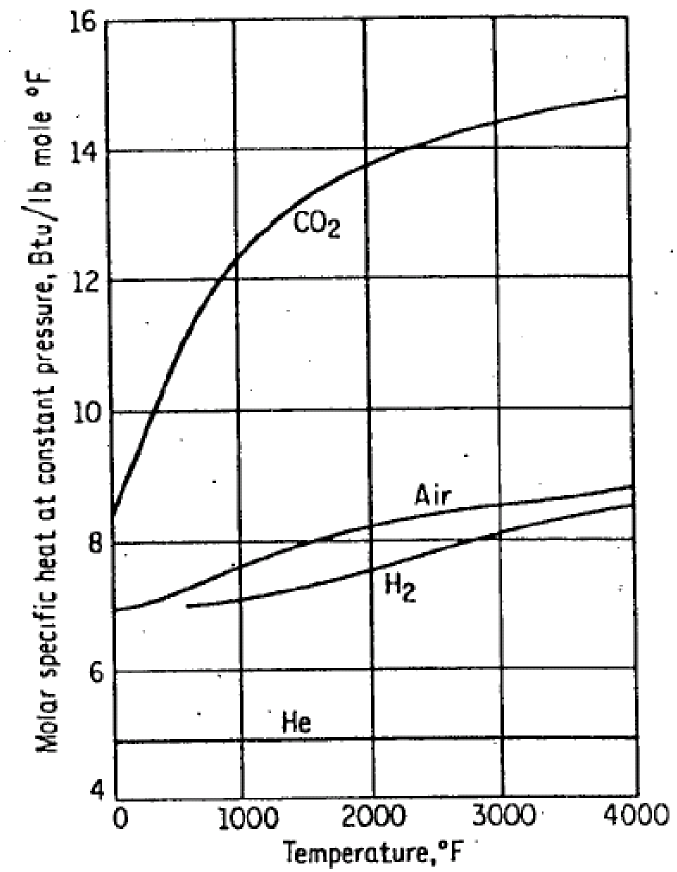


FIG. 7-6. Variation of molar c_p with temperature for various gases.

Ideal Brayton Cycle

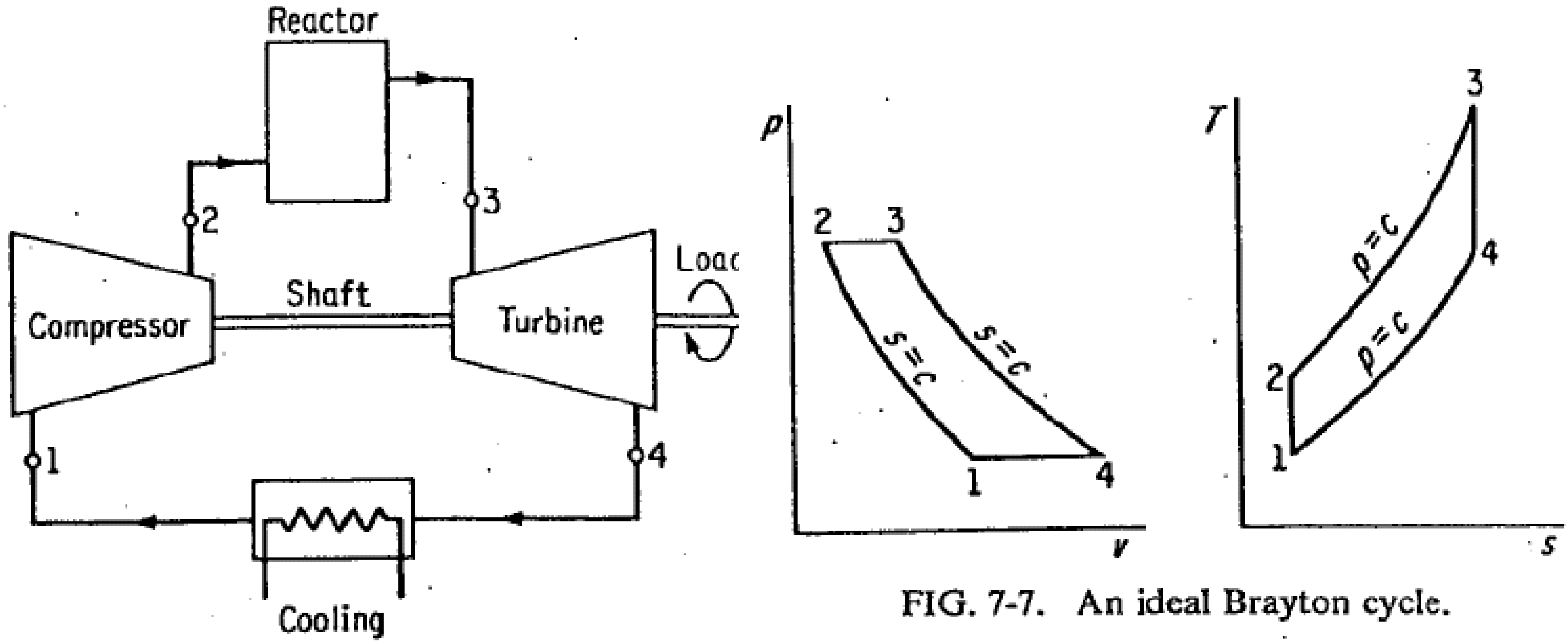
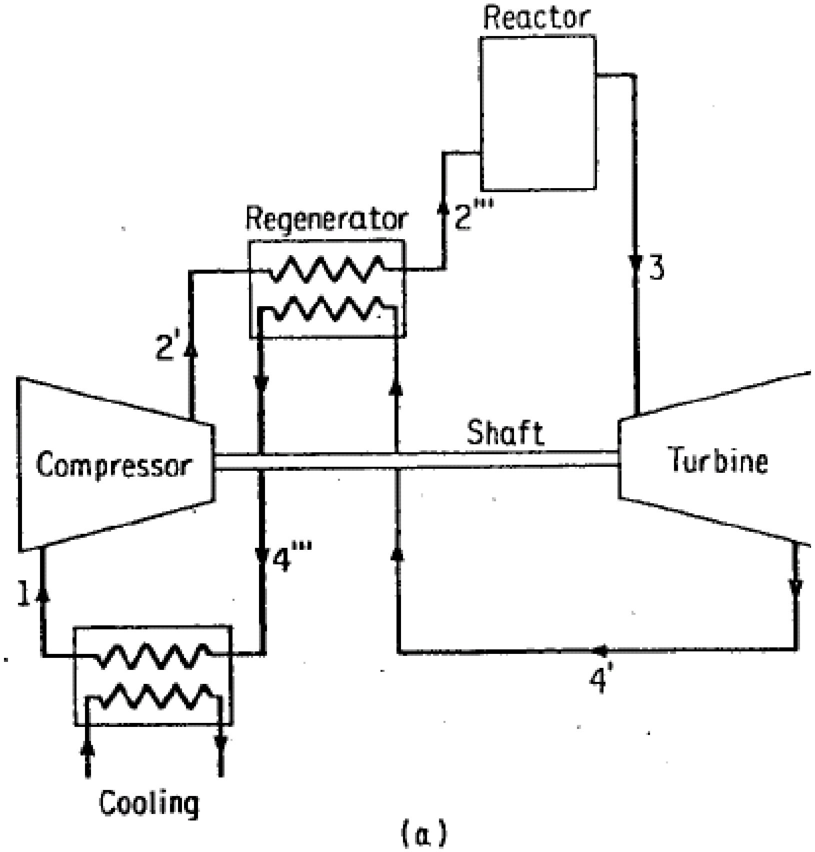


FIG. 7-7. An ideal Brayton cycle.

Non-Ideal Brayton Cycle



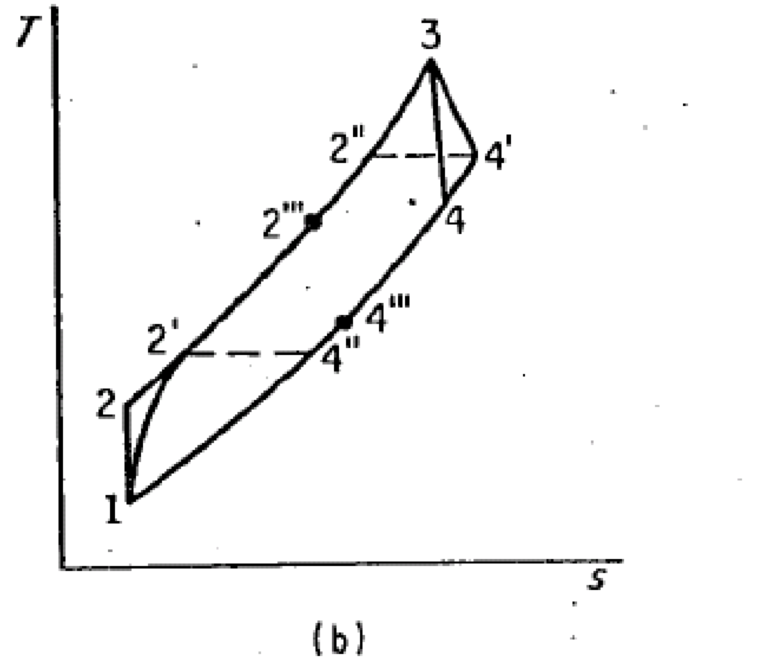


FIG. 7-12. Closed nonideal Brayton cycle with re generation.

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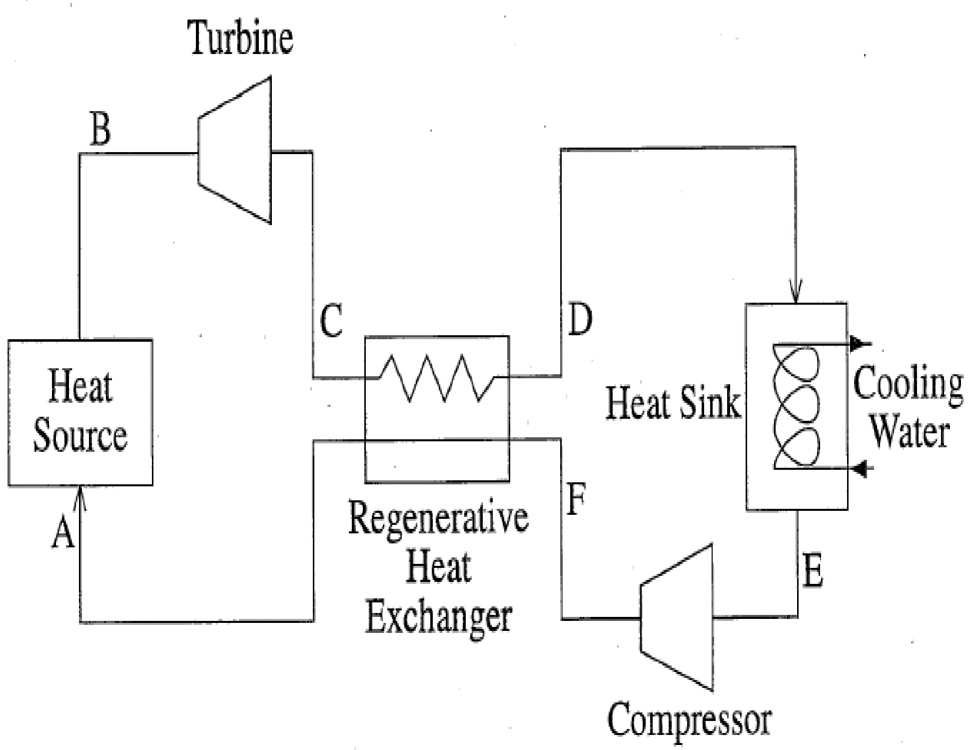
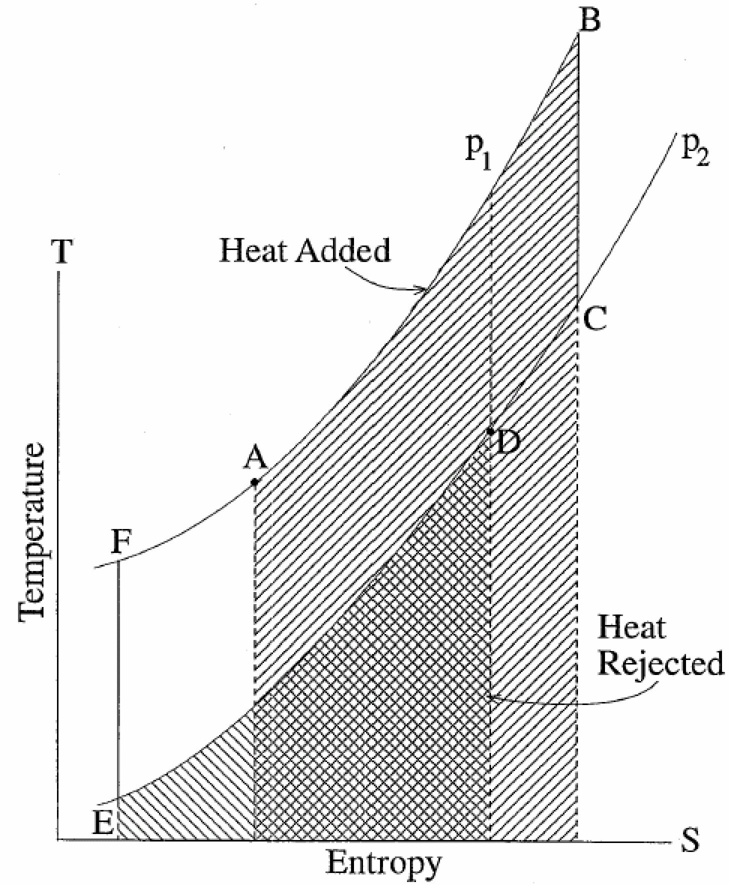


BRAYTON CYCLE WITH REGENERATIVE HEATING

BRAYTON CYCLE WITH REGENERATIVE HEATING



Gas-Steam Reactor Power Plant

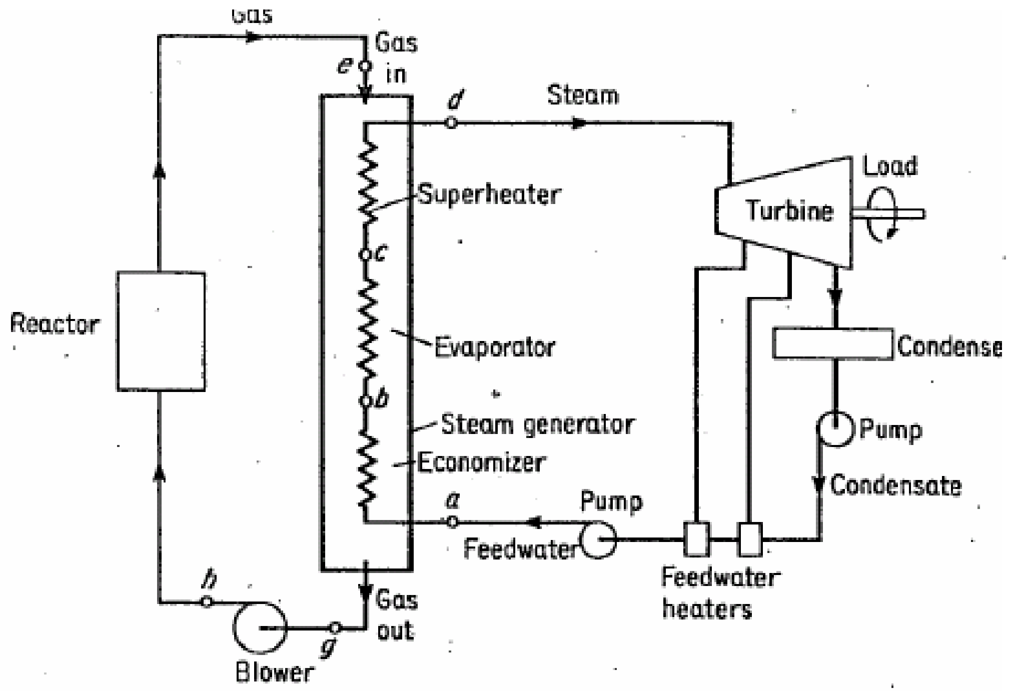


FIG. 8-1. Schematic of a simple-cycle gas-steam-reactor power plant.

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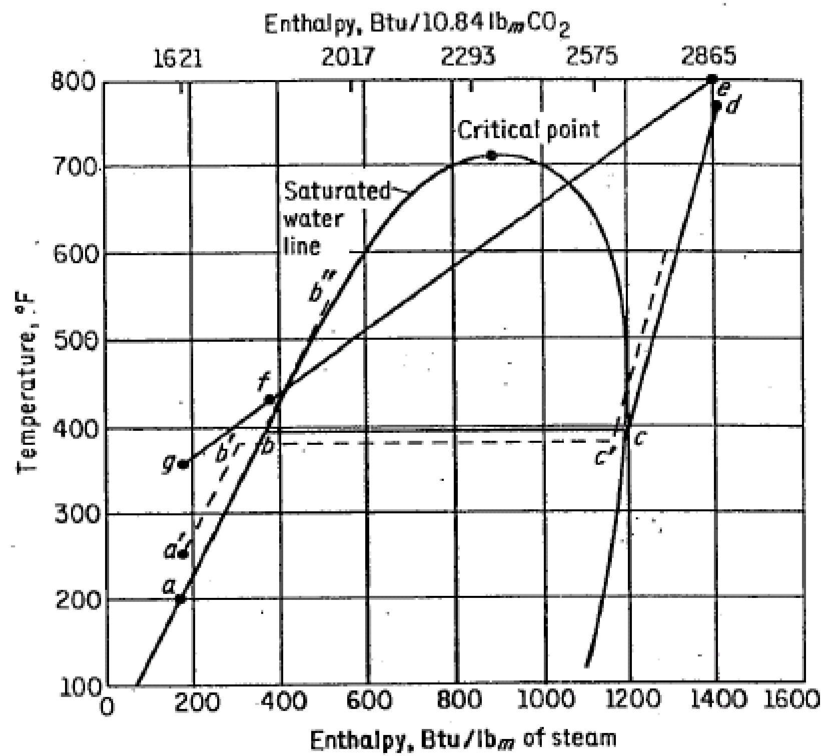
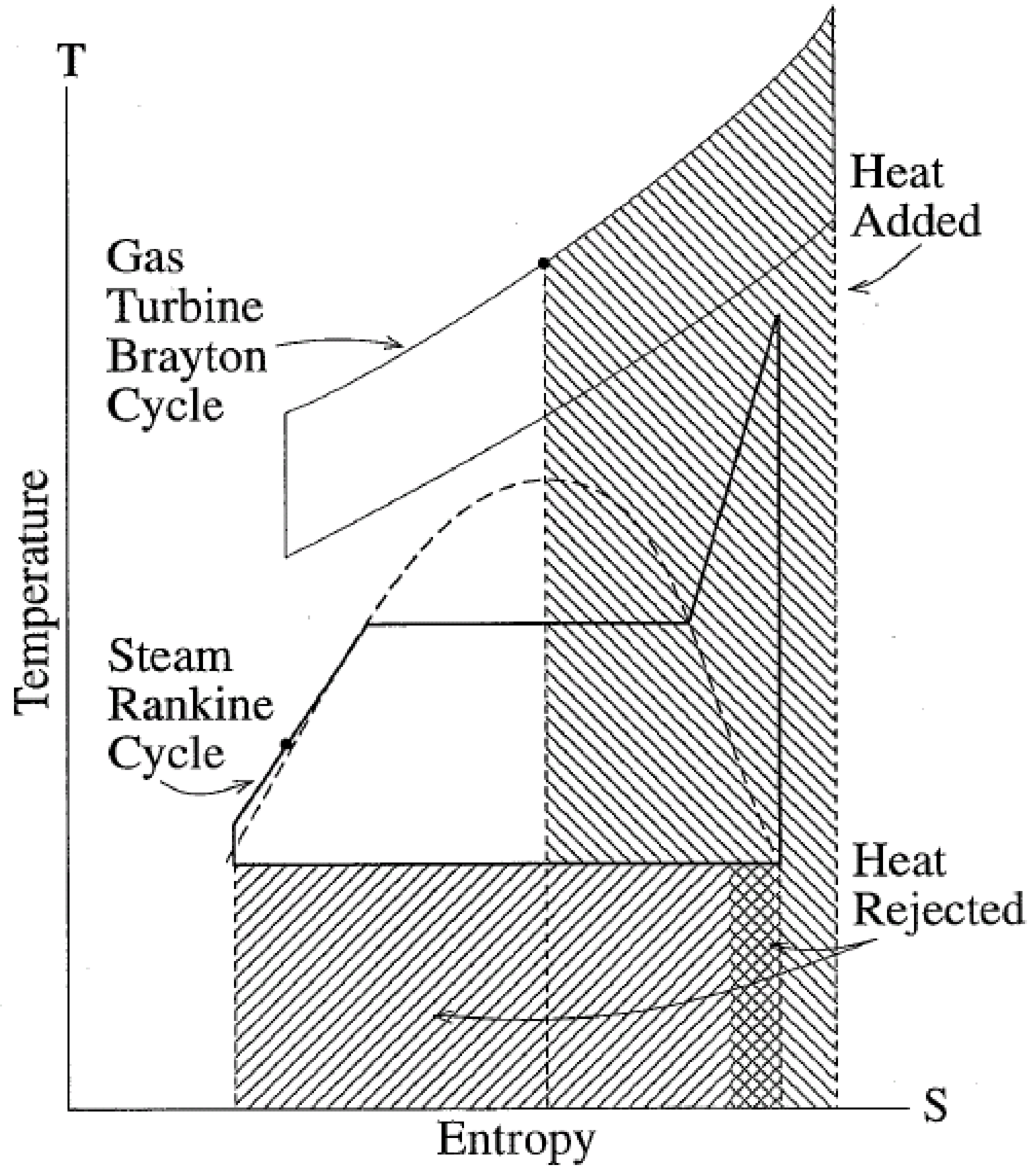
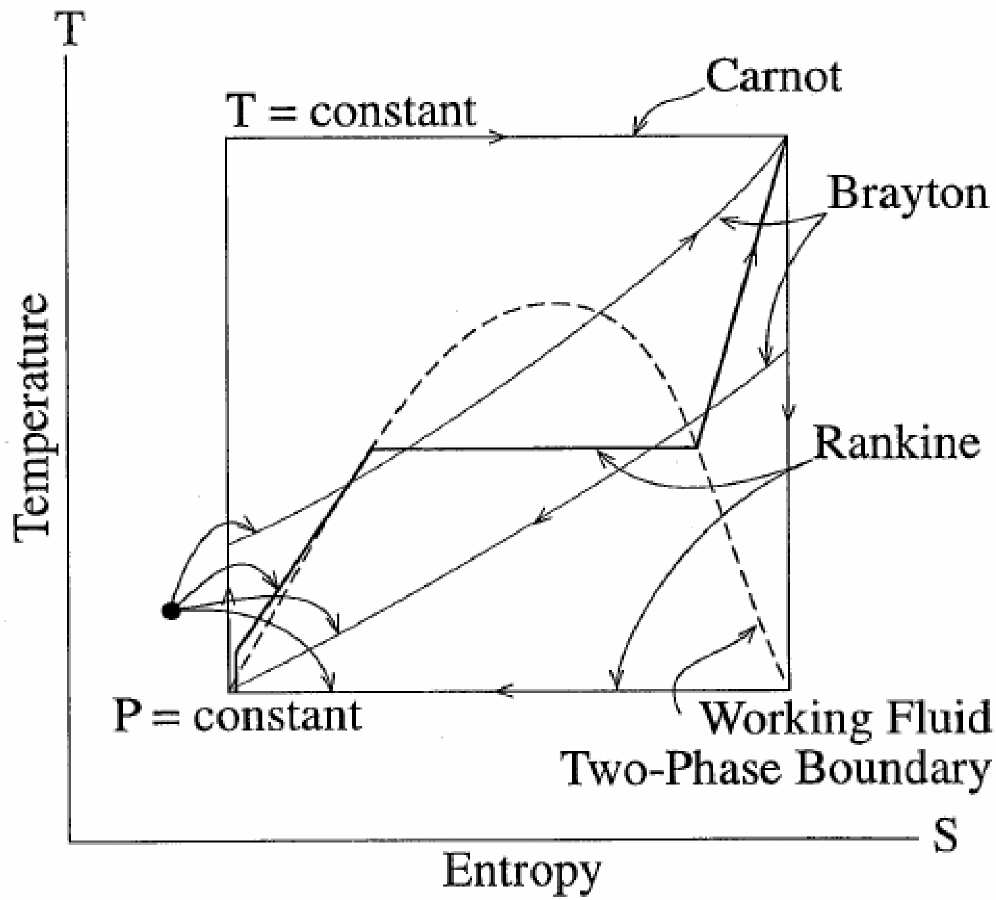


FIG. 8-2. Temperature-enthalpy diagram of a gas-steam heat exchanger in simple cycle.

COMBINED CYCLE BRAYTON (Topping), RANKINE (Bottoming)



VARIOUS VAPOR POWER CYCLES OPERATING BETWEEN THE SAME TEMPERATURE LIMITS



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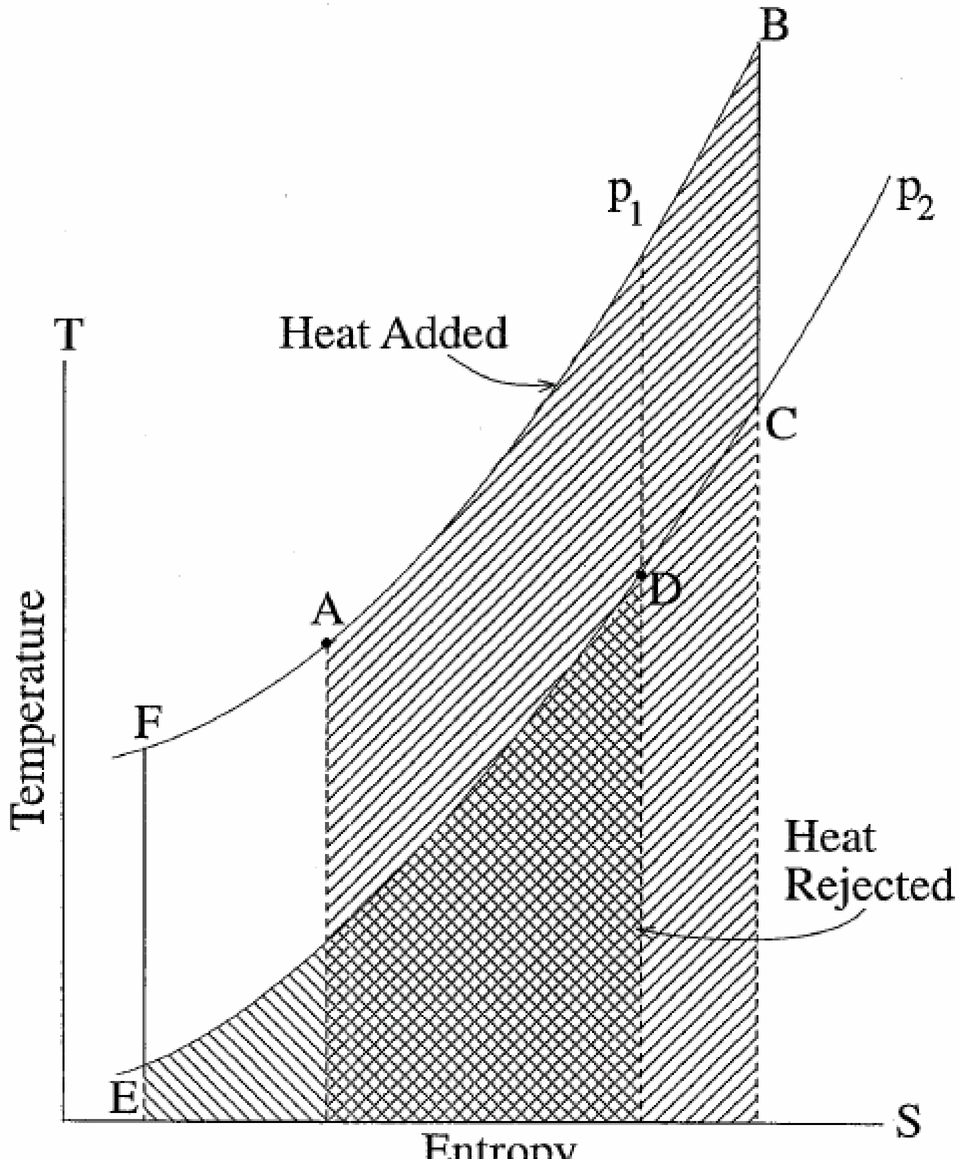
BRAYTON CYCLE WITH REGENERATIVE HEATING



Reading and Homework Assignment

1. Read Knief Chapter 8, 9, 10
2. Outside Reading El-Wakil Chapter 2
3. Problems 2.7, 7.4

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