The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

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Joint ICTP-IAEA Course on Science and Technology of Supercritical Water Cooled Reactors

27 June - 1 July, 2011

INTRODUCTION TO THERMODYNAMICS

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LECTURE SC06
Introduction to Thermodynamics

Joint ICTP-IAEA Course on Science and Technology of SCWRs, Trieste, Italy, 27 June - 1 July 2011

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Objectives

Objectives of this Lecture are to:

- Introduce Basic Thermodynamics of Power Plant Cycles;
- Present Thermodynamic Cycles of Thermal and Nuclear Power Plants; and
- Present Possible SCWR Cycles.

Part 1
Basic Thermodynamics

Textbook: Yunus A. Çengel and Michael A. Boles, "Thermodynamics. An Engineering Approach", 7th ed., McGraw-Hill, New York, NY, USA, 2011, 1024 pages.

Forms of Energy

Macroscopic

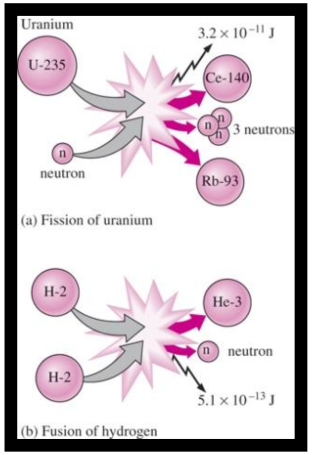
1. Thermal
2. Mechanical
   - **Kinetic** $KE = \frac{1}{2} mV^2 \text{..... Eq. 2-2}$
   - **Potential** $PE = mgz \text{..... Eq. 2-4}$
   - **Pressure** P
3. Electric
4. Magnetic

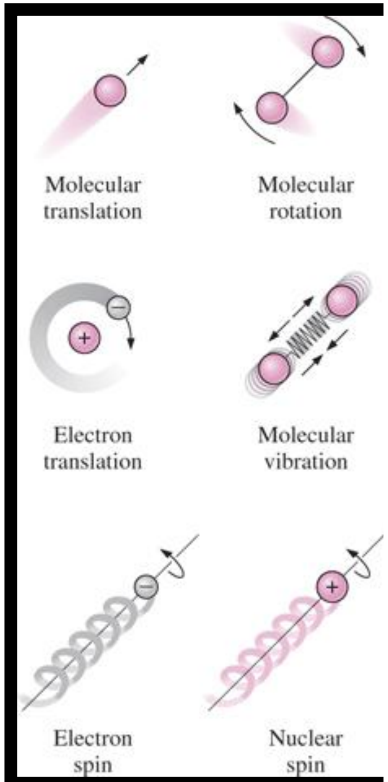
Microscopic

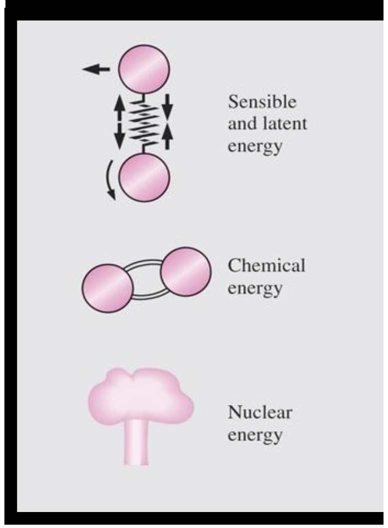
$$e = \frac{E}{m} = \frac{\text{Total energy}}{\text{mass}}$$

1. Internal
2. Nuclear
3. Chemical
4. Latent Heat

   (Phase Change)
5. Sensible – due to kinetic energy of the molecules

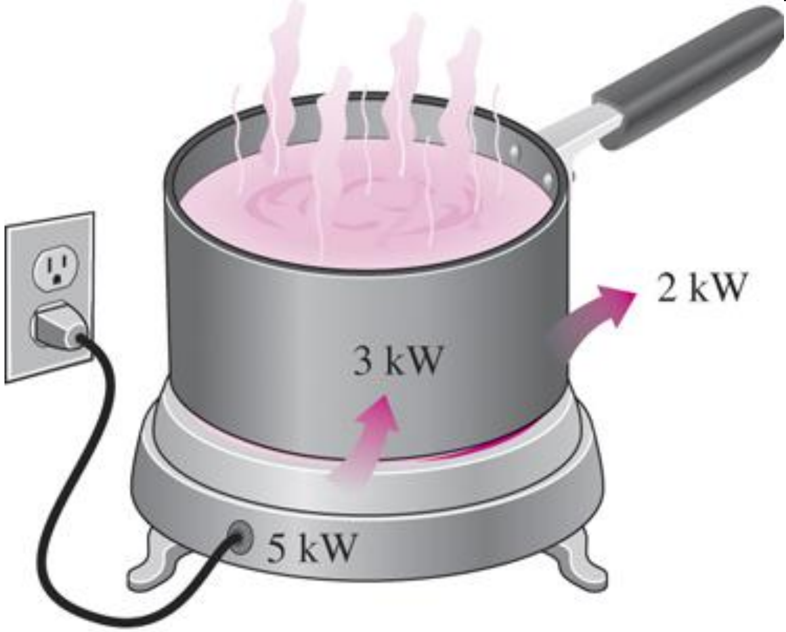






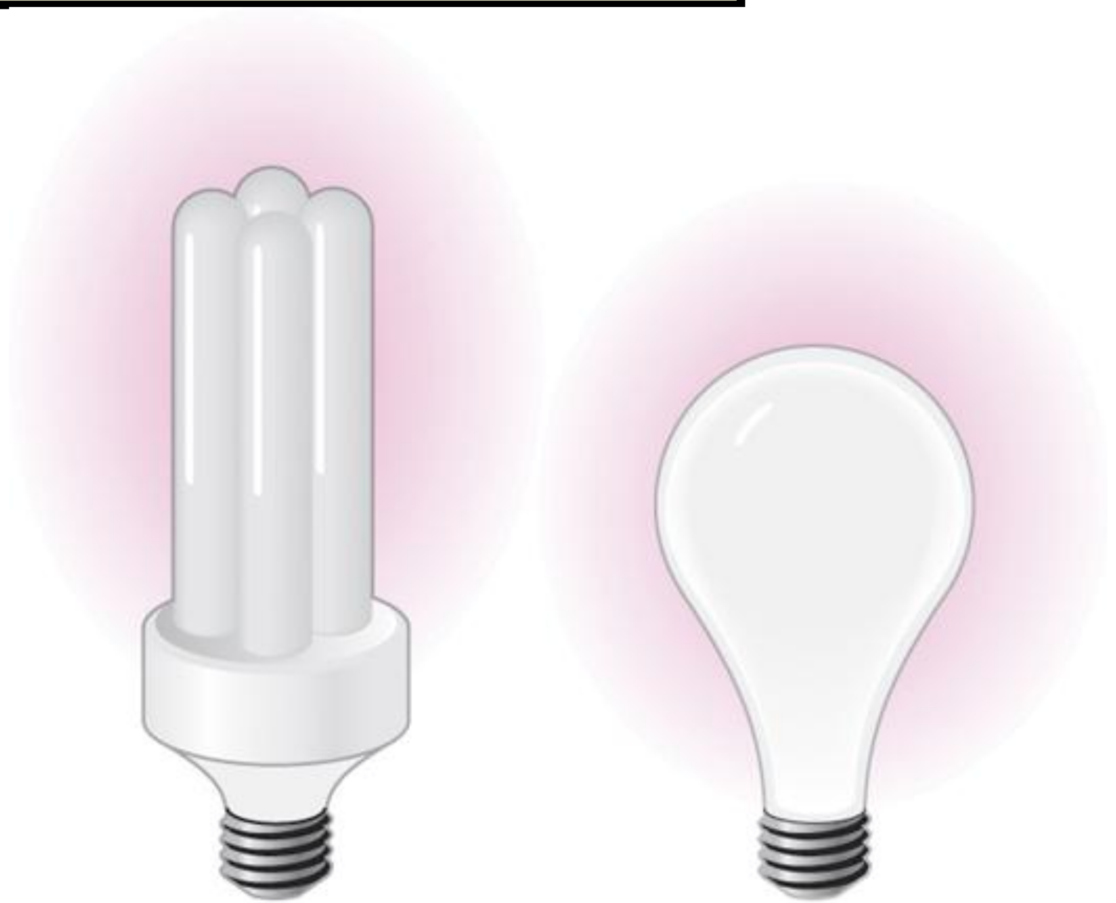
Energy Conversion Efficiencies

$$\text{Efficiency or Performance} = \frac{\text{Desired ouput}}{\text{Required output}}$$



$$\text{Efficiency} = \frac{\text{Energy utilized}}{\text{Energy supplied to appliance}}$$

$$= \frac{3\text{ kWh}}{5\text{ kWh}} = 0.60$$



15 W   60 W

Energy Conversion Efficiencies

Water heater

Type	Efficiency
Gas, conventional	55%
Gas, high-efficiency	62%
Electric, conventional	90%
Electric, high-efficiency	94%

Efficiency of Water Heater

$$\eta_{combustion} = \frac{Q}{HV} = \frac{\text{Amount of heat released during combustion}}{\text{Heating value of the fuel burned}}$$

Annual fuel utilization efficiency (AFUE)

Includes ,

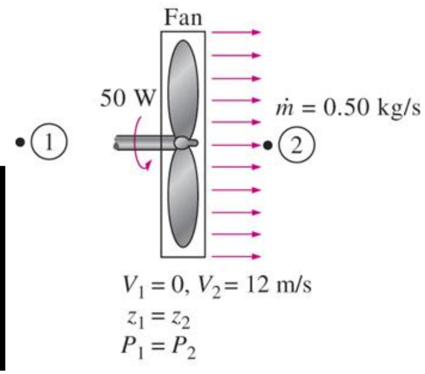
- **Combustion efficiency**
- **Heat loses to unheated areas**
- **Start up and cool down losses**

Overall Efficiency of a power plant

$$\eta_{overall} = \eta_{combustion}\eta_{thermal}\eta_{generator} = \frac{\dot{W}_{net,electric}}{HHV * \dot{m}_{net}}$$

Mechanical Efficiency

$$\eta_{mech} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy input}} = \frac{E_{mech,out}}{E_{mech,in}} = 1 - \frac{E_{mech,loss}}{E_{mech,in}}$$



$$\eta_{mech,\,fan} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{shaft,in}} = \frac{\dot{m}V_2^2/2}{\dot{W}_{shaft,in}} = \frac{(0.50\text{ kg/s})(12\text{ m/s})^2/2}{50\text{ W}} = 0.72$$

Pump Efficiency

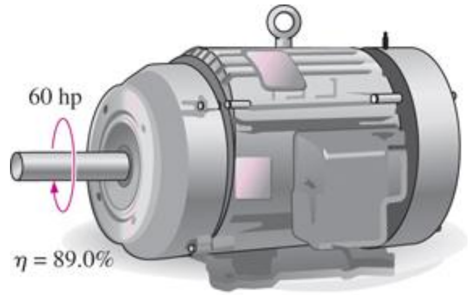
$$\eta_{pump} = \frac{\text{Mechanical energy increased in the fluid}}{\text{Mechanical energy input}} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{shaft,in}} = \frac{\dot{W}_{pump,u}}{\dot{W}_{pump}}$$

Turbine Efficiency

$$\eta_{turbine} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy decreased in the fluid}} = \frac{\dot{W}_{shaft,out}}{\left|\Delta \dot{E}_{mech,fluid}\right|} = \frac{\dot{W}_{turbine}}{\dot{W}_{turbine,e}}$$

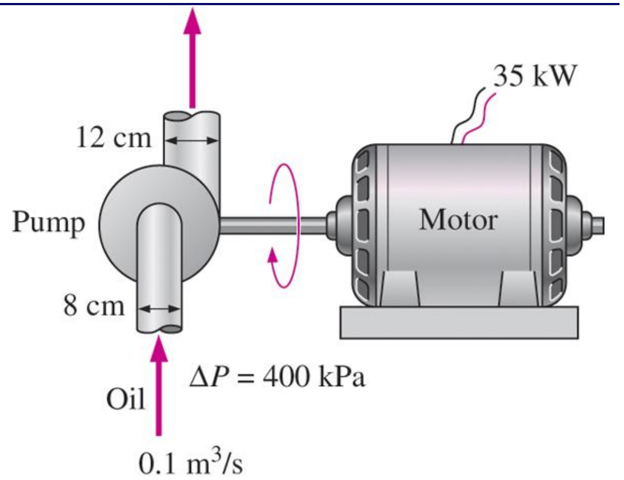
Motor Efficiency

$$\eta_{motor} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{shaft,out}}{\dot{W}_{elctric,in}}$$



Generator Efficiency

$$\eta_{generator} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{elect,out}}{\dot{W}_{shaft,in}}$$



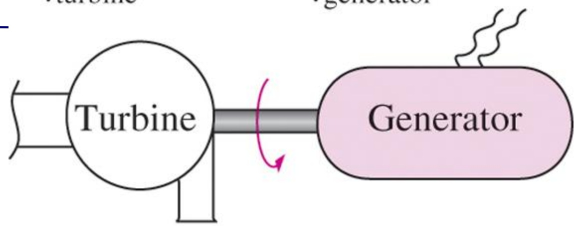
Combined pump and motor Efficiency

$$\eta_{pump-motor} = \eta_{pump}\eta_{motor} = \frac{\dot{W}_{pump,u}}{\dot{W}_{elect,in}} = \frac{\Delta \dot{E}_{mech,\ fluid}}{\dot{W}_{elect,in}}$$

Combined turbine and generator Efficiency

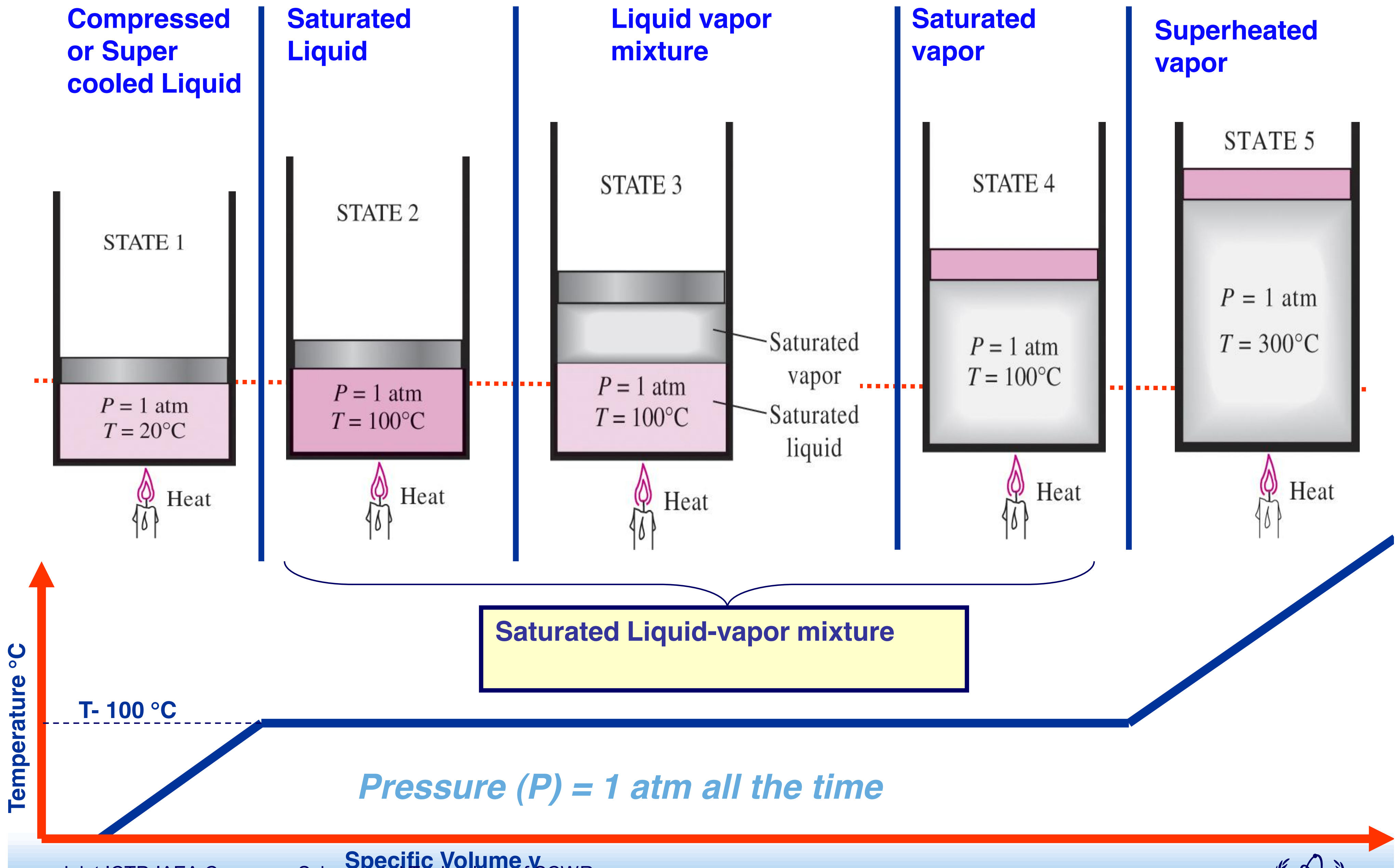
$$\eta_{turbine-gen} = \eta_{turbine}\eta_{generator} = \frac{\dot{W}_{elect,out}}{\dot{W}_{turbine,e}} = \frac{\dot{W}_{elect,out}}{\left|\Delta \dot{E}_{mech,\ fluid}\right|}$$

$\eta_{turbine} = 0.75$ $\eta_{generator} = 0.97$

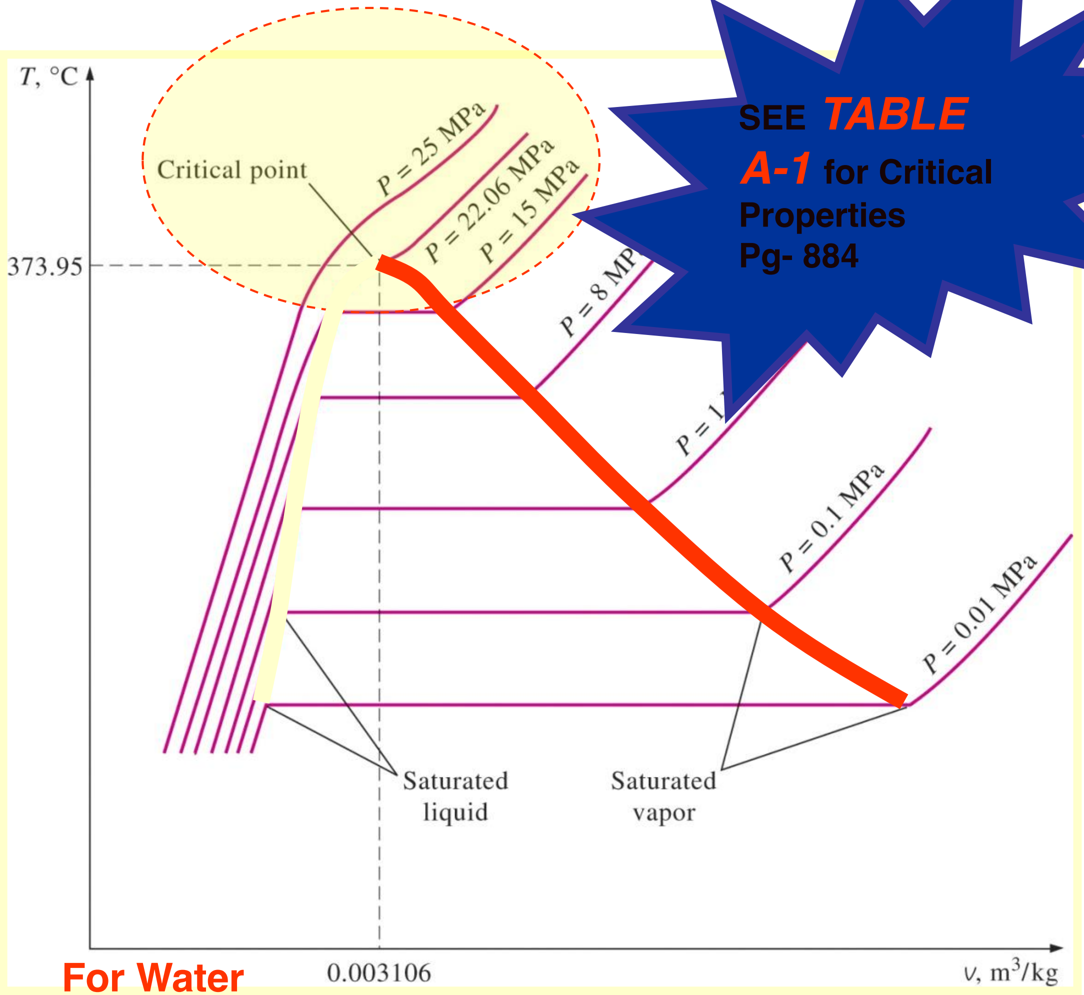


$$\eta_{turbine-gen} = \eta_{turbine}\eta_{generator} = 0.75 \times 0.97 = 0.73$$

Phase change process of Water under P= 1atm



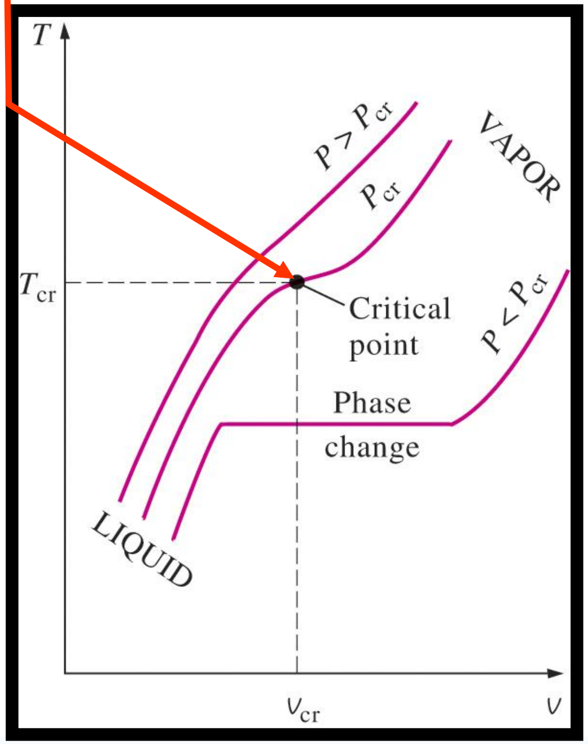
Property Diagram for Phase Change Process



SEE *TABLE A-1* for Critical Properties Pg- 884

Critical Point

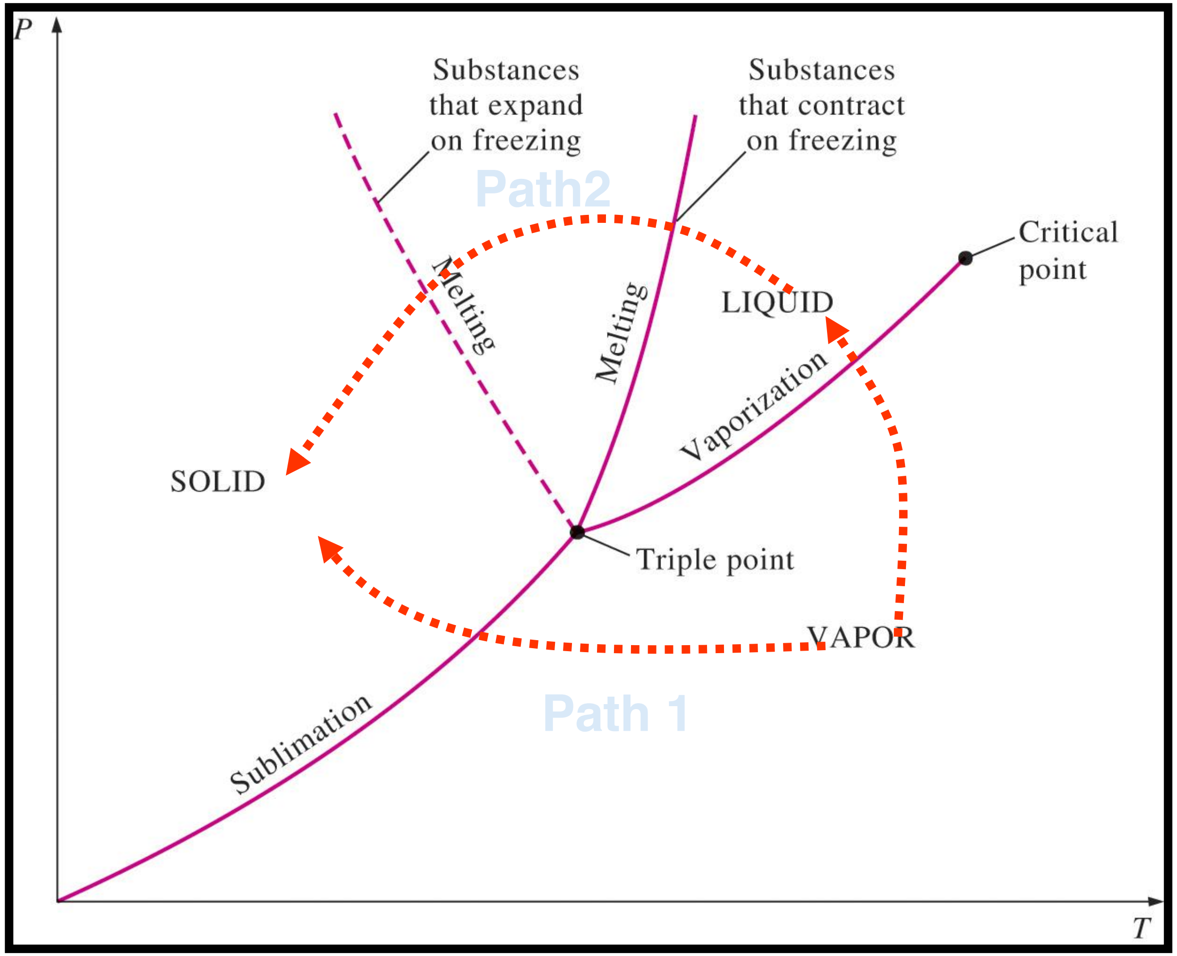
Point at which the saturated liquid and saturated vapor states are identical



For Water

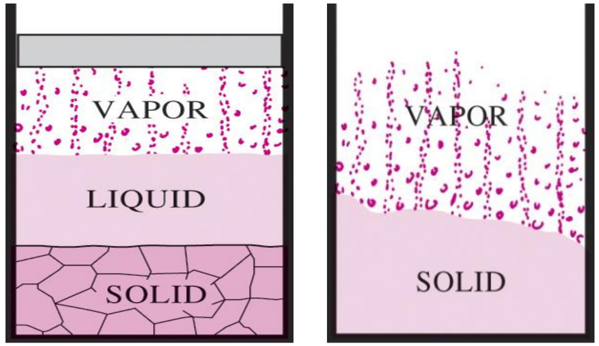
P_{cr}=22.06 MPa, T_{cr}=373.95°C, V_{cr}=0.003106 m^3/kg

The P-T Diagram



Paths a Substance passes from Solid to Vapor

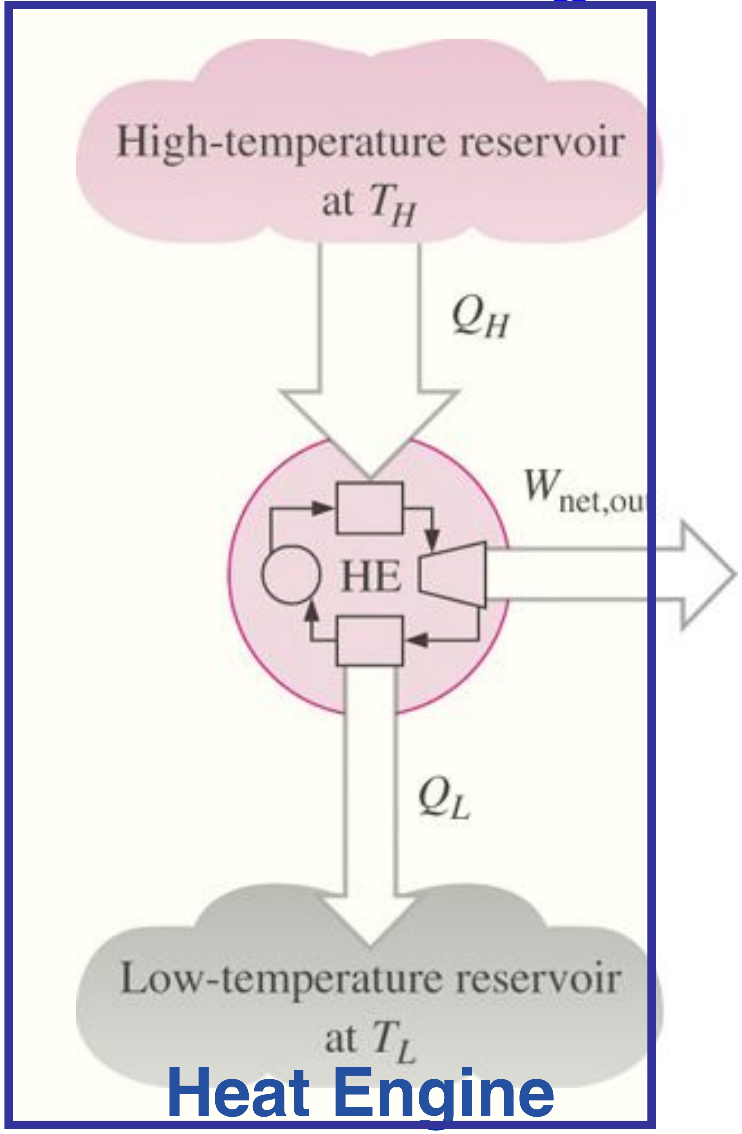
1. **Solid -> Vapor (We call this as SUBLIMATION)**
2. **Solid->Liquid->Vapor**



Triple Point

At triple-point pressure and temperature, a substance exists in three phases in equilibrium

Thermal efficiency for cyclic devices such as heat engines, refrigerators and heat pumps



Heat Engine

Always $\mu_{th} < 1$

$$\mu_{th} = \frac{W_{net,out}}{Q_H}$$

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

Here

$$W_{net,out} = Q_H - Q_L$$

Q_H = Magnitude of heat transfer between the cyclic device and the high-temperature medium at temperature T_H

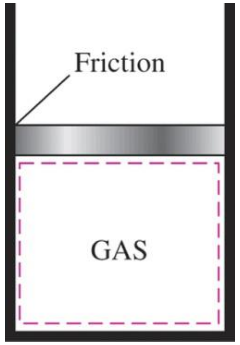
Q_L = Magnitude of heat transfer between the cyclic device and the low-temperature medium at temperature T_L

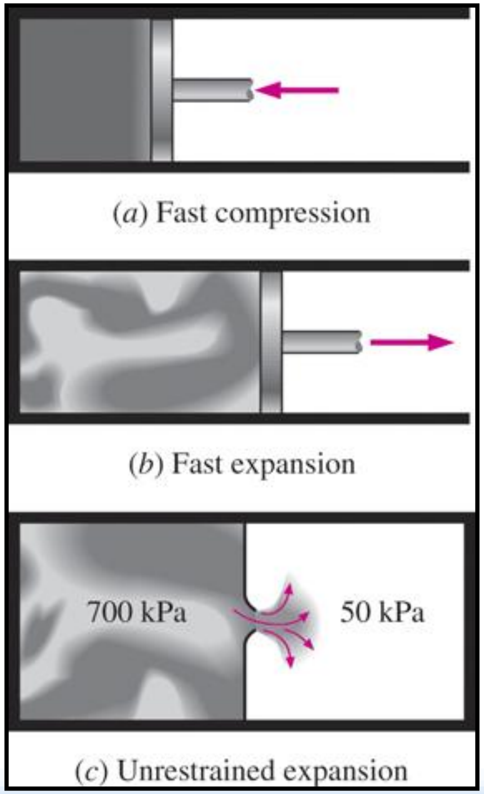
Irreversibilities

Factors that cause a process to be irreversible are called irreversibilites.

Factors

Friction
Unrestrained expansion
Mixing of two fluids
Electric Resistance
Inelastic deformation of Solids
Chemical Reactions
Heat transfer across a finite temperature difference





The Carnot Cycle

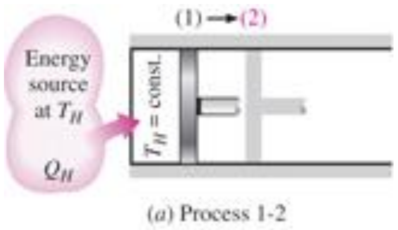
- **The Carnot cycle, first proposed in 1824 by French engineer Sadi Carnot.**

- **The Carnot Heat Engine: the *theoretical* heat engine that operates on the Carnot cycle.**

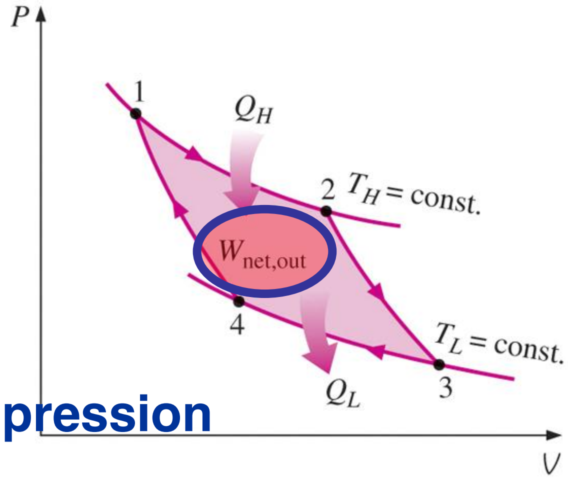
- **The Carnot Cycle: fully reversible and is composed of four processes, two isothermal and two adiabatic as given below.**

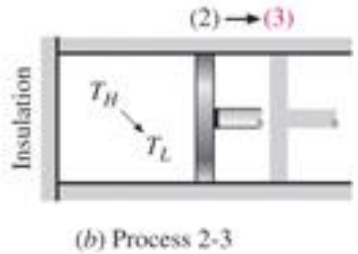
1. **Reversible Isothermal expansion**
2. **Reversible Adiabatic expansion**
3. **Reversible Isothermal Compression**
4. **Reversible Adiabatic Compression**

Carnot Heat Engine

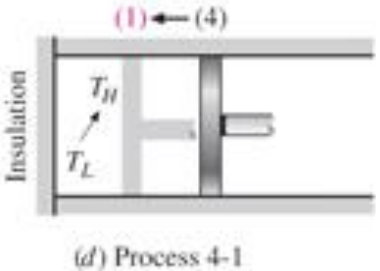


Reversible Isothermal expansion

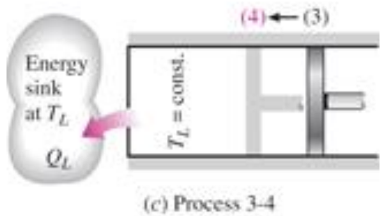




Reversible Adiabatic expansion



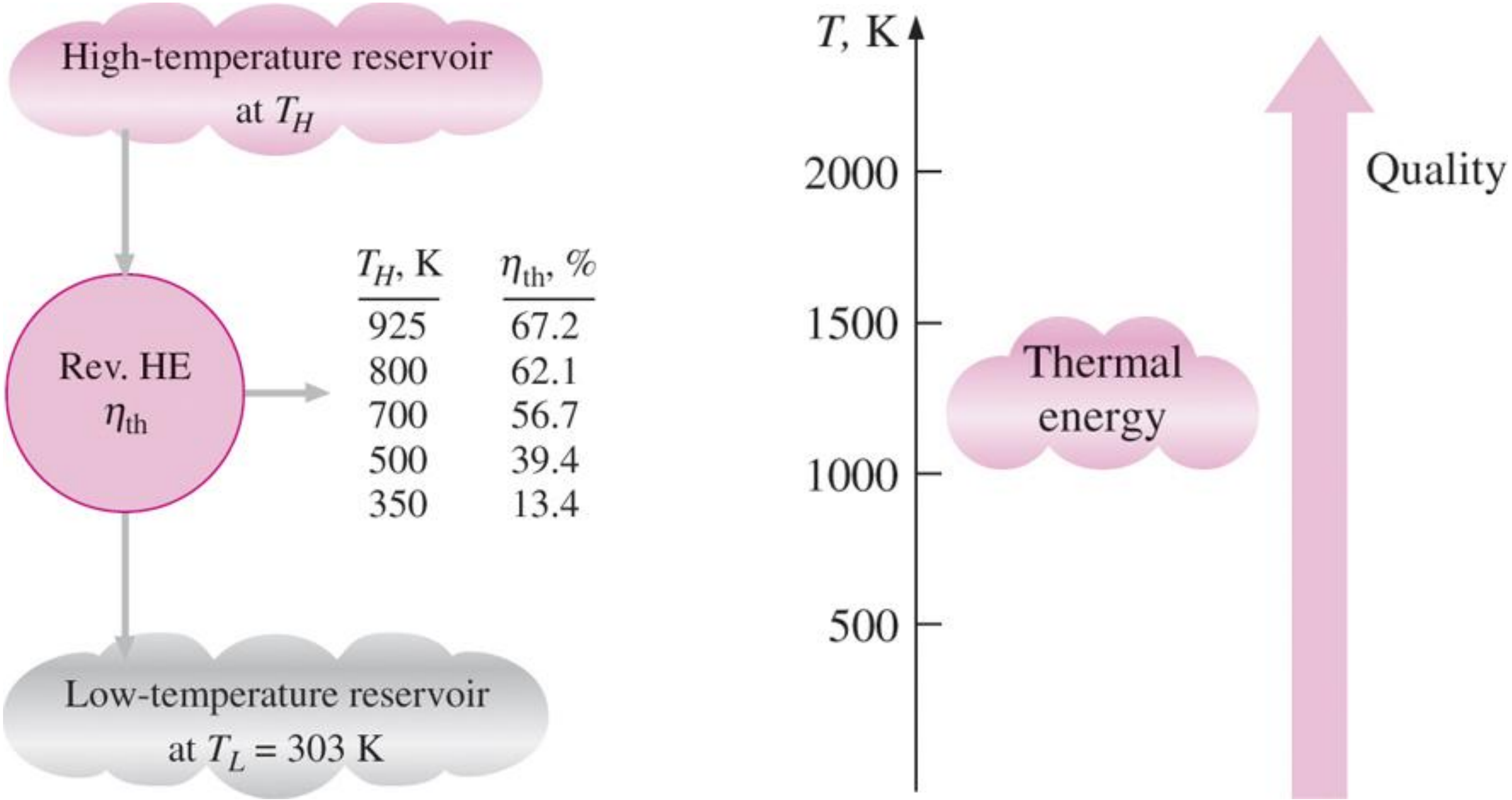
Reversible Adiabatic Compression



Reversible Isothermal Compression

Most efficient Cycle

Quality of Energy

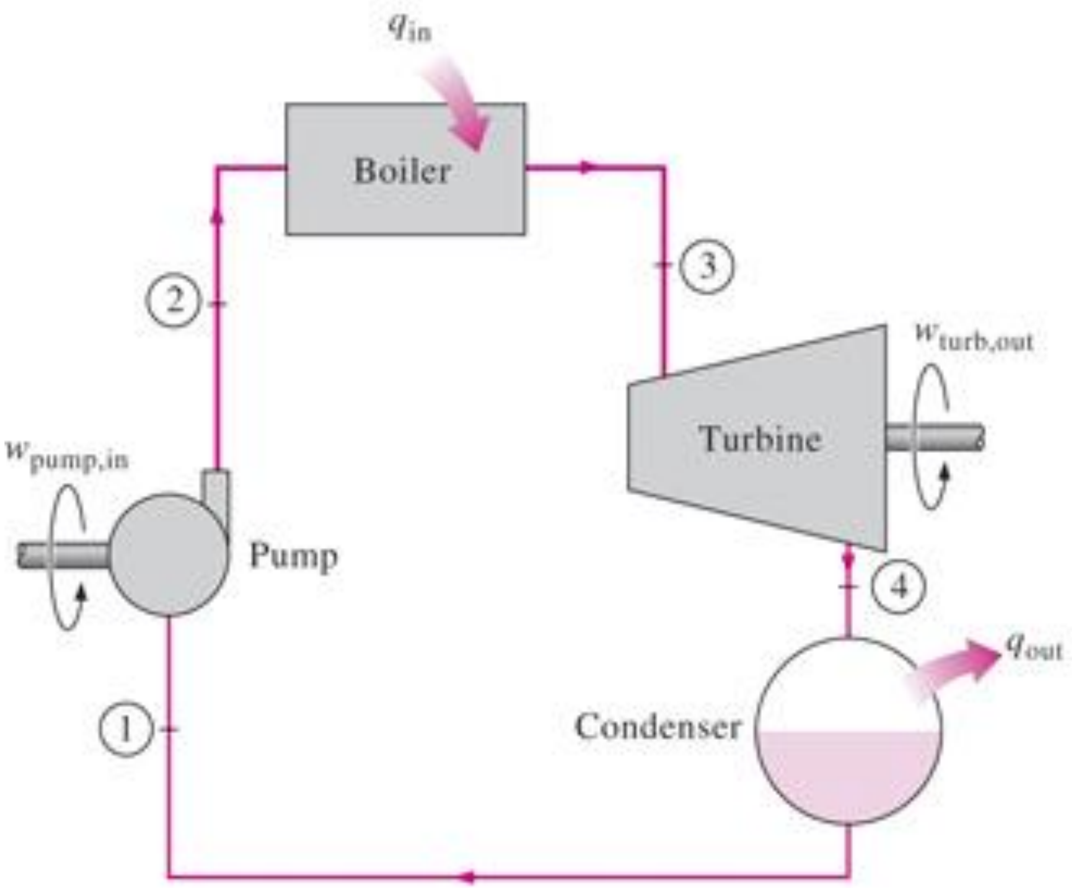


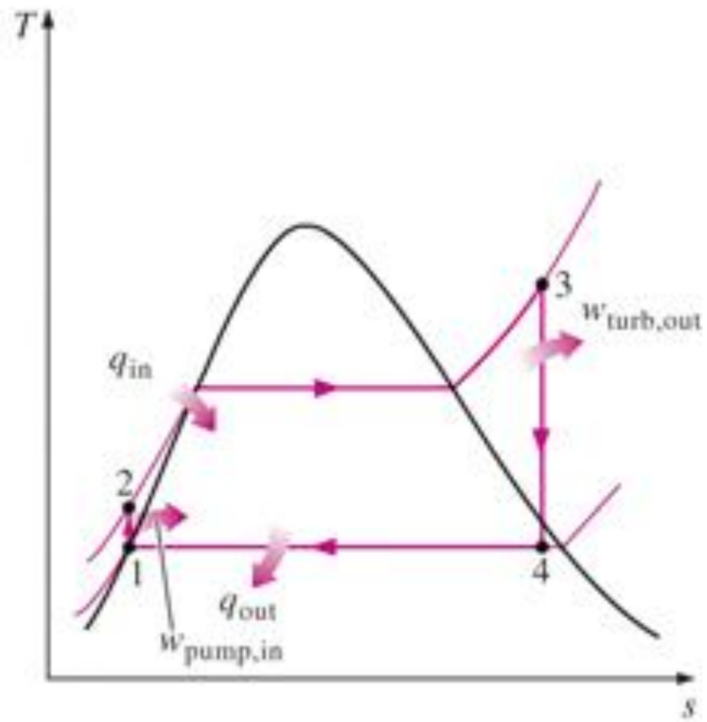
- **<u>Note:</u> Thermal efficiency values show that energy has Quality as well as quantity**

- **Higher the temperature higher the quality**

Part 2
Thermal Power Plants Thermodynamic Cycles

The simple ideal Rankine cycle





1-2 Isentropic compression in a pump

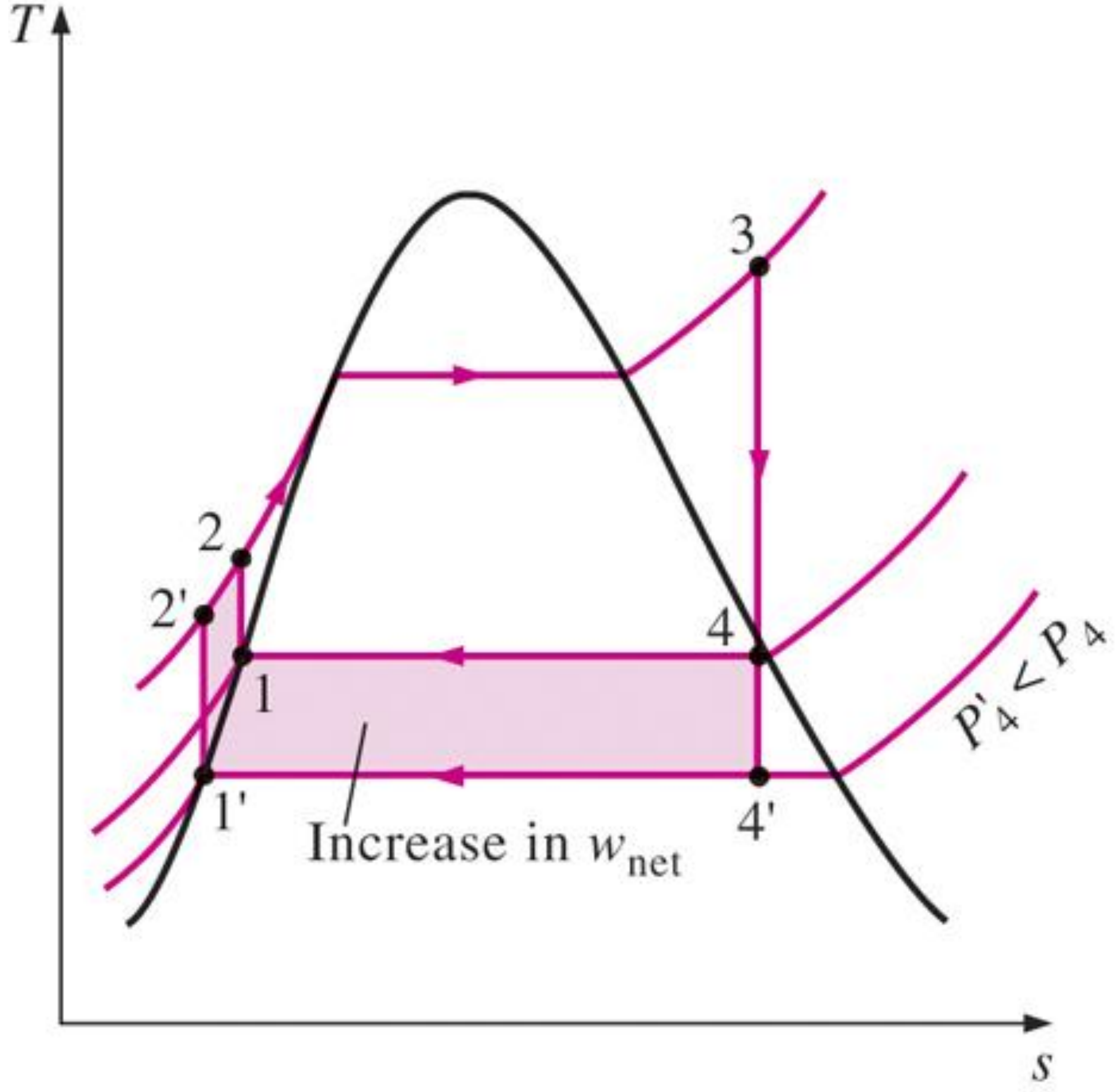
2-3 Constant pressure heat addition in a boiler

3-4 Isentropic expansion in a turbine

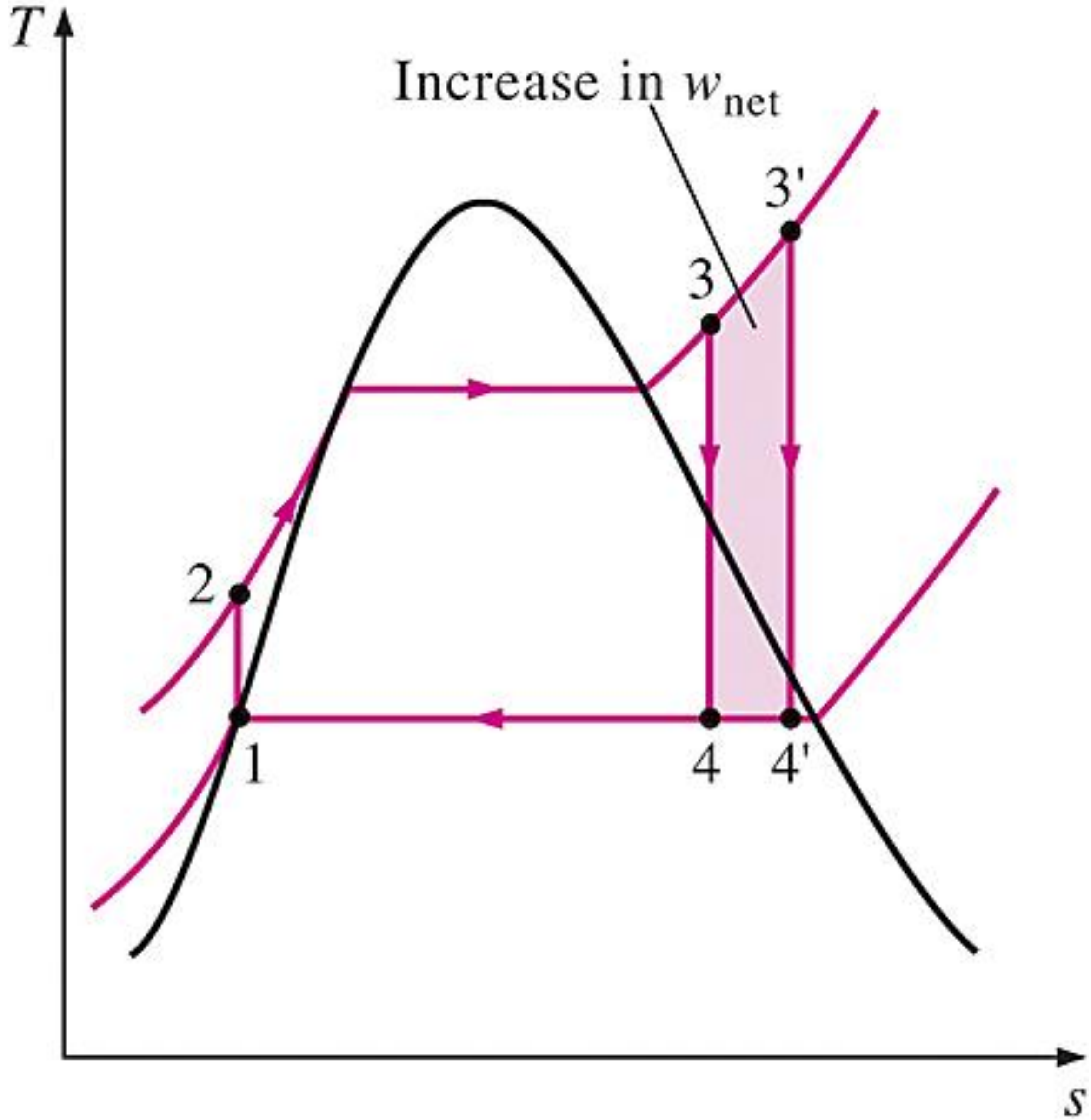
4-1 Constant pressure heat rejection in a condenser

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{W_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

Increasing the efficiency of the Rankine cycle

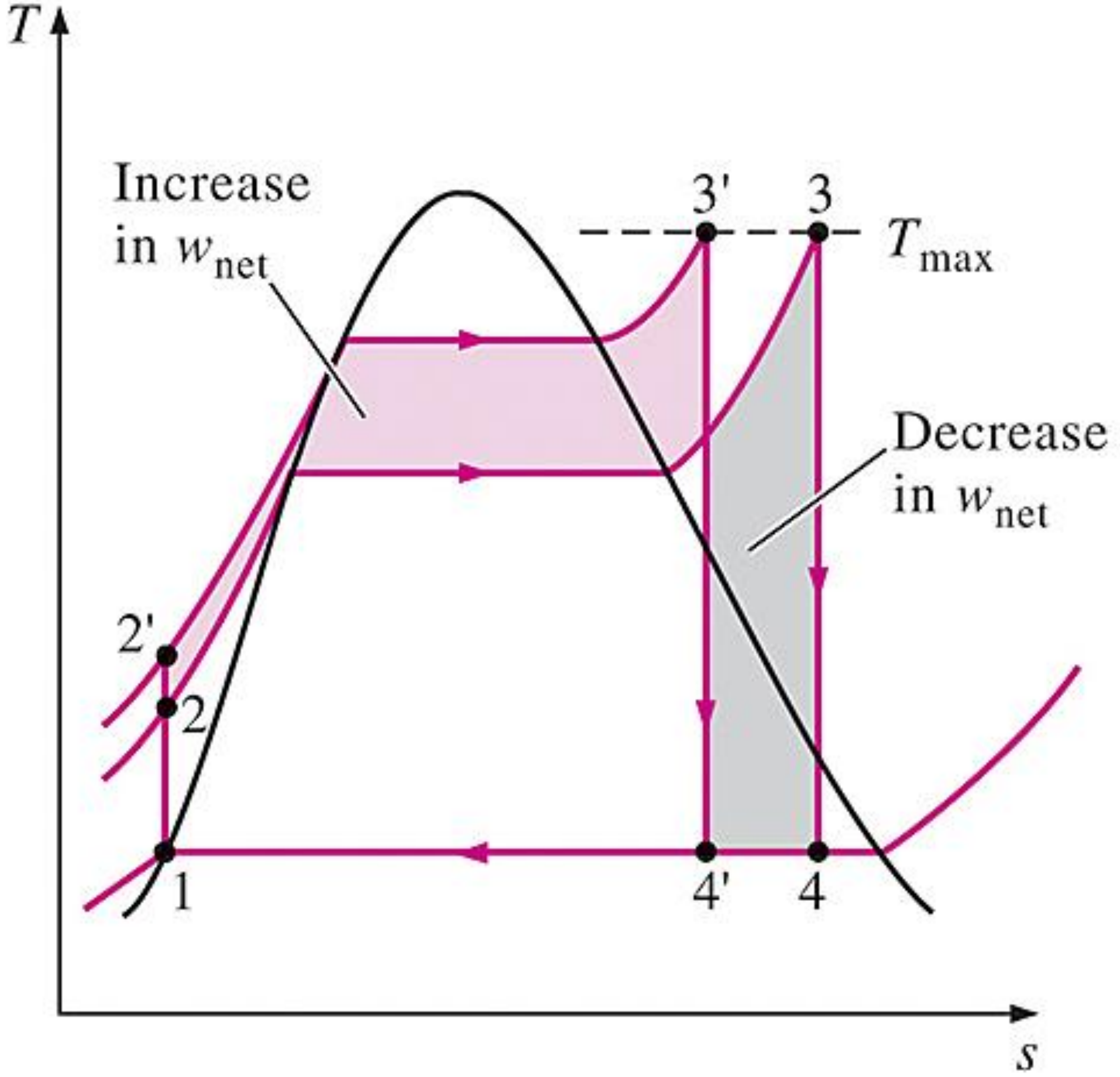


Increasing the efficiency of the Rankine cycle



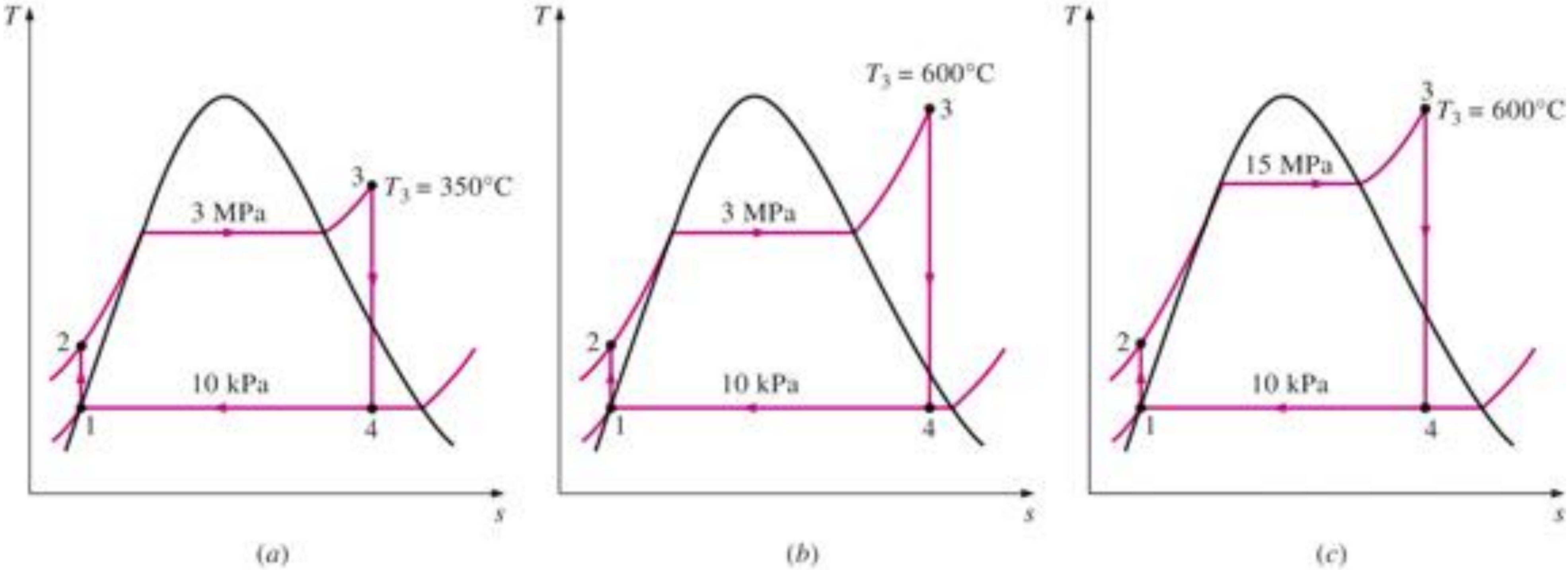
The effect of superheating the steam to higher temperatures on the ideal Rankine cycle

Increasing the efficiency of the Rankine cycle



The effect of increasing the boiler pressure on the ideal Rankine cycle

Increasing the efficiency of the Rankine cycle

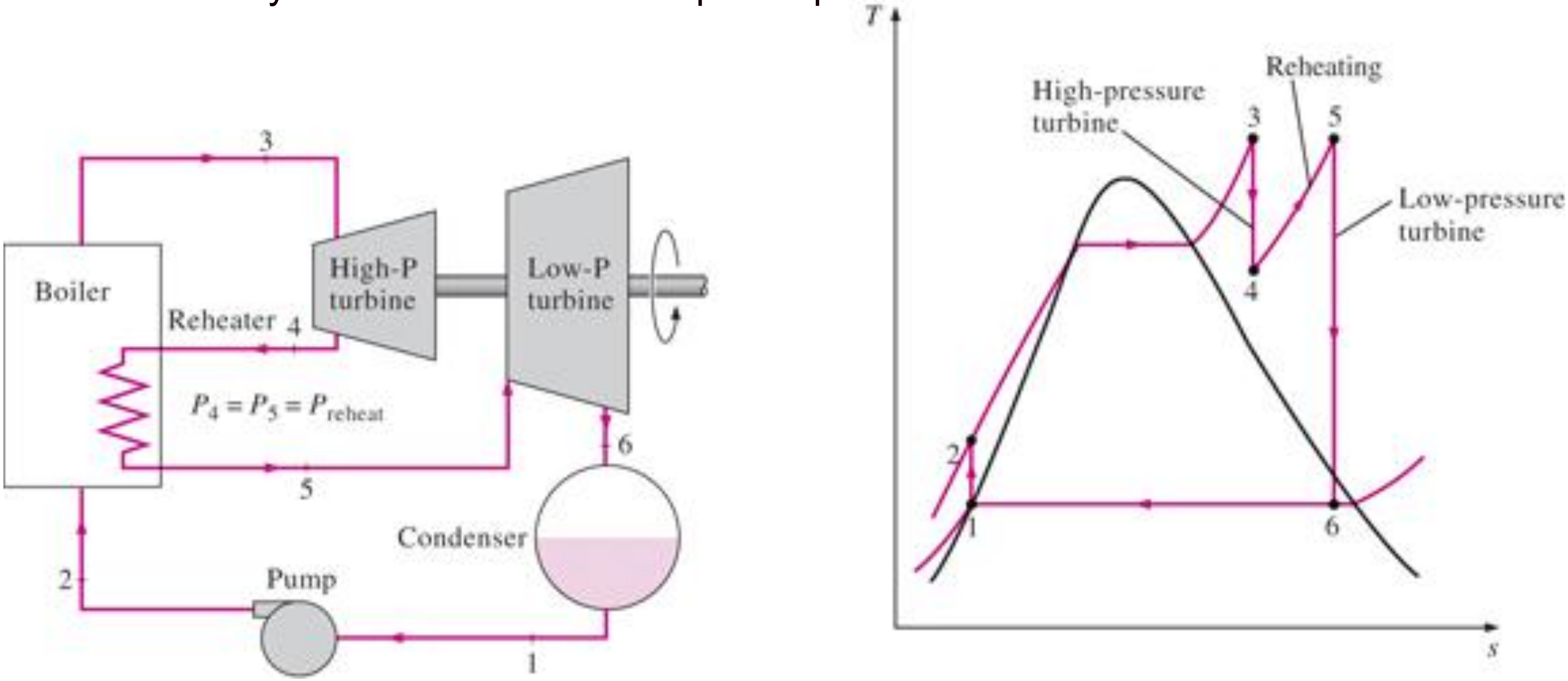


Thermal efficiency increases from 33.4% (a) to 37.3 (b) and to 43.0% (c)

Increasing the efficiency of the Rankine cycle

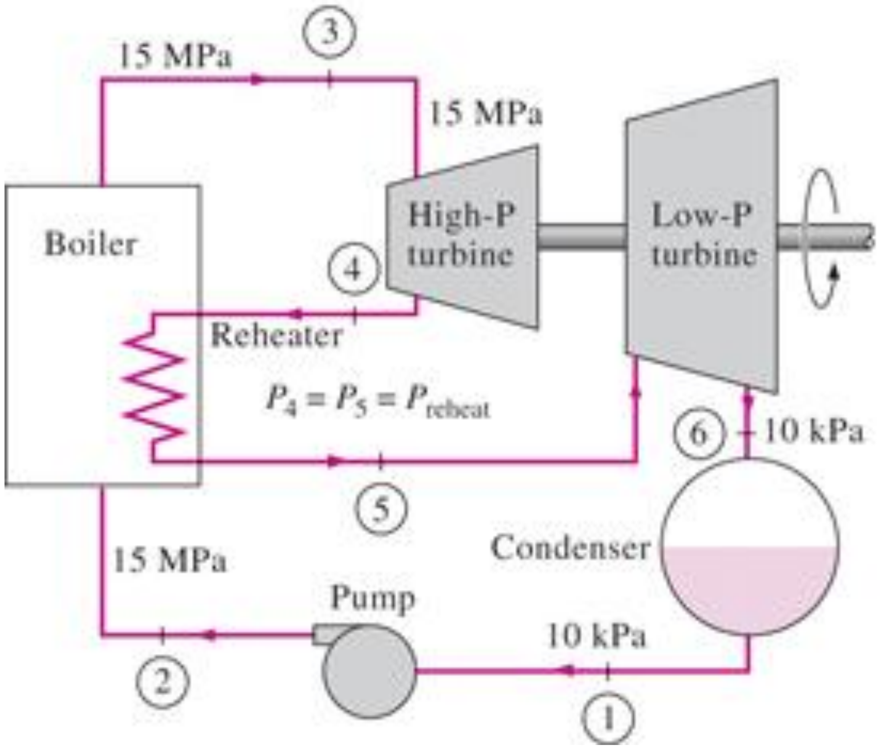
Two possibilities:

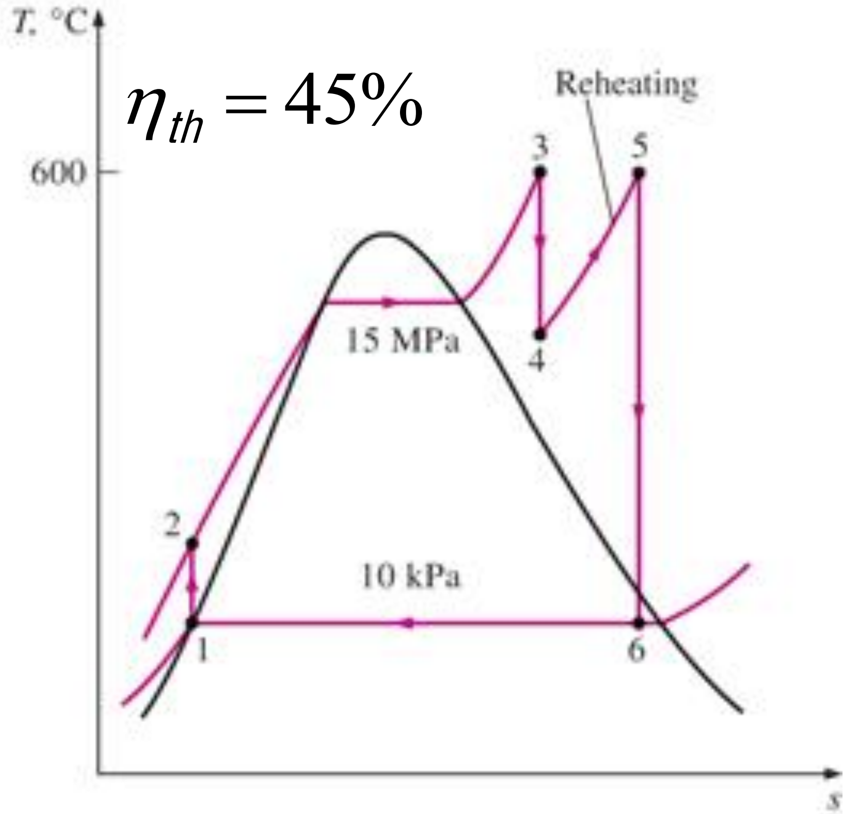
1. Superheat the steam to very high temperatures before it enters the turbine (problem – materials reliability at high temperatures).
2. Expand steam in the turbine in two stages, and reheat it in between. Reheating is a practical solution to the excessive moisture problem in turbines, and it is commonly used in modern steam power plants.



The ideal reheat Rankine cycle (thermal efficiency increases by 4-5%)

Increasing the efficiency of the Rankine cycle



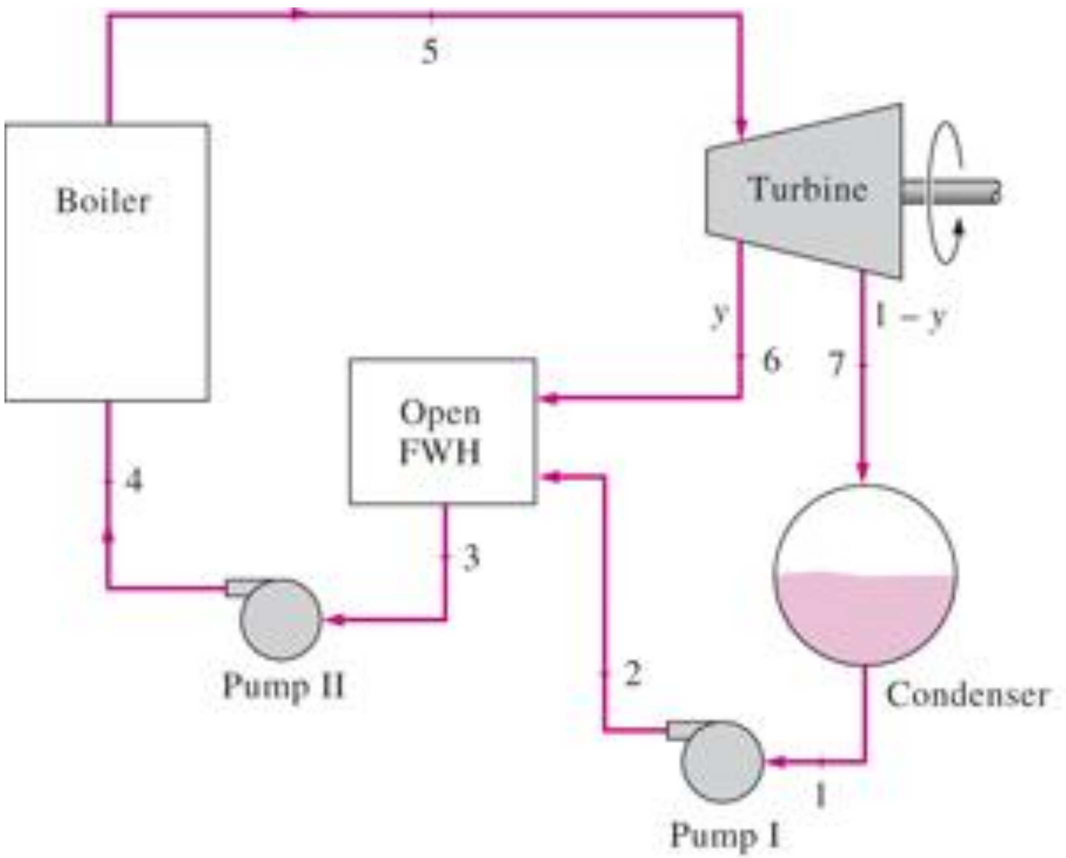


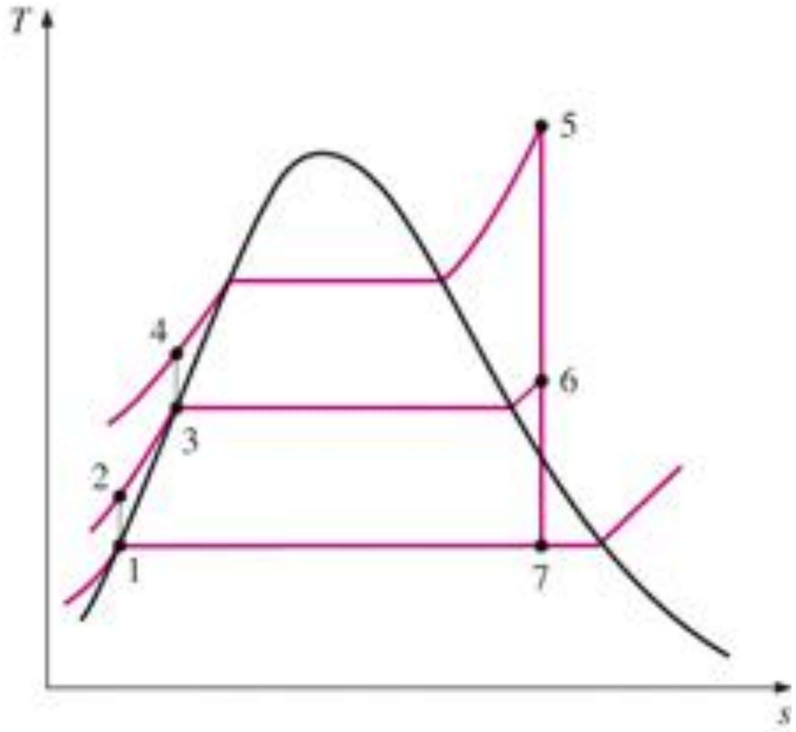
The reheat cycle was introduced in the mid-1920s, but was abandoned in the 1930s, because of operational difficulties. The steady increase in boiler pressures over the years made it necessary to reintroduce single reheat in the late 1940s and double reheat in the early 1950s.

The reheat temperatures are very close or equal to the turbine inlet temperature. The optimum reheat pressure is about one-fourth of the maximum cycle pressure.

The sole purpose of the reheat cycle is to reduce the moisture content of the steam at the final stages or the expansion process. If we had materials that could withstand sufficiently high temperatures, there would be no need for reheat cycle.

The ideal regenerative Rankine cycle



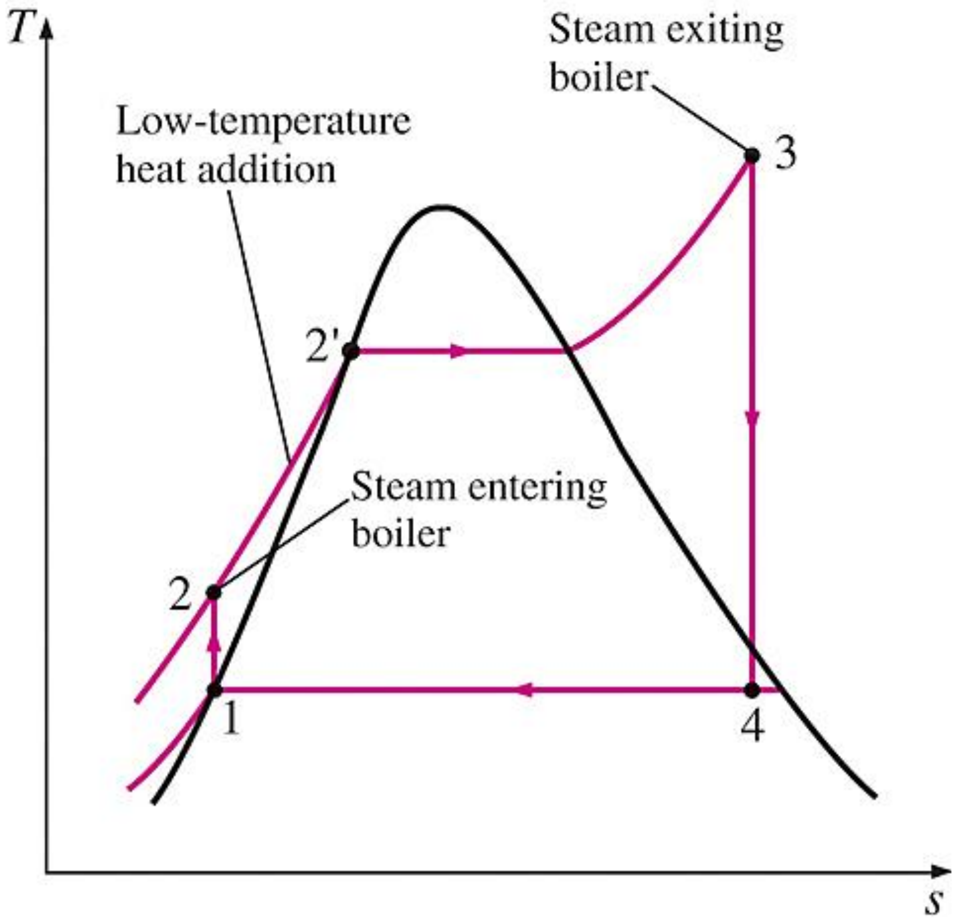


The ideal regenerative Rankine cycle with an open (direct-contact) feedwater heater. The thermal efficiency increases as a result of regeneration, because the regeneration raises the average temperature at which heat is transferred to the steam in the boiler by raising the temperature of the water before it enters the boiler. The cycle efficiency increases further as the number of feedwater heaters is increased (modern plants have up to eight heaters).

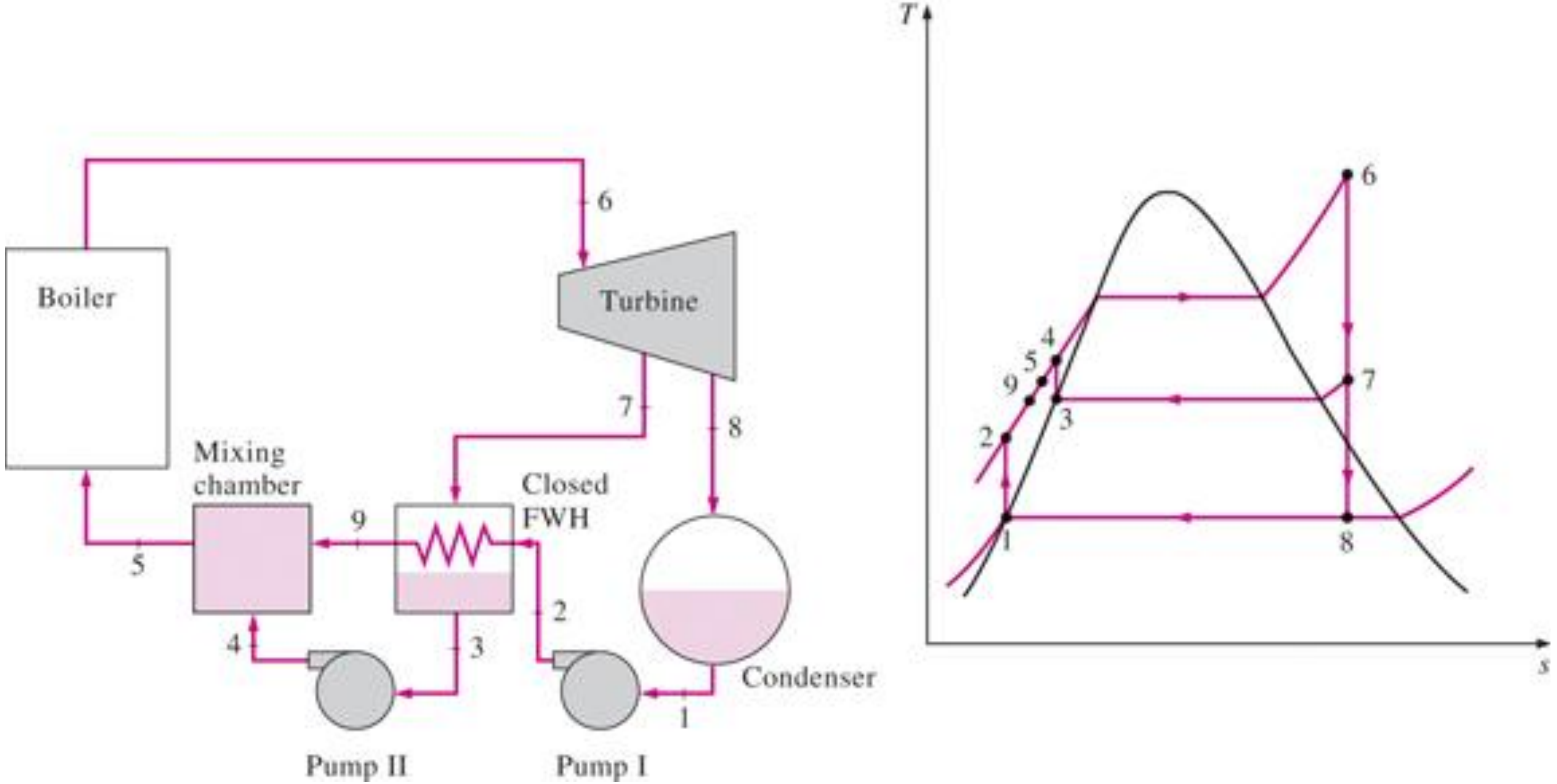
The ideal regenerative Rankine cycle

Ways to increase temperature of the feeding water before it enters the boiler:

1. Transfer heat to feed water from the expending steam in a counterflow heat exchanger built into the turbine, that is to use the regeneration. However, this solution is impractical because it is difficult to design such heat exchanger and it would increase the moister content of the steam at the final stages of the turbine.
2. Practical approach – extract or "bleed" steam from the turbine at various points. The device where the feedwater is heated by regeneration is a regenerator or a FeedWater Heater (FWH). Regeneration not only improves cycle efficiency, but also provides a convenient means deaerating the feedwater (removing air that leaks in at the condenser) to prevent corrosion in the boiler.



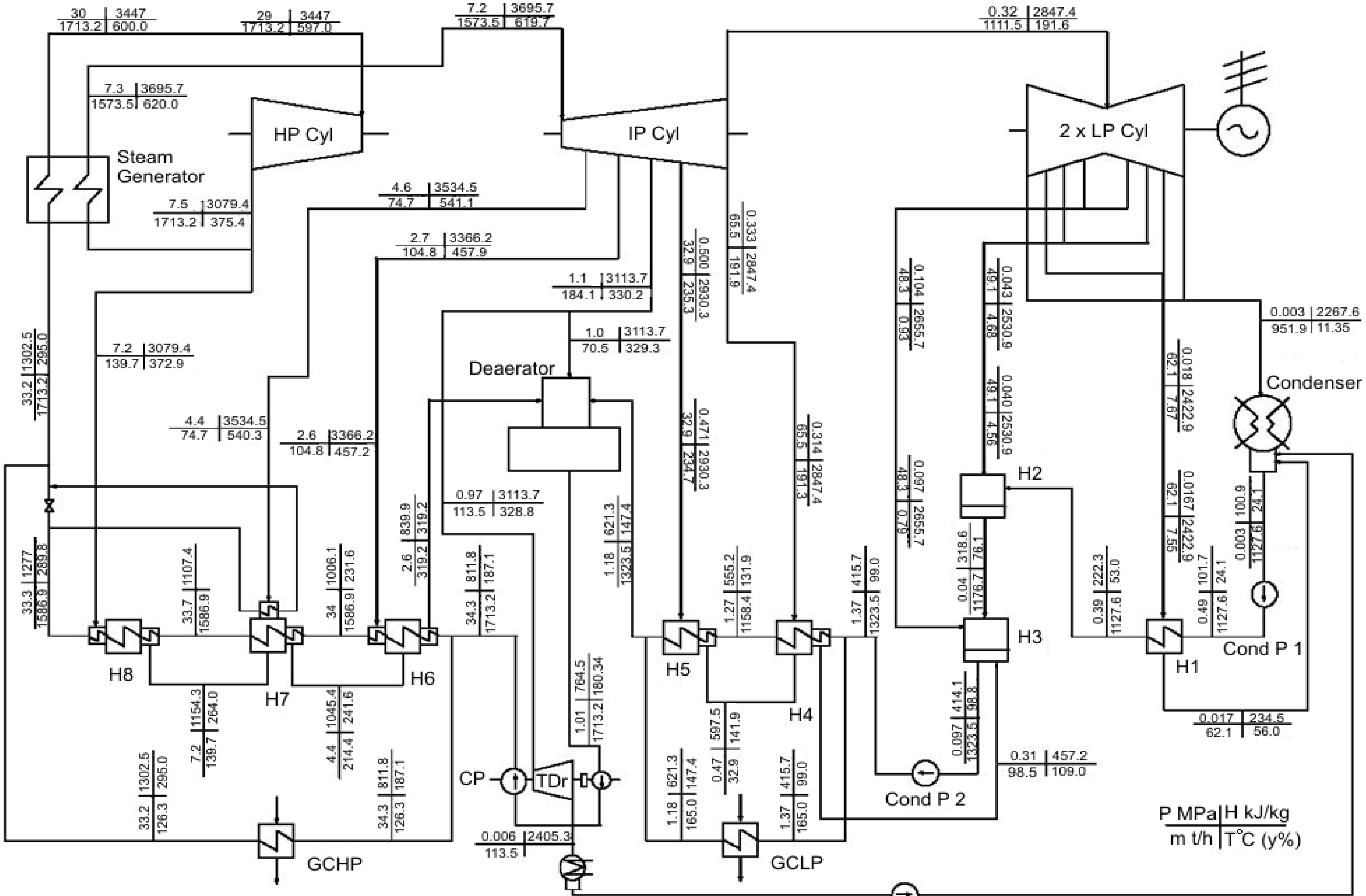
The ideal regenerative Rankine cycle



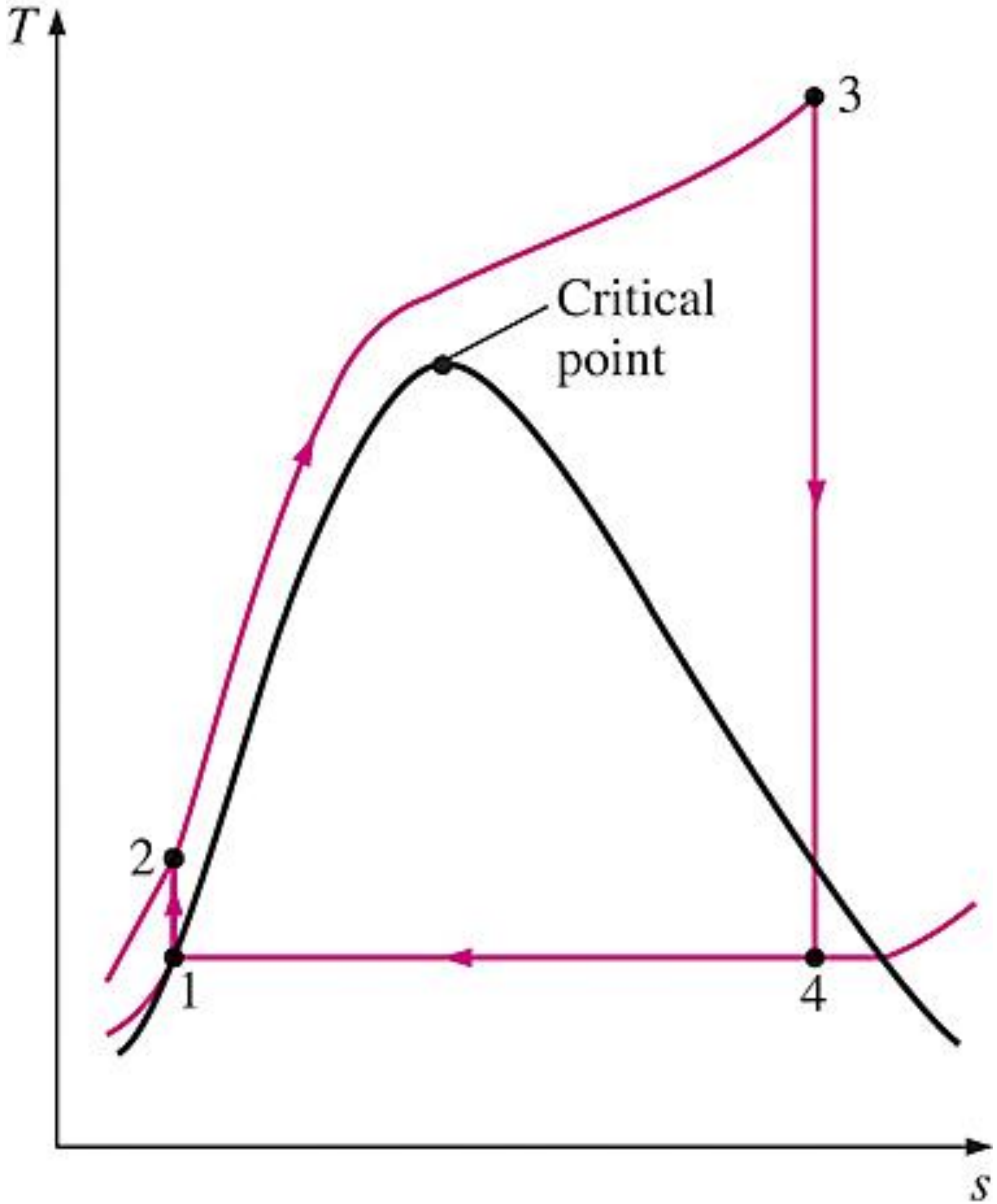
The ideal regenerative Rankine cycle with a closed feedwater heater.

Single-Reheat-Cycle 600-MW$_{el}$ Tom'-Usinsk Thermal Power Plant (Russia) Thermal Layout

Cyl – Cylinder; H – Heat exchanger (feedwater heater); CP – Circulation Pump; TDr – Turbine Drive; Cond P – Condensate Pump; GCHP – Gas Cooler of High Pressure; and GCLP – Gas Cooler of Low Pressure (Kruglikov et al., 2009)



Increasing the efficiency of the Rankine cycle



Increasing the efficiency of the Rankine cycle

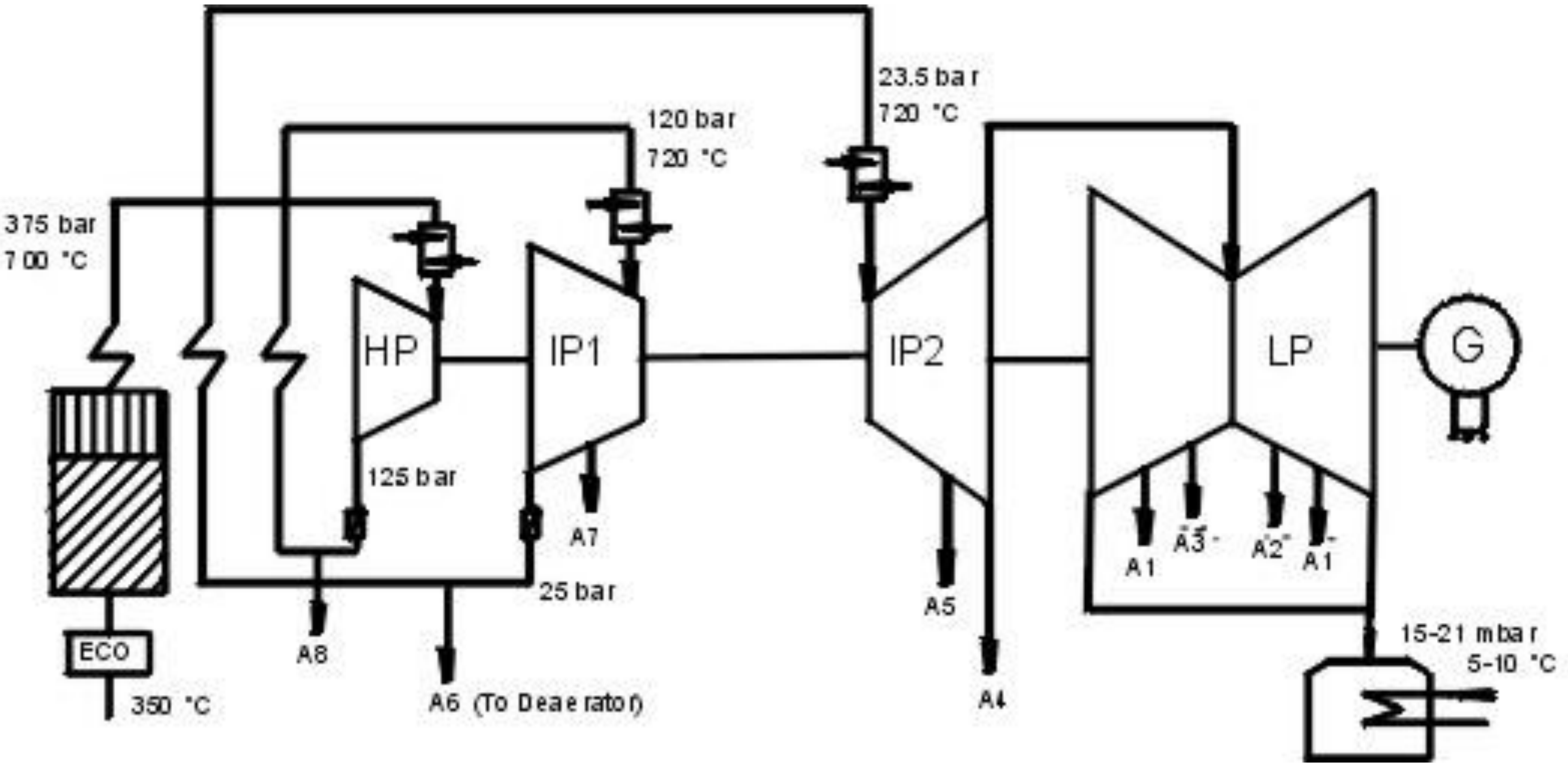
Steam parameters in modern supercritical turbines:
Main "steam": 28.5 MPa / 600°C
Reheat steam: 6 MPa / 620°C
Efficiency: 47%
Double pass reheat.

The High Pressure (HP) turbine design is based on a barrel-type concept so the HP turbine has no horizontal joint. The turbine sections use 12CrMoVCbN and similar Cr steels material to match the thermal expansion characteristics of the rotor material, using both forged 12CrMoVCbN and cast 10CrMoVCb or CrMoV steels.

Reheat limitations:

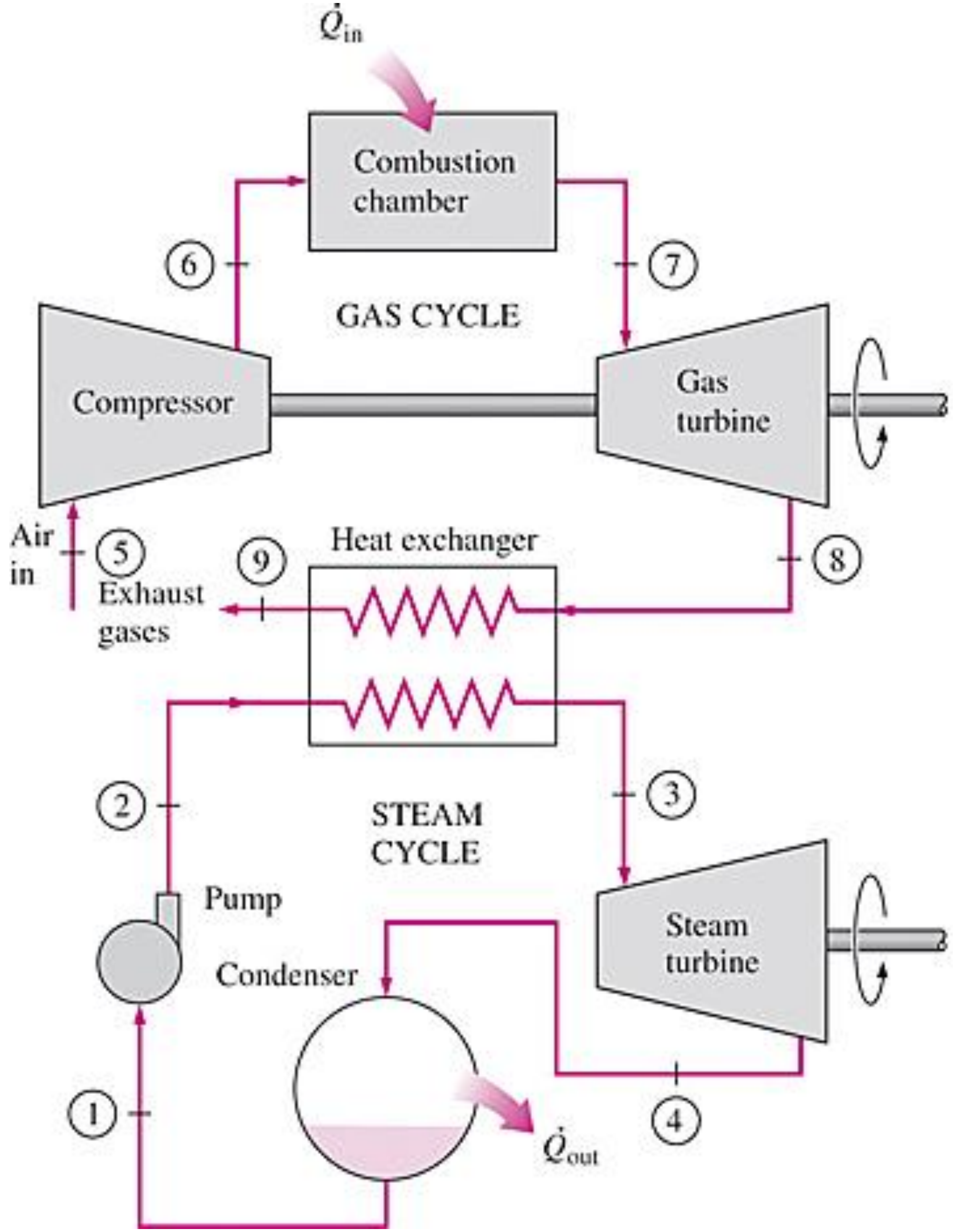
The use of more than two reheat stages is not practical. The theoretical improvement in efficiency from the second reheat is about half of that which results from a single reheat. If the turbine inlet pressure is not high enough, double reheat would result in superheated exhaust. This is undesirable as it would cause the average temperature for reheat rejection to increase and thus the cycle efficiency to decrease. Therefore, double reheat is used only on supercritical-pressure power plants.

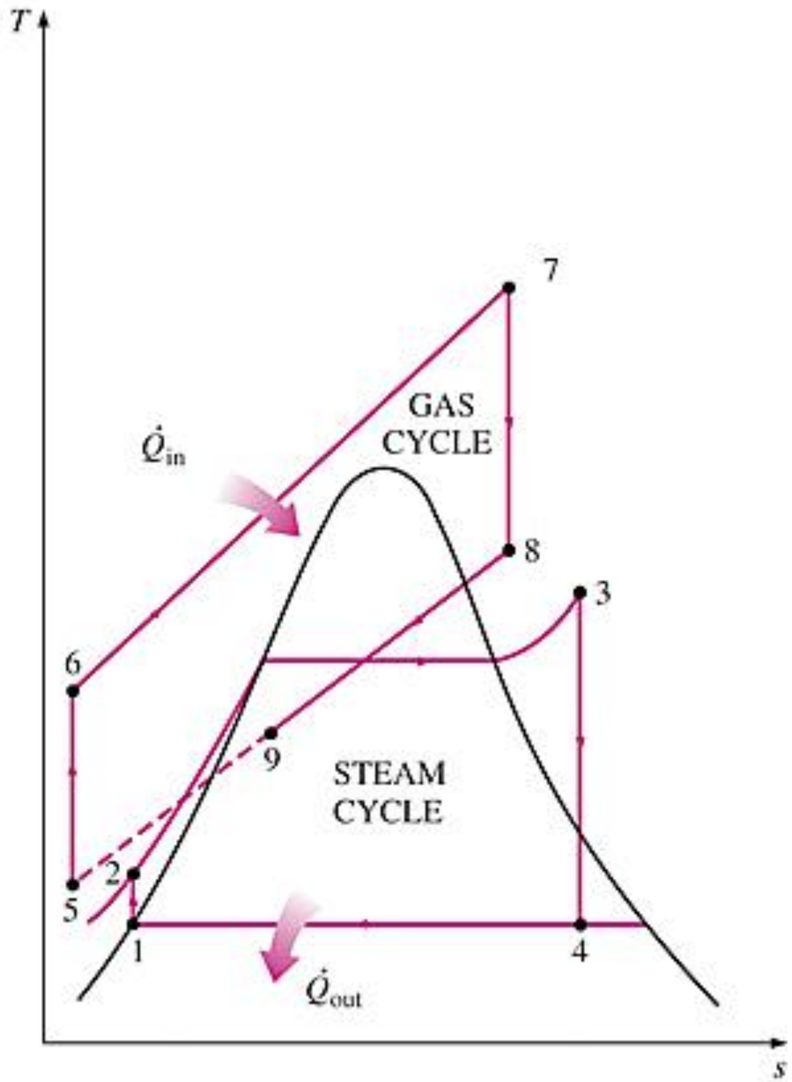
Increasing the efficiency of the Rankine cycle



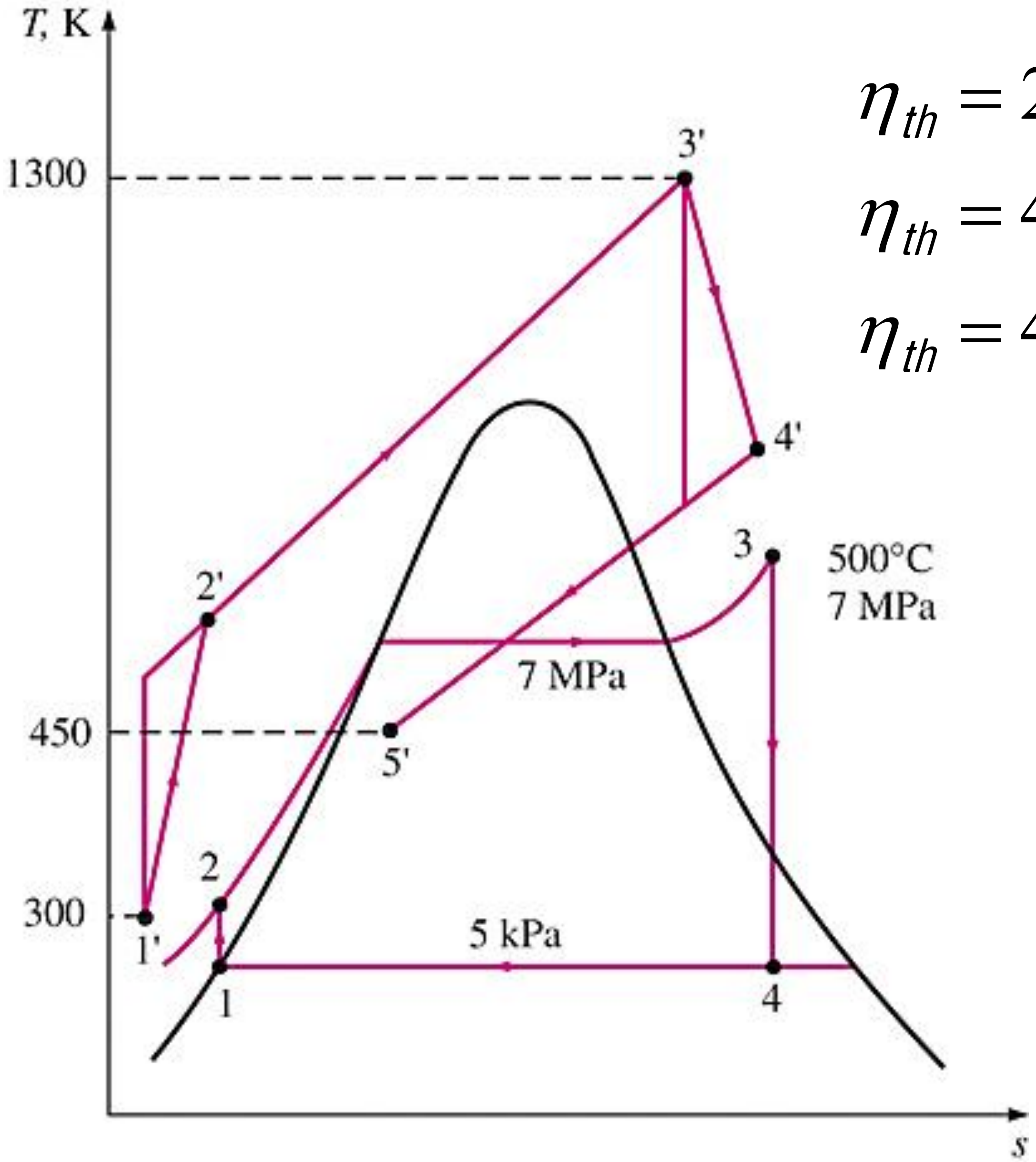
Advanced SC Power Plant of 2010 (Source: elsamprojekt.com)

Combined cycle gas-steam power plant





Example of actual combined-cycle power plant



$$\eta_{th} = 26.6\ \% \quad - \quad \text{gas cycle}$$

$$\eta_{th} = 40.8\ \% \quad - \quad \text{steam cycle}$$

$$\eta_{th} = 48.7\ \% \quad - \quad \text{combined cycle}$$

Examples of actual combined-cycle power plants

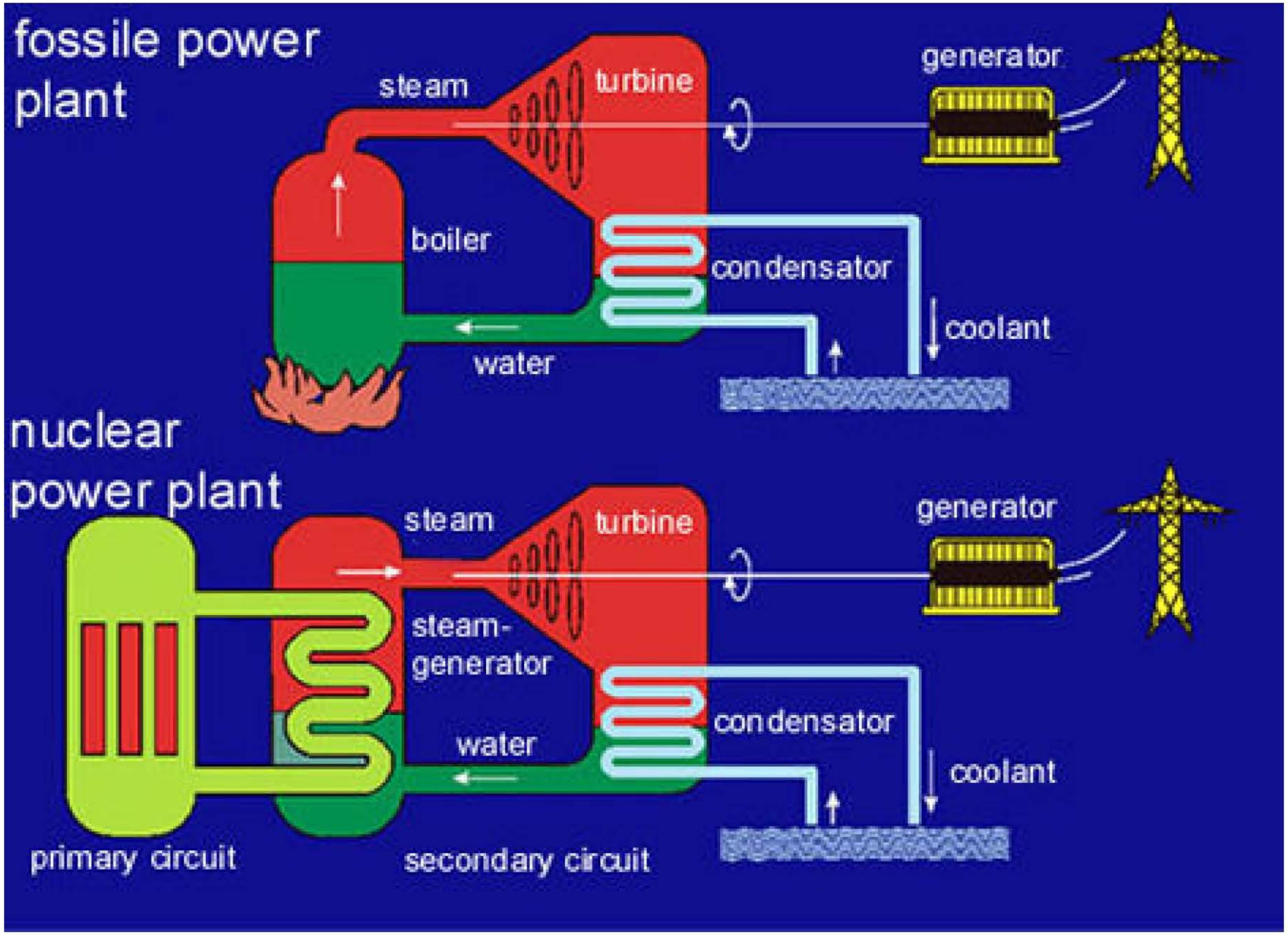
A 1090-MW Tohoku combined plant built in Japan in 1985 has efficiency of 44%. This plant has two-191-MW steam turbines and six 118-MW gas turbines. Hot combustion gases enter the gas turbine at 1154^{o}C, and steam enters steam turbines at 500^{o}C. Steam is cooled in the condenser by cooling water at an average temperature of 15^{o}C. The compressors have a pressure ratio of 14.

A 1350-MW combined-cycle power plant built in Turkey in 1988 by Siemens of Germany has efficiency of 52.5%. This plant has six 150-MW gas turbines and three 173-MW steam turbines.

Some modern combined-cycle power plants have efficiencies close to 60%.

Part 3
Subcritical-pressure water-cooled power-reactors cycles
(next slides are courtesy of AECL)

Nuclear-electric generation

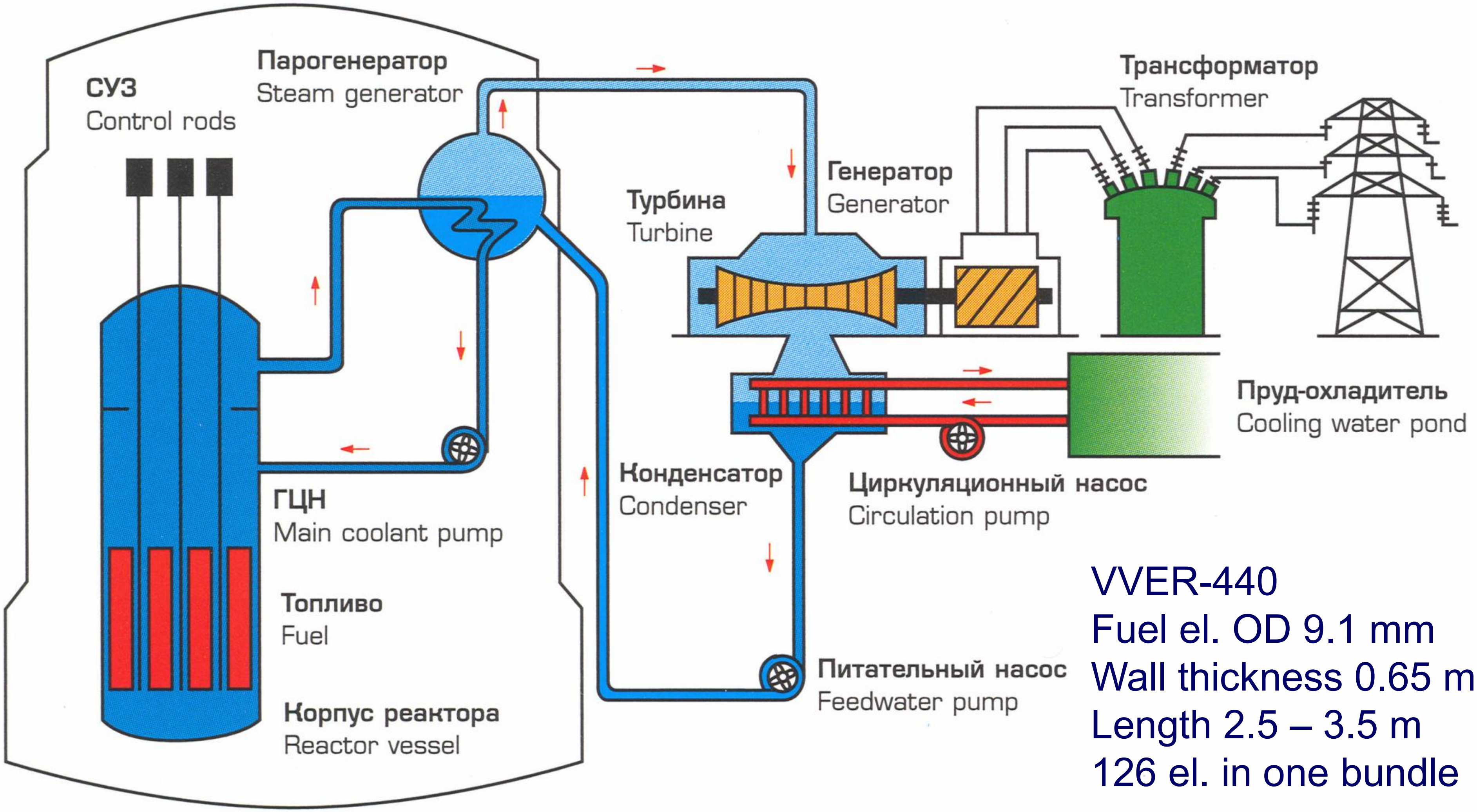


Courtesy of Professor G. Bereznai, UOIT

Реактор ВВЭР – отпуск электроэнергии потребителю

Reactor VVER – Electricity to the consumer

PWR-type reactor



VVER-440
Fuel el. OD 9.1 mm
Wall thickness 0.65 mm
Length 2.5 – 3.5 m
126 el. in one bundle

Major Parameters of Russian Power Reactors

Parameter	VVER-440	VVER-1000	RBMK-1000	RBMK-1500	BN-600
Thermal power, MW	1375	3000	3200	4800	1500
Electrical power, MW	440	1000	1000	1500	600
Thermal efficiency, %	32.0	33.3	31.3	31.3	40.0
Coolant P, MPa	12.3	15.7	6.9	6.9	~0.1
Coolant flow, t/h	40,800	84,800	32,000	48,000	25,000
Coolant T, °C	270/298	290/322	284	284	380/550
Thermodynamic cycle	Indirect*	Indirect*	Direct	Direct	Indirect*
Steam flow rate, t/h	2700	5880	5600	8400	660
Steam pressure, MPa	4.3	5.9	6.6	6.6	14.0
Steam T, °C	256	276	280	280	505
Core: D/H m/m	3.8/11.8	4.5/10.9	11.8/7	11.8/7	2.1/0.75

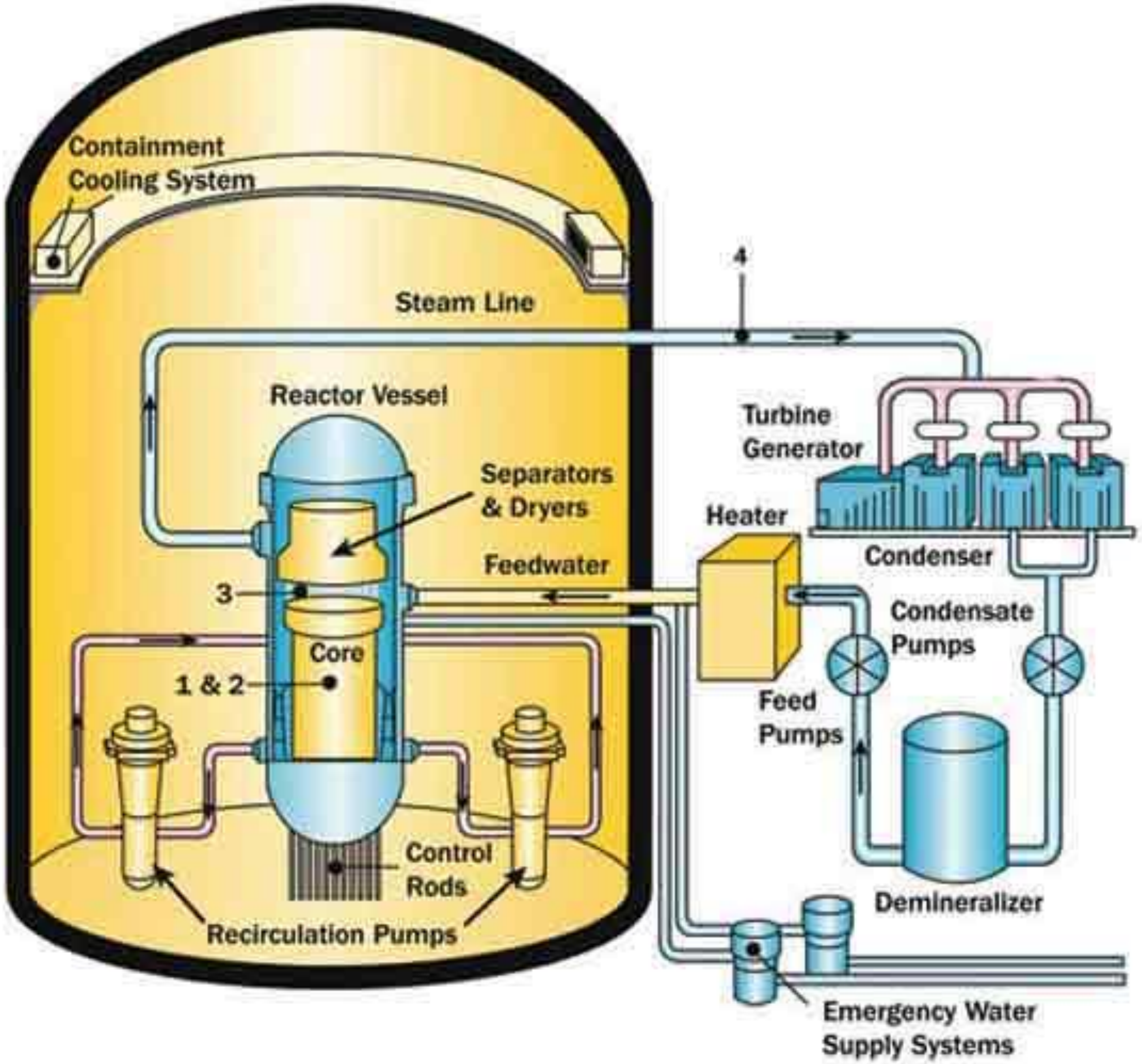
VVERs are PWRs; RBMKs are pressure-channel boiling reactors (outlet fuel-channel steam quality is 14% (maximum 30%) (in BWRs - about 10%); BNs are sodium-cooled fast reactors.
Usually, turbines consist of a high-pressure cylinder and 2-3 low-pressure cylinders with a single steam reheat / moisture separator in between them for higher efficiency. * Indirect - with a steam generator.

Typical parameters of US PWR (Shultis, J.K. and Faw, R.E., 2007)

Power		Steam generators	
Thermal output, MW_{th}	3800	No.	4
Electrical output, MW_e	1300	P_{out}, MPa	6.9
Thermal efficiency, %	34	T_{out}, ^oC	284
Core		m, kg/s	528
Length, m	4.17		
OD, m	3.37		
Reactor coolant system		**Reactor PV**	
P, MPa	15.5	OD, m	4.4
T_{in}, ^oC	292	Height, m	13.6
T_{out}, ^oC	329	Wall thickness, m	0.22
Mass flow rate (m), kg/s	531		

Usually, turbines consist of a high-pressure cylinder and 2-3 low-pressure cylinders with a single steam reheat / moisture separator in between them for higher efficiency.

Boiling Water Reactor (BWR)

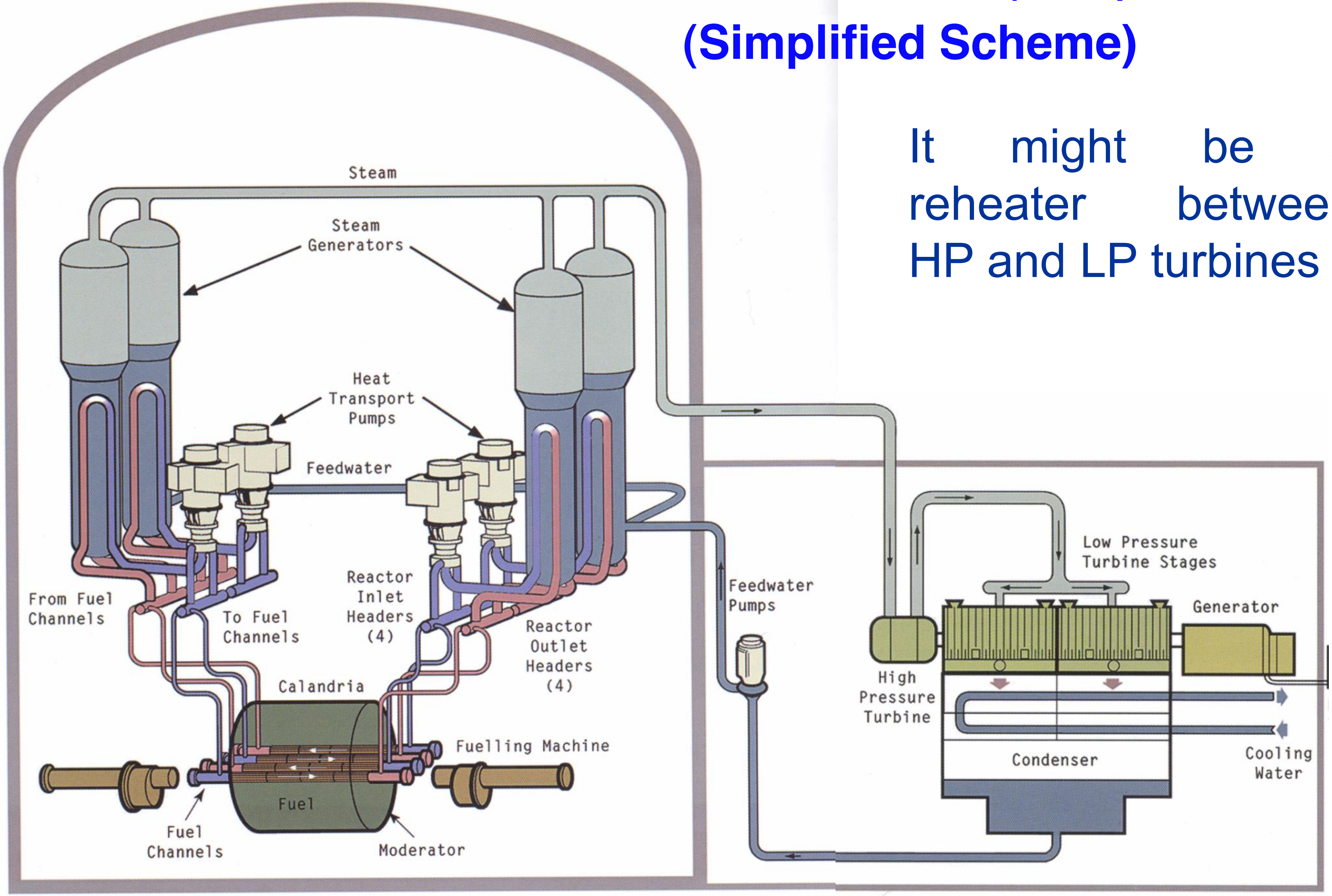


Typical parameters of US BWR (Shultis, J.K. and Faw, R.E., 2007)

Power		**Reactor coolant system**	
Thermal output, MW_{th}	3830	**Reactor coolant system**	
Electrical output, MW_{el}	1330	P, MPa	7.17
Thermal efficiency, %	34	$T_{feedwater}$, °C	216
Core		$T_{out\ steam}$, °C	290
Length, m	3.76	Outlet steam flow rate, kg/s	2083
OD, m	4.8	Core flow rate, kg/s	14,167
Reactor PV		Core void fraction ave/max	0.37/0.75
ID, m	6.4	Direct cycle	
Height, m	22.1		
Wall thickness, m	0.15		

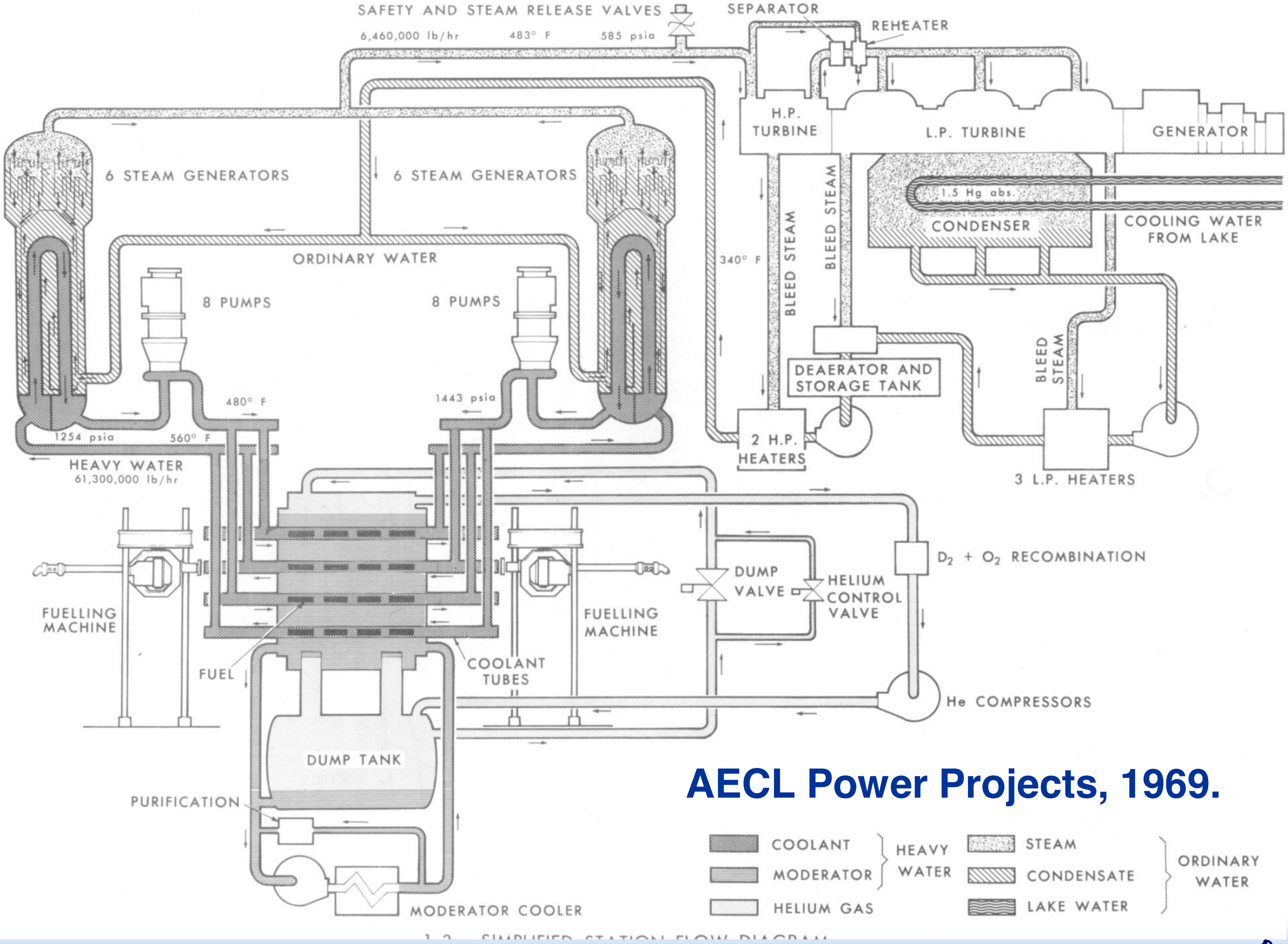
Usually, turbines consist of a high-pressure cylinder and 2-3 low-pressure cylinders with a single steam reheat / moisture separator in between them for higher efficiency.

CANDU-6 Nuclear Power Plant (NPP)
(Simplified Scheme)



It might be a reheater between HP and LP turbines

Current CANDU-6 NPP Layout (Pickering NPP)



AECL Power Projects, 1969.

Heat Transport System Design Data

Reactor outlet header pressure [MPa (g)]	9.9
Reactor outlet header temperature [°C]	310
Reactor inlet header pressure [MPa (g)]	11.2
Reactor inlet header temperature [°C]	260
Single-channel flow (maximum) [kg/s]	28

Heat Transport Pump Data

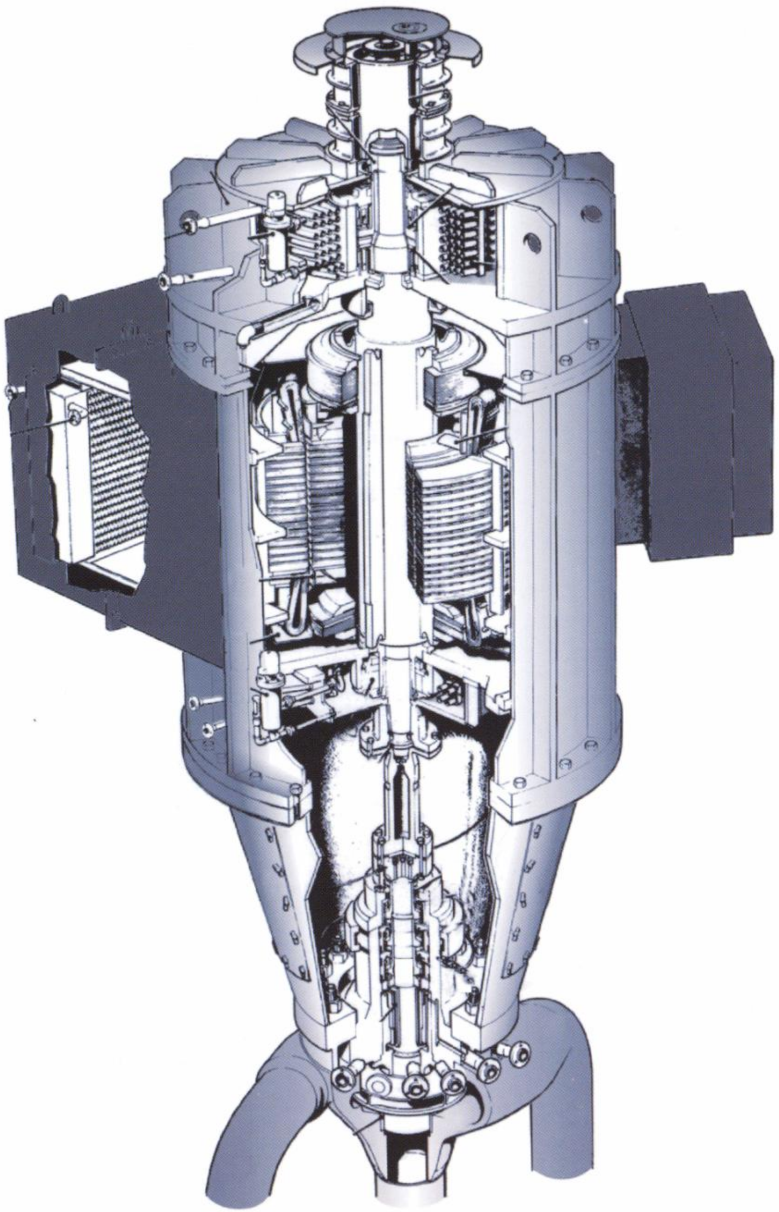


Figure 2-7 Heat Transport System Pump

Number	4
Rated flow [L/s]	2228
Motor rating [MWe]	6.7

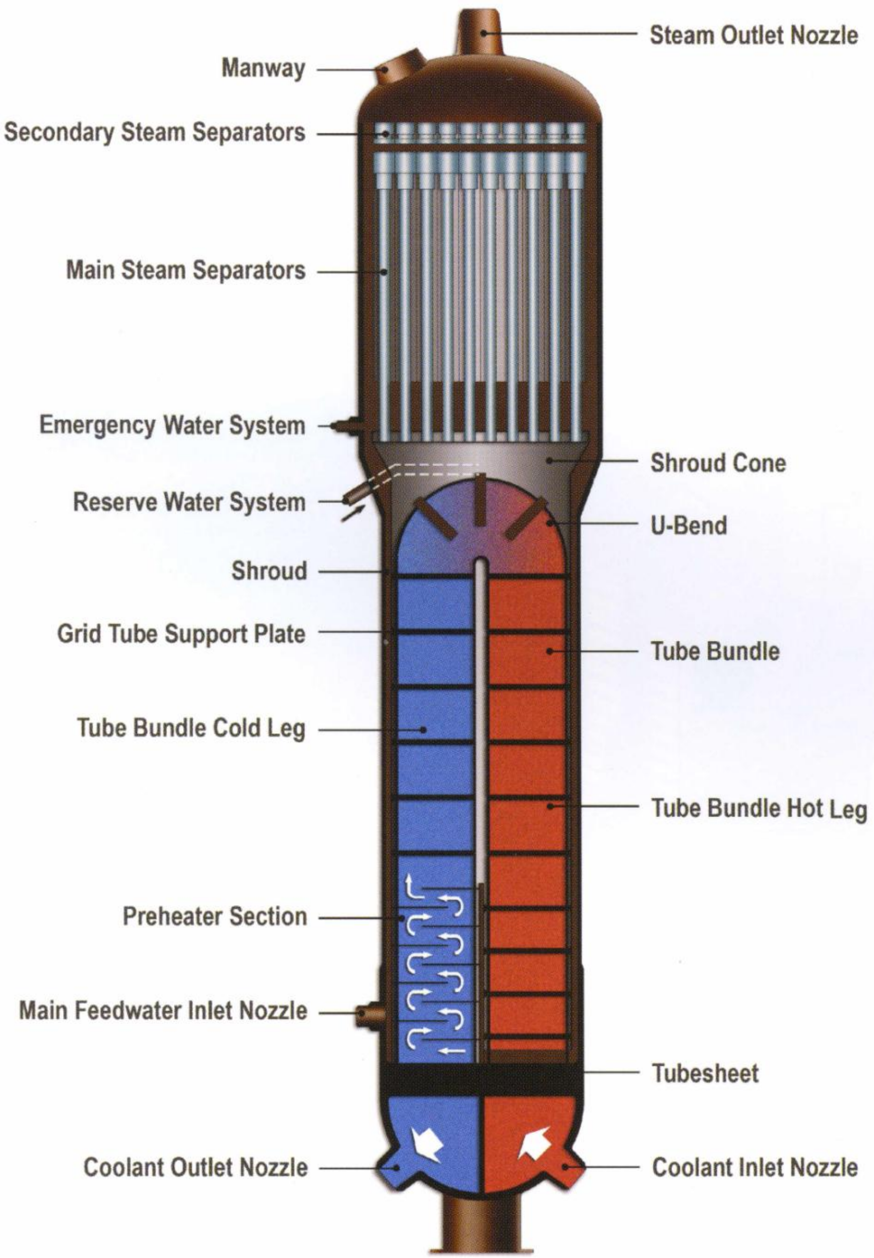


Figure 2-8 Steam Generator

Steam Generator Design Data

Number	4
Type	Vertical U-tube / integral preheater
Nominal Tube diameter [mm]	15.9 (5/8")
Steam temperature (nominal) [°C]	260
Steam pressure [MPa (g)]	4.6

CANDU NPP thermal efficiency about 30%

Figure 2-18 Qinshan Low-Pressure Turbine Rotor

Steam Turbine Type	Hitachi impulse-type, tandem-compound
Steam Turbine Composition	One high-pressure cylinder, two low-pressure cylinders
Net thermal output to turbine (MWth)	2080
Gross/Net electrical output* (nominal) [MWe]	740*/690
Steam temperature at main stop valve [°C]	257 @ 4.5 MPa
Final feedwater temperature [°C]	187
Condenser Vacuum [kPa (a)]	4.9

(*) Site cooling water dependent