Nuclear Reactor Technology, SH2702

Lecture No4

Title:
Nuclear Power Plants – Balance of Plant Systems

Spring 2023

Division of Nuclear Engineering
Royal Institute of Technology (KTH)
Stockholm, Sweden

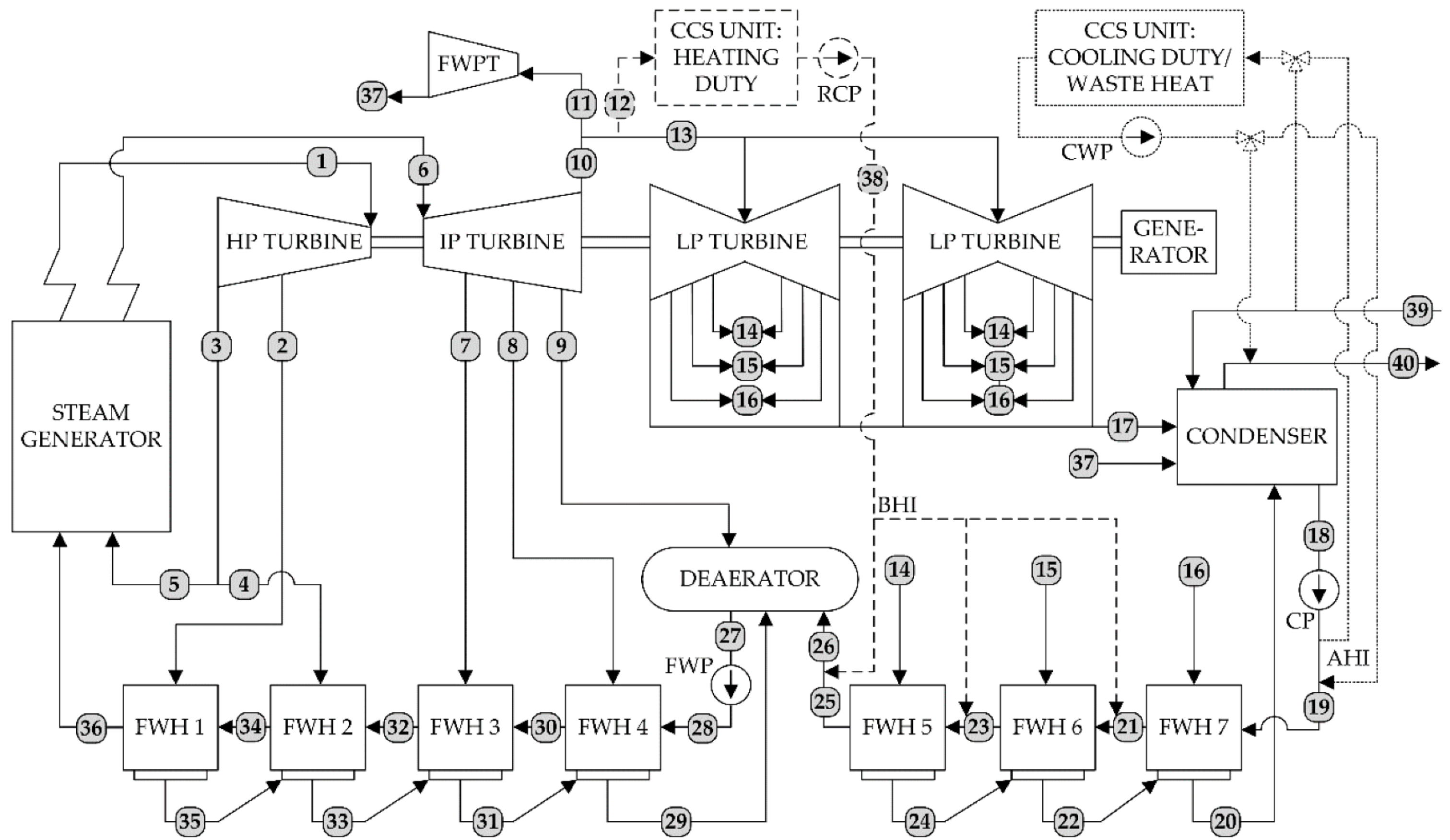
Outline of the Lecture

- Balance-of-Plant (BOP) examples
- Balance-of-Plant (BOP) components
  - Steam Lines
  - Turbines and generators
  - Moisture Separator Reheater (MSR)
  - Main condenser
  - Condensate pumps
  - Regeneration heaters
    - open feedwater heaters (OFWH)
    - closed feedwater heaters (CFWH)
  - Feed water pumps
- Power losses and plant efficiency

Definitions

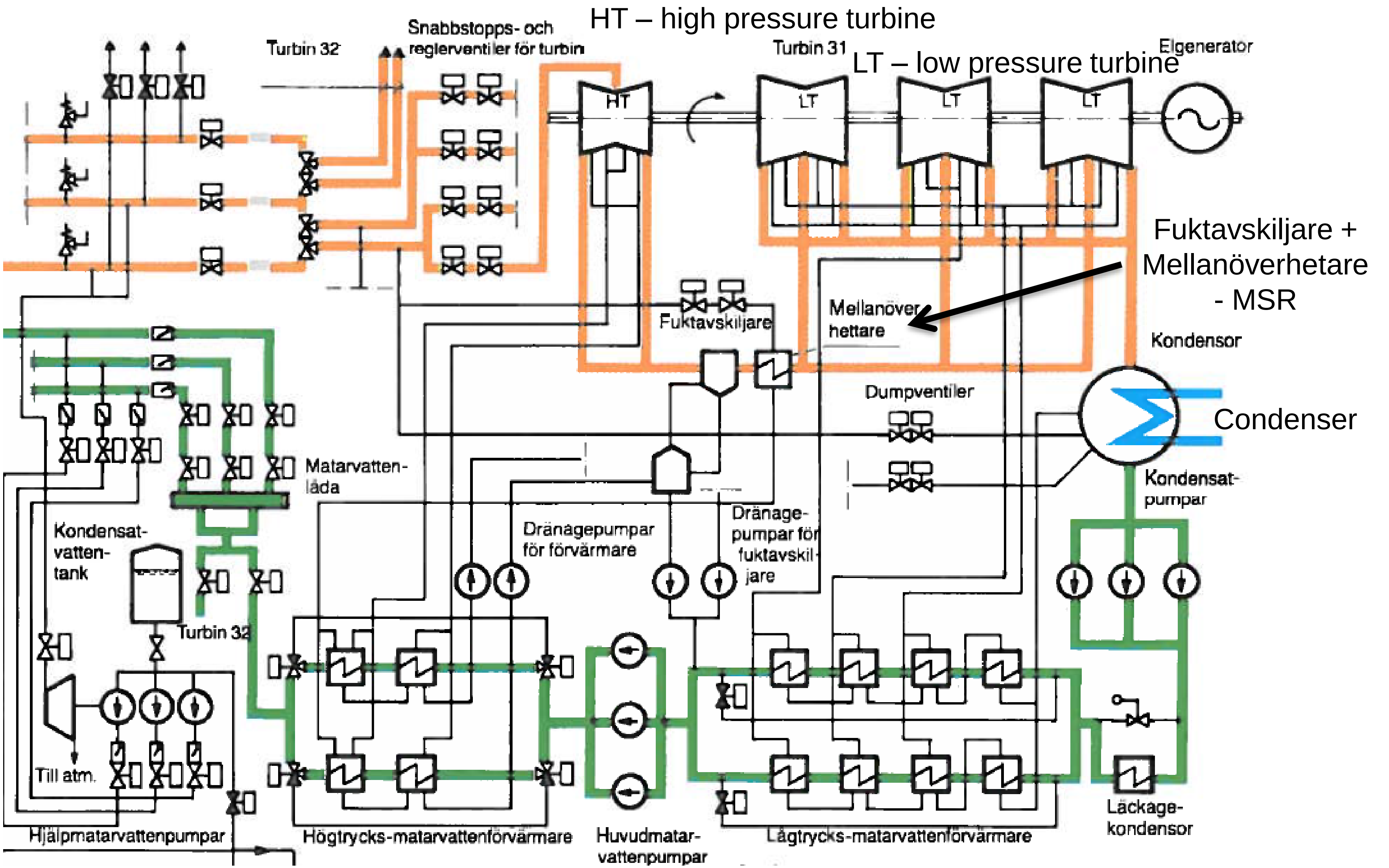
- Balance-of-Plant (BoP) is the conventional plant system used to generate electricity
- BoP contains several components and sub-systems, such as:
  - turbines
  - generators
  - condensers
  - feedwater sub-systems
  - auxiliary/emergency feedwater sub-systems
  - and others ...

Example BOP – FPP



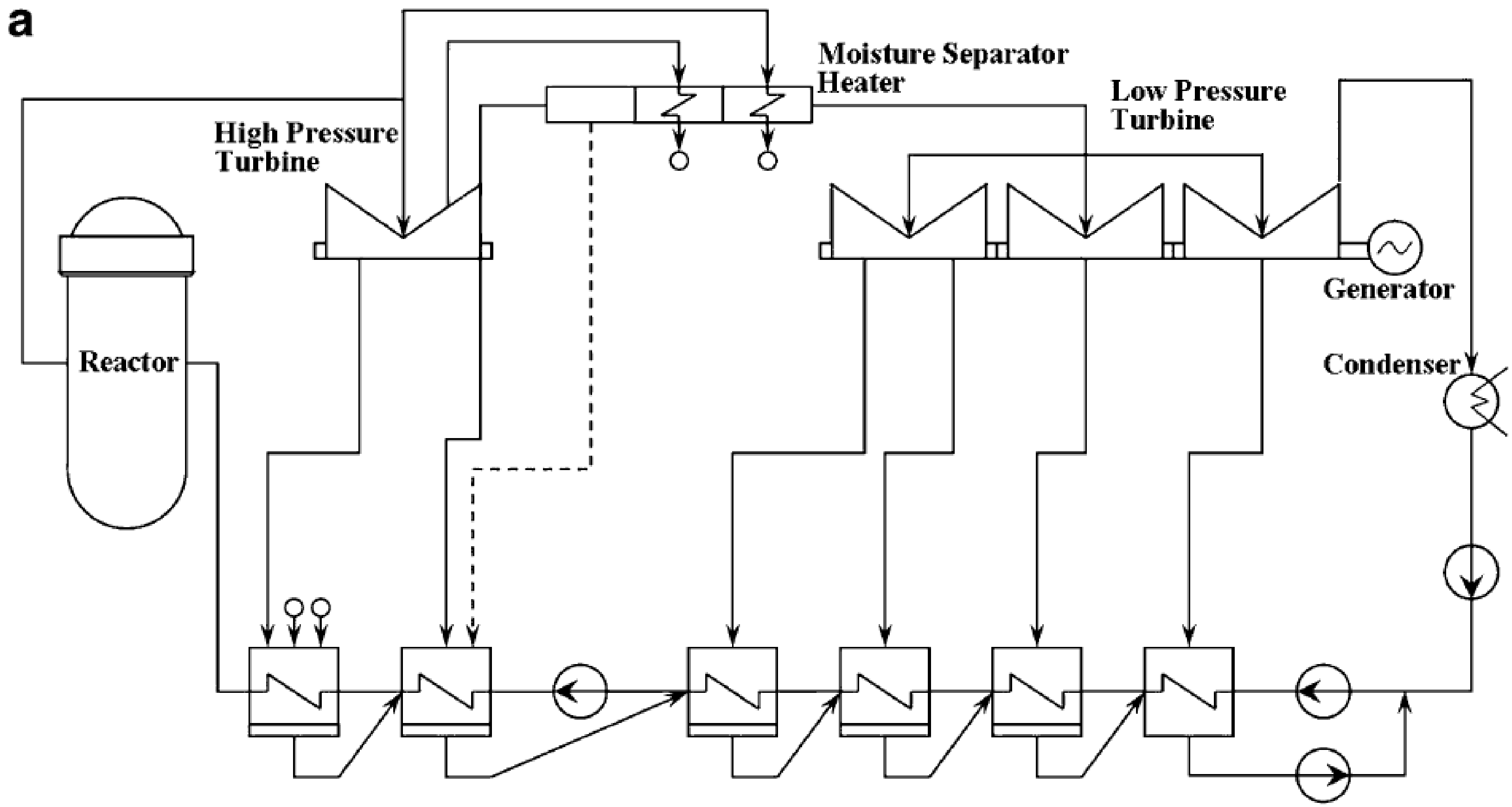
- Advanced Ultra-Supercritical Coal-Fired Power Plant Coal-fired power plant with net electricity capacity of 700MW.
- Steam cycle configuration with a single-stage reheat and eight feedwater heaters (FWH)
  - Without CCS net efficiency of 47.6%
  - Net efficiency of the CCS integrated unit is 36.8%
- The dashed and dotted components are present only in the carbon capture and storage (CCS) integrated steam cycle and represent the CCS heating and cooling duties with the respective basic (BHI) and advanced heat integration (AHI).

Example BOP – PWR



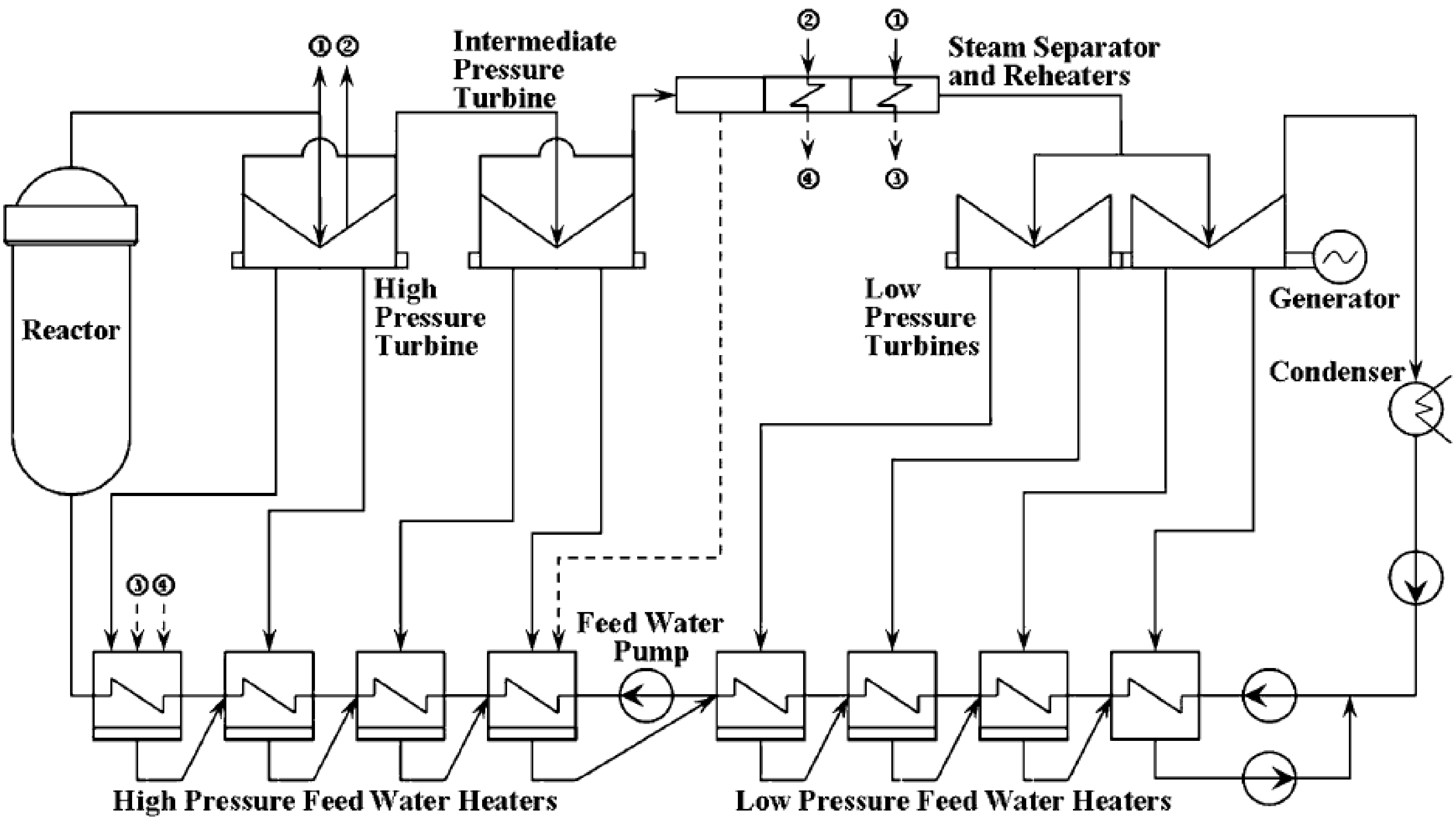
- No reheating
  - Efficiency ~33% (EPR~36%)

Example BOP – ABWR



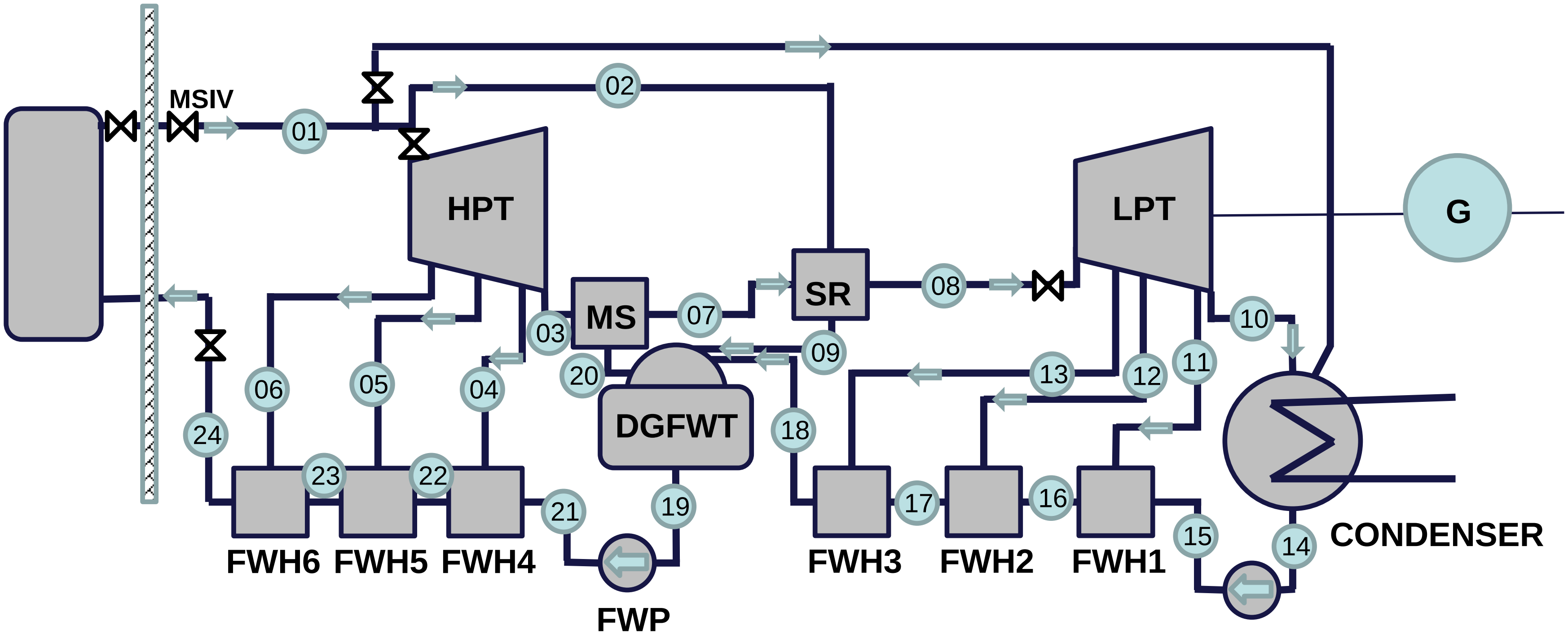
- ABWR net efficiency ~34.4%

Example BOP – SCWCR



- SCWR can approach ~44%

Schematic of BOP



- HPT – high pressure turbine
- LPT – low pressure turbine
- G – generator
- MS – moisture separator
- SR – steam reheater
- DGFWT – degasifier and feedwater tank
- FWH – feed water heater
- FWP – feed water pump
- CP – condensate pump
- MSIV – main steam isolation valve

Main Steam Lines and Bypass

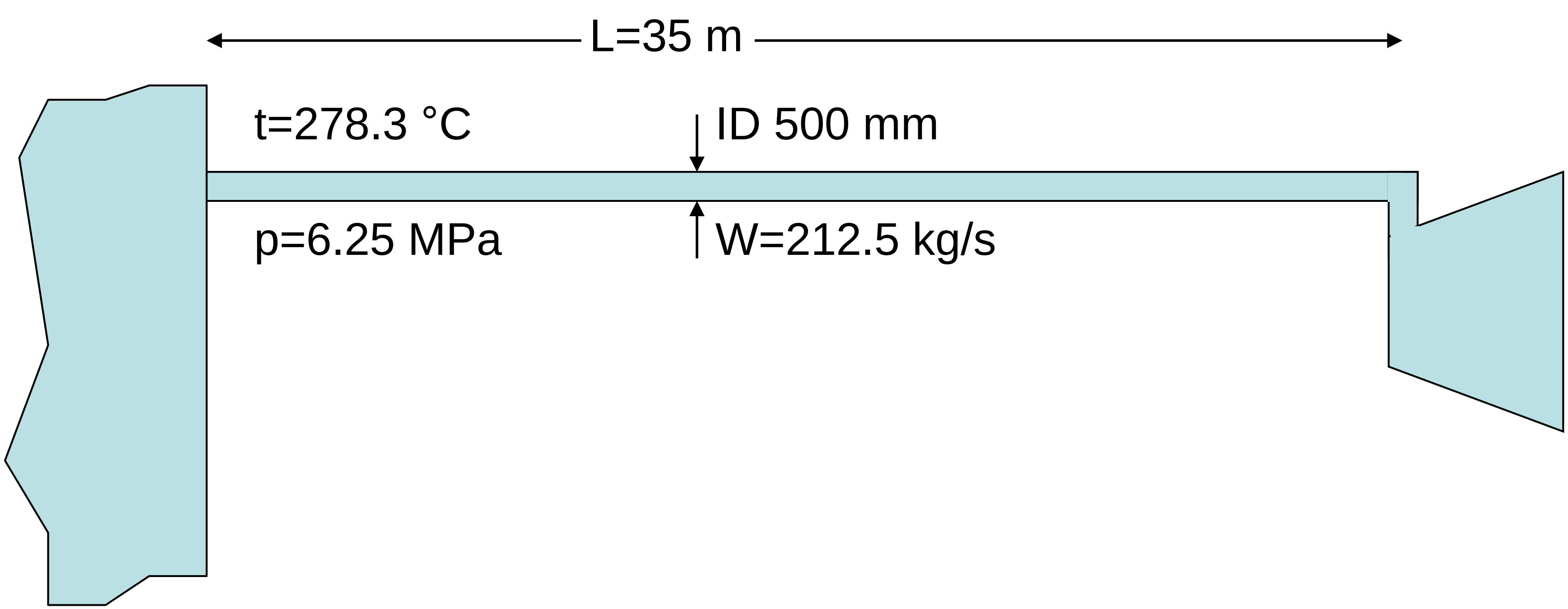
- The live steam lines go from the upper parts of steam generators or BWR pressure vessel to the main steam manifold

- Each line includes:
  - flow limiter
  - safety valves (to protect against overpressure)
  - isolation valve (to stop flow when turbine loses load)

- Design from materials to avoid thermal and mechanical stresses
- Anchored to avoid vibrations

Steam Lines

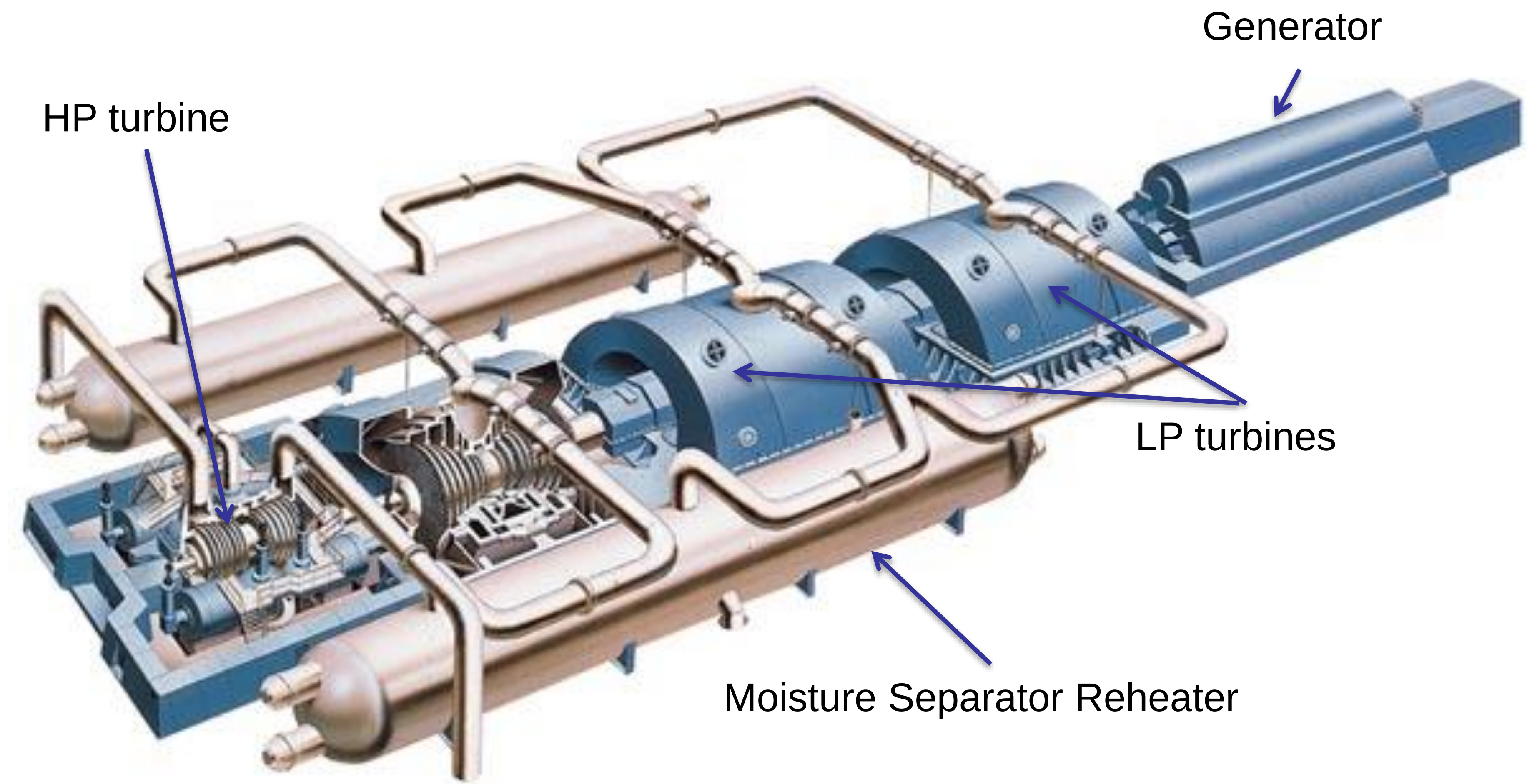
- In BWR, steam is leaving the reactor pressure vessel through steam lines and enters turbines.
- Typical task to calculate:
  - (a) total pressure loss,
  - (b) steam parameters at the inlet to turbine,
  - (c) steam dynamics when Main Steam Isolation Valve (MSIV) is closed



Turbine

- One of the main components is a steam turbine used to drive the electrical generator
- The turbine is characterized by:
  - type
    - saturated steam condensing turbine, superheated steam condensing turbine
  - number of turbine-generators per unit/reactor
  - turbine speed
    - rotation in revolutions per minute (rpm) when connected to the grid (1500, 1800, 3000, 3600)
  - number of high-pressure (HP) cylinders per turbine
  - number of intermediate-pressure (IP) cylinders per turbine
  - number of low-pressure (LP) cylinders per turbine
  - HP cylinder inlet steam pressure, temperature, moisture, mass flow rate

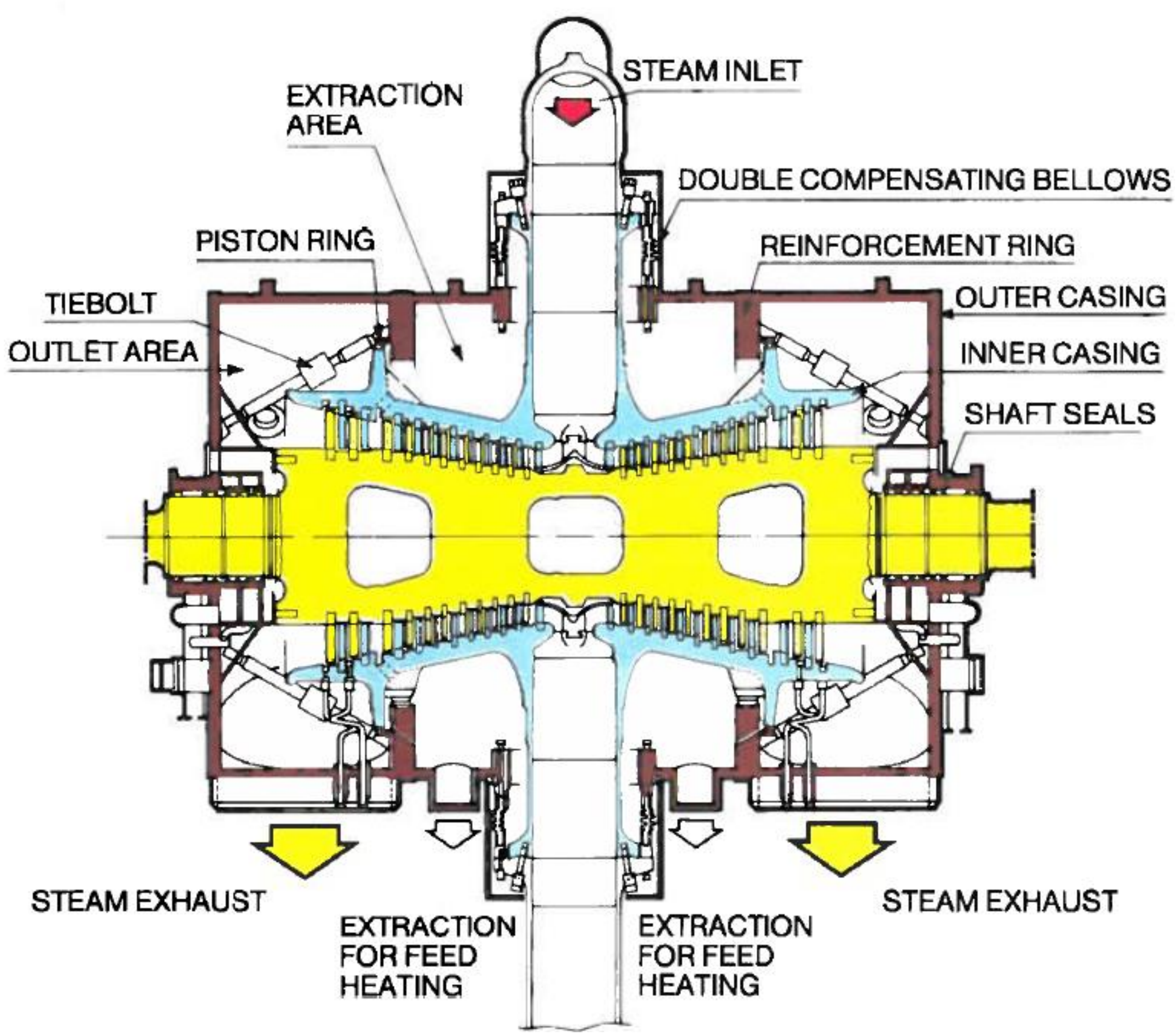
Steam Turbine Set



- A typical turbine set in steam driven plants consists of high-pressure turbine, low pressure turbine and a generator.
- Dry steam is supplied to the high-pressure turbine; however, the steam that leaves it is slightly wet (5-10% of the mass is in form of liquid droplets).
- It is thus desirable to dry and possibly superheat the steam (to avoid turbine blade erosion) before it is supplied to the low-pressure turbine.
- A Moisture Separator Reheater (MSR) fulfils this role in nuclear power plants.
- After expansion in the low-pressure turbine, the steam is cooled and condensed at low pressure in the condenser.

High Pressure Steam Turbine

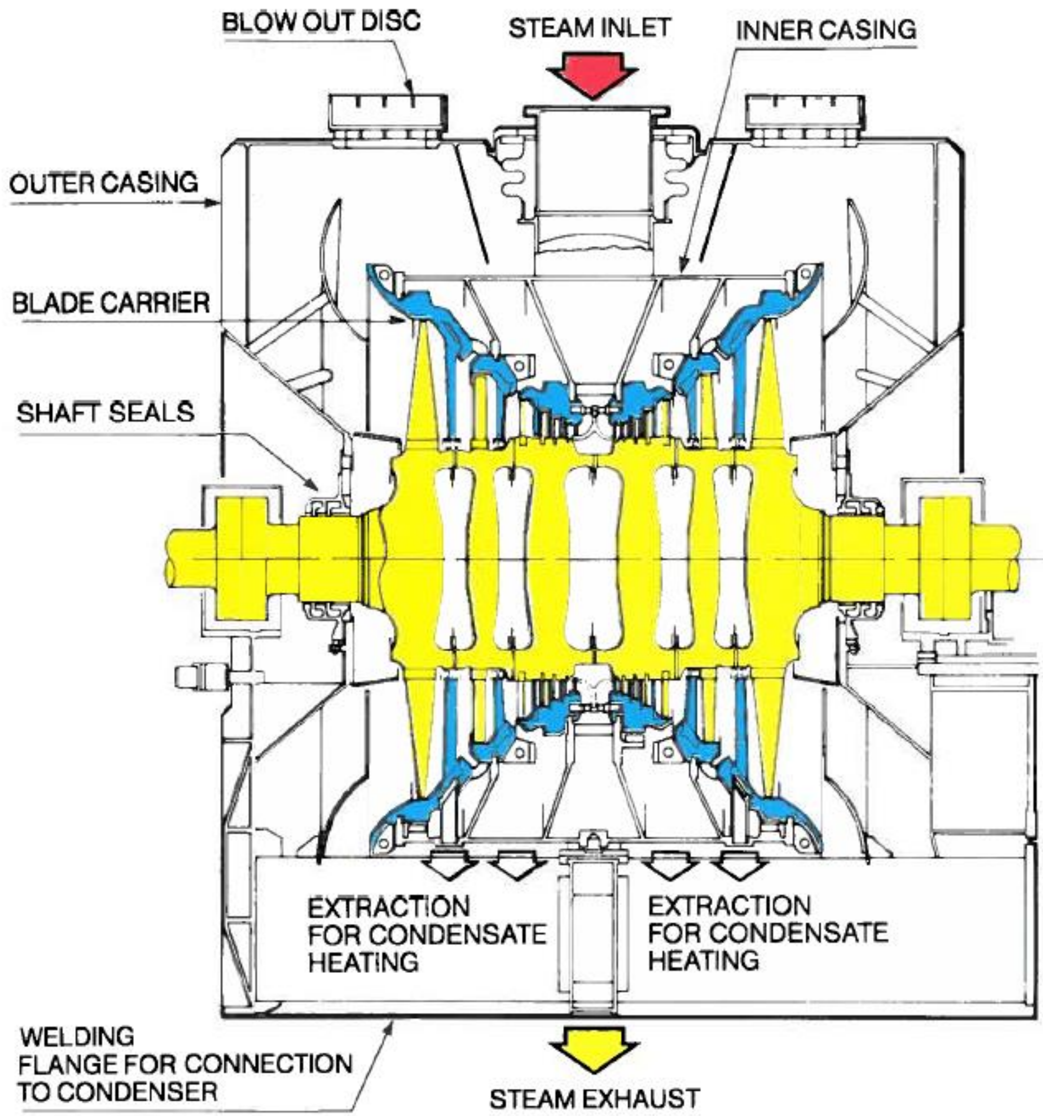
- Live steam is supplied from the reactor to the HP turbine through main steam lines via a control valve and an emergency stop valve.
- Exhaust steam is discharged via transfer pipes to moisture-separators and steam re-heaters (MSRs).



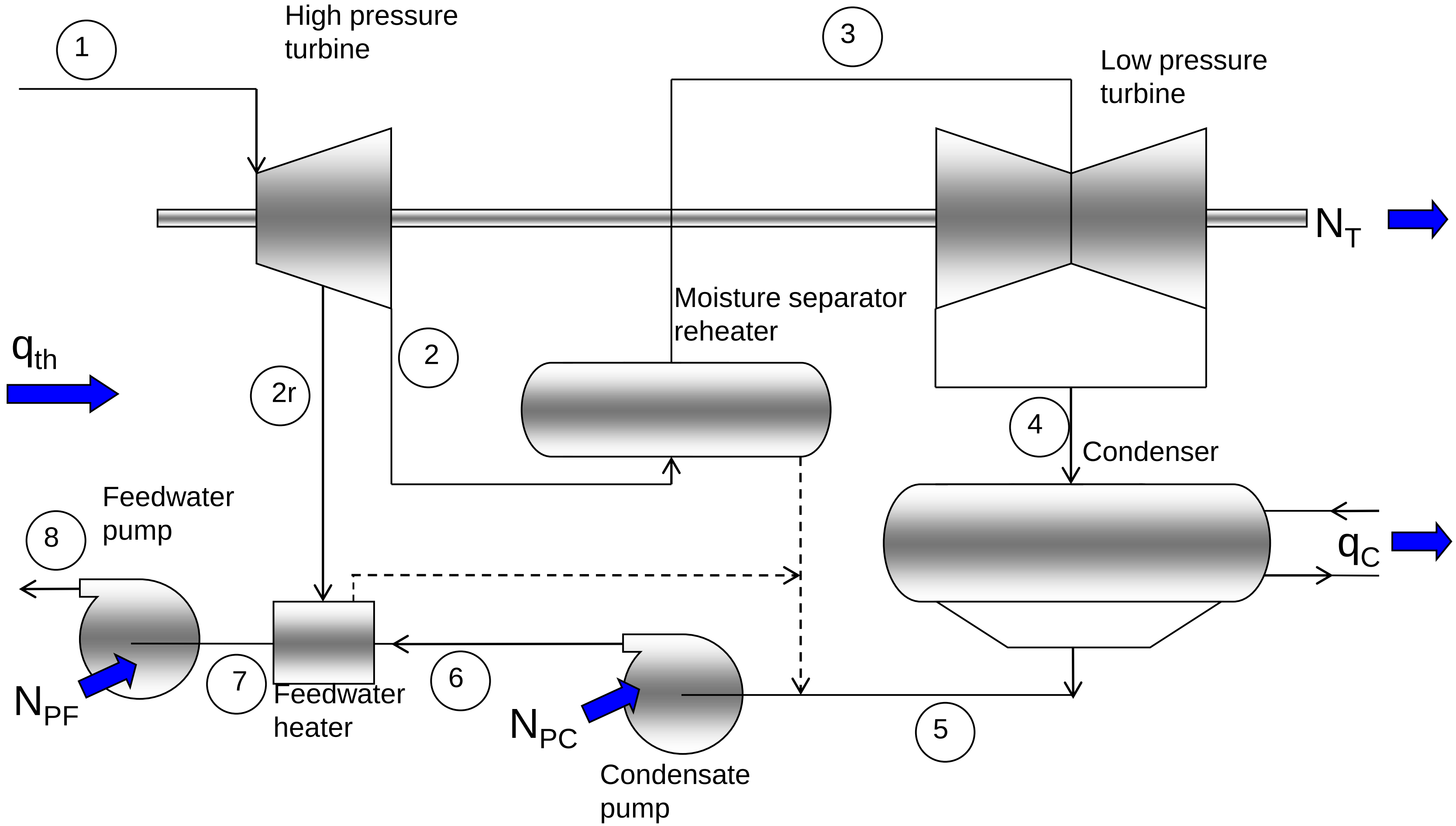
Low Pressure Steam Turbine

- Steam enters the turbine from MSR units through crossover pipes, in which low-pressure intercept valves are fitted.

- The turbines are provided with blow-out discs. They are protecting the turbine against high pressure, when other safety equipment is not functioning as expected.



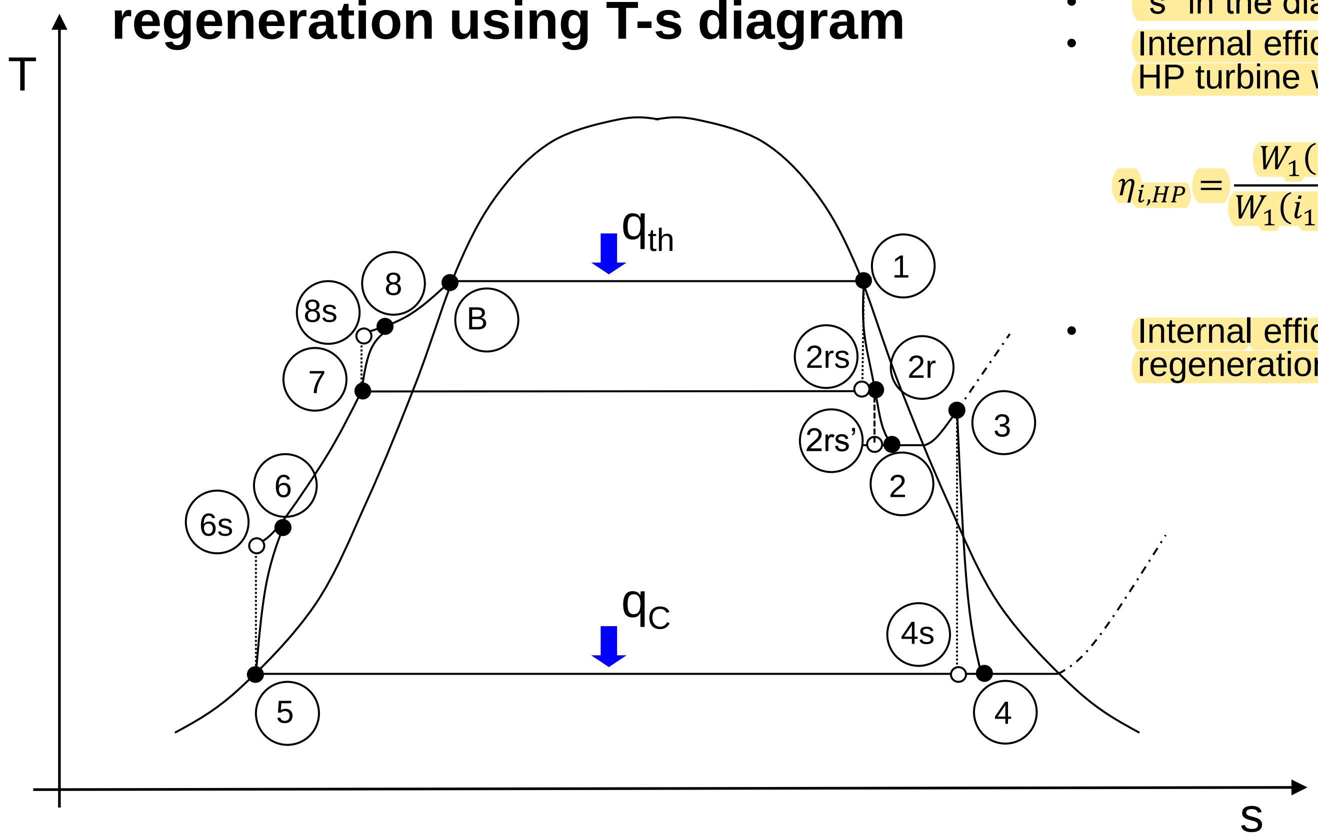
Rankine Cycle with Regeneration



- Stream 1 represents dry saturated steam flowing from the reactor to the high pressure turbine.
  - A fraction of stream 1 flows to the moisture separator reheater as a hot stream.
- Stream 2 represents wet steam leaving the high-pressure turbine and entering the moisture separator reheater as a "cold" stream.
- After moisture separation and being superheated, the stream – now labelled as stream 3 – enters the low-pressure turbine.

Rankine Cycle with Regeneration

Rankine cycle for saturated HPT with regeneration using T-s diagram



- "s" in the diagram indicates "isentropic"
- Internal efficiency (or isentropic efficiency) of HP turbine with regeneration:

$$\eta_{i,HP} = \frac{W_1(i_1 - i_{2r}) + (W_1 - W_r)(i_{2r} - i_2)}{W_1(i_1 - i_{2rs}) + (W_1 - W_r)(i_{2r} - i_{2rs'})}$$

- Internal efficiency of LP turbine (no regeneration)

$$\eta_{i,LP} = \frac{i_3 - i_4}{(i_3 - i_{4s})}$$

Turbine Efficiency – Wet Steam

- The internal efficiency of turbines decreases with increasing moisture in the steam

- Since almost all turbines in nuclear power plants operate with saturated and wet steam, their efficiency is deteriorated

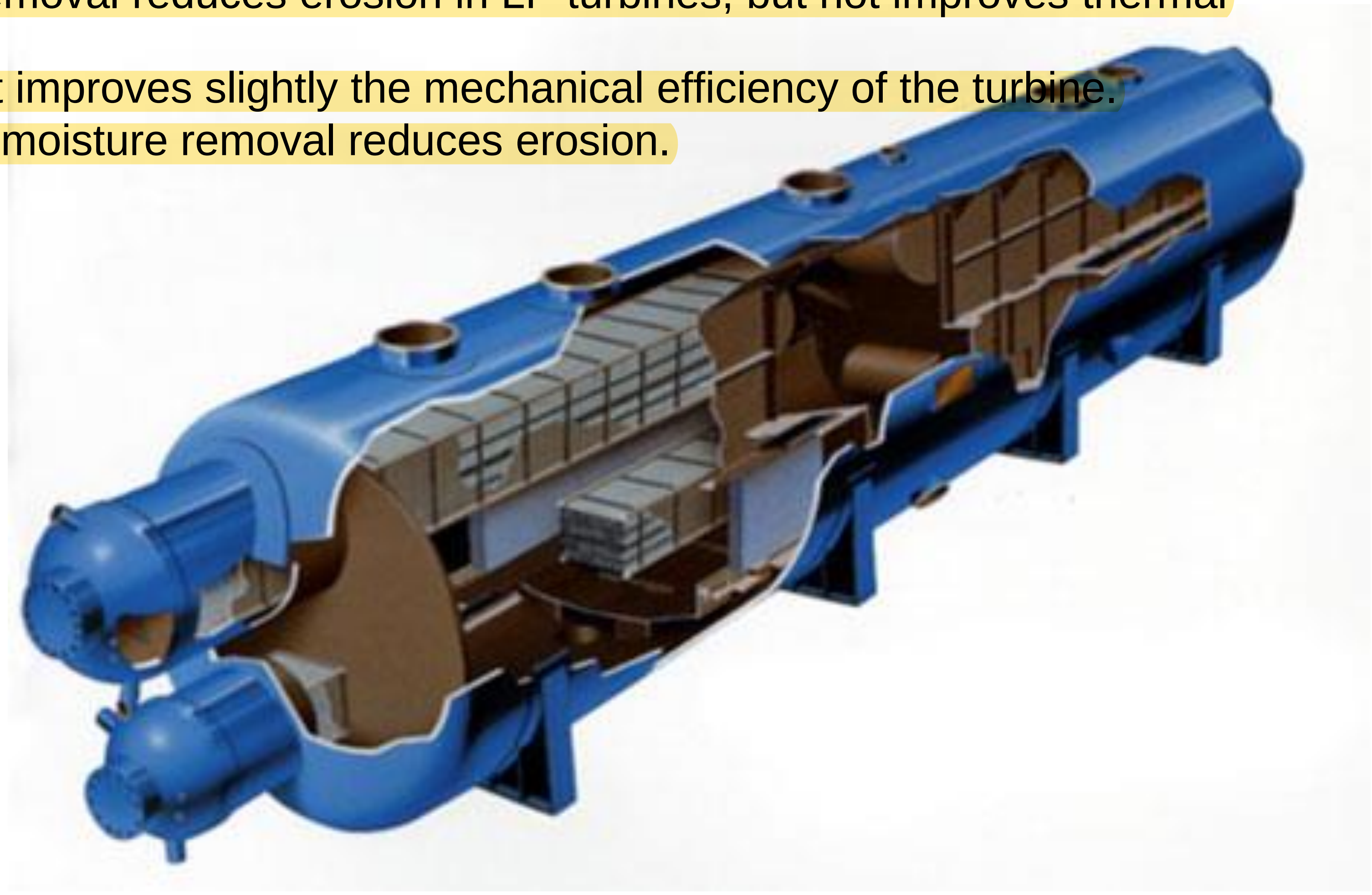
- An estimation of the internal efficiency of a turbine working with wet steam is given by the following equation:

$$\eta_{iw} = \eta_{id} \cdot x$$

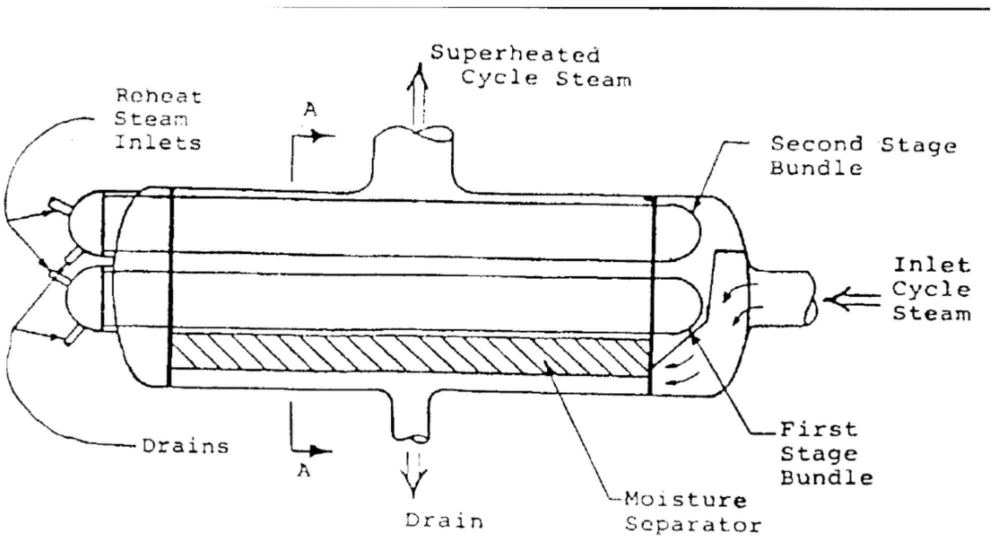
- η_{id} - efficiency of turbine on dry steam
- x - steam quality

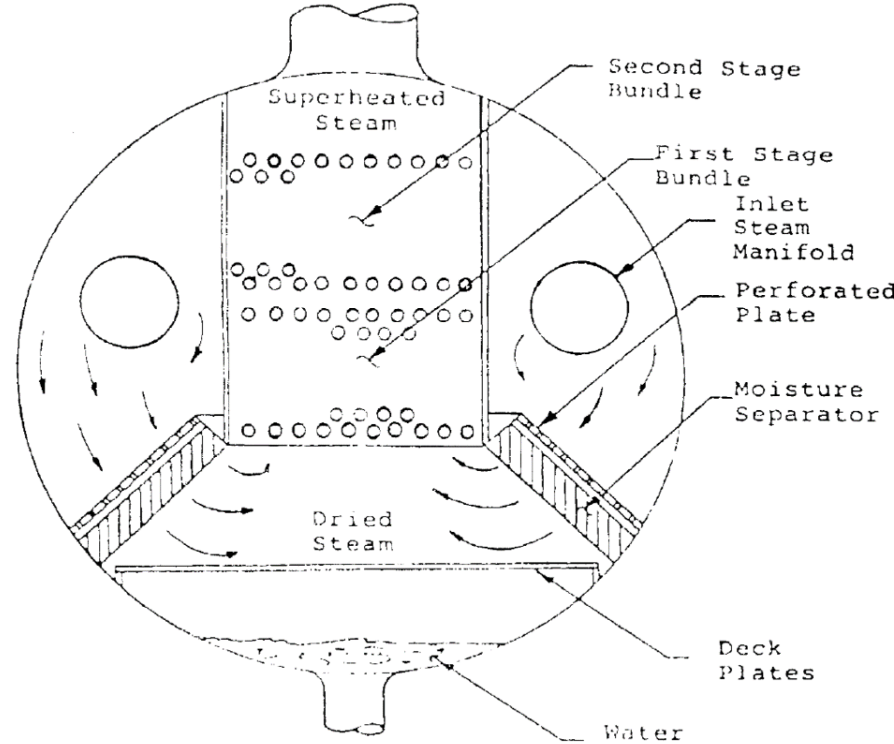
Moisture Separator Reheater MSR

- Steam passes through moisture separator and steam reheater (MSR) between HP and LP turbines
- The moisture in steam increases to 12% at the exit from HP turbine.
- The function of MSR is to remove that moisture and to dry (reheat) that steam.
- Moisture removal reduces erosion in LP turbines, but not improves thermal efficiency.
- However, it improves slightly the mechanical efficiency of the turbine.
- But mainly moisture removal reduces erosion.



Moisture Separator Reheater MSR





- Heat losses in moisture separator reheaters are not negligible.
- The losses at full power can be about 9% of the total heat given up by the hot stream.
- That would correspond to 91% efficiency in transferring heat from the hot to cold stream.

Main Generator

- Major unit component attached to the turbine and designed to produce electric power from the unit
- The main generator is characterized by:
  - rated active power - the maximum active (real) power the generator can produce without any risk of damage.
  - The active power is defined as:

$$N = U_{rms} \cdot I_{rms} \cdot \cos\varphi$$

here:

U_{rms} – root mean square (effective) voltage
I_{rms} – root mean square (effective) current
$\cos\varphi$ – power factor,

φ – phase angle between the AC voltage and the current sinusoidal waveforms

Main Generator

- The main generator is characterized by (continued):
  - rated apparent power
    - a measure of the alternating current (AC) power that is computed as:

$$N = U_{rms} \cdot I_{rms}$$

  - rated output voltage
    - the effective (rms) voltage for which the generator is designed
  - rated output frequency (50 Hz, 60 Hz)
    - the standard frequency of the generator output

Main Condenser

- A component designed to maintain a pressure drop along the turbine and to condense the turbine outlet steam
- The main condenser is characterized by:
  - primary means of condenser cooling
    - the predominant ultimate heat sink from where the cooling water is taken (cooling towers, lake, river, sea)
  - number of condensers per turbine-generator
    - usually the same as the number of low-pressure turbine cylinders
  - condenser tube material
    - (copper, brass, stainless steel, titanium)
  - number of main condensate pumps per turbine
    - (designed to pump the main condensate from the condenser to a feed water tank)

Main Condenser

- The main condenser is characterized by (continued):
  - number of main condensate pumps per turbine required for full power
    - (pumps that are normally in operation at the rated power)
  - condenser vacuum at full power
    - the absolute pressure in the condenser at full turbine power and standard cooling water temperature (usually 20 °C)

Main Condenser

- Condenser ensures condensation of the exhaust steam from the main turbine and from the turbines driving feedwater pumps during normal operation.

- It must also be able to absorb the steam flow of the turbine bypass (~85% of maximum calculated steam flow) in abnormal situations.

Feedwater System

- This system:
  - draws the condensate from the condenser well
  - heats up this water
  - ensures normal feed of steam generators

- It is typically divided into parts:
  - low pressure part
  - high pressure part
  - drain water part

Feedwater System

- This system is characterized by:
  - number of turbine-driven main feedwater pumps
    - (in some NPPs there are feed water pumps driven by a steam turbine)
  - number of motor-driven main feedwater pumps
    - number of pumps driven by electrical motor, if any
  - number of start-up feedwater pumps
    - smaller feedwater pumps that may be used to feed the steam generators or the reactor at low reactor power
  - number of feedwater pumps required for full power operation
    - pumps that are normally in operation at rated unit power (usually some pumps are on stand-by and are used in case of a feedwater pump trip)
  - feedwater discharge pressure
    - typical pressure at the feedwater pump discharge at the rated unit power

Emergency/Auxiliary Feedwater System

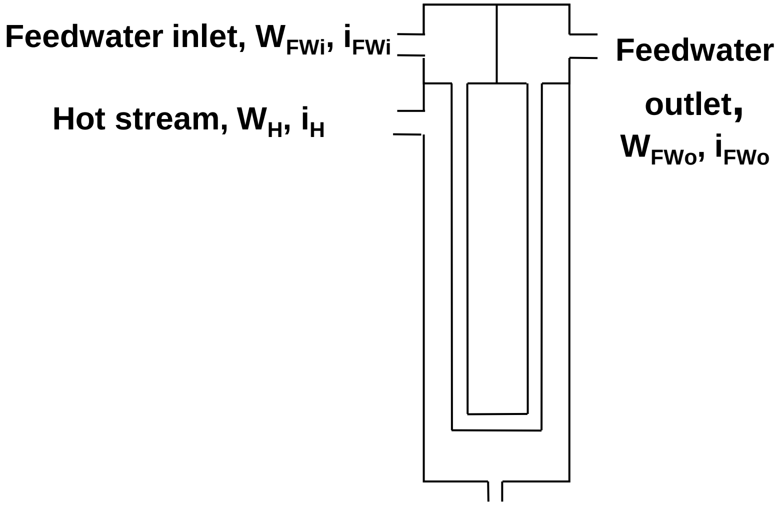
- The auxiliary feedwater system is a standby feedwater system that is started if the main feedwater system is not available because of failure.
- The system should have an **independent power source** available after loss-of-offsite-power events.
- The **auxiliary feedwater pumps** are usually connected to the main feedwater tank and may also be used as normal start-up feedwater pumps at low reactor power.
- The **emergency feedwater system** is designed to be used in case of a catastrophic failure of the main feedwater system.

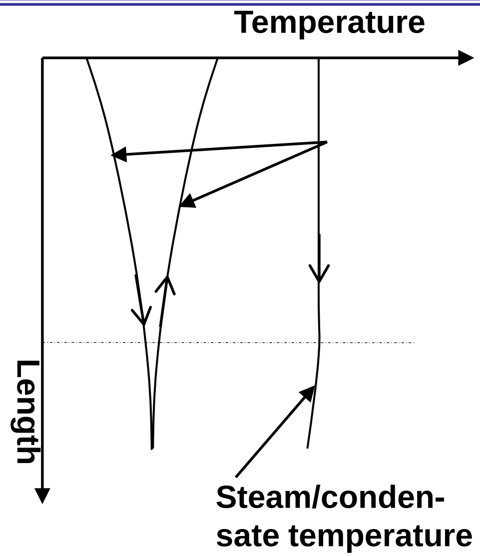
Emergency/Auxiliary Feedwater System

- The emergency feedwater system pumps and flow paths should be different to those of the main and auxiliary feedwater.

- The systems are characterized by:
  – number of electrical-motor-driven pumps
    - (the number of auxiliary or emergency feedwater pumps driven by an electrical motor)
  – number of diesel-driven pumps
  – number of turbine-driven pumps

Feed Water Heaters





- Closed feedwater heaters - CFWH (streams are separated):
- Mass conservation:

$$W_{FWi} = W_{FWo} = W_{FW},\ W_H = W_C$$

- Energy conservation:

$$W_{FWi} \cdot (i_{FWo} - i_{FWi}) = W_H \cdot (i_H - i_C)$$

- Exit FW enthalpy

$$i_{FWo} = i_{FWi} + \frac{W_H \cdot (i_H - i_C)}{W_{FWi}}$$

- Sometimes we know the required temperature increase in CFWH:

$$\Delta T_{CFWH} \equiv T_{FWo} - T_{FWi}$$

- Then

$$i_{FWo} = i(p_{FWo}, T_{FWo})$$

$$i_C = i_H - \frac{W_{FWi} \cdot (i_{FWo} - i_{FWi})}{W_H}$$

Feed Water Heaters

- Open feedwater heaters - OFWH (streams are mixing):
- Mass conservation:

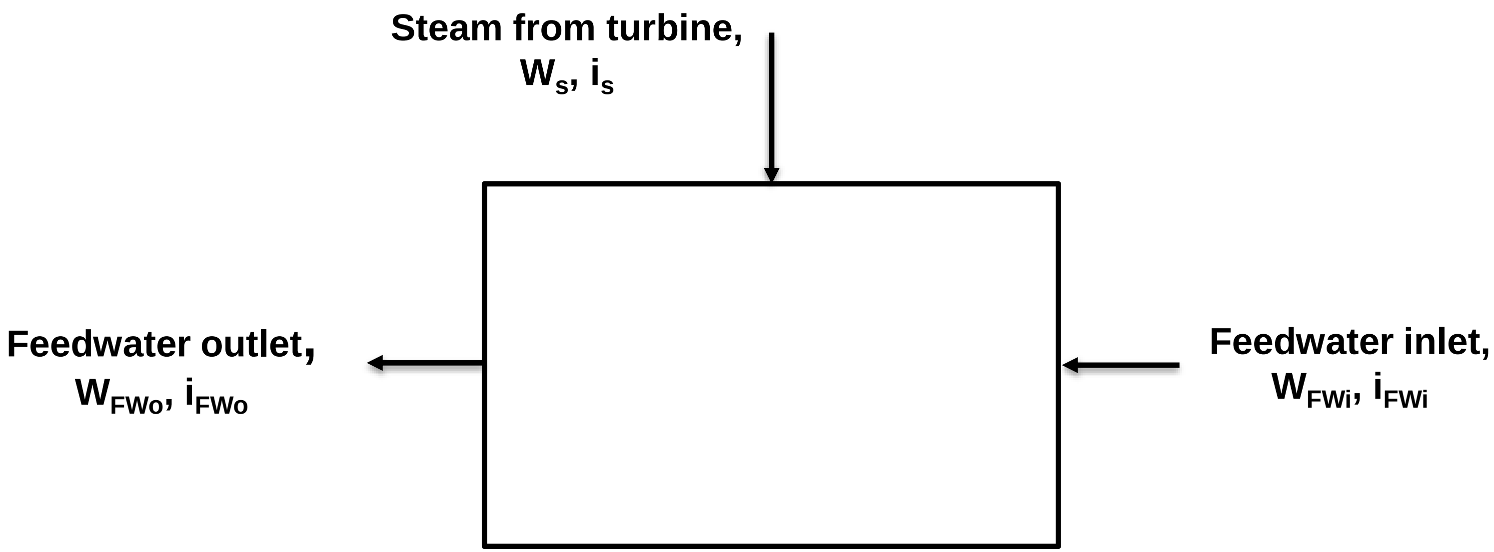
$$W_{FWo} = W_s + W_{FWi}$$

- Energy conservation:

$$W_{FWi} \cdot i_{FWi} + W_s \cdot i_s = W_{FWo} \cdot i_{FWo}$$

- Exit FW enthalpy:

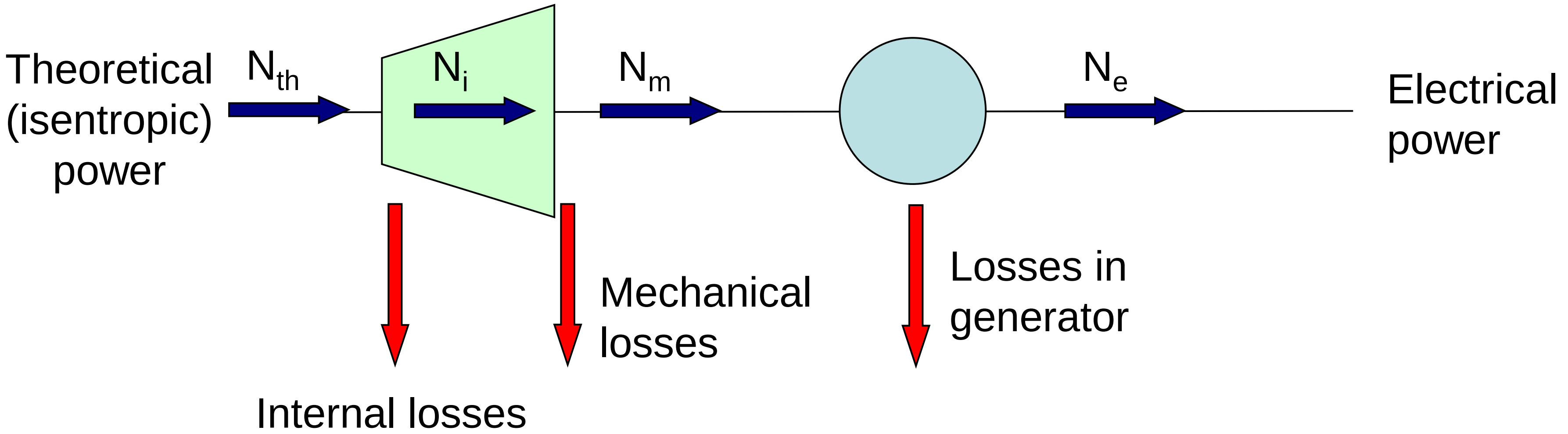
$$i_{FWo} = \frac{W_{FWi} \cdot i_{FWi} + W_s \cdot i_s}{W_{FWi} + W_s}$$



Power Losses

- Power losses in a turbine set and generator are as follows:

$$N_i = \eta_i N_{th} \qquad N_m = \eta_m \eta_i N_{th} \qquad N_e = \eta_g \eta_m \eta_i N_{th}$$



Plant Energy Efficiency

- Reference efficiency:

$$\eta_{Ref} \equiv \frac{\sum N_{Turb,i}}{q_{th}} = \frac{total\ internal\ power\ of\ turbines}{Reactor\ power}$$

  – Internal power is sometimes called "actual useful" power

- Thermodynamic efficiency (equivalent to the reference efficiency):

$$\eta_{th} \equiv \frac{\sum N_{Turb}}{q_{th}} = \frac{total\ useful\ power\ of\ turbines}{Reactor\ power}$$

- Gross efficiency:

$$\eta_{Gross} \equiv \frac{\sum N_g}{q_{th}} = \frac{total\ power\ of\ generators}{Reactor\ power}$$

- Net efficiency:

$$\eta_{Net} \equiv \frac{\sum N_g - \sum N_{own}}{q_{th}} = \frac{total\ power\ of\ generators - own\ needs}{Reactor\ power}$$