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UNIT-04

Nuclear Power Plant

* It uses nuclear energy to generate power.
* Nuclear fuels used in power industry are principally uranium and thorium.
* One kg of Uranium can produce the energy equivalent to burning of about 4×10^6 kg of High grade coal.

Advantages:

* Nuclear Power plants high initial cost but has low operating cost compared to conventional thermal power plant.
* These plants become more economical if built in large capacities.
* It reduces the demand on depleting resources of energy (coal, oil and gas)
* The problem of transportation of conventional fuels is avoided since requirement of nuclear fuel for nuclear power station is negligible.
* Large storage facilities of fuel are not needed.

Principles of nuclear energy:

Nuclear Binding energy:

Nucleus is made up of proton and neutron, but the mass of a nucleus is always less than the sum of the individual masses of protons and neutrons.

* The difference in mass is called 'mass defect' (Δm) (2)

* This mass defect is found by adding up the masses of all the individual particles (proton, neutrons and electrons) and substracting the actual mass (m) of atom.

$$\therefore \boxed{\Delta m = n_p m_p + n_n m_n + n_e m_e - m}$$

where n → no. of particle.

* This mass defect is converted into energy in a nuclear reaction

$$\boxed{\Delta E = \Delta m \cdot c^2}$$

* This energy is known as 'Binding Energy'.

Equivalent of 1 gm mass defect is

$$\Delta E = 1 \times 10^{-3} \times (3 \times 10^8)^2 = 9 \times 10^7 \, MJ$$

Similarly energy equivalent to 1 amu (1.66×10^{-27} kg)

$$\Delta E = (1.66 \times 10^{-27}) \times (3 \times 10^8)^2$$

$$\boxed{\Delta E = 931 \, MeV}$$

Nuclear fission:-

* It means the splitting of a heavy nucleus into lighter nuclei with the release of a large amount of energy.

* $${}_{92}U^{238} + {}_0n^1 \longrightarrow {}_{92}U^{239} \longrightarrow {}_{56}Ba^{148} + {}_{36}Kr + 3({}_0n^1) + 200 \, MeV$$

Nuclear fusion:

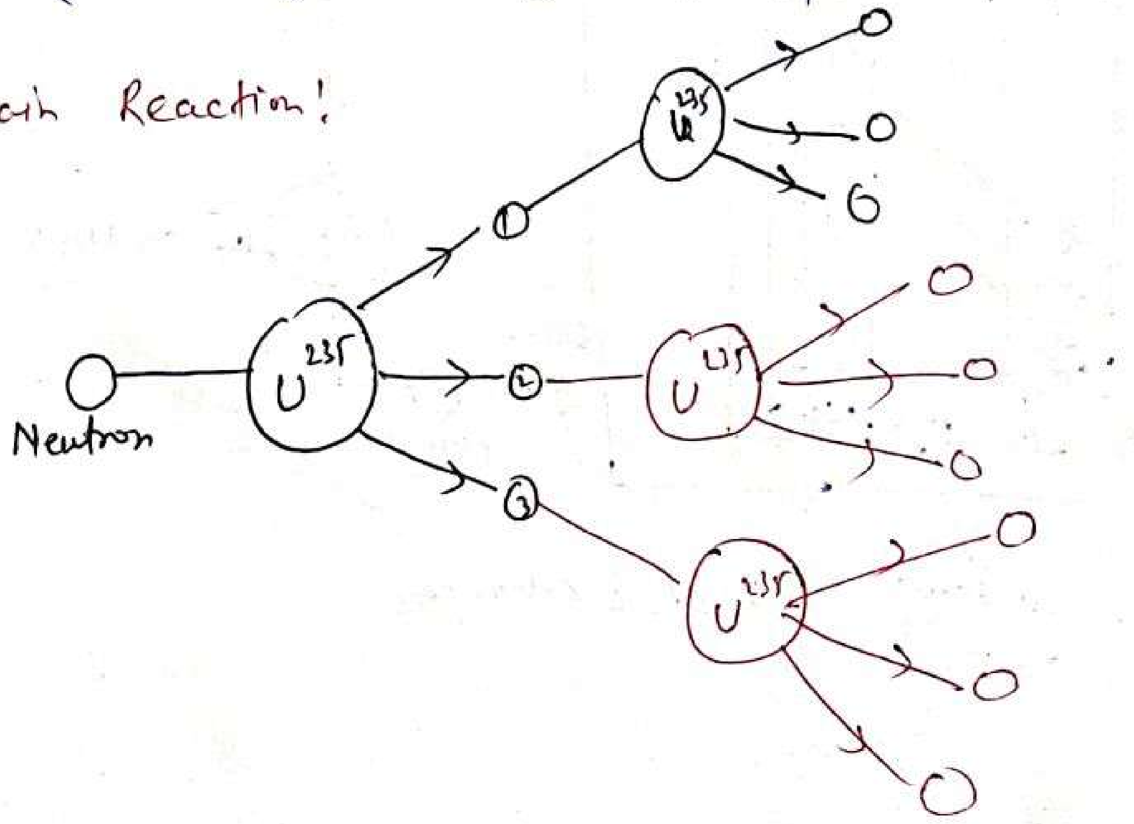
* Nuclear fusion is the process in which two lighter nuclei are combined to be fused together to form a heavier and stable nucleus.
* The mass of the product nucleus formed is less than the sum of the masses of the nuclei fused.
* This mass defect is converted into energy.

$${}_{1}H^{1} + {}_{1}H^{1} \longrightarrow {}_{1}^{2}H \text{ (Deuterium)} + {}_{+1}^{0}e + \text{Energy}$$

$${}_{1}^{2}H + {}_{1}^{1}H \longrightarrow {}_{2}^{3}He$$

$${}_{2}^{3}He + {}_{2}^{3}He \rightarrow {}_{2}^{4}He + 2\,{}_{1}^{1}H + \text{Energy}$$

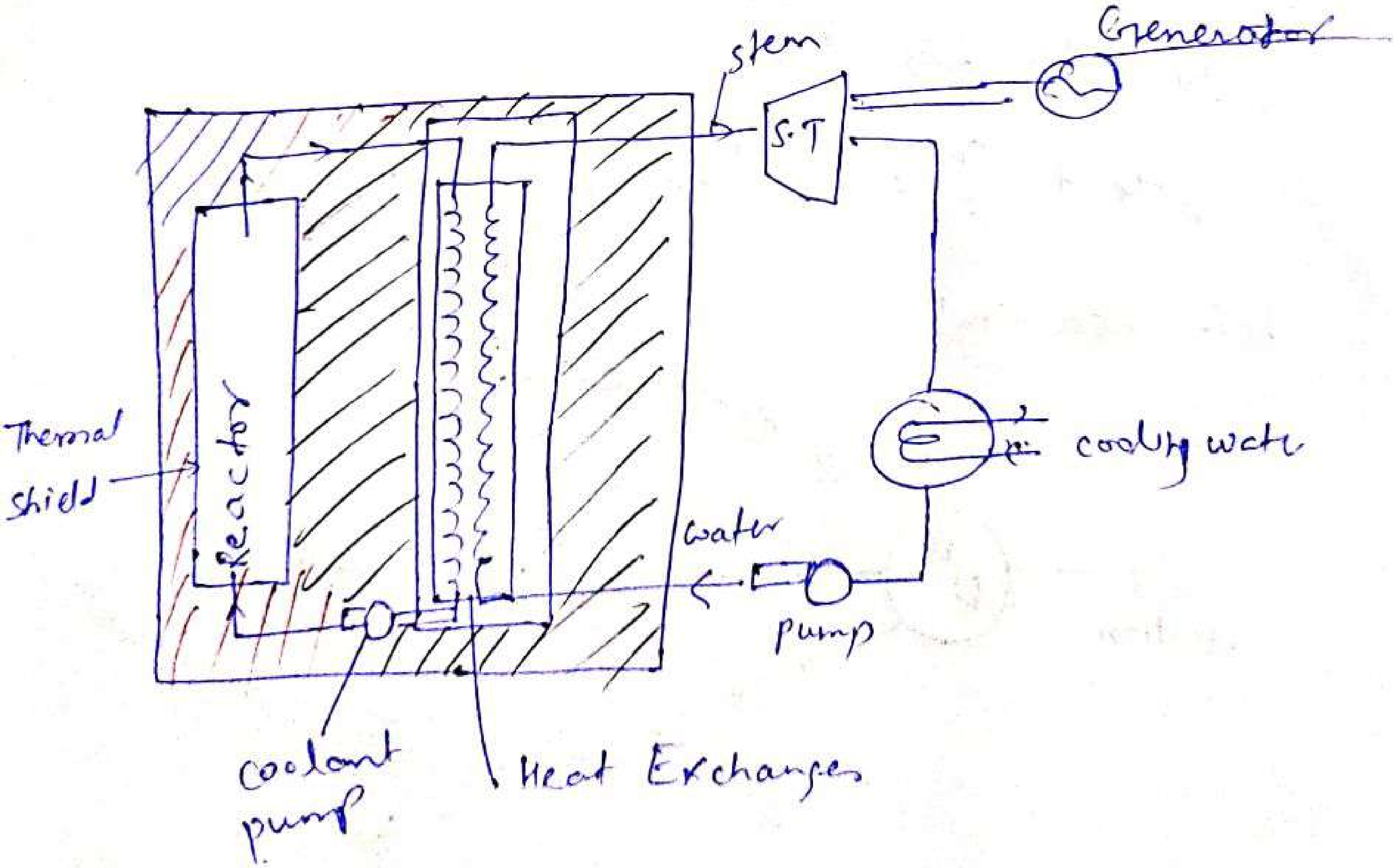
Chain Reaction:



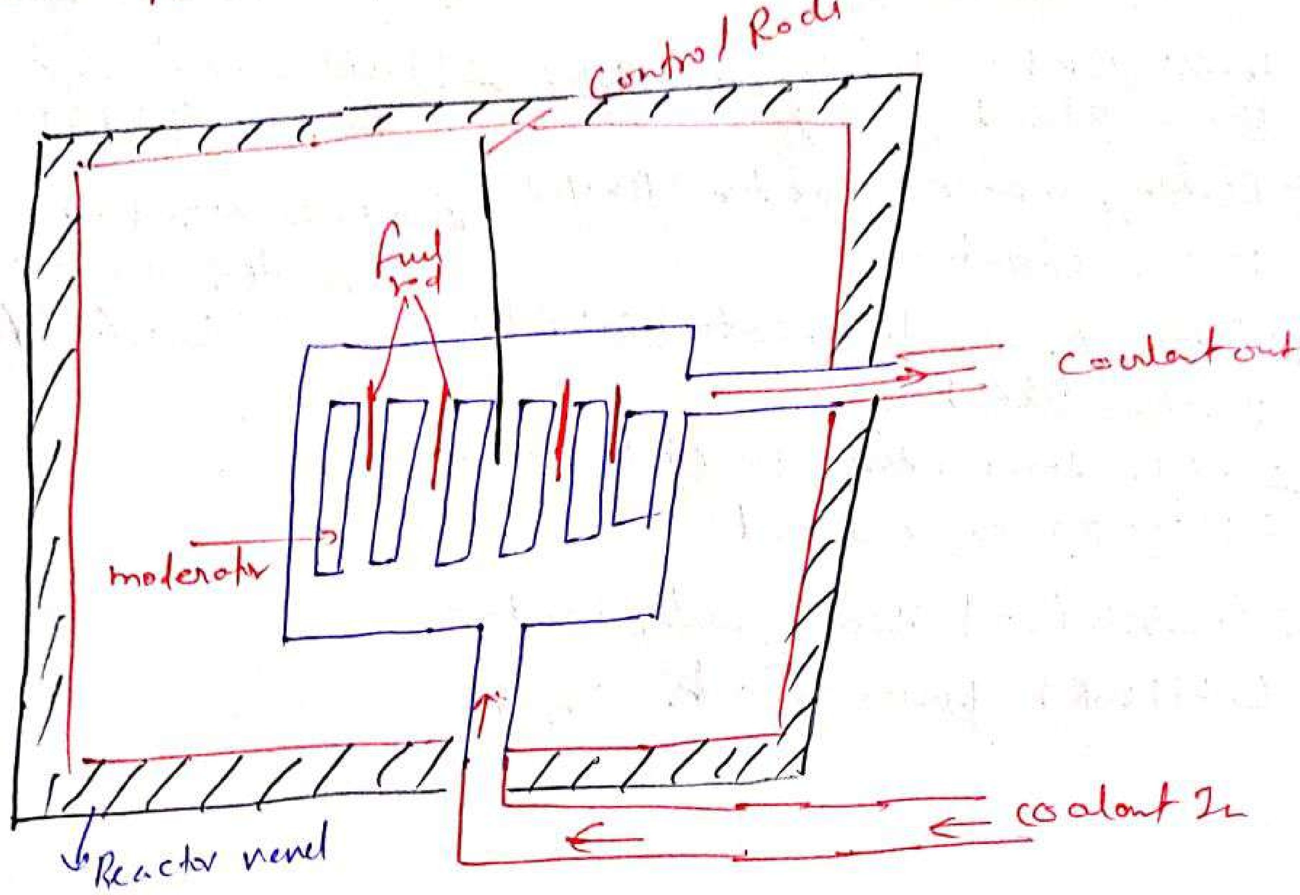
Elements of Nuclear Power Plant:-

* Nuclear Reactor
* Coolant and coolant Pump
* Heat exchanger
* Steam turbine, condenser and generator.

* Nuclear Reactor is used to generate heat energy
* This heat energy is used in a heat exchanger for formation of steam which is used for power generation.
* Nuclear Power plants are used as base load plants



Main Component of Nuclear Reactor and Their function!



Fuel Rod:- * $_{92}U^{235}$, $_{94}Pu^{239}$ and $_{92}U^{233}$

* The fuel rod is fabricated in various shapes like rods, plates, tins, pallets etc.

Moderator! * The moderator are the substance which help in reducing the speed of neutrons. ~~and~~

* Moderators are light water (H_2O), deuterium (D_2O), graphite and beryllium.

Control Rods! * It is used to control the chain reaction by absorbing required neutrons.

* materials used are boron and cadmium.

Reflector! * It is desirable that the neutrons are not allowed to escape the reactor core. Hence a reflector surrounding is provided.

Types of Nuclear Reactor Power Plants:

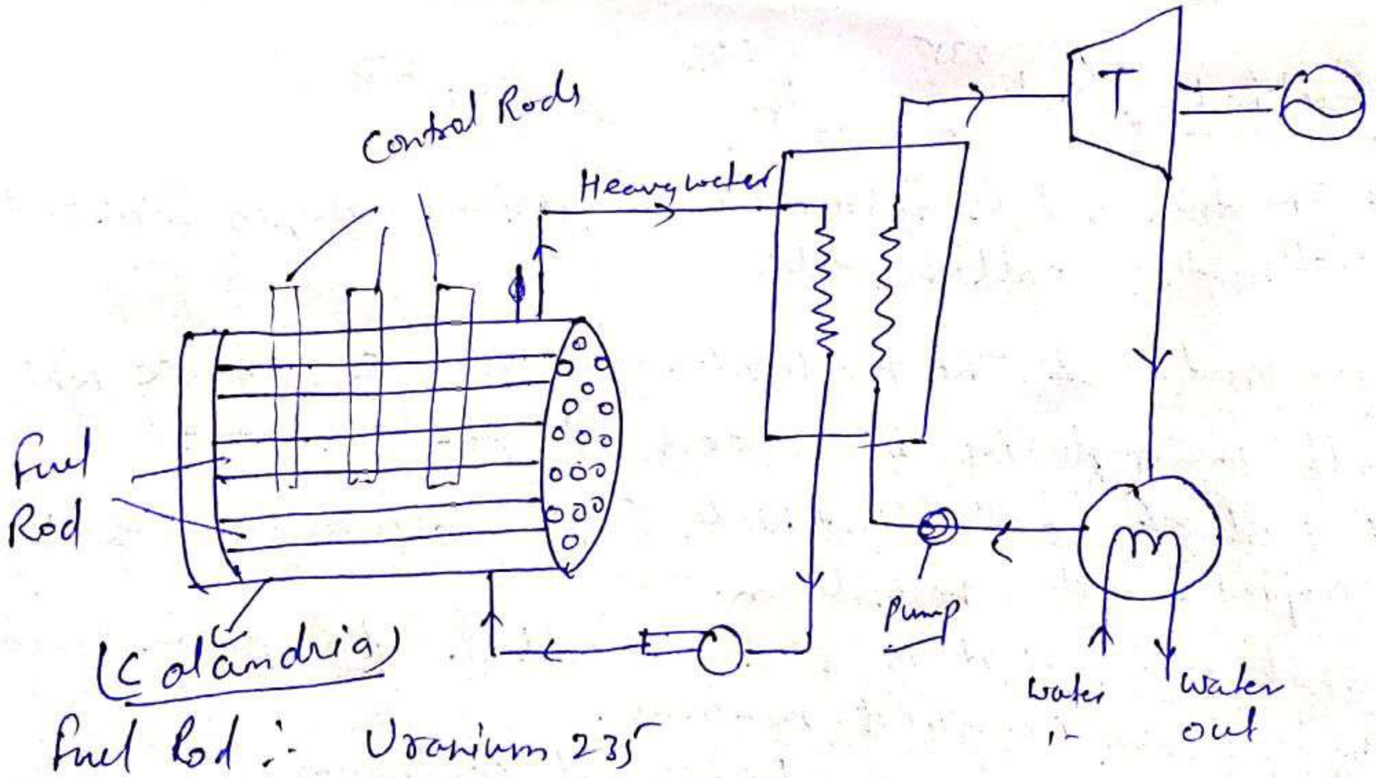
Thermal Reactors

* Pressurized water Reactor (PWR) power plant (Imp.)
* Boiling water Reactor (BWR) power plant
* The gas cooled Reactor (GCR) power plant
* High temprature gas cooled reactor (HTGR) power plant
* Pressurized Heavy water Reactor (PHWR) power plants (Imp.)

Fast Breeder Reactor

* Liquid metal fast breeder Reactor (LMFBR)
* Gas cooled fast breeder reactor (GCFBR)

CANDU Reactor (Canadian Deutorium Uranium)



Fuel Rod :- Uranium 235

coolant and moderator = D_2O

10.15 The Pressurized Water Reactor (PWR) Power Plant :

The schematic diagram of PWR power plant is shown in Fig. 10.15.1.

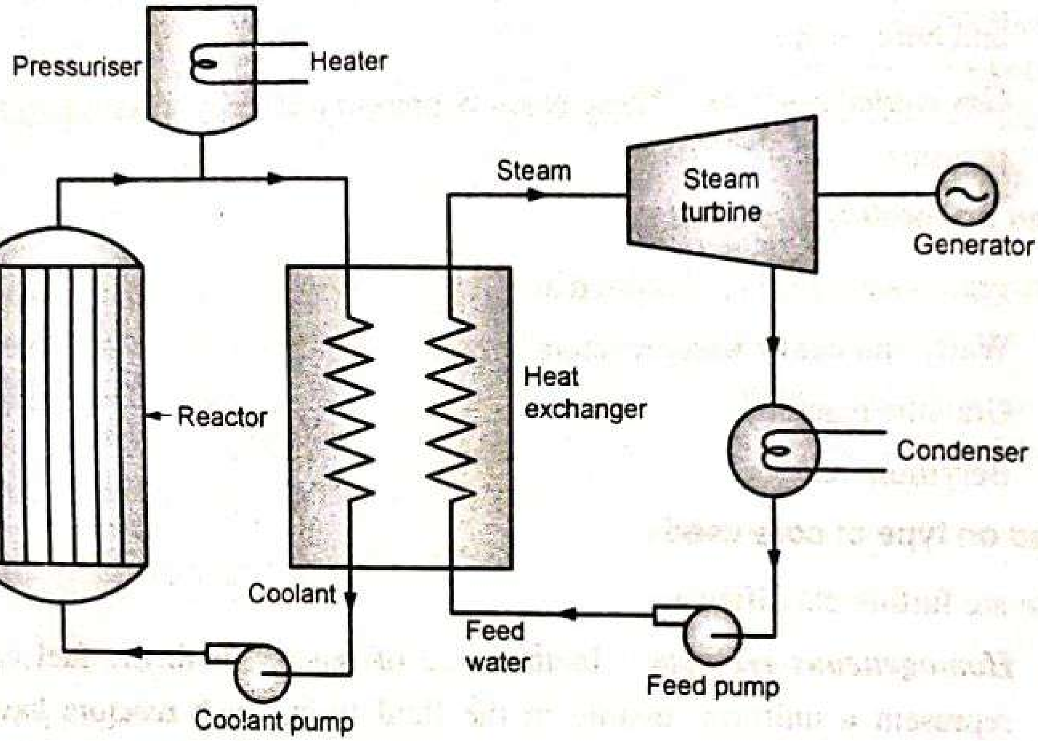


Fig. 10.15.1 : Pressurized water reactor power plant

It uses enriched uranium. The water or heavy water under pressure is used both as coolant and moderator. Before starting the reactor the water in pressuriser is boiled and converted into steam by electric heating coil. In order to prevent the boiling of water in the core, it is kept under pressure of about 130 to 150 bar. It helps in absorbing the heat by water in the liquid state in the reactor.

The heat energy absored by water in the reactor is used for converting the water into steam in a heat exchanger. This stem is used in a conventional way in the steam power plant cycle as shown in Fig. 10.15.1. The water coolant from heat exchanger is recirculated to the reactor with the help of coolant pump.

These power plants are compact and its cost is reduced since it uses water both as coolant and moderator. However, the high pressure in the primary circuit of water absorbing heat in the reactor requires a strong reactor shell which increases its cost.

In this reactors, the water flowing through the reactor becomes radioactive, therefore this primary circuit must be heavily shielded to protect the operators.

10.15.1 Advantages of PWR :

1. Water is used both as coolant and moderator which is cheap and easily available.
2. Reactor is compact.
3. Small number of control rods are required.
4. Fission products remain contained in the reactor.

10.15.2 Disadvantages of PWR :

1. Capital cost is high since the reactor and primary circuit works under pressure.
2. Only saturated steam can be generated in secondary circuit, therefore the efficiency of plant is low.
3. Costly shielding is required to shield the operators in primary circuit since the coolant becomes radioactive.
4. Severe corrosion problems.
5. Fuel suffers from radiations. Therefore, its reprocessing is difficult.
6. Plants needs to be shut down for fuel charging.

10.16 The Boiling Water Reactor (BWR) Power Plant :

The arrangement of a boiling water reactor power plant is shown in Fig. 10.16.1.

It uses **enriched uranium as fuel** and water is used both as coolant and moderator. These reactors do not require a heat exchanger as needed in case of pressurized water reactors since the water is directly converted in a saturated steam at about 285°C at 70 bar pressure.

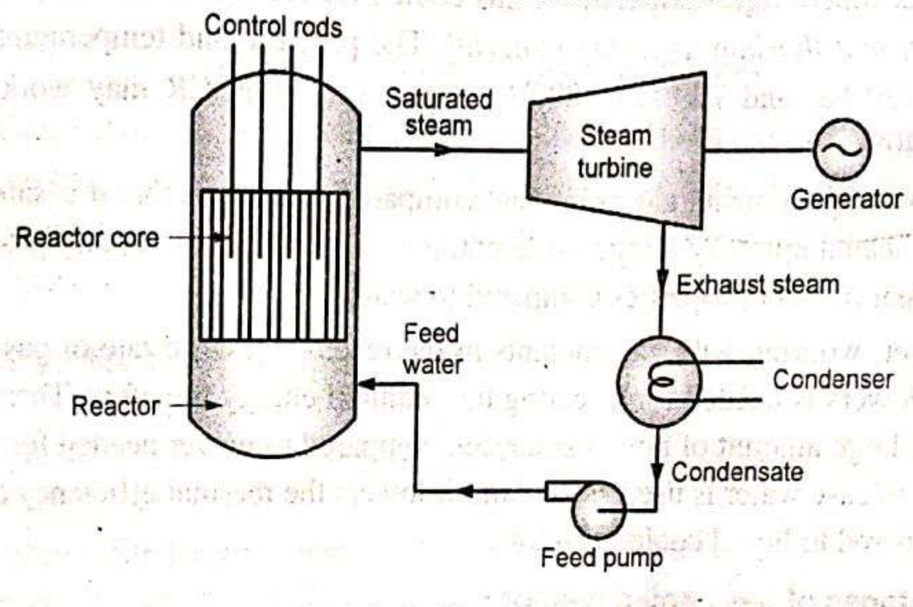


Fig. 10.16.1 : Boiling water reactor

For these reason, this system is also called as direct cycle boiling water reactor power plant.

The feed water circulated in the reactor is converted into saturated steam by transfer of energy released by fission in the reactor core. This steam is supplied to steam turbine in a conventional power plant working on the cycle. The mechanical power developed by the turbine is converted into electric energy by the generator. The exhaust of steam from turbine is condensed in the condenser. The condensate is returned to reactor as feed water by the feed water pump.

In India the Tarapur atomic power plant works on BWR principle.

10.16.1 Advantages of BWR :

1. It eliminates the use of heat exchanger, pressuriser, circulating pump and piping. Therefore system is simple, cheap and efficiency is high.
2. Use of low pressure reactor further reduces the cost of plant.

10.16.2 Disadvantages of BWR :

1. It has the possibility of radioactive contamination of steam turbine.
2. It cannot meet the sudden changes in load on the plant.
3. System requires extensive safety devices against radioactive radiations which are costly.

10.17 The Gas Cooled Reactors (GCR) :

A gas cooled reactor was first developed in U.K. uses CO_2 *as coolant* instead of water and *graphite as moderator*. It is called ***gas cooled graphite moderated (GCGM) reactor***. It uses *natural uranium as fuel*. The coolant pressure is about 7 bar and temperature 336°C.

Another gas cooled reactor developed in U.S.A uses *helium as coolant* and *graphite as moderator*. It is called **high temperature gas cooled (HTGC)** reactor. *The fuel used in* U^{233} *as fissile material and thorium as fertile material.* The pressure and temperatures of the coolant are 15 bar to 30 bar and 700°C to 800°C respectively. HTGCR may work upto a thermal efficiency of 40%.

The advantage of using gas as coolant compared to water is that it is safe, easy to handle and it can be heated upto any temperature without change of phase at any pressure though the gas has low heat transfer properties compared to water.

However, working with gas coolants in the reactors, a large rate of gas circulation with the help of blowers is needed for affecting the required energy transfers. Therefore for driving the blowers a large amount of power is needed compared to power needed for running the feed water pumps in case water is used as coolant. It lowers the thermal efficiency of the gas cooled reactors compared to liquid cooled reactors.

1. Advantages of gas cooled reactor :

1. It has no corrosion problem.
2. Gases are safe and easy to handle.
3. Graphite remains stable at high temperatures and radiation problems are minimum.
4. These can be operated at high temperatures.
5. Gases can be pressurized easily.

2. Disadvantages of gas cooled reactor :

1. Gases have lower heat transfer coefficient thus it requires large heat exchangers.
2. Fuels have to be operated at high temperatures.

3. Large amount of fuel loading is required.
4. If helium is used as in case of HTGC, leakage is a major problem.
5. More power is needed for coolant circulation compared to liquid cooled reactors.

Schematic diagram of gas cooled reactor power plant is shown in Fig. 10.17.1.

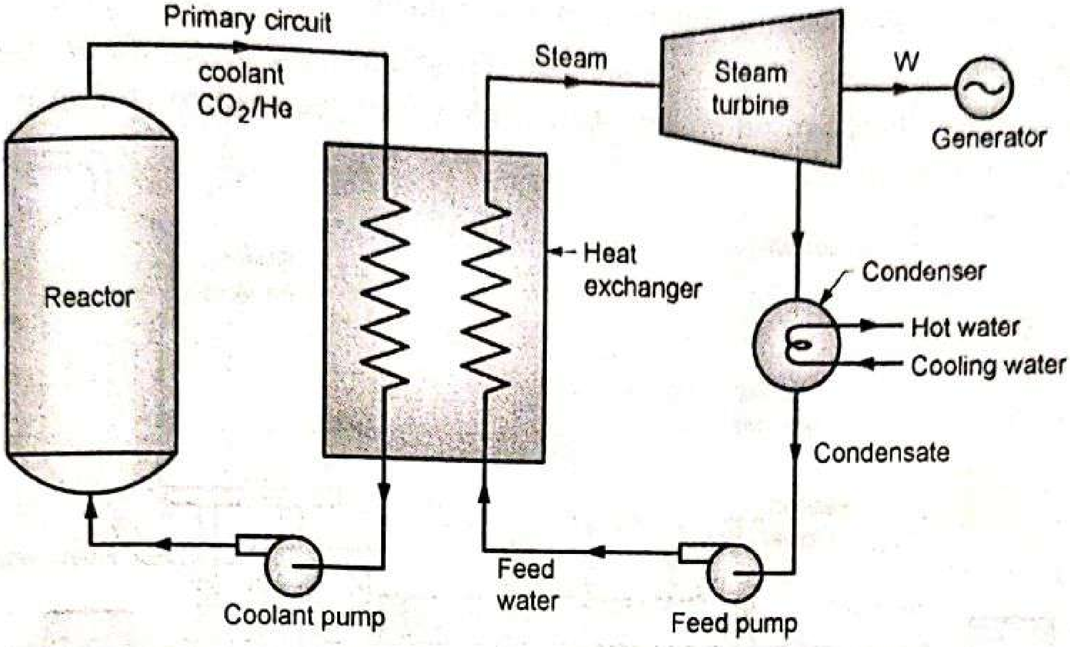


Fig. 10.17.1 : Gas cooler reactor power plant

As discussed above, coolant used is CO_2 for (GCGM) reactor and He in case of HTGC reactor in the primary circuit. The coolant transfers the heat energy to feed water in the heat exchanger. The steam so generated is used in conventional power plant to generate power working on Rankine cycle.

10.18 CANDU Reactor Power Plant :

A reactor developed and designed by Canadian is called as CANDU (Canadian Deutorium Uranium) reactor.

It uses **pressurized heavy water** (PHW) (which is 99.8% deutorium oxide, D_2O) *as moderator and primary coolant while the fuel used is natural uranium.*

A CANDUPHW (Canadian Deutoriam Uranium Pressurized Heavy Water) power plant is shown in Fig. 10.18.1.

Natural uranium oxide fuel is in the form of small cylinder pallets. These are packed in a corrosion resistant zirconium alloy tubes 0.5 cm long and 1.3 cm diameter to form a fuel rod. These short rods are combined in 37 bundles of 37 rods and 12 bundles are placed end to end in each pressure tubes. This type of arrangement helps in refuelling the reactor while in operation.

Reactor vessel is a steel cylinder called calandria. It is placed horizontally. It has pressure tubes penetrating the reactor vessel. The active core is about 6 m high and 7 to 8 m in diameter.

In the primary circuit, the D_2O coolant enters the array of pressure tubes at 110 bar and 260°C. It flows through the fuel element and leaves the pressure tubes at about 370°C after absorbing the heat generated by fission of fuel material.

The coolant at 110 bar, 370°C leaving the reactor enters the steam generator where the generated steam is used in conventional steam power plant.

Control rods are made up of *cadmium*. These are used to *start and shut down* the reactor. In addition there are other *absorbing rods* which are used to control power output during reactor operation.

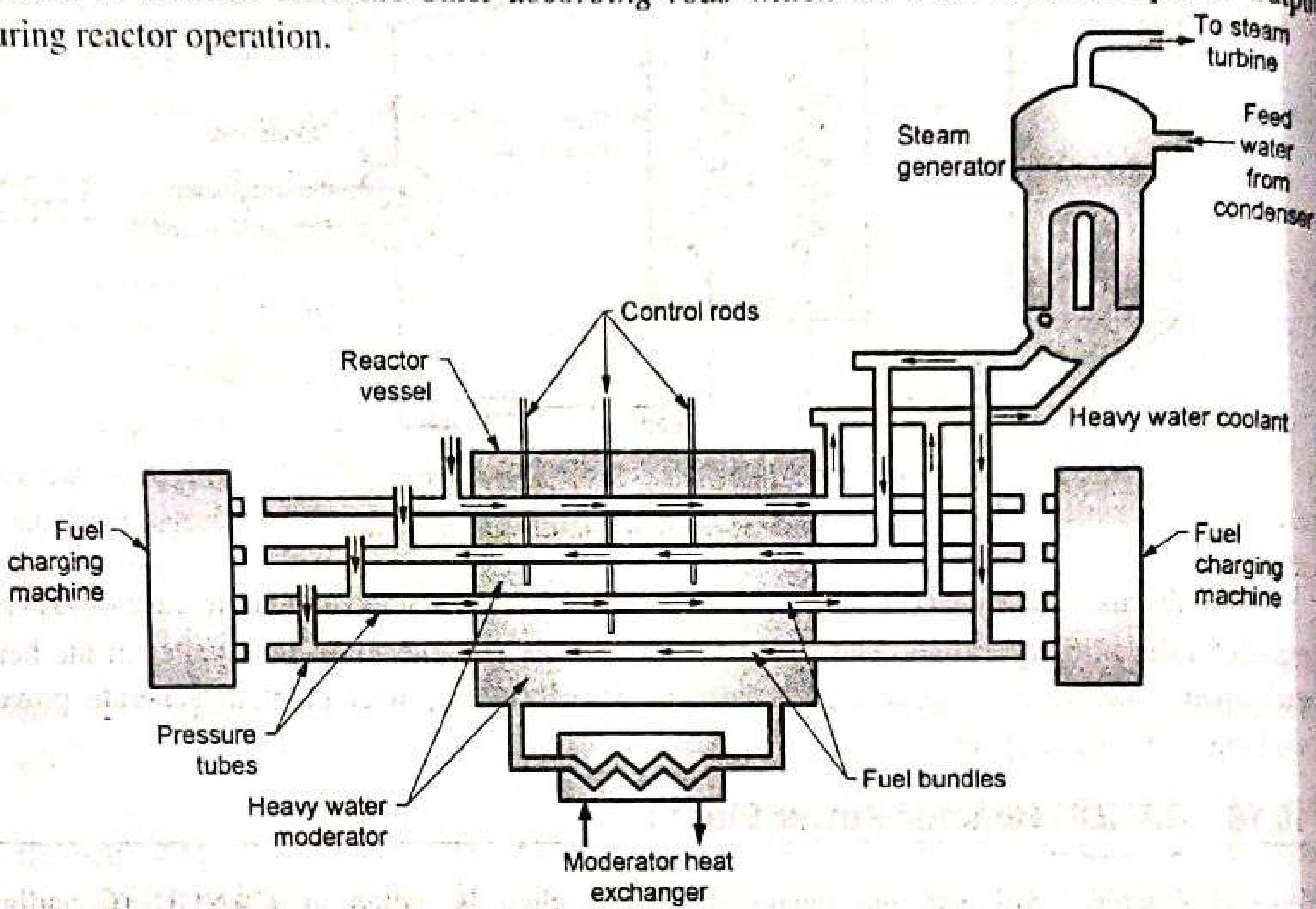


Fig. 10.18.1 : CANDU reactor

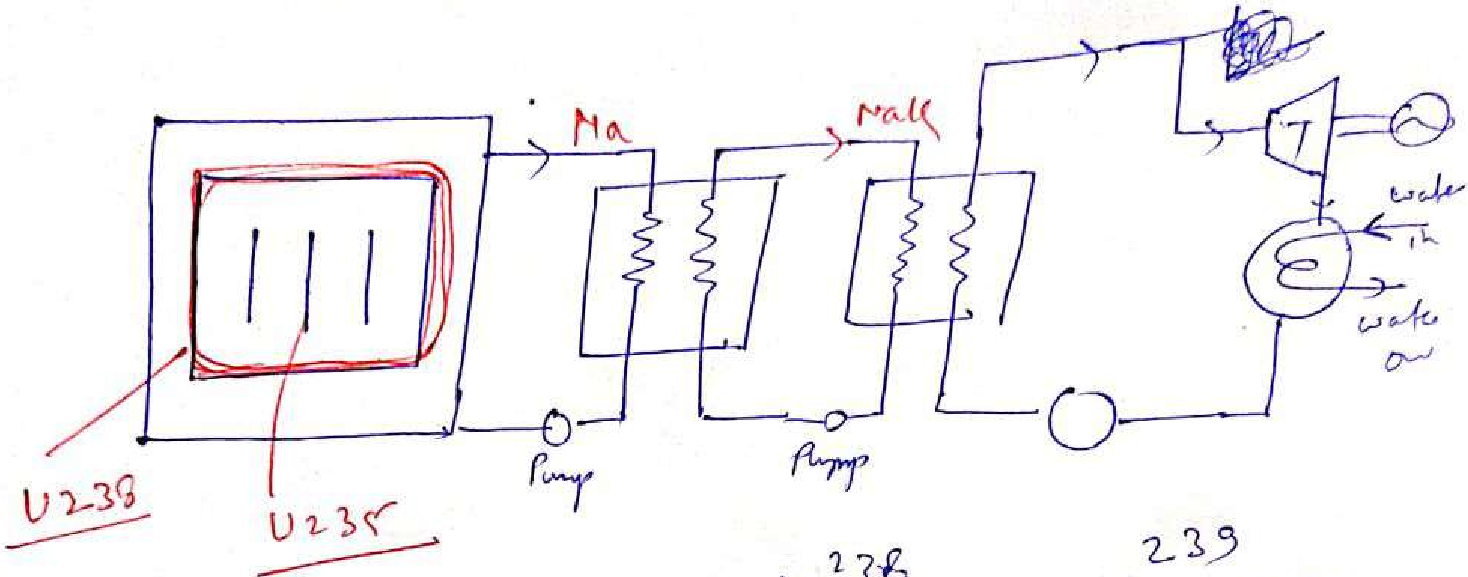
Advantages of CANDU reactor :

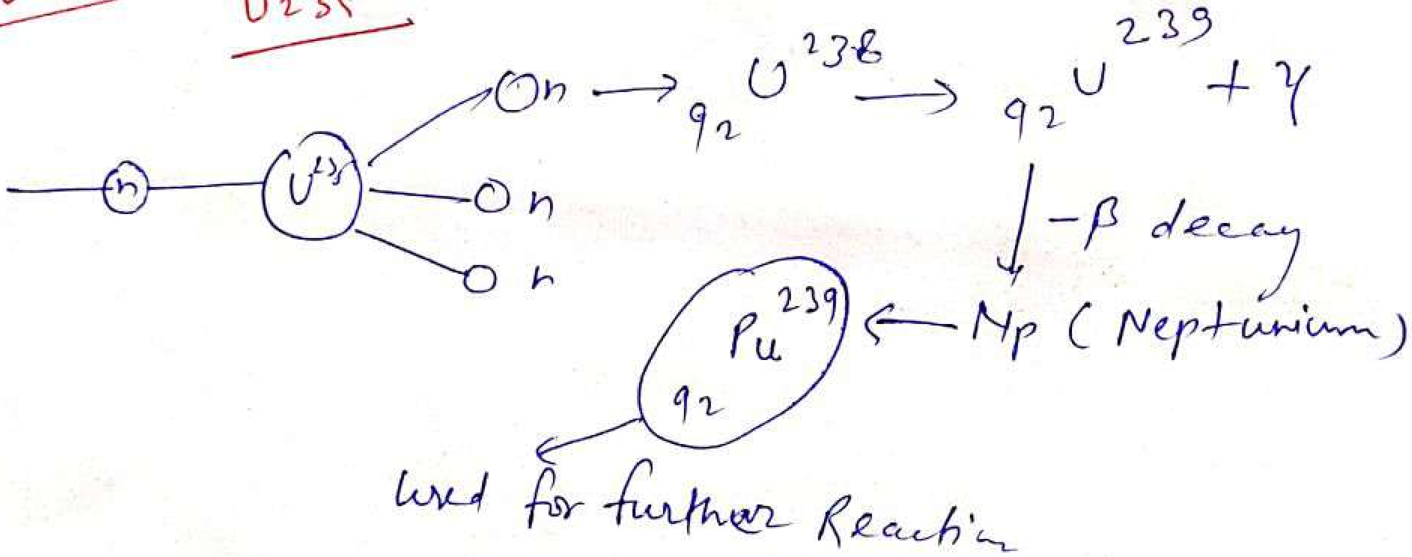
1. Heavy water is used as moderator which has low fuel consumption.
2. Enriched fuel is not required.
3. Cost and time of construction is less.
4. It has good neutron economy resulting into good breeding ratio.

Disadvantages of CANDU reactor :

1. Heavy water used is costly.
2. It has critical temperature limitations.
3. Leakage problems may occur.
4. Size of plant is large.
5. It requires high standards of design, manufacture and maintenance.

Fast Breeder Reactor:





10.19 Liquid Metal Reactor or Sodium Graphite Reactor (SGR) Power Plant :

Sodium graphite reactor is a typical **liquid metal reactor**. The arrangement of a sodium graphite reactor power plant is shown in Fig. 10.19.1.

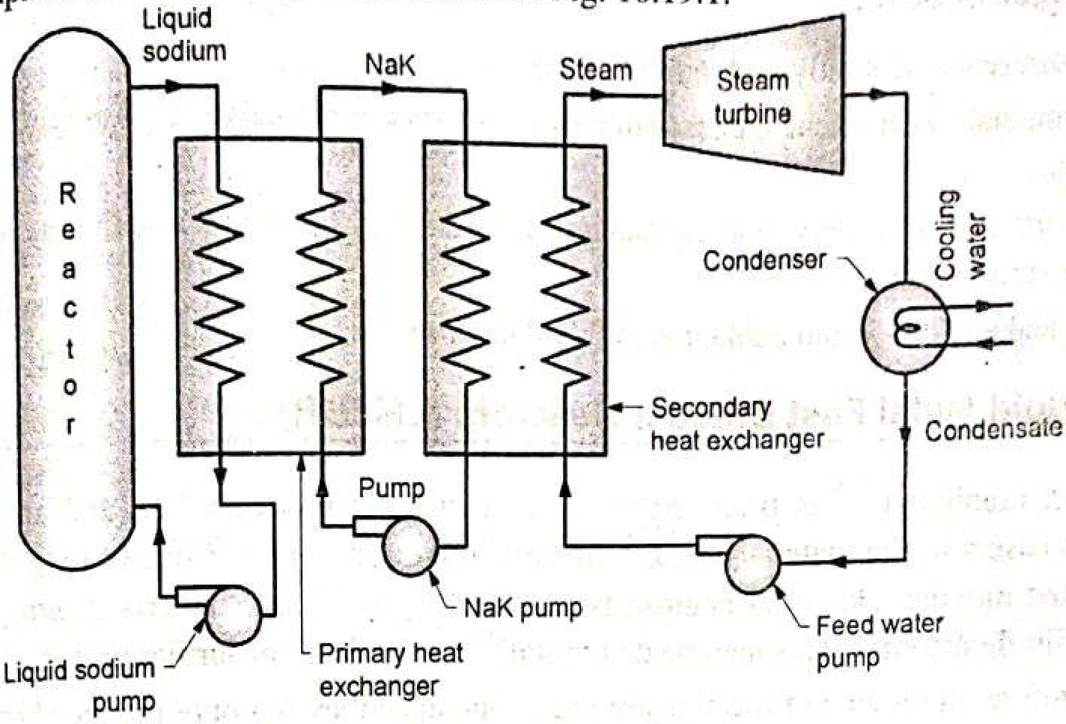


Fig. 10.19.1 : Sodium graphite reactor

It uses graphite as the moderator and liquid sodium as coolant which can reach a temperature of about 850°C at low pressure of only 7 bar.

In the primary circuit the heat is absorbed by liquid sodium in the reactor.

The sodium becomes radioactive while it passes through the core and reacts chemically with water.

Therefore, the heat absorbed by sodium is transferred to *secondary coolant sodium potassium (NaK) in the primary heat exchanger* which in turn transfers the heat in the secondary heat exchanger called **steam generator**.

Water leaving the steam generator is converted into superheated steam upto a temperature of 540°C. This steam is used for power generation in the steam plant circuit in the usual manner.

The reactor vessel, primary circuit and the primary heat exchanger have to be shielded from radiations.

The liquid metal is required to be handled under the cover of an inert gas like helium to prevent contact with air while charging or draining in the primary and secondary heat exchangers.

Advantages of SGR :

1. High temperatures of steam can be obtained due to use of liquid sodium as coolant.
2. System need not be pressurized.

10.21 Selection of Site for Nuclear Power Plants :

Various points to be considered in selection of site for nuclear power plants are as follows :

1. **Availability of water** for steam generation and cooling water for condenser. It should be nearer to sea, river or reservoir.
2. **Nearer to load centre** to reduce power transmission losses.
3. **Away from populated area** to safeguard the people from hazardous radioactive radiations.
4. **Availability of transport facility** for transporation of people and material at the time of its construction by road and rail.
5. **Safeguard against earthquakes :** The site should be away from seismic zone.
6. **Radioactive waste disposal :** The wastes of nuclear power plants being radioactive, the site should have sufficient space near the plant for its disposal.
7. **Soil conditions for foundation : The** bearing capacity of soil should be high so as to support heavy reactors on its foundations. The bearing capacity must be atleast 50 N /cm^2.

10.23 Nuclear Waste Disposal :

Waste disposal of nuclear power station is of prime importance since the nuclear waste is likely to have radioactivity. Therefore, these wastes are disposed off in such a manner that it does not cause harm to human or plant life. The various methods adopted are :

(i) In case of gaseous wastes, it is passed through filters and discharged at a high level through stacks.

(ii) Moderate liquid wastes can be discharged after filtration, preliminary treatment (its PH value is adjusted) and by diluting and mixing with cooling water discharge into deep pits or dry wells.

(iii) Highly radioactive liquid wastes are kept in concrete tanks and buried into ground till their decay of radioactivity.

(iv) Solid wastes arising from discarded control rods, fuel cans etc. are stored in shielded concrete vaults.

(v) The combustible and chemically incompatible wastes are regretted. The combustible waste is burnt in incinerators and the flue gases formed are filtered and disposed off through stocks.

Active solid wastes are stored in water for about 100 or more days to allow radioactivity to decay. Then these are disposed off to deep salt mines or on ocean floor or in deep wells drilled in stable geological strata.

10.24 Comparison between Nuclear and Conventional Thermal Power Plants :

1. Advantages of nuclear power plants over thermal power plants :

(i) For similar capacity plants, the space required is less.

(ii) Cost of fuel transportation, storage and handling is very less since nuclear fuel requirements is much less compared to coal.

(iii) It is more economical to operate, particularly in the areas remote to coal field.

(iv) Ash handling problem is avoided.

(v) Number of persons needed for operation are less.

(vi) These are more reliable in operation.

(vii) The capital cost is low for large sized power plants and the running cost is competitive.

(viii) It has better performance at high load factors.