LECTURE NOTES ON

POWER PLANT ENGINEERING

PREPARED BY:

PROF.CHANDRA SEKHAR SARAN
ASST. PROFESSOR
DEPT.OF MECHANICAL ENGINEERING
GOVT.COLLEGE OF ENGINEERING
KALAHANDI
BHAWANIPATNA

MODULE – IV

NUCLEAR POWER PLANT

SYLLABUS

NUCLEAR POWER PLANT:
Introduction, Nuclear fuels, Nuclear fission, Reactor components, & materials and classification,, Boiling Water Reactor (BWR), Pressurized water Reactor (PWR),CANDU Reactor, Gas cooled Reactors, Liquid metal fast breeder Reactor. Heavy water Reactors. Waste disposal and Safety of Nuclear power plant.

IMPORTANT TERMS RELATED TO NUCLEAR POWER PLANT

1.Isotopes:
Those pairs of atoms which have the same atomic number and hence similar chemical properties but different atomic mass number are called isotopes.

2.Isobars:
Those atoms which have the same mass number but different atomic numbers are called isobars. Obviously, these atoms belong to different chemical elements.

3.Isomers :
Those pairs of atoms (nuclides) which have the same atomic number and atomic mass number but have different radioactive properties are called isomers and their existence is referred to as nuclear isomerism.

4. isotones:
Those atoms whose nuclei have the same number of neutrons are called isotones.

5.Radioactivity:
The phenomenon of spontaneous emission of powerful radiations exhibited by heavy element is called radioactivity. The radioactivity may be natural or artificial.

6. Types of Nuclear radiations:
The five types of nuclear radiations are :

(i) Gamma rays (or photons) : electromagnetic radiation.
(ii) Neutrons : uncharged particles, mass approximately 1.
(iii) Protons : + 1 charged particles, mass approximately 1.
(iv) Alpha particles : helium nuclei, charge + 2, mass 4.
(v) Beta particles : electrons (charge – 1), positrons (charge + 1), mass very small.

7. Fertile Materials:
It has been found that some materials are not fissionable by themselves but they can be converted to the fissionable materials, these are known as fertile materials.

8.Fission:
Fission is the process that occurs when a neutron collides with the nucleus of certain of heavy atoms, causing the original nucleus to split into two or more unequal fragments which carry-off most of the energy of fission as kinetic energy. This process is accompanied by the emission of neutrons and gamma rays.

9.chain reaction:
A chain reaction is that process in which the number of neutrons keeps on multiplying rapidly (in geometrical progression) during fission till whole the fissionable material is disintegrated. The multiplication or reproduction factor (K) is given by:

K=No of neutrons in any particular generation/No. of neutrons in the preceding generation

If K > 1, chain reaction will continue and if K < 1, chain reaction cannot be maintained.

10. Nuclear fusion:

Nuclear fusion is the process of combining or fusing two lighter nuclei into a stable and heavier nuclide. In this case large amount of energy is released because mass of the product nucleus is less than the masses of the two nuclei which are fused.

11. Nuclear Reactor:

A nuclear reactor is an apparatus in which nuclear fission is produced is the form of a controlled self-sustaining chain reaction.

12. Essential components of a nuclear reactor:

Essential components of a nuclear reactor are: (i) Reactor core (ii) Reflector (iii) Control mechanism (iv) Moderator (v) Coolants (vi) Measuring instruments (vii) Shielding.

13. Main components of a nuclear power plant:

The main components of a nuclear power plant are: (i) Nuclear reactor
(ii) Heat exchanger (steam generator)
(iii) Steam turbine (iv) Condenser (v) Electric generator

Important reactors:

Some important reactors are : (i) Pressurized water reactor (PWR) (ii) Boiling water reactor (BWR) (iii) Gas-cooled reactor (iv) Liquid metal-cooled reactor (v) Breeder reactor.

The factors considered for selecting the site for Nuclear power plant:

Following factors should be considered while selecting the site for a nuclear power plant:

(i) Proximity to load centre
(ii) Population distribution
(iii) Land use
(iv) Meteorology
(v) Geology
(vi) Seismology
(vii) Hydrology

Types of Reactors:

1. On the basis of neutron energy. 2. On the basis of fuel used. 3. On the basis of Moderate used. 4. On the basis of coolent used.

Advantages of nuclear power plant:

1. It can be easily adopted where water and coal resources are not available.
2. The Nuclear power plant requires very small quantity of fuel. Hence fuel transport cost is less.
3. Space requirement is very less compared to other power plant of equal capacity.
4. It is not affected by adverse weather condition.

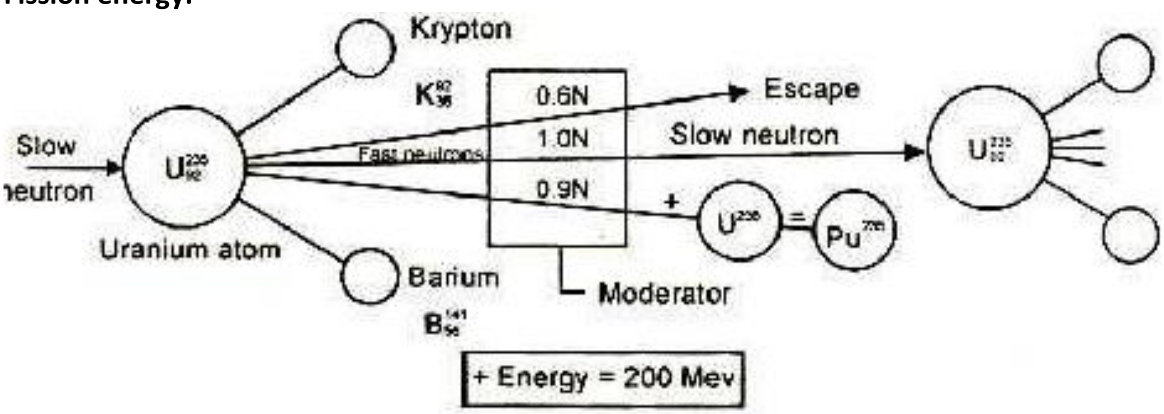
Ways the liquid wastes are disposed:

1. Dilution 2. Concentration to small volumes and storages.

Working of a NUCLEAR POWER PLANT:

A nuclear power plant is similar to a conventional steam power plant except how that energy is evolved. The heat is produced in the nuclear power plant by fission, whereas in steam and gas turbine plants, the heat is produced by combustion in the furnace. The nuclear reactor acts as a furnace where nuclear energy is evolved by splitting or fissioning of the nucleus of fissionable material like Uranium U-235. It is claimed that 1 kg U-235 can produce as much heat energy that can be produced by burning 4500 tones of high grade coal or 1700 tons of oil.

Fission energy:



Nuclear energy is divided from splitting (or) fissioning of the nucleus of fissionable material like Uranium U-235. Uranium has several isotopes (Isotopes are atoms of the same element having different atomic masses) such as U-234, U-235 and U-238. Of the several isotopes, U-235 is the most unstable isotope, which is easily fissionable and hence used as fuel in an atomic reactor. When a neutron enters the nucleus of an unstable U-235, the nucleus splits into two equal fragments (Krypton and Barium) and also releases 2.5 fast moving neutrons with a velocity of 1.5×10^7 m/sec and along with this produces a large amount of energy, nearly 200 million electro- volts. This is called nuclear fission.

Chain reaction:

The neutrons released during fission are very fast and can be made to initiate the fission of other nuclei of U-235, thus causing a chain reaction. When a large number of fission occurs, enormous amount of heat is generated, which is used to produce steam. The chain reaction under controlled conditions can release extremely large amount of energy causing ‚atomic explosion'.

Energy released in chain reaction, according to Einstein law is $E = mc^2$.

Where E = Energy liberated (J)

m= Mass (kg)

c = Velocity of light (3×10^8 m/sec).

Out of 2.5 neutrons released in fission of each nucleus of U-235, one neutron is used to sustain the chain reaction, about 0.9 neutron is captured by U-238, which gets converted into fissionable material Pu-239 and about 0.6 neutron is partially absorbed by control rod materials, coolant and moderator.

If thorium is used in the reactor core, it gets converted to fissionable material U-233.

Thorium 232 + Neutron = U-233

Pr-239 and U-233 so produced are fissionable materials are called secondary fuels. They can be used as nuclear fuels. U-238 and Th-232 are called fertile materials.

Fusion energy :

Energy is produced in the sun and stars by continuous fusion reactions in which four nuclei of hydrogen fuse in a series of reactions involving other particles that continually appear and disappear in the course of the reaction, such as He3, nitrogen, carbon, and other nuclei, but culminating in one nucleus of helium of two positrons.

To cause fusion, it is necessary to accelerate the positively charged unclei to high kinetic energies, in order to overcome electrical repulsive forces, by raising their temperature to hundreds of millions of degrees resulting in plasma. The plasma must be prevented from contacting the walls of the container, and must be confined for a period of time (of the order of a second) at a minimum density. Fusion reactions are called thermonuclear because very high temperatures are required to trigger and sustain them. Table lists the possible fusion reactions and the energies produced by them. n, p, D, and T are the symbols for the neutron, proton, deuterium (H^2), and tritium (H^3), respectively.

Number	**Fusion reaction** **Reactants** **Products**	Energy perreaction MeV
1	D + D T + p	4
2	D + D He^3 + n	3.2
3	T + D He^4 + n	17.6
4	He^3 + D He^4 + p	18.3

Many problems have to be solved before an artificially made fusion reactor becomes a reality. The most important of these are the difficulty in generating and maintaining high temperatures and the instabilities in the medium (plasma), the conversion of fusion energy to electricity, and many other problems of an operational nature.

Types of Reactors:

The nuclear reactors are classified on the following basis:

1. On the basis of neutron energy :

a) Fast reactors In these reactors, the fission is effected by fast neutrons without any use of moderators.

b) Thermal reactors In these reactors, the fast neutrons are slowed with the use of moderators. The slow neutrons are absorbed by the fissionable fuel and chain reaction is maintained. The moderator is the most essential component in these reactors.

2. On the basis of fuel used :

a) Natural fuel In this reactor, the natural uranium is used as fuel and generally heavey water or graphite is used as moderator. b) Enriched uranium In this reactor, the Uranium used contains 5 to 10% U^{235} and ordinary water can be used as moderator.

3. On the basis of moderator used:

a) Water moderated b) Heavy water moderated c) Graphite moderated d) Beryllium moderated

4. On the basis of coolant used:

a) Water cooled reactors (ordinary or heavy), b) Gas cooled reactors c) Liquid metal cooled reactors d) Organic liquid cooled reactors

Construction and working principle of Pressurized Water Reactor (PWR) Pressurized Water Reactor (PWR)

Working principle: A nuclear power plant differs from a conventional steam power plant only in the steam generating part. There is no change in the turbo-alternator and the condensing system. The nuclear fuel which is at present in commercial use is Uranium. Heat energy evolved by the fission reaction of one kg of U235 can produce as much energy as can be produced by burning 4500 tons of high grade coal. Uranium exists in the isotopic form of U235 which is unstable. When a neutron enters the nucleus of U235, the nucleus splits into two equal fragments and also releases 2.5 fast moving neutrons with a velocity of 1.5 × 107 metres / sec producing a large amount of energy, nearly 200 millions electron-volts. This is called ‚nuclear fission‛.

Chain reaction

The neutrons released during the fission can be made to fission other nuclei of U^{235} causing a ‚chain reaction. A chain reaction produces enormous amount of heat, which is used to produce steam‛.

The chain reaction under uncontrolled conditions can release extremely large amounts of energy causing ‚atomic explosion‛.

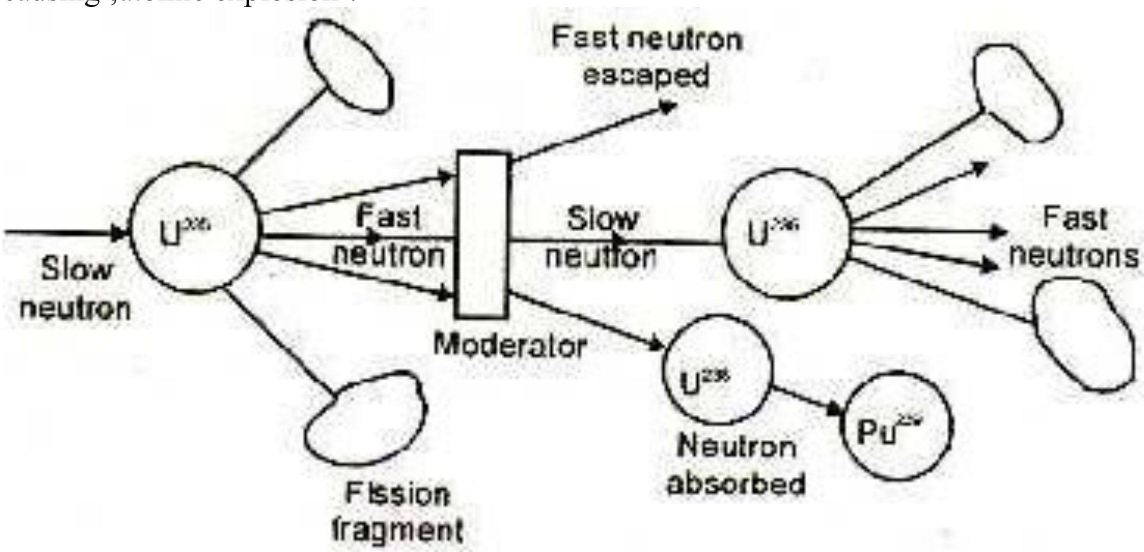


Figure: Nuclear fission

Energy liberated in chain reaction, according to Einstein Law, is $E = mc^2$, where E = energy liberated, m = mass in grams, c = speed of light = 3×10^{10} cm/sec.

Out of 2.5 neutrons released in fission of each nuclei of U^{235}, one neutron is used to sustain the chain reaction, 0.9 neutron is converted into fissionable material Pu^{239} and 0.6 neutron is absorbed by control rod and coolant moderator. Function of the moderator is to reduce the energy of neutrons evolved during fission in order to maintain the chain reaction. The moderators which are commonly used are ordinary water and heavy water.

Main components of nuclear power plants:

i) **Moderators :**
In any chain reaction, the neutrons produced are fast moving neutrons. These are less effective in causing fission of U^{235} and they try to escape from the reactor. It is thus implicit that speed of these neutrons must be reduced if their effectiveness is carrying out fission is to be increased. This is done by making these neutrons collide with lighter nuclei of other materials, which does not absorb these neutrons but simply scatter them. Each collision causes loss of energy and thus the speed of neutrons is reduced. Such a material is called a 'Moderator'. The neutrons thus slowed down are easily captured by the fuel element at the chain reaction proceeds
slowly.

ii**) Reflectors** :
Some of the neutrons produced during fission will be partly absorbed by the fuel elements, moderator, coolant and other materials. The remaining neutrons will try to escape from the reactor and will be lost. Such losses are minimized by surrounding (lining) the reactor core with a material called a reflector which will reflect the neutrons back to the core. They improve the neutron economy. Economy: Graphite, Beryllium.

iii) **Shielding** :
During Nuclear fission α,γ,β particles and neutrons are also produced. They are harmful to human life. Therefore it is necessary to shield the reactor with thick layers of lead, or concrete to protect both the operating personnel as well as environment from radiation hazards.

iv) **Cladding :**
In order to prevent the contamination of the coolant by fission products, the fuel element is covered with a protective coating. This is known as cladding. Control rods are used to control the reaction to prevent it from becoming violent. They control the reaction by absorbing neutrons. These rods are made of boron or cadmium. Whenever the reaction needs to be stopped, the rods are fully inserted and placed against their seats and when the reaction is to be started the rods are pulled out.

v) **Coolant** :
The main purpose of the coolant in the reactor is to transfer the heat produced inside the reactor. The same heat carried by the coolant is used in the heat exchanger for further utilization in the power generation.
Some of the desirable properties of good coolant are listed below:
1. It must not absorb the neutrons.
2. It must have high chemical and radiation stability
3. It must be non-corrosive.
4. It must have high boiling point (if liquid) and low melting point (if solid)
5. It must be non-oxidising and non-toxic. The above-mentioned properties are essential to keep the reactor core in safe condition as well as for the better functioning of the content.
6. It must also have high density, low viscosity, high conductivity and high specific heat. These properties are essential for better heat transfer and low pumping power.

The water, heavy water, gas (He, CO_2), a metal in liquid form (Na) and an organic liquid are used as coolants. The coolant not only carries large amounts of heat from the core but also keeps the fuel assemblies at a safe temperature to avoid their melting and destruction.

vi) **Nuclear reactor** :
A nuclear reactor may be regarded as a substitute for the boiler fire box of a steam power

plant. Heat is produced in the reactor due to nuclear fission of the fuel U^{235}

The heat liberated in the reactor is taken up by the coolant circulating through the core. Hot coolant leaves the reactor at top and flows into the steam generator (boiler).

Radiation hazards and Shieldings :

The reactor is a source of intense radioactivity. These radiations are very harmful to human life. It requires strong control to ensure that this radioactivity is not released into the atmosphere to avoid atmospheric pollution. A thick concrete shielding and a pressure vessel are provided to prevent the escape of these radiations to atmosphere

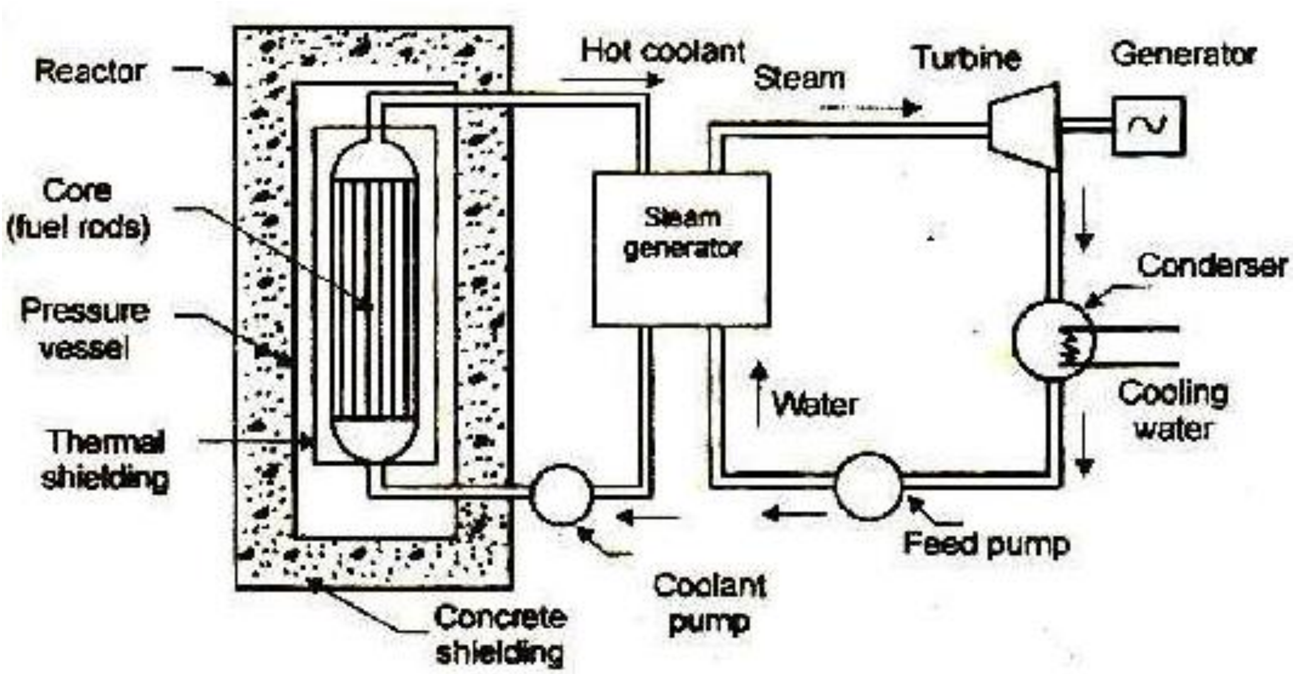


Figure : Nuclear Power Plant (PWR)

vii) **Steam generator** :

The steam generator is fed with feed water which is converted into steam by the heat of the hot coolant. The purpose of the coolant is to transfer the heat generated in the reactor core and use it for steam generation. Ordinary water or heavy water is a common coolant.

viii) **Turbine** :

The steam produced in the steam generator is passed to the turbine and work is done by the expansion of steam in the turbine.

ix) **Coolant pump and Feed pump :**

The steam from the turbine flows to the condenser where cooling water is circulated. Coolant pump and feed pump are provided to maintain the flow of coolant and feed water respectively.

Advantages of nuclear power plant:

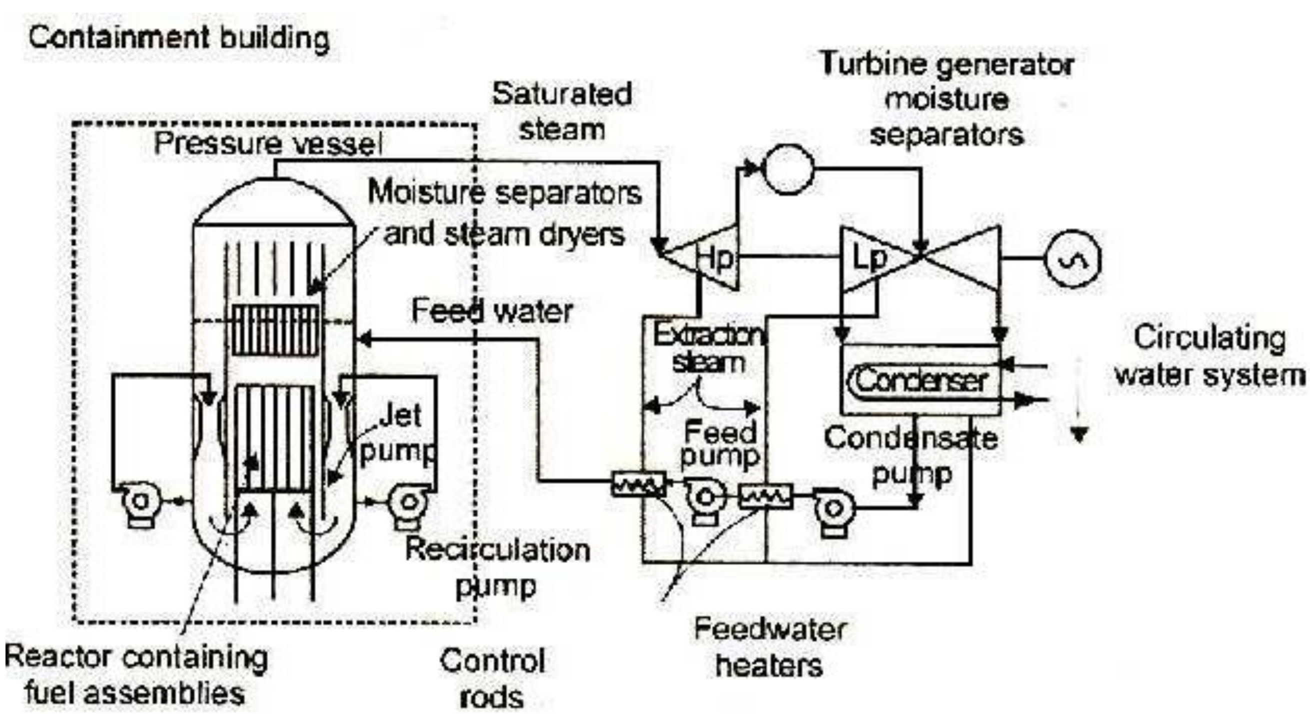
1. It can be easily adopted where water and coal resources are not available.
2. The nuclear power plant requires very small quantity of fuel. Hence fuel transportation cost is less.
3. Space requirement is less compared to other power plants of equal capacity.
4. It is not affected by adverse weather conditions.

5. Fuel storage facilities are not needed as in the case of the thermal power plant.
6. Nuclear power plants will converse the fossils fuels (coal, petroleum) for other energy needs.
7. Number of workmen required at nuclear plant is far less than thermal plant.
8. It does not require large quantity of water.

Disadvantages :
1. Radioactive wastes, if not disposed of carefully, have adverse effect on the health of workmen and the population surrounding the plant.
2. It is not suitable for varying load condition.
3. It requires well-trained personnel.
4. It requires high initial cost compared to hydro or thermal power plants.

Construction and working principle of Boiling Water Reactor (BWR)

Figure shows a simplified BWR. Light water, which acts as the coolant and moderator, passes through the core where boiling takes place in the upper part of the core. The wet steam then passes through a bank of moisture separators and steam dryers in the upper part of the pressure vessel. The water that is not vaporized to steam is recirculated through the core with the entering feed water using two recirculation pumps coupled to jet pumps (usually 10 to 12 per recirculation pump). The steam leaving the top of the pressure vessel is at saturated conditions of 7.2 MPa and 278^{O}C.
The steam then expands through a turbine coupled to an electrical generator. After condensing to liquid in the condenser, the liquid is returned to the reactors as feedwater. Prior to entering the reactor, the feedwater is preheated in several stages of feedwater heaters. The balance of plant systems (Example: Turbine generator, feedwater heaters) are similar for both PWR and BWRs.

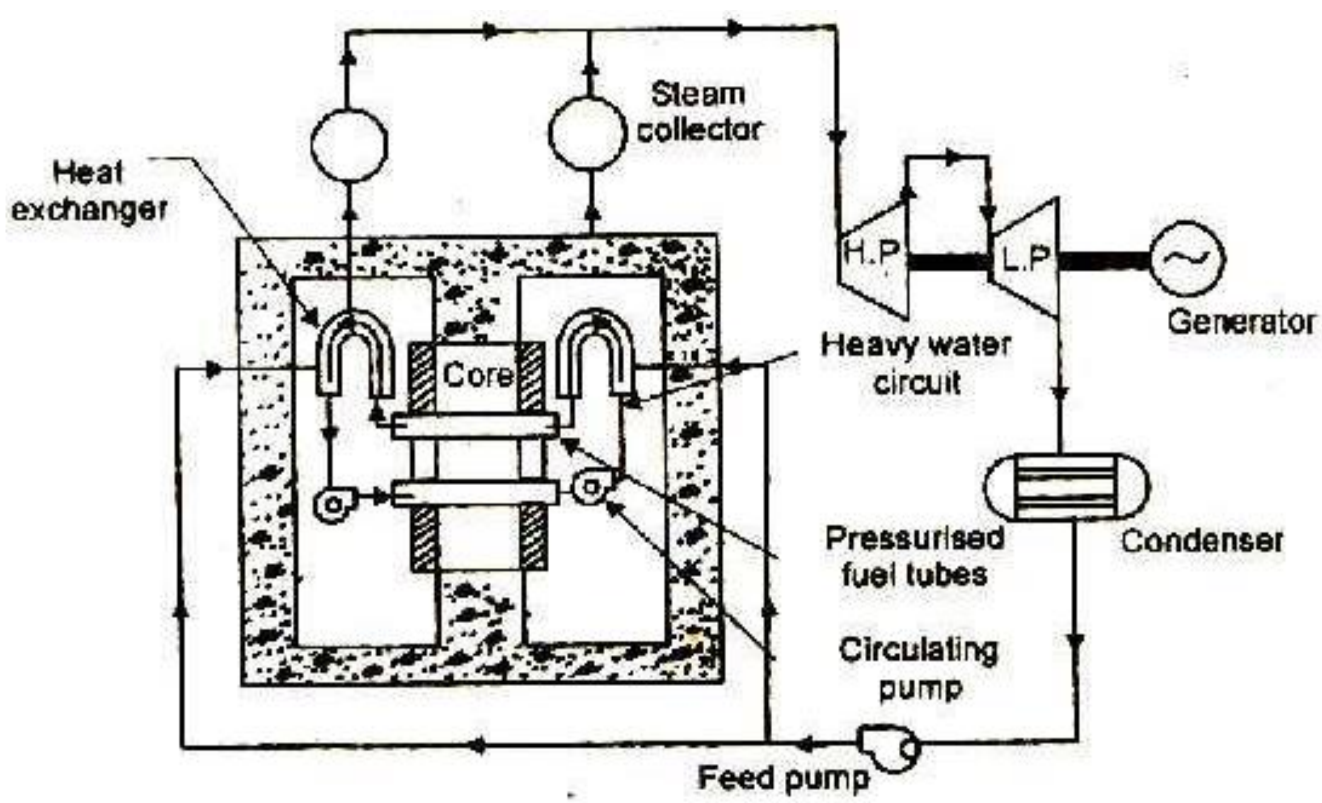


Schematic for a boiling water reactor.

The BWR reactor core, like that in a PWR, consists of a large number of fuel rods housed in fuel assemblies in a nearly cylindrical arrangement. Each fuel assembly contains an 8×8 or 9×9 square array of 64 or 81 fuel rods (typically two of the fuel rods contain water rather than fuel) surrounded by a square Zircaloy channel box to ensure no coolant crossflow in the core. The fuell rods are similar to the PWR rods, although larger in diameter. Each fuel rod is a zirconium alloy- clad tube containing pellets of slightly enriched uranium dioxide (2% to 5% U-235) stacked end-to- end. The reactor is controlled by control rods housed in a cross-shaped, or cruciform, arrangement called a control element. The control elements enter from the bottom of the reactor and move in spaces between the fuel assemblies. The BWR reactor core is housed in a pressure vessel that is larger than that of a PWR. A typical BWR pressure vessel, which also houses the reactor core, moisture separators, and steam dryers, has a diameter of 6.4 m, with a height of 22 m. Since a BWR operators at a nominal pressure of 6.9 MPa, its pressure vessel is thinner that that of a PWR.

Construction and working principle of Heavy Water Cooled Reactor (HWR) (or) CANDU Type Reactor (CANDU – Canadium, Deutrium, Uranium).

These reactors are more economically to those nations which do not produce enriched uranium as the enrichment of uranium is very costly. In this type of reactors, the natural uranium (0.7% U^{235}) is used as fuel and heavy water as moderator. This type of reactor was first designed and developed in Canada. The first heavy water reactor in Canada using heavy water as coolant and moderator of 200 MW capacity with 29.1% thermal efficiency was established at Douglas (Ontario known as Douglas power station. The arrangement of the different components of CANDU type reactor is shown in figure.



Douglas-point candu type heavy water moderated and cooled nuclear reactor power plant

The coolant heavy water is passed through the fuel pressure tubes and heat-exchanger. The heavy water is circulated in the primary circuit in the same way as with a PWR and the steam is raised in the secondary circuit transferring the heat in the heat exchanger to the ordinary water. The control of the reactor is achieved by varying the moderator level in the reactor and, therefore, control rods are not required. For rapid shutdown purpose, the moderator can be dumped through a very large area into a tank provided below the reactor.

Advantages and disadvantages of HWR (or) CANDU type Reactor.

Advantages:

1. The major advantage of this reactor is that the fuel need not be enriched.
2. The reactor vessel may be built to withstand low pressure, therefore, the cost of the vessel is less.
3. No control rods are required, therefore, control is much easier than other types.
4. The moderator can be kept at low temperature which increases its effectiveness in slowing-down neutrons.
5. Heavy water being a very good moderator, this type of reactor has higher multiplication factor and low fuel consumption.
6. A shorter period is required for the site construction compared with PWR and BWR.

Disadvantages :

1. The cost of heavy water is extremely high (Rs. 300/kg).
2. The leakage is a major problem as there are two mechanically sealed closures per fuel channel. Canadian designs generally are based or recovering high proportion of heavy water leakages as absolute leak-tightness cannot be assured.
3. Very high standard of design, manufacture inspection and maintenance are required.
4. The power density is considerably low (9.7 kW/litre) compared with PWR and BWR, therefore, the reactor size is extremely large.

Even though CANDU-type reactors look promising in future, light water reactors all over the world proved more efficient than heavy water and in fact only 36 out of 529 power reactors in the world are based on heavy water.

Sodium Graphite Reactor (SGR)

The reactor shown in figure uses two liquid metal coolants. Liquid sodium (Na) serves as the primary coolant and an alloy of sodium potassium (NaK) as the secondary coolant.

Sodium melts at 208 ^{O}C and boils at 885 ^{O}C . This enables to achieve high outlet coolant temperature in the reactor at moderate pressure nearly atmospheric which can be utilized in producing steam of high temperature, thereby increasing the efficiency of the plant. Steam at temperature as high as 540 ^{O}C has been obtained by this system. This shows that by using liquid sodium as coolant more electrical power can be generated for a given quantity of the fuel burn up.

Secondly low pressure in the primary and secondary coolant circuits, permits the use of less expensive pressure vessel and pipes etc. Further sodium can transfer its heat very easily. The only disadvantage in this system is that sodium becomes radioactive while passing through the core and reacts chemically with water. So it is not used directly to transfer its heat to the feed water, but a secondary coolant is used. Primary coolant while passing through the tubes of intermediate heat exchanges (I.H.X) transfers its heat to the secondary coolant. The secondary coolant then flows through the tubes of steam generator and passes on its heat to the feed water. Graphite is used as heat transfer media have certain advantages of using liquids used for heat transfer purposes. The various advantages of using liquid metals as heat transfer media are that they have relatively low melting points and combine high densities with low vapour pressure at high temperatures as well as with large thermal conductivities.

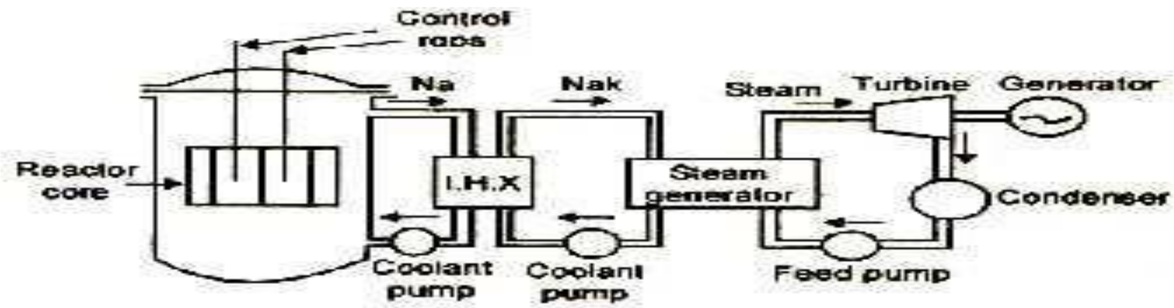
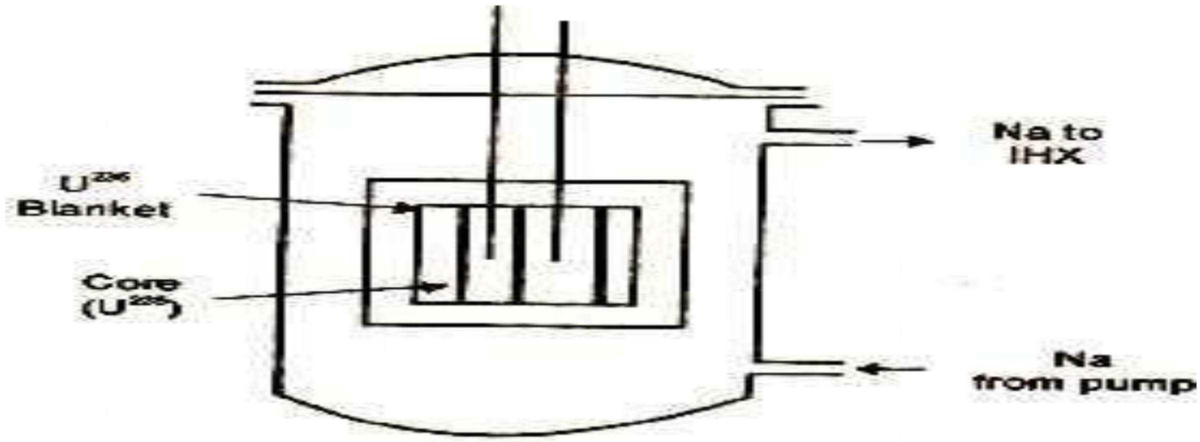


Figure:Sodium graphite reactor

Fast Breeder Reactor

Figure shows a fast breeder reactor system. In this reactor the core containing U^{235} in surrounded by a blanket (a layer of fertile material placed outside the core) of fertile material U^{238}. In this reactor no moderator is used. The fast moving neutrons liberated due to fission of U^{235} are absorbed by U^{238} which gets converted into fissionable material Pu^{239} which is capable of sustaining chain reaction. Thus this reactor is important because it breeds fissionable material from fertile material U^{238} available in large quantities. Like sodium graphite nuclear reactor this reactor also uses two liquid metal coolant circuits. Liquid sodium is used as primary coolant when circulated through the tubes of intermediate heat exchange transfers its heat to secondary coolant sodium potassium alloy. The secondary coolant while flowing through the tubes of steam generator transfers its heat to feed water.

Fast breeder reactors are better than conventional reactors both from the point of view of safety and thermal efficiency. For India which already is fast advancing towards self reliance in the field of nuclear power technology, the fast breeder reactor becomes inescapable in view of the massive reserves of thorium and the finite limits of its uranium resources. The research and development efforts in the fast breeder reactor technology will have to be stepped up considerably if nuclear power generation is to make any impact on the country’s total energy needs in the not too distant future.



Fast breeder reactor.

Coolants used for Fast Breeder Reactors :

The commonly used coolants for fast breeder reactors are as follows:

i) Liquid metal (Na or NaK).
ii) Helium (He)
iii) carbon dioxide.

Sodium has the following advantages:

i) It has very low absorption cross-sectional area.
ii) It possesses good heat transfer properties at high temperature and low pressure.
iii) It does not react on any of the structural materials used in primary circuits.

Safety Measures carried out in Nuclear Power Plant

Safety for nuclear power plants:

Nuclear power plants should be located far away from the populated area to avoid the radioactive hazard. A nuclear reactor produces α and β particles, neutrons and γ - quanta which can disturb the normal functioning of living organisms. Nuclear power plants involve radiation leaks, health hazard to workers and community, and negative effect on surrounding forests.

At nuclear power plants there are three main sources of radioactive contamination of air.

1. Fission of nuclei of nuclear fuels.
2. The second source is due to the effect of neutron fluxes on the heat carrier in the primary cooling system and on the ambient air.
3. Third source of air contamination is damage of shells of fuel elements.

This calls for special safety measures for a nuclear power plant. Some of the safety measures are as follows.

1. Nuclear power plant should be located away from human habitation.
2. Quality of construction should be of required standards.
3. Waste water from nuclear power plant should be purified.The water purification plants must have efficiency of water purification and satisfy rigid requirements as regards the volume of radioactive wastes disposed to burial.

4. An atomic power plant should have an extensive ventilation system. The main purpose of this ventilation system is to maintain the concentration of all radioactive impurities in the air below the permissible concentrations.

5. An exclusion zone of 1.6 km radius around the plant should be provided where no public habitation is permitted.

6. The safety system of the plant should be such as to enable safe shut down of the reactor whenever required.

Waste Disposal:

Waste disposal problem is common in every industry. Wastes from atomic energy installations are radioactive, create radioactive hazard and require strong control to ensure that radioactivity is not released into the atmosphere to avoid atmospheric pollution. The wastes produced in a nuclear power plant may be in the form of liquid, gas or solid and each is treated in a different manner:

TEXT BOOKS

1. Power plant Engineering ; – By P.K. Nag (2nd edition) TMH
2. Power Plant Engineering by Arora and Domkundwar, Dhanpat Rai publications

REFERENCE:

1. Power Plant Engineering by Rajput
2. Power plant technology : By E.I. Wakil TMH