INTRODUCTION TO NUCLEAR POWER PLANTS (NPPs):

Ever growing demand to electricity as a result of industrialisation and increasing population prompted to look for alternate sources of energy. Over the years there is a depletion of fossil fuels reserves (such as coal, oil and gas) across the globe. Exploration for fossil fuels is still undertaken in remote locations. As an alternative to these fossil fuel, nuclear energy is found to be more attractive. This is because of the reason that the energy content per volume of nuclear material is the highest. When compared to coal, energy produced by one kilogram of Uranium is equivalent to burning 3000 tonnes of coal. Thus the energy content of uranium is roughly 30 lakhs times that of coal.

A study made by the committee appointed by government of India, found that nuclear energy is cheaper by 8 to 10 paise per kWh than the thermal plants when coal is available at distance of 800kms from the plant.

The capital cost of NPPs is highest due to cost of building reactor, strong building and fuel. The cost varies from Rs. 15,000 to 60,000 per kWh installed capacity, whereas conventional thermal power plant is about Rs. 3000 to 4000 per kWh. But the operating costs are much cheaper (around 40 to 45 Paise per kWh), which is little higher compared to hydroelectric power plants

The steam turbine employed in NPPs is different in design when compared to turbines used in coal fired steam power plants. The operating temperature and pressure of the turbines is much higher than regular steam power plants.

Economics of NPPs:

In water-cooled, water-moderated reactors, 0.35% of energy is realized with the assumption that each atom of the fuel undergoes nuclear reaction. Where as in breeder reactor with plutonium as the fuel, the efficiency is around 1%. With improvement in design and development it is expected to go around 10%.

The cost of fuel is considerably less which is around 4 to 20% of the total cost per kWh. This mainly depends upon the enrichment of Uranium 235. The cost of the fuel is calculated on the basis of “target irradiation”. The quantity of fuel in the nuclear reactor in a given period will not have significant relationship with the kWh generated.

The amount of fuel to be spent in the reactor is determined from the electrical output of the plant and fuel cost allocation is based on this factor and other operating costs (salaries of operating and maintenance personnel, oil, water, materials for maintenance and cost involved on day to day basis).

The reduction in investment and operating costs is realized by increasing the fuel expenditure and also reducing the enrichment of natural U235 from to 5 to 2.5%.

MERITS AND DEMERITS OF NPPs

The main merits of NPPs over conventional power plants are as follows: -

- Quantity of fuel required is very less. Once the fuel is loaded it will remain in the reactor for several months.
- Requires less site area compared to other type of plants of same size. A typical 200MW NPP requires around 80 acres whereas the coal fired steam power plant require about 250 acres of land.
- No problem with storage and transportation.
- The product of fission results in additional fissile materials which can be used as fuel in other type of reactor.
- Can be located near to the load centre and primary distribution cost can be minimised.
- More economical when the plant capacity is above 100MVA.
- The output power can be easily regulated with proper heat exchanger system.
- Nuclear fuel is abundant in nature in most parts of the globe. If properly mined and processed it can serve the fuel requirement for thousands of years to come.
- Can be operated as a base load plant (for load factor $\geq$ 80%). This is because the amount of the loading will have no effect on the generation cost.
- Auxiliary equipments, transporting trucks and coal/ash handling problems will not exist. So can be neat and tidy.

De-merits:

- High initial capital cost compared to other plants.
- High technology area and requires technical knowhow.
- The by-products of nuclear fission are highly radioactive in nature and there is a potential of radiation pollution.
- Not well suited for varying loads since the reactor cannot respond to load fluctuations.
- The cost of processing the fuel is expensive since it requires enrichment for use in reactors after mining from the ores. This technology is mastered by few nations.

- Specially trained operators are required for proper operation of the plants and also proper shielding is required from radiation effects.
- The radioactive waste (fission by products) is to be properly disposed off since the half-life of these is in several thousand years. This causes health issues and other issues. Requires to be buried deep in earth enclosed in steel containers or to be disposed in deep sea in proper manner.
- More quantity of cooling water requirement compared to thermal power plants of same capacity. More number of cooling towers or larger capacity towers required.

SELECTION OF SITE FOR NPPs:

For efficient, economical and safety operation of NPPs, the following factors are considered.

1. **Availability of adequate quantity of water supply:**
   - Since for producing steam/cooling of various components, sufficient quantity of water is required and hence the site should be nearer to river, lake or sea.

2. **Type of land:**
   - The soil at the selected site to be such that it supports heavy reactor which along with concrete shield weigh as much as one lakh tonnes with pressure withstand capability of 50 tonnes/m^2.
   - The location should not be prone to earth quakes (seismic activity).

3. **Populated area and safety:**
   - The plant is to be far away from populated area for safety purpose.
   - Proper shielding is to be done so that radio activity should not spread through wind and underground waterways.

4. **Location from load centre:**
   - With proper safety measures, the plants are to be located as near as load centres in order to reduce transmission costs and losses.

5. **Disposal of radioactive waste:**

- There should be suitable area nearby for proper disposal of nuclear waste as per norms and standards.

NUCLEAR REACTION:

Radio activity: In nature, some of the elements (uranium, thorium and radium) are heavier elements and unstable. The atomic nucleus breaks on its own and forms elements (new nucleus) of smaller atomic number by the way of regrouping of protons and neutrons. By this process some of the excess particles in the original atom are released along with energy and this process is called radiation. The elements which emits radiation by breaking up into smaller elements is called radioactive elements (radio activity). This process of spontaneous breaking up of unstable atoms is called radioactive disintegration or radioactive decay.

The radio activity is accompanied by the emission of radiation in the form of $\boldsymbol{\alpha}$ (alpha), $\boldsymbol{\beta}$ (beta) particles and $\boldsymbol{\gamma}$ (gamma) rays (electromagnetic radiation with wave length shorter than x-rays). The radioactive decay of Uranium and Plutonium are given below.

$$\boldsymbol{{}^{238}_{92}U = {}^{4}_{2}He + {}^{234}_{90}Th}$$

$$\boldsymbol{{}^{239}_{94}Pu = {}^{4}_{2}He + {}^{235}_{92}U}$$

The $\boldsymbol{\alpha}$ particles are positively charged with a mass of 4 with 2 protons and 2 neutrons (the nuclei of Helium ${}^{4}_{2}He$) and ejected from the radioactive element at 1/10 the velocity of light and travels only short distance in air.

The $\boldsymbol{\beta}$ particles are identical with electrons with negative charge and travel with the speed of light. They are more penetrating than the $\boldsymbol{\alpha}$ particles. The continuous exposure to these particles can cause skin damages and cancerous growth in animals. Using metal or wood / substance of suitable thickness it can be stopped from penetrating.

Gamma rays (electromagnetic radiation with wave length shorter than x-rays) have no mass and which is a stream of high energy protons. Travel with velocity of light and most penetrating among all. They can travel through 5 cm thick sheet of lead or several meters thick concrete walls.

When the nucleus of a radioactive element remains same at highly excited state, neutron emission takes place to form different isotope.

Nuclear reaction is the process of converting mass into energy by the Einstein equation which is given by $\boldsymbol{E = m \times C^2}$.

Where, $\boldsymbol{E}$ = energy in joules, $\boldsymbol{m}$ is the mass in kg and $\boldsymbol{C}$ is the velocity of light which is 3×10^8 m/sec. If a chemical reaction results in imbalance among the mass of reactants and products, then the difference gives the energy absorbed or released. In the reaction process if there is a decrease of mass then there will be a release of energy.

If one gram of matter is destroyed, then corresponding energy produced is 9×10^{11} joules or 25000MW. The common term for energy is in electron volts (eV) and one eV corresponds to 1.6×10^{-19} joules (watt-seconds) and one million electron volts (1MeV) = 1.6×10^{-13} joules.

Nuclear Fission:

- Nuclear fission is the process of splitting heavy nucleus by bombarding with certain type of particles.
- Process is possible with heavy nucleus such as ${}^{233}_{92}U$, ${}^{235}_{92}U$ & ${}^{239}_{94}Pu$.
- The high energy particles may be X-ray, protons and neutrons.
- Modern reactors use neutrons for bombarding since it is having no charge and can easily make its way through the electrons of atom and then to the nucleus at low energy.
- Thus fission is the process of splitting heavy nucleus into two or more smaller nuclei.
- Additionally, fission process releases two or more neutrons along with lot of energy.

The large nucleuses can fission in many ways forming variety of resultant nuclei. Two types of reactions with uranium-235 is given in the following equations.

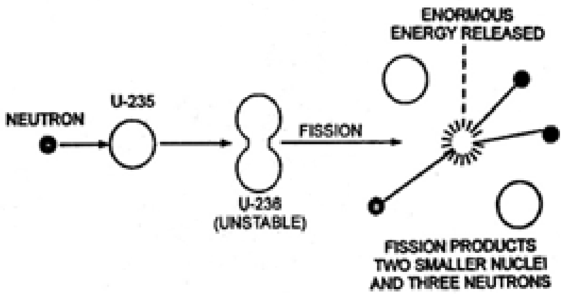
$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{139}_{56}Ba + {}^{94}_{36}Kr + 3\,{}^{1}_{0}n + \text{energy}$$

i.e. (Uranium + Neutron = Barium + Krypton + 3 Neutrons + energy)

the second reaction possible is;

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{106}_{42}Mo + {}^{128}_{50}Sn + 2\,{}^{1}_{0}n + \text{energy}$$

i.e. (Uranium + Neutron = Molybdenum + Tin + 2 Neutrons + energy)



Fission Process showing uranium nucleus split into two smaller nuclei, protons and liberation of energy

The mass of the products is less than the reactants and this loss of about 0.207 ***amu*** (atomic mass unit) in uranium atom is converted into energy (0.207 × 931.5 = 193 MeV) which is approximately taken as 200MeV of energy.

Equivalently, 200MeV = $200 \times 1.6 \times 10^{-13} = 3.2 \times 10^{-11}$ joules (watt-seconds)

Conversely, 1 watt (1 J/s) requires = $\frac{1}{3.2 \times 10^{-11}} = 3.1 \times 10^{10}$ fissions per second. And if all the atoms of 1 kg of pure Uranium (25.64×10^{23} atoms) is involved in fission process then the total energy released will be equivalent to the energy contained in 3×10^{6} kg coal having a calorific value of 6000 K calories/kg. Natural uranium contains only 0.7% of ${}^{235}_{92}U$ and with fission efficiency of 50%, fission of 1 kg of natural uranium gives energy equivalent of coal as per the following equation.

$$\frac{0.7}{100} \times 3 \times 10^{6} \times 0.5 = 10{,}500 \text{ kg of coal}$$

It is to be noted that all the fission products are also radioactive in nature.

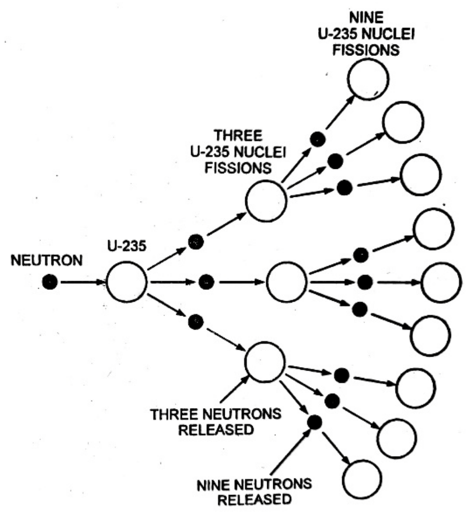
NUCLEAR CHAIN REACTION:

From one of the possible reaction considered in the below equation-

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{139}_{56}Ba + {}^{94}_{36}Kr + 3{}^{1}_{0}n + \text{energy}$$

- If one neutron hits one atom of uranium, the reaction releases two more neutrons in addition to the original one.
- These three neutrons can be made to bombard three more uranium atoms causing three more reactions and nine neutrons released in this process causes nine reactions and this process continues in the same fashion.

- This process of propagation of the nuclear reaction by 3 times in each step is called as a chain reaction. In other words, chain reaction is a fission reaction where in neutrons from previous step continues to multiply and repeat the reaction.
- The chain reaction continues till all of the original nuclei in the given sample is fissioned.
- It is possible that all the neutrons released during nuclear fission process may not be available for next fission they may be lost to the surroundings.
- In order to sustain chain reaction, the fissile material should be of sufficient quantity to capture all of the released neutrons in the fission process.
- The minimum mass of the fissile material required for sustaining the chain reaction is called as the critical mass and differs for different elements.
- By thermal or low speed neutrons the materials which can be fissioned are U_{235}, U_{233} & Pu_{239}.

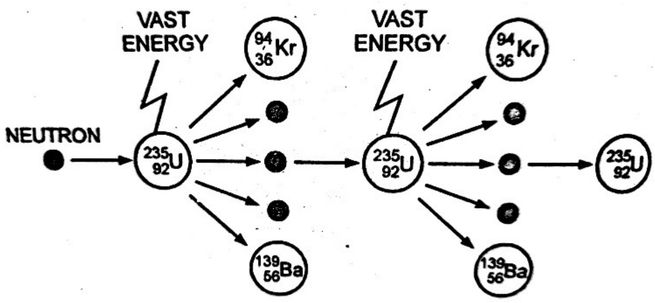


Chain reaction process showing the propagation of nuclear fission reaction

NUCLEAR ENERGY:

- Heavy isotopes like Uranium-235 or Plutonium-239 can be made to undergo nuclear chain reaction and release vast amount of energy.
- The energy released by the fission of nuclei is commonly referred as nuclear fission / nuclear energy.
- Fission reaction takes extremely short time and considered to be instantaneous.
- The fission process releases huge amount of energy in the form of heat and radiation.

- If the fission process is uncontrolled it results in exponential fission reaction releasing energy at each step and finally results in explosion. This is the principle of atomic bombs.
- In nuclear reactors, the fission process is controlled and sustained for the power generation.



Chain reaction of Uranium-235 for releasing vast amount of energy

NUCLEAR FUELS:

The elements used for obtaining fission reaction are the fuels used in nuclear reactor for generation of energy**.**

- Natural Uranium U-235 is the basis for most of fuels. Enriched Uranium is used for better output.
- Plutonium can be used as a secondary fuel.
- Uranium-233 as a secondary fuel obtained from breeder reactor.
- Uranium obtained from nature is consisting of three isotopes namely $^{238}_{92}U$(99.3%), $^{235}_{92}U$(0.7%), & traces of $^{234}_{92}U$ and only the uranium-235 sustains chain reaction in fission process.
- The fissile materials $^{233}_{92}U$ and $^{239}_{92}Pu$ are produced artificially from $^{238}_{92}U$ and $^{232}_{90}Th$, in nuclear reactors. These are available in nature and called as ***fertile materials***.
- $^{239}_{94}Pu$ is derived from $^{238}_{92}U$ as follows:

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U + \gamma$$

$$^{239}_{92}U \rightarrow ^{239}_{93}Np + ^{0}_{-1}e \text{ again } ^{239}_{93}Np \rightarrow ^{239}_{94}Pu + ^{0}_{-1}e$$

This is the conversion process where absorption of a neutron by uranium-238 produces uranium-239 which is unstable with half-life period of 23 minutes which decays into neptunium along with emission of one electron. This neptunium with half-life of 2.3 days is again transformed into plutonium-239 with emission of one electron. Plutonium-239 is having long half-life period which is a fissionable isotope of plutonium.

- U-233 is obtained in following manner using thorium as

$$^{232}_{90}Th + ^{1}_{0}n \rightarrow ^{233}_{90}Th + \gamma$$

$$^{233}_{90}Th \xrightarrow{23.3\ minutes} ^{233}_{91}Pa + ^{0}_{-1}e \quad \rightarrow \quad ^{233}_{91}Pa \xrightarrow{27.4\ day} ^{233}_{92}U + ^{0}_{-1}e$$

The above process of converting some of the non-fissile materials into fertile materials (fissile) is known as ***breeding***.

CONSTITUENTS OF NPP AND LAYOUT:

The schematic arrangement of conventional NPP is shown in the below diagram.

- For generation of heat energy required to produce steam, nuclear reactor is employed.
- The heat energy liberated during fission process of the fissile material in atomic reactor is immediately extracted by pumping suitable fluid / molten metal like sodium or gaseous medium through the reactor pile (say primary medium).
- Heat energy extracted from the core of the through above process is then made to exchange its heat to the water (to produce steam) or suitable gas (to produce super-heated gas) for driving the turbine.
- The turbine is coupled to the alternator / AC generator for generation of electrical energy.
- A condenser, to condense the steam and recirculate back into the heat exchanger system as a closed feed system.
- The reactor and the cooling system is to be heavily shielded in order to eliminate the radiation hazard in the plant and surroundings.

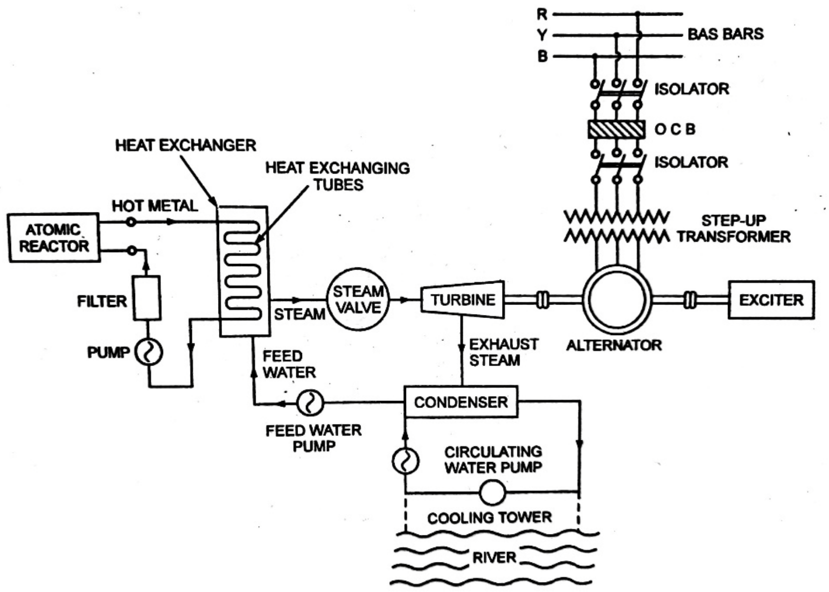
Layout:

- ➢ The layout of NPP is decided by considering the safety factor as the prime importance, then on operating convenience and capital cost. The layout of the NPP will be simple.

- ➢ The charge hall is the important operational area where the fuel is loaded and refuelled. This will be located directly over the reactor core.

- The main control room is provided centrally and comprises of all the necessary equipment for controlling during normal and emergency operation of the reactors. The other controls are for the boilers, turbine and alternators.

- The ancillary rooms such as maintenance yard, stores, switchyard instrument shop office railway siding are located suitably for normal operation.



Schematic arrangement of Nuclear Power Plants

Nuclear Reactors- main parts and functions:

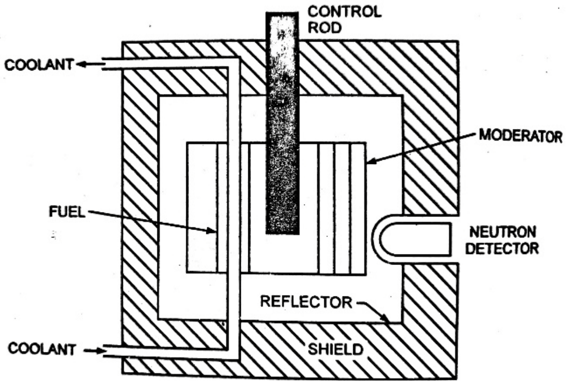
Nuclear reactor is the part of the NPP where nuclear fuel is subjected to nuclear fission and the energy released during this process is utilized indirectly to run turbine (heat energy to mechanical energy) and then to electrical energy. The reactor is used for controlled fission reaction by regulating the number of neutrons.

The neutrons released during chain reaction process can be traced in the following ways:

- Absorption by control rod materials, moderator, fission fragments and impurities and this will not cause additional fission.
- Absorption by U-238 present in the natural uranium to form fissile material Pu-239.
- Fission reaction process for U-235, U-233 and Pu-239.
- Non interactive escape from the fissionable elements.

The basic components of a nuclear reactor are:

- Reactor Core
- Moderator
- Control Rods
- Coolant
- Reflector
- Thermal Shielding
- Reactor Vessel
- Biological Shield



Basic component of a nuclear reactor

Reactor Core:

- The core of nuclear reactor consists of number of rod shaped fissile material which acts as fuel.
- In order to achieve better control over the fission process and to reduce the deterioration the fuel, the fission material is diluted with non-fissile materials.
- The fuel rods will be cladded with Aluminium or zirconium or stainless steel in order avoid oxidation of uranium fuel.
- The size of the core is on the basis of critical mass required for sustained fission reaction with enriched fuel the size can be brought down.

Moderator:

- Neutrons produced by fission process are ejected with high velocity of around 1.5×10^7 m/s such that it possesses high kinetic energy and are termed as ***fast neutrons.***
- These fast neutrons can fissile the three basic fuels so as to continue the chain reaction.
- With lesser enriching of U-235, the U-238 present in the fuel absorbs these fast neutrons such that chain reaction may not be maintained.

- To sustain chain reaction, either to enrich the U-235 by some percentage OR to slow down the fast neutrons to about 2.2×10^3 m/s.
- At this speed, neutrons are the slow / thermal neutrons and U-238 cannot absorb these neutrons and chain reaction continues.
- In order to reduce the speed of neutrons, moderator is employed in the core. The moderator ensures that fast neutrons only loose fraction of their energy.
- Most suited elements for moderator are: Hydrogen, Deuterium, Helium, Lithium, Boron, Carbon, Nitrogen and Oxygen.
- Moderator should have high scattering cross section and low neutron absorption cross section.
- Out of these, considering stability, economy and related factors, either Carbon or Deuterium (Heavy water) are used as moderators. With highly enriched uranium, even water can be used as a moderator.
- The moderator is mixed with the fuel and is called as homogeneous arrangement.
- The fuel may be scattered throughout the moderator and this is called heterogeneous arrangement.

Control Rods:

- Control rods are employed to control the rate of fission of the nuclear fuel by absorbing some of the slow neutrons.
- Made up of Boron-10, Cadmium or Hafnium.
- When starting from cold, the fission process has to be initiated and afterwards chain reaction to be sustained in a controlled manner during operation of the reactor.
- During emergency conditions the reactor is to be shut down.
- Control rods are employed for the above two purpose. It also prevents the meltdown of fuel rods, disintegration of the coolant and finally the destruction of the reactor itself.
- Inserted into the reactor core from the top of the reactor vessel and can be moved in and out through the holes provided.
- In order to increase the fission reaction, the control roads are moved out (slightly) of the core in order to absorb slow neutrons and vice-versa.

Coolant:

- Coolant is the medium which absorbs the heat generated in the reactor core during chain reaction and transfers it to a heat exchanger.
- Water can also be used as coolant which takes up heat and converted into steam for driving turbines.
- Coolant is circulated through and around the reactor and also maintains the temperature of the core within desired limits.
- In some types of reactors, coolant is also used as moderator.
- Good quality of coolant should be non-toxic, non-oxidising, non-corrosive with high chemical and radiation stability along with good heat transfer capability.
- Gaseous coolant medium: Air, Helium, Hydrogen and CO_2, out of these carbon dioxide has low neutron absorption cross section, colourless and odourless and non-reactive with core material. It reacts with graphite of the core and this should be taken care in the design and employed in advanced gas cooled reactors.
- Liquid coolant medium: Water and Heavy water are employed in boiling water reactors and pressurized water reactors. Good thermal capacity per unit volume and can also be employed as moderator.
- Molten metal medium: Sodium and Lithium which have high heat transfer capabilities, low vapour pressure which are employed in fast breeder reactors.

Reflectors:

- Reflector completely surrounds the reactor core within the thermal shielding.
- Should be able to scatter neutrons with little absorption.
- It bounces back most of the low speed neutrons that escape from the fuel during fission and helps in maintains the chain reaction.
- Cooling of the reflector is necessary because of collision with neutrons, it gets heated up.
- In some cases, moderator material itself is used as a reflector.

Thermal shielding:

- This shielding is mainly constructed with iron.
- Provides protection from harmful $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ particles and $\boldsymbol{\gamma}$ rays as well as neutrons emitted from the fission process.

- It gets heated up due to shielding process and it also carries some heat from reactor wall. The shielding also requires cooling by suitable means.

Reactor Vessel:

- This encloses the reactor core, reflector and thermal shielding as a main body and also known as tank.
- As a strong wall container, it provides inlet and outlet for coolant and its circulation through and around the core.
- The reactor core is placed in the lower portion of the vessel and it is built to withstand pressure up to 21 MPa (21 × 9.87= 207atmospheres).

Biological Shield:

- The whole of the reactor including the vessel are enclosed in this shield in order to prevent the escape or leak proofing against fast / slow neutrons and the harmful radiations which is harmful to the living organisms.
- It is made up of lead iron or dense concrete of few meters thick.

Control of Nuclear Reactors:

- Controlling is the process of adjusting the fission process such that energy is generated as per the load requirement.
- In case of emergency the reactor is to be shut down immediately for safety purposes.
- The fission process is controlled by adjusting the neutron population (also called as ***flux***) in the reactor core as per the power requirement.
- Cadmium and Carbon are the ideal elements which have high neutron absorption coefficient and suited for this purpose. With the help of adjustable control rod any these can be inserted into to the reactor core.
- The adjustment is done automatically using electronic sensing circuit which measures the neutron flux density in the reactor for accurate regulation of power output.
- For sustaining chain reaction, the number of neutrons released as a result of fission process should be more than the neutrons available before fission process.
- Some of these released neutrons will be leaked into the surroundings of the core.
- Multiplication factor ***k*** is the ratio given by the following formula:

$$\boldsymbol{k} = \frac{\boldsymbol{Number\ of\ neutrons\ prouced\ in\ current\ fission\ process}}{\boldsymbol{Number\ of\ neutrons\ produced\ in\ the\ preceeding\ fission\ process}}$$

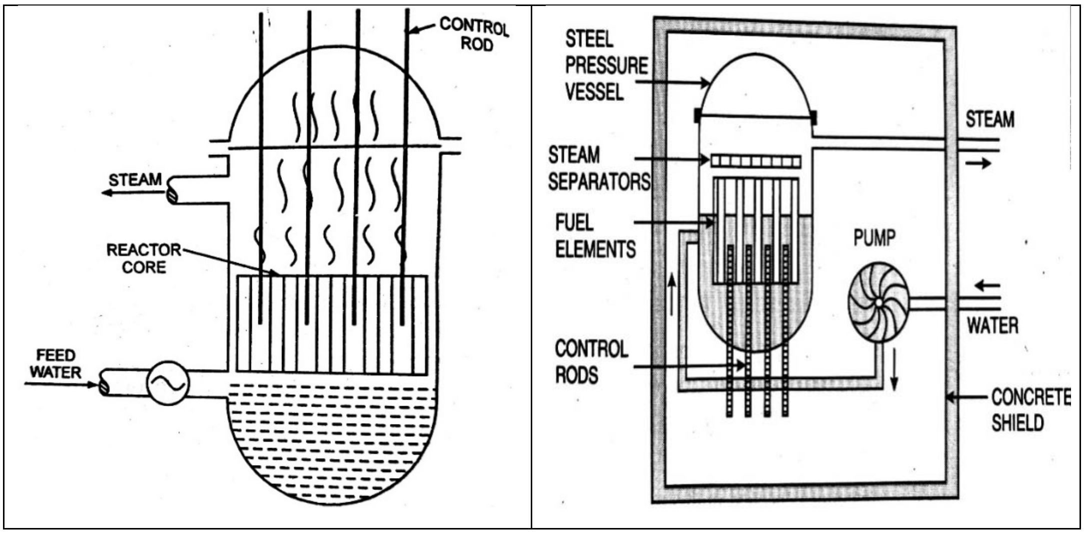
- If ***k*** is less than unity, then the condition is known as *subcritical* and the fission reaction stops.
- For unity value of ***k***, the chain reaction sustains at steady rate (***critical***). This is the desirable condition in a reactor where neutrons generated is just sufficient balance the lost and absorbed neutrons such that chain reaction is sustained at a constant level.
- The chain reaction will build up and the condition is known as ***super-critical*** for values of ***k*** > unity.
- At the time of starting the reactor from cold, the value of ***k*** is kept above unity in order to build up the chain reaction.This effectively increases the power level and upon reaching the required power output, ***k*** value is essentially maintained at unity so that the output remains at steady value.
- For decreasing the power output from reactor from its current value, again value of ***k*** is reduced slightly below unity till the required power level is attained. After this again ***k*** is made unity to sustain this new output level.

Commonly employed nuclear power reactors for the intended purpose-

Some of the practical and widely used nuclear power reactors are as follows:

1. Boiling Water Reactor (BWR):

- One of the simplest type reactors employed in practice.
- The pressure vessel is made up of steel which is surrounded by concrete shield for protection.
- Normal water is employed for dual purpose of moderator and cooling.
- The thermal energy liberated during fission process is carried away by the water entering from the bottom of the reactor vessel.
- Water is converted into steam and it leaves from the top of reactor which is then passed through steam turbine.
- After extracting energy from steam it is then condensed in condenser and then returned back to the reactor.
- The fuel rods are placed in a pattern to form lattice structure inside the pressure vessel and surrounded by water.



Schematic showing Boiling Water Reactor arrangements employing water as coolant and moderator

<u>Merits of BWR:</u>

- The size of the pressure vessel will be smaller due to the cooling medium as water without intermediate heat exchanger.
- Works at higher steam pressure.
- Reduction in capital cost and better thermal efficiency.
- Overall efficiency is around 33%.

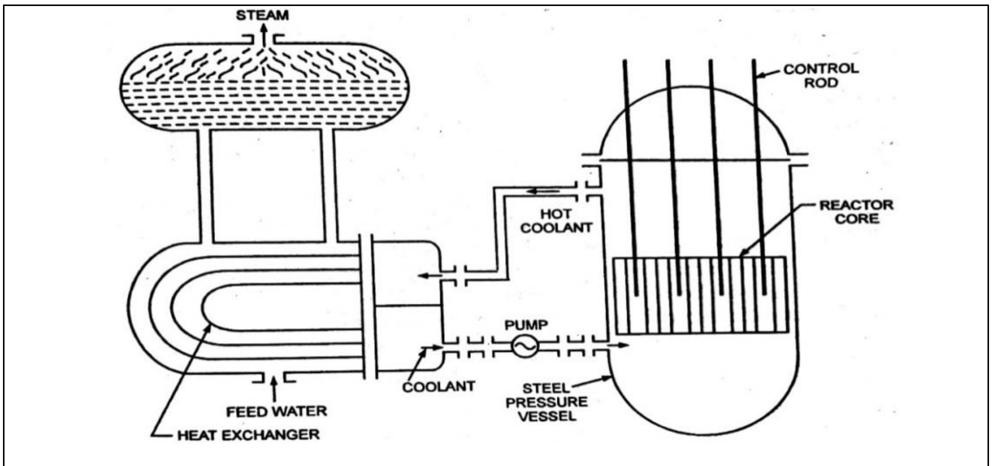
<u>De-merits of BWR:</u>

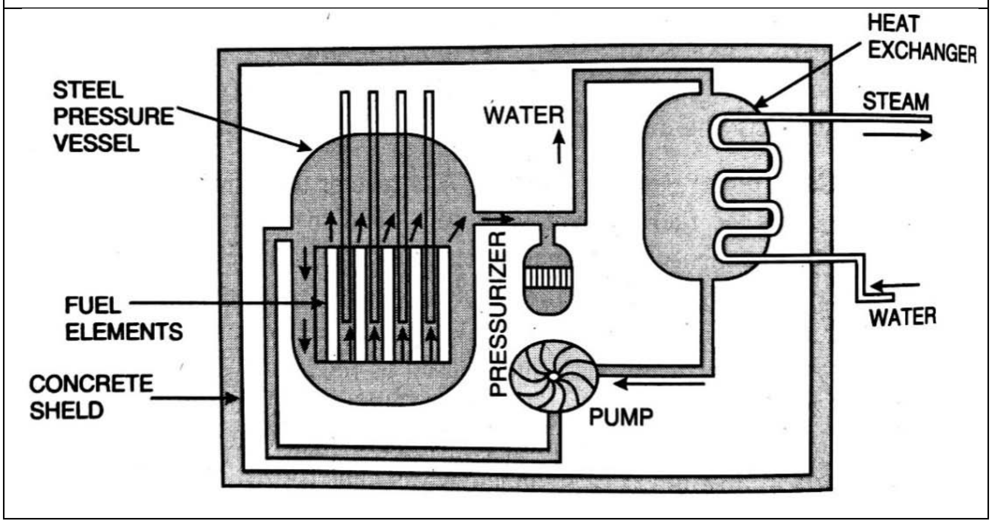
- The direct cooling cycle employing water poses threat of radio-active contamination of steam and this require additional safety measures at extra cost.
- Some amount of the fissile materials also gets circulated along with water coolant and this requires biological protection measures.
- Reduction in thermal efficiency during part load operation due to wastage of steam.
- Cannot respond to sudden increase in load demand.
- This type of reactors is employed in Tarapur Atomic Power Station.

2. Pressurized Water Reactor (PWR):

- It uses enriched uranium oxide cladded with Zirconium alloys (Zircaloy). Zirconium has very low absorption cross-section of thermal neutrons, added with high hardness, ductility and corrosion resistance. A typical composition of nuclear-grade zirconium alloys is more than 95% weight zirconium and less than 2% of tin, niobium, iron, chromium, nickel and other metals, which are added to improve mechanical properties and corrosion resistance.

- Water under pressure (150 atmospheres) is employed for both cooling and moderating purpose. The pressurization is required for minimizing the quantity of water requirement.
- The vessel is made up of steel.
- The hot pressurized water flows into a heat exchanger (or steam generator) so as to transfer its heat energy to feed water for the generation of steam. This primary coolant is then pumped back into the reactor through circulating pump.
- The steam from the feed water is fed to turbine after that condensed and fed back to heat exchanger so as to form a closed circuit.
- The steam generated at temperatures of about 250^0 C at pressure of 42 kg/m^2.
- The overall efficiency is around 33%.





Schematics of Pressurised Water Reactor which uses additional pressure pump for increasing the pressure of water inside the reactor.

Merits of PWR:

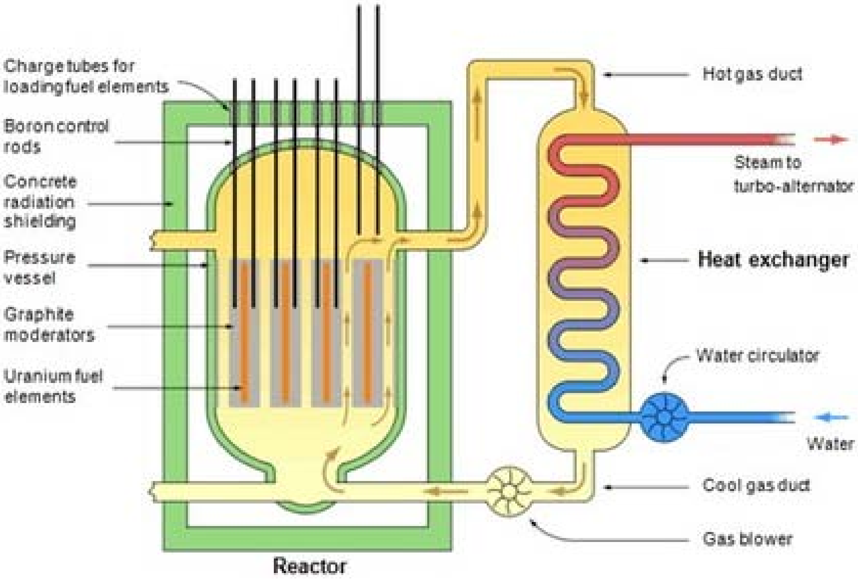
- Compact in size.
- Isolation of radio-active materials from the main steam system used for turbines.
- High power density.
- Both moderator and coolant action is by natural water which is abundant in nature and cheap.
- It is possible to breed plutonium.

Drawbacks of the PWR:

- Requires water at high pressure and the vessel should be built with high pressure withstanding capability.
- Loss of heat in the exchanger is considerable and the steam temperature is around 250^0C.
- In order to prevent corrosion, expensive cladding material is required.
- Auxiliary equipments need considerable power.
- Extra safety to be provided compared to other types.

Instead of normal pressurised water, pressurised heavy water reactors are built in India namely, Rajasthan, Kalpakkam and Narora Atomic Power Projects.

3. Gas Cooled Reactors:



Schematic of a gas cooled reactor

- In these reactors, gas medium is used as coolant. CO_2 or Helium is usually employed for this purpose.
- The graphite serves as a moderator.
- Gas is circulated in between the reactor and the heat exchanger using blower or gas compressor at pressure of 14 to 28 kg/m^2.
- The heat exchanger pipes where water is circulated to obtain steam are made up of fins on the surface for more effective heat transfer.
- Heat removal by gas is better, when the graphite is used as a moderator.

Advantages of Gas cooled reactors:

- Natural uranium can be employed as fuel.
- Corrosion problem is less severe.
- When compared to water reactors, it comes with enhanced safety features.
- Moderate contamination problems.
- The reactor can operate at higher temperatures and operating pressure of the coolant is lesser than pressurised water reactors.

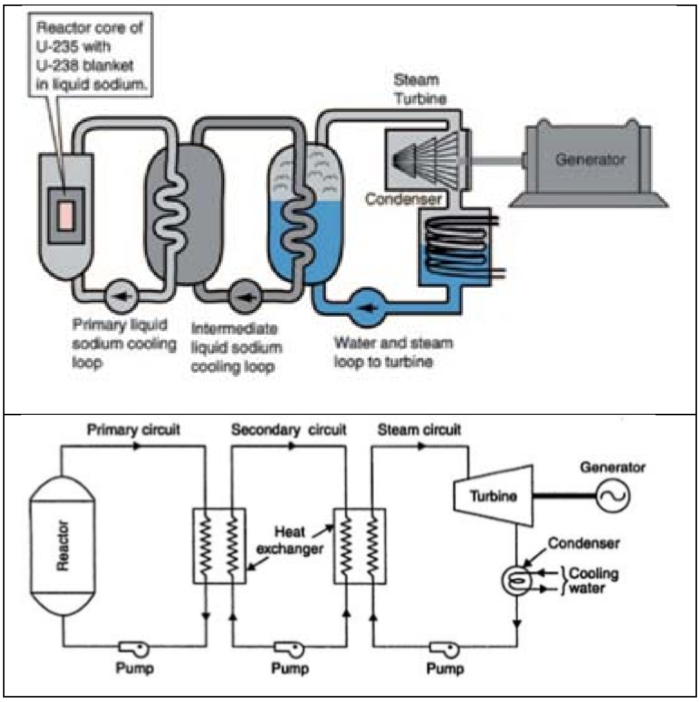
Main drawbacks:

- Larger size reactor due to usage of natural fuel and graphite moderator.
- Lesser power density compared to other types.
- Lower operating steam pressure and temperature.
- Additional power consumption by the gas blowers/pumps
- Poor heat transfer capability of the coolant gases employed.

4. Liquid Metal Cooled Reactors:

- Developed mainly to overcome some of the drawbacks of PWR and advantages of liquid metals as a primary coolant in the reactor core.
- Metals in liquid state possess good thermal conductivity. It can reach high temperatures at moderate pressures.
- In this type of reactors, additional heat exchanger is provided which acts as the intermediate stage.
- Sodium is melted by electric heating system around 880^0C and pressurized up to 7 bars using pumps in reactor.

- Molten sodium in the reactor is then circulated between the reactor core and the intermediate heat exchanger in order to transfer the thermal energy from the reactor (i.e. from primary circuit to secondary circuit).
- In the intermediate heat exchanger (secondary circuit) heat from sodium is transferred to sodium-potassium alloy (NaK) liquid metal as a closed loop.
- In steam circuit, the water extracts the heat energy from the NaK to form steam which is then fed into steam turbine as a closed loop.
- Sodium and Potassium both react violently with water and air so whole arrangement must be leak proof and air tight. Further, charging and draining of coolants from any of the loops is to be done in inert atmosphere.



Schematics of Liquid Metal Cooled Reactors

Salient points of the reactor:

- High boiling point of liquid metal.
- Generation of steam at higher temperature and pressures.
- Corrosion is not severe it is minimal.
- Reactor operates at high temperature.
- Coolant operates at lesser pressure and correspondingly enforcement required is less.

Drawbacks:

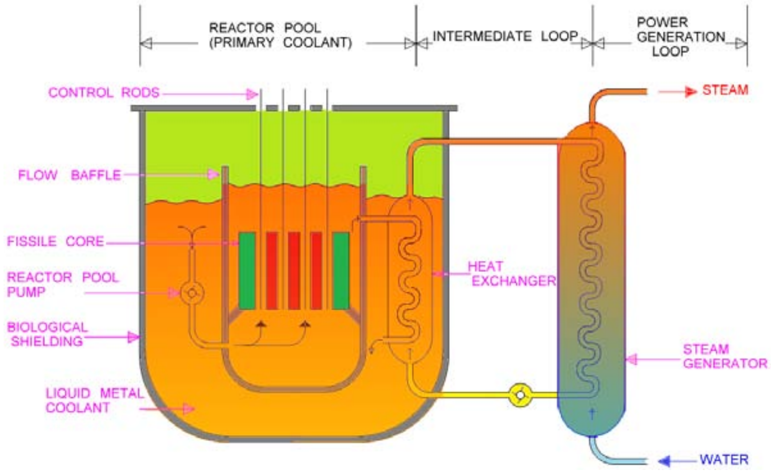
- Reactor core is complex in design.

- ➢ Requires enriched fuel for operation.
- ➢ Necessity of triple cooling systems with duel heat exchangers. This is the additional cost incurred for enhancing the safety requirements.

5. Fast Breeder Reactor:

- It comprises of small vessel containing enriched uranium or plutonium of required quantity (corresponding to critical mass).
- Moderator is not used but liquid metal cooling is employed (sodium or potassium).
- The fuel core (fissile material) is surrounded by a layer of fertile material such as (U-238 or Th-232).
- The neutrons from the fission of the fuel are absorbed by the fertile materials to produce additional fissile materials such as Pu-239 & U-233.
- Both the reactor core and the secondary heat exchanger use liquid metal coolant.
- This double cooling arrangement action reduces the possibility of sodium water reaction with radioactive sodium.
- Neutron shielding is provided by boron, graphite, water or suitable oil.
- Shielding against gamma rays is by lead, concrete which is added with magnetite or barium etc.
- Requires highly enriched fuel (10% of fissile material).
- Two primary types of loop design are realized for heat exchanging system they are –

a) **Pool type system:**

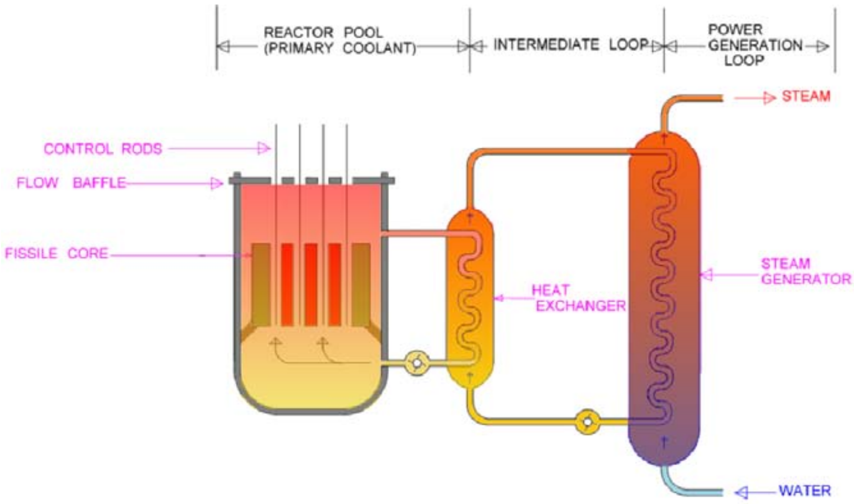


Schematic of a Pool Type Fast Breeder Nuclear Reactor

The reactor core, primary pumps and intermediate heat exchanger are all placed in the reactor vessel. The liquid sodium is discharged from the intermediate heat exchanger to the pool then it is pumped upward through the core and recirculated. The schematic of this pool system is given in the below figure.

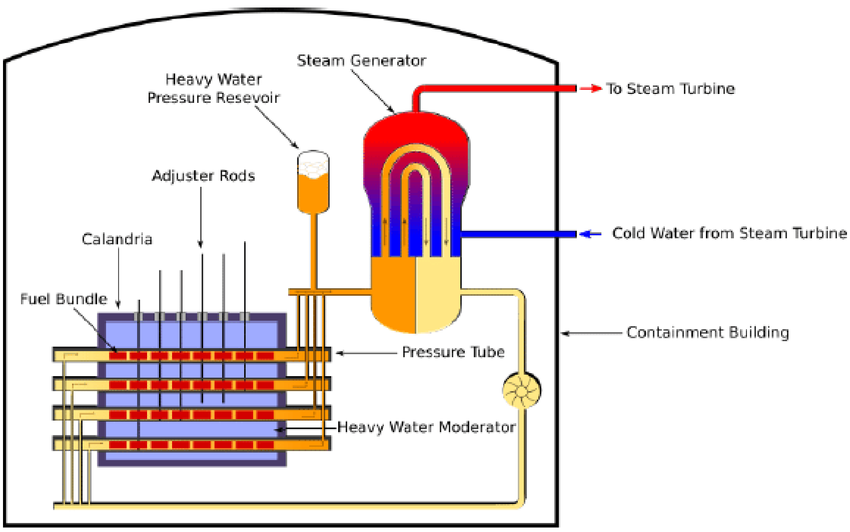
b) **Loop type system:**

The intermediate heat exchanger is located outside the reactor vessel. This loop system is illustrated in the below figure shown.



Schematic of a Loop Type Fast Breeder Nuclear Reactor

6. Canadian Deuterium Uranium Pressurised Heavy Water Reactor (CANDU Reactor):



Schematic of a CANDU Type Nuclear Reactor

- This type of reactor was indigenously developed in Canada which employs heavy water as the moderator for cooling and also to achieve cost saving.
- Commonly referred as CANDU reactor.

- Uses natural uranium as the fuel in places where enrichment of uranium is a costlier procedure and places that do not have the facilities to enrich uranium.
- The primary and secondary cooling circuit are similar to pressurised water reactor (PWR). The coolant in the primary circuit is heavy water.
- Steam from water is produced from the secondary cooling circuit heat exchanger.
- Separation of heavy hydrogen from water is expensive process. But when employed as a moderator, the process will be simpler compared to enrichment of uranium.
- Control rods are not employed. Instead it is controlled by varying the level of moderator in the reactor.
- The reactor vessel CALANDRIA is a horizontal, cylindrical structure of stainless steel with end plates. Calandria tubes are provided inside this vessel which is filled with low pressure heavy water moderator at pressure little above atmospheric pressure and fuel channel assemblies.
- The Calandria tubes are made of annealed Zircaloy-2, which is an alloy specifically developed for reactor components. This is surrounded by shield tank.
- In the place of control rods, adjustor rods are employed which are made of stainless steel (or cobalt) and these only distribute the neutron flux in the core for power distribution (also called as power shaping/flattening).
- The moderator can be drained out quickly into a separate tank which is provided below the reactor during shut down times.
- Pressurization of the moderator is done using pressurizer chamber (pressure reservoir).

Advantages:

- Heavy water has low neutron absorption coefficient and no enrichment of uranium is required in thermal reactors.
- Reactor control is simpler due to absence of control rods and low fuel consumption.
- The moderator temperature in the reactor core effectively slows down the fast neutrons.
- Period required for construction of the site is lesser than other types of reactors.
- Some of the equipments required for the reactor can be produced locally.

Drawbacks:

- Exorbitant cost of heavy water and problems of leakage.
- Complex design of the Calandria and reactor requires high standard design.

Effects of Nuclear Power Plants:

The effects of fission by products and pollution from NPPs are discussed –

- No combustion of fuel is involved and its immediate effects of it on the atmosphere are insignificant.
- The isotopes formed during fission process are toxic in nature and it has profound effect on the living beings.
- Removal of harmful isotopes and its transportation and proper disposal / storage are extremely significant for environmental concerns.
- With suitable shielding, safety measures and proper disposal of nuclear wastes, the harmful effect on bio-sphere by the nuclear plants is insignificant.
- The effects of exposure to ***α, β*** particles and ***γ*** radiations are in the increasing order of severity.
- The effects of radiation are from damage skin burn, malignant growth, radiation sickness, genetic mutations causing abnormal child birth etc.
- The neutrons escaping from the reactor possess high energy and when exposed to it, will cause harmful effect similar to γ radiations.
- The following factors have impact on biological effects of nuclear radiations –

➢ The time duration of exposure.
➢ Quantity or dosage absorbed by the body.
➢ Distribution of the radioactive materials within different organs of the body.
➢ Sensitivity and recovering capacity of the exposed organisms.

- Small quantity of radiation exposure over a period of time may not be noticed immediately but cause significant damage in long term such as reduced lifespan, genetic mutation, leukaemia (blood cancer) and other types of cancer. Also exposure during pregnancy can result in genetic birth defects.

- The radiation dose and exposure are expressed in terms of the following –
    - ➢ **Radiation Absorbed Dose (RAD):** The amount of radiant energy absorbed in a certain tissue.
    - ➢ **Roentgen-equivalent-man (REM):** A unit of measurement that takes into account different biological responses to different kinds of radiation.

- **Roentgen:** The international unit of exposure dose for x-rays or gamma rays.
- **Sievert (Sv):** The unit for measuring ionizing radiation effective dose.

- The radiation levels in nuclear power plant sites needs to be checked periodically.
- NPP sites are sanitized to minimize the risk of radiation and residential dwellings will be located far away from the plants.
- Radioactive contamination of air in NPPs can be due to three main reasons i.e.

1. Gaseous fission fragments which are likely to leak into the air are inert gases such as Xenon, Krypton etc. along with radio-active iodine.
2. Effect of neutron flux on the coolant in the primary heat exchanger system and surrounding air. The inert gas present in the air such as Argon-40 will form radioactive isotope Argon-41, with a half-life period of 1.82 hours. The dust particles present in air may be prone to induced radioactivity.
3. Damage of shells which contain fuel elements, presence of activated inert gases and leakages.

- Others sources of contamination are auxiliary structures and equipments such as cooling ponds, radioactive leak collecting tanks (which is the source of radio-active inert gases), gas blow-off during overload operation due to elevated radiation activity.
- Whatever may the cause of radio-active pollution, the combined radiation from all these should not exceed the prescribed limits.

Disposal of Nuclear Waste and Effluent:

- Radioactive waste materials are produced in most of the forms at nuclear plants.
- Solid radioactive waste materials include used filters, sludge from the cooling ponds.
- Fragments of discarded fuel cans and discarded control rods are to be stored in concrete shields during onsite storage.
- Disposal of solid fission products are done by placing them in boro-silicate glass enclosure and whole of this within leak proof capsules. These capsules are then buried deep in salt mines/ deep wells drilled in the stable ocean floor. There should not be any underground water in the vicinity of salt mines over a long period of time.
- The radioactive wastes are enclosed in suitable containers and sunk to the deepest part of oceans and seas. There are chances of leakage of radioactive waste through seepage.

- The isotopes with long half-life period are segregated and transformed (also called transmutation) to elements of short life period or stable products with the neutron absorption in a breeder or fusion reactor.
- In future these products may be transported through rockets as to dump over the surface of sun which is a natural incinerator.

Liquid Wastes:

The radioactive liquid effluents are the result of some activities such as

- Laundry, result of personal decontamination etc.
- Result of corrosion on the irradiated fuel elements in the storage ponds.

Dispersal of liquid effluents:

- The liquid wastes are diluted by passing through ion exchange resins which absorb majority of the radioactive elements. The level of any isotope discharged to sea/ocean will be well below the minimum limit specified for drinking water.
- Clinkering of liquid waste results in reduction in volume and enhanced protection. It is the process of fusing the liquid radioactive waste by sintering so as to form lump of material ranging from 3 to 25 mm thick substance.
- Through heating and evaporation, the liquid waste is solidified such that it can be enclosed in metal container to be buried deep in the earth where ground water is absent.

Dispersal of gaseous effluents:

- Gaseous effluents are properly filtered and discharged into atmosphere at sufficient height for proper dispersing.
- The nuclear plant does not emit CO_2 but when CO_2 cooled (gas cooled reactors) then its level and leakage to be monitored near the surroundings of nuclear plant. There is a maximum limit imposed on leakage of carbon dioxide into the atmosphere near such plants.

Shielding of the Nuclear Reactor:

- For protection against radiation emissions and fast / slow neutrons produced in the reactor core during fission process proper shielding is required for biological safety.

- There is no single material available such that it can shield radiations of all kinds.
- The density of the shielding material mainly decides its efficacy. Lead has the highest density of 11,300 kg/m^3 followed by cadmium (8,650), steel (7,800) and concrete (2,400).
- Lead is commonly used as shielding material due to low cost and availability. Steel possess good structural properties which is employed as attenuating shield. Cadmium effectively absorbs slow neutrons. Boron or steel can absorb thermal neutrons.
- Concrete mixed with iron, barium or steel turnings for providing shielding against thermal neutrons and gamma rays.
- In most of the nuclear plants, by steel shielding which is several centimetres of thickness and in turn surrounded by 3-metre-thick concrete is employed for safety.

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