Power Generation and Economics (15EE361) (PGE)

Module-3

Nuclear Power plants

* Introduction :

- A generating station in which nuclear energy is converted into electrical energy is known as a nuclear power station.
- In nuclear power station, heavy elements such as Uranium (U^{235}) or Thorium (Th^{232}) are subjected to nuclear fission in a special apparatus known as reactor. The heat energy thus released is utilised in raising steam at high temperature & pressure. The steam runs the steam turbine which converts steam energy into mechanical energy. The turbine drives the alternator which converts mechanical energy into electrical energy.
- The most important feature of a nuclear power station is that huge amount of electrical energy can be produced from relatively small amount of nuclear fuel as compared to other conventional types of power plants. It has been found that complete fission of 1kg of Uranium (U^{235}) can produce as much energy as can be produced by burning of 4500 tonnes of high grade coal. Although the recovery of principal nuclear fuels (i.e Uranium & Thorium) is difficult & expensive, yet the total energy content of ~~the~~ of the estimated world reserves of these fuels are considerably higher than those of conventional fuels, viz, coal, oil & gas. At present energy crisis is gripping up and, therefore, nuclear energy can be successfully employed for producing low cost ~~ener~~ electrical energy on a large scale to meet growing commercial & industrial demands.

* Economics of Nuclear power plants :

- Nuclear power is cost competitive with other forms of electricity generation, except in regions where there is direct access to low-cost fossil fuels.
- The decreasing cost of fossil fuels in the past decade has eroded nuclear power's previous cost advantage in many countries.
- Fuel costs for nuclear plants are a minor proportion of total generating costs & often about one-third those for coal-fired plants.
- In accessing the cost competitiveness of nuclear energy, decommissioning & waste disposal costs are taken into account.

The relative costs of generating electricity from coal, gas & nuclear plants ~~are~~ vary considerably depending on location. Coal is, and will probably remain, economically attractive in countries such as India, USA and Australia with abundant and accessible domestic coal resources. Gas is also competitive for base-load ~~plants~~ power in many places, particularly with combine cycle plants. Nuclear energy is, in many places, competitive with fossil fuel for electricity generation despite relatively high capital costs and the need to internalize all waste disposal & dicommissioning costs. If the social, health & environmental costs of fossil fuels are also taken into account, nuclear is outstanding. Nuclear energy averages 0.4 euro cents/kWh, much the same as hydro, coal is over 4.0 cents (4.1-7.3), gas ranges 1.3-2.3 cents and only wind shows up better than nuclear, at 0.1-0.2 cents/kWh average.

Merits and Demerits of Nuclear power station:

Merits:

(i) The amount of fuel required is quite small. Therefore, there is a considerable saving in the cost of fuel ~~consumption~~ transportation.

(ii) A nuclear power plant requires less space as compared to any other type of the same size.

(iii) It has low running charges as a small amount of fuel is used for producing bulk electrical energy.

(iv) This type of plant is very economical for producing bulk electric power.

(v) It can be located near the load centres because it does not require large quantities of water & need not be near coal mines. Therefore cost of primary distribution is reduced.

(vi) There are large deposits of nuclear fuels available all over the world. Therefore such plants can ensure continued supply of electrical energy for thousands of years.

(vii) It ensures reliability of operation.

(viii) Very well suited for large power demands.

(ix) No atmospheric pollution as there is no combustible products.

(x) Generation of power is not affected by weather conditions.

(xi) These plants are neat & clean than other plants.

* Demerits of Nuclear power station :

(i) The fuel used is expensive and is difficult to recover.

(ii) The capital cost on nuclear plant is very high as compared to other type of plants

(iii) The erection & commissioning of the plant requires greater technical know-how.

(iv) The fission-by products are generally radiactive and may cause dangerous amount of radiactive pollution.

(v) Maintenance charges are high due to lack of standardisation. Moreover high salaries of specially trained personnel employed to handle the plant further raise the cost.

(vi) Nuclear power plants are not well suited for varying loads as the reactor does not respond to load fluctuations efficiently.

(vii) The disposal of the by-products, which are radioactive, is a big problem. They have either to be disposed off in a deep trench or in a deep sea away from sea-shore.

(viii) Failure of Controls may lead to nuclear explosion.

* Selection of site for Nuclear power plant :

There are several factors, which are considered in selecting the site for nuclear power station. The selection of site is similar to the thermal power station as water is used as working fluid i.e steam.

(1) Availability of water : As in the case of steam power stations, nuclear power stations also requires ample amount of water for cooling & steam generation.

(2) Disposal of waste : It is one of the very important considerations in the nuclear power station due to dangerous waste/residue of the nuclear substances. Hence an extra care is needed in this respect. The storage of waste, which is to be disposed deep under the ground in sea so that radioactive effect is eliminated.

(3) Away from populated area : Although there is always tight safety but still there are chances of radioactive radiation, which affects the health of people. Therefore it must be away from the populated areas.

(4) Nearest to the load centres : Since the transportation & storage requirements are less compared to the coal fired plants. It is preferred to construct the nuclear power plant near the load centres so that transportation of energy at minimum cost can be achieved.

Accessibility by rail and road : Accessibility to the road and rail are the general consideration of almost all the power plants as heavy equipments are to be transported to the sites during the construction. The fuels are also required to transport from the mines during the operation.

* Nuclear Reaction : Nuclear fission Process, Nuclear chain Reaction :

- Types : There are four types of nuclear reactions taking place in nature. These are ① Inelastic scattering ② Elastic Scattering ③ Neutron Capture ④ fission.
- The last reaction (fission) is the most important from nuclear power engineering. This type of reaction possible only with heavy nuclei such as $^{232}_{92}U$, $^{235}_{92}U$ and $^{239}_{94}Pu$. The nuclei produced after reaction are lighter than original nuclei & since they are now having more binding energies per nucleon they release the energy. This release of energy is due to the increase of mass defect of the lighter nuclei.
- We may say that as a result of fission the target nucleus absorbs thermalised (slow neutron) and becomes highly excited. Therefore it splits into two different masses. The product masses will also be in excited state and they will try to become stable by emmitting neutrons.

Methods of producing nuclear reaction : There are a number of methods of starting a nuclear reaction. In one method neutrons are used as bombarding particles. The main advantage of neutrons is that they are neutral (having no charge) and therefore they can make their own way through the shells of electrons & then through the nucleus even at low energy. This is the practical method used in almost all modern fission reactors. Neutrons can be produced in a number of ways.

Chain Reaction : Neutral Uranium occurs in three isotopes, U-238 (99.3%), U-235 (0.7%) and U-234 (minute traces). Of these isotopes U-235 is very easily and readily fissionable. If a neutron enters a U-235 atom there is a probability that the nucleus will split and release the enormous amount of energy that binds the nucleus together. This will generate heat in the mass of the Uranium. Each fissioned nucleus ejects two or three neutrons which can again hit Uranium nuclei & accelerate the splitting process even if some of the neutrons are not fully absorbed. This reaction is known as Chain reaction.

Materials fissionable by thermal or low-speed neutrons are U-233, U-235, Pu-239 (plutonium).

Fertile Materials : There are some materials which are not fertile but can be converted to fissile materials. These are known as fertile materials. Pu-239 & U-233 are not found in nature but U-238 & Th-232 can ~~provide~~ produce them by nuclear reactions. When U-238 is bombarded with slow neutrons it produces $^{239}_{92}U$ (with half life of 23.5 minutes) which is unstable & undergoes two beta disintegrations. The resultant $^{239}_{94}Pu$ has half life of 2.44×10^4 years & is a good alpha emitter. Thus

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

$$^{239}_{92}U + ^{0}_{-1}e \longrightarrow ^{239}_{93}Np$$

$$^{239}_{93}Np + ^{0}_{-1}e \longrightarrow ^{239}_{94}Pu$$

During conversion the above noted reactions will takes place. The other isotopes of neptunium such as 2.1 day Np-238 and plutonium can also be produced by the bombardment of heavy particles accelerated by the cyclotron.

The nuclear transformations to convert $^{232}_{90}Th$ to U-233 are expressed as under

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

$$^{233}_{90}Th + ^{0}_{-1}e \longrightarrow ^{233}_{91}Pa$$

$$^{233}_{91}Pa + ^{0}_{-1}e \longrightarrow ^{233}_{92}U$$

U-235 isotope of uranium is the source of neutrons required to derive Pu-239 and U-233 and U-238 & Th-232 respectively. This process of conversion is performed in the breeder reactors.

* Nuclear Energy :

In nuclear physics the energy is expressed in Mega electron volt (MeV) & mass is in atomic mass unit (amu). One electron volt is the energy gained by an electron passing through the potential difference of one voltage. Since the charge of electron is 1.602×10^{-19} C.

$$1\,eV = 1.602\times10^{-19}\ \text{Joule}$$

$$1\,MeV = 10^{6}\times1.602\times10^{-19} = 1.602\times10^{-13}\ J$$

According to Einstein Mass- Energy relation ($E = MC^2$), where m is mass in Kg, E is Energy in joules & C is the velocity of light in metre/second), the energy corresponding to 1 amu is ($= 1.66 \times 10^{-27}$ Kg) will be as follows.

$$1 \text{ amu} = 1.66 \times 10^{-27} \times (3 \times 10^8)^2 = 1.494 \times 10^{-10} J$$

$$1 \text{ amu} = \frac{1.494 \times 10^{-10}}{1.602 \times 10^{-13}} \text{ Mev} = 931 \text{ Mev}$$

The sum of masses of the protons and neutrons exceeds the mass of the atomic nucleus. This difference in mass is called as Mass defect. The ~~ne~~ energy associated with the mass defect is known as the binding energy of the nucleus, which is a direct measure of nuclear stability. The energy can be released in two ways:

1. By combining the light nucleus and the energy released, known as Fusion.
2. By breaking the heavy nucleus and the energy released, known as Fission

Fission is most widely used in nuclear power stations. The materials fissionable by thermal or low speed neutrons are $_{92}U^{233}$, $_{92}U^{235}$ & $_{94}Pu^{239}$

* Nuclear Fuels :

- The ~~energy to~~ Fuels mainly used are natural uranium (0.7% U-235), Enriched Uranium, Plutonium (Secondary fuel) and U-233 (Secondary fuel available from breeder reactor), Natural uranium is the parent material
- In order to use a naturally occurring uranium as fuel, it must go through the purification process.

* The materials U-235, U-233 and Pu-239 are called fissionable materials. The fissionable nuclear fuel occurring in nature is uranium, of which 99.3% is $^{238}_{92}U$ and 0.7% is $^{235}_{92}U$ and $^{234}_{92}U$ is only a trace amount, out of these isotopes only $^{235}_{92}U$ will fission in a chain reaction.

* Fissionable material $^{239}_{94}Pu$ and $^{233}_{92}U$ are formed in the nuclear reactors during fission process from $^{238}_{92}U$ and $^{232}_{90}Th$ respectively due to absorption of neutrons without fission.

16, 43, 45, 61, ~~63~~, 64,

The process is given as below.

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

$$^{239}_{92}U \longrightarrow ^{239}_{93}Np + ^{0}_{-1}e$$

$$^{239}_{93}U \longrightarrow ^{239}_{94}U + ^{0}_{-1}e$$

The above process is called conversion. Absorption of a neutron by U-238 produces U-239, which is unstable with life period of 23 minutes, and decays in to neptunium with emission of an electron.

^{239}Np which has half life period of 2.3 days & transformed into Pu-239 which is long life fissionable isotope of plutonium.

Fissionable U-233 is produced in the following way

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

$$^{233}_{90}Th \xrightarrow{23.3\,min} ^{233}_{91}Pa + ^{0}_{-1}e$$

$$^{233}_{91}Pa \xrightarrow{27.4\,day} ^{233}_{92}U + ^{0}_{-1}e$$ process is known as breeding.

* Nuclear power plant layout

The concept of Nuclear power generation is much more similar to that of the conventional steam power generation, The difference lies in the steam power plant, coal or oil burning furnace is replaced by the nuclear reactor and heat exchanger in nuclear power plant.

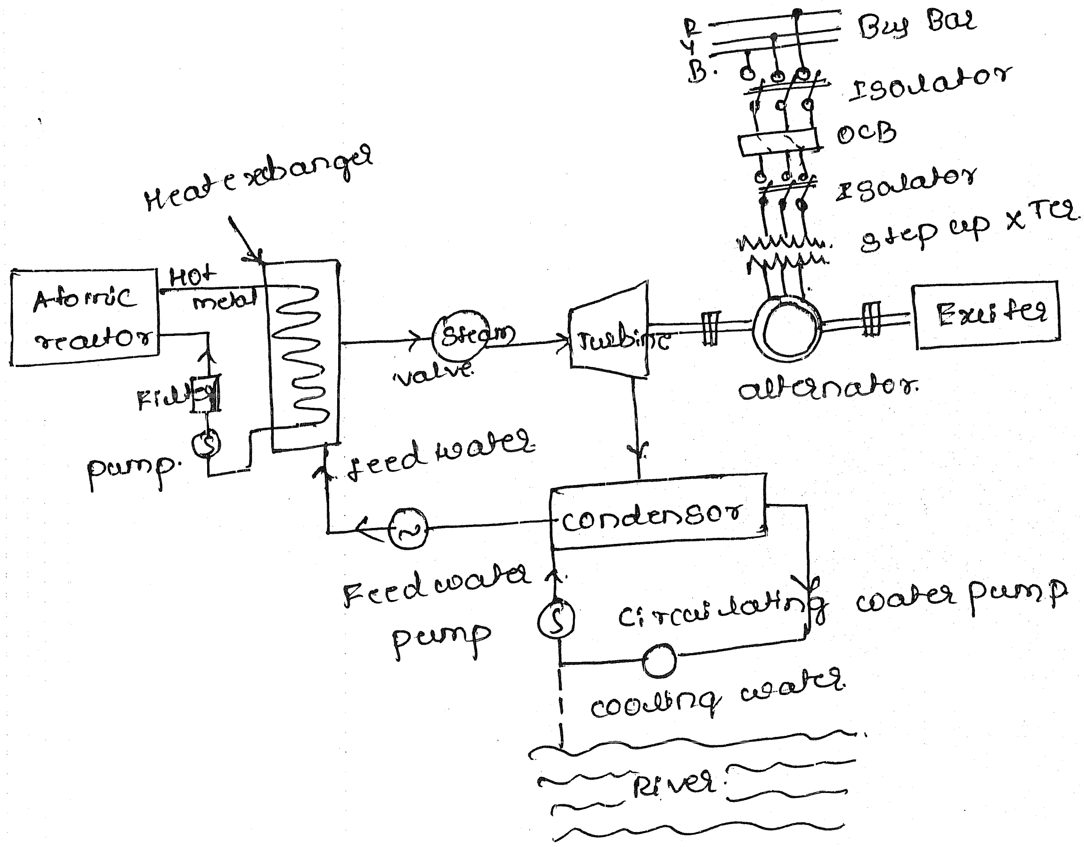

fig- Schematic arrangement of Nuclear power plant.

The Schematic arrangement of Nuclear power plant is as shown in the above fig., A nuclear power plant consists of Nuclear reactor, Heat exchanger, Steam turbine, alternator, condensor, water pumps etc.

* The large amount of heat energy is produced in breaking of atoms of uranium or other similar metals of large atomic weight into metals of lower atomic weight by fission process in a atomic reactor.
* Now the generated heat energy is extracted by pumping fluid or molten metal like liquid sodium or gas through the pile.
* The Hot metal or gas is then allowed to exchange its heat with the help of Heat exchanger as shown

above. In heat exchanger the gas is heated or steam is generated which is used to drive gas or steam turbine coupled to the alternator, thereby generating electrical energy.

* While deciding the layout of nuclear power plant, care must be taken that, the operation of plant must be safe, operating convenience & capital economy.

* Nuclear reactor & its control.

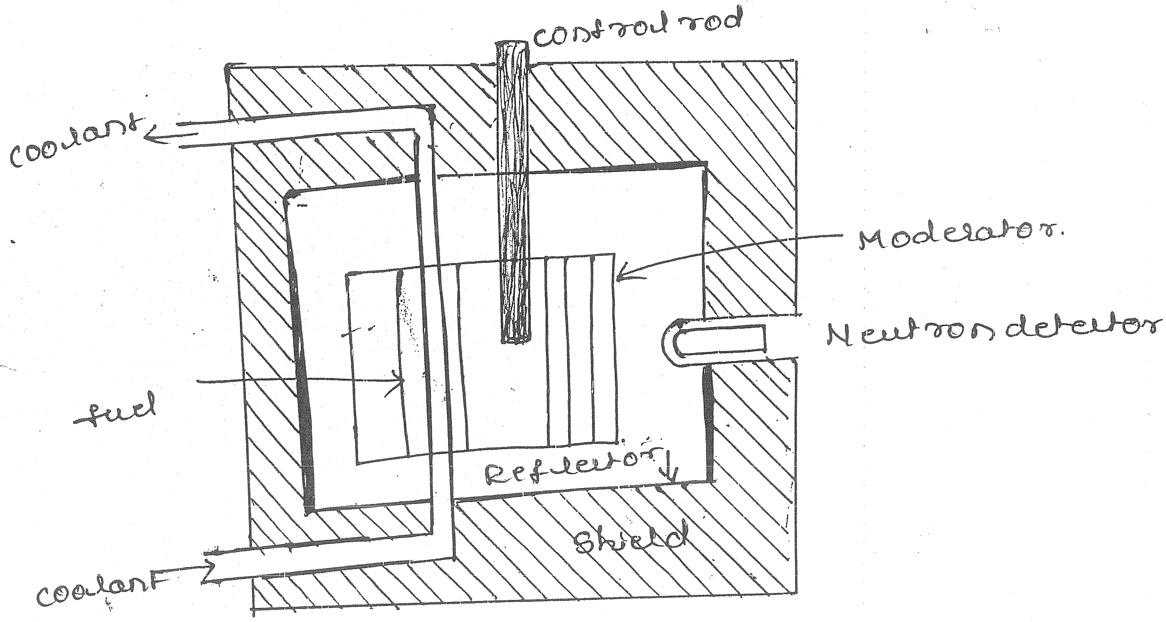

fig a. Basic components of a Nuclear reactor.

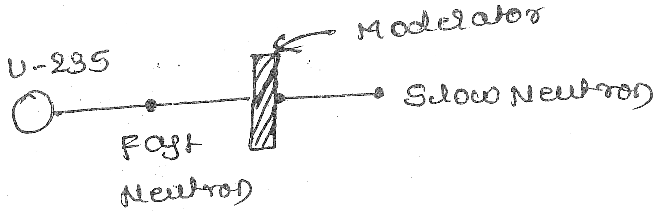

fig-b) Moderator slows down a Fast Neutron.

Nuclear reactor is a part of Nuclear power plant where fuel is subjected to nuclear fission process and energy is released.

* The main function of reactor is to control the emission and absorption of neutrons.

Nuclear reactor is consisting of →

① Fuel rods ② Reactor core ③ moderator
④ Shielding ⑤ control rods ⑥ Reflector ⑦ coolant
⑧ Reactor vessel.

* Fuel rods :- A fuel rod is a tube, filled with pellets of uranium, normally used fuels in a reactor are $^{235}_{92}U$, $^{235}_{92}Pu$, $^{233}_{92}U$, among three $^{235}_{92}U$ is naturally available upto 0.7 % in the uranium ore.

* Reactor core :- It contains a number of fuel rods which are made up of fissile material; they may be diluted with non-fissionable material for better control of the reaction or to reduce the damage from fission product poison.

It is desirable to use reactor core as cubical or cylindrical in shape rather than spherical.

* moderator :- The purpose of moderator is to moderate or to reduce the neutron speed to a value that increases the probability of fission occuring. The Graphite, heavy water or beryllium can be used as moderator with natural uranium. However the ordinary water is used as moderator with enriched uranium.

* Shielding :- Its purpose is to provide the protection from the α and β particle radiations, and γ-rays as well as neutrons which are produced due to the nuclear fission process. & it helps to prevent the reactor wall from getting heated.

(4) control rods :- In a reactor, nuclear chain reaction has to be initiated, when started from cold and chain reaction is to be maintained at steady value during the ~~chain~~ operation of reactor, also the reactor must be able to shut down automatically under emergency conditions.

chain reaction can be controlled either by removing fuel rods or either by inserting neutron absorbing materials, which are known as control rods. The control rods must have very high absorption capacity for neutrons. The commonly used control rods are cadmium, boron or hafnium.

(5) reflector :- The reflector surrounds the reactor core within the thermal shielding. & it helps to bounce escaping neutrons back into the core.

(6) coolant :- A coolant transfers heat produced inside the reactor to a heat exchanger ~~from~~ for further utilization in power generation.

(7) Reactor vessel :- This encloses the reactor core, reflector, and shield. It is a strong walled container which also provides entrance and exit passages for directing the flow of coolant.

* Reactor control.