Nuclear Energy and Nuclear Power Reactor

Nuclear Energy: We know, in a nuclear fission reaction of Uranium-235 atom, huge amount of energy is generated. This energy can be used for development of mankind. Actually nuclear energy originates as heat from the splitting of Uranium-235 atom. This energy is used to produce steam, which is used by a turbine generator to generate electricity. Today, nuclear energy is an important part to meet total electricity demand of a country. To generate nuclear energy, a special type of instrumental setup is used which is known ***as Nuclear Power Reactor or Nuclear Power Plant.*** There is no greenhouse gas emission or any carbon emission occurs in the Nuclear Power Plant. So, it may be an important clean energy resource for the future world.

Nuclear Power Reactor (Atomic Pile): A nuclear power station or nuclear power plant consists of a nuclear reactor in which a controlled chain reaction occurs using either ^{235}U or ^{239}Pu as fuel element. The heat produce in the fission reaction involved are extracted from the reactor and used to generate steam which drives a Turbine and produce electricity.

Different Components of a nuclear Reactor:

- *(i)* *Nuclear Fuel (used ^{235}U as U_3O_8)*
- *(ii)* *Moderator (used D_2O or Graphite etc.)*
- *(iii)* *Controlling Rods (Cd or B rods)*
- *(iv)* *Coolant (Used H_2O, D_2O or liquid Sodium)*

(For details studies consult any text book or AKD Vol-1, page-420)

Reaction Cross Section: The nuclear reaction cross section, gives a measure of the effective area around a target nucleus available for a projectile in a particular type of nuclear reaction.

[Reff. For details study see A.K.D, Vol-1, page-392]

Multiplication Factor (K): In a fission chain reaction, all the neutrons emitted are not generally available for carrying out the next fissions. To make a fission reaction as a self-sustaining chain reaction, some measure are to be taken and in this connection the parameter multiplication factor or reproduction factor (K) has been introduce. It is defined as:

$$K = \frac{Number\ of\ neutrons\ in\ one generation}{Number\ of\ neutrons\ in\ the\ just\ preceding\ generation}$$

[Reff. For details study see A.K.D, Vol-1, page-415]

$K_{\infty}N = \eta N\varepsilon fp$, ($\infty$ stands for the large size reactor) i.e. $K_{\infty} = \eta\varepsilon fp$

The above relation is described as **Fermi's *four factor formula*.** Depending on the value of K, the following situations may arise :

(i) **$K \approx 1$ (*steady state*)** : The number of available slow neutrons in each generation or cycle remains the same. It makes the rate of energy output constant. In reality, for the *steady state* condition, K should be slightly greater than unity because in practice l_f and l_s can never be zero.

(ii) **$K > 1$ (*divergent state*)** : The energy output rate increases from cycle to cycle. Ultimately, it leads to an *explosion*.

(iii) **$K < 1$ (*convergent state*)** : It leads to stop the fission chain and the energy output rate gradually decreases and ultimately the reactor is quenched.

(b) Construction of a nuclear reactor

The construction of a reactor depends on the purpose for which it is being designed. It is being constructed for various purposes such as : conversion of atomic energy into electricity; atomic energy to run ships, submarines etc.; synthesis of different radioisotopes; research works; etc.

The principal units of a reactor are discussed below.

(i) ***The Reaction Core*** : Here the nuclear fission goes on. The nuclear fuels along with the nonfissionable material are arranged in such a way that K becomes unity.

(ii) ***The Moderator*** : It has been already discussed that the fission cross-section for the slow neutrons is about 450 times higher than that for the fast neutrons in the case of ^{235}U. Hence to carry out the nuclear fission effectively, the emitted ***prompt neutrons*** which are fast neutrons must be thermalised. For this purpose, moderators are required. To maximise the loss of kinetic energy of the neutrons through collisions, **the materials of low atomic mass** (see Sec. 6.18.3) **are preferred.** *But the material chosen must have a very low cross-section with respect to the neutron capture process.* For this purpose, graphite, beryllium oxide and heavy water (D_2O) are the most promising ones. The process of slowing down and thermalisation is represented in Fig. 7.13.4.2.

Here it may be noted that the deuterons (present in heavy water) are less likely to capture the neutrons than the protons (present in ordinary water). ***This is why, heavy water is used as a moderator but ordinary water is not used as a moderator.***

Depending on the nature and use of moderator, the reactors are classified as ***thermal reactors*** and ***fast reactors.*** Generally, the coolant used very often acts as the moderator. In thermal reactors, the use of a good moderator produces the sufficient thermal or slow neutrons from the fast neutrons. These thermal neutrons are highly efficient in causing the nuclear fission of ^{235}U (σ for the thermal neutrons ~ 580 barn). **Such neutrons as in PHWR (pressurised heavy water reactor) needs no enriched fuel. In fast reactors, the moderator is not efficient and it needs enriched fuel.** It happens so in BWR (boiling water reactor), PWR (pressurised water reactor) and LWGR (light water cooled graphite reactor) (to be discussed later). The loss of neutrons is reduced by using a neutron reflector.

(iii) ***The Controlling Device*** : To control the process, the necessary preventive measures must be taken so that the reproduction factor does not significantly exceed unity. For this purpose, some materials are used to absorb the thermalised neutrons efficiently. In this regard, *the*

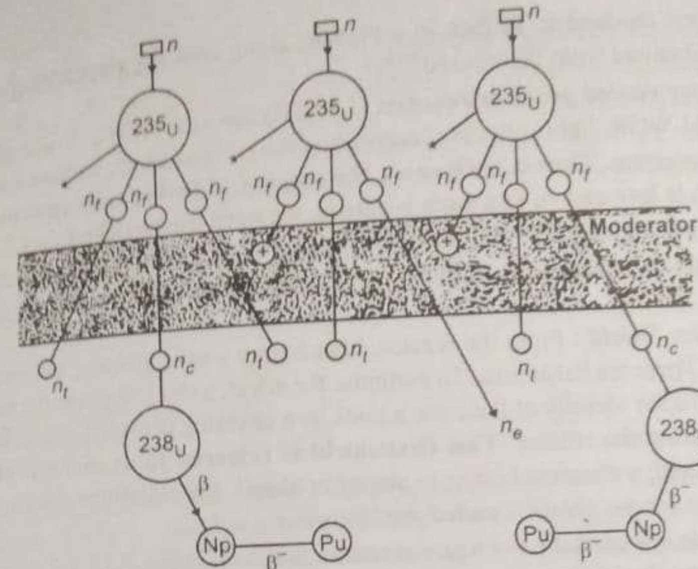

Fig. 7.13.4.2. Schematic representation of a moderator, * denotes the fission product, n = thermal (i.e. slow) neutron to start the process, n_f = fast neutron, n_t = thermalised neutrons available for fission at the next steps, n_c = neutrons captured by ^{238}U, n_e = escaping neutron, + indicates absorbed neutron by the moderator.

nonfissile material such as boron or cadmium having a large neutron capture cross-section is selected. These are placed in the reactor in such a way that they can be moved up and down by an external mechanical device. When the energy release becomes violent (exceeding a certain limit), the rods are pushed down to absorb the thermal neutrons and thus the reactor dies down. To activate or build up the reactor, the rods are pulled out. In practice, an automatic device works on the controlling rods depending on the temperature raised in the reactor.

(iv) ***Cladding of nuclear fuel*** : Fuel materials (either in the form of rod or tablet) are packed (i.e. clothed) in *clad tubes*. The clad tubes are metal casing (*Al* or *Zr-Al* alloy) and the clad tubes prevent the release of fission products to the surrounding coolant. Thus, *cladding (≡ clothing) of nuclear fuel is quite important.*

(v) ***The Coolant*** : It is required to remove the heat generated in the fission to the site of utilisation. For this purpose, different fluids such as : *high boiling liquids* (e.g. liquid *Na* or *K*), *water*, *air blast*, etc. are used. Thus, the heat transferred from the reactor is utilised in generating power. **Water at *high pressure*** (so that it cannot boil easily) is very often used as a coolant. In a ***pressurised water reactor* (PWR)**, water is circulated at about 150 atm pressure to abstract the heat which is utilised in a *heat exchanger* to produce steam. Thus the steam produced is used to drive a turbine to generate electricity. In a ***boiling water reactor* (BWR)**, water is circulated at about 70 atm pressure and it is *directly* allowed to boil to produce the steam. In a ***pressurised heavy water reactor* (PHWR)**, heavy water is used both as a *moderator* and as a *coolant*. In a PHWR, *natural uranium can be used as a fuel* without any enrichment because heavy water is a very good moderator. In fact, in a PHWR, along with the electricity, another nuclear fuel ^{239}Pu is obtained from the unused ^{238}U.

Light water cooled graphite reactors **(LWGR)** are also known. It is evident that in BWR, PWR and LWGR, light water (i.e. ordinary water) is used as the coolant and light water is not a good moderator. **Thus in such cases, the number of fission causing neutrons (i.e. thermal neutrons) is less and to run such reactors, we need the enriched fuel** (i.e. % ^{235}U **should be relatively high**). In PHWR, the heavy water used as a coolant is also a very good moderator and no such enriched fuel is required. Among the different reactors, PWR is the most popular one.

(vi) ***The Reactor Shield*** **:** From the reactor, high energy γ-rays, β^--rays, neutrons and heat waves come out. These are hazardous. To minimise the effect, a shielding over the reactor is essentially required. To the vicinity of the core, a thick iron covering is placed to cut down the radiations emerging from the reactor. **This first shield is referred to as *thermal shield*.** Outside the thermal shield, a concrete barrier is placed to absorb the radiations coming from the thermal shield. *This second shield is called the biological shield.*

A schematic representation of a power reactor is shown in Fig. 7.13.4.3. In a ^{235}U-run reactor, for initiating the process, the neutrons are generated by the action of alpha-particles from polonium on beryllium.

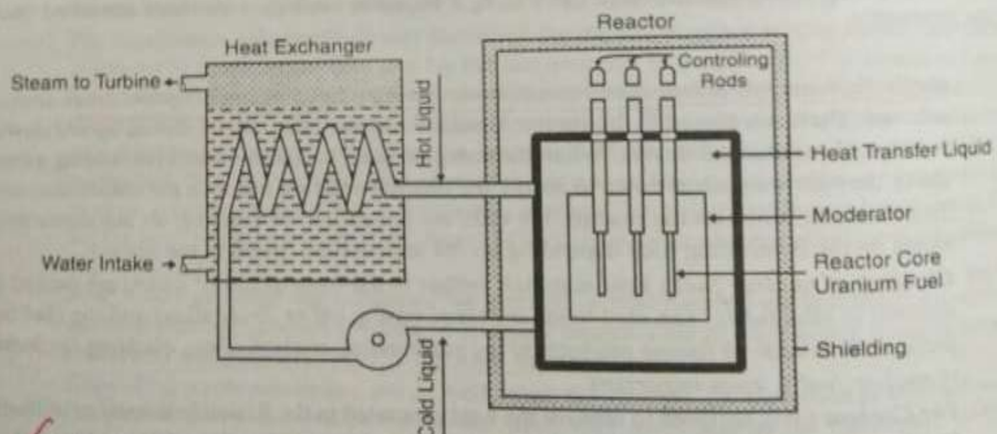

Fig. 7.13.4.3. Schematic representation of the different units of a nuclear reactor.

7.13.5 Breeder Reactor

To enrich ^{235}U content from the naturally occurring source containing predominantly ^{238}U is a very laborious task. This is why, in a Breeder Reactor, ^{239}Pu produced from ^{238}U is utilised as a nuclear fuel. ^{239}Pu **is a fissile nuclide *by both the slow and fast neutrons.***

$$^{238}_{92}U + ^{1}_{0}n \xrightarrow{\text{resonance capture}} {}^{239}_{92}U^{*} \xrightarrow[(t_{1/2} = 23.5\text{ min})]{\beta^-,\ \gamma} {}^{239}_{93}Np \xrightarrow[(t_{1/2} = 2.3\text{ d})]{\beta^-,\ \gamma} {}^{239}_{94}Pu$$

In this process, first, a significant amount of ^{239}Pu is generated by using a flux of slow neutrons on natural uranium containing predominantly ^{238}U. The produced ^{239}Pu being chemically different from uranium can be separated easily. When a sufficient amount of ^{239}Pu is produced, it is used in the form of a rod as a nuclear fuel in the reactor known as ***fast breeder reactor***. The ^{239}Pu rods are enclosed by the natural uranium. ***No moderator is used as the fission of ^{239}Pu goes on by both the fast and slow neutrons***. The neutrons escaping from the core get absorbed by the surrounding uranium-238 to generate the fuel ^{239}Pu. **Thus, in one zone, the fuel is being consumed, while in the other zone, the same fuel is being generated. It is also possible to generate more fuels than that gets consumed.**

Similarly the mixture of uranium-233 and thorium-232 can also be used as a fuel in the breeder reactor.

$$^{232}_{90}Th + ^{1}_{0}n \xrightarrow{\text{resonance capture}} {}^{233}_{90}Th \xrightarrow[(t_{1/2} = 23.5\ \text{min})]{\beta^-,\ \gamma} {}^{233}_{91}Pa \xrightarrow[(t_{1/2} = 27.5\ \text{d})]{\beta^-,\ \gamma} {}^{233}_{92}U$$

^{233}U is a fissionable nuclide. Thus, compared to the reactor run by ^{235}U, the breeder reactor in which a mixture of natural uranium and plutonium-239 (or, $^{233}U + ^{232}Th$) is used gains some advantages. The main problem in the ^{235}U-run reactor is to get the fuel, but in the breeder reactor, no such problem appears. Because of this fact, this ***miracle machine***, i.e. the breeder reactor, has appeared with an enormous promise.

Uranium-plutonium mixed oxide ($UO_2 + ^{239}PuO_2$) having about 25% PuO_2 is generally used as a fuel in fast breeder reactors.

7.13.6 A Natural Fission Reactor : Okla Phenomenon

It is now established that about two billion years ago when ^{235}U content in natural sources was relatively higher, nature had set up a fission reactor at ***Okla mine*** (in Western Africa). It is believed that rain water leached uranium salts present in Okla rocks into some pockets where ^{235}U was concentrated enough to initiate a fission chain reaction. Water accumulated there acted as a moderator. Probably it went on for about 60,000 to 150,000 years.

7.13.7 Nuclear Reactors in India

In India, there are establishments of a number of reactors. These are : Apsara (1956), Cirus (1960), Zerlina (1961), Tarapur (1969), Purnima I (1972), Kota (1973), Purnima II (1976), Kalpakkam I (1983), Kalpakkam II (1985), Dhruva (1985), Fast Breeder Reactor at Kalpakkam (1985), Narora-I (1990), Narora-II (1991), Kakrapar-I, II (1991-92), Kaiga-I and II (1995-96), Rajasthan III (1995-96), Kaiga-III-VI (1996-97), Tarapur-III and IV (1997-98), Rajasthan-V-VIII (1998-2000), Kudankulam-I and II (1998-99) and many other new projects.

Note : The topics like ***Nuclear Reactor Waste Management***, ***Nuclear Reactor Accidents*** (e.g. *Chernobyl* in USSR in 1986, *Three Mile Island* in USA in 1979, etc.) have been discussed in the book "Inorganic Chemistry : Biological and Environmental Aspects" by Asim K. Das, Books & Allied, Kolkata, 2004.

7.13.8 Recovery of Uranium and Plutonium from Spent Fuel

The spent fuel is cooled and kept in a safety place to allow the decay of all short-lived radioisotopes