Unit-IV

Nuclear fusion and it's application

Nuclear fusion, P-P chain reaction as the source of energy in the sun like stars, thermal nuclear reactor, the neutron cycle, controlled and uncontrolled thermonuclear reaction.

* Nuclear Fusion:-

"When two or more very light nuclei moving at very high speeds combine together to form a single heavy nucleus, the process is known as nuclear fusion." The mass of the product nucleus is less than the sum of the masses of the nuclei that have been fused. The difference in mass is converted into energy in accordance with the Einsteins mass energy relation.

$$E = mc^2$$

This energy is released in the process. this property of light nuclei can very well be depicted by the binding energy curve, in which the average binding energy per nucleon rises rapidly with increase in mass number in the range of low mass number nuclei.

For ex. let us consider the formation of a helium nucleus by the fusion of two deuterium nuclei according to the equation

$${}_1H^2 + {}_1H^2 = {}_2He^4 + Q \text{ (Energy)}$$

The energy liberated Q can be calculated as follows:
The initial mass of two deuterium nuclei

$= 2 \times 2.01471$

$= 4.02942$ a.m.u

Mass of the Helium atom $= 4.00388$ a.m.u.
Difference in mass $= 0.02554$ a.m.u
But 1 a.m.u $= 931$ Mev energy

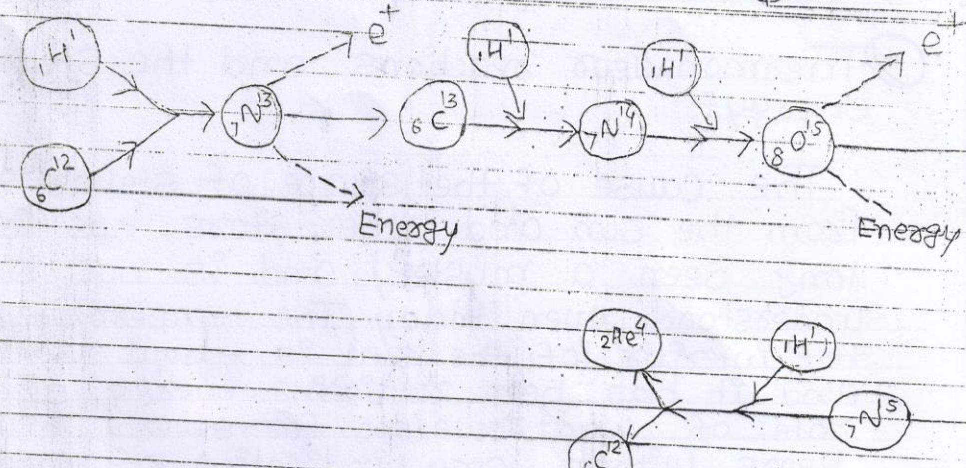
$\therefore$ Energy released $= 0.02554 \times 931$

$= 24$ mev

Thus the energy released in the fusion process is equal to 24 Mev and is much less than the energy produced in the fission of uranium which is equal to 200 Mev. However, if one calculates the energy released per unit mass during fusion of light nuclei, it comes out to be much greater as compared to the fission of uranium.

(*) Proton-proton cycle or chain reaction as the source of energy in the sun like star:-

Recent experiments have suggested that a proton-proton cycle is more efficient at low (stellar) temperature, while a carbon, Nitrogen cycle is predominant at high temperature in the interior of the sun and both the cycles of reactions have almost equal probabilities. Hence the stars which are hotter than the sun get their energy (known as stellar energy) from the carbon nitrogen cycle while those cooler than the sun get energy through the proton-proton cycle, the reactions corresponding to which can expressed as,



Carbon Nitrogen cycle (a)

$$2\,_1H^1 + 2\,_1H^1 \longrightarrow 2\,_1H^2 + 2\,_1e^0 + \text{Energy}$$

$$2\,_1H^1 + 2\,_1H^2 \longrightarrow 2\,_2He^3 + \text{Energy}$$

$$2\,_2He^3 \longrightarrow {}_2He^4 + 2\,_1H^1 + \text{Energy}$$

Summing up, we get

$$4\,_1H^1 \longrightarrow {}_2He^4 + 2\,_1e^0 + \text{Energy}$$

Which is the same equation as obtained in a Carbon-nitrogen cycle.

The calculations based on the rate at which the energy is received from the sun show that 2×10^{19} Kilograms of hydrogen in the sun is converted into helium annually. The total mass of hydrogen in the sun is estimated to be about 2×10^{30} Kilograms. Therefore, the sun is in a position to continue to emite energy at this rate for about five billion years and during this period it will loose only 5% of its store of hydrog

(*) Thermonuclear reactions and the stellar energy:-

The cause of the source of stellar energy from the sun and other stars has for long been a mystery and is not clearly understood even today. The temperature of the interior of the sun is about $2 \times 10^6 K$ and it has been radiating energy at the rate of 4×10^{26} Joule/sec for several billion years without any indication of cooling off. The origin of such a tremendous energy is neither chemical nor gravitational.

The process of nuclear fission can also not be supposed to be responsible for the source of sun's energy because the abundance of heavy elements in the sun is quite small. However, helium and hydrogen are found to constitute about 90% of the sun's mass in almost equal proportions. The fusion of protons by the thermonuclear reactions, therefore, was supposed to release the energy in the sun and in other stars (having a temperature as high as $10^8 K$). Bethe has given a detailed theory of nuclear reactions in the sun and stars.

He proposed a Carbon-Nitrogen cycle as one of the most important nuclear reactions for the release of energy from the sun. In the carbon nitrogen cycle, protons are fused together to give helium. Carbon acts as a catalyst in the reaction. The light elements like hydrogen and helium are in a state of plasma at very high temperature and all the extra nuclear electrons are stripped off the atoms.

The energy produced in fusion is responsible for the maintenance of high temperature of the stars and also for emission of energy by radiations.

Carbon - Nitrogen cycle

The cycle is as follows:

$$_{6}C^{12} + {}_{1}H^{1} \longrightarrow {}_{7}N^{13} + \text{energy} \quad \text{------ (1)}$$

$$_{7}N^{13} \longrightarrow {}_{6}C^{13} + {}_{1}e^{0} \ (\text{Positron}) \quad \text{----- (2)}$$

$$_{6}C^{13} + {}_{1}H^{1} \longrightarrow {}_{7}N^{14} + \text{Energy} \quad \text{---- (3)}$$

$$_{7}N^{14} + {}_{1}H^{1} \longrightarrow {}_{8}O^{15} + \text{Energy} \quad \text{------ (4)}$$

$$_{8}O^{15} \longrightarrow {}_{7}N^{15} + {}_{1}e^{0} + \text{Energy} \quad \text{--- (5)}$$

$$_{7}N^{15} + {}_{1}H^{1} \longrightarrow {}_{6}C^{12} + {}_{2}He^{4} \quad \text{------ (6)}$$

Summing up all the above equations and cancelling out the nuclides which occur on both sides, we have

$$4\,{}_{1}H^{1} \longrightarrow {}_{2}He^{4} + 2\,{}_{1}e^{0} + \text{Energy}$$

It follows, therefore, that four protons fuse together to yield one helium nucleus and two positrons and an energy equal to about 24.7 Mev, as a result of mass difference, is liberated in the process. The initial carbon atom returns unchanged at the end of the reaction. The whole scheme described in the above diagram. (a)

"The process of nuclear fusion requires a very high temperature, the nuclear fusion reactions are called the thermonuclear reactions and the energy released is termed as the thermonuclear energy."

* Thermal nuclear reactor :-

Neutron induced fission releases energy plus extra fast neutrons

fast neutrons are slowed down by a 'moderator' such as water or graphite, allowing chain reaction to take place (rapid increase in neutron population) In water reactors, the coolant is also the moderator.

chain reaction is controlled by controlling the condition of the moderator or by use of neutron absorbing materials.

Heat is removed by some form of heat exchange where it is used to run a heat engine

$$_0n^1 + {}_{92}U^{235} \longrightarrow X + Y + (2\text{-}3)\,\text{neutrons} + 200\,\text{MeV}$$

Each fission liberates 2-3 neutron for a net increases of 1-2 neutrons ~~for~~ per fission when these neutron are slowed down by the moderator they can cause more fissions.

Chain reactors.

if N = number of neutrons

Initially

$$\frac{dN}{dt} \propto N \Rightarrow \text{Exponential growth of neutron}$$

How there are neutron loss mechanisms

1. Neutrons can escape from the reactor
2. Neutrons can be absorbed by non-fissionable isotopes

loss mechanisms oppose the strong increase in neutron population.

(I) A nuclear reactor used for the purpose of power generation or for the production of radio isotopes is defined as a system where in a nuclear fission is carried out as a controlled chain reaction.

(II) Nuclear reactor that utilize thermal neutrons to initiate and sustain fission are called thermal reactors and those that utilize ~~that~~ fast neutrons are called fast reactors.

The most important components of a nuclear reactor are as

1. Fuel
2. Moderator
3. Coolant
4. Control material

(1) Fuel :- Analogous to the role of fuel in any heating application, the fuel in a nuclear reactor is the source of energy and hence it is the material containing a fission material.

Materials that undergo nuclear fission when bombarded with thermal neutron are called fissile material and their respective nuclei called fissile nuclei.

(2) Moderator : moderator with respect to nuclear reactors implies slowing down of neutron

③ Coolant :- The purpose of coolant is to remove the heat liberated during fission and to utilize the same for steam generation.
Water and heavy water are the most common liquid coolants in thermal reactors.

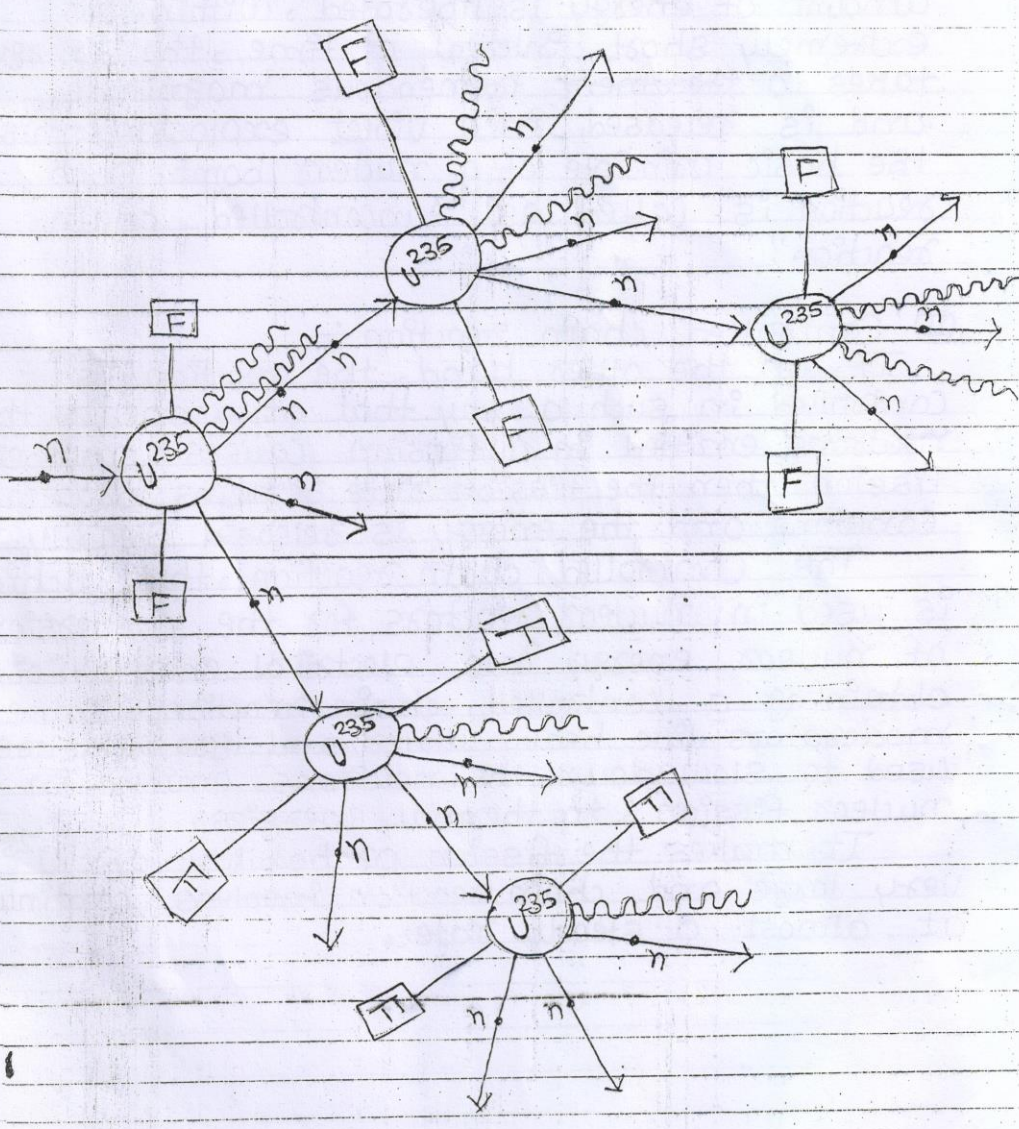
④ Control materials :- Sustance of a controlled fission is tricky for generating electricity from nuclear reactors.

⑤ Other components :- Apart the above four Important components include structural components and control system.

* Nuclear chain reaction or neutron cycle :-

Natural Uranium consists of 99.28% of U^{238} and only 0.72% of U^{235}. As most of the mass of natural uranium consists of U^{238}, the neutrons released during the fission will try to bombarded the nuclei of U^{238} mostly and very few will bombard U^{235}. It has been found that while very few neutrons can cause a fission of U^{238}, the neutrons of all possible energies can cause fission of a U^{235} nucleus. Thus the chain reaction (i.e. a reaction in which fission process may continue for long) is not possible in natural uranium.

If however, U^{238} is removed from some process and only U^{235} or Pu^{239} is used, a chain reaction is possible. In a chain reaction three neutrons liberated from a single nucleus cause fission in 3 more nuclei which emit 9 neutrons. these 9 neutrons by causing fission in other nuclei multiply at each step and the chain reaction continues with the emission of a tremendous amount of energy because of the fission of all nuclei



(I) Uncontrolled chain reaction :-

As discussed above, a number of neutrons in a particular fission cause further fission and the number of fissions increases rapidly with them since in every fission a large amount of energy is liberated, within an extremely short interval of time, the energy takes a ~~treatment~~ tremendous magnitude and is released in a violet explosion. this is the basic principle of a nuclear bomb. such reaction is called as "uncontrolled chain reaction".

(II) Controlled chain reaction :-

If, on the other hand, the reaction is controlled in such a way that only one of the neutrons emitted in a fission causes another fission, then the fission rate remains practically constant and the energy is released steadily.

The controlled chain reaction, thus achieved, is used in nuclear reactors for the conversion of nuclear energy into electrical energy. For obtaining a controlled chain reaction, some moderators like heavy water and graphite are used to slow down the neutrons, emitted in nuclear fission, to thermal energies.

It makes the fission probability of U^{235} very large and chain reaction ~~involves~~ continues at almost a steady rate.