

Nuclear Fission

Nuclear fission was discovered by **Otto Hahn** and **Strassmann** in 1939.

The splitting of a heavier nucleus into two smaller fragments with the bombardment of slow moving neutrons is called Nuclear fission.

Energy released in this process is called nuclear energy.

The fission of a nucleus does not occur in exactly the same way each time: More than 100 different fission pathways have been identified for uranium-235, yielding more than 200 different fission products. One of the more frequently occurring pathways generates barium-142 and krypton-91, along with two additional neutrons plus the one neutron that initiated the fission:

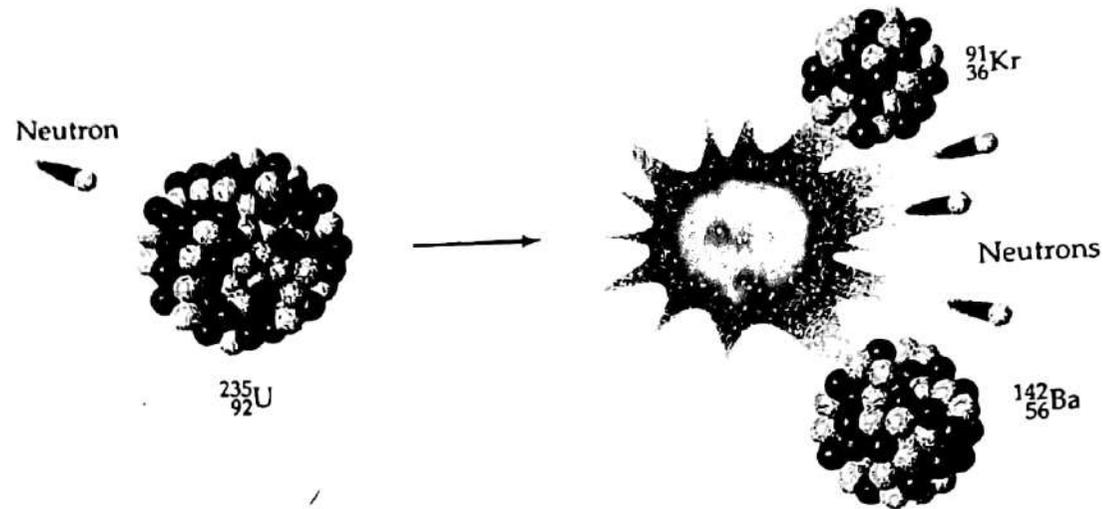
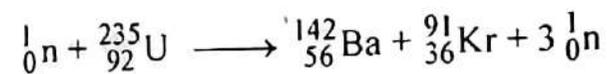
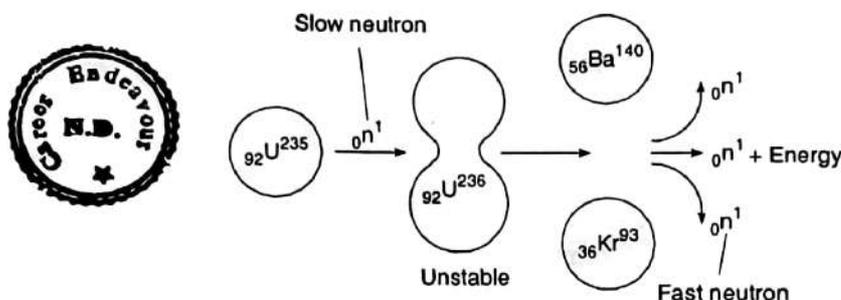


Figure A representation of nuclear fission. A uranium-235 nucleus fragments when struck by a neutron, yielding two smaller nuclei and releasing a large amount of energy ;



The three neutrons released by fission of a ^{235}U nucleus can induce three more fissions yielding nine neutrons, which can induce nine more fissions yielding 27 neutrons, and so on indefinitely. The result is a **chain reaction** that continues to occur even if the supply of neutrons from outside is cut off. If the sample size is small, many of the neutrons escape before initiating additional fission events, and the chain reaction soon stops. If there is a sufficient amount of ^{235}U , though—an amount called the **critical mass**—enough neutrons remain in the sample for the chain reaction to become self-sustaining. At some point, the chain reaction may even occur so rapidly that a nuclear explosion results. For ^{235}U , the critical mass is about 56 kg, although the amount can be reduced to 15 kg by placing a coating of ^{238}U around the ^{235}U to reflect back some of the escaping neutrons.



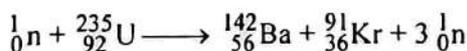
An aspect which is extremely important for a chain reaction to continue is that the fissionable material (uranium-235) must have a minimum size. If the size is smaller than this minimum size, the neutrons escape from the sample without hitting the nucleus and causing fission and thus the chain reaction stops.

The minimum mass which the fissionable material must have so that one of the neutrons released in every fission hits another nucleus and causes fission so that the chain reaction continues at a constant rate is called **critical mass**. If the mass is less than the critical mass, it is called **sub-critical**. If the mass is more than the critical mass, it is called **super-critical**. In this case, many of the neutrons released in every fission are able to hit the other nuclei and thus the number of fission multiply in the chain reaction.

A difficulty that arises with the use of U-235 is that the naturally occurring uranium contains mostly U-238 isotope (about 99.3%) which is not fissionable with the slow neutrons and the separation of U-235 from U-238 is extremely difficult.

The tremendous amount of energy released, if uncontrolled, can be used for destructive purposes e.g., in the formation of an **atomic bomb**. However, if the chain reaction is controlled, the energy released can be used for constructive purposes, e.g., in the **nuclear reactor**. The principle of each of these devices is briefly explained below:

Example. How much energy (in kJ/mol) is released by the fission of uranium-235 to form barium-142 and krypton-91? The fragment masses are ^{235}U (235.0439 amu), ^{142}Ba (141.9164 amu), ^{91}Kr (90.9234 amu), and n (1.008 66 amu).



Solution. First calculate the mass change by subtracting the masses of the products from the mass of the ^{235}U reactant:

Mass of ^{235}U	= 235.0439 amu
– Mass of ^{142}Ba	= –141.9164 amu
– Mass of ^{91}Kr	= –90.9234 amu
– Mass of 2 n = –(2)(1.008 66 amu)	= 02.0173 amu
Mass change	= 0.1868 amu (or 0.1868g/mol)



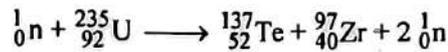
$$\Delta E = \Delta mc^2$$

$$= \left(0.1868 \frac{\text{g}}{\text{mol}}\right) \left(1 \times 10^{-3} \frac{\text{kg}}{\text{g}}\right) \left(3.00 \times 10^8 \frac{\text{m}}{\text{s}}\right)^2$$

$$= 1.68 \times 10^{13} \text{ kg} \cdot \text{m}^2 / (\text{s}^2 \cdot \text{mol}) = 1.68 \times 10^{10} \text{ kJ/mol}$$

Nuclear fission of 1 mol of ^{235}U releases 1.68×10^{10} kJ.

Problem: An alternate pathway for the nuclear fission of ^{235}U produces tellurium-137 and zirconium-97. How much energy (in kJ/mol) is released in this fission pathway?

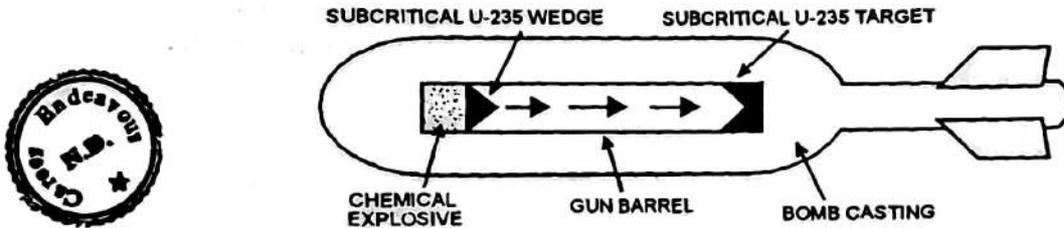


The masses are ^{235}U (235.0439 amu), ^{137}Te (136.9254 amu), ^{97}Zr (96.9110 amu) and n (1.008 66 amu).

Solution:

Do yourself

1 Atomic Bomb: A simple design of an atomic bomb is shown in following fig.

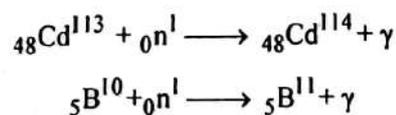


Principally, it contains two pieces of U-235 (or plutonium 239) each of sub-critical mass, one called the wedge and the other the target. A chemical explosive is packed at the back of the wedge which can push the wedge to the target and the two join together to form super-critical mass. The reaction is started by a slow neutron.

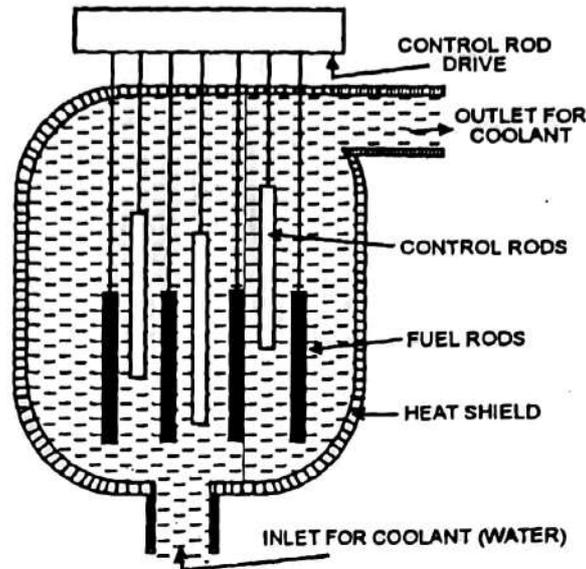
2. Nuclear Reactor: A nuclear reactor is an arrangement in which the energy produced (in the form of heat) in a nuclear fission can be used in a controlled manner to produce steam which can run the turbine and produce electricity.

The energy can be controlled by controlling the nuclear fission which, in turn, can be controlled by controlling the number of neutrons released during the fission.

To control the number of neutrons, advantage is taken of the fact that cadmium and boron can absorb neutrons to form the corresponding isotopes which are not radioactive *i.e.*



The main part of the nuclear reactor is the **reactor core**.



It consists essentially of the following parts:

(1) Fuel rods:

The fissile (fissionable) material used in the reactor is called **fuel**. The fuel used is *enriched* Uranium —235 (in the form of U_3O_8). This is obtained from the naturally occurring U-235 (containing about 0.7% of U-235) by raising the percentage of U-235 to about 2-3%. The solid fuel is made into the form of rods or pellets, shielded by placing them in stainless steel tubes.

(2) Control rods:

To control the fission process, rods made of cadmium or boron are suspended between the fuel rods. These rods can be raised or lowered and control the fission process by absorbing neutrons. That is why they are called 'control rods'.

(3) Moderator:

The neutrons produced in the fission have to be slowed down to speeds at which they are easily captured by the fuel so that the fission process can take place most efficiently. This is done by surrounding the fuel rods with heavy water (D_2O). The material thus used to slow down the neutrons (without absorbing them) is called a 'moderator'. Graphite is also a good moderator.

(4) Coolant:

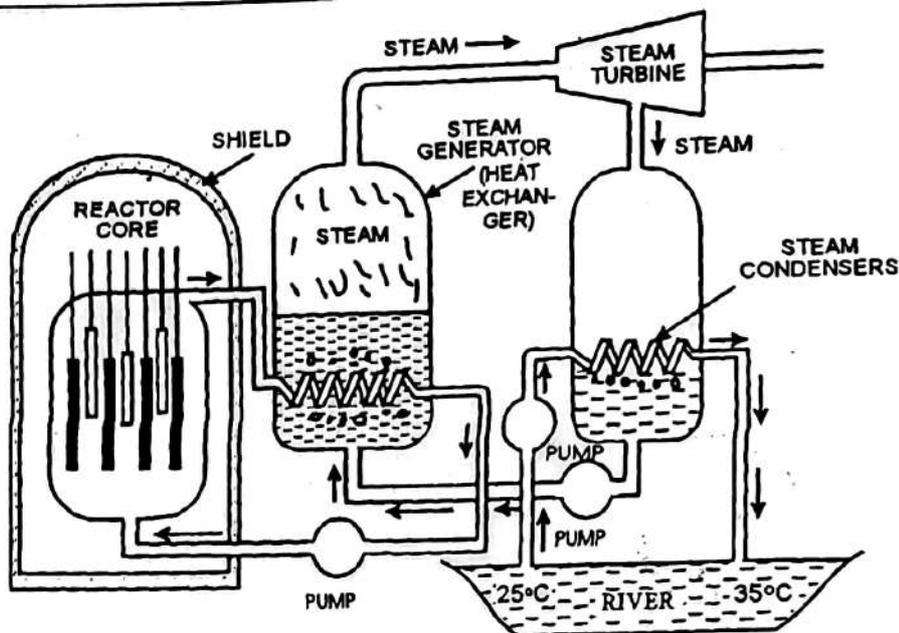
To carry away the heat produced during fission, a liquid is circulated in the reactor core. This liquid enters the base of the reactor core and leaves at the top. The heat carried by the outgoing liquid is used for producing steam. As a result, the liquid cools down and is pumped back to the base of the reactor core. The liquid thus used is called a "coolant". Usually the coolant used is heavy water so that it also acts as a moderator.

(5) Shield:

To prevent the losses of heat and to protect the persons operating the reactor from the radiation and heat, the entire reactor core is enclosed in a heavy steel or concrete dome, called the 'Shield'.

The complete design of a nuclear power plant is shown in following Fig.





The steam after driving the turbine has to be condensed. For this purpose additional cooling water is needed. This is usually obtained from a large source such as river or lake which has flowing water. This is essential because it is evident that after condensing the steam, the water is returned to the source at a higher temperature. Thus a complete nuclear power plant consists essentially of the following four parts:

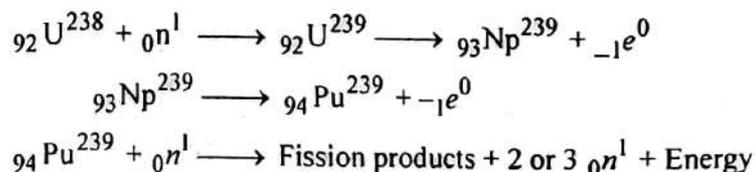
- (i) Reactor core
- (ii) Steam generator (Heat exchanger)
- (iii) Steam turbine
- (iv) Steam condensing system.

The design of a thermal power plant is exactly similar except that in place of reactor core there is arrangement for producing heat by burning coal.

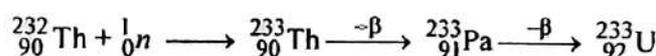
Breeder Reactor:

It may be mentioned that the rate at which U-235 is being used up to produce power, the stocks are likely to exhaust very soon. Scientists have, therefore, been actively engaged in investigating other fissionable materials. They have found plutonium-239 and uranium-233 to be quite suitable. These are produced by bombardment of more abundantly available U-238 and Th-232 with neutrons. Scientists have been, therefore, trying to build reactors in which the neutrons produced from fission of U-235 are partly used up for carrying on the fission of U-235 and partly to produce Pu-239 or U-233. Such reactors would produce more fissionable material (as Pu-239 or U-233) than they consume (as U-235). These reactors have been named as **Breeder reactors**. The first such reactor began operation in 1972 in Russia.

The sequence of reactions that take place when ${}_{92}\text{U}^{238}$ is bombarded with fast neutrons producing the fissionable nuclei of plutonium-239 may be represented as follows:



Similarly, the fissionable isotope of uranium ${}_{92}^{233}\text{U}$ is produced from the naturally occurring abundant isotope of thorium, ${}_{90}^{232}\text{Th}$ as follows:



In breeder reactors, the coolant used is an alloy of sodium and potassium which is in the molten state and transfers heat to water in the steam generator (heat exchanger).

India is the first country in the Asian region to use uranium-233, a man-made fissionable material derived from thorium, as a fuel in the 30 MW Kalpakkam mini reactor, Kamini (on Oct 29, 1996).

The nuclides such as U-238 and Th-232 which can be converted into fissionable nuclides are called **fertile nuclides** whereas nuclides such as U-235, Pu-239 which are fissionable are called **fissile nuclides**.