Moderating ratio — The *moderating ratio* (*M.R.*) is a parameter that measures the effectiveness of a moderator and is the capacity for the nuclei in 1 cm^3 of the material to slow down neutrons. It is given by :

$$M.R = \xi \frac{\sigma_s}{\sigma_a} \qquad \text{(iii)}$$

16.20 Nuclear reactor

A *nuclear reactor* is a device wherein a neutron induced self-sustaining chain reaction involving fission of heavy elements takes place. The purpose of the reactor is to (i) *initiate nuclear fission reaction,* (ii) *control these reactions,* and (iii) *extract the energy produced.* The control of neutrons is the key to the functioning of the reactor.

The first nuclear reactor that came into operation was obtained in July 1941 at the Columbia University under the leadership of Enrico Fermi and was then called a *uranium-carbon pile*. A schematic diagram of a reactor is shown in Fig.16.9.

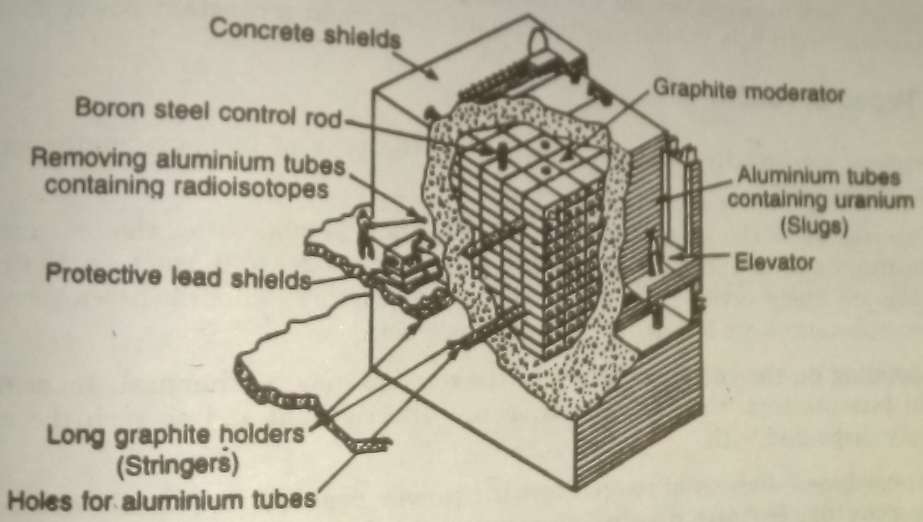

Fig.16.9 Schematic diagram of a reactor

Basic elements of a reactor — All types of reactors contain the following essential *basic* elements :

(a) the *fuel,* a material that fissions and supplies neutrons for further fissions;

(b) the *moderator* for slowing down the speed of fast neutrons (this, however, is not necessary for fast reactors);

(c) the *neutron reflector;*

(d) the *cooling system;* and

(e) the *control and safety arrangements.*

The commonly used *fissionable materials* are the uranium isotopes : U-233, U-235, U-238; the thorium isotope Th-232 and the plutonium isotopes: Pu-239, Pu-240 and Pu-241.

The materials to be used as *moderators* should have a large inelastic scattering cross-section and small neutron capture (absorption) cross-section. The usual moderators are : graphite, heavy water (D_2O), beryllium oxide, hydrides of metals and organic liquids. The nuclei of these materials hardly absorb neutrons.

A *reflector* is a material placed around the reactor core (that contains the fuel and the moderator) to prevent neutrons from escaping from the core. Good moderators are usually good reflectors and the efficiency of a reflector increases rapidly with its thickness.

The *cooling system* in a reactor helps to control the temperature of the fuel element and transports the heat generated by fission of the fuel to the heat engine. There are four types of possible coollants for reactors. These are (i) *gases* : air, CO_2, He or steam, (ii) *water type liquids* : water or heavy water, (iii) *molten metals* : Hg, Na, K, Na-K eutectic, Pb, Bi or Pb-Bi eutectic and (iv) *fused salts*. Each type has its own merits and demerits.

The *control and safety system* is intended to control the chain reaction against its 'running away' spontaneously and also for protecting the surroundings against the intense neutron flux and dangerous γ-radiation inside the core. While the first is achieved by pushing *control rods* of a material having large neutron absorption cross-section (e.g. boron, cadmium) into the core, the second one is accomplished by surrounding the reactor with massive layers of concrete and lead and by providing completely closed coolant circuits.

To *control the criticality* of a reactor, control rods are inserted into the reactor. In the process, so many neutrons are absorbed that the reactor *shuts down*. Rods are then withdrawn until enough neutrons are present for the reactor to start toward *supercritical* and then they are re-inserted until it is *critical* and the reactor operates at a constant power level.

16.21 Types of reactors

Reactors are broadly classified according to the type of fuel, moderator and the heat transfer agents used.

With respect to the arrangements of the fuel and the moderator, the reactors are classed as (i) **homogeneous** and (ii) **heterogeneous.** In homogeneous reactors, the fuel and the moderator are finely divided and uniformly mixed together, while in heterogeneous reactors these two substances are in separate elements as blocks.

Depending on the energy of neutrons, the reactors may be **thermal, intermediate** and **fast.** In fast reactors, the fission-neutrons are directly used and as such the moderator is completely dispensed with.

Purpose-based division of the reactors is : **power reactor, test and research reactor, breeder reactor, isotope producing reactor** etc. In a power reactor, the energy available from the chain reaction is transformed into useful power form such as electricity. The test and research reactors are designed for a number of different testing purposes such as dimensional stability or instability of materials under irradiation and other radiation damage phenomena. In a breeder reactor, the fissionable materials are bred and in an isotope producing reactors radioactive isotopes, to be used for various purposes e.g. in industry, agriculture, medicine etc. are produced.

Taking into account all the above features, the nuclear reactors can be classed as : *uranium-graphite, water-cooled, water-moderated, boiling* etc.

16.22 Breeder reactor

U-235 is the only naturally occurring isotope that undergoes fission by thermal neutrons. As this fuel in a uranium reactor gets used up by fission and the neutrons themselves are lost in the fission products by absorption, the reproduction factor k becomes less than 1. The reactor thus ceases to function as a chain-reacting source within a few decades of operation and the nuclear fuel has to be replenished to restart the reactor. If nuclear energy is to be used for the generation of power, such a continuous depletion of world's uranium resource should be halted. The *breeder reactor* is the way out of this difficulty.

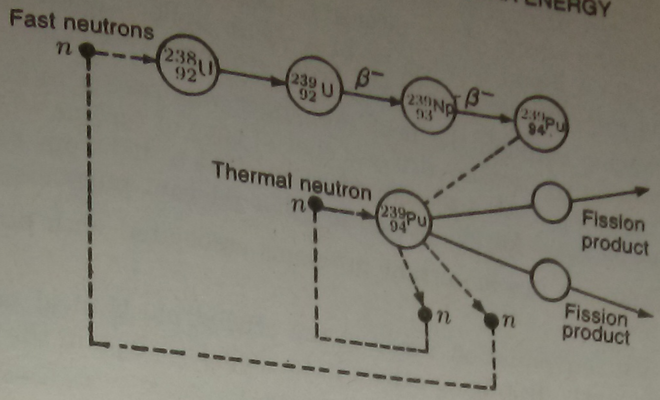

Fig.16.10 Scheme for a Breeder reactor

Breeder reactors, also called *breeders,* transform nuclei of one fissionable material into another fissionable one through reaction with the reactor neutrons themselves such that they make available more fuel than what they consume. Hence the name. For instance, breeders use fast neutrons which are captured by fertile materials like U-238; by consecutive β^- decays U-238 decays into fissile Pu-239 which is fissionable by thermal as well as high energy neutrons.

$$^{238}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{239}_{92}\text{U} \xrightarrow{\beta^-} ^{239}_{93}\text{Np} \xrightarrow{\beta^-} ^{239}_{94}\text{Pu}.$$

The scheme for the breeder reactor is shown in Fig.16.10. Note that two neutrons in excess of those captured and lost by other processes must be produced to maintain the reaction and it is so designed that more fissile materials are produced than consumed for fission.

Another fertile material that can be used in breeders to produce fissile fuel is Th-232, available in plenty. It captures low energy neutrons to finally result in U-233, a stable α-emitter and can be fissioned with thermal neutrons.

Within a few years, breeder can make available double the original quantity of fuel.

16.23 Power reactor : Nuclear power plant

The basic principle of one type of power reactor is illustrated in Fig.16.11.

A quantity of enriched U-235 in the form of a pure metal or in the form of a solution of soluble salt in water forms the *core* of the power plant. The energy released by fission produces great quantities of heat and the rising temperature is regulated to a certain pre-determined

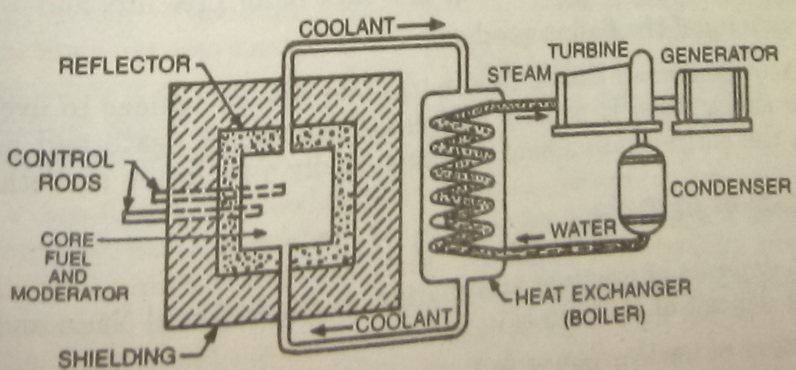

Fig.16.11 Basic principle of a power reactor

value by cadmium *control rods.* To reduce the fission rate, and thereby the temperature, the control rods are pushed in a little further to absorb more neutrons, while to raise the temperature they are pulled out a little further.

Because of the harmful effects of the intense radiation to both men and equipments, it is not resonable to vaporise a liquid directly as in a steam boiler. Instead, a fluid (*coolant*) is circulated through the *shielded* reactor and the *heat exchanger* (boiler).

The hot liquid flowing through the heat exchanger vaporises a more volatile liquid, say water; the issuing steam under pressure drives a special type of *turbine* which in turn drives an *electric generator*. The power that is developed is supplied to light our cities and factories or drive ships and submarines and for being used in other relevant purposes.

Problems — There are *two* important problems associated with power reactors. These are :

(i) The intense neutron radiation weakens the crucial mechanical parts by transmuting some atoms and permanently dislodging others from their positions in the crystal lattice of the solids.

(ii) The coolant used must be able to withstand high temperatures, not absorb neutrons and become appreciably radioactive and yet transfer heat efficiently in both the reactor and the heat-exchanger. Certain metals with low melting points appear highly promising.

16.24 Fission bomb : A-bomb

In a uranium or plutonium bomb (also called *fission bomb*), an uncontrolled nuclear chain reaction occurs. The device is designed to be as *supercritical* as possible, the chain reaction grows as high a rate as possible and maximum energy is released in minimum time – within a fraction of a second. The explosive nature is due to the release of huge energy all on a sudden. A fission bomb (and a reactor) has a *critical size*. If the dimensions are too small, too many neutrons escape from the surface without fission. The secret of detonating a fission bomb lies in keeping it divided into subcritical sections until the moment of explosion, (for otherwise, a passing cosmic radiation may trigger the bomb) when they are to be brought together rapidly to form a size exceeding the critical size (Fig.16.12).

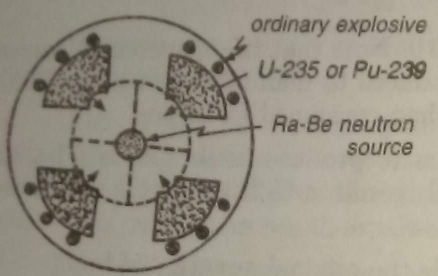

Fig.16.12 Sub-critical sections of a fission bomb

The *chief effects* of explosion of a fission bomb are the following :

(a) the *intense heat* forming thermal waves that propagate with the speed of light. The temperature rises to as high as 5×10^7 K ;

(b) the mechanical *shock wave* consisting of a blast of air pressure, and

(c) the *radioactivity* of the fission products.

The intense heat generated causes fatal burns and serious damage to lives and properties due to fires. The shock wave is equally dangerous and causes death and devastation. The radiation pollutes the entire environment emitting deadly γ-radiation and other rays.

16.25 Nuclear power in India

India has rich deposits of uranium and thorium in Bihar, Tamil Nadu and Kerala. In fact, the world's largest deposit of thorium is in India.

The development of nuclear power in India dates back to 1956 when the first Indian, nay the first Asian outside the then Soviet Union, reactor *Apsara* was commissioned. The second Indian reactor is *Cirus* and was commissioned in 1961. It was built with the assistance of Canada and has an energy of about 40 MW. The third reactor in the series is *Zerlina*, a zero energy experimental reactor. All these reactors are used for experimental researches and for the production of radio-isotopes to be provided to industry, agriculture and medicine. In 1964, India commissioned its first *plutonium plant* in Trombay. Plutonium helps to breed a fissionable material U-233 from thorium. Recently, India had her first *breeder reactor* set up at Kalapakkam in Tamil Nadu.

India built her first *atomic power station* at Tarapur in Maharashtra with the assistance of the United States. It has an estimated energy of 380 MW. Similar power stations are being set up at Rajasthan and Tamil Nadu.

India became a member of the so-called World Nuclear Club by initiating in 1974 the first *nuclear explosion* (underground) at Pokhran in Rajasthan. India undertook series of nuclear explosions recently in May 1998, also at Pokhran.

16.26 Fusion : Thermonuclear reaction

The release of energy in fission is essentially due to the binding energy per nucleon being less in heavier nuclei than in those of intermediate mass numbers formed as fission fragments. The binding energy curve (Fig.10.1) shows that precisely an equivalent situation exists at the low mass number end. The binding energy per nucleon in light nuclei on the steep portion of the curve is less than for nuclei of intermediate mass numbers. So if two light nuclei combine or fuse together to produce a relatively heavier nucleus, there would be a greater binding energy and consequent decrease in nuclear mass. This would therefore result in a positive Q-value and a release of energy. This type of nuclear reactions is known as **nuclear fusion**, a process opposite to that of nuclear fission.

Fusion reactions are now readily observed in experiments with high energy beam of protons and deuterons, energised by accelerators.

$$^{1}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H} \rightarrow ^{2}_{1}\mathrm{H} + ^{0}_{1}\mathrm{e} + \nu; \quad Q = 0.42 \text{ MeV}$$
$$^{2}_{1}\mathrm{H} + ^{2}_{1}\mathrm{H} \rightarrow ^{3}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n}; \quad Q = 3.3 \text{ MeV}$$

with accompanied release of energy as shown.

Fusion depends for its action on the collisions of two very energetic nuclei, a subsequent re-arrangement of nucleons and the release of energy as kinetic energy of the product particles and their excitation energy. The primary nuclei are positively charged and repel each other electrostatically. For fusion, therefore, the kinetic energy of the colliding particles must be high enough to overcome the electrostatic coulomb repulsion. And in order that fusion could be of any practical value as an alternative source of energy production, the reaction must be self-sustaining, i.e. more energy must be released than what is consumed in initiating the reaction. A large kinetic energy implies a high temperature such that fusion energy should be sufficient to provide enough energy to secondary particle to make the process self-sustaining. For this reason, fusion reactions are also known as **thermonuclear reactions.** Unfortunately, the so-called high temperature is as high as $\sim 10^{9}\,^{\circ}\mathrm{C}$ and it increases rapidly with atomic number. That is why promising experiments in the field have been carried out with the three isotopes of hydrogen, particularly deuterium.

Since there is practically an inexhaustible store of deuterium fuel (in water $^{2}\mathrm{H} : ^{1}\mathrm{H} = 1:5000$), thermonuclear reactions hold a great promise for a permanent solution of the problem of depletion of chemical, mineral and fossil fuels. We have yet to be fully successful to control thermonuclear reactions so as to produce thermonuclear reactors. But once made, and physicists are quite optimistic, they would have a number of *advantages* over the fission reactors. *First*, the process of extraction of fission fuel from the limited amount of ores is quite complicated and costly, but the fusion fuel like $^{2}\mathrm{D}$ is rather easily obtainable from natural water which is almost an inexhaustible source. *Secondly*, unlike fission, fusion is *clean* for it does not leave behind any harmful radioactive waste for disposal. *Thirdly*, the fusion reactor will have an inherent safety unlike the fission reactor that may 'run away'. Also, the nuclei taking part in fusion are light and so the energy released per unit mass of the reaction material is comparatively much greater.

16.27 Source of stellar energy

The sun discharges energy at the rate of 10^{26} joules a second. This is also more or less true with any star with the interior temperature of about 20 million degrees. The estimated age of the sun is at least 5×10^9 years. So the loss of energy by the sun during this time is tremendously high. What then is the source of this exceedingly high stellar energy? Helmholtz and Kelvin suggested that a slow gravitational attraction might be the source. Jeans proposed annihilation of high energy protons and electrons in the stars as the source. It was indeed a puzzle until the discovery of nuclear reactions.

R. Atkinson and F. Houtermans were the first to suggest in 1928 that successive capture of four protons by some light nuclei to produce an α-particle could release energy at such rates as to account for the loss of energy by the sun for so long a time. They proposed the idea of cyclic nuclear reactions.

In 1938, Hans Bethe suggested that the stellar energy is produced by thermonuclear reactions in which protons are combined and transformed into helium nuclei. This is known as **proton-proton cycle** applicable for relatively low stellar temperature. The cycle is :

(a) $^1_1H + ^1_1H \rightarrow ^2_1H + ^0_1e + \nu + 0.42$ MeV

(b) $^2_1H + ^1_1H \rightarrow ^3_2He + \gamma + 5.5$ MeV

(c) $^3_2He + ^3_2He \rightarrow ^4_2He + 2\,^1_1H + 12.8$ MeV

In this cycle of reactions, fusion reaction (a) and (b) must occur twice to yield two ^3_2He nuclei in (c). The net result of these reactions is that four protons are fused to produce an α-particle, two positrons, two neutrinos and two γ-photons.

$$4\,^1_1H \rightarrow ^4_2He + 2\,^0_1e + 2\nu + 2\gamma.$$

The energy released in the cycle is 24.6 MeV, for the mass difference is $(4 \times 1.0078 - 4.0026)$ or 0.0286 u. Since the neutrinos escape, the energy left is about 24.3 MeV after the fusion of 4 protons into 1 helium nucleus. The protons thus get gradually depleted and the concentration of helium builds up.

The proton-proton cycle is an important source of energy in the sun and in stars of comparatively low temperatures (*red dwarfs*). A conclusion that follows from the above cycle is that the older stars are expectedly richer in helium compared to the younger ones.

For the *main sequence stars* having higher temperatures, Bethe suggested an alternative to the proton-proton cycle – the **carbon-nitrogen cycle.** The cycle is (* means radioactive)

(a) $^1_1H + ^{12}_6C \rightarrow ^{13}_7N^* + \gamma + 1.95$ MeV

(b) $^{13}_7N^* \xrightarrow{10.1\text{ min}} ^{13}_6C + ^0_1e + \nu + 2.22$ MeV

(c) $^1_1H + ^{13}_6C \rightarrow ^{14}_7N + \gamma + 7.54$ MeV

(d) $^{14}_7N + ^1_1H \rightarrow ^{15}_8O^* + \gamma + 7.35$ MeV

(e) $^{15}_8O^* \xrightarrow{2.05\text{ min}} ^{15}_7N + ^0_1e + \nu + 2.7$ MeV

(f) $^1_1H + ^{15}_7N \rightarrow ^{12}_6C + ^4_2He + 4.96$ MeV

Adding up, the net result is

$$4\,^1_1H \rightarrow ^4_2He + 2\,^0_1e + 2\nu + 3\gamma + 26.72\text{ MeV}$$

the energy release being almost the same as in proton-proton cycle.

The conversion of hydrogen into helium is a mass-exchange reaction and would continue till the whole of hydrogen in the star is completely used. For sun, both the cycles occur with equal probability. The estimated time for the complete conversion of all the hydrogen of the sun into helium is about 3×10^{10} years, the calculation being based essentially on the mean reaction times for the reactions (a) and (d) only which are 2.5×10^6 yr and 3×10^8 yr respectively. Our sun is therefore still in its prime of life.

Note 1. C-12 acts as a catalyst only in that it was a part of the initial reaction and a product of the final reaction. Instead of taking (a) as the starting point and (f) the end point of the cycle, one could as well take (f) and (e) as the beginning and end of the cycle respectively in which case N-15 would act as the catalyst.

Note 2. Fusion of 4 protons into helium, overcoming the coulomb repulsion, is possible only because of the extremely high initial temperature.

There are evidences to believe that the *carbon-nitrogen cycle* starts at a rather late stage in the life of a star. According to the modern view of stellar evolution, a star is formed by way of condensation of an enormous amount of matter at a certain point in space. As the mass contracts, its temperature increases and when it reaches the value of about 2,00,000°C, the *proton-proton cycle* starts operating.

When the deuterons, formed as a product in the proton-proton cycle, are completely exhausted, the star shrinks and the temperature again increases. At a temperature of about million degrees, protons interact with heavier elements such as beryllium, lithium and boron forming helium nucleus. At this stage, the star looks very bright and is called a *red giant.* When the above type of nuclei is also exhausted, further contraction takes place and the temperature rises to about 20×10^6 °C. The carbon-nitrogen cycle operates at this stage and supplies the energy for the major portion of the radiating life of a star. When the protons are all exhausted, further contraction takes place at a rapid rate; the star releases a large amount of energy and quickly attains the last phase of its life which may be one of the *three* end states : the *white dwarf,* the *neutron star* or the *black hole.* The *white dwarf* is usually the common end state of stellar evolution. The *neutron star* is comparatively a recent discovery through radio-astronomy. *Pulsars,* identified since 1967, are regarded as pulsating, that is, rotating neutron stars. The *black hole* is believed to be formed by the gravitational collapse of a neutron star. It is too dense for even photons (light) to escape from its pull.

Note. Stars with masses between 0.4-2.5 solar mass produce energy mainly by carbon-nitrogen cycle rather than the proton-proton cycle. Stars having masses of 0.4 solar mass or lower, which constitute the bulk of stellar population in our galaxy, mainly derive energy from proton-proton cycle.

16.28 Uncontrolled fusion : H-bomb

When the trial atomic bomb (A-bomb) exploded at Alamogordo on July 16, 1945, it was realised that it would be possible now to make fusion-energy the way the sun does. When an A-bomb containing U-235 or Pu-239 explodes, the temperature at the central core becomes, for a fraction of a second, comparable to that at the heart of the sun. And there are millions of pounds of pressure also.

The exact materials used, their proportion, the physical size, the shape of the device and the mechanical and electrical systems used in hydrogen bomb (H-bomb) are all hidden in military secrecy. Nevertheless, an H-bomb, in principle, consists of a device in which *fission-fusion* process is applied. The central part of the device is a fission bomb (A-bomb) containing U-235 or Pu-239 and this is surrounded by an atmosphere of deuterium and tritium. The A-bomb acts as the igniting 'fuse' of the H-bomb, providing an extremely high temperature (10^7-10^8 °C) necessary for the fusion process to start. The reactions are :

$${}^2_1\mathrm{H} + {}^2_1\mathrm{H} \rightarrow {}^3_1\mathrm{H} + {}^1_1\mathrm{H} + 4.04 \text{ MeV}$$

followed by

$${}^2_1\mathrm{H} + {}^3_1\mathrm{H} \rightarrow {}^4_2\mathrm{He} + {}^1_0\mathrm{n} + 17.6 \text{ MeV}$$

and $${}^2_1H + {}^2_1H \rightarrow {}^3_2He + {}^1_0n + 3.26 \text{ MeV}$$

followed by $${}^2_1H + {}^3_2He \rightarrow {}^4_2He + {}^1_1H + 18.3 \text{ MeV}$$

Fusion reactions based on deuteron-deuteron and deuteron-triton are known as *wet hydrogen bomb* reactions.

The first successful H-bomb was exploded on Eniwetok Atoll in the Pacific on November 1, 1952. The explosion not only melted the whole island but boiled it away. India exploded its first successful H-bomb in Pokhran (underground) during May, 1998.

There is no limit to the size of an H-bomb as there is no necessity for any critical mass in the process.

16.29 Controlled fusion : Possibility of fusion reactor

Ever since the realisation of the fusion process in a hydrogen bomb, the physicists had been after a controlled fusion reaction for making fusion reactor a possibility. While there are still much to be discovered before any successful power source based on fusion is achieved, much has already been learnt from the various study projects in the field.

One of the main difficulties involved in reproducing in the laboratory the conditions favourable to thermonuclear reactions is that the temperature requirement is extremely high – millions of degrees – and fusion cannot be effected in a container with material walls for that would at once vaporise at such high temperatures. The problem was to a great extent solved by first converting the fusion fuel into the *plasma state.* A *plasma* is a neutral assembly of ionised atoms, molecules and electrons and could be produced in a number of ways. A high current arc constitutes a good source of plasma. Plasma is usually held in suspension in space by the lines of force of an electromagnet, the so-called *magnetic bottle.* The basic principle of this magnetic confinement of plasma is this : Moving charged particles get deflected from their straight paths by magnetic field. A high pressure hot plasma, under appropriate conditions, develops a magnetic field of its own. This field may be strong enough to exclude the external applied field. Particles would move in such a plasma in straight lines except at the boundary whence they would be deflected back. So the strong magnetic field will confine the plasma like a gas in a bottle – the *magnetic bottle.*

First, a 'cool' dilute plasma is formed by an electric discharge. The plasma is next imparted sufficient kinetic energy by passing a heavy induced current through it so that the nuclei in it overcome the coulomb repulsion. In terms of the kinetic energies of the nuclei, the temperature is then in the range of 100 million Kelvin. The chances of fusion in such a hot plasma at a given temperature are functions of the density of the particles and their confinement time. By *Lawson criterion,*

$$\text{density} \times \text{confinement time} \sim 2 \times 10^{16} \text{cm}^{-3}\,\text{s} \quad \cdots\cdots \quad \text{(DD-fusion)}$$

$$\sim 10^{14}\,\text{cm}^{-3}\,\text{s} \quad \cdots\cdots \quad \text{(DT-fusion)}$$

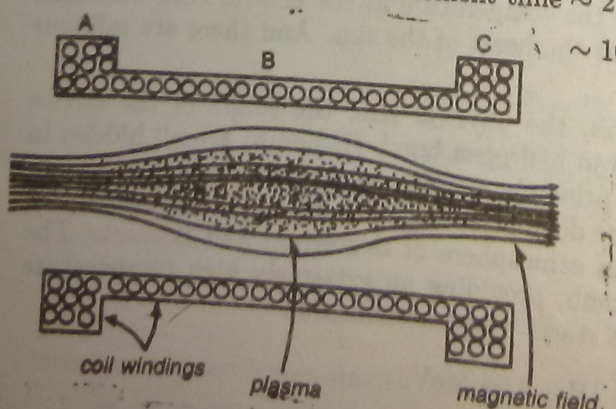

Fig.16.13 Schematic diagram of a plasma held in a magnetic bottle

An interesting feature of a magnetic bottle is that a fusion reaction sustained in it can never 'run away', unlike the chain reaction of fission process. Whenever the plasma pressure exceeds the magnetic field, the plasma moves towards the chamber wall causing rupture of the magnetic walls and this immediately quenches the fusion reaction. A fusion reaction, by its very character, can never explode.

A schematic diagram of a plasma held in a magnetic bottle is shown in Fig.16.13. *AC* is a hollow solenoid into the central region of which is injected a stream of ionised atoms.