# 14

# Nuclear Power Station

## 14.1. Overview

Nuclear energy is the usable energy extracted from atomic nuclei via controlled nuclear reactions and nuclear power plants have been used for commercial electricity generation for over half a century. In 2005, 16% of the world's electricity was generated by nuclear power and as of July 2008, there were more than 439 operating nuclear electric power plants worldwide (Source: Nuclear Energy Institute NEI). In addition, over 150 nuclear powered naval vessels have been built. A simple schematic of energy conversion in nuclear power station is shown in figure 14.1. Nuclear power plants use a variety of fuels, moderators, coolants and reactor designs all of which are very complex but the reactors themselves do not generate electricity directly. They are simply used as nuclear boilers to heat water, raising steam to drive conventional turbine generators, a crude but controllable (safe) way of harnessing nuclear energy.

Thus a nuclear power station works same as a conventional thermal power station, except for the fuel, which in this case is nuclear fuel.

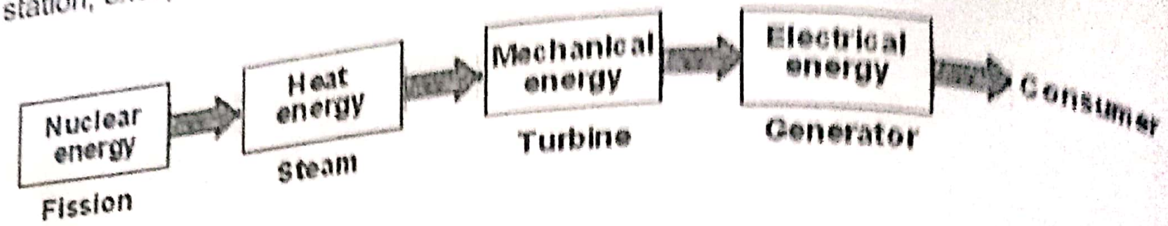


Figure 14.1: Energy Conversion in Nuclear Power Station

Commercial nuclear energy began in the 1950s, and the world's first nuclear powered electricity generating station (experimental breeder reactor EBR 1), a pilot plant generating 100 KW started in Arco, Idaho in 1953, and other countries followed. The early developments in nuclear power plants are given in table 14.1.

Table 14.1: Early Nuclear Plants

| Country | Year | Capacity (MW) |
|---|---|---|
| USSR | 1954 | 5 |
| UK | 1956 | 50 |
| France | 1956 | 5 |
| USA (Penn:) | 1957 | 90 |
| Canada | 1962 | 20 |

In 2007, the IAEA (International Atomic Energy Agency) reported there were 439 nuclear power reactors (although not all are producing electricity) in operation in the world, operating in 31 countries. However, many have now ceased operation in the wake of the Fukushima nuclear disaster while they are assessed for safety. Annual generation of nuclear power has been on a slight downward trend since 2007, decreasing 1.8% in 2009 to 2558 TWh with nuclear power meeting 13–14% of the world's electricity demand. In 2011 nuclear power provided 10% of the world's electricity. In 2011 worldwide nuclear output fell by 4.3%, the largest decline on record, on the back of sharp declines in Japan (44.3%) and Germany (23.2%). In 2013, the IAEA report that there are 437 operational nuclear power reactors in different countries worldwide.

## 14.2. The Political Issue

It seems ironic that these complex, high technology, fission and fusion energy sources are only used as heat sources to boil water with the electricity being generated by decades old steam turbine technology. Although there is agreement that new sources of clean, renewable energy are required, whether or not nuclear power is the answer, is heavily disputed with the battle being fought on two fronts, political and safety. Both proponents (pros) and critics (contras) use the same facts, to justify their claims. Differences revolve around how the facts are interpreted, the emphasis placed on what is relevant or important and how intangible benefits and drawbacks are valued. There are also unknowns, mostly about the risks involved and our ability to control them. Opponents of nuclear power point out that nuclear technology is often dual-use, and much of the same materials and knowledge used in a civilian nuclear program can be used to develop nuclear weapons. This concern is known as nuclear proliferation and is a major reactor design criterion. The military and civil purposes for nuclear energy are intertwined in most countries with nuclear capabilities. It must be remembered that the enriched uranium used in most nuclear reactors is not concentrated enough to build a bomb. Most nuclear reactors run on 4% enriched uranium. However, the technology used to enrich uranium for power generation could be used to make the highly enriched uranium needed to build a nuclear bomb. In addition, the plutonium produced in power reactors, if concentrated through reprocessing, can be used for a nuclear bomb. While the plutonium resulting from normal reactor fuelling cycles is less than ideal for weapons use because of the concentration of Pu-240, a usable weapon can be produced from it. If the reactor is operated on very short fuelling cycles, bomb-grade plutonium can be produced.

To prevent weapons proliferation, safeguards on nuclear technology were published in the Nuclear Non-Proliferation Treaty (NPT) and monitored since 1968 by the IAEA. Several states did not sign the treaty and were able to use international nuclear technology to develop nuclear weapons. Certain types of reactors are more conducive to producing nuclear weapons materials than others, and a number of international disputes over proliferation have centered on the specific model of reactor being contracted for in a country suspected of nuclear weapon ambitions. Some proponents of nuclear power agree that the risk of nuclear proliferation may be a reason to prevent non-democratic, developing nations from gaining any nuclear technology. Proponents also note that nuclear power, like some other power sources, provides steady energy at a consistent price without competing for energy resources from other countries, something that may contribute to wars.

One possible obstacle for expanding the use of nuclear power might be a limited supply of uranium ore, without which it would become necessary to build and operate breeder reactors. However, at current usage there is sufficient uranium for an extended period. In summary, the actual recoverable uranium supply is likely to be enough to last several hundred (up to 1000) years, even using standard reactors.

## 14.3. Nuclear Fuel

Nuclear fuel refers to any fuel that is consumed or used as the driving force for nuclear energy, most often generated through a fission process where the fuel's atomic elements are forcibly divided in order to produce energy. This fuel typically has to have highly fissionable elements that can absorb neutrons that bombard them in order to be easily split and allow for the harnessing the energy that is produced. Nuclear fuel can also either refer directly to the material that is directly used for the nuclear fission process or the physical objects that are developed from the base fuel and are compositions of both the base material and other elements. Uranium, the heaviest naturally occurring element, is 40 times more abundant in the earth's crust than silver and is about as common as tin or zinc. Naturally occurring uranium is 99.2745 percent uranium-238, with uranium-235 the fissile isotope used in most reactors making up only about 0.72%, and uranium-234 filling in the remainder at less than 0.0055%. The uranium fuel is normally used in its ceramic uranium oxide form which has a melting point of 2800°C and for most applications the percentage of the fissile uranium-235 is enriched to increase the probability of neutron capture thus facilitating the fission process. Using enriched uranium also allows the reactor core to be made physically smaller than the core needed for an un-enriched uranium reactor. The target percentage of U-235 used in the typical light water reactors used for electrical power generation is from 3–5% of the total uranium charge. For weapons grade uranium, however, the concentration is much higher at around 85–90%. The most common base fuels that are used in nuclear reactors are either uranium 235 or plutonium 239, both of which form the backbones of nuclear power generation in the modern era. Bombarding uranium-238 with both slow and fast neutrons produces plutonium. Plutonium is also produced by bombarding uranium with deuterons (isotope of hydrogen; containing one proton and one neutron). Huge diffusion plants like those used to enrich uranium-235 are not needed for the production of plutonium since it is produced in large quantities in breeder and other reactors and is relatively easy to separate chemically from uranium.

Uranium differs from the fossil fuels in that it must be processed both before and after it is used in a nuclear reactor. The series of steps that converts natural uranium to nuclear fuel, irradiates it in a reactor and processes the spent fuel is referred to as the nuclear fuel cycle, illustrated in figure 14.2. A thorough assessment of nuclear power benefits, drawbacks and risks requires a sound understanding of this cycle and its products and waste streams. Knowledge of this cycle is also necessary to comprehend the possible connection between nuclear power and nuclear weapons.

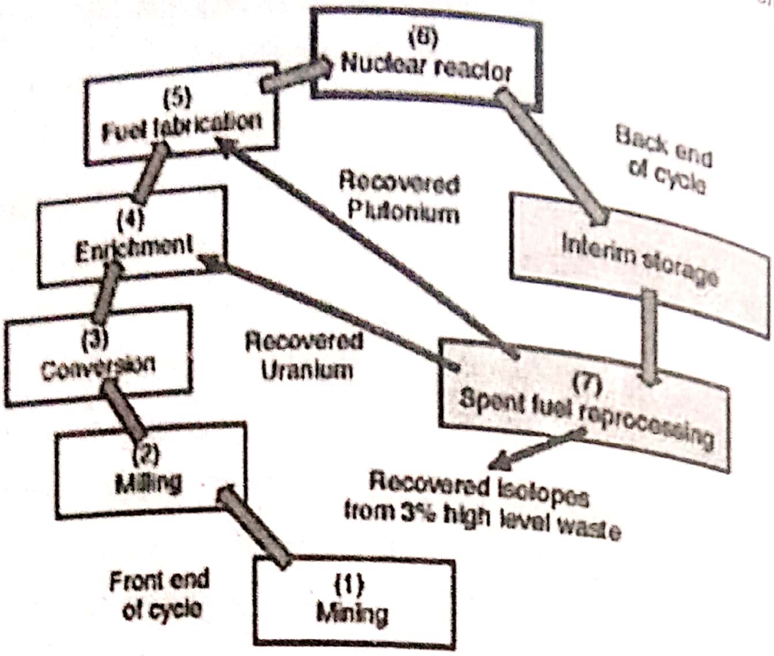
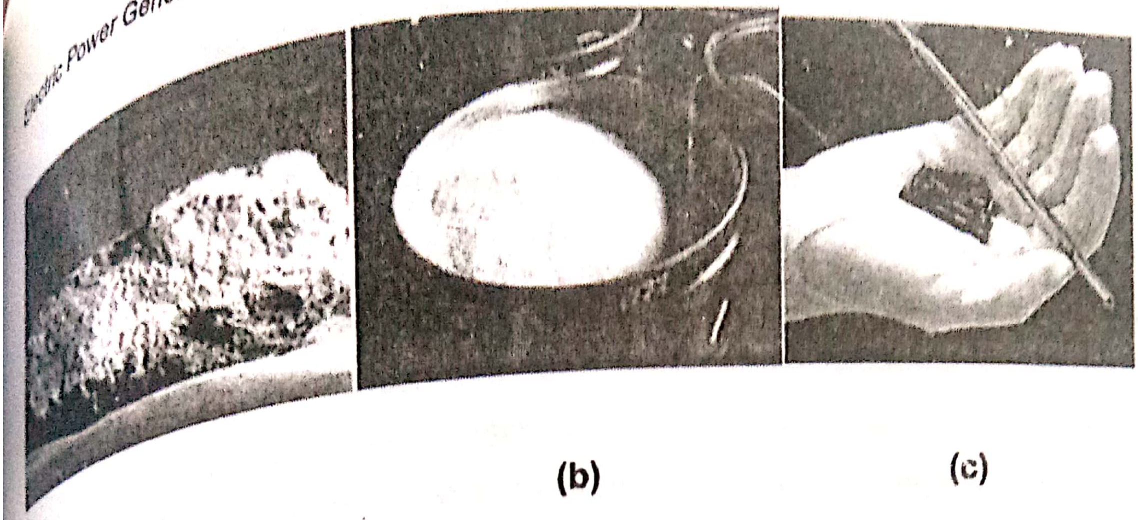


Figure 14.2: The Nuclear Fuel Cycle

### 14.3.1. Extraction of Uranium

It is estimated that the world's present measured resources of uranium are enough to last for about 100 years at current and projected consumption rates. This represents a higher level of assured resources than is normal for most minerals. Further exploration and higher prices will certainly yield further resources as present ones are used up. The initial processes take place near to where the uranium is mined. Uranium ores are crushed into small particles about 1 cm diameter and treated in a leaching process with steam, sodium chlorate and sulphuric acid to dissolve the uranium out of the rock. The resulting aqueous solution is decanted and filtered and then concentrated, first into an organic phase by treatment with various organic solvents, then further concentrated into a second aqueous phase and finally precipitated into a solid oxide form by treatment with ammonia. After filtering and drying the solid uranium oxide ($U_3O_8$) is known as yellowcake. Figure 14.3 shows the photograph of uranium ore, powdered form and pellets, which are then stacked together in suitable numbers to form fuel rods.



(a) (b) (c)

Figure 14.3: Uranium Fuel (a) Ore (b) Powder form (c) Pellets

### 14.3.2. Conversion and Enrichment

The fuel preparation usually takes place nearer to where the fuel is used. Only 14% of all reactors use natural uranium fuel, whereas 85% use enriched fuel and 1% use other fuels. The process of enrichment is to concentrate the percentage of the isotope U-235 in the fuel involving differentiating between the isotopes present in the refined material on the basis of differences in their physical properties. The separation process is thus based on the mass and size of the molecules and since these differences are minute, the processes used involve many repetitive stages to achieve appreciable separation.

Practical enrichment processes need the fuel to be in gaseous form. The 'yellowcake' must therefore be converted through a series of chemical process and steps, into uranium hexafluoride $UF_6$ that is the only compound of uranium, which exists as a gas at a suitable temperature. At atmospheric pressure $UF_6$ is a is a white, dense, crystalline solid resembling rock salt below a temperature of 57°C and transforms directly from a solid to a gas at that temperature without going through a liquid phase. Liquid $UF_6$ is formed only at temperatures greater than 64°C and at pressures greater than 1.5 times atmospheric pressure.

### 14.3.3. Gas Centrifuge

The $UF_6$ gas is rotated at extremely high speeds of 100,000 rpm or more in a centrifuge and due to the centrifugal force the heavier U-238 isotopes tend to move towards the outside increasing very slightly the concentration of the heavier isotopes at the periphery compared with a slightly higher concentration of the lighter U-235 isotopes nearer the centre. The gases are withdrawn and the heavier gases are then passed through a series of centrifuges to concentrate the proportion of U-238 while the lighter gases are recycled back to lower stages to concentrate the proportion of U-235.

### 14.3.4. Gaseous Diffusion

In the diffusion process the $UF_6$ gas is passed through a series of several hundred sets of very fine membranes. Separation depends on the lighter U-235 isotopes passing more quickly through the barriers than the larger U-238 isotopes. The holes in the membrane must be microscopic (approximately one-millionth of an inch in diameter) and uniform in size. The porosity must always be high enough to enable high flow rates and the membrane must not react with the highly corrosive hexafluoride. After the enriched uranium has been separated from the natural fuel, the percentage of fissile uranium-235 remaining in the so called depleted uranium is reduced between 0.025–0.03%. The rest is fertile uranium-238, which can be used in breeder reactors to create more fuel.

### 14.3.5. Fuel Charge Production

Once the $UF_6$ gas has been enriched the uranium must be converted into a form suitable for use in the nuclear reactor. This is generally as uranium dioxide $UO_2$ since in this metallic oxide form and is chemically stable up to temperatures over 2000°C, high enough to survive the high temperatures in the reactor core. First the gas is converted into powder of $UO_2$, and then subsequently sintered to form pellets about 10 mm in diameter and 10 mm high.

### 14.3.6. Fuel Canisters

Fuel canisters must be able to withstand high temperature working and have high mechanical strength with low neutron absorption characteristics. In large Light Water Reactors (LWR) and Pressurized Water Reactors (PWR), pellets of enriched uranium oxide arranged in rods of zircaloy an alloy of Zirconium. Early Gas Cooled Reactors (GCR) used magnesium alloy to contain the fuel but this was replaced in later reactors by stainless steel, which is able to withstand higher temperatures.

## 14.4. Nuclear Energy

Nuclear fuels are the source of immense amount of energy. For example, it would take 2 million grams of oil or 3 million grams of coal to equal the power contained in 1 gram of uranium fuel. Unlike oil and coal, nuclear fue! is recyclable and, in a breeder reactor, can actually produce more fuel than is used. For these reasons, nuclear energy is by far the best means now available to power a modern industrial economy. Nuclear power is a gift to humanity, and only the propaganda of Malthusian extremists, dedicated to stopping human progress has created public fear and skepticism. Nuclear energy cycle is schematically shown in figure 14.4. As illustrated in figure 14.4, the nuclear fuel cycle begins when uranium is mined, enriched; and manufactured into nuclear fuel, (1) which is delivered to a nuclear power plant. After usage in the power plant, the spent fuel is delivered to a reprocessing plant (2) or to a final repository (3) for geological disposition. In reprocessing 95% of spent fuel can be recycled to be returned to usage in a power plant (4). Nuclear energy is produced by atomic fission in which a large atom (usually uranium or plutonium) breaks into two smaller ones, releasing energy and neutrons. In the process of fission, the neutrons then trigger further break-ups, and so on forming a chain reaction. If this chain reaction can be controlled, the energy released can be used to boil water, produce steam and drive a turbine that generates electricity. If it runs away, the result is a meltdown and an accident or, in extreme circumstances, a nuclear explosion; though circumstances are never that extreme in a reactor because the fuel is less fissile than the material in a nuclear bomb.

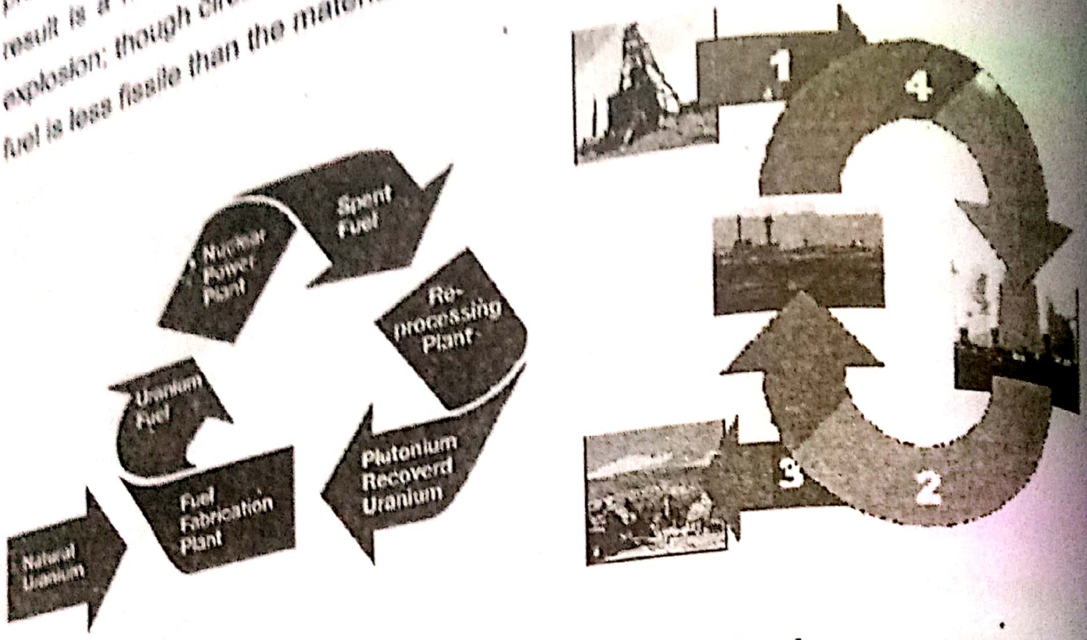


Figure 14.4: The Nuclear Energy Cycle

## 14.4. Fission Reaction (Nuclear Fission)

The process of bombarding radioactive nuclei by high energy neutrons producing a large amount of energy is referred to as fission reaction or nuclear fission. In a nuclear fission the bombarded nuclei splits into several smaller fragments known as fission products. These fragments, or fission products, are about equal to half the original mass. Two or three neutrons are also emitted. The sum of the masses of these fragments, however, is less than the mass of the original radioactive element. This 'missing' mass (about 0.1 percent of the original mass) is converted into tremendous amount of energy according to Einstein's equation; ($E = mc^2$). Fission can occur when a nucleus of a heavy atom captures a neutron, or it can happen spontaneously.

Fission reaction requires a fissile material and a neutron source. Fissile materials are those fissionable materials, which are capable of sustaining a chain reaction when bombardment by neutrons with low kinetic energy (slow or thermal neutrons). Fissionable materials are those whose atoms can undergo induced nuclear fission when bombarded by a free neutron. The three most important fissile materials which can be obtained in large enough useful quantities are uranium-233 and uranium-235 (both dense soft silvery metals), and plutonium-239, also a dense silvery white metal. Fertile materials need a fast moving neutron to initiate fission while fissile materials need a slow moving neutron for fission. Fertile materials are isotopes, which are capable of becoming fissile by capturing fast moving neutrons possibly followed by radioactive decay. Examples are uranium-238, plutonium-240 and thorium-232. Fissionable materials are not necessarily fissile. Thus, although uranium-238 is fissionable, it is fertile but not fissile.

Nuclear fission is initiated by bombarding the nuclei of large unstable atoms with neutrons, which cause nuclei to split into fragments; releasing more neutrons. Nuclear fission occurs when a neutron collides with a nucleus of a large atom such as uranium and is absorbed into it causing the nucleus to become unstable and thus split into two smaller more stable atoms with the release of more neutrons and a considerable energy amounting to 200 MeV as illustrated in figure 14.5. The process can be represented by the following equation:

$$^{235}U_{92} + {}^{1}n_{0} = {}^{140}Ba_{56} + {}^{96}Kr_{36} + 3\,({}^{1}n_{0}) + 200\ \text{MeV}$$

These neutrons released by the fission process can go on to split further atoms thus releasing even more neutrons. If the number of fissile atoms is small, as in a low mass sample, or if they are widely dispersed, as in an impure sample, most of the neutrons released by the initial fission will not encounter more fissile atoms. They will lose their energy by collision with other atoms and molecules and the reaction will eventually die out.

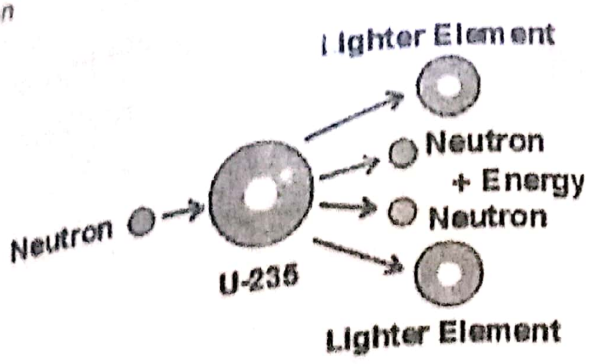


Figure 14.5: Fission of Uranium

Nuclear fission that can occur naturally with the spontaneous decay of radioactive material or initiated by bombarding the fuel consisting of fissionable atoms with neutrons will produce further neutrons. Neutrons, which are electrically neutral, are used as the 'bullets' to initiate the fission rather than protons because, with a positive charge, the protons would be strongly repelled by the positively charged nucleus. If, however, there is a large mass of more concentrated fuel, a larger number of neutrons will impinge on more fissile atoms triggering yet more fissions in a chain of events creating more neutrons as each neutron is absorbed, leading to a chain reaction. The reaction thus becomes self-sustaining and the mass at which the chain reaction just becomes possible is called the critical mass. The chain reaction is illustrated in figure 14.6. In practical terms the effective critical mass depends on many other attributes, such as the degree of enrichment of the fuel, its shape, temperature, density, and whether it is contained within a neutron-reflective substance. The minimum critical mass of uranium-235 is a 52 kg in the form of a sphere 17 cm in diameter. For plutonium-239 the corresponding figures are 10 kg in a sphere of 9.9 cm diameter. Taking into account the degree of dilution of the desired isotope in the fuel bulk, the critical mass of uranium-235 enriched to 20% will be 400 kg rising exponentially as the enrichment is decreased further.

In many new designs the neutrons, and thus the chain reaction, are kept under control by passing them through water to slow them down. (Slow neutrons trigger more break ups than fast ones). This water is exposed to a pressure of about 150 atmospheres; a pressure that means it remains liquid even at high temperatures. When nuclear reactions warm the water, its density drops, and the neutrons passing through it are no longer slowed enough to trigger further reactions. That negative feedback stabilizes the reaction rate.

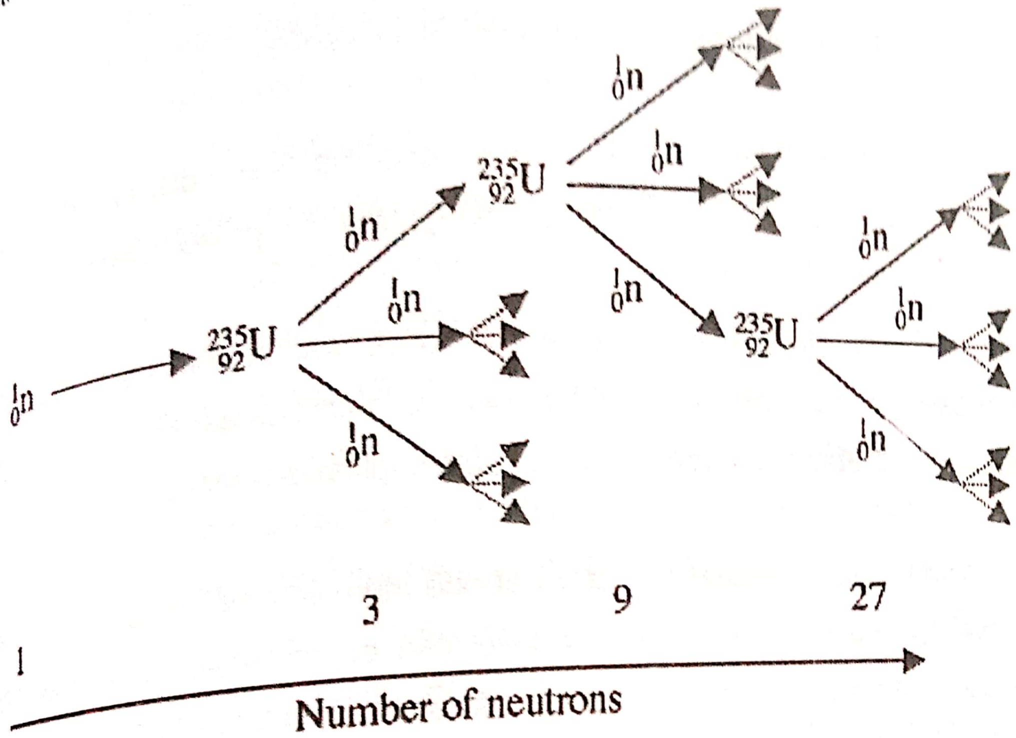


Figure 14.6: The Chain Reaction

Once a critical mass of fuel has been assembled, the population and energy of the neutrons must be controlled to prevent the possibility of a runaway action with disastrous consequences, while at the same time maintaining the chain reaction. This is the function of the control rods whose purpose is to remove excess neutrons from the reactor core and the chain reaction is thereby controlled. The control of the chain reaction can be understood by incorporating a *K*-factor. *K* is the effective multiplication factor and is defined as the ratio of the number of neutrons produced by fission in one generation to the number in the preceding generation. *K* thus refers to the conditions of the population of neutrons within the reactor core. This is not the same as the average number of neutrons created by the fission reaction ($K = 2.4$ in the case of uranium-235) since some neutrons are absorbed in non-fission reactions and others escape from the system without being absorbed. The way in which a fission chain reaction proceeds depends on the value of $K$.

**Sub-criticality ($K < 1$):** The system cannot sustain a chain reaction. External neutrons may start a reaction but it dies out fairly rapidly.

**Criticality ($K = 1$):** Every fission cause on average one more and the reaction continues at steady rate. This is the operating state of a power reactor.

**Super-criticality ($K > 1$):** With a very high concentration of fissile material, each fission cause $K$ more fission and the number of neutrons escalates exponentially in an uncontrollable chain reaction a possible explosive release of energy.

The energy released by fission of one atom of uranium-235 is 200 MeV. The energy released at the atomic level can be calculated from the binding energies of the parent and daughter atoms as shown in table 14.2.

**Table 14.2: Binding Energies Change with Fission**

| Atom | Nucleons | Binding Energy per Nucleon (MeV) | Binding Energy per Nucleon (MeV) | Combined Binding Energy (MeV) | Released Fission Energy (MeV) |
|---|---|---|---|---|---|
| U-235 | 235 | 7.6 | 1786 | 1786 | 166.3 |
| Ba-141 | 141 | 8.3 | 1170.3 | 1952.3 | 166.3 |
| Kr-92 | 92 | 8.5 | 782 | 1952.3 | 166.3 |
| Other Fission Products (particles and radiations) | | | | | 33.7 |

From table 14.2 it can be noted that uranium-235 nuclide has a binding energy of about 1786 MeV. The total binding energy of the nuclides of barium and krypton, which remain after fission, amounts to about 1952 MeV. The difference of 166.3 MeV corresponds to the energy released in the fission process. In addition there will also be several small energy releases totaling about 33.7 MeV associated with ejection of the neutrons and other particles as well as beta and gamma radiation. Thus the total energy released by the fission of one atom of uranium-235 is about 200 MeV ($3.2 \times 10^{-11}$ Joules).

When the reactor is loaded with new fuel rods there are no free neutrons (theoretically) to initiate the reaction, even if there is a critical mass of fuel. The radioactive decay of the uranium isotopes used emits only ionization particles but not neutrons. A neutron source is therefore needed to get the reaction going. Suitable neutron trigger sources are alpha particle emitters, such as americium-241, polonium-210 or radium bromide, mixed with a lightweight isotope such as beryllium-9. Alpha particles from the decay cause the beryllium to transmute into carbon-12 releasing neutrons. Once the chain reaction begins, the starter source is removed from the core to prevent damage from the subsequent hostile conditions in the reactor core. Immense amount of energy is produced as a result of fission. Most of this energy appears as heat, which is used to raise steam. The majority of fission reactors are designed to capture the energy released by the fission of uranium-235 in a controlled chain reaction. Though neutrons produced by previous fissions initiate fissions, the process is not spontaneous. The energy released from practical amounts of fuel can be calculated.

**Example 14.1:** Calculate the amount of electrical energy that can be obtained from the fission of 1 kg of uranium-235 in a nuclear power station. Assume overall efficiency of the system to be 40%.

One atom of uranium-235 weighs 235 amu, equals $3.9 \times 10^{-25}$ kg. Therefore, 1 kilogram of uranium 235 contains 1/235amu atoms, which are:

$$\text{Number of atoms} = \frac{1}{3.9\times10^{-25}} = 2.56 \times 10^{24} \text{ atoms.}$$

The energy released from 1 kilogram of fuel is therefore calculated by considering that the energy resulting from fission of one uranium atom is 200 MeV or $200 \times 10^6 \times 1.6 \times 10^{-19} = 3.2 \times 10^{-11}$ Joules. Therefore energy $E$ obtainable from 1 kilogram of uranium containing $2.56 \times 10^{24}$ atoms is

$$E=(2.56\times10^{24})\times3.2\times10^{-11}=\mathbf{8.2\times10^{13}\ Joules}$$

or

$$E=\mathbf{22.77\ GWh}$$

Estimate shows that one ton of natural or slightly enriched uranium can produce 10,000 MW-days of heat energy; this equals 240 GWh. On the average, when 1 lb of U-235 fissions, 0.00091 lb of its mass converts to energy. This energy is then equals to: 11.3 x $10^9$ x 0.00091 = 10.3 x $10^6$ kWh per lb of U-235. Then at 240 x $10^6$ kWh per ton only $\frac{240\times10^6}{10.3\times10^6}$ = 23.3 lb of uranium per ton fission. In other words, this is a burn-up of only $\frac{23.3}{2000}\times100$=1.2% of the total fissionable and fertile material. A 1% burn-up seems wasteful of uranium, but this will probably increase over the years. By comparison, the fission of one atom of uranium produces 10 million times the energy produced by the combustion of one atom of carbon from coal.

**Example 14.2:** A nuclear power station can deliver 500 MW at full load. If due to fission of each atom of U-235 the energy released is 200 MeV, calculate the mass of uranium fissioned per hour.

Given that:

Plant capacity: $P_g$ = 500 MW

Energy that can be delivered from the power station at full load is:

$$E_g=500\times10^6\times3600=1.8\times10^{12}\text{ Joules}$$

The amount of energy produced per fission is:

$$E=200\times10^6\times1.6\times10^{-19}=3.2\times10^{-11}\text{ Joules}$$

Therefore number of uranium atom fissioned (*N*) is calculated as:

$$N=\frac{E_g}{E}=\frac{1.8\times10^{12}}{3.2\times10^{-11}}=5.625\times10^{22}\text{ atoms}$$

1 gm-atom that is 235 gms of uranium has 6.022 x $10^{23}$ atoms. Therefore the mass of uranium $m$ required for fission is calculated as:

$$m=\frac{235}{6.022\times10^{23}}\times5.625\times10^{22}=\mathbf{21.95\ grams\ or\ 0.022\ kg}$$

**Example 14.3:** A nuclear power station uses 2 kg of U-235 as fuel each month at a conversion efficiency of 33%. Calculate the full load power that can be obtained from the power station if the generator efficiency is 92%.

Given that: Mass of uranium used: $m$ = 2 kg = 2000 grams

Conversion efficiency: $\eta$ = 33% or 0.33

Generator efficiency: $\eta_g$ = 92% or 0.92

The energy produced by fission of 1 atom of U-235 amounts to 200 MeV and there are 6.022 x $10^{23}$ atoms in 1 mole (235 grams) of uranium. The number of atoms of uranium required each month for fission is:

$$N=\frac{m}{235}\times 6.022\times 10^{23}=\frac{2000}{235}\times 6.022\times 10^{23} = 5.125 \times 10^{24} \text{ atoms}$$

The number of atoms (n) fissioned per second will be:

$$n=\frac{5.125\times 10^{24}}{30\times 24\times 3600} = 1.977 \times 10^{18} \text{ atoms}$$

The energy produced per second will is the power output of the reactor $P_0$ and is calculated on the basis of conversion efficiency as:

$$P_0 = 0.33\times 3.2\times 10^{-11}\times 1.977\times 10^{18} = 20.88 \times 10^{6} \text{ Watts}$$

The electrical power output will then be:

$$P_g = \eta_g \times P_0 = 0.92\times 20.88\times 10^{6} = \mathbf{19.2 \times 10^{6}\ W\ or\ 19.2\ MW}$$

### 14.5. The Fusion Reaction (Nuclear Fusion)

Nuclear fusion is the process by which the nuclei two light atoms combine to form a single, bigger nucleus of a new atom releasing large amounts of energy as a consequence. For example two hydrogen atoms fused to form helium is the fusion of hydrogen and is illustrated in figure 14.7.

$$\mathbf{{}^{2}H_{1} + {}^{3}H_{1} = {}^{4}He_{2} + {}^{1}n_{0} + 17.6\ MeV}$$

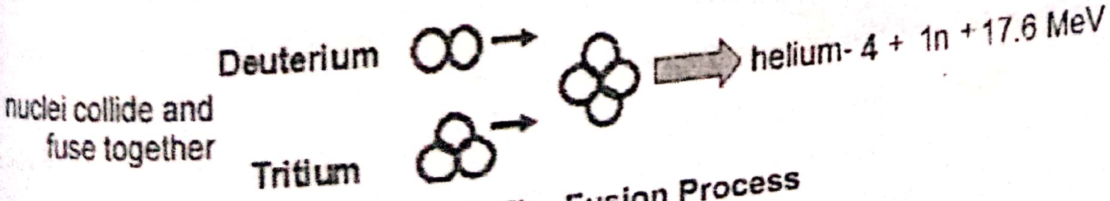


Figure 14.7: The Fusion Process

Fusing two light nuclei can liberate almost as much energy as the fission of uranium-235 or plutonium-239. Ideal fuels are the lightest elements and fusion has been attempted using deuterium and tritium, gaseous isotopes of hydrogen, amongst others. Nuclear fusion is the process by which the sun generates its extraordinary energy providing us with the warmth and light we receive. The great attractions of nuclear fusion as an energy source are that the fuel, mostly isotopes of hydrogen, is plentiful and easy to obtain, and the elements produced as a result of the fusion are usually light and stable atoms rather than the heavy radioactive products which result from nuclear fission. The potential release of energy per unit mass of the fuel is much higher in the case of fusion than in fission since reactions allowing greater increases in binding energy are possible with fusion reactions. There are actually four possible fusion reactions, which could take place in a reactor fuelled by deuterium only.

$$^{2}H_{1} + {}^{2}H_{1} = {}^{3}He_{2} + {}^{1}n_{0} + 3.3\ \text{MeV}$$
$$^{2}H_{1} + {}^{2}H_{1} = {}^{3}H_{1} + {}^{1}H_{1} + 4.0\ \text{MeV}$$
$$^{2}H_{1} + {}^{3}H_{1} = {}^{4}He_{2} + {}^{1}n_{0} + 17.6\ \text{MeV}$$
$$^{2}H_{1} + {}^{3}He_{2} = {}^{4}He_{2} + {}^{1}H_{1} + 18.6\ \text{MeV}$$

Unfortunately immense amount of energy is needed to create the conditions for self-sustaining fusion to take place and in practice there are serious technical problems to overcome in order to achieve a net energy gain. The energy released at the atomic level by the fusion of deuterium and tritium can be calculated from the binding energies of the parent and daughter atoms as shown in table 14.3. Table 14.3 shows that the combined binding energy of the deuterium and tritium atoms of 10.7 MeV increases to 28.3 MeV when the atoms fuse into helium releasing energy of 17.6 MeV, equivalent to $2.8 \times 10^{-12}$ Joules. Note that 80% of the released energy is carried by the neutron with the helium alpha particle accounting for only 20%. The actual energy delivered by fusion from the various experimental reactors rarely approaches the amount of energy used to create the fusion reaction with the very best just breaking even. The fusion conversion gain or quality factor $Q_F$ is defined as the ratio of the energy delivered by the fusion process and the energy used to create and sustain the fusion. Sometimes the ratio is defined in terms of power rather than energy. Unless $Q_F > 1$ (break even) there will be no surplus usable energy.

**Table 14.3: Binding Energies Change with Fusion**

| Atom | Nucleons | Binding Energy per Nucleon (MeV) | Binding Energy per Nucleon (MeV) | Combined Binding Energy (MeV) | Released Fusion Energy (MeV) |
|---|---|---|---|---|---|
| H-2 | 2 | 1.11 | 2.22 | 10.7 | 3.5 |
| H-3 | 3 | 2.83 | 8.48 | 10.7 | 3.5 |
| He-4 | 4 | 7.1 | 28.3 | 28.3 | 3.5 |
| Neutron | 1 | 0 | 0 | 0 | 14.1 |

**Example 14.4:** Calculate the possible electrical energy that can be produced from the fusion of 1 kg of deuterium with 1.5 kg of tritium. Assume overall efficiency of the plant to be 40%.

The atomic mass of the deuterium nuclide is 2 amu = $3.32 \times 10^{-27}$kg

1 kg of deuterium therefore contains 1kg/2 amu = $3.01 \times 10^{26}$ atoms.

The atomic mass of the tritium nuclide = 3 amu

Hence 1.5 kg of tritium = $3.01 \times 10^{26}$ atoms.

The energy released by fusion of 1 atom of deuterium with 1 atom of tritium is 17.6 MeV = $2.8 \times 10^{-12}$ Joules. The energy liberated by the fusion of 1 kg of deuterium with 1.5 kg of tritium is:

$$= (2.8 \times 10^{-12}) \times (3.01 \times 10^{26})$$

$$= 8.42 \times 10^{14} \text{ Joules}$$

$$= (8.42 \times 10^{14}) / (3.6 \times 10^{12}) \text{ Watt-hours} = \mathbf{234\ GWh.}$$

This energy appears in the form of heat. If it were used to generate electricity in a conventional steam turbine power plant with an efficiency of 38%, it would provide 88,920 MWh of electricity, which is near enough equivalent to one year's full-load operation with a constant output power of 10 MW. It must be noted that the 234 GWh released by the fusion of the above fuel compares with 22.77 GWh of energy released by the fission of 1 kg of U-235 in example 14.1.

However, the surplus energy appears in the form of heat there will be a further conversion loss involved in generating electricity from the heat. This means that only 35–45% of this surplus energy can be extracted as electricity reflecting the efficiency of steam turbine generating plants. The first stage is extract energy from the fusion process. Up to now, no fusion reactors have produced significant power with a conversion gain better than unity.

## 14.6. The Nuclear Reactor

Reactor is a component of nuclear power plant where nuclear reaction takes place to produce energy. The only nuclear plants producing nuclear power commercially use fission reactions. Attempts to generate power by fusion reactions have so far not produced commercial success. Nuclear reactors are basically heat engines. All utility scale nuclear power plants simply use the reactor as a 'nuclear boiler' to raise the steam which is then used to drive conventional steam turbine powered generators using the Rankine steam cycle in much the same way as in fossil fuel plants with much of the same equipment. Instead of burning fossil fuels to provide the heat source to the boiler, heat is generated in a nuclear reactor by the controlled nuclear fission of unstable isotopes of radioactive elements such as uranium. As uranium fissions, the breaking apart of atoms releases energy, much of it in the form of heat, which can then be used to do work. Reactors thus perform the function of furnace in conventional thermal power plant. A nuclear reactor produces and controls the release of energy from splitting the atoms of certain elements. The essentials of a reactor and nuclear power plant are described in figure 14.8. The energy released from continuous fission of the atoms of the fuel is harnessed as heat in either a gas or water, and is used to produce steam. The steam is used to drive the turbines which produce electricity (as in most fossil fuel plants).

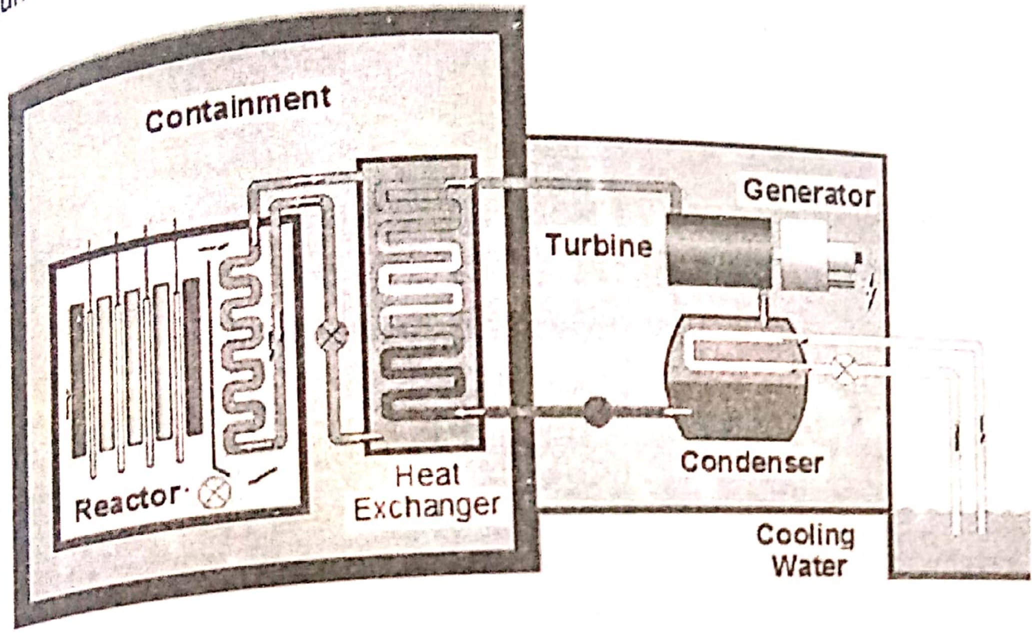


Figure 14.8: Nuclear Power Plant

Reactors are of two types; depending on whether a moderator is used or not, these are:

1. Reactors with moderators, known as thermal reactors in which the speed of neutrons is controlled.
2. Reactors without moderators, termed as Fast Neutron Reactors in which the speed of the neutrons is not controlled.

Reactors can also be classified as:

1. A nuclear power reactor, in which the energy released, is used as heat to produce superheated steam to generate electricity.
2. A research reactor, the main purpose of which is to utilize the actual neutrons produced in the core.
3. A marine or naval reactor, which produce steam that drives a turbine directly for propulsion.

The type of reactor will of course depend on the type of fuel, moderator and the coolant used. Types of reactors are discussed later in this chapter. The principles for using nuclear power to produce electricity are, however, the same for most types of reactors. The various components of a reactor, with their distinct function are described as follows:

### 14.6.1. The Reactor Core

At the centre of the reactor is the core where the nuclear reaction takes place. Figure 14.9 shows a simplified diagram of reactor core. The reactor core contains the fissile material (uranium and plutonium) in the form of long fuel rods, which are usually placed vertically in the core.

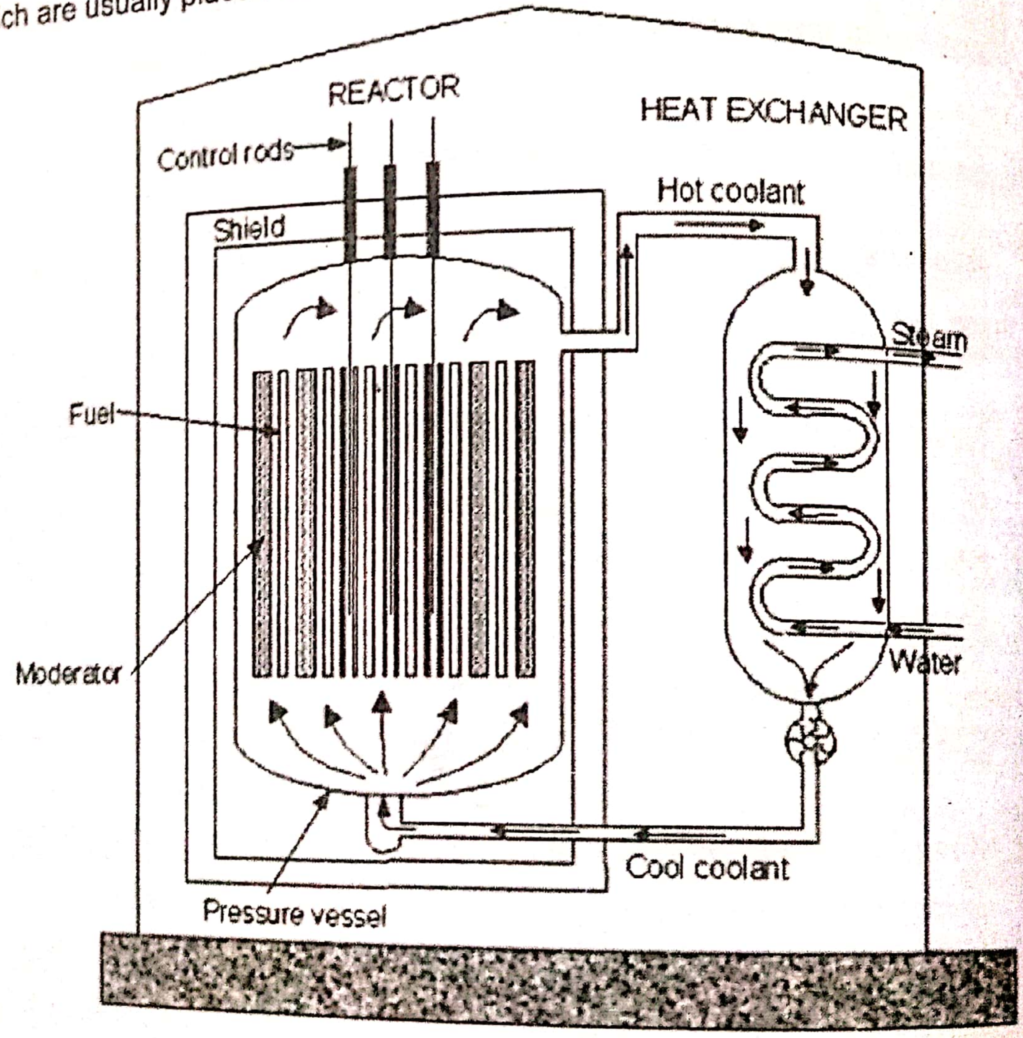


Figure 14.9: The Reactor Core

Inside the fuel rods, the fuel pellets are stacked very carefully. One atom in one pellet is disturbed when the power plant is online, and it starts a chain reaction heating up the core. There are three different types of uranium used in nuclear power production. These are radioactive U-235, U-238 and U-234. Of these, U-234 and U-238 are the two major forms of uranium in the fuel. The reactor core assembly is contained in a pressure vessel located in a pool of coolant medium. The top of the pressure vessel is below the pool surface. The control plate drive mechanisms are located in a sub-pile room beneath the pressure vessel. These features provide the necessary shielding for working above the reactor core and greatly facilitate access to the pressure vessel, core, and reflector regions. The pressure vessel usually made from steel, contains the reactor core, the control rods and the surrounding moderator and coolant.

### 14.6.2. Containment Building

Reactors containment generally consists of a huge reinforced concrete casing often incorporating a steel inner structure which acts as a radiation shield and is designed to prevent the release of radioactivity into the environment in case of an accident in the reactor as well as to protect the reactor from external events such as earthquakes, aircraft impacts and deliberate acts of sabotage. A typical containment for nuclear reactors is shown in figure 14.10. The meltdown of the Chernobyl nuclear reactor in 1986 was initiated by inadequate safety systems. Since the reactor was not enclosed in containment building, vast areas of the countryside were contaminated with deadly radioactive debris. In the 1979 accident at Three Mile Island due to partial meltdown, reactor core, was destroyed when the cooling system failed due to the loss of coolant, the radioactive debris were still contained within the containment building.

The containment system is the same as what is used to store the liquid metal sodium. The uranium is stored at a very controlled temperature. As soon as the plutonium is produced, it is separated and put into a containment system until it is needed. The uranium that has already produced as much plutonium as it can is put in a separate containment plant. When it is needed, it is packed into the fuel pellets with plutonium that it may or may not have created. The reactor breeds its fuel by just letting it housed in a containment plant.

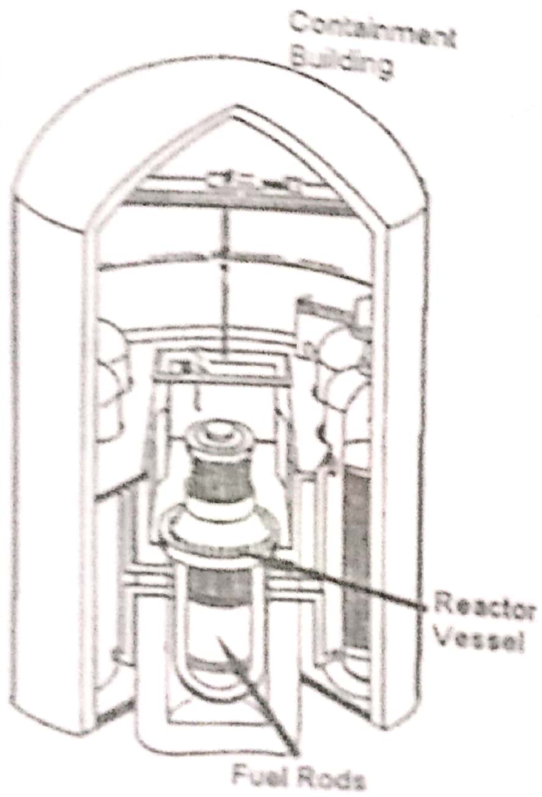


**Figure 14.10: Containment Building**

### 14.6.3. Coolant

In a reactor, there is something called a coolant. It has two purposes. It prevents the reactor from melting and it is what turns the turbine. Cooling is a major challenge in reactor design. Heat is extracted from the reactor core by one or more tightly controlled, closed, heat transfer circuits and used to power a conventional steam or gas turbine generator. Many variations are possible. The reactor core acts as a heat exchanger in which the coolant, which may be either a liquid or a gas, surrounds the fuel rods and captures the heat generated by the nuclear reaction. The coolant also acts as the thermal working fluid which is used either directly or indirectly to raise steam to drive a turbine generator. Coolants must be good conductors of heat with low susceptibility to induced radioactivity and capable of operating at high temperatures. A variety of substances, including light water, heavy water, air, carbon dioxide, helium, molten metals such as sodium, sodium-potassium alloy, lead and lead-bismuth alloy as well as hydrocarbons (oils), have been used for this purpose.

### 14.6.4. Control Rods

Every reactor needs a set of control rods. The control rods are made of materials that quickly stop the nuclear reaction by absorbing the neutrons. These are made of a mixture of materials that are very strong and can take a large amount of heat. They are placed inside of the fuel rods and functions in the same manner as moderators. They are meant to stop the chain reaction of atoms inside of the fuel rods, which, in turn, stops the plant and are used to regulate the distribution of power in the reactor while the reactor is operating. An automatic control system, or the operator, can initiate the shutdown. In some reactors, all rods may insert in as short a time as few seconds. Materials used include boron carbide, silver, indium, cadmium, and hafnium. They are also able to stop the coolant from flowing. An image of control rod assembly in a nuclear reactor is shown in figure 14.11.

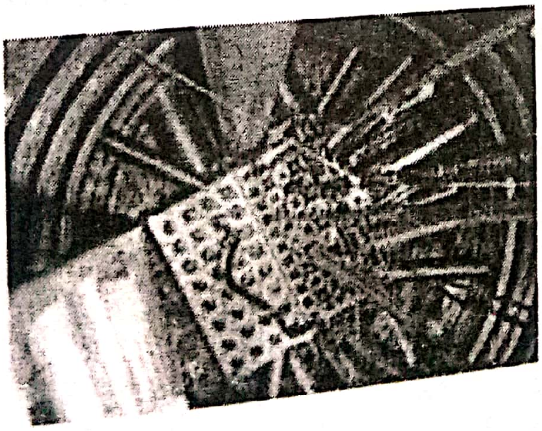


**Figure 14.11: Control Rod Assembly (Source: Wikipedia)**

A major safety system in nuclear reactors is provided by control rods of boron, cadmium or graphite, which absorb neutrons created by the fission process removing them from the active mass thus preventing further fissions from taking place. Because of their atomic structure these elements absorb neutrons, but do not fission or split. The rate of the chain reaction can be controlled by progressively inserting the control rods into, or dropping the control rods into the core thus absorbing neutrons, which can then quickly shut down the reactor.

### 14.6.5. Moderators

The energy of the free neutrons must be within certain limits for fission to occur. High energy neutrons emitted by the fission process move too quickly to be captured by the fissile atoms and so must be slowed down or moderated to increase their chances of causing fission. Water, heavy water and graphite are moderators, which are commonly used in the reactor core to slow down the neutrons. Certain hydrides, hydrocarbons, beryllium and beryllium oxide are also used for this purpose. It must also be noted that some moderators can also act as coolants.

## 14.7. Pressurized Water Reactor (PWR)

A typical pressurized water reactor is shown in figure 14.12 and is the most commonly used reactor in nuclear industry. Pressurized water reactors are also known as WER reactors in Russia that means water-moderated and cooled. The design of PWR originated initially for use as a submarine power plant with over 230 in use for power generation and several hundred more employed for ship propulsion. The design is distinguished by having a primary cooling circuit and a secondary circuit. It mainly consists of a reactor core containing fuel elements and control rods. Water is used as a coolant and is allowed to circulate in a primary water circuit (cooling water loop) by means of a pump.

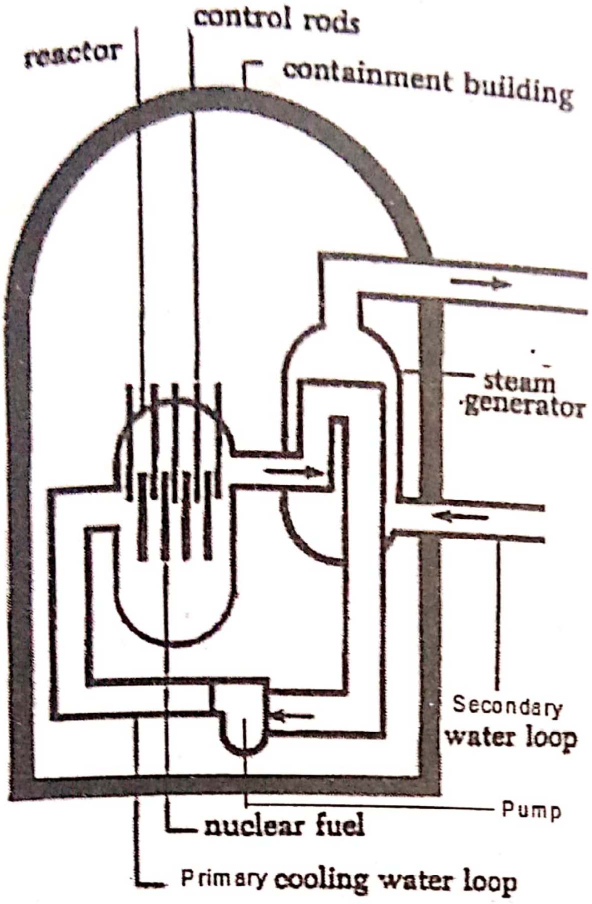


**Figure 14.12: Pressurized Water Reactor**

Water in the reactor core reaches about 325°C; hence, it must be kept under about 150 times atmospheric pressure (maintained by steam in a pressurizer); typically 1000-2200 psi (7-15 MPa) to prevent it from boiling. If any of it were converted to steam, the fission reaction would slow down. This negative feedback effect is one of the safety features of PWR. The secondary circuit is under less pressure and the water boils in the heat exchangers, which are thus steam generators. A steam generator takes heat energy generated by nuclear fission of fuel. The water to the steam generator is supplied by the secondary water loop, which provides feed water to the steam generator. The entire assembly of reactor core and steam generator is enclosed in a containment building. While the secondary circuit works under less pressure and the water generate steam by boiling in the heat exchangers or steam generator, which produces the steam in the turbine circuit based on the Rankine cycle. After this processing, the condensed steam returns to the heat exchangers which attach with the primary circuit. Typical output power is 1000 MW with a system efficiency of 33%. The steam turns the turbine to generate electricity. PWR reactors use a two-stage heat transfer system with ordinary (light) water acting as both a moderator and the coolant in the primary circuit. The secondary shutdown system involves adding boron to the primary circuit.

Over 60% of all installed commercial reactors are pressurized water reactors and like 85% of all reactors they use enriched uranium as the fuel. The use of enriched fuel means that a higher power density is achievable in the core and thus better efficiency. A typical PWR has fuel assemblies of 200-300 rods each, arranged vertically in the core, and a large reactor would have about 150-250 fuel assemblies containing 80-100 tones of uranium.

### 14.8. Boiling Water Reactor (BWR)

Boiling water reactors have many similarities to the pressurized water reactor and are used in over 20% of nuclear power installations. A schematic diagram of a boiling water reactor is shown in figure 14.13. It consists of a reactor containing nuclear fuel and control rods. The water circuit admits water into the reactor core by means of a pump. The entire assembly is enclosed in a containment building. The design of boiling water reactors (BWR) is similar to that of the PWR, except that there is only a single circuit in which the water is at lower pressure (about 75 times atmospheric pressure) so that it boils in the core at about 285°C. The reactor is designed to operate with 12-15% of the water in the top part of the core in steam form, equipping the reactor with less moderating effect. The nuclear reaction produces heat that boils the water admitted into the reactor, thus generating steam. A steam-water mixture is produced when very pure water (reactor coolant) moves upward through the core absorbing heat. The steam-water mixture leaves the top of the core and enters the two stages of moisture separation where water droplets are removed before the steam is allowed to enter the steam line. The steam line directs the steam to pass through drier plates (steam separators) above the core, which are thus part of the reactor circuit. The steam is then directed to the turbine system, which couples the generator to produce electricity. Since the water around the core of a reactor is always contaminated with traces of radionuclides, the turbine must be shielded and radiological protection provided during maintenance. The unused steam is exhausted to the condenser where it is condensed into water. The resulting water is pumped out of the condenser with a series of pumps, reheated, and pumped back to the reactor vessel. The reactor's core contains fuel assemblies, which are cooled by water, which is force-circulated by electrically powered pumps. The coolant used is ordinary light water, which acts both as the moderator and a coolant but in a single stage heat transfer circuit. Because of the low steam pressure and temperature the efficiency of the system is also low about 33%. Typical output powers are up to 1400 MW.

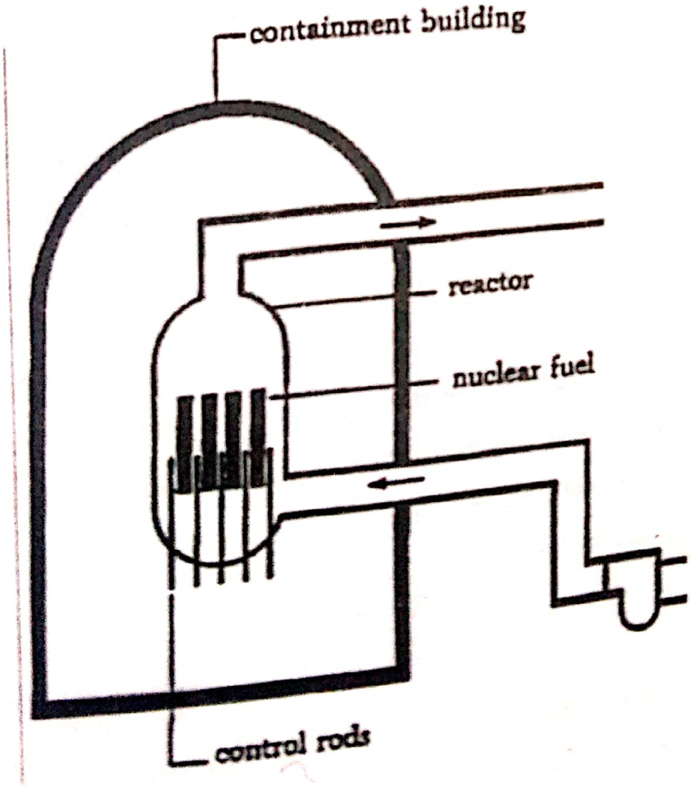


Figure 14.13: Boiling Water Reactor

BWR use enriched uranium as fuel. A typical fuel assembly in today comprises 90-100 fuel rods, and there are up to 750 assemblies in a reactor core, holding up to 140 tones of uranium. The secondary control system involves restricting water flow through the core so that more steam in the top part reduces moderation. Emergency cooling water is supplied by other pumps, which can be powered by onsite diesel generators. Other safety systems, such as the containment cooling system, also need electric power. The cost of this tends to balance the savings due to the simpler design. Most of the radioactivity in the water is very short-lived, so the turbine hall can be entered soon after the reactor is shut down.

## 14.11. Canadian Deuterium Uranium (CANDU) Reactor

This is also called PHWR (pressurized heavy water reactor) whose design has been developed since the 1950s in Canada and hence named as the CANDU (CANada Deuterium Uranium). Figure 14.14 is a schematic diagram of a CANDU reactor. The moderator is in a large tank called a calandria, which is penetrated by several hundred horizontal pressure tubes that form channels for the fuel, cooled by a flow of heavy water under high pressure in the primary cooling circuit, reaching a temperature of 290°C. Heavy water has an advantage of absorbing fewer neutrons and therefore can sustain the chain reaction with un-enriched fuel. It uses a two-stage heat transfer system similar to the PWR. As in the PWR, the primary coolant generates steam in a secondary circuit to drive the turbines. In CANDU reactor, the primary cooling circuit uses heavy water under high pressure as both the coolant and the moderator. Efficiencies of 33% are typical but systems using very high coolant pressures can take this to 45% or more.

CANDU reactors use un-enriched natural uranium oxide fuel. It uses natural uranium oxide (0.7% U-235) as fuel, thus requiring a more efficient moderator, in this case heavy water (deuterium oxide, $D_2O$). A typical CANDU fuel assembly consists of a bundle of 37 half-meter-long fuel rods (ceramic fuel pellets in zircaloy tubes) along with a support structure, with 12 bundles lying end to end in a fuel channel. Control rods penetrate the calandria vertically, and a secondary shutdown system involves adding gadolinium (Gd) to the moderator. The heavy water moderator circulating through the body of the calandria vessel also yields some heat. The pressure tube is designed so that the reactor can be refuelled progressively without shutting down, by isolating individual pressure tubes from the cooling circuit.

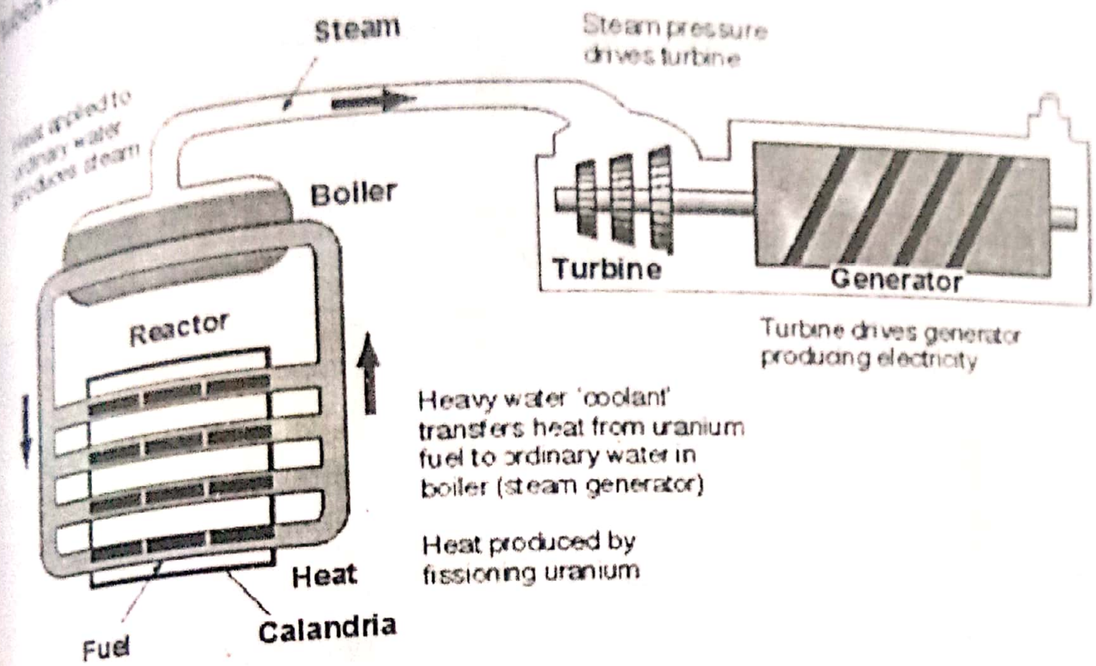


Figure 14.14: Schematic of CANDU Reactor

## 14.9. Gas Cooled Reactor (GCR)

The schematic diagram of a gas cooled reactor is shown in figure 14 15. Gas cooled reactors use a double loop cooling system with the gas coolant in the primary circuit and steam in the secondary turbine circuit. Gases, which are suitable or use in the primary cooling circuit unfortunately do not provide the capability for slowing down the free neutrons in the core and a separate material must be used to moderate the speed of the neutrons. Graphite is typically used as the neutron moderator in gas cooled reactors but beryllium is also used. Early designs used an alloy of magnesium, called magnox to contain the uranium fuel and reactors were called magnox reactors. Gas cooled reactors have the added advantage that the gas coolant can be heated to higher temperatures than water reaching as high as 650°C enabling higher plant efficiencies of up to 40% to be achieved. Higher temperature operation is made possible by cladding the uranium-235 in stainless steel tubes but stainless steel tends to absorb neutrons slowing down the chain reactions so the fuel is slightly enriched to 2.5% or 3.5% to compensate.

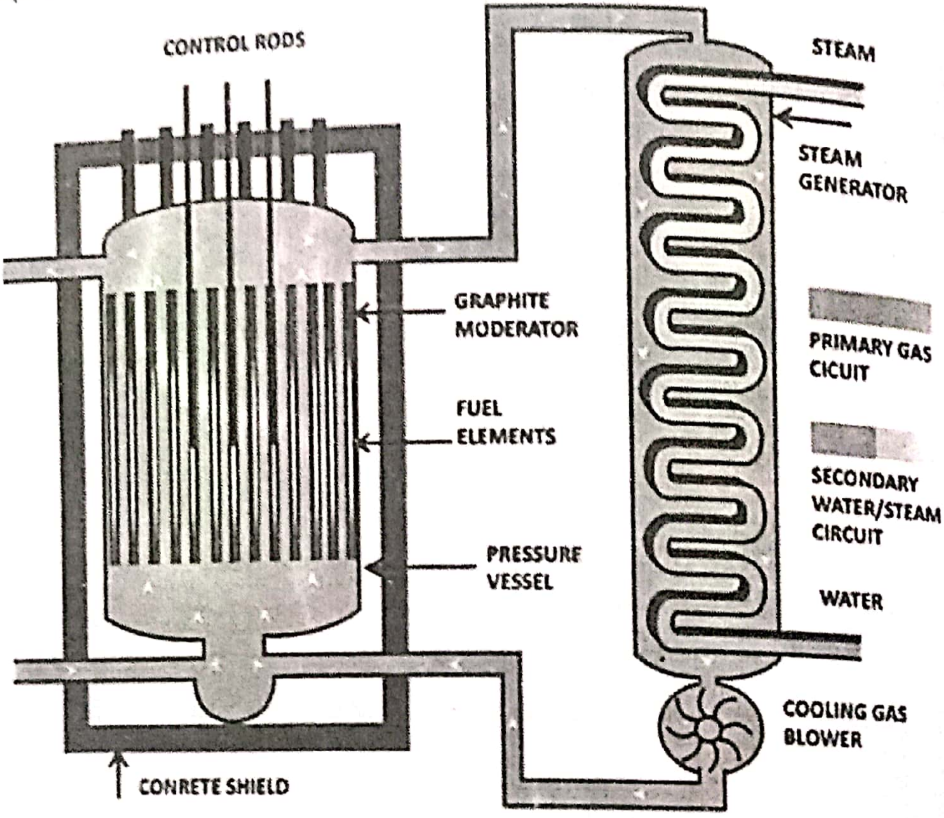


**Figure 14.15: Gas Cooled Reactor**

A modified version of the GCR is the advanced gas-cooled reactors (AGCR) are the second generation of British gas-cooled reactors, using graphite moderators and carbon dioxide as a coolant. AGCR are fuelled with uranium oxide pellets, enriched to 2.5–3.5%, in stainless steel tubes. The carbon dioxide circulates through the core, reaching 650°C, and then past steam generator tubes outside the core, but still inside the concrete and steel pressure vessel. Control rods penetrate the moderator and a secondary shutdown system involves injecting nitrogen into the coolant. Gas cooled reactors use natural uranium fuel in metal form.

## 14.10. Light Water Graphite-Moderated Reactor (RBMK)

RBMK (Reaktor Bolshoy Moshchnosti Kanalniy) is a high-power channel reactor, which is a former Soviet design developed from plutonium production reactors whose schematic diagram is shown in figure 14.16. A series of graphite blocks surround, and hence separate, the pressure tubes. The graphite blocks act as moderators to slow down the neutrons released during fission so that a continuous fission chain reaction can be maintained. With moderation largely due to the fixed graphite, excess boiling simply reduces the cooling and neutron absorption without inhibiting the fission reaction and problems due to positive feedback can arise.

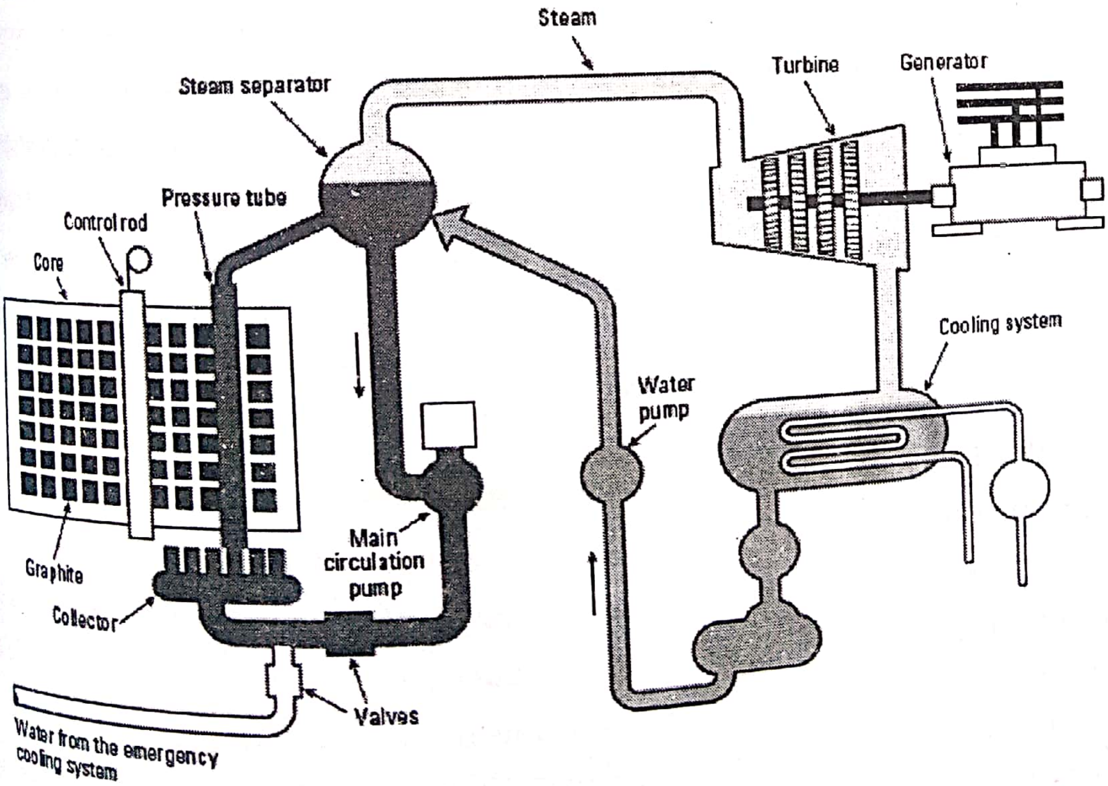


Figure 14.16: RBMK Reactor

In RBMK reactors heat conduction between the blocks is enhanced by a mixture of helium and nitrogen gas. Boron carbide control rods absorb neutrons to control the rate of fission. A few short rods inserted upwards from the bottom of the core evens the distribution of power across the reactor. The main control rods are inserted from the top down and provide automatic, manual, or emergency control. The automatic rods are regulated by feedback from in-core detectors. If there is a deviation from normal operating parameters for example, increased reactor power level, the rods can be dropped into the core to reduce or stop reactor activity. A number of rods remain in the core during operation. The reactor core is located in a reinforced concrete lined cavity that acts as a radiation shield. The core is placed on a heavy steel plate; with typically a 1000 ton steel cover plate on the top. The extensions of the fuel channels penetrate the lower plate and the cover plate and are welded to each other. The steam separators of the coolant systems are housed in their own concrete shields.

Two separate water coolant loops each with four pumps circulate water through the pressure tubes to remove most of the heat from fission. There is also an emergency core cooling system which is designed to come into operation if either coolant circuit is interrupted. Each of the two loops has two steam drums, or separators, where steam from the heated coolant is fed to the turbine to produce electricity in the generator. The steam is then condensed and fed back into the circulating coolant.

The most significant difference between the RBMK design and most of the world's nuclear power plants is that RBMK's lack of a massive steel and/or concrete containment structure as the final barrier against large releases of radiation in an accident. The reactor produces faster and less stable nuclear chain reactions and power increases in the event of coolant loss, known as a 'positive void coefficient'. Soviet engineers sought to mitigate this tendency by back-fitting RBMKs with faster-acting control rods and other improvements.

Pellets of slightly enriched uranium oxide are enclosed in a zircaloy tube, forming a fuel rod. A set of several rods is arranged cylindrically in a carriage to form a fuel assembly. When fuel channels are isolated, the fuel assemblies can be lifted into and out of the reactor, allowing fuel replenishment while the reactor is in operation. Within the reactor each fuel assembly is positioned in its own vertical pressure tube or channel. Each channel is individually cooled by pressurized water which is allowed to boil in the tube and emerges at about 290°C.

## 14.11. Fast Breeder Reactors

The reactor types described so far are thermal reactors, most of the fission being caused by thermal neutrons. Fast breeder reactors are designed so as to make use of fast neutrons with much higher kinetic energies. These types of reactors do not contain moderator and fast neutrons are used to generate power. Plutonium or uranium-238 is used as fuel, which produces 60 times more energy than the original uranium in the normal reactors, but they are expensive. A typical schematic arrangement is shown in figure 14.17.

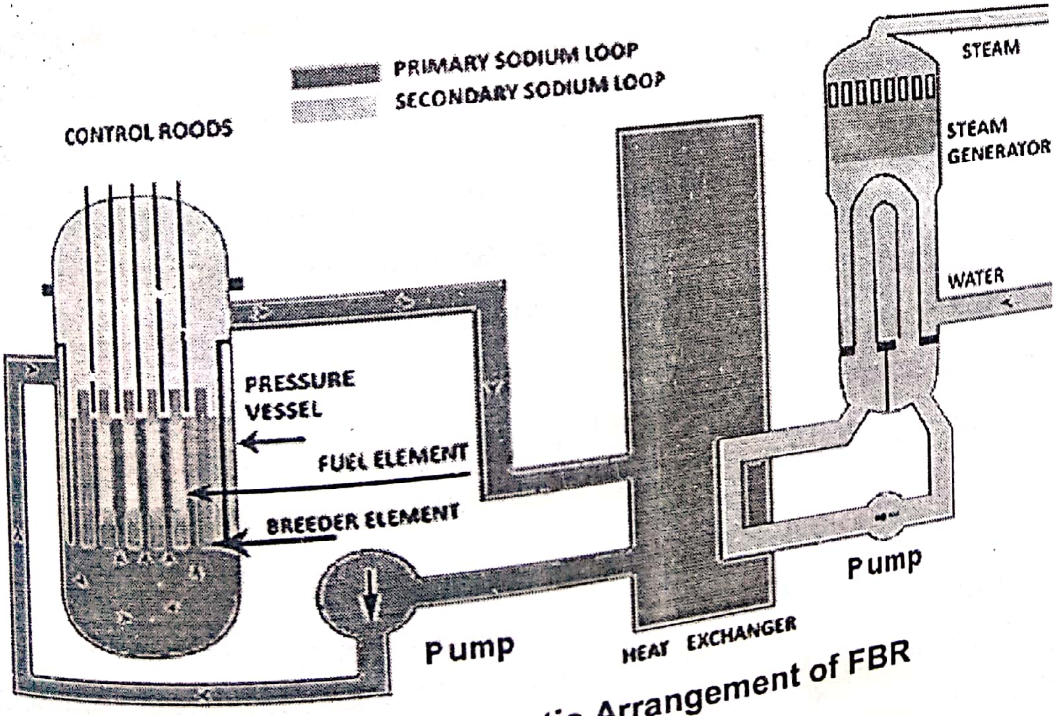


Figure 14.17: Schematic Arrangement of FBR

Fast breeder reactors release more neutrons per fission than therma reactors, and therefore make better use of the neutrons because the relative probability of neutron capture (compared with fission) decreases at higher neutron energies. These excess neutrons can also be used to convert fertile materials, for example uranium-238 and thorium-232, into fissile materials through neutron capture. This newly created fissile material can in turn fuel the reactor. It is therefore possible to design reactors to produce more fuel than they consume in breeder reactors. Typically, breeder reactors are fast reactors, though designs exist that could use thermal neutrons. Fast breeder reactors, by creating fuel from non-fissile isotopes and improving the efficiency of utilization through recycling, can potentially increase available world nuclear fuel resources up to 50 times and are therefore considered as a key element in the sustainability of nuclear energy in the long term. Breeder reactors have been built and operated in a number of countries.

Unlike uranium-235, plutonium-239 is fissionable with both slow and fast neutrons. Nuclear reactors designed to use fast neutrons, using plutonium as the fuel, therefore do not need a moderator. There is, however, extra demand on the coolants used in fast neutron reactors because they should provide efficient heat transfer and does not slow down the fast neutrons. Molten metals such as sodium and sodium-potassium mixtures, which are used for this purpose, can satisfy this requirement. Being transparent to neutrons, fewer neutrons are lost in the coolant, which as a consequence does not become so radioactive. Molten lead is also being used in some reactors since it has the added advantages that it provides excellent radiation shielding, and allows for operation at very high temperatures. It is also inert and thus safer to handle than the chemically reactive sodium.

Plutonium breeder reactors use a blanket of fertile uranium-238 (depleted uranium) or thorium-232 around the core of fissile plutonium-239. Fission of the plutonium-239 releases more neutrons into the core than conventional thermal reactors and since the reactor does not use a moderator, these are fast, high-energy neutrons. The higher concentration of neutrons in the core is sufficient to maintain the chain reaction while at the same time transmuting the non-fissile uranium-238 or thorium-232 in the fertile blanket into plutonium-239. In this way the breeder reactor can generate 20% to 40% more fissionable fuel than it consumes. Fuelling a fast breeder reactor with plutonium requires a reprocessing plant, which can handle large amounts of spent fuel with high plutonium concentrations. Very few of these reactors have been built due to their expense and the fire hazards associated with sodium coolant. In the breeding of plutonium fuel in breeder reactors, an important concept is the breeding ratio, which is the amount of fissile plutonium-239 produced compared to the amount of fissionable fuel (such as U-235) used to produce it. The time required for a breeder reactor to produce enough material to fuel a second reactor is called its doubling time, and present design plans target about ten years as a doubling time. Thus a reactor could use the heat of the reaction to produce energy for 10 years, and at the end of that time have enough fuel, to fuel another reactor for 10 years.

## 14.12. Sodium Cooled Reactor

Sodium-cooled liquid-metal reactors (LMRs) received much attention during the 1960s and 1970s when it appeared that their breeding capabilities would soon be needed to supply fissile material to a rapidly expanding nuclear industry. When it became clear in the 1980s that this was not a realistic expectation, enthusiasm waned. The developmental work of the previous decades, however, resulted in the construction of a number of LMRs around the world. Most LMRs are fueled with uranium dioxide or mixed uranium-plutonium dioxides. A schematic diagram of LMR is shown in figure 14.18. In LMR heat is extracted from the reactor core by primary sodium loop, which is transferred to a secondary non-radioactive sodium loop, which serves as the heat source for a steam generator that heats the water in a tertiary loop to power a turbine.

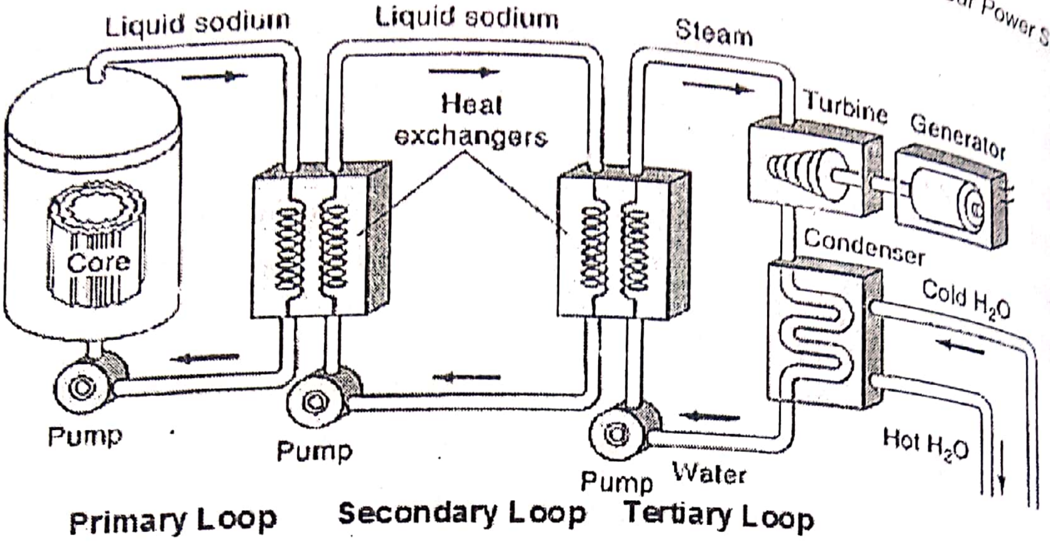


**Figure 14.18: Liquid Metal Reactor**

While some LMRs are of the loop type, equipped with heat exchangers and pumps outside the primary reactor vessel, others are of the pool variety, featuring a large volume of primary sodium in a pool that also contains the primary pumps and the primary-to-secondary heat exchanger. The pool type seems to have some safety advantage in that the large volume of primary sodium heats up only slowly even if no power is extracted; thus, the reactor is effectively isolated from upsets in the balance of the plant. The reactor core in all such systems is a tightly packed bundle of fuel in steel cladding through which the sodium coolant flows to extract the heat. Most LMRs are breeders or are capable of breeding, which is to say that they all produce more fissile material than they consume.

## 14.13. Natural Uranium Reactors

Enriched uranium was not generally available in the early days of nuclear power development and reactors had to be designed to use natural uranium as the fuel. Because of the low concentration of mobile neutrons in the un-enriched fuel, this imposed limitations on the types of coolants and moderators, which could be used. The purpose of the moderator is to slow down fast neutrons to enable them to be captured by the fissile fuel. However, many materials used as moderators also absorb neutrons thus reducing the probability of fission. For this reason ordinary (light) water is not suitable as a coolant or moderator in reactors using natural uranium fuel since it absorbs too many neutrons leaving insufficient neutrons to allow the initiation of a sustained chain reaction. Coolants, which do not absorb appreciable quantities of neutrons, are heavy water because the hydrogen atom has already absorbed an extra neutron to form the deuterium nucleus and have no real affinity for absorbing any more. Some inert gases with a low neutron affinity and a low molecular density such as carbon dioxide, nitrogen and helium are also used as coolants.

Table 14.4 provides a summary of the types of reactors in terms of the major fuels, moderators and coolants used in practical nuclear power generating plants.

**Table 14.4: Summary of Types of Nuclear Reactors**

| Type | Fuel | Moderator | Coolant |
|---|---|---|---|
| PWR | Enriched Uranium Oxide | Water | Water |
| BWR | Enriched Uranium Oxide | Water | Water |
| PHWR (CANDU) | Natural Uranium Oxide | Heavy Water | Heavy Water |
| GCR | Natural Uranium | Carbon | Carbon Dioxide |
| AGCR | Enriched Uranium Oxide | Carbon | Carbon Dioxide |
| LWGR | Enriched Uranium Oxide | Carbon | Water |

## 14.14. The Nuclear Power Station

The function of a nuclear power station is to produce electric power The power generation is in the same way as conventional thermal power plants using fossil fuels, such as coal, oil, and natural gas; namely, it heats water into steam in order to power a mechanical device (turbine) that drives an electric generator. The difference, however, is the way that it heats water to convert it into steam and the fuel used. Instead of burning fossil fuel in a furnace in the case of a conventional thermal power plant, a nuclear power plant has a reactor that heats water by fission of nuclear fuel. Most reactors use enriched uranium as fuel, which is processed in the form of pellets. By bringing pellets of uranium close together until they form a critical mass, fission can be started. In nuclear power stations the conversion of nuclear energy into electrical energy take place through series of processes. Figure 14.19 shows a simplified schematic diagram of a nuclear power station. The basic nuclear energy process takes place in reactor.

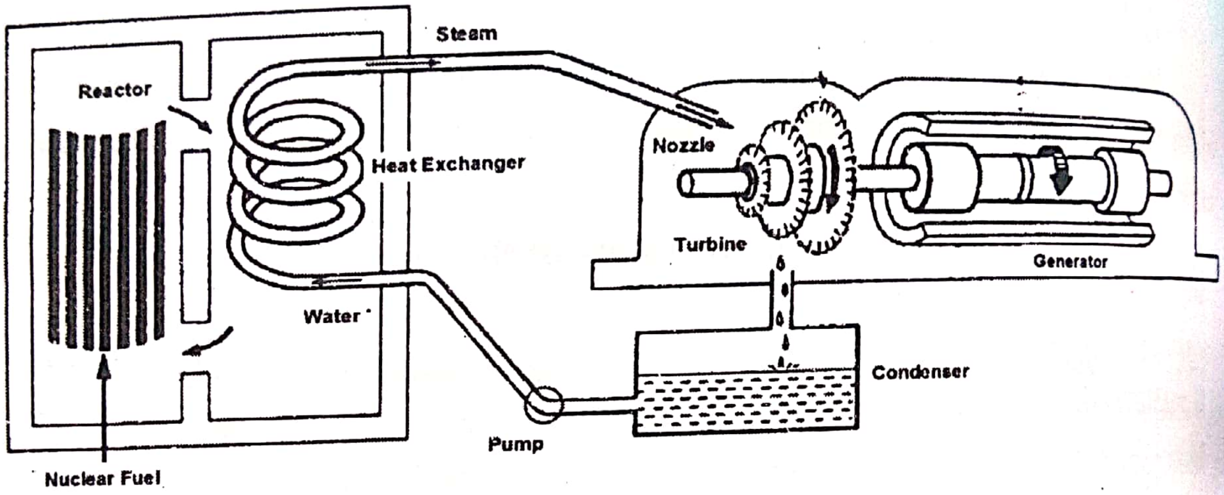


**Figure 14.19: Simplified Schematic of a Nuclear Power Station**

The basic component is a nuclear reactor, which is a cylindrical heavy pressure vessel that houses fuel rods of enriched uranium, moderator and control rods. When uranium decays in fission process, neutrons and heat are released. If enough uranium is near by, then the neutrons will run into other uranium atoms, causing them to split apart, or fission, and release more neutrons and more heat and thus resulting in a chain reaction. The nuclear fuel used is usually enriched uranium, which is typically formed into small pellets of suitable size as discussed earlier. The pellets are usually arranged into long rods, termed as fuel rods and the rods are collected together into bundles referred to as fuel canister as shown in figure 14.20. Nuclear reactors operate at surprisingly low temperatures considering the immense energy released by the nuclear reaction.

Most operate well below 850°C with some working up to 1000°C and the low temperature range of the thermal working fluid limits the Carnot efficiency of the nuclear power plant. The energy process is the nuclear fission, which is chain reaction thus resulting in large amount of energy and fission products. Most of this energy appears as heat. Nuclear reactors submerge the fission uranium in water. The bundles are submerged in water inside a pressure vessel with water or any appropriate substance that acts as a coolant. Without coolant, the uranium would eventually overheat to very temperatures that can cause melt down of the reactor. In order to turn nuclear fission into electrical energy, nuclear power plant operators have to control the energy given off by the enriched uranium. The coolant gives up the heat to the heat exchanger which is utilized in raising the steam. It heats the water and turns it to superheated steam in the boiler by thermodynamic process based on Rankine cycle.

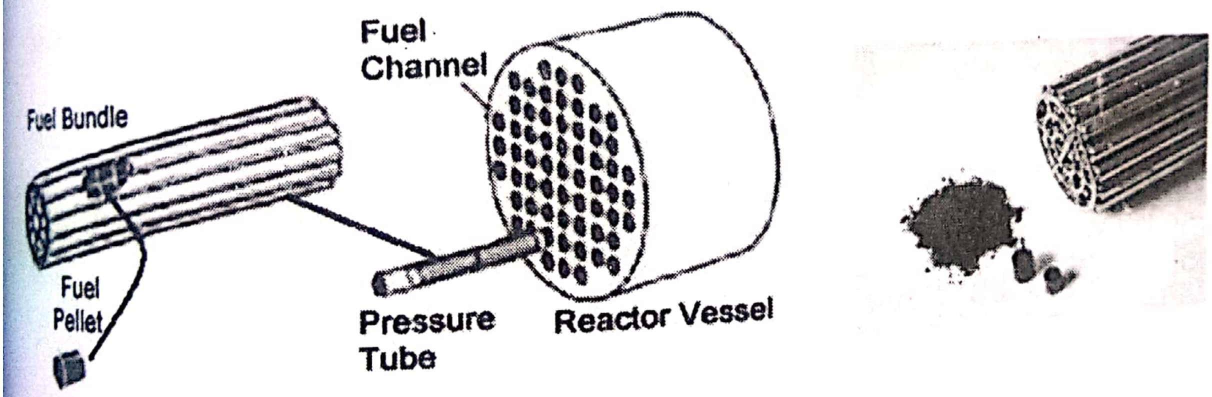


Figure 14.20: Nuclear Fuel

After giving up heat, the coolant is again fed to the reactor. The steam is allowed to pass through a system of piping to the turbine through nozzles. The steam is allowed to expand to do the useful work that drives a turbine. A generator is mechanically coupled to the turbine, which produces electric power. In some nuclear power stations, the steam from the reactor goes through a secondary, intermediate heat exchanger to convert another loop of water to steam, which drives the turbine. The advantage to this design is that the radioactive water/steam never contacts the turbine. Also, in some reactors, the coolant fluid in contact with the reactor core is gas (carbon dioxide) or liquid metal (sodium, potassium); these types of reactors allow the core to be operated at higher temperatures. The steam after doing the useful work is allowed to pass into the condenser where it is condensed into water by cooling medium, such as water that can either be directly obtained from a water source or from the pond with a cooling tower. The water from the condenser is the fed back as feed water.

To prevent overheating and the chain reaction to go out of control, control rods made of a material that absorbs neutrons are inserted into the uranium fuel using a mechanism that can raise or lower them. Raising and lowering the control rods allow operators to control the rate of the nuclear reaction. When an operator wants the uranium core to produce more heat, the control rods are lifted out of the uranium bundle (thus absorbing fewer neutrons). To reduce heat, they are lowered into the uranium bundle. In order to shut down the reactor in the event of an emergency or to change the fuel, the control rods can also be lowered completely into the uranium bundle to shut the reactor down.

High temperature reactors using molten metal coolants in the primary circuit may use helium in a Brayton cycle (or Joule cycle) in the secondary circuit operating at 1000°C to achieve efficiencies of up to 60%. A third thermal circuit, referred to as a tertiary thermal circuit is used in both the single and two stage systems to cool the working fluid at the end of the work cycle. This is typically an open cycle employing a conventional cooling tower as used in fossil fuelled power plants. The system efficiency is similar to the boiling water reactor between 33% and 36%.