SIMULATION OF USING CONTROL RODS TO CONTROL NUCLEAR REACTOR CORE

REPORT-I

ON

BASIC CONCEPTS OF NUCLEAR ENERGY AND NUCLEAR POWER

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CONTENTS

PART I – BASIC CONCEPTS OF NUCLEAR ENERGY

3.0. Concept of nuclear fission in nuclear reactor

PART II –NUCLEAR POWER

4.0. Nuclear power plant

PART I – BASIC CONCEPTS OF NUCLEAR ENERGY

1.0 NUCLEAR ENERGY

1.1 FISSION

Nuclear fission is a nuclear reaction in which the nucleus of an atom splits into smaller parts (lighter nuclei), often producing free neutrons and photons (in the form of gamma rays), as well.

1.1.1 Fission reaction

Unstable (radioactive) elements spontaneously split (radioactive decay), emitting high energy particles. Collision of particles with other atomic nuclei can trigger further nuclear decompositions. A small amount of mass is converted into a large amount of energy, when atomic nuclei are split.

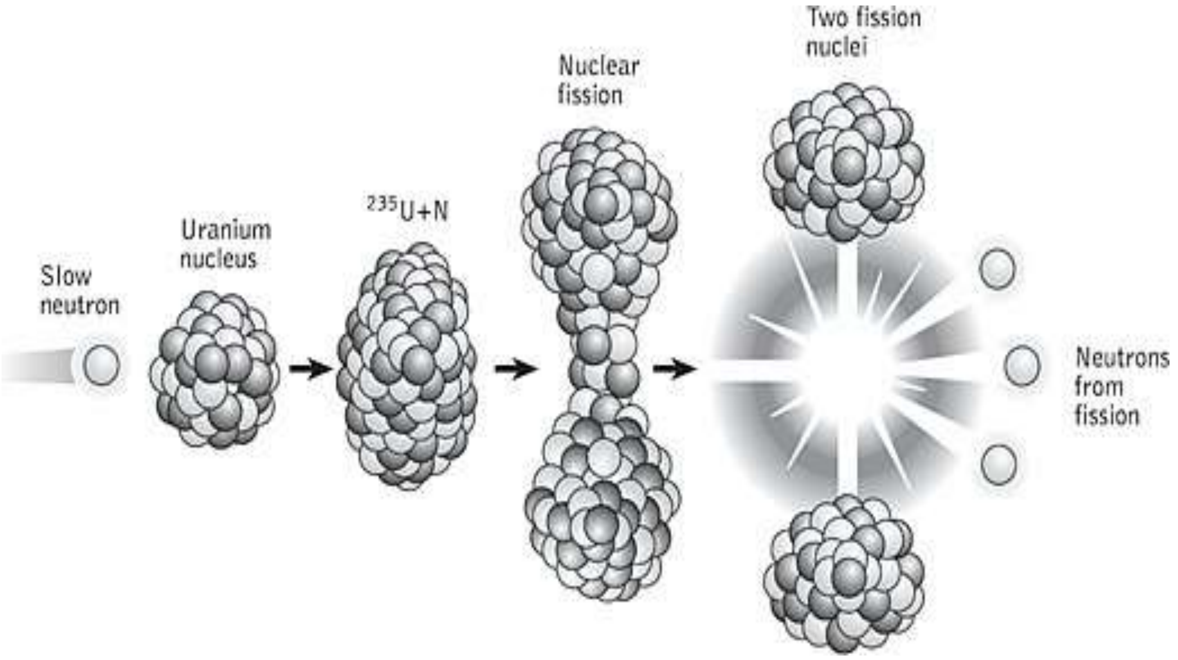


Fig. 1.1: Nuclear fission of U-235 in sequence

Figure 1.1 shows the sequence of events, using the reaction with U-235 to illustrate. firstly, the neutron approaches the U-235 nucleus. Then next , the U-236 nucleus has been formed, in an excited state. The excess energy in some cases may be released as a gamma ray, but more frequently, the energy causes distortions of the nucleus into a dumbbell shape, as in figure sequence . The parts of the nucleus oscillate in a manner analogous to the motion of a drop of liquid. Because of the dominance of electrostatic repulsion over nuclear attraction, the two parts can separate, as shown. They are then called fission fragments, bearing most of the energy released. They fly apart at high speeds, carrying some 166 MeV of kinetic energy out of the total of around 200 MeV released in the whole process.

Here neutrons of very slow moving also can be absorbed by only U-235 and give rise to a chain reaction, but coming to other heavier elements like U-238 ,it requires atleast neutrons of 0.9 MeV. It is always better to use neutrons in the order of 1 MeV to cause a fission reaction.

1.1.2 Fission yield

The nuclear reaction equation for fission resulting from neutron absorption in U-235 may be written in general form, letting the chemical symbols for the two fragments be labeled $F1$ and $F2$ to indicate many possible ways of splitting. Thus

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{A_1}_{Z_1}F_1 + {}^{A_2}_{Z_2}F_2 + \nu\ {}^{1}_{0}\mathrm{n} + \text{energy} . \quad \text{....(1.1)} $$

The appropriate mass numbers and atomic numbers are attached. One example, in which the fission fragments are isotopes of krypton and barium is

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{90}_{36}\mathrm{Kr} + {}^{144}_{56}\mathrm{Ba} + 2\,{}^{1}_{0}\mathrm{n} + E . \quad \text{.......(1.2)} $$

Mass numbers ranging from 75 to 160 are observed, with the most probable at around 92 and 144 as sketched in Fig. 6.3. The ordinate on this graph is the percentage yield of each mass number, e.g., about 6% for mass numbers 90 and 144. If the number of fissions is given, the numbers of atoms from those types are 0.06 as large.

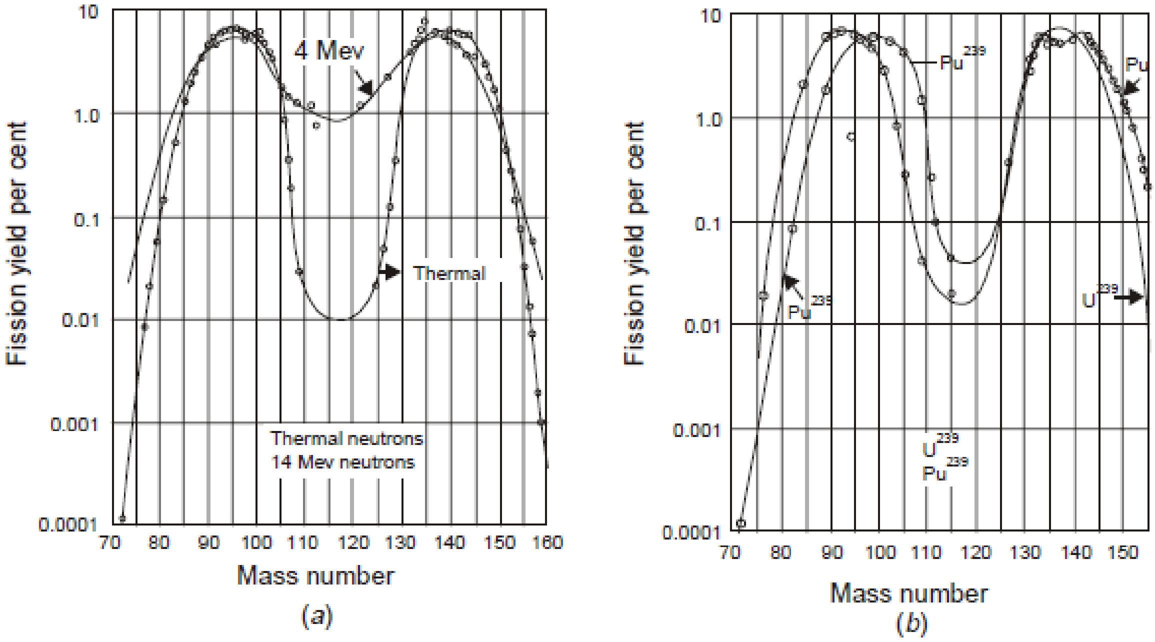


Fig.1.2: **fission product data for U_{235} by thermal and fast neutrons and for U_{233} and Pu_{239} by thermal neutrons**

1.1.3 Energy from fission

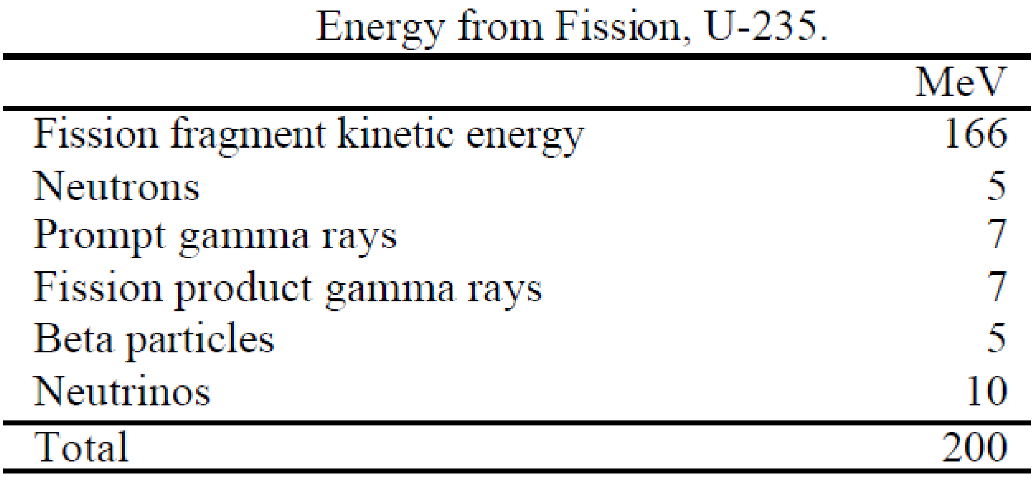
Typical fission events release about two hundred million eV (200 MeV) of energy for each fission event. By contrast, most chemical oxidation reactions (such as burning coal or TNT) release at most a few eV per event, so nuclear fuel contains at least ten million times more usable energy per unit mass than does chemical fuel. The energy of nuclear fission is released as kinetic energy of the fission products and fragments, and as electromagnetic radiation in the form of gamma rays; in a nuclear reactor, the energy is converted to heat as the particles and gamma rays collide with the atoms that make up the reactor and its working fluid, usually water or occasionally heavy water.

When an uranium nucleus fissions into two daughter nuclei fragments, an energy of ~200 MeV is released. For uranium-235 (total mean fission energy 202.5 MeV), typically ~169 MeV appears as the kinetic energy of the daughter nuclei, which fly apart at about 3% of the speed of light, due to Coulomb repulsion. Also, an average of 2.5 neutrons are emitted with a kinetic energy of ~2 MeV each (total of 4.8 MeV). The fission reaction also releases ~7 MeV in prompt gamma ray photons. The latter figure means that a nuclear fission explosion or criticality accident emits about 3.5% of its energy as gamma rays, less than 2.5% of its energy as fast neutrons (total ~ 6%), and the rest as kinetic energy of fission fragments ("heat"). In an atomic bomb, this heat may serve to raise the temperature of the bomb core to

100 million kelvin and cause secondary emission of soft X-rays, which convert some of this energy to ionizing radiation. However, in nuclear generators, the fission fragment kinetic energy remains as low-temperature heat which causes little or no ionization.

So-called neutron bombs (enhanced radiation weapons) have been constructed which release a larger fraction of their energy as ionizing radiation (specifically, neutrons), but these are all thermonuclear devices which rely on the nuclear fusion stage to produce the extra radiation. The energy dynamics of pure fission bombs always remain at about 6% yield of the total in radiation, as a prompt result of fission.

The total prompt fission energy amounts to about 181 MeV, or ~ 89% of the total energy which is eventually released by fission over time. The remaining ~ 11% is released in beta decays which have various half-lives, but begin as a process in the fission products immediately; and in delayed gamma emissions associated with these beta decays. For example, in uranium-235 this delayed energy is divided into about 6.5 MeV in betas, 8.8 MeV in antineutrinos (released at the same time as the betas), and finally, an additional 6.3 MeV in delayed gamma emission from the excited beta-decay products (for a mean total of ~10 gamma ray emissions per fission, in all). Thus, an additional 6% of the total energy of fission is also released eventually as non-prompt ionizing radiation, and this is about evenly divided between gamma and beta ray energy. The remainder is antineutrinos.



Energy from Fission, U-235.

	MeV
Fission fragment kinetic energy	166
Neutrons	5
Prompt gamma rays	7
Fission product gamma rays	7
Beta particles	5
Neutrinos	10
Total	200

Tab.1.1: energy from fission of U-235.

1.2. NUCLEAR FUSION

Nuclear fusion is the process in which two or more atomic nuclei join together to form a single heavier nucleus.it is the energy producing process taking place in the core of the sun .fusion is accompanied by the release of large quantities of energy.

1.2.1. Hydrogen fusion

In hydrogen fusion two protons have to be brought close enough for the weak nuclear force to convert either of the identical protons into a neutron forming the hydrogen isotope deuterium .deuterium and tritium are the reactant for the fusion reaction

1.2.2. Reactants of fusion reaction

(i)Deuterium

It is called heavy hydrogen.it is a stable isotope of hydrogen .it is found in natural abundance in the oceans. Deuterium accounts for approximately 0.0156% of all naturally occurring hydrogen in the oceans on earth

Nucleus of deuterium contains proton and one neutron Deuterium is represented by chemical symbol d $^{2}h_{2}$ or $d_{2,\text{natural}}$ deuterium

(ii)Tritium

It is a radioactive isotope of hydrogen .the nucleus of tritium contains one proton and two neutrons. The most abundant hydrogen isotope of tritium is protium contains one proton and no neutrons. Naturally occurring tritium is rare on earth, where trace amounts are formed by the interaction of the atmosphere

Symbol **t** or $\mathbf{^{3}h}$

1.2.3. Fusion reaction

Deuterium is obtained from water (0.02% of all hydrogen is heavy hydrogen or deuterium) Tritium from lithium (light metal common in earth crust) .The nucleus of a hydrogen atom is a single proton, a positively charged particle. If fusion is to occur, two protons must combine with each other to form a single particle

$$P^{+} + p^{+} \rightarrow \text{combined particle}$$

Forcing two like charged particles together requires a lot of energy.

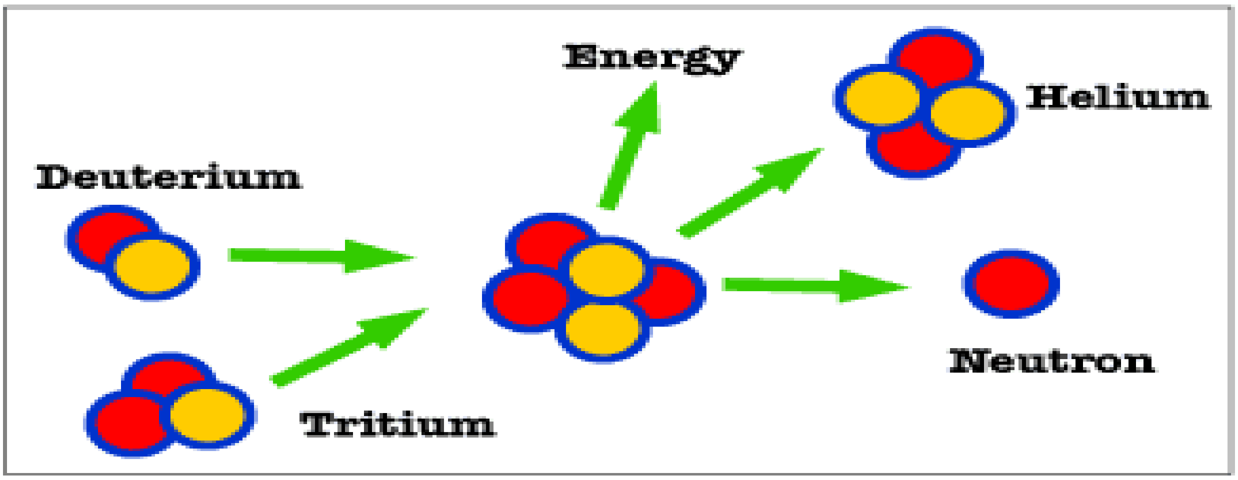


Fig.1.3: fusion of deuterium & tritium

In fig.1.3

Deuterium reacts with tritium and fuse together and release helium, neutron and a lot of energy.The weight of the product nuclei is less than the reactant nuclei. One gram of hydrogen releases $6.2x10^{10}$j of energy where as one gram of coal produces 33kj of energy.

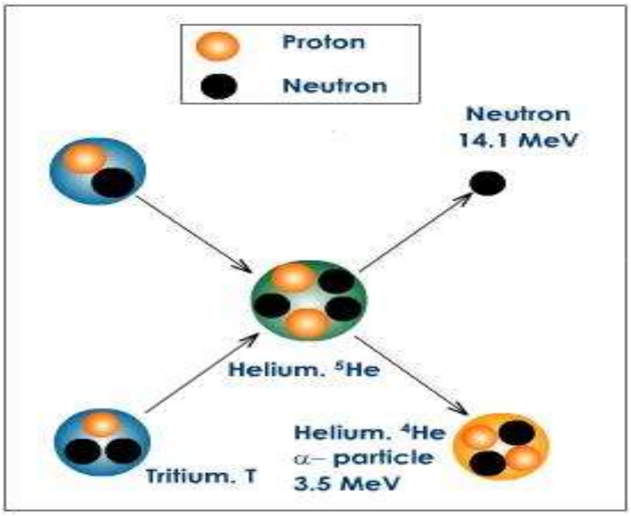


Fig.1.4:Fusion products

In fig:1.4, 1 deuterium and 1tritium fuses to form helium -5,which further splits releasing neutron ,helium-4,alpha particles and energy of 3.5 mev.

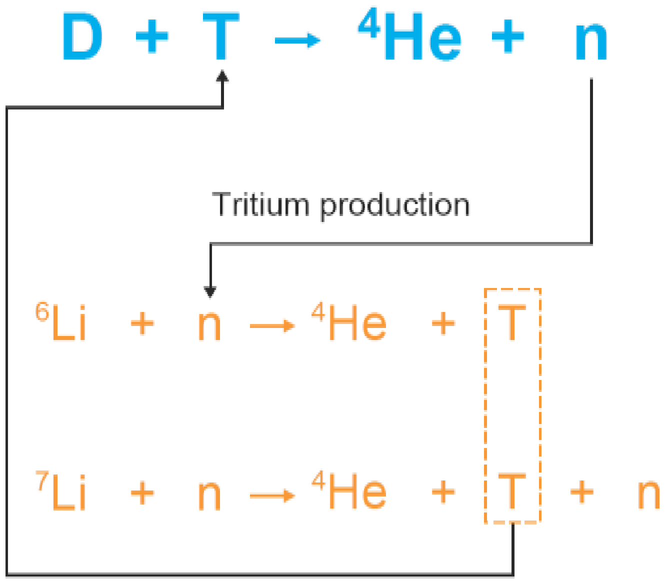


Fig.1.5: reactions of fusion of D and T

Deuterium +lithium → helium + energy

This reaction has the highest reaction rate .It can be used for energy production.

Nuclear fusion takes place at a very high temperature which is equal to 4million degree Celsius .fusion is the combination of two light nuclei and the nuclei must have sufficiently high kinetic energy to overcome the force of repulsion between the like nuclei. Therefore ,for fusion reactions to occurs, the two hydrogen nuclei have to collide at very high speeds ,which is possible only at a very high temperature ,equal to 4 *10^6 Celsius . Hence a fusion reaction is also known as thermonuclear reaction. Fusion releases more energy than fission because the mass lost during fusion is more than that lost during fission .hydrogen bomb is a practical application of nuclear fusion .

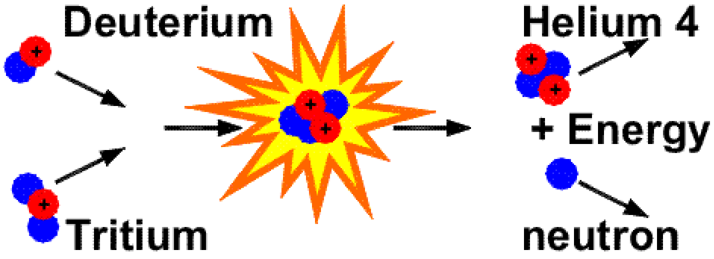


Fig.1.6:basic fusion showing energy release

1.2.4 Nuclear reaction at sun

The Sun is made of atoms too. Mostly they are ionized, so we should think of the Sun as being made of nuclei and electrons.

- About 75% (by mass) H.
- About 25% (by mass) He.
- A small amount of heavier elements.

The middle of the Sun is a very hot gas. It is ionized: all of the electrons have been ripped away from the nuclei because it is so hot. The nuclei available are mostly ^1H, quite a lot of ^4He, and a few ^2H and ^3He. (There are a few other types, but they are not so important for us.)

What is happening in the middle of the Sun is analogous to burning methane:

$$C H_4 + 2 O_2 \dashrightarrow C O_2 + 2 H_2 O$$

In this reaction, the final molecules have less internal energy than the starting molecules. Since energy is conserved, the extra energy is released as energy of motion of the molecules. That is the gas gets hotter. The amount of energy involved is 5.5 eV each time the reaction above happens.

As we have seen, much more energy than that must be involved in the reactions inside the Sun and other stars. The evidence is strong that the overall reaction is "burning" hydrogen to make helium:

$$4\ {}^{1}\mathrm{H} + 2\ \mathrm{e} \dashrightarrow {}^{4}\mathrm{He} + 2\ \text{neutrinos} + 6\ \text{photons}$$

The high energy photons produced by the nuclear process don't get far. They are absorbed and heat the gas. The helium remains in the middle of the Sun. The neutrinos easily zip out of the Sun. (Neutrino

1.2.5. IMPORTANT THINGS IN NUCLEAR ENERGY

(a)COLD FUSION: A form of fusion that some researchers believe can occur at or near room temperatures as the result of the combination of deuterons during the electrolysis of water.

(b)ELECTROLYSIS: The process by which an electrical current causes a chemical change, usually the breakdown of some substance.

(c)ISOTOPES: Two or more forms of an element that have the same chemical properties but that differ in mass because of differences in the number of neutrons in their nuclei.

(d)NEUTRON: A subatomic particle with a mass of about one atomic mass unit and no electrical charge.

(e)NUCLEAR FISSION: A nuclear reaction in which one large atomic nucleus breaks apart into at least two smaller particles.

(f)NUCLEUS: The core of an atom consisting of one or more protons and, usually, one or more neutrons.

(g)PLASMA: a form of matter that consists of positively charged particles and electrons completely independent of each other.

(h)PROTON: a subatomic particle with a mass of about one atomic mass unit and a single positive charge.

(i)SUBATOMIC PARTICLE: Basic unit of matter and energy (proton, neutron, electron, neutrino, and positron) smaller than an atom.

(j)THERMONUCLEAR REACTION: A nuclear reaction that takes place only at very high temperatures, usually on the order of a few million degrees.

(k)SOME NUCLEAR FUSION REACTION

1) 21D + 31T → 42He (3.5 MeV) + n^0 (14.1 MeV)

2)21D + 21D → 31T (1.01 MeV) + p^+ (3.02 MeV)   50%   →

32He (0.82 MeV) + n^0 (2.45 MeV)   50%

3) 21D + 32He → 42He (3.6 MeV) + p^+ (14.7 MeV)

4) 31T + 31T → 42He   + 2 n^0 + 11.3 MeV

5) 32He + 32He → 42He   + 2 p^+ + 12.9 MeV

2.0. HARNESSING ENERGY FROM NUCLEAR FISSION

Nuclear Energy is achieved through natural processes and nuclear reactions have been going on for millions of years. Nuclear Reactions are abundantly found on our Sun as well as in the billions of stars found in our galaxy. Moreover, even Earth is full with nuclear reactions and natural radioactivity. Currently fission is the only way to feasibly harness the energy that is available through nuclear reactions. By containing the fission reaction within a nuclear reactor, it can be possible to harness the nuclear energy and convert it into electricity through various means.

Einstein equation: E = mc^2

The Conversion of mass to energy: E = energy, *m* = mass converted, *c* = speed of light

There are many fission reactions that release different energy values. Another has the mass balance

$$_{92}U^{235} + {}_0n^1 \longrightarrow {}_{56}Ba^{137} + {}_{36}Kr^{97} + 2\,{}_0n^1 \quad \text{................(2.1)}$$

$$\begin{aligned}
&235.0439 + 1.00867 \longrightarrow 136.9061 + 96.9212 + 2 \times 1.00867\\
&\qquad\qquad 236.0526 \longrightarrow 235.8446\\
&\Delta m = 235.8446 - 236.0526 = -\ 0.2080 \text{ amu} \quad \text{............(2.2)}\\
&\Delta E = 931 \times -\ 0.2080 = -\ 193.6 \text{ MeV} = -\ 3.1 \times 10^{-11} \text{ J} \quad \text{..........(2.3)}
\end{aligned}$$

On the average the fission of a U235 nucleus yields about 193 MeV. The same figure roughly applies to U233 and Pu239. This amount of energy is prompt, i.e., released at the time of fission. More energy, however, is produced because of (1), the slow decay of the fission fragments into fission products and (2) the non-fission capture of excess neutrons in reactions that produce energy, though much less than that of fission. The total energy, produced per fission reaction, therefore, is greater than the prompt energy and is about 200 MeV, a useful number to remember. The complete fission of 1 g of UZ nuclei thus produces

$$\begin{aligned}
\frac{\text{Avogadro's number}}{U^{235}\text{ isotope mass}} &= 200 \text{ MeV} = \frac{0.60225 \times 10^{24}}{235.0439} \times 200\\
&= 0.513 \times 10^{24} \text{ MeV} = 2.276 \times 10^{24} \text{ kWh}\\
&= 8.190 \times 10^{10} \text{ J} = 0.948 \text{ MW-day.}
\end{aligned}$$

Another convenient figure to remember is that a reactor burning 1 g of fissionable material generates nearly 1 MW-day of energy. This relates to fuel burn-up. Maximum theoretical burn-up would therefore be about a million MW-day/ton (metric) of fuel. This figure applies if the fuel were entirely composed of fissionable nuclei and all of them fission. Reactor fuel, however, contains other non-fissionable isotopes of uranium, plutonium, or thorium. Fuel is defined as all uranium, plutonium, and thorium isotopes. It does not include alloying or other chemical compounds or mixtures. The term fuel material is used to refer to fuel plus such other materials. Even the fissionable isotopes cannot be all fissioned because of the accumulation of fission products that absorb neutrons and eventually stop the chain reaction. Because of this-and owing to metallurgical reasons such as the inability of the fuel material to operate at high temperatures or to retain gaseous fission products [such as Xe and Kr, in its structure except for limited periods of time-burnup values are much lower than this figure. They are, however, increased somewhat by the fissioning of some fissionable nuclei, such as Puz3y, which are newly converted from fertile nuclei, such as U238. Depending upon fuel type and *enrichment* (*mass* percent of fissionable fuel in all fuel), burn ups may vary from about 1000 to 100,000 MW-day/ton and higher.

PART II - NUCLEAR POWER

3.0. CONCEPT OF USING FISSION IN A NUCLEAR REACTOR

3.1. Fission in nuclear reactor:

When unstable heavy nucleus is bombarded with the high energy neutron's, it splits into two fragments more or less of equal mass. This process is known as "Nuclear fission" as explained in 1.1

The fission fragments formed due to fission are the isotopes which are located in the middle of the periodic table. The binding energy per nucleon for the elements in the middle range of periodic table is more than that of heavy nuclei. Therefore, the nuclear fission is always associated with the release of large amount of energy

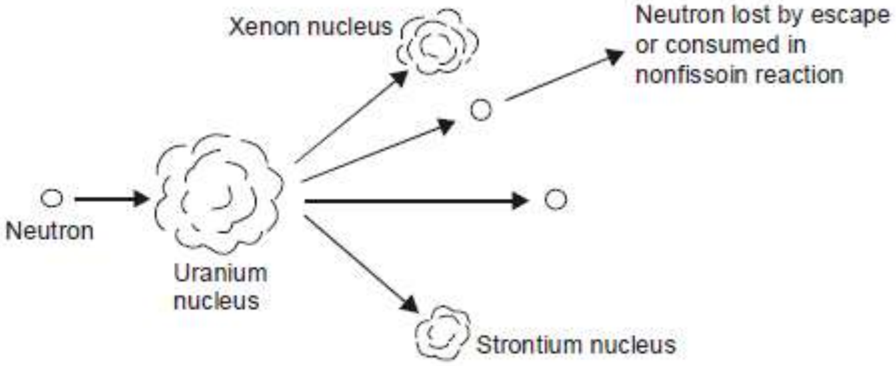


Fig.3.1: fission of uranium nucleus.

3.2. Self-sustaining chain reaction:

The self-sustaining nuclear fission reaction associated with release of energy is very important in the nuclear reactor for power generation.

The energy required to break the nucleus must be sufficient to overcome the repulsive forces (nuclear binding energy) between the two fragments .The excitation energy required to split the nucleus is called the critical energy.

An assembly that supports a sustained nuclear chain reaction is called a critical assembly or, if the assembly is almost entirely made of a nuclear fuel, a critical mass. The word "critical" refers to a cusp in the behavior of the differential equation that governs the number of free neutrons present in the fuel: if less than a critical mass is present, then the amount of neutrons is determined by radioactive decay, but if a critical mass or more is present, then the amount of neutrons is controlled instead by the physics of the chain reaction. The actual mass of a critical mass of nuclear fuel depends strongly on the geometry and surrounding materials.

Not all fissionable isotopes can sustain a chain reaction. For example, 238U, the most abundant form of uranium, is fissionable but not fissile: it undergoes induced fission when impacted by an energetic neutron with over 1 MeV of kinetic energy. But too few of the neutrons produced by 238U fission are energetic enough to induce further fissions in 238U, so no chain reaction is possible with this isotope. Instead, bombarding 238U with slow neutrons causes it to absorb them (becoming 239U) and decay by beta emission to 239Np which then decays again by the same process to 239Pu; that process is used to manufacture 239Pu in breeder reactors. In-situ plutonium production also contributes to the neutron chain reaction in other types of reactors after sufficient plutonium-239 has been produced, since plutonium-239 is also a fissile element which serves as fuel. It is estimated that up to half of the power produced by a standard "non-breeder" reactor is produced by the fission of plutonium-239 produced in place, over the total life-cycle of a fuel load.

Fissionable, non-fissile isotopes can be used as fission energy source even without a chain reaction. Bombarding 238U with fast neutrons induces fissions, releasing energy as long as the external neutron source is present. This is an important effect in all reactors where fast neutrons from the fissile isotope can cause the fission of nearby 238U nuclei, which means that some small part of the 238U is "burned-up" in all nuclear fuels, especially in fast breeder reactors that operate with higher-energy neutrons. That same fast-fission effect is used to augment the energy released by modern thermonuclear weapons, by jacketing the weapon with 238U to react with neutrons released by nuclear fusion at the center of the device.

3.2.1 Fission products

Small amounts of fission products are naturally formed as the result of either spontaneous fission of natural uranium, which occurs at a low rate or as a result of neutrons from radioactive decay or reactions with cosmic ray particles. The microscopic tracks left by these fission products in some natural minerals (mainly apatite and zircon) are used in fission track dating to provide the cooling ages of natural rocks. The technique has an effective dating range of 0.1 Ma to >1.0 Ga depending on the mineral used and the concentration on uranium in that mineral.

Fission products are produced in nuclear weapon explosions, with the amount depending on the type of weapon. After the Castle Bravo test, the United States refused to tell the Japanese doctors treating the Daigo Fukuryu Maru crew the composition of the fallout they were subjected to, out of fear it would reveal clues about the bomb's design.

The largest source of fission products is from nuclear reactors. In current nuclear power reactors, about 3% of the uranium in the fuel is converted into fission products as an unavoidable by-product of energy generation. Most of these fission products remain in the fuel unless there is fuel element failure, or a nuclear accident, or the fuel is reprocessed.

The nuclear fission is accompanied by the release of enormous amount of energy, fission products and variable numbers of neutrons. When the fission products and variable numbers of neutrons. When the fission of 92U235 takes place; all nuclei do not fission in an identical way.

In a nuclear power reactor, the main types of radioactivity are fission products, actinides and activation products. Fission products are the largest amount of radioactivity for the first several hundred years, while actinides are dominant roughly 10^3 to 10^5 years after fuel use.

Fission occurs in the nuclear fuel, and the fission products are primarily retained within the fuel close to where they are produced. These fission products are important to the operation of the reactor because (as noted above) some fission products contribute delayed neutrons that are useful for reactor control while others are neutron poisons that tend to inhibit the nuclear reaction. The buildup of the fission product poisons is a key factor in determining the maximum duration a given fuel element can be kept within the reactor. The decay of short-lived fission products also provide a source of heat within the fuel that continues even after the reactor has been shut down and the fission reactions stopped. It is this decay heat that sets the requirements for cooling of a reactor after shutdown. More details on these topics are provided in the articles on nuclear power plants and used nuclear fuel.

If the fuel cladding around the fuel develops holes, then fission products can leak into the primary coolant. Depending on the fission product chemistry, it may settle within the reactor core or travel through the coolant system. Coolant systems include chemistry control systems that among other purposes, will tend to remove such fission products. In a well-designed power reactor running under normal conditions, the radioactivity of the coolant is very low.

3.2.2. Reproduction factor

It is defined as the ratio of no of neutrons of any one generation to the no of neutrons of immediately preceding generation.

If $k<1$, the system is known as subcritical and

If $k>1$, the system is known as supercritical and

If $k=1$, the system is known as critical

And this is the desirable requirement for power factor

The behavior of neutrons in a nuclear reactor can be understood through Multiplication Factors analogy with populations of living organisms; for example, of human beings. There are two ways to look at changes in numbers of people: as individuals and as a group. A person is born and throughout life has various chances of fatal illness or accident. On average the life expectancy at birth might be 75 years, according to statistical data.

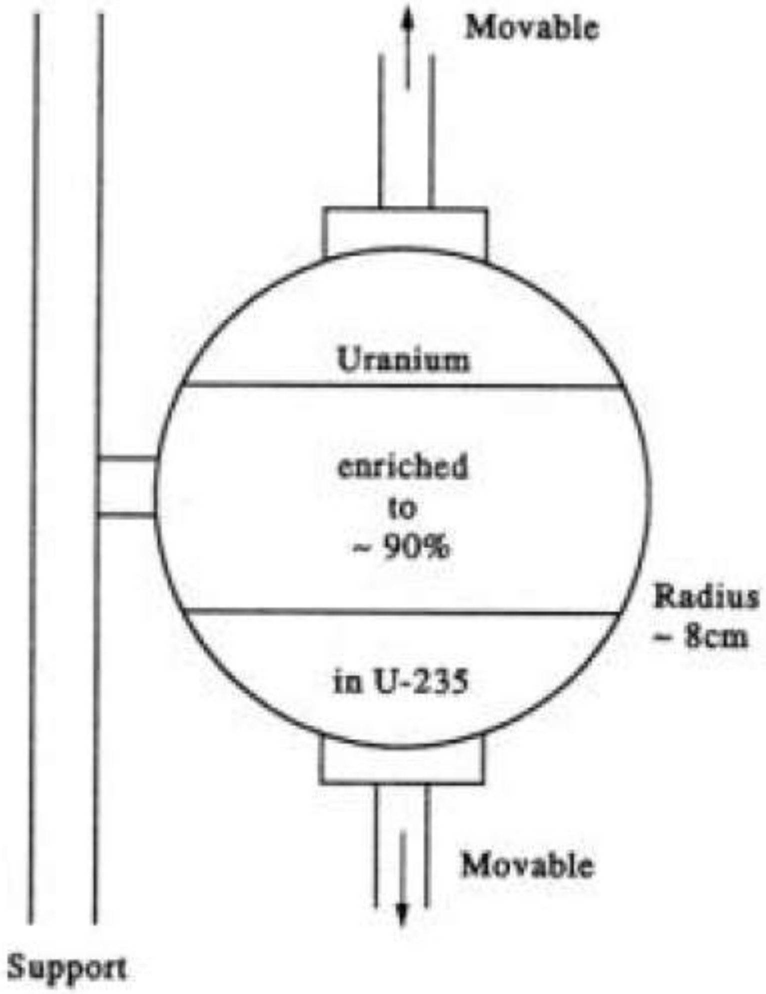


Fig. 3.2: Fast moving assembly "Lady Godiva"

An individual may die without an heir, with one, or with many. If on average there is exactly 1, the population is constant. From the other viewpoint, if the rates of birth and death are the same in a group of people, the population is again steady. If there are more births than deaths by 1% per year, the population will grow accordingly. This approach emphasizes the competition of process rates. The same ideas apply to neutrons in a multiplying assembly. We can focus attention on a typical neutron that was born in fission, and has various chances of dropping out of the cycle because of leakage and absorption in other materials besides fuel. On the other hand we can compare the reaction rates for the processes of neutron absorption, fission, and leakage to see if the number of neutrons is increasing, steady, or decreasing. Each of the methods has its merits for purposes of discussion, analysis, and calculation. For any arrangement of nuclear fuel and other materials, a single number *k* tells the net number of neutrons per initial neutron, accounting for all losses and reproduction by fission. If *k* is less than 1 the system is subcritical; if *k* is equal to 1 it is critical, and if *k* is greater than 1 it is supercritical. The design and operation of all reactors is focused on k or on related quantities such as $dk = k - 1$, called delta-k, or dk/k, called *reactivity*, 130 Neutron Chain Reactions symbolized by r. The choice of materials and size is made to assure that k has the desired value. For safe storage of fissionable material k should be well below 1. In the critical experiment, a process of bringing materials together with a neutron source present, observations on neutron flux are made to yield estimates of k. During operation, variations in k are made as needed by adjustments of neutron-absorbing rods or dispersed chemicals. Eventually, in the operation of the reactor, enough fuel is consumed to bring k below 1 regardless of adjustments in control materials, and the reactor must shut down for refueling.

3.2.3. Neutron cycle in thermal reactor:

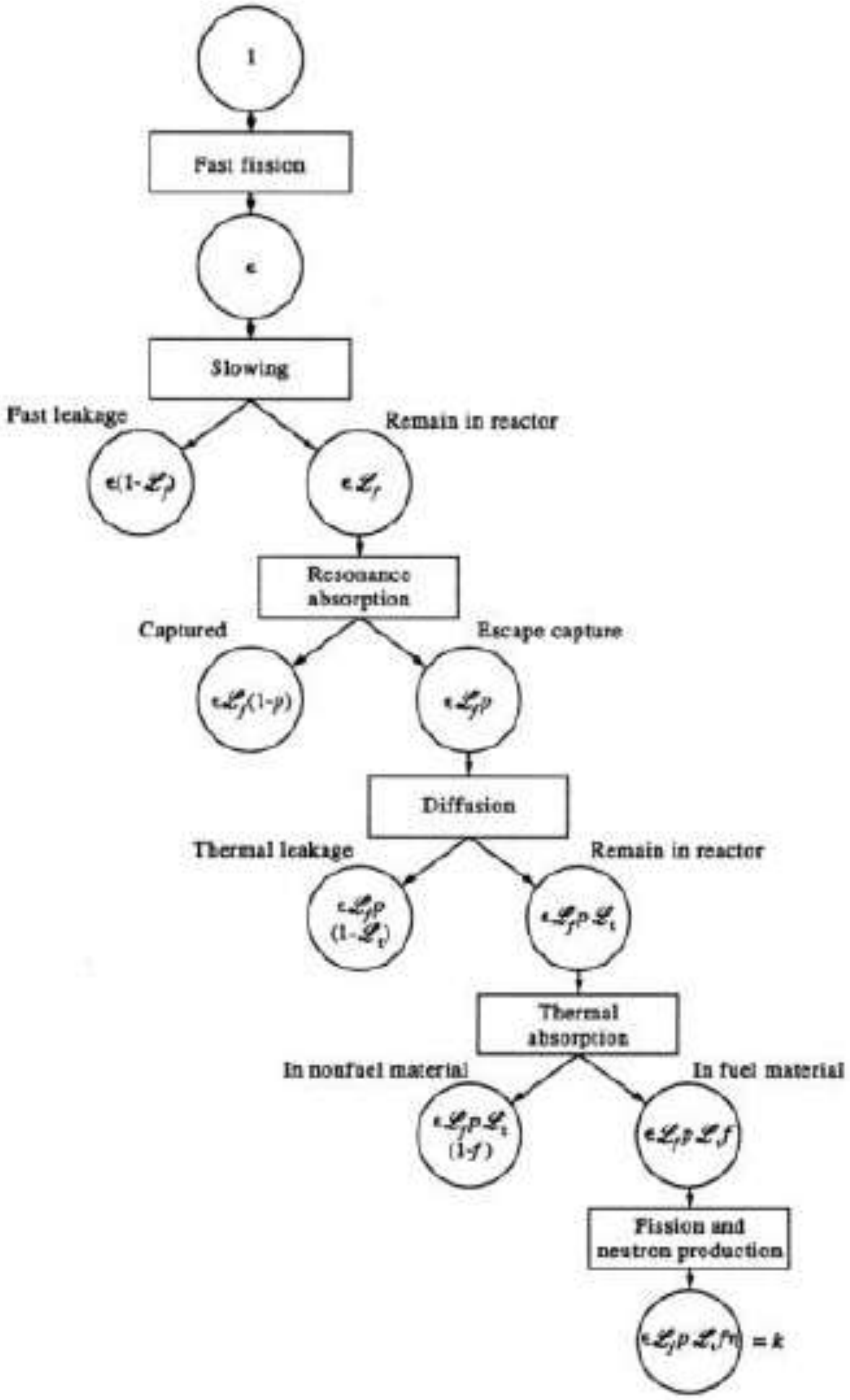


Fig.3.3: Neutron cycle in a reactor.

The description of the multiplication cycle for a thermal reactor is somewhat more complicate as seen in Fig.3.3, The set of reactor parameters are (a) the fast fission factor *e*, representing the immediate multiplication because of fission at high neutron energy, mainly in U-238; (b) the fast non-leakage probability $\mathcal{L}_f$, being the fraction remaining in the core during neutron slowing; (c) the resonance escape probability *p*, the fraction of neutrons not captured during slowing; (d) the thermal non-leakage probability $\mathcal{L}_t$, the fraction of neutrons remaining in the core during diffusion at thermal energy; (e) the thermal utilization *f*, the fraction of thermal neutrons absorbed in fuel; and (f) the reproduction factor *h*, as the number of new fission neutrons per absorption in fuel. At the end of the cycle starting with one fission neutron, the number of fast neutrons produced is seen to be *e pfh* $\mathcal{L}_f \mathcal{L}_t$,which may be also labeled *k*, the effective multiplication factor. It is convenient to group four of the factors to form *k*¥ = *e pfh*, the so-called "infinite multiplication factor" which would be identical to *k* if the medium were infinite in extent, without leakage. If we form a composite non-leakage probability $\mathcal{L} = \mathcal{L}_f \mathcal{L}_t$ then we may write

$$k = k_\infty \mathcal{L}$$

For a reactor to be critical, *k* must equal 1

4.0. NUCLEAR POWER PLANT

4.1. Concept of nuclear power

In the present world scenario, electricity is the most utilized form of energy for industry and Domestic purposes. The role of fuel for producing electricity is very important. The carbon based fuels which are being used as fuel mostly are diminishing and they may last only for 30-40 years. Many other renewable energy sources have failed to establish their efficiency. So, there comes the need for Nuclear energy. Nuclear Energy is the only viable alternative to produce enough electricity for our civilization. The nuclear energy can made utilized by having a nuclear fission reaction in nuclear reactor.

4.1.1. Basic principle

In a nuclear power plant, nuclear energy is not directly converted to electrical energy. The energy generated in a nuclear reactor is used as a heat source to heat water to steam and then direct towards a steam turbine, by the motion of turbine the electricity is generated by the generator connected to the turbine.

4.2. Structure of nuclear power plant

4.2.1. Components of nuclear power plant

The nuclear powerplant setup consists of

1. Nuclear reactor
2. Steam generator (or) heat exchanger
3. Steam turbine
4. Generator
5. Condenser.

4.2.1.1. Nuclear Reactor

A nuclear reactor is an apparatus in which heat is produced due to nuclear fission chain reaction.

Fig. shows the various parts of reactor, which are as follows :
1. Nuclear Fuel

2. Moderator
3. Control Rods
4. Reflector
5. Reactors Vessel
6. Biological Shielding
7. Coolant.

Fig.1 shows a schematic diagram of nuclear reactor.

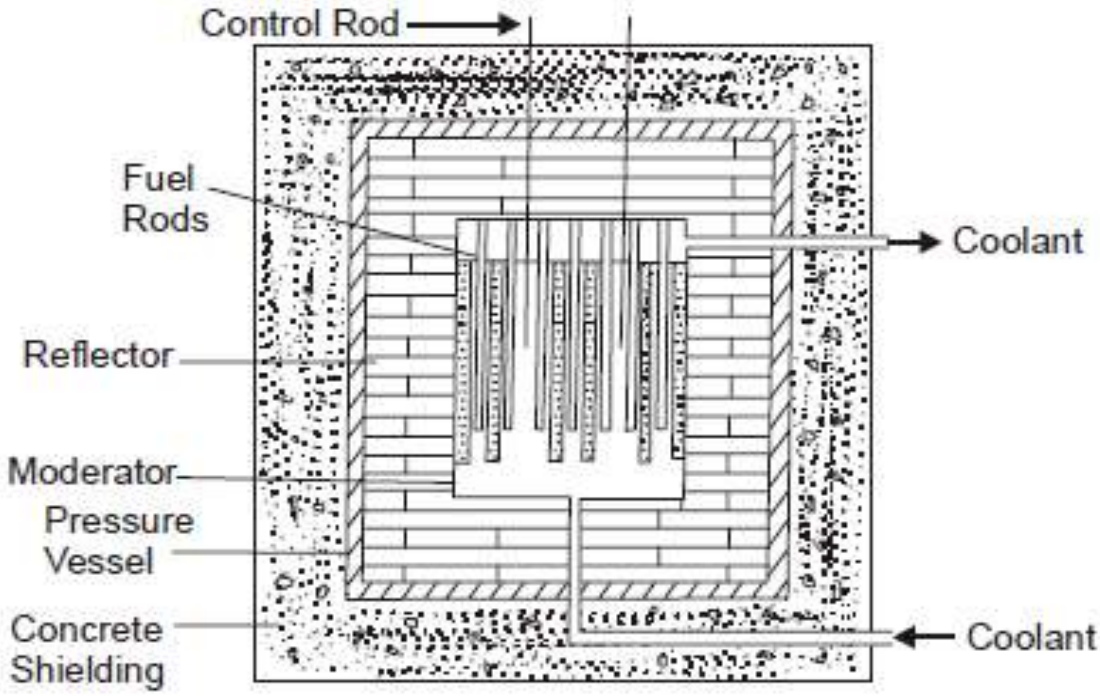


Fig4.1: Nuclear Reactor

4.2.1.2. NUCLEAR FUEL

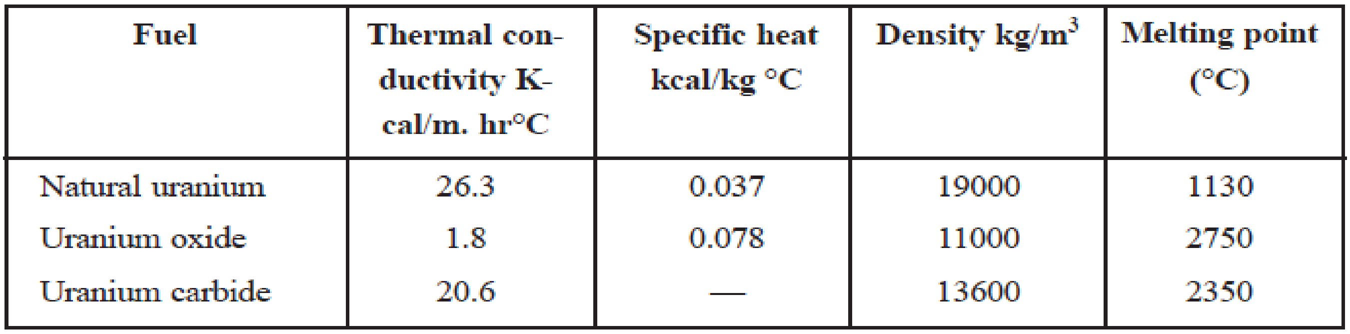
Fuel of a nuclear reactor should be fissionable material which can be defined as an element or isotope whose nuclei can be caused to undergo nuclear fission by nuclear bombardment and to produce a fission chain reaction. It can be one or all of the following U233, U235 and

Pu239. Natural uranium found in earth crust contains three isotopes namely U234, U235 and U238 and their average percentage is as follows

U238 — 99.3%
U235 — 0.7%
U234 — Trace

Out of these U235 is most unstable and is capable of sustaining chain reaction and has been given the name as primary fuel. U233 arid Pu239 are artificially produced from Th232 and U238 respectively and are called secondary fuel. Pu239 and U233 so produced can be fissioned by thermal neutrons. Nuclear fuel should not be expensive to fabricate. It should be able to operate at high temperatures and should be resistant to radiation damage.

Table indicates some of the:



Fuel	Thermal conductivity K-cal/m. hr°C	Specific heat kcal/kg °C	Density kg/m^3	Melting point (°C)
Natural uranium	26.3	0.037	19000	1130
Uranium oxide	1.8	0.078	11000	2750
Uranium carbide	20.6	—	13600	2350

Table 4.1: physical properties of nuclear fuels

4.2.1.3. Moderator

In the chain reaction the neutrons produced are fast moving neutrons. These fast moving neutrons are far less effective in causing the fission of U235 and try to escape from the reactor. To improve the utilization of these neutrons their speed is reduced. It is done by colliding them with the nuclei of other material which is lighter, does not capture the neutrons but scatters them. Each such collision causes loss of energy, and the speed of the fast moving neutrons is reduced. Such material is called Moderator. The slow neutrons (Thermal Neutrons) so produced are easily captured by the nuclear fuel and the chain reaction proceeds smoothly. Graphite, heavy water and beryllium are generally used as moderator. Reactors using enriched uranium do not require moderator. But enriched uranium is costly due to processing needed.

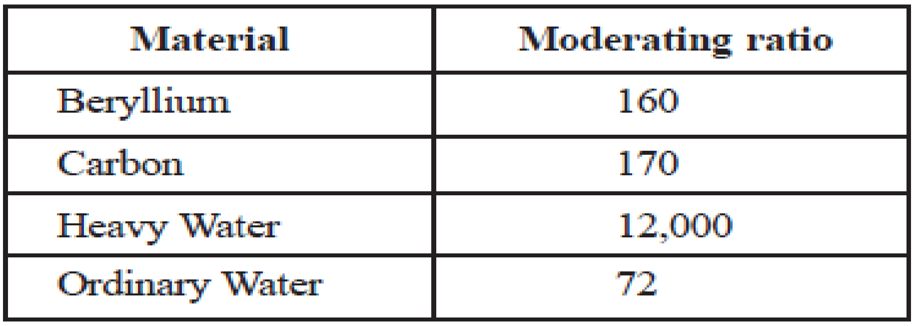
A moderator should process the following properties :

1. It should have high thermal conductivity.
2. It should be available in large quantities in pure form.
3. It should have high melting point in case of solid moderators and low melting point in case of liquid moderators. Solid moderators should also possess good strength and machinability.
4. It should provide good resistance to corrosion.
5. It should be stable under heat and radiation.
6. It should be able to slow down neutrons

4.2.1.4. Moderating Ratio

To characterize a moderator it is best to use so called moderating ratio which is the ratio of the moderating power to the macroscopic neuron capture coefficient. A high value of moderating ratio indicates that the given substance is more suitable for slowing down the neutrons in a reactor

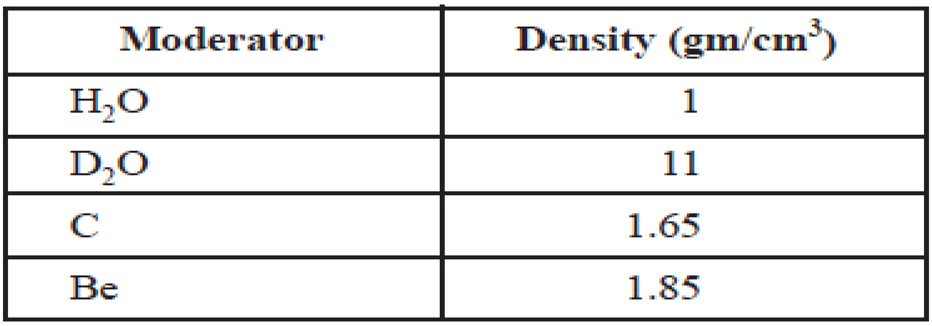
Table indicates the moderating ratio for some of the material used as moderator.



Material	Moderating ratio
Beryllium	160
Carbon	170
Heavy Water	12,000
Ordinary Water	72

Table 4.2:moderating ratios of materials

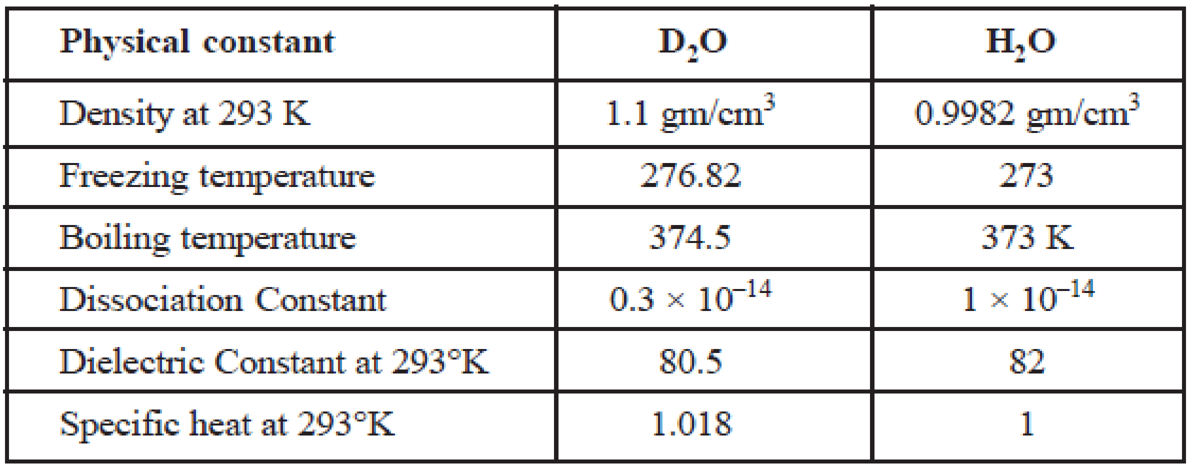
This shows that heavy water, carbon and, beryllium are the best moderators.



Moderator	Density (gm/cm^3)
H_2O	1
D_2O	11
C	1.65
Be	1.85

Table 4.3:Densities of moderators

Table 4.4. shows some of the physical constants of heavy water and ordinary water



Physical constant	D_2O	H_2O
Density at 293 K	1.1 gm/cm^3	0.9982 gm/cm^3
Freezing temperature	276.82	273
Boiling temperature	374.5	373 K
Dissociation Constant	0.3×10^{-14}	1×10^{-14}
Dielectric Constant at 293°K	80.5	82
Specific heat at 293°K	1.018	1

Table 4.4.: Physical constants of heavy water and water

4.2.1.5.Control Rods

The energy produced in the reactor due to fission of nuclear fuel during chain reaction is so much that if it is not controlled properly the entire core and surrounding structure may melt and radioactive fission products may come out of the reactor thus making it uninhabitable. This implies that we should have some means to control the power of reactor. This is done by means of control rods. Control rods in the cylindrical or sheet form are made of boron or cadmium. These rods can be moved in and out of the holes in the reactor core assembly. Their insertion absorbs more neutrons and damps down the reaction and their withdrawal absorbs less neutrons. Thus power of reaction is controlled by shifting control rods which may be done manually or automatically.

Control rods should possess the following properties :

1. They should have adequate heat transfer properties.
2. They should be stable under heat and radiation.
3. They should be corrosion resistant.
4. They should be sufficient strong and should be able to shut down the reactor almost instantly under all conditions.
5. They should have sufficient cross-sectional area for the absorption.

4.2.1.6. Reflector

The neutrons produced during the fission process will be partly absorbed by the fuel rods, moderator, coolant or structural material etc. Neutrons left unabsorbed will try to leave the reactor core never to return to it and will be lost. Such losses should be minimized. It is done by surrounding the reactor core by a material called reflector which will send the neutrons back into the core. The returned neutrons can then cause more fission and improve the neutrons economy of' the reactor. Generally the reflector is made up of graphite and beryllium.

4.2.1.7.Reactor Vessel

It is a. strong walled container housing the cure of the power reactor. It contains moderator, reflector, thermal shielding and control rods.

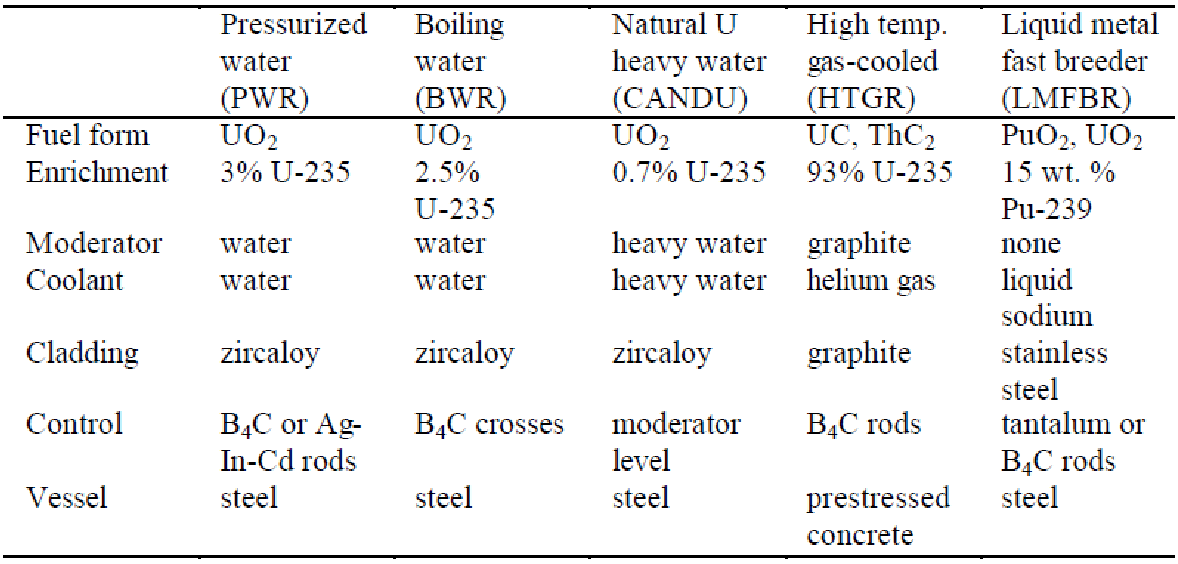
4.2.1.8. Biological Shielding

Shielding the radioactive zones in the reactor roan possible radiation hazard is essential to protect, the operating men from the harmful effects. During fission of nuclear fuel, alpha particles, beta particles, deadly gamma rays and neutrons are produced. Out oil these nc-1utroxrs and gamma rays are of main significance. A protection must be provided against them. Thick layers of lead or concrete are provided round the reactor for stopping the gamma rays. Thick layers of metals or plastics are sufficient to stop the alpha and beta particles.

4.2.1.9Coolant

Coolant flows through and around the reactor core. It is used to transfer the large amount of heat produced in the reactor due to fission of the nuclear fuel during chain reaction. The coolant either transfers its heat to another medium or if the coolant used is water it takes up the heat and gets converted into steam in the reactor which is directly sent to the turbine.

Coolant used should be stable under thermal condition. It should have a low melting point and high boiling point. It should not corrode the material with which it comes in contact. The coolant should have high heat transfer coefficient. The radioactivity induced in coolant by the neutrons bombardment should be nil. The various fluids used as coolant are water (light water or heavy water), gas (Air, CO2, Hydrogen, Helium) and liquid metals such as sodium or mixture of sodium and potassium and inorganic and organic fluids.



	Pressurized water (PWR)	Boiling water (BWR)	Natural U heavy water (CANDU)	High temp. gas-cooled (HTGR)	Liquid metal fast breeder (LMFBR)
Fuel form	UO_2	UO_2	UO_2	UC, ThC_2	PuO_2, UO_2
Enrichment	3% U-235	2.5% U-235	0.7% U-235	93% U-235	15 wt. % Pu-239
Moderator	water	water	heavy water	graphite	none
Coolant	water	water	heavy water	helium gas	liquid sodium
Cladding	zircaloy	zircaloy	zircaloy	graphite	stainless steel
Control	B_4C or Ag-In-Cd rods	B_4C crosses	moderator level	B_4C rods	tantalum or B_4C rods
Vessel	steel	steel	steel	prestressed concrete	steel

Tab.4.5: Reactor materials

4.2.2. Types of reactors

4.2.2.1. Pressurized water reactor (PWR)

A pressurized water reactor, in its simplest form ,is a light water cooled and moderated thermal reactor having an unusual core design, using both natural and highly enriched fuel. Pressurized water reactors (PWRs) constitute a majority of all western nuclear power plants. In a PWR the primary coolant (water) is pumped under high pressure to the reactor core, then the heated water transfers thermal energy to a steam generator. In contrast to a boiling water reactor, pressure in the primary coolant loop prevents the water from boiling within the reactor.

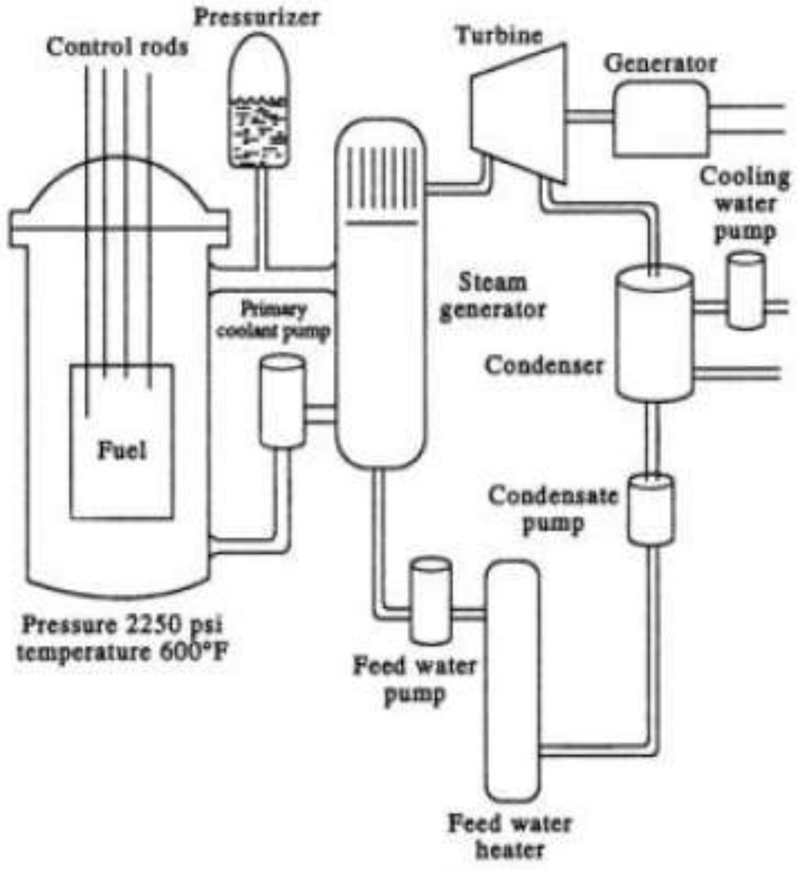


Fig.4.4: flow diagram of power plant with PWR reactor.

Advantages:

- PWR reactors are very stable due to their tendency to produce less power as temperatures increase; this makes the reactor easier to operate from a stability standpoint.
- PWR turbine cycle loop is separate from the primary loop, so the water in the secondary loop is not contaminated by radioactive materials.
- PWRs can passively SCRAM the reactor in the event that offsite power is lost. The control rods are held by electromagnets and fall by gravity when current is lost.

Disadvantages:

- The coolant water must be highly pressurized to remain liquid at high temperatures. This requires high strength piping and a heavy pressure vessel and hence increases construction costs. The higher pressure can increase the consequences of a loss of coolant accident.[14] The reactor pressure vessel is manufactured from ductile steel but, as the plant is operated, neutron flux from the reactor causes this steel to become less ductile. Eventually the ductility of the steel will reach limits determined by the applicable boiler and pressure vessel standards, and the pressure vessel must be repaired or replaced. This might not be practical or economic, and so determine the life of the plant.

- Pressurized water reactors cannot be refueled while operating. This decreases the availability of the reactor—it has to go offline for relatively long periods of time (~14 days).[*citation needed*]

- The high temperature water coolant with boric acid dissolved in it is corrosive to carbon steel (but not stainless steel); this can cause radioactive corrosion products to circulate in the primary coolant loop. This not only limits the lifetime of the reactor, but the systems that filter out the corrosion products and adjust the boric acid concentration add significantly to the overall cost of the reactor and to radiation exposure. Occasionally, this has resulted in severe corrosion to control rod drive mechanisms when the boric acid solution leaked through the seal between the mechanism of itself and the primary system.

- Natural uranium is only 0.7% uranium-235, the isotope necessary for thermal reactors. This makes it necessary to enrich the uranium fuel, which increases the costs of fuel production. If heavy water is used, it is possible to operate the reactor with natural uranium, but the production of heavy water requires large amounts of energy and is hence expensive.

- Because water acts as a neutron moderator, it is not possible to build a fast neutron reactor with a PWR design. A reduced moderation water reactor may however achieve a breeding ratio greater than unity, though this reactor design has disadvantages of its own.

4.2.2.2. Boiling water reactor (BWR)

The boiling water reactor (BWR) is a type of nuclear reactor used for the generation of electrical power. It is the second most common type of electricity-generating nuclear reactor after the pressurized water reactor (PWR). As compared to PWR, the arrangement of BWR plant is simple. The plant can be safely operated using natural convection with in the core or forced circulation for the safe operation of the reactor, the pressure in the forced circulation must be maintained constant irrespective of the load.

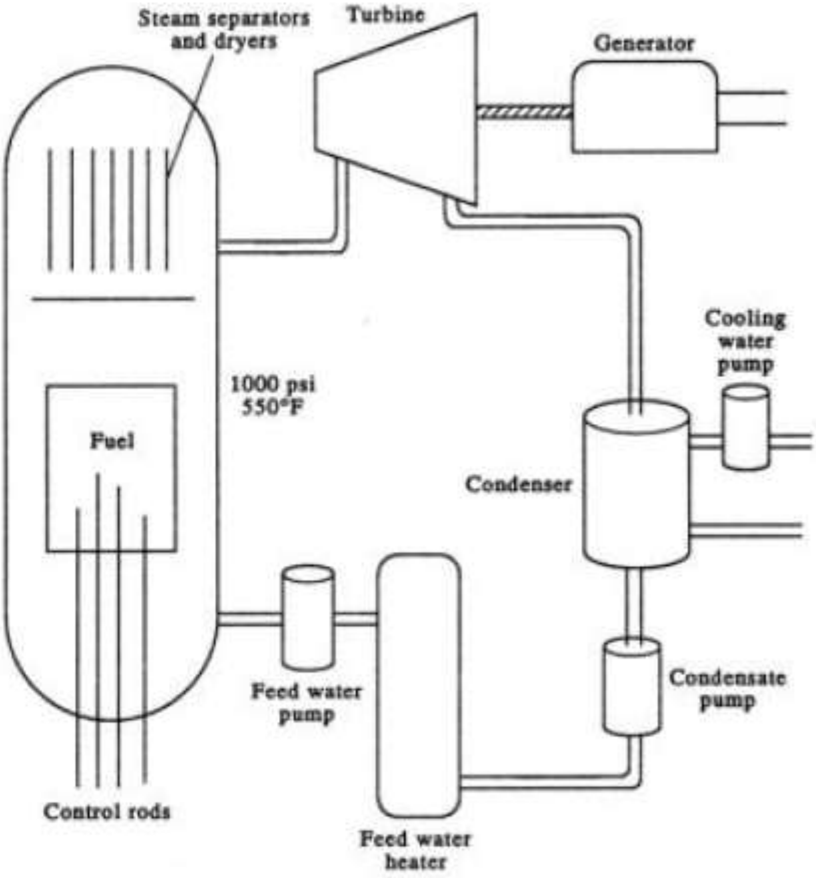


Fig.4.5: Flow diagram of power plant with BWR reactor

Advantages:

- The reactor vessel and associated components operate at a substantially lower pressure (about 75 times atmospheric pressure) compared to a PWR (about 158 times atmospheric pressure).
- Pressure vessel is subject to significantly less irradiation compared to a PWR, and so does not become as brittle with age.
- Operates at a lower nuclear fuel temperature.
- Fewer components due to no steam generators and no pressurizer vessel. (Older BWRs have external recirculation loops, but even this piping is eliminated in modern BWRs, such as the ABWR.)
- Lower risk (probability) of a rupture causing loss of coolant compared to a PWR, and lower risk of core damage should such a rupture occur. This is due to fewer pipes, fewer large diameter pipes, fewer welds and no steam generator tubes.

Disadvantages:

- Complex calculations for managing consumption of nuclear fuel during operation due to "two phase (water and steam) fluid flow" in the upper part of the core. This requires more instrumentation in the reactor core. The innovation of computers, however, makes this less of an issue.
- Much larger pressure vessel than for a PWR of similar power, with correspondingly higher cost. (However, the overall cost is reduced because a modern BWR has no main steam generators and associated piping.)
- Contamination of the turbine by short-lived activation products. This means that shielding and access control around the steam turbine are required during normal operations due to the radiation levels arising from the steam entering directly from the reactor core. This is a moderately minor concern, as most of the radiation flux is due to Nitrogen - 16, which has a half-life measured in seconds, allowing the turbine chamber to be entered into within minutes of shutdown.
- Though the present fleet of BWRs are less likely to suffer core damage from the 1 in 100,000 reactor-year limiting fault than the present fleet of PWRs are (due to increased ECCS robustness and redundancy) there have been concerns raised about the pressure containment ability of the as-built, unmodified Mark I containment - that such may be insufficient to contain pressures generated by a limiting fault combined with complete ECCS failure that results in extremely severe core damage. In this double worst-case, 1 in 100,000,000 reactor-year scenario, an unmodified Mark I containment is speculated to allow some degree of radioactive release to occur. However, this is mitigated by the modification of the Mark I containment; namely, the addition of an outgas stack system that, if containment pressure exceeds critical setpoints, will allow the orderly discharge of pressurizing gasses after the gasses pass through activated carbon filters designed to trap radionuclides.
- Control rods are inserted from below for current BWR designs. There are two available hydraulic power sources that can drive the control rods into the core for a BWR under emergency conditions. There is a dedicated high pressure hydraulic accumulator and also the pressure inside of the reactor pressure vessel available to each control rod. Either the dedicated accumulator (one per rod) or reactor pressure is capable of fully inserting each rod. Most other reactor types use top entry control rods that are held up in the withdrawn position by electromagnets, causing them to fall into the reactor by gravity if power is lost.

4.3. Complete working of a nuclear power plant:

Thermal energy in the circulating reactor coolant is transferred to a working fluid such as steam, by means of a heat exchanger or steamgenerator. In simplest construction, this device consists of a vessel partly filled with water, through which many tubes containing heated water from the reactor pass. Steam from the generator flows to a turbine, while the water returns to the reactor. The conversion of thermal energy of steam into mechanical energy of rotation of a turbine and then to electrical energy from a generator is achieved by conventional means. Steam at high pressure and temperature strikes the blades of the turbine, which drives the generator.

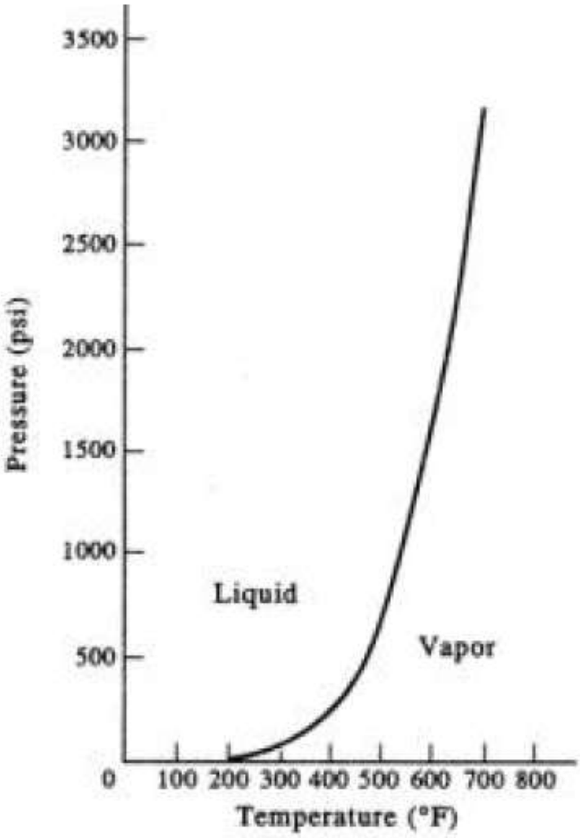


Fig.4.6: Relationship between pressure and temperature of water

The exhaust steam is passed through a heat exchanger that serves as condenser, and the condensate is returned to the steam generator as feed water. Cooling water for the condenser is pumped from a nearby body of water or cooling tower.