24. (*a*) Describe the function of surge tank and penstock used in the storage type hydro-electric plant.

(*b*) Explain briefly with line sketch a typical high pressure intake head works for a hydro-electric power station.

(*c*) A model is to be designed to find the performance of a prototype Francis runner. The prototype turbine has to develop 50,000 hp under a head of 225 m. The available head and flow in the laboratory for model testing are 36 m and 0.17 m^3/sec. The prototype runner runs at 600 r.p.m. and assuming overall efficiency of 90%, calculate (*i*) suitable scale ratio for the model, (*ii*) power developed by the model and (*iii*) the speed of the model runner.

25. (*a*) What are the factors to be taken into consideration for the selection of a hydroelectric plant ?

(*b*) Draw line sketch of a small medium head hydroplant showing dam, headworks, penstock and powerhouse.

(*c*) A hydroelectric station is to be designed for a catchment area of 102.5 sq. km, run-off 70 percent and the average rain as 127 cm. The head available is 381 metres. What power in MW can be developed if the overall efficiency of the plant is 80 percent ?

26. (*a*) What are the principal factors that make up the unit cost of power generation in a power plant ? Explain in brief how each affects the output cost.

(*b*) Compare steam and hydro plants as regards fixed and operating costs.

(*c*) The yearly duration curve of a certain plant can be considered as a straight line from 20000 to 3000 kW. To meet this load three turbo-generator units, two rated at 10000 kW each and one at 5000 kW, are installed. Determine installed capacity, capacity factor load factor and utilization factor.

27. (*a*) What are the advantages and disadvantages of a hydroelectric power plant over a thermal one ?

(*b*) What do you mean by 'specific speed' of a water turbine ? State its significance.

(*c*) Describe a method of governing a Pelton wheel with a neat sketch.

28. (*a*) Name the different types of hydraulic turbines used in hydel power stations. Also discuss briefly the suitability of each type for a particular range of net heads.

(*b*) Classify hydro plants and explain the use of each plant.

(*c*) Describe briefly the working of a pumped storage plant. Where can each type of plant be installed ?

29. (*a*) Explain the importance of hydrograph and flow duration curve on the selection of reservoir storage capacity. What do you understand by a 'pump storage plant' ?

(*b*) The table below provides data on the load requirement during 24-hour period at a certain location :

Time period	12 mid-night to 6 am	6 am to 10 am	10 am to 6 pm	6 pm to 8 pm	8 pm to 12 mid-night
Load in mW	20	100	160	80	40

If the load is shared by a combination of thermal and 'pump storage hydroplant' with the thermal plant carrying the base load lying somewhere between 80 MW, 100 MW, estimate the energy supplied to the thermal plant in MWh during 24 hours and the overall efficiency of the combined plant.

Assume η_{thermal} at full load = 35%

$\eta_{\text{pump}} = 80\%$

$\eta_{\text{hydraulic turbine}} = 90\%$.

30. (*a*) Enumerate the factors that you would consider while installing a hydropower plant.

(*b*) A turbine developing 7353 kW at a head of 27.4 with an overall efficiency of 80%, is to be supplied from a reservoir. The estimated run-off in m^3/month for 12 consecutive months of 30 days is given below :

$10^7 \times (9.64, 10.2, 8.64, 7.51, 6.8, 8.08, 11.34, 9.07, 8.64, 11.35, 9.92, 8.93)$

Assuming that the reservoir is full at the beginning determine (*i*) the minimum capacity of the reservoir to assure the required demand and (*ii*) the quantity that is wasted during the year.

31. Write notes on any two of the following :

(*i*) Surge tanks ;
(*ii*) Storage and pondage ;
(*iii*) Electrostatic precipitators.

7

Nuclear Power Plant

7.1. General aspects of nuclear engineering—Atomic structure—Atomic mass unit—Isotopes—Radioactivity—Nuclear radiation—Binding energy—Radioactive decay—Nuclear reactions—Nuclear cross-sections—Fertile materials—Fission of nuclear fuel—Nuclear Fusion—Comparison of fission and fusion processes. 7.2. Nuclear power systems. 7.3. Nuclear reactors—Introduction—Classification of nuclear reactors—Essential components of a nuclear reactor—Power of a nuclear reactor—7.4. Main components of a nuclear power plant. 7.5. Description of reactors—Pressurised water reactor (PWR)—Boiling water reactor (BWR)—CANDU (Canadian-Deuterium-Uranium) reactor—Gas cooled reactor—Liquid metal cooled reactors—Breeder reactor. 7.6. Selection of materials for reactor components. 7.7. Metals for nuclear energy. 7.8. Advantages of nuclear power plants. 7.9. Nuclear-plant site selection. 7.10. Application of nuclear power plants. 7.11. Economics of nuclear power plants. 7.12. Safety measures for nuclear power plants. 7.13. Nuclear power plants in India. 7.14. Future of nuclear power. 7.15. Useful by-products of nuclear power generation and their uses—Worked Examples—Highlights— Theoretical Questions—Unsolved Examples—Competitive Examinations Questions.

7.1. GENERAL ASPECTS OF NUCLEAR ENGINEERING

7.1.1. Atomic Structure

— **Atomic model.** An element is defined as a substance *which cannot be decomposed into other substances.* The *smallest particle* of an element which takes part in chemical reaction is known as an *'atom'*. The word atom is derived from Greek word 'Atom' which means indivisible and for a long time the atom was considered as such. *Dalton's atomic theory* states that (*i*) all the atoms of one element are precisely alike, have the same mass but differs from the atoms of other elements (*ii*) the chemical combination consists of the union of a small fixed number of atoms of one element with a small fixed number of other elements.

Various atomic models proposed by scientists over the last few decades are : 1. Thompson's plum puddling model, 2. Rutherford's nuclear model, 3. Bohr's model, 4. Sommerfeld's model, 5. Vector model, 6. Wave-mechanical model.

— The complex structure of atom can be classified into *electrons* and *nucleus.* The nucleus consists of *protons* and *neutrons* both being referred as *nucleons. Protons* are *positively* charged and *neutrons* are *neutral,* thus making complete nucleus as positively charged.

— The *electrons* carry *negative* charge and circulate about the nucleus. As the positive charge on proton particle is equal to the negative charge on electron particle, and the *number of electrons is equal to the number of protons,* atom is a neutral element. Any addition of the number of electrons to the neutral atom will make it negatively charged. Similarly any subtraction of the electrons will make it positively charged. Such an atom is known as *ion* and the process of charging the atom is termed an *ionisation.*

— The nuclear power engineering is specially connected with *variation of nucleons in nucleus.* Protons and neutrons are the particles having the mass of about 1837 times and 1839 times the mass of an electron.

— The modern atomic theory tells that the atom has a diameter of about 10^{-7} mm. In a neutral atom the electrons are bound to the nucleus by the electrostatic forces, which follows the Coloumb's law of forces, *i.e.*, like charges repel and unlike charges attract each other. The function of electrostatic force is similar to the gravitational force.

— The atomic spectrum study has revealed that every electron in an atom is in one group of specific states of motion which is corresponding to its total energy. In an atom the electrons are spinning around the nucleus in orbits. These orbits are called *shells*, which represent the energy levels for the electrons. *All the electrons having very nearly the same total energy are said to be in the same shell.* The shells have been named as *K*, *L*, *M*, *N* etc. Each shell consists of the specific maximum number of electrons. The *K* shell (inner shell) contains **2** electrons, *L* shell has **8** electrons, *M* shell is limited to **18** and the *N* shell possesses **32** electrons. In fact, the number of electrons in any orbit is equal to $2n^2$ where n is the serial number of the orbit taking first orbit nearest to the nucleus, *with the exception that the outermost orbit cannot have more than eight electrons* . In a given atom all orbits may not be complete. It is obvious from the study that *amplitude difference in energy between two shells is much more than the difference in between energy levels in one shell.* In a *shell less than the specified number of electrons may exist but not a large number.* The inner shell is filled up first and then the other successive shells are completed.

— The *chemical properties of the atom varies with composition of number of electrons in various shells and the state of energies within the shells determine the electrical characteristics of the atom.* For example, *Hydrogen* (H_2) consists of one electron in the *first shell*, *Helium* (He) has two electrons in the first sheli, *Lithium* (Li) has two electrons in first shell and one is second shell, *Carbon* (C) consists of two electrons in first and four in second shell.

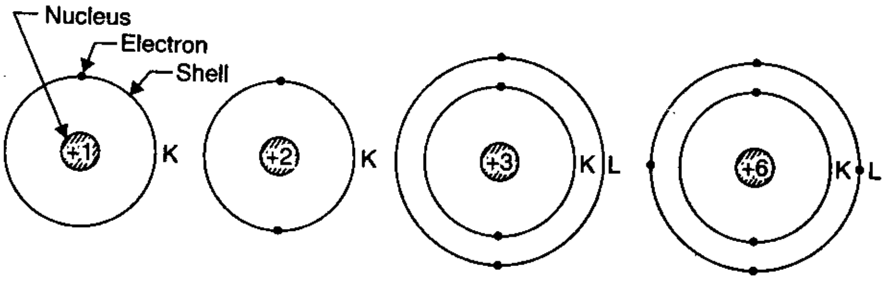


Fig. 7.1 (*a*). Atomic structure of H_2, He, Li and C.

— The electrons lying in the outermost shell are termed *valence electrons.* If the outermost shell is completely filled, the atom is stable and will not take any electron to fill up the gap. However, the incomplete outer shell will try to *snatch* the required number of electrons from the adjacent atom in a matter. The binding force between the electron and nucleus is the electrostatic force of attraction. *To emit one electron energy required is more than the electrostatic force of attraction. When the energy is supplied, the electron jumps from one discrete energy level to another permissible level. The process starts from outer shell.* The electron possesses the energy in two forms, *i.e.*, kinetic energy due to its motion and potential energy due to its position with respect to the nucleus. It is obvious that *electrons cannot exist in between the permissible orbits.*

— The charge of nucleus is represented by the *number of protons* present. This number is known as *atomic number* and designated by the letter *Z*. It also shows the position of atom in the periodic table. Hydrogen has only one number but natural uranium has ninety two. The atoms having *higher atomic number* have been developed artificially ranging from 93 to 102. These are einsteinium (Z = 99), Ferinium (Z = 100), and mendelevium (Z = 101). Platonium (Z = 94) is an important element to the nuclear power field.

The *mass number* (*A*) is the sum of total number of protons and neutrons in a nucleus. The number of electrons is represented by the letter *N*, *i.e.*, $N = (A - Z)$.

7.1.2. Atomic Mass Unit

The *mass of the atom is expressed in terms of the mass of the electron.* The unit of mass has been considered as $\frac{1}{16}$ th of the mass of neutral oxygen atom which contains 8 protons and 8 neutrons. The atomic mass unit (a.m.u.) is equal to $\frac{1}{16}$ th the mass of oxygen neutral atom.

One a.m.u. = 1.66×10^{-24} g

$$\text{Mass of proton} = 1837 \text{ me} = \frac{1837 \times 9.1 \times 10^{-28}}{1.66 \times 10^{-24}} = 1.00758 \text{ a.m.u.}$$

$$\text{Mass of neutron} = 1839 \text{ me} = \frac{1839 \times 9.1 \times 10^{-28}}{1.66 \times 10^{-24}} = 1.00893 \text{ a.m.u.}$$

It has been concluded that the density of matter in a nucleus is enormous. It has been investigated that the *radius of nucleus is equal* to $1.57 \times 10^{-3} \times 3\sqrt{A}$, where *A* is the number of nucleons in nucleus.

The density of uranium by calculations comes to 1.65×10^{14} g/cm^3. It has been found by calculations that *natural substance has density millions of times lower than that of nuclear matter.*

Electron volt. The energy is expressed in electron volt unit. An electron volt = *work done in moving an electron by a potential difference of one volt.* Or *it is the amount of energy acquired by any particle with one electronic charge, when it falls through a potential of one volt.*

One electron volt = 1.602×10^{-19} joule.

7.1.3. Isotopes

In any atom, the *number of electrons = number of protons.* This is independent of neutrons in the nucleus. *Atoms having different number of neutrons than the number of protons are known as 'Isotopes.'*

Example. Isotopes of hydrogen are shown below [Fig. 7.1 (*b*)].

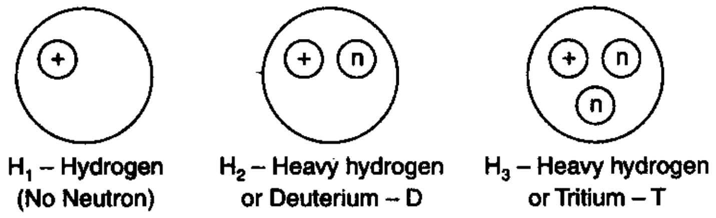


Fig. 7.1 (*b*)

These isotopes have the *same chemical properties* and *have the same atomic number* and *occupy the same place in the periodic table.* But the *nuclear properties* of each of the isotopes are different *because of the different number of neutrons in the nucleus.*

The isotopes of oxygen vary from O_{14} to O_{19}. The change of number of neutrons in nucleus affect the mass of atom.

Example. Weight of heavy hydrogen is twice the weight of simple hydrogen. This means a volume of H_2O weighs less than the same volume of D_2O.

The isotopes can be represented with mass number (*A*) as subscript and atomic number (*Z*) as subscript like $_ZH^A$.

Example. Hydrogen isotopes are represented as $_1H^2$ (Deuterium), $_1H^3$ (Tritium) and Uranium isotopes as U^{234}, U^{235}, U^{238}.

— The isotopes are *not stable* and *disintegrate* at a certain rate. The isotope which disintegrates at a fixed rate is called *Radioactive isotope* or *Radio isotope*.

The instability of the nucleus can be either by the separation of parent nucleus into 2 or more nuclei or by the rearrangement of nucleons in the matter so that there is an emission of particles or energy in the form of rays or by rearrangement of electrons. During this transformation there is emission of particles at a very high velocity. This is known as *radiation*.

We must note that for any specific isotope, the rate of radiation from a unit mass and also the energy distribution are fixed and cannot be changed by any method. Thus, for any isotope, the quantity of radiation per unit time can be determined easily.

7.1.4. Radioactivity

Radioactivity was originally discovered by Becquerel in 1896. This phenomenon is *confined almost entirely to the heaviest element* from 83 to 106 in the periodic table.

The phenomenon of spontaneous emission of powerful radiations exhibited by heavy elements is called 'radioactivity'. Radioactivity is essentially a *nuclear phenomenon* and is a *drastic process* because the element changes its kind. It is *spontaneous* and an *irreversible self-disintegrating activity* because the element breaks itself up for good. Those elements which exhibit this activity are called *radioactive elements*. Examples are : *Uranium, polonium, radium, radon, ionium, thorium, actinium* and *mesothorium.*

The radioactive radiations emitted by the radioactive elements are found to consist of the following :

(*i*) Alpha (α) rays or α-particles

(*ii*) β rays or β-particles

(*iii*) γ-rays or photons.

The radioactivity may be *natural* or *artificial.*

Natural radioactivity. It is that *which is exhibited by elements as found in Nature.* It is always found in heavier elements in the periodic table.

Artificial or induced radioactivity. The modern techniques of artifical transmutation of elements have made it possible to produce radioactivity in many other elements much lighter than those that occur in Nature. Such type of radioactivity is known as artificial or induced radioactivity.

The general *properties* of radioactive radiations are :

1. These radiations are *highly penetrating, they affect photographic plates, ionise gases, cause scintillations on fluorescent screen, develop heat and produce chemical changes.*

2. As radiations are given out, *new elements are formed* in an irreversible process—the new elements themselves being usually radioactive.

3. The emission of radiations is *spontaneous* and is not affected by external agents.

4. The emission is *not instantaneous* but is prolonged *i.e.*, it is extented over a period of time otherwise it would not have been discovered at all.

5. Except for radioactivity, there is nothing abnormal about the radioactivity elements as regards their physical and chemical properties.

7.1.5. Nuclear Radiation

In nuclear power technology there are only *five* types of radiation of interest, but there many mechanisms by which these five are produced in reactor systems. The five types of radiation (with electrical charges indicated as + or – for positive or negative, respectively, and mass in atomic mass units) are :

1. **Gamma rays** (or photons) : electromagnetic radiation.
2. **Neutrons** : uncharged particles, mass approximately 1.
3. **Photons** : + 1 charged particles, mass approximately 1.
4. **Alpha particles** : helium nuclei, charge + 2, mass 4.
5. **Beta particles** : electrons (charge – 1), positrons (charge + 1), mass very small.

1. Gamma rays

Prompt-fission gamma rays. These are produced as a result of the fissioning of a U^{235} (or other fissile-material) nucleus. The gamma rays are emitted within a fraction of a microsecond after fission takes place and are considered to be coincident with the fission process. Prompt-fission gamma rays carry off about 7 MeV/fission, with individual photon energies ranging from less than 0.5 MeV to greater than 1.5 MeV.

Fission-product-decay gamma rays. These are emitted from the fragments resulting from the fission process and their decay products. These radioactive fission products have half lives (the time it takes for one-half the atoms originally present to decay) from a fraction of a second to million of years. In most cases, they emit soft (low-energy) gamma rays and beta particles with energies lower than 1 MeV.

Capture gamma rays. These are emitted by nucleus of an atom instantaneously upon the capture of a neutron. The energy of these gamma rays is generally higher than those released by fission or decay. Many elements yield capture gamma rays in the 6 to 8 MeV range.

Activation-decay gamma rays. These are often omitted from the nucleus after a neutron-capture process, if the new nucleus formed is unstable. Most decays of this type are accomplished by electron emission accompanied by one or more gamma-rays photons. Each unstable (radioactive) isotope has a specific half-life and mode of decay which is an intrinsic property.

Inelastic-scattering gamma rays. These are emitted from a nucleus that has been excited to level above its ground state by interaction with an energetic neutron. These are emitted within an extremely short time after the interaction takes place, and the total energy carried off by these photons is less than or equal to the kinetic energy of the incident neutron.

2. Neutrons

Prompt-fission neutrons. These are produced as a result of the fissioning of a fissile material and, as in the case of prompt gamma rays, are considered to be emitted coincidentally with the fission process.

Delayed neutrons. These are emitted from several of the fission products with apparent half-lives of upto about 2 min. Although half-lives are usually ascribed to the production of delayed neutrons, they are actually emitted within less than a microsecond after the formation of a highly excited nucleus. The half-life actually describes the decay of a fission fragment to the highly excited fission product.

Photoneutrons. These are produced when a photon with energy greater than the binding energy of a neutron (the energy required to bind a neutron to the nucleus) interacts with a nucleus and ejects a neutron. This process is generally not important, since most isotopes have a high threshold for the reaction and a low probability of occurence above the threshold. Two isotopes used in some reactor systems which have low thresholds and a fairly significant probability of photoneutron interaction are hydrogen 2 (deuterium) and beryllium 9.

Activation neutrons. Neutron decay of an activated material occurs occasionally in cases other than delayed neutron decay of fission products. The only case which is of some interest in nuclear-reactor technology is the neutron decay of nitrogen 17, formed by fast-neutron irridiation of oxygen 17.

Reaction neutrons. These are the neutrons ejected from a nucleus by interaction with one of several particles. There are known cases of neutron emission resulting from a nucleus interacting with a neutron, proton, or alpha particle. Important use is made of this process in producing neutron sources for reactor start-up.

3. Protons

Protons are produced in a few radioactive-decay processes and more frequently by neutron-proton reactions in which an incident neutron causes a proton to be emitted from the nucleus.

4. Alpha particles

Alpha particles are produced by the decay of several fission products and a few activated materials as well as by a few neutron-alpha reactions in which an incident neutron interacts with and causes an alpha particle to be emitted from the nucleus.

5. Beta particles

Beta particles (electrons and positrons) are produced by several mechanisms, such as radioactive decay and pair production (in which a photon of high energy is converted into an electron-positron pair).

Effects of nuclear radiation on matter

Nuclear radiation, when it interacts with any material, deposits energy in the material and can have various effects. In chemical components the chemical form will be changed, in solids the crystalline structure may be altered, in any case heat will be generated. For charged particles and gamma rays the mechanisms of energy transfer is ionisation of the material traversed by the radiation. Ionization is the production of electrically charged particles by stripping orbital electrons from the electrically neutral atoms. In the case of neutrons, the primary energy-transfer process is a kinetic-energy exchange caused by collision of neutrons with nuclei of the matter traversed.

7.1.6. Binding Energy

The nucleus of an atom is formed when the nucleons come closer to each other and this distance between the two nucleons is of the order of nearly 10^{-12} mm. At the *moment of combination there is a release of energy* and is known as *'binding energy'*. Further if it is required to separate out or to disintegrate two nucleons the equivalent amount of binding energy is to be supplied from the external source to overcome the force of attraction. The binding energy can also be defined as the *energy required to overcome the binding forces of nucleus.*

When two nuclear particles are combined to form a nucleus, it is observed that, there is a difference in the mass of the resultant nucleus and the sum of the masses of two parent nuclear particles. This decrement of mass is known as *'mass defect'*. The *amount of mass defect is directly proportional to the amount of energy released.*

The nuclear binding energy per nucleon increases with the increase of the number of nucleons in the nucleus. Example : The binding energy per nucleon for H^2 is 1.109 MeV and for He^4 it is $28.2 \div 4 \approx 7.05$ MeV. A curve representing the variation of nuclear binding energy per nucleon with the mass number is shown in Fig. 7.2. Here the average value of binding energy per nucleon has been considered. The curve indicates that the average binding energy per nucleon increases as the mass number increases initially with the peak value of about 8.8 MeV at nearly 60 mass number. The elements falling in this region are nickel and iron. As the mass number increases still further, the binding energy curve falls gradually to 7.6 MeV for U^{238}. For U^{235} from the Fig. 7.2 the binding energy per nucleon is 7.7 MeV. At the point where mass number is 117, binding energy per nucleon is nearly 8.6 MeV.

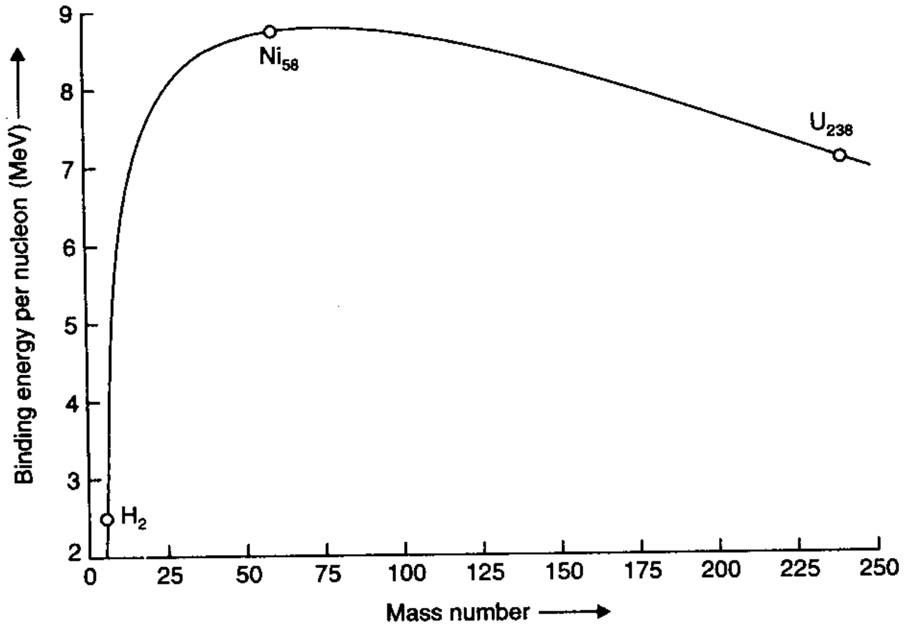


Fig. 7.2. Variation of average binding energy per nucleon with mass number.

U^{235} nucleus is splitted into two approximately equal nuclei. The formation of two nuclei will release the energy of about 0.9 MeV per nucleon. There is a release of energy as the mass number decreases within the range of 60 to 250 mass number. This release of energy is corresponding to the increase of mass defect. In fission process, the U^{235} nuclei is splitted to two other nuclei and energy is liberated.

It is evident from the above discussion that the nuclear transformations of other nucleus is also possible such as U^{235}, U^{233} and Pu^{239} (these are the important fuels used in the production of nuclear power).

An atom with even number of protons of mass number is more stable because of the pairing of protons and neutrons. This type of atom also possesses *higher binding energy per nucleon* and is represented as *even type of atom.* In nuclear physics, the first even or odd represents the even or odd number of protons respectively and second one represents the even or odd mass number. This is obvious from the practical data that the U^{235} is fissionable with slow neutrons (neutrons having less energy) but U^{238} is fissionable only when the neutrons are having energy more than 1 MeV.

7.1.7. Radioactive Decay

If has been observed that the emission of the particles in the form of alpha, beta or gamma radiations is not an instantaneous process. For various elements the decay time is different, which follows a certain *law*. Obviously the process is independent of the physical and chemical properties of the given isotope at a particular temperature and pressure.

The *law* states that the *small amount of disintegration of the isotope in a small period is directly proportional to the total number of radioactive nuclei and proportionality constant.*

If, N = Number of radioactive nuclei present at any time t,

N_0 = Initial number of such nuclei,

λ = Proportionality constant (also known as disintegration constant or the radioactive decay constant of the material), Then the above law can be stated in the form of equation as follows :

$$\Delta N = -\lambda N \Delta t \quad \text{...(7.1)}$$

or

$$\frac{dN}{dt} = -\lambda N \quad \text{...(7.2)}$$

The *negative* sign represents that during disintegration the number of the nuclei is *decreasing*.

Integrating the above equation (7.2) after proper arrangement within the proper limits, we get

$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_0^t dt \quad \text{...(7.3)}$$

or

$$\log_e N - \log_e N_0 = -\lambda t \quad \text{or} \quad \log_e \frac{N}{N_0} = -\lambda t$$

or

$$\frac{N}{N_0} = e^{-\lambda t} \quad \text{or} \quad N = N_0 e^{-\lambda t} \quad \text{...(7.4)}$$

$$\frac{dN}{dt} = -\lambda N = -\lambda N_0 e^{-\lambda t} \quad \text{...(7.5)}$$

The eqn. (7.5) represents that the *decay scheme follows the exponential law.*

Activity :

The *intensity of emitted radiation is termed activity.*

This is directly dependent on the rate of disintegration of the element.

If, A = activity at time t,

A_1 = initial activity,

k = detection coefficient,

Then,

$$A = k\left(-\frac{dN}{dt}\right) = k\lambda N = k\lambda N_0 e^{-\lambda t} = A_1 e^{-\lambda t} \quad \text{...(7.6)}$$

Half-life :

Half-life *represents the rate of decay of the radioactive isotopes.* The half-life is the *time required for half of the parent nuclei to decay or to disintegrate.*

Putting $N = \frac{N_0}{2}$ and $t = t_{1/2}$ in eqn. (7.6), we get

$$\frac{N_0}{2} = N_0 e^{-\lambda t_{1/2}} \quad \therefore \quad e^{-\lambda t_{1/2}} = 1/2$$

$$\therefore \quad \lambda t_{1/2} = \log_e 2 = 0.693 \quad \therefore \quad t_{1/2} = \frac{0.693}{\lambda} \quad \text{...(7.7)}$$

Here $t_{1/2}$ is the half-life of radioactive nuclei. After passing every half-life the number of nuclei is reduced to half and so is the activity. This process is repeated for the several half lives till the activity becomes negligible. The variation of half-life is from fraction of seconds to million of years.

Half-life of some of the metals is given below :

Metal	*Half-life*
Po-214	170 μ sec
I-137	25 sec
Carbon-14	5100 years
Th-232	1.4×10^{10} years
Uranium-238	4.525×10^9 years

Average (mean) life :

This indicates the average of total time for which the radioactive nuclei has disintegrated for several half lives. Hence this is *greater than half-life.* This is obtained by taking the sum of the decay time of the radioactive nuclei and then it is divided by the initial number of nuclei.

If T is the time of average life, then

$$T = \frac{-\int_0^\infty t\,dN}{N_0} = \frac{\lambda N_0 \int_0^\infty t e^{-\lambda t}\,dt}{N_0} \qquad \text{...(7.8)}$$

Now integrating by parts, we get

$$T = \left[-t e^{-\lambda t} - \frac{e^{-\lambda t}}{\lambda} \right]_0^\infty = \frac{1}{\lambda} \qquad \text{...(7.9)}$$

But $\quad t_{1/2} = \frac{0.693}{\lambda}$

From the above eqns. it is clear that mean life is 1.445 times greater than half-life.

Note. Number of disintegrations per second is the unit of radioactivity and is termed *curie*, as this phenomenon was first discovered by Curie.

7.1.8. Nuclear Reactions

During a nuclear reaction, the *change in the mass of the particle represents the release or an absorption of energy.* If the total mass of the particle after the reaction is reduced, the process releases the energy, consequently, the increase in the mass of the resultant particle, will cause the absorption of energy.

The equations of nuclear reactions are connected with the resettlement of protons and neutrons within the atom. The equations are much similar to chemical reactions. The energy variation is also of the order of MeV. In simple term the equation shows the *balance of neutron and proton.*

A nuclear reaction is written as follows :

(*i*) The bombarded nuclei or the target nuclei is written first from left hand side.

(*ii*) In the middle within brackets, first is the incident particle and second one the ejected.

(*iii*) On the right hand side, the resultant nucleus is placed.

A *neutron* is written as : ${}_0n^1$ because it has unit mass and it does not have any charge.

An *electron* is written as : ${}_{-1}e^0$ because its mass is negligible as compared to proton or neutron and its charge is equal but opposite to the charge of proton.

Some of the examples of reactions are given below :

(*i*) When ${}_{11}\text{Na}^{23}$ is bombarded with protons possessing high energy, it is converted to ${}_{12}\text{Mg}^{23}$

$${}_{11}\text{Na}^{23} + {}_1\text{H}^1 \longrightarrow {}_{12}\text{Mg}^{23} + {}_0n^1 + q \qquad \text{...(7.10)}$$

(where q = release or absorption of energy in the reaction)

(*ii*) When ${}_{13}\text{Al}^{27}$ is bombarded with high energy protons it is transformed to ${}_{14}\text{Si}^{27}$.

$${}_{13}\text{Al}^{27} + {}_1\text{H}^1 \longrightarrow {}_{14}\text{Si}^{27} + {}_0n^1 + q \qquad \text{...(7.11)}$$

(*iii*) When ${}_{13}\text{Al}^{27}$ is bombarded with deutrons, Al^{28} and proton may be produced.

$${}_{13}\text{Al}^{27} + {}_1\text{H}^2 \longrightarrow {}_{13}\text{Al}^{28} + {}_1\text{H}^1 \qquad \text{...(7.12)}$$

The eqns. (7.10), (7.11) and (7.12) may be written in the equation form as given below :

$$\text{Na}^{23}(p, n)\text{Mg}^{23} \qquad \text{...(7.13)}$$

$${}_{13}\text{Al}^{27}(p, n)\text{Si}^{27} \qquad \text{...(7.14)}$$

$$\text{Al}^{27}(d, p)\text{Al}^{28} \qquad \text{...(7.15)}$$

It is evident from the above mentioned reactions that the *nuclear reaction is followed by capturing a particle, resulting in a compound excited nucleus, which undergoes further transformation in a short period of time.*

The *transformation may adopt the following five main different paths :*

1. Elastic scattering. The neutron interacts with the nucleus and after transformation the compound nucleus emits a particle which is identical to the captured one. There is also no change in the resultant nucleus. The *total internal energy* of the bombarded nucleus and the restriking particle *will not change* at all. The process is known as *elastic scattering*. Elastic scattering is also termed as *elastic collision*. When the neutron strikes the nucleus, it imparts the part of initial kinetic energy and momentum to the nucleus which causes the displacement of the nucleus in the crystal lattice by a significant distance and can *change the structural properties of the material.*

In elastic scattering process the *kinetic energy of neutron is reduced and is beneficial to slow down the neutron is reactor.* In this transformation, *there is neither release nor absorption of energy but as a result of collision, redistribution of kinetic energy takes place.*

Example of elastic scattering. When a neutron strikes a light nucleus (*e.g.* hydrogen nucleus), the velocity of the neutron is very much reduced and the energy is transferred to the proton. Here most of the energy is transferred because both the particles are having nearly the *same masses*. It has been observed that in such a single collision, the loss of energy of the proton is nearly 70 to 75 percent. In case the neutron impacts with the heavy nucleus, the energy loss in single collision is *less*. With carbon nucleus this loss amounts to nearly 12 to 17 percent of the initial value. The reaction is written as $C^{12}(n, n)C^{12}$.

2. Inelastic scattering. The composition of the incident particle and ejected particle remains unchanged. When the particle interacts with the nuclei it loses its kinetic energy and the target nucleus is excited. The energy is released in the form of gamma emission. This transformation is known as *inelastic scattering* or collision. The process is limited to the condition that the neutron should have minimum energy sufficient to excite the target nucleus. The reaction is completed with the absorption or release of energy. The neutron energy loss is of the order of 10 to 20 percent of the initial value.

When a fast moving neutron hits the U^{238} nucleus, the nucleus is excited and there is an emission of gamma quantum $[U^{238}\ (n, \eta\gamma)\ U^{238}]$.

3. Capture. In this process the incident particle may be captured or absorbed by the nucleus and may raise the mass number by unity. The nucleus is excited and the energy is emitted in the form of gamma quantum. The *artificial radioactive materials are produced by this process.* In a reactor, Co-60 isotope is produced by bombarding the natural Co-59 with neutrons. The reaction has both the possibilities of producing the stable and unstable nucleus and may result in (n, γ) or (p, γ) reactions. This transformation may take place with elastic scattering. When a neutron interacts with light hydrogen, it forms heavy hydrogen, deuterium. The mass of deuterium is less than its components. This mass defect is corresponding to the release of gamma quantum.

4. In this reaction, the *impinging particle is trapped in the nucleus but the ejected particle is a different one. The composition of the resultant nucleus is also different from the parent nucleus.*

5. Fission. *When the nucleus is excited too much, it splits into two mostly equal masses.* This particular reaction is suited only to the *heavy nucleus* such as U^{233}, U^{235}, Pu^{239} etc. The transformation is known as *fission*. The produced two nuclei are lighter nuclei ; they have *more binding energies per nucleon and hence this reaction always releases the energy* (Fig. 7.2).

7.1.9. Nuclear Cross-sections

Cross-sections (or attenuation coefficients) *are measures of the probability that a given reaction will take place between a nucleus or nuclei and incident radiation.*

Cross-sections are called either *microscopic* or *macroscopic*, depending on whether the reference is to a single nucleus or to the nuclei contained in a unit volume of material.

Microscopic cross-section

It is a measure of the probability that a given reaction will take place between a single nucleus and an incident particle. Microscopic cross-section is usually denoted by the symbol σ and is expressed in terms of the *effective area that a single nucleus presents for the specified reaction*. Since these cross sections are usually quite small, in the range of 10^{-22} to 10^{-26} cm²/nucleus it is general practice to express them in terms of a unit called the *barn*, which is 10^{-24} cm²/nucleus.

Macroscopic cross-sections

These are the products of microscopic cross-sections and the atomic density in nuclei per cubic centimeter and are equivalent to the total cross-section, for a specific reaction of, all the nuclei in 1 cm³ of material. Macroscopic cross-sections are denoted by the symbol Σ for *neutrons* and μ for *gamma rays* and have the units cm^{-1}.

Gamma ray cross-sections

Although there are a large number of interaction processes that take place between gamma rays and matter, the most commonly used are the energy-absorption cross-section (used to determine gamma heating and dose rates) and the total attenuation cross-section (used to determine material gamma-ray attenuation and for shielding design).

Neutron cross-sections

Neutrons undergo a large number of different interaction processes with matter, and, unlike gamma rays, many of these individual interactions must be evaluated. Neutron cross-sections of general use are :

(*i*) Fission	(*ii*) Gamma-ray production
(*iii*) Activation	(*iv*) Elastic scattering
(*v*) Inelastic scattering	(*vi*) Reaction particle production
(*vii*) Total absorption	(*viii*) Total attenuation.

Both neutron and gamma-ray cross-sections are *energy-dependent properties*. Plots of gamma-ray cross-section *vs* photon energy for all materials are, over the energy range of interest, *smooth curves*, whereas for neutron cross sections the curves of many materials *show gross variations from a smooth curve*. The variations in neutron cross-sections show up as peaks and valleys on the cross-section plot ; these peaks are called *resonances*. When a material has a large number of resonance peaks over a portion of the energy range, this portion of the cross-section plot is called a *resonance region*. The *resonance region can have a significant effect on reactor design*, since the material U^{238} which is present in most fuels has a relatively wide resonance region which can cause extensive neutron absorption during the slowing down of neutrons to thermal energy.

The known cross-sections for materials potentially useful in reactor systems are used as primary criteria in materials selection. For example, high-neutron-absorption cross-section materials would not normally be used as materials of construction in the vicinity of a reactor core to prevent competition for the neutrons required to sustain the fission process ; and high activation cross-section materials would not be chosen, if they can be avoided, in a region exposed to a high neutron flux during operation, if that region is to be accessible after reactor shut-down.

7.1.10. Fertile Materials

It has been found that some materials are not fissionable by themselves but they *can be converted to the fissionable materials*, these are known as *fertile materials*.

Pu^{239} and U^{233} are not found in nature but U^{238} and Th^{232} can produce them by nuclear reactions. When U^{238} is bombarded with slow neutrons it produces ${}_{92}U^{239}$ with half-life of 23.5 days which is unstable and undergoes two beta disintegrations. The resultant Pu^{239} has half-life of 2.44×10^4 yrs and is a good alpha emitter.

$$_{92}U^{238} + {}_0n^1 \longrightarrow {}_{92}U^{239} + \gamma \qquad ...(7.16)$$

$$_{92}U^{239} \xrightarrow{23.5 \text{ min.}} - {}_{-1}e^0 + {}_{91}Np^{231} \qquad ...(7.17)$$

$$_{93}Np^{239} \xrightarrow{2.3 \text{ days}} {}_{-1}e^0 + {}_{94}Pu^{239} \qquad ...(7.18)$$

During conversion the above noted reactions will take place. The other isotopes of neptunium such as 2.1 day Np^{238} and plutonium can also be produced by the bombardment of heavy particles accelerated by the cyclotron.

The nuclear transformations to convert $_{90}Th^{232}$ to U^{233} are given below :

$$_{90}Th^{232} + {}_0n^1 \longrightarrow {}_{90}Th^{233} + \gamma \qquad ...(7.19)$$

$$_{90}Th^{233} \xrightarrow{23.3 \text{ min.}} {}_{91}Pa^{233} + {}_{-1}e^0 \qquad ...(7.20)$$

$$_{91}Pu^{233} \xrightarrow{27.4 \text{ days}} {}_{92}U^{233} + {}_{-1}e^0 \qquad ...(7.21)$$

U^{235} is the source of neutrons required to derive Pu^{239} and U^{233} from Th^{232} and U^{238} respectively. This process of conversion is performed in the *breeder reactors*.

Other fissionable materials : Th^{227}, Pa^{232}, U^{231}, Np^{238} and Pu^{241} are the other nuclides which are having high cross-sections for neutron thermal fission. Pu^{241} is the important nuclide which is used in plutonium fueled power reactors.

7.1.11. Fission of Nuclear Fuel

Fission is the *process that occurs when a neutron collides with the nucleus of certain of the heavy atoms, causing the original nucleus to split into two or more unequal fragments which carry off most of the energy of fission as kinetic energy*. This process is *accompanied by the emission of neutron and gamma rays.*

Fig. 7.3 is a representation of the fission of uranium 235. The *energy released as a result of fission is the basis for nuclear-power generation*. The release of about *2.5 neutrons/fission* makes it possible to produce *sustained fissioning*.

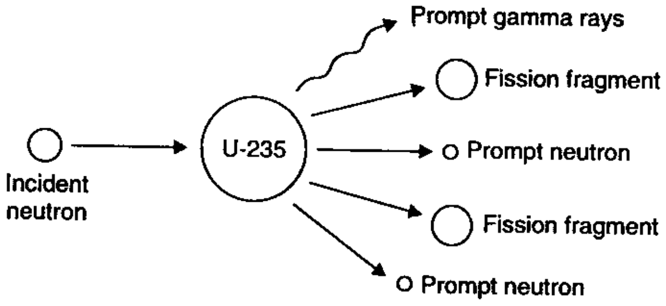


Fig. 7.3. Fission of uranium 235. Incident neutron, upon colliding with U^{235} nucleus, causes fission to take place, resulting in the production of fission fragments, prompt neutrons and prompt gamma rays.

The *fission fragments* that result from the fission process are *radioactive* and decay by emission of beta particles, gamma rays and to a lesser extent alpha particles and neutrons. The neutrons that are emitted after fission, by decay of some of the fission fragments, are called *delayed neutrons*. These are of the utmost importance, since *they permit the fission chain reaction to be easily controlled.*

The total detectable *energy released* owing to the fission of a single nucleus of uranium 235 is 193 MeV (milli electron volts), distributed as shown below :

Distribution of Fission Energy

	MeV
Instantaneous energy release :	
Kinetic energy of fission fragments	168
Prompt-gamma-ray energy	7
Kinetic energy of prompt neutrons	5
Instantaneous total	180
Delayed energy release :	
Beta particle decay of fission products	7
Gamma-ray decay of fission products	6
Delayed total	13

As is shown above, the neutron emitted as a result of fission of a uranium 235 nucleus carry off 5 MeV of kinetic energy. Since on average there are about 2.5 neutrons emitted/U^{235} fission, the average neutron energy is 2 MeV. Actually fission neutrons are emitted with an energy speed of from nearly zero energy to approximately 16 MeV, the bulk of the them being in the 1- to 2-MeV energy region.

Note. Although not strictly a result of the fission process, there is an additional 5 to 8 MeV emitted per fission as a result of the capture of neutrons not used in the fission chain reaction. About 1 MeV of this total is emitted over a period of time owing to decay of activation products, and the remainder is emitted immediately upon neutron capture.

Most of the reactors in existence today or planned for the near future are called *thermal reactors*, since they depend on neutrons which are in or near thermal equilibrium with their surroundings to cause the bulk of fissions. *These reactors make use of the fact that the probability for fission is highest at low energy by slowing down the neutrons emitted as a result of fissioning to enhance fission captures in the fuel.* Loss of neutrons to non-fission-capture processes is lessened by minimising the quantity of non-fissile material in or near the reactor core. *The materials used to decelerate fast neutrons to thermal energy levels* are called **moderators.** Effective and efficient moderators must slow the fission neutrons, in the 1- to 2-MeV range to thermal energy at about 0.025 eV to less that 0.1 eV. This effect must be produced in a small volume and with very little absorption.

The Chain reaction

A chain reaction is that process in which the number of neutrons keeps on multiplying rapidly (in geometrical progression) during fission till whole of the fissionable material is disintegrated. The chain reaction will become self-sustaining or self propagating only if, for every neutron absorbed, at least one fission neutron becomes available for causing fission of another nucleus. This condition can be conveniently expressed in the form of *multiplication factor or reproduction factor* of the system which may be definded as

$$K = \frac{\text{No. of neutrons in any particular generation}}{\text{No. of neutrons in the preceding generation}}$$

If $K > 1$, chain reaction will continue and if $K < 1$, chain reaction cannot be maintained.

Fig. 7.4 shows schematically a chain reaction which when set off ultimately leads to a rapidly growing avalanche having the characteristic of an explosion. The rate of growth of the chain process is shown in Fig. 7.5.

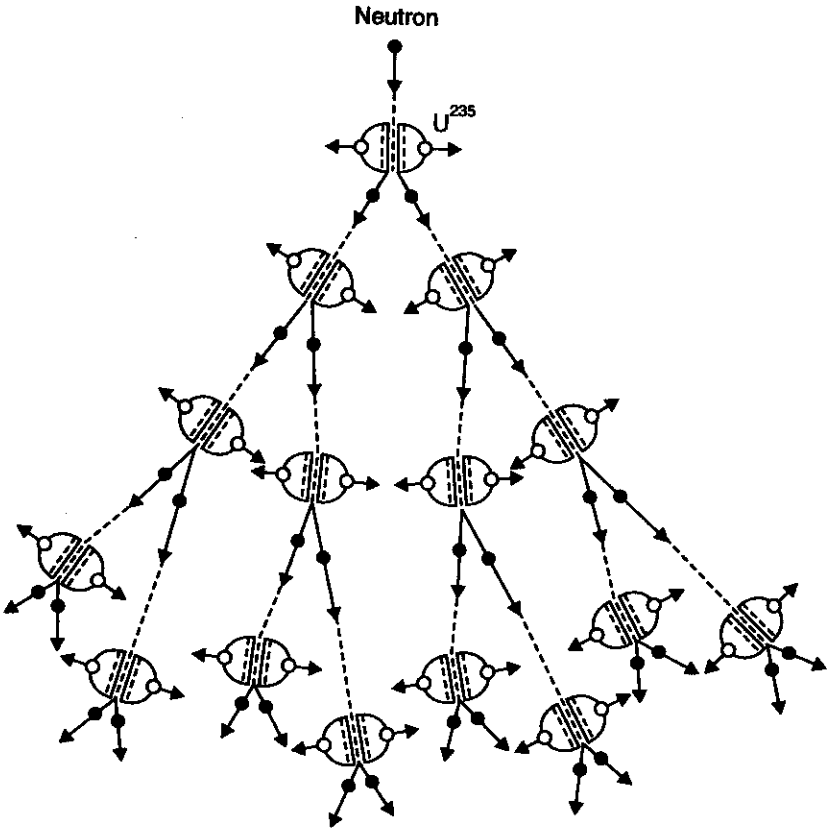


Fig. 7.4. Chain reaction.

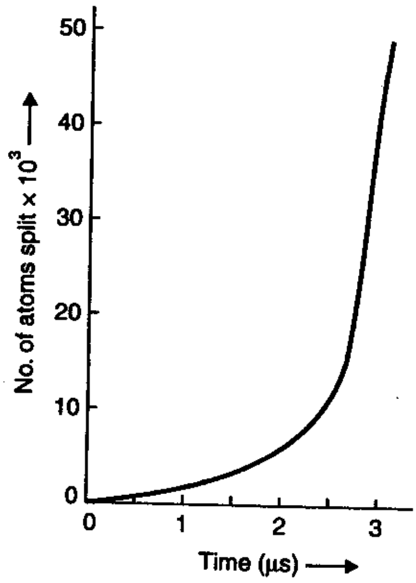


Fig. 7.5. The rate of growth of the chain process.

Requirements of fission process

The *requirements of fission process* may be summed up as follows :

1. The neutrons emitted in fission must have adequate energy to cause fission of another nuclei.

2. The produced number of neutrons must be able not only to sustain the fission process but also to increase the rate of fission. Certain loss of neutrons during the process is also to be accounted.

3. The process must be followed by the liberation of energy.

4. It must be possible to control the rate of energy liberation *i.e.*, the rate of fission by some means.

Since the chain reaction requires that one neutron from each fission cause another fission, it is worth noting that there are several processes competing for the neutrons produced. These processes are non-fission capture in the fuel material, capture in the fuel container (cladding), core structural materials, moderator and coolant, and leakage of neutrons from the core. *To permit a chain reaction to take place, it is necessary to design a system in which, after accounting for all neutron losses due to non-fission absorption and leakage, there is still at least one neutron remaining to produce another fission.*

The *minimum quantity of fuel required for any specific reactor system* is called the '*critical mass*' and the size associated with this mass is called the '*critical size*'. When nuclear fuel is assembled just to the point of a critical mass, the reactor is said to "*go critical*" *i.e.*, to reach the point of just sustaining a chain reaction. Natural uranium contains only about 0.7% of the fissile isotope U^{235}. Since U^{238} which makes up the balance absorbs neutrons, a nuclear reactor which will sustain a chain reaction with natural uranium requires a large critical mass (and size) and the use of moderator and materials of construction which have very low absorption cross-sections. To reduce the critical mass required and permit more flexibility in material and design choice, uranium fuel is frequently *enriched* in U^{235} content, thereby increasing the fraction of neutron captures that occur in U^{235} and cause fission.

7.1.12. Nuclear Fusion

'Nuclear Fusion' is the process of combining or fusing two lighter nuclei into a stable and heavier nuclide. In this case also, *large amount of energy is released* because mass of the product nucleus is *less* than the masses of the two nuclei which are fused.

Several reactions between nuclei of low mass numbers have been brought about by accelerating one or the other nucleus in a suitable manner. These are often fusion processes accompanied by release of energy. However, reactions involving artificially-accelerated particles cannot be regarded as of much significance for the utilisation of nuclear energy. To have practical value, fusion reactions must occur in such a manner as to make them *self-sustaining, i.e., more energy must be released than is consumed in initiating the reaction.*

It is thought the energy liberated in the sun and other stars of the main sequence type is due to the nuclear fusion reactions occurring at the very high stellar temperature of 30 million °K. Such processes are called *thermonuclear reactions* because they are temperature-dependent.

7.1.13. Comparison of Fission and Fusion Processes

The comparison between '*Fission*' and '*Fusion*' processes is given below :

Fission	Fusion
1. When heavy unstable nucleon is bombarded with neutrons, the nucleus *splits* into fragments of equal mass and energy is released.	1. Some light elements *fuse together* with the release of energy.

2. About *one thousandth* of the mass is *converted into energy.*	2. It is possible to have *four thousandths* of mass *converted into energy.*
3. Nuclear reaction *residual problem is great.*	3. Residual problem is *much less.*
4. Amount of radioactive material in a fission reactor is *high.*	4. A possible advantage is that the total amount of radioactive material in a working fusion reactor is likely to be *very much less* than that in a fission reactor.
5. Because of higher radioactive material, *health hazards is high in case of accidents.*	5. Because of lesser radioactive material, *health hazards is much less.*
6. It is *possible to construct self-sustained fission reactors* and have positive energy release.	6. It is *extremely difficult to construct controlled fusion reactors.*
7. *Manageable temperatures* are obtained.	7. Needs *unmanageable temperatures* like 30 million degrees for fusion process to occur.
8. Raw fissionable material is *not available in plenty.*	8. Reserves of deuterium, the fusion element, *is available in great quantity.*

7.2. NUCLEAR POWER SYSTEMS

A nuclear-fueled power-producing system consists essentially of the following :

(*i*) *A controlled fission heat source.*

(*ii*) *A coolant system to remove and transfer the heat produced.*

(*iii*) *Equipment to convert the thermal energy contained in the hot coolant to electric power.*

Regardless of the type of fission heat source used, the basic mechanism is fission of nuclear fuel to produce thermal energy. This thermal energy is removed from the heat source (reactor core) by contacting the fuel with a coolant which can be used directly as the working fluid in the power-conversion cycle or indirectly to heat another fluid to be used as the working fluid.

In some cases an intermediate heat-transfer loop is inserted between the reactor coolant and the working fluid, to increase isolation of the radioactive reactor coolant from the conventional power-producing equipment. The working fluid is then used to drive a turbo-generator set to produce electrical power.

Though several other methods are feasible for direct conversion of fission energy to electric power (*i.e.*, thermoelectric, thermionic, photoelectric, etc.), these methods are not at present suitable for the production of large quantities of power.

Schematic representations of nuclear power systems using the direct, indirect, and indirect with intermediate heat-transfer approaches are shown in Fig. 7.6.

Nuclear power systems differ in a number of respects from fossil-fuel systems. Some of the more important *considerations* that differentiate nuclear-fueled plants from fossil-fueled plants are listed below :

1. Nuclear fuel is charged to a power plant infrequently and has a relatively long life, usually measured in months or years, as compared with the continuous fuel-feed requirements for fossil-fueled plants.

2. Burned nuclear fuel is radioactive ; it requires remote handling and special processing and disposal.

3. Major portions of a nuclear plant are radioactive during and after operation, requiring special precautions for maintenance of much of the plant.

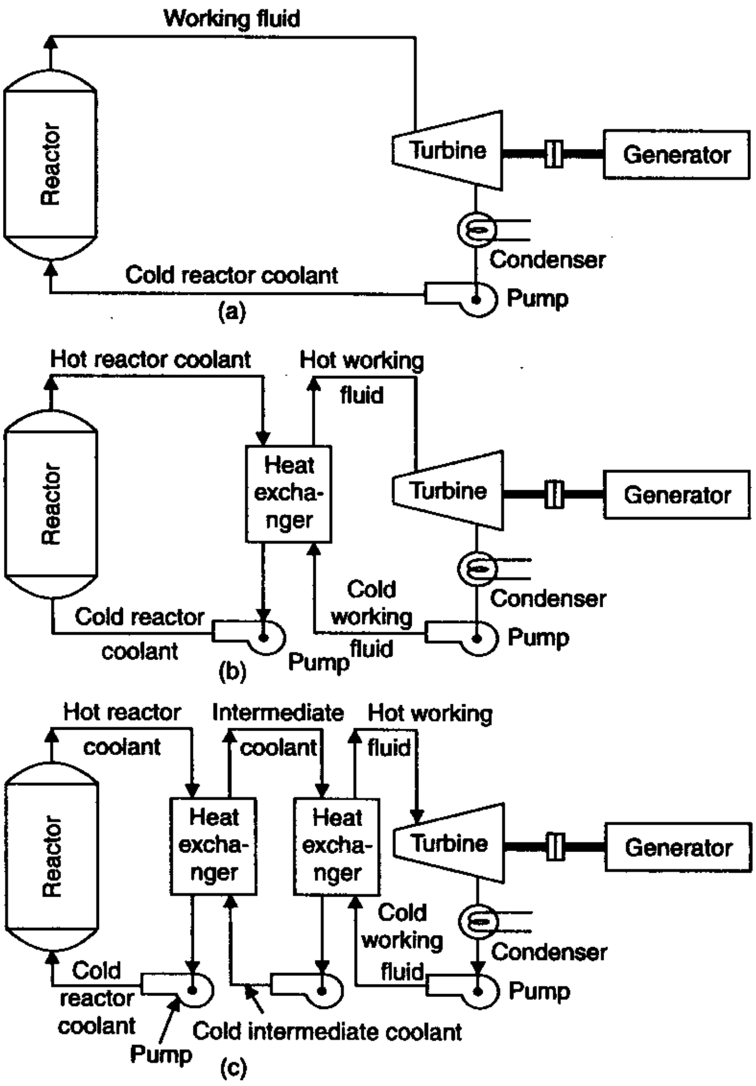


Fig. 7.6. Schematics of nuclear power systems. (*a*) Direct cycle, reactor coolant used as the working fluid ; (*b*) indirect cycle, reactor coolant transfers heat to separate working fluid ; (*c*) indirect cycle with intermediate loop, reactor coolant transfers heat through intermediate heat-transfer loop to working fluid.

4. Special system designs are required to prevent radioactivity release during normal operation or due to accidents.

5. Control and instrumentation requirements are strongly influenced by safety requirements and are related to reactor stability, load-following requirements, and the capability of a reactor to increase power output with no additional fuel input.

6. Nuclear fuel is highly processed material generally used in a precise fabricated form, as opposed to fossil fuels, which are essentially raw materials used with only minimal rough processing.

7. The use of nuclear fuel does not require combustion air, thus obviating thermal stack losses and related problems.

These considerations give rise to the general requirements, complexities, and problems of nuclear systems.

7.3. NUCLEAR REACTORS

7.3.1. Introduction

Definition. *A nuclear reactor is an apparatus in which nuclear fission is produced in the form of a controlled self-sustaining chain reaction.* In other words, it is a controlled chain-reacting system supplying nuclear energy. It may be looked upon as a sort of nuclear furnace which burns fuels like U^{235}, U^{233} or Pu^{239} and, in turn, *produces many useful products like heat, neutrons and radioisotopes.*

Mechanism of heat production. Most of the energy is imparted to the two fission fragments into which the nucleus divides causing them to move at high speed. However, because they have taken birth in a dense mass of metal, they are rapidly slowed down and brought to rest by colliding with other atoms of the metal. In so doing, their energy is converted into heat in much the same way as energy given up by a slowing motor can be converted into heat in the brake lining. In this way, the mass of uranium metal gets heated up.

7.3.2. Classification of Nuclear Reactors

Nuclear reactors are **classified** according to the *chain reacting system, use, coolants, fuel material etc.*

1. Neutron energies at which the fission occurs

(*i*) Fast fission is caused by high energy neutrons	*Fast reactors*
(*ii*) Intermediate or epithermal	*Intermediate reactors*
(*iii*) Low energy *i.e.*, thermal	*Slow reactors*

On the basis of the energy of the neutrons to cause fission the reactors have been divided into three groups—*fast, intermediate and thermal*. (*a*) In ***fast reactors*** the high velocity neutrons produced by fission are *utilised directly* to cause fission of the fuel in the reactor. The velocity of the neutrons is *not reduced deliberately*. (*b*) If in a reactor the fission process is maintained due to the slow neutrons capture, the reactor is known as ***slow reactor***. The minimum velocity to which neutrons *are slowed down* before the fission is equal to the thermal velocity which the slow neutrons may acquire in a state of thermal equilibrium with the medium. This velocity is of the order of 2150 m/s at room temperature which is equivalent to $\frac{1}{40}$ eV or neutron energy. The neutrons associated with the energy of this order are known as *thermal neutrons* and the reactor as *thermal reactors*. With the *moderator the neutrons are slowed down*. The *main advantage is that the probability of reaction increases*. (*c*) If the velocity of neutrons is kept between both the above noted limits, the reactors are termed as '***intermediate reactors***'.

2. Fuel-moderator assembly

(*i*) Homogeneous reactors (*ii*) Heterogeneous reactors.

In '*homogeneous reactor*' *the fuel and moderator are mixed to form a homogeneous material*, *i.e.*, uranium fuel salt forms a homogeneous solution in water which is a moderator or fine particles of uranium and carbon gives a mechanical mixture.

In '*heterogeneous reactor*' the fuel is used in the form of rods, plates, lamps or wires and the moderator surrounds the each fuel element in the reactor core.

3. Fuel state

(*i*) Solid (*ii*) Liquid (*iii*) Gas

The nuclear fuel is available in three states—solid, liquid and gas. In reactors the fuel is mostly used in solid state or in the form of solution dissolved in water. The *liquid metal reactors are in practical use.*

4. Fuel material

(*i*) Natural uranium with U^{235} contents (occurs in nature)

(*ii*) Enriched uranium with more than 0.71 of U^{235}

(*iii*) Pu^{239}, Pu^{241} or Pu^{239} (man made)

(*iv*) U^{-233} (man made)

Considering the necessary requirement of fission process and its availability economically the fuels used in reactors are *uranium, plutonium* and *thorium.* U^{235} is easily available in natural uranium (*i.e.*, 0.7%) and its content increases upto 90% in enriched uranium.

5. Moderator

(*i*) Water (H_2O)

(*ii*) Heavy water (D_2O)

(*iii*) Graphite

(*iv*) Beryllium or beryllium oxide

(*v*) Hydrocarbons or hydrides.

A moderator's function is to *absorbs the part of the kinetic energy of the neutrons.* The neutrons collide directly with the moderator and thus slowed down. No ideal moderator is available in nature or has been produced artificially. The light weight nuclei materials are not suited at all as a moderator because they do not possess the property of absorption of neutrons.

Light water, heavy water and *graphite* are the *most common moderators* used in reactors.

6. Principal product

(*i*) Research features to produce neutrons	*Research reactors*
(*ii*) Power reactor to produce heat	*Power reactors*
(*iii*) Breeder reactors to produce fissionable materials	*Breeder reactors*
(*iv*) Production reactors to produce isotopes	*Production reactors*

Research reactors. These are designed to produce the high neutron flux for research work and these neutrons are used to determine the neutron properties of interaction with the nuclei and the effect of bombardment of neutrons on the materials. The reactors are operated at high neutron flux and low power level otherwise the cooling will be a problem. The unit is cooled constantly during operation. The by-products are heat and fission products which are removed during operation.

Power reactors. In these reactors the energy is produced in heat form which is carried away to the heat exchanger by circulating the coolant through the reactor and heat exchanger. In the heat exchanger the coolant converts the water into steam to run the turbine. The by-products are fission products, neutrons and other radiation particles.

These reactors are useful to produce *huge amount of power* and are *widely used in power plant stations.* In such reactors *consumption is very low.*

Breeder reactors. A breeder reactor *converts fertile materials into fissionable materials* such as U^{238} and Th^{232} to Pu^{239} and U^{233} respectively *besides the power production.* It is worth noting that the amount of fissionable material produced is *more* than its consumption of fissionable material. By-products are the same as those of power reactors.

Production reactors. The output of such reactors is radioactive materials which are used as sources of radiation and tracers in research in all areas of science. By-products are the same as those of power reactors.

7. Coolant

(*i*) Air, carbon or helium cooled reactors

(*ii*) Water or other liquid cooled reactors

(*iii*) Liquid metal cooled reactors.

In *gas-cooled reactors* the amount of gas required to extract the heat is too much and therefore these reactors are expensive. Gases have poor heat carrying capacity. CO_2 and He have been used in the early reactors. *Mostly water is used as a coolant.*

Liquid metal cooled reactors are also suitable as the metal is having high boiling point and low steam pressure. These are the power reactors.

8. Construction of core

(*i*) Cubical
(*ii*) Cylindrical
(*iii*) Octagonal
(*iv*) Spherical
(*v*) Slab
(*vi*) Annulus.

The proper shape to the core is given on the practical consideration and can have cubical, cylindrical or ring type construction.

7.3.3. Essential Components of a Nuclear Reactor

The essential components of a nuclear reactor are as follows :

1. Reactor core
2. Reflector
3. Control mechanism
4. Moderator
5. Coolants
6. Measuring instruments
7. Shielding.

1. Reactor core :

The reactor core is that part of a nuclear power plant where fission chain reaction is made to occur and where *fission energy is liberated in the form of heat for operating power conversion equipment.* The *core* of the reactor consists of an assemblage of fuel elements, control rods, coolant and moderator. Reactor cores generally have a shape approximating to a right circular cylinder with diameters ranging from 0.5 m to 15 m. The pressure vessels which houses the reactor core is also considered a part of the core (Fig. 7.7). The fuel elements are made of plates or rods of uranium metal. These plates or rods are usually clod in a thin sheath of stainless steel, zirconium

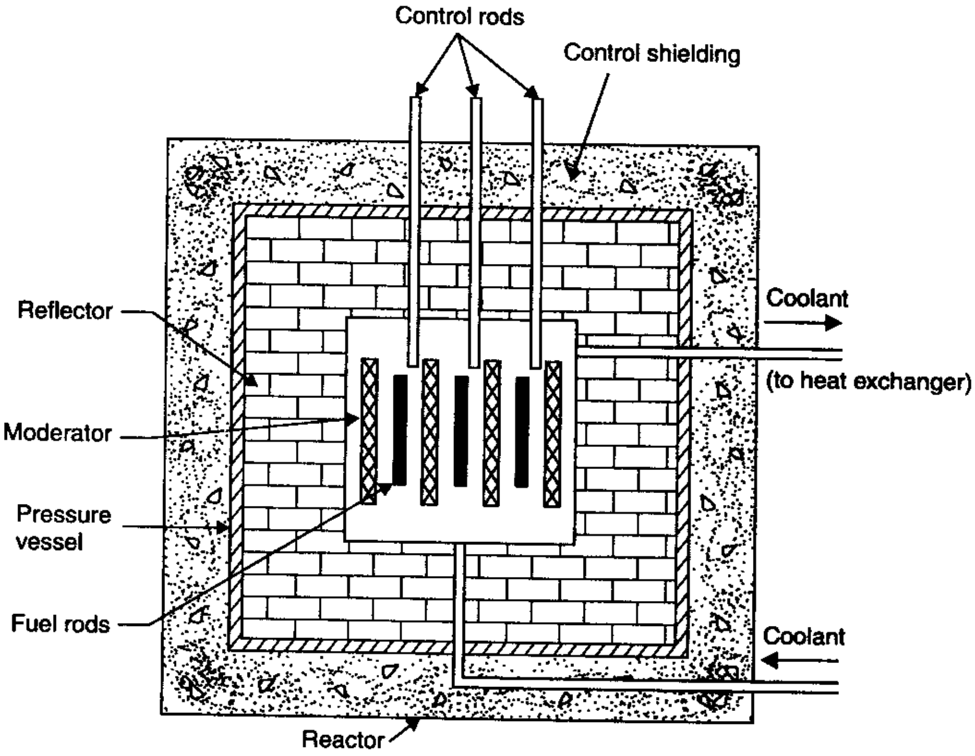


Fig. 7.7. Nuclear reactor.

or aluminium to provide corrosion resistance, retention of radioactivity and in some cases, structural support. Enough space is provided between individual plates or rods to allow free passage of the coolant.

2. Reflector :

A reflector is usually placed round the core to reflect back some of the neutrons that leak out from the surface of the core. It is generally made of the same material as the moderator.

3. Control mechanism :

It is an essential part of a reactor and serves the following purposes :

(*i*) For starting the reactor *i.e.*, to bring the reactor up to its *normal operating level.*

(*ii*) For maintaining at *that level i.e.*, keep power production at a steady state.

(*iii*) For shutting the reactor down under normal or emergency conditions.

The control system is also necessary to prevent the chain reaction from becoming violent and consequently damaging the reactor. The effective multiplication factor of the reactor is always kept *greater than unity* in order that the number of neutrons keeps on increasing in successive generations. As the number of neutrons and hence the neutron flux density increases, the temperature also increases. Unless the growth is checked at some point, the reactor is likely to be damaged as a result of too rapid liberation of energy.

Note. The *control system* works on the simple *principle of absorbing the excess neutrons* with the help of control rods either made of boron steel or cadmium strips. Both these materials have very large cross-section for thermal neutrons *i.e.*, they are very good absorbers of slow neutrons and also have the advantage of not becoming radioactive due to neutron capture. By pushing these rods deeper into the central core, any amount of excess neutrons can be absorbed. Once the reactor has reached pre-determined power level, these control rods serve to keep the value of $K = 1$ so that there is no further increase in the number of neutrons from one generation to another. If, at some stage, it is desired to increase the neutron flux density and hence the power level, the rods are *partially pulled out* thereby allowing K to *exceed unity*. For shutting down the reactor, the control rods are inserted to a considerable depth so that K becomes *less than unity* and the chain-reaction can no longer be maintained. To start up the reactor, all that is necessary is to carefully withdraw the control rods and then adjust them till required output level is attained. Movement of control rods can be manual or made automatic with the help of carefully designed *servomechanism*.

4. Moderator :

In a nuclear reactor the function of a moderator is :

(*i*) *To slow down the neutrons from the high velocities* and hence high energy level, which they have on being released from the fission process. Neutrons are slowed down most effectively in scattering collisions with nuclei of the light elements, such as hydrogen, graphite, beryllium etc.

(*ii*) *To slow down the neutrons but not absorb them*

The *desirable properties of a moderator* in a reactor are :

1. High slowing down power.
2. Low parasite capture.
3. Non-corrosiveness (or corrosiveness resistance).
4. Machinability (if solid).
5. High melting point for solids and low melting point for liquids.
6. Chemical and radiation stability.
7. High thermal conductivity.
8. Abundance in pure form.

H_2O, D_2O (heavy water), He (gas), Be and C (graphite) are the commonly used moderators.

As a moderator D_2O is the best material available, (moderating ratio of D_2O is 12000 as compared to 72 for H_2O and 170 for carbon) because (*i*) it has excellent neutron slowing properties (*ii*) it has very small cross-section for neutron capture (*iii*) it can be used as a coolant as well. Its *disadvantages* are : (*i*) it has low boiling point so that it *necessitates pressurisation* (*ii*) it is *very expensive*. But, the advantages of D_2O as moderator or moderator coolant outweigh its high cost.

5. Coolants :

The function of a coolant is to remove the intense heat produced in the reactor and to bring out for being utilised.

The desirable characteristics for a reactor coolant are :

1. Low parasite capture.
2. Low melting point.
3. High boiling point.
4. Chemical and radiation stability.
5. Low viscosity.
6. Non-toxicity.
7. Non-corrosiveness.
8. Minimum induced activity (short half lives, low energy emission).
9. High specific heat (reduces pumping power and thermal stresses).
10. High density (reduces pumping power and physical plant size).

Commonly used coolants : Santiwax R (organic, Hg, He, CO_2)

The most widely-used gaseous coolant is CO_2 particularly in large-power reactors. It is (*i*) cheap (*ii*) does not attack metals at reasonable temperatures and (*iii*) has small cross-section for neutron capture.

Some possible reactor cooling systems :

Some possible reactor cooling systems are illustrated schematically in Figs. 7.8, 7.9 and 7.10.

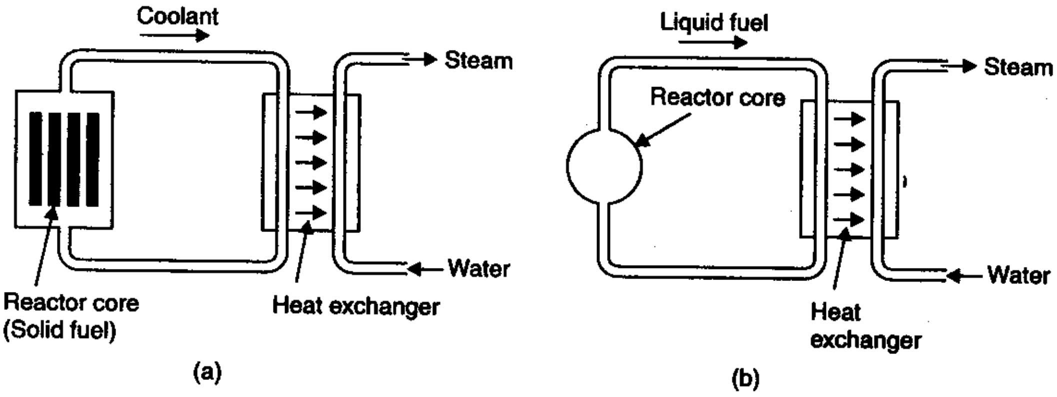


Fig. 7.8. Cooling systems : (*a*) Indirect cooling ; (*b*) Direct cooling.

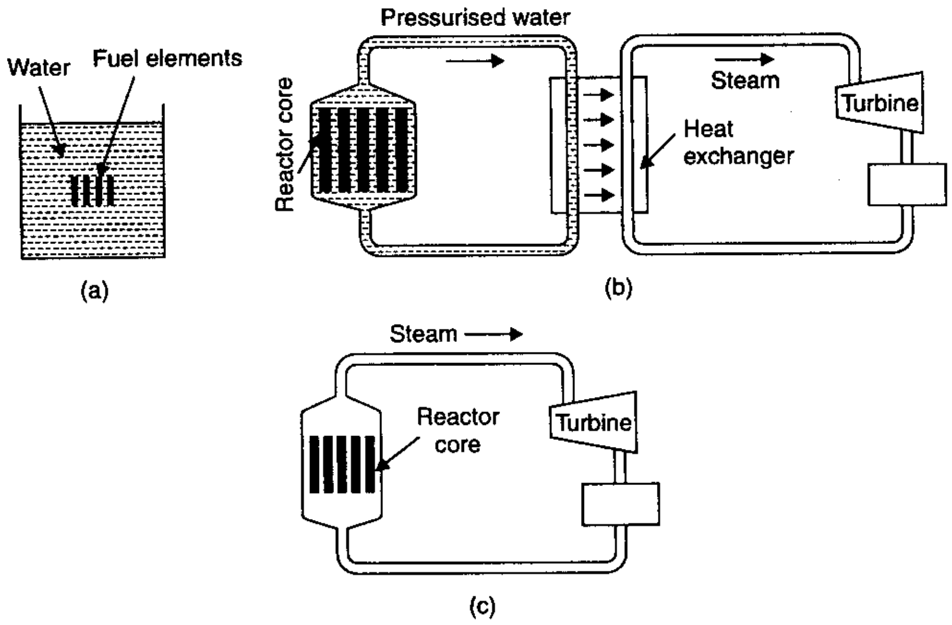


Fig. 7.9. Water cooled reactors : (*a*) Swimming-pool reactor ; (*b*) Pressurised-water reactor ; (*c*) Boiling water reactor.

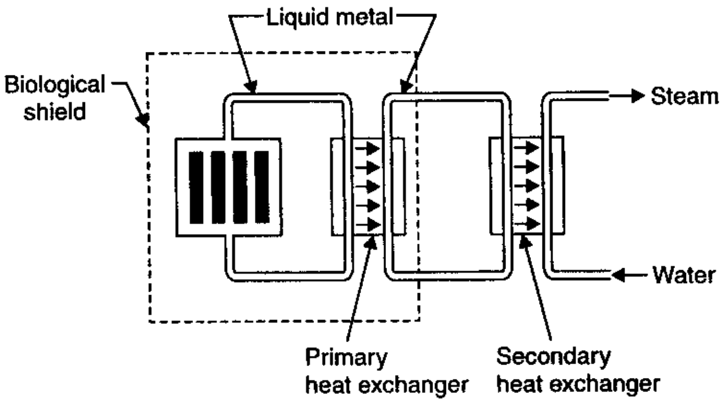


Fig. 7.10. Liquid-metal-cooled reactor.

6. Measuring instruments :

Main instrument required is for the purpose of measuring thermal neutron flux which determines the power developed by the reactor.

7. Shielding :

Shielding is necessary in order to :

(*i*) protect the walls of the reactor vessel from radiation damage, and also to

(*ii*) protect operating personnel from exposure to radiation.

The first known as *thermal shield* is provided through the *steel lining*, while the other called *external* or *biological* shield is generally made of *thick concrete surrounding the reactor installation*.

Among the nuclear radiations produced in a reactor the alpha and beta particles, thermal (slow) neutrons, fast neutrons and gamma rays are harmful ones and must be shielded against. Of these only the fast neutrons and gamma rays present some serious difficulty in designing the reactor shielding, since alpha and beta particles can be stopped by a fraction of an inch of a solid substance, while thermal neutrons can be automatically guarded against with a shield thick enough to provide protection against fast neutrons and gamma rays.

The effectiveness of a nuclear shield against gamma rays approximately depends upon its mass. A heavy material like lead will be a more effective shield per unit weight, than a light element such as carbon. On the other hand, light elements, particularly hydrogen are much more effective per unit weight than heavy elements for fast neutron shielding. Concrete is a material that offers a compromise between these two extreme characteristics of shielding material for *both gamma rays and fast neutrons*. It is a material which has *low cost* and is *easily available.*

The actual design of the shield, however, involves the following considerations :

(*i*) The total amount of radiation produced in the reactor.

(*ii*) The amount of radiation that can be permitted to leak through the shield.

(*iii*) The shielding properties of material.

7.3.4. Power of a Nuclear Reactor

The fission rate of a reactor *i.e.*, total number of nuclei undergoing fission per second in a reactor is

$$= nC\sigma NV = \phi_{nu}\,\sigma NV$$

where,

n = Average neutron density *i.e.*, number per m^3,

C = Average speed in m/s,

$\phi_{nu} = nC$ = Average neutron flux,

N = Number of fissile nuclei /m^3,

σ = Fission cross-section in m^2, and

V = Volume of the nuclear fuel.

Since 3.1×10^{10} fission per second generate a power of one watt, the power P of a nuclear reactor is given by

$$P = \frac{nC\sigma NV}{3.1 \times 10^{10}} \text{ watt}$$

$$= 3.2 \times 10^{-11}\, nC\sigma\, NV \text{ watt}$$

$$= 3.2 \times 10^{-11}\, \phi_{nu}\, \sigma\, NV \text{ watt}$$

Now, NV = Total number of fissile nuclei in the reactor fuel

$$= m \times 6.02 \times 10^{26}/235$$

where m is the mass of the U^{235} fuel. It is known that fission cross-section σ of U^{235} for thermal neutrons is 582 barns = $582 \times 10^{-28}\ m^2$.

$$\therefore \quad P = \frac{3.2 \times 10^{-11} \times \phi_{nu} \times 582 \times 10^{-28} \times m \times 6.02 \times 10^{26}}{235}$$

$$= 4.77 \times 10^{-12}\, m\, \phi_{nu} \text{ watt}$$

$$\simeq 4.8 \times 10^{-12}\, mnC \text{ watt.}$$

7.4. MAIN COMPONENTS OF A NUCLEAR POWER PLANT

Fig. 7.11 shows schematically a nuclear power plant.

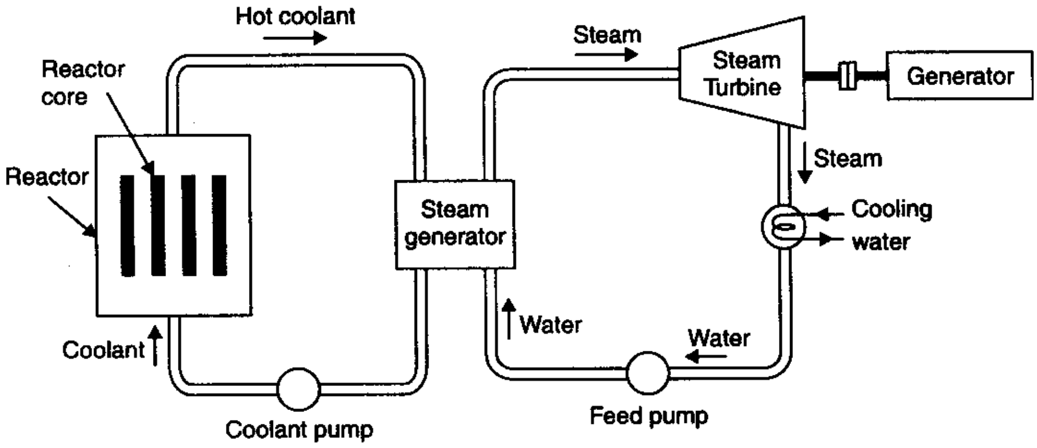


Fig. 7.11. Nuclear power plant.

The main components of a nuclear power plant are :

1. Nuclear reactor
2. Heat exchanger (steam generator)
3. Steam turbine
4. Condenser
5. Electric generator.

In a nuclear power plant the reactor performs the same function as that of the furnace of steam power plant (*i.e.*, produces heat). The heat liberated in the reactor as a result of the nuclear fission of the fuel is taken up by the coolant circulating through the reactor core. Hot coolant leaves the reactor at the top and then flows through the tubes of steam generator and passes on it heat to the feed water. The steam so produced expands in the steam turbine, producing work and thereafter is condensed in the condenser. The steam turbine in turn runs an electric generator thereby producing electrical energy. In order to maintain the flow of coolant, condensate and feed water pumps are provided as shown in Fig. 7.11.

7.5. DESCRIPTION OF REACTORS

7.5.1. Pressurised Water Reactor (PWR)

A pressurised 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. The principal parts of the reactor are :

1. Pressure vessel
2. Reactor thermal shield
3. Fuel elements
4. Control rods
5. Reactor containment
6. Reactor pressuriser.

The components of the secondary system of pressurised water plant are similar to those in a normal steam station.

Refer Fig. 7.12. In PWR, there are two circuits of water, one *primary circuit* which passes through the fuel core and is *radioactive*. This primary circuit then produces steam in a *secondary* *cirtuit* which consists of heat exchanger or the boiler and the turbine. As such the steam in the turbine is *not radioactive* and need not be shielded. The *pressure* in the primary circuit should be *high* so that the boiling of water takes place at high pressure. A *pressuring tank* keeps the water at about 100 kgf/cm^2 *so that is will not boil*. Electric heating coils in the pressuriser boil some of the water to form steam that collects in the dome. As more steam is forced into the dome by boiling, its pressure rises and pressurises the entire circuit. The pressure may be reduced by providing cooling coils or spraying water on the steam.

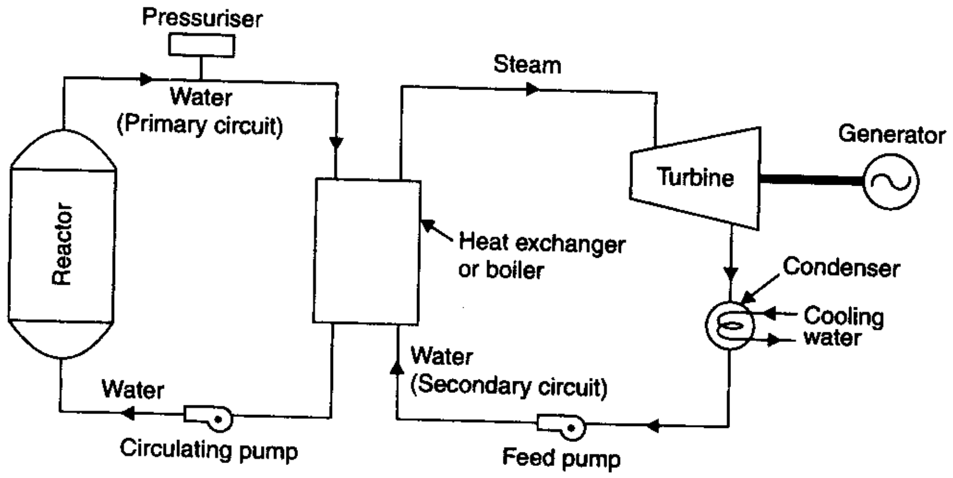


Fig. 7.12. Pressurised water reactor.

Water acts both as coolant as well as moderator. Either heavy water or the light water may be used for the above purpose.

A pressurised water reactor *can produce only saturated steam*. By providing a separate furnace, the steam formed from the reactor could be super-heated.

Advantages of PWR :

1. Water used in reactor (as coolant, moderator and reflector) is cheap and easily available.
2. The reactor is compact and power density is high.
3. Fission products remain contained in the reactor and are not circulated.
4. A small number of control rods is required.
5. There is a complete freedom to inspect and maintain the turbine, feed heaters and condenser during operation.
6. This reactor allows to reduce the fuel cost extracting more energy per unit weight of fuel as it is ideally suited to the utilisation of fuel designed for higher burn-ups.

Disadvantages :

1. Capital cost is high as high primary circuit requires strong pressure vessel.
2. In the secondary circuit the thermodynamic efficiency of this plant is quite low.
3. Fuel suffers radiation damage and, therefore its reprocessing is difficult.
4. Severe corrosion problems.
5. It is imperative to shut down the reactor for fuel charging which requires a couple of month's time.
6. Low volume ratio of moderator to fuel makes fuel element design and insertion of control rods difficult.
7. Fuel element fabrication is expensive.

7.5.2. Boiling Water Reactor (BWR)

In a boiling water reactor *enriched fuel* is used. As compared to PWR, the arrangement of BWR plant is simple. The plant can be safely operated using natural convection within the core or forced circulation as shown in the Fig. 7.13. For the safe operation of the reactor the pressure in the forced circulation must be maintained constant irrespective of the load. In case of *part load operation of the turbine some steam is by-passed.*

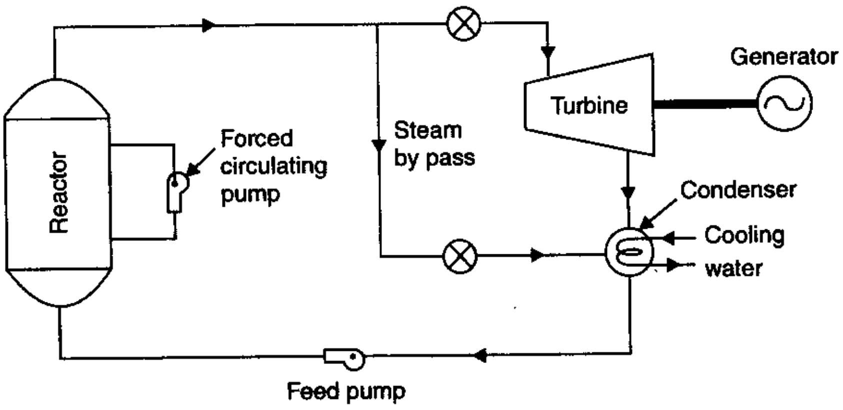


Fig. 7.13. Boiling water reactor.

Advantages of BWR :

1. Heat exchanger circuit is eliminated and consequently there is gain in thermal efficiency and gain in cost.
2. There is use of a lower pressure vessel for the reactor which further reduces cost and simplifies containment problems.
3. The metal temperature remains low for given output conditions.
4. The cycle for BWR is more efficient than PWR for given containment pressure, the outlet temperature of steam is appreciably higher in BWR.
5. The pressure inside the pressure vessel is not high so a thicker vessel is not required.

Disadvantages :

1. Possibility of radioactive contamination in the turbine mechanism, should there be any failure of fuel elements.
2. More elaborate safety precautions needed which are costly.
3. Wastage of steam resulting in lowering of thermal efficiency on part load operation.
4. Boiling limits power density ; only 3 to 5% by mass can be converted to steam per pass through the boiler.
5. The possibility of "burn out" of fuel is more in this reactor than PWR as boiling of water on the surface of the fuel is allowed.

7.5.3. CANDU (Canadian-Deuterium-Uranium) Reactor

CANDU is a thermal nuclear power reactor in which *heavy water* (99.8% deuterium oxide D_2O) *is the moderator and coolant as well as the neutron reflector.* This reactor was developed in Canada and is being extensively used in this company. A few CANDU reactors are operating or under construction in some other countries as well.

In this type of reactor the *natural uranium* (0.7% U^{235}) *is used as fuel and heavy water as moderator.* There reactors are more economical to those countries which do not produce enriched uranium, as the *enrichment of uranium is very costly.*

CANDU (heavy water) reactor, differs basically from light-water reactors (LWRS) in that in the latter the *same water serves as both moderator and coolant,* whereas in the *CANDU reactor the moderator and coolant are kept separate.* Consequently unlike the pressure vessel of a LWR, the CANDU reactor vessel, which contains the relatively cool heavy water moderator, *does not have to withstand a high pressure. Only the heavy water coolant circuit has to be pressurised to inhibit boiling in the reactor core.*

Description of CANDU reactor

Fig. 7.14 shows the schematic arrangement of a CANDU reactor.

Reactor vessel and core. The reactor vessel is a steel cylinder with a horizontal axis ; the length and diameter of a typical cylinder being 6 m and 8 m respectively. The vessel is penetrated by some 380 horizontal channels called *pressure tubes* because they are designed to withstand a high internal pressure. The channels contain the fuel elements and the pressurised coolant flows along the channels and around the fuel elements to remove the heat generated by fission. Coolant flows in the opposite directions in adjacent channels.

The high pressure (10 MPa) and high temperature (370°C) coolant leaving the reactor core enters the steam generator. About 5% of fission heat is generated by fast neutrons escaping into the moderator, and this is removed by circulation through a separate heat exchanger.

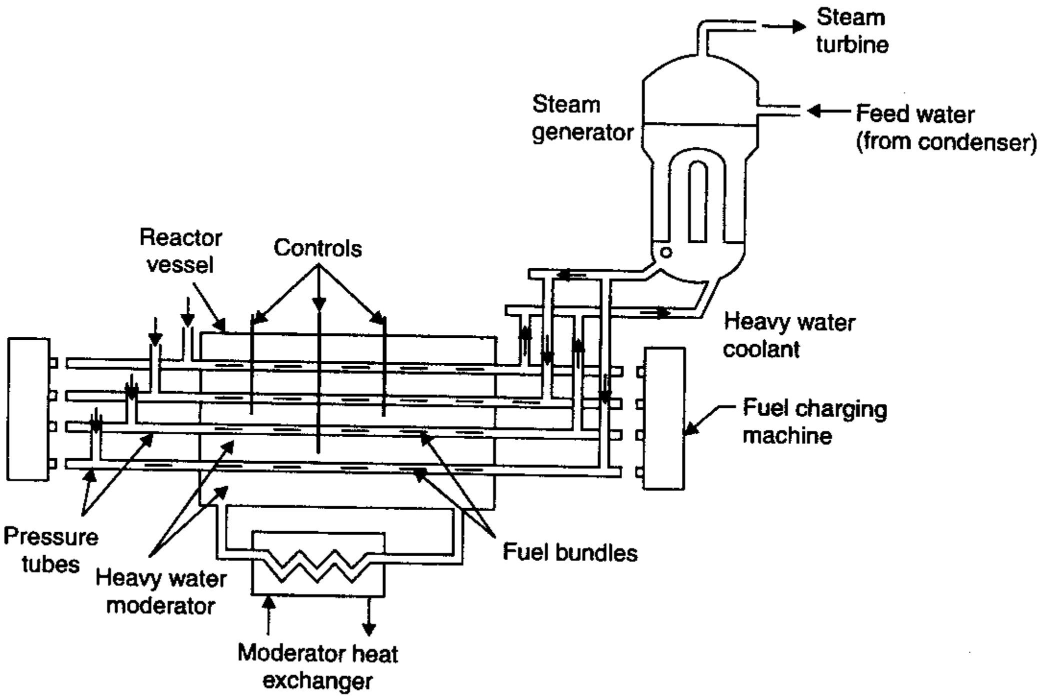


Fig. 7.14. CANDU reactor.

Fuel. In a CANDU reactor the fuel is *normal* (*i.e.*, unenriched) *uranium oxide* as small cylinder pellets. The pellets are packed in a corrosion resistance zirconium alloy tube, nearly 0.5 long and 1.3 cm diameter, to form a fuel rod. The relatively short rods are combined in bundles of 37 rods, and

12 bundles are placed end to end in each pressure tube. The total mass of fuel in the core is about 97,000 kg. The CANDU reactor is *unusual* in *that refueling is conducted while the reactor is operating.*

Control and protection system

There are the various types of vertical control system incorporated in the CANDU reactor :

- A number of strong neutron absorber *rods of cadmium* which are used mainly for *reactor shut-down* and *start-up.*
- In addition to above there are other *less strongly,* absorbing rods to *control power variations* during reactor operation and *to produce an approximately uniform heat* (power) distribution throughout the core.

In an emergency situation, the shut-down rods would immediately drop into the core, followed, if necessary by the injection of a gadolinium nitrate solution into the moderator.

Steam system. Steam system is discussed below :

- The respective ends of the pressure tubes are all connected into inlet and outlet headers.
- The high temperature coolant leaving the reactor passes out the outlet header to a steam generator of the conventional inverted U-tube and is then pumped back into the reactor by way of the inlet header.
- Steam is generated at a temperature of about 265°C.

There are two coolant outlet (and two inlet) headers, one at each end of the reactor vessel, corresponding to the opposite directions of coolant flow through the core. Each inlet (and outlet) header is connected to a separate steam generator and pump loop. A single pressurizer (of the type used in pressurised water reactors) maintains an essentially constant coolant system pressure.

The reactor vessel and the steam generator system are enclosed by a *concrete containment structure.* A water spray in the containment would condense the steam and reduce the pressure that would result from a large break in the coolant circuit.

Advantages of CANDU reactor :

1. Heavy water is used as moderator, which has higher multiplication factor and low fuel consumption.
2. Enriched fuel is not required.
3. The cost of the vessel is less as it has not to withstand a high pressure.
4. Less time is needed (as compared to PWR and BWR) to construct the reactor.
5. The moderator can be kept at low temperature which increases its effectiveness in slowing down neutrons.

Disadvantages :

1. It requires a very high standard of design, manufacture and maintenance.
2. The cost of heavy water is very high.
3. There are leakage problems.
4. The size of the reactor is extremely large as power density is low as compared with PWR and BWR.

7.5.4. Gas-cooled Reactor

In such a type of reactor, the coolant used can be air, hydrogen, helium or carbondioxide. Generally inert gases are used such as helium and carbondioxide. The moderator used is graphite. The problem of corrosion is reduced much in such reactors. This type of reactor is more safe specially in case of accidents and the failure of circulating pumps. The thickness of gas cooled reactor shield is much reduced as compared to the other type of reactor.

There are two principal types of gas cooled reactors developed for centre station service and these are :

(*i*) The gas cooled, graphite moderator reactor (GCGM)

(*ii*) The high temperature gas cooled reactor (HTGC).

Both types are graphite moderated. The former (GCGM) uses natural uranium fuel while the latter (HTGC) employs highly enriched uranium carbide mixed with thorium carbide and clad with graphite.

The *coolant pressure* and *temperature* in *GCGM* are about 7 bar 336°C respectively, for *HTGC*, there figures are 15 to 30 bar and 700°C to 800°C.

Arrangement of high temperature, gas cooled reactor is shown in Fig. 7.15.

Advantages of Gas-cooled reactor :

1. The processing of the fuel is simpler.
2. No corrosion problem.
3. As a result of low parasitic absorption it gives better neutron economy.
4. Graphite remains stable under irradiation at high temperatures.
5. The use of carbondioxide as coolant completely eliminates the possibility of explosion in the reactor which is always present in water-cooled plants.
6. The uranium carbide and graphite are able to resist high temperatures, and, therefore, the problem of limiting the fuel element temperature is not as serious as in other reactors.

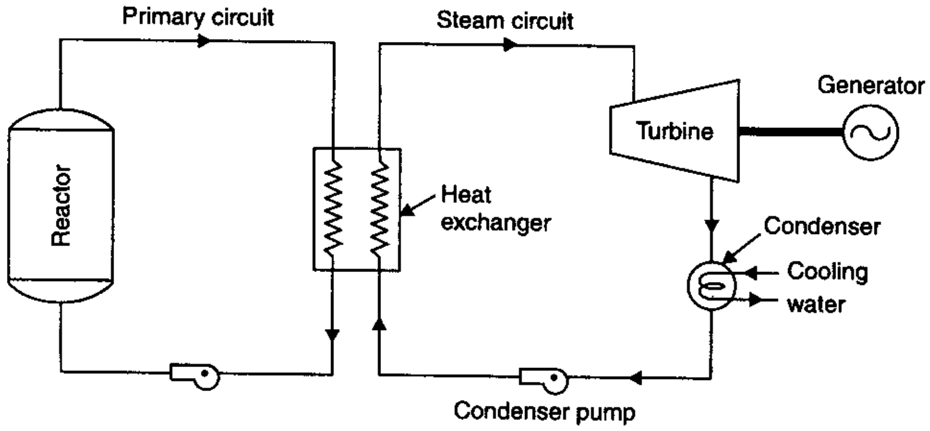


Fig. 7.15. Gas-cooled reactor.

Disadvantages :

1. Fuel loading is more elaborate and costly.
2. Power density is very low (due to low heat transfer coefficient), therefore large vessel is required.
3. Since the critical mass is high therefore large amount of fuel loading is initially required.
4. If helium is used in stead of carbondioxide, the leakage of gas is a major problem.
5. More power is required for coolant circulation (as compared with water-cooled reactors).
6. The control is more complicated due to low negative coefficient as helium does not absorb neutrons.

7.5.5. Liquid Metal Cooled Reactors

Sodium-graphite reactor (SGR) is one of the typical *liquid metal reactors.* In this reactor *sodium works as a coolant* and *graphite works as moderator.*

Sodium boils at 880°C under atmospheric pressure and freezes at 95°C. Hence *sodium* is first *melted* by electric heating system and be pressurised to about 7 bar. The liquid sodium is then circulated by the circulation pump. The reactor will have *two coolant circuits or loops* :

(*i*) The *primary circuit* has *liquid sodium* which circulates through the fuel core and gets heated by the fissioning of the fuel. This liquid sodium gets cooled in the intermediate heat exchanger and goes back to the reactor vessel.

(*ii*) The *secondary circuit* has an *alloy* of *sodium and potassium in liquid form.* This coolant takes heat from the intermediate heat exchanger and gets heat from liquid sodium of primary circuit. The liquid sodium-potassium then passes through a boiler which is once through type having tubes only. The steam generated from this boiler will be superheated. Feed water from the condenser enters the boiler, the heated sodium-potassium passing through the tubes gives it heat to the water thus converting it into steam. The sodium-potassium liquid in the second circuit is then pumped back to the intermediate heat exchanger thus making it a closed circuit.

The reactor vessel, primary loop and the intermediate heat exchanger is to be shielded for radio-activity. The liquid metal be handled under the cover of an inert gas, such as helium, to prevent contact with air while charging or draining the primary or secondary circuit/loop.

The arrangement of a sodium-graphite reactor (SGR) is shown in Fig. 7.16.

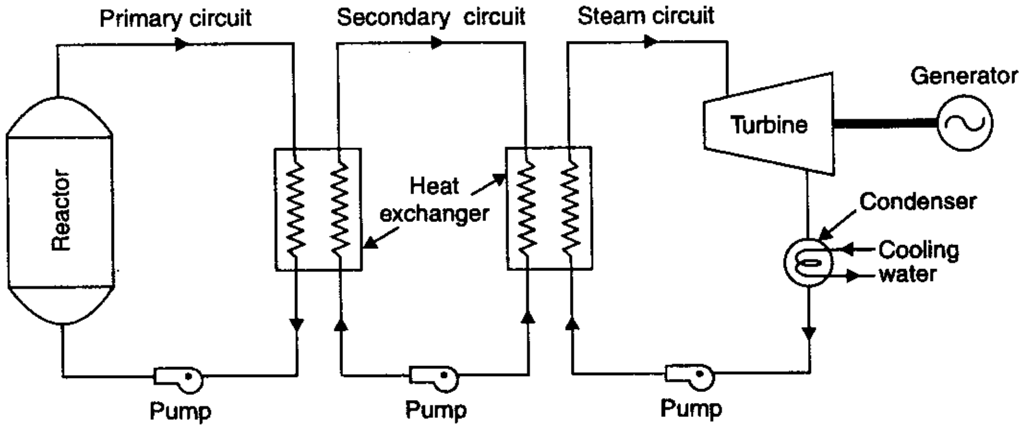


Fig. 7.16. Liquid metal cooled reactor.

Advantages of SGR :

1. The sodium as a coolant need not be pressurised.
2. High thermal efficiency at low cost.
3. The low cost graphite moderator can be used as it can retain its mechanical strength and purity at high temperatures.
4. Excellent heat removal.
5. High conversion ratio.
6. Superheating of steam is possible.
7. The size of the reactor is comparatively small.
8. The neutron absorption cross-section of sodium is low and, therefore, it is best suited to thermal reactor with slightly enriched fuel.

Disadvantages :

1. Sodium reacts violently with water and actively with air.
2. Thermal stresses are a problem.
3. Intermediate system is necessary to separate active sodium from water.
4. Heat exchanger must be leak proof.
5. It is necessary to shield the primary and secondary cooling systems with concrete blocks as sodium becomes highly radioactive.
6. The leak of sodium is very dangerous as compared with other coolants.

7.5.6. Breeder Reactor

In its simplest form a *fast breeder reactor* is a small vessel in which necessary amount of *enriched plutonium* is kept *without using moderator.* A fissible material, which absorbs neutrons, surrounds the vessel. The reactor core is cooled by liquid metal. Necessary *neutron shielding* is provided by the use of *light water, oil* or *graphite*. Additional shielding is also provided for gamma rays. (It is worth noting that when U^{235} is fissioned, it produces heat and additional neutrons. If some U^{238} is kept in the same reactor, part of the additional neutrons available, after reaction with U^{235}, convert U^{238} into fissible plutonium).

Fig. 7.17 shows a schematic diagram of a breeder reactor.

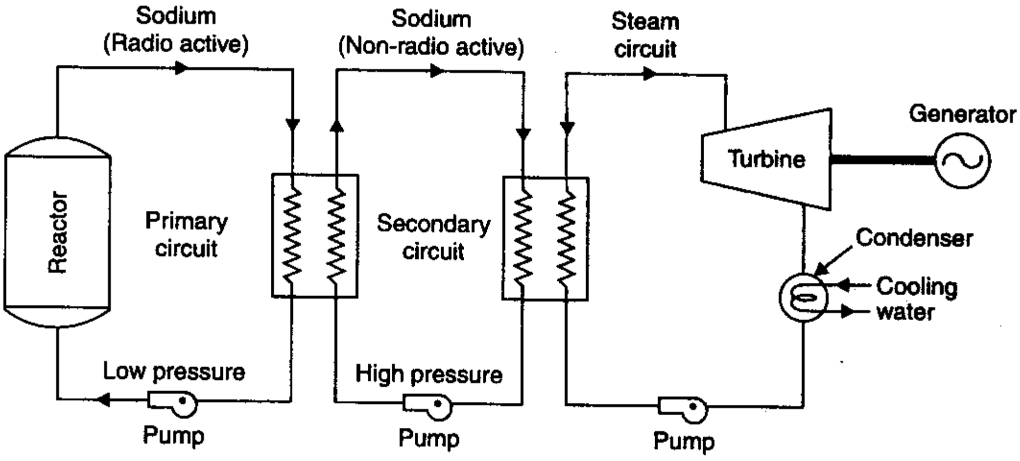


Fig. 7.17. Breeder reactor.

Advantages of a breeder reactor :

1. The moderator is not required.
2. High breeding is possible.
3. Small core is sufficient (since it gives high power density than any other reactor).
4. The parasite absorption of fuel is achievable.
5. High burn-up of fuel is achievable.
6. Absorption of neutrons is low.

Disadvantages :

1. Requires highly enriched (15 percent) fuel.
2. It is necessary to provide safety against *melt-down.*
3. Neutron flux is high at the centre of the core.

4. The specific power of the reactor is low.
5. There is a major problem of handling sodium as it becomes hot and radioactive.

7.6. SELECTION OF MATERIALS FOR REACTOR COMPONENTS

Some of the factors governing the selection of materials for the various reactor components are considered below :

1. Structural material :

The structural units implied are :

(*i*) The cladding material for fuel elements.
(*ii*) Fuel element assemblies.
(*iii*) Containers for coolants, ducts, etc., in the core.
(*iv*) Any general structure in the reaction zone.

Obviously the *purely mechanical properties must be adequate at the normal working temperature*, and the *material must be capable of the necessary fabrication and working.*

In case where liquids are involved, corrosion or erosion problems may be present. These may be especially troublesome in aqueous homogeneous reactors or in reactors employing liquid metals.

From the standpoint of the nuclear physics the *basic requirement is low neutron absorption cross-section.* Since absorption cross-sections are less at high than at low neutron energy levels, a material which is entirely unsuitable at thermal energies may be acceptable in fast reactors. In addition to the effect on the neutron economy of the system, structural materials may become dangerous to handle due to induced radioactivity.

Some *structural materials* are discussed below :

Aluminium. In a very pure state it is being extensively used as a *cladding material for fuel elements.*

Magnesium. It is *more costly* and is *difficult to work.*

Beryllium. It offers advantages in that it would *serve* also as a *moderator* but it is again *costly* and *difficult to work.*

Zirconium. It is a comparatively new material commercially, but offers considerable promise. It is *extremely corrosion resistant at low temperatures,* but less so above 400°C. Its mechanical properties are also impaired above this temperature. In the intermediate cross-section range *titanium* has a very good strength/weight ratio from 100 to 450°C and is corrosion resistant to aqueous solutions of high temperatures.

Alloys. *Silicon steels* may be used in some fast reactors, but considerable care is needed in their heat treatment.

A number of nickel alloys are of interest and offer considerable resistance to attack by fused salts and alkali hydroxide.

Silicon, of absorption cross-section 0.1 barn and tin, absorption cross-section 0.6 barn, might prove useful for alloying with other material.

2. Reactor coolants :

Gaseous coolants. There coolants have much to recommend them from the standpoint of *general radiation* and *thermal stability* and *ease of handling.* Gases are poor, however, from the standpoint of heat transfer and at high temperatures some of them, for example *oxygen* and *hydrogen,* may attack other materials present in the core. *Air* has been used in some research reactors operating on open cycle with discharge to the atmosphere at a high level to minimise the effect of Ar. *Helium* is attractive but is expensive. *Gases involve high pumping cost.*

Water. Water has *better thermal properties* than gases and the pumping power is roughly $\frac{1}{10}$th that for gases operated at ten atmospheres pressure. Its moderating properties may be usefully utilised when used as a coolant. It has a *fairly large absorption cross section,* and *undergoes decomposition by radiation.* It is *subjected to induced radioactivity,* and it has a *corrosive action on metals,* and a *low boiling point. Degasification may be necessary.*

For efficient power production high pressure operation is necessary. This necessitates the use of a pressure vessel to enclose the reactor. Boiling water reactors (BWR) in which the coolant serves also as a moderator show promise.

Heavy water has a lower absorption cross-section than natural water and its use leads to economy in fissile material. If it were cheaper it would be attractive for use in boiling water type reactor.

Liquid metals are of special interest in relation to reactors operating at high thermal flux. Their main disadvantage is in *difficulty of handling,* and in their *corrosive properties.* Their *heat transfer properties are better than those* of *water,* but their volumetric heat capacity is not as good, so that the pumping power may be greater or less than that of water. ***Sodium*** is the most favoured at present, for *if free from oxygen it does not attack stainless steel, nickel and nickel alloys, beryllium or graphite at temperatures below 600°C.*

3. Moderators and reflectors :

Possible materials for use as moderator and reflectors are :

(*i*) Ordinary and heavy water
(*ii*) Beryllium
(*iii*) Beryllia
(*iv*) Graphite.

Ordinary water has *excellent slowing down properties for neutrons,* but unfortunately, neutron capture is also high. This means that enriched uranium fuel is required in ordinary water moderated reactors, but the small migration length still permits a reactor of relatively small size. Some of *disadvantages* of water are (*i*) *attendant corrosion problems,* (*ii*) *its relatively low boiling point,* and (*iii*) decomposition by nuclear radiations, resulting in the liberation of oxygen and hydrogen which may require to be recombined in ancillary plant. The low boiling point requires the use of a pressure vessel when high temperatures are involved.

Heavy water is an *excellent moderator* and *has a high moderating ratio compared with the other materials.*

Beryllium. The nuclear properties of beryllium are *eminently suitable, but it is expensive, brittle and difficult to fabricate and is corroded by water.*

Graphite. It has been used *most extensively as a reactor moderator* despite the fact that its moderating properties are not as good as heavy water or beryllium. However, (*i*) it is *reasonably cheap,* even when the necessary high degree of purity is achieved, (*ii*) it has *good mechanical properties* and *thermal stability,* and (*iii*) is a *good conductor of heat.*

Its chief *disadvantages* are the possibility of reaction with air at high temperatures and its relatively low mechanical strength.

4. Fuel :

The proportion of the fissile material in the fuel is of considerable importance in determining the *critical size* of the reactor. This is because the ratio of fissile to non-fissile material in the fuel determines the neutron economy at the source. The following table gives the average number of neutrons liberated per neutron absorbed in the fuel.

Neutron type	U^{235}	Pu^{239}	Natural uranium
Thermal	2.11	1.95	1.32
Fast	2	2	1

5. Shielding and radiation protection :

Protection of personnel is achieved partly by the use of remote control and, in some cases, the provision of a pressure vessel to contain the fission products which might result from an accident. However, shielding of the reactor itself is invariably required.

A biological shield must slow down the fast neutrons leaving the core of the reactor, must capture the slowed down neutrons and must absorb all gamma and similar radiation produced. It must be borne in mind that neutron capture in the shield itself may give rise to further gamma radiation. A combination of light (moderating or slowing down) and heavy elements is the best. The latter reduces the energy of very fast neutrons by inelastic scattering. The incorporation of a good neutron absorber (*e.g.* boron 10) is beneficial. *Cadmium* is not particularly suitable since it emits high energy photons, with energies of the order 7.5 MeV. The *heavy elements* may be *metallic iron* or *lead*, or *iron oxide* or *barytes*. The *light element* is usually *hydrogen in the form of water,* often combined in concrete, but in research reactors in particular, possibly as water. A *homogeneous arrangement of heavy and light elements* is best, for example, the *use of a laminated construction or the use of iron concrete.* The latter consists of iron mixed in barytes concrete, or alternatively limonite (iron ore) is used partially to replace barytes in the mix.

Thermal shield. Every absorption in a shield is roughly exponential. Thus 90% of the radiation is absorbed in the first 10% of the thickness. This results in considerable liberation of heat. For this reason that part of the shield nearest to the core is usually of *iron* in thickness 5 to 10 cm which may be ***air-cooled.*** *This part of the shield is referred to as the* ***'thermal shield'.***

Summary of Materials for Nuclear Power Reactors

Structural :

(*i*) Aluminium
(*ii*) Stainless steel
(*iii*) Nickle alloys
(*iv*) Zirconium
(*v*) Magnesium

Fuel :

(*i*) Uranium
(*ii*) Uranium ceramics
(*iii*) Thorium
(*iv*) Thorium oxide

Coolant :

(*i*) Water
(*ii*) Liquid metals
(*iii*) Sodium, potassium
(*iv*) Mercury
(*v*) Lead bismuth
(*vi*) Gases
(*vii*) Helium
(*viii*) Nitrogen
(*ix*) Carbondioxide

Control :

(*i*) Boron steel
(*ii*) Cadmium
(*iii*) Samarium oxide
(*iv*) Gadolinium oxide

Mederator reflector :

(*i*) Water
(*ii*) Heavy water
(*iii*) Beryllium
(*iv*) Beryllium oxide
(*v*) Graphite
(*vi*) Metal hydrides

Shielding :

(*i*) Water
(*ii*) Cement and concrete
(*iii*) Iron
(*iv*) Lead
(*v*) Tantalum
(*vi*) Bismuth
(*vii*) Boron.

7.7. METALS FOR NUCLEAR ENERGY

Several metals such as *uranium, thorium and plutonium* are used for nuclear energy. The most important among them is Uranium. These metals are discussed below :

1. Uranium :

Occurrence :

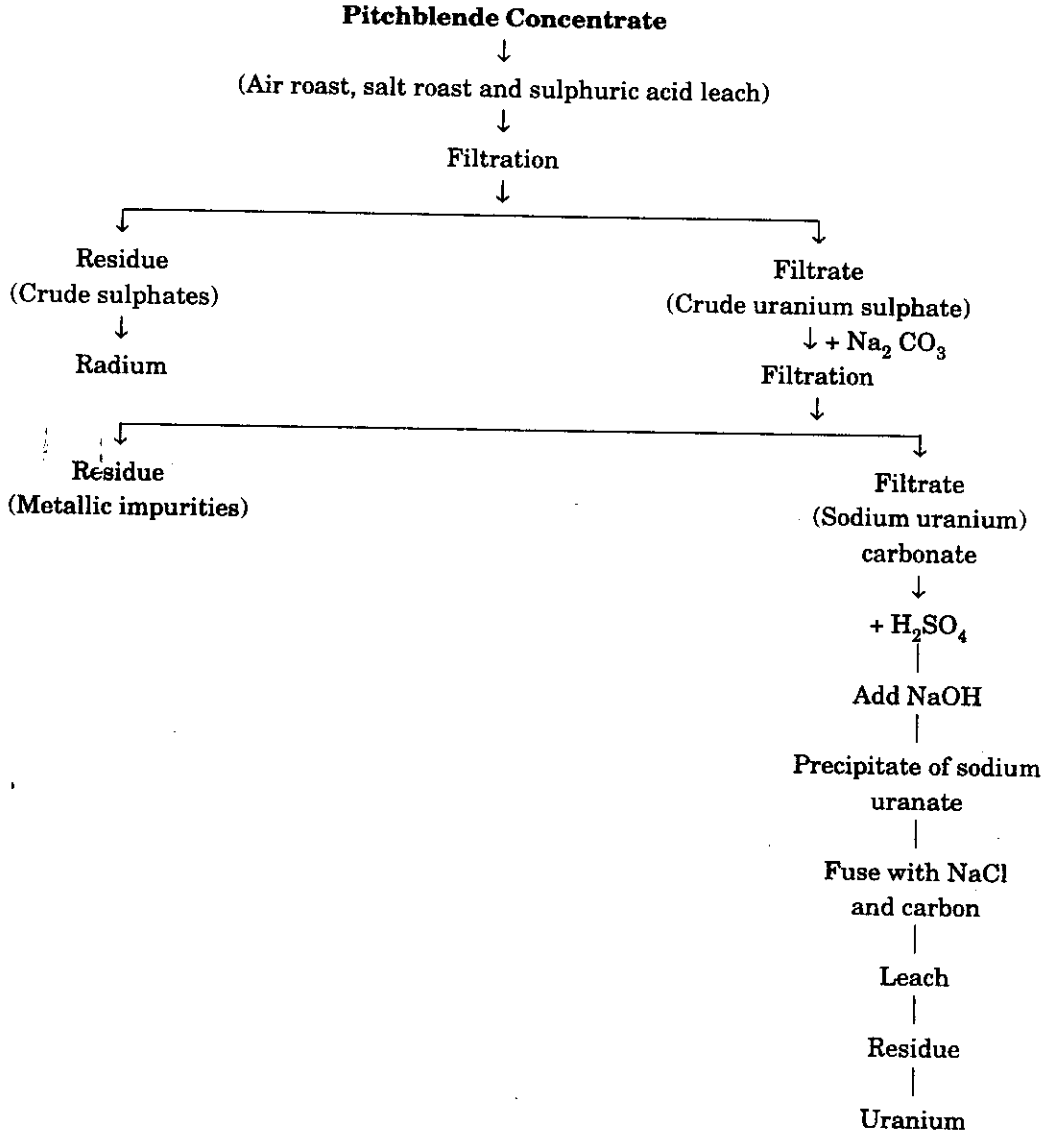
The following are the important ores :

(*i*) Uranite UO_2 (contains Th, rare earths)

(*ii*) Pitchblende UO_{2+x}

(*iii*) Carnotite $K_2(UO_2)_2(VO_4)_{2x} \cdot H_2O$.

The flow sheet for recovery of Uranium from Pitchblende is given below :



Extraction of Uranium :

The uranium can be produced by numerous processing treatments. In general, one of the two leaching treatments is used at the initial step in chemical concentration. One of those is the *acid leaching* and the other *carbonate leaching*. The choice depends upon the nature of the ore. The concentrate is treated chemically to give a uranyl nitrate solution than can be further purified by solvent extraction. The impurities remain in the acqueous phase while uranium is extracted from organic phase. The pure uranium is then stripped from organic phase and recovered as nitrate crystals or precipitated from the solution. The largest tonnage of uranium metal of good quality have been prepared from UF_4 by reduction with calcium or magnesium.

Mechanical properties :

	Annealed	Cold-drawn
Hardness (BHN)	92	112

Oxidation and corrosion resistance. Uranium is not chemically stable in air ; it reacts slowly in cold water and more rapidly in hot water.

Special properties. Uranium is the element having the largest number and atomic weight that is native in earth's crust ; hence it is a logical material for making heavier atoms by adding neutrons to the nucleus of uranium in atomic energy piles, and these by acquiring energy and radio active elements by fusion of relatively unstable transuranic elements which form.

Fabricating characteristics

(*i*) Pure uranium is malleable and very ductile however, small amounts of aluminium and iron embrittle it.

(*ii*) It dissolves oxygen and hydrogen readily ; consequently it is usually vacuum-annealed between cold-working operations.

(*iii*) Above 1400°C it is worked as a body-centered cubic metal.

(*iv*) It acquires distinct directional properties on cold working.

(*v*) The metal may be welded by resistance welding or inert gas arc welding processes.

(*vi*) Uranium is usually processed by powder metallurgical methods, or melted with inert arc process or high frequency furnaces using beryllia or thoria crucibles.

2. Thorium :

Thorium is one of the many metals which have become available as engineering materials as a result of the programme of the Atomic Energy Commission. The metal is difficult to prepare in the pure state because of its high melting pointing, 1690°C and its chemical reactivity with both gases and refractories. Once obtained, the silvery white metal is soft and ductile.

How to produce thorium ?

Metallic thorium can be produced by the reduction of the oxide or halides with alkali and alkaline-earth metals, by thermal decomposition of thorium iodide, and by the electrolysis of thorium compounds in fused salts. Marden and other produced powdered metal by reduction of thoria with calcium. This powdered metal is pressed and sintered into solid bars of good ductility and purity. Methods similar to those used for uranium are used to obtain thorium and the metal is now available in tonne quantities.

Physical constants of thorium. The principal physical constants are given below :

Density, g/cm^3	
(*a*) Theoretical	11.71
(*b*) Typical casting	11.63
Melting point	1690 ± 10°C
Boiling point	3000°C

Electrical resistivity, ohm-cm (20°C)	18×10^{-6}
Crystallography :	
(*a*) Structure	Face-centered cube
(*b*) Atomic diameter	3.59
(*c*) Transformation temperature	1400°C ± 25

Mechanical properties. Thorium is a soft material having a 75 to 80 VPN (Vickers Pyramid Number) and an annealed strength of 2600 kg/cm^2 nearly. The mechanical properties of thorium are grossly affected by small amounts of impurities. Carbon in particular tends to increase the hardness and strength of high-purity iodide metal. Poisson's ratio averages 0.265 in both tension and compression. The metal work hardens rapidly. In impact thorium exhibits a transition from brittle to ductile behaviour in temperature range (100 to 200°C).

Corrosion and oxidation resistance. Thorium is stable in air if the oxide content of the metal is low. The metal becomes covered with a stable oxide film which prevents further attack. It is stable in water and acqueous alkali solutions but is attacked by sulphuric or hydrochloric acids, halogen gases, and fused alkali.

Fine thorium powder may burn spontaneously ; wire or solid metal deoxidizes slowly in air. On heating in air, it will ignite and burn with great brilliancy.

Special properties. All thorium is *radio active* ; it is a potential source of *nuclear fuel.* It has good electron emission, and hence it is used in filaments and electric arc electrodes.

Fabricating characteristics. Thorium is very malleable metal and is ductile after some cold work, being much like lead. It may be rolled and swaged easily, and it can be cold-drawn after annealing and some swaging to work-harden it sufficiently, for the wire has a very low tensile strength in the annealed state. By cladding with copper or iron, it may be drawn to extremely fine wire.

Thorium is easy to machine and shape and may be welded by resistance-welding or inert arc welding methods.

Health hazards. Thorium like uranium, is an alpha emitter and the parent element of radio active thorium series. Highly radio active products may be released in grinding the ores and during the reduction and casting of the primary metal. The processed metal has a relatively low activity level and is handled without protective clothing or shielding. Competent medical authorities should be consulted regarding the handling of and tolerances for thorium.

3. Plutonium :

(*i*) It is very reactive.

(*ii*) It is easily oxidised.

(*iii*) It is highly toxic.

(*iv*) Its low temperature phases are very complex. In general it exists in six allotropic forms.

7.8. ADVANTAGES OF NUCLEAR POWER PLANTS

Some of the *major advantages* of nuclear power plants are :

1. A nuclear power plant *needs less space* as compared to other conventional power plant of equal size.
2. Nuclear power plants are well suited to meet large power demands. They give better performance at high load factors (80 to 90%).
3. Since the fuel consumption is very small as compared to conventional type of power plants, therefore, there is *saving in cost of the fuel transportation.*
4. The nuclear power plants, besides producing large amount of power, *produce valuable fissible material* which is produced when the fuel is renewed.

5. The operation of a nuclear power plant is *more reliable.*
6. Nuclear power plants are not affected by adverse weather conditions.
7. Bigger capacity of a nuclear power plant is an additional advantage.
8. The expenditure on metal structures piping, storage mechanisms is much lower for a nuclear power plant than a coal burning power plant.

Disadvantages/Limitations

1. The *capital cost* of a nuclear power station is always *high.*
2. The *danger of radioactivity* always persists in the nuclear stations (inspite of utmost precautions and care).
3. These plants *cannot be operated at varying load efficiently.*
4. The *maintenance cost is always high* (due to lack of standardisation and high salaries of the trained personnel in this field of specialisation).
5. The disposal of fission products is a big problem.
6. Working conditions in nuclear power station are always detrimental to the health of the workers.

Comparative Ratings of 10 MW Nuclear and Coal-burning Power Plant

S. No.	Ratings	Nuclear plant	Coal-burning plant
1.	Weight of machines and mechanisms, *tons*	700	2700
2.	Weight of metal structures, *tons*	900	1250
3.	Weight of pipes and fittings, *tons*	200	300
4.	Weight of masonary/graphite assembly, *tons*	500	1500
5.	Weight of fuel storage mechanism, *tons*	—	2500
6.	Weight of rolling stock, *tons*	—	300
7.	Volume of plain and reinforced concrete work, *cum*	9000	4000
8.	Capacity of buildings (without turbine room and electrical facilities), *cum*	50000	75000
9.	Area of construction site, *hectares*	5	15
10.	Internal power consumption, *kW*	5000	8000

7.9. NUCLEAR-PLANT SITE SELECTION

Nuclear power plants *must meet all the economic and technical and most of the legal criteria* that apply to the siting of conventional fossil-fuel-fired power plants. *In addition, the importance of site characteristics in the assessment of public safety results in greater concern in siting nuclear plants than with any other type of industrial facility.* Of particular concern are the population distribution with respect to the site and the natural factors which could affect the transport of radioactive material to the public, under normal operating conditions and in the highly unlikely event of an accident which could release radioactive material to the environment.

The various factors to be considered while selecting the site for a nuclear power plant are enumerated and described in detail below :

1. Proximity to load centre
2. Population distribution
3. Land use
4. Meteorology
5. Geology
6. Seismology
7. Hydrology.

1. Proximity to load center :

Electrical power can be transmitted over considerable distances by power-transmission lines, but, because of the capital cost of the lines and rights-of-way and transmission losses, an economic penalty is incurred which increases with increasing distance between the generating station and the load center. It is apparent, therefore, that *the closer the power-plant site can be located to the load center* (while meeting other requirements such as reasonable land cost, adequate cooling water, local zone restrictions, accessibility for fuel shipment, etc.), *the lower can be the cost of power delivered to the consumer.* Although nuclear plants should be built close to their load centers, regulatory bodies have been very cautious, despite the unparalleled nuclear plant safety record. Most plants built to date have not been in or near heavily populated areas.

2. Population distribution :

Since power reactors must be located reasonably close to load centers, the *population distribution around the site is a necessary consideration* in the evaluation of a nuclear power-plant site. The distances, the site meteorological conditions and the amount of radioactive material which could be released from the plant during a major accident are used to evaluate the suitability of the site from the standpoint of safety to the public. In addition to the permanent population surrounding a site, it is also necessary to consider part-time peaks in population, such as during the day or on weekends in recreational areas, and seasonal variation in population, particularly in resort areas. Consideration also should be given to estimates of future increases or changes in population distribution.

To permit placing nuclear plants in desirable locations, it is necessary to provide effective engineered safeguard features to offset, at least in part, the present requirement for large distances from population centers. The trade-off between distance requirements and engineered safeguards is qualitative, and there are no established rules or principles by which such a trade-off can be factored into the evaluation of possible sites for a nuclear power plant. Such a trade-off can, at present, be based only on engineering judgement and on precedents established in the siting of other nuclear plants having different degrees of safeguards and located at various distances from population centers.

3. Land use :

The use to which the land surrounding a nuclear-plant site is being put, even though it may not be densely populated, *may have an effect on the suitability of the site for a nuclear plant.* For example, if land is used for agriculture, ingestion of food which has been contaminated by fallout after an accident might conceivably result in a greater radiation dose to the public than might be received from direct exposure to radioactive materials transported downwind from the plants. Of similar concern, but possible as a result of normal operation, is the chance that certain marine life, stationary shellfish in particular, can concentrate the small quantities of radioactivity normally released into the cooling water discharged from the plant. Over a long period of time, the concentration of radioactivity conceivable could build up to levels approaching maximum permissible concentrations.

4. Meteorology :

Because the atmosphere is the principal means by which radioactivity released from a nuclear plant might be transported to the public, *site meteorological conditions* are considered in selecting a nuclear plant site. Meteorology is of concern both for normal discharges of gaseous radioactive wastes and for the much less likely releases of larger quantities of airborne radioactive material which might result from an accident. A number of meteorological variables are normally evaluated for the site to determine appropriate atmospheric dilution factors. Among these variables are : *wind-direction frequencies, in conjunction with the population distribution ; wind velocities and the frequencies of each velocity increment ; frequency and duration of calms ; atmospheric lapse rate ; frequency and duration of inversion conditions.* Atmospheric dilution is increased, and thus the meteorological conditions are more favourable, the more unstable the atmosphere and the greater the wind velocity.

Other meteorological conditions of concern are the following : *precipitation,* since it may significantly increase deposition of radioactive materials from the atmosphere, *i.e.*, "rain-out" ; possible effects of topography on the local meteorology ; *seasonal variations in meteorological conditions* ; and *the frequency and severity of storms,* particularly tornadoes and hurricanes, which could severely damage the plant. Meteorological information collected at the plant site provides the greatest assurance that it is representative of actual site conditions, provided that sufficiently accurate instrumentation is used and the data are collected over a long enough period of time to be statistically valid. Usually the only meteorological information available during selection and evaluation of a site is data collected at the locations in the same general area, over a long period of time.

At sites where meteorological conditions are particularly favourable or unfavourable, *more careful consideration would be given to meteorological characteristics.*

5. Geology :

Investigation of the site geology is necessary to determine the *bearing capacity of the soil* and the types of foundations which must be used for the major portions of the plant. Test borings are usually made for this purpose, just as for any other large structures. Of particular concern for nuclear plants, because of the implications for public safety, is the possibility of *sudden earth movement* which could severely damage the plant. Earth slides due to soil instability, subsidence due to consolidation of subsurface materials or to removal of oil or water from subsurface formations, and ground displacements during earthquakes along geologic faults traversing the site—each receives very careful consideration.

If the possibility exists for releasing radioactive liquids from the plant, the ion-exchange and filtering characteristics of the surrounding soil may be important. *If the soil could reliably retain any radioactivity released and prevent it from entering water sources or otherwise coming in contact with persons or animals, the site would be that* much more favorable.

6. Seismology :

Seismology is of particular concern is areas of *high seismic activity* because of the possibility that the forces which can be produced by earthquakes could be sufficient to damage the reactor system and rupture the containment structure. Careful consideration is given to the general seismic history of the area, including a description of all earthquakes which have been observed at the site, their magnitude or intensity, and the frequency spectrum for which structures should be analyzed. *The proximity of the site to known active faults must be determined, and any significant faulting at or near the plant site must be evaluated.* Conservative earthquake design factors, usually substantially greater than those required by the Uniform Building Code, are used for critical equipment and structures in areas of high seismic activity.

In coastal areas the possibility of tsunamis may have to be considered. These earthquake-generated sea waves may travel long distances very rapidly and, under certain shore conditions, can build up to substantial heights. Standard seismic design is generally adequate to meet the design criteria based on the factors described above, and with the conservative design factors ordinarily used, reactor systems are adequate for even worse conditions than could be realistically expected to occur.

7. Hydrology :

An important consideration is selecting a site for any power plant is the *local hydrology*. Present-day type of nuclear plants *require substantially greater quantities of cooling water* than do modern fossil steam plants because of their higher turbine heat rates. In areas of limited water supply, cooling towers can be used but at some cost penalty. *An additional consideration for nuclear plants is that there be sufficient water flow for the discharge of low-level radioactive liquid wastes.* This usually imposes no limitation because of the small quantities of wastes to be discharged and because it is possible to dilute or clean up the wastes to nearly any required concentration. *If necessary, it is possible to collect and ship these wastes off site.*

Another area of concern is the *possibility of flooding,* which could cause damage to the plant and equipment and cause plant shutdown. Seismic sea waves and hurricanes may increase the possibility of flooding at coastal sites. Seiches (Periodic surface oscillations) could result in flooding adjacent to large, enclosed bodies of water. *The flooding history of the site must be determined to permit adequate site evaluation and plant design.*

The characteristics of the ground water and the level of the water table at the site must be evaluated to ensure that contamination of local water sources by the discharge of liquid radioactive wastes does not occur. It there is any possibility of significant discharge of radioactive contamination to ground water, the absorption characteristics of the soil and the drainage characteristics of the ground water, including its depth and estimated direction of flow, and the characteristics of wells in the area may have to be determined as part of the site evaluation.

7.10. APPLICATION OF NUCLEAR POWER PLANTS

A nuclear power station is ideally suited under the following situations :

(*i*) In an area with *potential for industrial development,* but *limited conventional power resources,* nuclear power generation appears as an only alternative.

(*ii*) If the existing power grid is to be firmed up or additional power demand is to be met while all available hydro power resource have been exploited, and coal is scarce or expensive to transport, a nuclear power station may be used with advantage.

7.11. ECONOMICS OF NUCLEAR POWER PLANTS

Typically, all costs of nuclear power plants are broken down into the following categories :

1. *Capital costs (total).*
2. *Fuel costs (per year).*
3. *Other operating and maintenance costs (per year).*

With a knowledge of these total and annual costs, and a knowledge of the pertinent factors relating to production, anticipated plant life, and the costs of invested money, unit costs may be determined for any time period desired.

Although such unit costs may be determined on a single plant basis, it should be noted that the addition of any new plant will normally provide excess capacity in the system under study. Thus, *a more valuable analysis involves the inclusion of the additional costs incurred by the new plant in the total system cost pattern and the redetermination of total system costs.* Simplified analysis requires the assumption of an immediate load availability to the new plant at the expense of load availability to the older existing plants. *Although more complicated, a system analysis using the lowest system incremental loading cost will provide a more accurate picture of real annual unit costs for the various alternatives considered.*

1. Capital costs :

Capital costs are those costs which *occur only once* and are usually limited to the costs of procurement and construction of the facilities prior to the time of commercial operation. These are normally *"capitalized"* ; *i.e., they are treated as an investment which is depreciated over the useful life of the plant rather than being treated as an annual or other shorter-term operating cost.*

Determination of those costs which may be allowed within the capital-cost structure often depends on review by the appropriate public-utility commission or other regulatory body and on corporate accounting policies. Allocation of the capital-cost items over the life of the plant is normally accomplished by applying factors, or percentage rates, *which will account for depreciation,* *return on investment, and taxes applied to income and property value*. The product of the total of these factors and the allowable capital costs gives the annual fixed charge per year for the capitalized investment. Within this structure, several different depreciation methods are used, such as *sinking fund, straight-line depreciation*, etc., depending upon the accounting structure already in existence.

2. Fuel costs :

Fuel cycle. An understanding of *nuclear-fuel costs* requires an understanding of the *nuclear-fuel cycle*, since the fuel-management programmes are significantly different from those used for fossil-fueled plants.

Fig. 7.18 shows the basic fuel cycle. The word *"cycle"* is intentionally used, for, unlike fossil fuels, a single pass through the reactor does not consume all the nuclear fuel. Further, a valuable new fuel, plutonium, is generated during power production.

Fuel costs are affected by the number of functional services which must be performed on the uranium fuel to prepare if for use, the additional services which must be performed to recover the "ash" value of the spent fuel, and the variation in the design data for each batch of fuel employed.

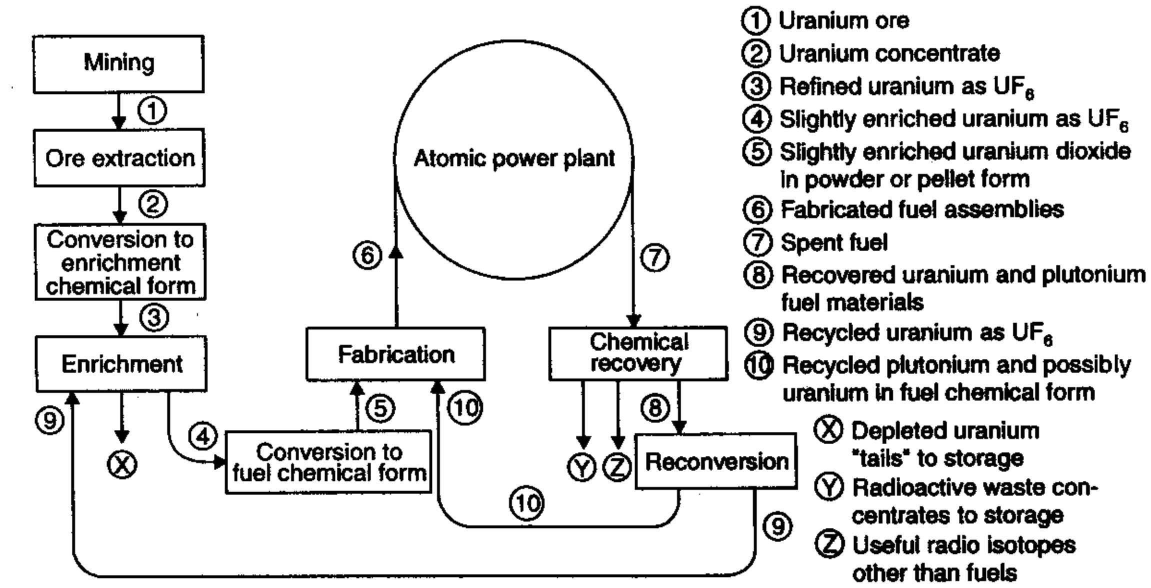


Fig. 7.18. Nuclear fuel cycle (based on water-cooled reactors).

The calculation of nuclear-fuel costs using various data is particularly complex if a high degree of sophistication is desired, such as in the evaluation of competitive fixed-price bids or in the determination of minimum incremental operating costs between two or more plants. However, for project scoping purposes and general familiarization with the principles involved, the following simplified method may be used to determine *equilibrium fuel-cycle costs* :

1. Determine the initial uranium-procurement unit cost in Rs. per kilogram of uranium. This cost will vary with the price of uranium yellow cake, the cost of converting it to uranium hexafluoride, and the cost of toll enrichment. This latter item is, in turn, dependent upon the enrichment required (which determines the amount of separative work required) and the unit cost of separative work.

2. Determine the fabrication unit cost, in terms of Rs. per kilogram, of combined uranium.

3. Determine the spent-fuel-element shipping, reprocessing, and reconversion costs in terms of Rs. per kilogram of contained uranium.

4. Determine the credit available for the recovered uranium and plutonium.

5. Determine the indirect costs, *i.e.*, return on investment and provision for applicable taxes, by determining the average investment level throughout the procurement period, energy-production period, and spent-fuel recovery period and multiplying by the appropriate interest of fixed-charge rates.

6. Sum items 1 through 5 to give the total unit costs, in terms of Rs. per kilogram of uranium.

7. Determine the unit energy production, based upon the average fuel energy production (usually given in terms of megawatt-days thermal per metric ton of uranium) and the thermal efficiency of the plant.

8. Divide item 6 by item 7 to give the unit costs.

The results of such simplified calculations are likely to be somewhat low, since they *do not recognize the various minor material losses*. However, they are also not likely accurately to reflect the true investment costs, since the *investment value is a complex value varying with energy production*.

The complications inherent in a complete fuel-cycle cost, coupled with the need to compute costs over an extended period involving changing cost patterns and also over the several fuel loadings required to reach an equilibrium fuel-flow requirement, have led to the development of computerized calculational methods.

3. Operations and maintenance costs :

Operating and maintenance costs categories fall in the following groups :

(*i*) Labour

(*ii*) Materials, supplies and services

(*iii*) Insurance

(*iv*) Fuel management

(*v*) Working capital.

(*i*) The *plant staff* required is relatively independent of plant size, typically running 60 to 70 men, including all supervision, technical assistance, operations, maintenance and miscellaneous supporting services. The costs for this staff may vary substantially, being highly dependent upon the local labour market and the labour costs.

(*ii*) *Materials, supplies, and services* are also relatively insensitive to plant size, although certain items are directly proportional to the thermal power level and the frequency and extent of power-level changes.

(*iii*) *Insurance costs* may be divided into two component parts, *property insurance* and *liability insurance*. Property insurance is normally a direct function of the capital value.

(*iv*) *Fuel-management services* may be provided either by contracting for external services or by adding staff to that already discussed. This cost is also essentially independent of plant size.

Total Energy Costs. The total unit cost of energy delivered at the bus bar is the sum of all of the preceding cost components which are related to the energy-production period divided by the energy produced during the same period. If escalation is disregarded, technological improvements and lower fuel costs will tend to reduce this value.

— From economical considerations, the Nuclear Power Plant are designed for 75% of the base load. Fig. 7.19 shows the comparison of cost of production of power by thermal plants with the cost of production by nuclear plants.

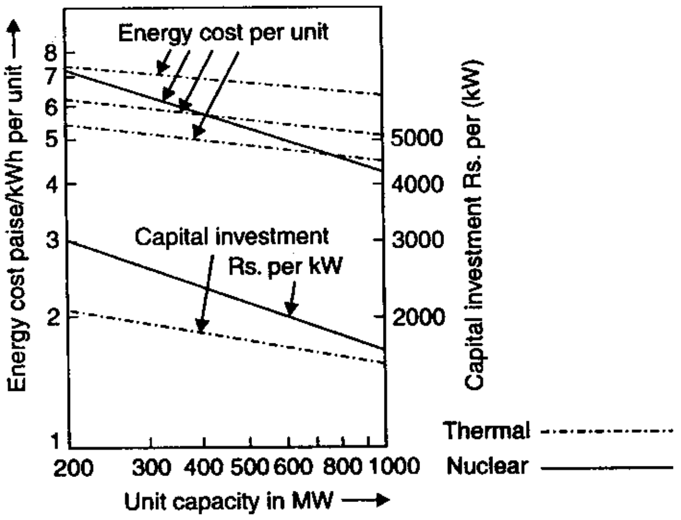


Fig. 7.19. Comparison of costs between nuclear and thermal power plants.

As can be seen, at low installed capacities, both the capital investment and the energy cost per unit are less for thermal power plants. But when the installed capacity reaches 1000 MW, both the plants become comparable. Further, the increased cost of coal production and also the far flung coal mines will eventually make the nuclear power a cheaper one.

In spite of the inevitability of our option to go nuclear for power production, the hazards are enormous and we shall have to be extremely careful in designing, constructing and operating the nuclear power plants. The disaster in Russia and elsewhere cannot be ignored easily.

7.12. SAFETY MEASURES FOR NUCLEAR POWER PLANTS

In case of nuclear power plants the three main sources of radioactive contamination of the air are : (*i*) Fission of nuclei of nuclear fuels (*ii*) The effect of neutron fluxes on the heat carries in the primary cooling system and on the ambient air (*iii*) Damage of shells of fuel elements.

The above, mentioned contamination of air can cause health hazard to workers and community and negative effect on surrounding forests. This calls for safety measures for a nuclear power plant, some of them are listed below :

1. A nuclear power plant should be constructed away from human habitation. An *exclusion zone* of 106 km radius around the plant should be provided where no public habitation is permitted.

2. The materials to be used for the construction of a nuclear power plant should be of required standards.

3. Waste water from nuclear power plant should be purified.

4. The nuclear power plant must be provided with such a safety system which should safely shut down the plant as and when necessity arises.

Narora Atomic Power Project (NAPP) design entails the following significant design improvements : (*i*) An integral reactor vessel and end shield assemblies (*ii*) Two independent shut down systems (*iii*) Total double containment with suppression pool.

5. There must be periodic checks to ensure that radioactivity does not exceed the permissible value is the environment.

6. While disposing off the wastes from the nuclear plants it should be ensured that there is no pollution of water of river or sea where these wastes are disposed.

7.13. NUCLEAR POWER PLANTS IN INDIA

The various nuclear power plants situated in India are as follows :

1. Tarapur power plant
2. Rana-Partap Sagar power plant
3. Kalpakkam power plant
4. Narora power plant
5. Kakrapar power plant.

The particulars of these plants are given in tabular form below :

Particulars	Power plants				
	Tarapur	**Rana-Partap Sagar**	**Kalpakkam**	**Narora**	**Kakrapar**
1. Location	Maharashtra (65 miles north Mumbai)	Near Kota in Rajasthan	Near Chennai in Tamil Nadu state	U.P	Surat district, Gujrat
2. Capacity	380 MW	400 MW (2 × 200 MW)	470 MW (2 × 235 MW)	2 × 235 MW (under construction) 40 bar at 250°C	4 × 235 MW (proposed)
3. Steam pressure and temperature	35 bar at 240°C	40 bar at 250°C	—	—	—

7.14. FUTURE OF NUCLEAR POWER

India has hydro-power potential, and some coal reserves ; unfortunately these are not very well distributed throughout the country. Moreover, most of the economically feasible hydropower schemes have already been developed. The quality of Indian coal is not very good, and the reserves are concentrated in one or two parts of the country. These reserves are also being depleted at a fast rate, the railways consuming a large quantity. On the other hand, India has *adequate deposits of fissionable material-thorium*, which can eventually be used for generation of power. Therefore, development of nuclear power, to supply the growing electricity demand of the country is quite logical and necessary. Thus the future of nuclear power is quite bright. The following three factors, however, need discussion :

(*i*) *Cost of power generation*. Although cost of power generation in a nuclear power plant is comparatively more, yet with research in the nuclear technology the cost is bound to come down to a value comparable with that for conventional plant.

(*ii*) *Availability of nuclear fuel*. The problem of availability of large amount of nuclear fuel can be overcome to a great extent by switching over to breeder reactor in which fissionable fuel is produced at the same time they are consuming it.

(*iii*) *Safety of the nuclear plants*. If the nuclear plants are designed in such a way that they do not explode like a nuclear bomb they can give a safe operation, since they contain only a small amount of fissionable material (as compared to 90% fissionable fuel in the atomic bomb core).

7.15. USEFUL BY-PRODUCTS OF NUCLEAR POWER GENERATION AND THEIR USES

The Nuclear plants supply many by-products like isotopes which have many useful applications in our day-to-day life.

The fission products consist of Beta and Gamma emiting radioactive isotopes with different half-lives. Only a very small percentage of nucleon waste is used for industrial purposes. 90% of the nucleon wastes have short half-lives and decay in a few years. It is the remaining 10% who have centuries as half-lives which pose disposal problems.

Industrial isotopes must satisfy the following two conditions :

(1) Yield of the isotope should be quite high.

(2) The half-life should neither be too short nor too long.

Some of the Isotopes and their characteristics are shown below :

Isotopes	**%Yield**	**Half-life**	**Type of Radiation**	
			Beta MeV	**Gamma MeV**
Cesium—137	6.22	33 years	0.5, 1.2	None
Barium—137	6.22	2.6 mins.	None	0.658
Strontium—90	5.3	28 years	0.605	None
Cerium—144	5.28	285 days	0.351	None
Praseodymium—144	5.28	17.3 minutes	3.02	0.2
Zirconium—95	6.39	65 days	0.391, 1.0	0.915
Niobium—95	6.39	35 days	0.15	0.76
Technetium—99	6.19	2.1 × 10 years	0.295	None
Promethium—147	2.61	2.5 years	0.219	None

The radioactive isotopes are widely used in *Biology, Medicine, Agriculture and Industries*.

Industrial Applications :

(1) *Position location* : Buried pipelines can be traced by using portable geiger Counters.

(2) *Flow patterns* in pipes can be detected by injecting radioactive isotopes into the flow. The radiation will be different for laminar and turbulent flows.

(3) *Leakage detection* can be done by injecting isotopes into fluid in pipes. The reactivity will be different at leakage points.

(4) *Ground water path* is detected by mixing short lived radioactive material with water (to avoid contamination).

(5) *Thickness gauges.*

(6) *Liquid level gauges.*

(7) *Radiography (Flaw detection).*

X-rays, which are having a high penetrating power are made to pass through castings, welds etc. and on the other side, the photographic plate receives the radiation. The attenuation (reduced intensity) is a function of the thickness of the test material and its density. Thus the film is exposed to varying intensities of radiation which help in detecting internal flaws of welds and castings.

Co^{60} is a good source of Gamma rays and is cheaper than X-ray tube and has a longer life. But this needs constant heavy shielding whereas X-ray tube needs shielding only during operation.

(8) *Density and content gauges :*

The Through Gauge is used for this purpose. If the reactivity is a function of density of the material and thus the density of the content can be measured. This method is used in cigarette packing line and a relay arrangement is made to reject the faulty cigarettes.

(9) *Application in chemistry :*

Substances deteriorate when exposed to radiation and the destroyed molecules are rejoined chemically to yield new materials. This technique has been exploited in the fields of polymerization, oxidation and halogenation processes.

In polymerization process, used in the manufacturing of synthetic rubber and plastics, the elements react at high temperature and pressures. But by irradiating the ingredients by Gamma radiation, the process can be carried out at 202°C and atmospheric pressure. This has helped in revolutionizing the polythene industry.

(10) *Sterilization of foods and drugs :*

Bacteria are produced in food-stuffs and vegetables and cause fermentation. Heating process can help in sterilization (complete destruction of Bacteria) and pasteurization (90% destruction of Bacteria). But this heating process cannot be done for fruits, vegetables and drugs. For these items, irradiation is the process adopted to kill the bacteria. In this process, the materials are kept in an air-tight container and are subjected to Gamma Radiation. After irradiation, these materials can be stored at room temperature for longer durations.

(11) *Direct electrical power generation :*

Direct electrical power generation can be done in devices called atomic battery.

(12) *Tracer applications :*

In this method, small dozes of isotopes of small half-lives are injected into reactants and then traced. This helps to trace the elements and their functions in the reactions. Determining the role of sulphur in the vulcanization is one such example.

In circuit breakers, the transfer of small amount of materials between the contact points can be detected by this methods. Similarly, flows in the bonding of two materials and the flaws can be detected, as in the case of bonding between asphalt and stone.

WORKED EXAMPLES

Example 7.1. *Calculate the following :*

(i) The fission rate of U^{235} *for producing a power of one watt.*

(ii) The energy released in the complete fissioning of 1 kg of U^{235}.

Assume that 200 MeV are released per fission of the uranium nucleus.

Solution. (*i*) Energy released per fission of U^{235} nuclide

$$= 200 \text{ MeV} = 200 \times 1.6 \times 10^{-13} \text{ J} = 3.2 \times 10^{-11} \text{ J or W-s}$$

Hence, *fission rate for producing one watt of power*

$$= \frac{1}{3.2 \times 10^{-11}} = \mathbf{3.1 \times 10^{10}} \textbf{ fission/second.} \quad \textbf{(Ans.)}$$

(*ii*) One kg-atom of U^{235} *i.e.*, a mass of 235 kg of U^{235} contains 6.02 × 10^{26} **atoms** (nuclides). Hence, energy released by 1 kg-atom of U^{235} is

$$= 200 \times 6.02 \times 10^{26} \text{ MeV}$$

∴ *Energy released per kg of* U^{235} *is*

$$= \frac{200 \times 6.02 \times 10^{26}}{235} \text{ MeV}$$

$$= \frac{200 \times 6.02 \times 10^{26} \times 1.6 \times 10^{-13}}{235} \text{ J}$$

$$= \mathbf{8.2 \times 10^{13}} \textbf{ J.} \quad \textbf{(Ans.)}$$

Example 7.2. *A nuclear reactor consumes 10 kg of* U^{235} *per day. Calculate its power output if the average energy released per U-235 fission is 200 MeV.*

Solution. Quantity of U^{235} consumed per day = 10 kg

Average energy released per U^{235} fission = 200 MeV

Number of atoms in 235 kg of U^{235} = 6.02×10^{26} (Avogadro's number)

Hence, number of atoms contained in 10 kg of U^{235}

$$= \frac{6.02 \times 10^{26}}{235} \times 10 = 2.56 \times 10^{25}$$

Fission energy produced by these atoms

$$= 200 \times 2.56 \times 10^{25} \text{ MeV}$$

$$= 200 \times 2.56 \times 10^{25} \times 1.6 \times 10^{-13} \text{ J} = 819.2 \times 10^{12} \text{ J}$$

Time taken to consume 10 kg of U^{235}

= one day = 24 × 3600 seconds

$\therefore$ *Power produced* $= \frac{819.2 \times 10^{12}}{24 \times 3600} = \mathbf{9.48 \times 10^{9}}$ **W. (Ans.)**

Example 7.3. *During a 10-hour run from one station to another, a railway engine develops an average power of 1200 kW. If the engine is driven by an atomic power plant of 20% efficiency, how much U^{235} would be consumed on the run ? Each U^{235} atom on fission releases 180 MeV of energy.*

Solution. Duration of the run between two stations = 10 hour

Average power developed by the railway engine = 1200 kW

Efficiency of the atomic power plant, $\eta = 20\%$

Energy released by each atom of U^{235} = 180 MeV

Mass of U^{235} consumed, m :

Energy consumed by the engine for the run

= 1200 × 10 = 12000 kWh

Since 1 kWh = 36×10^{5} J

$\therefore$ Energy consumed $= 12000 \times 36 \times 10^{5} = 432 \times 10^{8}$ J

Since the efficiency of atomic power plant is only 20%, energy required to produce it

$$= \frac{432 \times 10^{8}}{\eta} = \frac{432 \times 10^{8}}{0.2} = 216 \times 10^{9} \text{ J}$$

Energy produced per disintegration of U^{235} atom is

$$= 180 \text{ MeV} = 180 \times 1.6 \times 10^{-13} \text{ J}$$

Hence number of U^{235} atoms which must disintegrate for producing 216×10^{9} J is

$$= \frac{216 \times 10^{9}}{180 \times 1.6 \times 10^{-13}} = 7.5 \times 10^{21}$$

Now, 6.02×10^{26} atoms are contained in 235 kg of U^{235}.

Hence, the mass which contains 7.5×10^{21} atoms is

$$m = \frac{235 \times 7.5 \times 10^{21}}{6.02 \times 10^{26}} = 2.928 \times 10^{-3} \text{ kg}$$

= **2.928 gm. (Ans.)**

Example 7.4. *A power of 6 MW is being developed in a nuclear reactor.*

(i) How many atoms of U^{235} undergo fission per second ?

(ii) How many kg of U^{235} would be used in 1000 hours.

Assume that on an average 200 MeV is released per fission.

Solution. Power being developed in the reactor = 6 MW = 6×10^6 W

Average energy released per fission = 200 MeV

(*i*) **Number of atoms which undergo fission :**

The fission rate for producing 1 watt = 3.1×10^{10} fissions/second (Refer Example 7.1)

Hence, fission rate for 6×10^6 W is

$$= 3.1 \times 10^{10} \times 6 \times 10^6 = \mathbf{18.6 \times 10^{16}}. \quad \textbf{(Ans.)}$$

(*ii*) **Mass of U^{235} consumed :**

Number of atoms (or nuclides) which would undergo fission in 1000 hours

$$= 18.6 \times 10^{16} \times (1000 \times 3600) = 6.696 \times 10^{23}$$

Now, 1 kg-atom of U^{235} *i.e.*, 235 kg of U^{235} contains 6.02×10^{26} nuclides, hence

$$\text{Mass of } U^{235} \text{ consumed} = \frac{235 \times 6.696 \times 10^{23}}{6.02 \times 10^{26}} = \mathbf{0.2614\ kg.} \quad \textbf{(Ans.)}$$

Example 7.5. *200 MW of electrical power (average) is required for a city. If this is to be supplied by a nuclear reactor of efficiency 20 percent, using U^{235} as the nuclear fuel, calculate the amount of fuel required for one day's operation.*

Assume that energy released per fission of U^{235} nuclide = 200 MeV.

Solution. Average electrical power required by a city = 200 MW = 200×10^6 W

Efficiency of the nuclear reactor, $\eta = 20\%$.

Amount of fuel required for one day's operation :

Energy consumed by the city in one day

$$= 200 \times 10^6 \times 24 \times 3600 = 1728 \times 10^{10} \text{ J}$$

Since efficiency is 20%, energy required to be produced by the nuclear reactor is

$$= \frac{1728 \times 10^{10}}{0.2} = 864 \times 10^{11} \text{ J}$$

Energy released/atom $= 200 \times 1.6 \times 10^{-13} = 32 \times 10^{-12}$ J

$\therefore$ Number of atoms to be fissioned

$$= \frac{864 \times 10^{11}}{32 \times 10^{-12}} = 27 \times 10^{23}$$

Now, 6.02×10^{26} atoms are contained in 235 kg of U^{235}, hence 27×10^{23} atoms are contained in a mass

$$m = \frac{235 \times 27 \times 10^{23}}{6.02 \times 10^{26}} = \mathbf{1.054\ kg.} \quad \textbf{(Ans.)}$$

Example 7.6. *A city requires 1500 MWh of electric energy per day. It is to be supplied by a reactor which converts nuclear energy into electric energy with an efficiency of 20 percent. If reactor used nuclear fuel of U^{235}, calculate the mass of U^{235} needed for one day's operation.*

Solution. Amount of electric energy required per day = 1500 MWh

Efficiency of the nuclear plant = 20%.

Mass of U^{235} needed :

$$\text{Nuclear energy input} = \frac{\text{Electrical output}}{\text{Efficiency}} = \frac{1500}{0.2} = 7500 \text{ MWh}$$

Now 1 kWh $= 36 \times 10^8$ J

$\therefore$ Nuclear energy input per day

$$= 7500 \times 36 \times 10^8 = 2.7 \times 10^{13} \text{ J}$$

Now, energy released per fission of U^{235} nuclide

$$= 200 \times 1.6 \times 10^{-13} \text{ J} = 3.2 \times 10^{-11} \text{ J}$$

∴ Number of U^{235} nuclides required per day

$$= \frac{2.7 \times 10^{13}}{3.2 \times 10^{-11}} = 0.844 \times 10^{24}$$

Since, 235 kg of U^{235} contains 6.02×10^{26} number of atoms, the mass of U^{235} required for 0.844×10^{24} atoms is

$$= \frac{235 \times 0.844 \times 10^{24}}{6.02 \times 10^{26}} = 0.329 \text{ kg}$$

Hence mass of U^{235} needed for one day's operation = **0.329 kg. (Ans.)**

Example 7.7. *The motors of an atomic ice-breaker deliver 30000 kW. Calculate the fuel consumption of reactor per day if its efficiency is 22%. Average fission energy release of U^{235} nuclide is 200 MeV.*

What would be the daily amount of 29300 kJ/kg coal needed to obtain the same power if the efficiency now is 78%.

Solution. Electric power delivered by atomic ice-breaker = 30000 kW

Efficiency of the nuclear reactor = 22%

Average fission energy release of U^{235} = 200 MeV.

Calorific value of coal = 29300 kJ/kg

Efficiency = 78%

(*i*) **Fuel consumption of the reactor :**

Power output $= 30000 \times 1000 = 3 \times 10^7$ W or J/s

Daily output $= 3 \times 10^7 \times 24 \times 3600 = 25.92 \times 10^{11}$ J

Since efficiency is = 22%, the daily energy input

$$= \frac{25.92 \times 10^{11}}{0.22} = 11.78 \times 10^{12} \text{ J}$$

Now, as seen from Ex. 7.1, 1 kg of U^{235} provides 8.2×10^{13} J of energy,

∴ *Daily fuel consumption* $= \dfrac{11.78 \times 10^{12}}{8.2 \times 10^{13}}$ = **0.1436 kg. (Ans.)**

(*ii*) **Coal required per day :**

With an efficiency of 78%, daily energy input is

$$= \frac{25.92 \times 10^{11}}{0.78} = 33.23 \times 10^{11} \text{ J or } 33.23 \times 10^8 \text{ kJ}$$

∴ *Coal required per day* $= \dfrac{33.23 \times 10^8}{29300 \times 1000}$ = **113.4 tonnes. (Ans.)**

Example 7.8. *What is the energy equivalence of 1 atomic mass unit ?*

Solution. 1 atomic mass unit (a.m.u.) $= 1.66 \times 10^{-24}$ g

Using Einstein's equation

$$E = mC^2$$

where, E = energy ; m = mass ; C = velocity of light (= 3×10^8 m/s)

Substituting the values, we get

$$E = (1.66 \times 10^{-24}) \times (3 \times 10^8 \times 10^2)^2 = 1.494 \times 10^{-3} \text{ ergs}$$

Now, 1 erg = 0.625×10^6 MeV

$$\therefore \quad E = 1.494 \times 10^{-3} \times 0.625 \times 10^6 = 933.75 \text{ MeV}$$

Hence energy equivalence of 1 a.m.u. = **933.75 MeV. (Ans.)**

Example 7.9. *Calculate the total binding energy and the binding energy per nucleon for the* $_8O^{16}$ *isotope.*

Solution. The atomic weight of $_8O^{16}$, by definition, is 16.000 a.m.u.

The predicted mass of $_8O^{16}$ is given as under :

Mass of 8 protons = 1.00759 × 8 = 8.06072 a.m.u.

Mass of 8 neutrons = 1.00898 × 8 = 8.07184 a.m.u.

Mass of 8 electrons = 0.00055 × 8 = 0.00440 a.m.u.

Total = 16.13696 a.m.u.

Isotopic mass = 16.00000 a.m.u.

∴ Mass defect = 16.13696 – 16.00000 = 0.13696 a.m.u.

But energy equivalent of 1 a.m.u. = 933.75 MeV

∴ *Total binding energy* = 933.75 × 0.13696

= **127.88 MeV. (Ans.)**

Binding energy per nucleon $= \dfrac{127.88}{16}$ = **7.99 MeV. (Ans.)**

Example 7.10. *The half-life of Radon gas is 3.83 days. What is its radioactive decay constant ?*

What percentage of the radon atoms originally present will decay in a period of 45 days.

Solution. Let $t_{1/2}$ = Half-life of radioactive nuclei,

N = Number of radioactive nuclei present at any time t,

N_0 = Initial number of such nuclei, and

λ = Proportionality constant (also known as *radioactive decay constant*).

From eqn. (7.7), the half-life is given as

$$t_{1/2} = \frac{0.693}{\lambda}$$

But $t_{1/2} = 3.83$ days ...(given)

∴ Radioactive decay constant,

$$\lambda = \frac{0.693}{3.83} = 0.181 \text{ day}^{-1}$$

From eqn. (7.4),

$$N = N_0 \, e^{-\lambda t}$$

Here $t = 45$ days

$$\therefore \quad N = N_0 \times e^{-(0.181 \times 45)} = 0.00029 \, N_0$$

% age of radon atoms those will decay in a period of 45 days

$$= \frac{N_0 - N}{N_0} \times 100 = \frac{N_0 - 0.00029\, N_0}{N_0} \times 100 = \mathbf{99.971\%}. \quad \textbf{(Ans.)}$$

Example 7.11. *A U^{235} nucleus is bombarded by a neutron, resulting in its fission into Barium 137 and Krypton 97 nuclei. Write the complete nuclear equation and find the amount of energy liberated in the reaction.*

Solution. The nuclear reaction can be written as :

$$_{92}U^{235} + {}_0n^1 \longrightarrow {}_{56}Ba^{137} + {}_{36}Kr^{97} + x$$

In a nuclear reaction, since the atomic numbers and mass numbers must balance on both sides of the equation therefore, the above equation is balanced with the addition of a particle or particles having combined Z = 0 and A = 2 to the products. Thus

$$x = 2\,{}_0n^1$$

∴ The complete nuclear equation becomes as :

$$_{92}U^{235} + {}_0n^1 = {}_{56}Ba^{137} + {}_{36}Kr^{97} + 2\,{}_0n^1$$

Mass before the reaction = Mass of $_{92}U^{235}$ + mass of $_0n^1$

= 235.116 + 1.00898 = 236.125 a.m.u.

Mass after the reaction = Mass of Ba^{137} + mass of Kr^{97} + mass of two $_0n^1$

= 136.9514 + 96.9520 + 2 × 1.00898 = 235.9214 a.m.u.

Thus, *there is decrease in the mass after the reaction, so energy will be liberated.*

The mass defect = 236.125 – 235.9214 = 0.2036 a.m.u.

∴ *Energy released* = 0.2036 × 933.75 = **190.11 MeV. (Ans.)**

HIGHLIGHTS

1. Those pairs of atoms which have the same atomic number and hence similar chemical properties but different atomic mass number are called isotopes.
2. Those atoms which have the same mass number but different atomic numbers are called *isobars.* Obviously, these atoms belong to different chemical elements.
3. Those pairs of atoms (nuclides) which have the same atomic number and atomic mass number but have different *radioactive properties* are called isomers and their existence is referred to as nuclear isomerism.
4. Those atoms whose nuclei have the same number of neutrons are called isotones.
5. The phenomenon of spontaneous emission of powerful radiations exhibited by heavy elements is called radioactivity. The radioactivity may be natural or artificial.
6. The five types of nuclear radiations are :
   (*i*) Gamma rays (or photons) : electromagnetic radiation.
   (*ii*) Neutrons : uncharged particles, mass approximately 1.
   (*iii*) Protons : + 1 charged particles, mass approximately 1.
   (*iv*) Alpha particles : helium nuclei, charge + 2, mass 4.
   (*v*) Beta particles : electrons (charge – 1), positrons (charge + 1), mass very small.
7. *Half life* represents the rate of decay of the radioactive isotopes. The half life is the time required for half of the parent nuclei to decay or to disintegrate.
8. *Nuclear cross sections* (or attenuation co-efficients) are measures of the probability that a given reaction will take place between a nucleus or nuclei and incident rediation.
9. It has been found that some materials are not fissionable by themselves but they can be converted to the fissionable materials, these are known as *fertile materials.*
10. Fission is the process that occurs when a neutron collides with the nucleus of certain of the heavy atoms, causing the original nucleus to split into two or more unequal fragments which carry off most of the energy of fission as kinetic energy. This process is accompanied by the emission of neutrons and gamma rays.
11. A *chain reaction* is that process in which the number of neutrons keeps on multiplying rapidly (in geometrical progression) during fission till whole the fissionable material is disintegrated. The multiplication or reproduction factor (K) is given by :

$$K = \frac{\text{No. of neutrons in any particular generation}}{\text{No. of neutrons in the preceding generation}}$$

If $K > 1$, chain reaction will continue and if $K < 1$, chain reaction cannot be maintained.

12. *Nuclear fusion* is the process of combining or fusing two lighter nuclei into a stable and heavier nuclide. In this case large amount of energy is released because mass of the product nucleus is less than the masses of the two nuclei which are fused.
13. A *nuclear reactor* is an apparatus in which nuclear fission is produced is the form of a controlled self-sustaining chain reaction.
14. Essential components of a nuclear reactor are :
    (*i*) Reactor core
    (*ii*) Reflector
    (*iii*) Control mechanism
    (*iv*) Moderator
    (*v*) Coolants
    (*vi*) Measuring instruments
    (*vii*) Shielding.
15. The main components of a nuclear power plant are :
    (*i*) Nuclear reactor
    (*ii*) Heat exchanger (steam generator)
    (*iii*) Steam turbine
    (*iv*) Condenser
    (*v*) Electric generator.
16. Some important reactors are :
    (*i*) Pressurised water reactor (PWR)
    (*ii*) Boiling water reactor (BWR)
    (*iii*) Gas cooled reactor
    (*iv*) Liquid metal cooled reactor
    (*v*) Breeder reactor.
17. Following factors should be considered while selecting the site for a nuclear power plant :
    (*i*) Proximity to load centre
    (*ii*) Population distribution
    (*iii*) Land use
    (*iv*) Meteorology
    (*v*) Geology
    (*vi*) Seismology
    (*vii*) Hydrology.
18. Typically, all costs of nuclear power plants are broken down into the following categories :
    (*i*) Capital costs (total)
    (*ii*) Fuel costs (per year)
    (*iii*) Other operating and maintenance cost (per year).

THEORETICAL QUESTIONS

1. Explain the following terms :
    (*i*) Atomic model
    (*ii*) Atomic mass unit
    (*iii*) Isotopes
    (*iv*) Isobars
    (*v*) Isomers
    (*vi*) Isotones
2. What do you mean by the term 'Radioactivity' ?
3. What is the difference between 'Artificial radioactivity' and 'Natural radioactivity' ?
4. Name five types of radiation of interest, in nuclear power technology.
5. Explain briefly the following :
    (*i*) Prompt-fission gamma rays
    (*ii*) Fission-product-decay gamma rays
    (*iii*) Capture gamma rays
    (*iv*) Activation gamma rays
    (*v*) Inelastic scattering gamma rays.
6. Explain briefly the following types of neutrons :
    (*i*) Prompt-fission neutrons
    (*ii*) Delayed neutrons
    (*iii*) Photoneutrons
    (*iv*) Activation neutrons
    (*v*) Reaction neutrons.
7. What do you mean by 'Binding Energy' ? What are the total binding energy and binding energy per nucleon for the ${}_6C^{12}$ nucleus ?
8. Explain briefly the following terms relating radioactive decay :
    (*i*) Activity
    (*ii*) Half life
    (*iii*) Average (mean) life.

9. What do you mean by the following :
   (*i*) Elastic scattering (*ii*) Inelastic scattering
   (*iii*) Capture (*iv*) Fission.
10. Write a short note on 'Fertile materials'.
11. What do you mean by 'Fission of nuclear fuel' ?
12. What is a chain reaction ?
13. What are the requirement of fission process.
14. How are the following defined ?
   (*i*) Critical mass (*ii*) Critical size.
15. What is 'nuclear fusion' ? How does it differ from '*nuclear fission*' ?
16. What is a nuclear reactor ?
17. How are nuclear reactors classified ?
18. Enumerate and explain essential components of a nuclear reactor.
19. Explain with help of neat diagram the construction and working of a nuclear power plant.
20. What is a moderator ? Name common moderators and discuss their advantages and limitations.
21. Give the functions and materials for the following :
   (*i*) Reflector (*ii*) Control rods
   (*iii*) Biological shield.
22. Describe with the help of a neat sketch the construction working of a Pressurised Water Reactor (PWR). What are its advantages and disadvantages ?
23. What is 'Boiling Water Reactor' (BWR) ? How does it differ from 'Pressurised Water Reactor' (PWR) ?
24. Give the construction and working of a 'Gas cooled reactor'. What are its advantages and disadvantages ?
25. What is a 'Liquid Metal cooled Reactor' ? Explain briefly a typical liquid metal reactor.
26. Describe a breeder reactor. What are its advantages and disadvantages ?
27. What factors must be considered while selecting materials for the various reactor components ?
28. List the advantages and disadvantages/limitations of nuclear power plants.
29. Discuss the various factors which must be considered while selecting a site for a nuclear power plant.
30. Give the application of nuclear power plants.
31. What do you mean by 'Economics of nuclear power plants' ?
32. List down some safety measures for nuclear power plants.
33. What is the future of nuclear power ?

UNSOLVED EXAMPLES

1. A nuclear reactor is developing a power of 3 MW. How many atoms of U^{235} undergo fission per second ? How many kg of U^{235} would be used in 1000 hours of operation assuming that on an average 200 MeV is released per fission. **[Ans.** 9.3 × 10^6 ; 0.132 kg]
2. A city requires 100 MW of electric power on an average. If this is to be supplied by a nuclear reactor of efficiency 20 percent, using U^{235} as the nuclear fuel, calculate the amount of fuel required for one days's operation. Given that energy released per fission of U^{235} nuclide = 200 MeV. **[Ans.** 0.53 kg]
3. Bombay requires 3000 MWh of electric energy per day. It is to be supplied by a reactor which converts nuclear energy into electric energy with an efficiency of 20 percent. If reactor uses nuclear fuel of U^{235}, calculate the mass of U^{235} needed for one day's operation. **[Ans.** 0.66 kg]
4. The motors of an atomic ice breaker deliver 32824 kW. Calculate the fuel consumption of reactor per day if its efficiency is 20 percent. Average fission energy release of U^{235} nuclide is 200 MeV. What would be the daily amount of 7000 kcal/kg coal needed to obtain the same power if the efficiency now is 80%. **[Ans.** 0.173 kg ; 12100 tonnes]

COMPETITIVE EXAMINATIONS QUESTIONS

1. (*a*) With the help of a sketch show all the important parts of a nuclear reactor, describing briefly the functions of each part.
   Under what circumstances would a nuclear power station be recommended for installation ?
   (*b*) Give a brief comparison, between a nuclear and a conventional thermal power station, in respect of (*i*) Capital cost, (*ii*) fuel cost, and (*iii*) operating and overhead cost, as a percentage of the total cost given by the sum of (*i*), (*ii*), and (*iii*).
2. (*a*) What are the principal parts of a nuclear reactor ? Explain each part in brief.
   (*b*) Why are nuclear power stations not so popular and successful in this country ?
3. (*a*) "The source of future power generation will be only nuclear fuel". Write your comments.
   (*b*) Explain the working of a reactor in a nuclear power station.
4. (*a*) Why is shielding of a reactor necessary ? What do you understand by thermal shielding ?
   (*b*) Explain the working of a reactor in a nuclear power station.
5. (*a*) Explain the generation of nuclear energy in a nuclear power plant.
   (*b*) Describe a boiling water reactor with diagram.
6. (*a*) What are the principal parts of a nuclear reactor ? Explain each part in brief.
   (*b*) Explain the working of a steam surface condenser.
7. (*a*) What do you understand by the following terms :
   (*i*) binding energy, (*ii*) half life,
   (*iii*) isotope, and (*iv*) moderator.
   (*b*) Discuss the boiling water reactor with the help of a neat sketch and write down its chief characteristics.
8. (*a*) How are nuclear power plants classified ? Explain how fission reaction takes place and how the chain reaction is controlled.
   (*b*) Discuss briefly boiling water reactor plant.
9. (*a*) Describe in brief giving neat sketch, the working of a pressurised water reactor plant.
   (*b*) Draw a line diagram of a diesel power plant and describe briefly the cooling system and the lubrication system.
10. (*a*) What is a moderator in nuclear reactor ? Explain the desirable properties of good moderator.
    (*b*) Draw a neat diagram of CANDU type reactor and explain its working principle and give its advantages over the other types.
11. (*a*) Draw a neat diagram of nuclear reactor and explain the functions of different components.
    (*b*) Explain the working principle of a closed cycle gas turbine plant.
12. (*a*) Draw a neat diagram of nuclear reactor and explain the functions of different components.
    (*b*) Explain the working principle of a closed cycle gas turbine plant.
13. (*a*) How are nuclear reactors classified ? Explain with neat sketch the working of a pressurised water reactor.
    (*b*) What different methods are used to thermal efficiency of the open cycle gas turbine plant ? Explain *any one* of them.
14. (*a*) Using neat sketches explain the construction and working of an air preheater.
    (*b*) Explain the layout of *any one* type of nuclear power plant system used in India.
    (*c*) Clearly bring out the differences in the constructional features of steam turbines of 500 MW rating used in conventional coal fired steam power plant and PWR plant.
15. (*a*) Explain the following terms with reference to a nuclear reactor :
    (*i*) Moderator (*ii*) Coolant
    (*iii*) Control rods (*iv*) Reflector.
    (*b*) Give the layout of a fast breeder reactor power plant and explain its salient features.
    (*c*) Give a brief account of nuclear waste disposal.

8

Combined Operation of Different Power Plants

8.1. General aspects. 8.2. Advantages of combined operation of plants. 8.3. Load division between power stations. 8.4. Hydro-electric (storage type) plant in combination with steam plant. 8.5. Run-of-river plant in combination with steam plant. 8.6. Pump storage plant in combination with steam or nuclear power plant. 8.7. Co-ordination of hydro-electric and gas turbine stations. 8.8. Co-ordination of different types of power plants. Worked Examples—Theoretical Questions—Unsolved Examples.

8.1. GENERAL ASPECTS

The leading aim of the national economy is to make available maximum amount of generating capacity with the available funds and ensure power generation at the cheapest rate possible. Since a large investment is required in power supply industry, therefore, once generating facilities are created it is desirable to utilise them in optimum manner. It is also of paramount importance that most economic generating scheme should be selected to supply power at lowest cost before huge amount of money is invested. When the generating facilities are established it is a wiser step to think of having integrated operation of neighbouring power systems so that maximum energy generation takes place from power stations like *thermal* and *nuclear* and maximum energy and capacity are utilised from the *hydro-electric* power stations. This is possible only if we have close combined operation of different power systems which if operated individually cannot be utilized to the maximum advantage. This leads to conclusion that if maximum benefit is to be yielded then power systems of different states should be interconnected. It is beyond doubt that the rapid pace of interconnection between the power systems can greatly improve the *continuity, security* and *integrity of power supply* provided it is associated with sound mechanism for monitoring and control.

8.2. ADVANTAGES OF COMBINED OPERATION OF PLANTS

If several power stations (such as hydro, thermal, nuclear etc.) work together to meet the demand of the consumers then the system is known as *'Interconnected system'*. Such a combined system claims the following **advantages** over a single power plant/station :

1. Greater reliability of supply to the consumers.
2. When one of the stations fails to operate the consumers can be fed from the other station, thus avoiding complete shut down.
3. The overall cost of energy per unit of an interconnected system is less.
4. There is a more effective use of transmission line facilities at higher voltage.
5. Less capital investment required.
6. Less expenses on supervision, operation and maintenance.