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Nuclear Materials

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29.1. INTRODUCTION

The materials used in nuclear reactors must satisfy the mechanical and metallurgical requirements as adequate strength and corrosion resistance during operation and good ductility and machineability during fabrication. It is also necessary that the materials used should fulfill the required nuclear properties in addition to the above-mentioned properties. In many cases, the nuclear properties play more important role in selecting the materials than their engineering properties. The major nuclear properties required for the materials used in nuclear reactors are low absorption cross-section and high resistance to irradiation. The resistance to irradiation is very important because many materials lose engineering properties after irradiation and become unsuitable even during operation. The number of materials having adequate engineering and nuclear properties are rather limited and costly also.

29.2. NUCLEAR FUELS

The main fuel materials which are used are natural uranium (0.7% U^{235}), enriched uranium, plutonium (secondary fuel) and U^{233} (secondary fuel available from breeder reactor). The natural uranium is the parent material so it is proper to learn more details about this fuel.

Resources of Uranium. Granite rocks are the primary uranium sources. They contain nearly 4 ppm uranium. Uranium enriched residue of granitic magna is forced into the upper crest of the earth where they are precipitated. Uranium concentration in upper crest is as high as 5%.

Second source of uranium deposits is sediments originated from volcanic rocks. The sand stone is one more source of uranium. These sources contain 3% uranium.

It is estimated that almost all the resources of uranium are situated in U.S.A. (33%), South Africa (20%), Australia (20%) and Canada (20%). The largest reserve of most economical and low cost uranium lies in Australia.

The sea water is also considered as vast source of uranium but the difficulty lies in its extraction as the content of uranium in the sea water is very low (3.3 micrograms per litre). A scientist in Japan has developed a method to extract U^{235} from sea water using $Ca(OH)_2$. Amount of $Ca(OH)_2$ required is 200 gms to treat one ton of sea water.

Presently, the ground resources of uranium are considerably large but it is estimated that the cumulative demand for uranium predicted will exhaust all present known economic resources within coming 20 years. Therefore, it is necessary to continue to extract low grade uranium ores until large new resources of high grades ore are found.

The nations like Britain who have very limited ground resources of uranium are looking for the new source of uranium like oceans. The steps are already taken to find out the potentialities of extracting uranium economically from sea water. It is estimated that uranium is present in form of carbonate ion with a concentration of 3.3 micrograms per litre of sea water. This concentration is constant over a wide range of areas and depths in the water of English channel, Atlantic oceran and Pacific ocean. It is estimated that the total volume of oceans is 1.37×10^9 cubic kilometres and the quantity of dissolved uranium is about 4×10^9 tons. This shows an unlimited source of uranium which may last number of years to come but the only task of the engineers is to find out the economical method to extract uranium from sea water. The method of extraction of uranium from earth sources (solvent extraction and ion exchange) is also used for the extraction of uranium from sea water. It has been found that titanium oxide bed of 30 cm in diameter and 10 cm height extracts 52% of uranium from 170 × 10^3 litres of sea water (0.56 grams) flowing at 900 litres per hour within eight days. Greater extraction can be achieved with lower water flow rates, with finer granulars and deeper beds. It is estimated that the production of 1000 tons of uranium per year would require complete extraction of uranium from water when one cubic kilometre water is coming in contact with absorbing bed per day. The supply of huge quantity of water and its disposal without recirculation and prevention of blocking the beds by suspended solid in sea water are the great problems in the selection of a suitable site for the plant. This source of uranium is still in experimental stage.

The uranium reserves should be known nearly 8 to 10 years ahead of their requirements. Because this period is required for exploration, construction of mine and mill, yellow cake production, conversion and enrichment and manufacturing of fuel elements. Secondly the known reserves should allow the extraction minimum for 10 years so that the capital investment decision can be taken. The economic reserve situation is the amount of uranium available at the selected site which is 10 times larger than the yearly requirements 10 years later.

The natural uranium is used as a fuel in Magnox and CANDU type reactors and slightly enriched uranium is used in light water reactors and gas cooled reactors. Some of the engineering properties required by the uranium fuel are listed below.

1. High tensile strength at high temperature is necessary to prevent the buckling of fuel elements and to bear thermal stresses.

2. The high conductivity is desirable due to two reasons :

(*a*) First, because the large amount of energy released should be transferred without raising the centre temperature of the fuel element above safe limit.

(*b*) Secondly, because high temperature of the element and low temperature gradient causing heat flow impart higher thermal stresses in the element.

3. Better machinability and higher ductility are desired as the cost of machining is reduced.

4. The fuel element must be corrosion-resistant so that the element if exposed to the coolant will not corrode away and enter the coolant system. Once the fuel element enters into the coolant, it spreads through the primary circuit causing the whole circuit to become radioactive.

5. The fuel should have high radiation stability, so that nuclear radiation will not distort and cause the fuel elements to buckle.

The common uranium fuels used are natural uranium, uranium oxide and uranium carbide. The engineering properties of these fuel elements are discussed below :

1. Natural Uranium. Natural uranium is chemically stable at room temperature but oxidizes rapidly even at low temperature (100°C). The uranium is strongly corroded in the presence of water. The uranium melts at 1129°C.

The mechanical strength of the fuel is a factor of great importance when natural uranium is used as fuel. This is because, the uranium exists in α-phase upto the temperature of 660°C. The ultimate strength of α-phase is sufficiently high 28 bar. The ultimate strength can be increased to 140 bar by cold-rolling treatment. Above the temperature 660°C, α-phase of uranium changes to β-phase and metal becomes soft and fragile. On changing from α to β phase, the metal grows by 1% and causes the fuel element to buckle. The swelling of metal due to this phase change may clog the coolant flow passages and subsequent burn out of some part of the fuel takes place. This characteristic of uranium fuel limits its operating temperature to 600°C instead of being limited by the melting point of the metal.

The mechanical strength of uranium also goes down even at lower temperature due to radiation damage. The gaseous fission products (Xenon and Krypton) diffuse through the uranium and cause the swelling of the uranium bar.

Uranium oxidizes rapidly in air at high temperatures but fuel elements can be operated upto 350°C surface temperature without any risk in the event of can failure. The rate of reaction is still less in presence of CO_2, therefore, uranium fuel can be operated safely upto 450°C in CO_2 cooled reactor.

2. Uranium oxide. The uranium oxide (UO_2) is another important fuel element. It is a brittle ceramic, produced as a powder and then sintered to form fuel pellets.

The advantages of UO_2 fuel over the natural uranium are listed below.

1. As it is already oxidised, it is more stable than natural uranium and presents less problems of oxidation.

2. It is more compatible with most of the coolants and is not attacked by H_2, He or N_2.

3. UO_2 does not present the problems of phase changes, therefore, it can be used for higher temperatures (2750°C melting temperature). This fuel is more preferable in high temperature gascooled reactors. The can surface temperature as high as 800°C is common against the can surface temperature of 450°C with the use of natural uranium. The fuel centre temperatures are still higher.

4. UO_2 does not corrode as easily as natural uranium, therefore, the cladding failure is not as serious as cladding failure of natural uranium.

5. Greater dimensional stability is possible due to the absence of irradiation effects. This fuel is free from wrinking, buckling and swelling which are major problems with natural uranium fuel.

6. The fuel rating is as high as 8.5 MW/te against 3 MW/te for natural uranium.

A few disadvantages of this fuel are listed below.

1. The undesirable characteristic of UO_2 is low thermal conductivity (8 kW/m-°C) compared with natural uranium (80 to 180 kJ/m-hr-°C). This presents a great problem of heat removal and thermal stresses are far greater than natural uranium fuel. To avoid this difficulty, the diameter of the fuel element is reduced.

2. The enrichment is necessary with the use of UO_2 as the presence of two oxygen atoms for every uranium atom reduces the proportion of fissile uranium U^{235}.

3. Being more brittle than natural uranium, it tries to crack under thermal stresses. Therefore, strength must be provided by canning.

4. The UO_2 may disintegrate into a powder and this causes serious consequences if the can fails.

5. The powder is oxidised to U_4O_9 by carbon dioxide under irradiation forming CO. The CO will build up inside the can and promote the ingress of CO_2. The newly formed oxide is far inferior in physical properties compared with UO_2. This further causes deterioration of the fuel assembly.

3. Uranium carbide. The uranium carbide is another fuel used in the reactor. It is a black ceramic used in the form of pellets. It has high density, high melting point, possesses good thermal conductivity and is free from the trouble of phase change. It is more stable under irradiation and gives high rate of reaction with CO_2. The use of uranium carbide is not yet economically justified.

The physical properties of these fuels are listed in the table given below.

Fuel	*Density*	*Melting point in °C*	*Specific heat in kJ/kg°C*	*Thermal conductivity in kW/m-°C*	*Coefficient of linear expansion 10^{-6}/°C*
Natural uranium	19000	1129	0.128	105.2	18.20
UO_2	10600	2750	0.312	7.2	12.9
UC	13600	2350	–	82.4	10.5

Enrichment of Uranium Fuel. It has already been seen that the chain reaction cannot be maintained in some reactors (PWR, BWR) with natural uranium having 0.7% fissionable U^{235}. Therefore, it is necessary to increase the percentage of U^{235} in the fuel if used in reactor for maintaining the chain reaction. The process used to increase the percentage of U^{235} is known as enrichment. The enrichment required may lie from 1.5% to 90% according to its use in a particular reactor. The enrichment of fuel also reduces size of the reactor.

The practical methods for enrichment are based on the slight difference in the atomic masses of U^{238} and U^{235}.

The different methods which are used for the enrichment are discussed below.

1. **Gaseous Diffusion Method.** The principle of separation depends upon the fact that the molecules of lighter gas diffuse (penetrate) through a porous barrier quicker than the molecules of heavier gas. In a gas having two isotopes, the lighter isotope diffuses quicker than that of heavier isotope. Therefore enrichment of lighter isotope (U^{235}) is possible in this method. To use this method of enrichment, one must have a uranium compound in gaseous form under normal temperature and pressure conditions. Presently, only known gas is uranium hexafluoxide (UF_6), which is solid at room temperature but it transforms into vapour at 64.5°C temperature and 110 mm of Hg pressure. Therefore unsaturated UF_6 can be used for diffusion process. UF_6 contains two isotopes, one is $U^{235}F_6$ having a molecular weight of 349 and another is $U^{238}F_6$ having a molecular weight of 352. It has been known that the thermal velocity of a molecule is inversely proportional to the square root of its mass. Therefore, the thermal velocity ratio U^{235} and U^{238} molecules is equal to $\sqrt{352/349} = 1.0043$. This shows that the velocity of lighter molecules is 0.43% higher than the velocity of heavier molecules. This slight difference in the molecular velocities is sufficient for partial separation of U^{235} from U^{235} and U^{238} mixture by means of diffusion through a porous membrane.

Fig. 18.1 (*a*) shows a membrane box for gaseous diffusion. UF_6 is compressed in axial flow compressor and is passed through the tube having membrane as shown in figure. The membrane box is so designed that 50% of the input material passes through the porous barrier while the remaining 50% passes through the box without penetrating the membrane. The gas passed through the membrane is enriched in $U^{235}F_6$. For better diffusion, the molecules must collide with the membrane wall and not with the other molecules. If the collisions take place between the lighter and heavy molecules both would be pushed in forward direction instead of getting diffused.

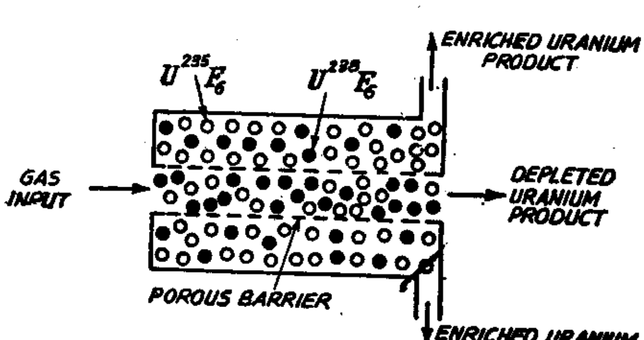


Fig. 29.1. (*a*) Gaseous diffusion through porous barrier.

The enrichment with single stage is extremely poor therefore core system (diffusion membrane in series) is used as shown in Fig. 29.1 (*b*). In cascade system, the enriched product of one stage is fed to the next stage for further enrichment and depleted product of the same stage being fed to the previous stage. The major drawback of this system is, a large number of cascades (hundreds or thousands) nearly 1500 to 1800 are required to get the enrichment of 3 to 5%. The plant must be air-sealed because UF_6 decomposes in the presence of water vapour.

This method was developed first by an American scientist Hertz and used for enrichment in 1932.

2. **Thermal Diffusion Method.** If a mixture of two gases or liquids is placed in a vessel with a temperature difference maintained between the walls, the concentration of lighter material (gas or liquid) at the hot walls is greater than at the cold wall. This phenomenon is known as "thermal diffusion" and used for the enrichment of U^{235}. The phenomenon is shown in Fig. 29.2 (*a*).

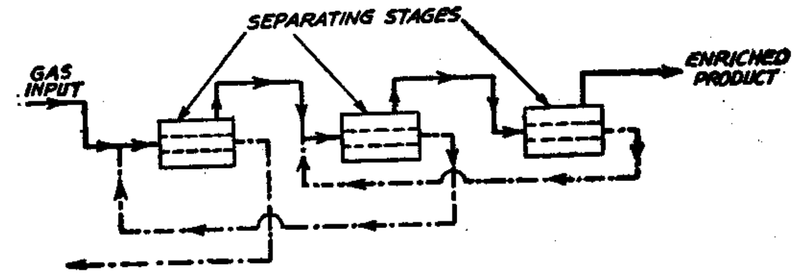


Fig. 29.1. (*b*) 3-stage cascade gaseous diffusion system.

For the enrichment of uranium-235, a vessel consisting of two concentric cylinders as shown in Fig. 29.2 (*b*) is used. The space between the pipes is filled with uranium hexafluoxide ($U^{235}F_6$ + $U^{238}F_6$). The temperature of the inner pipe is maintained higher than the output pipe. The circulation of the fluid (UF_6) sets in as shown in Fig. 29.2 (*b*). The liquid rises along the hot wall and comes down along the cold wall. During this circulation, the lighter $U^{235}F_6$ is concentrated along the hot wall due to thermal diffusion and heavier $U^{238}F_6$ is concentrated along the cold wall. This thermal diffusion concentrates $U^{235}F_6$ in the upper part of the column so that it is taken out from the top as shown in figure. The enrichment achieved in a single column is not very high and number of columns in series are used for higher enrichment purposes. This process is better than gaseous diffusion but great amount of power is required to maintain the required temperature difference between the column walls.

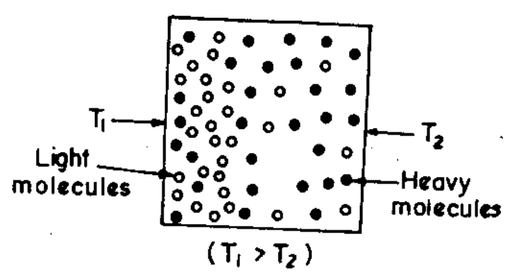


Fig. 29.2. (*a*) Principle of thermal diffusion.

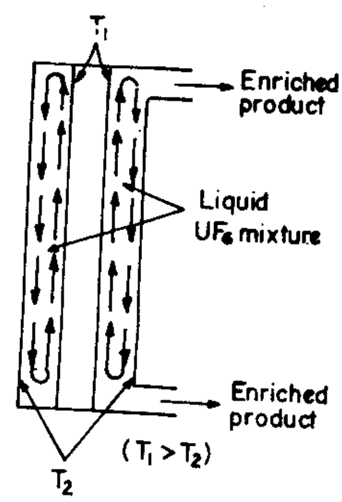


Fig. 29.2. (*b*) Single stage thermal diffusion column used for uranium enrichment.

3. **Centrifugal Method.** If a mixture of two gases of different molecular weights are enclosed in a centrifuge and rotated at a high speed, the heavier gas is concentrated near the outer periphery as shown in Fig. 29.3. This method is used to separate $U^{238}F_6$ at the periphery and $U^{235}F_6$ at the axis of the centrifuge from the mixture of the two. The major problem faced in the development of this process is in feeding the vapour mixture and removing enriched $U^{235}F_6$ from axis and $U^{238}F_6$ from the periphery of the centrifuge.

This method of enrichment was first developed in U.S.A. during second world war.

Gas centrifuge enrichment of U^{235} for nuclear plant would be economically superior to the gaseous diffusion process as per the study made by Tennessee Valley Authority.

A $ one billion centrifuge plant would produce enriched uranium at a cost significantly lower than would a $ 3-billion gaseous diffusion plant.

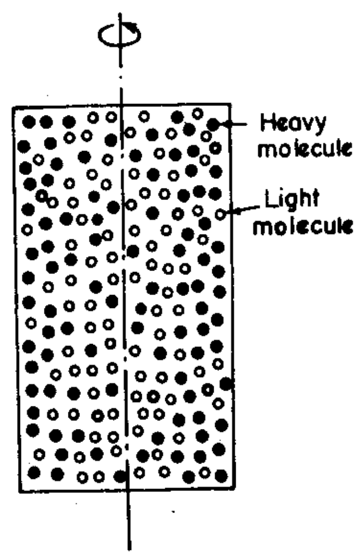


Fig. 29.3. Centrifuge method of enrichment.

4. **Electro-magnetic Method.** It is observed that the direction of motion of the ions is affected by the magnetic field. If the ion with different masses moving in same direction along a straight line and enter into a magnetic field which acts perpendicular to the direction of motion ; deviates the path of ions motion in semi-circular direction. The radius of semi-circle along which the ions move is dependent upon the mass of the ion. The paths of ions of different masses with same initial velocity through the magnetic field is shown in Fig. 29.4 (*a*).

This principle is used to separate the ions of $U^{235}F_6$ and $F^{238}F_6$ from the mixture of two.

For force equilibrium when the ion enters into the magnetic field, the required condition is

$$evH \text{ (magnetic force)} = \frac{mv^2}{R} \text{ (centripetal force)}$$

where e = charge of ion, v = ion velocity

H = magnetic field strength, m = mass of ion

R = Radius of ion path curvature.

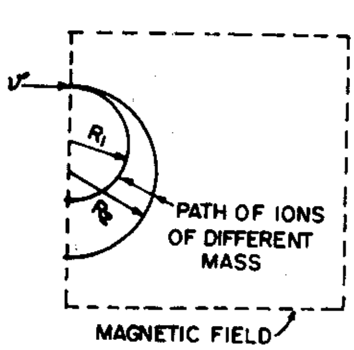


Fig. 29.4. (*a*) Motion of ions of different masses with same initial velocity in a magnetic field.

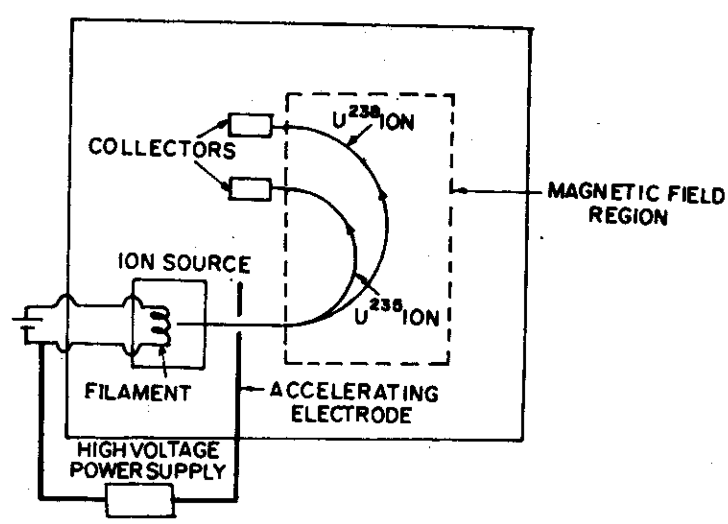


Fig. 29.4. (*b*) Electromagnetic plant used for enrichment of Uranium-235.

$$\therefore \qquad eH = \frac{mv}{R}.$$

But
$$E = \frac{1}{2} mv^2$$

$$\therefore \qquad v = \sqrt{\frac{2E}{m}}$$

$\therefore$ Substituting this value in the above equation

$$eH = \frac{m}{R}\sqrt{\frac{2E}{m}}$$

$$\therefore \quad R = \frac{\sqrt{2Em}}{eH}.$$

This expression states that the radii of circumferences of different masses having same initial energy are directly proportional to the square root of their ion masses when passing through the magnetic field.

This principle is used in separating $U^{235}F_6$ gas from the mixture of $U^{235}F_6$ and $U^{238}F_6$. The arrangement of the system is shown in Fig. 29.5 (*b*). A gaseous mixture is introduced into the ion source as shown in figure where the neutral atoms are ionized. Then the ion beam is passed through an electric field where the ions are highly accelerated. The accelerated ions of the mixture are then passed though the magnetic field where $U^{238}F_6$ and $U^{235}F_6$ move along the different radii as shown in figure for the reason mentioned above. These ions moving along different radii are collected in different collectors as shown in figure. The collected ions are neutralised and deposited on the wall as the coating of uranium compounds. These collectors are removed to collect the uranium compounds when the enrichment process is over.

By using this method, very high enrichment, even 100%, is possible. To obtain large quantities of U^{235}, it is necessary to run number of units simultaneously.

29.3. CLADDING AND STRUCTURAL MATERIALS

The cladding material is necessary to prevent the fuel from corrosion by the coolant. The required properties of a good cladding material are listed below :

1. The thermal absorption cross-section of the material used should be as small as possible because it covers a good portion of the reactor core.
2. It must have high resistance to corrosion during operation under high temperature and pressure.
3. It must have high thermal conductivity which reduces the thermal stress problem and helps for quicker heat flow.
4. It must maintain high strength under working pressure and temperature.
5. It must have good ductility and high machinability to reduce the fabrication cost of the element.
6. It must have high melting point to avoid the danger of melting under emergency conditions.
7. It should be non-toxic.

The properties which are essential for the canning material are equally essential for structural material (pressure vessel) also. One more essential requirement for structural material is low cost as the material required is quite large compared with cladding material.

The properties of few materials used for the above purposes are given below :

Magnesium. Magnesium alloys are commonly used in a gascooled reactor with little enriched uranium. The advantages of magnesium as cladding material are low neutron absorption cross-section, high resistance to oxidation and compatibility with uranium. Magnesium alloys can be easily fabricated by extrusion process. The magnesium can be easily sealed using arc welding as it can be easily welded.

The can failure may occur as a result of ratchetting because it has high thermal expansion, about 5% greater than uranium fuel. It oxidises readily in presence of air at about 350°C. Another difficulty with magnesium is, it catches fire at a temperature above its melting point.

Beryllium. Beryllium is considered best and most economical cladding material as it has low neutron absorption section, high melting point, high strength and good thermal conductivity and is less costly than zirconium.

The points which are not in its favour are : low ductility, more toxic, difficult to fabricate and costly compared with magnesium and stainless steel. The major difficulty experienced with this metal as can metal is the accelerated corrosion of metal at 600°C in the presence of small percentage of moisture (100 ppm) This metal is generally preferred for AGR fuel. To avoid the difficulty of corrosion, it is always necessary to remove the moisture from CO_2 below the permissible level.

Stainless Steel. High resistance to oxidation and better machinability are in favour of stainless steel as can material. It can be used at a temperature as high as 800°C. Higher thermal expansion of the stainless steel compared with UO_2 compensates the higher temperature of fuel. Its use in thermal reactors is restricted due to its high neutron absorption cross-section. This is generally preferred in fast breeder reactors.

Zirconium. Zirconium is preferred as best can material due to its better physical and nuclear properties but its use is undesirable unless unavoidable due to its very high cost. The properties which are strongly in its favour are low thermal neutron absorption cross-section, high melting point, good thermal conductivity and high resistance to corrosion even at high pressure and temperature. The only undesirable characteristic is high cost and scrap left after machining cannot be re-used. It is generally used in PWR and BWR reactors.

Aluminium alloys are commonly used for coolant pipes, heat exchangers and jacketing the uranium slugs upto 300 to 400°C as the cost is comparatively less than other materials.

29.4. COOLANTS

It is necessary to remove the heat generated from the reactor which prevents the attainment of limiting temperature determined by the properties of reactor core components.

The common coolants which are used are liquids, metals and gases. The desirable properties of an ideal coolant are listed below :

1. **Low melting point.** This is an important property for liquid metal coolant because a high melting point would require an auxiliary heating system to ensure a liquid coolant prior to start-up and it would cause complications of the coolant system.

2. **High boiling point.** This is required to ensure better heat transfer in the heat exchanger. This is generally done by pressurising the coolant like water but it complicates the design of reactor.

3. The low cost of coolant is always necessary as it is the basic component of the nuclear power plant. Its cost directly affects the cost of power generation.

4. It should not attack on the reactor materials and should have low corrosion properties. The compatibility must be extended to more conventional structural materials.

5. The high coefficient of heat transfer is essential as it gives high specific power in the reactor core, reduces the cost of reactor, heat exchanger, pumps and other equipments by reducing their sizes for the given output.

6. The thermal and radiation stability of the coolant are the primary requirements as any breakdown of the material may cause serious accidents. This may occur as a result of formation of gases which may produce heavy pressures in reactor or the formation of deposits may impair the heat transfer rates causing high temperature rises which may cause melting of many components.

7. The neutron economy is the prime consideration in the design of the nuclear reactor, therefore, the coolant used (occupies large area of reactor) must not absorb the neutrons. Therefore, the coolant must have low thermal absorption cross-section.

8. The size of shielding (thickness) depends upon the radioactivity induced in the coolant. Because the radiations are passed to shielding through coolant, the formation of long lived radioactive isotopes in the coolant is highly undesirable. High radioactivity in the coolant may require the shielding in the secondary circuit.

9. If the coolant is used as a moderator also, there is a definite advantage in thermal power reactors because it reduces the size of the core and hence the cost of the reactor.

10. It must have high specific heat and thermal conductivity. High specific heat minimises the thermal stresses.

11. It must be non-oxidising.

12. It must have high density because high density reduces plant size.

The properties of coolants which are commonly used in atomic reactors are discussed below.

Water. The water is the most familiar and cheapest coolant readily available. It is far better coolant than gas because of its better heat transfer properties The pumping power required is hardly 10% of the gas cooled reactors of same capacity using gas at 10 bar. Maximum temperature at which the water can be maintained in liquid form is 374°C under a very high pressure of 225 bar. It is not possible to prevent water from converting into steam even with the increase in pressure. Therefore, the thermal efficiency of the water cooled reactor is less. It also works as a moderator which is an added advantage using water as coolant.

The major difficulty associated with the water cooled reactor is the high corrosion effect of water on the reactor component under high pressure and temperature (300°C) conditions. Therefore, special materials are required to prevent the corrosion and at the same time bear the existing pressures in the reactor core. Water suffers radiation decomposition but this can be minimised by proper purification.

The heavy water as coolant offers the same advantages and disadvantages as ordinary water. Its added advantage is high moderating capacity compared with ordinary water.

Gases. Gases are more attractive coolant than liquids due to their better thermal and radiation stability, ease of handling and absence of hazardous conditions. The use of air as coolant was considered during the early stages of reactor development due to low cost, easy availability and known physical properties. The high pumping power, low heat transfer properties compared with other gases and high chemical reaction on reactor components at elevated temperatures restricted its use as coolant.

The nitrogen was used as coolant in EI-2 heavy water moderator reactor at Saclay in France. It offers the same advantages and disadvantages like air. The added disadvantage is the formation of radioactive Carbon-14 which is highly poisonous and presents a health problem if escapes from pressure vessel.

Hydrogen is an attractive coolant due to its better heat transfer proerties and low pumping power requirements and very low absorption cross-section. However, explosion hazards associated with leaks and its effect of embrittlement on the metal at elevated temperature eliminates its use as coolant.

Helium's negligible thermal absorption cross-section, chemically inert, high thermal and radiation stability and good heat transfer properties offer itself as a best gaseous coolant. Its high cost and scarcity prevented its use as coolant.

Most of the present world's supply of He comes from two wells in Texas and few wells newly discovered in Canada.

The CO_2 is the only gas used successfully in power reactors, particularly in Britain. The CO_2 is not efficient as helium as heat transfer property and absorption cross-section are concerned but it is much more readily available at low cost. It is free from toxic and explosion hazards. The metal like mild steel can be used for pressure vessel with gas cooled reactors which reduces the cost of the plant compared with other gases. The main problem yet to be solved is its reaction with the graphite at elevated temperature.

$$CO_2 + C \longrightarrow 2\ CO.$$

This indicates the eating of graphite. Considerable research work is going on to reduce the formation of CO. It has been found that the above action can be reduced by injecting methane gas in the coolant. The drying of CO_2 before passing into the reactor is extremely essential as moisture reacts with CO_2 and free H_2 is involved which makes many metals brittle. The maximum allowable moisture in CO_2 is 500 ppm by weight.

Liquid Metal Coolants. The use of liquid metal as coolant offers many advantages over other coolants for reactors which operate at elevated temperatures. Particularly high thermal conductivity and low vapour pressure are in favour of liquid metals.

The major difficulty in using liquid metals is their corrosive action on most of the metals in the presence of air and water. Therefore, liquid metal coolant system must be very airtight. The pumping of liquid-metals posed many problems but electromagnetic pump gave a workable solution.

The types of the liquid metals and their properties considered as coolant are listed below :

Metal	*Lithium*	*Bismuth*	*Lead*	*Sodium*
Melting point				
Cross-section in barns	0.033	0.032	0.017	0.5

The lithium is best liquid coolant among all available metal liquids as it has high heat transfer properties. It is considered attractive coolant for fast breeder reactors. The only drawback is its high melting point.

The use of bismuth as coolant is suggested in liquid metal fuels. The major disadvantage of bismuth is the formation of radioactive Bi^{210} due to neutron irradiation which is highly toxic and one of the most powerful poisons yet known. Bismuth expands on freezing and could result in complete destruction of heat exchanger and other components. This property adds an additional complication in the design of the reactor.

The lead is also not used due to its high melting point and higher cross-sectional area.

The sodium is the only metal which is presently used in reactors as coolant. It is chemically active, burns readily in air and acts violently in presence of moisture. Therefore, the cooling circuit must be free from air and moisture. Another problem posed by the sodium is, it becomes highly radio-active and creates problems if leakage occurs. The moderating capacity is reduced by using Na K alloy instead of sodium whose cross-section is less than sodium and melting point is reduced to 19°C which is below room temperature in most cases.

Organic Liquids. Organic liquids would be better coolants and moderators than water as they consist of hydrogen and carbon and have high boiling point at considerably low pressures. Further advantage of organic liquids is less corrosive than water, therefore, conventional metals can be used. They also exhibit a very low level of induced radioactivity. All the favourable factors reduce the overall size and cost of the reactor.

The disadvantages of organic liquids are poor thermal and radiation stability and poor heat transfer properties compared with water. The benzene, diphenyl and terphenyle are considered possible coolants of this group.

29.5. MODERATING AND REFLECTING MATERIALS

The materials used as moderators can also be used as reflectors as the properties required for moderator and reflector are more or less same. The materials which are commonly used as moderators are graphite, beryllium and heavy water. Ordinary water is also used only in reactors which use enriched uranium as fuel and high neutron loss can be tolerated. The helium gas can also be used as moderator, if pressurised.

The desirable properties of a good moderator are listed below :

1. It must have high slowing down power.
2. It should have low parasitic capture.
3. It must have high resistance to corrosion.
4. It should have good machinability if moderator is solid material.
5. It must have high melting point if solid and low boiling point if liquid.
6. It must have chemical and radiation stability.
7. It must be easily available in pure form in abundance and it should be cheap.
8. It must have good thermal conductivity.

The properties of different moderators are discussed below.

Water (H_2O). It is the cheapest material available as moderator and also available in abundance. The only requirement is, it must be used in pure form. It should not contain the sodium salt, cadmium and boron at all. It works as moderator only in reactors where enriched uranium is used as fuel.

HEAVY WATER AND ITS PRODUCTION

Heavy water or deuterium oxide is the most effective moderator, both because its cross-section is the smallest known (*0.0004 barns) and because of the small weight of the deuterium atom (2). Its boiling point is 101.4°C and therefore it cannot be used where very high temperatures are needed, even at lower temperature it must be used under pressure to prevent evaporation and loss. The cost of D-20 (Rs. 2000/kg) is prohibitive in a large power reactor which may require as much as 200 tons of it or a total cost of Rs. 4×10^8 (40 crore) for heavy water alone.

(1) Heavy water is produced by separating it from natural water, all of which contains about 0.015% of deuterium oxide or about one part in 6500. The separation of two isotopes of H_2 cannot be done through any difference in chemical properties, which are identical, but must depend on the difference in the mass between light and heavy hydrogen atoms. Thus when hydrogen gas is liquified at a temp. below – 250°C, there is difference of as much as 3.12°C in the two boiling points, the ordinary hydrogen being the more volatile. Consequently evaporation of liquid H_2 offers a means of concentrating the deuterium in the residue. This was the method used by Prof. Harold C. Vrey when he first discovered the existence of deuterium in 1932. This being the most efficient method, the difficulty and cost of operating at a temperature of several hundred degrees below zero have prevented commercial use of this process.

(2) The second method for the production of heavy water is by the distillation of water itself. Ordinary water is slightly more volatile than heavy water, thus the latter concentrates in the residue. Such a plant is simple to operate and it was adopted by U.S.A. during IInd World War. Three water distillation plants were designed and built for Govt. and their combined production of heavy water was 1.2 tons per month and cost of production was $ 176/lb.

(3) The third process by which all heavy water was manufactured until 1943, involves the passage of direct current through water to decompose it into H_2 and O_2. Here again the larger mass of deuterium makes it slightly more sluggish under the action of the current so that the H_2 evolved is reduced in deuterium content and latter accumulates in the residual water. This process requires nearly 58000 kW-hours of electrical energy per pound of D-20 produced and can therefore be used only where electrical power is extremely cheap. The largest producer of heavy water was Norsk Hydro Company at Riukan, Norway, which separated 1.7 tons of D-20 per year as a by-product in the production of 640,000 ft^{-3} of H_2 per hour. The cost of D_2O by this process was only $ 13 a pound. At a few places in the world where power is cheap enough to make H_2 gas at a cost of 50 cents per 1000 ft^{-3} or less, the production of heavy water as a by-product is economically sound. But under ideal conditions, a larger plant producing 500×10^3 ft^{-3} of H_2 per hour could make only 5 tons of D-20 per year which is totally inadequate for the needs of the nuclear industries.

1 barn = 10^{-24} cm^2

(4) The last method which is used for the production of D_2O is steam-hydrogen exchange process. When H_2 and steam are passed together in a gaseous phase over a catalyst, an interchange takes place whereby deuterium is concentrated in the water and is extracted from the hydrogen gas by the steam, thus leaving the hydrogen still available as the major product. The plant of the Consolidated Mining and Smelting Company at Trail is the largest electrolytic hydrogen plant in North America and in 1945 produced slightly over 500,000 cu. ft. of Hydrogen per hour for the production of NH_3. By the combination of the steam-hydrogen exchange and the electrolytic methods, this plant was producing 1100 lbs per month of D_2O at a operating cost of $ 27.5/Lb. The plant is still in operation at a cost of $ 60/Lb including overhead and profit.

In all processes used at present, the production of heavy water is a by-product of the manufacture of H_2 and is therefore limited to the demand for H_2. With the growth of nuclear industries, the demand for D_2O will exceed such limitations and will require special production of D_2O as a primary product.

Three processes have been used in large scale commercial preparation of heavy water namely

(*a*) Distillation of water. (*b*) Catalytic exchange. (*c*) Electrolysis.

The electrolytic method is used only as an adjunct to the other two processes to obtain a final concentration of 99.8% D_2O.

Economic Considerations in Production of D_2O by Three Methods in 1955*

	Catalytic exchange	*Distillation of H_{20} with electrolytic finishing*	*Distillation of H_2 with electrolytic finishing*
Investment per ton	$ 2800000	$ 6050000	$ 5000000
Operating cost per ton	$ 36000	$ 175000	$ 46,000
Production per month	0.84	2.4	2.4
Operation man-months per ton	55	167	36

*The above costs are based on the prices of 1980.

Advantages and Disadvantages of 3 Methods

	Catalytic exchange	*Distillation of H_{20}*	*Distillation of H_2*
Location	Large source of H_2 from electrolysis of water	Near cheap source of heat	In conjunction with NH_3
Industrial Hazard	H_2 is explosive	None	H_2 is explosive
Limitation of production	0.8 ton per month	Unlimited	5 – 10 tons per month
Materials required for construction	Copper	Steel	Steel
Fabrication problems	Normal	Normal	Low temp. operation requires special insulation and precautions
Control	Easy to control	Requires precise control	Easy to control
Scale-up Experience	Sufficient information is available to build up any size plant.	Sufficient information is available to build up any size plant.	No information is available.

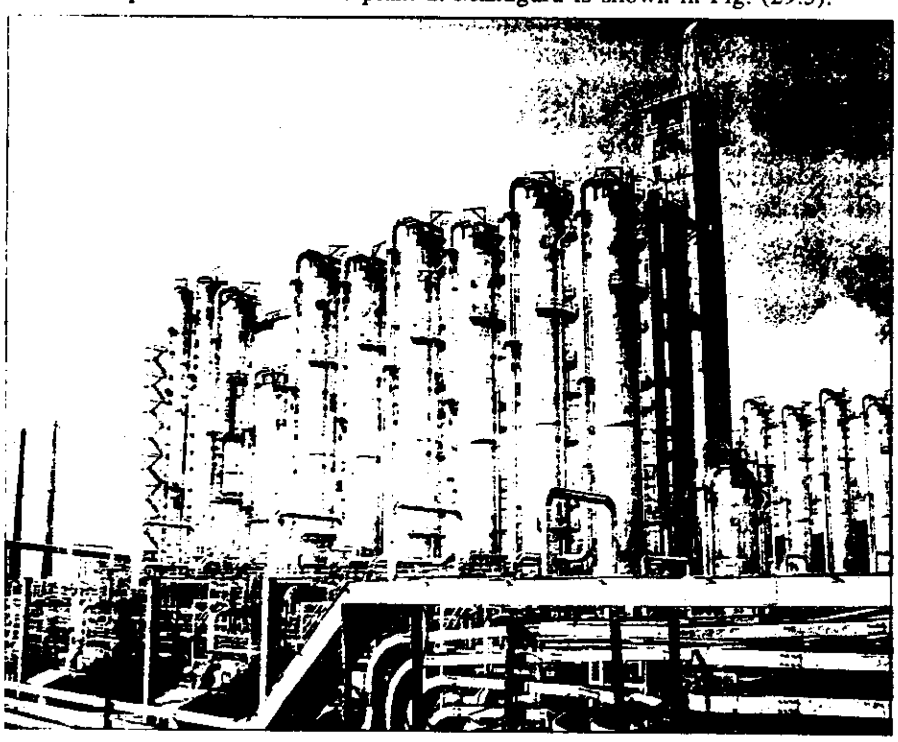
Production of Heavy Water in India

For 3-stage nuclear power programme, the development of PHWR forms the I-st stage-was very crucial as this would not only help India to produce power using natural uranium but also produce plutonium required for II-stage of the programme using FBRs.

For the PHWRs, heavy water is one of the key inputs. To meet the demand of heavy water indigenously, it was necessary to build heavy water plants of large capacities. Development of heavy water technology in India has gone through a complete cycle. The growth of Heavy Water Board (HWB) has also gone through the phases associated with the growth of any hightech corporation. The late sixties and early seventies were the initial periods for developing new processes for production of heavy water. Since the technology was the monopoly of a few developed countries, the required information was difficult to get from them. Therefore, it was necessary to develop own technology for the production of heavy water.

The early phase of the choice of suitable technologies and setting up of production plants based on the same was followed during 1970-80. HWB was faced with many problems related to process, equipment, materials and operation. There were problems in both the technologies (1) Ammonia-Hydrogen Exchange (2) *Hydrogen Sulphide-Water Exchange* Process (indigenously developed). *The* NH_3-H_2 exchange technology even though developed by Sulzar Corporation was tested on a large scale for the first time in India. A large amount of process modifications are done during construction and commissioning and this process was operated successfully. In late 1980, the Board had a real turn around and with the commissioning of heavy water plants at Hazira and Manuguru (H_2S-H_2O process used), the trend in terms of production of heavy water began.

A picturial view of the plant at Manuguru is shown in Fig. (29.5).



SALIENT FEATURES

Process Used : H_2S-H_2O Exchange
Process Know-how : Indigenous
Capacity of the Plant : 185 MT/Yr
Zero Date of the Project : 1.9.1982
Date of Completion : Dec. 1991
Operating Pressure : 20 kg/cm^{2}G
Maximum Diameter of Towers : 4.5 M approx.
Maximum Height of Towers : 58 M approx.
Total Length of Piping : 264 km
Power Consumption : 42 MW
Water Consumption : 30,000 m^3/Day
Steam Consumption : 4800 MT/Day
Inventory of H_2S : 400 T

Fig. 29.5. Heavy Water Plant, Manuguru. The Plant is based on indigenously developed technology developed at Trombay

All the problems faced in the production of heavy water at Kota, Tuticorin and Baroda were taken care of in the new generation plants at Manuguru, Thal and Hazira. Both the technologies for the production of heavy water are mastered in India and India is the only country in the world which is producing heavy water using both the processes.

The period of the 1990 has been a period of consolidation for HWB. The long term perspective of the DAE (Department of Atomic Energy), envisages a 20,000 MWe of nuclear power by 2020. The requirement of heavy water for any size of PHWR programme can be fully met from the presently operating plants and by setting up of new heavy water plants when required ahead of the demand. The present heavy water required for PHWR in excess of 6000 MWe has to be supplied by setting up of plants based on H_2S-H_2O and NH_3-H_2 exchange process.

To meet the heavy water requirements of the Indian PHWRs, eight plants are installed at Talcher (Orissa), Manuguru (Andhra), Tuticorin (Kerala), Thal (Maharashtra), Hazira and Baroda (Gujarat), Kota (Rajasthan). and Nangal (U.P.). The production of heavy water during the year 1999 was close to the target. HWB exported 100 metric tons of heavy water to Korea in 1998.

Graphite. Graphite is considered superior moderator compared with H_2O as its required nuclear properties are better than H_2O and it is also superior to D_2O as its cost is concerned. The outstanding features of graphite as moderator are it does not react with other materials and it can be used at high temperatures. Therefore, the corrosion problems are not as severe as associated with other moderators. It is also non-toxic unlike beryllium.

The major difficulty experienced with graphite is, it becomes brittle, harder and swells abruptly due to irradiation. The other disadvantage is, its thermal conductivity also decreases rapidly with irradiation and makes the heat flow problem more difficult. Further, it loses its weight due to the reaction of CO_2 under irradiation. The loss in weight as high as 8.5% and changes in dimensions as high as 40% are noted due to reaction and irradiation. It loses its oxidation resistance above 350°C, therefore, it is necessary to clad graphite with more resistant material if it is operated above 350°C.

The natural graphite is not suitable as moderator because of inherent high impurity content which reduces its efficiency of moderation. Presently natural graphite is produced with a satisfactory purity level. The density of artificially produced graphite is considerably less than natural graphite, therefore, it occupies greater volume in reactor. Present research is devoted to increase the density of the artificially produced graphite with effective extraction of impurities.

Beryllium. It is considered a very good moderator as it has excellent chemical and corrosion resistant properties. It has high radiation stability. Irrespective of all these favourable properties, it is not used in practice as its cost is very high and it is more toxic. The cost of the beryllium moderator for a power reactor is nearly equal to the cost of a small reactor.

Beryllium is chemically stable at room temperature but readily combines with oxygen when heated. Therefore, beryllium oxide is preferred to beryllium as it is heat resistant inert material with a melting point of 2530°C. The serious disadvantage of beryllium oxide is drastic decrease in thermal conductivity with increase in temperature.

The absorption cross-section of moderator should be as low as possible for maintaining the chain reaction. The details of few moderators are listed below.

	H_2O	D_2O	*Metallic Beryllium*	*Beryllium Oxide*	*Graphite*
Atomic or molecular weight	18	20	9.01	25	12
Density gms/cm^3	1.0	1.1	1.84	2.86	1.57
Atoms or molecules per cm^3	3.3×10^{22}	3.3×10^{22}	1.2×10^{23}	6.7×10^{22}	8.1×10^{22}
Absorption cross-section in barns*	0.66	0.0026	0.009	0.0092	0.0045
Slowing down time in sec	10^{-5}	4.6×10^{-5}	6.7×10^{-5}	—	1.5×10^{-4}
No. of collisions to thermalise from 2 MeV to 0.02 MeV	19.6	35.7	88.4	107	115

*1 barn = 10^{-24} cm^2.

29.6. CONTROL ROD MATERIALS

The desirable properties of materials used for control rod are listed below :

1. It must have high thermal cross-section unlike most of the materials used in reactor.
2. It must have high strength during operation and good machinability.
3. It must have chemical and radiation stability.
4. It must have high resistance to corrosion under operating conditions.
5. It must have high thermal conductivity to ease the problem of heat transfer.
6. It must have high density and low mass because it helps for rapid movement of the control rods and easy construction of the controlling mechanism.
7. It must have high melting point.
8. It must be available at low cost.

The possible control rod materials are boron (high neutron absorption), cadmium (adequate strength), hafnium (high density), rare earths (high corrosion resistance), Europium and dysposium (high stability under heat and radiation), and gradolinium and orbium (good heat transfer properties). There is no single material which fulfills all the desirable requirements. The details of elements used as control rods are given below :

Boron. Boron is commonly used as control rod material as it has high melting point (2300°C), high resistance to corrosion and radiation. The major difficulty with boron is, it becomes brittle at high temperature and cracks. The boron stainless steel rods were used in Dresden boiling water reactor and boron rods clad with stainless steel were used in Calder Hall plant. A boron-carbide clad with stainless steel works as a better control rod material and it was used in Dresden plant.

Cadmium. Despite high resistance to corrosion in presence of water and air ; cadmium is not used for high temperature reactors because of rapid oxidation and relatively low melting point (320°C). Cadmium or its alloys originally do not have sufficient strength and, therefore, some other material must be used for strengthening. Generally one sheet of cadmium between two sheets of aluminium is used. Such type of control plates were used in CP-5 heavy water reactor.

Hafnium. Presently, interest is developed in hafnium to use as control rod material. In general, it is similar to zirconium in its properties, as corrosion resistance and fabrication. Although its thermal neutron absorption cross-section is relatively low but due to its large epithermal resonance capture cross-section, it is most desirable material for control rods. The major advantage of hafnium over boron or cadmium is, it does not require any cladding to provide the strength as it has adequate strength and stability in itself.

29.7. SHIELDING MATERIALS

The radiation from nuclear reactors is extremely varied in character and its ability to penetrate. The common nuclear radiations are γ-rays, neutrons, X-rays, α and β radiations.

The α and β radiations are absorbed in a smaller thickness of the shielding. γ-radiations which penetrate much due to their high energy level and frequency require higher thickness of shielding material. Neutrons have high power of penetration and do not follow any defined path through the shield materials. During slowing down the neutrons or absorption due to collision with the nuclei of the other materials, some materials also emit secondary γ-radiations. The shield should be designed only to reduce or absorb γ and neutron radiations. The magnitude of nuclear radiations is extremely high and if it is not prevented, it will have very bad effects on the human life and biological plants. The radiation of 60 MW (e) plant was estimated to be equivalent to 1000 tons of radium.

The desirable properties of good shielding material are listed below :

1. It must have high efficiency for absorbing γ-radiations with minimum thickness of shielding material.

2. Density of the material must remain constant during operation. It should not have local cavities and cracks through which radiation may leak. The material must have uniform density.

3. It must have high density to attenuate the γ-radiation and it must contain light material (hydrogen or water) to attenuate neutron.

4. It should not be decomposed or weaken under the influence of radiation.

5. It must be fire-resistant.

The materials and their properties which are commonly used for shielding are described below :

Majority of the elements having cross-section greater than 25 barns are rare earth. Boron, Cadmium and Hafnium are considered better material as they fulfill most of the requirements. But the cost is very high as Rs. 20,000 to Rs. 50,000 per kg.

The most important property of control rod material is thermal neutron capture cross-section. The following table gives the cross-sections of few materials which are important as control rods :

10 – 25 barns	*25 – 100 barns*	*100 – 1000 barns*	*> 1000 barns*
Manganese Selenium Praseodymium Tantalum Tungsten	Cobalt Silver Cesium Rhenium Lithium Terbium Holmium Gold	Boron Hafnium Rohodium Iridium Erbium Thulium Lutelium	Cadmium Samarium Europium Gadolinium Dysprosium

The properties of materials which are used as shielding materials are discussed below :

Concrete. Concrete is one of the cheapest and most effective shielding materials because it contains heavy as well as light materials (H_2O) which are essential to attenuate γ-radiations and neutrons respectively. The density of the concrete varies with the ingredients used. The commonly used concrete has a density of 2400 kg/m^3 and contains 5—10% water and it is also satisfactory shielding material. Thus, the shielding properties of heavy substances (sand, gravel and cement) against γ-radiations and light substances (H_2O) against neutrons radiations are combined together in the concrete. Some of the sand and gravel aggregate is replaced by minerals (barium sulphate) if increased concentration of heavy material is desired. Presently variety of concretes are developed with densities of 6000 kg/m^3.

The addition of boron compound in concrete during preparation is recommended by American designers. The addition of boron in concrete helps to arrest thermal neutrons and secondary radiations almost instantaneously.

Steel. The absorption of radiation generates large amount of heat and concrete has relatively low ability to withstand high temperature gradients. The strengthening of the concrete is necessary as high thermal stress is developed due to large thermal gradients and this is generally done by reinforcement.

Rockwell suggests that the critical temperature of concrete is 65.6°C. Because with an increase in temperature above 65.6°C, the content of chemically bound water decreases rapidly with increase in temperature, *e.g.* the concrete loses more than 50% of bound water at 100°C. Therefore, the means must be provided to protect the concrete from drying out as the bound water plays very important part as a shielding material to attenuate the neutrons.

The most of the heat liberated lies in the first 10% of the shield thickness as radiation absorption decreases exponentially with distance. The temperature gradient in the concrete can be reduced greatly by placing a thin iron shield between the core and biological concrete shield. Iron is used as thermal shield because high mass number material is most effective in absorbing γ-radiations and causing inelastic scattering of fast neutrons.

Generally two layers of iron alloy, each 10 cm thick providing 10 cm passage between them for air cooling, are generally used as thermal shield. 96% of the heat generated is taken by thermal shield and remaining 4% is passed through the concrete shield of 3 metre thick.

EXERCISES

29.1. Why uranium oxide is preferred over uranium as fuel ?

29.2. Why cladding is necessary ? What are the requirements of a good cladding material ? What clading materials are used for PWR, BWR, AGR, MAGNOX and CANDU reactors ? Why ?

29.3. What properties are required for a good coolant ? Which gases are used as coolant ? Why CO_2 is more preferable over other gases ? Which is most promising gas in future and why ?

29.4. What are the desirable properties of a good moderator ? Compare H_2O, D_2O and C as moderators.

29.5. What are the desirable properties of a control rod materials ? Compare the merits and demerits of Boron, Cadmium and Hafnium as control rod materials.

29.6. Why shielding of a reactor is necessary ? What do you understand by thermal shielding ?

29.7. What are the desirable properties of a shielding material ? Why concrete is considered as best shielding material ? Why drying out of concrete is undesirable ?

29.8. Compare the properties of stainless steel and zirconium for use as reactor fuel element cladding.

29.9. Considering the problem of induced radioactivity which coolant among water and sodium is more desirable ? How induced radioactivity affects the cost of shielding ?

29.10. Discuss the advantages and disadvantages of Lithium, Bismutch and Sodium as coolants for nuclear reactor.

30
Nuclear Waste & Its Disposal

30.1. Introduction. 30.2. Unit of Nuclear Radiation. 30.3. Types of Nuclear Waste. 30.4. Effects of Nuclear Radiation. 30.5. Radioactive Waste Disposal Systems. 30.6. Gas Disposal System.

30.1. INTRODUCTION

Nuclear power installed capacity in the world accounted for 16.8% in 1990-91. The nuclear power generation in India accounts only 2.5% of total. The department of atomic energy plans to install 10,000 MW of nuclear capacity by the end of the century. The favour was given for nuclear power development because, it is a clean source of electricity characterised by the absence of noxious combustion products and a supply of fuel that will last for centuries when breeder reactors become operational. It was estimated in 1970 that nuclear power installed capacity would be about 350×10^3 MW in 1980 and about 4300×10^3 MW by the end of century. It was also predicted that many breeder reactors would be available for commercial use by 1990. The progress of nuclear power has become slow throughout the world during last one decade because of danger posed by the nuclear plants in case of accident. Chernobyl accident in Russia has once more posed a question before the world, whether the nuclear power is really safe ? The nuclear power generation poses mainly two problems, one, the management of radioactive waste and the danger posed in case of accident is so deep and long standing. This chapter is concerned mainly with safe disposal of nuclear waste which is very dangerous to the human and crop life.

The radioactive emission during the operation of the plant is negligible but the emission intensity is very high which comes out from the waste. Therefore, safe nuclear waste disposal is a major problem before the nuclear industry. Because, they emit large quantities of γ-rays which can destroy all living matter through which they pass.

It is estimated that the radioactive products of 400 MW power station would be equivalent to 100 tons of radium daily and the radioactive effect of this plant products if exposed to atmosphere would kill all the living organisms within the area of about 160 square kilometres. Therefore, safe disposal of nuclear waste really poses a problem for nuclear scientists and engineers. Many methods are developed during the last 25 years to dispose off the different types of nuclear wastes safely.

30.2. UNITS OF NUCLEAR RADIATION

The common unit of nuclear radiation is "Roentgen". This is equivalent to the amount of radiation, which will, on passing through pure air under standard conditions, produce one electrostatic unit of ions per cu. cm. of air. This is equivalent to 86.9 ergs of energy absorbed per gram of air. The unit Roentgen was originally defined in connection with X-rays or γ-rays. Because, the effects of other kinds of radiation from nuclear reactor were similar to those of γ-rays.

Since the relative absorptivities of tissues for different radiations differ and are not same as that of air. It is, therefore, apparent that the limit of radiation dose expressed in Roentgen units will be different for different nuclear radiations, for different energies of radiation and different types of tissues. To avoid this, a new unit called Rem (Roentgen equivalent man) which is the dose of absorbed radiation that will have the same effect that exposure to one Roentgen of γ-radiation will have. This is also equivalent to the absorption of 100 ergs/gm of tissue. For various radiations, the rem values are listed below.

Type of Radiation	*X or γ-rays*	*β-particles*	*Slow neutrons*	*Fast neutrons*	*Protons*	*α-Particles*
Rem (value)	1	1	3 – 5	10	10	10 – 20

The maximum permissible exposure is that dose of whole body exposure to external radiation extending many years which will not cause any permanent injurious effects. The total dose received during a person's life time should not exceed 200 rem and weekly dose should be kept below 0.3 rem which is accepted by health physicists. The exposure over number of years may also shorten the life or may come out in the form of leukaemia.

30.3. TYPES OF NUCLEAR WASTES

The nuclear wastes are classified on the basis of half-life time as well as on the basis of the intensity of radiation as low, medium and high level radioactive wastes. The wastes produced from reactor operations include fission products and plutonium (and plutonium like elements called actinides). The half-lives of most of the fission products are 30 years or less. But their toxic lifetime is of the order of 500 to 1000 years. Plutonium and other actinides, which are not initially dominant become dominant after 1000 years. Therefore, the question of giving assurance against the future nuclear hazard of highly radioactive waste is very uncertain. If our intention is to guard against this waste in perpetuity, this indeed would be an unanswerable question. But our efforts are to predict and provide reasonable safeguard as maximum as possible.

To date, billions of curies of radioactivity, accumulated for over 30 years, have been stored with no harm to the human, bird or plant life.

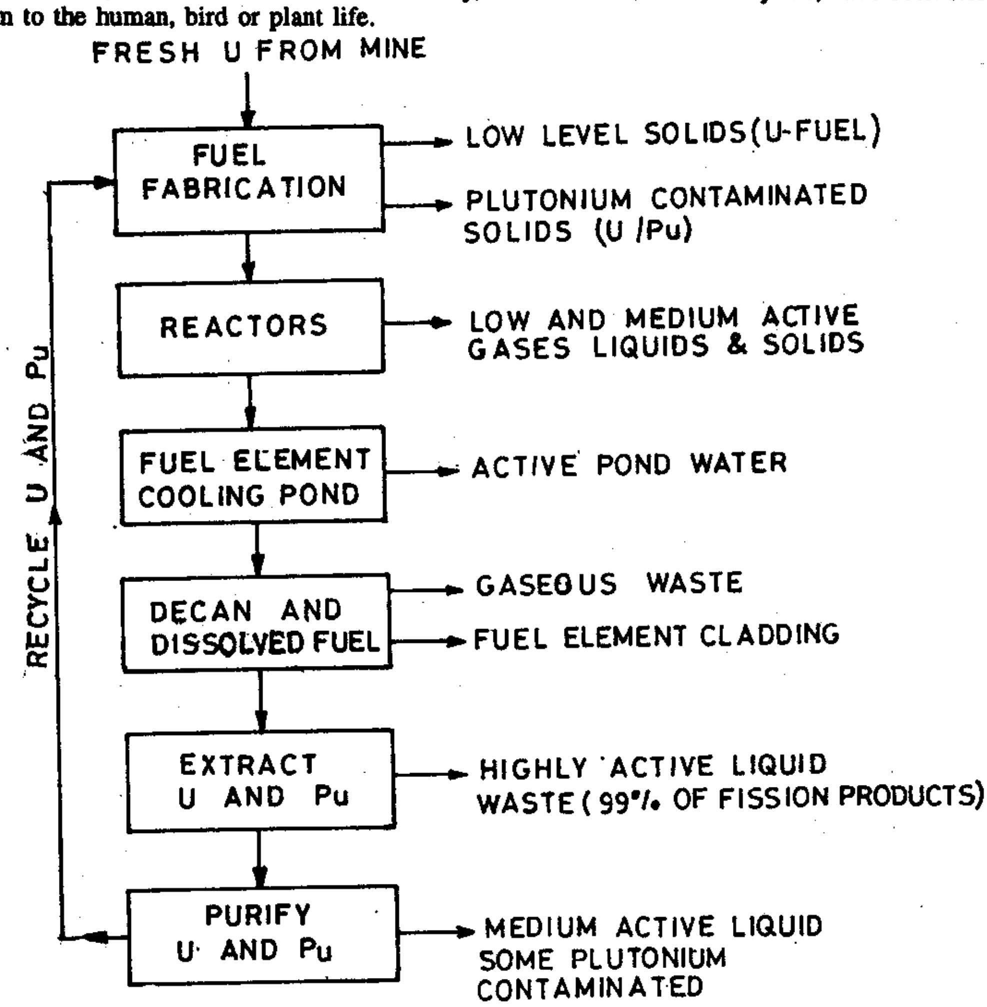


Fig. 30.1.

The outline of nuclear fuel cycle is shown in Fig. 30.1 and different types of wastes coming out at different stages are also labelled on the figure. The wastes coming out from reactor are classified as :

(1) **Fission Products.** Most of the fission products are initially radioactive and decay with the emission of β and γ-rays, until a stable isotope is produced. The principal fission products are listed in table 30.1. The most important from point of view of potential hazard, have half-lives lie in the range of 30 years.

(2) **Actinides.** Elements in this group are produced in nuclear reactors as a result of neutron capture by uranium. The most important is plutonium (which is important fission fuel). The other actinides ore neptunium, amercium and curium which do not have any use and are considered as wastes only. The actinides decay mainly by emission of α-particles until a stable isotope of lead is formed, α-particles can be easily stopped and therefore actinide contaminated particles do not require thick shielding. However, α-particles are very energetic and toxic if inhaled as dusts. Table 30.2 shows the half-lives of actinides which vary from a few years to a billion years.

Table 30.1. Output of some selected fission products from an AGR (for production of 1 gigawatt-year of electricity)

Nuclide	*Half-life*	*Output at time of discharge of fuel (curies)*
Group 1 : half-lives less than 10 Years		
Iodine-131	8 d	1.7×10^7
Cerium-141	32.5 d	3.0×10^7
Zirconium-95	65 d	3.1×10^7
Cerium-144	284 d	2.5×10^7
Ruthenium-106	1 y	1.0×10^7
Caesium-134	2.1 y	3.3×10^6
Promethium-147	2.6 y	4.9×10^6
Europium-154	8.6 y	1.1×10^6
Group 2 : half-lives 10 – 30 Years		
Krypton-85	10.8 y	2.8×10^5
Tritium	12.3 y	1.2×10^3
Strontium-90	29 y	2.3×10^6
Caesium-137	30 y	2.8×10^6
Group 3 : half-lives greater than 100 000 Years		
Technetium-99	2×10^5 y	3.9×10^2
Zirconium-93	1.5×10^6 y	8.3×10
Caesium-135	2.3×10^6 y	1.2×10
Iodine-129	1.7×10^7 y	7.4×10^{-1}

Table 30.2. Half-life and activities of selected actinides produced in generation of 1 gigawatt-year of electricity

Nuclide	*Half-life*	*Radiation emitted*	*Activity AGR**	*(curies) FBR #*
Uranium-235	7.1×10^8 y	α	–	–
Uranium-238	4.5×10^9 y	α	–	–
Neptunium-237	2.1×10^6 y	α	4.6	1.6
Plutonium-238	87 y	α	2.9×10^4	5.4×10^4
Plutonium-239	2.4×10^4 y	α	1.0×10^4	1.4×10^5
Plutonium-240	6.6×10^3 y	α	1.9×10^4	1.7×10^5
Plutonium-241	15 y	β	3.1×10^6	1.2×10^7
Plutonium-242	3.9×10^5 y	α	3.6×10	8.6×10
Americium-241	433 y	α	3.9×10^3	2.2×10^4
Americium-243	7.4×10^3 y	α	1.7×10^2	2.4×10^2
Cerium-242	163 d	α	8.2×10^5	2.5×10^6
Cerium-244	18 y	α	1.0×10^4	1.6×10^4

* irradiation time 1370 days, mean burn-up 17 250 MW d/t

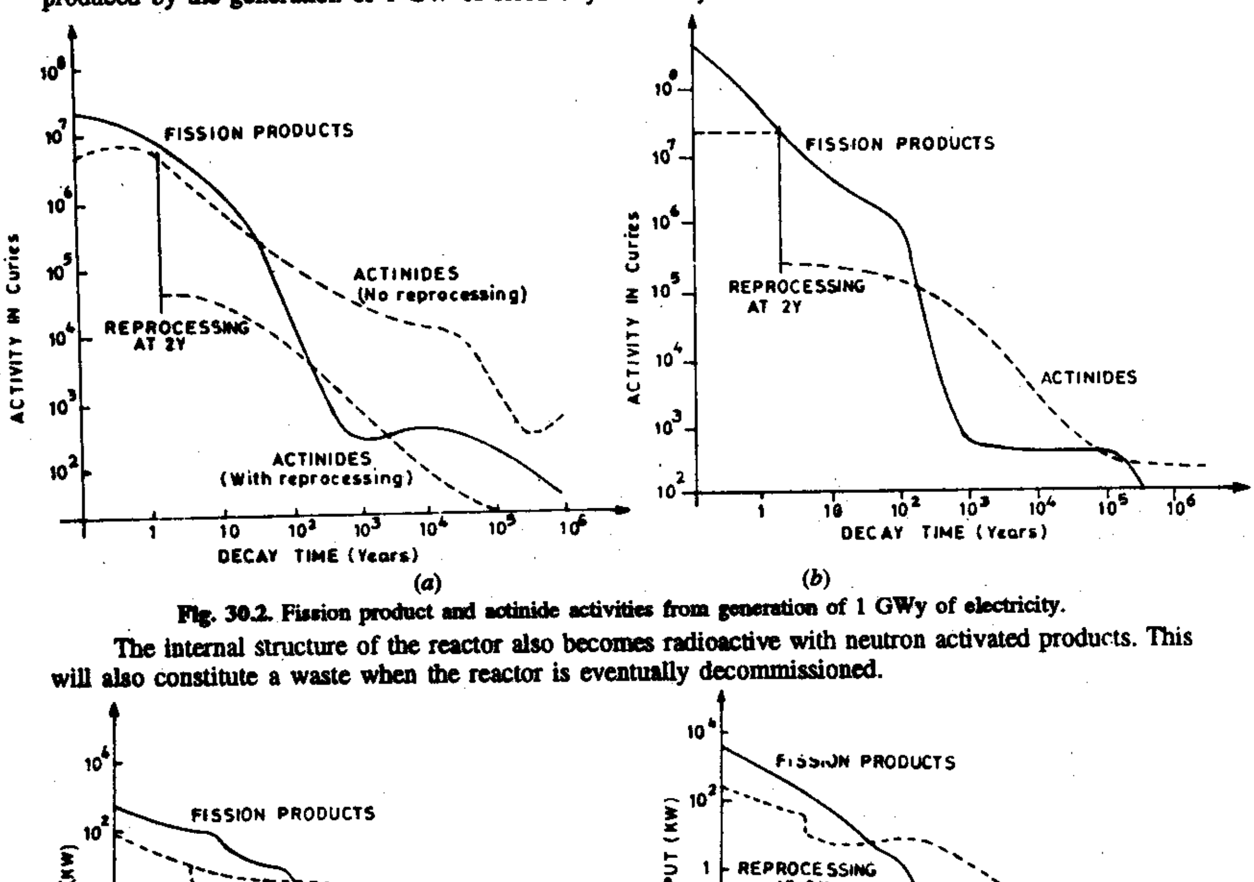
core fuel only (plutonium ex Magnox after 1 year storage), irradiation time 372 days, mean burn-up 80 000 MW d/t

(3) **The Neutron Activation Products.** These are produced when fast neutrons are absorbed by structural materials in the reactors as coolant, fuel cladding etc. They decay with the emission of β and γ-radiations.

Qualities of Fission Products and Actinide Activity in Nuclear Waste

Practically all fission products and actinides are retained in the fuel elements and majority radioactivity is retained in waste stream, known as highly active liquid waste when the spent fuel is reprocessed to separate uranium and plutonium. Whenever the fuel elements are withdrawn from the reactor, the initial high radioactivity decays rapidly since much of it is due to species with short half lives. Therefore, the fuel is stored for some time to allow this to happen before further operations are undertaken. Thus the fuel is not likely to be reprocessed until half a year.

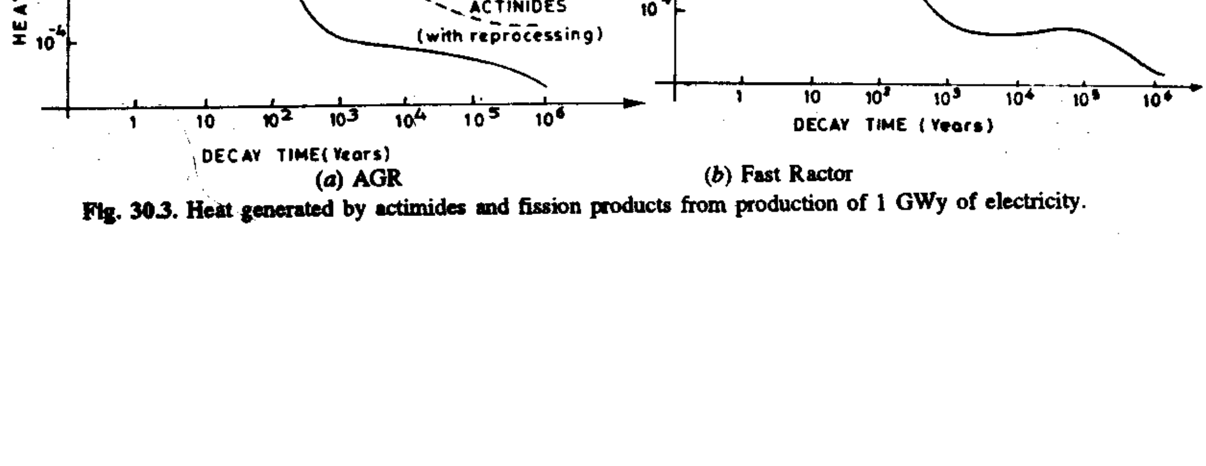
Figure 30.2 (*a*) and Fig. 30.2 (*b*) show the fission products and actinide radio-activities in the waste produced by the generation of 1 GW of electricity for one year in AGR and FBR reactors.



(*a*) (*b*)

Fig. 30.2. Fission product and actinide activities from generation of 1 GWy of electricity.

The internal structure of the reactor also becomes radioactive with neutron activated products. This will also constitute a waste when the reactor is eventually decommissioned.



(*a*) AGR (*b*) Fast Ractor

Fig. 30.3. Heat generated by actimides and fission products from production of 1 GWy of electricity.

The decay of fission products and actinides in high level waste results in generation of a considerable amount of heat as α, β and γ-radiations are emitted. The heat output from the wastes for the same two reactors is shown in Fig. 30.3 (*a*) and Fig. 30.3 (*b*).

30.4. EFFECTS OF NUCLEAR RADIATION

Biological Damage. Biological effects upon living tissues exposed to a radiation field result from the interaction of the radiation and the tissue. The interaction between radiation and tissue is manifested in three ways, ionization, displacement of atoms and absorption of neutrons by nuclei of tissue.

(1) **Ionization.** The formation of ion-pair in tissue requires 32.5 eV of energy. About 3100 ion-pairs are formed when a single 1 MeV beta particle is stopped by tissue. If one cm^2 area of tissue surface is subjected to a beam of β-radiation of 1000 β-particles/cm^2/sec, about 31×10^6 ion-pairs are formed each second. This absorption results in complete damage of tissues in the body of man or beast or bird. α, β and γ-radiations all ionise tissues into which they penetrate.

(2) **Displacement.** If the energy of the impinging particle is sufficiently high, an atom in the tissue is displaced from its normal lattice position with possible adverse effects. Neutron and γ-radiation result in atomic displacement.

(3) **Absorption.** Absorption of neutron by a tissue nucleus results in forming a radioactive nucleus and change the chemical nature of the nucleus. This severe alteration of the tissue causes malfunctioning of the cell and cell damage may have severe biological effects including genetic modifications.

The inhalation of radioactive materials in air, water or food also presents a radiation hazard. Some body elements are eliminated from the body rapidly, others become chemically involved in such a way as to give a serious long time problem. Strontium-90 has an affinity for bones and if it is absorbed by the bones through water, air or food, it will have a serious effect as bone marrow.

30.5. RADIOACTIVE WASTE DISPOSAL SYSTEMS

The fission products serve no purpose and, therefore, they should be removed and dumped in a safe place. To remove 10 kg of impurities from 50 tons of uranium is not a difficult problem. What is difficult is that, the fission fragments of uranium atom are many and diverse. More than 200 isotopes are formed ranging from Zn^{30} to rare element gadolinium. Thus the regeneration of uranium from the spent fuel is chemically complicated.

Many radioactive isotopes have their own rate of decay. The weak isotopes are harmless, the intensely active soon disappear. To eliminate the latter, it is merely necessary to store the spent fuel under 6 m deep water until they have cooled. The cooling period may be as long as 100 days. During the cooling period, the intensely active and short-lived isotopes and their radiations disappear. About half of the radioactive elements that remain after cooling offer no great difficulty in the processing.

Several kinds of radioactive wastes—gaseous, liquid and solid—are formed in the various phases of nuclear fuel cycle. These must be disposed off in such a manner that there is no hazard to human, animal or plant life. Solids of low and moderate activity are buried at depths of few metres at carefully selected sites. Gaseous wastes are discharged to the atmosphere through high stacks, liquids having low or intermediate levels of radioactivity are often given a preliminary treatment to remove most of the activity in form of solid precipitate and then discharged in dry wells or deep pits. Sometimes, treated liquids are kept in hold-up tanks before discharge for a period to allow part of the radioactivity to decay.

The disposal of the radioactive wastes after recovery of uranium and plutonium from waste fuel poses a real problem. The waste solution which is rich in fission products is concentrated by evaporation under vacuum and then stored in a stainless steel tank, enclosed in a concrete vault and buried under the earth (nearly 1 km below). The radioactivity of this waste solution generates heat to cause trouble from corrosion or even boiling, so that submerged tanks are provided with cooling coil to keep the temperature at 50°C.

Different Methods for Nuclear Waste Disposal

The nuclear waste from the reactor is classified as (*i*) High level waste (*ii*) Medium level waste and (*iii*) Low level waste.

The high level waste has radioactivity above 1000 curie. The medium level waste radioactivity lies 100 to 1000 curie and low level waste radioactivity is below 100 curie.

The spent fuel is withdrawn from the reactor and placed in a water pond where heat is removed and shorter lived radionuclides decay. The pond water is continually treated to remove activity due to release of fuel from defective cladding.

The spent fuel is then transferred to the reprocessing plant where cladding that contains the fuel is removed and the fuel is dissolved in nitric acid. The U^{235} (20 to 90%) and Pu^{239} are then removed leaving 99% non-volatile fission products behind in solution known as *"Highly Active Liquid Waste"*. The separated U^{235} and Pu^{239} are further purified and either stored for future use or fabricated into fresh fuel for reactor.

The waste from the cooling pond (known as central storage) is then transferred to intermediate storage and kept there for a period of 30 to 100 years where most of the reaction heat and radioactive nature is reduced to a considerably low level. Then the waste is permanently shifted in the final storage where it is permanently buried either in the earth or sea.

Disposal of Low Level Solid Waste

The nuclear waste of this category is cast in cement in steel drum. These drums are buried either below the soil (a few metres) or kept at the bed of the ocean. The safety of the method lies in the vast dilution of the activity as it disperses at the bottom of the ocean. Radiologically, the disposal of waste in this category to sea seems to be the best option to avoid risks due to unnecessary handling and storage.

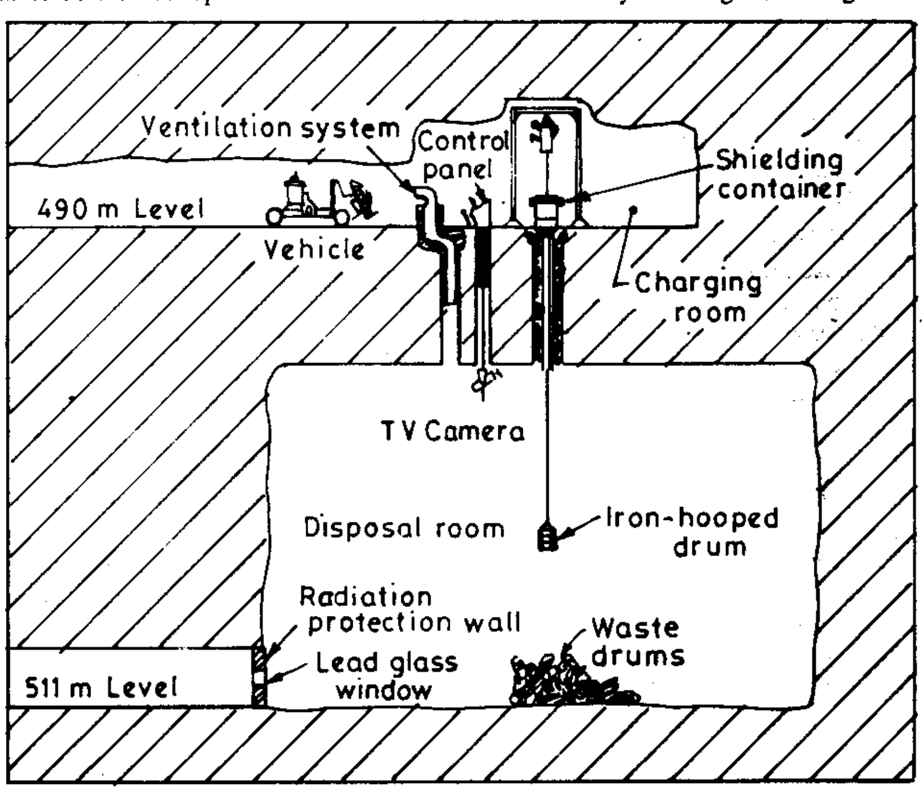


Fig. 30.4. (*a*)

Disposal of Medium Level Solid Waste

These wastes are mainly contaminated with neutron activation product isotopes. They are incorporated into cement cylinders as cement is non-combustible and provides shielding against external exposure. Another ability of cement is resistance to leaching by ground water.

Disposal of High Level Liquid Waste

This is the solution remaining after useful fuel is dissolved in nitric acid and U^{235} and Pu^{239} are extracted. The remaining liquid is stored on the site in special steel tanks in concrete vaults. They are water cooled and then taken to the storage area.

An underground system used in West-Germany for the storage of tanks is shown in Fig. 30.4 (*a*). A cavity is excavated at 511 m in salt mine and the cylinders are stored in this cavity as shown in figure. It has a special advantage as salt is strong absorber of radioactive emissions and has good thermal conductivity which helps to keep the temperature within acceptable limit. This arrangement is for intermediate storage where these cylinders are kept for 30 to 100 years and then they are discharged for final disposal still below the intermediate storage in the ground or discharged into the sea bed.

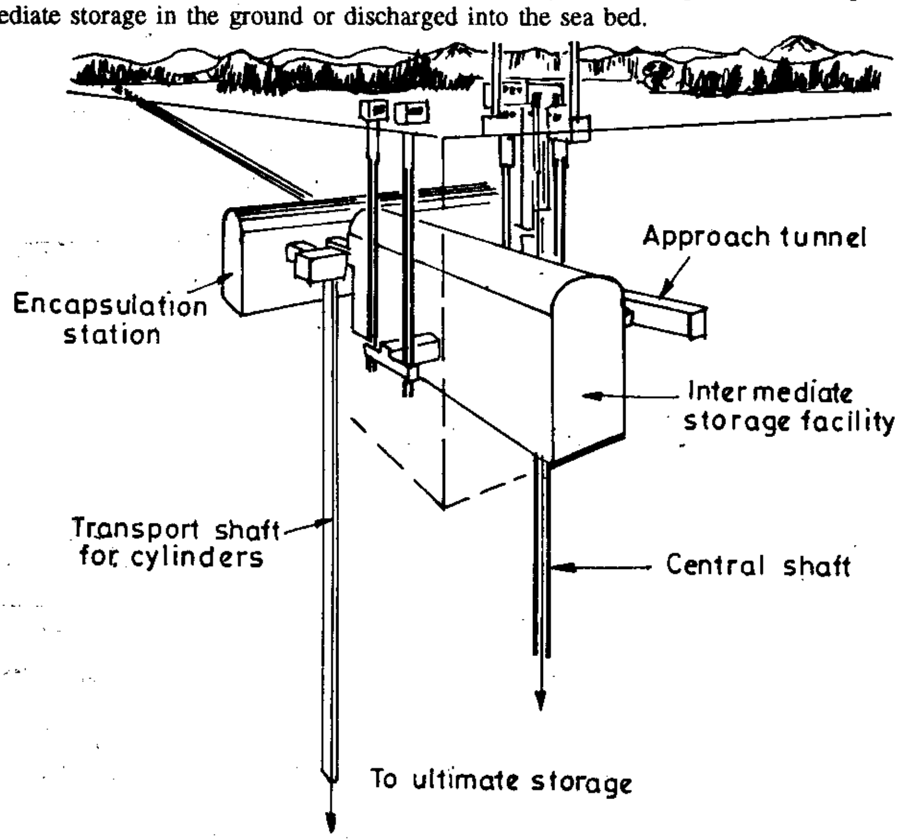


Fig. 30.4. (*b*) Intermediate storage facility and encapsulation station.

The final storage is provided with 10 cm thick lead wall surrounded by 6 mm titanium. Both materials are corrosive resistant and also serves as a shield to prevent radio-emission to ground water.

This facility can store 10,000 waste containers (each of 40 cm in diam 1.5 m of height) and require nearly 1 km^2 area for the whole facility.

(A) Geological Formations

Geological formations considered for the location of waste cylinders are rock salt, argillaceous sediments and hard rocks.

(1) **Rock Salt.** Disposals in salt domes is used in USA and Germany as salt has some special qualities for the storage of high level waste.

(*i*) It is powerful absorber of radioactive emission.

(*ii*) Its plasticity provides a barrier between the repository and the biosphere.

(*iii*) It has good thermal conductivity which helps to keep temperature within acceptable limits.

(*iv*) Big cavities and tunnels can be easily made.

(*v*) The salt domes in Northern Germany have hardly changed their shape during last 100 million years even though geological events (as Alps, glaciers and floods) had a catastrophic impact on the surface area.

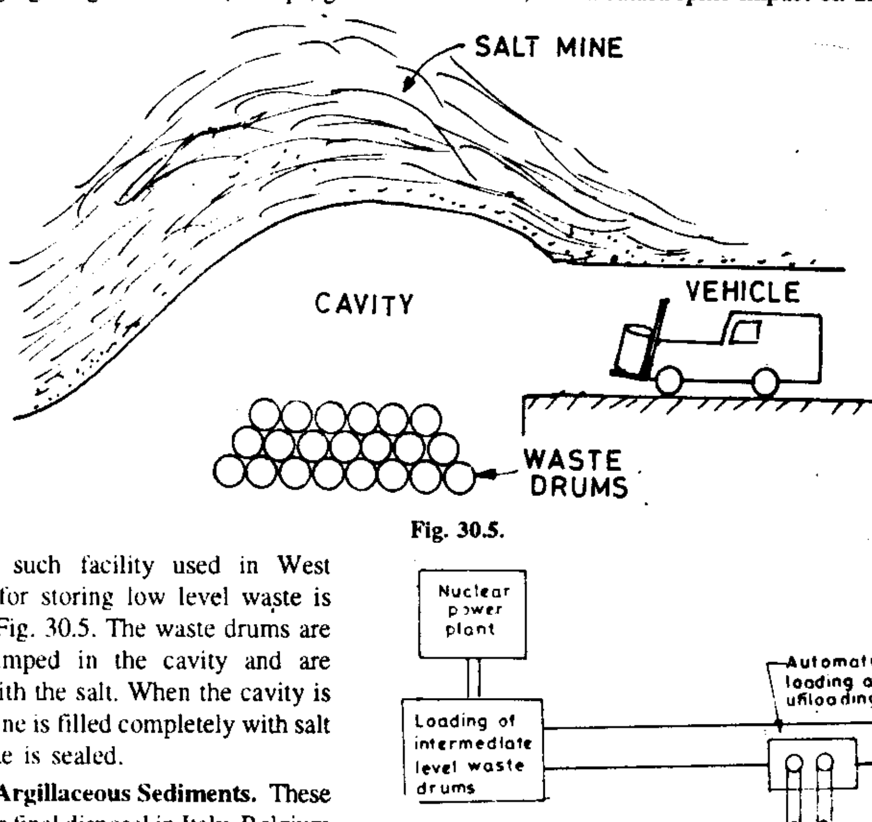


Fig. 30.5.

One such facility used in West Germany for storing low level waste is shown in Fig. 30.5. The waste drums are simply dumped in the cavity and are covered with the salt. When the cavity is full, the mine is filled completely with salt and the site is sealed.

(2) **Argillaceous Sediments.** These are used for final disposal in Italy, Belgium and U.S.A. In Belgium, boreholes are provided at 160 m to 260 m depth in a 100 metre thick bed of clay. It is necessary to study the ground water flow to find out the suitability of geology for final disposal. The analysis of sediments has confined the high plasticity, high ion exchange capacity and low permeability required for safe storage.

(3) **Hard Rocks.** A variety of igneous, metamorphic and sedimentary rocks can be classified as hard rocks. It is considered as a potential disposal media.

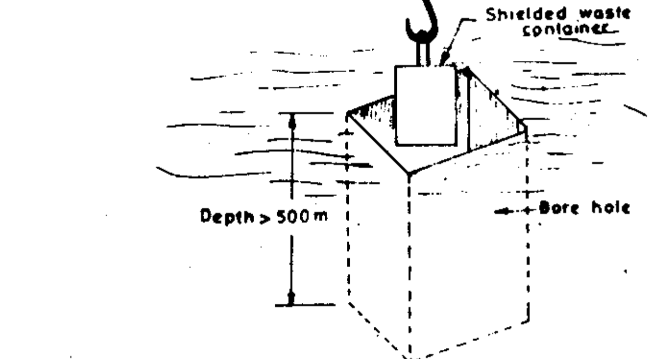


Fig. 30.6.

The essential requirement for considering hard rocks for waste disposal is that (*i*) there should be no ground water flow through a repository (*ii*) The rock area (300 m deep) should be reasonably free from seismic activity and should not be adjacent to major civil engineering development like dams. It is internationally accepted that the most promising solution is storage in geological formation.

One such arrangement for intermediate level waste used in Germany is shown in Fig. 30.6. This facility is built for the disposal of 10,000 containers. The whole arrangement is automatic. For sealing the bore holes, they are filled with a mixture of sand and benionite which is a mixture of low permeability and makes the system safe and free from environment.

Nuclear-Waste Facility in Rajasthan

India's nuclear wastes are to be permanently buried at a site in Rajasthan presently identified. The Atomic Energy Board has already identified 100 square kilometer area and now drilling is started. K. Bala (the director of nuclear recycle group) said that vault dug out in granitic rocks 800 meters below the ground will hold all the waste from India's nuclear facilities. There is hardly any chance of radioactivity escaping from the vault because of multiple barriers.

First, the radio-active waste is embedded in tough, boro-silicate vitrified glass. Each glass block is enclosed by stainless steel box and two such boxes will be put inside another stainless steel box welded on all sides and stacked in the vault. The vitrified glass blocks, in which the radioactive wastes are held must be stored in water for at least 25 years before burial. One such facility is operating at Tarapur and another is to be built by 2002 to provide the facility for coming planned nuclear power plants.

(B) Ocean. The countries situated near the sea are considering the ocean floor, a safe place, for the permanent waste disposal of nuclear power plant. The floors of the deep ocean provide safe and potential disposal sites for solidified high level radioactive waste. In disposing of waste into the sea, the care should be taken to see that the activity level is not harmful to the fish and seewids. The countries like U.S.A., Canada and Japan are using this system of disposal from last few years.

The following points should be considered before selecting the sea site for waste disposal.

(1) Design of waste containers and their corrosive and thermal conductive properties.

(2) Water flow current and sea bed properties.

(3) Water flow pattern at the site and the sea so that the movement and dilution of the dissolved species can be predicted.

(4) Chemical and thermal properties of the sediments and underlying rocks concerning absorption and migration of long lived nuclides must be known.

Ocean can be considered a safe place for discharging high level waste provided it is kept in intermediate storage until they decay to a sufficiently low level. The corrosion resistant containers can be kept on the sea floor provided they last for 300 years or more. This provides sufficient time for the fission products to decay and later if there will be release of the long lived actinides, the effect on man would be similar to that from the radioactive element (mainly Ra^{226}) which is contained naturally in sea water.

One added advantage of ocean disposal is that, added protection is obtained if the containers are embedded in suitable sediments because it absorbs transuranic isotopes strongly. In addition to this, water movements are extremely slow. If the containers are buried deep enough, the possibility of reaching the radioactivity to the overlying water column is rare.

(C) New Methods to Treat High Level Waste

(1) **Harvest Process.** (Highly active residues vitrification engineering study). This process was developed in 1970. In this method, liquid waste together with glass forming materials are fed continuously into a heated stainless steel vessel as shown in Fig. 30.7 in which, the mixture fuses to a homogeneous glass. When the vessel is full, it is removed from the furnace, cooled, sealed and discharged to the storage place.

(2) **AVM Process. (Atelier de Vitrification Marcoule).** This method is developed in France. In this process, glass is made in two stages. In the first stage, liquid waste is dried to a free flowing powder in

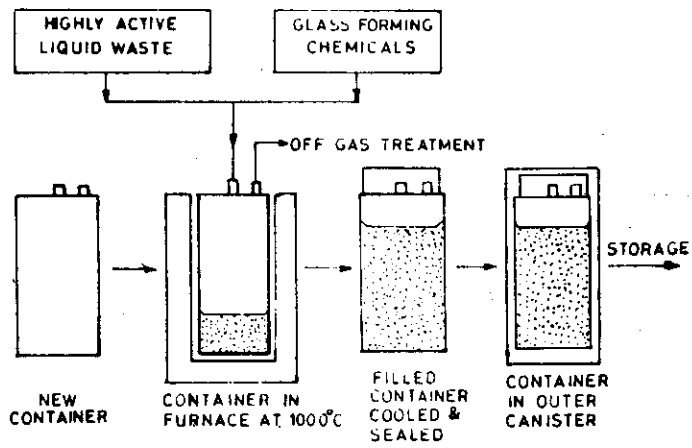


Fig. 30.7. Principle of 'Harvest' Process.

a rotary kiln as shown in Fig. 30.8 and then the powder is fed together with glass powder into a glass making furnace. The advantage is, greater potential with higher production rate.

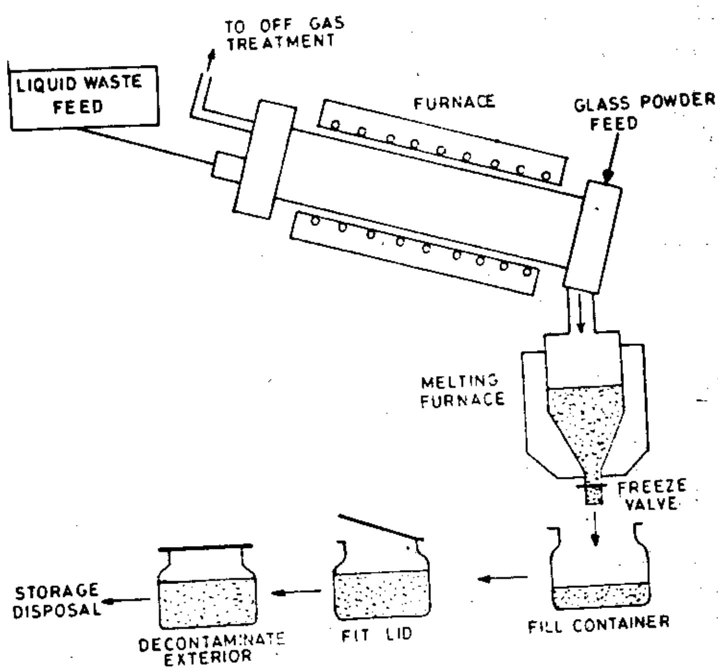


Fig. 30.8. Principle of AVM process.

Torching the Nuclear Waste

Using nuclear reactions to generate electricity is a messy business. Reactors that exploit nuclear fission have produced thousands of tonnes of spent fuel and other radioactive by-products. Meanwhile, research into fusion power has left behind a different kind of debris : a trail of experimental reactors, none of which has yet reached the break-even point where the amount of energy that comes out exceeds the amount put in. Bernard Eastlund, a physicist and veteran of the American nuclear industry, has proposed an ingenious way to deal with these nuclear leftovers. The experimental fusion reactors, he suggests, could be used to clean up the waste generated by the fission reactors.

Dr. Eastlund first came up with the idea for what he calls a fusion torch in 1968, in collaboration with an electrical engineer called William Gough. The two physicists suggested that their surplus plasma gas heated to around 10 million °C, so that individual atoms have their electrons stripped off might be used for recycling industrial waste.

The idea of the fusion torch attracted a lot of attention, and won its inventors an award from America's Atomic Energy Commission. But nothing came of it. And the idea lay dormant for many years.

The growing mountain of nuclear waste from fission reactors, however, has recently rekindled interest in the scheme.

At present, the plan is for it to be reprocessed using solvents and chemical processes to separate it into high-level and low-level components. The high-level waste would then be enclosed in glass canisters and buried deep underground while the low-level waste was stored above ground in special secure facilities. The cost of treating the waste from the decommissioned plutonium-manufacturing plant in Handford, Washington, alone is estimated at over $40 billion.

Fig. 30.8A. Breaking Hanford down.

According to Dr. Eastlund, breaking nuclear waste up into its constituent elements using a fusion torch would have a number of advantages over the chemical approach. For a start, it would produce much less waste. Chemical reprocessing at Hanford would generate 22,000 tonnes of high-level waste and 500,000 tonnes of low-level waste. For a fusion torch the figures are around 5,000 tonnes and 1,000 tonnes respectively. This is because the waste consists of barrels of sludge containing compounds such as nitrides, oxides and water that are not, themselves, radioactive. Another advantage is cost. The fusion torch could, he reckons, handle the waste at the Hanford plant for around $10 billion.

Dr. Eastlund's proposal, which is now being circulated more widely within the department, lays out a $70 m research programme that would involve recommissioning a tokamak at the University of Texas to test the concept, and then proceeding to a prototype system within five years. If successful, the system could then be scaled up by building several such machines.

(D) Nuclear Waste Calcining at Idaho National Engineering Laboratory (INEL)

It is always desirable if the nuclear waste is immobilized in some solid form as solidification reduces the volume to 10% of its original. This further reduces the cost of transport and storage also.

Rodger pointed out that if as tittle as 0.0001% of strontium remains in the waste to be dumped, a storage of about 100 years is required instead of 13 years. Mr. Rodger's solution to this problem is to reduce all liquid into solid and limit the problem to the smaller volume and easier storage of the solid materials. The present solid discharge of about 15000 m^3/year, even at a cost of \$ 15000/m^3, would cost \$ 225 $\times 10^6$ million per year for storage and 2000 $\times 10^6$ million for concentrating to solid form.

The INEL was established in 1963 where spent nuclear fuels were solidified by calcining spent fuel which was received at INEL from more than 100 reactors. The spent fuels fall into four classes based on the composition of the fuel rod cladding as aluminium alloyed, stainless-steel based and graphite-based. To handle this variety, the process plant has four separate head end sections. The function is to reduce the fuel to a liquid that can be processed in the extraction plant.

Aluminium alloyed fuel is dissolved in HNO_3, zirconium alloyed fuel is dissolved in aqueous hydrofluoric acid, stainless steel fuel is electrolytically dissolved in NHO_3, graphite based fuel first is reduced in combustion process and then the uranium is dissolved out of the ash.

The second step in the process is the extraction of usable fuel fractions from the liquid stream. There are three cycles of extraction. The first produces a high level liquid waste, the second and third produce

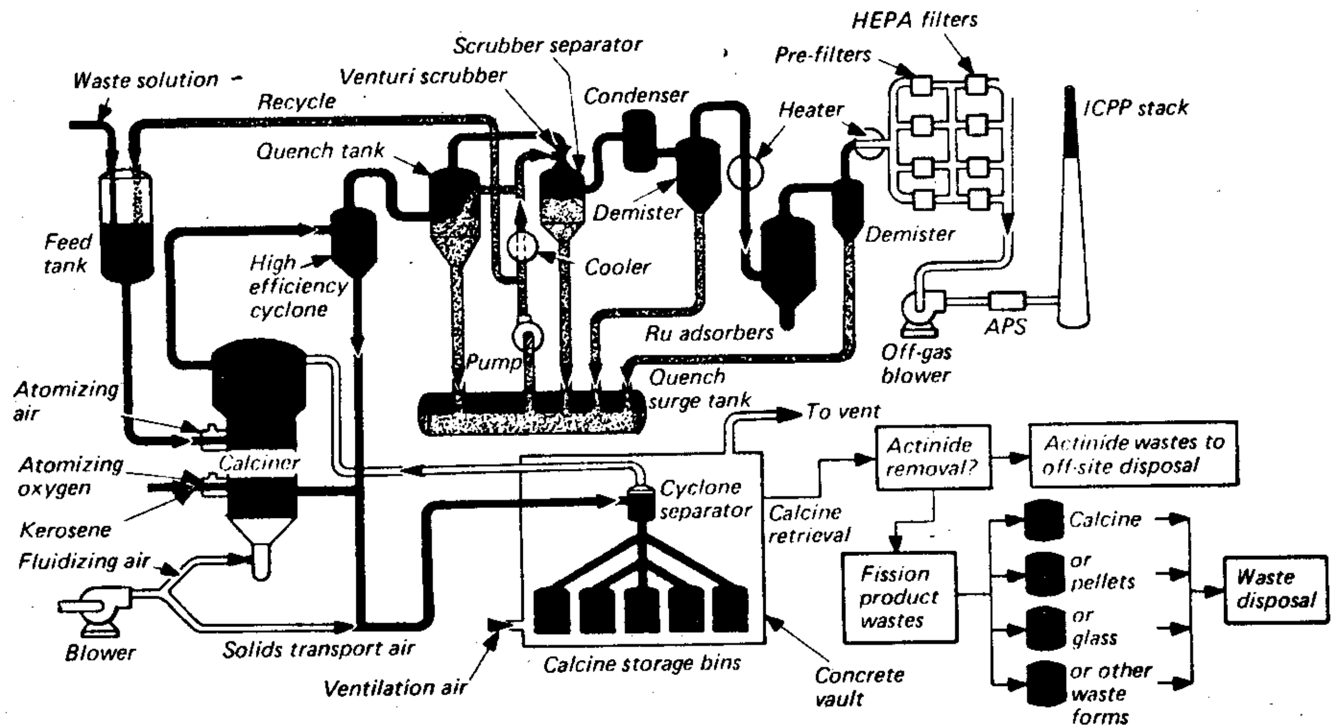


Fig. 30.9.

APS – Automatic Protection System

Using in-bed combustion, waste solution calcination takes place in the calciner vessel. The off-gas is processed through a sophisticated filtering and cleaning system and the solid waste is sent to underground storage bins.

an intermediate level liquid waste. These liquids are stored separately. Removed fuel is returned to fuel manufacturing facilities.

The third step in the process is calcining the liquid wastes. Calcining produces a free flowing non-corrosive granule that is stored in stainless steel tanks within concrete vaults.

This method has several advantages. The liquid volume was reduced by a factor 8 by calcining. The waste was less mobile and easier to handle and calcining reduced the need for additional liquid waste storage tanks (each tank costs $ 6 million as per cost in 1982).

The old INEL plant is renewed in 1982 incorporating a fluidized bed calcination, off-gas clean up and remote operation. The Fig. 30.9 shows the flow diagram of new calciner. The liquid waste is chemically conditioned for calcining and then pumped to the feed tank.

The liquid is sprayed continuously into the fluidized bed calciner through 4-nozzles. The bed is heated to 500°C by burning kerosene in the presence of pressurized oxygen. Fluidized air enters below the bed through a distributor plate. The feed rate is 3500 gpd.

In the bed, the liquid deposits on the particles and evaporates. The material left behind increases the size of the particles and they are drawn off continuously. The particle size is controlled to 0.3 mm. The product is transported from the calciner main air fed system to storage bins. Air and product are separated by a cyclone separator and the product falls by gravity into the bin (4 m diam and 20 m tall). The bin life is expected to be 500 years and they are monitored for corrosion. In this system, 15000 m^3 of liquid waste has been calcined and stored in the bin since 1983. The volume reduction was about 7.5 : 1.

Off-Gas Clean-up System

All air and gases leaving the calciner pass through an elaborate clean-up system. Major part of the entire calcining process is dedicated to off-gas clean-up.

The hot gas is first quenched and then passed through venturi scrubbers. The gas stream is dried in condensers and demisters, reheated and then passed through silica gel adsorbers to remove any traces of ruthenium.

At regular intervals, the adsorbers are washed and the ruthenium is recycled back into the feed tank. Hence, most of the ruthenium becomes part of the calcine solids. After leaving the adsorbers, the gas stream passes through demisters and then through high efficiency filters. Then gases pass through an atmospheric protection system and then discharged to the atmosphere through a stack of 80 m high.

30.6. GAS DISPOSAL SYSTEM

Methods are well developed for removing krypton and iodine gases coming out from spent nuclear fuel. Methods for removing tritium and CO_2 are also being developed. Krypton is removed by cryogenic treatment and packed in gas cylinders under pressure. An advance method is also developed for storing the recovered krypton in a sodalite zeolite matrix at atmospheric pressure. Iodine can be removed from off-gases by caustic scrubbing or HNO_3 scrubbing. Development of processes for separating and concentrating tritium are based on voloxidetion, pyrochemical processing and isotopic enrichment. Processes for removing radioactive CO_2 by caustic scrubbing and adorption on molecular sieves are also developed.

The disposal of radioactive gases into the air creates lot of problems. Strong radioactive gases like iodine and strontium are absorbed by the plants and enter into the human body through the food. Cesium is absorbed by muscle and strontium in bones and paralyses the health.

Generally radioactive gases are collected and stored in the tank buried in the ground and disposed off to the atmosphere when activity level sufficiently comes down.

Provision is made for the disposal of radioactive gases as shown in Fig. 30.10. The gaseous waste problem arises from the possibility of ruptures in the fuel element cladding which might release gaseous

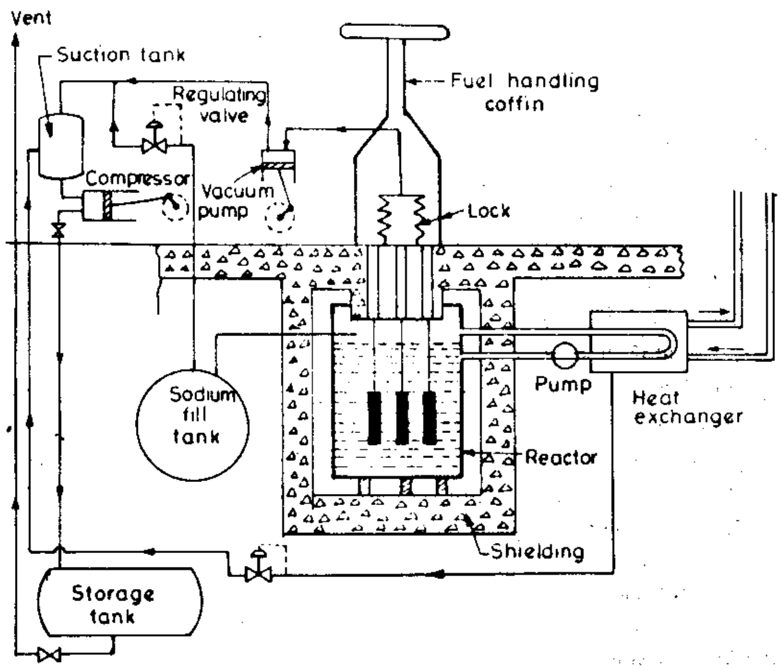


Fig. 30.10. General Arrangement for gaseous waste disposal system in sodium cooled graphite moderated reactor

fission products into primary sodium system. As a result, each gas line which connects into the primary system is connected in such a way that if excessive radioactivity is detected, this gas will be pumped into radioactive storage tank. This is accomplished by means of a radioactive detector coupled to valves which automatically shunt the gas stream being vented into a compressor suction tank whenever an excessive level of radioactivity is detected. From the suction tank, the compressor forces this gas into a storage tank where it can undergo radioactive decay. The tank capacity may be 150 m^3 at 7 bar. If some later time, the activity level is determined to be sufficiently low, this gas may be bled from the storage tanks and discharged out through the building vent line.

Fuel Reprocessing Plant at Kalpakkam (Chennai) (KARP)

This indigenously designed and built facility has a capacity for processing 100 MT of spent fuel per year. The plant would reprocess spent fuel discharged from Madras Atomic Power Station.

Reprocessing of spent fuel is the most vital link between the first stage of Indian nuclear power programme and its growth through the next two stages. The present uranium reserves are just sufficient to support 10,000 MWe capacity if used in the PHWR technology which is well developed in this country. However, with the plutonium produced in the PHWRs is recovered in the reprocessing plant and recycled in fast breeder reactors, the nuclear generating capacity could be increased to 350,000 MWe. The nuclear power programme beyond this would be sustained on the basis of fissile material U^{233} produced by irradiation of thorium which is abundantly available in India. Reprocessing the spent uranium fuel from PHWRs of the first stage, for creating a plutonium base for the fast breeder programme of the II-stage, is thus one of the key elements of III-stage development programme.

The present deprocessing plant is most modern and largest in the country among the 3-reprocessing plants. It is built over an area of 12.3 hectres and housing 20-buildings. It is the largest radiochemical plant in the country with around 400 process equipments and involving a total length of 85 km of piping in a row of 7-concrete cells. The special features of this plant include multiple containment for storing active materials and control of radioactivity released to negligible level.

As most of the radioactivity contained in spent fuel would be confined to high level liquid wastes produced in a reprocessing facility, highest levels of safety and engineering have been incorporated for handling and storage of these wastes. These wastes will be stored in a stainless steel and carbon steel tanks which are installed in underground concrete vaults. The safety of this storage is further ensured by a close surveillance of the integrity of the tanks and multiple barries.

These high level liquid wastes will be vitrified to form stable, solid glass products that are considered suitable for their long term retention of radioactivity.

The pictorial view of the plant is shown in Fig. (30.11).

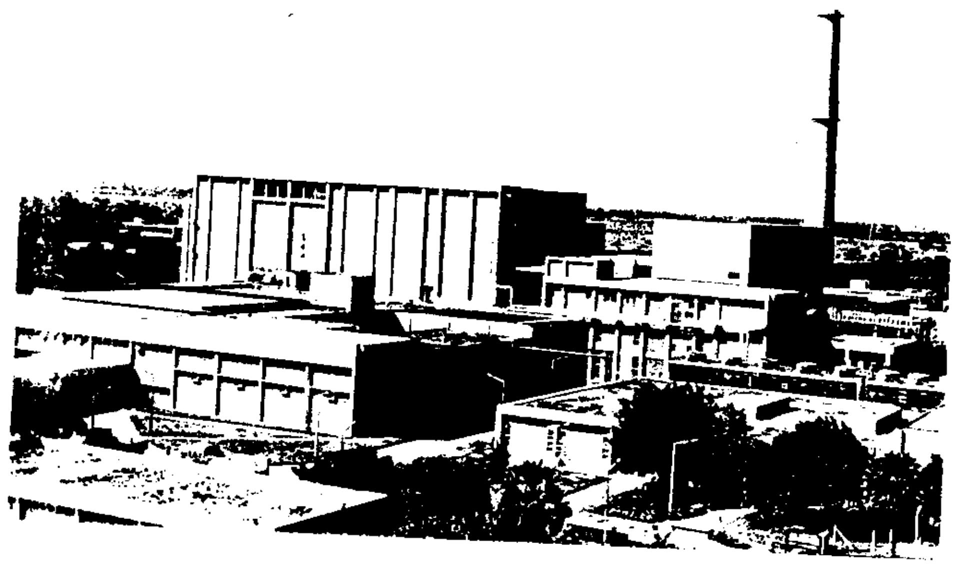


Fig. 28.11. KARP.

EXERCISES

30.1. What are the different types of nuclear wastes ? Which are more dangerous and why ?
30.2. Define the unit of Nuclear radiation and classify the waste accordingly.
30.3. What are the types of nuclear radiation and their major effects on human and plant life ?
30.4. Discuss with the help of diagrams, the methods used for treating the medium and high radioactive wastes.
30.5. What is calcination method ? What are the major advantages of this ? Explain its working with the help of neat sketch.

□□□

PART V

31

Non-Conventional Power Generation and Direct Energy Conversion Systems

31.1. Introduction. 31.2. Geothermal Power Plants. 31.3. Tidal Power Plants. 31.4. Wind Power Plants. 31.5. Solar Plants. 31.6. Direct Energy Conversion Systems.

31.1. INTRODUCTION

The energy consumption in the world, particularly in the industrialised countries, has been growing at an alarming rate. Fossil fuels which today meet major part of the energy demand are being depleted quickly. World has started running out of oil and it is estimated that 80% of the world's supply will be consumed in our life times. Coal supplies may appear to be large but even this stock may not last longer than a few decades. Moreover, the pollution hazard arising out of fossil fuel-burning has become quite significant in recent years. Nuclear power has posed a number of problems and nuclear fusion is still a speculative technology.

Thus we are forced to look for unconventional energy sources such as geothermal, ocean tides, wind and sun. It is also hoped that these alternative energy sources will be able to meet considerable part of the energy demand in coming future. Among all these, solar energy seems to hold out the greatest promise for the mankind. It is free, inexhaustible, non-polluting and devoid of political control. Solar water heaters, space heaters and cookers are already on the market and seem to be economically viable. Solar photo-voltaic cells, solar refrigerators and solar thermal power plants will be technically and economically viable in a short time. It is optimistically estimated that 50% of the world power requirements in the middle of 21st century will come only from solar energy.

Enough strides have been made during last two decades to develop the direct energy conversion systems to increase the plant efficiency from 60 to 70% by avoiding the conversion of thermal energy into mechanical energy. Still this technology is on the threshold of the success and it is hoped that this will also play a vital role in power generation in coming future.

Power from Renewables
(Solar, Wind, Biomass and Small Hydro)

The power potentials from renewables in India with their advantages and measures taken by the Govt. to develop these resources are listed below :

Advantages

- Non-depletable
- Low gestation
- Modularity
- No Transmission and Distribution losses
- No fossil fuels
- Environment friendly
- Low operating and maintenance cost
- Cost-effective

Potential

Wind Power	20,000 MW
Small Hydro Power	10,000 MW
Biomass Power	19,500 MW
Solar Power	35 MW/Sq.km

Facilities

- 100% Accelerated Depreciation
- Five Year Tax Holiday
- Customs Duty Reliefs
- Excise Duty Exemption
- Soft Loans from IREDA
- Power Purchase Policy by States
- State Support

Goals

		Installed Capacity
9th Plant end (2002)	–	2,500 MW
11th Plan end (2012)	–	12,000 MW

Installed Status

Wind Power	1080 MW
Small Hydro Power	210 MW
Biomass Power	222 MW
Solar Photovoltaic System	49 MW

Promotional Measures

- Resource Assessment
- Support for Project Preparation
- Capital Subsidy for Demo-Projects
- Interest Subsidy for Commercial Projects
- Industry, FI and SEB Co-ordination
- Facilities by SEBs of Wheeling, Banking, Buy-back and Third Party Sale
- Support to Industry
- R & D and Technology Development
- HRD and Training
- Public Information and Awareness

The purpose of the present chapter is only to introduce the new comers in the energy field and to the readers of the power plant engineering as these sources are going to play very important role in the world energy resources and demand in future.

31.2. GEOTHERMAL POWER PLANTS

The growing demand of power will exhaust all fossil recoverable resources within few decades as mentioned earlier. Therefore, there is a permanent need for tapping new unconventional sources of energy like sun, wind, tidal and geothermal. While all others are periodical and not dependable, the geothermal energy has a great potential and is already being commercially exploited in some of the developed countries.

Approximately 94% of the earth is molten. Only the thin outer shell is solidified rock which ranges in thickness from 15 to 150 km. The temperature at the centre of the earth is around 3100°C while the temperature at the juncture between the magma body and the crust approaches 1200°C, the temperature at which most rocks are molten. Fortunately the crust of the earth is an excellent insulator, allowing very little heat to reach the surface. However, the crust is also highly fractured and technically active, which creates conditions for heat to approach close to the surface in many regions.

For most people, geothermal fields probably call to mind visions of hot spring areas like those of Yellowstone National Parts of New Zealand. But natural hot waters are now being used in many countries for space heating, agricultural purposes and the power stations in Italy, U.S.A. and New Zealand that produce electricity from geothermal steam have received considerable publicity. Plans to utilize geothermal energy are being made worldwide, and although the technology is still at an early stage of development, rapid development may be expected as a result of the current energy crisis.

At present about 1500 MW of power is being generated in the world from geothermal source. Presently this source contributes only about 1/1600th part of the world's electrical needs, the smallness of this fraction should not be disposed. Moreover, it seems highly probable that the geothermal power growth rate is accelerating, as more and more countries are exploring and evaluating their sources of earth heat.

In addition to USA, Itlay and New Zealand, recently Indonesia and USSR have also entered in the field of geothermal power generation. A 300 MW Kamojang geothermal power station, first of its kind in Indonesia, has been completed and presently operated successfully.

The ejection of steam and hot water by Mutnovski volcano on Kamchetka (USSR) can ensure the power of about 400 MW. The energy sources are concentrated mainly in the two merged craters with a diameter of about 2 km. The thermal potential of this volcano has remained unchanged over the past 20 years. Geologists have started exploration work on 800 m high mountain. The first well drilled to a depth of 1500 m has confirmed great energy potential of steam. The surveying for the first stage is finished by 1986. This plant will supply the energy to the industry around Petropavlovsk (80 km from power station) and adjacent agricultural area.

The Geological Survey of India is installing a 1 MW power plant using hot steam at Puga Valley in Ladakh. Six out of eleven wells drilled in the area have yielded encouraging results. A unique feature of these wells is high temperature (140°C) and high pressure (4.5 bar) around the depth of 80 m, a phenomenon unknown in any part of the world. The further investigation in this area are continued. The potential power at Puga is estimated to be 5 MW.

Forms of Geothermal Energy. The earth is also a vast energy source like the sun. The utilization of this geothermal furnace is still in its infancy. The heat flow from the mantle of the surface (or 0.063 W/m^2) is the energy equivalent to 2×10^{11} barrels of oil per year which is about fourfold greater than the present yearly total world energy consumption. Although, today only local heat spots yielding dry and wet steams are used economically, future technology may well lead to a much greater utilization.

Figure 31.1 shows a schematic diagram depicting how hot springs are produced through the hot magma,

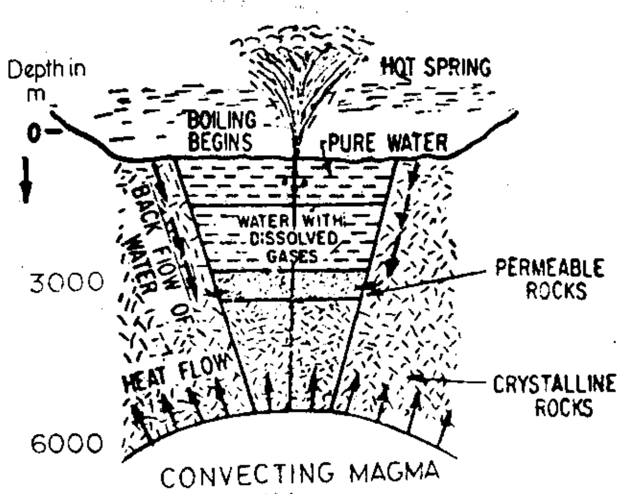


Fig. 31.1. Hot spring system structure.

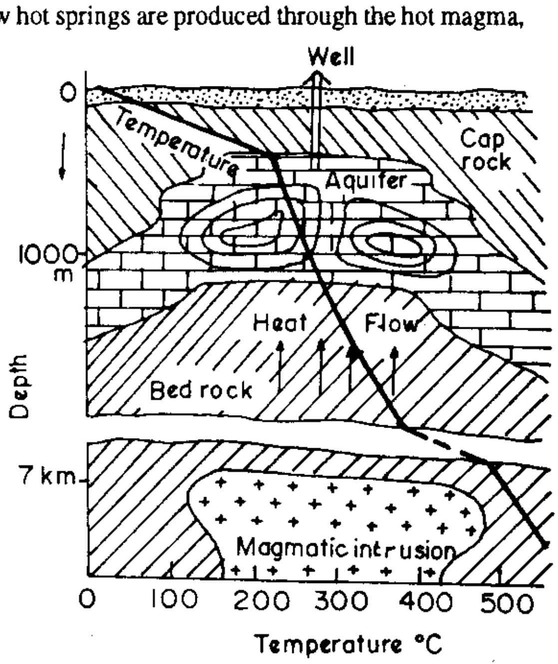


Fig. 31.2. Basic model of steam field.

the fractured crystalline rocks, the permeable rocks and the percolating ground water. Figure 31.2 shows a basic model of steam field which consists of a magma heat source at 7 to 15 km depth, an adequate water supply, a permeable rocks reservoir (aquifer) at 1000 m depth and a sealing cap rock above. A plot of the temperature with depth is also indicated on the diagram.

The available geothermal energy is classified in four categories.

1. **Dry-Steam Systems.** These are the best available sites for electric power generation as steam from the geothermal field is directly fed to the turbine. Such sites are available in Italy, U.S.A. and Japan. The first electric power generating station in the world using natural dry-steam was built in Larderello in Italy in 1904. This was followed by an installation at Geyser (130 km north of San Francisco) in 1960. These fields now produce about 500 MW power. By 1995, they may produce over 1600 MW or more.

The arrangement of the components of this system used at Larderello and Geysers is shown in Fig 31.3. The liquid particles and suspended solids are eliminated by using centrifugal separators. The condensate coming out of condenser was fed back to the hot field with the help of a pump. The supply of steam diminishes due to depletion of thermal energy of that region or insufficient supply of ground water. Therefore, to keep up the steam supply, new wells must be drilled.

2. **Wet Steam Systems.** (*a*) Many hot water sites at 125°C and above are also available in New Zealand, Japan and Mexico. Flashed steam produced from the hot water at such sites is used for power generation. The Wairakei Power Plant in New Zealand, Cerro-Prieto Power Plant in Mexico, and few power plants in Japan and U.S.A. are of this type. These power plants mainly suffer from the problems of salt corrosion, a need for steam separation and brine re-injection to avoid ground subsidence. Their environmental impact is greater than dry-steam systems and they require a large use of land areas. The power generation from such systems can be made more economical by associating chemical industry with power plant to make use of the brine and gaseous effluent.

The arrangement of the components of this system used at Cerro-Prieto (Mexico), Wairakei (New Zealand), Otake (Japan) is shown in Fig. 31.4. Water at high temperature coming out from hot well is flashed in flash chamber to produce the steam and the steam produced is passed through the turbine. The condensed steam with brine separated in the flash chamber is again pumped back to the geothermal field as shown in figure.

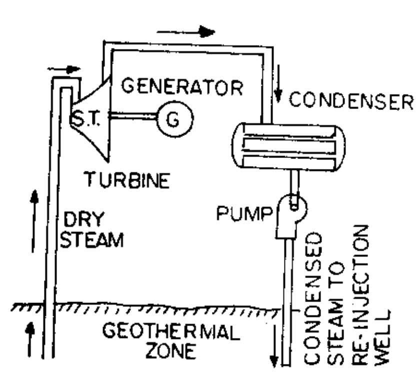


Fig. 31.3. Dry-steam open system used in Larderello (Italy) and Geyser (USA).

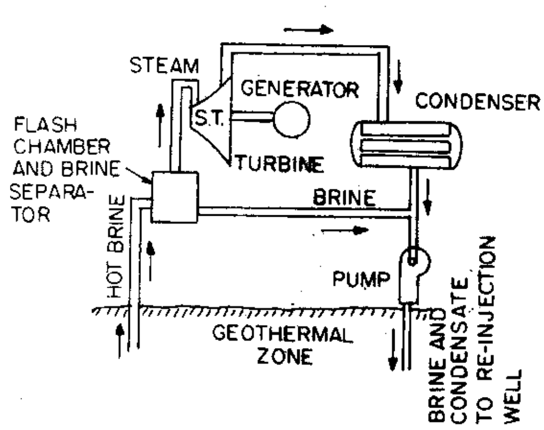


Fig. 31.4. Flash steam open type used in Cerro Prietol Mexico, Wairakei (N.Z.), Otake (Japan).

Reservoir temperatures between 200° to 300°C and reservoir volumes of many tens of cubic kilometres are required for power generation of 100 MW capacity plant. The cap rock that contains the reservoir must have a low permeability to keep in the heat and the water. A good recharge of the reservoir from the surrounding is also essential. The water should not contain excessive salt otherwise salt-corrosion and effluence deposition become serious problems. The source should last for 20 to 30 years to be viable economically. However, it is quite possible that most areas will produce for a century or longer with continued drilling and replacement of non-productive depleted wells.

(*b*) Many times the temperature and pressure of the water are not sufficient to produce the flash steam. Under this situation, the heat in the water is used in a closed system as shown in Fig. 31.5. In this system, Freon or Isobutane is used as working fluid which is continuously recirculated. Such systems are under investigation in Russia. The advantages of the closed systems are that, lower hot water temperature can be used and brine corrosion is prevented in the closed portion of the system.

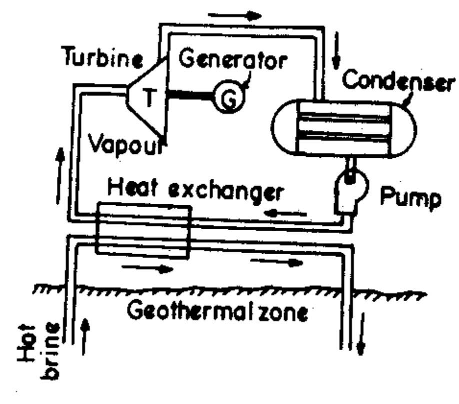


Fig. 31.5. Hot water closed (Binary) system is under development in Russia and USA.

3. **Hot dry rock systems.** Another type of concentrated geothermal energy is found in the form of the heat content of hot dry rock. With this form of energy, heat will have to be transferred to the surface by means of artificially injected water through specially constructed pathways. In addition, the rock will have to be fractured to allow good heat contact between the water and rock.

This geothermal source is more attractive as it is estimated that one cubic mile of hot rock when cooled from 350°C to 180°C has the energy equivalent of a major oil field, about (1/3) billion barrels of oil and it could yield about 8000 MW-year of energy, if it could be efficiently recovered. It is more attractive to utilise the existing hot dry rock areas that have temperature gradients of 150 – 180°C/km compared to world average gradient of 30°C/km.

4. **Magmatic (Molten rock) – Chamber systems.** The average density of volcanoes is 2.79 grams/cm^3 and specific heat is 0.25 kcal/g-°C in the temperature range of 1000 to 1300°C. More than 30% of the energy from a volcano between 1150°C and ambient temperature of 25°C is recoverable above the solidification temperature of lava. The energy per unit volume of magna is approximately 32×10^{14} kJ/km^3.

Extraction of heat energy from hot magma is presently studied at a temperature of about 1450°C under laboratory conditions. Based on these results, the operation of a 100 MW power plant would require approximately 400 m^2 of heat exchanger surface area, using an average value of 250 kW/m^2 heat extraction rate. This much area could be provided by a single 20 cm diameter tube extending 700 metres into the volcanic chamber. Extension of heat exchanger tube into the magma chamber may be possible for magma sources with 4 to 5 kilometres of the surfaces. The energy recovery from deeper sources is more difficult because of need of drilling substantial distances. Solidification of magma around the heat exchanger tubes and resulting decrease in heat extraction rate are some of the major problems in the development of such systems.

Although the geothermal energy sources that are now used for electric power generation are of the shallow-steam reservoir type but in near future, deeper reservoirs, fractured rocks and other schemes like molten magma will probably be used.

Economical justification of Geothermal plants. The economic justification of geothermal plants depends mostly on present and future costs of competing sources of power. This source of energy for electric generation has proved most economical judging from the performance of the installations in Larderello (Italy). Wairakei (New Zealand), Geysers (California) and Otake (Japan). The very important question in its economical justification is that of the lifespan of the source. However, it appears that if a site lasts for 20 to 30 years, it would be aceptable from an economic viewpoint.

The following table provides a comparison of estimated power costs as per 1985 from three different sources and shows that geothermal is most economical and reliable method of producing electric power.

Comparison of Capital and Generation cost of different electric power plants in 1980

Cost	*Geothermal*	*Nuclear*	*Coal*
Dollar/kW	250 – 600	1300	1200
Mills/kW-hr	20 – 38	55 – 60	60

The present figures are optimistic and are only applicable to natural dry steam sites of large capacity. It can be anticipated that with technological developments, hot water sites, fractured hot dry-rock sites and molten magma sites may become more economical in future.

Environmental effects. Detrimental effects from geothermal electric power generation promise to be at a very low level. There are no solid pollutants to be emitted into the atmosphere, no radiation hazards like nuclear plants. The emission of H_2S and other toxic gases into the atmosphere is a source of annoyance. It is estimated that a geothermal plant of 200 MW capacity (same capacity at Geyser) would emit 500 kg of H_2S per day using steam about 1400 tons per hour. The highly mineralized effluents resulting from the condensed stream can pollute streams of ground water. Therefore, it is necessary to reinject the fluids into a well or reservoir which can also take care of thermal pollution and subsidence problems.

It is worth noting that unlike other thermal power plants, natural steam geothermal installations do not require additional condenser cooling water. The condensed steam can be resued for cooling in the condenser as no feed is required like conventional systems.

It was estimated by Dr. Carel Otte (manager of geothermal division of Union Oil Co., USA) that by the year 1990, California could be receiving upto 25% of all its electric power from clean and cheap geothermal energy. The present power station is already supplying the needs of 500,000 homes. By the end of 1978, the geothermal fields supplied the energy for almost one million homes. Officials at the US Energy Research see a geological opportunity to develop some 20 million kilowatts of generating capacity in the next 20 years. This would save some 700,000 barrels of oil a day or 8.5% of today's US crude oil production and would save some $ 3.8 billion annually in foreign exchange.

There are about 250 geothermal sources in India (Himalaya 80, Peninsula 170) and most potential ones lie in Puga valley of Ladakh and at Manikaran in Himachal Pradesh. The Puga valley has potential geothermal field of about 4 sq. km. out of which 0.5 sq. km has been subjected to deep drilling and testing by Geological Survey of India and proved to contain thermal resources adequate for generation of 1 MW of power. It is estimated that the average steam flow is about 20 tonnes per hour at 100 to 140°C temperature.

5 kW Geothermal Pilot Power Plant

The National Aeronautical Laboratory (NAL), Bangalore, has demonstrated the feasibility of a low grade heat recovery turbopack system that can harness the energy contained in low temperature heat and convert it into useful shaft power. The system operates on a closed loop Rankine cycle and was rated for a nominal output of 1 kW. The unique feature of the system is that it employed acetone as the working Rankine fluid and requires a turbine entry temperature of only 60°C. The turnine is designed to run at 10,000 rpm.

In view of this successful feasibility demonstration and as a follow-up leading to a practical application, developmental work on a 5 kW geothermal pilot power plant has been initiated under a joint collaborative project with Geological Survey of India and the Himachal Pradesh Government sponsored by the Commission for Additional Sources of Energy.

The 5 kW pilot power plant, which will be located at Manikaran, Himachal Pradesh, will utilize the heat available in low temperature (around 90°C), low pressure geothermal fluids issuing from wells drilled in a water dominated reservoir area. This turbopack system, which will operate on a closed loop Rankine cycle, will employ trichlorotrifluoroethane (R-113) as the Rankine fluid. Thermodynamic and other design studies have revealed that R-113 is the best Rankine fluid for this application. Geothermal waters from the wells are passed through the evaporator where they transfer their heat to vaporize R-113. The R-113 vapour is then superheated a few degrees before being expanded in the turbine. The turbine entry temperature will be about 60°C. The single stage partial admission impulse turbine will rotate at 3,000 rpm and directly drive the alternator avoiding the gear box. The vapour after expansion in the turbine is then condensed in the condenser, which is supplied with cooling water from the nearby river Parbati. The condensate is subcooled to prevent cavitation in the condensate pump before being pumped back to the evaporator to complete the cycle.

The turbopack system will be designed keeping in view its final operation in rural/remote areas. Therefore, simplicity, low cost, easy maintainability and long life have been the primary factors in evolving the design configuration for this turbopack system. The working Rankine fluid (R-113), which is non-toxic and non-corrosive, is a liquid at ambient pressures and temperatures. Hence, its handling is easy and it is possible to operate the condenser at about atmospheric pressure to simplify sealing problems.

It is estimated that the thermal value of the geothermal field in the world is probably equivalent to 5×10^{10} barrels of oil per year for several centuries to come. To put this into perspective, this is nearly equivalent to the present world yearly energy consumption. Although such a comparison is useful mainly to give a feeling for the size of the source and not all of it would be available for exploitation and extraction.

31.3. TIDAL POWER PLANTS

Introduction to Tidal Power Plants. The development of a nation is estimated from the total amount of energy it produces and consumes in relation to its size and population. Human progress has been judged from the ways in which man has been able to develop and harness energy.

The present shortage of the energy production sources due to depletable nature of fossil fuels has awakened the world human community to search for new unconventional and replenishable energy sources. According to the energy experts, exhaustible resources extracted from the ground (coal, oil, gas, uranium), in the face of increasing demand, results into a cycle. This cycle starts at zero production, increases exponentially, then decreases exponentially and finally comes to zero. It is estimated that petroleum reserve of the world will be nearly exhausted by 2020. Under such circumstances, man has to find out some source of energy for his survival. In this context, three sources of energy, tidal, wind and solar have been thought to be most promising.

What is tidal power ? Tide is periodic rise and fall of the water level of the sea. Tides occur due to the attraction of sea water by the moon. These tides can be used to produce electrical power which is known as tidal power.

When the water is above the mean sea level, it is called flood tide and when the level is below the mean level, it is called ebb tide. A dam is constructed in such a way that a basin gets separated from the sea and a difference in the waterlevel is obtained between the basin and sea. The constructed basin is filled during high tide and emptied during low tide passing through sluices and turbine respectively. The potential energy of the water stored in the basin is used to drive the turbine which in turn generates electricity as it is directly coupled to an alternator.

Though the idea of utilising tides for human service relates to eleventh century when tidal mills were used in England, but the use of tidal power for electric power generation is hardly four decades old as the world's first Rance Tidal Power plant of 240 MW capacity in France was commissioned by President De Gaulle in 1965 who described it a magnificent achievement in the human life.

Tidal power had been a dream for engineers for many years and it remained dream because of large capital cost involved in its development. But after the inauguration of Rance Tidal Project, a new chapter in the history is now opened.

Factors affecting the suitability of the site for tidal power plant. The feasibility and economic vulnerability of a tidal power depends upon the following factors :

1. The power produced by a tidal plant depends mainly on the range of tide and on the height tidal flow occurring in the estuary during a tidal cycle which can be stored and utilised for power generation. The nature of the tidal flow not only depends on the tidal range but on the width of estuary mouth.

2. The minimum average tide range required for economical power production is 4.6 m or more.

3. The site should be such that with a minimum cost of barrage, it should be possible to create maximum storage volume. In addition to this, the site selected should be well protected from wave's action and storms as these factors affect the cost of embankment.

4. The site should not create interruption to the shipping traffic running through the estuary otherwise the cost of the plant will increase as locks are to be provided.

5. Silt index of the water of the estuary should be as small as possible to avoid the siltation troubles. The siltation leads to reduction of the range of tides and reduces the power potential of the plant.

6. The fresh water prism that falls into the reservoir of the tidal plant (due to the surface flows in the streams having outfall in the estuary) eats away the valuable storage created for storing the tidal prism. Therefore, the ratio of fresh water prism to tidal water prism becomes an important index in determining the economic feasibility of a tidal scheme. The effective and cheaper will be the power production with decreasing the ratio mentioned above.

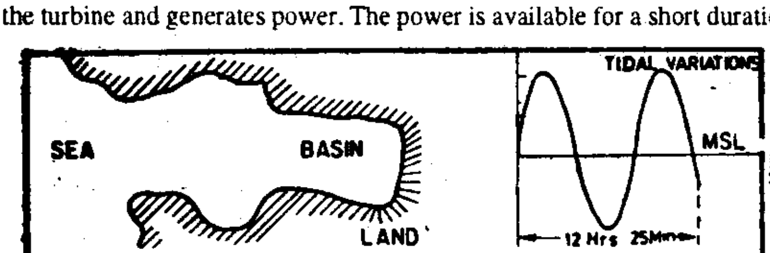
Classification of tidal power plants. The tidal power plants are generally classified on the basis of the number of basins used for the power generation. They are further subdivided as one-way or two-way system as per the cycle of operation for power generation.

The classification is represented with the help of a line diagram is given below :

Classification
- Single basin systems
  - One-way system
  - Two-way system
  - Two-way with pump storage
- Double basin systems
  - Simple double basin
  - Double basin with pumping

Working of Different Tidal Power Plants

1. **Single basin-one-way cycle.** This is the simplest form of tidal power plant. In this system, a basin is allowed to get filled during flood tide and during the ebb tide, the water flows from the basin to the sea passing through the turbine and generates power. The power is available for a short duration during ebb tide.



MSL = Main Sea Level.

Fig. 31.6. (*a*) Tidal region before construction of the power plant and tidal variation.

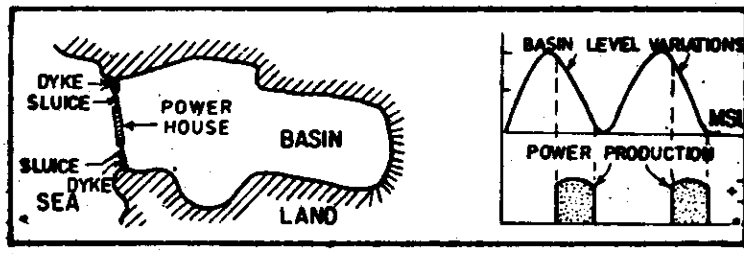


Fig. 31.6. (*b*) Single basin, one-way tidal power plant.

Figure 31.6 (*a*) shows a single tide basin before the construction of dam and Fig. 31.6 (*b*) shows the diagrammatic representation of a dam at the mouth of the basin and power generation during the falling tide.

2. **Single-basin two-way cycle.** In this arrangement, power is generated both during flood tide as well as ebb tide also. The power generation is also intermittent but generation period is increased compared with one-way cycle. However, the peak power obtained is less than the one-way cycle. The arrangement of the basin and the power cycle is shown in Fig. 31.7.

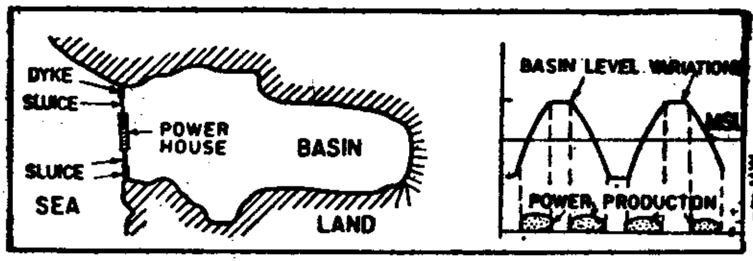


Fig. 31.7. Single-basin two-way tidal power plant.

The main difficulty with this arrangement, the same turbine must be used as prime mover as ebb and tide flows pass through the turbine in opposite directions. Variable pitch turbine and dual rotation generator are used for such schemes.

3. **Single-basin two-way cycle with pump storage.** The Rance Tidal Power Plant in France uses this type of arrangement. In this system, power is generated both during flood and ebb tides. Complex machines capable of generating power and pumping the water in either directions are used. A part of the energy produced is used for introducing the difference in the water levels between the basin and sea at any time of the tide and this is done by pumping water into the basin up or down. The period of power production with this system is much longer than the other two described earlier. The cycle of operation is shown in Fig. 31.8.

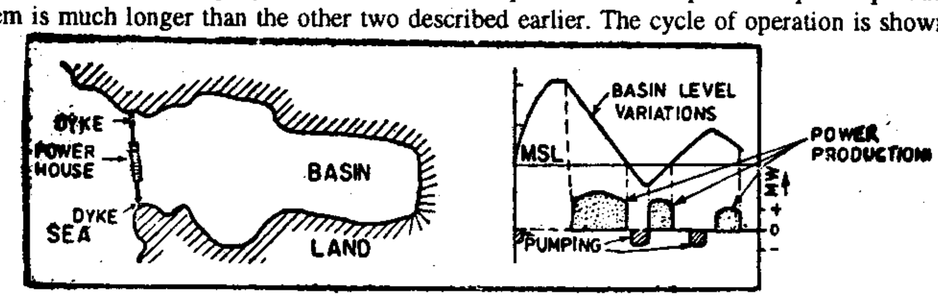


Fig. 31.8. Single-bsin, two-way tidal plant coupled with pump storage system.

4. **Double basin type.** In this arrangement, the turbine is set up between the two basins as shown in Fig. 31.9. One basin is intermittently filled by the flood tide and other is intermittently drained by the ebb tide. Therefore, a small capacity but continuous power is made available with this system as shown in Fig. 31.9. The main disadvantage of this system is that 50% of the potential energy is sacrificed in introducing the variation in the water levels of the two basins.

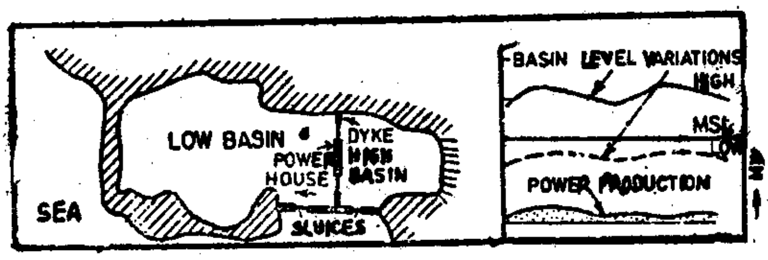


Fig. 31.9. Double basin, one-way tidal plant.

5. **Double basin with pumping.** In this case, off peak power from the base load plant in a interconnected transmission system is used either to pump the water up the high basin. Net energy gain is possible with such a system if the pumping head is lower than the basin-to-basin turbine generating head.

Advantages and disadvantages of Tidal Power Plants

Advantages : 1. Exploitation of tidal energy will in no case make demand for large area of valuable land because they are on bays.

2. It is free from pollution as it does not use any fuel.

3. It is much superior to hydro-power plants as it is totally independent of rain which always fluctuates year to year. Therefore, there is certainty of power supply as the tide cycle is very definite.

4. As in every form of water power, this will also not produce any unhealthy waste like gases, ash, atomic refuse which entails heavy removal costs.

5. Tidal power is superior to conventional hydropower as the hydro plants are known for their large seasonal and yearly fluctuations in the output of energy because they are entirely dependent upon the nature's cycle of rainfall, which is not the case with tidal as monthly certain power is assured. The tides are totally independent on nature's cycle of rainfall.

6. Another notable advantage of tidal power is that it has a unique capacity to meet the peak power demand effectively when it works in combination with thermal or hydroelectric system.

7. It can provide better recreational facilities to visitors and holiday makers, in addition to the possibility of fish farming in the tidal basins.

A few disadvantages are listed below :

1. These power plants can be developed only if natural sites are available.

2. As the sites are available on the bay which will be always far away from the load centres, the power generated must be transported to long distances. This increases the transportation cost.

3. The supply of power is not continuous as it depends upon the timing of tides. Therefore, some arrangements (double basin or double basin with pump storage) must be made to supply the continuous power. This also further increases the capital cost of the plant.

4. The capital cost of the plant (Rs. 5000/kW) is considerably large compared with conventional power plants (hydro, thermal).

5. Sedimentation and siltration of the basins are some of the added problems with tidal power plants.

6. The navigation is obstructed.

7. It is interesting to note that the output of power from tidal power plant varies with lunar cycle, because the moon largely influences the tidal rhythm, whereas our daily power requirement is directly related to solar cycle.

In addition to all the above-mentioned limitations of tidal power, the utilization of tidal energy on small scale has not yet proved economical.

Tidal power plants (TPP) of the world. France was the first country to complete a small pilot TPP in 1957. Another pilot TPP of 90 MW in France near the present Rance TPP was constructed in 1959. The most well-known Rance TPP of 240 MW capacity was commissioned in 1966. This is the only tidal power plant in the world which is totally controlled and monitored by computers. Another important TPP is Kislaya Guba in Russia. In this plant the power house was prefabricated, floated to the site and then sunk into a carefully prepared foundation.

There are large number of schemes under planning and investigations in other countries too, the Chansey Tidal Scheme (France, 15000 MW). Severn Barrage and Solway Firth Scheme (U.K., 1980, MW), White Sea Tidal Scheme (Russia). Tidal Power Scheme in the bay of Fundy (U.S.A.) are the notable TPPs in the world.

Rance Tidal Power Plant. Rance TPP works on single basin, two-way system with pumping. Four kilometres from the mouth of estuary, at a sheltered site protected by rocks and promontories from storms and wave action, the estuary narrows to a width of 750 metres and barrage has been built here. Upstream of the barrage, a large reservoir is created which extends 21 kilometre to the town of Dinnar. The useful storage capacity is 184×10^6 cu. m and has a surface area of 22 square kilometres. The barrage is 163.6 m long, 25 m high and its width at the crest is 38.2 m and at the base is 100 m.

The tides at Rance TPP are among the largest in the world. The equinoctical spring tide is 14.6 m, the ordinary neap tide is 5.5 m and minimum neap tide is 3 m. The maximum rate of natural flow of the barrage site at flood or ebb of the equinoctical spring tide is 18,000 cumecs and the corresponding velocity is 2.5 m/sec.

Twenty-four turbo-generator sets of 10 MW capacity have been installed and these sets are bulb type, reversible, both capable of acting as pump and turbine in either direction. These sets constitute an engineering novelty and cost about 42.8% of the total cost of the scheme. The turbine-cum-pump units of scheme in conjunction with the sluice gates are so controlled and monitored by computers depending on the load demand so as to maximise power generation.

Probable sites for Tidal Power plants on Indian coast. The possible sites identified for TPP in India are Gulf of Cambay, Gulf of Kutch in Gujarat and Sunderban area in West Bengal.

1. **Gulf of Cambay.** The tidal range in the Gulf of Cambay is quite large (10.8 m) which qualifies this estuary for setting TPP. There are two possible sites on western bank : Sonari Creek and Bhavnagar Creek and two sites on eastern bank : Dhadar River outfall and Kim River outfall into the Gulf. The most promising site is Sonari Creek, but in this case, embankments will have to be built for a considerable length along both banks so as to prevent water spreading on both the banks. The probable potential of this scheme is estimated to be 15 MW. The major problem in the Gulf of Cambay is high silt index (5000 ppm) which may cause high erosion of the barrage.

2. **Gulf of Kutch.** The maximum tidal range in this area is 7.5 metre which is less compared with Gulf of Cambay. Lara Creek and Wank Cleek near Navlakhi are considered attractive sites of TPPs. It is estimated that the power potential from these sites will be greater than that of the Gulf of Cambay. Tidal location near Navlakhi will cause little disruption to the shipping traffic. Another added advantage of TPP in this region is that the silt charge is much smaller (1000 ppm) than that in Gulf of Cambay (5,000 ppm).

The survey conducted by the National Institute of Oceanography in the Gulf of Cambay and Kutch has indicated that the water in the Gulf of Kutch contains very little suspended matter compared with Gulf of Cambay. Because of the possibility of silting in the tidal basin due to the settlement of suspended material, the Gulf of Kutch in spite of its having a lower tidal range than the Gulf of Cambay may prove to be a better location for TPP.

3. **Sundarban Area in West Bengal.** The tide range (4.8 m) in this area is less than the Gulf of Cambay and Kutch. Therefore, it is doubted whether the power generated with TPP in this area will be economical or not as the minimum tide range should be 5 m for economical power generation. Even then, it is anticipated that the power of 40 MW can be developed in this area with the present developed technology in this field.

The report submitted by Prof. E.W. Wilson who visited India as a tidal power expert of U.S.A. to the Government of India states that there are 4 possible schemes of TPP in Gulf of Cambay and 5 schemes in the Sundarbans area. He has also recommended an approach to bring in "Blue-Coal" in India.

The projects suggested by him are too large to be attempted for India as the capital cost involved is very large. The Cambay Scheme 1 of Prof. Wilson which can generate 4000 to 7400 MW of power would cost about Rs. 1,925 crores. What appears to be important for India is small schemes at the ideally located sites involving a minimum capital cost.

31.4. WIND POWER PLANTS

Introduction to wind power plant. Among the replenishable sources as an alternative to fossil fuels, wind energy is also in equal race. The power generation on the large scale using the wind as a source of energy is not yet so successful but it is forecasted that the small wind power units will play a vital role in the present condition of shortage. The development of villages is one major phase of the national development and this can be achieved through wind power. The power requirement for irrigation, lighting, small industrial units can be fulfilled with the use of wind energy provided sufficient wind is available.

The winds on earth surface are caused primarily by the unequal heating of the land and water by the sun. The differences in temperature gradients induce the circulation of air from one zone to another. It has been estimated that roughly 10 million MWs of energy are continuously available in the earth's winds. The utilization of some of this energy through various mechanical conversion devices has played a decisive role in the economic development of many countries where winds are strong and steady.

Since the mid-19th century, more than 6 million small wind-mills of less than 1 H.P. each have been built and used in U.S.A. to pump water, generate electricity and perform similar functions in rural and farm communities. Over 150,000 are still in operation. Water pumping wind mills are still used in remote areas of western U.S. However, most of the wind powered electrical generators were displaced as the electric power to the rural area was provided from central power stations through the national grid. Now, because of increasing cost of power, the trend is going to be reversed and again more wind mills be set up to provide the power needs of the rural areas.

Wind energy is one of America's greatest natural resources. According to NASA study, the U.S. has enough harvestable wind to generate 1.28 trillion kWh of electrical energy per year. This is equivalent to about 200 GW (1G = 10^9) or half of the annual output if all fossil-fuelled generating plants were powered by the wind, the nation would save millions of barrels of oil per day and eliminate a major source of air pollution. The U.S. Government has planned for installation of wind turbine generators with a total capacity of 1 GW by 1985, 20 GW by 2000 and 60 GW by 2020. Assuming that each wind turbine-generator has a rated capacity of 1.5 MW—a size which is achievable within present technology – over 600 units were in operation by 1985, more than 13,000 units by 2000 and 40,000 by 2020. A huge wind mill with blade spanning 100 m atop, a 60 m tower will be built by the Boeing Co. under a $ 10 million federal contract. This giant wind mill will be biggest ever built.

Windmills have been used for several centuries in countries like Netherland and Denmark where high velocity wind is available in abundant quantity. Nearly 30,000 house mills capable of producing 100 MW and 3,000 industrial wind mills generating another 100 MW will be in operation in Denmark at the turn of this century. It may be feasible to effectively utilise wind power in every location. In general, open locations with less ground resistance to wind flow are advantageous compared to crowded cities.

Considering these possibilities of developing power from this source, it is also estimated that the power production cost with the present technology available may not compete with the conventional power generating systems. This is because, 1000 of units are required to provide the power output of one nuclear or fossil-fuelled plant. It is neither possible (due to lack of technology and material) nor economical to build individual wind units of higher capacity than 2 MW which is the most desired requirement to reduce the capital cost of the plant.

Keeping this view in mind that gigantic power potential is available free of pollution. Research activities have been already started by most of the countries in the world to develop this source of power. It is optimistically hoped that this source of power will play a significant role in the power generation industry in the next century.

Different types of wind power plants. Windmills had been widely used in Persia, China, Europe and the USA for pumping water and grinding grains. Efficient wind electric generators were later developed in the USA, thousands of which produced electricity for farms and homes.

A windmill converts the K.E. energy of moving air mass into mechanical motion that can be either used directly to run the machine or to turn the generator to produce electricity.

Windmills for water pumping. The windmill used for water pumping is simplest form of using wind energy. The windmills used for pumping are classified as low lift high discharge and high lift low discharge type. The low lift type wind pumps are shown in Fig. 31.10. (*a*) and Fig. 31.10. (*b*). The first type as shown in Fig. 31.10 (*a*) is coupled to Archemedian screw pump which pumps the water from the well into the tank. The second type as shown in Fig. 31.10 (*b*) uses a Persian wheel which is driven through a belt. Such devices can discharge 500 gallons of water per minute.

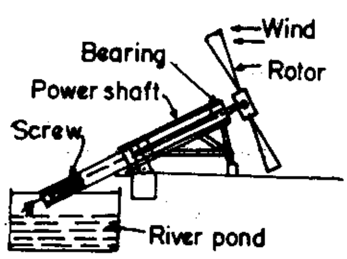


Fig. 31.10 (*a*) Dutch screw type wind pump.

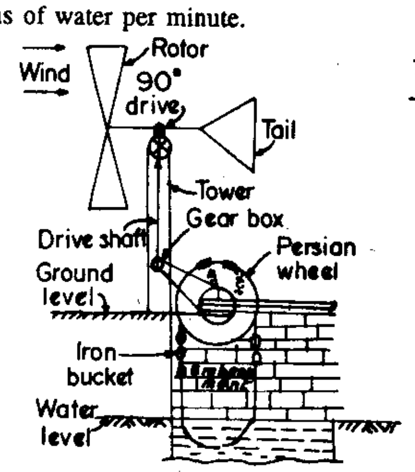


Fig. 31.10 (*b*) Persian wheel type wind pump.

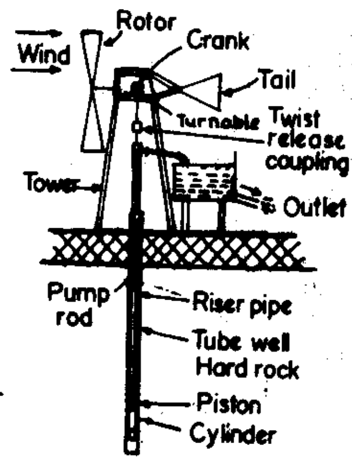


Fig. 31.11. Deep well type wind pump.

High lift wind pumps are widely used in the USA, Europe and Australia to pump water from deep wells. A high lift wind pump is shown in Fig. 31.11. In this arrangement, a reciprocating motion is transferred from a crank attached to a rotor shaft via a plunger rod which goes down the water riser pipe, through the top of the pump cylinder located near the bottom of the tube well and hence to the piston yoke and bucket washer assembly. Valves located in the piston yoke and the foot of the cylinder assure positive lift to the column of water at each upward stroke of the plunger.

The wind mills are generally classified as horizontal axis and vertical axis wind mills. Horizontal axis wind mills are further classified as single-bladed, double-bladed, multibladed and by cycle multibladed type.

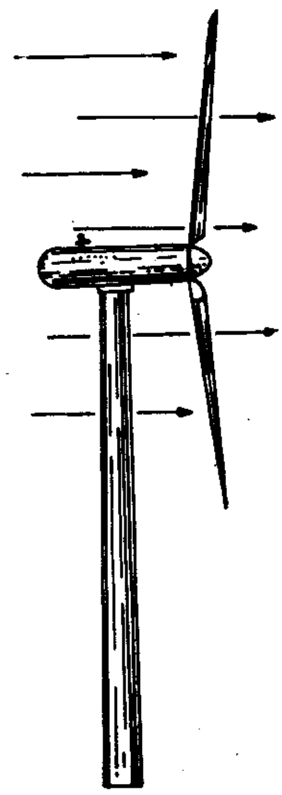
1. **Horizontal Axis Two Blades wind mill.** In this arrangement, rotor drives a generator through a step-up gearbox. The components are mounted on a bed plate which is mounted on a pintle at the top of the tower. The two blade rotor is usually designed to be oriented downwind of the tower. The arrangement of all the components used in horizontal axis wind mill is shown in Fig. 31.12.

When the machine is operating, its rotor blades are continuously flexed by unsteady aerodynamic, gravitational and inertial loads. If the blades are made of metal, flexing reduces their fatigue life. The tower is also subjected to unsteady load and dynamic interactions between the components of the machine-tower system can cause serious damage. For example, if the vibrational modes of the rotor happen to couple with one of the natural mode of vibration of the tower, the system may shake itself to pieces.

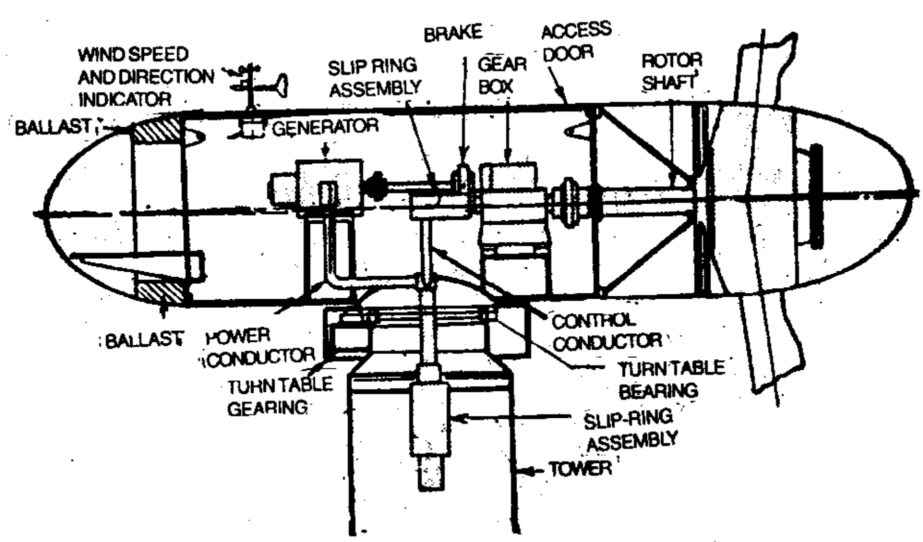
All modern wind-turbine generators have just two rotor blades. Rotors with more than two (3 or 4) blades would have slightly higher power coefficient, but because of the high cost of the blade (10 lakh rupees per blade), rotors, with more than two blades are not cost effective. The most effective way to get more torque out of a rotor is simply to lengthen its blades. The area of a rotor disc increases with the square of its diameter, so a fairly small increase in blade length can result in large torque.

2. **Horizontal Axis-single Blade Wind mill.** If extremely long blades are mounted on rigid hub, large blade-root bending moments can occur due to tower shadow, gravity and sudden shifts in wind directions. On a 200 ft long blade, fatigue load may be enough to cause blade root failure.

To reduce rotor cost, Boeing vertol has proposed the use of single long blade centrifugally balanced by a low cost counter-weight as shown in Fig. 31.13. The relatively simple rotor hub consists of a universal joint between the rotor shaft and blade as shown in Fig. 31.13 (*b*) allowing for blade flapping and pitch motions. This eliminates centrifugal loading on feathering bearings. This type of hub design contains fewer parts and costs less.



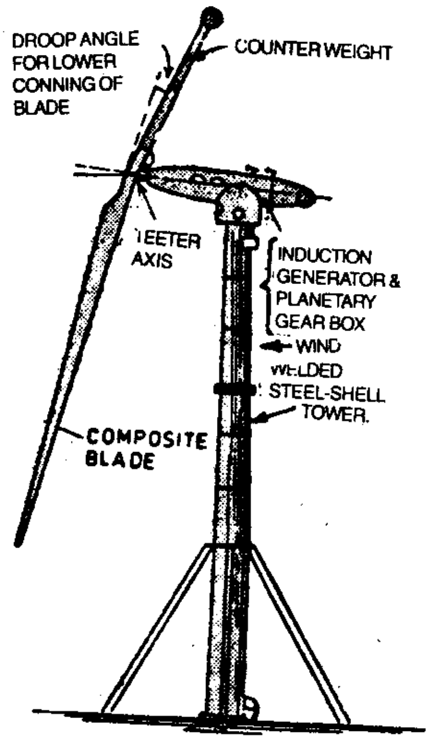
(*a*) Horizontal axis two blades wind mill.



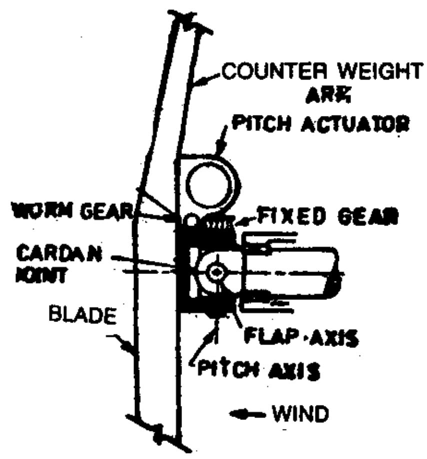
(*b*) Details of transmission system of horizontal axis wind mill.

Fig. 31.12.

3. **Horizontal axis-Bicycle Wheel Wind Mill.** The engineers at the 'University of Oklahomas' school have demonstrated the feasibility of wind mill using arrays of 16 feet diameter, bicycle wheel rotor as shown



(*a*) Horizontal axis single blade wind mill.



(*b*) Details of transmission system of horizontal axis single blade wind mill.

Fig. 31.13.

in Fig. 31.14. This type of wheel has narrow rims and wire spokes. The wire spokes support light weight aluminium blades. The rotors of this design have high strength to weight ratios and have been known to survive hours of free-wheeling operation in 100 mph winds. They have go,d power coefficient, high starting torque and added advantage of simplicity and low cost.

Power can be taken from bicycle-wheel rotors through a belt drive or directly from the rim. The estimated output from 16 ft. diameter rotor is 2 kW at 12 mph wind speed. It is also estimated that an output of a 100 ft. diameter rotor of the same design would be fifty times higher. Such wind mills are yet to be used for practical applications.

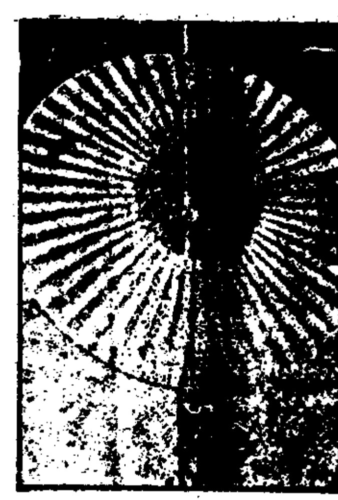


Fig. 31.14. Horizontal axis bicycle wheel type wind mill.

A horizontal shaft design of 1200 kW requires a shaft of 2.5 tons weight, gear-box 22 tons weight, generator of 5.5 tons weight. All these components are to be mounted on 10 m long bed-plate, along with rotor hub bearing and main shaft thrust bearing. The rotor assembly which includes 10 m diameter hub and the hydraulically actuated mechanism for varying blade pitch weighs 18 tons. The total weight of the machine including protective devices and generator is 67 tons. It is necessary to lift this weight to a height of 43 m where the wind velocity is capable to generate electric power. Conventional steel-truss or prestressed concrete towers could be used to support such a heavy weight of machine. The required weight of the steel for the steel tower is 60 tonnes whereas concrete tower weighs 350 tonnes.

4. Vertical axis wind mill. A promising way to reduce the cost of large wind turbine-generator is to design them with rotors that spin on vertical axis. One major advantage of this design is that the rotor blades can accept the wind from any point of the compass. Another added advantage is that the machine can be mounted on the ground eliminating tower structures and lifting of huge weight of the machine assembly as described above.

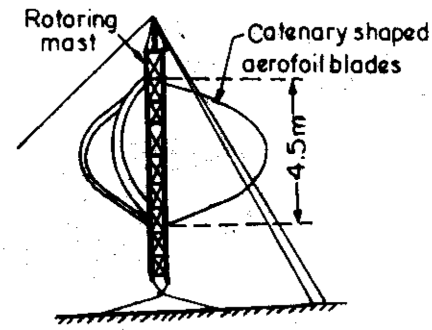


Fig. 31.15. Vertical axis wind mill.

Figure 31.15 shows a vertical-axis machine called the "catenary" or Darriens mill invented by a French Engineer G.J.M. Darriens in 1972. This type of wind mills are already in use in Canada. Darriens rotors have three symmetrical aerofoil blades curved into a shape of skipping rope and both ends of the blades are attached to a vertical shaft. Because the blades are precurved to the shape they would assume when the rotor is shipping at high speed, centrifugal forces cannot bend them further. They are held in tension in their plane of greatest strength.

Canada had built a 80 ft. diameter rotor of Darriens type on an island of the coast of Quebec which generates 200 kW power and it feeds 560,000 kWh of power per year into the Quebec hydrogrid. The estimated capital cost of this design is 50% of the conventional horizontal axis system and gives same power coefficient (0.35) as horizontal axis system of sophisticated design.

5. Flexible Boom wind mill. Steve Sieradzki built a mobile model of windmill which can generate 400 watts. A flexible tower as shown in Fig. 31.16 is the main beauty of this windmill. This can be taken on a car and can be lifted up 3.5 m to generate the power at any place and at any time required (say picnic). The energy generated will be sufficient to cook the food, to cool the beer and to put on the radio and TV sets. Unlike most rigs, it is not mounted on a fixed tower, but on a flexible boom (like hoist) which rises or falls with the wind for safety and ease of maintenance. The cost of the construction except the generator is approximately Rs. 10000.

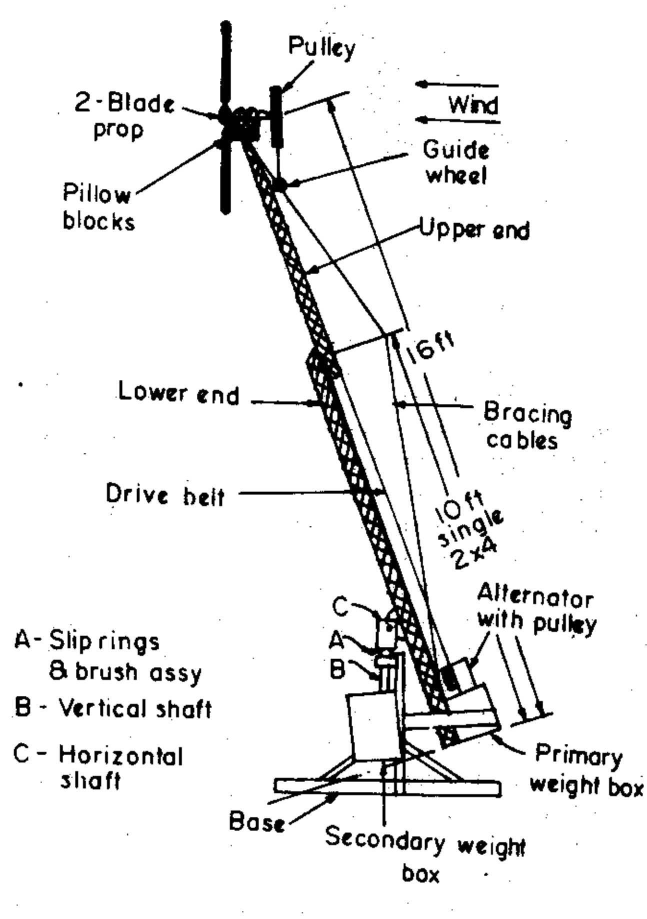


Fig. 31.16. Flexible boom wind mill.

Blade materials. Not a single large wind turbine-generator with metal blades has operated for longer than one year without a blade failure.

For reasons of cost and productivity, composite materials for rotor blades are used. Composite material is a glass filaments in an epoxy matrix. Composites have high strength-to-weight ratio compared with metal blade. They are less sensitive so minor damage would not result in major crack propagation. Another advantage of composite materials is, blades of almost any desired shape or length can be produced by standard types of automatic filament-winding machines.

Fluctuating Load of Wind Power and Methods used to Overcome the Difficulty. The wind power plant does not provide any firm power on account of its random occurrence. This has created many problems in the utilization of wind energy for the generation of electricity. The period of load demand does not coincide with the times at which high wind blows and the intensity of wind blow changes hour to hour and minute to minute. Therefore, some form of shortage is necessary during no demand period.

Commercial power alternates polarity at 60 cycles per second. This is necessary to operate the transformers that step voltage to different values. Extremely precise governors hold the rotating speed of the generator to an exact rpm to keep 60 cycles dead accurate. Wind generators vary in speed instant by instant with the wind. If a standard alternater is used with wind power, then the frequency would vary so badly that appliances would not run. The wind machines produce DC current which cannot be used with AC but can be used to charge the batteries. Even so, this DC varies in amperages as the wind rises and falls ; even a light bulb would brighten and dim if hooked directly to it. Charged through a simple voltage regulator, batteries level out these ups and downs and store electricity for use when there is no wind.

Alternatives to Generate Electricity. The four alternatives suggested by the experts in the field are to overcome the difficulties mentioned above and to utilize the energy economically with full stability depending upon the capacity of the wind mill.

(*a*) **Simple on-site Domestic Unit with Battery Storage (2 to 5 kW).** The arrangement is shown in Fig. 31.17 (*a*). The D.C. output (varying) is passed to batteries through voltage regulator. The DC from the batteries is used for lights, appliances and tools whereas part of the energy from battery is converted into AC and fed to loads as radios, TV sets and motor appliances where AC is prime requirement.

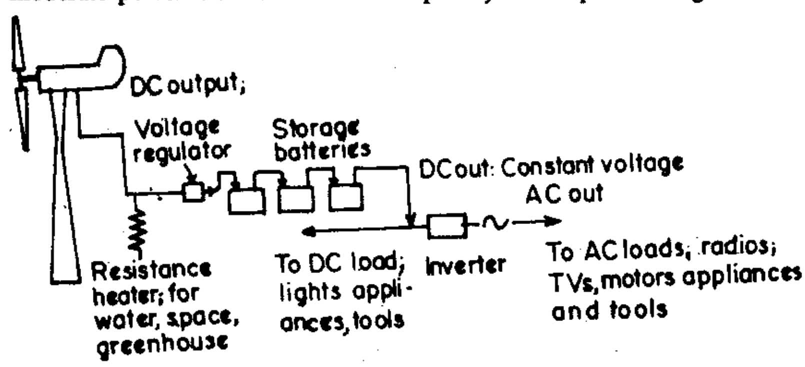
Recently, National Wind Research and Development Centre has developed an aerogenerator at the Institute of Engineering and Rural Technology, Allahabad. The wind turbine of 7 m diameter horizontal axis rotor mounted on a 4-legged 10 m high tower generates 3 kW power at 8 m/s wind velocity. A safety device is also provided to protect the turbine at winds higher than 12 m/s wind speed. The generated energy is stored in lead acid accumulator for continuous power generation. This is converted to 230 V, 50 Hz, single phase by invertors with 85% efficiency.

(*b*) **Simple System with Mechanical and Solar Storage.** The arrangement is shown in Fig. 31.17 (*b*). In this arrangement, a constant frequency-generator is used which generates AC power which is directly fed to the customers. The surplus energy is stored in the form of solar source input and flywheel input. The energy stored in the second form can supply again AC during no sun and no wind periods.

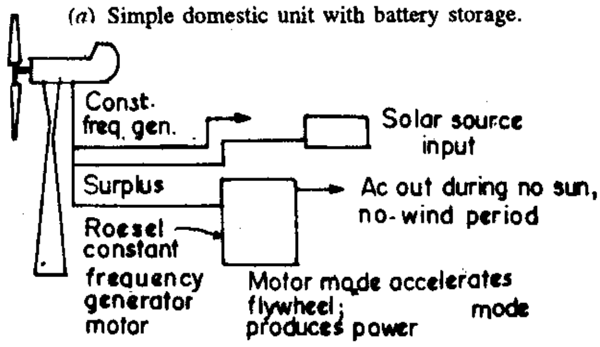
(*c*) **Complex, Intermediate Energy conversion with chemical, Flywheel storage in Medium Power Range.** (50 to 100 kW). The arrangement of this system is shown in Fig. 31.17 (*c*). In this system, the power coming out may be DC or AC with variable voltage and wattage. This fluctuating energy output is used for electrolysis of pure water which generate H_2 and O_2 and these generated gases are storaged as shown in figure. These are further used in fuel cells and gas turbines to generate AC power which can be fed at constant voltage.

(*d*) **Simple, Direct Feed to Main Bus-Bar (MW Range).** In this case, a constant frequency AC output (with a special type of AC generator) is directly fed to the AC mains. An antireserve device is used in the line as shown in Fig. 31.17 (*d*) to overcome the difficulties of low wind conditions.

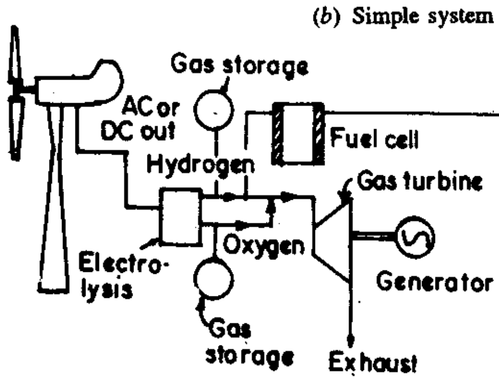
The constant frequency (60-Hz) power desired by utilities as mentioned earlier is to run the rotor at constant speed when the wind velocity keeps changing constantly. This is accomplished by varying the pitch of rotor blades. Operating at constant speed has another significant advantage as stresses can be kept under control and natural resonant frequencies of the system can be controlled during design. Variable-pitch blades are desirable from the stand-point of machine protection. When the wind velocities get dangerously high during wind storm (70 km/hr), the rotor blades can be fully feathered. With blades feathered, the machine can withstand winds of hurricane velocity (200 km/hr). The only disadvantage in varying the pitch of the rotor blades to moderate power are the cost and complexity of the pitch change mechanism.



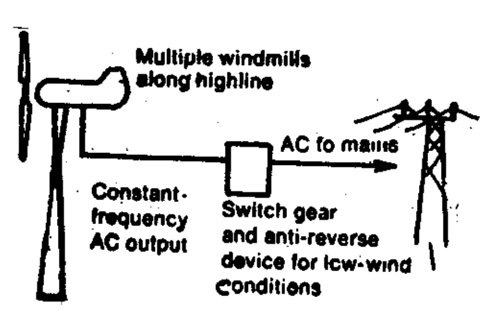
(a) Simple domestic unit with battery storage.



(b) Simple system with mechanical and solar storage.



(c) Complex system with chemical and mechanical storage



(d) Direct feed to the main bus-bar.

Fig. 31.17.

Advantages and Disadvantages of Wind Power

Advantages : 1. The wind energy is free, inexhaustible and does not need transportation.

2. Hydroelectric power projects take several years to complete, the growth of nuclear power has been even slower, and coal fired thermal plants face the problem of long transportation. Wind power plant, on the other hand, does not take long time to construct. Such windmills will be highly desirable and economical to the rural areas which are far remote places from existing grids.

3. Some facts on rainfall in India are relevant. Of the total annual rainfall of 370 million hectare-metre (MHMS), 120 MHMS lost by evaporation, 80 MHMS seep into the ground and 170 MHMS flow into the rivers. Of this last 170 MHMS of water in river flows, 113 MHMS are not available for utilization. It is this unutilised water which often causes floods.

Obviously, proper water managements would demand large energy inputs for controlling drainage and run-off during monsoon. Wind energy can be used for this purpose economically as 80% of the annual rainfall and 60% annual wind energy (in India) are both confined to the monsoon months. This combination definitely warrants a serious consideration for exploiting it.

4. There is strong reason why wind power should be welcomed by grids which have some hydroelectric inputs in India. The water level in the hydel reservoir is at its lowest before the onset of the south-west monsoon. If less water is drawn during the monsoon, a high level could be maintained for longer period. During the monsoon period, wind energy can be used to feed the grid.

Disadvantages : 1. The major disadvantage associated with wind power is that it is not consistent and steady which makes the complications in designing the whole plant.

2. Although there is plenty of energy in wind as mentioned earlier, it is in the words of R.J. Templin of Canada's National Research Council "disappointingly dilute". For this reason, the rotor blades of wind turbine generators must sweep out large areas to produce worthwhile amount of power. Even with large rotor discs, power output is surprisingly low. A 125 ft. diameter rotor develops only 180 H.P. at a wind velocity of 18 mph.

3. The wind is a very hazardous, treacherous and unpredictable commodity. Blowing in strong gusts from varying directions and leaving out of account such phenomena as hurricanes and tornadoes – it can cause tremendous shear stresses which may smash the whole plant within no time. To avoid this, special and costly designs and controls are always required.

4. The power coefficient (ratio of the power actually delivered by the rotor to the power of the wind in the rotor disc) can be 0.593 maximum for aerodynamic reason. The machine developed todate (ERDA's Plum Brook Unit) has power coefficient of 0.4.

5. The suitable material required is one of the major difficulties as mentioned earlier.

6. Among all the disadvantages mentioned above, the cost factor is major which has restricted the development of wind power on large scale for feeding to the existing grid. The estimated cost of wind electricity generation, storage and distribution system is over 1 lakh rupees which may be considered beyond the means of most Indian villages.

With all these disadvantages, this source of power has a bright future as the use of small aerogenerator producing 200 to 500 watts which is sufficient to power a house of one family at a reasonable cost will definitely attract the villagers for the good standard of life.

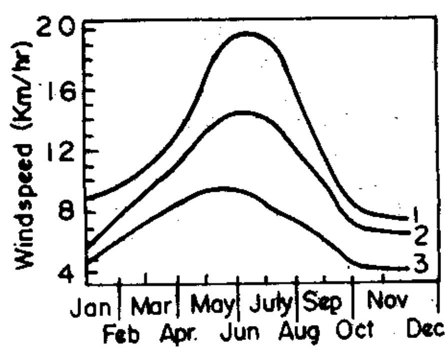
Potential of wind power in India. There is considerable scope of harnessing wind power to meet part of the growing energy demand of rural communities in India.

In India today, the bulk of energy needed to maintain various activities in our villages and to sustain agricultural production comes from human and animal muscle power. Villages form the core of India and if this core is to progress, it needs supplementary inputs of energy either supplied from central power plants or preferably, from within its own environment through the utilization of renewable local resources like wind, sunlight and agricultural wastes.

In spite of steady progress in the implementation of rural electrification schemes, over 2,50,000 villages still remain in darkness (in 1980). Indefinite monsoons, inadequate facilities for transportation of coal to thermal power plants and low load factors contribute to the unfavourable economics of electric distribution to the backward and remote areas of the country.

Unfortunately, the wind is neither strong nor steady in India. Figure 31.18 shows the prevailing wind velocity throughout the year for different states as per the data collected by Meteorological Department of India. It is also obvious that the Gujarat, Rajasthan and south Indian states have better potential for wind power development particularly during March and September as the wind power can be developed economically only above the wind speed of 10 kilometres per hour.

Windmill power can be economically and beneficially used to irrigate the rabi crops (during Sept. and March) as there is rain during this period and simultaneously large wind powers are also available. Since the possibility of getting sufficient wind power at an hour or on a particular day, is highly unreliable, therefore, it would be necessary to pump the water when suitable wind prevails and the water thus collected on a surface for a week may be led into the crops.



1 – Gujarat

2 – Kerala, T.N., Karnataka, A.P., Rajasthan, Orissa

3 – M.P., Bihar, West Bengal, U.P., Punjab.

Fig. 31.18.

REDA (Rajasthan Energy Development Agency) has identified five potential locations at Dhamotar and Sawa in Chittorgarh district, Jaswantgarh in Udaipur district, Bhagwanpura in Ajmer district and Sheopura in Bhilwara district for setting up wind power generators for production of electricity. The wind power will be developed through independent power producers. The REDA has issued global tenders (Sept. 1995) for the projects. The bidders will develop and maintain the power projects and the state Government will make land available and purchase the entire power generated by them.

Despite all the efforts taken by the planning, electricity has not yet reached several isolated areas of the country and nor will reach for several years to come for the reasons mentioned earlier. Such localities could probably use locally available energy sources based on wind, solar and gobar gas. These resources can be combined in an optimum manner to meet the community demands depending on the location.

The wind power has very little chance of serving as independent energy source due to high investments required mainly for energy storage system and higher prevailing interest rates. It is estimated that a technological break-through in energy storage alone can create a favourable situation for its use in India.

Present Wind-Power Position in India

The wind power potential estimated in India is 20000 MW. Extensive wind resource surveys have been done and IX-plan has a budgetary support of Rs. 200 crores for this sector. The capacity planned to be installed during IX-plan is 2000 MW.

The Govt. of Maharashtra plays very important role in developing this source of energy. After constantly monitoring 177 sites in the country over a period of 10-years, 21 sites have been identified for harnessing wind power.

The Govt. of Maharashtra has modified the wind energy policy to attract more private participation in this sector. Govt. has set a target to add 100 MW wind power this year to achive the national target of 1000 MW. The incentives given by the Govt. are sale tax benefits and power sale to MSEB or third party also.

Presently on the Sahyadria Plateau at Vankuswade near Koyna, 250 MW capacity wind turbines are installed and it will go to 500 MW in the coming two years. There are 300 wind mills with a height of 45 meters. The whole Sahyadria Plateau looks like a wind farm. Suzlon, Aircon, Windiya ; Wastas from Germany, Netherland and Denmark, Tata, Bajaj, Bharat Forge, Dhariwal and Ghodapat (31-companies) from India are providing technical nowhow for installing the wind turbines. Many wind turbines are of 250, 350 and 750 kW capacities and many companies are planning 1000 kW capacity wind turbine. Having installed 25 MW of wind power during 1998-99, the Maharashtra state now ranks first in wind generation in the country.

The advantages of wind as a source of energy include, a short installation period, low capital cost and pollution free energy. The wind farms do not cause any ecological imbalance. There is no recurring cost of fuel throughout as wind is free. The generation cost becomes negligible after the payback period.

31.5. SOLAR POWER PLANTS

Introduction to solar power. The sun gives out 3.7×10^{26} watts of energy into space, out of which earth intercepts only 5×10^{-10}th part of the solar energy output. The energy intercepted by earth is equivalent to 1.7×10^{17} watts. The energy emitted by the sun within three munutes is equivalent to the world energy consumption during a year. Most of the solar radiation reaches earth as electromagnetic waves of about 0.25 to 3 μ wavelength. About half of this radiation is visible as light and the rest is infrared which accounts for heat.

Solar radiation is reduced in intensity in the atmosphere by clouds, haze, dust, smog and fog. The intensity of solar energy on sunny day in India is approximately 1.12 kW/m². Integrated daily average on a horizontal surface is 4.5 kWhr/m². The monthly average solar energy in India is 50 kJ/cm²/month as per the record of meteorological department of India. We receive about 600 kJ/cm²/year giving a total incidence on India of approximately 60×10^{16} kWh/year.

The enormous rate of the world's energy consumption can be gauged from the fact that, in the USA, for one food calorie available at the table for human consumption, about 10 calories of industrial energy are consumed in production, processing and distribution. Thus, at the present alarming rate of energy consumption, all the stored energy of the earth will last only for a few decades.

Rapid depletion of fossil fuels and the threat of pollution and of steep rise in oil prices have brought about an upsurge of interest in solar energy. Solar energy has three attractive characteristics—first, the sun is essentially an infinite source of energy ; second, this energy is available to all nations ; and third, this can be harnessed with minimum detrimental effects on the environment.

On the other hand, the practical applications of solar energy are not free from problems. Solar energy is not available at night or during periods when local weather conditions obscure the sun. Moreover, solar energy is diffused in its nature and is at a low potential. Consequently, if solar energy is to be economically competitive, it must be converted to a usable form of energy with maximum effectiveness to reduce the capital costs.

Solar energy is unique source of energy which can be exploited in many different ways as

(1) By direct conversion to a fuel by photosynthesis.

(2) By direct conversion to electricity by photovoltaic.

(3) By conversion to electricity via thermo-electric power system.

Among the above-mentioned three ways of converting solar energy, the thermo-electric system is most promising presently as the technology and economics for the other two systems are still far away from acceptable limits. Therefore, the discussion in the present chapter is restricted to the third mode of conversion.

The following systems are presently in various stages of study, experimentation, design and testing.

(1) Low temperature cycles using flat plate collectors.

(2) Concentrator collectors for medium and high temperature cycle.

(3) Power tower concept.

Low temperature system with flat plate collectors. The flat plate collectors are classified as low temperature collectors because it gives a temperature range of 60 to 100°C with a collection efficiency of 30 to 50%. Figure 31.19 shows the basic components of a flat plate collector. A plate coated with black coke powder is the solar energy absorber and is covered by one or more transparent plates of glass.

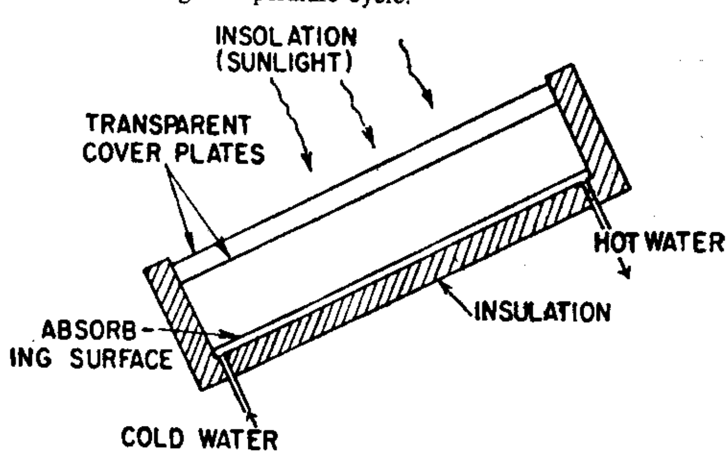


Fig. 31.19. Flat plate collector.

The sides and bottom of the box are insulated. The sunlight passes through the transparent covers and get absorbed by the black surface. Thus, the black plate heats up and in turn heats a fluid flowing under or through it. Usually water is used as the fluid since the temperatures involved are usually below 100°C. It is not possible to generate steam with flat plate collectors so this cannot be directly used to run the prime mover. Therefore, some other organic liquid is used (Freon-114, isobutane) which evaporates at lower temperature and high pressure by absorbing the heat from the heated water.

The vapour formed can be used to run a turbine or engine which may generate power which will be sufficient to light the house or a group of houses in villages and for irrigation purposes. The power generated from this source with individual unit may not play much important part in the national grid but such hundred and thousands of sets will solve the power problems in villages and provide better life to the villagers and improve the irrigation facilities.

A low temperature solar engine, using heated water in the flat-plate collector and butane as a working fluid, developed in France for lift irrigation is shown in Fig. 31.20. It uses a large number of flat plate collectors to heat water up to 70°C and this heated water is used for boiling butane in a heat exchanger (butane boiler). This high pressure butane vapour runs a turbine which operates a hydraulic-pump which pumps the water from the well and supply for irrigation purposes. The butane vapour coming out of turbine at low pressure is condensed with the help of water pumped by the pump as shown in figure. The condensed liquid is again fed to the butane boiler with the help of the pump to repeat the cycle.

For rural applications with small power outputs ; it has the advantage of simplicity which reduces the cost required to concentrate on high temperature and high efficiency collectors. A plant for 10 kW capacity based on this concept has been commissioned in Madras in Jan. 1978 under an Indo-German joint development programme.

Medium temperature systems with concentrator collectors. Medium temperature concentrating collectors such as parabolic cylinders give a temperature range of 260 to 650°C with collection efficiency of 57 – 70%. High temperature collectors such as parabolic concentrators composed of many flat mirrors focussed at the same point gives a temperature range of 550 – 2000°C with an efficiency of 60 – 76%.

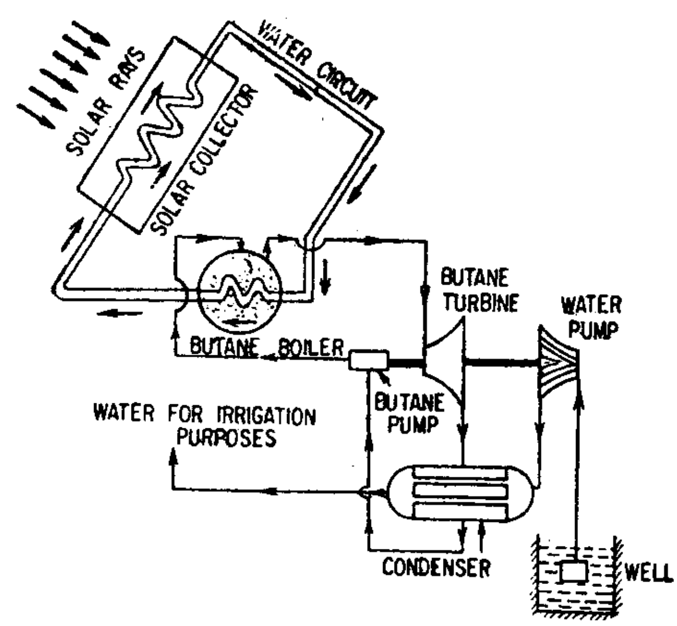


Fig. 31.20. Low temperature solar engine coupled to generator.

To produce high temperatures for power generation, parabolic reflectors are used which give high concentration. However to keep the concentration of solar energy constant all through the day, the reflector must be steered to remain directed towards the sun and heat exchanger must remain located at its focus. A simple parabolic concentrator is shown in Fig. 31.21 which consists of parabolic cylinder, reflector to concentrate sunlight on to a collecting pipe within a pyrex envelope. The pipe can be coated with a selective coating to retard infrared emission and the transparent tube surrounding the pipe can be evacuated to reduce convective heat losses. The reflector is steered during day time to keep sunlight focussed on the collector. This type of concentrator produces much higher temperatures than flat plate collectors.

Large parabolic concentrators are subject to large wind loads and so require a strong supporting structure. For this reason, parabolic concentrators are seldom used for solar energy power generation. An alternative to steering the concentrator is to use auxiliary mirrors. Here large flat plane mirrors are used to track the sun and reflect its rays on to a parabolic concentrator. The cost factor along with the advantages of a fixed working surface make auxiliary mirrors common in modern parabolic solar concentrators.

Tower concept for power generation. The tower concept consists of an array of plane mirrors or heliostats which are individually controlled to reflect radiation from the sun into a boiler mounted on a 500 m high tower as shown in Fig. 31.22. The steam is raised in the boiler which may attain a temperature upto 1000 K. The electricity is generated by passing stream through the turbine coupled to a generator. A 50 kW plant based on this concept has been built and successfully operated in Italy.

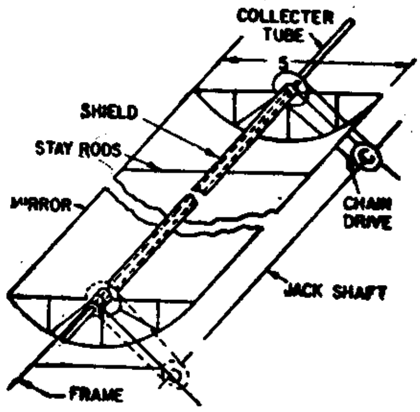


Fig. 31.21. Concentrator type collector.

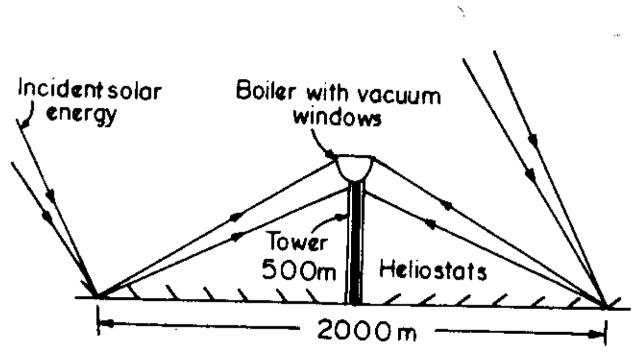


Fig. 31.22. Tower concept type solar power plant.

Another similar power plant system is shown in Fig. 31.23 uses arrays of heliostat guided mirrors to focus sunlight into a cavity type boiler near the ground to produce high temperature, high pressure steam. Sunlight striking the mirrored faces of the heliostat modules is reflected and concentrated in the cavity of the heat exchanger. A 1000 kW plant of this type is operating at Pyrentes in France.

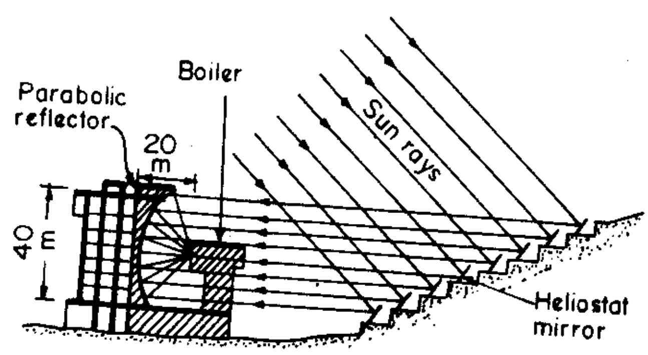


Fig. 31.23. Concentrator type solar power plant.

Solar farms have been proposed using parabolic trough concentrators to focus sunlight into a central pipe surrounded by an evacuated quartz envelope. Heat collected by a fluid flowing through the pipes could be stored at a temperature over 500°C in a molten eutectic salt and used as required (say night time) to produce steam for electric power generation. Another approach is to store the heat in rocks and extract it as required to generate steam on demand.

Satellite solar power station. Direct conversion of solar energy is achieved by solar cells (Photo-voltaic cells). These cells convert the solar radiation, incident on their surface, directly into electrical energy. The solar cell material can either be silicon, cadmium sulphide or gallium arsenide. During the last two decades, solar cells have been widely used in space applications to power satellite systems. These solar cells are of extremely high quality, and, therefore, they cost very high as Rs. 1000 to 1500 per watt. This cost must be reduced by at least 100 times to enable it to compete with conventional sources of electric power generation.

A new concept of placing a large array of solar cells in geosynchronous orbit and transmitting the power to earth via microwaves was first proposed by Dr. Peter Glaser in 1968 and now it is receiving increasing attention as a potential major energy source for the next century. A solar panel made of solar cells and located in the space would receive 15 times as much solar energy it would receive on the ground. Further advantage is that this energy is available continuously round the clock.

With the arrangement of this system, the concentration would reflect the sunlight on light-weight solar cell panel. The two symmetrically arranged collectors would convert solar energy directly into electricity to power micro-wave generators within the transmitting antenna located between the two large collecting panels. The antenna would transmit the micro wave beam to a receiving antenna on the ground as shown in Fig. 31.24. The array is expected to suffer 1% loss of solar cells from micrometeoroid impacts over a 30 years period.

According to Glaser, such stations can be designed to give useful power in the range of 3,000 to 15,000 MW. He further estimated that the size of a solar array for a 5000 MW station would be 22 km^2, the transmitting antenna around 1 km in diameter and receiving antenna about 7 km in diameter.

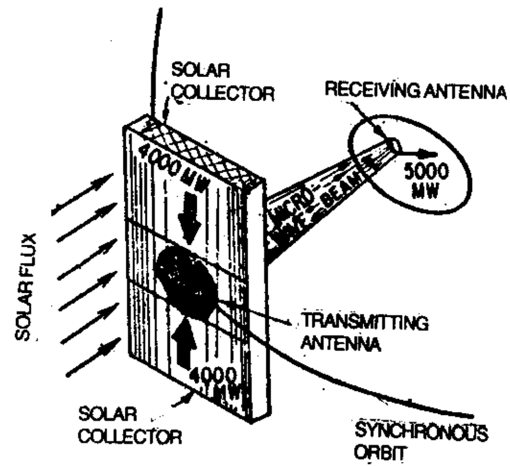


Fig. 31.24. Satellite solar power station.

A big problem, of course, is the multibillion-dollar price tag which would rival the entire lunar landing programme in magnitude. There is also the problem of deciding whether power satellites are the most effective way to meet the predicted energy needs of the 21st century.

A space city 200,000 km up in the space to provide a wide range from of services to man on earth has been planned by a group of 19 top scientists, among them, Dr. Mayur is Indian. Planned to build by the year 2005 at a cost of Rs. 3500 crores, the city would house 10,000 people according to Dr. Gerad O'Nell, head of the project (Princeton University). Solar energy would be converted into electricity up there at 2 to 3% of its cost on earth, crops would be grown in the germ free temperature controlled environment in one-fifth of the time. Electricity would be sent to earth by microwaves as discussed earlier, and information services would undergo a revolution.

Zero Energy House Concept. A house which is totally independent on the power and water supply from the public utilities and which produces the required food in farm around the house with necessary gas for cooking is termed as zero energy house. The arrangement of different equipments is made in the house which generates electricity from the natural sources as sun and wind. It supplies hot water for heating and washing with the use of sun energy. It collects the water during rainy season which will be sufficient for drinking throughout the year. It generates the gas from the waste which will be used for cooking. The farm around the house will be used for the production of food which will be sufficient for one family for a year. The land will be partly irrigated with the help of pump run on solar energy during summer period. Such house will be an ideal one but it is yet to be economically justified.

The pictorial view of the zero energy house suggested by Dr. Mukerjee (Architect in Dubai) is shown in Fig. 31.25, which is based on solar energy

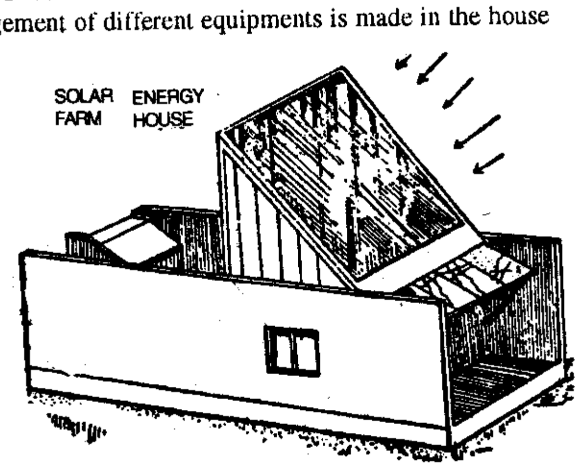


Fig. 31.25. Zero energy house.

utilization and waste recycling. The flat plate solar collector mounted on the roof could be used for obtaining the hot water and to operate solar pump. The hot water will be used for heating the house in winter and washing the clothes whereas the solar pump could be used for irrigation purposes. A recycling system for sewage waste could produce biogas for cooking and other purposes. The area of the prototype one room is estimated to be 40 m^2. The roof, sloped at 45°, will face south which will have the advantage of draining water faster because of the steep slope.

The large glass area of the flat plate collectors covering 20 m^2 is perhaps the only element that will raise the cost of the prototype house, though Mr. Mukerjee visualizes the whole project to be economical in the long run. He expects the rest of the house to cost at the rate of Rs. 3000 per m^2 floor area or even less (cost estimated in 1970) depending on the design specifications.

An experimental zero energy house is constructed at Pondicherry by Government of India, where solar and wind energies will be used to power the house. The construction of the house is already completed and the house will be commissioned soon after fitting the collectors and other required equipments.

Recent Solar Energy Activities in the world concerning Power Generation. The world's biggest solar power plant will start by the end of this year at Dire, a town on the banks of the Niger River in Mali (France) 10 kW capacity plant costing 1 million dollars will be far greater than anything ever before run by the sun. This plant consists of 3200 m^2 of collector. Five collectors will roof the hotel and the farm co-operative and 12 others, looking something like low green houses will rest on the ground. It will pump 8500 m^3 of water per day from Nigar river to irrigate 15 hectares of land in addition to 600 m^3/day of drinking water for 10000 people in Dire from a well of 18 m deep. It will also refrigerate a cold storage for an agricultural co-operative and 40 rooms tourist hotel after sun-down.

The world's first total solar energy house is being constructed in Lakeside, California, by M.J. Sandoval Builders of Escondico which is providing the solar technology to equip the house with electricity, hot water, and space cooling and heating.

By the year 1990 a "sun city" with 4000 housing units and 15000 inhabitants is completed in Brisbane, capital of Australian Federal State of Queensland. The cost is estimated at 250 million dollars. The University of Queensland has constructed a prototype house which can supply itself with electricity.

A solar power plant in Seibersdorf, Australia, is operating from 1979 onwards. The water which acts as a heat carrier and is heated to a 130°C transfers its heat via a heat exchanger to a freon cycle, where a turbine coupled to a generator is operated. It is claimed that the generator has a capacity of 10 kW. 108 parabolic cylindrical mirrors divided into 9 groups with a surface of 3 m^2 each acts as collector. The mirrors are adjusted to follow the sun. The hot water tank which acts as heat store has a capacity of 5 m^3.

A Rankine cycle solar cooling system will be developed over the next three years at the University of Pennsylvania. The Head of the project, Prof. Noam Lior, hopes to develop a solar power vapour compression cycle driven by efficient small steam engines. Steam for the engine will be generated from heating system which uses about 80% solar and 20% fossil energy. The head of the project believes that the hybrid cycle will optimise both solar and fossil fuel to raise the steam instead of organic fluid like freons. Successful operation of the project would reduce operational costs and save significant amounts of fossil fuels.

The country's first solar power tower electric generating plant will be built in the Mojane desert near Barstow according to recent announcement by an official at ERDA. It will be a project of 10 MW generating capacity with an estimated cost of $ 100 million and started in 1978. The plant had been tested for 5 MW capacity.

Cythnos, in the Greek Islands, will convert solar energy directly into electricity using silicon cells. The system generated 175 × 10^3 kWh of energy per year from 1985 onwards, replacing the presently used diesel generators. It is equipped with 144 modules, each made up of 144 monocrystalline silicon wafers

(100 mm in diameter). The system in operation would produce more solar current than required at a time. This surplus solar energy will be stored in a battery with a capacity of 600 kWh.

Recent Solar Activities in India

Rajasthan Government floated a global tender through REDA for the solar power plant to be set up in Jaisalmer district which is close to Pakistan border. The lower limit of capacity is 50 MW and there is no restriction for upper limit. Enron and American Oil Company (AMOCO) are among the six bidders to set up solar project in the range of 100 to 300 MW capacity. The bidding companies have come forward with newest technology in the area of solar energy as solar chimney, amorphous silicon solar panels, solar crystallined silicon cell, the traditional photo-voltaic cell and dish technology.

Enron-AMOCO had shown interest in starting a solar power project in Rajasthan. They are the leaders in the field as they have set up a similar plant in Nevada in USA. They have proposed to set up a plant of 2.8 MW by 1996 and its capacity will be 150 MW by 2007 A.D. Enron has also asked for 30,000 acres of land in Jaisalmar and is ready to sell the power at the rate of Rs. 2.25/kWh.

READ in conjunction with the ministry of non-conventional energy intends to put up a 35 MW solar thermal plant at Mathania, near Jodhpur. The estimated cost of the project is Rs. 400 crores.

31.6. DIRECT ENERGY CONVERSION SYSTEM

1. **Introduction to Direct Energy Conversion.** The efficiencies of all modern thermal power generating systems lie between 35 to 42% as they have to reject large quantities of heat to the environment. In all conventional power plants (steam turbine, gas turbine and diesel power plants), first the thermal energy is converted into mechanical energy which is further used to run the electric generator. The conversion from thermal to mechanical remained poor with all modifications made in the basic thermodynamic cycles. Great strides have been made during the last two decades to eliminate the conversion of thermal energy to mechanical energy and to convert thermal energy directly into electrical energy with a hope to increase the thermodynamic efficiency to 60 to 75%. Such energy conversion systems are known as direct energy conversion systems. Enough success has been achieved in this direction but unfortunately no system has achieved the standard to generate electricity which can be fed directly to the existing grids. It is anticipated that few systems will be available on commercial basis by the end of this century.

The direct energy conversion systems which are in present use are discussed below.

2. **Thermo-Electric Conversion System.** In 1821, the German physicist T.J. Seebeck discovered that in an electric circuit made of two dissimilar conductors, a potential difference sets in if the junctions of these two conductors are held at different temperatures as shown in Fig. 31.26.

The relation between the potential difference developed and difference between the temperatures of the junctions of the dissimilar conductors is given by

$$dE = \alpha \, dT \qquad \text{...(31.1)}$$

where α is called *thermoelectric power* or Seebeck coefficient. The thermoelectric power is usually measured in volts per degree and it is assumed that it is independent of temperature in the present analysis.

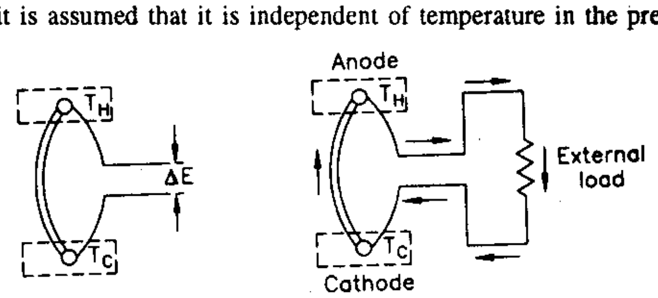


Fig. 31.26. Concept of thermoelectric conversion system.

Integrating equation (31.1)

$$E_h - E_c = \alpha\ (T_h - T_c) \qquad ...(31.2)$$

where the subscripts h and c pertain to hot and cold junctions of the thermoelectric circuit. This thermoelectric effect can be used to generate electricity. A thermocouple generator based on Seebeck effect was first suggested as early as 1885 by the English Physicist Lord Rayleigh. However, this idea was not available for the construction of thermoelectric generators. In 1929, the Soviet physicist A.F. Ioffe pointed out that semiconductor thermoelectrodes had great potential. Further research by his collaborators has fully substantiated his conclusions.

A Peltier effect is always associated with Seebeck effect. It states that if a circuit composed of two dissimilar conductors carrying a current from an external source of electrical energy, one of this junctions of this circuit absorbs heat and other releases heat. The quantity of heat Q absorbed by or released from a junction is proportional to current I.

$$\therefore \qquad Q = \pi I \qquad ...(31.3)$$

where π is known as Peltier coefficient.

The Peltier coefficient π is related to Seebeck coefficient α by the following expression :

$$\pi = \alpha\ T \qquad ...(31.4)$$

Using equations (31.3) and (31.4), we can write

$$Q = \alpha\ IT \qquad ...(31.5)$$

In accordance with Seebeck's law as soon as a closed thermoelectric circuit begins to carry a current, the Peltier effect comes immediately into action and hot junction begins to absorb heat Q_1 from source and cold junction begins to transfer heat Q_2 to sink (environment).

Consider the hot junction is maintained at a temperature T_h and cold junction at temperature T_c, the thermo-electromotive force is given by

$$\Delta E = \alpha\ (T_h - T_c).$$

If this circuit is closed across an external resistance as shown in Fig. 31.26 (*b*), a current I will begin to flow through the circuit, with the hot junction absorbing heat and cold junction rejecting the heat to low temperature source.

$$\therefore \qquad Q_1 = \alpha T_h I \qquad ...(31.6)$$

and

$$Q_2 = \alpha T_c I \qquad ...(31.7)$$

The work performed by the current is given by

$$W = \Delta E.I = \alpha\ (T_h - T_c)\ I \qquad ...(31.8)$$

As the current passes through the internal resistance R of the thermoelectric circuit, it generates heat energy I^2R (joule's loss) and it passes through the elements. Therefore, the network of the circuit will be reduced by an amount equal to Q_J ($Q_J = I^2R$).

$$\therefore \qquad W = W - Q_J = \alpha.\ (T_h - T_c)\ I - Q_J. \qquad ...(31.9)$$

The temperature potential existing between the two ends of thermoelectric circuit causes the flow of heat Q_c from hot junction to cold junction.

Thus, while the thermoelectric generator is in operation, the Peltier heat Q_1 and the heat Q_c transferred by conduction are rejected from the high temperature source. At the same time, half of the joule heat, lost in the thermoelectrodes is returned to the high temperature source. Hence the quantity of heat Q_1' rejected from high temperature source is equal to

$$Q_1' = Q_1 + Q_c - \tfrac{1}{2}\ Q_J \qquad ...(31.10)$$

The heat transferred to the low temperature source includes the Peltier heat Q_2, the heat Q_c conducted from high temperature source and half of the joule heat. Hence

$$Q_2' = Q_2 + Q_c + \tfrac{1}{2} Q_J \qquad ...(31.11)$$

In the above equations, it is assumed that one half of the joules heat Q_J is transferred to hot and other half to the cold junctions.

In accordance with the second law of thermodynamics, the useful work transferred from the thermoelectric generator to an external consumer amounts to :

$$W_n = Q_1' - Q_2' = Q_1 - Q_2 - Q_J \qquad ...(31.12)$$

Substituting the values of Q_1 and Q_2 from equations (31.6) and (31.7)

$$W_n = \alpha\,(T_h - T_c)\, I - Q_J \qquad ...(31.13)$$

which is same given by equation (31.9) as expected.

The power used by the consumer from the circuit is given by

$$W_n = I^2 R \qquad ...(31.14)$$

where R is the electrical resistance of the external load.

The conversion efficiency of the system is given by $= \dfrac{W_n}{Q_1} = \dfrac{I^2 R}{(Q_1 + Q_c - 0.5\, Q_J)}$. ...(31.15)

This expression can be transformed in terms of junction temperatures as

$$\eta = \left(\frac{T_h - T_c}{T_h}\right)\left[\frac{1}{1 + \dfrac{\Omega_r}{\alpha^2}\dfrac{(1+C)^2}{T_h C} + \dfrac{1}{2C}\left(\dfrac{T_h + T_c}{T_h}\right)}\right] \qquad ...(31.16)$$

where Ω_r and α are the properties of thermoelectric materials and $C = (r/R)$ where r is the internal resistance of thermoelectric device and R is the resistance of the external load.

The equation 31.16 shows that the efficiency of this system is always less than Carnot engine working in the temperature range of T_h and T_c. This can be improved by improving the property of the thermoelectric material $(\alpha^2/\Omega r)$ that is known as figure of merit and denoted by Z.

Lot of research has been done to improve the efficiency of the system by increasing the value of Z.

The effect of value of Z on the efficiency is shown in Fig. 31.27 for different values of T_h. Even then the efficiency of this system still is very much low compared with the efficiency of the conventional systems.

3. **Thermoionic Conversion System.** As we have seen the main reason for low thermal efficiency of thermoelectric generators is the conduction heat transfer from the high temperature source to low temperature source. All attempts made to reduce Q_c by increasing the value of Z have so far failed. In this connection, thermionic converters can be regarded as a kind of thermoelectric generators in which the hot and cold "junctions" are separated by a vacuum preventing the transfer of heat by way of conduction. The electric current is maintained in the circuit of the converter by electric emission.

The operational principle of a thermionic converter is based on the ability of heated metals to emit electrons from their surface. As it is known from elementary physics, any metal has free electrons whose emission from the surface of the metal is opposed by a potential barrier equal to the difference between

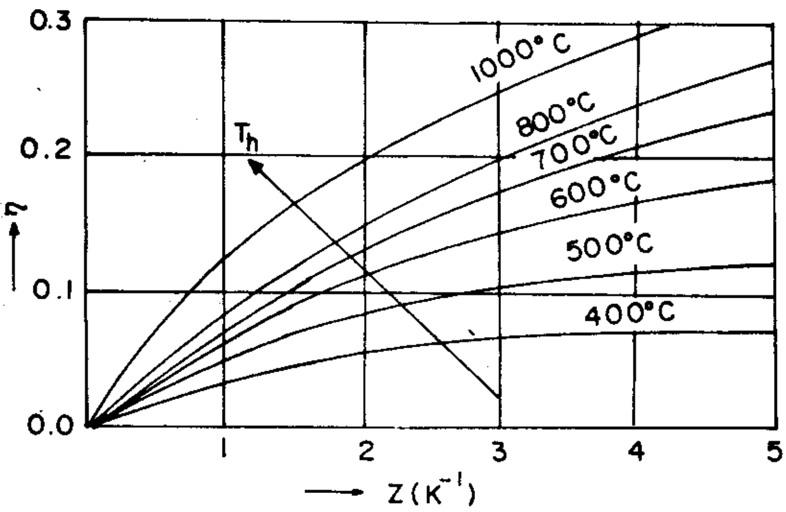


Fig. 31.27. Effect of Z on the efficiency of thermo-electric system.

the energies of an electron outside and inside the metal. In order to overcome this barrier and conduct the electron from the metal into the surroundings, a certain amount of work must be spent referred to as the work function. This differs from substance to substance and it ranges from 1 eV to 10 eV.

The schematic diagram of the thermionic converter is shown in Fig. 31.28 (*a*) and the distribution of potential work functions is shown in Fig. 31.28 (*b*). The two metallic surfaces are separated by a vacuum and maintained at temperatures T_1 and T_2 ($T_1 >> T_2$). As $T_1 >> T_2$, more electrons will be emitted by surface-1 than surface-2 and as a result, the surface-2 will be negatively charged and potential difference will appear between the two plates. If the circuit is completed by inserting an external resistance R, an electric current will flow through the circuit.

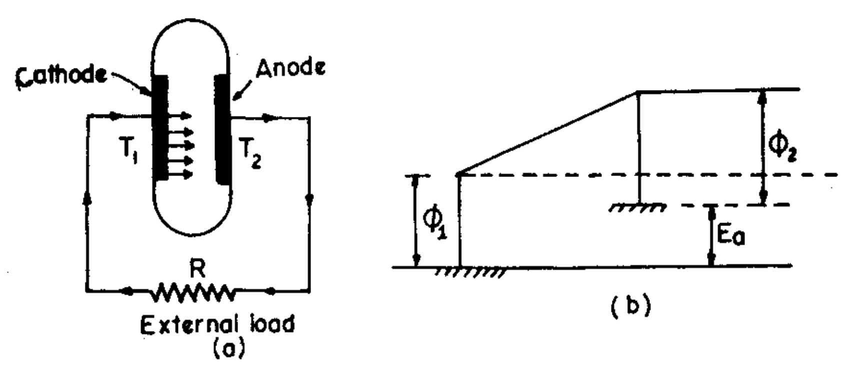


Fig. 31.28. Arrangement of thermionic conversion systems.

The emission of electron from surface-1 is regarded as evaporation of electrons from the surface of emitter and accumulation of electrons on surface-2 is regarded as condensation of electrons.

According to Richardson's equation, the maximum emission of ion current from the surface-1 is given by

$$J_1 = BT_1^2 \, (e)^{-(\phi_1/KT_1)} \qquad \text{...(31.17)}$$

where ϕ_1 is the electron work function, B is constant (120 A/cm^2 – K^2) and K is Boltzmann's constant. For various materials, the work function ϕ varies from 1 to 5 eV.

If the electrons escaping from surface-1 accumulate on surface-2, the problem becomes more difficult. That is because, as the surface-2 becomes more and more negatively charged due to accumulation of electrons, it becomes more difficult for the electrons emitted from surface-1 to reach surface-2, since, in addition to the work function ϕ_1, the electrons have to overcome a space charge barrier due to potential difference between the plates. Let us denote this potential by E_α.

Therefore, the electron emission current from surface-1 considering the space resistance is given by

$$J_1 = BT_1^2 \, (e)^{\{-(\phi_2+E\alpha)/KT_1\}} \quad ...(31.18)$$

Similarly, the electron emission current from surface-2 is given by

$$J_2 = BT_2^2 \, (e)^{(-\phi_2/KT_2)} \quad ...(31.19)$$

It is clear from Fig. 31.28 (*b*) that electfons emitted by the anode have to overcome a space charge barrier equal to ϕ_2.

Therefore, the net current density flow is given by

$$J = J_1 - J_2$$
$$= BT_1^2 \, (e)^{\{-(\phi_2+E\alpha)/KT_1\}} - BT_2^2 (e)^{-(\phi_2/KT)} \quad ...(31.20)$$

The current flow through the circuit of a thermionic converter is given by

$$I = J \, . \, A \quad ...(31.21)$$

and the converter's output is given by

$$W = IE_\alpha \quad ...(31.22)$$

where A is the area of the anode and cathode.

In real thermionic converters, the distribution of potential in the vacuum between the anode and cathode is far from the linear distribution as shown in Fig. 31.28 (*b*) due to the appearance of negative space charge created by the electron cloud present in the vacuum. This results to a smaller current density J and less power output.

The space charge (E_α) significantly diminishes the effectiveness of thermionic converters. Therefore, one of the main problems in their creation is to reduce the space charge in all possible ways. This can be achieved by reducing the size of the gap between the anode and cathode (0.1 m) but it creates the operational difficulties. It should be noted that effective method of suppressing the space charge has not yet been known.

Thermionic converters have recently drawn great attention of scientists due to the development of high temperature nuclear reactors.

The two methods discussed above have little potential as the sources of electric generation to feed to the existing grids as their efficiencies and power capacities are very small. These can only be used for localised purposes where the power requirement is less.

4. **Photovoltaic power system (Solar Cell).** Direct conversion of solar energy is achieved by solar cells. These devices convert sunlight directly to D.C. power without discharging waste products. They need little maintenance and are long lived, their energy source is unlimited, and they can be made from raw materials that are available in huge quantities.

Unfortunately the factors against large scale commercial use of solar cells are at present equally impressive. Compared with most other power sources, the solar cells produce very little power at very high cost. Solar cell arrays now cost Rs. 2000/W. The cost of electricity from such cells also costs Rs. 8 to 15 per kilo watt-hour. Another big minus, solar cell output is not constant and it varies with the time of the day and the weather.

The present reasearch work in USA is devoted to reduce the capital cost to Rs. 20/watt and generating cost to 40 to 60 mills/kWh. (Presently the conventional power systems cost is 10 to 30 mills kWh).

This can be ahieved by

1. Reducing the cost of manufacturing the single crystal silicon cells that are now in the market.

2. Developing techniques for mass producing and increasing the performance of cells made from thin films of materials such as CdS/Cu_2S or amorphous silicon.

Developing high efficiency cells which can be installed are of magnifying optical systems. Lens and reflectors of various configurations are being tried. With concentrators, the cells can operate with lower sunlight intensities or fewer cells can deliver a given amount of power.

If these goals are achieved, it is estimated that 20,000 MW of solar cell power will be available in the year 2000 in U.S.A.

Solar cell materials. Solar cells made of single crystal silicon are commonly used as its theoretical highest efficiency is 24%. But actual efficiency for commercially available cells is now 10 to 12%. Raw material for the cell is high purity silicon of the type used in commercial semiconductor devices. The cost of the material is now about Rs. 5000/kg. A major research goal is to reduce this cost to Rs. 700/kg. Single crystal silicon cell arrays are virtually hand made with resulting high labour costs. After a single large crystal is grown from a bath of molten material, the resulting silicon cylinder is sawed into thin wafers. The wafers are polished and chemically treated. After leads are attached, they are fitted to arrays.

Gallium arsenide is another solar cell materials which is likely to replace silicon. Cells of this material may achieve efficiencies of 20 to 25%. Gallium arsenide cells can retain efficiency at much higher temperatures than silicon and, therefore, are a good contender for systems which operate with concentrators that focus the sun's energy. Silicon cells can function at 10 sun amplification whereas Gallium arsenide cells can operate at 1000 sun amplification.

Silicon cell life now ranges from 5 to 8 years. The problem is not the cell material but it lies with the leads and protective encapsulation. Thermal cycling, air contaminants, lead corrode glass encapsulation, material deterioration and blocking light to the cell are some major problems. Research has been also directed to find out the materials less sensitive to contaminants. The life of the cells which would be used in terrestrial power plants is estimated to lie between 50 and 100 years as the question of cell contamination does not arise.

Storing electric energy, a major problem for all electric power systems, is particularly critical for solar cell systems. Ways must be found to eliminate solar-cell output fluctuations caused by the day/night cycle and weather shifts. Batteries are the only near term solution. Despite the energy loss, which can be as high as 50% with present batteries, solar cell systems with lead-acid storage batteries are finding some applications as pumping water to a reservoir for later use is now commonly practised with hydroelectric power plants, and this same scheme might be adopted to solar power.

Solar cells were chosen for supplying power in space because nothing else would do the job and cost was not a major problem. The chief applications of the solar cells are in remote, unmanned devices where utility power is unavailable and batteries are impractical. Marine buoys, road signs and remote telephones now operate by solar power. One of the largest existing solar cell installations powers a mountain-top radio station with 3 kW is in USA.

It is predicted that for the near future, one may see small solar cell ground power plants capable of delivering a few MWs. supplying power for such installations as shopping centres, small industries or housing complexes.

For the distant future, NASA is studying a plan to supply terrestrial power from massive solar cell satellites as mentioned earlier. Arrays several square kilometres in area would send solar-cell-generated power to earth in form of micro wave. Ground stations would convert the microwaves to AC power for the national grid. Planners now see that as a remote future possibility at best.

Wafer-Thin Solar Cells

The solar cells thinner than human hair can be moulded to fit any surface have been created by American researchers. The cells, developed at the University of Florida, can be produced far more cheaply than existing semi-conducting solar panels. Prof. Sheng Li says, the end result of the present research will allow third world countries affordable access to solar energy, using solar panels 100 times lighter and thinner than at present.

The present solar cells made of semi-conducting material are expensive and panels are also heavy and difficult to move. The new panels are made by placing an extremely thin film of new material, "*Copper indium diselenide*" (CIS) on a base surface of plastic or glass. The CIS is 2 to 3μ thick making it thinner than human hair. The layer can be placed on almost any base material and moulded to fit it during production, allowing solar cells to be fitted almost any where. The present efficiency of these cells is 10% and expected to increase to 18%.

It is proved that the above mentioned technology works but it is difficult to make it in large volumes presently. The thin-film cells have a far more complex chemical structure than basic solar cells in use today.

The team working on the project hopes that if it can workout a suitable manufacturing process, the new cells will be far easier and cheaper to mass produce than semi-conductor rich cells.

The market for solar cell was just over $ 1 billion in 1988 and is experiencing a growth of 15 to 20% a year as, more and more companies realise, it is viable way to produce energy without causing pollution.

5. **Fuel cells.** Fuel cells are efficient and quiet, operate on a veriety of hydrocarbon fuels, and produces almost no objectionable emissions. The concept has been proven in numerous small scale applications. The recent infusion of power cost from fossile fuels may convert this promising device into a major source of electric power generation.

The Electric Power Research Institute and United Technologies Corporation recently agreed to construct a 4.8 MW capacity plant, with an investment of 25 million dollars. It is predicted that if the fuel cell clears a number of technical hurdles and proves financially viable, it could contribute 20,000 MW power to the US grid. This would save $ 1 billion in power generating costs and 100 million barrels of fuel oil annually.

Working of fuel cell. The fuel cell represents one of the successful ways of bypassing the heat cycle and converting the chemical energy of fuels directly into electricity. It may be defined as an electrochemical device for the continuous conversion of the portion of the free energy change in a chemical reaction to electrical energy. It is distinguished from a battery in that it operates with continuous replenishment of the fuel and the oxidant at active electrode areas and does not require recharging.

The arrangement of fuel cell components is shown in Fig. 31.29.

The working of the fuel cell is explained here with reference to the Hydrogen-Oxygen fuel cell using aqueous electrolyte. The fuel cell consists of an anode, a cathode, and an electrolyte. Hydrogen fuel is fed into the anode side of the cell. Positive H_2 ions move from the anode-side and enter the electrolyte through porous cell walls. The anode is left with a negative charge. Air is fed into the cathode side. O_2 ions enter the electrolyte leaving the cathode with a positive charge. Excess anode electrons flow to the cathode creating a current flow. H_2 and O_2 ions combine in the electrolyte to form water which leaves the cell as steam.

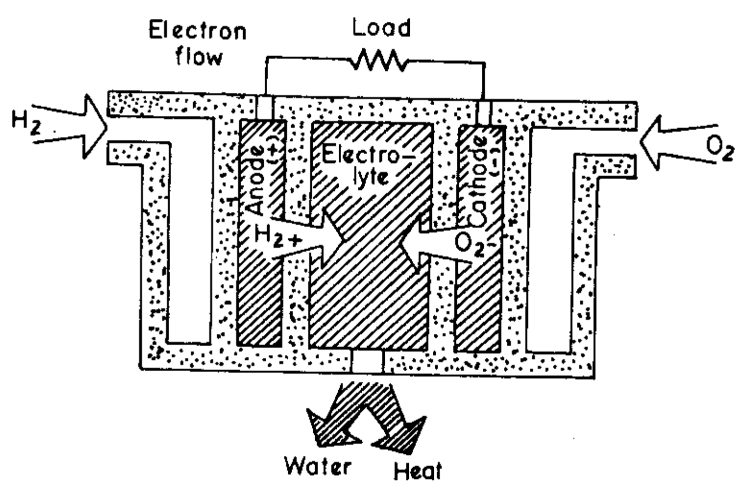


Fig. 31.29.

The reactions taking place at the electrodes are given below.

(1) Hydrogen electrode (anode)

$$2H_2 = 4H$$
$$4H + 4\overline{OH} = 4H_2O + 4e$$

(2) Oxygen electrode (cathode)

$$O_2 = 2O$$
$$2O + 2H_2O + 4e = 4\overline{OH}$$

(3) Overall cell reaction

$$2H_2 + O_2 = 2H_2O$$

The above reactions indicate that H_2 molecules break up into H atoms at the anode and they combine with OH ion to form water and free electron at anode. The formed free electrons travel to the cathode, through the external circuit as shown in Fig. 31.29. At the cathode, O_2 molecules break up into two O_2 atoms and these atoms combine with the four electrons arriving by the external circuit and two molecules of water (out of 4 molecules produced at the anode to form 4 $\overline{OH}$ ions.) The $\overline{OH}$ ions migrate towards the anode and are consumed there. The electrolyte remains invariant. It is prime requirement that the composition of electrolyte should not change as the cell operates. The major difficulty experienced in the design of fuel cell is to obtain sufficient fuel-electrode-electrolyte reaction sites in a given volume. There are many other types of cells as ion exchange membrane cell, direct and indirect oxidation fuel cells, molten carbonate fuel cells and many others. It is not possible to give the details of all the cells in the present text.

The present research work done in this area is to increase the efficiencies or modify the design of the three major components of fuel cell power plant to increase the overall efficiency of the system. The arrangement of the fuel cell power plant which will be used in future is shown in Fig. 31.30.

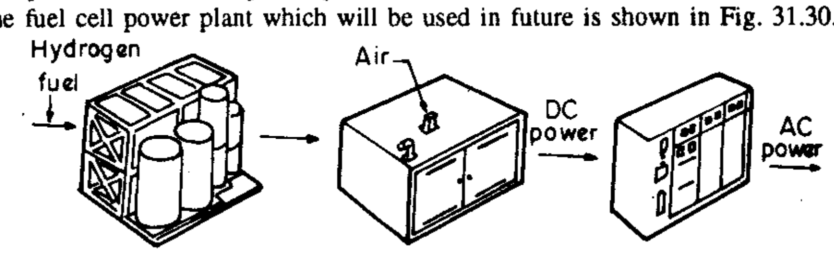


Fig. 31.30.

(*a*) **Processor.** It converts a hydrocarbon fuel into a hydrogen rich gas that can be accepted by the cell. One of the main problems regarding fuel-cell development is finding a way to convert low grade fuel into H_2 rich gas that has a minimum of impurities. Material such as sulphur in fuel can adversely affect the fuel processor. Presently, the research is directed to find a cell electrolyte that is more tolerant of fuel impurities. It is predicted that the developments in both processor and electrolyte will allow the use of standard fuel oil as fuel in the 1990s and ultimately residual oil and coal gas.

Hydrogen generation processes from the petrochemical industry are being adopted to the fuel cell's needs. Steam reforming is another successful fuel processing technique now commonly used with phosphoric-acid electrolyte fuel cells. The life of such a processor is presently limited to about 15,000 hrs.

(*b*) **Electrolyte.** Initial work has been done chiefly with phosphoric acid which has an operating temperature of 160°C to 200°C. This electrolyte can give fuel cell efficiency of 50%.

Next generation of fuel cells will use molten carbonate electrolyte. Operating at a temperature of 500 to 750°C, this material is more tolerant of fuel impurities and gives a fuel cell efficiency of 40 to 50%. Life for existing molten carbonate fuel cells is about 10,000 hours. A 50,000 hr. life is expected to be achieved by 2000.

Solid oxide may be electrolyte of the third generation of fuel cells, which are probably 20 years away. This electrolyte will give a fuel efficiency of 60% or better and will be compatible with many of the coal gasification processes.

(*c*) **Inverter.** The last element in the fuel cell power generation system which converts DC to AC does not yet exist commercially in the sizes needed for large scale power conversion. To date, inverters with a capacity of 20 to 40 kW are in limited use and some capable of 1.8 MW have been tested. Major research work is presently directed to develop the inverters of high capacity.

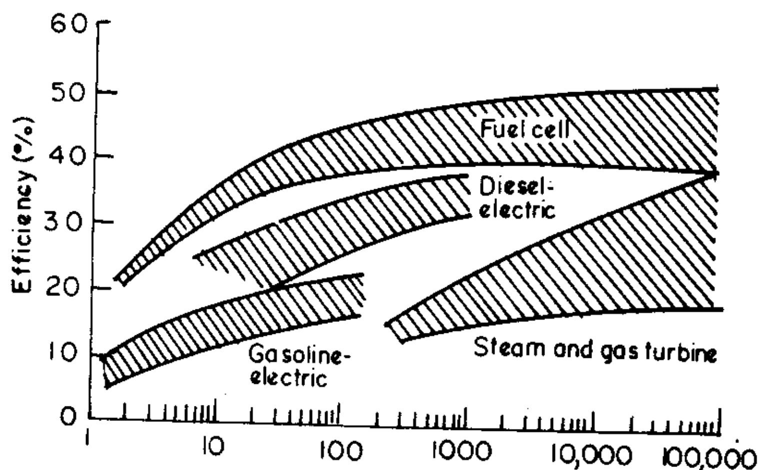


Fig. 31.31.

The predicted performance of fuel cell power plant is shown in Fig. 31.31 relative to three other generation methods.

Advantages of fuel cells. (1) The fuel cell converts its fuel directly to electric power. Pollutant levels range from 1/10 to 1/50,000 of those produced by a fossil fuel power plant as there is no combustion.

(2) No cooling water is needed so it can be located at any desired place.

(3) As it does not make noise, it can be readily accepted in residential areas.

(4) The fuel cell takes little time to go into operation.

(5) It would be an ideal reserve power source within large conventional power plants to handle peak or emergency loads.

(6) There is no efficiency penalty for part-load operation. Efficiency remains constant from 100% to 25% of rated load.

(7) There is no maximum or minimum size for a fuel cell power plant. Individual fuel cells are joined to form stacks. The stacks are joined to form power modules. The number of modules can be tailored to power plant requirements.

(8) The land requirement is considerably less compared with conventional power plants.

(9) Possibly the greatest advantage of the fuel cell is its high operating efficiency. Present-day fuel cell efficiency is 38% and it is expected to reach to 60% before the end of this century.

(10) Fuel cell power plants may further cut generation costs by eliminating or reducing line losses. Fuel cell power plant in rural areas or highly congested residential areas would eliminate the need for long lines to bring in power from remote generating stations.

(11) A wide variety of fuels can be used with the fuel cell. Although, presently limited to using substances that produce pure H_2 rich gas, the cell may one day be able to operate on fuels derived from low grade shale oils.

(12) The maintenance charges are low as there are no moving parts and outages are also less.

(13) Fuel cells have an overload capacity of 50 to 100% for a short duration.

(14) The weight and volume of the fuel cell is considerably low compared to other energy sources.

(15) In $H_2 - O_2$ cell, the reaction product is water which is portable.

6. **Magneto Hydrodynamic System (MHD).** This direct energy conversion system is most promising among all till described. It is in race with a faster development and it is forecast that this system will definitely play a vital role in the electric generation system.

As its name implies, magnetohydrodynamics (MHD) is concerned with the flow of a conducting fluid in the presence of magnetic and electric field. The fluid may be gas at elevated temperature or liquid like sodium or potassium.

Principle of working. The basic principle of MHD is just similar to dynamo except that the solid conductor (cu) of high electrical conductivity is replaced by a gas with comparatively low value of electrical conductivity.

Copper is a good conductor of electricity but gases are not good conductors. Their electrons are tied up as electrically neutral particles. But there is a way to turn a gas into a conductor, dislodging its electrons by ionizing. If the gas is heated to a high temperature, it gets converted into plasma and plasma is conductor of electricity. The level of ionization in plasma decides its conductivity. Everything now seems rosy. The designers of high efficiency MHD generator have to shoot up some hot gas through a magnetic field and spout into electrodes in the gas path.

But, unfortunately, things are not so simple as they look. To achieve even a millionth of the conductivity of copper, the plasma must be heated to some tens of thousands of degrees which is enough to make the whole generator-varnish in a puff of vapour. Fortunately an MHD generator can operate usefully at ionization levels well below this and the ionization can be simulated at lower temperature by 'seeding' the gas with small quantities of alkali metals such as cesium or potassium. Even though temperatures of 3000 to 5000°C must be maintained and this level of temperature also makes a practical MHD generator difficult to design.

The principal components of the system are shown in Fig. 31.32. A temperature plasma is passed through a static magnetic field at near sonic velocity. The induced currents are collected by suitably placed electrodes and simplest system would carry direct current to the external load. When the gas flows across a magnetic field, a current is induced and a force tending to slow down the motion of the gas is experienced. Therefore, MHD generator ducts are made diverging to accommodate the same mass of gas at smaller velocity. Both

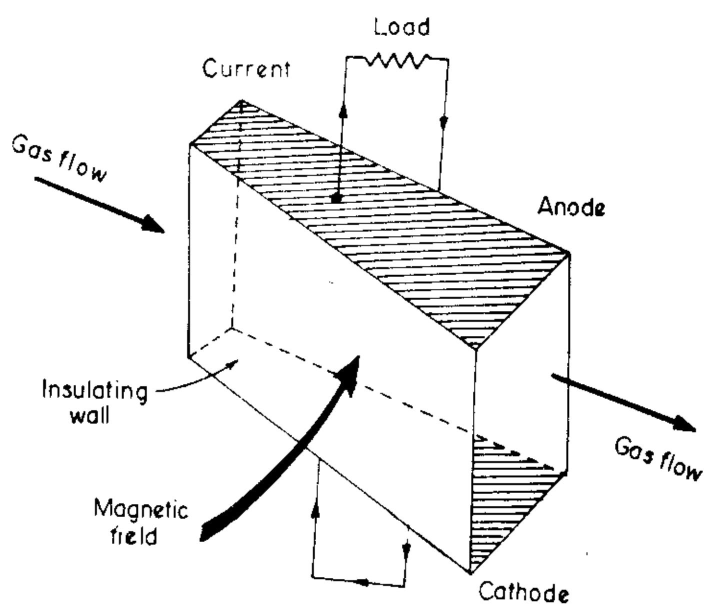


Fig. 31.32.

insulators and electrodes must withstand the high temperature (3000°C) for months together as well as must have good resistance to thermal shock, ablation and chemical attack. Partially cooled hafnia or thoria may make a possible insulator and a doped zirconia a possible electrode.

Analysis. An induced emf depends on the velocity of plasma and magnetic field strength. If V is the velocity of the plasma and B is the strength of magnetic field at right angles to it, the emf. E, generated normal to the flow and normal to the magnetic field is given by

$$E = V \cdot B.$$

This is the well-known Hall effect observed in solids and liquids, and also in gases under suitable conditions.

The power output per unit volume of such a system is given by

$$P(\text{power}) = \sigma\, V^2\, B^2 \,.\, K(1 - K)$$

where σ is the electrical conductivity of the gas and K is the load factor.

The load factor (K) is a measure of the emf E due to the flow of current through the circuit and is given by

$$K = \frac{\text{Closed circuit voltage}}{\text{Open circuit voltage}}$$

The recommended value of K is $\frac{1}{2}$, so the power output P per unit volume is given by

$$P = \frac{\sigma\, V^2 \,.\, B^2}{4}$$

The above expression indicates that the power output increases directly with the conductivity of the gas and squares of the flow velocity and magnetic field strength.

Problems encountered in Design. 1. Sufficient high temperature for required thermal ionisation (2000 to 3000°C) can be sustained by known refractory materials. A more practical method of reducing the required temperature is to seed the gas and use higher field super-conductors. With these modifications, it has been estimated that a reduction in temperature of as much as 700°C can be expected.

2. Seed material potassium attacks insulating materials and makes them conducting.

3. Electrode materials are chemically eroded by combustion gases.

4. The major problem forced by this generator is the economics. Although the overall thermal efficiency is 60% against 40% for conventional thermal plant, additional investment in the magnet, generator, duct, compressors, scrubbers, seed recovery plant and DC to AC converters may increase the plant cost and it may be much higher than conventional plant.

5.1. TYPES OF MHD GENERATORS

The MHD generators are classified into three groups as (1) Open cycle MHD (2) Closed cycle MHD and (3) Liquid Metal-closed cycle MHD.

Open cycle MHD. The arrangement of the system is shown in Fig. 31.33. In this system, the gaseous fuel (produced from coal gasification plant) is supplied to the combustion chamber where it is burnt in the presence of high pressure air (5 bar). The gases coming out at high temperature (2000°C) after seeding is passed through MHD at a velocity of 700 to 800 m/sec. The interaction between the flowing plasma and magnetic field produces electricity. The gas leaving the MHD still contains large amount of heat and seed material. It is essential to recover the seed material and the heat from the gases to economise the plant. The heat of the hot gases coming out from MHD is used for steam generation before it is exhausted to atmosphere. The generated steam is used in conventional steam power plants. The power from the generator coupled to steam turbine and power from MHD after converting from DC to AC is fed to the grid.

This arrangement gives overall efficiency of the MHD steam plant higher than that of the conventional steam plant. It is estimated that the thermal efficiency of MHD steam plant of 500 MW capacity would be around 50% and efficiencies upto 60% are expected in future.

An MHD generator of 16 MW capacity based on open cycle plant developed by Arnold, Engineering Development Centre in Jullahome used to supply the power to a town of 5000 population. The largest generator

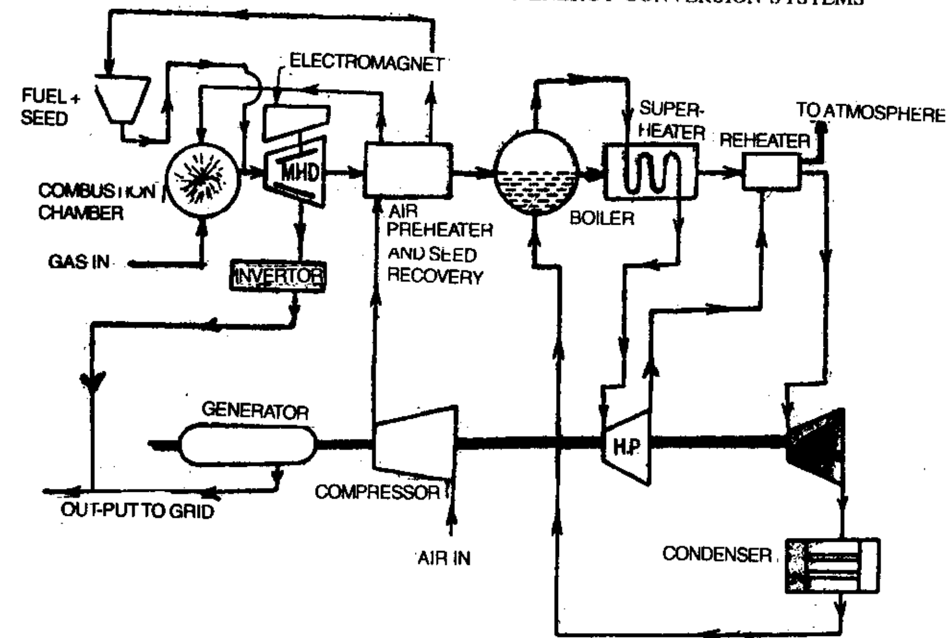


Fig. 31.33. Open cycle MHD generator coupled with steam plant using heat from fossil fuel.

todate working on open cycle without steam cycle is the American AVCO company machine of 40 MW gross capacity.

5.2. CLOSED CYCLE MHD

The closed cycle MHD using rare gases as working fluid is also developed and it is the most promising system among all. Generally, the heat source used is gas cooled nuclear reactor. The arrangement of the system is shown in Fig. 31.34. The high temperature gas which is coming out of MHD is also used for

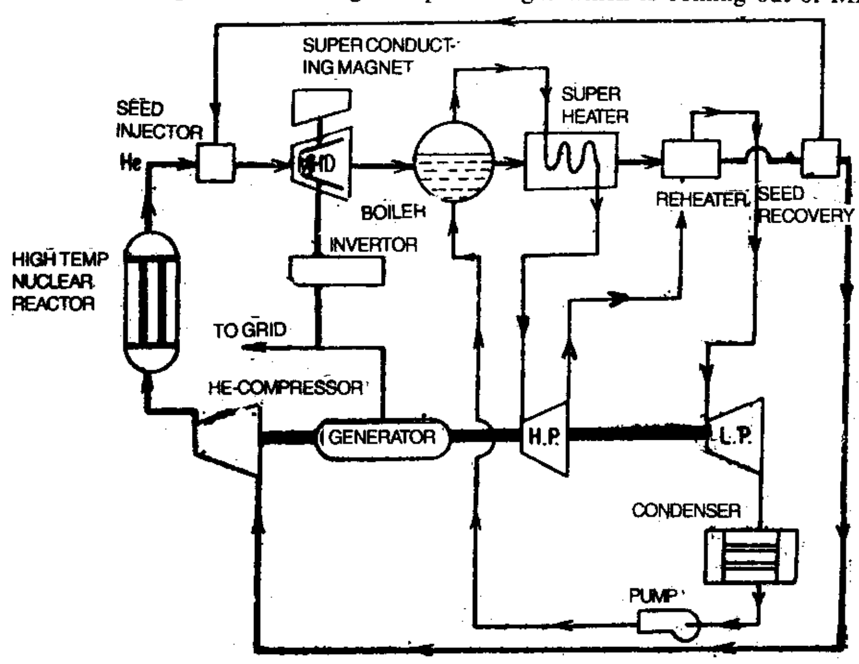


Fig. 31.34. Closed cycle MHD generator coupled with steam plant using heat from breeder reactor.

steam generator similar to open gas system. The working of the system is exactly similar to open cycle MHD except the working fluid is continuously circulated in the cycle instead of exhausting to the atmosphere. As there is no loss of working fluid, this can be chosen for its better heat transfer and electrical properties. The noble gases (helium, neon, argon, krypton and xenon) with their low electron affinity are most suitable. Neon is considered most suitable but helium is commonly used as it is readily available compared with neon. With the use of noble gas as working fluid, it also becomes economical to use calcium instead of potassium as seed material (calcium has 3.89 ev ionization potential against 4.34 ev for potassium).

The closed cycle MHD retains the seeding element, gives pollution free operation and saves exhaust heat.

5.3. CLOSED CYCLE MHD WITH LIQUID METAL

The use of liquid metals instead of gas as working fluid is proposed since they have high electrical conductivity (about 10^6 times that of plasma). Such a generator could be linked with high thermal flux source such as breeder reactors. The major difficulty in such a system is the production of liquid flow with high kinetic energy from a thermal power source.

A liquid metal MHD cycle is shown in Fig. 31.35. The liquid potassium coming out of breeder reactor at high temperature is passed through a nozzle to increase its velocity before passing to MHD generator. The vapours formed due to nozzle action are separated in the separator and condensed and pumped back to the reactor as shown in figure. The liquid potassium coming out of MHD generator is passed through the conventional steam power plant to use its remaining heat and then pump back to the reactor. The cycle is more simple but there are lot of constructional and operational difficulties. Therefore, this concept will take enough time to implement for practical purposes.

Advantages of MHD System. 1. The MHD-steam power plant gives considerable high thermal efficiency (50-55%) and still higher thermal efficiencies (60-65%) are expected in future.

2. It has great advantage over conventional one as it can be started and put on the line within few seconds. It provides almost instantaneous standby power. It can be used most economically as peak load plant.

As it works at higher thermal efficiency, (open cycle), the amounts of pollutants thrown into the air are reduced. As a happy bonus, the recovery method also gets rid of the exhaust gases as NO_x, SO_2 and flyash all of them contaminate the air.

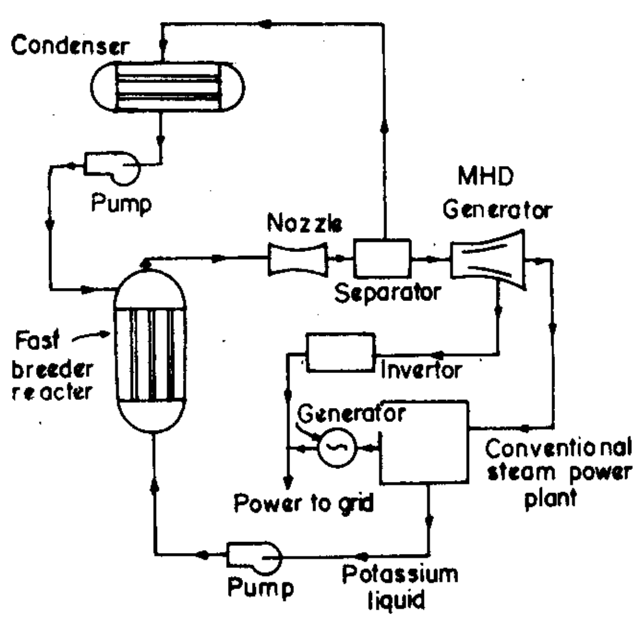


Fig. 31.35. Closed cycle MHD generator using liquid metal as working fluid coupled with steam plant.

3. The closed cycle system produces power, free of pollution.

4. The size of the plant (m^2/kW) is considerably smaller than conventional fossil fuel plants. A size of shoe-box could generate millions of watts with the help of extremely compact super-conducting magnet. A shoe-box size MHD will be sufficient to illuminate a whole battlefield from a plane.

The open cycle technology is in an advanced stage today and is near commercial utilization. It is hoped that by the year 2000, large MHD power plants will be in operation in various countries of the world.

The purpose of the present chapter is just to introduce the readers to the new power sources which will be used in near future to overcome present threat of disappearing of the fossil fuels. It is not possible to give constructional and design details as well as analysis and economics involved as the present text is intended to help the undergraduate students in the subject of power plant engineering.

The threat of disappearing of the fossil fuels within few decades compelled the human beings to search for new energy sources which will last for a longer time. Extensive research is going on in different countries throughout the world to find out the new sources to replace the conventional fossil one.

The content of the present chapter is devoted to the study of non-conventional sources and direct energy conversion systems. The chapter discussion indicates that there is enough in the nature to be tapped for power generation and human society need not worry very much. No doubt, the available energy sources are tremendous but the major hurdle lies in the conversion of these sources for potential use.

With the present research and development programmes, the non-conventional power sources may play an important role in the power industry in near future. The development of breeder, tapping solar energy through satellite power stations, Fusion and MHD generators are expected to come out with great success to help the present crisis of power.

All power sources discussed play a minor role presently and their use on the vast scale is yet to be confirmed as majority of them are in childhood stage. Their role is still doubtful as they have not yet left the four walls of the laboratory.

Man being optimistic should not leave the hopes with any of these sources as the technology took the man to moon which was a dream just a 3-decades back, the same technology will help the human being to survive from the present crisis of power shortage.

EXERCISES

31.1. Which are the non-conventional sources of energy and why they are seriously thought throughout the world ?

31.2. What are the different sources of geothermal energy ?

31.3. Discuss different systems used for generating the power using geothermal energy.

31.4. What are the specific environmental effects if the geothermal source of energy is used for power generation ?

31.5. What factors are considered for selecting a suitable site for tidal power plants ?

31.6. Differentiate with neat sketches the difference between single basin and double basin systems.

31.7. List out the advantages of Tidal power plants over the conventional hydel power plants.

31.8. What are the basic requirements for locating a wind power plant ? Which factors affect the size of a wind power plant ?

31.9. Discuss the advantages and disadvantages of horizontal and vertical axis wind mills with neat sketches.

31.10. Explain the working of a vertical axis wind mill mentioning the specific arrangement of the blades.

31.11. What control arrangements are used with a wind mill when the speed of wind exceeds the rated speed ? Illustrate your answer with a neat sketch.

31.12. What methods are used to overcome the fluctuating power generation of a wind mill ? Discuss their merits and demerits.

31.13. What is the importance of solar power in the present energy crisis in the world ?

31.14. Describe the basic principle of photovoltaic and list out its merits over the other systems. What are the main hurdles in the development of this mode of power generation ?

31.15. Draw a neat diagram of a power generating system illustrating the use of flat plate collector as a source of energy and R-113 as a working fluid of the system.
What are the main advantages of using flat plate collector and R-113 as working fluid for such systems ?

31.16. What do you understand by *Zero Energy House* ?

31.17. What are the advantages and disadvantages of direct energy conversion systems over the conventional power generation systems ?

31.18. Explain the basic principle of thermo-electric power generation.
Define the figure of merit and show its effect on the efficiency of the thermoelectric power plant taking source temperature as a parameter.

31.19. What is the basic difference between thermo-electric and thermionic conversion systems ? Explain the working of thermionic system with neat sketch and explain the effects of those factors which control the power generation capacity.

31.20. Explain the working of a fuel cell and list out its advantages over other non-conventional systems of power generation.

31.21. What do you understand by MHD ? Explain the working principle of MHD with neat sketches.

31.22. Explain the difference between open and closed cycle MHD systems and discuss their relative merits.

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