10

Diesel Engine Power Plants

10.1 INTRODUCTION

Diesel engine power plant is suitable for small and medium outputs. It is used as central power station for smaller power supplies and as a standby plants to hydro-electric power plants and steam power plants for starting under emergency conditions.

The diesel power plants are commonly used where fuel prices or reliability of supply favour oil over coal, where water supply is limited, where loads are relatively small, and where electric line service is unavailable or is available at too high rates. Diesel power plants in common use have capacities up to about 5 MW.

The diesel power plants are cheap in first cost and can be started quickly and brought into service. It can burn a fairly wide range of fuels. Manufacturing periods of diesel plants are short and, therefore can be rapidly extended to keep pace with load growth by adding generating units of suitable sizes.

Thus, diesel power plants provide the most economic means of generating electricity on small scale in remote areas.

10.2 FIELDS OF APPLICATION (USE)

Important applications of diesel power plants are as under:

1. They are quite suitable for mobile power generation and are widely used in transportation systems consisting of rail roads, ships, automobiles and aeroplanes.
2. They can be used for electrical power generation in capacities from 100 to 5000 H.P.
3. They can be used as standby power plants.

4. They can be used as peak load plants for some other types of power plants.
5. Industrial concerns where power requirement are small say of the order of 500 kW, diesel power plants become more economical due to their higher overall efficiency.
6. Diesel power plant is quite suitable at places where
   (i) Fuel prices or reliability of fuel supply favour oil over coal.
   (ii) Water supply is limited.
   (iii) Loads are relatively small.
   (iv) Power from other power plants such as steam, hydropower plants etc. is not available or is available at too high rates.
7. These are used for emergency purposes and normally remain idle but are used where power interruption mean serious problems, *e.g.*, in key industrial processes, hospitals (especially for operating rooms), tunnel lighting, banks etc.
8. These are used to supply power in small townships in the absence/failure of main grid.
9. To supply power in remote areas.
10. These are used to run the auxiliaries for starting the large plants.
11. These are used for small commercial purposes and public utilities, *e.g.,* cinema halls, commercial complexes, offices etc. when normal electric supply fails.

10.3 ADVANTAGES OF DIESEL ENGINE PLANTS

Both diesel engine and steam engine are basically heat engines but in diesel engine the combustion of fuel takes place inside the engine cylinder whereas the combustion of fuel in steam engine takes place outside the cylinder. In diesel engine the pressure and temperature inside the cylinder is very high and therefore, construction material with better resistance are required

The various advantages of diesel engine over steam engine are as follow :

1. Diesel engine has higher efficiency ranging from 35 to 40% whereas the efficiency of steam engine lies between 15 to 20%.
2. Diesel engine has low weight to power ratio due to its compact design.
3. Diesel engines are usually single acting and hence there is no necessity of stuffing box glands for piston rod.
4. To start a steam engine firstly the boiler is to be fired and steam to be raised whereas diesel engine can be quickly started.
5. Plant layout is simple.
6. In this plant handling of fuel is easier. Small storage space for fuel is required, there is no refuse to be disposed off and oil needed can be easily transported.
7. In can be located near load centre.
8. A diesel engine extracts more useful work from each heat unit than other types or I.C. engines. Therefore, it becomes an attractive prime mover wherever first cost is written off and operating cost is important.
9. The plant can be quickly started and can pick up load in very short time.
10. There are no standby losses.
11. It does not require large amount of water for cooling.
12. The plant is smaller in size than steam power plant for the same capacity.

13. The operation of the plant is easy and less labour is needed to operate the plant.
14. Compared to steam power plant using steam turbine, the life of diesel power plant is longer.
15. Diesel engines operate at higher thermal efficiency as compared to steam power plants.

Disadvantages

1. Diesel oil is costly.
2. The plant does not work satisfactorily under overload conditions for longer times.
3. Lubrication cost is high.
4. The capacity of plant is limited.
5. High operating and maintenance cost.
6. Unhygienic emissions.
7. Noise pollution.

10.4 COMPARISON OF GAS TURBINE WITH DIESEL ENGINES

Advantages of gas turbines over I.C. engines are as follows :

(i) Gas turbines has lesser number of parts.

(ii) Mechanical losses in gas turbines are less because in gas turbine the single rotating units consists of a compressor and a turbine together with a few main bearings compared to complicated reciprocating mechanism with its valve gear arrangement which are the prime source of losses due to friction. Further oil and fuel supply pumps are not used thus reducing mechanical losses.

(iii) The life of gas turbine is longer than I.C. engine.

(iv) It is easier to carry out heat transfer process.

(v) Gas turbine has large power to weight ratio. This reduces cost of gas turbine. This makes it more suitable prime mover in mobile power units particularly in air crafts.

(vi) Gas turbine is simple in construction.

(vii) The gas turbine is reliable in operation because balancing of rotating masses both static and dynamic, can be very accurately done and unlike reciprocating engines the torsional vibration effects due to combustion load changes and inertia effects are absent due to the steady flow nature that renders continuous effect on the rotor blades of compressor and turbine.

Further the absence of valve and valve gears is another reason for quiet running of gas turbines.

(viii) In gas turbine the parts that are to be lubricated are few in numbers.

(ix) Maintenance is easier.

10.5 SITE SELECTION

While selecting the site for diesel engine power plant the following factors should be considered.

1. *Distance from load centre.* The plant should be located near the load centre. This will minimize the cost of transmission lines, the maintenance and power losses through them.

2. *Availability of water.* Water should be available in sufficient quantity at the site selected.

3. *Foundation conditions.* Sub-soil conditions should be such that a foundation at a reasonable depth should be capable of providing a strong support to the engine.

4. *Fuel transporation.* The site selected should be near to the source of fuel supply so that transportation charges are low.

5. *Access to site.* The site selected should have road and rail transporation facilities.

The site selected should be away from the town so that the smoke and other gases coming out of the chimneys do not effect the inhabitants.

10.6 CLASSIFICATION OF I.C. ENGINES

Internal combustion engines can be classified according to the following criteria :

1. **Method of Ignition :** According to method of ignition. I.C. engines are of two types :

(a) Spark Ignition engines (S.I. Engines).

(b) Compression Ignition engines (C.I. Engines).

In spark ignition engines such as in petrol engines, the air fuel mixture is compressed and ignited at the end of compression stroke by an electric spark. The compression ratio in such engines varies between 5 to 8. In compression ignition engines or diesel engines as they are often called air admitted into the cylinder is compressed. The compression ratio being nearly 12 to 20. The temperature of air becomes very high due to compression. At or near to the end of compression stroke fuel is injected through an injection nozzle into the hot air in the engine cylinder. Due to high temperature of air the fuel oil burns. The burning gases expand do work on the piston and hence on the load coupled to the engine. The gases are then exhausted from the cylinder and this cycle is repeated. In I.C. engines the charge of fuel and air in correct proportions should be supplied and combustion products should be exhausted from the cylinder when air expansion is complete in order that fresh charge may enter the cylinder.

Usually well designed compression ignition engines show greater efficiency than spark ignition engines because of their higher compression ratios. Part load efficiency of compression ignition engines is higher.

2. **Cycle of Operation.** According to cycle of operation I.C. engines are of two types :
   (a) Two-stroke cycle engine.
   (b) Four-stroke cycle engine.

The relative advantages and disadvantages of these engines are as follows :

(i) The working or power stroke is complete in two revolutions of the crank shaft in four stroke cycle engine whereas in two-stroke cycle engine the working stroke is completed in one revolution. Thus the power obtained from a two-stroke engine should be twice that of power obtained from four-stroke engine but due to charge loss and power needed to drive scavenge compressor the actual power obtained from a two-stroke engine is 50 to 60% more than four-stroke engine. As one working stroke is completed for every revolution of crankshaft the turning moment on crankshaft is more uniform in case of two stroke engine and, therefore, a lighter flywheel serves the purpose.

(ii) Two-stroke engine is lighter is weight and requires less space than a four-stroke engine of the same power. This makes it suitable for marine engines.

(iii) In two stroke engine the power needed to overcome frictional resistance during suction and exhaust stroke is saved.

(iv) In a two-stroke engine there is more noise and wear.

(v) The consumption of lubricating oil is greater in a two-stroke engine due to large amount of heat generated.

(vi) Two-stroke engine is simple and its maintenance cost is low.

(vii) Scavenging is better in four-stroke engine.

(viii) In two-stroke engine the exhaust port remains open for a very short time which results in incomplete scavenging and thus dilution of fresh charge.

(ix) Construction of combustion chamber is better and simple in two-stroke engine.

3. **Number of Cylinders.** According to number of cylinders, they are classified as single cylinder and multi-cylinder engines.

Internal combustion engines may have more than one cylinders such as 4, 6, 8 etc.

For any given engine the number of cylinders are fixed by the output desired, space available and balancing and torque considerations. With increase in number of cylinders the weight, cost, space occupied and number of working parts of the engine increase. The size of an engine is designated by the cylinder diameter (bore) stated first followed by the length of stroke.

4. **Arrangement of Cylinders.** According to the arrangement of cylinders the I.C. engines may be classified as Inlined engines, V-engines, radial engines, horizontal engines etc. (Fig. 10.1).

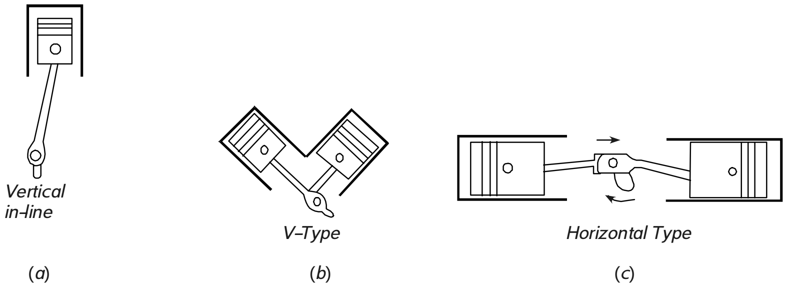


Fig. 10.1. Arrangement of cylinders.

5. **Speed.** According to speed I.C. engines may be classified as follows :
   (i) Low speed (upto 350 R.P.M.)
   (ii) Medium speed (From 350 top 1000 R.P.M.)
   (iii) High speed (Above 1000 R.P.M.)

6. **Method of Cooling the Cylinder.** According to the method of cooling the cylinder IC engines are of two types :
   (i) Air cooled.
   (ii) Water cooled.

7. **Purpose.** According to the purpose for which to be used. These are classified as stationary, mobile, locomotive, marine etc.

10.7 WORKING PRINCIPLE AND DESCRIPTION OF DIESEL ENGINES

Diesel engine is an internal combustion engine in which fuel is ignited by injecting it into air that has been heated to a high temperature by rapid compression. The diesel engines, therefore, are also called compression-ignition engines. This is a heat engine, as it converts heat partially into mechanical work and operates on an approximation to the idealized 'diesel cycle' in which combustion of the fuel (*i.e.* heat addition) occurs at a constant pressure.

Fig. 10.2 shows various parts of an I.C. engine. The cylinder is the main body of the engine where in direct combustion of fuel takes place. The cylinder is stationary and the piston reciprocates inside it. For cooling the cylinder, the fins are provided in small engines, where as water circulation jackets are provided for cooling the cylinders of large engines. The connecting rod transmits the force given by the piston to the crank, causing it to turn and thus convert the reciprocating motion of the piston into rotary motion of the crankshaft.

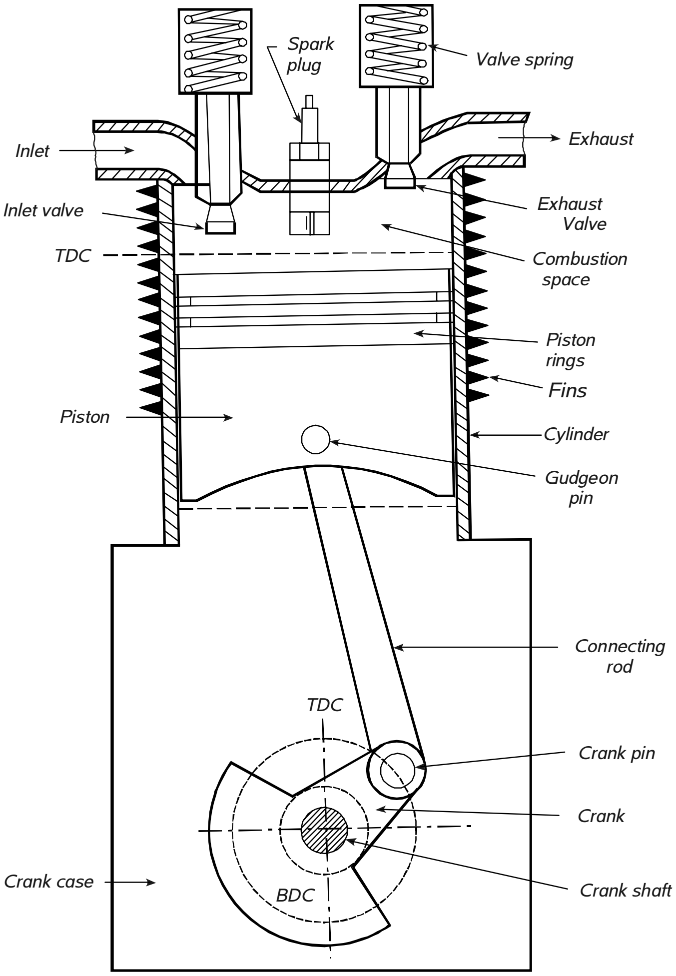


Fig. 10.2. Main parts of a single cylinder spark ignition engine.

The valves may be provided

(*i*) at the top, or (*ii*) on the side of the engine cylinder.

Fig. 10.3 shows a typical overhead valve assembly.

The cam lifts the push rod through cam follower and the push rod actuates the rocker arm lever at one end. The other end of the rocker arm then gets depressed and that opens the valve. The valve returns to its seating by the spring after the cam has rotated. The valve stem moves in a valve guide acts as a bearing.

On a four stroke engine, the inlet and exhaust valves operate once per cycle, i.e., in two revolutions of the crankshaft. Consequently, the cam shaft is driven by the crankshaft at exactly half its rotational speed.

In a diesel engine, the engine cylinder is closed at top by means of a cover known as cylinder head which contains inlet and exhaust valves. The fuel injector is also fitted in this cover. The two valves are kept closed with the help of springs and are opened mechanically by means of a rocker arms, and cams which are fitted on cam shaft. This cam shaft is driven by the crankshaft through a gear.

The crank case and different moving parts are supported by a frame. The lower part of the crank case contains oil for lubricating purposes. Multi-cylinder engines have a cylinder block which contains cylinder bores and openings for the valves. To protect the cylinder block from wearing, cylinder liners are provided. It also contain the passage for the flow of cooling water. The cylinder head is fitted over the cylinder block with studs and nuts.

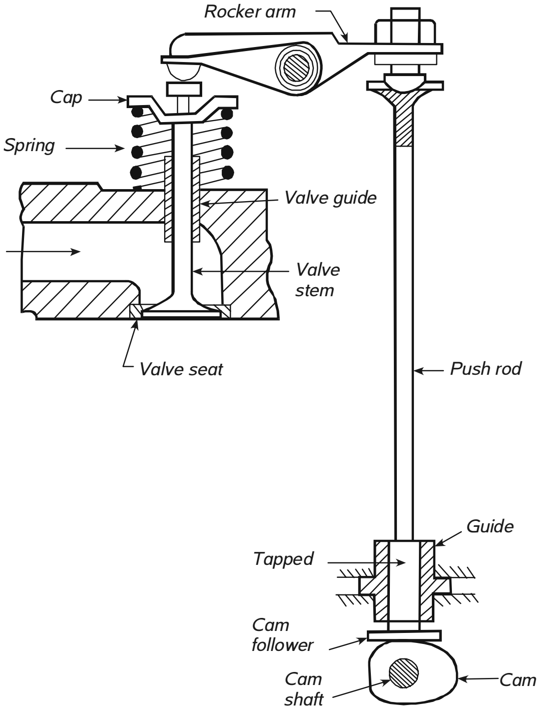


Fig. 10.3. Overhead valve mechanism.

The pistons, gas tight movable cylindrical discs, move up and down in the cylinder against which the hot gases act to cause the rotation of crank shaft through connecting rod. The small end of the connecting rod is fitted to the piston with the help of a pin (known as gudgeon pin). Piston rings are provided on the piston to prevent the leakage of hot high pressure gases. The connecting rod transmits the reciprocating motion of the piston and causes the crank to rotate. The other important components of a diesel engine will be discussed in this chapter in detail.

In diesel engines the intake is air alone and the fuel is injected at high pressure in the form of fine droplets near the end of compression. The normal compression ratios are in the range of 14 to 17. The air fuel ratio used in C.I. engines lie between 18 and 25 as against 14 in S.I. (spark ignition) engines. Therefore C.I. engines are bigger and heavier for the same power output than S.I. engine.

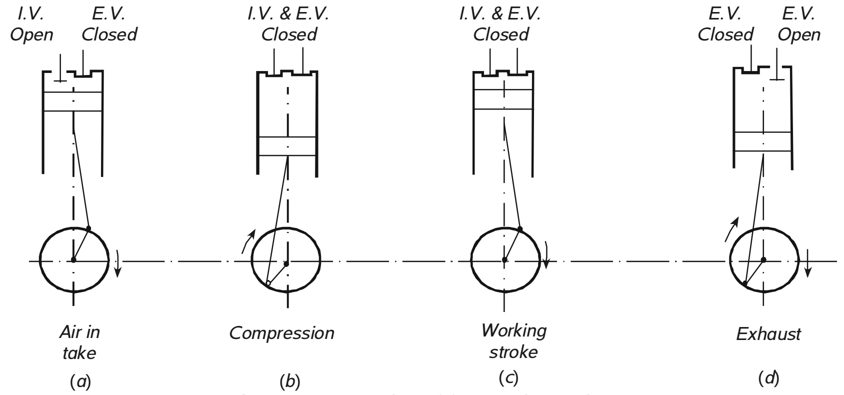
In C.I. (diesel) engine combustion occurs by the high temperature produced by the compression of air *i.e.* it is an auto ignition. Each minute droplet of fuel as it enters the highly heated air of engine cylinder is quickly surrounded by an envelope of its own vapour and this in turn and an appreciable internal is inflamed at the surface of envelope.

10.8 FOUR-STROKE DIESEL ENGINES

In four-stroke diesel engine the four operations are completed in two revolutions of crankshaft. The various operations are as follows :

(i) *Suction Stroke.* In this stroke inlet valve (I.V.) remains open [Fig. 10.4 (*a*)] and exhaust valve (E.V.) remains closed. The descending piston draws in a fresh charge of air to fill the cylinder with it. The air taken in during suction stroke is nearly at atmospheric pressure. Line *ab* in the indicator diagram (Fig. 10.5) represents this stroke.

(ii) *Compression Stroke.* In this stroke I.V. and E.V. remain closed. Piston moves up and the air sucked in during suction stroke is compressed to high pressure and temperature (nearly 3.5 kg/cm^2 and 600°C). This stroke is represented by the line *bc* in indicator diagram [Fig. 10.4(*b*)].



(*a*) (*b*) (*c*) (*d*)

Fig. 10.4. Operation of four-stroke engine.

(iii) *Expansion Stroke.* During the stroke Fig. 10.4(*c*), I.V. and E.V. remain closed. Injection of fuel through the fuel valve starts just before the beginning of this stroke. Due to compression the temperature of air inside the cylinder becomes high enough to ignite the fuel as soon as it is injected. The fuel is admitted into the cylinder gradually in such a way that fuel burns at constant pressure. In Fig. 10.5, *cd* represents the fuel burning operation. The ignited mixture of air and fuel expands and forces the piston downward. Expansion stroke is represented by *de* in Fig. 10.5.

(iv) *Exhaust Stroke.* This stroke is represented by *ea* in Fig. 10.5. In this stroke E.V. remains open, Fig. 10.4 (*d*) and the rising piston forces the burnt gases out of cylinder.

The exhaust of gases takes place at a pressure little above the atmospheric pressure because of restricted area of exhaust passages which do not allow the gases to move out of cylinder quickly. Fig. 10.6 shows the valve timing diagram for a four-stroke diesel engine. The approximate crank positions are shown when I.V., E.V., and fuel valves open and close. I.D.C. represents (inner dead centre) and O.D.C. (outer dead centre), I.V.O. represents (inlet valve opens) and I.V.C. represents (inlet valve closes). Similarly E.V.O. means exhaust valve open and E.V.C. means exhaust valve closes, F.V.O. represents fuel valve opens and F.V.C. represnets fuel valve closes and F.V.O. represents fuel valve opens.

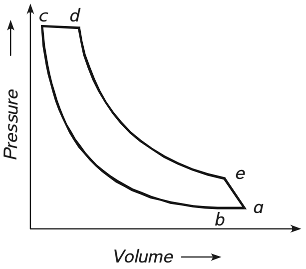


Fig. 10.5. P-V diagram.

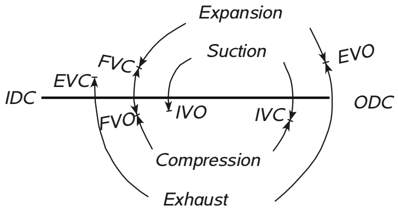


Fig. 10.6. Valve timing diagram.

10.9. TWO-STROKE DIESEL ENGINES

The various operations of a two-stroke diesel engine are shown in Fig. 10.7. During the downward movement of piston (down stroke) the exhaust port is uncovered and the removal of burnt gases takes place Fig. 10.7 (*a*). Further movement of the piston uncovers the transfer port Fig. 10.7 (*b*). At this stage the crank case and cylinder space are in direct communication. The slightly compressed air in the crank case is transferred to the cylinder (at a pressure of about 0.05 kg/cm^2 gauge) through the transfer port. While the transfer of charge from the crank case to the cylinder is taking place the removal of products of combustion is also taking place simultaneously, *i.e.* the incoming charge is helping in the rejection of burnt gases, this is known as scavenging. As the piston moves upward (up stroke) the compression of air starts, Fig. 10.7 (*c*).

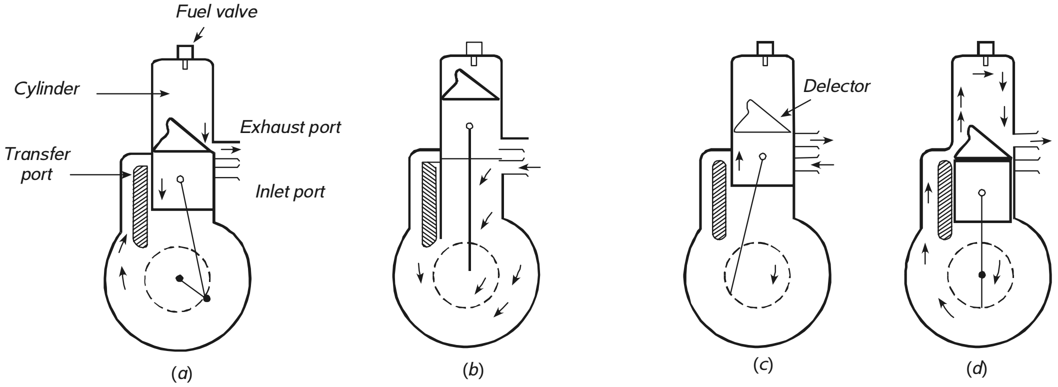


Fig. 10.7. Operation of two-stroke engine.

Near the end of compression stroke [Fig. 10.7 (*d*)] the fuel is injected and ignition of fuel takes place due to heat of compressed air. Then due to expansion of products of combustion the piston moves downward. As the inlet port is uncovered a fresh charge of air gets entered in the crank case.

Fig. 10.8 shows the indicator diagram for two stroke diesel engine. In this diagram *bc* represents the compression of air, *cd* represents constant pressure combustion line, *de* represents expansion and exhaust and scavenging are indicated by *eab*.

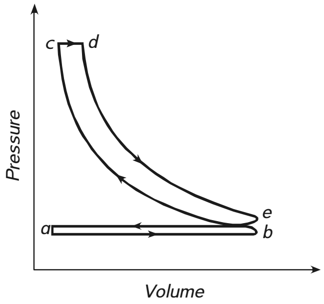


Fig. 10.8. P-V, diagram

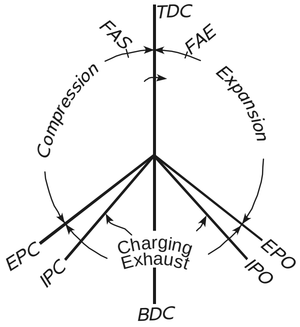


Fig. 10.9. Valve timing diagram.

Fig. 10.9 shows valve timing diagram for two-stroke diesel engine. TDC and BDC represents top dead centre and bottom dead centre respectively. IPO means inlet port opens and IPC means inlet port closes, EPO represent exhaust port opens and EPC represents exhaust port closes. FAS means fuel admission starts and FAE means fuel admission ends.

10.9.1 I.C. Engine Terminology

The important terms used in an I.C. engine are shown in Fig. 10.10. The inside diameter of engine cylinder is known as bore Top dead centre (TDC) in vertical engine and inner dead centre (IDC) in horizontal engine is the extreme position of the piston on head side of the engine. Whereas bottom dead centre (BDC) in vertical engine and outer dead centre (ODC) in horizontal engines indicate the extreme position at the bottom of the cylinder. Stroke is the distance between the two extreme positions of the piston. Stroke is the distance between the two extreme positions of piston.

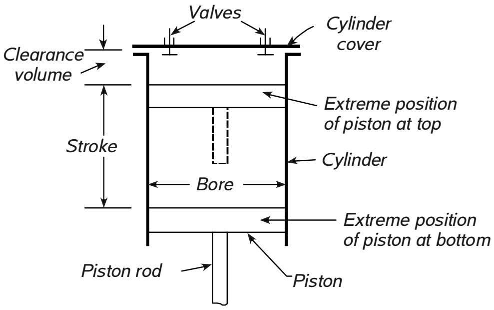


Fig. 10.10.

Let D = Bore

L = Stroke

V_1 = Swept volume = $(\pi/4)\ D^2 \times L$

Clearance volume is defined as the space above the piston at top dead centre.

V = Volume of cylinder = $V_1 + V_c$

where V_c is the clearance volume.

Comparison between Four and Two Stroke Engines

1. Two-stroke engine is much lighter, less bulky and occupies less floor area as compared with four-stroke engine.
2. The torque is uniform in two-stroke engine, therefore, it requires lighter flywheel and lighter foundation.
3. Two-stroke engines are mechanically simple as valves, rocker arms, push rods, cam and cam shaft are not required.
4. Starting of two-stroke engine is easy compared with four-stroke engine.
5. Overall efficiency of two-stroke engine is less than that of four-stroke engine.
6. The two-stroke engine is always overheated as power stroke exists after every revolution compared with after every two revolution in four-stroke engines.
7. The consumption of lubricating oil in two-stroke engine is more as it is subjected to higher temperatures.
8. The exhaust of two-stroke engine is more noisy, therefore more effective silencers are required.

Two-stroke engines, are therefore, are used in scooters and motor cycles where compactness, less space, and weight are the main considerations. Its use is also limited to small capacity engines.

10.10 COMPARISON BETWEEN PETROL AND DIESEL ENGINES

1. Petrol engines are lighter in weight.
2. Petrol engines require more maintenance of ignition system and frequent change of spark plugs, whereas fuel injection does not require that frequent maintenance.
3. Engine overhaul life of petrol engine is less.
4. Spares required for overhaul are less costly in case of petrol engines.
5. In diesel engines transmission is made for heavy duty due to high speed torque.
6. Diesel engines run smoothly and effectively even at idle speed.
7. Petrol engine can be started easily even in cold weather, where as it is difficult in diesel engines where heater plugs are required.
8. Petrol engines require small capacity battery as its starting torque is less.
9. Diesel engines run with more vibrations.
10. Due to heavy weight of engines and more vibrations in the diesel engine chassis/foundation is made extra strong.
11. Radiators used in diesel engines are heavy duty.
12. Engine running cost in case of diesel engines is less.

10.11. DIESEL ENGINE-POWER PLANT AUXILIARIES

Auxiliary equipment consists of the following systems :

1. *Fuel supply system.* It consists of fuel tank for the storage of fuel, fuel filters and pumps to transfer and inject the fuel. The fuel oil may be supplied at the plant site by trucks, rail, road, tank, cars etc.
2. *Air intake and exhaust system.* It consists of pipes for the supply of air and exhaust of the gases. Filters are provided to remove dust etc. from the incoming air. In the

exhaust system silencer is provided to reduce the noise.

Filters may be of dry type (made up of cloth, felt, glass, wool etc.) or oil bath type. In oil bath type of filters the air is swept over or through a bath of oil in order that the particles of dust get coated. The functions of the air intake systems are as follows :

(i) To clean the air intake supply.

(ii) To silence the intake air.

(iii) To supply air for super charging.

The intake system must cause a minimum pressure loss to avoid reducing engine capacity and raising the specific fuel consumption. Filters must be cleaned periodically to prevent pressure loss from clogging. Silencers must be used on some systems to reduce high velocity air noises.

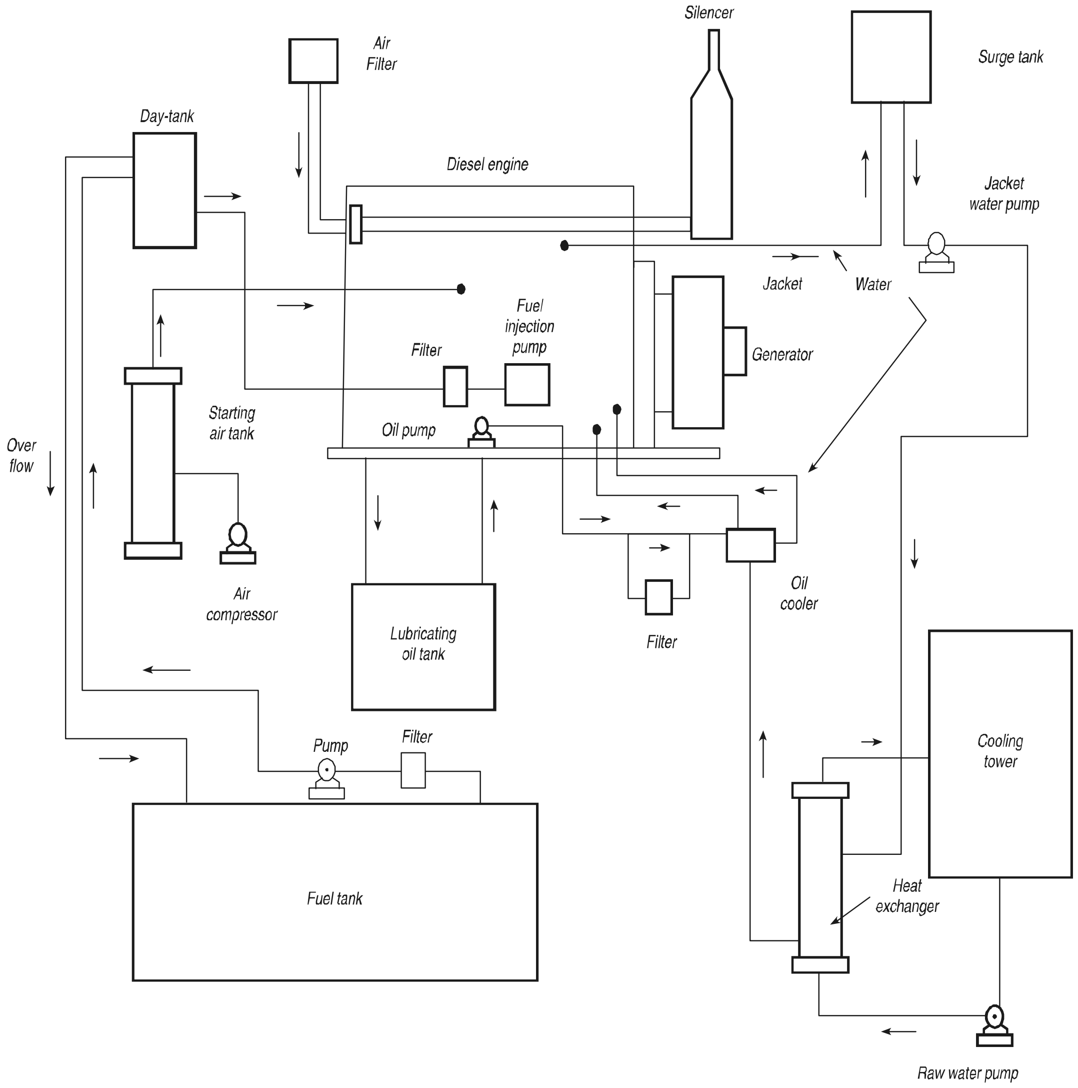


Fig. 10.11. A schematic arrangement for auxiliary equipment of diesel plant.

3. *Cooling system.* This system provides a proper amount of water circulation all around the engine to keep the temperature at reasonable level. Pumps are used to discharge the water inside and the hot water leaving the jacket is cooled in cooling ponds or other devices and is recirculated again.
4. *Lubricating system.* Lubrication is essential to reduce friction and wear of the rubbing parts. It includes lubricating oil tank, pumps, filters and lubricating oil cooler.
5. *Starting system.* For the initial starting of engine the various devices used are compressed air, battery, electric motor or self starter

Fig. 10.11 shows the auxiliary equipment of diesel engine power plant.

10.12 AIR INTAKE SYSTEM

The purpose of air intake system is to supply clean air to the engine. The atmospheric air contains dust and causes wear of piston rings and cylinder liners, if not removed. This system includes air filters, ducts, and supercharger and supplies required quantity of air for combustion. Air is drawn from outside the engine room and delivered to the intake manifold through the air filters which remove the dust and other suspended impurities from air. The filters are required to be cleaned periodically. As already discussed, the filters may be dry type (made up of cloth, felt, glass wool etc.) or oil bath type.

The supercharger increases the pressure of air supplied to the engine so as to develop an increased power output. Superchargers are generally driven by the engines, and would be discussed in the later part of this chapter.

10.13 FUEL SUPPLY SYSTEM

I.C. Engine Fuel

The internal combustion engines use both oil and gas fuels, the former being predominant. The oils used are specified according to the following properties:

(i) Cetane number
(ii) Viscosity
(iii) Volatility
(iv) Pour point
(v) Flash and fire point
(vi) Heating value
(vii) Distillation test
(viii) Aniline point
(ix) Conradson Carbon
(x) Ash

Cetane number indicates the ease with which fuel ignites when injected whereas viscosity is significant in oil-handling, volatility is an index of ease with which the combustible fuel air mixture can be prepared and pour point indicates the temperature at which oil flows. Fire hazards of an oil depend on flash and the fire point. Heating value measures the thermal energy in fuel and the distillation test is carried out to indicate whether oil contains any heavy ends of the refining process which generally burn poorly. Aniline point of oil fuel is used in calculating the diesel index which measures ignition quality. Conradson carbon indicates fire extent of components in oil with a tendency to form carbon deposits and ash indicates the components of oil believed to cause cylinder wear.

10.13.1. Fuel Supply

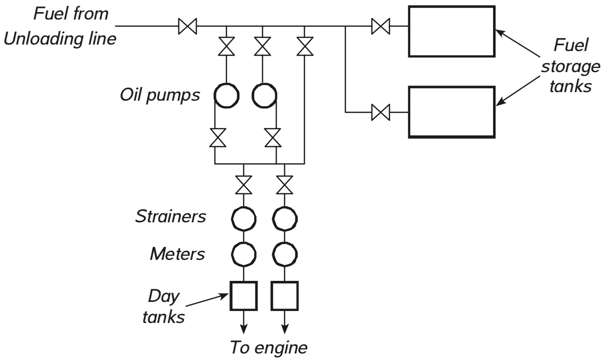


Fig. 10.12. Fuel supply system.

The fuels used in I.C. engines are in liquid form. They are preferred because of their high calorific value and ease of storage and handling. The storage of oil fuel is simpler than the solid fuel. The amount of fuel to be stored depends upon the service hours and varies for different installations. Bulk storage and engine day tanks hold the engine fuel. The fuel delivered to the power plant is received in storage tanks. Pumps draw the oil from storage tanks and supply it to the smaller day tanks from where the oil is supplied to the engine as shown in Fig.10.12.

The fuel oil used should be free from impurities. Efforts should be made to prevent contamination of the fuel. An important step is to reduce the number of times the fuel is handled. Greater amount of impurities settle down in the storage tank and remaining impurities are removed by passing the oil through filters. Storage tank may be located above the ground or underground. But underground storage tanks are preferred. Fig. 10.13 shows an underground storage tank. It is provided with coils, heated by steam or hot water to reduce the viscosity and to lower the pumping cost. Manhole is provided for internal access and repair. Vent pipe is provided to allow the tank to breathe as it is filled or emptied. Level indicator measures the quantity of oil in the tank, and an overflow line is provided to control the quantity of oil.

10.13.2. Diesel Engine Fuel Injection System

Fuel injection system performs the following functions :

(i) Filter the fuel.
(ii) Meter the correct quantity of fuel to be injected.
(iii) Time the injection process.
(iv) Regulate the fuel supply.
(v) Secure fine atomization of fuel oil.
(vi) Distribute the atomized fuel properly in the combustion chamber.

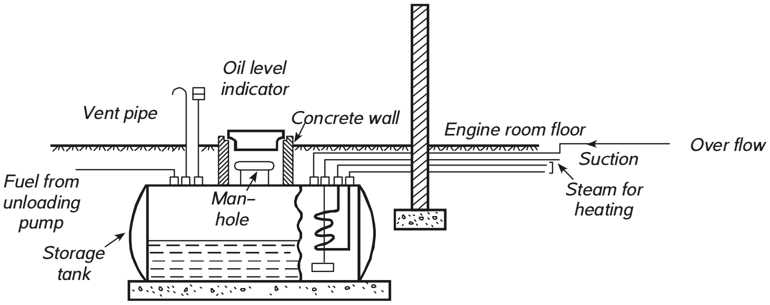


Fig. 10.13. Fuel storage.

The fuel injection system should be such that adequate quantity of fuel oil is measured by it, atomised, injected and mixed with the fuel oil because even the smallest particles of dirt can completely damage the fuel injection system.

The various system used for injection of fuel are as follows :

(i) Air injection *(ii)* Solid (airless) injection

(i) **Air Injection.** In this system a multistage compressor delivers the air at a pressure of 70 kg/cm^2 into the fuel nozzle. The fuel supplied by the fuel pump into the fuel nozzle is thus discharged into the engine cylinder.

(ii) **Solid Injection.** In this system the fuel is sprayed into the engine cylinder at a pressure of about 100 to 140 kg/cm^2. Solid injection systems are available in three types :

(a) Unit injector *(b)* Pump injection *(c)* Distribution injector

(a) **Unit injector.** In this system a pump plunger is actuated by a cam through a push rod and rocker arm mechanism. The plunger moving in a barrel raises the pressure of fuel oil, meters the quantity of fuel and controls the injection timing. There is a spring loaded delivery valve in the nozzle. This valve is actuated by the change in fuel oil pressure (Fig. 10.14).

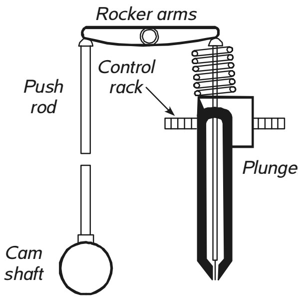


Fig. 10.14

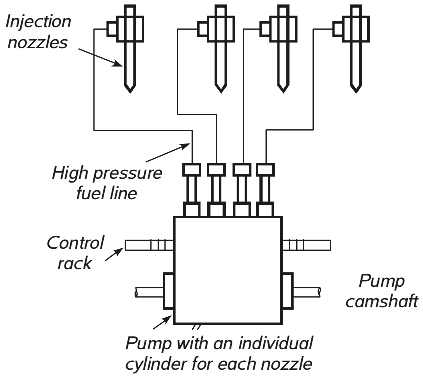


Fig. 10.15

(b) **Pump injection.** In this system individual pump is provided for each nozzle. The pump measures the fuel charge and controls the injection timing (Fig. 10.15).

(c) **Distribution injector.** In this system (Fig. 10.16) a pump measures and pressurizes the fuel and supplies to it the various nozzles through a distributor block.

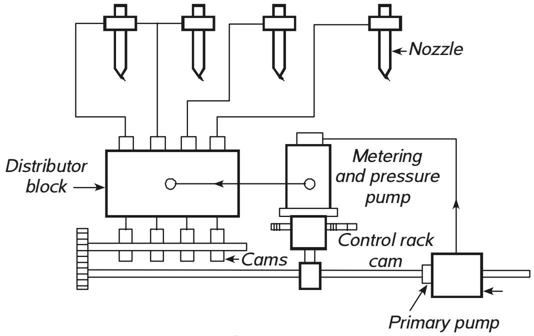
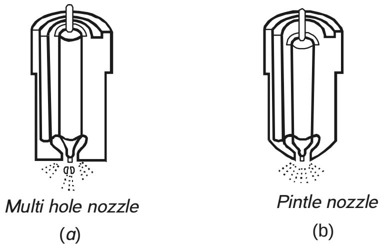


Fig. 10.16

10.13.3 Fuel Injection Nozzle

Fuel injection takes place through very fine holes in the nozzle body. There are several types of fuel injection nozzles. Two common types are multihole nozzle [Fig. 10.17 (*a*)] and pintle nozzle [Fig. 10.17 (*b*). In multihole nozzle each spray orifice produce a dense and compact spray. In pintle nozzle, fuel comes out in the form of conical spray.



Multi hole nozzle
(*a*)

Pintle nozzle
(b)

Fig. 10.17. Fuel injection system.

10.14 ENGINE EXHAUST SYSTEM

The function of the exhaust system is to discharge the engine exhaust to the atmosphere outside the building without making much noise. It consists of exhaust manifold, exhaust pipe and silencer. The exhaust manifold collects the exhaust gases from all the engine cylinders to lead to a common exhaust pipe. Then these exhaust gases are passed through a silencer to the atmosphere reducing the velocity.

A good exhaust system should keep the noise at a low level, exhaust well above the ground level to reduce the air pollution and should isolate the engine vibrations from the building. The exhaust pipe is provided with a muffler (silencer) to reduce the pressure in the exhaust line and reduce the noise level. The exhaust stak usually stands on the muffler top. A typical exhaust system is shown in Fig. 10.18.

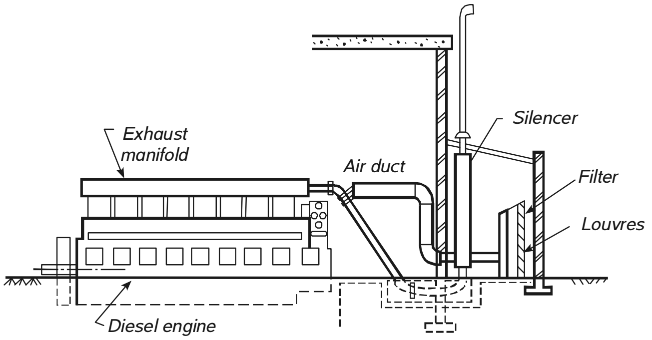


Fig. 10.18.

10.15 ENGINE COOLING SYSTEM

Due to combustion of fuel in the engine cylinder the temperature of burning gases is too high (nearly 1500° to 2000°C). This temperature may cause the distortion of some of the engine parts such as cylinder head and walls, piston and exhaust valves and may burn the lubricating oil. Thus a cooling arrangement is essential to carry away some of the heat from the cylinder to avoid the over heating. A well designed cooling system should provide adequate cooling but not excessive cooling. A cooling system should :

(i) Absorb and dissipate the excess heat from the engine in order to prevent damage to the engine.

(ii) Maintain sufficient high operating temperature so that smooth and efficient operation of the engine take place.

Cooling of the engine is necessary for the following reasons :

(a) At high temperatures the lubricating oil deteriorates very rapidly damaging the piston and cylinder surfaces. Piston seizure may also occur.

(b) Strength of the materials used for various engine parts decreases with increase in temperature, which may often resulting in cracking.

(c) High engine temperature may results in very hot exhaust valve, giving rise to pre-ignition and detonation or knocking.

(d) At high cylinder head temperature, the volumetric efficiency and hence power output of the engine is reduced.

It is observed that about 25 to 30% of the heat supplied is absorbed by the cooling medium. Fig. 10.19 indicates a typical heat distribution for a reciprocating internal combustion engine.

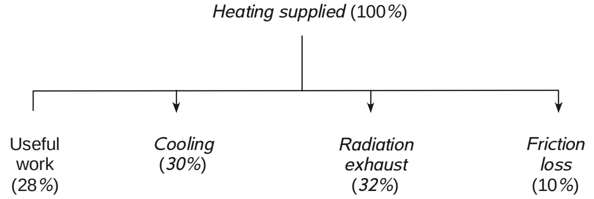


Fig. 10.19

The following points should be noted to achieve good cooling of diesel engine.

(i) Adequate quantity of water should continuously flow throughout the operation of the engine.

(ii) The cooling water should not be corrosive to metals.

(iii) The cooling water used for cylinder jackets should be free from scale forming impurities.

(iv) The temperature rise of cooling water should not be more than 11°C and the temperature of water leaving the engine should be limited to 60°C

10.15.1. Cooling methods

There are two methods of cooling the I.C. Engine :

(a) Air cooling *(b)* Water cooling.

Air Cooling. It is direct method of cooling. In air cooled engines fins are cast on the cylinder head and cylinder barrel to increase its exposed surface of contact with air. Air passes over fins and carries away heat with it. Air for cooling the fins may be obtained from a blower or fan driven by the engine. Air movement relative to engine may be used to cool the engine as in case of motor cycle engine. About 13 to 15% of heat is lost by this method. Fig. 10.20 shows air cooling system. Simplicity and lightness are the advantages of air cooling. But this system is not as effective as water cooling. The rate of cooling depends upon the velocity, quantity and temperature of cooling air and size of surface being cooled.

Fig. 10.20 shows position of valves, fins and head in air cooling system. This system is used in motor cycles, scooters and aeroplanes.

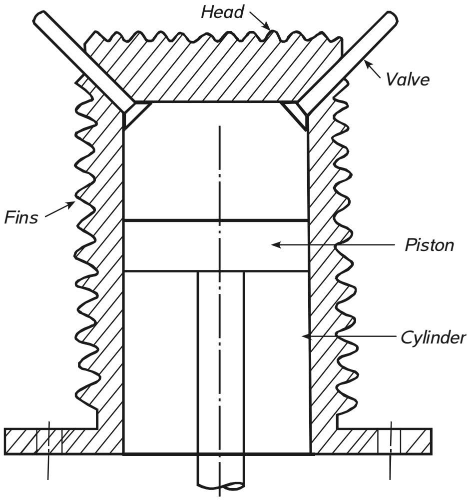


Fig. 10.20. Air cooling system.

Water Cooling. It is the indirect method of cooling the engine. The various cooling systems used are shown in Fig. 10.21. Water after circulating in water jackets (passages around the cylinder, combustion chamber, valves etc.) goes as waste [Fig. 10.21] or in recirculating method of cooling [Fig. 10.22] water is continuously circulated through water jackets. Water takes up the heat and leaves for radiator where it is cooled for recirculation.

Various methods used for circulating the water around the cylinder are :

(i) *Thermosiphon cooling*. In this method water flows due to density differences.

(ii) Forced cooling by pump.

(iii) *Thermostat cooling*. In this method a thermostal maintains the desired temperature.

(iv) Pressurized water cooling.

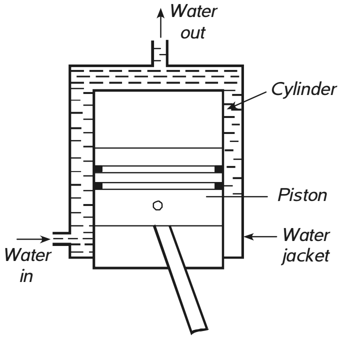


Fig. 10.21.

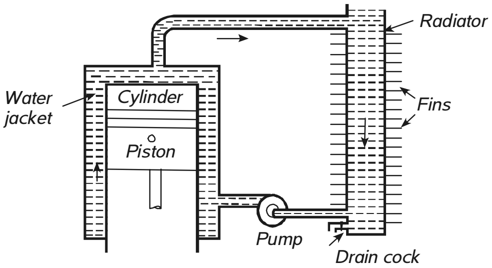


Fig. 10.22

In stationary diesel engine plants the water cooling systems used are as follows :

(i) *Open or Single Circuit System.* In this system [Fig. 10.23] pump draws the water from cooling pond and forces it into the main engine jackets. Water after circulating through the engine return to the cooling pond. This system is also known as direct evaporation system.

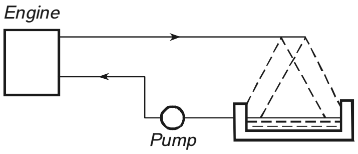


Fig. 10.23. Open or single circuit system.

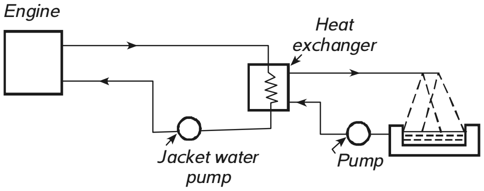


Fig. 10.24. Closed or double circuit system.

(ii) *Closed or Double Circuit System.* In this system [Fig. 10.24] raw water is made to flow through the heat exchanger when it takes up the heat of jacket water and returns back to the cooling pond.

(iii) *Radiator system.* This system have been discussed above and shown in Fig. 10.22. This system follows natural circulation of water due to difference in temperature.

Heat lost by water cooling is about 25 to 35%. The amount of heat lost is called jacket loss. The rate of flow of water should be so adjusted that the outlet temperature of cooling water does not exceed 60°C and rise in temperature of cooling water is limited to 11°C. The water used for cooling purposes should be free from impurities. Water cooling methods permit uniform cooling. Water cooling creates troubles in very cold weather. Cooling efficiency is reduced due to scaling in the pipes, jackets and radiator. Engine efficiency affected by power needed to drive the water pump and radiator fan.

Closed system of cooling is mostly used in power stations. A closed cooling system comprises the following equipment.

(i) A surge tank.

(ii) Soft water circulating pump.

(iii) Soft water circulation pipe.

(iv) Soft water heat exchanger or cooler.

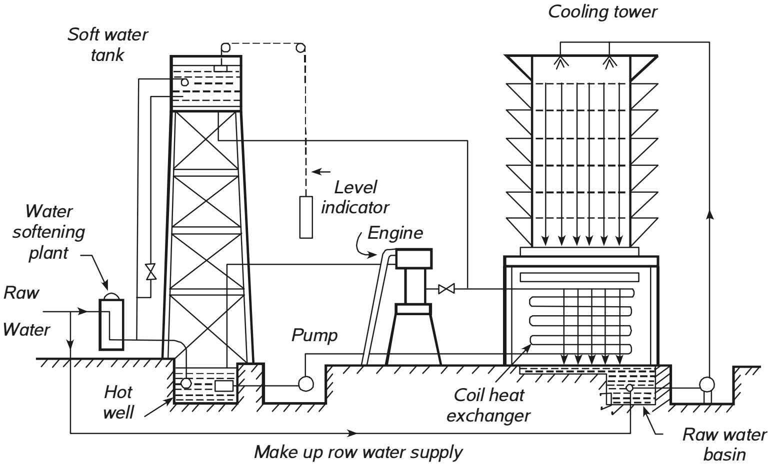


Fig. 10.25

(v) Raw water softening plant.
(vi) Raw water circulation pump.
(vii) Raw water circulation pipe.
(viii) Raw water cooling arrangement such as cooling tower.
(ix) Thermometer for measuring inlet and outlet temperatures.
(x) Temperature regulator to control the excessive jacket temperature.
(xi) Safety device to control the excessive jacket temperature.

This system shown in Fig 10.25 use soft water for jacket cooling. The hot jacket water from the engine is passed through the cooler (heat exchanger) where it is cooled with the help of raw water. The raw water in turn is cooled by cooling towers.

10.16 ENGINE LUBRICATION SYSTEM

Frictional forces causes wear and tear of rubbing parts of the engine and thereby the life of the engine is reduced. This requires that some substance should be introduced between the rubbing surfaces in order to decrease the frictional force between them. Such substance is called lubricant. The lubricant forms a thin film between the rubbing surfaces and prevents metal to metal contact. The various parts of an I.C. engine requiring lubrication are cylinder walls and pistons, big end bearings and crank pins, small end bearings and gudgeon pins, main bearing, cams and bearing valve tappet, and guides and timing gears etc. The functions of a lubricant are as follows:

1. *Lubrication.* It reduces wear and tear of various moving parts by minimising the force of friction and ensures smooth running of parts.
2. *Sealing.* It helps the piston ring to seal the gases in the cylinder.
3. *Cooling.* It removes the heat generated due to friction and keeps the parts cool.
4. *Cleaning.* To keep the bearings and piston rings clean of the products of wear by washing them away.
5. *Reducing noise.* To reduce the noise of the engine by absorbing vibrations.

The various lubricants used in engines are of three types :

(i) Liquid Lubricants.
(ii) Solid Lubricants.
(iii) Semi-solid Lubricants.

Liquid oil lubricants are most commonly used. Liquid lubricants are of two types : (*a*) Mineral Oils (*b*) Fatty oils. Graphite, white lead and mica are the solid lubricants. Semi solid lubricants or greases as they are often called are made from mineral oils and fatty-oils.

A good lubricant should possess the following properties :

(i) It should not change its state with change in temperature.
(ii) It should maintain a continuous films between the rubbing surfaces.
(iii) It should have high specific heat so that it can remove maximum amount of heat.
(*iv*) It should be free from corrosive acids.
(*v*) The lubricant should be purified before it enter the engine. It should be free from dust, moisture, metallic chips, etc. The lubricating oil consumed is nearly 1% of fuel consumption.

The lubricating oil gets heated because of friction of moving parts and should be cooled before recirculation. The cooling water used in the engine may be used for cooling the lubricant. Nearly 2½% of heat of fuel is dissipated as heat which is removed by the lubricating oil.

Lubricating oil is purified by following four methods :

(i) Settling,
(ii) Centrifuging,
(iii) Filtering,
(iv) Chemical reclaiming. The centrifuging widely used gives excellent purification when properly done.

Fig. 10.26 shows the lubricating oil external circuit.

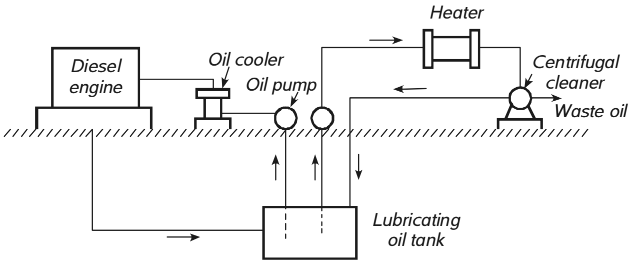


Fig. 10.26

10.17 ENGINE STARTING SYSTEM

10.17.1 Engine Starting Methods

Spark ignition engines (Petrol engines) are used mainly in smaller size where compression ratio to be outcome in cranking is only 5 to 7. Hand and electric motor (6 – 12 V, d – C) cranking are practical. Diesel engines are difficult to be started by hand cranking because of high compression required and therefore mechanical cranking system is used.

The various methods used for the starting of diesel engine are as follows :

1. *Compressed Air System.* Compressed air system is used to start large diesel engines. In this system compressed air at a pressure of about 20 kg per sq. cm is supplied from an air bottle to the engine by an inlet valve through the distributor or through inlet manifold. In a multi-cylinder engine compressed air enters one cylinder and forces down the piston to turn the engine shaft. Meanwhile the suction stroke of some other cylinder takes place and the compressed air again pushes the piston of this cylinder and causes the engine crank shaft assembly to rotate. Gradually the engine gains momentum and by supplying fuel the engine will start running.
2. *Engine Starting.* Electric starting arrangement consists of an electric motor with a drives pinion which engages a toothed rim on engine flywheel. Electric power supply for the motor is made available by a small electric generator driven from the engine. In case of small plants a storage battery of 12 to 36 volts is used to supply power to the electric motor.

   The electric motor disengages automatically after the engine has started. The advantages of electric starting are its simplicity and effectiveness.

3. *Starting by an Auxiliary Engine.* In this method a small petrol engine is connected to the main engine through clutch and gear arrangements. Firstly, the clutch is disengaged and petrol engine is started by hand. Then clutch is gradually engaged and the main engine is cranked for starting. Automatic disengagement of clutch takes place after the main engine has started.

10.17.2 Starting Procedure

Actual process of starting the engine differs from engine to engine. Some common steps for starting the engine are as follows :

1. Before starting the engine it is desirable to check fuel system, lubricating system and cooling water supply.
2. Depending upon the method of starting a check for the same is essential. If air starting is used the pressure of air should be checked and also the air system should be checked for possible leakage. The storage battery should be checked if electric motor is used for starting.
3. There should be no load on the engine.
4. Crank the engine and run it at slow speed for a few minutes and again check the working of various systems such as fuel, lubricating oil system etc.

The speed of the engine should be gradually increased till it synchronises with the bus bars. Then connect the generator to the bus bars and finally increase the engine speed so that it takes up the desired load.

10.17.3 Stopping the Engine

The engine should not be stopped abruptly. To stop the engine its speed should be decreased gradually until no power is delivered by the alternator. Then the engine is disconnected from the bus bars and is allowed to run idle for some time.

10.17.4 Starting Aids

Starting aids may be used during cold weather to obtain quicker starting of the engine. Ethyl ether is mostly used as such aid. Glow plugs are another starting aid. Glow plug forms a local hot spot thus initiating the combustion of fuel even if the compression temperature of air is insufficient.

10.17.5 Warming up of Diesel Engine

The diesel engine should be allowed to warm up for four to five minutes after the engine has started. During this time the following points should be checked:

(i) To check whether the firing is correct in all cylinders.
(ii) To check the operation of fuel pump.
(iii) To check the cooling water system, circulating water pump etc.
(iv) To check the lubrication system.
(v) To check the colour of exhaust gases etc. to know whether the combustion is proper.

After these checks the engine should be put on load. Then the speed of engine should be gradually increased in order to synchronise the incoming generator with the station bus bars.

10.18 SUPER CHARGING

The H.P. produced by an I.C. engine is almost directly proportional to the air consumed by the engine. Increasing the air consumption permits the greater quantities of fuel to be added and results in greater power produced by the engine. It is, therefore, desirable that the engine should take in the greatest possible mass of air. The supply of air is pumped into the cylinder at a pressure greater than the atmospheric pressure and is called supercharging. When greater quantity of air is supplied to an internal combustion engine it would be able to develop more power for the same size and conversely a small size engine fed with extra air would produce the same power as a larger engine supplied with its normal air feed. Supercharging is used to increase rated power output capacity of a given engine or to make the rating equal at high altitudes corresponding to the unsupercharged sea level rating.

Supercharging is done by installing a super charger between engine intake and air inlet through air cleaner. Super charger is merely a compressor which provides a denser charge to the engine thereby enabling the consumption of a greater mass of charge with the same total piston displacement. Power required to drive the super charger is taken from the engine and thereby removes from over all engine output some of the gain in power obtained through supercharging.

There are two types of compressors that may be used as superchargers. They are as follows :

(i) Positive displacement type super chargers.
(ii) Centrifugal type super chargers.

Positive displacement type super chargers are further of three types as follows :

(a) Rotary type *(b)* Screw type *(c)* Piston and cylinder type.

In rotary type super chargers the air is compressed by a meshing gear arrangement called Roots blower as shown in Fig. 10.27 or by a rotating vane element as shown in Fig. 10.28. The air is taken from intake and discharged at outlet end. In screw type supercharger the air is trapped between inter meshing helical shaped gears and forced out axially. In piston and cylinder type super-charger the piston compresses the air in a cylinder whereas a centrifugal type super-charger has an impeller running in a housing at a high speed, centrifugal supercharger is commonly by used in reciprocating power plants for aircraft.

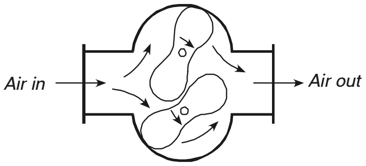


Fig. 10.27.

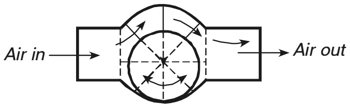


Fig. 10.28.

In supercharging, the higher pressure of intake air is obtained from a blower/compressor driven by the diesel engine or by an electric motor, as shown in Fig. 10.29.

In turbo-charging, the blower is driven by a turbine which operates on hot exhaust gases of the engine, as shown in Fig 10.30.

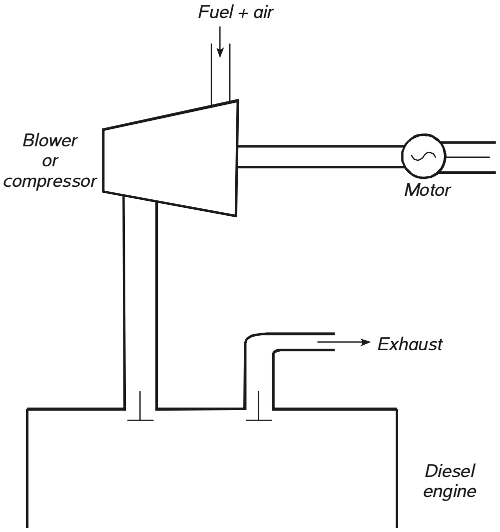


Fig. 10.29. Super-charging of a diesel engine.

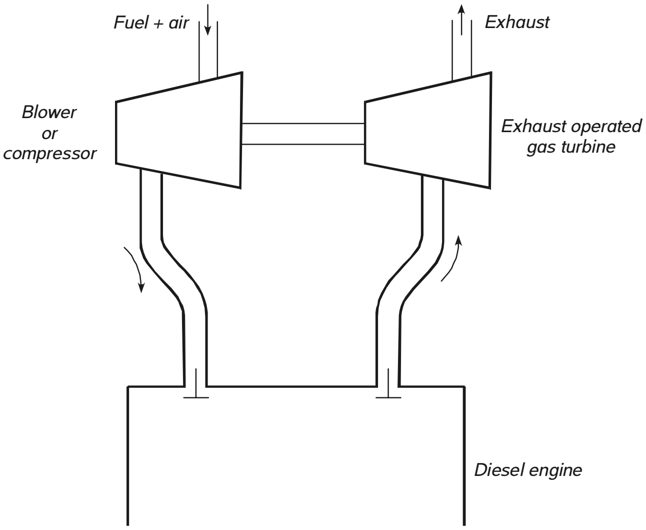


Fig. 10.30. Turbo-charging (compounding) of a diesel engine.

10.18.1 Advantages of Supercharging

Due to a number of advantages of supercharging, the modern diesel engines used in diesel plants are generally supercharged. The various advantages of supercharging are as follows :

(*i*) For given output engine size is reduced.
(*ii*) Engine output can be increased by about 30 to 50%.
(*iii*) The specific fuel consumption of a super charged engine is less than natural aspirated engine. This is due to the fact that combustion in supercharged engine is better due to better mixing of fuel and air.

(*iv*) Supercharged engine has higher mechanical efficiency.
(*v*) Supercharging reduces the possibility of knocking in diesel engine.

10.19 DIESEL ENGINE GOVERNING

The governing of an engine is required for maintaining the speed of the engine as constant irrepective of the load on the engine. For governing, the amount of fuel supplied to the engine cylinder per cycle is varied according to the load on the engine. The air supply is kept constant while the quantity of fuel supplied is changed, thus the quality of the (air-fuel ratio) changes according to the load on the engine.

10.20 MAINTENANCE OF DIESEL ENGINES

Diesel engine power plant maintenance depends on various factors. Careful supervision of the equipment used for recording temperature, pressure and electrical data are essential. The temperature inside the engine should not be allowed to exceed the safe limits as diesel engine is an all metal machine and there is no refractory protection. The temperature, flow and quality of fuel oil should be checked from time to time. The fuel oil must be cleaned from dirt and other impurities by means of filters. Filters may have fibre element, or cloth or fibre or a combination of cloth and fibre. When filter element becomes choke it should be replaced by a new one. Dirt in fuel oil ruins the fine lap of fuel injection pumps and plugs the injection nozzle orifice. Occasionally, all the fuel should be drained and the fuel tank cleaned thoroughly. The temperature and flow of coolant, lubricating oil and exhaust gases should be checked at regular interval.

Battery should be kept clean from dirt and dust. All corroded terminals and clamps are to be cleaned with petroleum jelly. Electrolite level should be checked regularly. The specific gravity of the electrolite should also be checked and, if required, the battery should be charged.

It is always desirable to follow manufacturer's instructions regarding schedule of maintenance and type/quality of lubricants and greases etc. It is also desirable to maintain correct record of instrument readings, duration of operation, condition of operation, fuel consumption rate etc. at regular interval, such records form log sheets.

Sound of the engine during working is the best indicator for its condition, and enables to know which part needs attention. The manufacturer's instructions should be adhered to strictly for better performance and trouble free operation. When engine gets clean air, fuel, water and lubrication, most of the problems would not arise. Recommended oils should be used in oil type air cleaners and oil sumps. During maintenance it should be ensured that all the joints between air cleaner and the engine are tight.

10.21 MAIN COMPONENTS AND LAYOUT OF DIESEL PLANT

A diesel power plant has following essential major components :

1. Engine coupled with generator.
2. Engine air intake system with supercharger.
3. Engine fuel system with storage tanks.
4. Engine exhaust system, including arrangement for heating the air supplied to the engine.

5. Engine cooling system with water filtration plant.
6. Engine lubrication system with oil tanks.
7. Engine starting system.
8. Governing system.

Items mentioned at serial numbers 2 to 8 above are known as auxiliary equipment. All above components of diesel power plants have already been discussed in earlier paragraphs. A schematic arrangement for a diesel engine power plant is shown in Fig. 10.11.

As diesel power stations are small capacity plants and have only a few auxiliaries, the design of their buildings is generally simple rectangular blocks to accommodate the engine-generator sets. The engine and alternator are placed on a large reinforced concrete block. The design of the foundation should provide for absorption of vibrations.

Layout of diesel engine power plant is shown in Fig. 10.31. Generally the various units are installed with parallel centre lines.

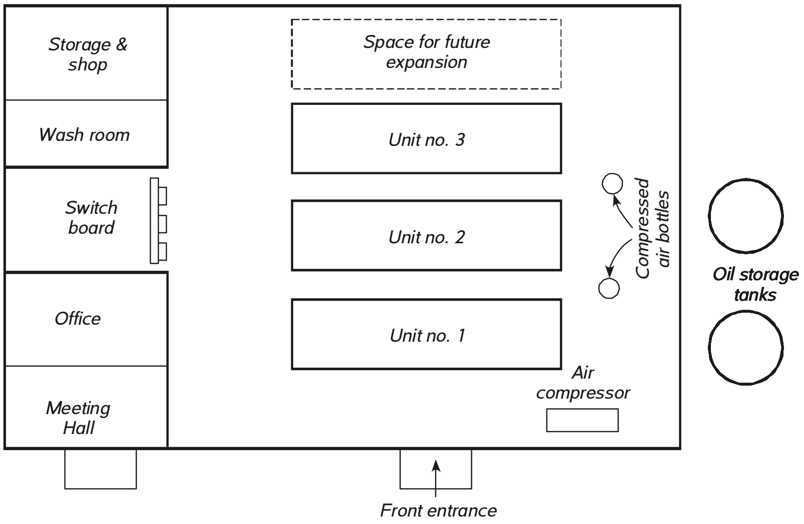


Fig. 10.31. Layout of diesel power plant.

Some space is left for future expansion. Sufficient space should be provided around various units for maintenance, dismantling and repairing the engine. The engine room should be provided with adequate ventilation and lighting. Fuel oil storage tanks may be located outside the main building.

While designing a layout plan, a due consideration should be given to the location of the switch board, station auxiliaries like transformers, battery room, fuel oil tank, compressed air cylinder bottle for engine starting, compressors, lubricating oil circuits and cooling arrangements for cylinder jackets, and suction and exhaust arrangements. Sometimes oil tanks are located underground. The air intakes and filters, and exhaust mufflers are located outside the engine room. Bulk oil storage are also located outside. Arrangement for cooling the water required for cylinder cooling may also be located near, preferably outside the building.

10.22. ENGINE PERFORMANCE AND HEAT BALANCE SHEET

10.22.1 Engine Performance

(i) **IMEP (Indicated Mean Effective Pressure).** In order to determine the power developed by the engine, the indicator diagram of engine should be available. From the area of indicator diagram it is possible to find an average gas pressure which while acting on piston throughout one stroke would account for the net work done. This pressure is called indicated mean effective pressure (I.M.E.P.).

(ii) **IHP (Indicated Horse Power).** The indicated horse power (I.H.P.) of the engine can be calculated as follows :

$$\text{I.H.P.} = \frac{P_m L.A.N.\,n}{4500 \times k}$$

where

P_m = I.M.E.P. in kg/cm^2
L = Length of stroke in metres
A = Piston area in cm^2
N = Speed in R.P.M.
n = Number of cylinders
k = 1 for two stroke engine
= 2 for four stroke engine.

(iii) **Brake Horse Power (B.H.P.).** Brake horse power is defined as the net power available at the crankshaft. It is found by measuring the output torque with a dynamometer.

$$\text{B.H.P.} = \frac{2\pi\, NT}{4500}$$

where

T = Torque in kg.m.
N = Speed in R.P.M.

(iv) **Frictional Horse Power (F.H.P.).** The difference of I.H.P. and B.H.P. is called F.H.P. It is utilised in overcoming frictional resistance of rotating and sliding parts of the engine.

$$\text{F.H.P.} = \text{IHP} - \text{BHP}.$$

(v) **Indicated Thermal Efficiency** (η_i). It is defined as the ratio of indicated work to thermal input.

$$\eta_i = \frac{I.H.P. \times 4500}{W \times C_v \times J}$$

where

W = Weight of fuel supplied in kg per minute.
C_v = Calorific value of fuel oil in kcal/kg.
J = Joules equivalent = 427.

(*vi*) **Brake Thermal Efficiency (Overall Efficiency).** It is defined as the ratio of brake output to thermal input.

$$\eta_b = \frac{B.H.P \times 4500}{W \times C_v \times J}$$

(*vii*) **Mechanical Efficiency (η_m).** It is defined as the ratio of B.H.P. to I.H.P. Therefore,

$$\eta_m = \text{B.H.P./I.H.P.}$$

10.22.2 Heat Balance Sheet

Heat balance sheet is a useful method to watch the performance of the plant. Of all the heat supplied to an engine only part of it is converted into useful work, the remaining goes as waste. The distribution of the heat imparted to an engine is called as its heat balance. The heat balance of an engine depends on a number of factors among which load is primarily importance. The heat balance of an internal combustion engine shows that the cooling water and exhaust gases carry away about 60-70% of heat produced during combustion of fuel. In order to draw the heat balance sheet of internal combustion engine, the engine is run at constant load and constant speed and the indicator diagram is drawn with the help of indicator. The following quantities are noted:

1. The quantity of fuel consumed during a given period.
2. Quantity of cooling water and its outlet and inlet temperatures.
3. Weight of exhaust gases.
4. Temperature of exhaust gases.
5. Temperature of flue gases supplied.

To calculate the heat in various items proceed as follows.

10.22.3 Heat in Fuel Supplied

Let W = Weight of fuel consumed per minute in kg.

C_v = Lower calorific value of fuel, kcal per kg.

Then heat in fuel supplied per minute = WC_v kcal.

The energy supplied to I.C. engine in the form of fuel input is usually broken into following items :

(*a*) *Heat energy absorbed in I.H.P.* The heat energy absorbed in indicated horse power, I.H.P. is found by the following expression :

Heat in I.H.P. per minute

$$= \frac{\text{I.H.P.} \times 4500}{J} \text{ kcal.}$$

(b) Heat rejected to cooling in water

Let W_1 = Weight of cooling water supplied per minute (kg)

T_1 = Inlet temperature of cooling water in °C

T_2 = Output temperature of cooling water in °C

Then heat rejected to cooling water = $W_1 (T_2 - T_1)$

(c) Heat carried away by exhaust gases

Let W_2 = Weight of exhaust gases leaving per minute in kg. (sum of weight of air and fuel supplied)

T_3 = Temperature of flue gases supplied per minute °C

T_4 = Temperature °C of exhaust gases.

K_p = Mean specific heat at constant pressure of exhaust gases.

The heat carried away by exhaust gases

$$= W_2 \times k_p \times (T_4 - T_3) \text{ kg cal.}$$

(d) Heat unaccounted for (Heat lost due to friction, radiation etc.)

The heat balance sheet is drawn as follows :

Item	*Heat units kcal*	*Per cent*
Heat in fuel supplied		
(a) Heat absorbed by I.H.P.		
(b) Heat rejected to cooling water.		
(c) Heat carried away by exhaust gases.		
(d) Heat unaccounted for (by difference)		
Total		

A typical heat balance sheet at full load for Diesel cycle (compression ignition) is as follows:

(i) Useful work = 30%
(ii) Heat rejected to cooling water = 30%
(iii) Heat carried away by exhaust gases = 26%
(iv) Heat unaccounted (Heat lost due to friction, radiation etc.) = 10%.

10.22.4 Testing Diesel Power Plant Performance

The performance of the engine is dependent on engine speed, compression ratio, weight of inducted air and friction losses. The newly purchased equipment is tested for various standards set up by the Indian Standards Institution and other such institutions. Tests such as checking of preliminary calibrations, accuracy of tolerances methods, specific thermal performance, accuracy of speed control, governor characteristics and cyclic irregularity are conducted to know whether the equipment supplied is up to the standards specified. Careful supervision of the equipment used for recording temperature, pressure and electrical data are essential. The temperature inside the engine should not be allowed to exceed safe limits as diesel engine is an all metal machine and there is no refractory protection. Incorrect working of pressure gauges, thermometers and automatic warning signals is very harmful. For testing the cycle of the engine mechanical indicators are used for low speed and for higher speed electronic indicators are used. Electronic indicators give pressure time data which can be converted into pressure volume (*p.v.*) data by graphical devices and then mean effective pressure, power, valve action etc. can be determined.

The important items can be measured for predicting the performance and making energy balance. They are as follow:

(i) Rate of fuel consumption
(ii) I.H.P.
(iii) B.H.P.
(iv) Quantity of cooling water and its rise in temperature
(v) Quantity of air
(vi) Atmospheric temperature
(vii) Temperature of exhaust gas
(viii) Orsat analysis.

To calculate air consumed by the engine the volumetric efficiency is calculated. To watch the performance of the plant heat balance sheet is drawn and for this flow of fuel, coolant, exhaust gases, temperature of these flows, quantity of fuel and air recorded. B.H.P. of the engine connected to the generator is calculated by finding the output of the generator (measurable by electrical instruments) and efficiency of the generator. The heat lost due to friction, radiation etc. can be found from the heat balance sheet.

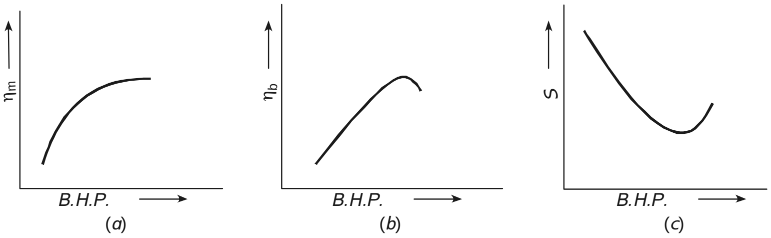


Fig. 10.32. Mechanical efficiencies of diesel engine.

The typical performance of a diesel engine is shown in Fig. 10.32. The variation of mechanical efficiency (η_m), brake thermal efficiency (η_b) and specific fuel consumption (S) with B.H.P. is indicated in the figure.

10.22.5 Factors Affecting Engine Performance

Various factors which affect performance of a diesel engine are as follows :

(i) Amount of fuel burnt per minute.
(ii) Brake mean effective pressure.
(iii) *Fuel injection system* : An efficient fuel injection system is needed. The required quantity of fuel should be measured out, injected, atomised and mixed with combustion-air.
(iv) Combustion process.
(v) Fuel-air ratio.

(vi) Type of engine such as two stroke or four stroke engine. Four stroke engines are generally used in diesel power plants.

(vii) Cooling method.

(viii) Size of cylinder.

SOLVED PROBLEMS

Example 10.1. *In a gas engine the mean effective pressure (m.e.p.) is 4.8 kg/cm*^{2} *and the ratio of diameter of piston to stroke is 2/3. Calculate the size of four stroke cycle gas engine if it runs at 250 R.P.M. and its B.H.P. is 16. The mechanical efficiency of the engine is 80%.*

Solution. Mechanical efficiency.

$$\eta_m = \frac{\text{B.H.P.}}{\text{I.H.P.}}$$

$$0.8 = \frac{16}{\text{I.H.P.}}$$

$$\text{I.H.P.} = \frac{16}{0.8} = 20$$

Let D = Diameter of piston

L = Stroke

$$\text{I.H.P.} = \frac{P_m L.A.N.}{4500 \times k}$$

$$20 = \frac{4.8 \times L.A. \times 250}{4500 \times 2}$$

$\therefore$ $L.A. = 150$

where L is in metres and A (area) is in cm^2.

Now $$\frac{D}{L} = \frac{2}{3}$$

If D is in centimetres $$L = \frac{3}{2} D \text{ cm} = \frac{3}{2} D \times \frac{1}{100} \text{ metres}$$

Now $L.A. = 150$

$$150 = \frac{3}{2} \times D \times \frac{1}{100} \times \frac{\pi}{4} D^2$$

$$150 = \frac{3\pi D^3}{800}$$

$$D^2 = \frac{150 \times 800}{3 \times \pi} = 12{,}727$$

D = 22.7 cm. **Ans.**

and $$L = \frac{3}{2} \times D = \frac{3}{2} \times 22.7$$

$$= 3 \times 11.35 = 34 \text{ cm.} \qquad \textbf{Ans.}$$

Example 10.2. *The following observations refer to trial on a four-stroke cycle gas engine :*

Mean effective pressure = *7 kg/cm*^{2}

Fuel gas supplied = *0.24 m*^{3}*/minute*

Calorific value of the gas = *4500 kcal/m*^{3}

Stroke = *50 cm.*

Bore = *20 cm.*

Speed = *300 R.P.M.*

Brake load = *70 kg.*

Radius of brake drum = *0.8 metres*

Determine the following :

(a) I.H.P. *(b) B.H.P.*

(c) Mechanical efficiency. *(d) Thermal efficiency.*

Solution. L = Stroke length = 0.5 m,

D = Bore = 20 cm.

$$\text{Area } (A) = \frac{\pi}{4}.(20)^2 = 314 \text{ cm}^2.$$

P_m = mean effective pressure = 7 kg.cm^2

$$\text{I.H.P.} = \frac{P_m L.A.N.}{4500 \times k} \qquad \text{where } k = 2$$

$$= \frac{7 \times 0.5 \times 314}{4500} \times \frac{300}{2} = 36.6$$

$$\text{B.H.P.} = \frac{2\pi NT}{4500} = \frac{2\pi \times 300 \times 56}{4500} = 23.4$$

where T = Torque in kgm = 70 × 0.8 = 56 kgm.

$$\text{Mechanical efficiency (\%)} = \frac{\text{B.H.P.}}{\text{I.H.P.}} \times 100 = \frac{23.4}{36.6} \times 100 = 63.8\%$$

Heat supplied in fuel/minute = 0.24 × 4500 = 1080 kcal.

Thermal efficiency on B.H.P. basis

$$= \frac{\text{B.H.P.} \times 4500}{1080 \times J} = \frac{23.4 \times 4500}{1080 \times 427} \times 100 = 22.7\%. \qquad \textbf{Ans.}$$

Example 10.3. *An internal combustion engine consumes 6 kg of fuel per hour and I.H.P. of engines is 27. It uses 12 kg of cooling water per minute and the inlet and outlet temperatures of water being 18°C and 48°C respectively. The exhaust gases raise the temperature of 8.40 kg of water through 32°C. The calorific value of fuel used is 10560 kcal per kg. Calculate the indicated thermal efficiency and draw heat balance sheet.*

Solution. Heat in fuel supplied per minute = WC_c

$$= \frac{6}{60} \times 10{,}560 = 1056 \text{ kg cal.}$$

Indicated thermal efficiency

$$\eta_i = \frac{\text{I.H.P.} \times 4500}{W.\, C_v \times J} \times 100$$

$$= \frac{27 \times 4500}{1056 \times 427} \times 100 = 27\%. \qquad \textbf{Ans.}$$

Heat energy absorbed in indicated horse power

$$= \frac{\text{I.H.P.} \times 4500}{J} = \frac{27 \times 4500}{427}$$

$$= 284 \text{ kcal}$$

Heat rejected to cooling water

$$= 12\,(48 - 18) = 12 \times 30 = 360 \text{ kcal.}$$

Heat carried away by exhaust gases

$$= 8.40 \times 32 = 268.8 \text{ kcal}$$

Heat Balance Sheet

Item	*Heat unit (kcal)*	*(per cent)*
Heat supplied in fuel	1056	100%
Heat energy absorbed in I.H.P.	284	26.90
Heat rejected to cooling water	360	34.19
Heat carried away by exhaust gases	268.3	25.35
Heat unaccounted for (By Difference)	143.2	13.36
Total	1056	100%

Example 10.4. *A diesel power station is to supply power demand of 30 kW. If the overall efficiency of the power generating unit is 40%, calculate the following :*

(a) Amount of diesel oil required per hour.

(b) The electric energy generated per tonne of the fuel oil.

The calorific value of fuel oil used is 12,000 kcal / kg.

Solution.

(a) Efficiency $= \dfrac{\text{Output}}{\text{Input}}$

Output = 30 kW

Efficiency = 40%

$\therefore \quad 0.4 = \dfrac{\text{Output}}{\text{Input}} = \dfrac{30}{\text{Input}} = \dfrac{30}{0.4} = 75 \text{ kW}$

Input per hour = 75 × 1 = 75 kWh.

Now 1 kWh = 860 kcal.

∴ Input per hour = 75 × 860 = 64,500 kcal.

Fuel oil required $= \dfrac{64{,}500}{12{,}000} = 5.37$ kg/hr. **Ans.**

(b) Input per tonne of fuel oil = 1 × 1000 × 12,000 kcal.

$= 12 \times 10^6$ kcal.

$= \dfrac{12 \times 10^6}{860} = 13{,}954$ kWh.

As, Efficiency $= \dfrac{\text{Output}}{\text{Input}}$

∴ Output = Efficiency × Input

= 0.4 × 13,954 = 5,581 kWh. **Ans.**

Example 10.5. *A diesel engine has a brake thermal efficiency of 30%. If the calorific value of fuel used is 10000 kcal/kg, calculate the broke specific fuel consumption.*

Solution. η_b = Break thermal efficiency = 0.3

I.H.P. hr = 632.5 kcal

$$\eta_b = \frac{\text{H.P. hr equivalent}}{w \times C.V.}$$

where w = Specific fuel consumption per H.P. hr.

$$\text{C.V.} = \text{Calorific value of fuel} = 10{,}000 \text{ kcal/kg}$$

$$\therefore \qquad \eta_b = 0.3 = \frac{632.5}{w \times 10{,}000}$$

$$w = \frac{632.5}{0.3 \times 10{,}000} = 0.21 \text{ kg/ H.P. hr.} \qquad \textbf{Ans.}$$

Example 10.6. *A six cylinder two stroke cycle marine diesel engine with 100 mm bore and 120 mm stroke delivers 200 B.H.P. at 2000 R.P.M. and uses 100 kg of fuel per hour. If I.H.P. is 240, determine the following :*

(a) Torque, (b) Mechanical efficiency, (c) Indicated specific fuel consumption.

Solution. (*a*) $$\text{B.H.P.} = \frac{2\pi NT}{4500}$$

where T = Torque

N = R.P.M.

$$200 = \frac{2\pi \times 2000 \times T}{4500}$$

$$= \mathbf{71.7 \ kg. \ m} \qquad \textbf{Ans.}$$

(*b*) $$\eta_m = \text{Machanical efficiency}$$

$$\frac{\text{B.H.P.}}{\text{I.H.P.}} = \frac{220}{240} = \mathbf{0.83.} \quad \textbf{Ans.}$$

(*c*) Indicated specific fuel consumption $= \dfrac{W}{\text{I.H.P.}}$

where W = Amount of fuel used per hour.

Indicated specific fuel consumption

$$= \frac{100}{240} = \mathbf{2.41 \ kg/I.H.P. \ hour.} \qquad \textbf{Ans.}$$

Example 10.7. *A diesel engine develops 200 H.P. to overcome friction and delivers 1000 BHP. Air consumption is 90 kg per minute. The air fuel ratio is 15 to 1. Find the following :*

(a) IHP, (b) Mechanical efficiency, (c) Specific fuel consumption.

Solution. (*a*) $$\text{B.H.P.} = 1000$$

$$\text{F.H.P.} = 200$$

$$\text{IHP} = \text{BHP} + \text{FHP} = 1000 + 200 = 1200 \qquad \textbf{Ans.}$$

(*b*)

$$\eta_m = \text{Mechanical efficiency}$$

$$= \frac{\text{B.H.P.}}{\text{I.H.P.}} = \frac{1000}{1200} = 0.83 = 83\% \qquad \textbf{Ans.}$$

(*c*)

$$K = \text{Air fuel ratio} = 15$$

$$W = \text{Air consumed per hour}$$

$$= 90 \times 60 = 5400 \text{ kg per hour}$$

$$S = \text{Amount of fuel consumed}$$

$$= \frac{W}{K} = \frac{5400}{15} = 360 \text{ kg per hour}$$

Specific fuel consumption $= \dfrac{S}{\text{I.H.P.}} = \dfrac{360}{1200} = 0.3$ kg/I.H.P. hr. **Ans.**

QUESTION

1. How will you classify I.C. engines? Describe the working of two stroke and four stroke cycle diesel engines. Discuss their relative merits and demerits.
2. What are the different methods of cooling diesel engine? Compare air cooling and water cooling.
3. Describe the various methods used for starting diesel engine. Describe in correct sequence the steps for starting and stopping procedure.
4. Describe the auxiliary equipment of diesel engine power plant.
5. Give the layout of a diesel engine plant.
6. What are the various methods of fuel injection? What precautions should be observed to ensure that fuel injection is satisfactory?
7. What are the various factors to be considered while selecting the site for diesel engine power plant? Discuss the advantages and disadvantages of the diesel power plant.
8. Compare I.C. engine with steam engine and state the advantages of I.C. engine over steam engine.
9. What is the importance of heat balance sheet? What are the various items considered while drawing the heat balance sheet of I.C. engine? Give a typical heat balance at full load for an I.C. engine.
10. Describe the procedure of testing diesel power plant performance. How is plant maintenance carried out ?
11. Write short notes on the following :
    (*a*) Lubrication of diesel power plant.
    (*b*) Indicated Thermal Efficiency, I.H.P and B.H.P.
    (*c*) Applications of diesel power plant.
    (*d*) Warming up of diesel engine.
12. Describe a typical filter and silencer installation for a diesel engine.
13. Define specific fuel consumption. Explain indicated specific fuel consumption and brake specific fuel consumption.
14. A four stroke diesel engine gave the following test results at a speed of 450 R.P.M.

Mean effective pressure = 8.50 kg/cm^2
Cylinder bore = 22 cm.
Stroke = 26 cm.
Specific fuel consumption = 0.32 kg/BHP/hr
Calorific value of fuel = 11800 kcal per kg.
Mechanical Efficiency = 38%

Determine the following :

(a) B.H.P. *(b)* I.H.P.
(c) Indicated thermal efficiency. *(d)* Brake thermal efficiency.

15. Compare a diesel and petrol engine.

16. Write short notes on the following :
(a) I.C. engine fuels. *(b)* Cost of diesel power plant.

17. *(a)* What is supercharging? What methods are used for supercharging diesel engines?
(b) Discuss the advantages of supercharging.

18. *(a)* Under what conditions diesel generating plants are preferred?
(b) On what factors is the size of the generating plant selected?
(c) Draw a net diagram of a cooling system used for diesel power plants showing all the essential components. What are the advantages of double circuit over single circuit system? What precautions should be taken to ensure that cooling is satisfactory?

19. Name the methods used to purify lubricating oil.

20. Draw a neat diagram of a diesel engine and explain the function of different parts.

21. Draw a neat sketch of a diesel power plant showing all the systems.

22. What are the applications of diesel electric power plants?

23. *(a)* Name the essential components of a diesel power plant.
(b) How is the noise of the diesel engine reduced?

24. Explain the scope of utilizing the waste heat in the diesel engine exhaust.

25. *(a)* Explain the important functions of the lubricating system in a diesel engine.
(b) Define cetane number of a fuel.

26. Give the typical valve timing diagram of a four stroke diesel engine.

27. Define different efficiencies of a diesel engine.

28. Give an energy balance of a C.I. engine.

29. What are the different types of compressors used for supercharging? Why are turbochargers superior to superchargers?

30. Give the layout of a diesel engine power plant.

31. Explain methods of improving thermal efficiency of diesel electric power plant.

32. Why the cooling and cleaning of lubricating oil is necessary? Draw a neat diagram of lubrication system used for medium capacity diesel power plant.

33. What are the outstanding features of diesel power plants over the thermal plants? Why diesel plants are not used for high capacity? What are its drawbacks when used for high capacity compared to steam plants?

34. Draw a neat diagram of a fuel storage and fuel supply system used for a diesel power plant. What are the advantages of underground fuel storage?

35. Draw a neat diagram of a cooling system used for diesel power plant showing all the essential components.

36. Write short notes on :
(a) Diesel engine governing. *(b)* Maintenance of diesel engines.

11

Nuclear Power Plant

11.1 INTRODUCTION

As large amount of coal and petroleum are being used to produce energy, time may come when their reserves may not be able to meet the energy requirements. Thus there is tendency to seek alternative sources of energy. The discovery that energy can be liberated by the nuclear fission of materials like uranium (U), plutonium (Pu), has opened up a new sources of power of great importance. The heat produced due to fission of U and Pu is used to heat water to generate steam which is used for running turbo-generator. It has been found that one kilogram of U can produce as much energy as can be produced by burning 4500 tonnes of high grade coal. This shows that nuclear energy can be successfully employed for producing low cost energy in abundance as required by the expanding and industrialising population of future.

Wisely used nuclear energy can be of great benefit for mankind. It can bridge the gap caused by inadequate coal and oil supplies. It should be used to as much extent as possible to solve power problem. Some of the factors which go in favour of nuclear energy are as follows:

1. Hydro-electric power is of storage type and is largely dependent on monsoons. The systems getting power from such plants have to shed load during the period of low rainfall.
2. Oil is mainly needed for transport, fertilizers and petrochemicals and thus cannot be used in large quantities for power generation.
3. Coal is available only in some parts of the country and transportation of coal requires big investments.
4. Nuclear power is partially independent of geographical factors, the only requirement being that there should be reasonably good supply of water. Fuel transportation networks and larger storage facilities are not needed and nuclear power plant is a clean source of power which does not pollute the air if radio active hazards are effectively prevented.
5. Large quantity of energy is released with consumption of only a small amount of fuel.

World's first nuclear power plant was commissioned in 1954 in U.S.S.R. Since then efforts are being made to make use of nuclear power.

In India, it was Dr. H.J. Bhabha who put India on the road to nuclear research, more than two decades ago. He had in his mind not the destructive power of atom but using this new source of immense energy for peaceful purposes like power production. First nuclear power plant is at Tarapur (Trombay), its first reactor went in 1956. It has two boiling water reactors (B.W.R.) each of 200 MeW capacity and each uses enriched U as fuel. These two reactors have been built with the help of U.S.A. The other two nuclear power plants with BWR are at Rawat Bhata in Rajasthan and at Kalpakkam in Tamil Nadu. As on January 2011, the status of operational nuclear power plants is as under :

1.	Koiga, Karnataka	220 × 4 = 880 MW
2.	Kakrapar, Gujrat	220 × 2 = 440 MW
3.	Kalpakkam, Tamil Nadu	220 × 2 = 440 MW
4.	Narora, U.P.	220 × 2 = 440 MW
5.	Rawat Bhata (Kota), Rajasthan	100 × 1 + 200 × 1 + 220 × 4 = 1180 MW
6.	Tarapur (Trombay), Maharashtra	160 × 2 + 540 × 2 = 1400 MW

The plants under construction are :

1.	Kundankulam, T.N.	1000 × 2 = 2000 MW
2.	Kolapakkam, T.N.	500 × 1 = 500 MW
3.	Rawatbhata	700 × 2 = 1400 MW
4.	Banswara, Rajasthan	700 × 2 = 1400 MW

Nuclear energy is the most useful power available to mankind today. In large parts of the world it is becoming a predominant source of electrical power and a versatile tool for use in many areas of human endeavour. In India too atomic energy is being used to generate electricity and to bring about improvement in industry, agriculture, medicine and in other fields through its varied applications.

The major centre for research and development work in atomic energy in our country is the Bhabha Atomic Research Centre (BARC) at Trombay. The centre is the largest single scientific establishment in India. Besides BARC three other national institutions associated with some important aspects of atomic energy programme are as follows:

1. Tata Institute of Fundamental Research, Bombay.
2. Tata Memorial Centre Bombay.
3. Saha Institute of Nuclear Physics, Calcutta.

Nuclear power plants resemble, convention thermal power plants insofar as they produce steam to drive a turbine whose rotational energy is converted into electricity by means of a generator. In contrast to power plants fired by coal, oil or gas, nuclear power plant use the energy released from splitting atoms to convert water into steam, The "fuel" that leads itself to this splitting procedure is the uranium atoms, and its splitting, or fission, is engineered within a reactor.

India went nuclear in 1956 when its first research reactor went critical at Trombay. Six units are now under various phases of operation construction or design two each at Kota, Kalpakkam and Narora. They are all of the CANDU (Canadian-Deuterium-Uranium) type, most suited to Indian conditions. India has limited deposits of uranium and would not be dependent on foreign enrichment facilities or a foreign supply to enriched fuel, (used in the Tarapur power plant). CANDU reactors, which use fuel available within the country, do not require large capital and operating outlays for fuel enrichment.

For the purpose of sustainable development it is advisable to use non-fossil energy source for electricity generation. The generation of electricity by nuclear power reactors help to achieve the major objective of sustainable development. The nuclear fuel does not have any industrial or any other major application today or in the future. On the other hand, fossil fuels got power generation *i.e.* coal, oil and gas have other industrial, domestic and agricultural applications. The vision prepared by Department of Atomic Energy (DAE) envisages setting up of 20,000 MW nuclear power capacities by 2020 which shall be increased to 64000 MW by 2032. At present (2010) 20 reactors of total 4780 MW capacities are in operation and 9 reactors of total 6700 MW capacity are under construction.

Nuclear power in the world is today avoiding approximately 8% additional CO_2 emissions that could occur if electricity produced by the nuclear power were to be produced by fossil fuels. On a global scale nuclear power currently reduces carbon dioxide emission by some 2.4 billion tones per year.

11.2 ADVANTAGES AND DISADVANTAGES

There are outstanding benefits and challenging problems in adopting the nuclear power generation before the developing countries and few of them are as listed below:

1. It minimises the ecological effects of power generation.
2. It upgrades the local industry through the use of less expensive electric energy output.
3. Space requirement of a nuclear power plant is less as compared to other conventional power plants of equal size.
4. A nuclear power plant consumes very small quantity of fuel. Thus fuel transportation cost is less and large fuel storage facilities are not needed. Further the nuclear power plants will conserve the fossil fuels (coal, oil, gas etc.) for other energy needs.
5. There is increased reliability of operation.
6. Nuclear power plants are not effected by adverse weather conditions.
7. Nuclear power plants are well suited to meet large power demands. They give better performance at higher load factors (80 to 90%).
8. Materials expenditure on metal structures, piping, storage mechanisms are much lower for a nuclear power plant than a coal burning power plant. For example for a 100 MW nuclear power plant the weight of machines and mechanisms, weight of metal structures, weight pipes and fittings and weight of masonry and bricking up required are nearly 700 tonnes, 900 tonnes, 200 tonnes and 500 tonnes respectively whereas for a 100 MW coal burning power plant the corresponding value are 2700 tonnes, 1250 tonnes, 300 tonnes and 1500 tonnes respectively. Further area of construction site required for 100 MW nuclear power plant is 5 hectares whereas for a 100 MW coal burning power plant the area of construction site in nearly 15 hectares.
9. It does not require large quantity of water.

Disadvantages

1. Initial cost of nuclear power plant is higher as compared to hydro or steam power plant.
2. Nuclear power plants are not well suited for varying load conditions.
3. Radioactive wastes if not disposed carefully may have bad effect on the health of workers and other population.

In a nuclear power plant the major problem faced is the disposal of highly radioactive waste in the form of liquid, solid and gas without any injury to the atmosphere. The preservation of waste for a long time creates lot of difficulties and requires huge capital.

4. Maintenance cost of the plant is high.
5. It requires trained personnel to handle nuclear power plants.

11.3 COMPARISON WITH STEAM PLANTS

Nuclear plants as well as thermal plants, both are presently installed with high unit capacity of 500 to 1000 MW. Now-a-days, the nuclear power is preferred where there are no hydro-potentials and the coal fields are far away from the required load centers.

(*i*) The number of workman required for the operation of nuclear power plant is much less than a steam power plant. This reduces the cost of operation.

(*ii*) The capital cost of nuclear power plant falls sharply if the size of plant is increased. The capital cost as structural materials, piping, storage mechanism etc. is much less in nuclear power plant than similar expenditure of steam power plant. However, the expenditure of nuclear reactor and building complex is much higher.

(*iii*) The cost of power generation by nuclear power plant become competitive with cost of steam power plant above the unit size of about 500 MW.

(*iv*) There are no fuel transportation, handling and storage charges, and also there is no problem of ash disposal.

(*v*) Nuclear plant occupies less space in comparison to thermal plants, therefore, the civil construction cost is also less.

(*vi*) The nuclear plant is more economical compared with thermal plants in areas which are remote from coal fields.

11.4 SITE SELECTION

In taking a decision on locating a new nuclear power plant, the following points have to be kept in view:

1. *Availability of water.* At the power plant site an ample quantity of water should be available for condenser cooling and make up water required for steam generation. Therefore the site should be nearer to a river, reservoir or sea.
2. *Distance from load centre*. The plant should be located near the load centre. This will minimise the power losses in transmission lines.
3. *Distance from populated area.* The power plant should be located far away from populated area to avoid the radioactive hazard.
4. *Accessibility to site.* The power plant should have rail and road transportation facilities.
5. *Waste disposal.* The wastes of a nuclear power plant are radioactive and there should be sufficient space near the plant site for the disposal of wastes.
6. *Safeguard against earthquakes.* The site is classified into its respective seismic zone 1, 2, 3, 4, or 5. The zone 5 being the most seismic and unsuitable for nuclear power plants. About 300 km of radius area around the proposed site is studied for its past history of tremors, and earth-quakes to assess the severest earth-quake that could occur for which the foundation building and equipment supports are designed accord-

ingly. This ensures that the plant will retain integrity of structure, piping and equipments should an earthquake occur. The site selected should also take into account the external natural events such as floods, including those by up-stream dam failures and tropical cyclones.

7. *Foundation condition.* The substrata must be strong enough to support the heavy reactor which may weigh as high as 100,000 tons and imposed nearing pressure of around 50 tons per square meter. Therefore, it is necessary to select a site with good foundation conditions to avoid the dangers of different settlements.

The most important consideration in selecting a site for a nuclear power plant is to ensure that the site-plant combination does not pose radiological or any hazards to either the public, plant personnel on the environment during normal operation of plant or in the unlikely event of an accident.

The Atomic Energy Regulatory Board (AERB) has stipulated a code of practice on safety in Nuclear Power Plant site and several safety guidelines for implementation.

In order to study prospective sites for a nuclear power plant the Department of Atomic Energy (DAE) of our country appoints a site selection committee with experts from the following:

(*i*) Central Electricity Authority (CEA).
(*ii*) Atomic Minerals Division (AMD).
(*iii*) Health and safety group and the Reactor Safety Review group of the Bhabha Atomic Research Centre (BARC).
(*iv*) Nuclear Power Corporation (NPC).

The committee carries out the study of sites proposed. The sites are then visited, assessed and ranked. The recommendations of the committee are then forwarded to DAE and the Atomic Energy Commission (AEC) for final selection.

The trend is to locate a number of units in a cluster at a selected site. The highest rated units in India are presently of 500 MW. The radiation dose at any site should not exceed 100 milligram per member of the public at 1.6 km boundary.

11.5 IMPORTANT TERMS IN NUCLEAR ENERGY

Some of the important terms associated with nuclear energy are being discussed hereunder:

11.5.1. Atom, Atomic Number and Mass Number

All matter is composed of unit particles called *atoms*. An atom consists of a relatively heavy, positively charged *nucleus* and a number of much lighter negatively charged *electrons* orbiting around the nucleus. The nucleus consists of positively charged *protons* and neutral *neutrons*. Protons and neutrons together are called *nucleons*. The electric charge on the proton is equal in magnitude but opposite in sign to that on an electron and therefore atom as a whole is electrically neutral and the number of protons in the nucleus is equal to the number of electrons in the orbit.

Any addition of electron to the neutral atom make the atom negatively charged. Similarly, any subtraction of electron will make it positively charged. Such atom is known as *ion* and the process of charging the atom is known as *ionisation.* Atomic energy is a consequence of the redistribution of particles with the atomic nuclei. Therefore, nuclear power engineering is specially with the variations of nucleons in nucleus.

The number of protons in an atom is known as *atomic number*. The total number of protons and neutrons in the nucleus of an atom is known as *mass number*. Some elements exist in more than one form, with the same atomic number but with different mass numbers. These are known as isotopes of an element.

11.5.2. Structure of the Atom

Atom of an element is the smallest (ultimate) particle that can exist and still retain the characteristics of that element. An atom consists of a nucleus at the centre and electrons revolving around the nucleus in well defined orbits. As already discussed, the nucleus consists of protons and neutrons. The nucleus contains practically the entire mass of the atom. The electrons are negatively charged and have very unsignificant mass as compared to the mass of protons and neutrons.

11.5.3. Binding Energy, Nuclear Stability and Mass Defect

Protons have positive charge and it is difficult to bring these together in a nucleus. Some energy is required to bring and keep the protons together in the nucleus of an atom. This energy is known as *binding energy*. Therefore, when a nucleus disintegrates, very large amount of energy is released. This energy, due to the fission of a nucleus, is used for power production.

The sum of the masses of the protons and neutrons that comprise the nucleus exceeds the mass of the atomic nucleus. This difference in mass is called the *mass defect*. The mass defect is found by adding up all the individual particle weights and subtracting the actual mass of the atom.

The binding energy acts as a glue which binds the protons and neutrons together in the nucleus. The binding energy per nucleon (*i.e.,* proton and neutron) determines the stability of the nucleus.

11.5.4. Radioactivity and Radioactive Decay

Most isotopes that occur in nature are stable. Some isotopes of heavy elements like thallium, lead and bismuth, and all isotopes of heavier elements starting with polonium are not stable (the binding energy per nucleon being small) and emit radiation till a more stable nucleus is reached. Thus, a spontaneous disintegration process, called *radioactive deay* occurs. The resulting nucleus is called the *daughter* and the original nucleus is called the *parent*.

Whenever the isotopes of higher atomic weight elements undergo fission α, β, γ rays are emitted. This is known as radio-active emission due to fission. Also many of the fission fragments are unstable and α, β or γ rays in reaching stabilised levels. This radioactive emission is injurious to health. Concrete is a good absorber of the radioactive emission and therefore, reactors are surrounded by thick concrete walls. This is known as *shielding*.

The naturally occurring elements of highest atomic weight, such as thorium, radium and uranium consist of unstable isotopes. These elements undergo spontaneous change referred as radioactive change. The radioactive change is accompanied by the emission of α-particles, β-particles or γ-particles or simultaneously two or all three from the atomic nucleus.

The basic unit of radioactivity is named as *Curie*. It is the rate of decay of one gram of radioactivity element radium. It has been estimated that rate of decay of one gram of radium is equal to 3.7×10^{10} disintegration per second. Therefore, 1 Curie = 3.7×10^{10} disintegration per second. It describes the intensity of radioactivity in a sample of material.

11.6 NUCLEAR FISSION AND CHAIN REACTION

Fission is the process in which heavy nucleus is split when it is bombarded by certain particles. Some of the isotopes of the heaviest elements, uranium 235, uranium 233 and plutonium 239, can upon absorbing neutrons, be readily fissioned. This fission of the nucleus produces two or rarely three, fragments moving at high speeds, two or three neutrons, and considerable energy. The nuclear fission process is used in nuclear power plants for generation of energy. The kinetic energy of the fission fragments and the radiant energy is ultimately converted into heat in the surrounding material. It is this heat which is finally used to produce steam for the operation of turbine and generators.

Uranium exist as isotopes of U^{238}, U^{234} and U^{235}. Out of these isotopes U^{235} is most unstable. When a neutron is captured by a nucleus of an atom of U^{235}, it splits up roughly into two equal fragments and about 2.5 neutrons are released and a large amount of energy (nearly 200 million electron volts MeV) is produced. This is called fission process. The neutrons so produced are very fast moving neutrons and can be made to fission other nuclei of U^{235} thus enabling a chain reaction to take place. When a large number of fissions occurs, enormous amount of hear is produced.

The neutrons released have a very high velocity of the order of 1.5×10^7 metres per second. The energy liberated in the chain reaction is according to Einstein law (also known as 'energy mass relationship'),

$$E = mc^2$$

where E = Energy produced
m = mass in grams
c = speed of light in cm/sec equivalent to 3×10^{10} cm/sec.

Out of 2.5 neutron released in fission of each nuclei of U^{235}, one neutron is used to sustain the chain reaction, about 0.9 neutron is captured by U^{235}, which gets converted into fissionable material, Pu^{239} and about 0.6 neutrons is partly absorbed by control rod material, coolant moderator and partly escape from the reactor. Production of the fissionable material Pu^{239} during chain reaction compensates the burn up of primary fuel U^{235} U^{238} + neutron = Pu^{239}. If thorium is used in the reactor core it produces fissionable material U^{233}.

$$Th^{232} + \text{Neutron} \rightarrow U^{233}$$

Pu^{239} and U^{233} so produced are fissionable material and can be used as nuclear fuel and are known as secondary fuel. U^{235} is called primary fuel.

The chain reaction producing a constant rate of heat energy can continue only if the neutron liberated by fission, balance the disposal of neutrons by different ways listed below:

1. Escape of neutrons from the fissionable materials.
2. Fission capture by U^{235}, and Pu^{239} and U^{233}.
3. Non-fission capture by moderator, control rods, fission fragments and by impurities etc.

If the neutrons produced in the chain reaction are less than the neutrons disposed off in different ways, the chain reaction will stop. Fig. 11.1. shows the chain reaction.

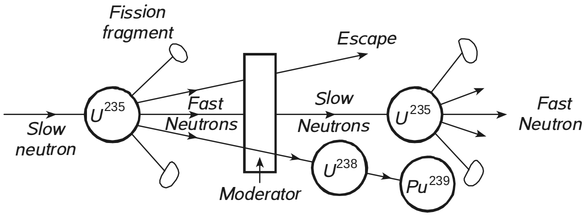


Fig. 11.1. Chain Reaction

11.6.1. Multiplication Factor

Multiplication factor is used to determine whether the chain reaction will continue at a steady rate, increase or decrease. It is given by the relation,

$$K = \frac{P}{A + E}$$

where K = Effective multiplication factor.
P = Rate of producction of neutrons.
A = Combined rate of absorption of neutrons.
E = Rate of leakage of neutrons.
K = 1 indicates that the chain reaction will continue at steady rate (critical) K >1 indicates that the chain reaction will be building up.

11.6.2. Neutron Energies

The newly born fission neutrons have energies varying between 0.075 to 17 MeV. As these neutrons travel through matter, they collide with other nuclei and get slowed down. This process is called *scattering*. The neutron gives up some of its energy with each successive collision. Neutrons are classified into three general categories according to their energy as fast, intermediate and slow.

11.6.2. Thermal (slow) Neutrons

When a large number of neutrons are slowed down in a medium, such as a moderator, the lowest energies that they can attain are those that put them in thermal equilibrium with the molecules of that medium. In this state they become thermalized and are called *thermal* (or slow) *neutrons*. A reactor primarily utilizing thermal neutrons for fission is called a *thermal reactor.*

11.6.3. Fast Neutrons

Fast neutrons are those neutrons which have lost relatively little energy since being produced in the fission process. The lower limit of their energy is taken as 0.1 MeV (million electron volts.)

The general neutrons energies are as follows:

(*a*) Thermal neutrons – 0.025 eV
(*b*) Intermediate neutrons – 0.01 to 0.1 MeV
(*c*) Fast neutrons – 0.1 MeV or more.

Thermal neutrons are the most effective in causing fission and, therefore it is desirable to slow down or moderate the fast neutrons which normally have an energy of about 1 MeV.

11.6.4. Neutron Flux

It is a measure of the intensity of neutron radiation and it is the number of neutons passing through 1 cm^2 of a given target in one second. It is expressed as uv, where u is number of neutrons per cubic centimeter and v is velocity of neutrons in cm/sec.

11.7 CLASSIFICATION OF REACTORS

The nuclear reactors can be classified as follows:

1. Neutron Energy. Depending upon the energy of the neutrons at the time they are captured by the fuel to induce fissions, the reactors can be named as follows:

(*a*) *Fast Reactors*. In such reactors fission is brought about by fast (non moderated) neutrons.
(*b*) *Thermal Reactors or Slow Reactors.* In these reactors the fast moving neutrons are slowed down by passing them through the moderator. These slow moving neutrons are then captured by the fuel material to bring about the fission.
(*c*) *Intermediate Reactors.* In such reactors most of the fission events are caused by neutrons in the course of slowing down.

2. **Type of Fuel Used.** Nuclear reactor may use U^{235}, U^{238} and Th^{232} as their fuels. Th^{232} and U^{238} get converted in fissionable materials like U^{233} and Pu^{239} respectively.

3. **Type of Coolant Used.** On the basis of coolant used the reactors may be classified as follows:

(*a*) Gas cooled reactor.
(*b*) Water (ordinary or heavy water) cooled reactors.
(*c*) Liquid metal cooled reactors.

4. **Type of Moderator Used.** On this basis the reactors may be classified as follows:

(*a*) Graphite reactors.
(*b*) Beryllium reactors.
(*c*) Water (ordinary or heavy water) reactors.

5. **Type of Core.** According to the type of core used the reactor may be classified as follows:

(*a*) *Homogeneous reactor.* In this reactor fuel and moderator represent a uniform mixture such as an aqueous solution of a uranium salt.
(*b*) *Heterogeneous reactor.* In such reactor fuel rods are inserted in moderator. The fuel elements are generally arranged in some regular order forming a lattice.

11.8 MAIN PARTS OF A NUCLEAR REACTOR

A nuclear reactor is an apparatus in which heat is produced due to nuclear fission chain reaction. Fig. 11.2 shows the various parts of reactor, which are as follows:

(*i*) Nuclear Fuel	(*ii*) Moderator
(*iii*) Control Rods	(*iv*) Reflector
(*v*) Reactor Vessel	(*vi*) Biological Shielding
(*vii*) Coolant.	

Fig. 11.3 shows a schematic diagram of nuclear reactor.

The nuclear reactor may be regarded as a substitute for the boiler fire box of steam plant or combustion chamber of a gas turbine plant. The heat produced in the nuclear power plant is by fission whereas in steam and gas turbine plants, the heat is produced by combustion. The other cycle of operation and components required are exactly same. The steam or the gas may be used as working fluid in nuclear power plant. The nuclear power plant may be of steam driven turbine or gas driven turbine as per the choice of the fluid.

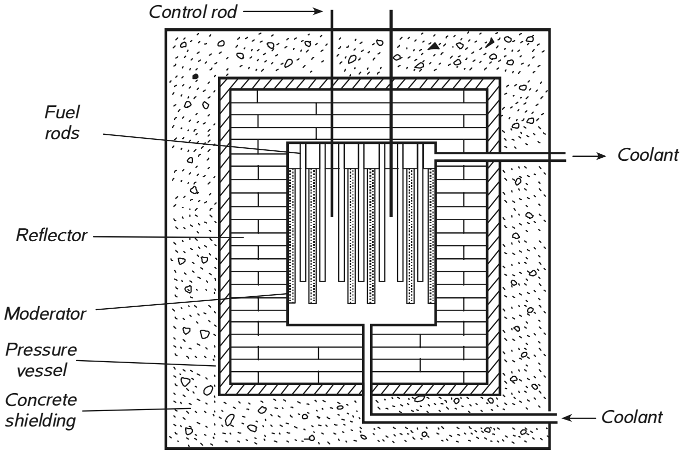


Fig. 11.2. Parts of a reactor.

11.8.1 Nuclear Fuel

Fuel of a nuclear reactor should be fissionable material which can be defined as an element or isotope whose nuclei can be caused to undergo nuclear fission by nuclear bombardment and to produce a fission chain reaction. It can be one or all of the following U^{233}, U^{235} and Pu^{239}.

Natural uranium found in earth crust contains three isotopes namely, U^{234}, U^{235}, U^{238} and their average percentage is as follows:

$$U^{238} - 99.3\%;\ U^{235} - 0.7\%;\ U^{234} - \text{Trace}.$$

Out of these, U^{235} is most unstable and is capable of sustaining chain reaction and has been given the name as primary fuel. U^{233} and Pu^{239} are artificially produced from Th^{232} and U^{238} respectively and are called secondary fuel.

Pu^{239} and U^{233} so produced can be fissioned by thermal neutrons. Nuclear fuel should not be expensive to fabricate. It should be able to operate at high temperatures and should be resistant to radiation damage.

Uranium deposits are found in various countries such as Congo, Canada, U.S.A., U.S.S.R., U.K., Australia, Czechoslovakia and Portugal etc.

The fuel should be protected from corrosion and erosion of the coolant and for this it is encased in metal cladding generally stainless steel or aluminium.

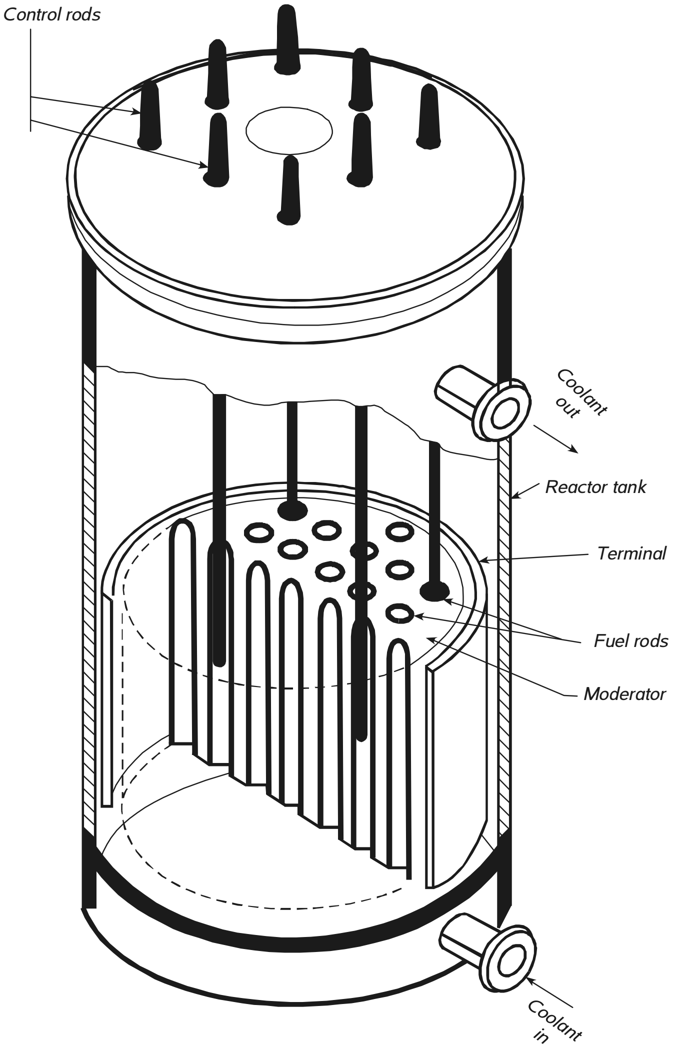


Fig. 11.3. Schematic diagram of nuclear reactor.

Adequate arrangements should be made for fuel supply, charging or discharging and storing of the fuel.

For economical operation of a nuclear power plant special attention should be paid to reprocess the spent up (burnt) fuel elements to recover the unconsumed fuel. The spent up fuel elements are intensively radioactive and emits some neutrons ad gamma rays and should be handled carefully.

In order to prevent the contamination of the coolant by fission products, a protective coating or cladding mist separate the fuel from the coolant stream. Fuel element cladding should possess the following properties:

(*i*) It should be able to withstand high temperature within the reactor.
(*ii*) It should have high corrosion resistance.
(*iii*) It should have high thermal conductivity.
(*iv*) It should not have a tendency to absorb neutrons.
(*v*) It should have sufficient strength to withstand the effect of radiations to which it is subjected.

Density of various nuclear fuel is indicated in Table 11.1

Table 11.1. Density of various nuclear fuels

Fuel	*Density (gm/cm^3)*
U-233	18.68
U-235	18.68
U-238	18.68
U-239	19.6

Uranium oxide (UO_2) is another important fuel element. Uranium oxide has the following **advantages** over natural uranium:

(*i*) It is more stable than natural uranium.
(*ii*) There is no problem or phase change in case of uranium oxide and therefore it can be used for higher temperatures.
(*iii*) It does not corrode as easily as natural uranium.
(*iv*) It is more compatible with most of the coolants and is not attacked by H_2, N_2.
(*v*) There is greater dimensional stability during use.

Uranium oxide possesses following **disadvantages**:

(*i*) It has low thermal conductivity.
(*ii*) It is more brittle than natural uranium and therefore it can break due to thermal stresses.
(*iii*) Its enrichment is essential.

Uranium oxide is a brittle ceramic produced as a powder and then sintered to form fuel pellets.

Another fuel used in the nuclear reactor is uranium carbide (UC). It is a black ceramic used in the form of pellets.

Table 11.2. indicates some of the physical properties of nuclear fuels.

Table 11.2. Physical properties of nuclear fuels.

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

11.18.2 Fertile Material

It is defined as the material which absorbs neutrons and undergoes spontaneous changes which lead to the formation of fissionable material. U^{238} and Th^{232} are fertile materials. They absorb neutrons and produce fissionable materials Pu^{239} and U^{233} respectively.

11.18.3 Conservation Ratio

It is defined as the ratio of number of secondary fuel atoms to the number of consumed primary fuel atoms. A reactor with a conversion ratio above unity is known as a breeder reactor. Breeder reactor produces more fissionable material than it consumes. If the fissionable material produced is equal to or less than the consumed, the reactor is called converter reactor.

11.18.4 Neutron Flux

It is a measure of the intensity of neutron radiation and it is the number of neutrons passing through 1 cm^2 of a given target in one second. It is expressed as uv, where u is number of neutrons per cubic centimetre and v is velocity of neutrons in cm/sec.

11.18.5 Breeding

It is the process of producing fissionable material (fissionable material) from a fertile material such as uranium 238 (U^{238}) and thorium 232 (Th^{232}) by neutron absorption.

$$(U^{238}) + \text{neutron} \rightarrow Pu^{239}$$

$$Th^{232} + \text{neutron} \rightarrow U^{233}$$

Pu^{239} and U^{233} are fissionable materials and can be used in chain reaction.

11.18.6 Burn Up

It is the amount of fissible material in a reactor that gets destroyed due to fission or neutron capture expressed as a percentage of the original quantity of fissionable materials.

A reactor burning of 1 gm of U^{235} generates nearly 1 MW-day of energy. This is referred to by the term *"fuel burnup"*, which is the amount of energy in MW-days produced of each metric ton of fuel.

11.18.7 Neutron Life Cycle

In a reactor core, neutrons are born at all times and in all places having fissionable material and diffuse in all directions. We will examine the life cycle of a group of neutrons, all assumed to be born at the same time, which undergo scatter, leakage, absorption and other reactions, and finally cause fission and attain the same energy levels simultaneously. This group of neutrons is called a 'generation'. The series of events or processes that such a group of neutrons undergoes from birth until a new generation is born by fission is called a 'life cycle of neutrons'.

11.18.8 Nuclear Fuel Cycle

Fuel cycle is a series of a sequential steps involved in supplying fuel to a nuclear power reactor and subsequent processing up to final disposal of wastes. The steps include: mining, refining uranium, fabrication of fuel elements, their use in nuclear reactor, chemical processing to recover remaining fissionable material, re-enrichment of fuel from recovered material, refabrication of new fuel elements, waste storage etc.

11.18.9. Moderator

In the chain reaction the neutrons produced are fast moving neutrons. These fast moving neutrons are far less effective in causing the fission of U^{235} and try to escape from the reactor. To improve the utilization of these neutrons their speed is reduced. It is done by colliding them with the nuclei of other material which is lighter, does not capture the neutrons but scatters them. Each such collision causes loss of energy, and the speed of the fast moving neutrons is reduced. Such material is called Moderator. The slow neutrons (Thermal Neutrons) so produced are easily captured by the nuclear fuel and the chain reaction proceeds smoothly. Graphite, heavy water and beryllium are generally used as moderator.

Reactors using enriched uranium do not require moderator. But enriched uranium is costly due to processing needed.

A moderator should process the following properties :

(*i*) It should have high thermal conductivity.
(*ii*) It should be available in large quantities in pure form.
(*iii*) It should have high melting point in case of solid moderators and low melting point in case of liquid moderators. Solid moderators should also possess good strength and machinability.
(*iv*) It should provide good resistance to corrosion.
(*v*) It should be stable under heat and radiation.
(*vi*) It should be able to slow down neutrons.

11.18.10 Moderating Ratio

To characterise a moderator it is best to use so called moderating ratio which is the ratio of moderating power to the macroscopic neutron capture coefficient. A high value of moderating ratio indicates that the given substance is more suitable for slowing down the neutrons in a reactor. Table 11.3 indicates the moderating ratio for some of the material used as moderator.

Table 11.3 Moderating Ratios

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

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

Table 11.4 indicates density of various moderators.

Table. 11.4. Densities of moderators

Moderator	*Density (gm/cm³)*
H_2O	1
D_2O	1.1
C	1.65
Be	72

Table 11.5 shows some of the physical constants of heavy water (D_2O) and ordinary water (H_2O).

Table 11.5. Physical constants of heavy and ordinary water

Physical constant	D_2O	H_2O
Density at 293°K	1.1 gm/cm³	0.9982 gm/cm³
Freezing temperature	276.82	273
Boiling temperature	374.5	373°K
Dissociation Constant	0.3×10^{-14}	1×10^{-14}
Dielectric Constant at 293°K	80.5	82
Specific heat at 293°K	1.018	1

11.18.11 Control Rods

Control rods are helpful in controlling the following functions:

(*a*) To start the nuclear chain reaction when the reactor is started from cold.
(*b*) The chain reaction should be maintained at steady state condition (controlled chain reaction) at the required level.
(*c*) To shut down the reactor automatically under emergency condition.

The control and operation of a nuclear reactor is quite different from a fossil and fuelled (coal or oil fired) furnace. The furnace is fed continuously and the heat energy in the furnace is controlled by regulating the fuel feed and the combustion air whereas a nuclear reactor contains as much fuel as is sufficient to operate a large power plant for some months. The consumption of this fuel and the power level of the reactor depends upon its neutron flux in the reactor core. The energy produced in the reactor due to fission of nuclear fuel during chain reaction is so much that if it is not controlled properly the entire core and surrounding structure may melt and radioactive fission products may come out of the reactor thus making it uninhabitable. This implies that we should have some means to control the power of the reactor. This is done by means of control rods.

Control rods in the cylindrical or sheet form are made of boron or cadmium. These rods can be moved in and out of the holes in the reactor core assembly. Their insertion absorbs more neutrons and damps down the reaction and their withdrawal absorbs less neutrons. Thus power of reaction is controlled by shifting control rods which may be done manually or automatically.

Control rods should possess the following properties:

(*i*) They should have adequate heat transfer properties.
(*ii*) They should be stable under heat and radiation.
(*iii*) They should be corrosion resistant.
(*iv*) They should be sufficiently strong and should be able to shut down the reactor almost instantly under all conditions.
(*v*) They should have sufficient cross-sectional area for the absorption.

11.18.12 Reflector

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

11.18.13 Reactor Vessel

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

11.18.14 Biological Shielding

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

11.18.15 Coolant

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

Coolant used should be stable under thermal condition. It should have a low melting point and the high boiling point. It should not corrode the material with which it comes in contact. The coolant should have high heat transfer coefficient. The radioactivity induced in coolant by the neutrons bombardment should be nil. The various fluids used as coolant are water (light water or heavy water), gas (Air, CO_2, hydrogen, Helium) and liquid metals such as sodium or mixture of sodium and potassium and inorganic and organic fluids.

Power required to pump the coolant should be minimum. A coolant of greater density and higher specific heat demands less pumping power and water satisfies this condition to a great extent. Water is a good coolant as it is available in large quantities, can be easily handled, provides some lubrication also and offers no unusual corrosion problems. But due to its low boiling point (212°F at atmospheric pressure) it is to be kept under high pressure to keep it in the liquid state to achieve a high heat transfer efficiency. Water when used as coolant should be free from impurities otherwise the impurities may become radioactive and handling of water will be difficult.

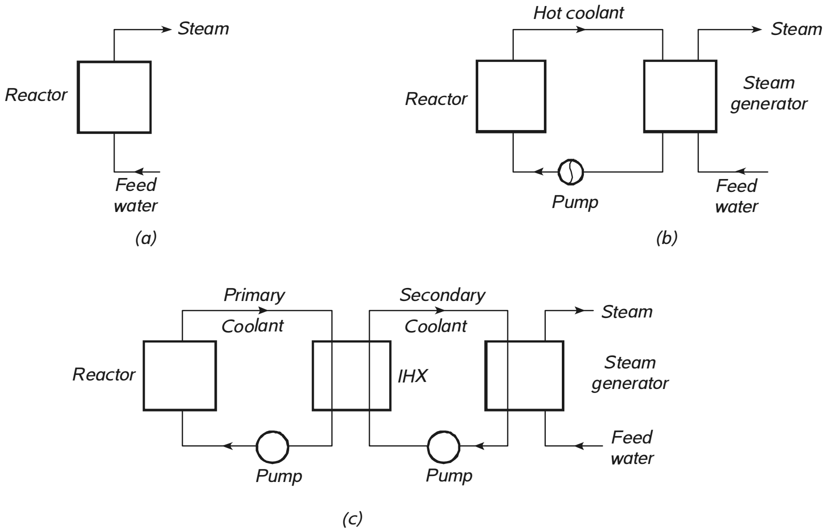
11.18.16 Coolant Cycles

The coolant while circulating through the reactor passages take up heat produced due to chain reaction and transfer this heat to the feed water in three ways as follows:

(*a*) *Direct Cycle.* In this system [Fig.11.4 (*a*)] coolant, which is water, leaves the reactor in the form of steam. Boiling water reactor uses this system.

(*b*) *Single Circuit System.* In this system [Fig.11.4 (*b*)] the coolant transfers the heat to the feed water in the steam generator. This system is used in pressurised reactor.

(*c*) *Double Circuit System.* In this system [Fig.11.4 (*c*)] two coolants are used. Primary coolant after circulating through the reactor flows through the intermediate heat exchanger (IHX) and passes on its heat to the secondary coolant which transfers its heat in the feed water in the steam generator. This system is used in sodium graphite reactor and fast breeder reactor.



(a) (b)

(c)

Fig. 11.4 .

11.18.17 Reactor Core

Reactor core consists of fuel rods, moderator and space through which the coolant flows.

11.9 TYPES OF REACTORS

11.9.1. Pressurised-Water Reactor (PWR)

A Pressurised-Water Reactor (PWR) nuclear plant is shown in Fig. 11.5. It uses enriched Uranium oxide as fuel. Water is used as coolant and moderator. Water passes through the reactor core and takes up the heat liberated due to nuclear fusion of the fuel. In order that water may not boil (due to its low boiling point 212°F at atmospheric conditions) and remain in liquid state it is kept under a pressure of about 1200 p.s.i.g. by the pressuriser. This enables water to take up more heat from the reactor. From the pressuriser water flows to the steam generator where it passes on its heat to the feed water which in turn gets converted into steam.

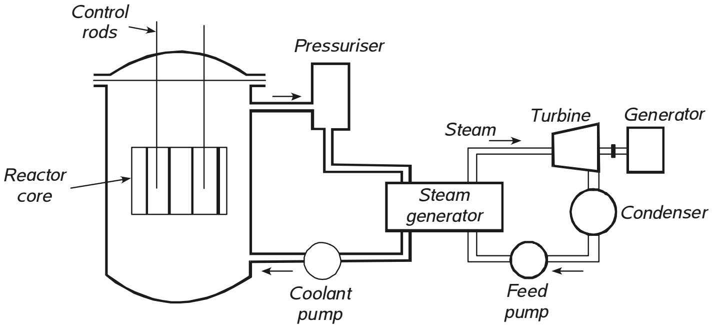


Fig. 11.5. P.W.R. nuclear plants.

The main **advantages** of this reactor are:

1. The steam supplied to the turbine is free from contamination.
2. The reactor is compact in size.
3. Light water is the cheapest coolant and moderator.
4. Cooling system is simple.
5. Fission products remain contained in the reactor and are not circulated. Therefore it provides complete freedom to inspect and maintain the turbine, feed heaters and condenser during operation.
6. It allows to reduce the fuel cost extracting more energy per unit weight of fuel.
7. When more power is demanded, the reactor responds to supply accordingly.

Disadvantages

1. High pressure requires strong pressure vessel and hence requiring high capital cost.
2. The cost of reactor is high as it uses enriched uranium.
3. The thermodynamic efficiency of the cycle is low (about 20%).
4. The corrosion problem is more severe due to high pressure and high temperature in the core.
5. The steam is produced at relatively low temperature and pressure and consequently needs superheating.
6. Reprocessing is difficult as fuel suffers radiation damage.

11.9.2. Boiling Water Reactor (BWR)

Fig. 11.6 shows nuclear power plant using B.W.R. In this reactor enriched uranium (enriched uranium contains more fissionable isotope U^{235} then the naturally occurring percentage 0.7%) is used as nuclear fuel and water is used as coolant. Water enters the reactor at the bottom. It takes up the heat generated due to the fission of fuel and gets converted into steam. Steam leaves the reactor at the top and flows into the turbine. Water also serves as moderator. India's first nuclear power plant at Tarapur has two reactors (each of 160 MW capacity) of boiling water reactor type.

In this reactor, ordinary (or light) water is the moderator and coolant, as well as the neutron reflector. The system pressure is high, but not as high as in a PWR, so that the water boils and steam is generated within the reactor core. In this plant cycle, also known as *'direct steam cycle'*, steam is produced in the reactor itself instead of in a heat exchanger. Since auxiliary power is reduced from 6% to 1% by elimination of the heat transfer circuit between reactor and steam generator, the overall plant efficiency increases with a BWR.

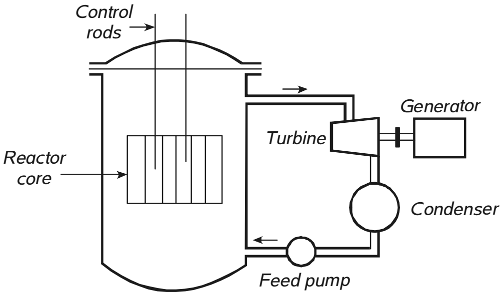


Fig. 11.6. BWR nuclear plant.

Advantages

1. As the steam is directly generated in this reactor, the thermal efficiency of this plant is higher (about 30%) than PWR.
2. The capital cost is lower as the reactor vessel is designed to take low stresses as the pressure in the vessel is lower than PWR. The number of equipment required is also less.
3. As the requirement of heat exchangers, pumps and auxiliary equipment are reduced or eliminated, this results in gain in thermal efficiency with reduction in cost.
4. The reactor is capable of promptly meeting the fluctuating load requirements.

Disadvantages

1. There is possibility of carry over of radioactivity to steam equipment. Therefore, turbine also require shielding.
2. On part load operation, there is wastage of steam resulting in lowering of thermal efficiency.
3. More elaborate safety precautions needed.
4. More biological protection is required.

11.9.3. CANDU (Canadian-Deuterium-Uranium) Reactor

Candu (Canadian-Deuterium uranium) reactor shown in Fig. 11.7 uses heavy water (99.8 per cent Deuterium oxide D_2O) as moderator and coolant. Natural uranium containing 0.7% U^{235} is used as fuel. The reactor vessel is a steel cylinder containing number of tubes which are subjected to high internal pressure. The tubes also called channels contain fuel elements and the pressurised coolant flows along the channels and around the fuel elements to remove the heat generated by fission. The coolant flow is in opposite directions in adjacent channels.

In this reactor refuelling (removal of spent fuel and replacement by fresh fuel) is carried out while the reactor is operating. Number of neutron absorber rods of cadmium are provided for control and protection of reactor. The high temperature coolant leaving the reactor flows to steam generator to heat the feed water so that it gets converted into steam. The coolant then returns to the reactor.

A basic design difference between the CANDU (heavy water) reactor and light water reactors (LWRs) is that in the latter the same water serves as both moderator and coolant, whereas in the CANDU reactor the moderator and coolant are kept separate.

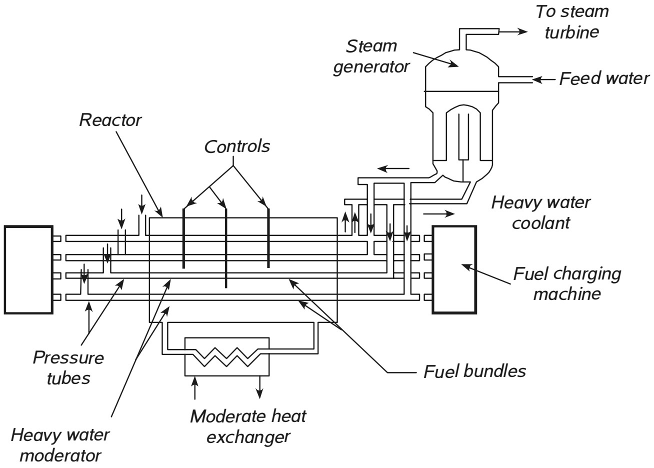


Fig. 11.7.

Advantages

1. Since enriched fuel is not required, these reactors are more economical to those countries which do not produce enriched uranium, as natural uranium can be used as fuel.
2. The reactor vessel does not have to withstand a high pressure like vessel of PWR and BWR. Only the heavy water coolant circuit (fuel tubes) has to be pressurized to allow boiling in the reactor core, therefore, the cost of vessel is less.
3. Heavy water is used as moderator, which has higher multiplication factor and low fuel consumption.
4. The period required for construction is shorter than for PWR and BWR.

Disadvantages

1. The cost of heavy water is very high.
2. Heat exchanger must be leakproof, therefore results higher initial cost.
3. Very high standard of design, manufacture and maintenance are needed.
4. The reactor size is very large as power density is low as compared with PWR and BWR.

11.9.4. Sodium Graphite Reactor (SGR)

The reactor shown in Fig. 11.8 uses two liquid metal coolants. Liquid sodium (Na) serves as the primary coolant and an alloy of sodium potassium (NaK) as the secondary coolant.

Sodium melts at 208°C and boils at 1625°F. This enable to achieve high outlet coolant temperature in the reactor at moderate pressure nearly atmospheric which can be utilized in producing steam of high temperature, thereby increasing the efficiency of the plant. Steam at temperature as high as 1000°F has been obtained by this system. This shows that by using liquid sodium as coolant more electrical power can be generated for a given quantity of the fuel burn up. Secondly low pressure in the primary and secondary coolant circuits, permit the use of less expensive pressure vessel and pipes etc. Further sodium can transfer its heat very easily.

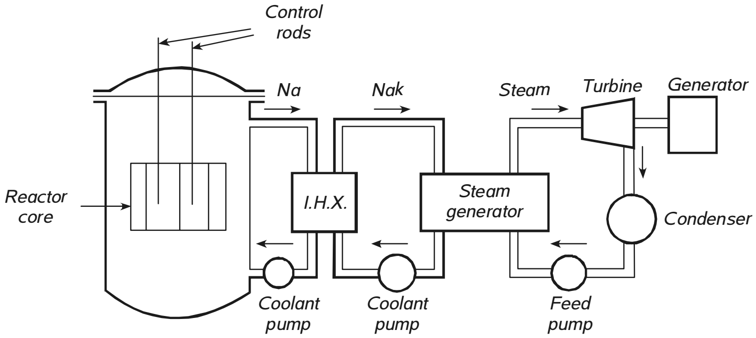


Fig. 11.8. Reactor using two liquid metal coolants.

The only disadvantage in this system is that sodium becomes radioactive while passing through the core and reacts chemically with water. So it is not used directly to transfer its heat to the feed water, but a secondary coolant is used. Primary coolant while passing through the tubes in intermediate heat exchanges (I.H.X.) transfers its heat to the secondary coolant. The secondary coolant then flows through the tubes of steam generator and passes on its heat to the feed water. Graphite is used as moderator in this reactor. Liquid metals used as heat transfer media have certain advantages over other common liquids used for heat transfer purposes. The various advantages of using liquid metals as heat transfer media are that they have relatively low melting points and combine high densities with low vapour pressure at high temperatures as well as with large thermal conductivities.

Advantages

1. It permits high reactor temperatures.
2. The high boiling point in liquid metal eliminates pressure on the reactor.
3. Steam is generated at relatively high temperatures and pressures.
4. Corrosion problems are minimised.
5. Excellent heat removal.
6. Supercharging of steam is possible.

Disadvantages

1. Heat exchanger must be leakproof, results into higher initial cost.
2. Thermal stresses are a problem.
3. The leak of sodium is very dangerous compared with other coolants as it comes out of reactor in highly radioactive state.

11.9.5 Heat Exchanger for SGR

The hear exchanger used in sodium graphite reactor is shown in Fig.11.9. The two coolants separated by a thin wall move in the opposite directions. The narrow space between the partition walls is filled with mercury to ensure a high efficiency of heat transfer. The mercury circulates in a small separate circuit. If some radioactivity is observed in mercury this indicates leakages in the primary circuit and serves as a warning.

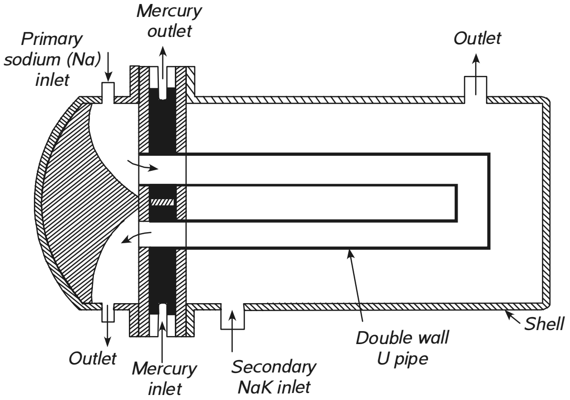


Fig. 11.9. Heat exchanger

11.9.5. Organic Moderated and Cooled Reactors

Some hydrocarbons, notably, the polyphenols, are used as coolants instead of sodium. These substances are powerful moderators as they contain only hydrogen and carbon. Since organic liquids are used as coolant as well as moderator, the use of separate moderator is not necessary. Organic coolants have the advantage of sodium that the vapour pressure is low at high useful temperatures and no heavy pressure is required in the reactor vessel. In addition, since organic coolant has non-corrosive property hence low cost mild steel piping can be used in the system.

This type of power plants have not yet been developed commercially, but expected to have better future prospects.

11.9.6. Fast Breeder Reactor (FBR)

Fig. 11.10 shows a fast breeder reactor system. In this reactor the core containing U^{235} is surrounded by a blanket (a layer of fertile material placed outside the core) or fertile material U^{238}. In this reactor no moderator is used. The fast moving neutrons liberated due to fission of U^{235} are absorbed by U^{238} which gets converted into fissionable material Pu^{239} which is capable of sustaining chain reaction. Thus this reactor is important because it breeds fissionable material from fertile material U^{238} available in large quantities. Like sodium graphite nuclear reactor this reactor also uses two liquid metal coolant circuits. Liquid sodium is used as primary coolant when circulated through the tubes of intermediate heat exchange transfers its heat to secondary coolant sodium potassium alloy. The secondary coolant while flowing through the tubes of steam generator transfer its heat to feed water. Since these reactors uses liquid sodium hence these are also known as **liquid metal reactors**.

Fast breeder reactors are better than conventional reactor both from the point of view of safety and thermal efficiency. For India which already is fast advancing towards self reliance in the field of nuclear power technology, the fast breeder reactor becomes inescapable in view of the massive reserves of thorium, and the finite limits of its uranium resources. The research and development efforts in the fast breeder reactor technology will have to be stepped up considerably if nuclear power generation is to make any impact on the country's total energy needs in the not too distant future. Since these reactors uses liquid sodium, hence these are also known as *liquid metal reactors*.

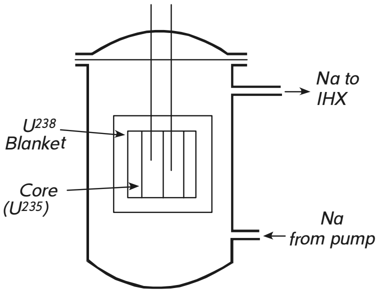


Fig. 11.10. FBR system

Coolant for Fast Breeder Reactors

The commonly used coolants for fast breeder reactor are as follows:

(*i*) Liquid metal (Na or NaK)
(*ii*) Helium (He)
(*iii*) Carbon dioxide.

Sodium has the following advantages:

(*i*) It has very low absorption cross-sectional area.
(*ii*) It possesses good heat transfer properties at high temperature and low pressure.
(*iii*) It does not react on any of the structural materials used in primary circuits.

Advantages

Main advantages of FBR are:

1. High breeding gain is possible.
2. No moderator is required.
3. High power density.
4. Low absorption of high energy neutrons as it permits high fuel burn up.

Disadvantages

1. Small core with a minimum area intensifies heat transfer problems.
2. Reactor needs enriched fuel.
3. Neutron flux is high at the center of the core.
4. Liquid sodium is extremely corrosive.
5. The handling of sodium is major problem, as it becomes extremely hot and radioactive.

Thermal *v/s* Fast Breeder Reactors

Thermal reactors have following **advantages** as compared to fast reactors:

1. Greater inherent safety.
2. Less heat generated per unit volume of core.
3. Easy to control.

Thermal reactors have following major **disadvantages** as compared to fast reactors:

1. The choice of fuel is severely restricted from the point of view of neutron economy when uranium is used as fuel.

2. The size and weight of the reactor per unit power are much greater.
3. More fissile material is consumed. In fast reactors more fertile material can be converted to fissile material and therefore the net fuel consumption is much less.

11.9.7. Homogeneous Reactor (Fluid Fuel Reactor)

Fig. 11.11 shows a Homogeneous Aqueous Reactor (H.A.R.). In this reactor heavy water is used as coolant and moderator. It makes use of both fertile and fissionable; material which circulate with coolant. Fissionable U^{238} solution is contained in one zone and slurry of Thorium oxide and Deuterium oxide is contained in the other zone. Main advantage of this reactor is that problems associated with solid fuels elements are avoided. As heavy water is used as moderator coolant there is good neutron economy. The disadvantages of this system are:

(i) Large amount of fuel is required.
(ii) Circulative fuel system causes the external components to become radioactive.
(iii) High vapour pressure of water.

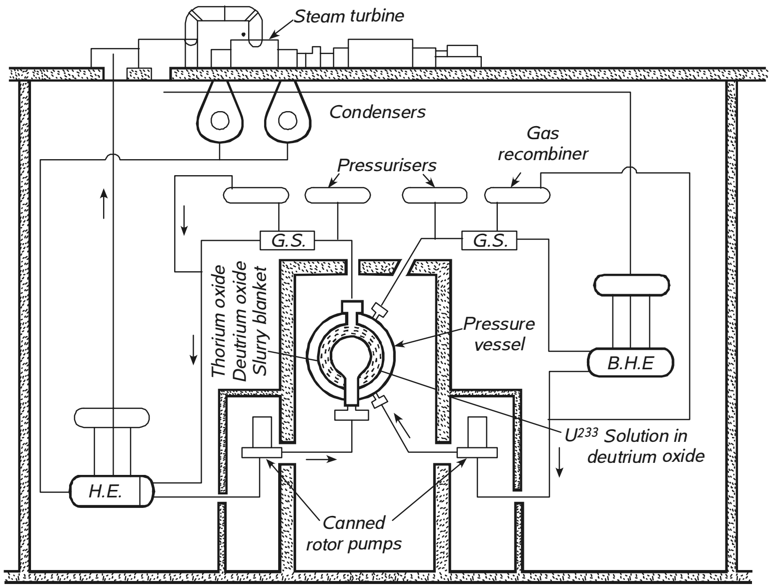


Fig. 11.11

In the figure, H.E. represents Heat Exchanger, B.H.E. represents Blanket Heat Exchanger, G.S. represents Gas Separator.

Advantages

1. The problems associated with solid fuel elements are eliminated, since heavy water is used as moderator and coolant. There is good neutron economy.
2. Core heat transfer requirements are low and high specific powers can be achieved as compared to a fast breeder reactor.
3. The potential for breeding is sufficient and refueling techniques are simple.
4. Continuous removal of neutron poisons is possible, thereby lowering the requirement for excess reactivity, and control of the reactor can be largely self regulating.

5. Few or no control rods are needed and such rods as may be present are needed only for safety during shut down or for trim control.

Disadvantages

1. Presence of large quantities of highly radioactive fission products circulating through the entire primary system at high pressure may cause external components to become radioactive.
2. Large amount of fuel is required.
3. Vapour pressure of water is high.

8. Gas Coolant Reactor (GCR)

In this reactor (Fig. 11.12) carbon dioxide gas is generally used to carry away the heat produced in the reactor. The gas is circulated at a pressure of about 7 kg/m^2. The gas flowing up through each of the channels round the elements leaves the reactor at the top and flows to heat exchanger where it transfer its heat to water which gets converted into steam. The gas is recirculated with the help of gas blowers. The steam drives the turbines which in turn drives alternator to generate electricity.

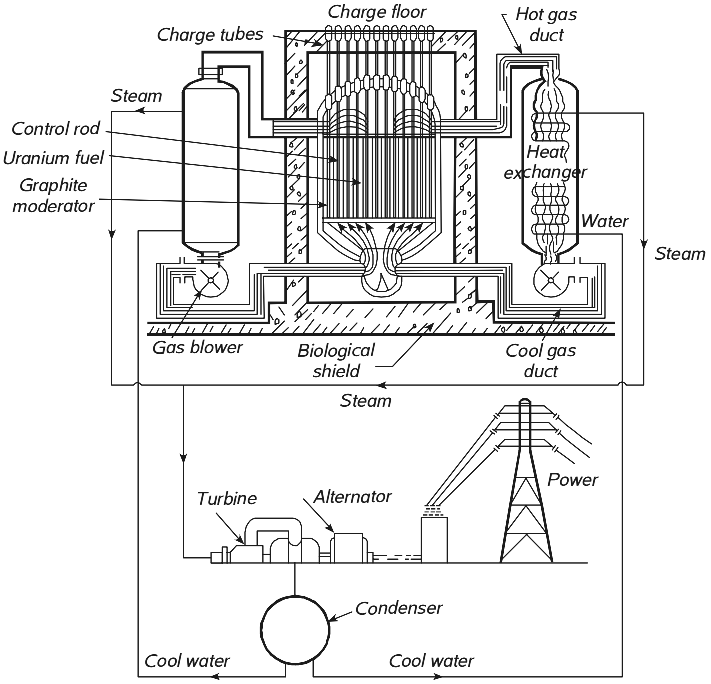


Fig. 11.12

Hydrogen or heliun can also be used in these reactors. Gas pressures would be less than 7 kg/cm^2, so that vessel wall thickness would not be a problem. There are two principal classes of gas cooled reactors developed for central power station service:

(*a*) The gas cooled graphite moderated reactor (GCGM), and
(*b*) The high temperature gas cooled (HTGC) reactor.

11.10 R&D IN NUCLEAR ENERGY

The Research and Development (R&D) activities in the field of nuclear energy in our country are directed towards the following:

(*i*) Development of nuclear fuels.
(*ii*) Development of reactor technologies for example fast breeder reactor (FBR) system.
(*iii*) Development of heavy water production technology.
(*iv*) Development of nuclear safety devices.
(*v*) Nuclear waste disposal.
(*vi*) Nuclear fuel reprocessing.
(*vii*) Safe operation of nuclear power plants.

In our country the Atomic Energy Commission (AEC) is responsible for formulation of policies and programmes in the field of nuclear energy. The Bhabha Atomic Research Center (BARC) at Trombay is the national research center for research and development work in nuclear energy and related disciplines.

Other institutes which provide research support in nuclear every are: (*i*) Saha Institute of Nuclear Physics (*ii*) Tata Institute.

11.10.1 Design of a Nuclear Reactor

The basic factors considered during the design of a nuclear power reactor are as follows:

(*i*) Type of reactor.
(*ii*) Type of fuel to be used.
(*iii*) Power rating of reactor in MW.
(*iv*) Coolant system.
(*v*) Control system.
(*vi*) Rates of neutron production and absorption.
(*vii*) Safety of reactor.

11.11 MAIN COMPONENTS OF A NUCLEAR POWER PLANT

The main components of a nuclear power plant are shown in Fig. 11.13. These include nuclear reactor, heat exchanger (steam generator), turbine, electric generator and condenser.

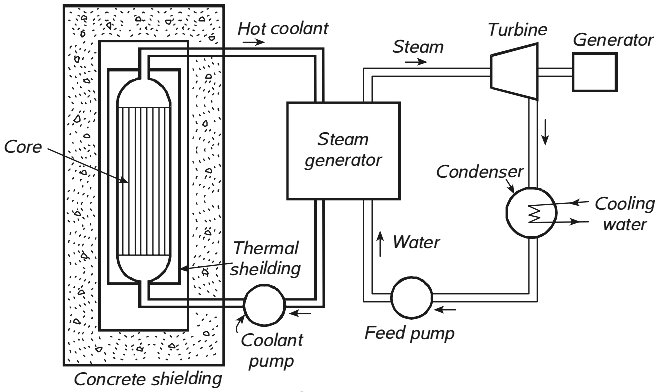


Fig. 11.13.

Reactor of a nuclear power plant is similar to the furnace of steam power plant. The heat liberation in the reactor due to the nuclear fission of the fuel is taken up by the coolant circulating through the reactor core. Hot coolant leaves the reactor at top and then flows through the tubes of steam generator (boiler) and passes on its heat to the feed water. The steam produced is passed through the turbine and after work has been done by the expansion of steam in the turbine steam leaves the turbine and flows to the condenser. Pumps are provided to maintain the flow of coolant, condensate and feed water.

11.12 HEAVY WATER

Light water reactor use ordinary water (technically known as light water) as coolant and moderator. They are simpler and cheaper. But they require enriched uranium as their fuel. Natural uranium contains 0.6% of fissionable isotope U^{235} and 99.3% of fertile U^{238} and to use natural uranium in such reactors it is to be enriched to about 3% U^{235} and for this uranium enrichment plant is needed which requires huge investment and high operational expenditure. Heavy water reactors use heavy water as their coolant and moderator. They have the advantages of using natural uranium as their fuel. Such reactors have some operation problem too. Heavy water preparation plants require sufficient investment and leakages of heavy water must be avoided as heavy water is very costly.

Heavy water required in primary circuits must be 99% pure and this requires purification plants. Heavy water should not absorb moisture as by absorbing moisture it gets degraded. In order to have sufficient quantity of heavy water required for nuclear power plants, the work is fast progressing in our country on four heavy water plants. These plants are situated at Kotah (100 tonnes per year), Baroda (69.2 tonnes), Tuticorin (71.3 tonnes) and Talcher (67.2 tonnes per year). These plants will give our country an installed heavy water production capacity of about 300 tonnes per year.

11.12.1 Importance of Heavy Water

The nuclear power plants of Kota in Rajasthan, Kalpakkam in Tamil Nadu and Narora in U.P. use heavy water as coolant and moderator. All these projects have CANDU reactors using natural uranium as fuel and heavy water as moderator. After this enriched uranium natural water reactor at Tarapur, the CANDU reactors are the second generation of reactors in India's nuclear power programme. The CANDU reactor will produce plutonium which will be the core fuel for fast breeder reactor. In fact in breeder reactor heavy water is used as moderator.

A CANDU reactor of 200 MW capacity requires about 220 tonnes of heavy water in the initial stages and about 18 to 24 tonnes each year subsequently. Therefore, about one thousand tonnes of heavy water will be required to start the different nuclear power stations using heavy water. The total capacity of different heavy water plants will be about 300 tonnes per year if all the heavy water plant under construction start production. It is expected that heavy water from domestic production will be available from Madras and Narora atomic power plants. The management of the heavy water system is a highly complicated affair and requires utmost caution. Heavy water is present in ordinary water in the ratio 1:6000. One of the methods of obtaining heavy water is electrolysis of ordinary water.

Heavy water or Deuterium oxide (D_2O) is the most effective moderator, both because its cross-section is the smaller known (0.0004 barns, where 1 barn=10^{-24} cm^2) and because of the small weight of deuterium atom (2). This water contains heavy isotopes of hydrogen (deuterium). Since it has low cross-section for absorption of neutrons than ordinary water, it slows down the fast neutrons and thus moderates the chain reaction.

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.

11.13 URANIUM ENRICHMENT

In some cases the reaction does not take place with natural uranium containing only 0.17% of U^{235}.

In such cases it becomes essential to use uraniun containing higher content of U^{235}. This is called U^{235} concentration of uranium enrichment. The various methods of uranium enrichment are as follows:

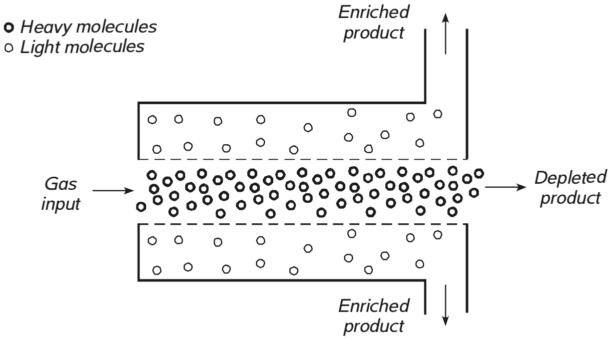


Fig. 11.14. Gaseous diffusion

1. *The gaseous diffusion method.* This method is based on the principle that the diffusion or penetration molecules of a gas with a given molecular weight through a porous barrier is quicker than the molecules of a heavier gas. Fig 11.14 shows a separating stage for gaseous diffusion. Non-saturated uranium hexa-flouride (UF_6) is used for gaseous diffusion. The diffusing molecules have small difference in mass. The molecular weight of $U^{235}F_6 = 235 + 6 \times 19 = 349$ and that of $U^{238}F_6 = 352$. The initial mixture is fed into the gap between the porous barrier. That part of the material which passes through the barrier is enriched product, enriched in U^{325} F_6 molecules and the remainder is depleted product.

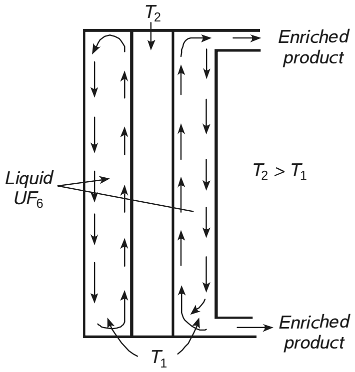


Fig. 11.15

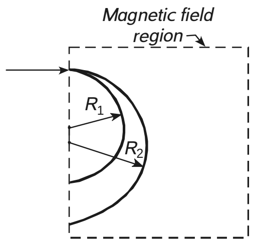


Fig. 11.16

2. *Thermal diffusion method.* In this method (Fig.11.15) a column consisting of two concentric pipes is used. Liquid UF_6 is filled in the space between the two pipes. Temperature of one of the pipes is kept high and that of other is kept low. Due to difference in temperature the circulation of the liquid starts, the liquid rising along the hot wall and falling along the cold wall. Thermal diffusion takes place in the column. The light $U^{235}F_6$ molecules are concentrated at the hot wall and high concentration of $U^{236}F_6$ is obtained in the upper part of the column.

3. *Electromagnetic Method.* This method is based on the fact that when ions moving at equal velocities along a straight line in the same direction are passed through a magnetic field, they are acted upon by forces perpendicular to the direction of ion movement and the field.

Let P = force acting on ion
e = charge on ion
v = velocity of ion
H = magnetic field strength
m = *Ion* mass
R = radius of ion path
$P = evH$

As this force is centripetal

$$\therefore \quad P = \frac{mv^2}{R}$$

$$\therefore \quad \frac{mv^2}{R} = evH$$

$$\therefore \quad R = \frac{mv}{eH}$$

This shows that ions moving at equal velocities but different masses move along circumferences of different radii (Fig. 11.16). Fig. 11.17 shows an electromagnetic separation unit for uranium isotopes. A gaseous uranium compound is fed into ion source, where neutral atoms are ionised with the help of ion bombardment. The ions produced come out in the form of narrow beam after passing through a number of silos. This beam enters the acceleration chamber. These ions then enter a separation chamber where a magnetic field is applied. Due to this magnetic field the ions of different masses move along different circumference.

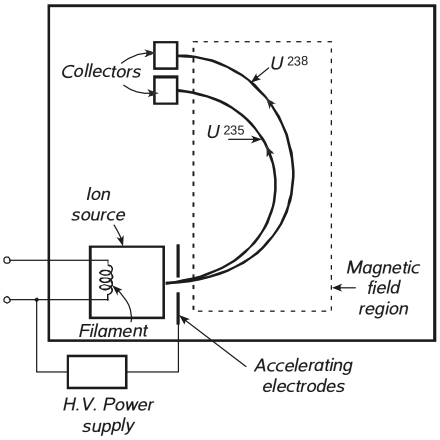


Fig. 11.17.

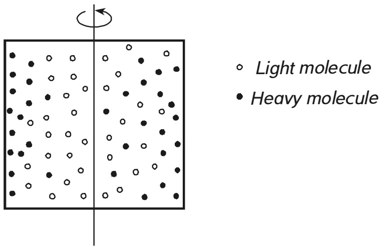


Fig. 11.18

4. *Centrifugation Method.* This method is based on the fact that when a mixture of two gases with different molecular weight is made to move at a high speed in a centrifuge, the heavier gas is obtained near the periphery (Fig. 11.18). UF_6 vapour may be filled in the centrifuge and rotated to separate uranium isotopes.

11.14 POWER OF A NUCLEAR REACTOR

In a nuclear reactor a large number of neutrons are incident on nuclear fuel atoms, causing fission and producing energy. A controlled chain reaction takes place so that the heat energy released can be controlled.

Let V = Volume of energy
N = Fuel atoms/m^3
n = Average neutron density, *i.e.,* number per m^3
a = Fission cross-section
ϕ = Neutron flux
v = Average speed of neutrons m/sec.

Fission cross-section represents the probability of fission per incident neutron. For example, if y is the number of incident neutron then those causing fission = $a \times y$. Neutron flux is the number of neutrons crossing a plane of area one metre square held at right angle to velocity v.

$$\phi = n \times v$$

S = total fuel atoms in reactor = $N.V.$

h = number of incident neutrons per second on fuel atoms

$$= S \times \phi = n.v.\ N.V.$$

x = Number of neutrons causing fission per second

$$= h \times a = n.v.\ N.V.a.$$

Now 3.1×10^{10} fission per second produce a power of one watt (See example 11.3)

P = Power of nuclear reactor

$$= \frac{x}{3.1 \times 10^{10}} = \frac{n.v.N.V.a.}{3.1 \times 10^{10}} \text{ watts.}$$

Let the fuel used in the reaction be U^{235}

Mass per atom of U^{235}

$$= \frac{\text{At. weight of } U^{235}}{\text{Avogadro Number}} = \frac{235}{6.02 \times 10^{26}} \text{ kg.}$$

Mass of NV atoms $= N.V. \times$ mass per atom

$$= NV \times \frac{235}{6.02 \times 10^{26}} = M \text{ kg (say)}$$

$$\therefore \qquad NV = \frac{6.02\times10^{26}\times m}{235}$$

Now

$$P = \frac{n.v.N.V.a.}{3.1\times10^{10}} \text{ watts}$$

$$= \frac{\phi\times6.02\times10^{26}M\times582\times10^{-28}}{3.1\times10^{10}\times235} \text{ watts}$$

$$= 4.8\times10^{-12}M\phi \text{ watts}$$

11.15 REACTOR POWER CONTROL

The power released in a nuclear reactor is proportional to the number of mole fissioned per unit time this number being in turn proportional to density of the neutron flux in the reactor. The power of a nuclear reactor can be controlled by shifting control rods which may be either actuated manually or automatically.

Power control of a nuclear reactor is simpler than that of conventional thermal power plant because power of a nuclear reactor is a function of only one variable whereas power of a thermal power plant depends on number of factors such as amount of fuel, its moisture content, air supply etc. This shows that power control of thermal plant requires measuring and regulating several quantities, which is of course considerably more complicated.

11.16 NUCLEAR POWER PLANT COMMISSIONING

Commissioning process involves testing and making operational individually as well as in an integral manner the various systems such as electrical service water, heavy water, reactor regulating and protection, steam turbine and generator. To meet the performance criteria including safe radiation levels in the plant area and radioactive affluents during operation the stage-wise clearance from Atomic Energy Regulatory Board (AERB) is mandatory before filling heavy water, loading fuel making the reactor critical, raising steam, synchronising and reaching levels of 25%, 50%,75% and 100% of full power. The commissioning period last for about two years.

11.17 NUCLEAR POWER PLANT ECONOMICS

Major factors governing the role of nuclear power are its economic development and availability of sufficient amount of nuclear fuel.

It is important to extract as much energy from a given amount of fuel as possible. The electrical energy extracted per unit of amount of fuel or expensive moderator might be called the “material efficiency”. In a chain reactor the high material efficiency as well as high thermal efficiency leads to low over all energy cost.

Since the most attractive aspect to nuclear energy is the possibility of achieving fuel costs considerably below that for coal, all nuclear power system being considered for large scale power production involve breeding or regenerative systems. This program includes the development of the technology of low neutron absorbing structural materials such as zirconium, the use of special moderating materials such a D_2O and consideration of special problems associated with fast reactors. In so far as economic factor are concerned it is necessary to consider neutron economy in general way such as that measured by the conversion ratio of the system. The conversion ratio is defined as the atoms of new fuel produced in fertile material per atom of fuel burnt. The conversion ratio varies with the reactor design. Its values for different reactors varies from 1.0 to 1.6.

11.18 NUCLEAR POWER STATIONS IN INDIA

In various developing and developed countries, the nuclear power plants contribute 5% to 75% of total electrical power generation. In France 75% power generation is by nuclear power plants. Total installed capacity of nuclear power plants in the world is over 500,000 MW with share of about 15% of world's total installed capacity of electrical power generation. India's nuclear power generation contribution is about 5% expected to rise to about 8%.

Nuclear Power Plants in India

S.No.	*Location*	*Installed capacity (units × MW)*	*Total (MW)*
1.	Tarapur, Bombay	2 × 210 + 2 × 500	1420
2.	Rawatbhata (Rajasthan) Atomic Power Station, Kota	100 + 200 + 4 × 220	1180
3.	Madras Atomic Power Station, Kalpakkam, Chinnai	2 × 235	470
4.	Narora Atomic Power Station, Narora, U.P.	2 × 235	470
5.	Kakrapar Atomic Power Station, Gujarat	2 × 235	470
6.	Kaiga Atomic Power Station, Karnataka	4 × 235	940

The vision prepared by Department of Atomic Energy (DAE) envisages setting up of 20,000 MW nuclear power plants capacities by 2020.

The various nuclear power stations in India are as follows:

(*i*) **Tarapur Nuclear Power Station.** It is India's first nuclear power plant. It has been built at Tarapur 100 km. North of Bombay with American collaboration. It has two boiling water reactors each of 200 MW capacity and uses enriched uranium as its fuel. Thereafter two units of 500 MW have been added.

Tarapur power plant is moving towards the stage of using mixed oxide fuels as an alternative to uranium. This process involves recycling of the plutonium contained in the spent fuel. In the last couple of years it has become necessary to limit the output of reactors to save the fuel cycle in view of the uncertainty of enriched uranium supplies from the United States.

(*ii*) **Rawatbhata (Rajasthan) Atomic Power Station.** It has been built at about 65 km south-west of Kota in Rajasthan on the right bank of Rana Pratap Sagar dam on Chambal river With Canadian collaboration. It has two reactors each of 200 MW capacity and uses natural uranium in the form of oxide as fuel and heavy water as moderator. An ambitious expansion plan is in process for this power station.

(*iii*) **Kalpakkam Nuclear Power Station.** It is the third nuclear power station in India and is built at about 60 kms from Chennai in Tamil Nadu. It is designed and constructed by

Indian scientists and engineers. It has two fast reactors each 235 MW capacity and use natural uranium as its fuel. A provision of another 500 MW unit has been made, which is under construction.

The first unit of 235 MW capacity has started generating power from 1983 and the second 235 MW unit is commissioned in 1985. The pressurised heavy water reactors use natural uranium available in plenty in India. In this power station about 88% local machinery and equipment have been used.

(*iv*) **Narora Nuclear Power Station.** It is India's fourth nuclear power station and is built at Narora in Bullandshahar District of Uttar Pradesh. This plant initially have two units of 235 MW each.

This plant have two reactors of the CANDU-PHW (Canadian Deutrium-Uranium-Pressurised Heavy Water) system and use natural uranium as its fuel. This plant is wholly designed and constructed by the Indian scientists and engineers. The two units have been commissioned in 1990 and 1991 respectively.

This plant use heavy water as moderator and coolant. Compared to the previous designs of Rajasthan and Madras nuclear power plants the design of this plant incorporates several improvements. This is said to be a major effort towards evolving a standardised design 235 MW reactors and a stepping stone towards the design of 500 MW reactors. In this plant one exclusion zone of 1.6 km radius has been provided where no public habitant is permitted. Moderate seismicity alluvial soil conditions in the region of Narora have been fully taken into account in the design of the structure systems and equipment in Narora power plant.

Narora stands as an example of a well coordinated work with important contributions from Bhabha Atomic Research Centre, Heavy Water Board, Nuclear Fuel Complex, Electronics Corporation of India Limited (ECIL) and other units of Department of Atomic Energy and Several private and public sector industries. Instrumentation and control systems are supplied by ECIL. Bharat Heavy Electricals Limited (BHEL) is actively associated with Nuclear Power Corporation of India. It has supplied steam generators, reactor headers and heat exchangers for Narora Atomic Power Plant (NAPP) 1 and 2 (2 × 235 MW).

NAPP is the fore-runner of a whole new generation of nuclear power plants that will come into operation in the next decade. The design of this reactor incorporates several new safety features ushering in the state of the art in reactor technology. The design also incorporates two fast acting and independent reactor shut down systems conceptually different from those of RAPP and MAPP.

Some of the new systems introduced are as follows:

(*i*) Emergency Core Cooling System (ECCS).
(*ii*) Double Containment System.
(*iii*) Primary Shut off rod System (PSS).
(*iv*) Secondary Shut off rod System (SSS).
(*v*) Automatic Liquid Poison Addition System (ALPAS).
(*vi*) Post accident clean up system.

According to Department of Atomic Energy (DAE) the Narora Atomic Power Plant (NAPP) has the following features:

(*i*) It does not pose safety and environmental problems for the people living in its vicinity. The safety measures are constantly reviewed to ensure that at all times radiation exposure is well within limits not only to the plant personnel but also to the public at large.

(*ii*) NAPP design meets all the requirement laid down in the revised safety standards. The design of power plant in-corporates two independent fast acting shut down systems high pressure, intermediate pressure and low pressure emergency core cooling systems to meet short and long term requirements and double containment of the reactor building.

Narora Atomic Power Plant (NAPP) is pressurised heavy water reactor (PHWR) that has been provided with double containment. The inner containment is of pre-stressed concrete designed to withstand the full pressure of 1.25 kg/cm^2 that is likely to be experienced in the event of an accident. The outer containment is of reinforced cement concrete capable of withstanding the pressure of 0.07 kg/cm^2. The angular space between the two containments is normally maintained at a pressure below atmosphere to ensure that any activity that might leak past primary containment is vented out through the stock and not allowed to come out to the environment in the immediate vicinity of the reactor building. The primary and the secondary containments are provided with highly efficient filtration systems which filter out the active fission products before any venting is done.

The moment containment gets pressurised it gets totally sealed from the environment. Subsequently the pressure in the primary containment is brought down with the help of the following provisions:

(*i*) Pressure suppression pool at the basement of the reactor building.

(*ii*) Special cooling fan units which are operated on electrical power obtainable from emergency diesel generators.

The containments provisions are proof tested to establish that they are capable of withstanding the pressures that are expected in the case of an accident. Fig.11.19 shows primary and secondary containment arrangement.

(*iii*) The cooling water to all the heavy water heat exchangers is maintained in a closed loop so that failure in these do not lead to escape of radioactivity. Very little water from River Ganga would be drawn for cooling purposes and most of water would be re-cycled.

(*iv*) The power plant has a waste management plant and waste burial facility within the plant area.

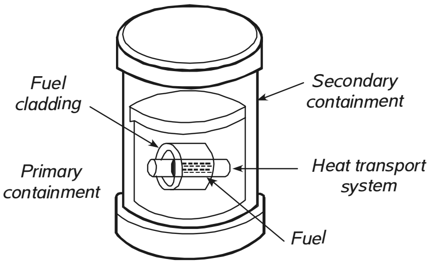


Fig. 11.19

(*v*) NAPP is the first pressurised heavy water reactor (PHWR) in the world to have been provided with double containment.

(*vi*) No radioactive effluent, treated or otherwise is discharged into Ganga River. Therefore there will be no danger of pollution of the Ganga water.

(*vii*) An exclusion zone of 1.6 km radius around the plant has been provided where no habitation is permitted.

(*viii*) A comprehensive fire fighting system on par with any modern power station has been provided at NAPP.

(*ix*) NAPP has safe foundations. It is located on the banks of river Ganges on alluvial soil. The foundations of the plant reach upto a depth where high relative densities and bearing capacities are met. The foundations design can cater to all requirements envisaged during life of plant.

(*x*) It is safe against earthquakes.

(*xi*) In the event of danger over heated core of the reactor would be diffused with in a few seconds by two features namely shut down through control rods followed by injection of boron rich water which will absorb the neutrons and stop their reaction in the core. This is in addition to other feature like double containment system provided in the reactor.

Above features assure total radiation safety of the plant personnel, general public and the environment during the operation of power plant. With the completion of NAPP it has made a useful contribution to the Northern grid thereby accelerating the pace of development in this region.

Narora Atomic Power Plant is the fourth atomic power project commissioned in India, the others in commercial operation being TAPS 1 and 2 (Tarapur, Maharashtra 1969), RAPS 1 and 2 (Kota, Rajasthan 1973 and 1981) and MAPS 1 and 2 (Kalpakkam Madras, Tamil Nadu 1983 and 1986). This power plant is meant to generate electricity and supply the same to the distribution system (grid) in Uttar Pradesh and other states in the northern region. It has two units each with a capacity of 235 MW of which about seven per cent will be used to run the in house equipment and the rest will be fed into the grid. The net output from the power plant will be about 440 MW. At this power plant all due precautions have been taken in the design, construction, commissioning and operation of the unit with safety as the over-riding consideration. Therefore there appears to be no danger to the public from the operation of this power plant.

(*v*) **Kakrapar Nuclear Power Plant.** This fifth nuclear power plant of India is located at Kakrapar near Surat in Gujarat. This power station have two reactors each of 235 MW capacity. The reactors constructed at Kakrapar are of the Candu type natural uranium fuelled and heavy water moderated reactor - incorporating the standardised basic design features of the Narora reactors suitably adapted to local conditions. The fuel for the power plant is being fabricated at the Nuclear Fuel complex, Hyderabad. The power plant was completed by 1992.

The Kakrapar unit has two fast shut down systems. The primary one works by cadmium shut off rods at 14 locations which drop down in case of heat build up and render the reactor sub-critical in two seconds. There are 12 liquid shut off rods as a back up, further backed by slow acting automatic liquid poison addition system which absorbs completely and stop the fissile reaction.

In case of sudden loss of coolant, heavy water inside the reactor, there is an emergency core cooling system which also stops the fissile reaction. Lastly, the pressure suppression system in which cool water under the reactor rises automatically to reduce pressure in case it increases and a double containment wall ensures that no radioactivity would be released at ground level even in case of an unlikely accident.

The Department of Atomic Energy (DAE) has also evolved emergency preparedness plans for meeting any accident even after all these safety measures. It ensures a high level of preparedness to face an accident including protecting the plant personnel and surrounding population. There is no human settlement for five km belt around a nuclear power installation as mandatory provision.

(*vi*) **Kaiga Atomic Power Plant.** The sixth atomic power plant is located on left bank of Kali river at Kaiga in Karnatka. Kaiga is located away from human habitation and is a well suited site for an atomic power plant.

It has two units of 235 MW each. It was commissioned by 2000, and supply the electricity to southern grid. Another two units of same size were added later on.

This nuclear power plant have CANDU type reactors. These reactors have modern systems to prevent accidents. The plant have two solid containment walls—inner and outer—to guard against any leakage. The inner containment wall could withstand a pressure of 1.7 kg/cm^2 and could prevent the plant from bursting. The outer containment walls of the reinforced cement concrete has been design to withstand pressure of 0.07 kg/cm^2. The annular space between the two containment walls is maintained at a lower pressure below that of the atmosphere to ensure that no radioactivity leaked past the primary containments.

11.19 INDIA'S 3-STAGE PROGRAMME FOR NUCLEAR POWER DEVELOPMENT

The nuclear energy programme in India has been visualised to grow in following three phases:

Phase 1—Construction of natural uraniun fueled, heavy water moderated and heavy water cooled thermal reactors producing electricity and plutonium.

Phase 2—Construction of FBRs which utilize plutonium and depleted uranium, the by-products of phase-1 reactors. FBRs produce more fuel than they consume while supplying electricity.

Phase 3—Use of thorium by converting it to uranium.

11.20 SAFETY MEASURES FOR NUCLEAR PLANTS

Nuclear power plants should be located far away from the populated area to avoid the radioactive hazard. A nuclear reactor produces α and β particles, neutrons and γ-quanta which can disturb the normal functioning of living organisms. Nuclear power plants involve radiation leaks, health hazard to workers and community, and negative effect on surrounding forests.

At nuclear power plants there are three main sources of radioactive contamination of air:

(*i*) Fission of nuclei of nuclear fuels.

(*ii*) The second source is due to the effect of neutron fluxes on the heat carrier in the primary cooling system and on the ambient air.

(*iii*) Third source of air contamination is damage of shells of fuel elements.

This calls for special safety measures for a nuclear power plant. Some of the safety measures are as follows:

(*i*) Nuclear power plant should be located away from human habitation.

(*ii*) Quality of construction should be of required standards

(*iii*) Waste water from nuclear power plant should be purified.

The water purification plants must have a high efficiency of water purification and satisfy rigid requirements as regards the volume of radioactive wastes disposed to burial.

(*iv*) An atomic power plant should have an extensive ventilation system. The main purpose of this ventilation system is to maintain the concentration of all radioactive impurities in the air below the permissible concentrations.

(*v*) An exclusion zone of 1.6 km radius around the plant should be provided where no public habitation is permitted.

(*vi*) The safety system of the plant should be such as to enable safe shut down of the reactor whenever required. Engineered safety features are built into the station so that during normal operation as well as during a severe design basics accident the radiation dose at the exclusion zone boundary will be within permissible limits as per internationally accepted values.

Adoption of a integral reactor vessel and end shield assemblies, two independent shut down systems, a high pressure emergency core cooling injection system and total double containment with suppression pool are some of the significant design improvements made in Narora Atomic Power Project (NAPP) design. With double containment NAPP is able to withstand seismic shocks.

In our country right from the beginning of nuclear power programme envisaged by our great pioneer Homi Bhabha in peaceful uses of nuclear energy have adopted safety measures of using double containment and moderation by heavy water one of the safest moderators of the nuclear reactors.

(*vii*) Periodical checks be carried out to check that there is no increase in radioactivity than permissible in the environment.

(*viii*) Wastes from nuclear power plant should be carefully disposed off. There should be no danger of pollution of water of river or sea where the wastes are disposed.

In nuclear power plant design, construction, commissioning and operation are arrived out as power international and national codes of protection with an over-riding place given to regulatory processes and safety of plant operating personnel, public and environment.

11.21 NUCLEAR WASTE MANAGEMENT

Waste disposal problem is common in every industry. Wastes from atomic energy installations are radioactive, create radioactive hazard and require strong control to ensure that radioactivity is not released into the atmosphere to avoid atmospheric pollution.

The wastes produced in a nuclear power plant may be in the form of liquid, gas or solid and each is treated in a different manner.

Liquid Wastes. The disposal of liquid wastes is done in two ways:

(*i*) *Dilution.* The liquid wastes are diluted with large quantities of water and then released into the ground. This method suffers from the drawback that there is a chance of contamination of underground water if the dilution factor is not adequate.

(*ii*) *Concentration to small volumes and storage.* When the dilution of radioactive liquid wastes is not desirable due to amount or nature of isotopes, the liquid wastes are concentrated to small volumes and stored in underground tanks. The tanks should be of assured long term strength and leakage of liquid from the tanks should not take place otherwise leakage or contents, from the tanks nay lead to significant underground water contamination.

Gaseous Wastes. Gaseous wastes can most easily result in atmospheric pollution. Gaseous wastes are generally diluted with air, passed through filters and then released to atmosphere through large stack (chimneys).

Solid Wastes. Solid wastes consist of scrap material or discarded objects contaminated with radioactive matter. These wastes if combustible are burnt and the radioactive matter is mixed with concrete, drummed and shipped for burial. Non-combustible solid wastes, are always buried deep in the ground.

SOLVED PROBLEMS

Example 11.1. *Calculate the number of fission in uranium per second required to produce 2 kW of power if energy released per fission is 200 meV.*

Solution

P = Power = 2 kW

E = Energy released per fission = 200 MeV

$= 200 \times 10^6$ eV $= 200 \times 10^6 \times 1.6 \times 10^{-12}$

$= 3.2 \times 10^{-4}$ ergs

P = 2 kW = 2000 watts = 2000 joules/sec.

$= 2000 \times 10^7$ ergs/sec. $= 2 \times 10^{10}$ ergs/sec.

N = Number of fissions per sec.

$$= \frac{P}{E} = \frac{2\times10^{10}}{3.2\times10^{-4}} = 6.25\times10^{13} \quad \textbf{Ans.}$$

Example 11.2. *A nuclear reactor uses U^{235} as fuel. If the mass of fuel is 1.2 kg and neutron flux is 10^{16} per sec. Calculate the power of reactor.*

Solution.

M = Mass of fuel = 1.2 kg

ϕ = Neutron flux = 10^{16}/sec

P = Power of reactor

$= 4.8 \times 10^{-12}\ m\ \phi$ watts

$= 4.8 \times 10^{-12} \times 1.2 \times 10^{16}$

$= 57.6 \times 10^3$ watt = 57.6 kW. **Ans.**

Example 11.3. *Calculate the fission rate of U^{235} for producing power of one watt if 200 MeV of energy is released per fission for U^{235}.*

Solution.

P = Power = 1 watt

E = Energy released per fission of U^{235} nucleus

$= 200$ MeV $= 200 \times 1.6 \times 10^{-13}$ J

$= 3.2 \times 10^{-11}$ watt sec.

as $\quad 1 \text{ MeV} = 1.6 \times 10^{-13}$ J

Fission rate of producing one watt of power

$$= \frac{P}{E} = \frac{1}{3.2 \times 10^{-11}} = 3.1 \times 10^{10} \text{ fissions/sec.} \quad \textbf{Ans.}$$

Example 11.4. *A railway engine is driven by atomic power at an efficiency of 40% and develops an average power of 1600 kW during 8 hour run from one station to another. Determine how much* U^{235} *would be consumed on the run if each atom on fission releases 200 MeV.*

Solution. $\quad \text{Output} = 1600 \text{ kW}$

$$\text{Efficiency} = 0.4 = \frac{\text{Output}}{\text{Input}}$$

$$\therefore \quad \text{Input} = \frac{1600}{0.4} = 4000 \text{ kW} = 4 \times 10^6 \text{ watts}$$

E = Energy released per fission = 200 MeV

$= 200 \times 1.6 \times 10^{-12} \text{ J} = 3.2 \times 10^{-11}$ J

t = Time = 8 hours = 8×3600 seconds.

Input nuclear energy required = Input × t

$= 4 \times 10^6 \times 8 \times 3600 \text{ J} = 115.2 \times 10^9$ J

Number of U^{235} atoms required for 8 hour run

$$= \frac{115.2 \times 10^9}{E} = \frac{115.2 \times 10^9}{3.2 \times 10^{-11}} = 36 \times 10^{20}$$

We know that 235 gm of U^{235} contains 6.02×10^{23} atoms (Avogadro's hypothesis).

Mass of U^{235} consumed

$$= \frac{36 \times 10^{20} \times 235}{6.02 \times 10^{28}} = 1.4 \text{ gm.} \quad \textbf{Ans.}$$

Example 11.5. *Determine the energy released by the fission of 1.5 gm of* U^{235} *in kWh assuming that energy released per fission is 200 MeV.*

Avogadro number = 6.025×10^{23}

Mass of Uranium = 235 *a.m.u.*

Solution. $\quad n$ = Number of atoms in 1.5 gm of U^{235}

$$= \frac{1.5 \times 6.025 \times 10^{23}}{235}$$

E_1 = Energy released per fission = 200 MeV

$= 200 \times 10^6 \times 1.6 \times 10^{-19} = 3.2 \times 10^{-11}$ Joules

E = Energy released by 1.5 gm of U^{235}

$= n \times E_1$ Joules

$$= \frac{1.5 \times 6.025 \times 10^{23}}{235} \times \frac{3.2 \times 10^{-11}}{60 \times 60 \times 10^{3}} \text{ kWh}$$

$= 3.42 \times 10^4$ kWh **Ans.**

Example 11.6. *Determine the fission energy released when a U-235 nucleus is fissioned by a thermal neutron and two fission fragments and two neutrons are produced. The average binding energy per nucleon is 8 MeV in the fissioned U-235 nucleus and 8.8 MeV in the fission fragments.*

Solution. E = fission energy released

$= 234 \times 8.8 - 236 \times 8$

$= 158.4$ MeV. **Ans.**

QUESTIONS

1. What is a chain reaction? How it is controlled?
2. What is a nuclear reactor ? Describe the various parts of nuclear reactor.
3. What are different types of reactors commonly used in nuclear power stations? Describe the fast breeder reactor ? What are its advantages over sodium graphite reactor?
4. How waste is disposed off in a nuclear power station? What are main difficulties in handling radioactive waste?
5. Discuss various factors to be considered while selecting the site for nuclear power station. Discuss its advantages and disadvantages.
6. Write short notes on the following:
   (*a*) Boiling water reactor (B.W.R.) (*b*) Pressurised water reactor (P.W.R.)
   (*c*) Multiplication factor. (*d*) Fertile and fissionable material.
7. What are the different components of a nuclear power plant? Explain the working of a nuclear power plant. What are the different fuels used in such a power plant?
8. What is a Homogeneous Reactor? Describe a Homogeneous Aqueous Reactor (H.A.R).
9. What is meant by Uranium enrichment? Describe some methods of Uranium enrichment.
10. Compare the ecomomics (cost) of nuclear power plant with steam power plant.
11. Explain the terms 'Breeding' and 'Burn up'.
12. Make a neat sketch and explain the working of a gas cooled reactor.
13. State the properties of control rods.
14. Explain the properties of moderator used in a nuclear reactor.
15. Explain the principle of operation of a sodium graphite reactor.
16. Discuss the factors which go in favour of nuclear power plant as compared to other types of power plants.
17. Write short notes on various nuclear power plants in India.
18. Write short notes on the following:
   (*a*) Multiplication factor. (*b*) Moderating ratio. (*c*) Conversion ratio.
19. Compare the control of nuclear reactor and steam power plant.
20. Discuss the economics of a nuclear power plant.
21. Discuss the safety measures in nuclear power plant.
22. Describe various types of nuclear fuels.
23. Describe the objectives of R&D in nuclear energy in India.

24. Discuss the safety measures provided at Narora Atomic Power Plant (NAPP).

25. Describe the site selection and commissioning procedure of Nuclear Power Plants in our country.

26. How are nuclear reactors classified? What are the general components of nuclear reactor? Describe them in brief.

27. Write short notes on:

(*a*) Radioactivity
(*b*) Principle of reactor control
(*c*) Moderator and coolant
(*d*) Radiation shielding.

28. What do you understand by breeding? What factors control the breeding?

29. How 'CANDU' type reactor differs from PWR? Draw a neat sketch of CANDU type reactor and give its advantages and disadvantages over other types.

30. (a) Discuss how energy crisis can be solved through nuclear power.

(*b*) Discuss the merits of those systems which have been adopted in India so far? State the reasons for adopting them.

31. Outline the Indian nuclear energy programme for the next decade. What are the indigenous resources of nuclear fuel available in India and how are these proposed to be exploited.

32. How waste is disposed off in a nuclear power station? What are the main difficulties in handling radioactive waste?

33. Write short notes on:

(*a*) Difference between atomic number and mass number.
(*b*) Amu
(*c*) Difference between chemical and nuclear reactors.
(*d*) Meaning of 'mass defect' and 'binding energy'.
(*e*) Nuclear stability.
(*f*) Radioactive decay.

34. Write short notes on the following:

(*a*) Curie
(*b*) Fission chain
(*c*) Average energy released per fission for U-233 and Pu-239
(*d*) Functions of a moderator
(*e*) Thermal reactor *v/s* gas reactor.

35. Explain the following in brief:

(*a*) Neutron flux.
(*b*) Barn
(*c*) Life cycle of neutrons.
(*d*) Multiplication factor.
(*e*) Functions of a reflector.
(*f*) Functions of a cladding.
(g) Functions of a pressurizer in a PWR.

36. What is an LMFBR? Why is a liquid metal preferred coolant on a fast reactor? What is its drawback.

37. What are the three stages in India's nuclear power progamme ?

38. What do you understand by nuclear fission? What are the essential requirements to cause nuclear fission?

39. Draw a neat diagram of nuclear reactor and explain the functions of different components.

40. What are the outstanding features of advanced gas cooled reactors over the other types? When they are preferred?

41. Availability of fuel and moderator generally controls the economic selection of the reactor. Justify the statement.

42. Why the moderator is not required in breeder reactors?

43. What factors are considered in selecting an economical site for nuclear power plant?

44. List out the advantages and disadvantages of nuclear plants over conventional thermal (steam) power plants.

45. What properties are required for a good coolant for nuclear reactor? What gases are used as coolant ? Why CO_2 is more preferable over other gases?

46. Explain in brief about the following:

(*a*) Control rod materials.
(*b*) Shielding of reactor.
(*c*) Desirable properties of a shielding material.

47. What are the different types of nuclear wastes? Which are more dangerous and why?

12

Hydrology

12.1 INTRODUCTION

Water is the most important resource for the mankind, since no life is possible without water. Water may occur in nature in liquid, solid, as well as gaseous form. Water can be put to various uses due to its unique properties. About 97% of the total available water on earth, is contained in oceans, and is saline in nature. Out of the balance 3%, which is available as fresh water, about 2% is contained as ice on poles and 0.75% as ground water. Out of the remaining about 0.25%, only about 0.01% is available in lakes and rivers, and rest occurs as glaciers and snow. Therefore the surface water, which can really be utilised by the society is very very small, being the quantity contained in lakes, or the one-flowing in rivers as surface runoff, caused by rain storms and melting of snow. Even the surface run off, that flows in rivers, mostly goes waste, as it flows down to the oceans in the absence of proper storage. About 96% of the total annual surface run off flowing in the rivers of the world, goes and joins the oceans and is not put to any worthwhile use.

Water is required by the community for fulfilling its several needs, and for surviving not only human life but also animal and plant life. The water is generally required for :

(*i*) municipal and industrial water supply,
(*ii*) irrigation,
(*iii*) hydropower generation, and navigation, recreation etc.

The development of power from flowing water depends :

(*i*) on the volume of flow, and
(*ii*) on the differential head.

12.1.1 Hydrology

It can be defined as the science which deals with the occurrence, distribution and movement of water over and under the surface of the earth. It deals with the solid, liquid and vapour forms of water. The knowledge of this science enable to design with greater reliability, the irrigation and flood control works, power projects, municipal and industrial water supply schemes etc. Development of hydroelectric project requires complete knowledge of stream flow and possible yearly flow.

Some of the answers, which during the process of planning and execution of water resources projects, are required to be given by this science are:

(*a*) The quantum of peak flood flows expected at the site of the proposed dam,

(*b*) Minimum long term yield of a given catchment, to decide the required reservoir capacity at the proposed dam site,

(*c*) The effects produced on river water levels, by the construction of proposed dams, embankments and other controlling hydraulic structures, etc.

12.2 HYDROLOGIC CYCLE

The various processes involved in the transfer of moisture from the sea to the land and back to the sea again constitute which is called hydrologic cycle (Fig. 12.1). Hydrologic equation is expressed as follows:

$$P = R + E$$

where P = Precipitation
R = Run off
E = Evaporation

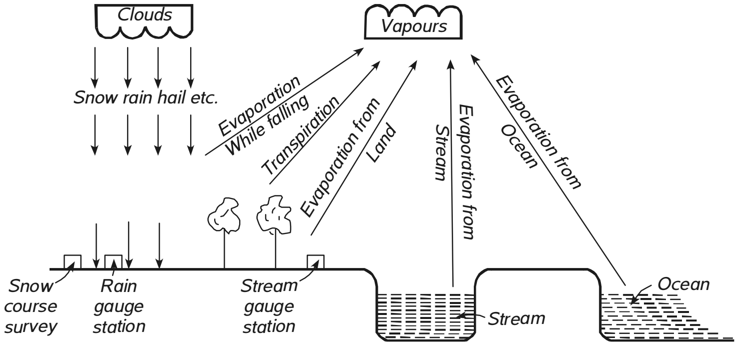


Fig. 12.1. Hydrological cycle

(*a*) **Precipitation.** It includes all the water that falls from atmosphere to the earth surface. Mainly precipitation is of two types:

(*i*) Liquid precipitation (Rainfall)

(*ii*) Solid precipitation (Snow, Hail storm).

(*b*) **Run-off.** Run off is that portion of precipitation which makes its way towards streams, lakes or oceans. Run off occurs only if the rate of precipitation exceeds the rate at which water infiltrates into the soil and after depressions small and large on the soil surface get filled with water. Rainfall duration, its intensity and a real distribution influence the rate and volume of run-off.

(*c*) **Evaporation.** Evaporation of water takes place from the surface of ocean, rivers, lakes and the moist soil due to the heat of sun. Evaporation taking place through the pores of vegetable surfaces is called *transpiration*.

Yield of a catchment. The yield of a catchment, also known as mean annual yield, is the net quantity of water available for storage, after all losses, for the purpose of water resources, utilisation and planning.

12.3 MEASUREMENT OF RAINFALL

The "rainfall", known as "precipitation", is the natural process of converting atmospheric vapour into water. The rainfall in general sense is defined as the total condensation of moisture from the atmosphere that reaches the earth, including all forms of rains, ice and snow.

In order to estimate the effect of precipitation, it is necessary to measure the precipitation and to find out its distribution at various places. Precipitation are measured as the vertical depth of water that would accumulate on a level surface, if the entire precipitation remained where it fell. The total amount of precipitation falling on earth in the given period is expressed as the depth to which it would accumulate on the horizontal projection of the earth's surface, if there were no losses by evaporation or runoff.

Since the amount of precipitation varies from place to place, it is necessary to install measuring devices at various key points. The simplest method of measuring precipitation is by setting up gauges with a horizontal circular aperture of known area and collecting and measuring at regular intervals the precipitation collected in them.

The amount of rain collected by a given rain gauge in 24 hours is known as *daily rainfall*, and the amount collected in one year is known as *annual rainfall.* This annual rainfall at a given station, when recorded over a number of years, say 35 to 40 years or so, the mean of annual rainfalls is known as *average annual rainfall* or *normal annual rainfall* of the given station.

12.4 MEASUREMENT OF STREAM FLOW

To evaluate the available capacity of energy in a given river, one must know the quantity of water flowing. Direct measurement by stream gauging at a given site for a long enough time is the only precise method of evaluation. It helps to estimate the following particulars about the power potential of the proposed project.

(*i*) The average annual energy output.

(*ii*) The additional energy and the increase in firm capacity provided by a storage reservoir.

(*iii*) The minimum annual energy output and firm capacity.

(*iv*) The capacity of a storage reservoir to ensure a minimum given flow.

(*v*) The minimum daily output without storage.

(*vi*) The necessary capacity of a flood control, limiting discharge necessary for power output.

(*vii*) The necessary spillway capacity to discharge excess water which cannot be stored.

The water-flow volume may be measured by providing or selecting a channel of fixed cross-section and at regular intervals measuring the water velocity through current meters at enough points in the cross-section for different water levels. By integrating the velocities over the cross-section for each level the total flow can be calculated and then plotted (Ref. Fig. 12.2). The discharge at the site for each level can be calculated using this curve.

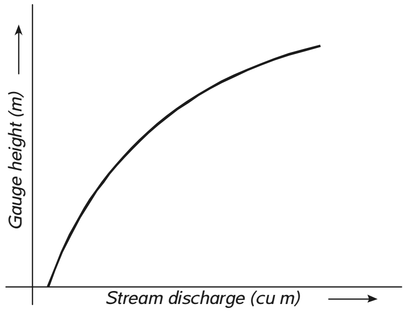


Fig. 12.2. A curve showing water level and stream flow at a gauging station.

12.5 STORAGE AND PONDAGE

The flow rate of a stream varies considerably with time. During rainy season it carries a huge quantity of water as compared to other times of the year. The demands for power, however, do not correspond to such variations of the natural flow of the stream.

In view of the above some arrangement in the form of storage and pondage of water is required for regulating the flow of water, so as to make it available in requisite quantity to meet the power demand at a given time.

Storage

Storage may be defined as impounding of a considerable amount of excess run off during the seasons of surplus flow for use in dry seasons. This is achieved by constructing a dam across the stream at a suitable site and building a storage reservoir on the upstream side of the dam.

Thus, storage means collection of water in reservoirs upstream of the dam to increase the capacity of the stream over an extended period of several months. Storage plants may work as base load and peak load power stations.

Pondage

Pondage may be defined as a regulating body of water in the from of a relatively small pond or reservoir provided at the hydropower plant. Thus pondage usually refers to the collection of water behind a dam near the plant, and increases the stream capacity for short periods. The pondage is used to regulate the variable water flow to meet power demand. It caters for short-term fluctuations which may occur due to (*a*) Sudden increase or decrease of load on the turbine, or (*b*) sudden changes in the inflow of water.

The head of water in the pond fluctuates with this type of operations: (a) rising when storing water (load less than energy in the river flow); (*b*) falling when drawing water (load greater than energy in the river flow); and (*c*) remaining constant when load equals energy in the river flow.

12.6 DRAINAGE AREA CHARACTERISTICS

The whole area behind the dam draining into a stream is called the *catchment area.* The characteristics of the catchment include its size, shape, surface, orientation, altitude, topography, and geology. The bigger the catchment, steeper is the slope, higher is the altitude, and greater is the total run off of water. The variation of stream flow in a given site depends on the geographical, geological and topographical features of the drainage area feeding the river, as well as the magnitude of the rainfall of the area. Some portion of the total precipitation in an area is lost by way of evaporation of water, percolation in soil etc.

12.7 HYDROGRAPH

It is a graphical representation between discharge (cubic metres per second) through a river and time.

A hydrograph may be plotted for several weeks or even months. Hydrograph indicates the power available from the stream at different times of the day, week or year. Extreme conditions of flow can also be studied from a hydrograph. Hydrograph of stream of a river will depend on the characteristics of the catchment and precipitation over the catchment. Hygrograph will assess the flood flow of rivers hence it is essential that anticipated hydrograph could be drawn for river for a given storm. A typical hydrograph is shown in Fig. 12.3. A hydrograph has a rising limb, peak and receding limb or recession curve.

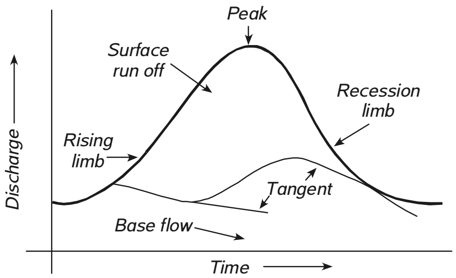


Fig. 12.3. Hydrograph

A hydrograph indicates:

(*i*) the power or discharge available from the stream at different times of the day, week or year,

(*ii*) extreme conditions of the flow (the maximum and minimum run off),

(*iii*) total volume of flow upto that instant as the area under hydrograph denotes the volume of water in that duration,

(*iv*) the mean annual run off or mean run off for each month of the year.

12.7.1 Unit Hydrograph

This type of hydrograph represents a volume of one cm of run off resulting from a rainfall of some unit duration and specified a real distribution.

Unit hygrographs of very large floods differ somewhat from those of small rainfalls. A unit hydrograph can be constructed from a hydrograph of the actual run off when there is uniform rainfall intensity and uniform a real distribution. The number of unit hydrographs for a given basin is theoretically infinite as there may be one unit hydrograph for every possible duration of rainfall and every possible distribution pattern of rainfall in the basin. In practice only a limited number of unit hydrographs are used for a given basin.

A unit hydrograph is constructed as follows:

(*i*) Measure the total volume of run off from actual hydrograph.

(*ii*) Determine the ordinates of unit hydrograph by dividing the ordinates of actual run off by the total volume of run off in cms over the drainage area. This gives unit hydrograph for the basin.

(*iii*) Determine effective duration of run off producing rain for which the unit hydrograph (UH) is applicable by a study of the rainfall records.

Unit hydrograph is a very useful tool in estimating the run off from a basin for a storm of given duration. It helps to predict the expected flood flow from a catchment if rainfall intensity in the catchment area is known.

Fig. 12.4 shows a typical unit hydrograph obtained from actual hydrograph of run off.

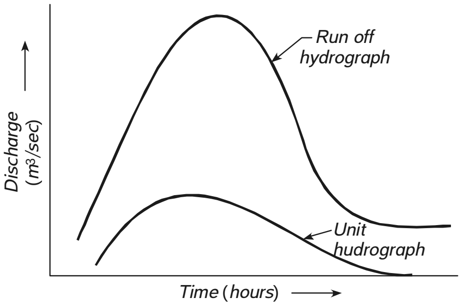


Fig. 12.4. Unit hydrograph.

12.8. FLOW DURATION CURVE

It is a method to represent the run off graphically. This curve is plotted between flow available during a period versus the fraction of time. The total power available at the site may be known by this curve which can be drawn with the help of hydrograph from the available run off data. Fig.12.5 shows a typical flow duration curve.

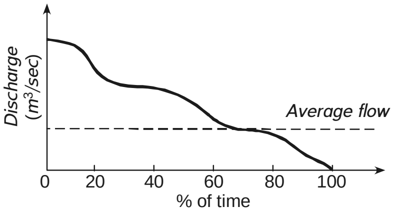


Fig. 12.5. flow duration curve

This curve is generally useful in the analysis of the development of water power.

Flow duration curves are not useful where the time sequence of flow is of importance such as in the study of floods. Flow duration curves are used in assessing the dependability of the discharge. If we infer from the flow duration curve that a discharge of 200 cu m/sec is available for 75 percent of time, we can approximately say that 200 cu m/sec flow has a 75 per cent dependability.

Flow duration curves are used for following purposes:

(*i*) For preliminary studies of hydro-project.

(*ii*) For comparison of streams.

(*iii*) For evaluation of low level flows.

(*iv*) For determination of firm power with no water storage and also with water storage.

(*v*) For determining power duration curve.

12.9 MASS CURVE

A reservoir is used to conserve water which can be used during the period of deficiency. A mass curve is a convenient device to determine storage requirement that is needed to produce a certain dependable flow from fluctuating discharge of a river by a reservoir. Mass curve is a plot of cumulative volume of water that can be stored from stream flow *versus* time in days, weeks or months. The slope of the mass curve at any point represent the change of volume per change of time in other words the rate of flow at the moment. Hence the mass curve is steep when the river flow is large and flat when the river flow is small.

Mass curve is another method of graphical representation of stream flow, and is obtained by plotting cumulative volume (generally in hectare-meter) of water that can be stored from stream flow as ordinate and time as abscissa (horizontal axis). The slope of a line connecting any two points on the curve is a measure of the average flow during that period. If a constant rate of withdrawal is required from the reservoir, the mass curve of demand will be a straight line having a slope equal to the demand rate. Demand curves or demand line are generally straight lines (representing uniform withdrawal) although, in practice, they may be curved also. The maximum ordinate (*cd* in Fig. 12.6) between the slope line and the curve indicates the capacity of the reservoir.

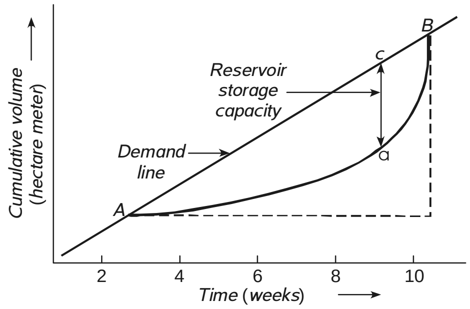


Fig. 12.6. Mass curve

12.9.1. Estimation of Storage Capacity of Reservoir

For the purpose of storage computation, mass curves are commonly used. A mass curve is plotted from the record of mean monthly flows of a stream (Fig. 12.7). The slope of the straight line *AB* joining the end points of the mass curve represents the average discharge over the total period.

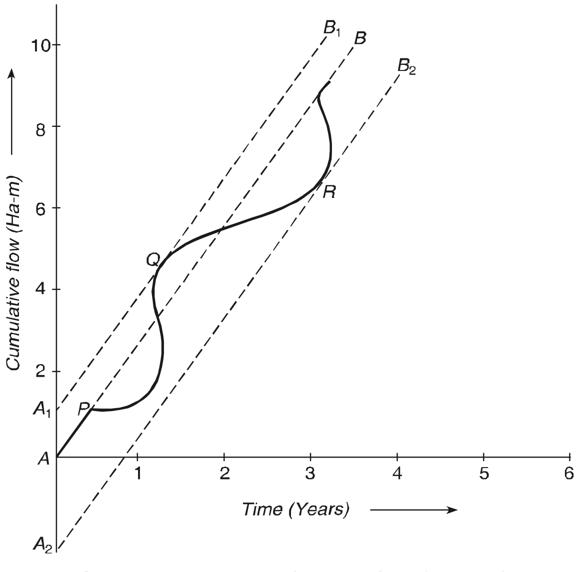


Fig. 12.7. Mass Curve (computation of storage)

If two straight lines A_1B_1 and A_2B_2 are drawn parallel to AB and tangent to the mass curve at the highest tangent point Q and lowest tangent R respectively, then the vertical intercept A_1A_2 represents the storage volume required to permit continuous release of water at this average discharge rate over the entire period. The rate at which water is required for use in a power plant is termed as the rate of demand. If mass curve is steeper than the demand line, some storage is possible and if it is flatter then water is withdrawn at a greater rate.

The above method is for determining the storage capacity for permitting continuous release of water at average rate over the entire period of the graph. Now we shall discuss the method for determining the reservoir capacity for a given demand.

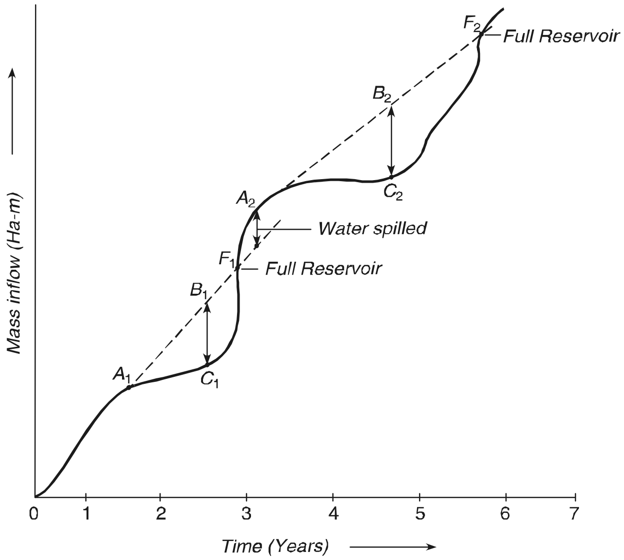


Fig. 12.8. Determining reservoir capacity for given demand.

In Fig 12.8, it is evident that the demand lines drawn tangent to the high points A_1 and A_2 of the mass curve, represent the rate of withdrawal from the reservoir. Assuming the reservoir to be full whenever the demand line intersects the mass curve (points F_1 and F_2), the maximum departure (B_1C_1, B_2C_2) between the two curves represents the reservoir capacity just required to satisfy the demand.

The biggest departure ordinate *i.e.,* the maximum of B_1C_1 and B_2C_2 represents the required storage capacity of the reservoir required to meet the demand.

The vertical distance between the successive tangents A_1B_1 and A_2B_2 represent the water wasted over the spillway. The spillway must be designed to have sufficient capacity to discharge this flood volume.

From the figure following can also be observed:

(*i*) Reservoir is full at F_1 and F_2.

(*ii*) Water is spilled over the spillway between F_1 and A_2 and after F_2.

(*iii*) The water starts reducing from A_1 till C_1 and again from A_2 till C_2, as inflow rate is less than demand rate during this period.

(*iv*) The water again starts collecting in the reservoir from C_1 till F_1 and also from C_2 till F_2, as inflow rate exceeds demand rate.

(*v*) A demand line must intersect the mass curve when extended forward, otherwise the reservoir is not going to refill.

(*vi*) If the storage capacity of the reservoir, from economic considerations, is kept lower, the demand rate cannot be maintained and hence have to be kept at lesser rate.

The observed inflow rates have to be adjusted for the monthly evaporation from the reservoir surface, precipitation, seepage through the dam, inflow from the adjacent basins, required release for downstream users, sediment inflow etc., while calculating for the storage capacity of the reservoir.

12.10 RUN-OFF

As discussed earlier, runoff is that balance of rain water, which flow or runs over the natural ground surface after losses by evaporation, interception and infiltration. It is that portion of precipitation which makes its way towards stream, lakes or oceans. Run off, also called as discharge or stream flow, and consists of the following three constituents:

1. Direct precipitation over the surface of the stream.
2. Surface runoff consisting of true surface runoff and sub-surface stream flow.
3. Ground water inflow, popularly knows as base flow.

The first part provides a very small portion of the total flow and depends upon the lake area of the stream channel. The evaporation from these water surfaces may nearly balance the precipitation on them and therefore, this constituted is ignored. Hence, the runoff of a river can be supposed to be consisting of surface runoff and ground water inflow only.

Here, runoff includes all the water flowing in the stream channel at any given section, while the surface runoff (also called as direct runoff or DRO) includes only the water that reaches the stream channel without first percolating down to the water table. This surface runoff may be divided into following two parts:

(*a*) Water that flows directly over the ground surface also called as true surface runoff.

(*b*) A part of the water that infiltrates through the soil, moves laterally, and before joining the water table, joins the river channel. This prompt interflow is known as sub-surface run off or sub-surface storm flow. It behaves nearly like the surface runoff and not like the ground water flow, because it reaches the stream so quickly that it is difficult to distinguish it from true surface runoff. The ground water flow generally long delayed before it reaches the stream.

Factors Affecting Run Off

Run-off from an area depends upon the following factors:

(*i*) *Precipitation characteristics.* They include type of storm, its intensity, extent and duration.

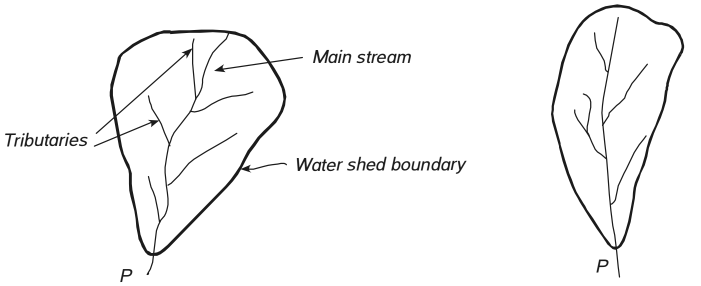
(*ii*) *Meterological characteristics.* They include temperature, humidity, wind, pressure variation etc. Greater temperature and wind velocity help evaporation.

(*iii*) *Catchment characteristics.* Geographical features of catchment such as size, shape and location of catchment produce significant effects on the run-off.

Two types of catchment shapes with different arrangement of drainage channel in the area are shown in Fig. 12.9. The fan shaped catchment produces greater flood intensity than a fern shaped catchment.

When rainfall takes place over the catchment water from the tributaries reach the point P simultaneously creating a sudden rise of discharge at P in case of fan shaped catchment.

On the other hand, in case of fern shaped catchment when rainfall takes place the tributaries are so distributed that water from different point takes different time to reach the point P. Hence rate of discharge at P is slow and takes place over a longer period.



(i) Fan shaped catchment. (ii) Fern shaped catchment.

Fig. 12.9. Shapes of catchment.

The surface of the catchment also has substantial effect on run-off. A base surface gives more run-off than a grassy surface.

(*iv*) *Storage characteristics*. Out of the total precipitation that falls on the catchment area a part is stored within the area and does not appear as run off. There may be a number of depressions, pools and lakes which store part of the precipitation and detain it either temporarily or permanently.

12.10.2 Run-off Estimation

The following three kinds of informations are generally required for run-off statistics:

(*i*) Annual, monthly or seasonal run-off (*ii*) Extreme low flows
(*iii*) Flood run-off.

The following methods are used to determine the runoff from a catchment :

(*i*) Empirical method (*ii*) Rational method
(*iii*) From hydrograph.

1. **Empirical Method.** The following few formulae are used to determine run-off. These formulae have been derived from limited regional use.

(*i*) *Lacey formula*

$$R = \frac{P^2}{Y + \dfrac{3048F}{S}}$$

(*ii*) *Inglis (De Souza) formula*

$$R = 0.85P - 304.8 \text{ for Ghat area}$$

$$= \frac{P(P - 177.8)}{2540} \quad \text{For non-Ghat area}$$

(*iii*) *Khosla formula* $R = P - 4.811\ T$

where R = Run off in mm

P = Rainfall in mm

T = Mean temperature in °C

F = Monsoon duration factor = 0.5 to 1.5 depending upon type of catchment

S = Catchment factor = 0.25 for flat lands to 3.5 for hilly areas.

2. **Rational Method.** The following rational formula is used to give a rainfall-run-off relationship:

$$R = K.A.P.$$

where R = Run off in hectare cm

A = Area of catchment in hectares

P = Precipitation in cm

K = Coefficient taking losses into account.

3. **Hydrograph method.** It is a graphical representation showing discharge (run-off) of flowing water with respect to time for a specified time. The time period for discharge may be hour, day, week or month. The rate of flow at any instant can be read from hydrograph.

12.10.3 Flood Run-off

It involves estimating the maximum peak value of the flow. Few empirical formulae listed below are used for finding maximum discharge.

(*i*) *Dicken's formula* $Q = CA^{0.75}$

(*ii*) *Inglis formula* $Q = \dfrac{123A}{\sqrt{A + 10}}$

where, Q = Discharge in m^3/sec.

A = Catchment area in km^2

SOLVED EXAMPLES

Example 12.1. *(a) What is a flow duration curve?*

(b) The mean weekly discharge at a hydro power plant site is as follows:

Week	*Discharge*	*Week*	*(discharge* m^3*/sec.)*
1	*160*	*7*	*700*
2	*200*	*8*	*600*
3	*300*	*9*	*1000*
4	*1100*	*10*	*600*
5	*700*	*11*	*400*
6	*900*	*12*	*300*

(*i*) *Draw the hydrograph and find average discharge available for the whole period.*

(*ii*) *Develop the flow duration curve and plot it.*

Solution. (*a*) A flow duration curve is used to determine the available power at the site. It indicates the daily, weekly, or monthly flows available as ordinates plotted against percentage of time.

(*b*) The hydrograph is plotted between discharge (m*3* sec.) and number pf weeks as shown in Fig 12.10

$$\text{Average discharge} = \frac{\text{Total discharge}}{\text{Total weaks}} = \frac{6960}{12} = 580 \text{ m}^3/\text{sec}$$

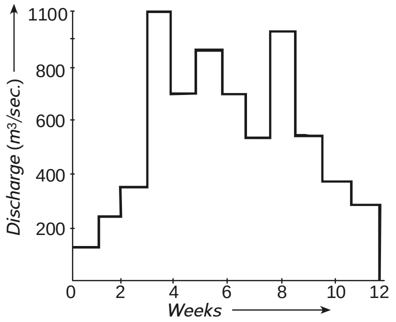


Fig. 12.10

In order to draw flow duration curve it is essential to find the length of time during which certain flows are available. This information is indicated in table shown below.

Discharge (m3/sec)	*Total number of week*	*Percentage time*
160 (and more)	12	100
200 (and more)	11	91.7
300 (and more)	10	83.3
400 (and more)	8	66.7
600 (and more)	7	58.3
700 (and more)	5	41.7
900 (and more)	3	25
1000 (and more)	2	16.7
1100 (and more)	1	8.3

Fig. 12.11 shows a flow duration curve. When selecting a suitable site for a hydro power plant the flow data for a number of years are collected and hydrographs and flow duration curves and the various periods are determined.

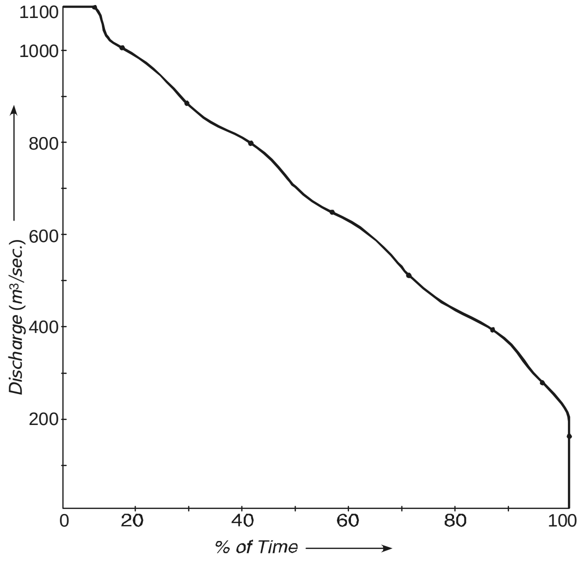


Fig. 12.11.

Example 12.2. *At a site for a hydro power plant a flow of 80 m³/sec is available at a head of 120 m. If turbine efficiency is 90% and generator efficiency is 94% determine the following:*

(a) Power that can be developed

(b) No. of units required and their capacities.

Solution. Q = Discharge = 80 m^3/sec.

H = Head = 120 m

η = Efficiency of turbine = 0.9

P = Power developed

$$= \frac{\omega Q H \eta}{75} = \frac{100 \times 80 \times 120 \times 0.9}{75}$$

= 115,200 Metric H.P.

Two turbines each of $\frac{115,200}{2}$ = 57,600 metric H.P. capacity should be used

η_g = Generator efficiency = 0.94

Generator capacity of each unit = 57,600 × 0.94 × 0.736

= 39,850 kW.

Total power generated by generator

$$= 39{,}850 \times 2 = 79{,}700 \text{ kW}$$

$$= 79.7 \text{ MW.}$$

Example 12.3. *(a) It is observed that a run of river power plant operates as peak load plant with a weekly load factor of 24% all this capacity being firm capacity. Determine the minimum flow in river so that power plant may act as base load plant. The following data is supplied:*

Rated installed capacity of generating plant = 12 MW

Operating head = 18 m

Plant efficiency = 85%

(b) Calculate the daily load factor of the plant if the stream flow is 17 cu mec.

Solution.

(*a*)

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum load}}$$

$$\text{Average load} = \text{Load factor} \times \text{Maximum load}$$

$$= 0.24 \times 12{,}000 = 2880 \text{ kW}$$

$$E = \text{Total energy generated in one week}$$

$$= \text{Average load} \times \text{Time}$$

$$= 2880 \times 24 \times 7 = 48.4 \times 10^4 \text{ kWH}$$

Let Q = Minimum flow rate (m^3/sec)

$$P = \text{Power developed} = \frac{\omega Q H \eta}{75}$$

where ω = Specific weight of water = 1000 kg/m^3

H = Head = 18 m

η = Efficiency of plant = 0.85

(*b*)

$$P = \frac{1000 Q H \eta}{75} = 13.3 Q H \eta \text{ (HP)}$$

$$= 0.736 \times 13.33\ Q H \eta \text{ (kW)}$$

$$= 9.8 \times Q H \eta \text{ (kW)}$$

$$= 9.8 \times Q \times 18 \times 0.85 \text{ kW}$$

$$= 149.9\, Q \text{ kW}$$

E_1 = Total energy generated in one week

$= P \times \text{Time} = 149.9\,Q \times 24 \times 7$

$= 2.5\,Q \times 10^4$ kWh

Now $E = E_1$

$48.4 \times 10^4 = 2.5\,Q \times 10^4$

$\therefore$ $Q = 19.36$ cumec. **Ans.**

P_1 = Power developed when stream flows is 17 cumec.

$= 149.9 \times 17 = 2548.3$ kW

E_2 = Energy generated per day

$= P_1 \times \text{Time} = 2548.3 \times 24 = 61{,}159$ kWh.

Daily load factor $= \dfrac{\text{Average load}}{\text{Max. load}} = \dfrac{61{,}159}{24 \times 12{,}000} = 0.212$ or 21.2%. **Ans.**

Example 12.4. *A run off river hydro-power plant with an effective head of 20 m and plant efficiency 78% supplies a variable load as shown below:*

Time (Hours)	*Load (× 10^3 kW)*
0 - 4	*8*
4 - 8	*15*
8 - 12	*28*
12 - 16	*32*
16 - 20	*42*
20 - 24	*50*

Draw load duration curve and determine

(a) Flow required for average load

(b) Load factor

Solution. The load duration curve is shown in Fig. 12.12

H = head = 20 m

η = Efficiency = 0.78

E = Energy supplied during 24 hours

$= (8 + 15 + 28 + 32 + 42 + 50) \times 4 \times 10^3 = 700 \times 10^3$ kWh

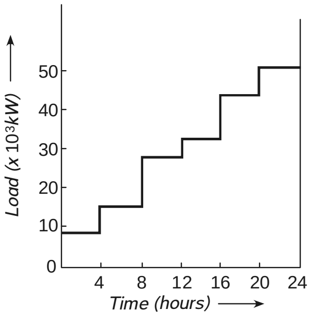


Fig. 12.12

Average load $= \dfrac{700 \times 10^3}{24} = 29 \times 10^3$kW

Load factor $= \dfrac{\text{Average load}}{\text{Maximum demand}} = \dfrac{29 \times 10^3}{50 \times 10^3} = 0.58 = 58\%$ **Ans.**

Let Q = Flow (m^3/sec)

Average Power (kW) $= \dfrac{\omega.Q.H.}{75} \times \eta \times 0.736.$

$$29 \times 10^3 = \frac{1000 \times Q \times 20}{75} \times 0.78 \times 0.736$$

∴ Q = 189 m3/second **Ans.**

Example 12.5 *The yield of water in Mm^3 from a catchment area during each successive month is given in the table below:*

1.4	*2.1*	*2.8*	*8.4*	*11.9*	*11.9*
7.7	*2.8*	*2.52*	*2.24*	*1.96*	*1.68*

Determine the minimum capacity of a reservoir required to allow the above volume of water to be drawn off at a uniform rate assuming that there is no loss of water over the spillway.

Solution. Now, to draw the mass curve of inflow, the cumulative inflow values are worked out in table below:

Table

Month	*Yield (Mm^3)*	*Cumulative yield (Mm^3)*
1	1.4	1.4
2	2.1	3.5
3	2.8	6.3
4	8.4	14.7
5	11.9	26.6
6	11.9	38.5
7	7.7	46.2
8	2.8	49.0
9	2.52	51.52
10	2.24	53.76
11	1.96	55.72
12	1.68	57.40

The average monthly rate at which the water is withdrawn to use the inflow fully

$$= \frac{\text{Total inflow of water in 12 months}}{12}$$

$$= \text{Average demand rate}$$

$$= \frac{57.4}{12} = 4.78 \text{ Mm}^3$$

The mass inflow curve is now plotted, as shown in Fig. 12.13. A line parallel to the demand rate line is now drawn through the high point A_1 on the inflow mass curve, as shown. The maximum departure between the inflow mass curve and this line, *i.e.*, B_1C_1, gives the min. storage capacity required. This value is read out as 20.78 Mm³. **Ans.**

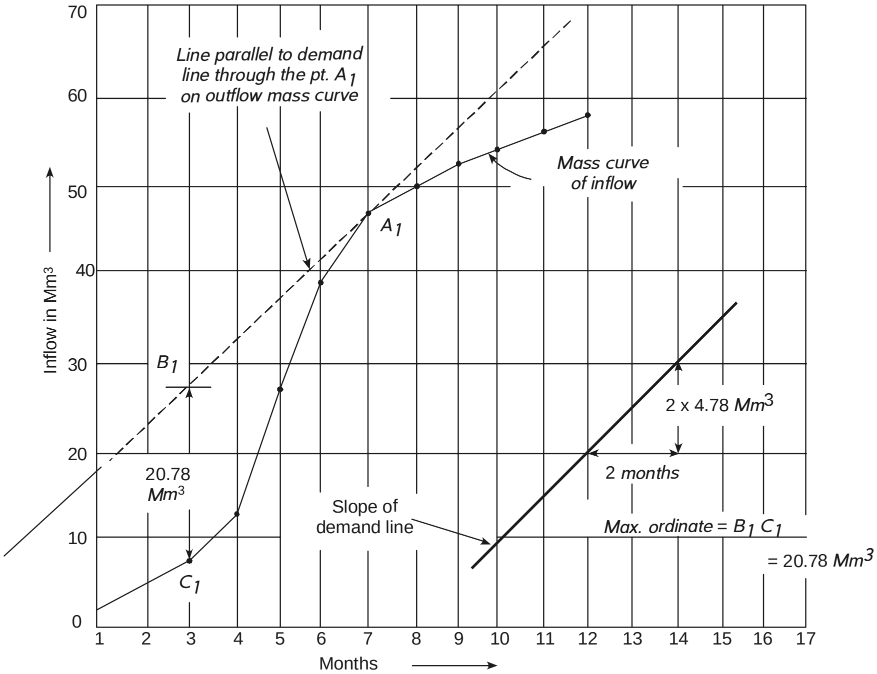


Fig. 12.13

Analytically, the solution to the problem can be worked out, as shown in table as under:

The highest value in col.(6) and 7 (as no spilling is allowed), is 20.78 Mm³, which gives the min., required reservoir storage. **Ans.**

Month	*Inflow Mm^3*	*Outflow (Demand) Mm^3*	*Deficit Mm^3*	*Surplus Mm^3*	*Cumulative Deficit Mm^3*	*Cumulative Surplus Mm^3*
1	1.4	4.78	3.38			
2	2.1	4.78	2.68			
3	2.8	4.78	1.98		8.04	
4	8.4	4.78		3.62		
5	11.9	4.78		7.12		
6	11.9	4.78		7.12		
7	7.7	4.78		2.92		20.78
8	2.8	4.78	1.98			
9	2.52	4.78	2.26			
10	2.24	4.78	2.54			
11	1.96	4.78	2.82			
12	1.68	4.78	3.10		12.70	

Ans.

Example 12.6. *The runoff data for a river during a lean year are given below:*

Month	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*June*	*July*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
River flow in 10^6 cum	*140*	*27*	*35*	*26*	*16*	*48*	*212*	*180*	*116*	*92*	*67*	*37*

What is the maximum uniform demand that can be met? What is the storage capacity required to meet this demand? What minimum initial storage is necessary ? When does the reservoir become empty?

Solution.

Total inflow in the year = Summation of the given monthly discharges = 996 M cum

Average monthly rate at which water can be withdrawn to avoid any wastage *i.e.*

$$\text{max average monthly rate} = \frac{996}{12} = 83 \text{ Mm}^3. \quad \textbf{Ans.}$$

Now, to determine storage capacity etc. we carry out the computations in table.

Month end	*Monthly Inflow in reservoir in Mm^3*	*Monthly outflow from reservoir in Mm^3*	*Monthly deficit in reservoir (to be supplied from storage) in Mm^3*	*Monthly surplus in reservoir in Mm^3*	*Consecutive cumulative deficit in Mm^3*	*Consecutive cumulative deficit in Mm^3*	*Net water available in the reservoire in Mm^3*
Jan	140	83		57		57	(+) 57
Feb	27	83	56				
Mar	35	83	48				
Apr	26	83	57				
May	16	83	67				
June	48	83	35		263		(–) 206
July	212	83		129			
Aug	180	83		97			
Sep.	116	83		33			
Oct.	92	83		9		268	(+) 62
Nov.	67	83	16				
Dec	37	83	46		62		0

The highest value in col. (6) and (7) is 268 Mm^3, which represents the minimum storage capacity required to meet the demand without any spilling. **Ans**.

To compute the min. initial storage, we compute in col. (8), the net storage left in the reservoir with the above inflows and outflows. The maximum negative storage here works out to be 206 Mm^3. In order that the reservoir fully meets the demand with the above inflow & outflow, there should be negative storage in it, and in the limiting case the max. negative storage should be equal to zero. Hence, the min. initial storage in the reservoir should be 206 Mm^3, which will just meet the shortage created in the reservoir by *June end,* when the reservoir will become empty. **Ans.**

QUESTIONS

1. What is hydrology? Discuss the term 'hydrological cycle' in detail.
2. What is hydrograph? What information does it provide?
3. How can a flow duration curve can be obtained from a hydrograph?
4. What is a mass curve ? What information does it provide? What is its use?
5. Write short notes on the following:
  (*a*) Hydrology
  (*b*) Hydrological cycle
  (*c*) Mass curve
  (*d*) Run off

6. Explain the rainfall process indicating all possible losses.

7. (*a*) Explain clearly the constituents of runoff.
(*b*) Differentiate runoff and surface runoff.

8. What is meant by reservoir? Describe briefly the techniques that are employed for computing the storage capacity of a reservoir.

9. (*a*) Explain briefly about flood control reservoir.
(*b*) Explain as to how the storage capacity of a reservoir is fixed.

10. Explain the mass curve method that can be used for determining the reservoir capacity for fulfilling given demand.

11. Enumerate and briefly discuss the various factors which affect the runoff from a catchment.

12. What do you understand by precipitation? How does it occur?

13. (*a*) How is rainfall measured in a catchment?
(*b*) How would you find the average rainfall over a given catchment?

14. What is a mass curve? What does the slope of the curve at a point indicate?

15. Explain, what do you mean by storage and pondage. Why are they required?

16. What is a catchment area? Why is a reservoir required?