5

Gas Turbine Stations and Combined Cycles

5.1 Field of Use and Advantages

Gas turbine plants can be used for power generation and have advantages in certain situations. They can be started and shut down quickly and are suitable for use as peak load stations. Gas power stations deal with variable load operations effectively. They have relatively low capital cost, require less space and a large quantity of water is not required, as in case of steam turbine plants. They do not need boiler and condensing plant and are, therefore, quite compact. They can be installed quickly. They are built in relatively smaller sizes, upto 70 MW. For large sizes, steam turbine plants are commonly used. Gas turbine plants are used for power generation where fuel oil is cheap, water scarce, natural gas available and the load factor very low, in the range of 15% to 18%. Waste heat during the working of gas turbines in the process of combustion can be used for the production of producer gas and for district heating. The gas cycle has inherently high thermodynamic efficiency, the thermal efficiency being of the order of 40%. It has low maintenance requirements.

Other details of the advantages of gas turbine plants and their use in a system having different types of power plants are explained in a later chapter. The gas turbine station can be used in parallel, with a tidal power station also.

Gas turbine stations can be used as standby plants. The plants can be located in cities and industrial centres in close proximity to areas having heavy electrical power demand. Gas turbines need fewer auxiliaries and their control is very simple.

They do not need high pressure piping. The gas turbine plant has one disadvantage. It needs a starting motor to bring it upto speed initially. A separate small Diesel driven alternator serves to supply the starting motor.

5.2 Main Parts of Gas Turbine Plant and Principle of Operation

A gas turbine in its simplest form consists of a compressor, combustion chamber and a turbine. The compressor draws air from the atmosphere and supplies it under pressure to the combustion chamber. The fuel is injected into the combustion chamber in atomised form and burnt. Once the combustion is started by an igniter, it is self-sustained. The hot gas formed in the combustion chamber expands through the turbine, producing mechanical power. The compressor is also connected to the same shaft and the turbine supplies power to drive the compressor, as well as the output shaft for driving the generator.

5.2.1 CYCLE

The gas turbine works on a constant pressure or Brayton cycle. The cycle can be represented by pressure/specific volume diagram or temperature/entropy diagram. This is shown in Fig. 5.1. Air existing at state '*a*' in the atmosphere is taken in the compressor and compressed to state '*b*'. The compressed air goes to the combustion chamber where fuel is burned in it. The fuel/air ratio used is such as to produce the temperature '*c*'. Heat is added at constant pressure, '*c*' is the highest temperature of the cycle. The highest temperature limit is set by the properties of the materials of the first stage turbine rotor blades and the lower one is the ambient temperature. Thus, the efficiency is greater the higher the turbine entry temperature is, and the lower the compressor entry temperature is. The high temperatures normally used at present are within the limits 650°C to 815°C. The products of combustion at state '*c*' are expanded in the turbine to state '*d*' where they are discharged into the atmosphere. The compression '*ab*' and expansion '*cd*' are isentropic. The gas turbine cycle operates at a low pressure compared with the steam turbine cycle, but the amount of air handled is very large. Also about 60% of its output is used to drive the compressor.

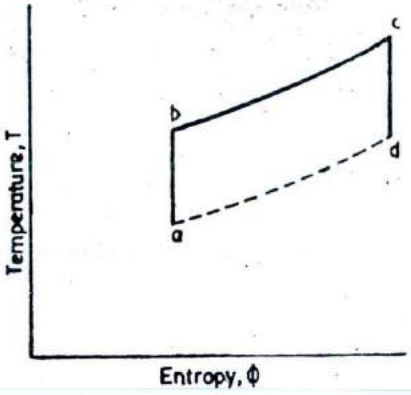


Fig. 5.1. Brayton (constant pressure) cycle for gas turbine.

The effect of turbine inlet temperature on efficiency of the turbine is shown in Fig. 5.2.

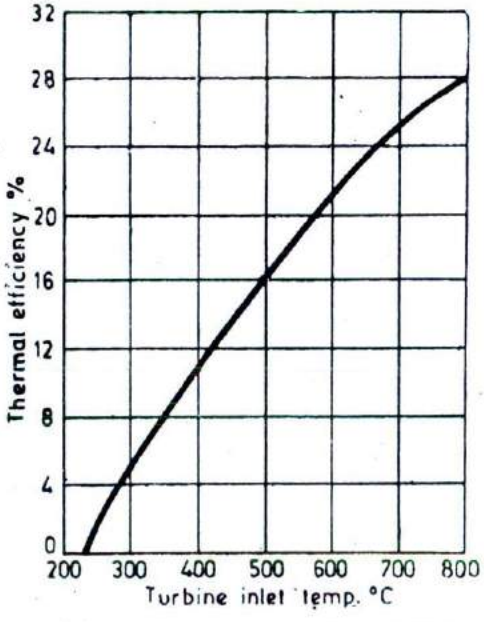


Fig. 5.2. Effect of temperature on thermal efficiency.

Fig. 5.3 shows the simple open cycle plant.

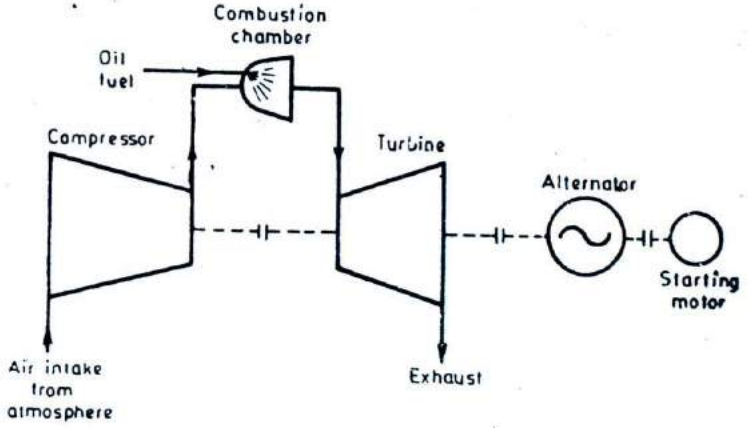


Fig. 5.3. Simple open cycle plant.

The main parts are compressor, combustion chamber and turbine. Two types of compressors are used in gas turbine plants, centrifugal or axial. In earlier stages of development of gas turbines, centrifugal type compressors were used, as they were easier to design and cheaper to manufacture. The axial flow type compressors are more efficient and have now reached a high stage of development and are used in most gas turbines. Each stage of an axial compressor consists of a row of rotor blades followed by a row of diffuser blades. The rotor vanes accelerate the air, and the diffusers convert the kinetic energy into pressure energy. An axial compressor has a large number of stages, as many as 17 in some cases. For a single rotor compressor, the maximum pressure ratio in practice is 6 : 1.

The combustion chamber consists of a vessel into which pressurised air and pressurised fuel are fed in appropriate proportions, finally mixed, ignited and fed into the turbine at correct turbine entry temperature. The pressure in the combustion chamber is decided by the outlet pressure of the compressor, which feeds air directly to the chamber. About 30% of the main flow of air passes into the burner area as primary air. The air fuel ratio in the area is maintained at about 15 : 1. The secondary air is used to dilute the burnt gas to reduce its temperature to one

which is acceptable and suitable for the turbine blades. The fuel burner contains an atomiser, which uses the pressure of the fuel to divide it into an extremely fine spray which mixes with the primary air in the right proportion for complete combustion. A high energy igniter used is an electric spark plug to ignite the gas initially. Provision is made to detect the flame optically so that in the event of flame failure, the fuel supply to the burners can immediately be shut off automatically.

The turbine has to perform two functions, the first is to provide power to drive the compressor, and the second to supply power to the output shaft from which alternator can be driven. In some cases, these two functions are separated; the high pressure turbine drives the compressor and the low pressure turbine gives power to the generator—this can be called the power turbine. This arrangement is very useful where gas turbine plants are used for electric power generation. For alternator drives power turbine speed must remain constant. Compressor turbine speed can be varied according to the output required. Fig. 5.4 shows an open cycle plant with separate power turbines.

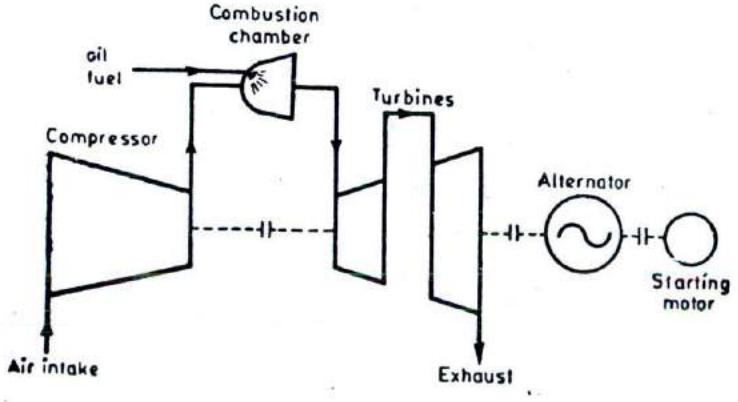


Fig. 5.4. Open cycle plant with separate power turbines.

In some cases the compressor turbine is split in two parts from which low pressure and high pressure compressors are used, rotating at different speeds. The turbine has fewer stages than

the compressor. The blades of the turbines have to withstand very high temperatures as well as high stresses.

5.2.2 THERMAL REFINEMENTS OF THE GAS TURBINE CYCLE

The efficiency of a simple gas turbine plant can be improved by adding a few refinements such as regeneration, inter-cooling and reheating. Regeheration is the transfer of heat energy from exhaust gases to compressed air flowing between the compressor and the combustion chamber. Inter-cooling is the removal of heat from the compressed air between the stages of compression. Reheating is the increase in temperature of gas which is partially expanded by burning more fuel in it. This method is good for improving the efficiency of the plant where the pressure ratio is high, but maximum cycle temperature is moderate. A gas turbine plant using the above refinements is shown in Fig. 5.5, indicating flow diagram.

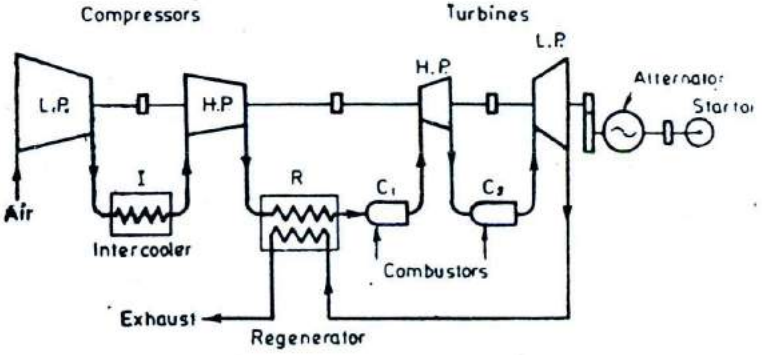


Fig. 5.5. Gas turbine plant with regeneration inter-cooling and reheat.

The compressor turbine is split into low pressure and high pressure turbine. *I* represents an inter-cooler to remove part of the heat from the compressed air between stages of compression. *R* represents regeneration where heat from the exhaust gases is used to raise the temperature of the compressed air before it is admitted to the turbine through the combustor. *C* represents combustors, where the fuel is burned, C_1 being the combustor before gas is admitted to the H. P. of the power turbine. C_2 represents

the combustor used for reheating the partially expanded gas between the H. P. and L. P. power turbines. The alternator is shown coupled through gears to reduce the speed to the required value (3000 r.p.m. for 50-c/s). The load is supplied by the alternator. The starter motor is coupled to the shaft of the alternator. The starter motor is used to start the gas turbine set initially, to bring it upto the speed required.

5.2.3 CLOSED CYCLE PLANT

In the closed cycle plant, the working medium used is air. This is continuously circulated through the compressor, heat exchanger, air heater, turbine and air cooler. Fig. 5.6 shows a closed cycle plant, using air as the working medium.

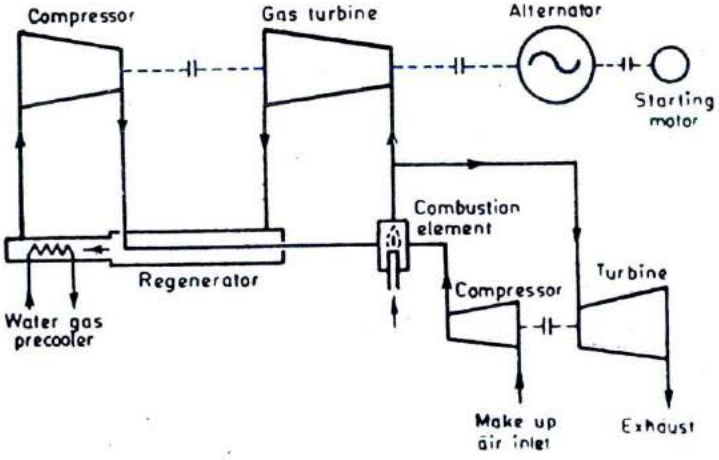


Fig. 5.6. Closed cycle gas turbine plant.

Load variation is affected by varying the absolute pressu and the mass flow of the circulating air. The pressure ratios, t temperatures and air velocities in the system remain practica constant. It is advantageous to have isolation of the worki medium within the closed circuit and its continuous recirculatic High efficiency is maintained over the full range of operati loads. Maximum unit capacity can be increased by adopti closed cycle, as in this cycle the gas is at relatively high pressu the physical dimensions of turbine and compressor are reduced.

Fig. 5.6 shows compressor and gas turbine. Gas before entering the compressor passes through water gas pre-cooler to cool it to the required temperature. After compression, it passes through a regenerator to combustion element and to the gas turbine. After expansion through the turbine it is again circulated to the compressor and the cycle is repeated. Make up air is provided by another compressor turbine set as shown. The main gas turbine drives an alternator which supplies the load. A starting motor is provided as usual.

5.3 Characteristics of Gas Turbine Plants

The higher the temperature limits under which the gas turbine plant can work, the higher the efficiency. The effect of the gas turbine inlet temperature on thermal efficiency was shown in Fig. 5.2. With the addition of regeneration, inter-cooler, and reheating, the efficiency is raised. The approximate thermal efficiencies for gas turbine stations are as follows :

Upto 7.5 MW uncompounded plant without regeneration 15 to 20%

Upto 7.5 MW uncompounded plant with regeneration 20 to 25%

From 10 MW to 30 MW compound plant with regeneration 28 to 32%

These figures are on the assumption of atmospheric temperature of 15°C.

A 5°C change in inlet air temperature varies efficiency by about 3% and the output by about 4% in open cycle plant.

5.3.1 FUELS USED

A number of fuels can be used in gas turbine plants. The usual fuels used are the following :

(*a*) Natural gas – methane – is ideal fuel; this has high calorific value, being clean. This can be used where it is available at low cost.

(*b*) Kerosene – paraffin – very clean, but normally used at airfields. Costly.

(*c*) Gas Oil—distillate oil—This is generally cheaper than kerosene. It, however, requires careful filtration.

(*d*) Diesel oil (DERV). This is similar to gas oil, but has low sulphur content. This is more expensive than gas oil, but cheaper than kerosene.

(*e*) Residual oil—Bunker C—is the cheapest of the fuels, but this has the disadvantage that it produces low melting point ash. It could be used by limiting the turbine inlet temperature to 625°C, by the use of additives to keep the ash powdery or by washing the oil before use to remove the sodium content in it. Both methods are expensive and shut down of the plants is necessary for blade washing every week.

5.3.2 COMPARISON WITH STEAM AND DIESEL PLANTS

Gas turbines have to work at high temperatures to obtain higher efficiency than steam turbines. This should be about 650°C and higher. The disadvantage is that nearly 60% of the power produced is lost in driving the compressor, and the remaining power is the useful power for alternator drive. Fuel for gas turbines is more expensive than coal for the steam turbine cycle. Cubic capacity of the buildings required for a gas turbine plant is about one half of that of a steam turbine plant of similar size. This saves capital cost for the gas plant. The cooling water requirement is less than that of the steam turbine plant. The chimney discharge is similar to that of oil fired boilers. The volume discharged to the atmosphere is about six times. The temperature is higher.

For large sizes above 100 MW or so, steam turbine plants are much superior. In lower sizes also, gas turbine plants can be considered only as peak load plants. They are not suitable for base load operation and continuous running for long periods. They can, however, pick up variable load quickly.

When compared to a Diesel plant, the gas turbine plant has the advantage of easier maintenance, lower initial cost, small size of buildings and plant dimensions, and improved reliability. There is no cyclic irregularity as in the Diesel plant.

The cost of the gas turbine plant is about Rs. 600 to Rs. 800 per kW; the steam station plant, and also Diesel, costs about Rs. 1,000 to Rs. 1,200 per kW.

The fuels used for gas turbine plants have calorific value of about 9,000 to 10,000 kilocalories per kilogram. The fuel consumption is about 0.22 to 0.25 kg/kWh.

5.4 Gas Turbine Power Plant Operation and Control

The starting up of the gas turbine plant and stopping it requires a certain procedure. Also the procedure has to be properly controlled in correct sequence. This can be done automatically.

Gas turbines are not self starting and do not become self sustaining until they reach about 50% speed. Means must be provided to crank the unit to firing speed and to assist acceleration after firing. Temperature control must be provided to limit the maximum temperature and the rate of change of turbine inlet temperature to prevent damage to the turbine. Turbines that normally operate on bunker C oil must be started on diesel oil and transferred to bunker C at or above idle speed.

Operation of a master switch initiates the starting or stopping sequence, which then proceeds automatically through the various steps required. The starting sequence requires the following steps :

1. Cranking the unit to approximately ten per cent speed to establish air flow through the combustion chambers.

2. Admitting correct amount of fuel, applying ignition and booster air to initiate combustion.

3. Accelerating the unit after firing assisted by the starting motor.

4. Disengaging the starting motor when the gas turbine reaches self sustaining speed.

5. Transferring from diesel oil to bunker C.

Stopping sequence requires the following steps :

1. Transferring from bunker C to diesel oil and operating on diesel oil for sufficient length of time to remove the heavy bunker C from the fuel pump, fuel lines, and fuel nozzles.

2. Shutting off the fuel supplied to the combustion chambers.

3. Rotate the unit after shut down to allow proper cooling of all parts.

The method of controlling the load depends on the type of plant cycle used. In the case of an open cycle, the regulation is obtained by controlling fuel flow to the combustion chamber. The governor is located on the output shaft and by its action regulates a valve in the fuel supply line. In a partly closed cycle, valves are introduced in the main circuit to regulate recirculation of air proportionately. In a closed cycle, the variable load is controlled by varying the density of air in the closed circuit. This is done by passing air into or out of the circuit from reservoirs under pressure. The fuel flow is also regulated simultaneously with the air density.

5.5 Plant Layout

The equipment to be accommodated consists of intercoolers, combustion chambers, heat exchangers, heat waste boilers, and interconnecting ductwork. The rotating parts, viz. turbines and generators, form a small part of the volume of the plant. The line arrangement layout of the plant is the best from the point of view of design, operation and maintenance. Combustion chambers, heat exchangers, inter-coolers and air filter units can be located on each side of and parallel to the set. The exhaust gases from gas turbine exhaust are taken out to the chimney. The other arrangements required will be for lubricating oil system, ventilation, cable chambers, control and switchgear rooms.

The general layout of the gas turbine station is similar to that of the steam turbine plant, having an operating floor and basement. The size of the building is, however, much smaller, and the equipment is not very complicated and involved as in the case of steam turbine station.

Fuel is brought to the station by road tankers. The fuel oil storage tanks are arranged outside the main building but adjoining the turbine house. The fuel pump house is located near the storage oil tanks. A circulating water pump house is located outside the main building at a suitable site. Generators are connected to the transformers through busbars as usual, and the high voltage supply can be taken out from the transformers to the system as required.

Fig. 5.7 shows a typical plan of a gas turbine station.

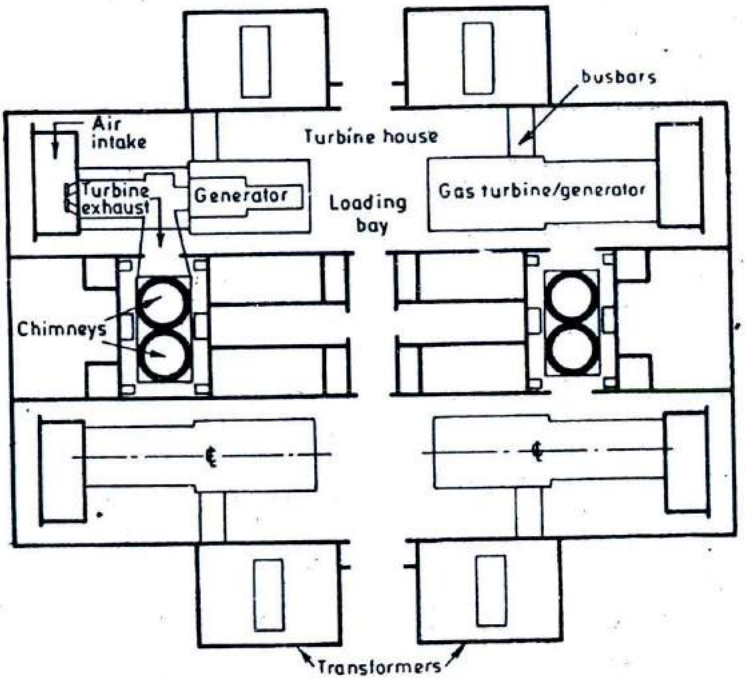


Fig. 5.7. A typical plan of a gas turbine station.

5.6 Combined Cycles

In a boiler, heat is transmitted from gas to steam and water through the tube walls of the boiler. Strength and economic considerations limit the working temperature of metallic tubing

to about 800°C. This puts a limit to the maximum possible thermal efficiency that can be obtained by the steam plant at about 47%. The combustion temperature that can be achieved by burning common fuels stoichiometrically in air is about 2000°C. If the heat in hot gases at this temperature is used and rejected at low temperatures corresponding to those obtained with condensing conditions in a steam cycle, the efficiency of the thermal plant will improve.

Gas turbines can convert the energy of hot combustion gases directly into mechanical work without using a secondary working fluid. Inlet gas temperatures of 1250°C are possible by blade cooling with a small amount of air. If clean fuel such as kerosene is available inexpensively it is possible to reach an efficiency upto 45%. Kerosene, however, is not cheap, and for gas turbines only residual fuel oil is available at economic price. Gas turbine plant and steam turbine plant can be considered for combined cycle operation. The gas temperature will have to be limited to 650°C with this fuel, and the advantage gained by combined cycle operation is marginal. The usual combined cycle of this type will be the gas turbine cycle to top the steam plant and exhaust into the combustion chamber of the boiler. The steam cycle is then as usual, steam being produced in the boiler and supplied to the steam turbine. The generators are driven both by the gas turbine and the steam turbine.

It is necessary to increase the inlet temperature of gas to have worthwhile improvement in the thermal efficiency, without using expensive fuel oil. Carbonisation of coal is being tried, by which a cheap raw fuel can be processed to obtain clean gaseous fuel. The coal in pulverised form is processed in an air fluidised bed under pressure. This produces a gaseous fraction and a hot char residue.

After cleaning the gases, they are burned in a combustion chamber and passed through the gas turbine at about 750°C. The hot char is fed to the conventional boiler and mixed with hot gases exhausted from the gas turbine for combustion purposes. Such a system may increase the efficiency by about 3.5%.

5.6.1 BINARY CYCLE : STEAM FREON CYCLE

L. P. steam turbines are expensive and increasing the steam flow through them does not improve the situation. For increasing the rating and reducing the capital cost per kW of the turbine, it is worthwhile considering the introduction of a secondary or binary fluid for the remaining part of expansion in the cycle. For improving the L. P. turbine design size, the properties of the binary fluid must be such that its specific volume must be considerably less than that of steam. It should also condense at about 27°C and at atmospheric pressure. In that case, by a suitable cut off point in I. P. turbine, the duty of the steam cycle can be taken over by this fluid cycle.

The fluid suggested with the required properties is Freon. Thus a Steam-Freon binary cycle can be used with advantage. The specific volume of Freon is about 1/300th that of steam at 26.7°C, but the mass flow required to develop the same power as steam when condensing at the same temperature is about 12 times. Still with these characteristics, the reduction in volume flow is approximately 1/20th of that of steam. Freon turbines are designed for a temperature range of 125°C to 265°C, and have one or two stages of turbine blading.

The cycle would need a Freon boiler and Freon condenser. The steam cycle has H. P. and I. P. turbines. Steam is taken from the I. P. turbine to the evaporator or Freon boiler where the expanded steam gives heat to the Freon. The Freon cycle then consists of its expansion through Freon turbines to the Freon condenser. The condensed Freon is pumped back to the Freon boiler/evaporator to complete the cycle. With this arrangement, it is possible to reach an efficiency of 45% or so.

5.6.2 BINARY CYCLE : MERCURY STEAM CYCLE

The cycle efficiency is increased to some extent by using a binary vapour cycle of mercury and steam. In this case, mercury tops the conventional steam components. The cycle consists of mercury boiler, mercury turbine and mercury condenser, mercury returning to the mercury boiler to complete the feed. Heat is

given in the mercury condenser to change water to steam (boiler) which is then admitted to the steam turbine and the cycle is conventional through the steam condenser and back to the steam boiler. The low vapour pressure of mercury at 565°C necessitates the use of multiple flow mercury vapour turbines. This becomes expensive, so that though some improvement in efficiency is achieved, there is no reduction in the cost of capital investment. The use of such a binary system is restricted to small size power systems where the sizes of the sets in the system are limited. The mercury steam cycle has been explained already in chapter 4 while dealing with the steam boilers and turbines.

5.7 Magneto-hydro-dynamics (MHD) Generation

Magneto-hydro-dynamics power generation works on the principle of Faraday's law of induction. Here the conductors are fluid hot gases. This law states that the motion of a conductor in a magnetic field induces an e. m. f. in it. In a MHD system, the advantage is the direct generation of electricity from hot combustion gases without moving parts. The conventional electrical machines are essentially electro-mechanical convertors; while an MHD generator is a heat engine operating on a turbine cycle transforming the internal energy of the gas to electrical energy.

An MHD system consists essentially of the following:

(*a*) A high intensity pressurised combustion chamber.
(*b*) An expansion nozzle to accelerate the gases.
(*c*) An aerodynamically shaped duct.
(*d*) An electrode system.
(*e*) A powerful magnet.

Fig. 5.8 shows the principle of the MHD cycle.

The direction of the flow of gas, the field produced by the magnet and the direction of the e. m. f. induced are shown. The voltage is generated across the electrodes. If the electrode is continuous, formed by electrode walls, electrode losses are brought about by longitudinally induced e. m. f. s. due to the Hall effect. The electrodes are, therefore, segmented and multiple load connexions are used.

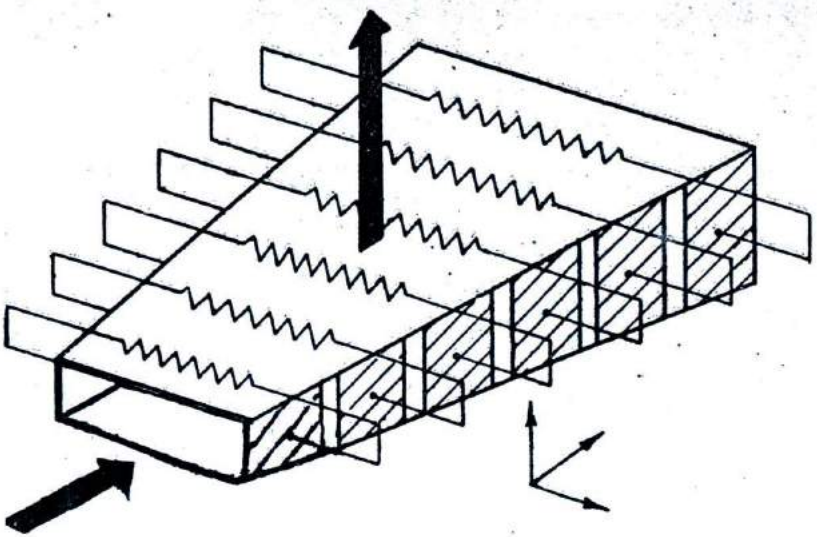


Fig. 5.8. MHD cycle.

Gas is produced by the combustion of fuel with pressurised air to achieve a high temperature of about 2000°C. It is then expanded through the MHD duct to an exhaust temperature of about 1000°C. While this expansion occurs at high temperatures, electric power is produced across electrodes. The heat from the exhaust gases of the MHD cycle is used and recovered efficiently by a conventional steam plant, and so this can also produce additional power.

An MHD generator needs a suitable working fluid which is electrically conducting. This may be a liquid metal or partially ionised gas. Gases become conducting when their atoms or molecules are stripped of one or more electrons thermally, electrically or by using radiations.

The gas is not conducting enough by itself at these temperatures. To make it conductive, it is necessary to add to it ionised seed materials such as alkali metal. Even with this the minimum temperature which gas should have is 2000°K to obtain some power out of it. (°K=Degree Kelvin=Degree C+273.15). The

temperature of gas should be raised to about 2800°K. To make this possible, air preheating is done. This is done by utilising the heat in the exhaust gases from the MHD duct or heating air in a separate combustion system.

The duct and electrode system should be constructed to withstand this temperature. Superconducting magnets should be used to produce high magnetic flux density from MHD generation. The flux density required will be of the order of 40×10^{-5} wb/cm^2 to 60×10^{-5} wb/cm^2 (4 to 6 Tesla).

One pair of walls of the duct forming the poles of the magnet are the insulating walls, while the other pair are electrodes. The motion of the plasma in a high magnetic field induces an e. m. f. at the electrode terminals. This is at right angles to the magnetic field as well as to the direction of flow of the plasma. Electrode pairs are externally connected to the load. The power which can be taken off the system is given by –

$$P = \sigma B^2 V^2 K(1 - K) \text{ W/m}^3 \qquad (5.1)$$

where B = magnetic field strength, Tesla.

V = velocity of gas, metres/second.

K = ratio of external load voltage to open circuit voltage.

σ = specific electric conductivity of gas mho/metre e.g., if $\sigma = 6$ mho/metre, $V = 2000$ metres/second, $K = 0.5$, $B = 4$ Tesla, the power density would be about 100 MW/m^3 or the nominal volume of a 500 MW MHD generator would be 5 m^3 which is 5 metre long tube with 1 square metre cross section.

An MHD system has large power and temperature handling capacities. As there are no moving parts, the system has high reliability.

5.8 MHD Systems

MHD systems can be classified broadly as follows:

(*a*) Open Cycle Systems.

(*b*) Closed Cycle Systems.

(i) Seeded inert gas systems

(ii) Liquid metal systems.

Fig. 5.9 shows a schematic diagram of an open MHD generation cycle.

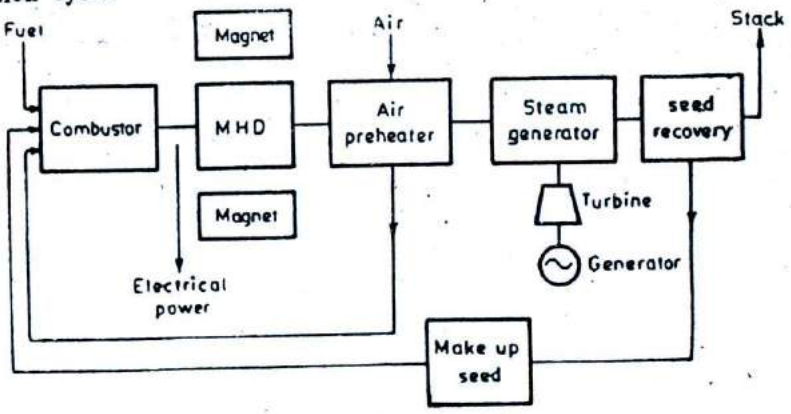


Fig. 5.9. Schematic diagram of an open MHD generator.

Fuel used may be oil through an oil tank or gasified coal through a coal gasification plant. The fuel is burnt in the combustor. The hot gases with necessary seed pass through MHD to produce electric power at the electrodes. The exhaust gases go through the air preheater and to the steam boiler, then to the seed recovery apparatus. The recovered seed is stacked. Make up seed is also fed to the combustor. The preheated air is also fed to the combustor as required by the loop.

The steam generator feeds the steam to the steam turbine which drives the generator to produce electric power.

The working medium in the open cycle MHD system will be products of combustion of fossil fuels such as coal, petrolium or natural gas. They are seeded with potassium salts. The inlet temperature at MHD is about 2500°C.

A seeded inert gas system consists of a working gas—argon or helium— seeded with cesium. The closed cycle metal system has the basic advantage of high electrical conductivity. However, liquids being practically incompressible, high velocities cannot be produced as in the case of gas. Both systems are still having a number of technological problems for full commercial development and use. They are in the experimental stage.

5.9 Costs

MHD programmes have been developed in U.S.S.R., U.S.A. Japan and Poland, and an MHD research programme has been started in India recently. The economics of MHD plant have been analysed by many workers in various countries. Table I gives the figures of studies by Oliver of MIT, U.S.A.

Table I

Comparison of Generation Costs

		Conventional Steam	MHD/Steam
Construction cost (Steam)	$ 250/kw	5.86 mil/kWh	3.40 mil/kWh
Construction cost (MHD)	$ 250/kW	—	2.50
Gas Cleaning	$ 50/kW	1.18	—
Cooling towers	$ 30/kW	0.71	0.41
Fuel Cost	$ 25/kW	2.40	1.85
Fuel cost	$ 25/MThU	2.40	1.85
Seed cost			0.20
		10.15 mil/kWh	8.36 mil/kWh

Based on steam plant efficiency of 40%

For MHD/Steam : 22% net MHD enthalpy extraction, 38% net steam, plant efficiency.

Table II

Coal requirement per kWh in kg.

Conventional			MHD		
100 MW	200 MW	500MW	500MW (Stage I)	500MW (Stage II)	
0.60	0.53	0.50	0.37	0.30	

The calorific value of coal is assumed to be 5000 kilocalories/kg.

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Problems

5.1. State the field of use and the advantages of gas turbine power plants.

5.2. Explain the principle of the working of gas turbines. Explain open cycle and closed cycle for gas turbines.

5.3. What are the various types of fuels used ? State their merits and limitations.

5.4. What are the methods of improving the thermal efficiency of gas turbines ? Explain regeneration, inter-cooling and reheat processes.

5.5. Compare gas turbine plants with Diesel and steam turbine plants.

5.6. Explain the methods of controlling the starting, stopping operation and controlling the variable load on gas turbine power plant.

5.7. Explain how combined cycles can be used to improve the efficiency of power plants.

(*a*) Explain the Mercury Steam binary cycle.

(*b*) Explain the Steam-Freon Cycle.

5.8. Explain the principle and main parts in MHD generation.

5.9. Explain open cycle MHD generation and show general layout of the plant.

5.10. Compare the economics of steam stations, gas turbine stations and MHD generation.

6

Elements of Nuclear Power Stations

6.1 Field of Use and Advantages

Conventional thermal power stations use oil or coal as the source of energy. The reserves of these fuels are becoming depleted in many countries, and thus there is a tendency to seek alternative sources of energy. In a nuclear power station instead of a furnace there is a nuclear reactor, in which heat is generated by splitting atoms of radioactive material under suitable conditions. For economical use in a power system a nuclear power station generally has to be large, and where large units are justifiable, nuclear power stations are considered as alternatives to conventional stations.

The nuclear power station has a number of advantages compared to the conventional thermal station.

1. It reduces the demand for coal, oil and gas, the costs of which are tending to rise as the stocks become depleted.

2. The transport of conventional fuel to the station involves cost as well as delay if the transport facilities are not available in time. The weight of the nuclear fuel required for a station of the same capacity is almost negligible in comparison, and problems of transport do not arise.

3. Besides producing large amounts of power, the nuclear power plant can produce valuable fissile material, which is extracted when the fuel has to be renewed.

4. The nuclear power station needs less area and volume compared to a conventional plant of equal capacity.

Nuclear power plants can be used as base load plants. They are not suitable for variable load operation as the reactors cannot be easily controlled to respond quickly to load changes. They are used at a load factor of not less than 80%.

6.2 Main Parts of a Nuclear Power Station

The main parts of a nuclear power station are the nuclear reactor and a heat exchanger, together with the familiar steam turbine, condenser and generator. In a furnace, heat is produced by burning fuel. In a reactor, heat is produced by the fissioning, or splitting, of uranium atoms. A cooling medium takes up this heat and delivers it to the heat exchanger, where steam for the turbine is raised. The reactor and heat exchanger are equivalent to the furnace and boiler in a conventional steam plant. When the uranium atoms split, there is radiation as well, so that the reactor and its cooling circuit must be heavily shielded against radiation hazards.

The rest of the plant is similar to the ordinary steam plant. The steam generated in the heat exchanger is admitted to the

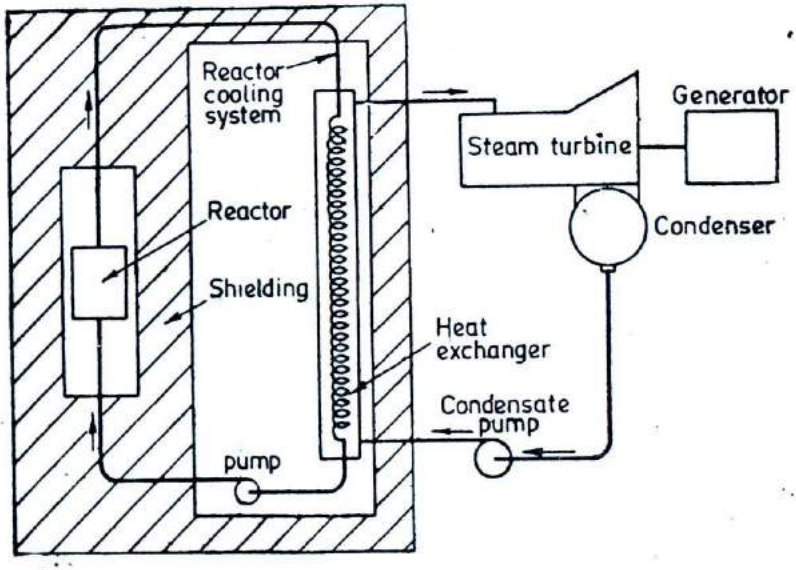


Fig. 6.1. Main parts of nuclear power plant.

turbine, and after work has been done by the expansion of steam through the turbine, the steam is condensed into condensate in the condenser. The condensate pump sends the condensate back to the heat exchanger, thus forming a closed-feed system. The other auxiliaries are similar to those in a familiar steam station.

Fig. 6.1 shows a simple diagrammatic arrangement of a common type of nuclear power station. Other types will be considered later.

6.3 Principle of Nuclear Energy

To appreciate the principle of nuclear energy and to understand how the nuclear reaction starts which produces heat, it is necessary for us to study a few basic principles of atomic physics. This involves a study of the structure of matter the stability of atoms, the binding energy of their nuclei, the interchanging of mass and energy, how a chain reaction starts and the emission of certain particles which produce radiation hazards.

6.3.1 STRUCTURE OF THE ATOM, STABILITY AND EMISSION OF RADIOACTIVE PARTICLES

All things around us contain one or more of the basic 103 elements. The smallest particle into which an element can be divided is termed an *atom*. Each element has its own type of atom.

The atom has an internal structure consisting of a densely packed nucleus, containing practically the entire mass of the atom, surrounded by electrons continuously moving round the nucleus. The nucleus consists of two kinds of infinitesimally small particles known as protons and neutrons, which are tightly bound together. Protons and neutrons are collectively known as nucleons. Each proton carries a positive electric charge of 1.602×10^{-19}C. The neutrons have no charge. The nucleus thus has a positive charge. Corresponding to each proton, with its positive charge, there is an electron orbiting round the nucleus some distance away. Each electron has a negative charge of 1.602×10^{-19}C. Thus, unless some electrons are removed or added, the whole atom has no net charge and is said to be electrically neutral. The

nucleus contains most of the mass of the atom. The system of atomic weights is based on the weight of the oxygen atom, chosen as 16. The *atomic mass unit* (amu) is, therefore, equal to 1/16 of the weight of the oxygen atom. The mass of a proton is 1.00759 atomic mass units (amu), the mass of a neutron is 1.0089 amu, while the mass of an electron, namely, 0.00054 amu, is negligible. Thus the mass of a proton or a neutron is approximately equal to 1 amu, and the atomic weight of an atom is nearly equal to the sum of the protons and neutrons, or the number of nucleons, in the atom. This is defined as the mass number of the element and is generally denoted by A. The atomic number of an element is defined as the number of protons in the nucleus of the atom and is indicated by Z. This is also the number of electrons orbiting round the nucleus of a neutral atom. The number of neutrons in the nucleus is given by $A-Z$, i.e., the mass number minus the atomic number of the element. An element is identified by its mass number and atomic number, its chemical symbol being preceded by its mass number and atomic number thus—

$$\begin{matrix}\text{Mass number}\\ \text{Atomic number}\end{matrix}\ \text{Chemical symbol or } {}^{A}_{Z}\text{X}$$

Thus ${}^{4}_{2}$ He represents helium, which contains 2 protons and 2 neutrons, and has an atomic weight of 4.003.

Some of the elements in nature exist in more than one form, i.e., they contain different numbers of neutrons in the nuclei of their atoms. Natural uranium, for example, consists largely of uranium-238, but includes a little U-235 and just a trace of U-234, the symbols for these three forms, or isotopes, being ${}^{234}_{92}$U and ${}^{235}_{92}$U and ${}^{238}_{92}$U. The number of protons in all three cases is 92 ; the difference lies in the number of neutrons. Some of the isotopes of some elements are unstable and change or disintegrate spontaneously. Those which do so are known as radio-active isotopes, and the phenomenon is called radioactive decay. Certain atoms give off radiation of particles and electromagnetic energy owing to changes in their nuclei. Some of the radioactive elements are radium, thorium and uranium.

Radiation or nuclear disintegration occurs at a definite rate, measured by half-life, or the time in which half of the atoms in a

specimen disintegrate. The disintegration of an isotope continues until it reaches a stable state. For example $^{226}_{88}$Ra (radium) continues to disintegrate through a series of atoms till it ends up as an isotope of lead. During disintegration, a number of particles or rays are emitted.

Alpha particals, or nuclei of helium-4 (α or $^{4}_{2}$He), are emitted from the nuclei of radio-active isotopes at a high velocity of about 3×10^9 cm/sec or $\frac{1}{10}$ of the speed of light, and carry a positive charge. Alpha particles do not have very great penetrating power compared to other forms of radiation, and their passage can be stopped by any shielding such as a few sheets of paper.

Beata particales (β or $_{-1}^{0}e$) are emitted from the nuclei of radio-active isotopes, also at velocities approaching that of light. The charge (—1) and mass (approximately zero) of a β-particle are the same as those of an electron.

Gamma rays (γ) are electro-magnetic waves. When an α- or a β-particle is expelled from the nucleus of a radio-active element and the smaller nucleus is still in an excited state, it emits the excess energy in the form of γ-radiation. Gamma rays are similar to X-rays or light rays but are of shorter wavelength and possess a very high energy level.

The depth of penetration of β-particles into surrounding matter is greater than that of α-particles and might be a few metres. They need better shielding than that required for α-particles. Gamma rays have high penetrating power and need thick lead shielding as a protection from their effects.

6.3.2 CHANGING MASS TO ENERGY : BINDING ENERGY : EINSTEIN'S LAW

Einstein proved mathematically that mass and energy are interchangeable and that the relation between them is given by

$$W = mc^2 \qquad (6\ 1)$$

where W = Energy (joules)
m = Mass (kilograms)
c = Speed of light (3×10^8 m/sec)

This is the most fundamental equation in the science of nuclear physics, expressed in engineering units.

The atomic mass unit (amu) is approximately equal to the mass of one neutron or one proton –

$$1 \text{ amu} = 1.66 \times 10^{-27} \text{ kg}$$

$$\text{Energy corresponding to 1 amu} = 1.66 \times 10^{-27} \times (3 \times 10^8)^2$$

$$= 1.494 \times 10^{-10} \text{J}$$

In nuclear physics, mass is expressed in atomic mass units, and energy in mega-electron-volts (Me.V). One electron-volt is the energy gained by an electron in 'falling' through a potential difference of one volt—

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{J}$$

$$1 \text{ MeV} = 1.602 \times 10^{-13} \text{J}$$

Since $$1 \text{ J} = \frac{1}{1.602 \times 10^{-13}} \text{MeV}$$

and also $$1 \text{ J} = \frac{1}{1.494 \times 10^{-10}} \text{ amu}$$

it follows th at

$$1 \text{ amu} = \frac{1.494 \times 10^{-10}}{1.602 \times 10^{-13}} = 931 \text{ MeV}$$

The weight of an atom is less than the sum of the weights of its protons, neutrons and electro ns, and the difference is termed as the mass defect. If particles are brought together quickly to form an atom, a mass equal to the mass defect is suddenly converted into energy, which may appear in the form of kinetic energy imparted to the atom being created. On the other hand, to break up an atom into its individual particles, energy equivalent to the mass defect must be supplied. The mass defect, therefore, indicates the existence of binding energy in the nucleus. The binding energy of nucleons is a direct measure of nuclear stability. Binding energy is obtained by the following relation

Binding energy (MeV)

$$= 931 \{\text{Atomic number} \times \text{Mass of proton (amu)} + \text{Number of neutrons} \times \text{Mass of neutron (amu)} - \text{Actual mass of assembled nucleons (amu)}\} \quad (6.2)$$

The energy release can be obtained in two ways—

1. By combining light nuclei, the process being known as *fusion*.

2. By breaking up heavy nuclei into nuclei of intermediate size the process being known as *fission*.

The result of fission is an increase in the binding energy per nucleon. The change in the binding energy develops kinetic energy and heat.

The mass of a nucleus depends upon the binding energy between the protons and neutrons. When there is an excess of neutrons in the nucleus and the neutron/proton ratio is well above unity, instability occurs in elements heavier than bismuth-209 ($^{209}_{83}$ Bi), i.e., nuclei heavier than this are radioactive. They emit γ-rays or nuclear particles in attempting to bring their neutron/proton ratio back within the proper range for stability.

6.3.3 NUCLEAR REACTION

Nuclear disintegration as it occurs in nature is slow and uncontrolled, and was the only kind of radioactivity known until it was found that particle accelerators can produce the different types of nuclear reaction. When charged particles such as protons or α-particles are accelerated, they acquire enough energy to cause nuclear reactions when they hit a "target nucleus". The following particles are commonly used to start and accelerate nuclear reactions—

Proton $^{1}_{1}H$ Alpha particle α or $^{4}_{2}He$

Deuteron $^{2}_{1}H$ Neutron $^{1}_{0}n$ Gamma rays γ

The charge of a neutron is zero and its mass is approximately 1 amu; its symbol is, therefore, $^{1}_{0}n$.

Alpha particles can be produced by bombardment of nitrogen nucleus by a proton—

$$^{15}_{7}N + ^{1}_{1}H \rightarrow ^{12}_{6}C + ^{4}_{2}He \quad (6.3)$$

In this reaction the nitrogen nucleus absorbs the proton, emits an α-particle and forms a carbon nucleus.

When the nucleus of an element is bombarded, the result may sometimes be a stable atom, but sometimes it may result in an unstable, smaller nucleus of an atom of different type, which may be radioactive and emit energy in the form of radiation or particles before finally reaching a stable state. The reactions depend on the element or the isotope initially chosen to be acted upon and on the kind of particle with which it is bombarded.

Of the various methods of bombarding an element enumerated above, neutron bombardment has many advantages. The neutron has no charge and can move through matter for longer distances than charged particles without being stopped. Thus in the fissioning of uranium, neutron bombardment is an important method.

There are various methods of producing neutrons—

1. Particle accelerators such as cyclotrons or Van de Graaff generators speed up charged particles to bombard a target nucleus such as lithium, beryllium, etc., which produces neutron beam.

2. Alpha particle reactions, use α-emitters such as radium to bombard a light element such as beryllium or boron—

$$^{9}_{4}\text{Be} + ^{4}_{2}\text{He} \rightarrow ^{12}_{6}\text{C} + ^{1}_{0}\text{n} \qquad (6.4)$$

3. Bombardment of a light element such as beryllium by γ-rays—

$$^{9}_{4}\text{Be} + ^{0}_{0}\gamma \rightarrow ^{8}_{4}\text{Be} + ^{1}_{0}\text{n} \qquad (6.5)$$

4. When neutrons are used to produce the fission reaction in nuclear reactors, some more high speed neutrons are emitted during the reaction.

When a neutron causes fission of uranium-235, a typical reaction produces barium, krypton, two or three neutrons and release of energy due to loss of mass—

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{137}_{56}\text{Ba} + ^{97}_{36}\text{Kr} + 2^{1}_{0}\text{n} + \gamma \qquad (6.6)$$

A neutron can be absorbed or captured by a nucleus of large atomic number to produce a neucleus, which may be unstable. In

some cases the unstable nucleus again splits into nuclei of approximately equal mass and emits several neutrons and considerable energy.

Natural uranium consists of three isotopes: 99.3% is U-238 and 0.7% is U-235. It also has minute traces of U-234. The following Table gives the structure of the nuclei of these isotopes—

Isotope	*Protons*	*Neutrons*	*Atomic mas-*
U-234	92	142	234
U-235	92	143	235
U-238	92	146	238

The U-235 isotope of uranium is easily and readily fissionable. If a neutron enters a U-235 atom, there is a probability that the nucleus will split and release the enormous amount of energy that binds the nucleus together. This will generate heat in the mass of the uranium. Each fissioned nucleus ejects two or three neutrons which can again hit uranium nuclei and accelerate the splitting process, even if some of the neutrons are not fully absorbed. This reaction is known as a chain reaction.

Materials fissionable by thermal or low-speed neutrons are U-233, U-235 and Pu-239 (plutonium).

Fertile materials, i.e., those which can be transformed into fissile materials, cannot sustain chain reactions. However, when a fertile material is hit by neutrons and absorbs some of them, it is converted to fissile material. U-238 and Th-232 (thorium) are examples of fertile materials, used for reactor purposes –

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U + \gamma \qquad (6.7)$$

Uranium-239 has a half life of 23.5 minutes only and hence is unstable—

$$^{239}_{92}U + ^{0}_{-1}e \rightarrow ^{239}_{93}Np \qquad (6.8)$$

Neptunium-239, again has a short half-life (a few days) and emits β-particles—

$$^{239}_{93}Np + ^{0}_{-1}e \rightarrow ^{239}_{94}Pu \qquad (6.9)$$

The process, therefore, results in the formation of an isotope of plutonium. The Pu-239 formed this way can be used as fuel in other reactors.

Thorium also can be converted to fissile material, U-233,

$$\left.\begin{array}{l} {}^{232}_{90}\mathrm{Th} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{233}_{90}\mathrm{Th} + \gamma \\ {}^{233}_{90}\mathrm{Th} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{233}_{91}\mathrm{Pa} \\ {}^{233}_{91}\mathrm{Pa} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{233}_{92}\mathrm{U} \end{array}\right\} \qquad (6.10)$$

Some substances help in reducing the speed of neutrons and make them lose their energy by collision, but at the same time do not absorb them. Such materials are known as moderators. Moderators brake the fast neutrons to thermal speeds – speeds of the same order as those of thermal agitation – that give better chances of neutron absorption. Moderators have low atomic numbers. Light water (H_2O), deuterium or heavy water (D_2O), carbon and beryllium make good moderators.

Some substances absorb neutrons and stop their further action on the fissionable material, e.g., boron. Such materials are used for controlling the chain reaction in a reactor.

Uranium-235 is normally used in a reactor, where it reacts easily to bombardment by slow neutrons. However, the neutrons with high speeds, or fast neutrons, are wasted and are not nearly so effective in producing reactions. If the quantity of U-235 in a reactor is increased by the addition of more U-235 than is available in natural uranium, then the reactor can work with fast as well as thermal neutrons. This is the principle of the enriched reactor.

6.4 Main Parts of a Reactor and Reactor Control

As indicated in Fig. 6.2, a nuclear reactor consists of the following parts—

1. *Reactor core.* This contains a number of fuel rods made of fissile material.

2. *Moderator.* This material in the reactor core is used to moderate, or reduce, the neutron speeds to a value that increases the probability of fission occurring.

3. *Reflector.* This completely surrounds the reactor core within the thermal shielding arrangement and helps to bounce escaping neutrons back into the core. This conserves the nuclear fuel, as the low speed neutrons thus returned are useful in continuing the chain reaction.

4. *Shielding.* Shielding helps in giving protection from the deadly α- and β-particle radiations and γ-rays as well as neutrons given off by the process of fission within the reactor.

5. *Control of reactor.* This is effected by inserting neutron absorbing materials to keep the chain reaction at a desired level.

6. *Cooling system.* This removes heat from the core produced by nuclear reaction, the heat being used to generate steam in other apparatus. The types of coolants used are carbon dioxide, air, hydrogen, helium, water, sodium or sodium potassium.

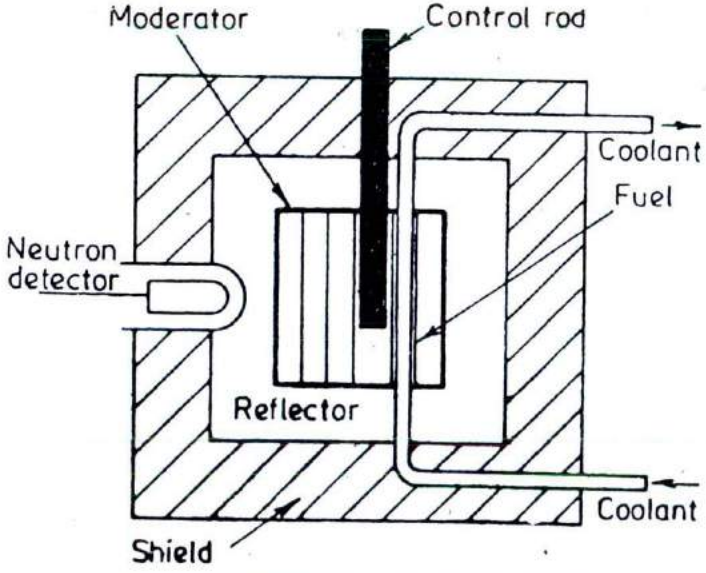


Fig. 6.2. Basic components of a nuclear reactor.

The Chain reaction and the principle of reactor control. When a nucleus captures a neutron the resulting compound nucleus is unstable. It splits into two fragments, releases energy and ejects

some neutrons. If conditions are favourable, neutrons ejected by the first fission may be captured by other nuclei and the chain reaction begins. If the energy output from a reactor is to be maintained constant, one neutron – and not more than one – from each fission must split another nucleus (multiplication factor, $k=1$). Otherwise control of the chain reaction will not be possible.

To keep the rate of output constant, the factor k must be maintained as 1.

Reactor control depends on the changing value of k. To start the reactor, raise the value of k above 1; this increases the power level. When the required power level is reached, reduce k to 1 and maintain this value to keep the output rate constant. To lower the load on the reactor, reduce k to slightly less than 1, and when the required power level is reached, bring k back to 1. To shut down the reactor, reduce k to less than 1, and the chain reaction will die down.

The critical size of a thermal reactor is one that produces just enough neutrons to balance those lost and absorbed and at the same time to maintain the chain reaction. The main factors that determine criticality are geometry, migration length and the multiplication factor. Geometry includes the external size and shape of the reactor and the detailed arrangement of the fissile and other materials within it. Migration length is the net distance travelled by the neutron from its birth in fission to its eventual loss or capture in collisions with materials in the reactor. This sets the geometrical scale for the size of the reactor and depends mainly on the nuclear properties of the materials of the reactor. The multiplication factor (k) is the ratio of the total number of neutrons produced during a small fraction of a second to the total number of neutrons lost or absorbed during the same time. The chief problem in reactor control is to keep this factor equal to 1, as explained above.

6.5 Types of Power Reactor

The main types of reactor are thermal reactors and fast reactors.

In thermal reactors, moderators are used to slow down the neutrons to a speed at which they can react readily with U-235 and cause fission. The energy of the neutrons causing fission corresponds to the ambient temperature inside the reactor. In fast reactors, the neutron energies are very nearly at a level at which they emerge as fragments from the fissile material during fission. In the thermal type, most of the neutrons have energies of about 0.03 eV; in fast reactors, most of the neutrons have energies of above 1,000 eV.

Another method of classifying reactors is to consider the physical arrangement of fissile material, moderator and coolant, etc. For example,

1. *Type of fuel.* Natural uranium or enriched uranium.
2. *Type of moderator.* Graphite, heavy water or ordinary water.
3. *Type of coolant.* Gas, water, heavy water or liquid metal.

In natural uranium reactors operating in the thermal neutron range, fuel elements are arranged in the form of slugs—uranium clad with aluminium, zirconium or stainless steel. The control rods are of boron or cadmium, as these materials are good absorbers of neutrons. Graphite is used as the moderator. The moderator and fuel rods form the core of the reactor. The coolant enters at the bottom of the reactor tank and flows up between the fuel rods to carry off heat from the core. The control rods are moved up and down to vary the multiplication factor k, thus controlling the reactor power output.

Three kinds of control rod may be mentioned : a regulating rod for rapid, fine adjustment; a shim rod for occasional, coarse adjustment; and a safety rod for scramming, or shutting down the reactor very quickly in the event of failure of the ordinary control system.

To start a reactor, withdraw the safety rods completely, withdraw the shim rods slowly and note the neutron build up. The

reactor will go critical at some point. The control rods are then adjusted to make $k=1$.

Some commercial types of reactor are described below.

6.5.1 CALDER HALL REACTOR

This type of reactor uses natural uranium as fuel, is graphite moderated and gas cooled.

6.5.2 MAGNOX REACTOR

This reactor uses natural uranium as fuel, graphite as moderator and CO_2 gas as coolant. The reactor pressure vessel is surrounded by a thick concrete biological shield, which attenuates the gamma and neutron radiation from the core. With concrete vessels, it is possible to have boilers accommodated inside the vessel and eliminate the cooling ducts. The steam pressure and temperature of the plant with this type of reactor are rather low

6.5.3 ADVANCED GAS COOLED REACTOR (AGR)

The advanced gas cooled reactor is a development from magnox and uses the same technology. It uses Uranium Oxide (UO_2) as fuel material enriched by a small percentage of U^{235} and CO_2 gas as coolant. But the coolant temperatures are higher. This enables generation of steam at higher temperature and pressure. Different fuel geometry is used in AGR. Another difference between the magnox type reactor and AGR is that the core temperature in AGR is much higher. Special measures are, therefore, required to be taken to cool the graphite moderator in order to limit the rate at which it reacts with CO_2. Owing to higher rating of the AGR the graphite has to withstand a higher neutron flux than the magnox reactor and a special grade of graphite has to be developed with an isotropic structure.

6.5.4 BOILING WATER REACTOR

Fig. 6.3 shows the principle of construction of this type of reactor. The fuel is enriched uranium, water is used as both the moderator and coolant. The uranium elements are arranged in a particular lattice form inside a pressure vessel containing

water. The heat released by the nuclear reaction is absorbed by the water and the steam is generated inside the vessel itself. Feed

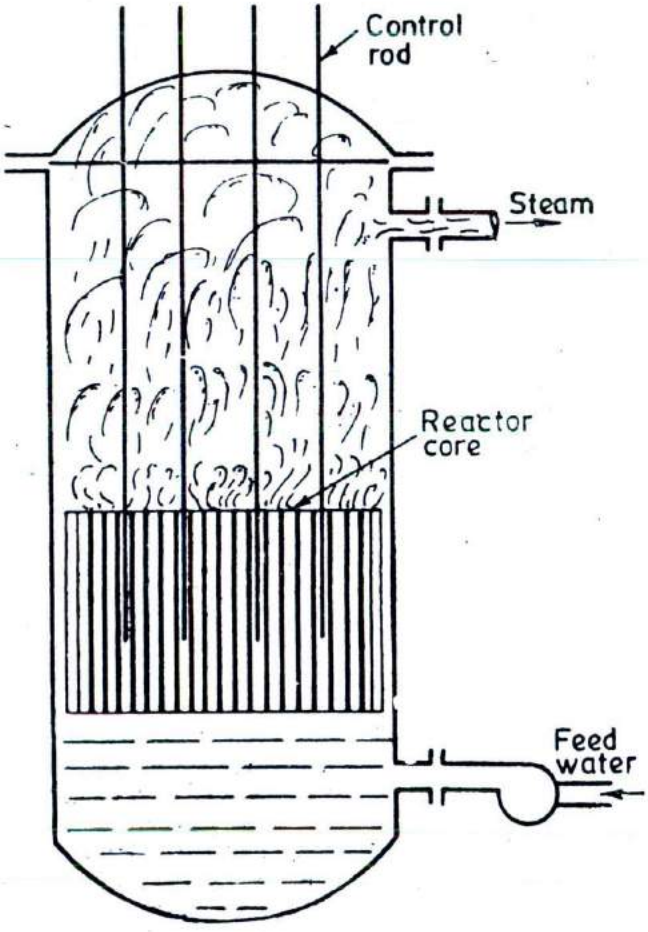


Fig. 6.3. Boiling Water Reactor.

water enters the reactor tank below to pass through the fuel elements in the core as coolant and also as moderator. In the boiling water reactor the cooling system of the pressurized water reactor is eliminated.

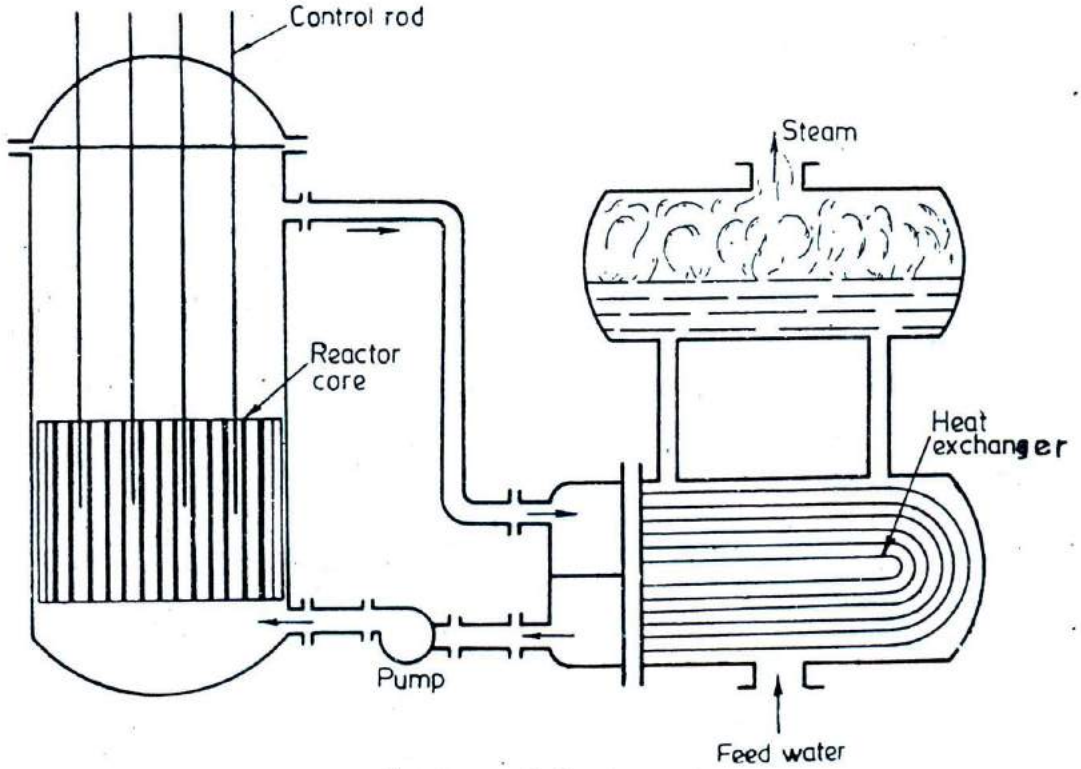


Fig. 6.4. Pressurized water reactor.

6.5.5 THE PRESSURIZED WATER REACTOR

Fig. 6.4 shows the principle of construction of this type of reactor. The fuel is enriched uranium, and water under pressure is used as both moderator and coolant. This type of reactor is designed to prevent the boiling of the water coolant in the uranium core. A pump circulates water at high pressure round the core so that the water in the liquid state absorbs heat from the uranium and transfers it to the secondary loop, the boiler. The boiler has a heat exchanger and a steam drum. A pressurized tank tapped into the pipe loop maintains pressure in the water system.

6.5.6 CANDU TYPE REACTOR

This was first developed by Canadians. Here heavy water is chosen as moderator. In order to get maximum neutron economy, the coolant used is also heavy water. Hence the name CANDU (Canadian Deuterium Uranium). With this combination and strict attention to minimizing absorption in core structural materials, high burn up with natural uranium fuel is obtained

The primary circuit passes through heat exchangers and pumps in the same way as a PWR raising steam from natural water in the secondary circuit.

Control of the reactor is achieved by varying the moderator level. For rapid shut down, moderator can be dumped through a very large area multiple trap into a tank below the reactor.

The disadvantage of the CANDU type reactor is that it uses heavy water at high pressure and temperature in the coolant circuit. Heavy water is very expensive. It costs about Rs. 280/- per kg.

6.5.7 SODIUM-GRAPHITE REACTOR

Fig. 6.5 shows the main parts and the principle of the sodium graphite reactor. Graphite is used as the moderator, and liquid sodium (Na) as the coolant. This coolant can reach high temperatures at a moderate pressure of only 7 kg/cm^2. An intermediate heat exchanger is necessary between the reactor and the boiler.

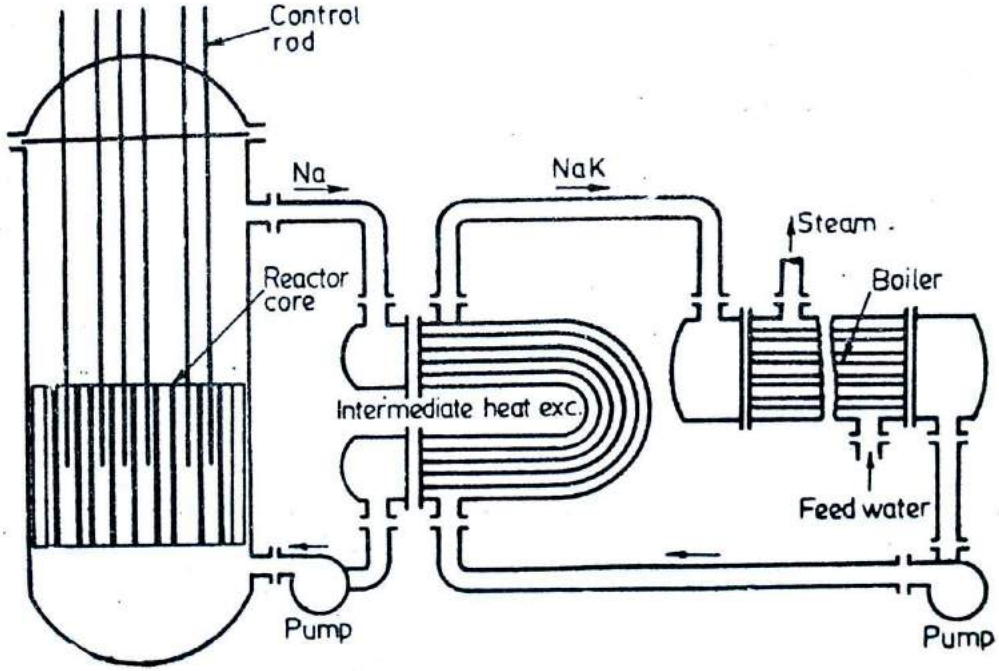


Fig. 6.5. Sodium-graphite reactor.

This intermediate heat exchanger uses liquid NaK, an alloy of sodium and potassium, to carry heat to the boiler.

6.5.8 FAST BREEDER REACTORS

When U-235 is fissioned, it produces heat and additional neutrons. If some U-238 is kept in the same reactor, part of the additional neutrons available after reacting with U-235 convert U-238 into plutonium, which is fissile. Thus the reactor not only produces heat, but at the same time can be profitably used to produce more fissile material. If the process is made efficient, more fissile material is produced than can be consumed and this is known as breeding.

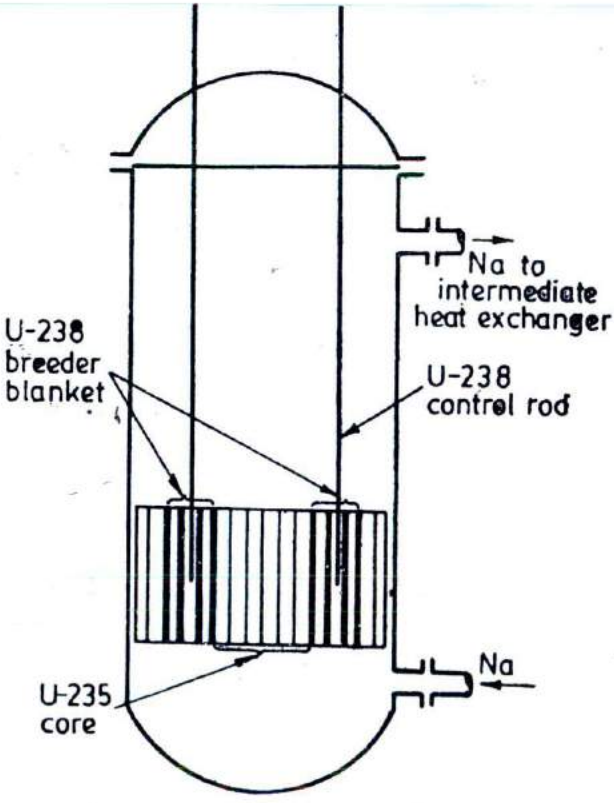


Fig. 6.6. Fast breeder reactor.

A fast breeder reactor (Fig. 6.6) is a small vessel in which the necessary quantity (corresponding to critical mass) of enriched uranium or plutonium is kept without a moderator. The vessel is surrounded by a fairly thick blanket of depleted uranium—fertile material—which absorbs neutrons from the new fissile material and converts the fertile material into fissile material. The reactor core is cooled by liquid metal. U-238 can be converted to Pu-239 (eqns 6.7-6.9), or Th-232 to U-233 (eqn. 6.10) which can be used in other thermal or fast reactors.

In fast breeder reactors, neutron shielding is provided by the use of boron, light water, oil or graphite. Gamma-ray shielding is effected by lead, concrete, concrete with added magnetite or barium, etc.

6.5.9 COMPARISON OF THERMAL AND FAST BREEDER REACTORS

There are some advantages in the use of thermal reactors compared to fast reactors –

1. Greater inherent safety.
2. Less heat generated per unit volume of core or per unit area of fuel surface.
3. Ease of control.

There are also some disadvantages 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 than could be automatically replaced.

In fast reactors, more fertile material can be converted to fissile material and thus the net fuel consumption is much less. In the ideal case, more fissile material would be produced than consumed. Fast breeder reactors are not yet in commercial production but their early development is probable.

6.5.10 COMPARISON OF VARIOUS TYPES OF REACTORS

With the large size of power stations, it is feasible to consider nuclear power stations in preference to conventional thermal stations.

For a size of plant of about 500 MW, the parameters and conditions of working and limitations can be compared as given in the following Table approximately.

Table 6.1

	Magnox	AGR	BWR	PWR	CANDU	Fast
Main parameters						
Fuel						
Fuel material	U	UO_2	UO_2	UO_2	UO_2	Puo_2 UO_2
Can material	Mg	SS	Zr	Zr	Zr	SS
Fuel enrichment (%U2 35 or Pu)	Natural	2-2.5%	2.5%	3.0%	Natural	15%
Coolant	CO_2	CO_2	H_2O	H_2O	D_2O	Na
Pressure (kg/cm²)	22	30	70	150	95	Zero
Inlet/outlet temp. °C.	245/400	300/700	275/285	275/300	250/290	400/600
Moderator	Graphite	Graphite	H_2O	H_2O	D_2O	None
Pressure vessel	Concrete	Concrete	Steel	Steel	Zr tubes	SS tank
Inside dia × ht (m)	30×30	20×19	6×20	4×13	0.1m dia.	14×14
Wall thickness (m)	3.4	3.6	0.15	0.2	0.006	0.015
Steam power Plant						
Steam pressure (kg/cm²)	48	162	68	52	42	162
Temperature °C	400	565	280	262	255	538
Station net thermal efficiency	31%	41%	33%	33%	30%	43%

The net output from the turbo generators used with the reactors is taken as the output after deducting auxiliary power consumption in the station.

6.6 Location of Nuclear Power Station

Some of the factors which should be considered in deciding the location of a nuclear reactor and power station are as follows:

Location near load centre. It is desirable to locate a nuclear power station as near to the load centre as possible, consistent with safety considerations. This avoids the losses in transmission otherwise required to take power over a long distance to the load area. If connected in a Grid system, the station should be located near the existing transmission lines. Compared to a hydro-electric station, there is a wider choice of suitable location. Hydro-electric plants have to be situated where a sufficient flow and head of water are available. Nuclear power stations can, therefore, be competitive in situations where hydro-electric stations would need long transmission lines.

Availability of water supply. The plant should be located near a river or lake so that an ample quantity of water will be available for condenser cooling as well as any make up water required for the steam turbine.

Safety. There should be a reasonable distance between the nuclear power station and the nearest populated area for the sake of safety. The reactor is covered with a containment dome so that, in case of accident, the radioactivity would not spread to the plant surroundings by wind, or by surface or underground water-ways.

Accessibility. There should be reasonable accessibility for plant personnel, hauling in equipment, and dispatching and receiving heavily shielded radio-active materials.

Radioactive waste disposal. The location should be suitable for short time storage as well as long time burial of the radioactive waste that is necessary when the plant is working.

6.7 Basic Factors in Design of Reactors and Choice of Cycle of Operation

The basic factors which are considered when designing a power reactor are as follows.

Reactor type. The various types of reactors were discussed in Section 6.5. The particular type to be selected will depend on the availability of fuel and the economic rating of the reactor under local conditions.

Power rating. The power rating of a reactor is expressed in terms of electrical output in megawatts. The choice of power rating is made after considering the detailed specifications of the reactor, namely type of reactor, type of cycle used, maximum temperature and pressure produced, thermal efficiency of the reactor, cooling medium and operation of the reactor on the load curve of the system; e.g., 80% or 90% load factor working on the base-load portion of the curve.

Safety in design. The reactor must be inherently safe. For example, it must have a negative temperature coefficient; as the temperature increases, the reactivity should decrease.

Coolant system. The coolant must be able to remove the decay heat when the reactor is suddenly stopped, or scrammed.

Control system. Reactivity is a measure of the extent to which the state of a reactor departs from critical, i.e., from a state in which a self-sustaining chain reaction can occur. Positive and negative reactivity correspond to states above and below critical, respectively. The control system must have enough negative reactivity to overcome all reasonable potential excess of positive reactivity.

Rates of neutron production and absorption. The effect of temperature changes in the reactor components on neutron production and absorption rates should be considered.

Safety. The effect of failure of the equipment and system, and system surges, on the safety of the reactor should be considered. If a reactor fails, there should be complete containment of the radioactivity. Basically, a reactor should be designed to be inherently self regulating, preferably with a negative temperature coefficient.

Choice of cycle of conversion of nuclear power to electric power.

There are four possible ways of producing electric power from nuclear fission—

1. A well established method of conversion of heat due to nuclear reaction to electric power is by the indirect use of the coolant. The reactor heat is transferred to the coolant. which heats water to produce steam for driving the turbine or other heat engine.

Gas cooled reactors, with a single heat exchanger in which the coolant conveys heat to the water, as well as reactors in which a liquid coolant transfers heat to another liquid in an intermediate heat exchanger, come in this category. Fig. 6.7 shows sodium (Na) transferring heat to sodium-potassium (NaK) in the intermediate heat exchanger, and NaK transferring heat to water in the boiler to convert it to steam.

2. Another method for the conversion of heat produced in the reactor to electric power is the direct use of the liquid or gas that cools the reactor to drive the turbine or other heat engine, which in turn drives the electric generator.

The boiling water reactor is of this type. It uses water for cooling as well as for conversion to steam in the turbine. The disadvantage is the possibility of the presence of radioactivity in the steam power plant. Fig. 6.8 is a simple single-line diagram of the circuit.

3. Direct generation of electric current from the heat produced during the nuclear reaction. An example of this type of conversion is the production of electric current by means of thermocouples.
4. Direct generation of electric current from electrons produced during a nuclear reaction.

Methods 3 and 4 are not yet very practical for economic power production on a large scale.

In considering the choice of coolant, a number of factors and the properties of the coolants are studied as follows : availability

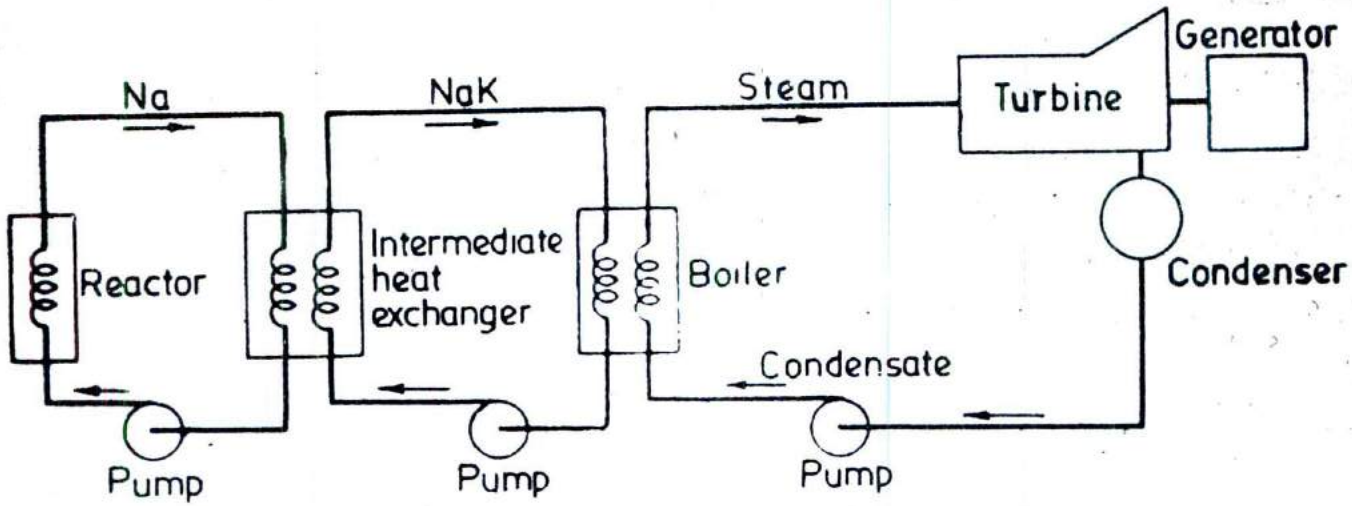


Fig. 6.7. Steam plant using sodium (Na) Sodium-potassium (NaK).

of coolant and its cost, suitability of coolant for use in conjunction with water or steam, its temperature range in the reactor as well as in the heat exchanger, the vapour-pressure/temperature relations of the coolant and its heat transfer properties.

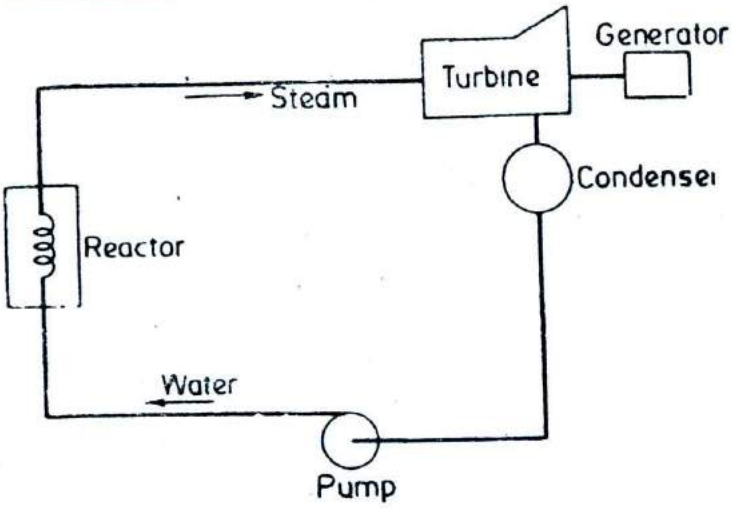


Fig. 6.8. Steam plant using a boiling water reactor.

6.8 Main Power Plant and Facilities

The most important part of a nuclear power station is the reactor. As explained above, the reactor type and rating are chosen to suit local conditions and the nature of the load duration curve. The size of the reactor unit is chosen on economic considerations. The specification of a reactor includes its rated heat output in kilocalories per hour, and its electrical output in kilowatts or megawatts; information about the type of coolant and its minimum and maximum temperatures ; the pressure and temperature of the boiler steam ; the types of fuel, moderator and control; the thermal efficiency of the reactor; the fuel consumption, etc.

The other important part of a nuclear power station is the turbo-alternator set. The rating of this is similar to the conventional thermal-station rating. Generally, nuclear power station units are designed to work on base load and at high load factor.

It is, however, not possible to reach high steam pressures and temperatures owing to the limited heat-carrying capacity of the coolants, and hence, compared to conventional plant of large-scale units, nuclear power station turbines use lower steam pressures and temperatures.

The generators are conventional 2-pole machines, but they have to operate at high load factor as base-load plants. They are rated in megawatts—electrical output—and at a power factor of 0.9 or 0.95. The rest of the specification follows conventional lines.

A nuclear plant will have conventional facilities -e.g., turbine room or building, switchyard, railway siding, machine shop, instrument shop, office, etc. In addition it will have special facilities, e.g., fuel element fabrication shop, fuel-element processing apparatus, radio-active storage, clean-up and waste-disposal equipment for fuel, gas and coolant, health physics facilities for personnel, facilities for dispatching and storing radio-active materials, and special plant security personnel.

In a nuclear power station, auxiliary supply system is arranged from unit transformers as in conventional power stations. However, the unit in this case is the reactor, even if this feeds more than one turbine. A.C. short break loads are pony motors, emergency feed battery chargers. No break loads are supplied by batteries in case of d.c. loads and by motor generators in case of a.c. loads. The batteries are charged by the rectifiers from the normal station system or from emergency generators. The batteries are rated for a minimum period of 15 minutes. The use of rectifiers automatically prevents feedback and isolates the essential auxiliaries in case of a.c. supply failure. D.C. no break loads are emergency oil pumps, emergency lighting, safety circuits, and motor generator sets, etc. A.C. no break loads are instrumentation, data processing, control rod supplies, etc. The supply circuits and voltages used, etc, for essential auxiliaries are similar to conventional thermal stations. This is discussed in a later chapter.

6.9 Layout of a Nuclear Power Station

The layout of plant and building of a nuclear power station is planned with due consideration to safety, operating convenience and capital economy. One of the important operational areas in a reactor building is the charge hall which is used for the refuelling operation. This is located directly over the reactor core.

The points mentioned previously in chapter 2 regarding the location and the provision of the necessary facilities at the site should be borne in mind while planning the layout. As far as the main important parts are concerned—the reactor, turbine and generator—the layout is simple. In some cases, the turbine and generator may be of the outdoor type, i.e., self protected with respect to weather, and not housed.

A main control room is provided in a central location and contains all the necessary equipment for controlling normal and emergency operation of the reactors as well as controls of boilers and turbo alternators. All other ancillary rooms such as maintenance rooms, change rooms, stores, etc., are suitably located for ease of operation.

6.10 Reactor Control

Nuclear power stations operate on base load and generally on constant load; however, they must have limited flexibility for limited changes in load. The reactor must also be in a position to operate at reduced load if the turbine capability is reduced for maintenance, etc., during working. The operator generally will have the following information at the control point :

(*i*) Nuclear flux sensing instruments.

(*ii*) Temperature instruments giving inlet and outlet temperatures of coolant.

(*iii*) Measurement of coolant flow through the reactor core.

(*iv*) Fuel element temperatures data.

The principal controls which the operator can consider are:—

(*a*) Use of control rods which govern the neutron population of the core and generation of power—

(*b*) Coolant flow can control the temperature level at which power is extracted from core.

These two methods are not used during normal operation of the reactors. Reactors should generally operate at constant temperatures, otherwise, the steam temperatures will vary, affecting the operation and efficiency of the turbo-generators. Because of such considerations, gas circulators are mainly used for power control. At constant temperature, the power output from the reactor is proportional to the flow of coolant. Therefore, control rods are used to maintain constant temperature for a fixed coolant flow, and the coolant circulators are used to determine the gross output at constant temperature.

6.11 Nuclear Waste Disposal

In nuclear power stations, it is very important to take care to dispose of the waste which is likely to have radioactivity. The main sources of gaseous discharge and any liquid effluent are sampled and records are kept of the radio-activity discharged from such sources. Gaseous wastes require no treatment other than filtration before being discharged at high level to assist in dispersion. In the extremely unlikely event of a fire in a reactor fuel channel, the gaseous fission products would be released. The gas should be passed through a clean up plant to remove radio active iodine which constitutes the major gaseous hazard.

The loss of Carbon dioxide from a reactor is monitored and should not exceed 1 or 1½ tons a day. The concentration of the coolant gas in the atmosphere in the working areas is checked and precautions are taken against toxic and radiological hazards. This is particularly required when the blowing down operation of the station is planned.

At several nuclear stations, liquid wastes can be discharged following filtration, by adjustment of pH value and by diluting and mixing with the station cooling water discharge. If the conditions in some stations demand this, some or most of the soluble radioactivity in the liquid effluent must be removed by the ion exchange process.

All potentially radio-active liquids discharged from stations are monitored and the quantities discharged are noted in a register. There should be kept within permissible limits as authorised for particular stations and locations.

Special care is taken to prevent leakage of liquids containing radioactive substances into the ground in the area around the stations. This is effected by providing double containment of drains and by designing concrete storage tanks as water retaining structures.

Solid wastes such as those arising from discarded control rods, pieces of fuel cans, etc. are stored in shielded concrete vaults. Care is taken to segregate materials which are chemically incompatible or combustible. Combustible waste of low specific radioactivity is burnt in an incinerator which incorporates a high standard of filtration of the flue gases. The irradiated fuel elements comprise the most highly radioactive wastes. These are stored in a water or air cooled shielded area to allow the activity to decay. These are then returned to the Atomic Energy Authority for processing.

6.12 Health Physics

It is necessary to control environmental activity arising from the operation of nuclear power stations in order to safeguard the health of personnel employed in the station and also of the general public living in the vicinity. The terminologies used in health physics technology are mainly in two categories : contamination and radiation.

Units of contamination are a measure of the amount of radioactive material contained in the object. The unit used for physical measurement of this quantity is the Curie.

1 Curie $= 3.7 \times 10^{10}$ nuclear disintegrations per second. This being a large unit, it is divided in smaller units such as millicurie, microcurie, micro-micro or pico curie, to indicate low levels of contamination.

'RONTGEN is the classical unit of radiation. This is equivalent to 86.7 ergs of energy absorbed per gram of air and is a measure

of ionisation. Instead of this odd figure of energy absorption, another unit known as RAD is used to measure ionisation. One RAD is the unit of dose equivalent to 100 ergs absorbed per gram of irradiated material at the point of interest. Another unit used is REM. REMS = RADs × R.B.E. R.B.E. = relative biological effectiveness. Smaller units are used in common such as millirad, millirem.

The types of radiation which occur normally are : α rays, β rays γ rays, Neutrons. The biological effects of radiation on man depend on the following factors :

(*i*) Amount of the dose absorbed.

(*ii*) Duration of explosure.

(*iii*) Sensitivity of the recipient organism and its recovery.

(*iv*) Distribution of active material within the body of the person.

Individual parts of the body may be able to withstand comparatively high doses of radiation but an irradiation dose of about 400 rems to the whole body will probably result in death. When part of the body is exposed to a radiation dose of about 200 rems it may result in a temporary effect of radiation sickness such as shock symptoms, nausea, etc. The following shielding materials are used in nuclear power stations :

(Shielding depends on the density of the material used and hence the material is specified by density, viz., grams/cm^3.)

(*a*) Lead has a density of 11.3 grams/cm^3.

(*b*) Concrete has an average density of 2.4 grams/cm^3. Barytes concrete is specially manufactured for nuclear purposes and has a density of 3.2 grams/cm.^{3}

(*c*) Steel has a density of 7.8 grams/cm^3 and is used as an attenuating shield.

(*d*) Cadmium has a density of 8.65 grams/cm^3 and is used. as a neutron absorber.

6.12.1 HEALTH PHYSICS CONTROL

There should be strict control on the persons working in nuclear power stations, so that they perform their duties without harm from over-exposure to nuclear radiation. The International Committee on Radiological Protection recommended that the maximum permissible whole body dose in rems (D) for a person of age N years is given by—

$$D=5\,(N-18) \qquad (6.11)$$

This is calculated on the basis of an average annual dose rate of 5 rems. This is for classified persons working continuously in nuclear stations. Members of the general public should not receive a dose of more than 0.5 rem per year. For persons employed on the premises, but not working as classified workers, the whole body radiation dose per year should not exceed 1.5 rems.

Radiation and/or contamination zones must be established in nuclear stations and marked conspicuously with notices and classifications according to the radiation levels which exist within the areas.

While entering into radiation or contamination zones, each person must wear a film badge. The visit of the person is controlled so that a dose exceeding that permitted cannot be accumulated. The film badge consists of a piece of photographic film unexposed to light and held in a container which can be attached to clothing or to part of the body. It has identification marks. It is so constructed that the extent of blackening of the developed film enables a measurement to be made of the radiation exposure to which it has been subjected, where it is necessary to use supplementary devises they are used, e.g., Lithium floride pads applied to fingers to assess the local dose at these extremities.

6.13 Economics of Nuclear Power Station

A number of factors have to be considered in the economic study of a power plant. With nuclear power stations, some of the considerations are similar to those for the other types of station,

but in addition there are some special points regarding fuel fabrication and reactor costs. Broadly speaking, the points for consideration are capital investment, plant life, fixed, operation and maintenance costs, plant operating condition such as plant load factor, etc.

The capital investment items include the following—

1. Reactor plant, i.e., reactor vessel, fuel elements, radiation shielding, fuel-handling equipment, containment vessel, etc.
2. Heat exchangers and equipment pertaining to the coolant system.
3. Plant for power generation, namely, steam turbines, generators, and the associated equipment for the steam-electric part of the station.
4. Land, site improvement, etc., as expenses for general plant.

Construction costs vary with the size and type of reactor. A small reactor is not a good investment from the point of view of neutron balance which depends on the surface to volume ratio of the reactor. The choice of reactor considerably affects not only the cost of building the power station, but also the cost of fuel. For example, plants of the Calder Hall type, equipped with a natural uranium graphite reactor cooled by carbon dioxide, are more expensive, on account of the large heat exchange surfaces they require, than plants of equal capacity equipped with pressurized water or boiling water reactors. The latter have a higher specific power and use smaller heat exchangers. However, the fuel required by these two types is enriched uranium, which is more expensive than natural uranium.

The custom in costing nuclear power stations is to regard the initial charge of fissile material as invested capital, the fuel cost covering only replacement. Fuel cost is the cost of renewing the fuel slugs less any allowance for the irradiated fuel, which may have a certain value as it contains uranium and plutonium.

The nuclear power station has a much higher capital cost than a thermal station. It costs about Rs. 2,000/- to Rs. 2,500/- per

kW. Some years back, this difference was much higher than it is today because it had to cover the initial development of reactors of the Calder Hall type.

	Nuclear plant of Calder Hall type per cent	*Conventional thermal plant* per cent
Capital charges	70	20
Cost of fuel	20	70
Operating cost and overheads	10	10
	100	100

As a rough comparison of the costs of production when using different types of reactor for a 100-MW power station with a utilization factor of 0.8, the following figures indicate the trend.

Charges	Cost of production in pence per kWh		
	Gas cooled graphite moderated reactor.	Pressurized Water reactor	Boiling Water reactor
Capital	0 48	0.35	0.34
Fuel	0.22	0.50	0.46
Operating	0.05	0.05	0.05
	0.75	0.90	0.85

In India, the first nuclear power station was installed at Tarapur, some 90 km north of Bombay. The station has two units, each of 190-MW electrical output. The reactors are of the boiling water type using enriched uranium as fuel. The cost of the project is about Rs. 1,300 per kW in 1966. The cost of power from the station, based on 75% load factor is expected to be about 3.5 p per kilowatt-hour sent out.

Fixed costs. The life of a reactor plant may be taken as between 15 and 20 years. For the other parts of the station equipment, the life may be taken as 30 years. The fixed costs would be interest, depreciation, taxes and insurance charges. The depreciation would be worked out on the basis of the life of the equipment in the plant as well as the building, etc. The insurance charges will be higher than for conventional plants.

Operation and maintenance costs. The average thermal efficiency of a modern nuclear power station is about 30 to 40%. The fuel, operation and maintenance costs will consist of the cost of the nuclear material, the cost of processing the material, the cost of fabricating the fuel elements, the cost of waste disposal, and the cost for operating and maintenance personnel. The cost of the natural uranium fresh fuel is approximately Rs. 200,000 per metric ton.

The initial investment and capital cost of a nuclear power station is higher compared to a thermal station, but the cost of transport and handling of coal for a thermal station is much higher than the cost of nuclear fuel. With further developments, it is likely that the cost of nuclear power stations will be lowered and that they will soon be competitive. With the depletion of fuel reserves and the question of transporting fuel over long distances, nuclear power stations are taking an important place in the development of the power potentials of the nations of the world today in the context of "the changing pattern of power".

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Problems

6.1. Discuss the advantages and field of use of nuclear power stations.

6.2. Discuss the following (*a*) Structure of an atom, (*b*) Einstein's law, (*c*) mass defect and binding energy, (*d*) radio-

active particle emission, (*e*) nuclear reaction, (*f*) a reactor goes critical.

6.3. What is a chain reaction ? How is the nuclear reaction controlled in a reactor ?

6.4. Discuss the various types of nuclear power reactor and compare them with reference to their application to nuclear power stations.

6.5. State the main parts of a nuclear power station, and describe the function of each.

6.6. What are the various factors to be considered in choosing the location of a nuclear power station from the point of view of operation and from the point of view of safety?

6.7. Enumerate the basic factors to be considered in the design of power reactors.

6.8. Compare the various methods of converting nuclear power to electric power.

6.9. What are the special facilities required for a nuclear power station with reference to fabrication of fuel elements and handling of radio active materials ?

6.10. State the main factors in evaluating the economics of a nuclear power station; compare with a conventional thermal station of the same size.

7

Hydro-Electric Stations : Preliminary Design –I

7.1 Introduction

Where water resources are available, hydro-electric power stations are used to supply electrical energy to consumers. This type of station, however, cannot be located everywhere. First, there must be an ample quantity of water at sufficient head, and a suitable site must be available. Stream flow data for a number of years should be studied. The possibility of constructing a dam at a suitable site to store water in the catchment area and the availability of water throughout the year are decisive factors. The amount of power that can be developed depends on the quantity of water available, the rate at which it is available, the head, etc.

Hydro-electric projects involve a large amount of civil engineering construction work. Often the project is a multipurpose one embracing irrigation and power, flood control and power, or flood control, navigation and power. One might imagine that hydro-electric power should be very cheap as water does not cost anything and there is no fuel cost. This, however, is not true. To store water at enough head, it is necessary to have a dam and civil engineering construction works. This costs money, and increases investment costs and fixed costs which are not required for other types of power plants. Whenever a hydro-electric project is considered for power purposes, it is always necessary to work out the economics comparing hydro-electric power costs with the costs for other forms of station.

7.2 Hydrology

When considering the possibility of a hydro-electric project, the first requirement is to obtain data regarding the stream flow of water that would be available, and to predict the yearly possible flow from the data. The water cycle in general consists of evaporation from seas or oceans and/or other water surfaces on the earth due to heat from the sun, the formation of moist air and clouds, the circulation of air currents, the condensation of vapour and precipitation in the form of rain, hail or snow. Determination of the amount of stream flow and its variation involves a study of hydrography (or hydrology) which deals with the occurrence and distribution of water over and under the earth's surface. The science of hydrology is based on meteorology, geology, agricultural physics, chemistry, botany and data obtained by observation and measurement. It is necessary to calculate the mean annual rainfall in the area under consideration from a record of the annual rainfall for a number of years, say 25 to 30, and also to note the frequency of dry years.

The precipitation or rainfall in a particular area can be measured by rain gauges at various places in the area. A rain gauge consists of a collecting cylinder which exposes a circular surface for collecting the rain and a storage vessel in which the water is retained until measured. Recording rain gauges, giving a continuous record, are used where possible. Frequency of precipitation is also carefully noted. A curve of precipitation in millimetres plotted against percentage of time gives a range of distribution of the rainfall over a period. If such data are available for a number of years, the range of distribution of mean monthly precipitation is obtained. The general character of the periodic distribution of the rainfall tends to be similar each year in each locality. There is some variation in the occurrence of rainfall from year to year, but when the record of a number of seasons is available, it is usually found that the occurrences of rainfall for a given month in a given locality are similar. The frequency of occurrence of a dry year or two consecutive dry years is also seen when records for a long period are available.

Precipitation in a particular locality depends to a certain extent on altitude. The general and fundamental tendency is for the precipitation to increase as the altitude increases on the coastal side of a mountain range, if the locality is not far from the general sources of water vapour. Data regarding maximum rainfall in a particular area and the nature of the drainage area help in the study of possible floods in the area. Knowledge of the frequency of high rainfall in the area is also helpful in the above studies. The mean precipitation on a drainage area over a period of time can be obtained by plotting isohyets, or lines of equal precipitation, from the records available and then finding a weighted average by planimeter.

Of the total precipitation, some part of the water is lost. Sources of loss are evaporation from the water area, soil evaporation, interception and transpiration losses from land area. The stream flow is known when the water losses have been subtracted from the precipitation. Stream flow consists of surface flow and percolation through the ground. The various factors which affect the distribution of precipitation are meteorological conditions, drainage area characteristics, topography of land, geology of land and vegetation in the area. Evaporation is effected by heat from the sun. Temperature and relative humidity affect evaporation, and so too does wind velocity. Plants absorb moisture from the ground, giving it off to the atmosphere, the process being known as transpiration. During the process, some water is lost, this is known as transpiration loss. Drainge area characteristics are the size and shape of the area. A small area tends to have a higher unit flood discharge than a large area. The topography of land and surface slopes affects the surface flow of water. Steep slopes tend towards a rapid and large surface flow. The size of the water area affects the losses. A large percentage of water area tends to a diminished run-off. The geological characteristics of the watershed affect run-off. Evaporation varies inversely with the porosity of soil. Percolation and water losses depend on whether the soil is pervious or impervious. A large surface run-off is experienced when pervious ground is saturated with rainwater or when the ground is of impervious material such as

rock or clay. Evaporation and percolation are increased by cultivation. Transpiration and interception losses occur owing to the presence of vegetation.

To find the evaporation from a water surface a shallow pan is partly immersed in a lake or reservoir, the evaporation being measured by the change in the water level in the pan. If the pan were placed on land, the temperature would differ from that of the lake. Humidity and wind, air and water temperatures are noted because evaporation varies with all these factors. Transpiration is estimated in a particular area in an approximate, empirical way. Changes in ground water level are found by measuring the water level in test tubes using a float operated with a water-level recorder. The amount of moisture in the soil above the water table is found by measuring the electrical resistance of gypsum blocks buried at different depths in the ground. The resistance of gypsum increases as it gets drier. The soil temperature is measured by means of thermocouples placed near the gypsum blocks.

In considering the factors affecting losses, the stream flow and the run-off available are determined. A drainage area and profile map is prepared. This shows the length of the river, the size and shape of the watershed, tributaries, lakes, reservoirs, etc. The watershed or drainage area is sometimes called the catchment area with respect to precipitation.

7.3 Stream Flow : Hydrographs : Flow Duration Curves

For water-power studies, it is essential to know the stream-flow data, over a long period if available. Daily, weekly or monthly flow data for a number of years at a site help in finding the average flow and output power that are likely to be available from the stream flow. The head available is determined by surveying the site. The minimum or low water flow data help in estimating the firm power that will be available at the site. The maximum flow helps in estimating the floods and in designing the spillway. Estimating the stream flow helps in determining the capacity of storage reservoir for equalising the flow to a given

minimum. Knowing the maximum stream flow conditions, it is possible to estimate the necessary capacity of a flood-control reservoir for limiting the discharge to a pre-determined maximum under all conditions except extreme floods.

When studying stream flow in a river, it is necessary to find the depth of the river at various sections by river gauging. The depth of the river is measured by wading in shallow water, by wire weight gauge, etc. Measurement of discharge in open channels is done by the velocity-area method or by the flow of water over a weir of known dimensions. In the velocity-area method, the discharge is obtained as the sum of the products of partial cross-sectional areas of the flowing water by the respective measured velocities in such areas. The cross-sectional areas are found by measuring the width and depth at suitably spaced points to show the shape of the river bed, and summation of the partial areas is computed from these measurements. Velocities in different areas are measured by float or current meters. The other method of computing the discharge is by observing the head on a weir and the known dimensions of the weir.

The discharge, or volume rate of flow, Q, in cubic metres per second, is given by

$$Q = CLh^{3/2} \tag{7.1}$$

where L is the length of the weir in metres, h is the head in metres, and C is a constant.

For a sharp-crested weir, C is 1.85 approximately.

Hydrographs. When a river discharge has been measured, a curve can be plotted showing discharge in cubic metres/second against time in hours. The curve is known as a hydrograph. The ordinates may be plotted in terms of the gauge height, the number of cubic metres per second per square kilometre, the power in kilowatts that can be developed theoretically per metre of fall, or the energy in kilowatt-hours recorded at the switchboard. The abscissae may be in terms of hours, days or weeks. A hydrograph shows the variation of flow with time. It will also indicate the power available from the stream at different times of the day or

year. It is similar to the load curve used in the study of electrical power. Hydrographs help in noting the extremes of flow more readily than the inspection of tabular values of the discharge. Hydrographs are essential in studies of the effect of storage on flow.

Flow duration curve. The flow duration curve is a very convenient form of hydrograph for determining the available power at the site. It indicates the daily, weekly or monthly flows available as ordinates plotted against percentage of time. The flow may be expressed as cubic metres per second per week or other unit of time. Knowing the head at which the flow is available, one can convert the cubic metres per second per week, or the discharge for the period, into power in kilowatts, so that the flow duration curve becomes the load duration curve for a hydro-electric plant. If storage is available at a site upstream from the power plant, a flow duration curve as modified by the use of storage, will be necessary. Low water flow decides the primary power that can be developed. The flow duration curve also shows the possible heavy flood flow and the time during which it may occur. The data are useful in designing a spillway on the dam to allow flood water to escape from the reservoir. It is easy to convert a hydrograph into a flow duration curve. The following examples illustrate the plotting of a hydrograph and flow duration curve from the flow data in terms of discharge per week.

Example 7.1

The mean weekly discharge at a particular site is given below. Draw the hydrograph.

Week	Discharge m^3/sec	Week	Discharge m^3/sec
1	100	7	800
2	200	8	600
3	300	9	1,000
4	1,200	10	600
5	600	11	400
6	900	12	200

The curve has been plotted in Fig. 7.1. The maximum discharge occurs in the fourth week. The lowest discharge is 100 m^3/sec for the whole period of 12 weeks. The average discharge available for the whole period is 575 m^3/sec, obtained by adding the 12 weekly discharges and dividing by 12.

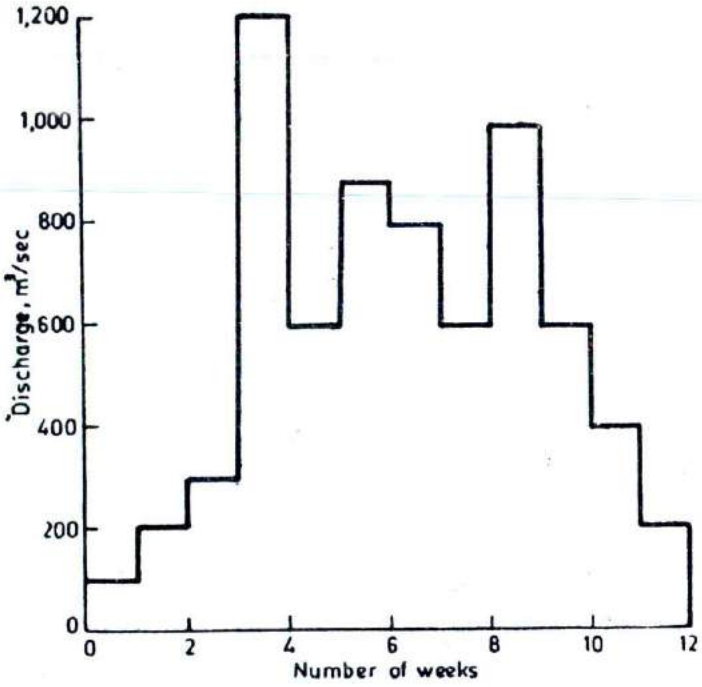


Fig. 7.1. A hydrograph

Example 7.2.

From the data in Example 7.1, develop the flow duration curve and plot it.

To obtain the flow duration curve, it is necessary to find the lengths of time during which certain flows are available; this information is tabulated as given below, and the curve is shown in Fig. 7.2.

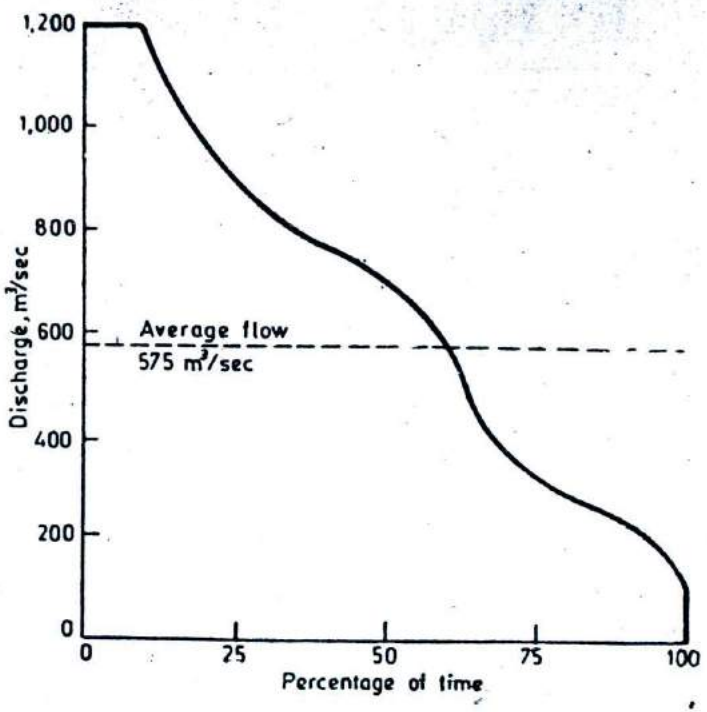


Fig. 7.2. Flow duration curve.

Discharge	Total number of weeks	percentage time
m^3/sec		
100 (and more)	12	100.0
200 (and more)	11	91.5
300 (and more)	9	75.0
400 (and more)	8	66.66
600 (and more)	7	58.2
800 (and more)	4	33.33
900 (and more)	3	25.00
1,000 (and more)	2	16.7
1,200	1	8.35

In practice, the flow data for a number of years are required when selecting a suitable site for a hydro electric project. Hydrograph and flow duration curve for the various periods are therefore determined. If the head at which the discharge of water is available is known, the possible power that can be developed from the

water can be determined. Thus the flow duration curve can be converted to a power duration curve with different scales. The power P, is given by

$$P = \frac{0.736}{75} Qwh\eta \text{ kilowatts}^* \qquad (7.2)$$

where Q = Discharge, m³/sec

w = Density of water = 1,000 kg/m³

h = Head, m

η = Efficiency of turbine and generator

If, for example, $Q = 1$ m³/sec, and $h = 1$ m, then at 100% efficiency, the power will be 9.82 kW, or 13.33 metric hp.

In some cases, the discharge in cubic metres per second per square kilometre of drainage area is given. The drainage area of the river is obtained by surveying it. Then the total discharge, Q, that would be available is calculated.

Example 7.3

If the flow duration curve is as shown in Fig. 7.2 and the head is 100 m, find the power that can be developed per cubic metre per second if the efficiency of the set—hydraulic turbine and electric generator—is 90%.

The power per cubic metre per second at a head of 100 m and an efficiency of 90% is $P = 9.82 \times 100 \times 0.9 = 883.8$ kW.

The scale for the flow duration curve is

1 graph unit = 200 m³/sec

and the scale for the power duration curve is

$$1 \text{ graph unit} = \frac{200 \times 883.8}{1{,}000} = 176.76 \text{ MW}$$

The average flow during the period is 575 m³/sec, and the corresponding average power is 575 × 883.8 kW or 508 MW.

7.4 Mass Curve : Storage

River water is stored by means of reservoirs. Storage may be required for a number of purposes, e.g., for the water supply

*75 kg. m/sec = 1 metric hp = 0.736 kW.

scheme of a town, for irrigation, for navigation, for flood control and for the production of power by hydro-electric stations. The reservoirs may be planned as single purpose conservation reservoirs, single purpose flood control reservoirs or multi-purpose reservoirs.

If the water supply required for a given purpose is in excess at one season and deficient during another, a conservation reservoir is needed. For flood control, retarding reservoirs are required. In this case, the outlet capacity should be such that the unregulated discharge with the reservoir full does not exceed the permissible carrying capacity of the channel through the protected areas. An example of a multi-purpose reservoir is one that is located on the tributary of a major river, designed to protect the downstream towns and cities against disastrous floods, and to increase the dependable water supply for a number of purposes, e.g., irrigation and the generation of hydro-electric energy. In reservoirs for power purposes only, the storage above the minimum drawdown level is effective. In a flood control reservoir, the effective storage is the difference between the actual capacity above the outlet elevation and the valley storage.

A suitable site is required to build a dam and store water behind it in the form of a reservoir. When finding the capacity of reservoir to make available the flow of water at a required rate, a mass curve is studied. This is a plot of the cumulative volume of water that can be stored from stream flow, against time in days, weeks or months. The units used for indicating storage are the cubic metre or the day-second metre*. A day-second-metre is a flow at the rate of 1 m^3/sec for one day and is equal to $60 \times 60 \times 24$, or 86,400 m^3.

Example 7.4

The data for weekly flow at a particular site are as given below.

(*a*) Draw the mass curve for the period, (*b*) Calculate the size of reservoir and (*c*) the possible rate at which flow would be available after the reservoir had been built. Assume that the site

*Or the acre-foot : 1 acre-ft = 1,233.48 m^3

is suitable for building the dam necessary to provide storage in the reservoir.

Week	Weekly flow	Week	Weekly flow
	m^3/sec		m^3/sec
1	6,000	7	1,000
2	5,000	8	4,000
3	4,000	9	8,000
4	2,000	10	5,000
5	1,000	11	2,000
6	500	12	1,000

To obtain the mass curve, the cumulative volume of water that can be stored week after week must be found. The rate of flow is given in cubic metres per second. If the mean flow in the week is available at that rate, it will have a volume of $7 \times$ day $\times$ number of cubic metres per second, or 7 day-second-metres. If the summation of the volume of water in cubic metres or day-second-metres week after week is plotted against weeks, the mass curve is obtained.

Week	Weekly flow (column 2)	Weekly volume (column 2×7)	Summation
	m^3/sec	day second metres	day second metres
1	6,000	42,000	42,000
2	5,000	35,000	77,000
3	4,000	28,000	105,000
4	2,000	14,000	119,000
5	1,000	7,000	126,000
6	500	3,500	129,500
7	1,000	7,000	136,500
8	4,000	28,000	164,500
9	8,000	56,000	220,500
10	5,000	35,000	255,500
11	2,000	14,000	269,500
12	1,000	7,000	276,500

The summation of the volume of water that can be stored is plotted against the number of weeks in Fig. 7.3. This is the mass curve.

Capacity of reservoir, 55×10^6 day second metres.

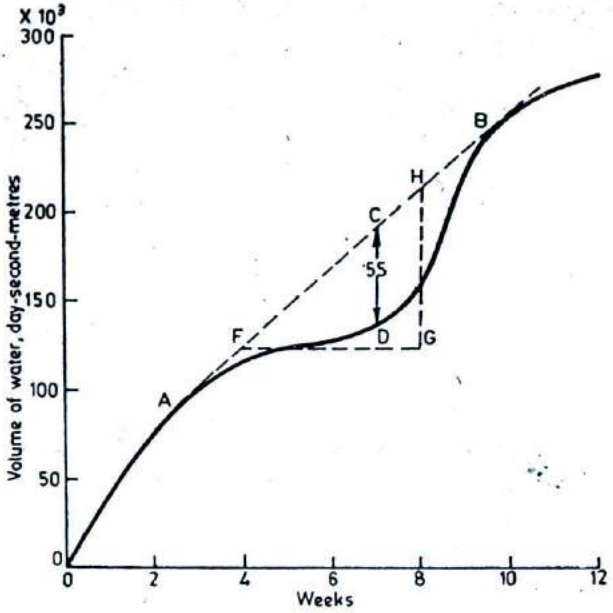


Fig. 7.3. Mass curve.

Drawing a tangent at the points of inflexions, A and B, the slope of the line AB is found. In the diagram it is

$$\frac{HG}{FG} = \frac{87.5 \times 1{,}000}{4 \times 7} = 3{,}120 \text{ m}^3/\text{sec.}$$

The maximum ordinate between the slope line and the mass curve, CD, gives the capacity of the reservoir. This comes out to be 55,000 day-second-metres. When a reservoir of this capacity has been built, it is possible to have a flow from the river at the rate of 3,120 m³/sec. If the rate at which water is drawn is higher than this, the reservoir level goes down; if the rate is less, the reservoir being full, there will be an overflow.

The above example was taken as a simple case for a short period of 12 weeks. In practice, the data for the flow should be available for a number of years to enable one to determine the rainfall and the flow cycle. A mass curve is plotted for two consecutive dry years to determine the size of the reservoir and the maximum rate of flow that would be available from the storage. In some cases, a mass curve for three consecutive dry years may be

desirable but a study of conditions during two consecutive dry years is normally enough.

When a large part of the natural flow is not to be wasted, storage and pondage must be provided to regulate the flow so that it may be made available at the time when it is required to generate power. Storage indicates the building up of a low natural flow of the stream to a uniform discharge. Pondage indicates the regulation of the resulting uniform flow, or natural flow if there is no storage, so as to satisfy the water requirement with variation in weekly demand. Storage has the effect of equalising the flow at different times of the year; it also lessens the average flow of the stream owing to increased evaporation from the water area. The storage that would be effective is therefore the accummulated water after it has been adjusted for evaporation and other losses.

When studying the effect of storage in the case of power development, it is necessary to consider the location of the storage – whether it is located at the power development site near the station, or whether it is at some distance above the power plant.

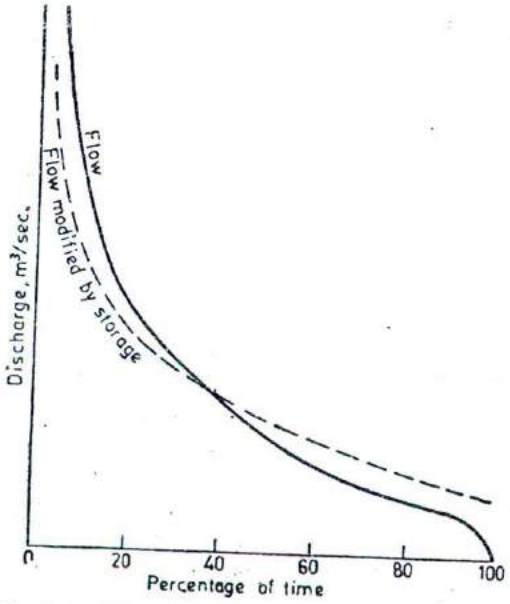


Fig. 7.4. Effect of storage on the flow duration curve.

In the latter event, the intervening uncontrolled area with respect to storage should be taken into consideration when determining the flow available at the power plant. The effect of storage is to lower the upper portion of the flow duration curve and raise the lower portion. Generally the mean, or average, point on a typical flow duration curve is between 30% and 40% of the time. The effect is shown in Fig. 7.4.

7.5 Investigation of Site

Preliminary investigations are made when selecting the site for a dam. The dam should be as close to the turbines as possible, and should have maximum size of pondage and the shortest length of conduit. The ideal site will be one where the dam will have the largest catchment area to store water at a high head, and yet be economical in construction. A general reconnaissance survey is first made from the air. Topographical mapping is then carried out by detailed surveying of the area. Geological studies are made. Methods of exploring the sub-surface are by digging pits, shafts and/or tunnels, etc. Supplementary methods used are the measurement of electrical resistivity and seismic methods of prospecting. The electrical resistivity method depends on the difference between the resistivities of the ledge rock and the overburden. The seismic method requires the measurement of the ratio of propagation of waves caused by explosion and is dependent on the difference in the elastic properties of the ledge rock and the overburden. Other methods of investigating the geological properties of rock are wash borings, churn drilling, rotary core drilling and diamond drilling. Sub-surface explorations should be made, and the condition of the soil determined in as great detail as possible. The science of soil mechanics helps a great deal in this respect. It is necessary to investigate the possibility and availability of construction materials in the neighbourhood, namely, earth, gravel, concrete aggregates, etc. Foundation conditions have to be studied.

After preliminary investigations of the possible sites for a dam, final investigations are made in detail to determine the relative merits of two or more sites for the project in question. After investigating the nature of the sub-surface conditions and the

foundation requirements, the type of dam to be built is decided. It is necessary to determine the cost of the land which will be submerged under water when the dam has been built, as the flowage or riparian rights will have to be bought. When land is submerged, it may be necessary to relocate railways and roads. Sufficient information should be available to enable the cost of the dam and project to be estimated. After the general location has been chosen, the exact positions of the various structures are fixed by considering the following factors –

1. Requirements of head, flow demands and storage capacity.
2. Details of foundation conditions.
3. Availability and character of construction material.
4. Arrangement and type of dam, intake, conduits, surge tank, power house, tail-race location, construction equipment, camps, coffer dam, construction of roads and railways.
5. Transport facilities and accessibility of site.
6. Cost of the project.

7.5.1 NUMBER OF DAMS FOR POWER PROJECT

An ideal power system on a river is one which would give the maximum uniform power theoretically possible with the head and water available. Of two systems each comprising a number of dams, the system with the smaller number of dams is theoretically the better, for, if it is practical for each system to use all the available water, the system with fewer dams may work at a greater uniform energy rate.

Theoretically, a single high dam gives a higher uniform energy rate than a number of small dams. Fig. 7.5 illustrates this point.

The profile of a river is given, and two alternatives are considered. A single dam at $D(C)$, 120 m in height, and three dams, each 40 m high at A, B and C are to be compared. Let the rates of flow and hence the energy per metre of height at A be x, at B be $2x$ and at C be $3x$.

For the single dam at $D(C)$, the energy rate is $120 \times 3x = 360x$, while for the dams at A, B and C the total energy rate is

$$(40 \times 3x) + (40 \times 2x) + (40 \times x) = 240x.$$

Thus when all the available water can be used, a single dam of 120 m height at $D(C)$ gives an energy rate $120x$ greater than that given by the three dams. Or, the uniform energy ratio of a single dam to three dams in the case illustrated is 3 : 2.

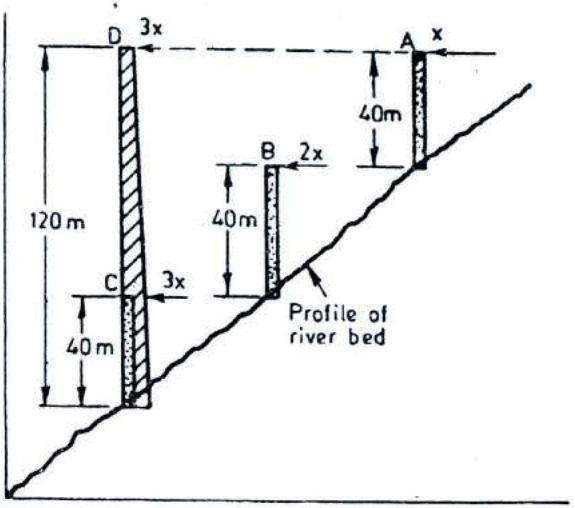


Fig. 7.5. Factors in dam location.

Although theoretically a single high dam at one point would be the first choice compared to a number of dams at different points on the river, practically this is objectionable, as the high dam might flood a number of towns, or a large area of land, railways, roads, etc., and it would certainly cost more on account of the foundation and construction conditions. Economically, it would be a better choice to have several smaller dams, e.g., three, as illustrated. If the rainfall at the site is uniform throughout the year, the size of dam required will be smaller for the same storage compared to the size required where the rainfall is not uniform.

Multi-purpose dams have to be a compromise between the different uses of water, and none of them obtains the maximum benefit from the reservoir behind the dam. There is a diversity between the demands of water for power, and water for irrigation or navigation. The object of flood control storage is directly

opposite to the object of storage for any other purpose. A multi-purpose dam must be higher than a single purpose dam having the same useful storage capacity. The cost of the dam and the volume of material used in it increase more rapidly than the square of the height of the dam. Thus, a higher dam costs more. The power output from a dam is reduced when the storage is drawn down.

In a hydro-electric power station, water turbines will be designed to work well under the condition that the head does not fall below a certain minimum value. The minimum head on the turbines determines the dead storage behind the dam that will be required. For navigation purposes, it is essential that a certain minimum depth should be maintained. The operation of locks for lifting the water level easily to the required extent should be possible under all conditions. The drawdown at the dam for navigation purposes is thus limited by the minimum depth required, and this also results in dead storage that would not be available for any other purpose. Deduct the dead storage from the total reservoir volume. The remainder is then the seasonal storage for power, irrigation and navigation. There has to be a compromise between drawdowns for various uses because their requirements do not occur at the same time.

For maximum protection, reservoirs built only for protection against floods should normally be empty and should be ready to receive and retard flood waters at all times. Their outlet works should operate entirely automatically. The outlets should discharge only the quantity of water that can safely be carried by the normal channel below.

7.5.2 HEAD AND POWER

The available gross head at a hydro-electric power plant is the difference between the water level in the pond or reservoir behind the dam and the water level in the river where the tailrace is located. When the level at the tailrace rises more rapidly than that in the pond above the dam as the discharge increases, a back-water effect takes place, and the net available head is reduced. For determination of power, the average head is used. The available power is known from the area under the flow duration curve converted to a power duration curve. The net or effective head on a

hydro-electric plant is the gross head minus all the losses above the entrance of the scroll case and below the exit from the draft tube. It is the total net height of the water column effective on the turbine runner when generating power.

Hydro-electric plants commonly have a wheel capacity corresponding to the flow available for about 20% to 40% of the time, depending on the load conditions, the load factor, and the position of the plant in the interconnected system. Water power can be divided into two types : Primary or firm power and secondary or surplus power. Primary power is that which is always available and dependable for carrying load, or that which corresponds to the minimum stream flow with due consideration to the effect of pondage and the load factor. Secondary power is the remainder; it is available only when the quantity of water and the storage are sufficient but is not available all the time or at any particular time. The storage or pondage affects the availability of primary power, which increases with storage. The effect can be seen from Fig. 7.4.

7.6 Types of Dam

The hydraulic structures required for a hydro-electric project include dams, spillways, headworks, conduits, etc. A dam is a barrier to confine water for storage and to raise its level to create a hydraulic head. A dam helps in diverting the flow of water from the river to the turbines at increased head. The selection of the type of dam for a particular location depends on topography, foundation surveys, and the geology and other characteristics of the location. The foundations must support the weight of the dam and all the forces acting upon it without crushing, sliding or permitting movement of the structure. The foundations must be sufficiently impervious so that there will be no objectionable passage of water. The types of dam used are gravity dams with solid masonry or concrete, arch dams, buttress dams, earth dams and rock-fill dams. The choice depends on the location, characteristics and costs involved.

Solid gravity concrete dam. This type of dam is adaptable to most locations. The height of a dam, however, is limited by the strength of its foundations. The height of a dam on an earth

foundation is very limited. High dams can be built on rock and good foundations.

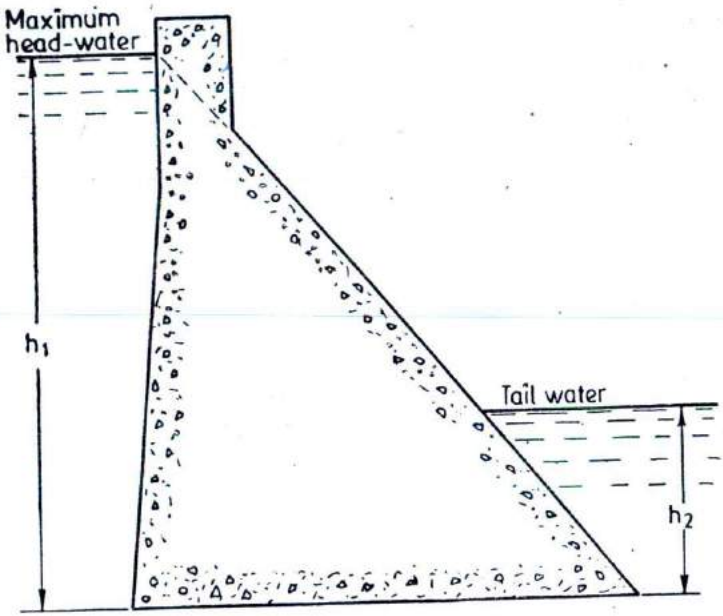


Fig. 7.6. Solid gravity concrete dam.

The dam is roughly of a triangular section with sides which are straight (Fig. 7.6) or slightly curved. The forces to be considered in its design are water pressure (1,000 kg/m³), ice pressure, where appropriate, earth pressure on the downstream and the upstream faces, weight of the dam (weight of concrete, about 1,685 kg/m³), weight of foundation and uplift. The dam structure should be stable. The possible causes of the failure of a dam are: (*a*) sliding on a horizontal joint above the foundation, on the foundation or on a horizontal seam in the foundation; and (*b*) overturning on a horizontal joint within the dam, at the base of the dam, or at a plane below the base. The direct cause of sliding is the presence of horizontal forces greater than the combined shearing resistance of the joint or base and the static friction induced by the vertical forces. The direct cause of pure overturning is the presence of horizontal forces which are so large in comparison with the vertical forces that the resultant force causes the turning effect. To avoid over-

turning, it is necessary to design the dam in such a way that there is no tension in any joint under any conditions of loading. For dams with rectangular joints, this condition is satisfied if the resultant of all the forces, including uplift acting on the dam above any horizontal joint whether the reservoir be full or empty, falls within the middle third of the base of the dam. To avoid sliding, the tangent of the angle between the vertical and the resultant of all forces, including the uplift, acting on the dam above the horizontal planes should be less than the allowable coefficient of friction at that plane. The total frictional resistance to sliding on any joint plus the ultimate shearing strength of the joint must exceed by a safe margin the total horizontal force above the joint for all conditions of loading.

Arch dams. The types of arch dam are single arch (Fig. 7.7), multiple arch or arched gravity dams. Single arch dams are common and are suitable when the length of the dam is small in proportion to its height, and when the sides of the valley are composed of good rock which can resist the end thrust. A good example of an arch dam is the Hoover Dam (or Boulder Dam) on the Colorado River in the United States.

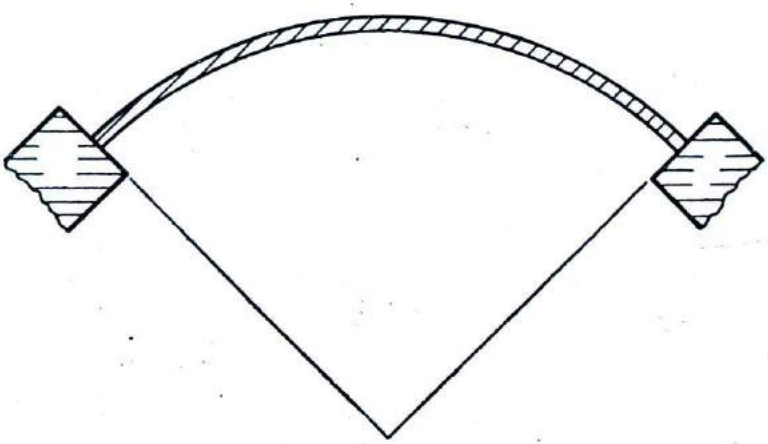


Fig. 7.7. Arch Dam.

An arch dam is a curved dam that carries a major part of its water load horizontally to the abutments by the arch action. The part that is carried by this action depends primarily on the radius

of curvature of the arch. The loads on arch dams are essentially the same as those of gravity dams. The principal dead load is the weight of the concrete; the principal live load is the reservoir water pressure. Additional loads are tail-race water pressure, uplift pressure, etc. An important difference between gravity dams and arch dams is the effect of temperature changes which cause important deflexions and stresses in arch dams. The arch dam can be built as a constant radius or a constant angle arch dam.

Buttress concrete dams. The principal structural elements of a buttress dam are the water-supporting upstream face, or deck, and the buttress. These water-supporting upstream members are supported on the buttresses and span between them. The buttresses are equally spaced triangular walls proportioned to transmit to the foundation the water load and the weight of the structure.

Earth dams. Earth dams are often the best and cheapest solution on earthen foundations and frequently on rock foundations. In general, an earth or rock dike will cost less per metre than a masonry dike. Earth dams have a long base in comparison to their height. They are commonly used wherever feasible for small projects with a maximum height of about 100 m. The advantages of earth dams are—

1. They are suitable for a relatively pervious foundation.
2. They are cheaper than masonry dams.
3. They blend with the natural surroundings.

The disadvantages of earth dams are—

1. They are subject to possible destruction or damage from erosion by water.
2. They need supplementary spillways of adequate capacity.
3. They have greater surface loss than the other types of dam.

In constructing an earth dam (Fig. 7.8), usually the impervious material is placed in the centre core with pervious material in the outer sections. This is graded so that the least pervious material

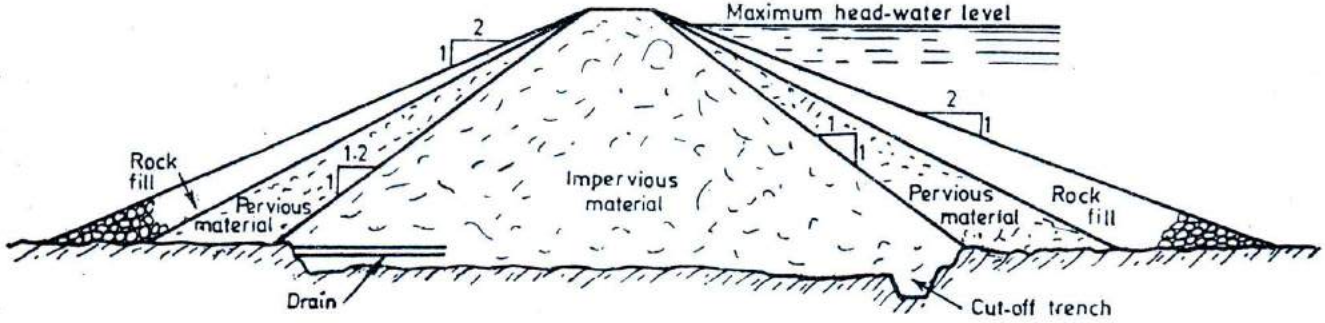


Fig. 7.8. Earth dam

is at the core and the most pervious at the slopes. The safety of an earth dam can be ensured by taking the following points into consideration when designing it :

1. There should be no danger of overtopping. This is avoided by providing sufficient spillway capacity to take care of floods. The spillways are located away from the dam.
2. The seepage line should be well within the downstream face. The seepage line is practically the line of saturation, *i.e.* the line above which there is no hydrostatic pressure and below which there is hydrostatic pressure.
3. The upstream face slope should be safe against sudden drawdown.
4. The upstream and downstream slopes should be safe for the materials to be stable.
5. There should be no opportunity for free water passage from upstream to the downstream face.

Rock-fill dams. These dams (Fig. 7.9) are characterised by the placement of fragmentary rock to form the embankment support necessary to withstand the reservoir water pressure and other forces exerted against or within the structure. Water-tightness is obtained through the medium of an impervious membrane, generally on the upstream face of the dam, connected to a cut-off wall extending into the foundation material. The cross-section of a rock-fill dam usually lies between those of a gravity dam and an earth dam. The foundation requirements for rock-fill dams are less severe than for earth dams. The safety of a rock-fill dam requires adequate spillway facilities independently placed with respect to the rock-fill structure. The rock-fill dam is one of the most satisfactory types of dam to resist earthquake shocks, for the flexible character of the impervious membrane and the supporting fill permits considerable movement without serious effect. The factors which are to be considered in cost estimates of rock-fill dams are—

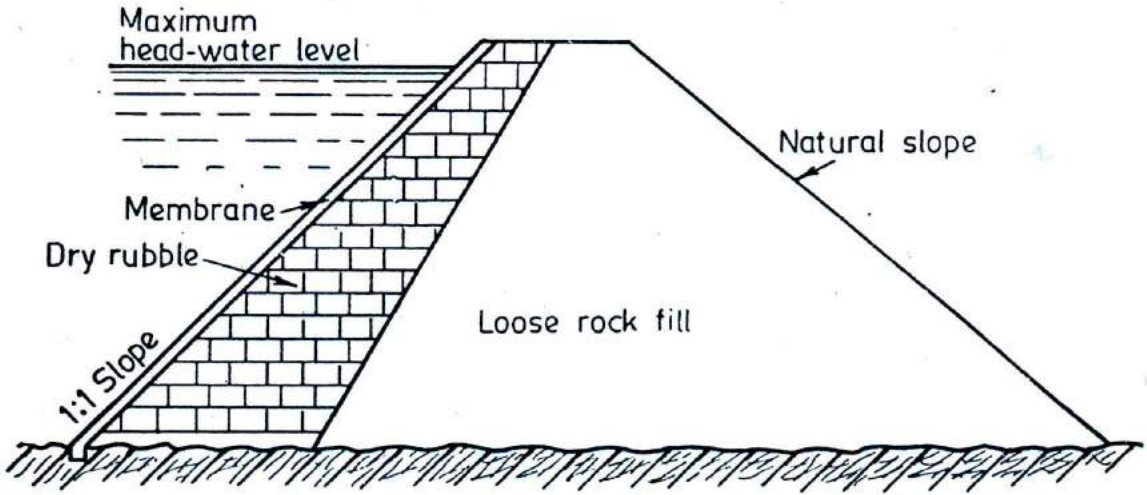


Fig. 7.9. Rock-fill dam.

1. Railway and highway transportation facilities.
2. Cost of foundation preparation and excavation.
3. Location, distance and elevation of quarry sites with respect to the proposed rock-fill dam.
4. Necessity for separate spillway and outlet works.
5. Costs of labour, material and equipment.

The above information gives the types of dam that are generally used. The type that will suit a particular project will depend on its location, materials available, foundations, geology, topography of the area and mainly the costs.

7.7 Arrangement and Location of Hydro-electric Station

7.7.1 SPILL WAYS

All dams for hydro-electric power plants are provided with spillways to discharge excess water in the reservoir beyond the full permissible level. Types of spillway are selected for various cases depending on the topography, geology and hydrological conditions at the site. Sometimes separate spillway dams (Fig. 7.10) are

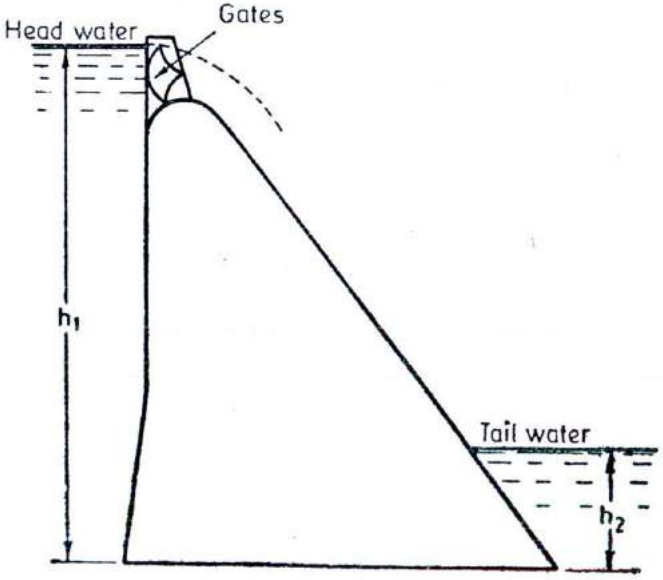


Fig. 7.10. Spillway dam.

built adjoining the main dam at suitable locations. Side-channel spillways, chute spillways, saddle spillways, shaft spillways and syphon spillways are other types of spillway used. In some cases emergency spillways are built which will operate only at the time of an emergency.

A simple spillway should be as long as possible consistent with economy to limit the head on the crest during floods. If the location is such that it is not possible to obtain sufficient length, the spillways should be equipped with crest gates to control and limit the fluctuation of the elevation of the headwater surface. This helps in avoiding the loss of head for the hydro-electric generating plant, particularly when the head is low.

7.7.2 INTAKE

The function of the intake in a hydro-electric development is to let the water into the conduit or penstock under controlled conditions. Screens, or trash racks, are used to prevent debris passing into the water-passage. A typical section through intake gates, trash racks and a crane arrangement is shown in Fig. 7.11.

In cold countries, ice in large blocks has to be prevented from entering the penstock. The intakes are of two types, high-pressure and low-pressure. High-pressure intakes are used where the drawdown is very heavy, e.g., in a reservoir which may be used both as a storage reservoir and as the headworks of a hydro-electric development. Low-pressure intakes are used where the drawdown is small, e.g., daily or weekly water-level variation in ponds for a hydro-station.

7.7.3 FOREBAY

The forebay is the enlarged body of water just above the intake. This may either be a pond behind the diversion dam or an enlarged section of a canal spread out to accommodate the required width of intake. The intake should not be exactly at right angles to the direction of the water, but should be at an angle of 30° to 40°. This helps in diverting some of the ice and debris to the spillway.

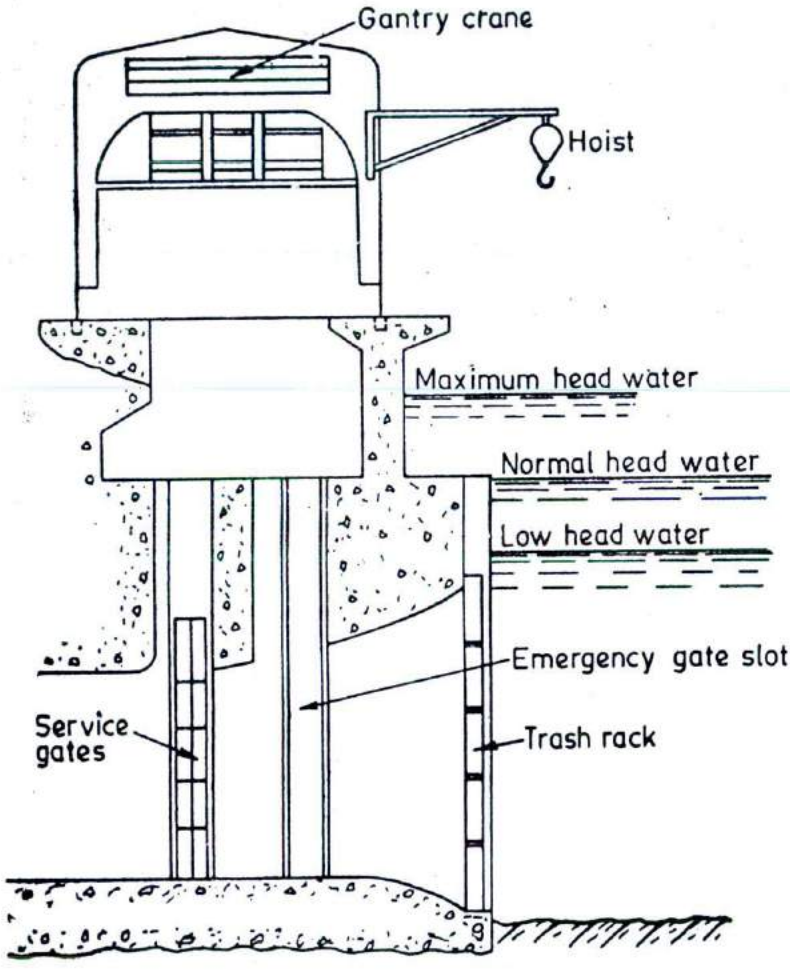


Fig. 7.11. Intake gates, trash racks and crane.

7.7.4 PENSTOCK

From the intake works and forebay, water is taken to the turbines by a conduit system known as a penstock. There are two types of penstock, the low-pressure and high-pressure. The low-pressure type consists of a canal, a flume or a pipe. The high pressure type consists of steel pipes which can take water under

pressure. Penstock pipes are generally of steel for high- and medium-head plants; they may be of concrete in low-head plants. The diameter and cross sectional area of a penstock pipe would be smaller if it were possible for the velocity of the water to be high. They would then be cheap in first costs, but with high velocities there is more friction and the head loss owing to friction increases, thus reducing the available head and therefore reducing the output of the plant. Thc choice of velocity in a penstock is thus a question of economics. Normally, for low-head plants the velocity of water in the penstock is chosen as 2 m/sec; for medium-head plants, about 4 m/sec; and for high head-plants the maximum allowed is about 7 m/sec. The thickness of a penstock pipe varies with the pressure and the diameter.

7.7.5 WATER HAMMER AND SURGE TANK

When the gates admitting water to the turbines are suddenly closed owing to the action of the governor when the load on the generator is suddenly reduced, there is a sudden change of pressure in the penstock pipes caused by the sudden change in the rate of water flow. This sudden change of pressure above normal is known as water hammer. When the turbine gates suddenly open because the turbines need more water to supply an increased load demand, water has to rush through the penstock, and there is a tendency to cause a vaccum or a negative pressure in the water system. The penstock must withstand the positive water hammer caused by sudden closing of the turbine gates, and no vaccum should be produced in the system when the gates suddenly open. To provide better regulation of water pressure in the system, a surge tank is used. The surge tank is always located as close to the power station as possible, preferably on high ground to reduce height of the tower. When the gates are closed and the water flow into the turbine is suddenly reduced, water rises in the surge tank. This produces a retarding head and decreases the velocity of water in the penstock. When the velocity of the water in the penstock is reduced to the value demanded by the turbine, the level of the water in the surge tank starts falling and fluctuates up and down until its motion is damped out by friction.

When there is a sudden rise in the load on the turbine, additional water is supplied from the surge tank. This lowers the water surface in the surge tank, thus producing an accelerating head which increases the flow of water in the penstock. When the discharge of water corresponds to the turbine demand, the water surface in the tank ceases to fall. The surge tank thus helps in stabilising the velocity and pressure in the penstock system and reduces water hammer. It also gives close regulation of the water flow quickly. A typical surge tank and penstock arrangement is shown in Fig. 7.12.

7.7.6 LOCATION OF A HYDRO-ELECTRIC STATION

The hydro-electric power station is generally located at the foot of the dam and near the storage reservoir whenever possible. When the power station is near the dam, the loss of head due to friction in the penstock is less. The location should also be such as to use the maximum possible head at the turbines. When the power station is as near the dam as possible, the length of the penstock is reduced to a minimum and there is a corresponding reduction in power loss. The final choice of location will depend on the comparative costs, output, storage capacity and maximum head of water.

In some locations it may be worthwhile to consider whether an underground power station would be economical. The cost of excavation, the possible increase in the head at the turbines, the saving in the length of penstock, the cost of tunnelling, the saving in the thickness of penstock when supported by the tunnel work with proper concreting – these are some of the points which should be taken into account when considering underground construction. To a certain extent, underground construction provides safety for the installation also. In India, the Koyna project is a very good example of an underground power station. It will generate 240 MW of electric power at an expected load factor of 60%; its ultimate capacity will be 600 MW. The head of water at the turbine is about 500 m. The final choice of the location of power station with respect to the dam is a question of economics.

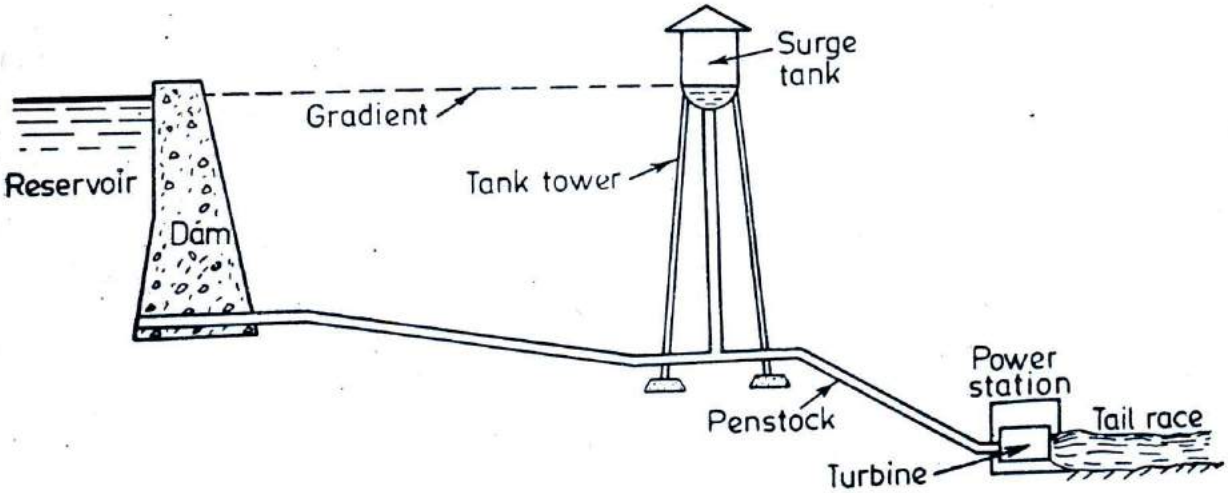


Fig. 7.12. Surge Tank and Penstock.

7.8 Types of Hydro-electric Plant and their Fields of Use

Run off river plants without pondage. Some hydro-plants are so located that the water is taken from the river directly, and no pondage or storage is possible. Such plants are known as run-off river plants. They can use water only as and when available; they cannot be used at any time at will or to fit any desired portion of the load curve. The firm capacity of such plant is low if the supply of water is not uniform throughout the year.

Run-off river plants with pondage. The usefulness of this type of plant is increased by pondage. Tail race conditions should be such that floods do not raise the tail race water level, thus reducing the head on the plant and impairing its effectiveness. Pondage is the storage at the plant which makes it possible to cope, hour to hour, with fluctuations of load throughout a week or some longer period depending on the size of the pondage. With enough pondage, the firm capacity of the hydro-electric plant is increased. This type of plant can be used on parts of the load curve as required, within certain limitations and is more useful than a plant without storage or pondage.

Reservoir plants. When water is stored behind a dam and is available to the hydro-electric plant with control as required, then the plant has better capacity and can be used efficiently throughout the year. Its firm capacity is increased and it can be used either as a base load plant or a peak load plant as required. It can also be used on any portion of the load curve in a Grid system. The majority of hydro-electric plants are of this type.

The three types described above are with reference to the storage of water. Hydro-electric plants may also be classified with reference to the type of load they can supply.

Base load plants. These are plants which can take up load on the base portion of the load curve of the power system; they are generally of large capacity. Run off river plants without pondage can be used as base load plants. Base load plants will be kept running practically on block load, i.e., load that is practically constant. Plants having large storage can best be used as base-load

plants, and particularly in rainy seasons, when the water level of the reservoir will be raised by rain water. The load factor of such plants is high.

Peak load plants. Plants used to supply the peak load of the system corresponding to the load at the top portion of the load curve are known as peak load plants. Run off river plants with pondage can be used as peak load plants. If the pondage is enough, a larger portion of the load can be supplied by such a plant if and when required. Reservoir plants with enough storage behind the dam can be used either as base load or peak load plants as required.

Pumped storage plant for peak load. If there is a shortage of water at a particular plant location, and if it is possible to have ponds at the head water and tail water locations, the water after passing through the turbine, may be pumped back from the tail race pond to the head water pond. During times of peak load, water is drawn from the head water pond through the penstock to operate the turbines, and during the off peak period, it is pumped back to the higher level. The pond capacity should be suitable for a 4 to 10 hour supply of energy at peak load time. A general arrangement of a pumped storage plant is shown in Fig. 7.13.

In carrying the peak loads of a system, pumped storage hydro-electric plants decrease the operating costs of the steam plants working in combination with them. Off peak energy from steam or Diesel plants is used to drive the pumps. Pumped storage peak load plants have an advantage over the usual reservoir peak load plants. If the reservoir is drawn too low, the firm capacity of the reservoir plant must be sacrificed, but the firm capacity of a pumped storage plant can be maintained by additional off peak pumping. Peak load hydro-electric plants are especially useful in systems subject to sharp and unexpected short time peaks.

A modern development in pumped hydro-plants is reversible turbine pump operation. While generating, the turbine drives the electric generator. In the reverse operation, the generator runs as a motor driving the turbine, which now acts as a pump. This saves the installation of a separate pump. The power for driving the generator as a motor is drawn from the system.

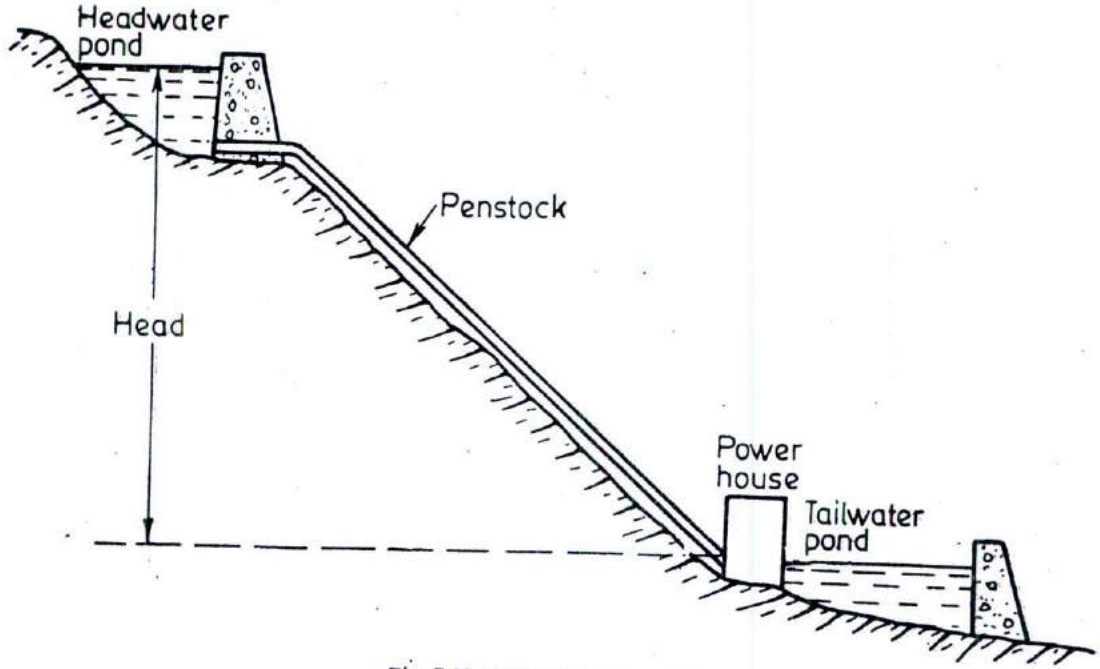


Fig. 7.13. Pumped storage plant.

A third way of classifying hydro-electric plants depends on hydraulic head : thus they may be high head, medium head or low head plants. This classification is necessary because the characteristics of these different types are different. Low head plants are those which have a head of 70 m or less; medium head plants between 70 and 300 m; and high head plants, above 300 m.

7.9 Principle of Working of a Hydro-electric Plant

A hydro-electric power station should have water available at enough head from the river or the reservoir behind the dam. The water is taken through the intake works and forebay, and then through the penstock to the turbines in the power station. The penstock carries water under pressure. There are basically two types of turbine, reaction and impulse. In a reaction turbine, the energy of water is used under pressure, and it is let out through a draft tube into the tail race without loss of pressure to the atmosphere anywhere in the system. Energy in the form of pressure is converted to kinetic energy when water at a pressure greater than atmospheric strikes the turbine vanes. The water is let into the turbine through a scroll case or scroll flume. After the water passes through the turbine runner giving it motion, it goes through the draft tube to the tail race. To avoid cavitation and pitting, no vacuum should be created in the draft tube by the passage of water through it. Thus the pressure energy is gradually converted into kinetic energy without loss as far as possible. While entering the turbine, water passes through the speed ring and a number of control gates at the speed ring control the quantity of water entering the turbine as required by the load conditions. The control gates are operated by a governor through a servo-mechanism and oil-pressure system.

In impulse turbines, which are used for high-head plants, the pressure head is converted to a velocity head by nozzles at the admission of water into the turbines. The water impinges on the buckets of the runner and gives it motion. Thus in this type of turbine, velocity head is converted to kinetic energy, and after the work has been done on the turbine runner, the water is let into the

tail-race. No draft tube is required. The quantity of water entering the turbine is controlled by varying the opening of the nozzle by needle or by throttling. This is effected by the use of a governor, again through the servo-mechanism arrangements and the oil-pressure system for operation of the controls.

The generators coupled to the turbines produce electric power corresponding to the power developed by the turbines less losses in the set. The speed of the set depends on the head, specific speed of the turbine and the power of the unit.

Reaction units are generally vertical, and the power station needs a good deal of substructure and superstructure to accommodate the necessary arrangements of draft tube, etc. Impulse units are either horizontal or vertical, and no special substructure is necessary.

7.10 Bulb Type Turbine Plants

A bulb unit can be defined as a hydro-electric power unit installed in a hydraulic duct with its centre line coinciding with the flow axis. It is thus an axial flow turbine - propeller or Kaplan type – with horizontal shaft. An inclined shaft is used for some installations. The first bulb units were commissioned at micro power stations. They have very low heads from 3 m to 15 m. Micro hydro stations use possible low head locations in isolated places to generate small power from 100 kW to 500 kW. Bulb type hydro stations were first developed and installed in large numbers in France. For Rance tidal power plant, 24 units of bulb type turbines are used, each of 10 MW capacity, with good results.

Many bulb type turbines have adjustable wicket gates and runner blades controlled by operating cams. In some units where fixed runner blades and wicket gates are used in the station equipment, there is 15% to 30% saving in investment costs. Bulb units in general need substantially reduced civil engineering costs while providing excellent performance. The maximum head that is permissible for operation of bulb turbines is 25 metres. At the present time, they are built for outputs upto 50 MW.

Bulb type turbines have high hydraulic efficiency, which is about 92% and compares well with that of Kaplan turbines. These turbines have low inertia. However, they are stable in operation. Bulb generator losses are slightly higher than those of conventional generators. The efficiency is about 97% at a power factor of about 98%. The average temperature is low and is within the permissible limits.

7.11 Tidal Power Plants

If tides are available with a large range of several metres, and suitable basin level is provided to store water energy from the tide, the tidal energy stored at height can be used to drive a turbine and produce electricity. The difference in basin level and sea level provides the head on the turbine. As the head is generally low, bulb type turbines are used for such projects. The best example of tidal power plant is 'The Rance Power Plant' in France.

7.11.1 THE RANCE POWER PLANT

Is located near Saint Malo on the northwest French Channel Coast, in an area in which the tide range is over 13.5 metres. The project was commissioned between August 1966 to December 1967 and has 24 units of bulb type turbines, each of 10 MW capacity. Thus the total capacity of the station is 240 MW. The annual production capacity is about 540 million kWh.

Fig. 7.14 shows the cross section of a bulb unit layout at the Rance Plant.

The units are designed for two way operation – from storage basin to sea and from sea to the storage basin. The two way operating cycle is shown in Fig. 7.15.

The units operate as pumps accelerating the tidal effect at small water level differences between the storage basin and the sea and they operate as turbines when one level is considerably above the other. The generators operate as motors driving the turbines as pumps during the pumping operation. Starting and coupling are asynchronous. The plant gates are used to accelerate filling

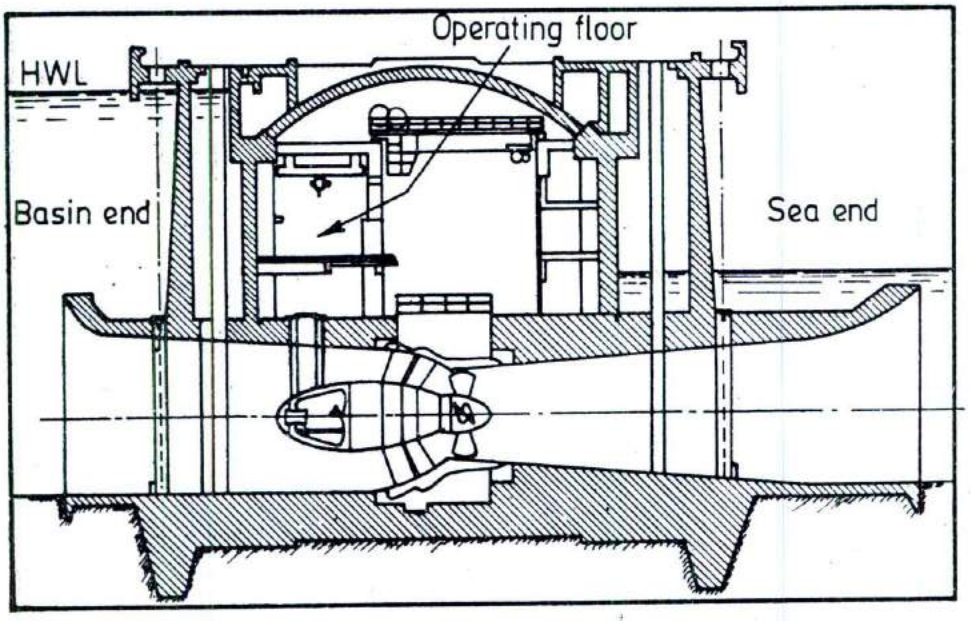


Fig. 7.14. Cross section of a bulb unit layout at the Rance plant.

and emptying of the storage basin at small differential water levels. This can be done with or without the operation of pumps.

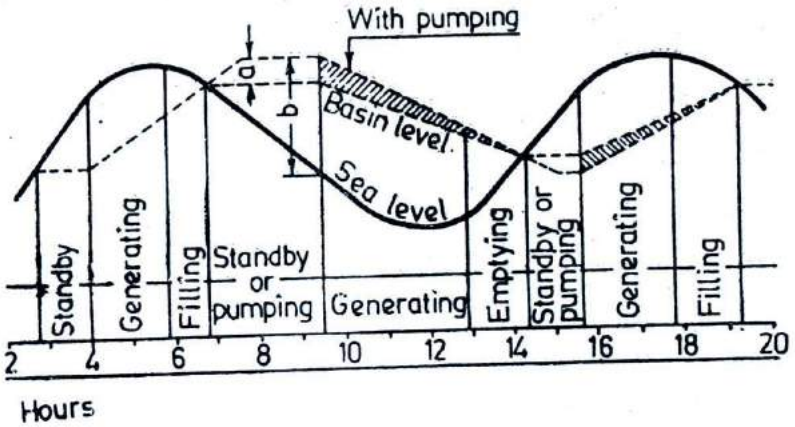


Fig. 7.15. Two way operating cycle for a bulb unit.

A computer with predicted tide level data storage optimises the two way operation cycle data and programmes gate operation and turbine and pump start up schedules. The programme accounts for the instantaneous cost of energy. It is arranged for maximum financial return and not for maximum power output. The operators in the station apply necessary corrections—small phase/time errors—to the data given by the main computer by the use of a micro computer.

For voltage control and excitation, adequate precautions against reverse over voltages should be provided, particularly during coupling. Rotating diodes have proved quite satisfactory.

The Rance tidal power plant has shown good performance with less than 7% non-availability out of which only 2% was due to operating trouble. Tidal conditions ensure that peak generation does not always coincide with the peak system demand. Tidal plants do not offer the same advantages as pumped storage plants for peak demand operation.

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Problems

7.1. Define hydrography (or hydrology). State various sources of loss which must be taken into account when estimating the available run off from known precipitations.

7.2. Define hydrograph, and explain its use in the study of water power.

The average weekly discharge as measured at a given site is as follows. Plot the hydrograph.

Week	Q	Week	Q
	m^3/sec		m^3/sec
1	1,000	14	1,200
2	900	15	1,000
3	900	16	900
4	800	17	800
5	800	18	500
6	600	19	400
7	500	20	400
8	500	21	300
9	800	22	300
10	800	23	400
11	1,000	24	400
12	1,100	25	500
13	1,100	26	500

7.3. Explain how to construct a flow duration curve from a hydrograph. From the data in Problem 7.2 construct a flow duration curve for the period of 26 weeks as 100% time.

7.4. Show how a flow duration curve can be used as a power duration curve. Using the flow duration curve of Problem 7.3 find the power that can be developed per cubic metre per second if the head available is 50 m and the efficiency of the turbine-generator sets is 85%. Find the maximum power, average power and energy (kilowatt-hours) produced during 26 weeks. (Ans. Power per cubic metre per second, 416 kW; average power 295 MW; maximum power, 500 MW; energy produced during 26 weeks, $1,290 \times 10^6$ kWh).

7.5. Explain mass curve and its use to estimate reservoir capacity and the rate of discharge that will be available when a reservoir has been built.

Construct a mass curve from the following data of flow for a dry year at a given site—

Weeks	Weekly flow m^3/sec
1 to 6	600
7 to 12	700
13 to 18	300
19 to 24	400
25 to 30	1,700
31 to 36	1,300
37 to 42	900
43 to 48	600
49 to 52	300

Estimate the size of reservoir and the possible maximum rate of flow that could be available from it (Ans. Size of reservoir, 51,000 day second metres; maximum rate of flow, 914.3m^3/sec).

7.6. Discuss the factors to be taken into account in the preliminary investigation when selecting a dam site.

7.7. Discuss the type of dam used in hydro electric projects.

7.8. Write short notes on the following : (*a*) spillway, (*b*) forebay, (*c*) water hammer and surge tank, and (*d*) location of hydro-electric power stations.

7.9. Define firm power and secondary power of a hydro electric station. Classify different types of hydro-electric power plant and explain their field of use.

7.10. Explain the principle and operation of pumped storage plant. How does it help to take up sudden peak loads in a power system?

7.11. Explain the principle and operation of bulb type power plants. State the characteristics.

7.12. Explain the working of a Tidal Power Plant and the two way operating cycle for its units. Illustrate by an example.

8

Hydro-Electric Stations : Preliminary Design—II

8.1 Power to be Developed

In the previous chapter, we studied the method of determining the resources available for hydro-electric power development and how to estimate the power that can be developed at the site, considering the flow of water available and the head at the plant. The maximum and minimum heads available at the turbine determine, respectively, the maximum possible power and the firm power that can be developed at the power station. The average head determines the average power that would be available and the total electrical energy that could be obtained during a given period, preferably a month or a year. The variation of head at the turbine gives the variation in power that can be developed.

Power duration curve. Knowing the discharge Q (cubic metres per second) and head h (metres), it was shown in the last chapter how the flow duration and power duration curves are constructed for a given period, preferably a year. Eqn. (7.2) is repeated here for convenience

$$P = \frac{0.736}{75} Qwh\eta \text{ kilowatts} \qquad (7.2)$$

w, it will be recalled, represents the density of water (1,000 kg/m^3), and η, the efficiency of the turbine and generator.

The effect of storage is to improve the shape of the flow duration curve and to increase the firm capacity, or primary power, of the station.

Fig. 8.1 shows the annual flow duration curve or, with a change of scale, the corresponding power duration curve of a hydro-station. If the quantity of water stored behind the dam corresponds to the area *abc*, this quantity of water will be available at the time of low flow, i. e., the area *ghk* will be equal to the area *abc*. Thus the firm power from the station corresponds to *de*. The area *dkhgfed* represents the primary energy that can be supplied by the power station during the year. The area *bckdb* represents secondary energy, and *bd* represents secondary power.

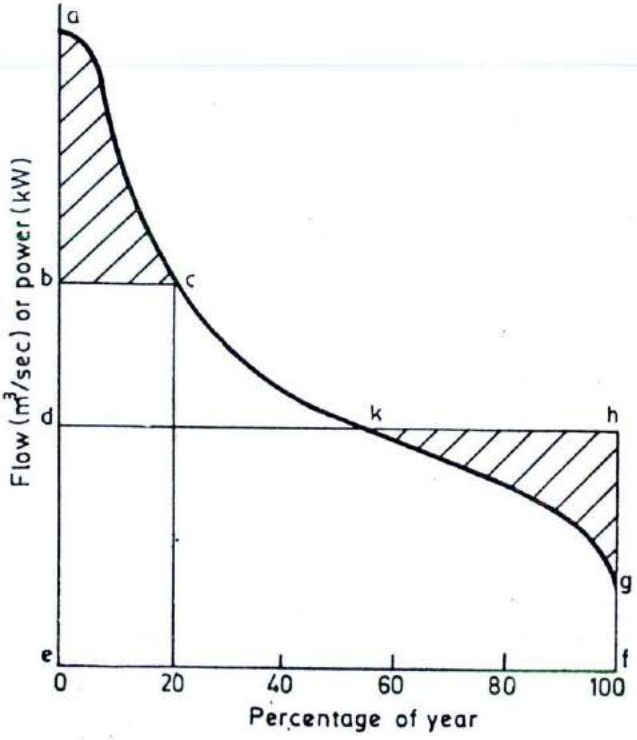


Fig. 8.1. Annual flow duration curve or power duration curve.

8.2 Size of Plant and Choice of Units

A hydro-electric power plant can be designed for either base-load or peak-load operation, the choice depending on the storage available during the year as well as the use of the power station on a particular portion of the load curve. The load factor at which the

plant is to operate during the year is determined from the system conditions. If the station is one of many in a power system, it can be allotted a particular portion of the load curve.

If the station is not interconnected with others, the annual load factor is determined from the power duration curve as well as the total energy that could be available corresponding to the area under the curve. The load curve of the power system is determined and the capacity of the plant chosen to fit the requirements. In general, for an isolated hydro-station the capacity of plant is chosen corresponding to the power available for 20% of the time as determined from the annual power duration curve.

If the station is to be designed as a peak-load station, the load factor of the station will be low. The plant capacity factor also will be low, between 20% and 25%. When the energy that could be available from the storage is known, and when the annual capacity factor has been selected, the capacity of the plant can be worked out. This is illustrated in the next example.

Example 8.1

The annual power duration curve for a hydro-electric installation shows that 876×10^5 kWh of electrical energy can be obtained during the year. The plant is to be designed as a peak-load plant for an annual load factor of 25%. Determine the capacity of the station. If the plant capacity factor is 20%, find the reserve capacity of the plant.

$$\text{Capacity required} = \frac{\text{Energy generated during a year (kWh)}}{8{,}760 \times \text{Annual load factor}}$$

$$= \frac{876 \times 10^5}{8{,}760 \times 0.25} = 40{,}000 \text{ kW}$$

Since the plant capacity factor is 20%,

$$\text{Capacity of plant installed} = \frac{876 \times 10^5}{8{,}760 \times 0.20} = 50{,}000 \text{ kW}.$$

The reserve capacity is, therefore, $50{,}000 - 40{,}000 = 10{,}000$ kW.

Choice of units. For an isolated hydro-station supplying all the power to a system, the principles of the choice of units as discussed in Chapter 2 hold good; the number and size of units are chosen considering the load curve of the power system to be supplied and should represent the best compromise between the plant capacity factor and the plant use factor.

In addition to this consideration, there is the economy that can be effected by choosing hydro-units of equal size, from the point of view of hydraulic equipment, penstock, draft tubes and construction details. It is, therefore, a good practice to choose units of equal size. The actual size is, of course, chosen consistent with the load curve and the availability of the particular size at the time when the station is being planned.

When a hydro-station is one of many stations supplying a power system, the sizes of units chosen are as large as possible and reserve at all stations is unnecessary. The reserve plant capacity may be provided in one station only

As an example of the choice of units, consider Example 8.1. When the total plant capacity of the station is 50,000 kW, of which 10,000 kW is the reserve, the choice will be 5 units each of 10,000 kW.

8.3 Types of Turbine and their Characteristics

8.3.1 TYPES OF TURBINE

Hydraulic turbines are simple in construction, efficient and easily controllable; they have the ability to work as either peak-load or standby plant; they can start from cold and pick up full load in a very short time; they can work on load variations and can run for weeks without much attention. These advantages make hydraulic turbines very useful as prime movers in power stations.

The main types of turbine used in hydro-electric power stations are, as we have seen, reaction and impulse.

In the reaction turbine, the water passages are completely filled with water, the water acting on the wheel vanes is under pressure greater than atmospheric, the water enters all round the periphery of the wheel, and the energy in the form of both pressure and kinetic energy is utilized by the wheel.

In the impulse or tangential wheel, the wheel passages are not completely filled, the water acting on the wheels is at atmospheric pressure and is supplied at a few points at the periphery of the wheel (one, two or four) and kinetic energy is supplied to the wheel.

With reference to the direction of flow of water, reaction turbines are divided into the following types –

1. *Radial flow inward.* The runner receives water under pressure in a radially inward direction and discharges it in a substantially axial direction. These are known as Francis turbines. A typical section and plan is shown in Fig. 8.2.

2. *Axial Flow.* The runner vanes of axial-flow turbines are either fixed or adjustable. These are propeller-type turbines (Fig. 8.3), and those with adjustable blades are known as Kaplan turbines. The fixed-vane type is preferred when the head and flow are substantially constant and where base-load operation is possible. The adjustable vane-type is preferred where the head and flow vary over a very wide range and the station is subjected to variable load operation.

The essential parts of a reaction turbine are the runner, the guides and gates, the speed ring, the casing or approach flume, and draft tube.

The runner is a rotating part with vanes suitably shaped. The admission of water through the guides is controlled by the gates. The speed ring is used for concrete or steel spiral flumes and for vertical units. This consists of an upper and lower flange joined together by a few vanes which are suitably shaped to conform with the flow into the guides. The casing surrounds the runner and guides water to it.

The draft tube connects the wheel at the exit from the runner with the water level in the tail race; this enables the wheel to be set some distance above the water level without loss of head between wheel and tail race.

Fig. 8.4 shows typical Francis turbine runners for two specific speeds. The dimensions D_1 and D_2 are marked and their variation with change of specific speed is indicated.

Fig. 8.5 shows a typical fixed blade propeller type turbine runner. The position of the wicket gates, speed ring and scroll case are shown, and the diameter of the propeller is marked D.

Fig. 8.6 shows a typical movable blade propeller turbine runner, with its speed ring, wicket gates and scroll case. The adjustable blades of the runner and the runner deflector are shown. The diameter of the runner is marked D.

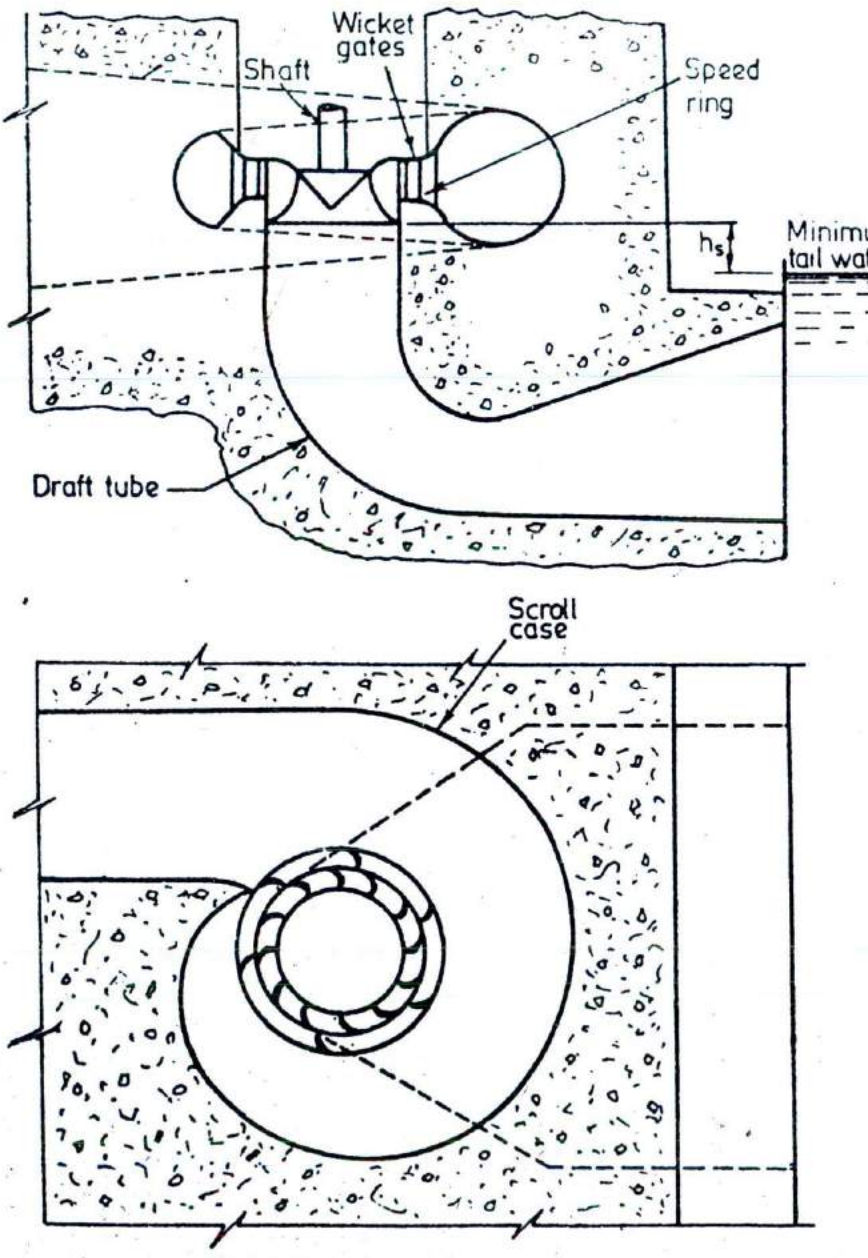


Fig. 8.2. Section and plan of a Francis turbine.

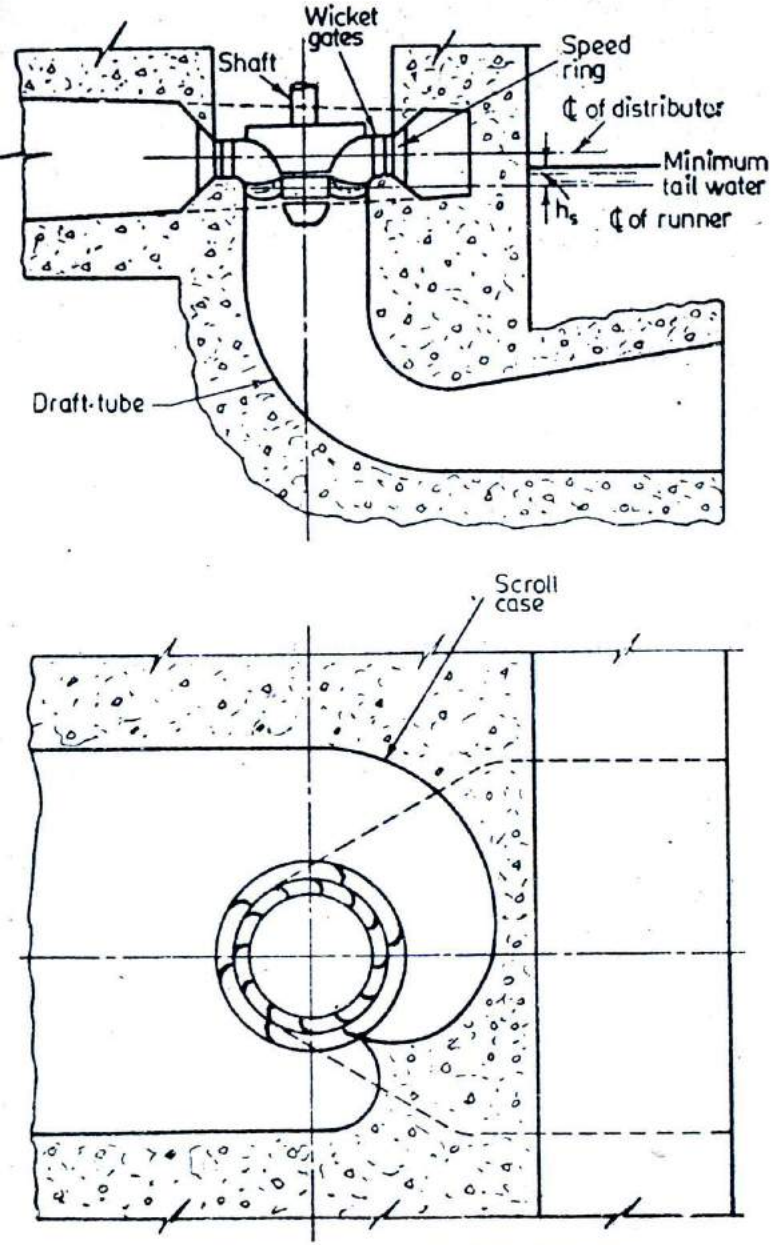


Fig. 8.3. Section and Plan of a Propeller turbine.

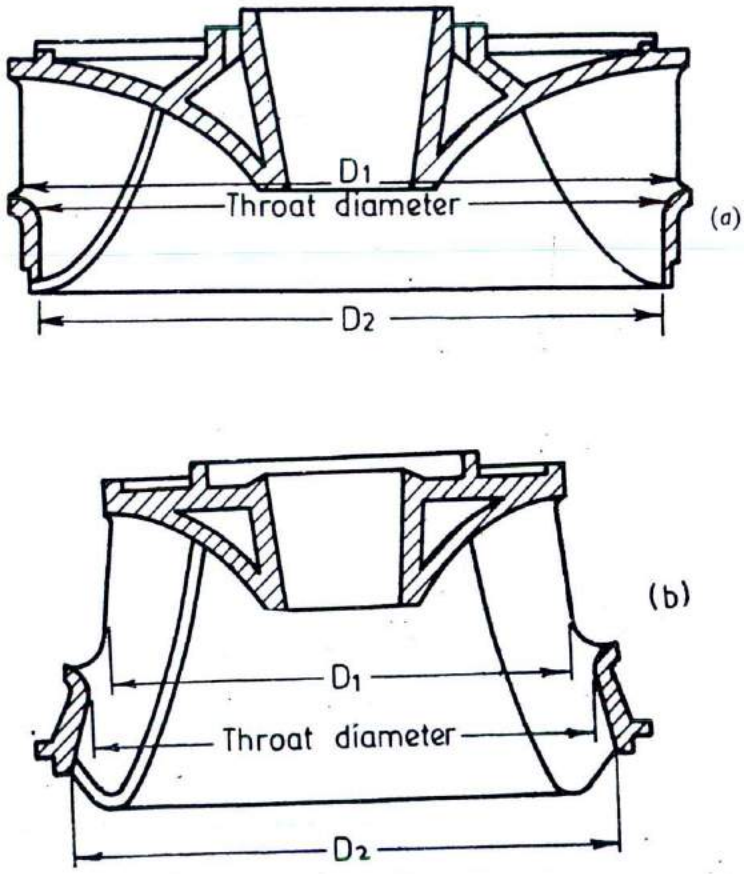


Fig. 8.4. Francis turbine runners.
(*a*) n_s' about 160 rev/min
(*b*) n_s' about3 00 rev/min
Specific speed, n_s', is defined on pages 301 and 302

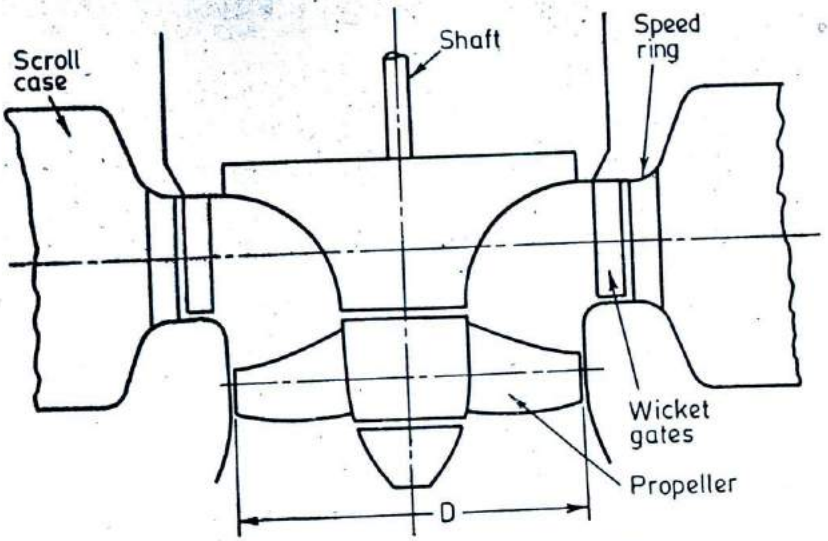


Fig. 8.5. Fixed blades propeller turbine runner.

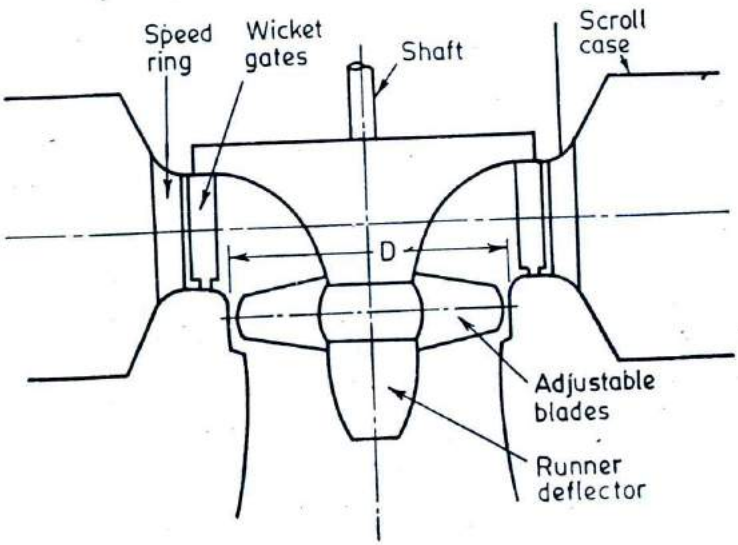


Fig. 8.6. movable blade propeller-turbine runner

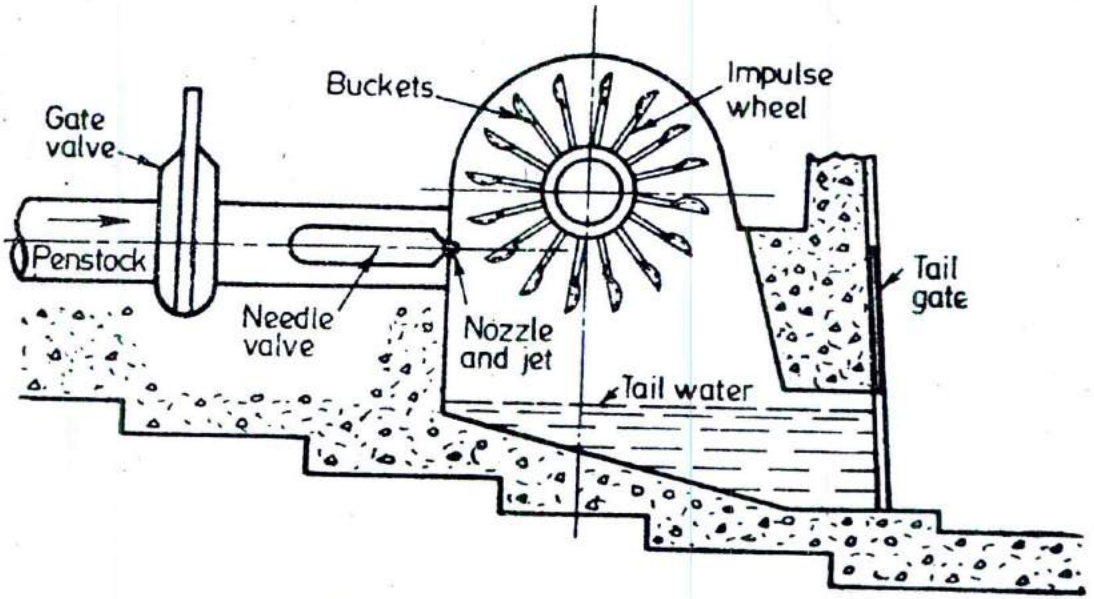


Fig. 8.7. Impulse turbine general arrangement.

The impulse wheel or turbine is generally a Pelton wheel. The runner consists of a single casting containing the central disc and the buckets. The runner is of cast steel. In some cases the buckets are cast separately and attached by bolts and lugs to the wheel hub. For runners, sometimes stainless steel with 12% to 14% chromium with or without 1% nickel is used. The spear and nozzle are made of stainless steel or special bronze, depending on the head and the quality of the water. The spear tip and nozzle control the jet of water impinging on the buckets. The jet deflector sometimes used for control is made of stainless steel.

Fig. 8.7 shows the arrangement of an impulse turbine, including the gate valve and needle valve for the control of water impinging on the Pelton wheel buckets. The nozzle and jet are also shown. Fig. 8.8 shows the disposition of the buckets fixed to the wheel, the pitch circle, of diameter D, and the jet diameter, d. Fig 8.9 shows a pair of buckets.

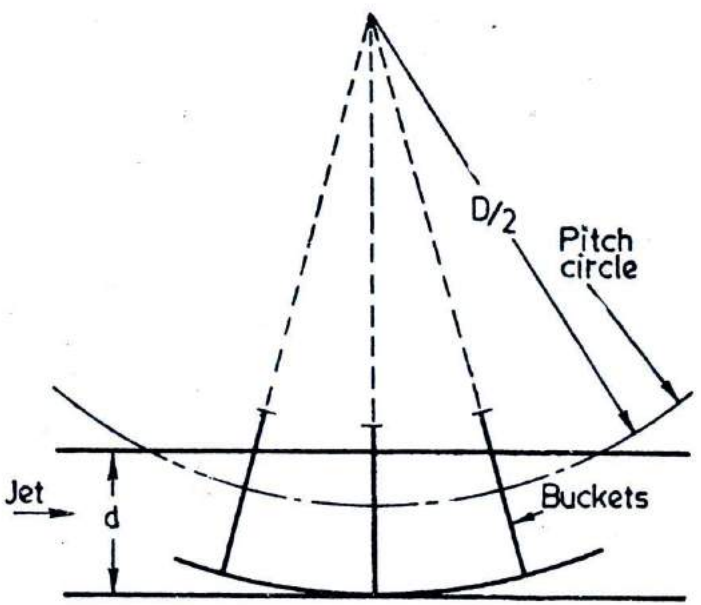


Fig. 8.8. Pelton wheel diameters.
D. Pitch circle diameter.
d. Jet diameter.

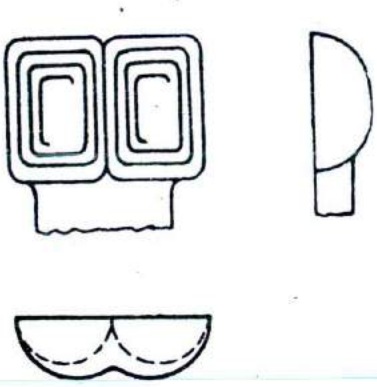


Fig. 8.9. Pelton wheel buckets.

8.3.2 CHARACTERISTICS OF TURBINES

Head at the turbine. Reaction turbines of various types are used for heads up to 500 m, the Francis type for heads of 70 to 500 m, and the propeller type for heads less than 70 m. For fairly constant load operation, fixed-vane propeller turbines are used. For heads lower than 30m and for variable-load operation, Kaplan or movable-vane turbines are used.

For heads above 500 m up to about 1,700 m, Pelton wheels with a single or multi-jet arrangement are used.

The design head of a turbine is the head for which the runner is designed to run at the best speed and to operate at the highest efficiency. Where the head on the turbine varies considerably from the nominal head, the lower head should be used; and where there is a small difference between the maximum and minimum heads not exceeding 10% above or below the nominal head, the higher head should be used.

The maximum head under which a Francis turbine operates should not exceed 125% of the design head, and the minimum head should not be less than 65% of the design head, in order to facilitate stable operation and avoid excessive cavitation. The maximum head under which a fixed-blade propeller wheel operates should not exceed 110% of the design head, and the minimum head should not be less than 90% of the design head. For the adjustable-blade, or Kaplan turbine the range of operation is from 50% to 150% of the

design head. Generally the design head is selected as the head above and below which the average annual generations of power are approximately equal. This is thus the point of best efficiency at the weighted average head. The rated head is that at which the full gate output of the turbine will produce the rated capacity of the generator in kilowatts. For run-off river plants having approximately constant heads, the design and rated heads are usually the same.

Efficiency of turbines at various loads. The nature of the efficiency curves for the various types of turbine are shown in Figs. 8.10, and 8.11. Fig. 8.10 shows these characteristics for reaction turbines. Francis turbines are suitable for operation of plant from 75% load to full load. Propeller turbines with fixed-blade construction are used at fairly constant load between 75% and 100% of their capacity, and if the variation of head is very small, the units can be operated at a point near their best efficiency. The Kaplan turbine efficiency curve shows that it is useful for frequent part load operation. It is possible to obtain considerably better efficiency at part-gate openings with adjustable-blade turbines than with fixed-blade turbines. An adjustable-blade unit is smaller than a fixed-blade unit of the same rating, and it will operate at a higher speed. An adjustable-blade unit requires a smaller power house than a fixed blade unit.

The efficiency curves shown are representative of particular types. The actual values will depend on the head, the size of turbine and its speed. The maximum efficiencies of Francis, fixed-blade propeller and Kaplan turbines are approximately 92% to 93%.

The adjustable-blade Kaplan turbine is used efficiently at loads from 40% to 80% or higher, the efficiency curve within this range being practically flat.

The efficiency curve of a Pelton wheel will remain slightly lower than that of a Francis turbine but will be less affected by variations of load. Pelton wheels are used for high-head plants. Fig. 8.11 shows a typical curve of a Pelton wheel unit. The efficiency curve does not vary much from 40% to 100% load, and so

the unit can work well within this range. The efficiency of a Pelton wheel unit is about 87% to 88%.

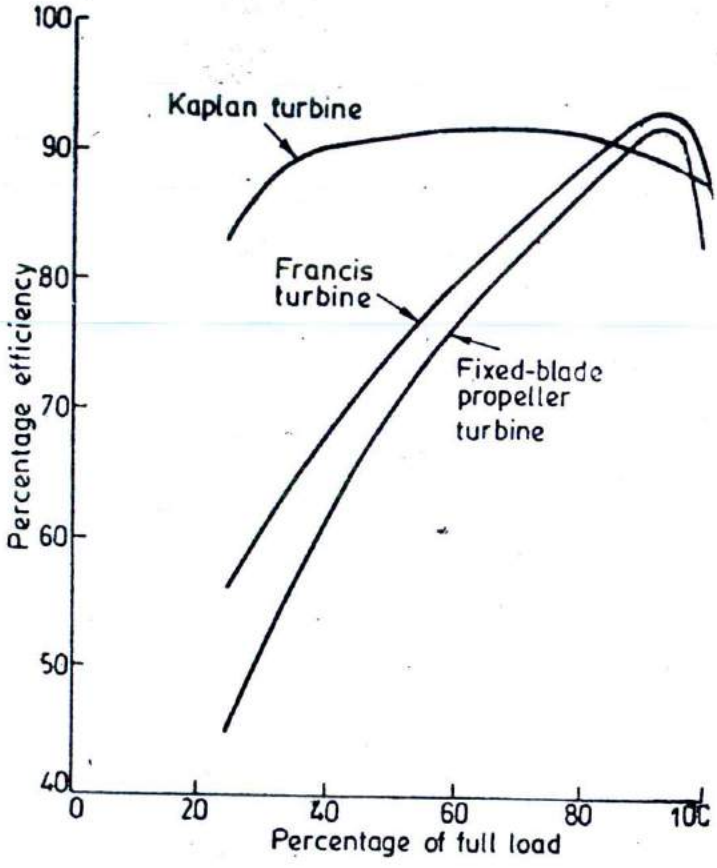


Fig. 8.10. Efficiency/load curves of various types of reaction turbine.

Speed: specific speed of turbine. The basis for comparison of the characteristics of hydraulic turbines is the specific speed, n_s, or the speed at which a turbine would run if the runner were reduced to a size which would develop 1 metric h. p. under 1 m head. This speed is proportional to the square root of the horsepower and inversely proportional to the 5/4 power of the head, i.e.,

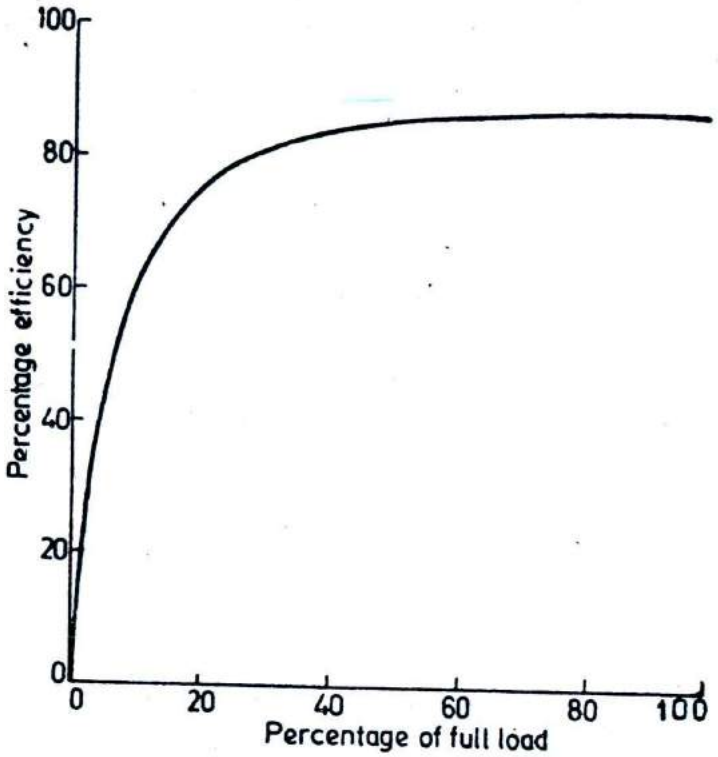


Fig. 8.11. Efficiency/load curve of an impluse turbine (Pelton wheel).

$$n_s = \frac{nP^{1/2}}{h^{5/4}} \text{ revolutions per minute.} \qquad (8.1)$$

where n_s = Specific rotational speed

n = Actual rotational speed.

P = Metric horsepower.

h = Head m.

From eqn. (8.1) the actual speed, n, is given by

$$n = \frac{n_s h^{5/4}}{P^{1/2}} \qquad (8.2)$$

In general, the higher the specific speed for a given head and horsepower output, the lower is the cost of the installation as a whole. There are certain limitations of n_s of a runner for a given

head and horsepower. Too high a specific speed would reduce the dimensions of the turbine to such a size that the discharge velocity of the water into the throat of the draft tube would be relatively high. This is undesirable because the energy of the discharging water can be only partially regained in the draft tube. In the extreme case, a vacuum may be created.

Too high a specific speed with a high head would increase the cost of the turbine disproportionately, on account of the high mechanical strength required. Too low a specific speed with a low head would increase the cost of the generator installation owing to the low turbine speed.

An increase in specific speed is usually accompanied by a lower maximum efficiency and a greater depth of excavation for the draft tube. When choosing a turbine, the incremental cost of excavation of the foundation should be considered in addition to the efficiency. Maximum efficiency may not be desirable; the weighted efficiency over the anticipated operating range of output is usually a more important criterion.

For an impulse wheel, the specific speed may be found for a single-jet turbine. If a greater output is required, a multi-jet turbine may be used. For a multi-jet turbine

$$n_{sn} = n_s \times \sqrt{(\text{Number of jets})} \qquad (8.3)$$

Type of turbine	Specific speed n_s (Metric) rev/min.
Pelton wheel with 1 nozzle	12 to 32
Pelton wheel with 2 nozzles	17 to 50
Pelton wheel with 4 nozzles	24 to 70
Francis (low speed)	80 to 120
Francis (normal)	120 to 220
Francis (high speed)	220 to 350
Francis (express)	350 to 420
Propeller and Kaplan	310 to 1,000

The specific speeds of different types of turbine are different. For high-head plants, where impulse and Pelton wheels would be used, the specific speed is low. For reaction turbines, the specific speed is higher, depending on the head, and is higher in the order: Francis, fixed-blade and Kaplan. The first step in the selection of a turbine for a particular plant is to choose a specific speed

depending on the head available at the plant and the power to be developed. The ranges of specific speeds for the various types of turbine to be considered are given on page 302.

With regard to strength and cavitation considerations, certain specific speeds are suitable for certain heads. In a first rough estimate the following empirical formulae are used (Justin and Creager).

Francis turbines

$$n_s \text{ (metric)} = \frac{6850}{h+9.8} + 84 \text{ revolutions per minute} \qquad (8.4)$$

where h is the head in m.

Fixed-blade propeller turbines

$$n_s \text{ (metric)} = \frac{9500}{h+9.8} + 84 \text{ revolutions per minute} \qquad (8.5)$$

where h is the head in m.

adjustable-blade or Kaplan, turbine

Add 10% to the specific speed of the corresponding fixed-blade turbine.

Impulse turbine

$$n_s \text{ (metric)} = \frac{422h^{3/4}}{p^{1/2}} \text{ revolutions per minute} \qquad (8.6)$$

Again h is in m; P is the metric horsepower.

The speed of a turbine has to match the generator speed, which, to give the correct frequency, is fixed by the number of pairs of poles. To that extent, the specific speed as estimated may have to be modified.

Example 8.2

Choose a suitable turbine for the following conditions: head, 200 m; available discharge, $2 m^3/sec$; efficiency of turbine, 88%. The turbine is to be used for hydro-electric power generation with the generator coupled to it, and the frequency is to be 50 c/s.

$$\text{Output} = \frac{Qwh\eta}{75} = \frac{2 \times 1{,}000 \times 200 \times 0.88}{75}$$

$$= 4{,}700 \text{ metric } hp$$

For a head of 200 m, the turbine will be of the Francis type. The first approximation to the specific speed is given by eqn. (8.4)—

$$n_s = \frac{6850}{h+9.8} + 84$$

$$= 117 \text{ rev/min}$$

Eqn. (8.2) gives the relation between specific speed and actual speed—

$$n = \frac{n_s h^{5/4}}{p^{1/2}} = \frac{117 \times 200^{5/4}}{4,700^{1/2}} = 1,280 \text{ rev/min}$$

At 50 c/s, the synchronous speeds of 4-pole and 6-pole generators are 1,500 and 1,000 rev/min respectively. A 4-pole machine would increase the specific speed too much. We therefore choose a 6-pole machine, and modify the specific speed accordingly—

$$n_s = \frac{1,000}{1,280} \times 117 = 92 \text{ rev/min.}$$

In the case under study, therefore, we choose a Francis turbine giving a full-load output of 4,700 metric *hp* at a specific speed of 92 rev/min and driving a 50-c/s generator at 1,000 rev/min.

Turbine setting. Reaction turbines have to be set correctly with reference to the tail-race water level so as to avoid cavitation in the draft-tube portion. Thus a Francis turbine runner should be placed at a level very near or below the lowest tail-race level. Francis turbines adjust themselves better to varying water levels in the storage reservoir, and, therefore, use the storage to better advantage and with improved mean efficiency.

Fixed-blade propeller turbines have higher specific speeds than Francis turbines and are, therefore, set at a lower level. Adjustable blade turbines have still higher specific speeds, and so, for the same head, the adjustable-blade runner would be set considerably lower than the fixed-blade runner.

A Pelton wheel is always set at a higher level than the highest tail-race level. This results in loss of head compared to the Francis turbine, which makes use of the total available head on account of the draft tube. A Pelton wheel is set at least 2 m above the highest tail-race water level. If the Francis and Pelton wheel types

are compared for the same head (common range if specific speed and head permit), the speed of the Francis turbine will always be higher than that of the Pelton wheel, with corresponding reduction in the cost of generators and dimensions of units, the size of the machine hall and power house equipment.

Speed and pressure regulation. When the load on the generator coupled to the turbine changes suddenly, the governor comes into action to regulate the inflow of water into the turbine, but this takes some time and depends on the speed at which the governor acts. With a sudden closing of the gates there is a pressure rise in the penstock. Part of it is sometimes counterbalanced by a suitable choice of surge tank installed at the end of the penstock line near the power station. Pressure-release openings or valves are sometimes provided on the pipelines at suitable places. It is necessary to study the problem of speed regulation and pressure rise with a given length of penstock. The ability to predetermine the speed changes in a turbine in terms of maximum change in speed or variation in speed with respect to time permits of the complete study of regulation problems in advance of the actual construction of a hydro-electric project.

The normal maximum pressure rise permissible with Francis turbines is of the order of 30%; with Pelton wheels it is between 10% and 20%. The governor time is generally 2 to 3 seconds, but in modern machines with automatic operation this has now been reduced considerably. With the pressure regulator, the permissible range of pressure rise changes and is improved. The following are approximate permissible pressure rises in different cases—

	per cent
Pelton wheel	12 to 16
Small Francis turbine with short penstock	20 to 25
Small Francis turbine with long penstock and pressure regulator	20 to 25
Francis turbine without pressure regulator	30

8.3.3 CHOICE OF TURBINE

In choosing the types of turbine for particular situations, the points mentioned in Section 8.3.2 are considered. In addition,

turbines are selected to operate at a load factor of not less than 50% of the rated capacity for multi-purpose projects, and not less than 60% for run off-river developments.

8.3.4 RUNAWAY SPEED

When a turbine is connected to a generator and the generator is fully loaded, the speed of the turbine will initially fall, and owing to governor action the gates will open wider to admit more water to suit the load condition and to bring the speed up to normal. In the event of the load suddenly being thrown off and the governor action failing to close the gates suddenly to keep the speed of the turbine constant, there is a tendency for the turbine to race. The maximum possible speed at which a turbine will run under the worst conditions of operation, with all gates open to allow all possible water inflow under maximum head, is known as the runaway speed.

In selecting the ratings and capacities of hydro-electric units, consideration must be given to the relation between the characteristics of the generator and those of the turbine. The generator must be designed to withstand the full runaway speed of the turbine under the maximum permissible head. A reaction turbine of the Francis type has a runaway speed of about 180% of its normal speed. If the maximum head is 15% above normal, this runaway speed is about 195% of normal. With a fixed-blade propeller turbine the maximum runaway speed for the generators would be about 2 to 2½ times the normal speed.

8.4 Design of the Main Dimensions of Turbines

With reaction turbines, both Francis and propeller types, the determination of the main dimensions of the turbines involves finding the nominal diameter, the outlet diameter or draft-tube inlet diameter, and the width of the distributor pertaining to the main runner. This has to be accompanied by a determination of the preliminary dimensions of the draft tube and scroll case, and the setting of the turbine runner with reference to the tail-race water level.

With Pelton wheels, it is necessary to determine the pitch diameter of the runner, the jet diameter and the number of buckets.

Once the main dimensions have been determined, it is possible to estimate the distance between the units and thus to plan the layout of the power station.

8.4.1 MAIN DIMENSIONS OF REACTION TURBINES

Once the desired capacity of the generator units has been determined from the load curve and the load conditions, the choice of the hydraulic equipment is made. The turbines may be chosen to produce a generator output at best efficiency, or to give maximum output under average head conditions during the low-flow periods. To obtain the best possible efficiency during the low-flow periods without considering other factors, it is desirable that the generator capacity be approximately equal to the output of the turbine at best efficiency under normal or average head conditions.

The rated head of a turbine unit is that at which the unit would produce the best efficiency under normal or average head during dry periods. Hydraulic turbines are customarily rated at maximum output and not necessarily at the point of the best efficiency. The maximum possible discharge will occur at the head for which the generator capacity is equal to the maximum turbine output. This is known as the critical head and determines the setting of the turbine. It is necessary to find the maximum output at various heads, and to study the relation between maximum out put and head.

With a known generator capacity per unit, if the turbine is required to produce a generator output at the point of best efficiency under normal or average head during the dry period, and if the ratio of the output of the turbine at best efficiency to its maximum output is known, it is possible to find the maximum output of the turbine under normal or average head, i.e., its rated output.

The main dimensions of reaction turbines are the nominal diameter, D_1, the diameter, D_2, of the runner at discharge or at the draft-tube inlet, and the width of the distributor. These dimensions depend on the type and size of the turbines as well as its specific speed.

The diameter at discharge, D_2, depends on the amount of water, Q, discharged through the turbine, and on the velocity of the water

at the outlet of the runner or the inlet of the draft tube. For Francis turbines, the ratio of nominal diameter, D_1 and outlet diameter, D_2 is dependent on the specific speed, n_s. For small values of n_s, $D_1 > D_2$; for large values of n_s, $D_1 < D_2$. For propeller turbines $D_1 = D_2$. The unit spacing of the turbines is governed by D_2.

The dimensions mentioned above could be approximately determined by studies on small wheels, a model ratio then being used to determine the dimensions of full size turbines. Table 8.1 (taken from the notes of Professor Doland of the University of Illinois, U. S. A.) gives the dimensions of a 1-metric *hp* wheel operating under a head of 1 m.

For the Francis turbine the diameter D_1 is found approximately by using the expressions--(8.7)

Table 8.1

Dimensions of 1-hp (metric) wheel operating under 1 m head for reaction turbines only

Turbine	Specific speed in metric units, n_s	Nominal diameter, D_1	Draft tube inlet diameter, D_2	Width of distributor
		cm	cm	cm
Francis	90	145	116	14.8
	110	121	104	16.5
	135	102	94	17.8
	180	78.5	83.5	19.5
	220	66.5	78	20.3
	270	56.5	72.5	22.0
	315	50	70	22.4
	360	44	66	22.2
	400	40.1	63.3	21.6
	445	36.8	62	27.9
Propeller type	445	60	60	32.8
	535	57	57	32.3
	670	53	53	31.2
	800	49.3	49.3	30.5

The dimensions of full-size turbines are found by multiplying the dimensions given in Table 8.1 by the model ratio, m.

$$D_1 = \frac{6.550}{n_s 0.85} \text{ centimetres} \tag{8.7}$$

n_s revolutions per minute being the specific speed in the metric system.

The model ratio, m, is given by

$$m = \frac{P^{1/2}}{2.46 + h^{3/4}} \tag{8.8}$$

P being the metric horsepower, and h the head in metres.

Example 8.3

Find the main dimensions of a turbine giving an output, P, of 10,000 metric *hp* working under a head, h, of 50 m.

Choosing a generator speed of 300 rev/min, which, for 50 c/s, gives a 20-pole machine, the specific speed will be

$$n_s = \frac{nP^{1/2}}{h^{5/4}} = \frac{300 \times 100}{134} = 224 \text{ rev/min}$$

From Table 8.1, for a small Francis turbine of specific speed 224 rev/min,

$D_1 = 65.7$ cm; $D_2 = 77.6$ cm; width of distributor = 20.4 cm. The model ratio will be

$$m = \frac{P^{1/2}}{2.46\, h^{3/4}} = \frac{100}{2.46 \times 18.8} = 2.16$$

Thus a Francis turbine of 10,000 metric *hp*, working under a 50 *m* head, will have the following dimensions –

$D_1 = 65.7 \times 2.16 = 142$ cm

$D_2 = 77.6 \times 2.16 = 167.6$ cm

Width of distributor $= 20.4 \times 2.16 = 44$ cm.

8.4.2 MAIN DIMENSIONS OF IMPULSE-WHEEL TURBINES

The diameter, D, of an impulse wheel is taken as the diameter of the pitch circle, i. e. a circle passing through the centres of the buckets of the wheel and to which the centre-line of the jet is tangential. The peripheral speed of the buckets is usually 45% to 50% of the spouting velocity under the acting head, depending on the number of jets and the size of the turbine.

From these considerations, it can be shown that the speed of an impulse wheel is related to D and h as follows –

$$n=3{,}880\frac{h^{1/2}}{D} \text{ revolutions per minute} \qquad (8.9)$$

h being in metres, and D in centimetres.

The full-load horsepower of an impulse wheel with a single power jet and having a full-load efficiency of 85% is given by

$$P=\frac{0.85}{75}\times\begin{pmatrix}\text{Area}\\ \text{of jet}\end{pmatrix}\times\begin{pmatrix}\text{Density}\\ \text{of water}\end{pmatrix}\times\begin{pmatrix}\text{Velocity}\\ \text{of water}\end{pmatrix}\times\text{Head} \qquad (8.10)$$

The diameter of the jet, d, in terms of horsepower, P, and head, h, is then,

$$d=16.35\frac{P^{1/2}}{h^{3/4}} \text{ centimetres} \qquad (8.11)$$

P being the metric horsepower, and h being in metres.

From the above equations for speed and power, it is possible to find the relation between the specific speed and the ratio d/D –

$$n_s=243\,\frac{d}{D} \text{ revolutions per minute.} \qquad (8.12)$$

d and D being in the same unit (usually the centimetres).

For an impulse wheel with more than one jet,

$$n_{sn}=n_s\sqrt{(\text{Number of jets})} \qquad (8.13)$$

Example 8.4

Choose a turbine suitable for a hydro-electric station in the following case : head, 400 m; flow available, 4 m³/sec; efficiency of turbine, 85%; generator frequency, 50 c/s. Find the main dimensions of the turbine.

$$\text{Output}=\frac{Qwh\eta}{75}=\frac{4\times1{,}000\times400\times0.85}{75}$$

$$=18{,}100 \text{ metric } hp$$

For a head of 400 m, the turbine will be a Pelton wheel (impulse wheel) with one jet. Choosing an approximate specific speed of about 24 (metric units), we find the corresponding actual speed –

$$n=\frac{n_s h^{5/4}}{P^{1/2}}=\frac{24\times400^{5/4}}{18{,}100^{1/2}}=320 \text{ rev/min}$$

At 50 c/s, the nearest synchronous speed is 300 rev/min, i.e., a 20-pole generator is required. The corrected specific speed, then, is

$$n_s = \frac{300}{320} \times 24 = 22.5 \text{ rev/min}$$

The turbine chosen for the purpose is, therefore, a Pelton wheel having a capacity of 18,100 metric *hp*, a specific speed of 22.5 rev/min, and an actual speed of 300 rev/min, driving a generator coupled to it to produce power at a frequency of 50 c/s.

The diameter, d, of the jet is

$$d = 16.35 \frac{P^{1/2}}{h^{3/4}} = \frac{16.35 \times 18{,}100^{1/2}}{400^{3/4}} = 24.7 \text{ cm.}$$

From eqn. (8.12) the pitch diameter, D, of the runner is

$$D = 243 \frac{d}{n_s} = \frac{243 \times 24.7}{22.5} = 266 \text{ cm}$$

The speed, n the best speed – can also be checked by the relation

$$n = 3{,}880 \frac{h^{1/2}}{D} = \frac{3{,}880 \times 400^{1/2}}{266} = 292 \text{ rev/min}$$

The choice of 300 rev/min, therefore, is satisfactory.

The main dimensions of the turbine, then, are the jet diameter, $d = 24.7$ cm, and the pitch diameter of the runner, $D = 266$ cm.

In an impulse wheel generally, n_s (D/d) is a constant, lying between 220 and 270 (metric units), where D is the pitch diameter of the runner, and d is the diameter of the jet.

With medium and low specific speeds, the buckets can be cast separately, and attached by bolts and lugs to the wheel hub. With specific speeds higher than normal, the buckets must be large and closely spaced and, therefore, should be cast integrally with the hub.

For a Pelton wheel of best efficiency, empirically,

$$\text{Number of buckets} = 0.5 \frac{D_1}{d_1} + 15 \qquad (8.13)$$

where D_1 is the mean diameter of the bucket wheel. and d_1 the least diameter of the jet. For the best efficiency this ratio, D_1/d_1, is 10; normally it varies between 10 and 18.

8.5 Draft Tubes : Types, Setting and Preliminary Dimensions

The draft tube is an extension of the reaction wheel passages from the point of exit from the wheel runner down to tail-race

water level. The primary purpose of a draft tube is to reduce the velocity-head losses of water and to use the head on the reaction turbine to the maximum extent. Another important purpose is to permit the setting of the runner of the reaction-turbine wheel at a level above that of the water in the tail-race under high-water and flood conditions of the river.

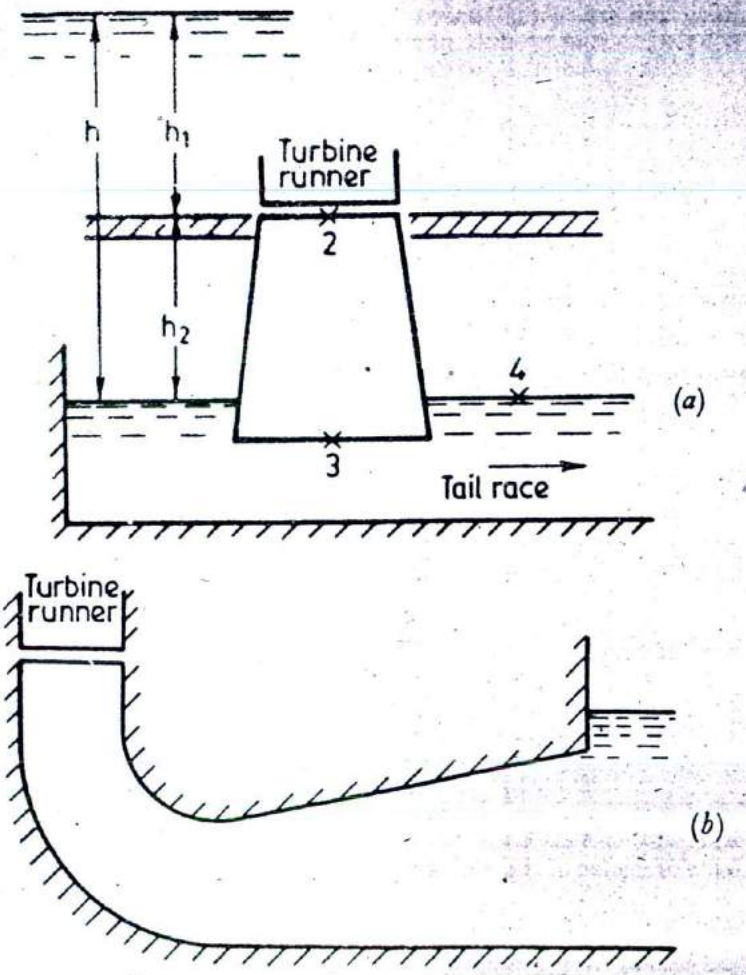


Fig. 8.12. Types of draft tube. (*a*) Vertical (*b*) Quarter-turn

The types of draft tube normally used are shown in Fig. 8.12.

Generally, draft tubes are either straight vertical tubes or quarter-turn tubes. The lower portion of a straight vertical tube is sometimes curved. In a quarter-turn tube, the section at the entrance is circular and the section at the exit is rectangular. The height of a draft tube is decided so as to avoid cavitation. Cavitation occurs in flowing water when a cavity, or void, filled with air and water vapour is formed; this is harmful and causes pitting of the turbine runners.

Applying Bernoulli's theorem to points 2 and 4 in Fig. 8.12 (*a*) we can equate the heads on both sides, namely the static head, pressure head, and velocity head; the head lost in friction is also accounted for –

$$\frac{v_2^2}{2g} + \frac{p_2}{w} + h_2 = \frac{v_4^2}{2g} + 0 + 0 + h_f + \frac{kv_3^2}{2g} \qquad (8.14)$$

where v_2 and v_4 are the velocities at points 2 and 4, h_2 is the height of the draft tube above the water level, and h_f is the friction head.

Neglecting the velocity head at point 4 and taking $k=1$,

$$h_2 = -\frac{p_2}{w} - \frac{v_2^2}{2g} + h_f + \frac{v_3^2}{2g} \qquad (8.15)$$

The theoretical limit for the pressure head, p_2/w, is 7.62 m. As the head increases, the wheel has to be lowered with reference to the tail-water level.

The dimensions of the draft tube at various sections depend on the permissible velocities at the sections, and should be such that the pressure head is used as much as possible and the loss of head in the form of velocity head at the exit is as low as possible, keeping in view the necessity to guard against cavitation.

The velocities normally permissible at the inlet and outlet of the draft tube are as follows –

Velocities	For higher specific speeds	For lower specific speeds
Inlet	$v_2 = 13 \times 10^{-2}\sqrt{2gh}$	$3.25 \times 10^{-2}\sqrt{2gh}$
Outlet	$v_3 = 3.25 \times 10^{-2}\sqrt{2gh}$	$0.65 \times 10^{-2}\sqrt{2gh}$

The velocities are expressed in centimetres per second with h in centimetres and $g=981$ cm/sec^2.

The proper setting of the turbine above the tail-race water level is important, since too great a height would result in cavitation of the runner blades and loss of efficiency, while too low a setting would involve unnecessary costs of excavations and substructures.

The desirable height is decided by considering the cavitation coefficient, σ :

$$\sigma=\frac{h_b-h_s-h_v}{h} \tag{8.16}$$

where h_b = Barometric pressure head at elevation of runner above mean sea-level.

h_v = Vapour pressure head at discharge side of runner blades at point of minimum pressure.

h_s = Distance from tail water to under-side of runner blades

h = Total head

if h_v is neglected,

$$\sigma=\frac{h_b-h_s}{h} \tag{8.16 a}$$

The recommended values of the cavitation coefficient, commonly known as the "plant sigma", are shown in Fig. 8.13 (from reference 8.2 at end of chapter) for different specific speeds of reaction turbines of the Francis and propeller types. For the plant sigma of a Kaplan turbine, add 10% to the value given for the propeller type.

Example 8.5

Find the setting of a Francis turbine above the tail-race water level from the following data: barometric pressure at the site, 9.75 m; metric horse-power to be developed, 5,000 at a head of 100 m. The set is to be used to drive a generator having a frequency of 50 c/s.

Since the only thing we know about the generator is its frequency, we select tentatively a 6-pole machine with a synchronous speed of 1,000 rev/min.

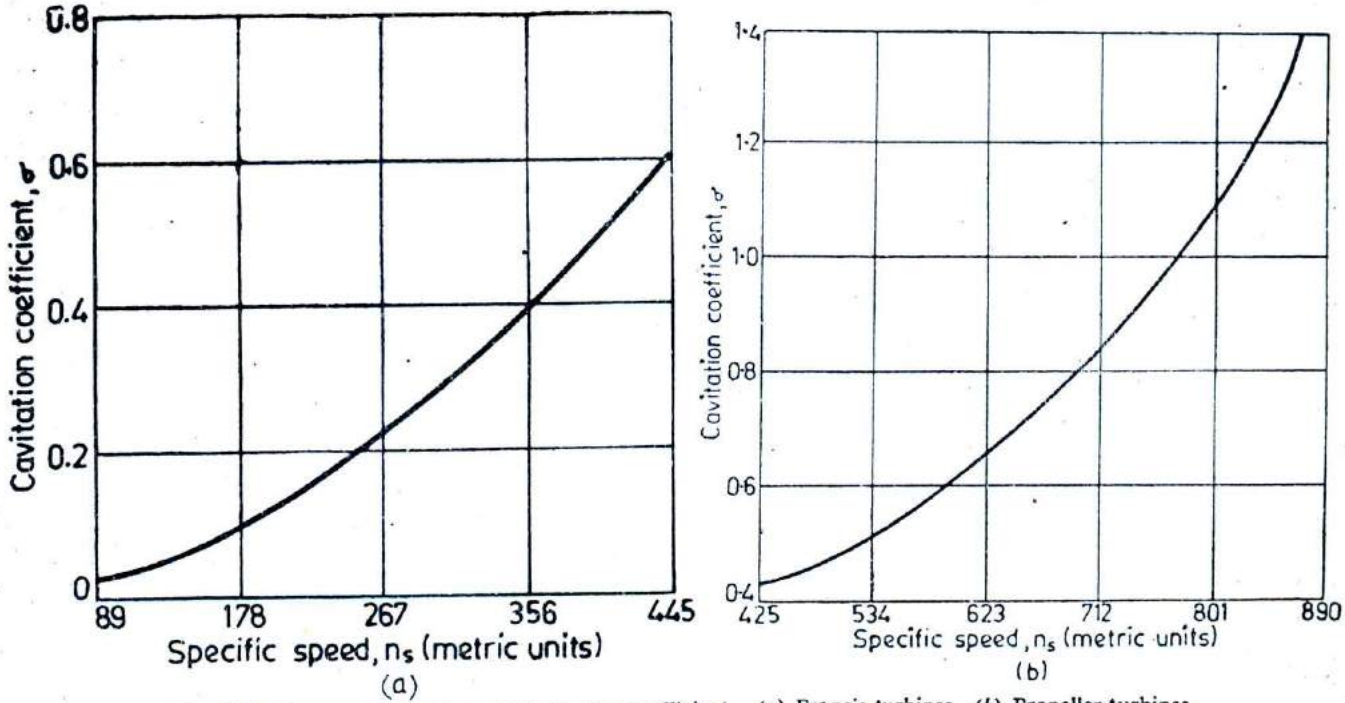


Fig. 8.13. Recommended values of Cavitation coefficient. (*a*) Francis turbines (*b*) Propeller turbines.

The specific speed is

$$n_s = 1{,}000 \times \frac{5{,}000^{1/2}}{100^{5/4}} = \frac{1{,}000 \times 71}{320} = 222 \text{ rev/min}$$

From Fig. 8.13 (*a*), the plant sigma is 0.15

$$\sigma = \frac{h_b - h_s}{h}$$

so that

$$-h_s = \sigma h - h_b = (0.15 \times 100) - 9.75 = 5.25 \text{ m}$$

Thus the turbine would have to be set 5.25 m below the tail-water level, which is not desirable. Moreover, if the vapour pressure is taken into account and $h_b = 7.62$ m, the setting becomes still lower for a speed of 1,000 rev/min.

If the speed chosen is 500 rev/min with a 12-poles generator, then for the same head and horsepower,

$$n_s = 111 \text{ rev/min}$$

$$\sigma = 0.04; \text{ and}$$

$h_s = 7.62 - (0.04 \times 100) = 3.62$ m above tail-water level. This is reasonable. The speed of the turbine and the generator in this case should be chosen as 500 rev/min, and not 1,000 rev/min.

8.6 Scroll Case

The scroll case for the turbine is generally made of plate steel. The purpose of the scroll case is to convert the pressure head gradually into higher velocities before water enters the turbine runner. This is necessary in reaction turbines as the energy has to be converted from the available pressure head without any opening to the atmosphere as is done in an impulse turbine, where jets are used to convert pressure head into velocity. The areas at the various points are suitably decided and shaped to accommodate the required quantity of water flowing through the machine. The dimensions are related to a certain extent to the inlet diameter of the draft tube or the outlet diameter of the turbine runner.

8.7 Preliminary Design of Penstock

Penstocks are conduits for the conveyance of water from reservoirs to hydraulic turbines. They should be hydraulically efficient to conserve the available head and structurally safe to

prevent operational failure. Penstocks may be divided into two types, low-pressure and high-pressure. The low-pressure penstock may be a canal, a flume or a pipe. It follows the hydraulic gradient or is placed slightly below it. With high-pressure penstocks, which consist of steel pipes, the flow to the turbine continues well below the hydraulic gradient. Penstocks may be placed above the ground on cradles, buried or half-buried, or on cradles within a tunnel. Occasionally, a pressure tunnel is used for a considerable length of the penstock.

Penstocks may be of concrete for low-head and of steel for high-head construction. Strength and flexibility make steel best suited to the range of pressure fluctuation in turbine operation. If the distance between the forebay and the power house is short, or if the head is high, a separate penstock for each turbine is preferable. For moderate heads and long lines, a single penstock may serve several turbines through a system of multiple bifurcations at the lower end. The header system is usually more economical in construction, but individual penstocks permit greater flexibility in operation and maintenance as well as simplifying turbine regulation. The individual penstock arrangement instead of a header system also avoids loss of head at the junction.

The size of a penstock and its main dimensions can be estimated from the following considerations.

The velocities allowed in a penstock are from 2 to 6 m/sec. depending on the head. Knowing the flow, Q, required through the penstock, and choosing the velocity, the area and hence the diameter of the penstock can be determined.

The thickness of a steel penstock depends on the head and the hoop stress allowed in the material. It is given approximately by

$$t = \frac{0.1hd}{2f\eta_j} \tag{8.17}$$

where t = Thickness of penstock, cm
h = Head, m
d = Diameter of penstock, cm
η_j = Joint efficiency
f = Permissible stress, kg/cm^2

The permissible stress, f, is taken as 950 kg/cm² if the static head alone is considered. If water hammer also is taken into account, f is taken as 1,125 kg/cm². The joint efficiency for riveted construction is about 80%; for welded structure, up to 90%.

In selecting the actual thickness of the penstock, t, 0.15 cm is added to the calculated thickness to allow for corrosion; the minimum thickness used is 1.25 cm. The thickness of penstock can vary in sections depending on the head at the point under consideration, particularly with long penstocks.

Other considerations in the design of penstocks are economic considerations including the loss due to friction, and the regulation of pressure rise on rejection of load. The economic diameter of a penstock is that for which its annual cost plus the value of power lost in friction is a minimum. The annual cost includes interest, depreciation, taxes and maintenance. For preliminary considerations with a relief valve on the penstock, the loss due to pipe friction may be taken as 5% of the gross head. For base-load operation this figure is generally 3½%, and for peak-load operation about 7%.

If the ratio of length of penstock to working head is not greater than 3 or 4, the closing time of the governor and the flywheel effect of the rotor can usually be so adjusted that satisfactory governing is obtained, although the speed and pressure rise with heavy load rejection may be considerable. If the ratio of the length of penstock to the working head is greater than 4, special precautions must be taken to assist good governing. Select sizes of conduit, penstock and surge tank, and adjust turbine capacity, speed, and weight moment of inertia of the generator, Wk^2. The penstock size, governor capacity and system load changes should be co-ordinated to produce variations in the velocity of water in the penstock according to the permissible rates of acceleration.

8.8 Characteristics of Generators

The specification of the generator for a hydro-station includes mainly the following information: continuous rated output in kilowatts, kilovolt-ampere capacity, number of phases (always 3), frequency, connexion of stator winding (nearly always star), volt-

age, current, power factor, speed, method of cooling, temperture rise, type of excitation, excitation voltage, short-circuit ratio, reactances of the machine. etc. The last two are the concern more of the designer than the user, and are seldom mentioned on the nameplate.

Hydro-electric generators are low-speed machines, of the salient-pole type, having a large number of poles, a large diameter and a short rotor. Thus they are quite different from turbo-alternators, which are high-speed machines so that they are generally 2-pole and have a small diameter and a very long rotor.

The capacities in which hydro-electric generators are available vary from 500 kW to 200 MW. For Example, 500 kW and 3, 5, 10, 15, 25, 37.5, 50, 75, 100, 125, 150 and 200 MW. Intermediate sizes are available. The power factor for which the generators are designed is 0.9, or nowadays as high as 0.95, lagging. This depends on the size of the generating sets as well as their relative position in a power system. When large units are used in a large power system with good power factor control, the tendency is to design generators for high power factors. This reduces the exciter capacity required.

The speed of a hydro-electric generator depends on the speed of the turbine driving it, which in its turn depends on the specific speed of the particular type of turbine. Thus there is a limitation in the choice of speed in addition to the frequency requirement.

Air-cooling is used in hydro-electric generators as these are low-speed machines. The air is diverted through the machine by different methods-radial, axial and circumferential. Air is taken in at one or both ends, forced through ducts between windings and sections of core and discharged again at the periphery. An intake may be taken from points over the tail-race at a safe distance above extreme high-water level. The amount of air required is about 3 m^3 per minute per kilowatt of loss in the generator, and the velocity of the air should not exceed 475 m/min. The larger generators are completely enclosed and the air recirculates in the housing, being cooled by means of water-cooled heat exchangers. The temperature rise is specified depending on the type of insulation used for the stator winding and the type of cooling; normally it is 50°C.

The efficiency of the generators on full load is about 95% for small machines and up to 97.5% for large ones. In India, the standard voltages used for generation are 3.3, 5 and 11 KV at 50 c/s.

The transient reactance of standard water-wheel generators varies from 15% for high-speed to 30% for low-speed designs. The short-circuit ratio is the ratio of the excitation required to develop the rated voltage of the generator on no-load to the excitation required for a short-circuit current equal to the full-load current. For hydro-generators this ratio is between 1 and 1.2. This information is useful in the study of the stability of the synchronous machines and the power system.

With hydro-generators, the flywheel effect in the form of Wk^2, or the weight moment of inertia, is an important consideration. This is the weight multiplied by the square of the radius of gyration. Most of the inertia is provided in the rotor of the generator. For a single generator or for a small system, Wk^2 should be sufficient to ensure satisfactory speed regulation under sudden load change. With a long penstock, the gates are operated relatively slowly to avoid water hammer, and this needs a larger flywheel effect to maintain satisfactory speed regulation.

For generators operating in parallel with others in a system, Wk^2 should be sufficient to avoid hunting and ensure stability under conditions of sudden load changes and fault conditions.

8.8.1 EXCITERS FOR HYDRO-GENERATORS

The exciter must develop and maintain the rated voltage of the generator at various loads at power factors decided by the load conditions. The amount of excitation depends upon speed, load and power factor, being much greater with low speed, lagging power factor and a heavy load. The exciter supplies the field winding of the generator. The type of machine used for the purpose is a d. c. generator, shunt or compound. A compound generator needs less adjustment to maintain a constant voltage. For small a. c. generators the capacity of the exciter is about 3% of that of the main generator; for very large hydro-generators the capacity of the exciter is about 0.5% of the generator capacity. If the exciter

is of large capacity, a pilot exciter is used to excite the main exciter. Pilot exciters have capacities of 1.5% to 5% of those of the main exciters. The exciter voltage is generally 125 V or 250 V.

The principal requirements of an excitation system are reliability, low first cost, economy of operation, simplicity and convenience. There are two types of excitation system, the centralised and the individual. The centralized excitation system consists of a few exciters connected to busbars and supplying all the generators in the station. They are driven by either induction motors or synchronous motors. At least one of the exciters should be driven by a prime mover so that it would be possible to start the station in case of complete supply failure. The minimum number of exciters required in the centralized system is two, but a third one should be kept driven by a prime mover as mentioned above. The advantages of centralized excitation are that the number of exciters required in the station is a minimum. A battery may be floated on the busbars to supply excitation in case of emergency. The disadvantage of centralized excitation is the possibility of a fault in one part of the system affecting the operation of the entire system.

Modern practice is to have individual exciters, one for each generator, directly coupled to the generator and the prime mover. An advantage of this method is that it is independent of faults in the other exciters. Another advantage is that the exciter connexions are shorter than in the centralized system. The disadvantage is that a number of small d. c. generators equal to the number of main generators is required, instead of only two or three larger ones as in the centralised system. Another objection to the individual system is that the generator voltage is sensitive to speed fluctuations, but this is reduced by using a pilot exciter.

In very large generator units, when individual excitation is used, there is sometimes a special generator coupled to the same shaft as the main generator. This is a 3-phase machine with a permanent magnet field, used to drive the essential auxiliaries, such as oil pumps, which start the main unit in case of complete supply failure, when no electric power is available for these drives, which are essential for starting the main units.

8.9 Power Station Control

The turbines driving the generators in hydro-stations have governors which act quickly in response to the load conditions as required. With reaction turbines, governing is effected by adjusting the wicket-gate openings through the speed rings; with impulse wheels, by opening the jet nozzles. The governor action is through a servo-mechanism operated by oil pressure. The electric motor controls the opening of the pilot valve in the servosystem.

When many generator units are operating in parallel, the load is shared between different units in proportion to the speed-droop characteristics. With hydraulic turbines the speed droops are from 0 to 6% of rated speed. The speed is adjusted to maintain a constant frequency and to share the load on the generator units as required. Load-frequency control equipment, which automatically compares the frequency and time with a highly accurate pendulum or turning fork and adjusts the frequency as needed, is usually installed in the power stations of a large system. The accurate control of frequency is required, as mains-operated electric clocks and synchronous machines have to work accurately.

The reactive load (kilovolt-amperes) taken by each generator is adjusted by the excitation, keeping the voltage at the busbars constant. Voltage regulators maintain the voltage of the unit at the desired value. The voltage regulators can be of the vibrating type. There are a number of contacts on the regulator shunted section of the exciter field rheostat so that when closed they raise the voltage to the maximum and when opened they lower the voltage to the minimum.

In modern hydro-electric stations, non-vibrating regulators are used. These may be rheostatic or face-plate-type regulators. The regulating rheostat arm is moved by a motor to a position demanded by the generator depending on the active and reactive loads which the generator has to handle.

The requirements of a good voltage regulator are sensitivity and speed of response. Normal contacts respond to 0.5% of the voltage change. The time of response is not more than 5 cycles.

To protect against the enormous rise of voltage of the generator in case of runaway speed conditions of the turbine, it is neces-

sary to prevent this rise immediately. This is done by means of a voltage regulator which inserts resistance in the pilot-exciter field circuit. This reduces the excitation voltage of the pilot exciter, and, therefore, the voltage of the main exciter and of the main generator.

It has been a standard practice to provide dual control facilities for control of generators in large hydro-electric stations. Local control near the generator units and central control for the station. Under instruction from the central control room operator, the local control operator would start a unit, adjust the speed and voltage and then transfer the unit to the central control room operator for synchronizing and loading. When stopping the unit, the central control room operator would unload it, open the generator breaker, and then transfer the control to the generator floor operator for stopping the unit and auxiliaries.

The recent practice is centralised control. In this method, unit starting is initiated by operation of a start switch in the central control room. This operation energizes master relays to start the unit auxiliaries, release the generator brakes, and open the turbine gates to bring the unit to synchronous speed and rated no load voltage. The operator then can energize the automatic synchronizing equipment which adjusts speed and closes the breaker at proper time.

The equipment in the central control room will have standard supervisory control of the spillway gates and digital indication of the selected gate opening. Provision is also available for digital indication of water levels. The forebay and tailwater levels are recorded on a dual pen recorder and other water levels are recorded on a multi point recorder. The other important equipment in the central control room will include automatic synchronizing equipment, supervisory control equipment, telemetering equipment and alarm or operation recording equipment.

8.10 Main Dimensions of Generators

The special features of generators driven by hydraulic turbines were discussed in the last section. The main dimensions of the generator are the diameter at the air-gap and the length of the

stator core. The output of the generator in kilovolt-amperes depends on these main dimensions and the speed of the machine. The general expression for the output of a generator as developed in Chapter 3 (eqn. 3.23) holds good for hydro-generators—

$$S = 10.4 \times 10^{-3} B a_c D^2 L n \qquad (3.23)$$

As already mentioned, the speed of the generator is determined by considering the specific speed of the turbine driving the generator, and the number of poles is selected to meet the requirement as closely as possible. Hydro-units are low-speed machines, and the specific loadings may be taken as follows-

$a_c = 300$ to 450, ampere-conductors per centimetre of stator periphery.

$B = 5.5 \times 10^{-5}$ to 6.5×10^{-5} Wb/cm^2

The length of the core may be taken as between 0.8 and 1.2 times the pole pitch.

The peripheral speed limit may be taken as between 3,500 and 5,000 m/min.

When the specific electric and magnetic loadings of the hydro-electric generator have been chosen, and the rating or KVA capacity for which it is to be designed is known, the main dimensions, D^2L, of the generator can easily be determined, n is the speed in revolutions per second. The diameter can be checked with reference to the permissible peripheral speed. The pole pitch is $\pi D/p$. The ratio of length of stator core to pole pitch having been chosen, and the product D^2L having been determined, D and L can be found separately. A number of possible alternatives may then be considered for final detailed design, with minor variations in dimensions to give the best possible performance of the generator.

8.11 Power Station Structure and Layout

The power house is divided into two sections, the substructure and the superstructure. The substructure supports the equipment and provides the necessary space for waterways. The superstructure is the part of the building above the generator floor; this houses the equipment and protects it from the weather.

The substructure consists mainly of the foundation of the building, draft tubes, scroll cases and setting of the turbines when they are of the reaction type. In low-head plants the substructure includes the penstock also. The substructure is generally a concrete block with passage and waterways moulded in it. The foundations are extended to the generator floor. In low-head plants the scroll case may be formed in concrete; in medium and high-head plants used with reaction turbines, the scroll case may be either formed in concrete or made of steel partly or fully embedded in concrete.

With an impulse-wheel turbine, the substructure is simple in arrangement and construction. The tail-race extends underneath the wheels. The penstock ends are contained in the substructure block, with galleries for the nozzles and governor mechanism. When the power house is close to the river, the tail-race may be the river itself; otherwise, a channel of some length may be necessary to connect the tail race to the river.

The shafts of the turbine and generator can be either horizontal or vertical. The horizontal arrangement is now practically obsolete for large units, but may be used to a certain extent for small units of the impulse type. For reaction turbines the horizontal arrangement is not convenient; where it is used, the substructure contains only the water passage to and from the turbines. With a vertical unit, the weight of the generator, turbine runner and shaft, and the hydraulic thrust, must be carried safely to the foundations, without vibration. The concrete above the draft tube must be sufficiently reinforced to take this load.

The superstructure is the main building above the generator floor. It houses the generator and the power house equipment including switchboards, etc. The main transformers, used for stepping up the voltage and supplying the transmission network are generally located outside the main building. The high-voltage switchyard is also of the outdoor type. In the building, there is a crane to lift the generator housing and other parts when overhauling work is undertaken. The height of the building is decided by considering the required clearance for the crane when handling the largest part of the equipment. A floor area, known as an erection

bay, is provided for use when erecting the equipment or dismantling it for overhaul. This area, which is $1\frac{1}{2}$ times that of the operation bay, is located at one end of the main floor.

The main generator units are arranged in a single row normal to the direction of the flow of water through the turbines. The spacing between the generator units is determined after finding the overall dimensions of the generators and turbines. The method of determining the main dimensions was explained in the last section. The distance between the centre-line of one unit and that of an adjacent unit depends on the outlet diameter of the turbine unit. Fig. 8.14 shows the relation between

$$X = \frac{\text{Distance between centre-lines of units}}{\text{Outlet diameter}}$$

and the specific speed of the turbine units in some of the Tennessee Valley Authority power stations in the United States with Francis Turbine units.

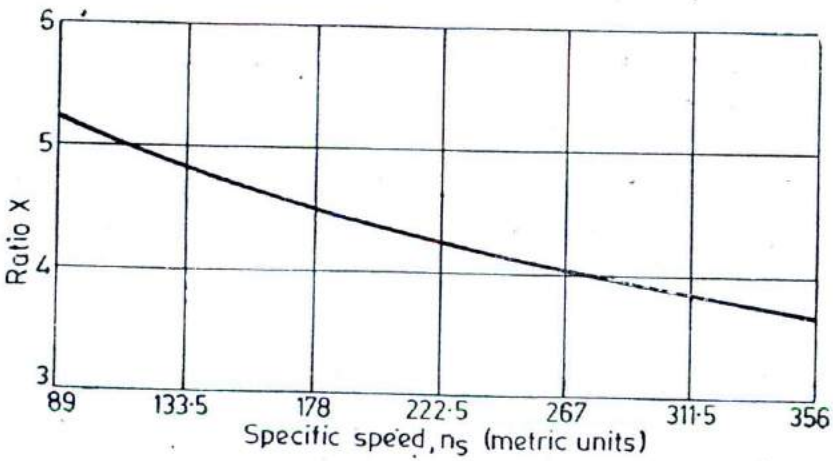


Fig. 8.14. Dependence of ratio X on specific speed.

Fig. 8.15 shows a section through a typical hydro-station using Francis turbines, and Fig. 8.16 shows a typical plan.

The electrical bay houses switchboards and switching apparatus. In large installations the power station building may

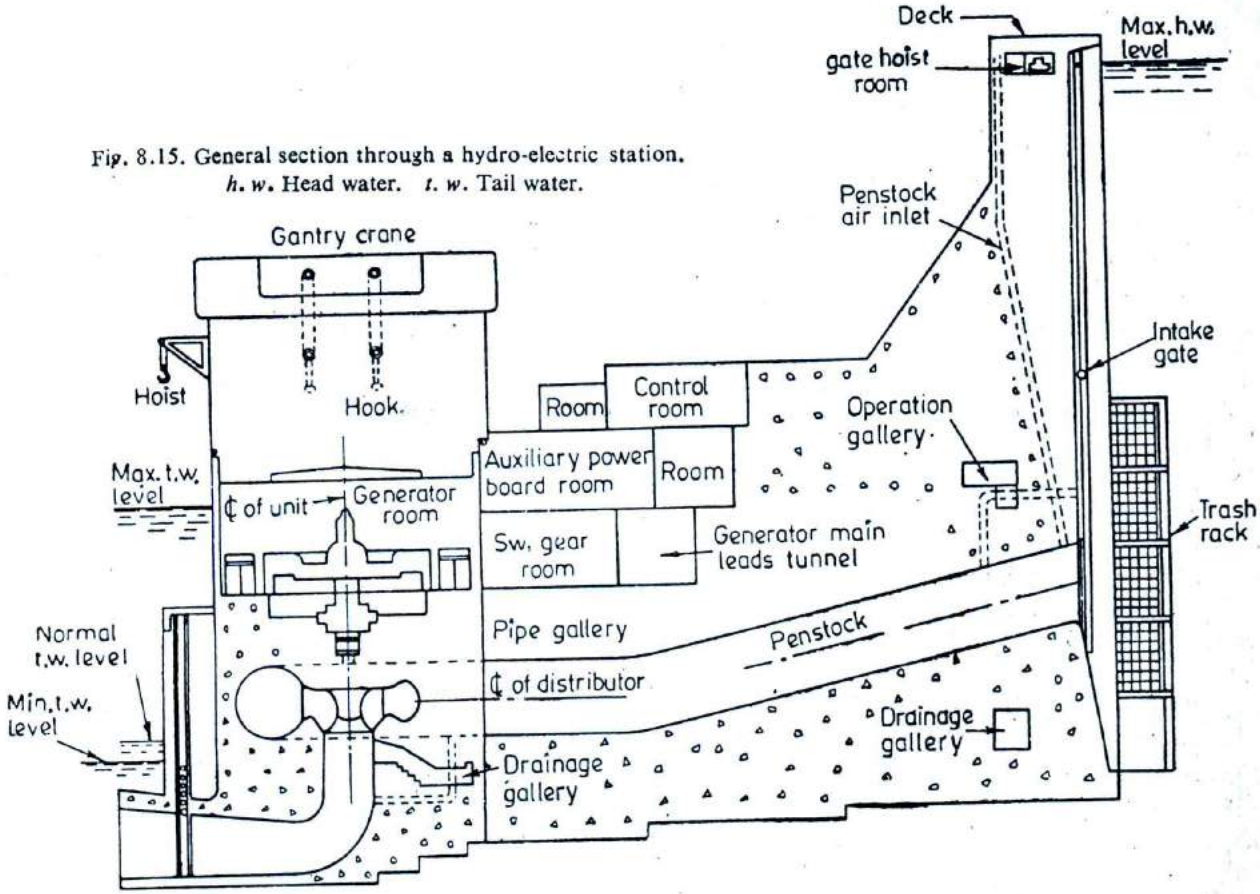


Fig. 8.15. General section through a hydro-electric station.
h. w. Head water. *t. w.* Tail water.

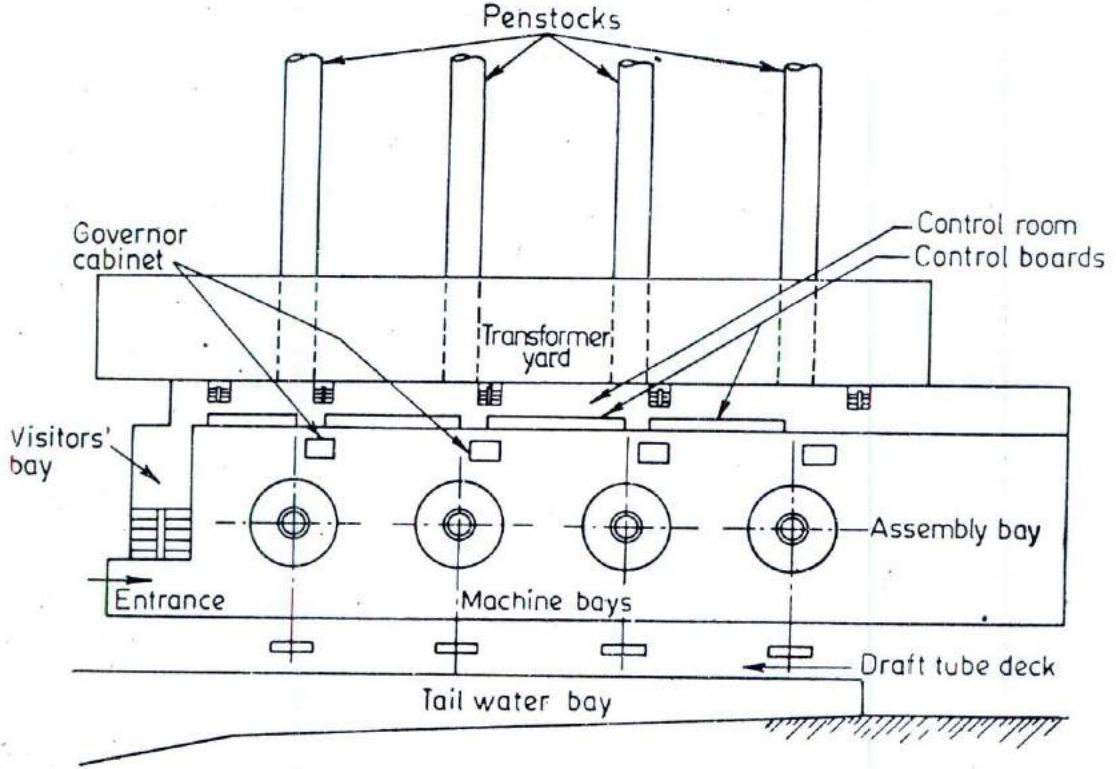


Fig. 8.16 Plan of a hydro-electric-station

be several storeys high, and should be designed for wind and equipment loadings. In some cases, the maximum water level may be well above the generator floor, so that the windows and doors must be protected and the walls and foundations designed for pressure and uplift.

An unobstructed passage about 3 m wide extends from one end to the other end of the power house. A clearance of 1.5 to 2 m is allowed between the generator units.

8.12 Costs of Hydro-electric Stations

The cost of a hydro-electric development includes cost of land and riparian rights, cost of railway and highway required for the construction work, cost of construction and engineering supervision of the project, cost of equipment and building, overhead charges as far as the low-voltage side of the step-up transformers used in the station. The various factors affecting the capital cost of hydro-electric development are riparian rights and control of the site, topography of the site, geological conditions at the dam and reservoir site, variation of flow and head at the site. The cost also varies with the capacity of the plant to be installed and the cost of labour, etc., prevailing at the time of undertaking the project.

In multi-purpose projects e.g. for power and irrigation; power, irrigation and flood con trol; or power, flood control and navigation – part of the civil engineering expenditure is charged to the other part of the project instead of all charges being for power only. The cost of a single-purpose hydro-electric power development is from Rs.1000 per kW to Rs 1,800 per kW, depending on the conditions. The main items in the total cost would be the costs for dam, waterways, power house equipment, road and railway facilities, and land and water rights to be obtained for the project The cost of intakes, penstocks, conduits and power-house equipment are to a certain extent proportional to the installation capacity of the station. The part of the cost depending on the capacity of the equipment can be considered as an incremental cost; this is about Rs 200/- to Rs. 250/- per kW.

Hydro-electric stations are located at suitable sites where water is available at sufficient head and having suitable topography

for storage by reservoir and dam. The capacity of the station is dependent on the above factors. It is possible to locate a thermal station at or near the load centre, and hence no special transmission is necessary. but the site of a hydro.station is normally remote from the load centres, and a transmission line or lines are necessary. The cost involved in transmitting power from a hydro-station to the load centre without being used on the way is known as the transmission liability of the project. This cost varies with the voltage and capacity of the transmission lines, and the degree of reliability required. In estimates the annual cost of transmission lines is taken as 12% of their capital cost. The annual cost includes fixed, operation and maintenance costs of the line. The transmission cost may be between Rs. 10 to Rs. 30 per year per kilowatt of the installed capacity depending on the distance of transmission.

The annual depreciation depends on the lives of the equipment and construction works. The average lives of some of the main electrical equipment may be taken as follows : generators, 25 years; transformers, 30 years; circuit-breakers, 15 years; lightning arresters, 10 years. The lives of dams and other civil engineering works should be very long.

The annual depreciation of a hydro-electric station is about 0.5% to 1.5% of the capital costs. The cost of money, or the interest on the capital required for the project, depends on the market position, it may vary between 5% and 8%.

The fixed charges for the station may be assumed as follows for a preliminary estimate: interest 7%; taxes and insurance, 1%; depreciation and obsolescence, 1%; i.e. total fixed charges, 9% per annum.

The operation and maintenance costs of a hydro-plant depend on the capacity of the plant and the number of units in the station, as well as the wage structure at the place where the station is located. This may be approximately Rs, 10 to Rs. 30 per kW per year for small plants of capacity upto 10 MW, and about Rs 4 per kW per year for large plants of 100 to 200-MW capacity.

The annual costs of a hydro-station depend mainly on the capacity of the station, and are practically the same for different energy outputs.

Total annual costs of hydro-electric station and development

$$= \left\{\begin{matrix}\text{Annual}\\ \text{fixed}\\ \text{charges}\end{matrix}\right\} + \left\{\begin{matrix}\text{Annual charges}\\ \text{of operation}\\ \text{and maintenance}\end{matrix}\right\} + \left\{\begin{matrix}\text{Annual cost of}\\ \text{transmission}\\ \text{liability}\end{matrix}\right\}$$

When developing a hydro-electric project for power purposes, it is necessary to study its economics compared to other possible sources of power, e.g., steam or other thermal stations to be located at or near the load centre. In addition, the type of load curve and load duration curve of the power system to which the station will supply power, the load factor and the extent to which the power station can be utilized on the load curve, as well as the amount of energy that can be obtained from the station, will decide whether a particular hydro-project will be economically feasible. In many instances, it is desirable and economical to supply power to a power system by working hydro-stations and steam or other thermal stations together. The next chapter deals with the problems of combined working of stations of different types.

Example 8.6

At a site for a hydro-electric power project, a flow 90 m^3/sec is available at a head of 100 m Sufficient storage is available. A hydro-electric power plant is to be chosen for the project.

(*a*) Find the power that could be developed, the number of units required, and the capacities of the turbines and generators. Efficiencies of turbines, 89.5%, and of generators 95%.

(*b*) Write specifications for the turbines and generator units.

(*c*) Calculate the main dimensions of the turbine units.

(*d*) Calculate the main dimensions of the generator units.

(*e*) Determine the draft tube areas at inlet and outlet.

(*f*) Determine the setting of the turbines with respect to the tail -water.

(*g*) Find the approximate dimensions of scroll case for each unit.

(*h*) Determine the main dimensions of penstock for each unit.

(*i*) Suggest a preliminary plan layout of the station units, and find the approximate dimensions of the main floor of the building.

(*j*) Find the cost of energy per kilowatt-hour at the load centre from the following data—

Load factor of power system supplied by the station 80%. Cost of the hydro-development, Rs. 1,500 per kW installed. Fixed costs, 9%. Operation and maintenance cost, Rs. 7 per kW per year. The load centre is 80 km from the station, and it is necessary to transmit the power to the load centre by means of a 110-KV transmission line. The transmission liability may be taken as Rs 20 per kW per year. Energy used in generating stations for auxiliaries, etc., 2%.

(*a*) *Power developed, number of units, capacities of units.* The power developed by the turbines is given by eqn. (7.2).

$$P = \frac{Qwh\eta}{75} = \frac{90 \times 1{,}000 \times 100 \times 0.895}{75} = 107,400 \text{ metric hp}$$

The power system has a load factor of 80%, so that there is not much variation of load. Choose two turbines each of 107,400/2 or 53,700 metric hp capacity.

Then the generator capacity of each unit will be

$$53{,}700 \times 0.95 \times 0.736 = 37{,}500 \text{ kW}$$

and the total power developed by the station will be 75,000 kW, provided by two generators each of 37,500 kW capacity.

(*b*) *Specifications for turbines and generators.* The turbine output of each unit being 53,700 metric hp, and the head being 100 *m*, fixed-blade Francis turbines would be used. The approximate specific speed of the turbines is given by eqn. (8.4)

$$n_s = \frac{6{,}850}{h + 9.8} + 84 = 147 \text{ rev/min}$$

The corresponding actual speed is given by eqn (8.2)—

$$n = \frac{n_s\, h^{5/4}}{P^{1/2}} = \frac{147 \times 100^{5/4}}{53{,}700^{1/2}} = 197 \text{ revs/min}$$

The synchronous speed of a generator is $n = 120\ f/p$ revolutions per minute, where f is the frequency and p is the number of

poles. A 30-pole machine with $n=200$ rev/min will be satisfactory, for the actual specific speed will be

$$n_s=\frac{200\times 53{,}700^{1/2}}{100^{5/4}}=149.5 \text{ rev/min.}$$

which is not very different from 147 rev/min.

A suitable generator specification will be : vertical axis, 37,500 kW, 0.9 power factor lagging, 41,675 KVA, 200 rev/min, star connected, 11 KV, 3-phase, 50-c/s, 60°C temperature rise.

(*c*) *Main dimensions of turbines.* For a specific speed $n_s=149.5$ rev/min, the main dimensions of a 1-metric-hp turbine unit working under a head of 1 *m* can be obtained from Table 8.1.

$D_1=94$ cm; $D_2=90$ cm; width of the distributor$=18.4$ cm

For a turbine of 53,700-hp capacity working under a head of 100 m, the model ratio, *m*, is given by eqn (8.8)

$$m=\frac{P^{1/2}}{2.46\times h^{3/4}}=\frac{53{,}700^{1/2}}{246\times 100^{3/4}}=3$$

The dimensions of the 53,700 hp turbines are, therefore,

$D_1=94\times 3=282$ cm; $D_2=90\times 3=270$ cm; width of distributor$=18.4\times 3=55.2$ cm.

(*d*) *Main dimensions of generator unit.* Three-phase 41,675-KVA 30-pole 200 rev/min 11-KV star-connected 50-c/s generator units have been chosen. The output is given by eqn. (3.23).

$$S=10.4\times 10^{-3}\, Ba_c\, D^2Ln$$

Choosing a mean flux density, *B*, of 6.5×10^{-5} Wb/cm^2 and an electric loading, a_c, of 400 ampere-conductors per centimetre of periphery, and given that the speed, *n*, is 200/60 rev/sec, we have

$$41{,}675=10.4\times 10^{-3}\times 6.5\times 10^{-5}\times 400\times D^2L\times\frac{200}{60}$$

so that $D^2L=46.2\times 10^6$ $cm^3=x$ (say)

Choosing a core length, L, equal to the pole pitch, $\pi D/p$, $D^2=x/L=xp/\pi D$, whence

$$D^3=\frac{46.2\times 10^6\times 30}{\pi}=442\times 10^6 \text{ cm}^3$$

$$D=765 \text{ cm}$$

$$L=\frac{\pi\times 765}{30}=80 \text{ cm approximately}$$

We now check the peripheral speed :

$$\pi Dn = \pi \times 765 \times 10^{-2} \times 200 = 4{,}800 \text{ m/min}$$

This is below the permissible limit.

The main dimensions. D and L, of the generator have now been found.

(*e*) Dimensions of draft tube (Fig 8.17)

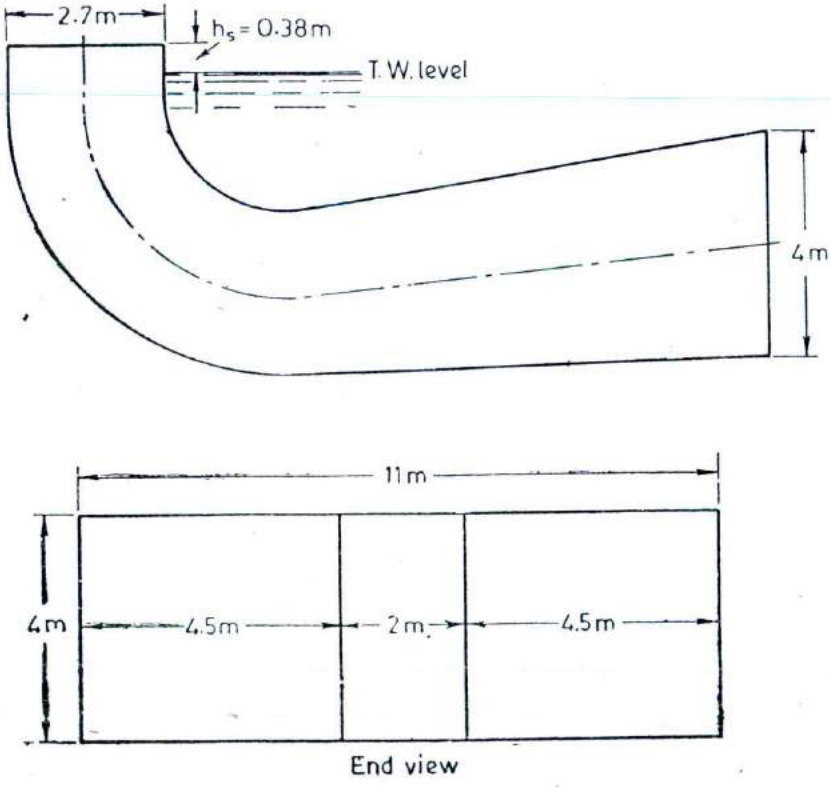


Fig. 8.17 Draft tube.

Length 16.6 m

Flow of water through each unit, $Q = 45$ m^3/sec

Diameter of turbine runner at outlet $D_2 = 270$ cm

This is the diameter at the inlet of the draft tube.

Velocity at inlet of draft tube, $v_2 = \dfrac{Q}{\pi/4 \times D^2}$

$$= \frac{45}{0.785 \times 2.7^2} = 7.9 \text{ m/sec}$$

This is below the limit of about $0.2\sqrt{(2gh)}$ m/sec.

Velocity at outlet of draft tube, $v_3 = 0.03\sqrt{(2gh)}$

$$= 0.03\sqrt{(2 \times 9.81 \times 100)}$$

$$= 1.335 \text{ m/sec}$$

or say about 1.25 m/sec

Area at exit of draft tube $= \dfrac{45}{1.25} = 36 \text{ m}^2$

Choose a cross-section at the exit of 4m × 9 m. With a central pier 2 m wide, the section would be as shown in the diagram, namely 4 m × 11 m, Use a quarter-turn draft tube.

If the flare is 1 in 4,

Length of draft tube $= \dfrac{11 - 2.7}{2} \times 4 = 16.6$ m

(*f*) *Setting of turbine.* The specific speed, n_s, is 149.5 rev/min. Fig. 8.13 (*a*), the cavitation coefficient, σ, for the value of n_s, is 0.0724. From eqn (8.16*a*), the distance h_s, from the tail-water to the under-side of the runner blades is given by

$$h_s = h_b - \sigma h = 7.62 - (0.0724 \times 100) = 0.38 \text{ m}$$

(*g*) *Dimension of scroll case:* A scroll case of plate steel will be used. The diameter, D, at the inlet to the draft tube is 2.7 m. The main dimensions of the scroll case will be approximately as shown in Fig 8.18. In this example,

1.43 D=3.86 m, 1.3 D=3.5 m, 2.00 D=5.4 m, 1.7 D=4.6 m, 2.2 D=5.68 m

(*h*) Dimensions of penstock for each unit:

Discharge through each penstock, $Q = 45$ m³/sec. Allowing a velocity through the penstock of 4 m/sec

$$\text{Area} = \frac{45}{4} = 11{:}25 \ m^2 = \frac{\pi d^2}{4}$$

Therefore,

Diameter of penstock, $d = \sqrt{\left(\dfrac{11.25 \times 4}{\pi}\right)} = 3.8$,

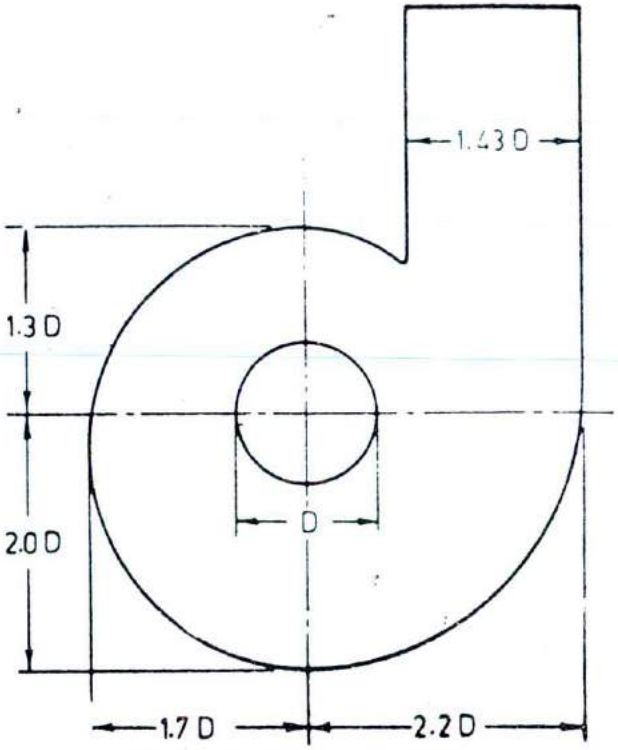


Fig. 8.18. Plate-steel scroll case.

From eqn. (8.17)

$$\text{Thickness of penstock, } t = \frac{0.1\ hd}{2f\eta_j}$$

Taking a permissible stress $f = 1{,}000$ kg/cm² and a joint efficiency $\eta_j = 90\%$, then, with $h = 100$ *m* and $d = 3.8$ *m*, the thickness, t, will be 2.1 cm. Adding 0.15 cm for corrosion, $t = 2.25$ cm.

The penstock will, therefore, be of diameter 3.8 m and thickness 2.25 cm.

(*i*) *Preliminary plan layout.* From Fig 8.14, the value of X corresponding to the ratio of the distance (centre to centre) between the units to the outlet diameter of the turbine for a specific speed $n_s = 149.5$ rev/min is 4.75. The outlet diameter, D_2, being 2.7 m.

Centre-to-centre distance between units $= 4.75 \times 2.7 = 12.75$m or say 13 m.

Also from the data of scroll-case dimensions, which are the largest dimensions of the unit parts, the horizontal distance is $1.7\ D+2.2\ D=4.6+5.68=10.28$ m. Allowing at least 2 m between the two adjacent units, the overall horizontal distance is $10.28+2=12.28$ m. The centre-to-centre distance between units is, therefore, kept as 13 m.

The area of the erection bay is kept as approximately $1\frac{1}{2}$ times that of the operation bay.

The main floor of the power station will, therefore, occupy an area 46 *m* long by 27 m wide. An outline of the arrangement is shown in Fig 8.19.

(*j*) *Cost of energy at load centre*

The capacity of the power station is 75,000 kW, the capital cost of the station is Rs 1,500 per kW, and the fixed costs are 9% of the capital costs.

$$\text{Fixed costs} = \frac{9}{100} \times 1{,}500 \times 75{,}000 = \text{Rs. } 10{,}125 \times 10^3$$

Operation and maintenance costs at Rs. 7 per kW per year

$$= 7 \times 75{,}000 = \text{Rs. } 525 \times 10^3$$

Transmission liability at Rs. 20 per kW per year

$$= 20 \times 75{,}000 = \text{Rs. } 1{,}500 \times 10^3$$

Total annual costs of station

$$= 10^3(10{,}125 + 525 + 1{,}500) = \text{Rs. } 12{,}150 \times 10^3$$

The station will work at a load factor of 80%.

Electrical energy generated per year

$$= 75{,}000 \times 8{,}760 \times 0.8 = 525 \times 10^6 \text{ kWh}$$

Energy used in station for auxiliaries per year (2%).

$$= 525 \times 10^6 \times 0.02 = 10.5 \times 10^6 \text{ kWh}$$

Energy available at load centre per year

$$= (525 - 10.5) \times 10^6 = 514.5 \times 10^6 \text{ kWh}$$

Cost at load centre

$$= \frac{12{,}150 \times 10^3}{514.5 \times 10^6} \times 100 = 2.37 \text{ p per kWh}$$

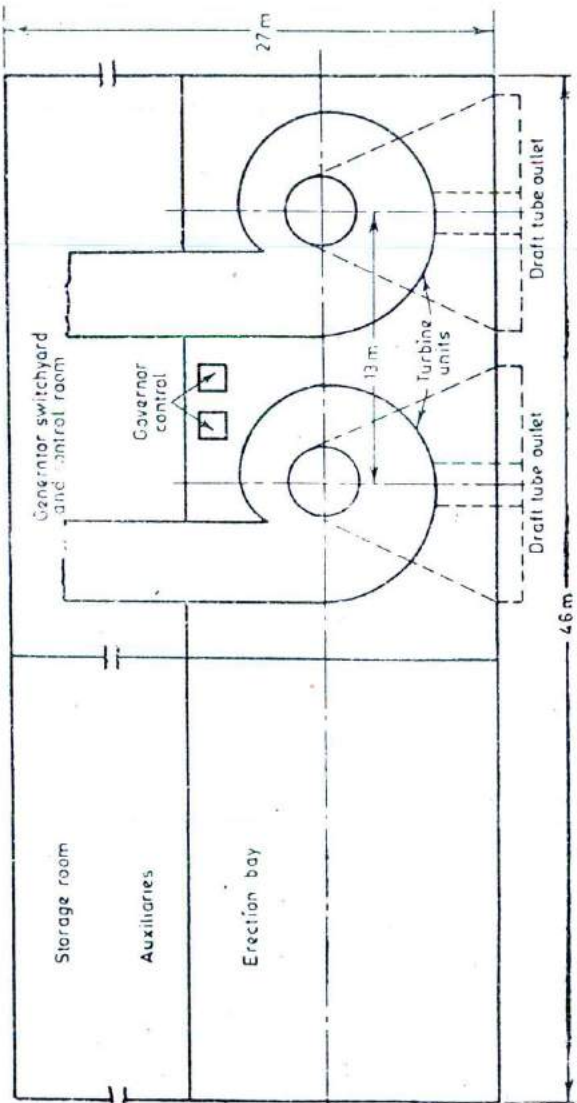


Fig. 8.19 Tentative layout of station units.

In the above example the loss in the transmission lines was not given. In practice, when the details of the load and of the transmission-line sections are known, the loss in transmission-lines can be taken into account, and then the net energy available for sale can be determined and the costs worked out.

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Problems

8.1. Describe the characteristics of the various types of turbine used in hydro-electric power stations with particular reference to (a) head, (b) efficiency at various loads, and (c) specific speed, and state how these factors help in the choice of the turbines.

8.2. State the factors to be considered in designing the main dimensions of reaction turbines.

Find the main dimensions of a 40,000-metric hp Francis turbine working under a head of 150 m. Choose a suitable speed for the turbine when the generator coupled to it is to have a frequency of 50 c/s. (Ans. Main dimensions, D_1 206 cm, D_2 183 cm; width of distributor, 32.8 cm; speed, 334 rev/min.)

8.3. State the method of designing the main dimensions of impulse-wheel turbines.

Determine the main dimensions and speed of a 20,000-metric hp Pelton wheel working under head of 500 m. The generator frequency is 50 c/s (Ans. Jet diameter, 22.3 cm; pitch diameter, 240 cm; speed 375 rev/min.)

8.4. Describe different types of draft tube used for reaction turbine installations.

Describe the principle of "setting a turbine" with reference to the tail-water level. What is the effect of speed on the setting of a turbine ?

Find the setting of the turbine of Problem 8.2 with respect to the tail-water level (Ans. 12 cm above tail-race water level.)

8.5. Design the main dimensions of a penstock for carrying a discharge of 20 m^3/sec under a head of 50 m. Take the permissible stress as 1,000 kg/cm^2 and the efficiency of joints as 92%. Choose a suitable velocity through the penstock (Ans. Diameter, 252 cm; thickness, 1.25 cm; velocity, 4 m/sec.)

8.6. Describe the characteristics and main features of the generators in hydro-electric power stations. Compare them with the main features of the generators in steam stations. Consider from the design point of view also.

8.7. Choose a generator suitable for the turbine in problem 8.2. Write a detailed specification. Assuming a generator efficiency of 96%, determine the main dimensions of the generator. (Ans. 28,300-kW 35,300-KVA 0.8-p.f. 11-kV 3-Phase 50-c/s 334-rev/min air-cooled generator. Diameter, 510 cm; length of core 89 cm).

8.8. Describe the main features of the substructure and superstructure of a hydro-electric power station. How are the layout and centre-to-centre distance between the units decided? Sketch a typical layout of a hydro-station.

8.9. State the method of determining the annual cost of a hydro-electric development. What is "transmission liability"?

The capacity of a hydro-electric power station is 50,000 kW. The load factor of the power system is 75%. The cost of the devleopment is Rs 1,300 per kW. The fixed cost may be taken as 9% per year, the operation and maintenance cost as Rs 10 per kW. per year, and the transmission liability as Rs. 15 per kW per year. Find the cost per kilowatt-hour (Ans 2.16 p.)

8.10. Discuss the various factors to be taken into account in deciding whether a particular hydro-electric development would be feasible economically compared to a steam station to supply a given power system.