Unit III – Steam Power Plant

Introduction

Steam is an important medium of producing mechanical energy. Steam has the advantage that, it can be raised from water which is available in abundance it does not react much with the materials of the equipment of power plant and is stable at the temperature required in the plant. Steam is used to drive steam engines, steam turbines etc. Steam power station is most suitable where coal is available in abundance. Thermal electrical power generation is one of the major method. Out of total power developed in India about 60% is thermal. For a thermal power plant the range of pressure may vary from 10 kg/cm2 to super critical pressures and the range of temperature may be from 250°C to 650°C.
The average all India Plant load factor (P.L.F.) of thermal power plants in 1987-88 has been worked out to be 56.4% which is the highest P.L.F. recorded by thermal sector so far.

Classification of Steam Power Plants

In steam power plants, the heat of combustion of fossil fuels (coal, oil or gas) is utilized by the boilers to raise steam at high pressure and temperature. The steam so produced is used in driving the steam turbines or sometimes steam engines coupled to generators and thus in generating electrical energy. Steam turbines or steam engines used in steam power plants not only act as prime movers but also as drives for auxiliary equip-ment, such as pumps, stokers fans etc.
Steam power plants may be either condensing or non-condensing type. In condensing type power plants the exhaust steam is discharged into a condenser, which creates suction at very low pressure and allows the expansion of steam in the turbine to a very low pressure and thus increases the efficiency. In non-condensing type power plants, the steam exhausted

from the turbine is discharged at atmospheric pressure or at a pressure greater than atmospheric.

The principal advantages of condensing operation are the increased amount of energy extracted per kg of steam and the greater amount of power developed by a given size of turbine or engine. Moreover, in non-condensing type power plants, a continuous supply of fresh feed water is required whereas in condensing type power plants steam condensed into the water in the condenser can be re-circulated to the boilers with the help of pumps. This point becomes very important at places where there is a shortage of pure water.

According to use such plants can be classified into:

(1) Industrial power plants or captive power plants, and

(2) Central power plants.

1. Industrial Power Plants:

The industries requiring steam for process purposes may use steam turbines for generation of electrical energy also for its own use. The steam for process purposes may be tapped from extraction bleeding of the turbines at a pressure of 1.4-7 kg/cm^2. Such plants are usually of non-condensing type. Industrial turbo-generator plants are usually of small capacity (say up to 10 MW).

Industrial turbo-generator plants, also known as captive power plants, otherwise also becoming more and more popular nowadays. The reasons for it are poor reliability of electric supply from the grid, frequent upward revision of power tariff charged by electric utilities and long power cuts. In the recent past many state governments have revised their policies as regards captive power generation and are encouraging setting up of captive power plants.

2. Central Power Plants:

Steam power plants are mainly used as central plants to generate electrical energy for supply to various consumers (industrial, agricultural, commercial, domestic etc.). Such plants are usually of condensing type. The size of the generating sets may be from 10-1,000 MW or even higher. When such power plants are used in a system having both hydro and steam power plants they can be used to supply load economically and to ensure reliability of power supply at all times.

Steam power plant for generation of electrical power is preferred, where large amount of power is required to be generated and financial, climatic, and geographical conditions do not permit the installation of hydroelectric power plants and coal is available in plenty.

layout of a modern steam power plant

Thermal electrical power generation is one of the major method. Out of total power developed in India about 60% is thermal. For a thermal power plant the range of pressure may vary from 10 kg/cm2 to super critical pressures and the range of temperature may be from 250°C to 650°C.

The average all India Plant load factor (P.L.F.) of thermal power plants in 1987-88 has been worked out to be 56.4% which is the highest P.L.F. recorded by thermal sector so far.

Fig. 1 shows a schematic Layout of a modern steam power plant. Coal received in coal storage yard of power station is transferred in the furnace by coal handling unit. Heat produced due to burning of coal is utilized in converting water contained in boiler drum into steam at suitable pressure and temperature. The steam generated is passed through the super-heater. Superheated steam then flows through the turbine. After doing work in the turbine die pressure of steam is reduced. Steam leaving the turbine passes through the condenser which maintain the low pressure of steam at the exhaust of turbine.

Steam pressure in the condenser depends upon flow rate and temperature of cooling water and on effectiveness of air removal equipment. Water circulating through the condenser may be taken from the various sources such as river, lake or sea. If sufficient quantity of water is not available the hot water coming out of the condenser may be cooled in cooling towers and circulated again through the condenser. Bled steam taken from the turbine at suitable extraction points is sent to low pressure and high pressure water heaters.

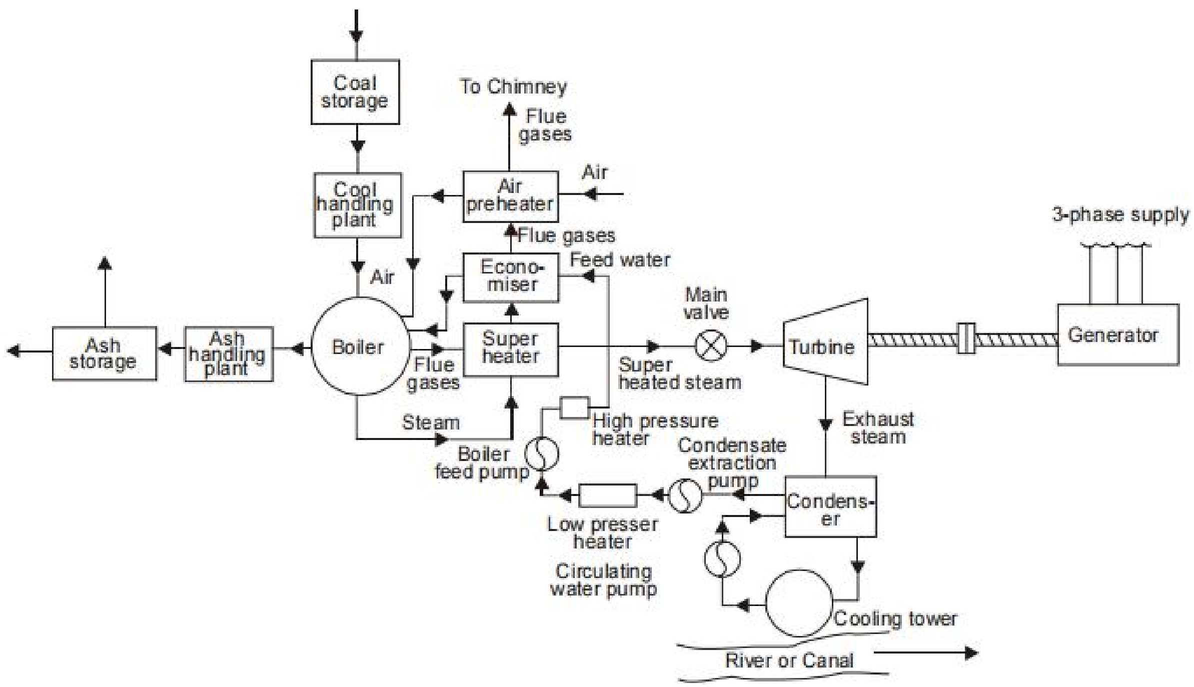


Fig. 1 Layout of a modern steam power plant.

Air taken from the atmosphere is first passed through the air pre-heater, where it is heated by flue gases. The hot air then passes through the furnace. The flue gases after passing over boiler and super-heater tubes, flow through the dust collector and then through economizer, air pre-heater and finally they are exhausted to the atmosphere through the chimney.

Steam condensing system consists of the following:

(*i*) Condenser

(*ii*) Cooling water

(*iii*) Cooling tower

(*iv*) Hot well

(*v*) Condenser cooling water pump

(*vi*) Condensate air extraction pump

(*vii*) Air extraction pump

(*viii*) Boiler feed pump

(*ix*) Make up water pump

POWER STATION DESIGN

Power station design requires wide experience. A satisfactory design consists of the following steps:

(i) Selection of site

(ii) Estimation of capacity of power station.

(iii) Selection of turbines and their auxiliaries.

(iv) Selection of boilers, and their auxiliaries.

(v) Design of fuel handling system.

(vi) Selection of condensers.

(vii) Design of cooling system.

(viii) Design of piping system to carry steam and water.

(ix) Selection of electrical generator.

(x) Design and control of instruments.

(xi) Design of layout of power station. Quality of coal used in steam power station plays an important role in the design of power plant.

The various factors to be considered while designing the boilers and coal handling units are as follows :

(a) Slagging and erosion properties of ash.

(b) Moisture in the coal. Excessive moisture creates additional problems particularly in case of pulverized fuel power plants.

(c) Burning characteristic of coal.

(d) Corrosive nature of ash.

CHARACTERISTICS OF STEAM POWER PLANT

The desirable characteristic for a steam power plant are as follows :

(i) Higher efficiency.

(ii) Lower cost.

(iii) Ability to burn coal especially of high ash content, and inferior coals.

(iv) Reduced environmental impact in terms of air pollution.

(v) Reduced water requirement.

(vi) Higher reliability and availability

Fuel handling

Coal delivery equipment is one of the major components of plant cost. The various steps involved in coal handling are as follows :

(*i*) Coal delivery
(*ii*) Unloading
(*iii*) Preparation
(*iv*) Transfer
(*v*) Outdoor storage
(*vi*) Covered storage
(*vii*) In plant handling
(*viii*) Weighing and measuring
(*ix*) Feeding the coal into furnace.

(i) Coal Delivery. The coal from supply points is delivered by ships or boats to power stations situated near to sea or river whereas coal is supplied by rail or trucks to the power stations which are situated away from sea or river. The transportation of coal by trucks is used if the railway facilities are not available.

(ii) Unloading. The type of equipment to be used for unloading the coal received at the power station depends on how coal is received at the power station. If coal is delivered by trucks, there is no need of unloading device as the trucks may dump the coal to the outdoor storage. Coal is easily handled if the lift trucks with scoop are used. In case the coal is brought by railway wagons, ships or boats, the unloading may be done by car shakes, rotary car dumpers, cranes, grab buckets and coal accelerators. Rotary car dumpers although costly are quite efficient for unloading closed wagons.

(iii) Preparation. When the coal delivered is in the form of big lumps and it is not of proper size, the preparation (sizing) of coal can be achieved by crushers, breakers, sizers driers and magnetic separators.

(iv) Transfer. After preparation coal is transferred to the dead storage by means of the following systems :

1. Belt conveyors.
2. Screw conveyors.
3. Bucket elevators.
4. Grab bucket elevators.
5. Skip hoists.
6. Flight conveyor

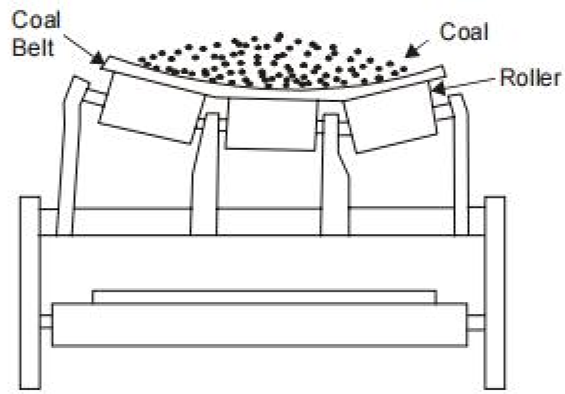


Fig. 2 Belt Conveyor.

1. ***Belt conveyor.*** **Fig. 2** shows a belt conveyor. It consists of an endless belt. moving over a pair of end drums (rollers). At some distance a supporting roller is provided at the center. The belt is made, up of rubber or canvas. Belt conveyor is suitable for the transfer of coal over long distances. It is used in medium and large power plants. The initial cost of the system is not high and power consumption is also low. The inclination at which coal can be successfully elevated by belt conveyor is about 20. Average speed of belt conveyors varies between 200-300 r.p.m. This conveyor is preferred than other types.

Advantages of belt conveyor

1. Its operation is smooth and clean.
2. It requires less power as compared to other types of systems.
3. Large quantities of coal can be discharged quickly and continuously.
4. Material can be transported on moderates inclines.

2. ***Screw conveyor.*** It consists of an endless helicoid screw fitted to a shaft (Fig. 3 left). The screw while rotating in a trough transfers the coal from feeding end to the discharge end. This system is suitable, where coal is to be transferred over shorter distance and space limitations exist. The initial cost of the system is low. It suffers from the drawbacks that the

power consumption is high and there is considerable wear of screw. Rotation of screw varies between 75-125 r.p.m.

3. ***Bucket elevator.*** It consists of buckets fixed to a chain (Fig. 3 (Right)). The chain moves over two wheels. The coal is carried by the buckets from bottom and discharged at the top.

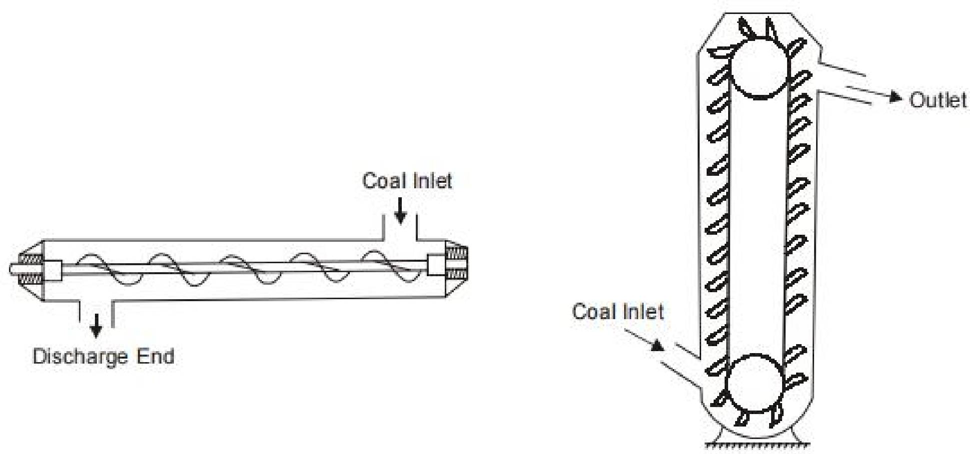


Fig. 3 Screw Conveyor (left) and Bucket Elevator (Right).

4. ***Grab bucket elevator***. It lifts and transfers coal on a single rail or track from one point to the other. The coal lifted by grab buckets is transferred to overhead bunker or storage. This system requires less power for operation and requires minimum maintenance. The grab bucket conveyor can be used with crane or tower as shown in **Fig.4**. Although the initial cost of this system is high but operating cost is less.

Fig.4 Grab Bucket Elevator.

5. Skip hoist. It consists of a vertical or inclined hoistway a bucket or a car guided by a frame and a cable for hoisting the bucket. The bucket is held in up right position. It is simple and compact method of elevating coal or ash. **Fig. 5** (**left**) shows a skip hoist.

6. Flight conveyor. It consists of one or two strands of chain to which steel scraper or flights are attached'. which scrap the coal through a trough having identical shape. This coal is discharged in the bottom of trough. It is low in first cost but has large energy consumption. There is considerable wear.

Skip hoist and bucket elevators lift the coal vertically while Belts and flight conveyors move the coal horizontally or on inclines.

Fig. 5 (**right**) shows a flight conveyor. Flight conveyors possess the following **advantages**.

(*i*) They can be used to transfer coal as well as ash.
(*ii*) The speed of conveyor can be regulated easily.
(*iii*) They have a rugged construction.
(*iv*) They need little operational care.

Disadvantages. Various disadvantages of flight conveyors are as follows :

(*i*) There is more wear due to dragging action.

(*ii*) Power consumption is more.

(*iii*) Maintenance cost is high.

(*iv*) Due to abrasive nature of material handled the speed of conveyors is low (10 to 30 m/min).

(v) Storage of coal. It is desirable that sufficient quantity of coal should be stored. Storage of coal gives protection against the interruption of coal supplies when there is delay in transportation of coal or due to strikes in coal mines. Also when the prices are low, the coal can be purchased and stored for future use. The amount of coal to be stored depends on the availability of space for storage, transportation facilities, the amount of coal that will whether away and nearness to coal mines of the power station.

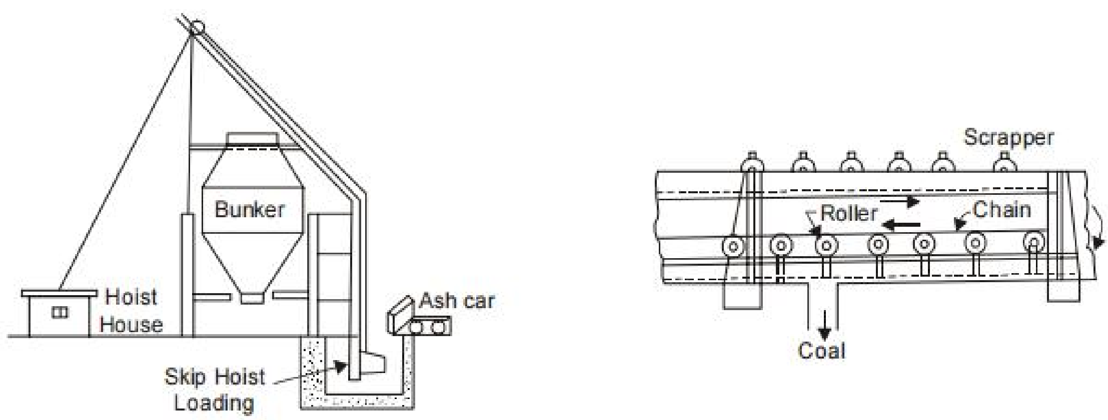


Fig.5 Skip Hoist (left) and Flight Conveyor (Right).

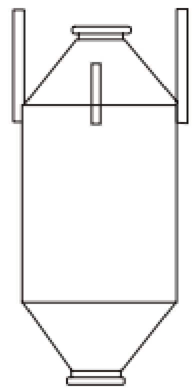


Fig.6 Cylindrical Bucket.

(*vi*) In Plant Handling. From the dead storage the coal is brought to **covered** storage (Live storage) (bins or bunkers). A cylindrical bunker shown in **Fig. 6**. In plant handling may include the equipment such as belt conveyors, screw conveyors, bucket elevators etc. to transfer the coal. Weigh lorries hoppers and automatic scales are used to record the quantity of coal delivered to the furnace.

(vii) Coal weighing methods. Weigh lorries, hoppers and automatic scales are used to weigh the quantity coal. The commonly used methods to weigh the coal are as follows:

(*i*) Mechanical (*ii*) Pneumatic (*iii*) Electronic.

The Mechanical method works on a suitable lever system mounted on knife edges and bearings connected to a resistance in the form of a spring of pendulum. The pneumatic weighters use a pneumatic transmitter weight head and the corresponding air pressure determined by the load applied. The electronic weighing machines make use of load cells that produce voltage signals proportional to the load applied. The important factor considered in selecting fuel handling systems are as follows:

(*i*) Plant flue rate

(*ii*) Plant location in respect to fuel shipping

(*iii*) Storage area available.

Combustion Equipment for Boilers

Combustion equipment for boilers are based on

1. Type of coal. The important factors which are considered for the selection of coal are as follows :

(i) Sizing

(ii) Caking

(iii) Swelling properties

(iv) Ash fusion temperature.

The characteristics which control the selection of coal for a particular combustion equipment are as follows:

(i) Size of coal

(ii) Ultimate and proximate analysis

(iii) Resistance of degradation

(iv) Grindability

(v) Caking characteristics

(vi) Slagging characteristics

(vii) Deterioration during storage

(viii) Corrosive characteristics

(ix) Ash Content.

The average ash content in Indian coal is about 20%. It is therefore desirable to design the furnace in such a way as to burn the coal of high ash content. The high ash content in coal has the following:

(i) It reduces thermal efficiency of the boiler as loss of heat through unburnt carbon, excessive clinker formation and heat in ashes is considerably high.

(ii) There is difficulty of hot ash disposal.

(iii) It increases size of plant.

(iv) It increases transportation cost of fuel per unit of heat produced.

(v) It makes the control difficult due to irregular combustion. High as content fuels can be used more economically in pulverised form. Pulverised fuel burning increases the thermal efficiency as high as 90% and controls can be simplified by just adjusting the position of burners in pulverised fuel boilers. The recent steam power plants in India are generally designed to use the pulverised coal.

2. Type of Combustion equipment. It includes the following:

(i) Type of furnace

(ii) Method of coal firing such as :

(a) Hand firing

(b) Stoker firing

(c) Pulverised fuel firing.

(iii) Method of air supply to the furnace. It is necessary to provide adequate quantity of secondary air with sufficient turbulence.

(iv) Type of burners used.

(v) Mixing arrangement of fuel and air.

The flames over the bed are due to the burning of volatile gases, lower the volatile content in the coal, shorter will be the flame. If the volatiles burn up intensely high temperature is generated over the furnace bed and helps to burn the carbon completely and vice versa. For complete burning of volatiles and prevent unburnt carbon going with ash adequate quantity of secondary air with sufficient turbulence should be provided.

Fluidised Bed Combustion (FBC)

Burning of pulverised coal has some problems such as particle size of coal used in pulverised firing is limited to 70-100 microns, the pulverised fuel fired furnances designed to burn a particular can not be used other type of coal with same efficiency, the generation of high temp. About (1650 C) in the furnace creates number of problems like slag formation on super heater, evaporation of alkali metals in ash and its deposition on heat transfer surfaces, formation of SO_2 and NOX in large amount.

Fluidised Bed combustion system can burn any fuel including low grade coals (even containing 70% ash), oil, gas or municipal waste. Improved desulphurisation and low NOX emission are its main characteristics. **Fig. 7** shows basic principle of Fluidized bed combustion (FBC) system. The fuel and inert material dolomite are fed on a distribution plate and air is supplied from the bottom of distribution plate. The air is supplied at high velocity so that solid feed material remains in suspension condition during burning. The heat produced is used to heat water flowing through the tube and convert water into steam: During burning SO_2 formed is absorbed by the dolomite and thus prevents its escape with the exhaust gases. The molten slag is tapped from the top surface of the bed. The bed temperature is nearly 800-900'C which is ideal for sulphur retention addition of limestone or dolomite to the bed brings down SO_2 emission level to about 15% of that in conventional firing methods.

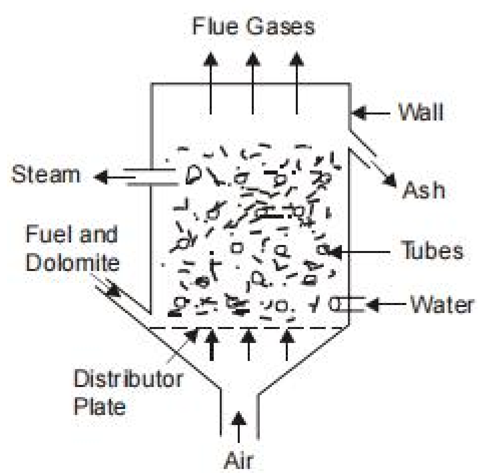


Fig.7 Fluidized bed combustion (FBC) system.

The amount of NOX is produced is also reduced because of low temperature of bed and low excess air as compared to pulverised fuel firing.

The inert material should be resistant to heat and disintegra-tion and should have similar density as that of coal. Limestone, or dolomite, fused alumina, sintered ash are commonly used as inert materials.

Various advantages of FBC system are as follows:

(*i*) FBC system can use any type of low grade fuel including municipal wastes and therefore is a cheaper method of power generation.

(*ii*) It is easier to control the amount of SO2 and NOX, formed during burning. Low emission of SO2 and NOX. will help in controlling the undesirable effects of SO2 and NOX. during combustion. SO2 emission is nearly 15% of that in conventional firing methods.

(*iii*) There is a saving of about 10% in operating cost and 15% in the capital cost of the power plant.

(*iv*) The size of coal used has pronounced effect on the operation and performance of FBC system. The particle size preferred is 6 to 13 mm but even 50 mm size coal can also be used in this system.

Stokers

Charging of fuel into the furnace is mechanized by means of stokers of various types. They are installed above the fire doors underneath the bunkers which supply the fuel. The bunkers receive the fuel from a conveyor.

Stoker types

(i) Chain Grate Stoker. Chain grate stoker and traveling grate stoker differ only in grate construction. A chain grate stoker (Figure A) consists of an endless chain which forms a support for the fuel bed.

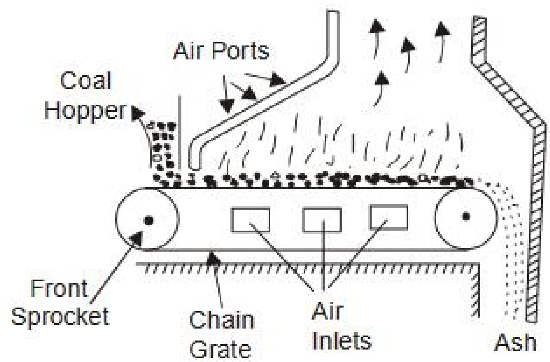


Fig. A. Chain Grate Stoker

The chain travels over two sprocket wheels, one at the front and one at the rear of furnace. The traveling chain receives coal at its front end through a hopper and carries it into the furnace. The ash is tipped from the rear end of chain. The speed of grate (chain) can be adjusted to suit the firing condition.

The air required for combustion enters through the air inlets situated below the grate. Stokers are used for burning non-coking free burning high volatile high ash coals. Although initial cost of this stoker is high but operation and maintenance cost is low.

The traveling grate stoker also uses an endless chain but differs in that it carries small grate bars which actually support the fuel fed. It is used to burn lignite, very small sizes of anthracites coke breeze etc.

The stokers are suitable for low ratings because the fuel must be burnt before it reaches the rear of the furnace. With forced draught, rate of combustion is nearly 30 to 50 lb of coal per square foot of grate area per hour, for bituminous 20 to 35 pounds per square foot per hour for anthracite.

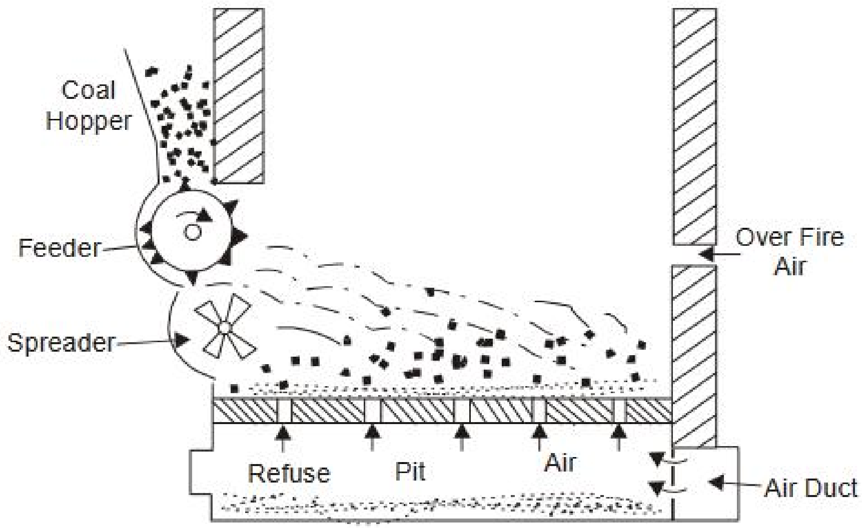


Fig. B. Spreader Stoker.

(ii) Spreader Stoker. A spreader stoker is shown in Fig. B. In this stoker the coal from the hopper is fed on to a feeder which measures the coal in accordance to the requirements. Feeder is a rotating drum fitted with blades. Feeders can be reciprocating rams, endless belts, spiral worms etc.

From the feeder the coal drops on to spreader distributor which spread the coal over the furnace. The spreader system should distribute the coal evenly over the entire grate area. The spreader speed depends on the size of coal.

Advantages

The various advantages of spreader stoker are as follows :

1. Its operation cost is low.

2. A wide variety of coal can be burnt easily by this stoker.

3. A thin fuel bed on the grate is helpful in meeting the fluctuating loads.

4. Ash under the fire is cooled by the incoming air and this minimizes clinkering.

5. The fuel burns rapidly and there is little coking with coking fuels.

Disadvantages

1. The spreader does not work satisfactorily with varying size of coal.

2. In this stoker the coal burns in suspension and due to this fly ash is discharged with flue gases

which requires an efficient dust collecting equipment

(iii) Multi-retort Stoker.

A multi-retort stoker is shown in Fig. C. The coal falling from the hopper is pushed forward during the inward stroke of stoker ram. The distributing rams (pushers) then slowly move the entire coal bed down the length of stoker. The length of stroke of pushers can be varied as desired. The slope of stroke helps in moving the fuel bed and this fuel bed movement keeps it slightly agitated to break up clinker formation. The primary air enters the fuel bed from main wind box situated below the stoker. Partly burnt coal moves on to the extension grate. A thinner fuel bed on the extension grate requires lower air pressure under it. The air entering from the main wind box into the extension grate wind box is regulated by an air damper.

As sufficient amount of coal always remains on the grate, this stoker can be used under large boilers (upto 500,000 lb per hr capacity) to obtain high rates of combustion. Due to thick fuel bed the air supplied from the main wind box should be at higher pressure.

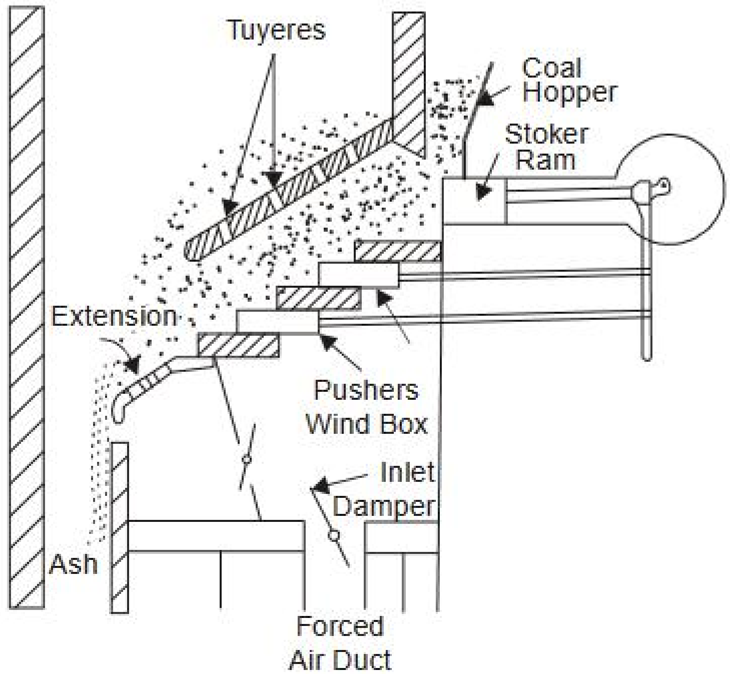


Fig. C Multi-retort Stoker

Advantages and Disadvantages of Steam Power Plant

(A) Advantages of Steam Power Plants :

1. Fuel used is cheaper.
2. They can respond quickly with changes in load on the plant.
3. Space required is less compared to hydro power plants.
4. A portion of steam can be used as process steam for various industries.
5. They can be overloaded upto 20% without difficulty. Cost of electric power generation and its initial cost is less compared to diesel plants.
6. Can be located near the load centre conveniently thus reduces the transmission line cost and loss of energy in transmission lines.

(B) Disadvantages of Steam Power Plants :

1. Operation and maintenance cost is high.
2. Time needed for errection of plant is high before it is put to operation.
3. Large quantity of water is needed.
4. Coal and ash handling poses a serious problem.
5. The part load efficiency is low.

6. Pollution causes health problems to workers and habitants near the thermal power plant.

Efficiency of Steam Power Plants

The thermal efficiency of steam power plants, defined as the ratio of the heat equivalent of mechanical energy transmitted to the turbine shaft and the heat of combustion is quite low (about 30%). Overall efficiency of the power plant, defined as the ratio of heat equivalent of electrical output to the heat of combustion, is about 29 per cent.

The overall efficiency is determined by multiplying the thermal efficiency of power plant by the efficiency of generation (or electrical efficiency). In case of most modern supercritical pressure steam plants employing many heat saving devices, the plant overall efficiency may reach the value of 50 per cent.

Losses occurring in steam power plants may be summarized as follows:

(a) Boiler House Losses:

(i) To dry flue gases – 5%

(ii) To moisture in gases – 5%

(iii) To ash and unburnt carbon – 1.0%

(iv) To radiation and leakage – 2.5%

(v) Unknown loses – 2.5%

Total = 16.0%

(b) Turbine Losses:

Heat rejected to condenser – 54%

Alternator losses – 1%

Thus output is about – 29%

From the above mentioned figures of various losses occurring in steam power plants it is obvious that more than 50 per cent of total heat of combustion is lost as heat rejected to the condenser. This loss of heat energy is unavoidable as heat energy cannot be converted into mechanical energy without a drop in temperature, and the steam in condenser is at the lowest temperature.

The thermal efficiency of the plant mainly depends upon the following factors:

(i) Pressure and

(ii) Temperature of the steam entering the turbine and the pressure in the condenser.

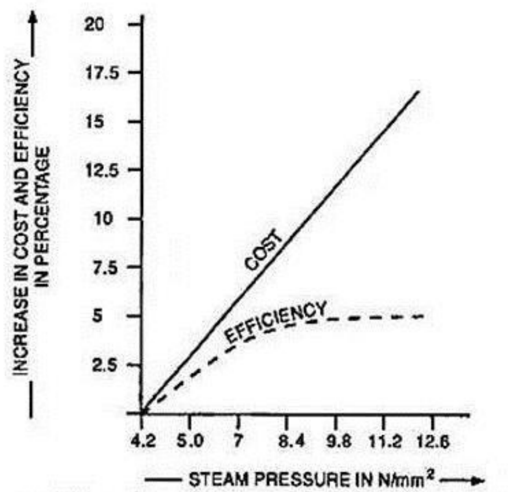
The thermal efficiency increases with the increase in temperature and pressure of the steam entering the turbine. For this reason high pressures and temperatures are used. The thermal efficiency is effectively increased by decreasing the pressure in the condenser. Pressure in the condenser is kept very low usually 0.04 kg/cm^2.

The thermal efficiency also increases by reheating the steam between turbine stages, but is somewhat inconvenient. Bleeding of steam also affects the thermal efficiency.

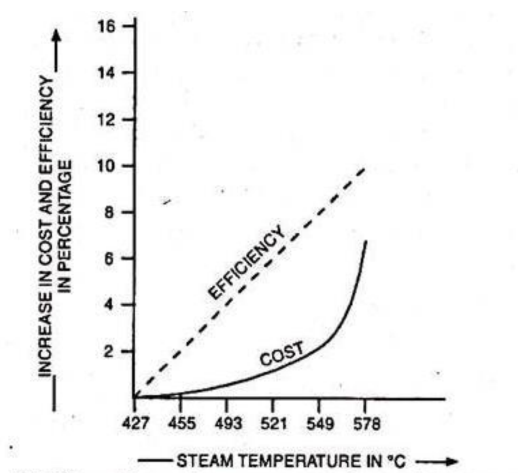
The overall thermal efficiency of 1st steam plant (50 MW units at Bokaro) commissioned in year 1952-53 in India was 28% while for the largest and most efficient thermal power plant having unit size of 160 MW at Trombay commissioned in 1965 it was 37% with heat rate 2,330 kcal/kWh of electrical energy produced. Each of the three major elements of a thermal power plant—the boiler, the turbine and the alternator have undergone intensive development and as a result the efficiency of electric generation has gone up to nearly 42% in 1980's.

Choice of Steam Pressure and Temperature:

The modern trend is towards high pressure and temperature, but the choice should be economical one. The effects of increased pressure and temperature on the efficiency and cost of the plant are illustrated in Figs. 3.2 (a) and 3.2 (b).



(a) Effect of Steam Pressure on Cost and Efficiency



(b) Effect of Steam Temperature on Cost and Efficiency

From curves shown in Figs. (a) and (b), it is obvious that the efficiency follows the law of diminishing return with the increase in pressure, but with the increase in temperature, the efficiency follows the straight line law. So use of highest possible temperature is desirable.

The highest temperature is limited due to the strength of material and beyond 480°C, the change in physical properties of the material is very rapid and the problem becomes complicated. With the increase in pressure, the degree of superheat is to be reduced so as to keep within limits the total temperature. The present practice is to use steam pressures of about 6.5 N/mm^2 for entirely new plant.

Supercritical Technology:

At a temperature of about 600°C and pressure of 30 N/mm^2, water enters a supercritical phase and has properties between those of liquid and gas. Water in supercritical stage can dissolve a number of organic compounds and gases and on addition of hydrogen peroxide and liquid oxygen combustion process starts. The steam power plants operating on this principle are called supercritical plants.

The advantages of such plants are that low grade fossil fuels (e.g., lignite) can be used, NO_2 emissions are completely eliminated and SO_2 emissions are reduced and complete burning of coal occurs. So the plant has no need of desulphurisation and denitrification equipment and soot collector.

With this system the cost of processing flue gas emissions (electrostatic precipitator etc.) is eliminated and cooling water requirements are also reduced, so the system becomes more economical and efficient. Supercritical power plants, these days have an overall efficiency of just over 40%. With the use of temperatures around 700°C (known as ultra-supercritical condition), the overall efficiency of the system may be improved to around 50%.

Calculate the overall efficiency of the steam thermal power plant, if boiler efficiency is 85%, turbine efficiency is 40% and alternator efficiency is 95%

Concept:

The overall efficiency of the power plant is given as

$$Overall\ Efficiency\ = \frac{Electrical\ energy\ output}{chemical\ energy\ input}$$

Overall efficiency is also expressed as

$$\eta_0 = \frac{Thermal\ Energy}{Chemical\ Energy} \times \frac{Mechanical\ Energy}{Thermal\ Energy} \times \frac{Electrical\ Energy}{Mechanical\ energy}$$

So, the overall efficiency of the power plant is equal to the multiplication of the efficiencies of the boiler, turbine, and generator.

Overall Efficiency = Boiler efficiency × turbine efficiency × generator efficiency

$\eta_{power\ plant} = \eta_{boiler} \times \eta_{turbine} \times \eta_{generator}$

Where,

Boiler efficiency = Thermal efficiency

Turbine efficiency × Generator efficiency = Electrical efficiency

∴ **Overall Efficiency = Thermal efficiency × Electrical efficiency**

Calculation:

Given that, Boiler efficiency = 85%

Turbine efficiency = 40%

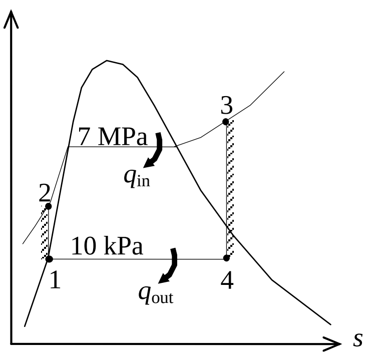
Alternator efficiency = 95%

Overall efficiency = 0.85 × 0.4 × 0.95 = 0.323 = 32.3%

1. A steam power plant operates on a simple ideal Rankine cycle between the specified pressure limits. The thermal efficiency of the cycle, the mass flow rate of the steam, and the temperature rise of the cooling water are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis (*a*) From the steam tables (Tables A-4, A-5, and A-6),



$$h_1 = h_{f\,@\,10\text{ kPa}} = 191.81 \text{ kJ/kg}$$

$$\boldsymbol{v}_1 = \boldsymbol{v}_{f\,@\,10\text{ kPa}} = 0.00101 \text{ m}^3\text{/kg}$$

$$w_{p,\text{in}} = \boldsymbol{v}_1(P_2 - P_1)$$

$$= (0.00101 \text{ m}^3\text{/kg})(7{,}000 - 10 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)$$

$$= 7.06 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{p,\text{in}} = 191.81 + 7.06 = 198.87 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 7 \text{ MPa} \\ T_3 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3411.4 \text{ kJ/kg} \\ s_3 = 6.8000 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 10 \text{ kPa} \\ s_4 = s_3 \end{array}\right\} x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.8000 - 0.6492}{7.4996} = 0.8201$$

$$h_4 = h_f + x_4 h_{fg} = 191.81 + (0.8201)(2392.1) = 2153.6 \text{ kJ/kg}$$

Thus,

$$q_{\text{in}} = h_3 - h_2 = 3411.4 - 198.87 = 3212.5 \text{ kJ/kg}$$

$$q_{\text{out}} = h_4 - h_1 = 2153.6 - 191.81 = 1961.8 \text{ kJ/kg}$$

$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 3212.5 - 1961.8 = 1250.7 \text{ kJ/kg}$$

and

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{1250.7 \text{ kJ/kg}}{3212.5 \text{ kJ/kg}} = \mathbf{38.9\%}$$

(*b*) $$\dot{m} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{45{,}000 \text{ kJ/s}}{1250.7 \text{ kJ/kg}} = \mathbf{36.0 \text{ kg/s}}$$

(*c*) The rate of heat rejection to the cooling water and its temperature rise are

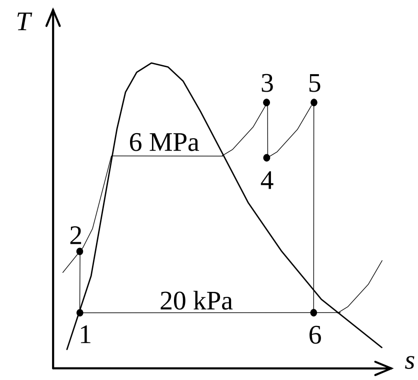
$$\dot{Q}_{\text{out}} = \dot{m}q_{\text{out}} = (35.98 \text{ kg/s})(1961.8 \text{ kJ/kg}) = 70{,}586 \text{ kJ/s}$$

$$\Delta T_{\text{cooling water}} = \frac{\dot{Q}_{\text{out}}}{(\dot{m}c)_{\text{cooling water}}} = \frac{70{,}586 \text{ kJ/s}}{(2000 \text{ kg/s})(4.18 \text{ kJ/kg}\cdot°\text{C})} = \mathbf{8.4°C}$$

2. A steam power plant that operates on the ideal reheat Rankine cycle is considered. The turbine work output and the thermal efficiency of the cycle are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis From the steam tables (Tables A-4, A-5, and A-6),



$$h_1 = h_{f\,@\,20\text{ kPa}} = 251.42\text{ kJ/kg}$$

$$v_1 = v_{f\,@\,20\text{ kPa}} = 0.001017\text{ m}^3/\text{kg}$$

$$\begin{aligned} w_{p,\text{in}} &= v_1(P_2 - P_1) \\ &= (0.001017\text{ m}^3/\text{kg})(6000 - 20\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ &= 6.08\text{ kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{p,\text{in}} = 251.42 + 6.08 = 257.50\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 6\text{ MPa} \\ T_3 = 400°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3178.3\text{ kJ/kg} \\ s_3 = 6.5432\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 2\text{ MPa} \\ s_4 = s_3 \end{array}\right\} h_4 = 2901.0\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_5 = 2\text{ MPa} \\ T_5 = 400°\text{C} \end{array}\right\} \begin{array}{l} h_5 = 3248.4\text{ kJ/kg} \\ s_5 = 7.1292\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_6 = 20\text{ kPa} \\ s_6 = s_5 \end{array}\right\} \begin{array}{l} x_6 = \dfrac{s_6 - s_f}{s_{fg}} = \dfrac{7.1292 - 0.8320}{7.0752} = 0.8900 \\ h_6 = h_f + x_6 h_{fg} = 251.42 + (0.8900)(2357.5) = 2349.7\text{ kJ/kg} \end{array}$$

The turbine work output and the thermal efficiency are determined from

$$w_{\text{T,out}} = (h_3 - h_4) + (h_5 - h_6) = 3178.3 - 2901.0 + 3248.4 - 2349.7 = \mathbf{1176\text{ kJ/kg}}$$

and

$$q_{\text{in}} = (h_3 - h_2) + (h_5 - h_4) = 3178.3 - 257.50 + 3248.4 - 2901.0 = 3268\text{ kJ/kg}$$

$$w_{\text{net}} = w_{T,out} - w_{p,\text{in}} = 1176 - 6.08 = 1170\text{ kJ/kg}$$

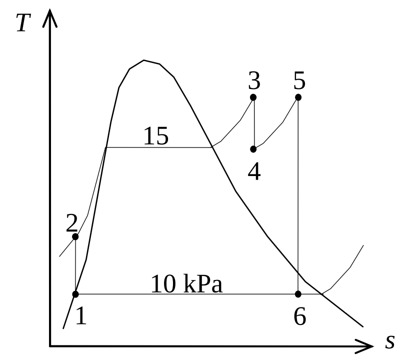
Thus,

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{1170\text{ kJ/kg}}{3268\text{ kJ/kg}} = 0.358 = \mathbf{35.8\%}$$

3. A steam power plant that operates on an ideal reheat Rankine cycle between the specified pressure limits is considered. The pressure at which reheating takes place, the total rate of heat input in the boiler, and the thermal efficiency of the cycle are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis (*a*) From the steam tables (Tables A-4, A-5, and A-6),



$$h_1 = h_{\text{sat@ 10 kPa}} = 191.81 \text{ kJ/kg}$$

$$\boldsymbol{v}_1 = \boldsymbol{v}_{\text{sat@ 10 kPa}} = 0.00101 \text{ m}^3/\text{kg}$$

$$\begin{aligned} w_{p,\text{in}} &= \boldsymbol{v}_1(P_2 - P_1) \\ &= (0.00101 \text{ m}^3/\text{kg})(15{,}000 - 10 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) \\ &= 15.14 \text{ kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{p,\text{in}} = 191.81 + 15.14 = 206.95 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 15 \text{ MPa} \\ T_3 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3310.8 \text{ kJ/kg} \\ s_3 = 6.3480 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_6 = 10 \text{ kPa} \\ s_6 = s_5 \end{array}\right\} \begin{array}{l} h_6 = h_f + x_6 h_{fg} = 191.81 + (0.90)(2392.1) = 2344.7 \text{ kJ/kg} \\ s_6 = s_f + x_6 s_{fg} = 0.6492 + (0.90)(7.4996) = 7.3988 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} T_5 = 500°\text{C} \\ s_5 = s_6 \end{array}\right\} \begin{array}{l} P_5 = \mathbf{2150 \text{ kPa}} \text{ (the reheat pressure)} \\ h_5 = 3466.61 \text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_4 = 2.15 \text{ MPa} \\ s_4 = s_3 \end{array}\right\} h_4 = 2817.2 \text{ kJ/kg}$$

(*b*) The rate of heat supply is

$$\begin{aligned} \dot{Q}_{\text{in}} &= \dot{m}[(h_3 - h_2) + (h_5 - h_4)] \\ &= (12 \text{ kg/s})(3310.8 - 206.95 + 3466.61 - 2817.2) \text{kJ/kg} \\ &= \mathbf{45{,}039 \text{ kW}} \end{aligned}$$

(*c*) The thermal efficiency is determined from

$$\dot{Q}_{\text{out}} = \dot{m}(h_6 - h_1) = (12 \text{ kJ/s})(2344.7 - 191.81) \text{kJ/kg} = 25{,}835 \text{ kJ/s}$$

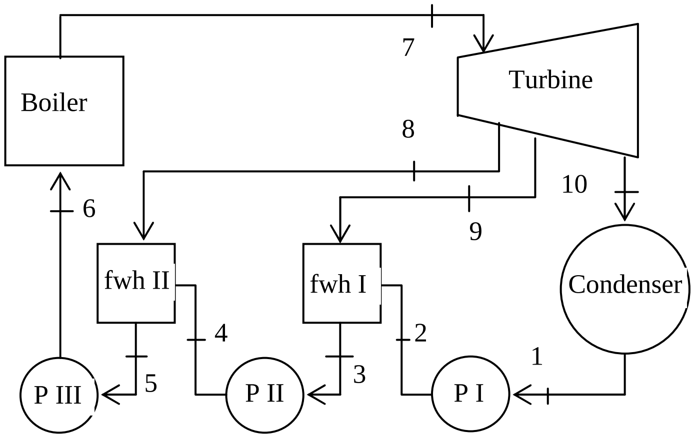
Thus,

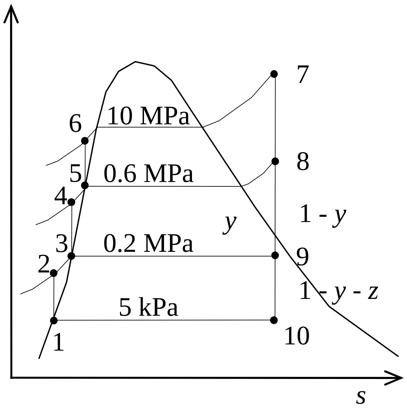
$$\eta_{\text{th}} = 1 - \frac{\dot{Q}_{\text{out}}}{\dot{Q}_{\text{in}}} = 1 - \frac{25{,}834 \text{ kJ/s}}{45{,}039 \text{ kJ/s}} = \mathbf{42.6\%}$$

4. A steam power plant operates on an ideal regenerative Rankine cycle with two open feedwater heaters. The net power output of the power plant and the thermal efficiency of the cycle are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis





(*a*) From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f @ 5\text{ kPa}} = 137.75 \text{ kJ/kg}$$
$$\boldsymbol{v}_1 = \boldsymbol{v}_{f @ 5\text{ kPa}} = 0.001005 \text{ m}^3\text{/kg}$$
$$w_{pI,\text{in}} = \boldsymbol{v}_1(P_2 - P_1) = (0.001005 \text{ m}^3\text{/kg})(200 - 5 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 0.20 \text{ kJ/kg}$$
$$h_2 = h_1 + w_{pI,\text{in}} = 137.75 + 0.20 = 137.95 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 0.2 \text{ MPa} \\ \text{sat.liquid} \end{array}\right\} \begin{array}{l} h_3 = h_{f @ 0.2\text{ MPa}} = 504.71 \text{ kJ/kg} \\ \boldsymbol{v}_3 = \boldsymbol{v}_{f @ 0.2\text{ MPa}} = 0.001061 \text{ m}^3\text{/kg} \end{array}$$

$$w_{pII,\text{in}} = \boldsymbol{v}_3(P_4 - P_3) = (0.001061 \text{ m}^3\text{/kg})(600 - 200 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)$$
$$= 0.42 \text{ kJ/kg}$$
$$h_4 = h_3 + w_{pII,\text{in}} = 504.71 + 0.42 = 505.13 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_5 = 0.6 \text{ MPa} \\ \text{sat.liquid} \end{array}\right\} \begin{array}{l} h_5 = h_{f @ 0.6\text{ MPa}} = 670.38 \text{ kJ/kg} \\ \boldsymbol{v}_5 = \boldsymbol{v}_{f @ 0.6\text{ MPa}} = 0.001101 \text{ m}^3\text{/kg} \end{array}$$

$$w_{pIII,\text{in}} = \boldsymbol{v}_5(P_6 - P_5) = (0.001101 \text{ m}^3\text{/kg})(10{,}000 - 600 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)$$
$$= 10.35 \text{ kJ/kg}$$

$$h_6 = h_5 + w_{pIII,\text{in}} = 670.38 + 10.35 = 680.73 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_7 = 10 \text{ MPa} \\ T_7 = 600°\text{C} \end{array}\right\} \begin{array}{l} h_7 = 3625.8 \text{ kJ/kg} \\ s_7 = 6.9045 \text{ kJ/kg}\cdot\text{K} \end{array}$$

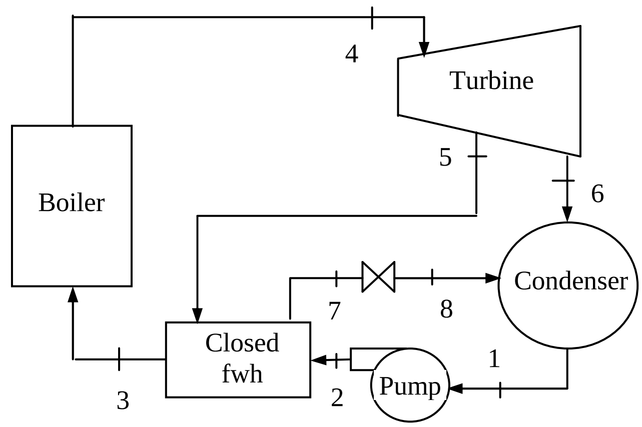
$$\left.\begin{array}{l} P_8 = 0.6 \text{ MPa} \\ s_8 = s_7 \end{array}\right\} h_8 = 2821.8 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_9 = 0.2 \text{ MPa} \\ s_9 = s_7 \end{array}\right\} \begin{array}{l} x_9 = \dfrac{s_9 - s_f}{s_{fg}} = \dfrac{6.9045 - 1.5302}{5.5968} = 0.9602 \\ h_9 = h_f + x_9 h_{fg} = 504.71 + (0.9602)(2201.6) = 2618.7 \text{ kJ/kg} \end{array}$$

5. An ideal regenerative Rankine cycle with a closed feedwater heater is considered. The work produced by the turbine, the work consumed by the pumps, and the heat added in the boiler are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis From the steam tables (Tables A-4, A-5, and A-6),



$$h_1 = h_{f\,@\,20\text{ kPa}} = 251.42\text{ kJ/kg}$$

$$\boldsymbol{v}_1 = \boldsymbol{v}_{f\,@\,20\text{ kPa}} = 0.001017\text{ m}^3\text{/kg}$$

$$\begin{aligned} w_{\text{p,in}} &= \boldsymbol{v}_1(P_2 - P_1) \\ &= (0.001017\text{ m}^3\text{/kg})(3000-20)\text{kPa}\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ &= 3.03\text{ kJ/kg} \end{aligned}$$

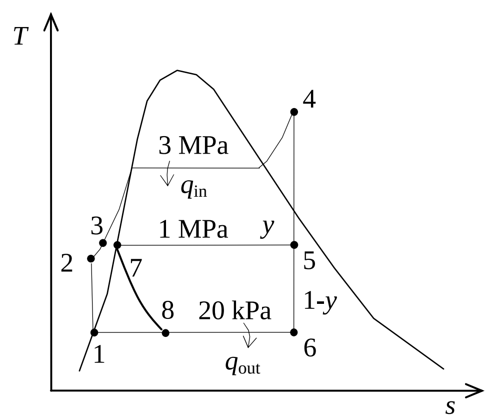
$$h_2 = h_1 + w_{\text{p,in}} = 251.42 + 3.03 = 254.45\text{ kJ/kg}$$

$$\left.\begin{aligned} P_4 &= 3000\text{ kPa} \\ T_4 &= 350°\text{C} \end{aligned}\right\} \begin{aligned} h_4 &= 3116.1\text{ kJ/kg} \\ s_4 &= 6.7450\text{ kJ/kg}\cdot\text{K} \end{aligned}$$

$$\left.\begin{aligned} P_5 &= 1000\text{ kPa} \\ s_5 &= s_4 \end{aligned}\right\} h_5 = 2851.9\text{ kJ/kg}$$

$$\left.\begin{aligned} P_6 &= 20\text{ kPa} \\ s_6 &= s_4 \end{aligned}\right\} \begin{aligned} x_6 &= \frac{s_6 - s_f}{s_{fg}} = \frac{6.7450-0.8320}{7.0752} = 0.8357 \\ h_6 &= h_f + x_6 h_{fg} = 251.42 + (0.8357)(2357.5) = 2221.7\text{ kJ/kg} \end{aligned}$$

For an ideal closed feedwater heater, the feedwater is heated to the exit temperature of the extracted steam, which ideally leaves the heater as a saturated liquid at the extraction pressure.



$$\left.\begin{aligned} P_7 &= 1000\text{ kPa} \\ x_7 &= 0 \end{aligned}\right\} \begin{aligned} h_7 &= 762.51\text{ kJ/kg} \\ T_7 &= 179.9°\text{C} \end{aligned}$$

$$h_8 = h_7 = 762.51\text{ kJ/kg}$$

$$\left.\begin{aligned} P_3 &= 3000\text{ kPa} \\ T_3 &= T_7 = 209.9°\text{C} \end{aligned}\right\} h_3 = 763.53\text{ kJ/kg}$$

An energy balance on the heat exchanger gives the fraction of steam extracted from the turbine ($= \dot{m}_5 / \dot{m}_4$) for closed feedwater heater:

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$

$$\dot{m}_5 h_5 + \dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_7 h_7$$

$$y h_5 + 1 h_2 = 1 h_3 + y h_7$$

Rearranging,

$$y = \frac{h_3 - h_2}{h_5 - h_7} = \frac{763.53 - 254.45}{2851.9 - 762.51} = 0.2437$$

Then,

$$w_{\text{T,out}} = h_4 - h_5 + (1-y)(h_5 - h_6) = 3116.1 - 2851.9 + (1-0.2437)(2851.9 - 2221.7) = \mathbf{740.9\ kJ/kg}$$

$$w_{\text{P,in}} = \mathbf{3.03\ kJ/kg}$$

$$q_{\text{in}} = h_4 - h_3 = 3116.1 - 763.53 = \mathbf{2353\ kJ/kg}$$

Also, $w_{\text{net}} = w_{\text{T,out}} - w_{\text{P,in}} = 740.9 - 3.03 = 737.8\text{ kJ/kg}$

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{737.8}{2353} = 0.3136$$

Unit 4: Gas Turbine Power Plant

I. General aspects

The gas turbine obtains its power by utilizing the energy of burnt gases and air, which is at high temperature and pressure by expanding through the several ring of fixed and moving blades. It thus resembles a steam turbine. To get a high pressure (of the order of 4 to 10 bar) of working fluid, which is essential for expansion a compressor, is required.

The quantity of the working fluid and speed required are more, so, generally, a centrifugal or an axial compressor is employed. The turbine drives the compressor and so it is coupled to the turbine shaft. If after compression the working fluid were to be expanded in a turbine, then assuming that there were no losses in either component the power developed by the turbine would be just equal to that absorbed by the compressor and the work done would be zero. But increasing the volume of the working fluid at constant pressure, or alternatively increasing the pressure at constant volume can increase the power developed by the turbine. Adding heat so that the temperature of the working fluid is increased after the compression may do either of these. To get a higher temperature of the working fluid a combustion chamber is required where combustion of air and fuel takes place giving temperature rise to the working fluid.

Thus, a simple gas turbine cycle consists of

(1) A Compressor,

(2) A Combustion Chamber and

(3) A Turbine.

Since the compressor is coupled with the turbine shaft, it absorbs some of the power produced by the turbine and hence lowers the efficiency. The network is therefore the difference between the turbine work and work required by the compressor to drive it.

Gas turbines have been constructed to work on the following: oil, natural gas, coal gas, producer gas, blast furnace and pulverized coal.

II. Closed cycle and open cycle plants

The gas turbine power plants which are used in electric power industry are classified into two groups as per the cycle of operation.

(*a*) Closed cycle gas turbine.

(*b*) Open cycle gas turbine.

Closed Cycle Gas Turbine Power Plant

Closed cycle gas turbine plant was originated and developed in Switzerland. In the year 1935, J. Ackeret and C. Keller first proposed this type of machine and first plant was completed in Zurich in 1944.

It used air as working medium and had a useful output of 2 mW. Since then, a number of closed cycle gas turbine plants have been built all over the world and largest of 17 mW capacity is at Gelsenkirchen, Germany and has been successfully operating since 1967. In closed cycle gas turbine plant, the working fluid (air or any other suitable gas) coming out from compressor is heated in a heater by an external source at constant pressure. The high temperature and high-pressure air coming out from the external heater is passed through the gas turbine. The fluid coming out from the turbine is cooled to its original temperature in the cooler using external cooling source before passing to the compressor.

The working fluid is continuously used in the system without its change of phase and the required heat is given to the working fluid in the heat exchanger. The arrangement of the components of the closed cycle gas turbine plant is shown in Fig. 1.

(A) Advantages

1. The inherent disadvantage of open cycle gas turbine is the atmospheric backpressure at the turbine exhaust. With closed cycle gas turbine plants, the backpressure can be increased. Due to the control on backpressure, unit rating can be increased about in proportion to the backpressure. Therefore the

machine can be smaller and cheaper than the machine used to develop the same power using open cycle plant.

2. The closed cycle avoids erosion of the turbine blades due to the contaminated gases and fouling of compressor blades due to dust. Therefore, it is practically free from deterioration of efficiency in service. The absence of corrosion and abrasion of the interiors of the compressor and turbine extends the life of the plant and maintains the efficiency of the plant constant throughout its life as they are kept free from the products of combustion.

3. The need for filtration of the incoming air which is a severe problem in open cycle plant is completely eliminated.

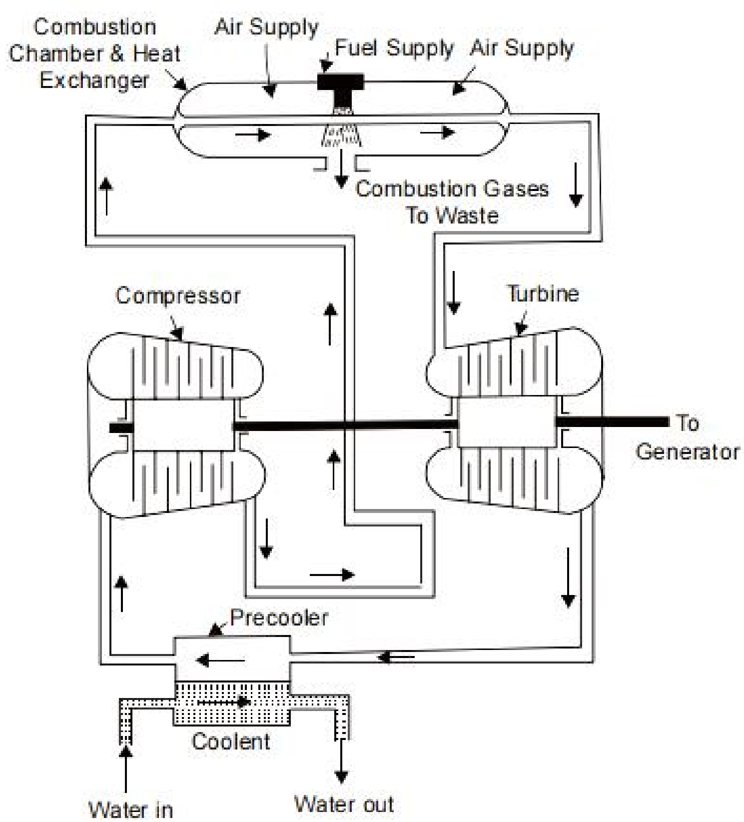


Fig. 1 Closed Cycle Gas Turbine Plant.

4. Load variation is usually obtained by varying the absolute pressure and mass flow of the circulating medium, while the pressure ratio, the temperatures and the air velocities remain almost constant. This result in

velocity ratio in the compressor and turbine independent of the load and full load thermal efficiency maintained over the full range of operating loads.

5. The density of the working medium can be maintained high by increasing internal pressure range, therefore, the compressor and turbine are smaller for their rated output. The high density of the working fluid further increases the heat transfer properties in the heat exchanger.

6. As indirect heating is used in closed cycle plant, the inferior oil or solid fuel can be used in the furnace and these fuels can be used more economically because these are available in abundance.

7. Finally the closed cycle opens the new field for the use of working medium (other than air as argon, CO_2, helium) having more desirable properties. The theoretical thermal efficiencies of the monoatomic gases will be highest for the closed cycle type gas turbine.

8. The maintenance cost is low and reliability is high due to longer useful life.

9. The thermal efficiency increases as the pressure ratio decreases. Therefore, appreciable higher thermal efficiencies are obtainable with closed cycle for the same maximum and minimum temperature limits as with the open cycle plant.

10. Starting of plane is simplified by reducing the pressure to atmospheric or even below atmosphere so that the power required for starting purposes is reduced considerably.

(B) Disadvantages

1. The system is dependent on external means as considerable quantity of cooling water is required in the pre-cooler.

2. Higher internal pressures involve complicated design of all components and high quality material is required which increases the cost of the plant.

3. The response to the load variations is poor compared to the open-cycle plant,

4. It requires very big heat-exchangers as the heating of workings fluid is done indirectly. The space required for the heat exchanger is considerably large. The full heat of the fuel is also not used in this plant.

The closed cycle is only preferable over open cycle where the inferior type of fuel or solid fuel is to be used and ample cooling water is available at the proposed site of the plant. However, closed cycle gas turbine plants have not as yet been used for electricity production.

This is mainly a consequence of the limitations imposed by the unit size of heat exchanger. The use of a large number of parallel heat exchangers would practically eliminate the economic advantage resulting from increased plant size.

Efficiency

The efficiency of a closed cycle gas turbine **can be explained with the help of the T-S diagram as shown below.**

The efficiency of this can be given as,

n = (available network) / input heat

n = Cp(Wt – Wc) / input heat

$$n = 1 - [(T4-T1) / (T3-T2)]$$

Where 'Wt' = work is done by the gas turbine per kg of air = Cp(T2-T3)

'Wc' = work is done by the compressor per kg of air = Cp(T1-T4)

'Cp' constant pressure is taken in KJ or Kg

'T' = temperature

Input heat = Cp (T3-T2)

The efficiency of this turbine is higher than the open cycle gas turbine

The **closed-cycle gas turbine applications** include the following.

- Used in the generation of electric power
- Used in many industrial applications

- Used in marine propulsion, locomotive propulsion, automotive propulsion
- Used in aviation to provide power to the jet Propulsion

Open Cycle Gas Turbine Power Plant

A simple open cycle gas turbine consists of a compressor, combustion chamber and a turbine as shown in Fig. 2. The compressor takes in ambient air and raises its pressure. Heat is added to the air in combustion chamber by burning the fuel and raises its temperature.

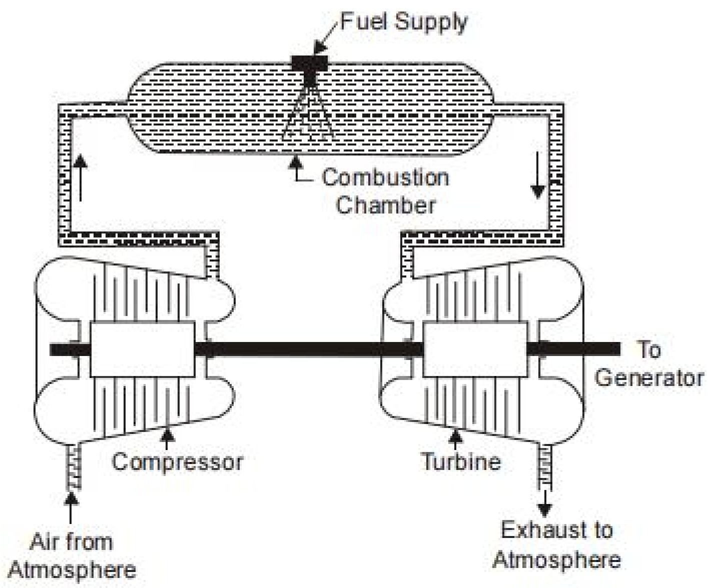


Fig. 2 Open Cycle Gas Turbine Plant.

The heated gases coming out of combustion chamber are then passed to the turbine where it expands doing mechanical work. Part of the power developed by the turbine is utilized in driving the compressor and other accessories and remaining is used for power generation. Since ambient air enters into the compressor and gases coming out of turbine are exhausted into the atmosphere, the working medium must be replaced continuously. This type of cycle is known as open cycle gas turbine plant and is mainly used in majority of gas turbine power plants as it has many inherent advantages.

(A) Advantages

1. **Warm-up time.** Once the turbine is brought up to the rated speed by the starting motor and the fuel is ignited, the gas turbine will be accelerated from cold start to full load without warm-up time.

2. **Low weight and size.** The weight in kg per kW developed is less.

3. **Fuels.** Almost any hydrocarbon fuel from high-octane gasoline to heavy diesel oils can be used in the combustion chamber.

4. Open cycle plants occupy comparatively little space.

5. The stipulation of a quick start and take-up of load frequently are the points in favour of open cycle plant when the plant is used as peak load plant.

6. Component or auxiliary refinements can usually be varied to improve the thermal efficiency and give the most economical overall cost for the plant load factors and other operating conditions envisaged.

7. Open-cycle gas turbine power plant, except those having an intercooler, does not require cooling water. Therefore, the plant is independent of cooling medium and becomes self-contained.

(B) Disadvantages

1. The part load efficiency of the open cycle plant decreases rapidly as the considerable percentage of power developed by the turbine is used to drive the compressor.

2. The system is sensitive to the component efficiency; particularly that of compressor. The open cycle plant is sensitive to changes in the atmospheric air temperature, pressure and humidity.

3. The open-cycle gas turbine plant has high air rate compared to the other cycles, therefore, it results in increased loss of heat in the exhaust gases and large diameter ductwork is necessary.

4. It is essential that the dust should be prevented from entering into the compressor in order to minimize erosion and depositions on the blades and passages of the compressor and turbine and so impairing their profile and efficiency. The deposition of the carbon and ash on the turbine blades is not at all desirable as it also reduces the efficiency of the turbine.

Difference between Open Cycle and Closed Cycle Gas Turbine

Heat source, type of fluid used for working, circulated air, turbine blades capacity, cost of maintenance and installation, etc gives the difference between the open cycle and closed gas turbine. The circulation of working fluid is the main difference.

Open Cycle Gas Turbine	Closed Cycle Gas Turbine
In this type, the combustion chamber is used for heating compressed air. Due to the mixing of products in the combustion chamber and heated air, the gas doesn't remain constant.	In this type, the heating chamber heats the compressed air, which is compressed firstly before heating. When an external source heats the air, then the gas remains constant.
The amount of gas that came out from the turbine is exhausted in the atmosphere	The amount of gas came out from the gas turbine is allowed to pass into the cooling chamber.
Replacement of working fluid is continues	Circulation of working fluid continues.
The working fluid is air	For better thermodynamic properties, helium is used as a working fluid
As the air in the combustion chamber gets contaminated, results in the earlier wearing of turbine blades	As there is no contamination of enclosed gas while passing through the heating chamber, results in no earlier wearing of turbine blades
Mainly used for moving vehicles	Mainly used for stationary installation and marine applications.
The cost of maintenance is low	The cost of maintenance is high
Installation mass per KW is less	Installation mass per KW is more.

III. Applications

1. Gas turbine plants are used as standby plants for the hydro-electric power plants.

2. Gas turbine power plants may be used as peak loads plant and standby plants for smaller power units.

3. Gas turbines are used in jet aircrafts and ships. Pulverised fuel fired plants are used in locomotive.

IV. Advantages And Disadvantages of A Gas Turbine Power Plant

Advantages

1. It is smaller in size and weight as compared to an equivalent steam power plant. For smaller capacities the size of the gas turbine power plant is appreciably greater than a high speed diesel engine plant but for larger capacities it is smaller in size than a comparable diesel engine plant. If size and weight are the main consideration such as in ships, aircraft engines and locomotives, gas turbines are more suitable.
2. The initial cost and operating cost of the plant is lower than an equivalent steam power plant. A thermal plant of 250 mW capacity cost about Rs. 250 crores. Presently whereas a gas turbine plant of that same-size cost nearly 70 crores.
3. The plant requires less water as compared to a condensing steam power plant.
4. The plant can be started quickly, and can be put on load in a very short time.
5. There are no standby losses in the gas turbine power plant whereas in steam power plant these losses occur because boiler is kept in operation even when the turbine is not supplying any load.
6. The maintenance of the plant is easier and maintenance cost is low.
7. The lubrication of the plant is easy. In this plant lubrication is needed mainly in compressor, turbine main bearing and bearings of auxiliary equipment.
8. The plant does not require heavy foundations and building.
9. There is great simplification of the plant over a steam plant due to the absence of boilers with their feed water evaporator and condensing system.

Disadvantages

1. Major part of the work developed in the turbine is used to derive the compressor. Therefore, network output of the plant is low.
2. Since the temperature of the products of combustion becomes too high so service conditions become complicated even at moderate pressures.

V. Components of a Gas Turbine Power Plant

It is always necessary for the engineers and designers to know about the construction and operation of the components of gas turbine plants.

1. Compressors

The high flow rates of turbines and relatively moderate pressure ratios necessitate the use of rotary compressors. The types of compressors, which are commonly used, are of two types, centrifugal and axial flow types.

The centrifugal compressor consists of an impeller (rotating component) and a diffuser (stationary component). The impeller imparts the high kinetic energy to the air and diffuser converts the kinetic energy into the pressure energy. The pressure ratio of 2 to 3 is possible with single stage compressor and it can be increased upto 20 with three-stage compressor.

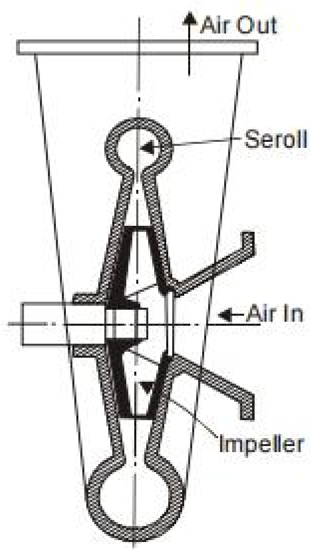


Fig. 3 Single Stage Single Entry centrifugal compressor.

The compressors may have single or double inlet. The **single inlet compressors** are designed to handle the air in the range of 15 to 300 m^3 /min and double inlets are preferred above 300 m^3 /min capacity. The single inlet centrifugal compressor is shown in Fig. 3. The efficiency of centrifugal compressor lies between 80 to 90%. The efficiency of multistage compressor is lower than a single stage due to the losses.

The **axial flow compressor** consists of a series of rotor and stator stages with decreasing diameters along the flow of air. The blades are fixed on the rotor and rotors are fixed on the shaft. The stator blades are fixed on the stator casing. The stator blades guide the air flow to the next rotor stage coming from the previous rotor stage. The air flows along the axis of the rotor. The kinetic energy is given to the air as it passes through the rotor and part of it is converted into pressure. The axial flow compressor is shown in Fig. 4.

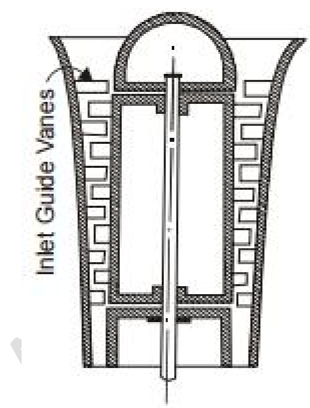


Fig. 4 Axial Flow Air Compressor.

The number of stages required for pressure ratio of 5 is as large as sixteen or more. A satisfactory air filter is absolutely necessary for cleaning the air before it enters the compressor because it is essential to maintain the designed profile of the aerofoil blades. The deposition of dust particles on the blade surfaces reduces the efficiency rapidly.

The advantages of axial flow compressor over centrifugal compressor are high isentropic efficiency (90-95%), high flow rate and small weight for the same flow quantity. The axial flow compressors are very sensitive to the changes in airflow and speed, which result in rapid drop in efficiency.

In both types of compressors, it has been found that lowering of the inlet air temperature by 15 to 20°C gives almost 25% greater output with an increase of

5% efficiency compressors may have single or double inlet. The single inlet compressors are designed to handle the air in the range of 15 to 300 m^3 /min and double inlets are preferred above 300 m^3 /min capacity. The single inlet centrifugal compressor is shown in **Fig. 3**. The efficiency of centrifugal compressor lies between 80 to 90%. The efficiency of multistage compressor is lower than a single stage due to the losses. The axial flow compressor consists of a series of rotor and stator stages with decreasing diameters along the flow of air.

2. Intercoolers and heat exchangers

The intercooler is generally used in gas turbine plant when the pressure ratio used is sufficiently large and the compression is completed with two or more stages. The cooling of compressed air is generally done with the use of cooling water. A cross-flow type intercooler is generally preferred for effective heat transfer. The regenerators, which are commonly used in gas turbine plant, are of two types, recuperator and regenerator. In a recuperative type of heat exchanger, the air and hot gases are made to flow in counter direction as the effect of counterflow gives high average temperature difference causing the higher heat flow.

A number of baffles in the path of airflow are used to make the air to flow in contact for longer time with heat transfer surface. The regenerator type heat exchanger consists of a heat-conducting member that is exposed alternately to the hot exhaust gases and the cooler compressed air. It absorbs the heat from hot gases and gives it up when exposed to the air. The heat, capacity member is made of a metallic mesh or matrix, which is rotated slowly (40-60 r.p.m.) and continuously exposed to hot and cold air.

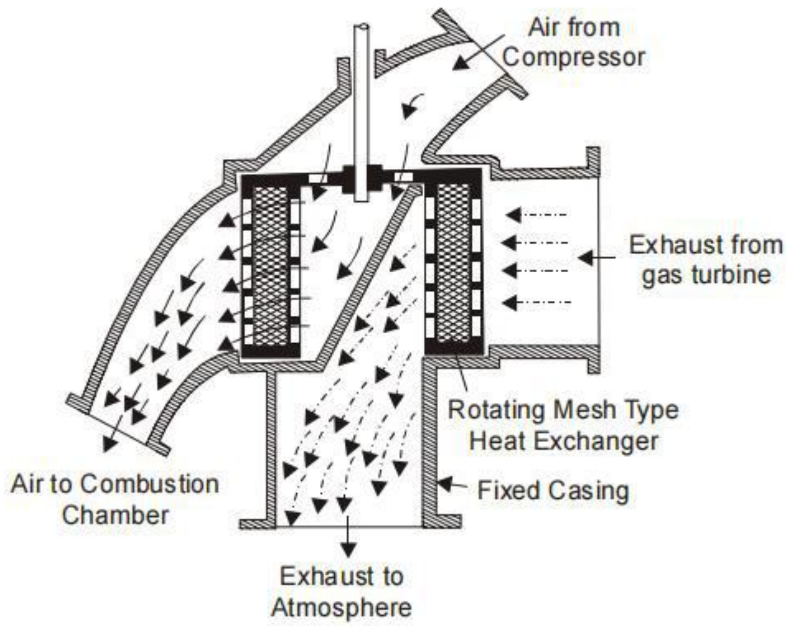


Fig. 5 Ritz Regenerative Heat Exchanger.

Prof. Ritz suggested the first application of regenerative heat exchanger to gas turbine plants of Germany and the heat exchanger was titled against his name. The arrangement of Ritz heat exchanger is shown in Fig. 5.

The heat-exchanging element A is slowly rotated by a drive from the gas turbine via shaft S. The rotation places the heat-transferring element A in the exhaust gas passage for one half of the time required for one r.p.m. and in the air supply passage for the remaining half. The heat element absorbs heat from the hot gases, when exposed to hot gases and gives out the same heat to the cold air when the heated part moves in the air region. By suitable design of the speed of rotation of transfer element and its mass in relation to the heat to be transferred, it is possible to secure a high effectiveness, values of 90% are claimed. The principal advantages claimed of this heat exchanger over the recuperative type are lightness, smaller mass, and small size for given effectiveness and low-pressure drop.

The major disadvantage of this heat exchanger is, there will be always a tendency for air leakage to the exhaust gases as the compressed air is at a much higher pressure than exhaust gases. This tendency of leakage reduces the efficiency gain due to heat exchanger. Therefore, the major problem in the design of this type of heat exchanger is to prevent or minimize the air loss due to leakage.

Recently very special seals are provided to prevent the air leakage. This seal stands at very high temperature and pressure and allows the freedom of movement.

The performance of the heat exchanger is determined by a factor known as effectiveness. The effectiveness of the heat exchanger is defined as

$$\varepsilon = \frac{\text{actual heat transfer to the air}}{\text{maximum heat transfer theoretically possible}}$$

The effectiveness is given by

$$\varepsilon = \frac{C_{pa}\, m_a\, (T_5 - T_2)}{C_{pg}\, m_g\, (T_4 - T_2)}$$

where m_a and m_g are the masses of the air and exhaust gases and C_{Pa} and C_{Pg} are the corresponding specific heats.

If the mass of the fuel compared with mass of the air, is neglected and $C_{Pa} = C_{Pg}$ is assumed, then the effectiveness is given by an expression

$$\varepsilon = \frac{T_5' - T_2}{T_4 - T_2}$$

3. Combustion Chambers

The gas turbine is a continuous flow system; therefore, the combustion in the gas turbine differs from the combustion in diesel engines. High rate of mass flow results in high velocities at various points throughout the cycle (300 m/sec). One of the vital problems associated with the design of gas turbine combustion system is to secure a steady and stable flame inside the combustion chamber. The gas turbine combustion system has to function under certain different operating conditions which are not usually met with the combustion systems of diesel engines. A few of them are listed below:

1. Combustion in the gas turbine takes place in a continuous flow system and, therefore, the advantage of high pressure and restricted volume available in

diesel engine is lost. The chemical reaction takes place relatively slowly thus requiring large residence time in the combustion chamber in order to achieve complete combustion.

2. The gas turbine requires about 100:1 air-fuel ratio by weight for the reasons mentioned earlier. But the air-fuel ratio required for the combustion in diesel engine is approximately 15:1.

Therefore, it is impossible to ignite and maintain a continuous combustion with such weak mixture. It is necessary to provide rich mixture fm ignition and continuous combustion, and therefore, it is necessary to allow required air in the combustion zone and the remaining air must be added after complete combustion to reduce the gas temperature before passing into the turbine.

3. A pilot or re-circulated zone should be created in the main flow to establish a stable flame that helps to ignite the combustible mixture continuously.

4. A stable continuous flame can be maintained inside the combustion chamber when the stream velocity and fuel burning velocity are equal. Unfortunately most of the fuels have low burning velocities of the order of a few meters per second, therefore, flame stabilization is not possible unless some technique is employed to anchor the flame in the combustion chamber.

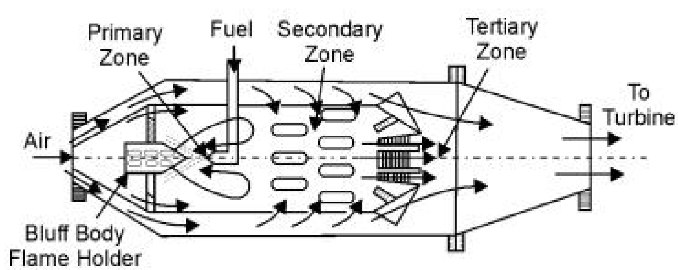


Fig. 6 Combustion Chamber with Upstream Injection with Bluff-body Flame Holder.

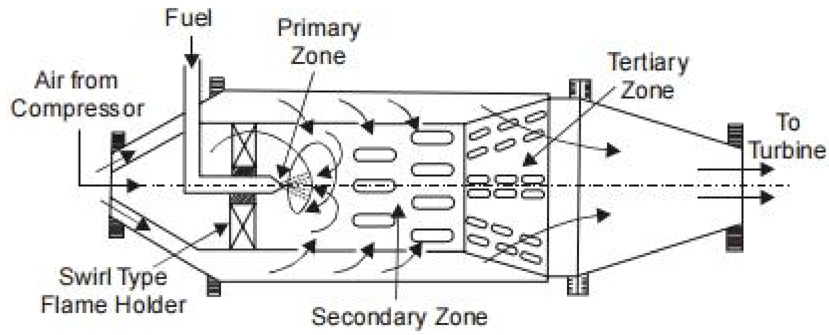


Fig. 7 Combustion Chamber with Downstream Injection and Swirl Holder.

The common methods of flame stabilization used in practice are bluff body method and swirl flow method. Two types of combustion chambers using bluff body and swirl for flame stabilization are shown in Fig. 6 and Fig. 7. The major difference between two is the use of different methods to create pilot zone for flame stabilization. Nearly 15 to 20% of the total air is passed around the jet of fuel providing rich mixture in the primary zone. This mixture burns continuously in the primary (pilot) zone and produces high temperature gases. About 30% of the total air is supplied in the secondary zone through the annuals around the flame tube to complete the combustion. The secondary air must be admitted at right points in the combustion chamber otherwise the cold injected air may chill the flame locally thereby reducing the rate of reaction. The secondary air helps to complete the combustion as well as helps to cool the flame tube. The remaining 50% air is mixed with burnt gases in the "tertiary zone" to cool the gases down to the temperature suited to the turbine blade materials.

By inserting a bluff body in mainstream, a low-pressure zone is created downstream side that causes the reversal of flow along the axis of the combustion chamber to stabilize the flame.

In case of swirl stabilization, the primary air is passed through the swirler, which produces a vortex motion creating a low-pressure zone along the axis of the chamber to cause the reversal of flow. Sufficient turbulence must be created in all three zones of combustion and uniform mixing of hot and cold bases to give uniform temperature gas stream at the outlet of the combustion chamber.

4. Gas Turbines

The common types of turbines, which are in use, are axial flow type. The basic requirements of the turbines are lightweight, high efficiency; reliability in operation and long working life. Large work output can be obtained per stage with high blade speeds when the blades are designed to sustain higher stresses. More stages of the turbine are always preferred in gas turbine power plant because it helps to reduce the stresses in the blades and increases the overall life of the turbine. More stages are further preferred with stationary power plants because weight is not the major consideration in the design which is essential in aircraft turbine-plant.

The cooling of the gas turbine blades is essential for long life as it is continuously subjected to high temperature gases. There are different methods of cooling the blades. The common method used is the air-cooling. The air is passed through the holes provided through the blade.

VI. Gas Turbine Fuels

Gas turbines can use a wide variety of liquid and gaseous fuels (conventional or nonconventional type). Conventional fuels used regularly at gas turbine installations in the power and process industries are natural gas and various grades of fuel oils, ranging from light petroleum naphthas to residual fuels. Nonconventional fuels used less frequently include crude oils, refinery gas, and propane. Other nonconventional fuels that can be used, and that are further characterized as synthetic fuels, include gaseous and liquid fuels derived, respectively, from coal gasification and liquefaction processes. In addition, research and development continues with regard to using coal-oil mixtures and coal-water mixtures as fuel for gas turbines.

1. Conventional Fuels

The fuel burned in the gas turbine has a decided effect on unit performance and fuel treatment requirements. A gas turbine, when firing natural gas, will have a higher output and a lower heat rate than the same gas turbine firing fuel oil.

a. Natural Gas

In general, natural gas is an ideal fuel for use in gas turbines because it is practically free from solid residue. Furthermore, natural gas usually has little inherent sulfur content and is environmentally acceptable because the resulting SO_2 emissions are inherently low.

Methane (CH_4) and ethane (C_2H_6) are the principal combustible constituents of natural gas. Natural gas may contain significant quantities of nitrogen, N_2 and CO_2. The lower heating value (LHV) of natural gas can range from 11 to 56 MJ/m^3 depending on composition, but the heating value for natural gas is normally in the range of 37 MJ/m^3.

b. Liquid Fuel Oil

Liquid fuel oils burned in gas turbines include both true distillates and ash-bearing fuels. Light distillates generally do not require preheating because they have sufficiently low pour points under most ambient conditions. Heavy distillates can have high pour points because of the high wax content. Preheating heavy distillates is desirable to prevent filter plugging.

2 Nonconventional Fuels

a. Crude Oil

Crude oils can also be burned in gas turbines. However, the flash point for crude oils is low because of the light fractions that are present. These light fractions are otherwise normally driven off during distillation processes. Because of the low flash point, crude oils represent a greater fire hazard than true distillates and require special handling methods. Plants firing crude oils may require more extensive fire protection systems and alternate, more conventional fuel for startup and shut-down.

b. Refinery Gas

Refinery gas is produced during the conversion of crude oil to gasoline and other products. Refinery gas generally has relatively high heating value and typically may be blended with lower heating value gas byproducts prior to burning. Because of its nature, limited quantities of refinery gas are available.

c. Propane

Propane is nonnally used only as a backup fuel for instances where an interruption in the primary fuel supply (natural gas or oil) may occur. Propane also may be used as a startup fuel.

d. Synthetic Fuels

Because of the abundance of coal, synthetic fuels produced from coal by chemical or physical processes hold much promise for future, large-scale use. In addition to chemical processing, coal can be physically mixed with a liquid (water or oil) to produce a liquid mixture that can then be used as fuel in gas turbines.

VII. Performance of Gas Turbine Plants

Starting sequence of any gas turbine from rest to its rated speed requires a certain order of events to be accomplished either manually or automatically. The major steps in sequence are cranking, ignition, acceleration and governing. The following is typical starting sequence of a gas turbine

1. Application of control power illuminates all the malfunctions lights.
2. Operate 'Reset switch' to reset malfunctions circuits: By doing so, malfunction lights go off and all control devices assume the condition for starting.

3. Operate “Start” switch to initiate starting sequence. By doing this, lube oil pump and cooling fan start. If there are separate switch for these, operate these.
4. When lube oil reaches a preset pressure, the starter is energized and cranking of the engine begins.
5. With the cranking of starting of starter, the engine and exhausts ducts are purged of any combustible gases that might be present.
6. During the cranking cycle, the fuel boost pump is used and operated to increase fuel pressure.
7. As soon as the fuel pressure has reached a prescribed minimum value, fuel and ignition switches are turned on provided a preset turbine speed has been reached.
8. The turbine accelerates due to combustion of fuel and assistance of cranking motor. At a preset value, say in the order of 70% of rated speed, the starter and ignition are cut-off automatically.
9. The turbine becomes self- sustaining and accelerates on its own to its governed speed till the governing system takes over the control.

To stop the gas turbine fuel supply should be turned off. This is accomplished by closing the fuel valve either manually or by de-energizing an electrically operated valve. In cases where sleeve bearings are used, circulation of lube oil to bearings after shutdown is necessary for cooling.

VIII. Analysis of a gas turbine power plant

Gas turbines may operate either on a closed or on an open cycle. The majority of gas turbines currently in use operate on the open cycle in which the working fluid, after completing the cycle is exhausted to the atmosphere. The air fuel ratio used in these gas turbines is approximately 60:1.

The ideal cycle for gas turbine is **Brayton** Cycle or **Joule** Cycle. This cycle is of the closed type using a perfect gas with constant specific heats as a working fluid. This cycle is a constant pressure cycle and is shown in **Fig. 9.24**. On P-V diagram and in **Fig. 9.25** on T-ϕ diagram.

This cycle consists of the following processes:

The cold air at 3 is fed to the inlet of the compressor where it is compressed along 3-4 and then fed to the combustion chamber where it is heated at constant pressure along 4-1. The hot air enters the turbine at 1 and expands adiabatically along 1-2 and is then cooled at constant pressure along 2-3.

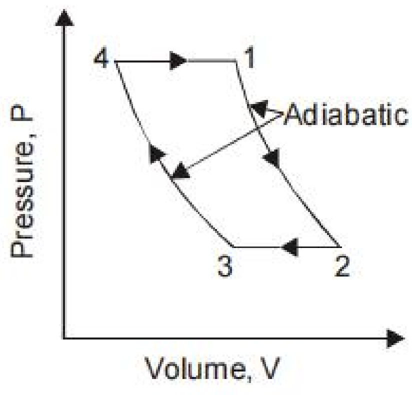


Fig. 9.24

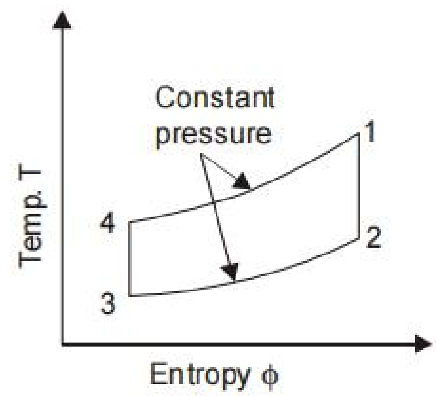


Fig. 9.25

Heat supplied to the system = $K_p(T_1 - T_4)$

Heat rejected from the system = $K_p(T_2 - T_3)$

where K_p = Specific heat at constant pressure,

Work done = Heat supplied – Heat rejected

$= K_p(T_1 - T_4) - K_p(T_2 - T_3)$

Thermal efficiency (η) of Brayton Cycle

$$\eta = \frac{\text{Work done}}{\text{Heat Supplied}} = \frac{[K_1\{(T_1 - T_4) - (T_2 - T_3)\}]}{[K_p(T_1 - T_4)]}$$

$$\eta = 1 - \frac{(T_2 - T_3)}{(T_1 - T_4)} \qquad \text{...(1)}$$

For expansion 1-2

$$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{(\gamma-1)/\gamma}$$

$$T_1 = T_2\left[\left(\frac{P_1}{P_2}\right)^{(\gamma-1)/\gamma}\right]$$

For compression 3-4

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{(\gamma-1)/\gamma} = \left(\frac{P_1}{P_2}\right)^{(\gamma-1)/\gamma}$$

$$T_4 = T_3\left[\left(\frac{P_1}{P_2}\right)^{(\gamma-1)/\gamma}\right]$$

Substituting the values of T_1 and T_4 in equation (1), we get

$$\eta = 1 - \frac{(T_2 - T_3)}{\left[\left\{T_2\left(\left(\frac{P_1}{P_2}\right)^{(\gamma-1)/\gamma}\right)\right\} - \left\{T_3\left(\left(\frac{P_1}{P_2}\right)^{(\gamma-1)/\gamma}\right)\right\}\right]}$$

$$\eta = 1 - \frac{(T_2 - T_3)}{\left[\left(\frac{P_1}{P_2}\right)^{(\gamma-1)/\gamma}(T_2 - T_3)\right]}$$

Effect of Blade Friction

In a gas turbine there is always some loss of useful heat drop due to frictional resistance offered by the nozzles and blades of gas turbine thus resulting drop in velocity. The energy so lost in friction is converted into heat and, therefore, the gases get reheated to some extent. Therefore, the actual heat drop is less than the adiabatic heat drop as shown in Fig. 9.26, where 1-2′ represents the adiabatic expansion and 1-2 represents the actual expansion.

Actual heat drop $= K_p(T_1 - T_2)$

Adiabatic heat drop $= K_p(T_1 - T_2')$

Adiabatic efficiency of turbine

$$= \frac{\text{Actual heat drop}}{\text{Adiabatic heat drop}} = \frac{[K_p (T_1 - T_2)]}{[K_p (T_1 - T_2)']} = \frac{(T_1 - T_2)}{(T_1 - T_2)'}$$

For adiabatic process $1 - 2'$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}$$

In the compressor also reheating takes place, which causes actual heat increase to be more than adiabatic heat increase. The process 3-4 represents the actual compression while 3-4′ represents adiabatic compression.

Adiabatic heat drop $= K_p(T'_4 - T_3)$

Actual heat drop $= K_p(T_4 - T_3)$

Adiabatic efficiency of compressor

$$= \frac{K_p (T'_p - T_3)}{K'_p (T_4 - T_3)} = \frac{T_4 - T_3}{T_4 - T_3}$$

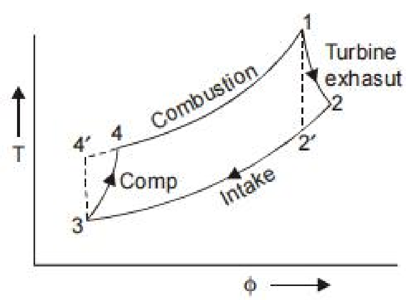


Fig. 9.26

Improvement In Open Cycle

The open cycle for gas turbine is shown in Fig. 9.26. The fresh atmospheric is taken in at the point 3 and exhaust of the gases after expansion in turbine takes place at the point 2. An improvement in open cycle performance can he effected by the addition of a heat exchanger that raises the temperature of the compressed air entering the turbine by lowering exhaust gas temperature that is a waste otherwise. Less fuel is now required in the combustion chamber to attain a specified turbine inlet temperature. This is called a regenerative cycle (Fig. 9.27). This regenerative cycle is shown on T-ϕ diagram in Fig. 9.28. Where ϕ = entropy

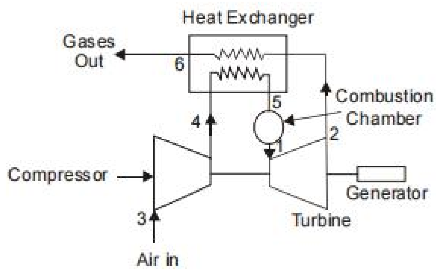


Fig. 9.27

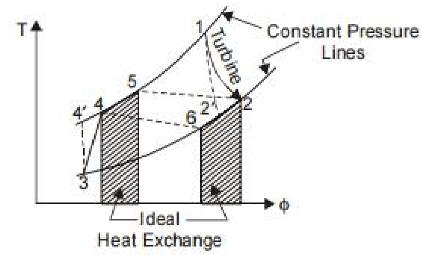


Fig. 9.28

Heat supplied = $K_p(T_1 - T_3) = K_p(T_1 - T_2)$

Heat rejected = $K_p(T_5 - T_3) = K_p(T_4 - T_3)$

(η) Thermal efficiency of theoretical regenerative cycle

$$(\eta) = \frac{K_p(T_1 - T_2) - K_p(T_4 - T_3)}{K_p(T_1 - T_5)}$$

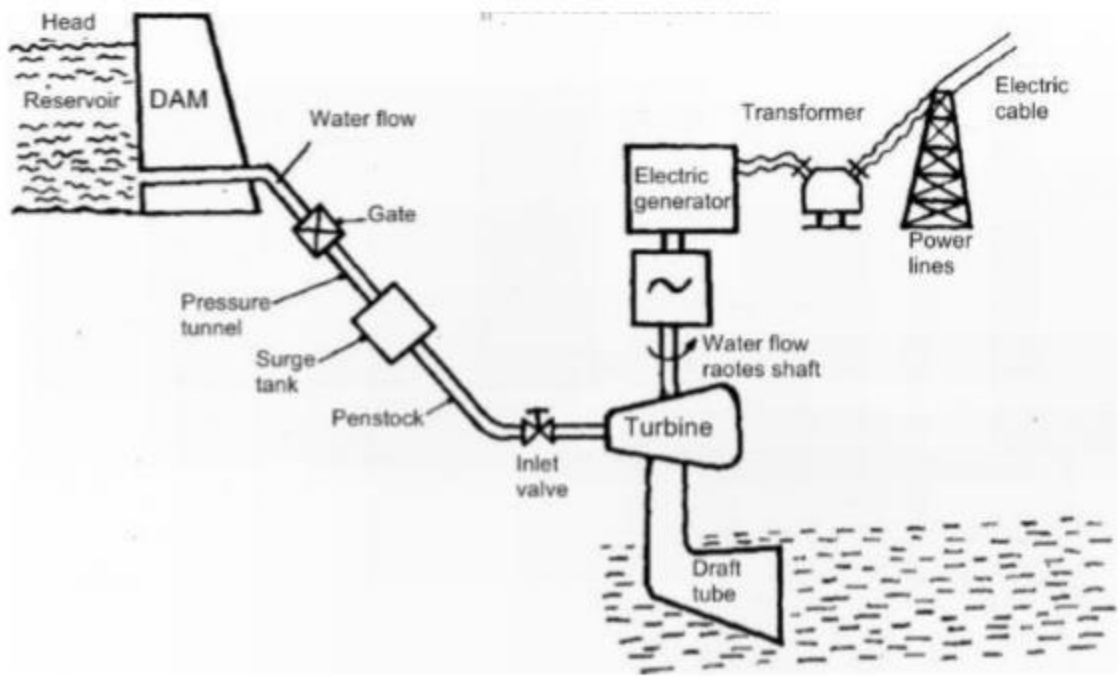
For isentropic compression and isentropic expansion thermal efficiency is given by

$$\eta = \frac{K_p(T_2 - T_2') - K_p(T_4 - T_3)}{K_p(T_1 - T_5)}$$

UNIT V (A) Hydraulic Power Plant

Hydro Electric Power Plant:

Working principle of hydroelectric power plant depends on the conversion of hydraulic energy into electrical energy. To get this hydroelectricity, hydroelectric power plant needs some arrangements for proper working and efficiency. The block diagram of hydroelectric power plant is shown below:



- Hydroelectric power station needs huge amount of water at sufficient head all the time. So a hydroelectric dam is constructed across the river or lake.
- An artificial storage reservoir where water is stored, is placed back side of the dam. This reservoir creates sufficient water head. A pressure tunnel is placed in between the reservoir to valve house and water is coming from reservoir to penstock via this tunnel.
- An automatic controlling sluice valve is placed in valve house and it controls water flow to the power station and the letter cuts off supply of water in case the

penstock bursts. Penstock is a huge steel pipe in which water is taken from valve house to turbine.

- A surge tank is also provided just before the valve house for better regulation of water pressure in the system. Now water turbine converts hydraulic energy into mechanical energy and an alternator which is couple to the water turbine converts this mechanical energy into electrical energy**.**

Hydroelectric Power Plant Components: It consists of mainly 5 Parts

1. Dam and Reservoir
2. Control Gate
3. Penstock
4. Water Turbine
5. Generator
6. Surge tank

1. Dam and Reservoir: When we hearing the word Dam that means sufficient water storage at some height (Because when the water from some height release so the velocity increase and which is further used for the generation of electricity with the use of turbine). The dam forms a large reservoir behind it. The height of the water level (called a water head) in the reservoir determines how much potential energy is stored in it.

2. Control Gate: In simple words, this is like controlling the flow of water (first Water from the reservoir is allowed to flow through the penstock and to the turbine). The amount of water that is to be released in the penstock can be controlled by a control gate.

When the control gate is fully opened, the maximum amount of water is released through the Penstock

3. Penstock: The potential energy of the water is converted into kinetic energy as it flows down through the Penstock due to gravity.

4. Water Turbine or Hydraulic Turbine: The flow of water from the Penstock is taken into the water turbine. The turbine is mechanically coupled to an electric generator. The kinetic energy of the water drives the turbine and consequently, the generator gets driven.

Generator: A generator is mounted in the powerhouse and it is mechanically coupled to the turbine shaft. When the turbine blades are rotated, it drives the generator, The electricity is generated which is then stepped up with the help of a transformer for the transmission purpose.

5. Surge Tank: The Surge tanks are usually provided in high or medium head power plants when considerably long Penstock is required. A surge tank is a small reservoir or tank which is open at the top. It is fitted between the reservoir and the powerhouse. The water level in the surge tank rises or falls to reduce the pressure swings in the Penstock

Advantages:

1. Low operating cost compared to a thermal power plant.
2. The cost of generation is unaffected by the load factor.
3. No fuel charges.
4. High useful life of about 100 – 125 years.
5. Low maintenance cost compared to the thermal power plant
6. Highly reliable.
7. It can be started quickly and synchronize the plant.
8. There is no problem with fuel and ash handling.
9. No nuisance of smoke exhaust gases and soots.
10. No health hazards due to air pollution.
11. It has no standby losses.
12. The machines used in hydel plants are robust and no problem of high temperature and pressure.
13. The efficiency of the hydel plant does not change with age.
14. The number of operations required is considerably small.
15. It can serve the purpose of flood control and stored water can be used for drinking and irrigation work.
16. Less labour is required to operate the plant.

Disadvantages:

1. High capital cost.
2. Power generation only dependent on the quantity of water availability.
3. It takes a considerably long time for the construction
4. Site of the hydro-electric power station is always away from the load centre, therefore transmission cost becomes high.
5. Sometimes isolated sites are difficult to access.

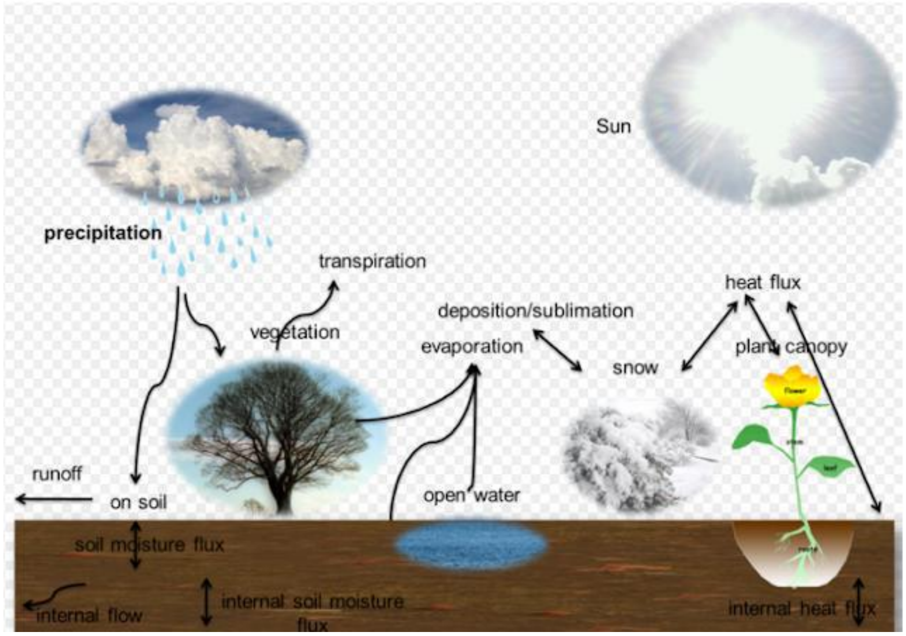
Introduction to Water Power:

Hydro power or water power (from Greek) is power derived from the energy of falling water or fast running water, which may be harnessed for useful purposes. Since ancient times, hydro power from many kinds of watermills has been used as a renewable energy source for irrigation and the operation of various mechanical devices, such as gristmills, sawmills, textile mills, trip hammers, dock cranes, domestic lifts, and ore mills. A tromp, which produces compressed air from falling water, is sometimes used to power other machinery at a distance.

Hydro Cycle / Water Cycle / Hydro-logical Cycle:

- The sun, which drives the water cycle, heats water in oceans and seas. Water evaporates as water vapor into the air. Some ice and snow sublimates directly into water vapor.
- Evapo-transpiration is water transpired from plants and evaporated from the soil. The water molecule H_2O has smaller molecular mass than the major components of the atmosphere, nitrogen and oxygen, N_2 and O_2, hence is less dense.
- Due to the significant difference in density, buoyancy drives humid air higher. As altitude increases, air pressure decreases and the temperature drops (see Gas laws).
- The lower temperature causes water vapor to condense into tiny liquid water droplets which are heavier than the air, and fall unless supported by an updraft. A huge concentration of these droplets over a large space up in the atmosphere become visible as cloud.
- Some condensation is near ground level, and called fog. Atmospheric circulation moves water vapor around the globe, cloud particles collide, grow, and fall out of the upper atmospheric layers as precipitation. Some precipitation falls as snow or hail, sleet, and can accumulate as ice caps and glaciers, which can store frozen water for thousands of years. Most water falls back into the oceans or onto land as rain, where the water flows over the ground as surface runoff.
- A portion of runoff enters rivers in valleys in the landscape, with stream flow moving water towards the oceans. Runoff and water emerging from the ground (groundwater) may be stored as freshwater in lakes. Not all runoff flows into rivers, much of it soaks into the ground as infiltration. Some water infiltrates deep into the ground and replenishes aquifers, which can store freshwater for long periods of time.
- Some infiltration stays close to the land surface and can seep back into surface-water bodies (and the ocean) as groundwater discharge.
- Some groundwater finds openings in the land surface and comes out as freshwater springs. In river valleys and floodplains, there is often continuous water exchange between surface water and ground water in the hyporheic zone. Over time, the water returns to the ocean, to continue the water cycle.

Process:



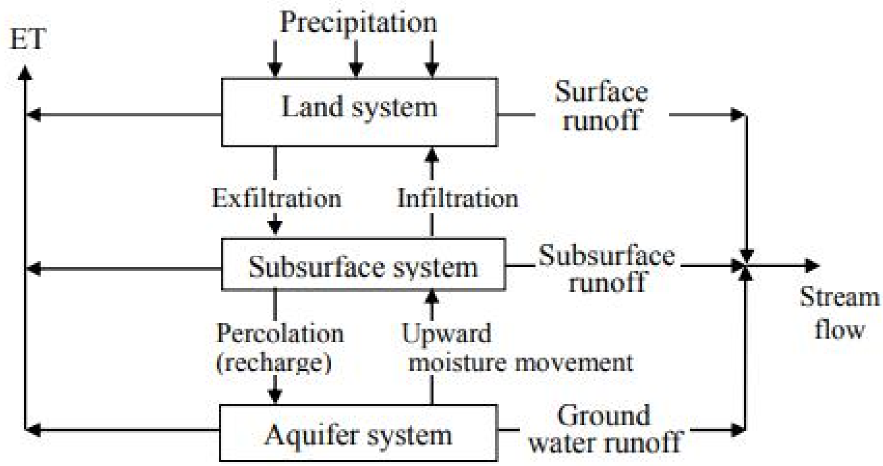
Precipitation: Condensed water vapor that falls to the Earth's surface. Most precipitation occurs as rain, but also includes snow, hail, fog drip, graupel, and sleet.
Canopy interception: The precipitation that is intercepted by plant foliage eventually evaporates back to the atmosphere rather than falling to the ground.
Snow melt: The runoff produced by melting snow.
Runoff: The variety of ways by which water moves across the land. This includes both surface runoff and channel runoff. As it flows, the water may seep into the ground, evaporate into the air, become stored in lakes or reservoirs, or be extracted for agricultural or other human uses.
Infiltration: The flow of water from the ground surface into the ground. Once infiltrated, the water becomes soil moisture or groundwater. A recent global study using water stable isotopes, however, shows that not all soil moisture is equally available for groundwater recharge or for plant transpiration.
Subsurface flow: The flow of water underground, in the vadose zone and aquifers. Subsurface water may return to the surface (e.g. as a spring or by being pumped) or eventually seep into the oceans. Water returns to the land surface at lower elevation than where it infiltrated, under the force of gravity or gravity induced pressures. Groundwater tends to move slowly and is replenished slowly, so it can remain in aquifers for thousands of years.
Evaporation: The transformation of water from liquid to gas phases as it moves from the ground or bodies of water into the overlying atmosphere. The source of energy for evaporation is primarily solar radiation. Evaporation often implicitly includes transpiration from plants, though together they are specifically referred to as evapo transpiration.

Sublimation: The state change directly from solid water (snow or ice) to water vapor by passing the liquid state.
Deposition: This refers to changing of water vapor directly to ice.
Advection: The movement of water through the atmosphere.Without advection, water that evaporated over the oceans could not precipitate over land.
Condensation: The transformation of water vapor to liquid water droplets in the air, creating clouds and fog.
Transpiration: The release of water vapor from plants and soil into the air.
Percolation: Water flows vertically through the soil and rocks under the influence of gravity.
Plate tectonics: Water enters the mantle via subduction of oceanic crust. Water returns to the surface via volcanism.
The water cycle involves many of these processes.

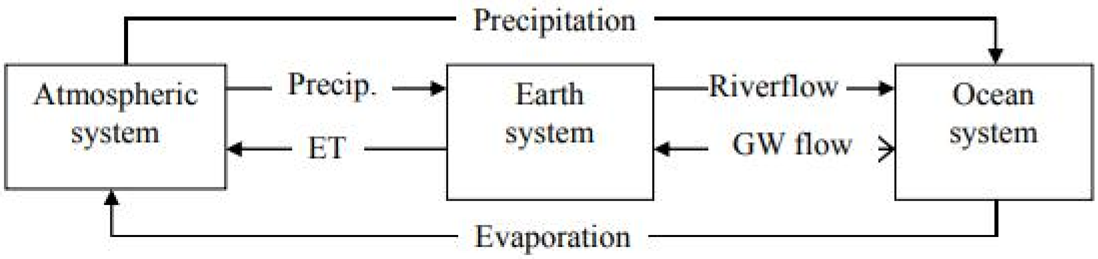
Scales for study of hydrologic cycle:

From the point of view of hydrologic studies, two scales are readily distinct. These are the global scale and the catchment scale.

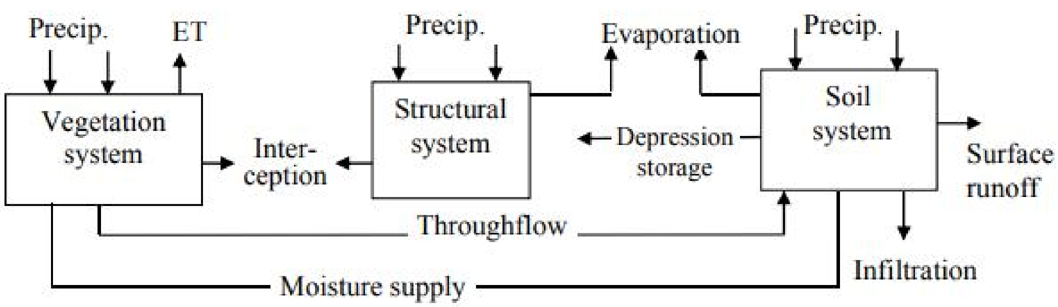
Global scale From a global perspective, the hydrologic cycle can be considered to be comprised of three major systems; the oceans, the atmosphere, and the landsphere. Precipitation, runoff and evaporation are the principal processes that transmit water from one system to the other. This illustration depicts a global geophysical view of the hydrologic cycle and shows the interactions between the earth (lithosphere), the oceans (hydrosphere), and the atmosphere. The study at the global scale is necessary to understand the global fluxes and global circulation patterns. The results of these studies form important inputs to water resources planning for a national, regional water resources assessment, weather forecasting, and study of climate changes. These results may also form the boundary conditions of small-scale models/applications.



A schematic of the hydrologic cycle of the earth system.



A global schematic of the hydrologic cycle.



A detailed schematic of the hydrologic cycle in the land system.

Catchment Scale

While studying the hydrologic cycle on a catchment scale, the spatial coverage can range from a few square km to thousands of square km. The time scale could be a storm lasting for a few hours to a study spanning many years. When the water movement of the earth system is considered, three systems can be recognized: the land (surface) system, the subsurface system, and the aquifer (or geologic) system. When the attention is focused on the hydrologic cycle of the land system, the dominant processes are precipitation, evapotranspiration, infiltration, and surface runoff. The land system itself comprises of three subsystems: vegetation subsystem, structural subsystem and soil subsystem. These subsystems subtract water from precipitation through interception, depression and detention storage. This water is either lost to the atmospheric system or enters subsurface system. The exchange of water among these subsystems takes place through the processes of infiltration, exfiltration, percolation, and capillary rise.

Timescales in the hydrologic cycle

The time required for the movement of water through various components of the hydrologic cycle varies considerably. The velocity of stream flow is much higher compared to the velocity of groundwater. The time-step size for analysis depends upon the purpose of the study, the availability of data, and how detailed the study is. The estimated periods of renewal of water resources in water bodies on the earth is given in Table.T he time step should be sufficiently small so that the variations in the processes can be captured in sufficient detail but at the same time, it should not put an undue burden on data collection and computational efforts.

Drainage Area Characteristics:

- A drainage basin is an area of land where precipitation collects and drains off into a common outlet, such as into a river, bay, or another body of water.
- The drainage basin includes all the surface water from rain runoff, snowmelt, and nearby streams that run downslope towards the shared outlet, as well as the groundwater underneath the earth's surface.
- Drainage basins connect into other drainage basins at lower elevations in a hierarchical pattern, with smaller sub-drainage basins, which in turn drain into another common outlet.
- Other terms used interchangeably with drainage basin are catchment area, catchment basin, drainage area, river basin, and water basin.
- In North America, the term watershed is commonly used to mean a drainage basin, though in other English-speaking countries, it is used only in its original sense, that of a drainage divide.
- In a closed drainage basin or endorheic basin, the water converges to a single point inside the basin, known as a sink, which may be a permanent lake, a dry lake, or a point where surface water is lost underground.
- The drainage basin acts as a funnel by collecting all the water within the area covered by the basin and channeling it to a single point.
- Each drainage basin is separated topographically from adjacent basins by a perimeter, the drainage divide, making up a succession of higher geographical features (such as a ridge, hill or mountains) forming a barrier.

- Drainage basins are **similar but not identical** to hydrologic units, which are drainage areas delineated so as to nest into a multi-level hierarchical drainage system.
- Hydrologic units are defined to allow multiple inlets, outlets, or sinks. In a strict sense, all drainage basins are hydrologic units but not all hydrologic units are drainage basins.

Characteristics:

Topography: Generally, topography plays a big part in how fast runoff will reach a river. The rain that falls in steep mountainous areas will reach the primary river in the drainage basin faster than flat or lightly sloping areas (e.g., > 1% gradient).
Shape: The shape will contribute to the speed with which the runoff reaches a river. A long thin catchment will take longer to drain than a circular catchment.
Size: Size will help determine the amount of water reaching the river, as the larger the catchment the greater the potential for flooding. It is also determined on the basis of length and width of the drainage basin.
Soil type: Soil type will help determine how much water reaches the river. Certain soil types such as sandy soils are very free-draining, and rainfall on sandy soil is likely to be absorbed by the ground. However, soils containing clay can be almost impermeable and therefore rainfall on clay soils will run off and contribute to flooding volumes. After prolonged rainfall even free-draining soils can become saturated, meaning that any further rainfall will reach the river rather than being absorbed by the ground. If the surface is impermeable the precipitation will create surface run-off which will lead to higher risk of flooding; if the ground is permeable, the precipitation will infiltrate the soil.
Land use: Land use can contribute to the volume of water reaching the river, in a similar way to clay soils. For example, rainfall on roofs, pavements, and roads will be collected by rivers with almost no absorption into the groundwater.

Classification of Dams & Spillways: Based on the functions of the dam, it can be classified as follows:
Storage dams: They are constructed to store water during the rainy season when there is a large flow in the river. Many small dams impound the spring runoff for later use in dry summers. Storage dams may also provide a water supply or improved habitat for fish and wildlife. They may store water for hydroelectric power generation, irrigation or for a flood control project. Storage dams are the most common type of dams and in general, the dam means a storage dam unless qualified otherwise.
Diversion dams: A diversion dam is constructed for the purpose of diverting water of the river into an off-taking canal (or a conduit). They provide sufficient pressure for pushing water into ditches, canals, or other conveyance systems. Such shorter dams are used for irrigation, and for diversion from a stream to a distant storage reservoir. A diversion dam is usually of low height and has a small storage reservoir on its

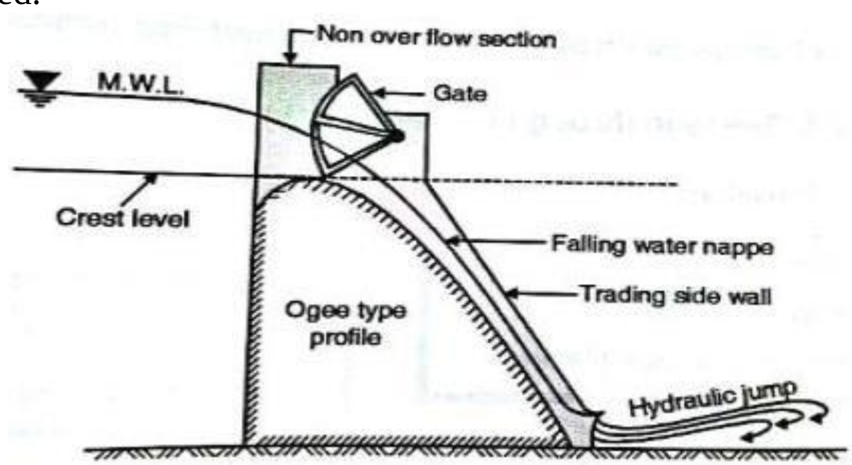
upstream. The diversion dam is a sort of storage weir which also diverts water and has small storage. Sometimes, the terms weirs and diversion dams are used synonymously.

Detention dams: Detention dams are constructed for flood control. A detention dam retards the flow in the river on its downstream during floods by storing some flood water. Thus the effect of sudden floods is reduced to some extent. The water retained in the reservoir is later released gradually at a controlled rate according to the carrying capacity of the channel downstream of the detention dam. Thus the area downstream of the dam is protected against the flood.

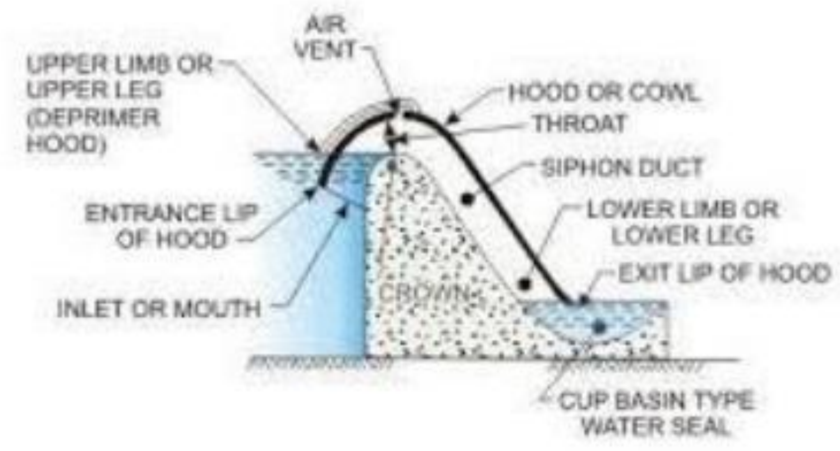
Debris dams: A debris dam is constructed to retain debris such as sand, gravel, and driftwood flowing in the river with water. The water after passing over a debris dam is relatively clear.

Cofferdams: It is an enclosure constructed around the construction site to exclude water so that the construction can be done in dry. A cofferdam is thus a temporary dam constructed for facilitating construction. A cofferdam is usually constructed on the upstream of the main dam to divert water into a diversion tunnel (or channel) during the construction of the dam. When the flow in the river during construction of the dam is not much, the site is usually enclosed by the cofferdam and pumped dry. Sometimes a coffer dam on the downstream of the dam is also required.

1)ogee (over flow) spillway: The upper part of the spillway surface matches closely to the profile of the lower nappe of a ventilated sheet of water falling freely from a sharp-crested weir. The lower part of the spillway surface is tangential to the upper curve and supports the falling sheet of water.The downstream end of the spillway is in the form of a reverse curve, which turns the flow onto the apron of a stilling basin or into the spillway discharge channel. Ogee spillway is generally used for concrete and masonry dams. It is ideally suited to wider valleys where sufficient crest length may be provided.



2) Siphon spillway: A siphon spillway (Fig.) is essentially a closed conduit system which uses the principle of siphonic action. The conduit system is in the shape of an inverted U of unequal legs with its inlet end at the normal reservoir storage level. When the reservoir water level rises above the normal level, the initial flow of water is similar to the flow over a weir. When the air in the bend has been exhausted, siphonic action starts and continuous flow is maintained until air enters the bend. The inlet end of the conduit is placed well below the normal reservoir water level to prevent ice and drift from entering the conduit. Therefore, once the siphonic action starts, the spillway continues to discharge even when the reservoir water level has fallen below the normal level.



3) Emergency spillway
4) Side channel spillway
5) Morning glory spillway

Classification of hydro electric power plant: Hydro electric power station may be classified different categories according to the water flow, water head and the demand of load supply in different season:

According to the extent of water flow regulation available:

According to the extent of water flow regulation, hydoelectric power plant may be classified into three categories:

a. Run off river power plants without pondage

b. Run off river power plants with pondage

c. Reservoir power plants

a. Run off river power plants without pondage:

This type of hydroelectric power plant, water is not available all the time. So this type of power station is not suitable for constant steady load. There is no pondage or storage facility available in such type of power plant. Plant is placed in such a area, where water is coming directly from the river or pond. This type of hydroelectric power plant is called run off power plant without pondage. Plant produces hydro electricity only when water is available. This type of plan cannot use all the time. During high flow and low load period, water is wasted and the lean flow periods the plan capacity is very low. Power development capacity of this type of plan is very low and it produces power incidentally. The development cost of such a plant is relatively cheaper than full-time power development hydro electric power plant. Though it is not used for constant steady load supply, it's objective is to generate electricity by using excessive flow of water during flood or rainy season or whatever flow is available to save some sort of our natural resource of energy such as coal etc., diesel etc.

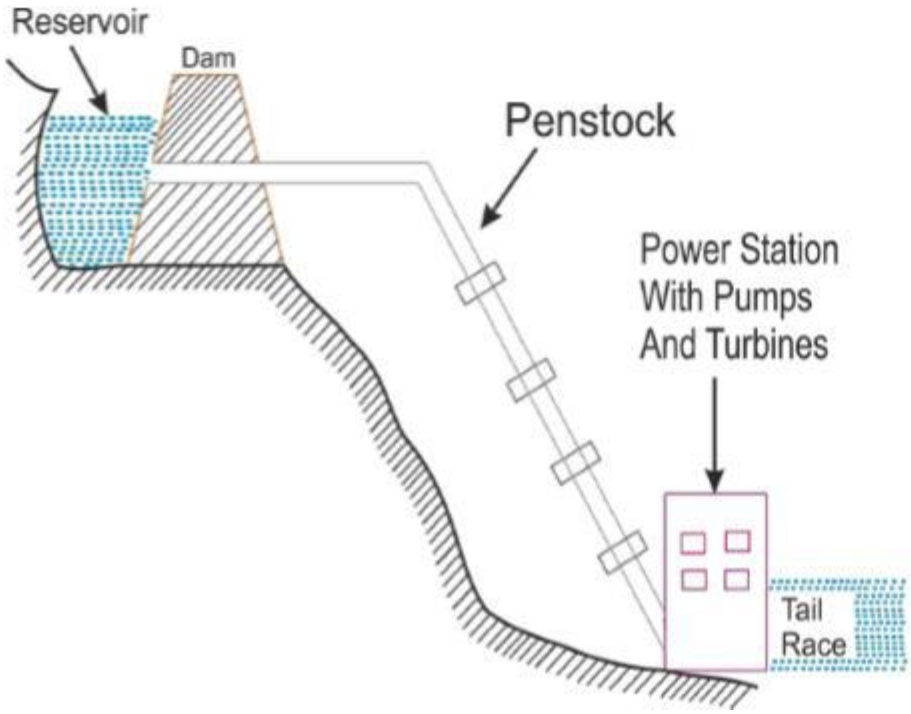
b. Run off river power plants with pondage: This type of plant is used to increase the capacity of pond. The pond is used as a storage water of hydro electric power plant. Increased the pond size means more water is available in the plant, so such type of hydro electric power plant is used fluctuating load period depending on the size of pondage. On a certain limitation, this type of power plant can be a part of load curve and it is more reliable than a hydro plant without pondage. Such type of plant is suitable for both base load or peak load period. During high flow period, this plant is suitable for base load and lean flow period it may be used to supply peak loads only. During high flood period, one thing should keep in mind that flood should not raise tail-race water level. Such types of power plant save conservation of coal.

c. Reservoir power plants

Most hydroelectric power plant in the world is reservoir power plant. This type of plant ,water is stored behind the dam and water is available throughout the year even in dry season. This type of power plant is very efficient and it is used both base and peak load period as per requirement. most importantly, it can also take a part of load curve in grid system

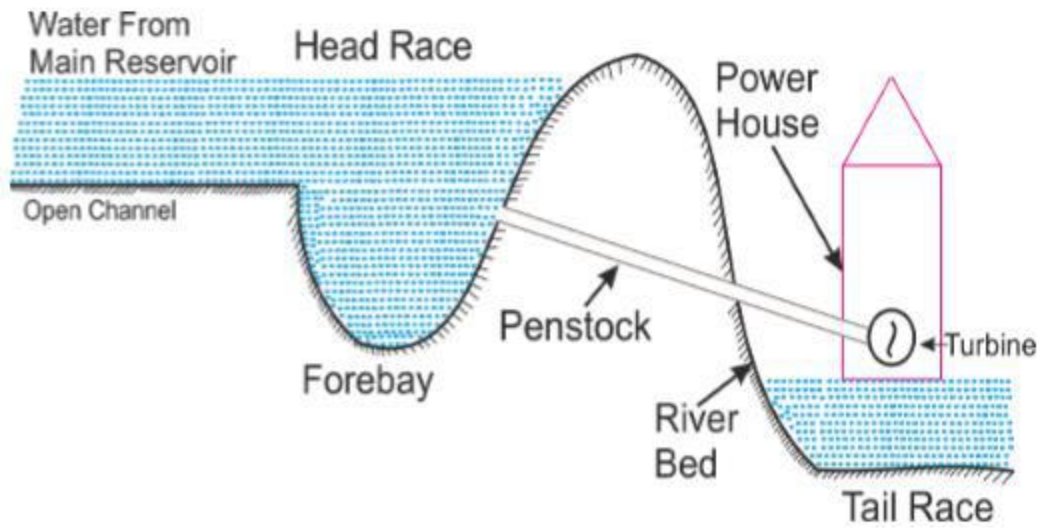
2. According to the availability of water flow: As per height of water or water head,hydro electric power plant can be divided three categories: a. Low Head b. Medium Head c. High Head Low head, medium head, high head. Though there is no rule regarding water head height but below 30 meters is considered as low head, above 30 meters to 300 meters is called medium head and above 300 meters is known as high head hydro electric power plant.

a. Low head hydro electric power plant : The block diagram of low head hydro electric power plant is given in fig:



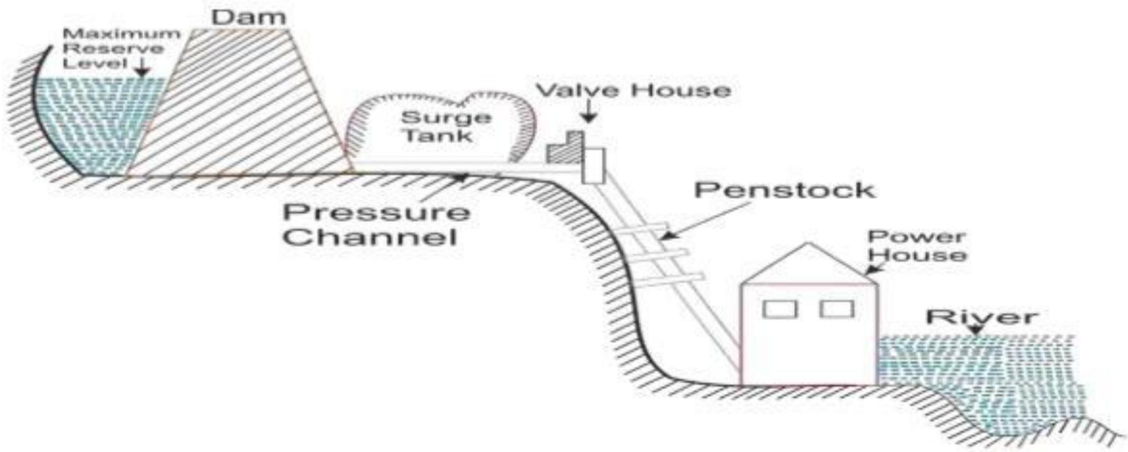
- Francis, Kaplan or propeller turbines are used for this type of hydro electric power plant. To create a low head , Dam construction is essential.
- Water resource level i.e. river or pond is placed just behind the dam to create a necessary water head level.
- Water is led to the turbine through the penstock.
- This type of hydro plant is located just below the dam and it creates a useful water level as well.
- No surge tank is required for this plant, dam itself discharge the surplus water from the river. Science head is low, huge amount of water is required for desire output. That's why large diameter and low length pipe is used for this plant. Such types of power plant use low speed and large diameter type generators

b. Medium head hydro electric power plant: Block diagram of medium head hydro electric power plant is shown below:



- A forebay is used for medium head hydro electric power plant. This forebay is worked as a surge tank. Forebay is tapped with the river and water is led to the turbine via penstock. Forebay is just beginning of penstock. For low head plant forebay itself serves as a surge tank.

c. High head hydro electric power plant:



- The head of this power plant is more than 300 meters. A dam is constructed such level that maximum reserve water level is formed.
- A pressure tunnel is constructed which is connected to the valve house. Water is coming from reservoir to valve house via this pressure tunnel and it is the starting of penstock.
- A surge tank is also constructed before valve house which reduces water hammering to the penstock in case of sudden closing of fixed gates of water turbine.

- Surge tank also store some extra water which is useful for pick load demand because it will serve extra water to the turbine.
- Valve house consists of a main valve sluice valves and automatic isolating valves, which operate on bursting of penstock and cut off further supply of water to penstock.
- The penstock is a connecting pipe which supplies water from valve house to turbine. For high head more than 500 meters , Pelton wheel turbine is used and for lower head Francis turbine is useful.

According to the types of load supply:

a. Base Load

b. Peak Load

c. Pumped storage plants for the peak load

a. Base load hydro electric power plant: This is a large capacity power plant. This plant work as a base portion of load curve of power system, that's why it is called base load plants. Base load plant is suitable for constant load. load factor of this plant is high and it is performed as a block load. Run off river plants without pondage and reservoir plants are used as base load plants.

b. Peak load hydro electric power plant: This plant is suitable for peak load curve of power system. when demand is high, this type of plant do their job very well. Run off river plants with pondage can be employed as peak load plants. If water supply is available, it generates large portion of load at a peak load period. It needs huge storage area. Reservoir plants can be used as peak load plants. This type of plant can serve power throughout the year.

c. Pumped storage hydro electric power plant for the peak load: This is unique design of peak load plants. Here two types of water pond is used, called upper head water pond and tail water pond. Two water ponds are connected each other by a penstock. Main generating pumping plant is lower end. During the off load period, surplus energy of this plant is utilized to pumping the lower head pond water to upper head pond water. This extra water is used to generate energy at pick load periods. By doing this arrangement, same water is used again and again. Extra water is required only to take care of evaporation and seepage.

Sizes of Hydroelectric Power Plants:

Facilities range in size from large power plants that supply many consumers with electricity to small and micro plants that individuals operate for their own energy needs or to sell power to utilities.

Large Hydropower: Although definitions vary, large hydropower as facilities that have a capacity of more than 30 megawatts (MW).

Medium Hydropower: Although definitions vary, small hydropower as projects that generate 10 MW or less of power.

Small Hydropower: A micro hydropower plant has a capacity of up to 100 kilowatts (0.1 MW). A small or micro-hydroelectric power system can produce enough electricity for a home, farm, ranch, or village.

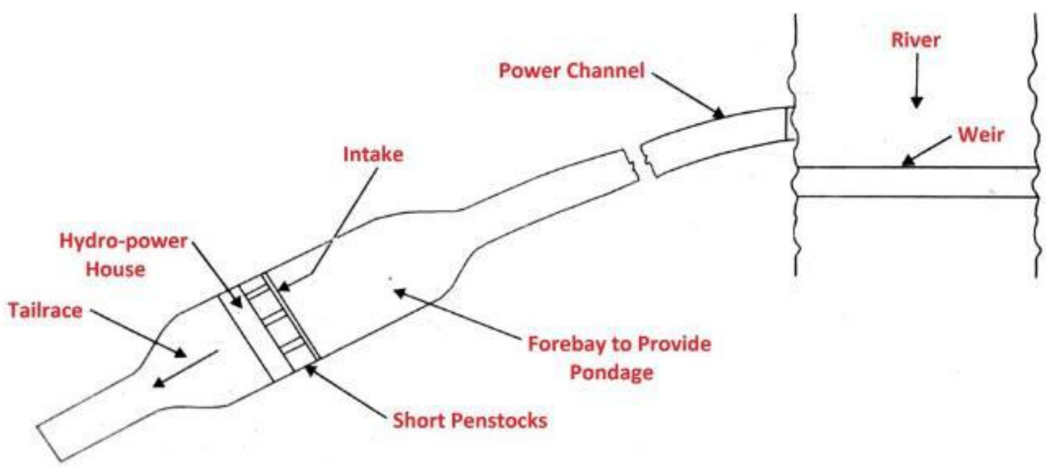
Storage and Pondage:

- During the rainy season, when the stream is in floods it carries a huge quantity of water as compared to the stream in other times of the year i.e. the quantity of water carried by it is very less.
- However, the demand for power normally does not match such variation of the natural flow of the stream.
- Therefore, some arrangement in the form of storage and pondage of water is required for the proper handling of the flow of water so as to make it available in important quantity to meet the power demand at a given time.
- The storage may be defined as the impounding of a considerable amount of excess runoff during seasons of surplus flow for use in dry seasons.
- This is achieved by constructing a dam across the stream at a suitable site and building a storage reservoir on the upstream side of the dam.

Pondage: The pondage may be defined as a regulating body of water in the form of a relatively small pond or reservoir provided at the plant. The pondage is used to regulate the variable water flow to meet power demand. It helps in short term variations which occur due to:

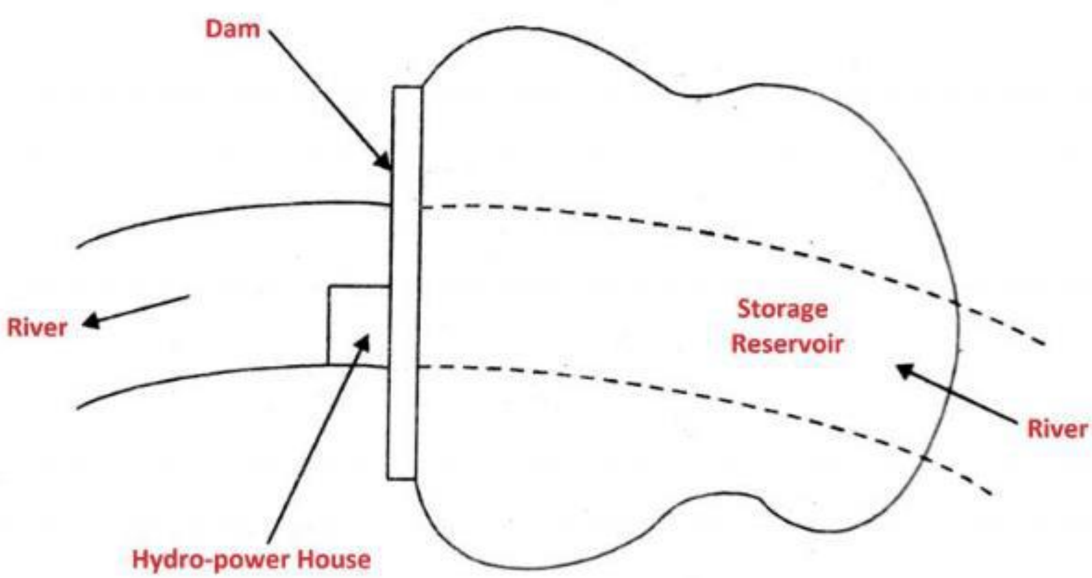
- Sudden rise or drop in load on the turbine.
- Sudden changes in the inflow of water.
- Change of water demand by turbines and the natural flow of water from time to time.

The turbines are required to meet the power demand higher than the average load when the pondage supplies the excess quantity of water required during that period.



Power House With Pondage

- Pondage increases the capacity of a river over a short time, such as a week.



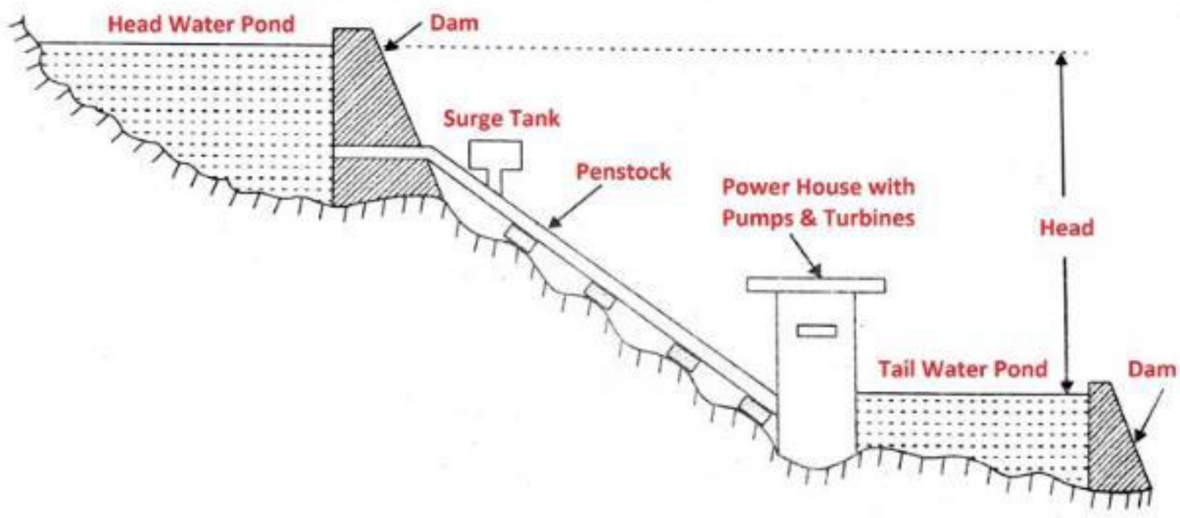
Power House With Storage

Factors to be considered for Selection of Site for Hydro Power Plant:

Following factors should be considered while selecting the site for hydro-power plant

1. Availability of water: Large quantity of water should be available throughout the year at the proposed site.
2. A requirement of head flow availability and storage capacity.
3. The character of foundation, particularly for the dams.
4. The land should be cheap and rocky.
5. The topography of the surface at the proposed location.
6. Accessibility of the site i.e. the site should have transportation facilities like road and rail.
7. Nearness to the load centre.
8. Availability of the materials for the construction.
9. Arrangement and type of dam, intakes, conduits, surge tank and powerhouse.
10. Cost of project and period required for completion.
11. Impacts of water pollution.

Plant Operation Pumped Storage Plants: The pumped storage plants are used at the places where the quantity of water available for power generation is low. Here the water passing through the turbine is stored in “tailrace pond”. During the low load periods, this water is drawn back to the head reservoir applying the extra energy available.



Pumped Storage Power Plant

- This water can be reused for generating power during peak load periods. The pumping of water may be done seasonally or regular depending upon the conditions of the site and the nature of the load on the plant.
- The simple construction of the stored hydro-power plant is shown in the figure. It consists of headwater pond and dam, penstock connected power house with pumps and turbines and trail race pond with the dam.
- The water from head water pond is supplied to the power house through the penstock, where turbines are rotated for power generation.
- From the turbine, the water is discharged into the tailrace pond.
- The water stored in the tailrace pond is pumped back to the head reservoir with the help of the pump during low load periods.
- This water is again used for power generation during peak load periods.
- Such plants are usually interconnected with steam or diesel power plants so that off-peak capacity of interconnecting stations is used in pumping water and the same is used during peak load periods.

Advantages of Pumped Storage Power Plants

1. There is a substantial increase in peak load capacity.
2. Increased operating efficiency.
3. It can be used as both base loads plant and peak load plant.
4. Load the plant remain uniform.
5. Improved load factor.

Mini and Micro-hydel Plants:

- The **hydro power plants** working with 5 m to 20 m head are known as mini hydel plants and the hydel power plants working with the heads less than 5 m head are known as micro hydel plants.
- These plants can generate power ranging from 100 KW to 5 MW with a period of one and half year.
- These plants having a small reservoir with the dam and small capacity power house using bulb turbines with straight diverging tube acts as a draft tube.
- The water flows from a small reservoir through the small penstock into the turbine in power house and generates the power.
- After generating the power the water is discharged into the tailrace through draft tube.
- Micro-hydel plants make use of standardised bulb sets with unit output ranging from 100 to 1000 KW working under heads between 1.5 to 5 m.

Unit V (B) Nuclear Power Plant

Introduction

Nuclear power plants are a type of power plant that use the process of nuclear fission in order to generate electricity. They do this by using nuclear reactors in combination with the Rankine cycle, where the heat generated by the reactor converts water into steam, which spins a turbine and a generator. Nuclear power provides the world with around 11% of its total electricity, with the largest producers being the United States and France.

Aside from the source of heat, nuclear power plants are very similar to coal-fired power plants. However, they require different safety measures since the use of nuclear fuel has vastly different properties from coal or other fossil fuels. They get their thermal power from splitting the nuclei of atoms in their reactor core, with uranium being the dominant choice of fuel in the world today. Thorium also has potential use in nuclear power production; however it is not currently in use. Below is the basic operation of a boiling water power plant, which shows the many components of a power plant, along with the generation of electricity.

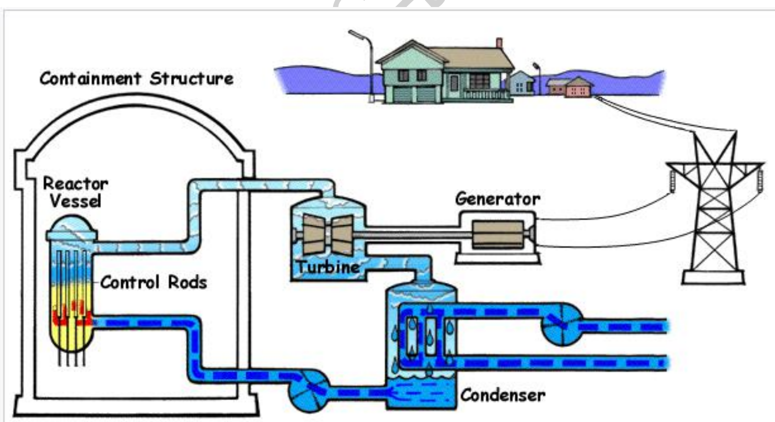


Fig. A boiling water nuclear reactor in combination with the Rankine cycle forms the basis of a nuclear power plant

General Components and Operation

Nuclear Reactor

The reactor is a key component of a power plant, as it contains the fuel and its nuclear chain reaction, along with all of the nuclear waste products. The reactor is the heat source for the power plant, just like the boiler is for a coal plant. Uranium is the dominant nuclear fuel used in nuclear reactors, and its fission reactions are what produce the heat within a reactor. This heat is then transferred to the reactor's coolant, which provides heat to other parts of the nuclear power plant. Besides their use in power generation, there are other types of nuclear reactors that are used for plutonium manufacturing, the propulsion of ships, aircraft and satellites, along with research and medical purposes. The power plant encompasses not just the reactor, but also cooling towers, turbines, generators, and various safety systems. The reactor is what makes it differ from other external heat engines.

Steam Generation

The production of steam is common among all nuclear power plants, but the way this is done varies immensely. The most common power plants in the world use pressurized water reactors, which use two loops of circling water to produce steam he first loop carries extremely hot liquid water to a heat exchanger, where water at a lower pressure is circulated. It then heats up and boils to steam, and can then be sent to the turbine section. Boiling water reactors, the second most common reactor in power generation, heat the water in the core directly to steam.

Turbine and Generator

Once steam has been produced, it travels at high pressures and speeds through one or more turbines. These get up to extremely high speeds, causing the steam to lose energy, therefore, condensing back to a cooler liquid water. The rotation of the turbines is used to spin an electric generator, which produces electricity that is sent out the electrical grid.

Cooling Towers

Perhaps the most iconic symbol of a nuclear power plant is the cooling towers. They work to reject waste heat to the atmosphere by the transfer of heat from hot water (from the turbine section) to the cooler outside air. Hot water cools in contact with the air and a small portion, around 2%, evaporates and raises up through the top. Moreover, these plants do not release any carbon dioxide—the primary greenhouse gas that contributes to climate change. Many nuclear power plants simply put the waste heat into a river, lake or ocean instead of having cooling towers. Many other power plants like coal-fired power plants have cooling towers or these large bodies of water as well. This similarity exists because the process of turning heat into electricity is almost identical between nuclear power plants and coal-fired power plants.

Nuclear fuel: Nuclear fuel is material used in nuclear power stations to produce heat to power turbines. Heat is created when nuclear fuel undergoes nuclear fission.

Most nuclear fuels contain heavy fissile actinide elements that are capable of undergoing and sustaining nuclear fission. The three most relevant fissile isotopes are uranium-233, uranium-235 and plutonium-239.

Nuclear reaction are of two types :

i. Nuclear Fission

ii. Nuclear Fusion

Nuclear Fission- The process in which one heavy nucleus (e.g uranium , polonium) splits into two light nuclei producing large amount of energy and neutrons along with it.

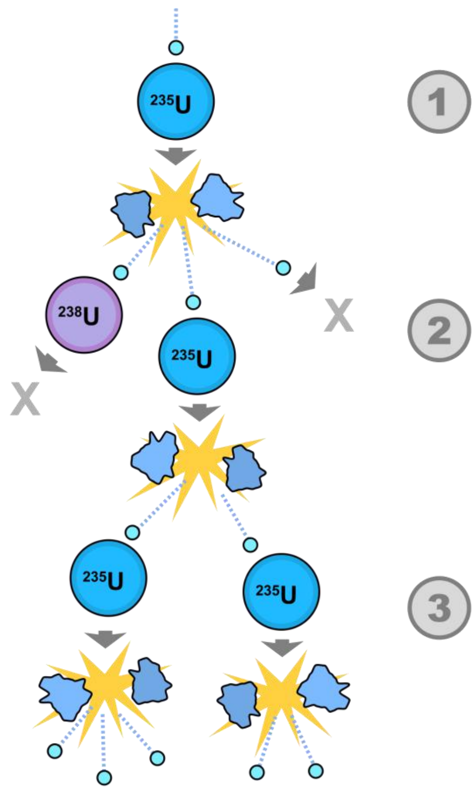
Nuclear Fusion- The process in which two light nuclei fuses into one heavy nucleus at a very high temperature and pressure, producing large amount of energy.

- In both the reaction, the origin of energy is loss in mass, the sum of the products is less than the sum of the products. The loss in mass in converted into energy according to Einstein's mass-energy equation**, E=mc2.**
- Though, nuclear reactions produces large amount of energy, but they are uncontrolled and can cause explosions.

Nuclear Fission Reaction

The definition of nuclear fission which says that in fission reaction, one heavy nucleus splits into two light nuclei and produces high amount energy and neutrons along with it. These neutrons goes and hit the other atoms of Uranium (or plutonium) and thus the chain reaction continues and each of this reaction emits a huge amount of energy in form of heat and light. This is the reason why nuclear reactions are uncontrollable.

Chain Reaction: A chain reaction refers to a process in which neutrons released in fission produce an additional fission in at least one further nucleus. This nucleus in turn produces neutrons, and the process repeats. The process may be controlled (nuclear power) or uncontrolled (nuclear weapons).



Chain Reaction Steps: A typical chain reaction follows a sequence of steps:

1. **Initiation**: Active particles form that serve as the basis for the reaction.
2. **Propagation**: Active particles react with each other and may serve as catalysts to perpetuate the cycle.
3. **Termination**: The active particles lose their activity, slowing and ending the reaction.

Fertile Material

- In nuclear engineering, fertile material (nuclide) can be converted to fissile material by neutron transmutation and subsequent nuclear decay.
- The process of the transmutation of fertile materials to fissile materials is referred to as fuel breeding.
- Fertile materials are not capable of undergoing fission reaction after absorbing thermal (slow or low energy) neutrons, and these materials are not capable of sustaining a nuclear fission chain reaction. There are two basic fertile materials: ^{238}U **and ^{232}Th.**
- **^{239}Pu and ^{241}Pu** are products of the transmutation of the fertile isotope ^{238}U, while ^{233}U is the product of the transmutation of the fertile isotope ^{232}Th. These two transmutations and decay chains are shown below:
- ^{233}U **breeding:**

$$n + {}^{232}_{90}\mathrm{Th} \rightarrow {}^{232}_{90}\mathrm{Th} + \gamma \rightarrow {}^{233}_{91}\mathrm{Pa} \rightarrow {}^{233}_{92}\mathrm{U}$$

^{239}Pu breeding:

$$n + {}^{238}_{92}\mathrm{U} \rightarrow {}^{239}_{92}\mathrm{U} + \gamma \rightarrow {}^{239}_{93}\mathrm{Np} \rightarrow {}^{239}_{94}\mathrm{Pu}$$

Neutron capture may also be used to create fissile **^{239}Pu** from **^{238}U**, the dominant constituent of naturally occurring uranium (99.28%). Absorption of a neutron in the **^{238}U** nucleus yields **^{239}U**. The half-life of **^{239}U** is approximately **23.5 minutes**. **^{239}U** decays (negative beta decay) to **^{239}Np** (neptunium), whose half-life is **2.36 days**. **^{239}Np** decays (negative beta decay) to **^{239}Pu.**

Breeding Fuel: All commercial light water reactors contain both fissile and fertile materials. For example, most PWRs use low enriched uranium fuel with enrichment of **^{235}U** up to 5%. Therefore more than 95% of the content of fresh fuel is fertile isotope **^{238}U**. During fuel burnup, the fertile materials (conversion of **^{238}U** to fissile **^{239}Pu** known as **fuel breeding**) partially replace fissile **^{235}U**, thus permitting the power reactor to operate longer before the amount of fissile material decreases to the point where reactor criticality is no longer manageable**.**

The fuel breeding in the fuel cycle of all commercial light water reactors plays a significant role. In recent years, the commercial power industry has been emphasizing **high-burnup fuels** (up to 60 – 70 GWd/tU), typically enriched to higher percentages of **^{235}U** (up to 5%). As burnup increases, a higher percentage of the total power produced in a reactor is due to the fuel bred inside the reactor.

Nuclear Reactor –Reactor Operation:

- A nuclear reactor produces and controls the release of energy from splitting the atoms of certain elements. In a nuclear power reactor, the energy released is used as heat to make steam to generate electricity. (In a research reactor the main purpose is to utilise the actual neutrons produced in the core. In most naval reactors, steam drives a turbine directly for propulsion.)

- The principles for using nuclear power to produce electricity are the same for most types of reactor. The energy released from continuous fission of the atoms of the fuel is harnessed as heat in either a gas or water, and is used to produce steam. The steam is used to drive the turbines which produce electricity (as in most fossil fuel plants).

Components of a nuclear reactor: There are several components common to most types of reactor:

Fuel:

Uranium is the basic fuel. Usually pellets of uranium oxide (UO_2) are arranged in tubes to form fuel rods. The rods are arranged into fuel assemblies in the reactor core.* In a 1000 MWe class PWR there might be 51,000 fuel rods with over 18 million pellets.

* In a new reactor with new fuel a neutron source is needed to get the reaction going. Usually this is beryllium mixed with polonium, radium or other alpha-emitter. Alpha particles from the decay cause a release of neutrons from the beryllium as it turns to carbon-12. Restarting a reactor with some used fuel may not require this, as there may be enough neutrons to achieve criticality when control rods are removed.

Moderator

Material in the core which slows down the neutrons released from fission so that they cause more fission. It is usually water, but may be heavy water or graphite.

Control rods or blades

These are made with neutron-absorbing material such as cadmium, hafnium or boron, and are inserted or withdrawn from the core to control the rate of reaction, or to halt it.* In some PWR reactors, special control rods are used to enable the core to sustain a low level of power efficiently. (Secondary control systems involve other neutron absorbers, usually boron in the coolant – its concentration can be adjusted over time as the fuel burns up.) PWR control rods are inserted from the top, BWR cruciform blades from the bottom of the core.

* In fission, most of the neutrons are released promptly, but some are delayed. These are crucial in enabling a chain reacting system (or reactor) to be controllable and to be able to be held precisely critical.

Coolant

A fluid circulating through the core so as to transfer the heat from it. In light water reactors the water moderator functions also as primary coolant. Except in BWRs, there is secondary coolant circuit where the water becomes steam. (See also later section on primary coolant characteristics.) A PWR has two to four primary coolant loops with pumps, driven either by steam or electricity – China's Hualong One design has three, each driven by a 6.6 MW electric motor, with each pump set weighing 110 tonnes.

Pressure vessel or pressure tubes

Usually a robust steel vessel containing the reactor core and moderator/coolant, but it may be a series of tubes holding the fuel and conveying the coolant through the surrounding moderator.

Steam generator
Part of the cooling system of pressurised water reactors (PWR & PHWR) where the high-pressure primary coolant bringing heat from the reactor is used to make steam for the turbine, in a secondary circuit. Essentially a heat exchanger like a motor car radiator.* Reactors have up to six 'loops', each with a steam generator. Since 1980 over 110 PWR reactors have had their steam generators replaced after 20-30 years service, over half of these in the USA.

* These are large heat exchangers for transferring heat from one fluid to another – here from high-pressure primary circuit in PWR to secondary circuit where water turns to steam. Each structure weighs up to 800 tonnes and contains from 300 to 16,000 tubes about 2 cm diameter for the primary coolant, which is radioactive due to nitrogen-16 (N-16, formed by neutron bombardment of oxygen, with half-life of 7 seconds). The secondary water must flow through the support structures for the tubes. The whole thing needs to be designed so that the tubes don't vibrate and fret, operated so that deposits do not build up to impede the flow, and maintained chemically to avoid corrosion. Tubes which fail and leak are plugged, and surplus capacity is designed to allow for this. Leaks can be detected by monitoring N-16 levels in the steam as it leaves the steam generator.

Containment
The structure around the reactor and associated steam generators which is designed to protect it from outside intrusion and to protect those outside from the effects of radiation in case of any serious malfunction inside. It is typically a metre-thick concrete and steel structure.

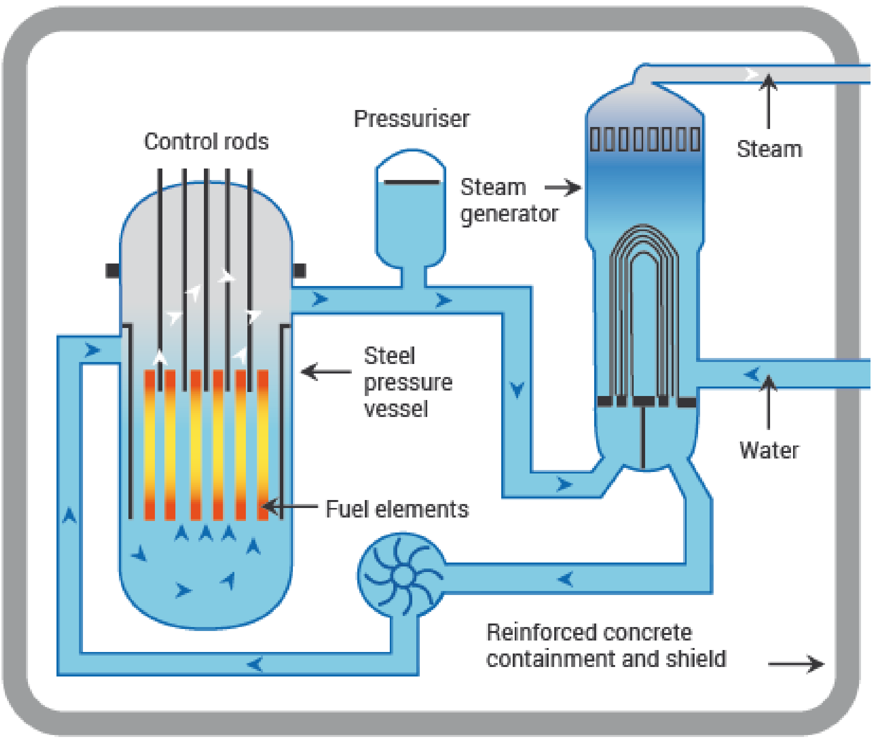
Fuelling a nuclear reactor
Most reactors need to be shut down for refuelling, so that the reactor vessel can be opened up. In this case refuelling is at intervals of 12, 18 or 24 months, when a quarter to a third of the fuel assemblies are replaced with fresh ones. The CANDU and RBMK types have pressure tubes (rather than a pressure vessel enclosing the reactor core) and can be refuelled under load by disconnecting individual pressure tubes. The AGR is also designed for refuelling on-load.

If graphite or heavy water is used as moderator, it is possible to run a power reactor on natural instead of enriched uranium. Natural uranium has the same elemental composition as when it was mined (0.7% U-235, over 99.2% U-238), enriched uranium has had the proportion of the fissile isotope (U-235) increased by a process called enrichment, commonly to 3.5-5.0%. In this case the moderator can be ordinary water, and such reactors are collectively called light water reactors. Because the light water absorbs neutrons as well as slowing them, it is less efficient as a moderator than heavy water or graphite. Some new small reactor designs require high-assay low-enriched uranium fuel, enriched to near 20% U-235.

Main types of nuclear reactor:

1. **Pressurised water reactor (PWR)**

This is the most common type, with about 300 operable reactors for power generation and several hundred more employed for naval propulsion. The design of PWRs originated as a submarine power plant. PWRs use ordinary water as both coolant and moderator. The design is distinguished by having a primary cooling circuit which flows through the core of the reactor under very high pressure, and a secondary circuit in which steam is generated to drive the turbine. In Russia these are known as VVER types – water-moderated and -cooled.



- A PWR has fuel assemblies of 200-300 rods each, arranged vertically in the core, and a large reactor would have about 150-250 fuel assemblies with 80-100 tonnes of uranium.
- Water in the reactor core reaches about 325°C, hence it must be kept under about 150 times atmospheric pressure to prevent it boiling. Pressure is maintained by steam in a pressuriser (see diagram).
- In the primary cooling circuit the water is also the moderator, and if any of it turned to steam the fission reaction would slow down. This negative feedback effect is one of the safety features of the type. The secondary shutdown system involves adding boron to the primary circuit.

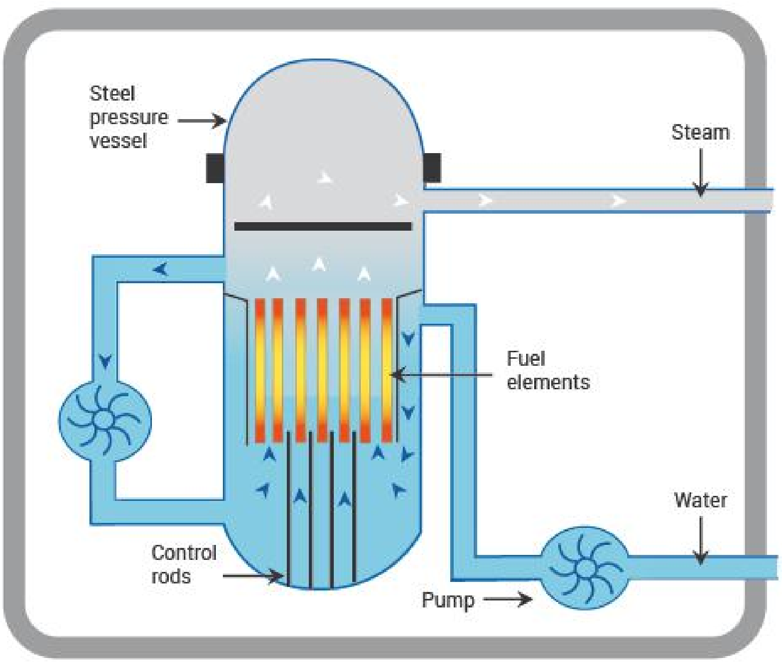
- The secondary circuit is under less pressure and the water here boils in the heat exchangers which are thus steam generators.
- The steam drives the turbine to produce electricity, and is then condensed and returned to the heat exchangers in contact with the primary circuit.

2. Boiling water reactor (BWR)

This type of reactor has many similarities to the PWR, except that there is only a single circuit in which the water is at lower pressure (about 75 times atmospheric pressure) so that it boils in the core at about 285°C. The reactor is designed to operate with 12-15% of the water in the top part of the core as steam, and hence with less moderating effect and thus efficiency there. BWR units can operate in load-following mode more readily than PWRs.

The steam passes through drier plates (steam separators) above the core and then directly to the turbines, which are thus part of the reactor circuit. Since the water around the core of a reactor is always contaminated with traces of radionuclides, it means that the turbine must be shielded and radiological protection provided during maintenance. The cost of this tends to balance the savings due to the simpler design. Most of the radioactivity in the water is very short-lived*, so the turbine hall can be entered soon after the reactor is shut down.

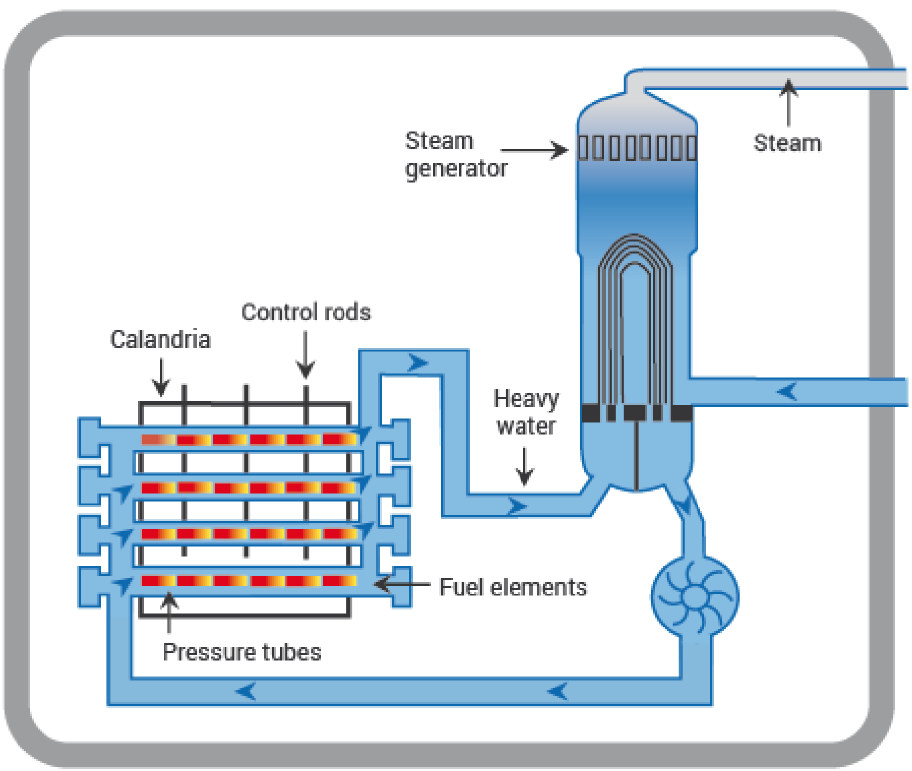
A BWR fuel assembly comprises 90-100 fuel rods, and there are up to 750 assemblies in a reactor core, holding up to 140 tonnes of uranium. The secondary control system involves restricting water flow through the core so that more steam in the top part reduces moderation.



3. Pressurised heavy water reactor (PHWR):

The PHWR reactor has been developed since the 1950s in Canada as the CANDU, and from 1980s also in India. PHWRs generally use natural uranium (0.7% U-235) oxide as fuel, hence needs a more efficient moderator, in this case heavy water (D_2O).** The PHWR produces more energy per kilogram of mined uranium than other designs, but also produces a much larger amount of used fuel per unit output.

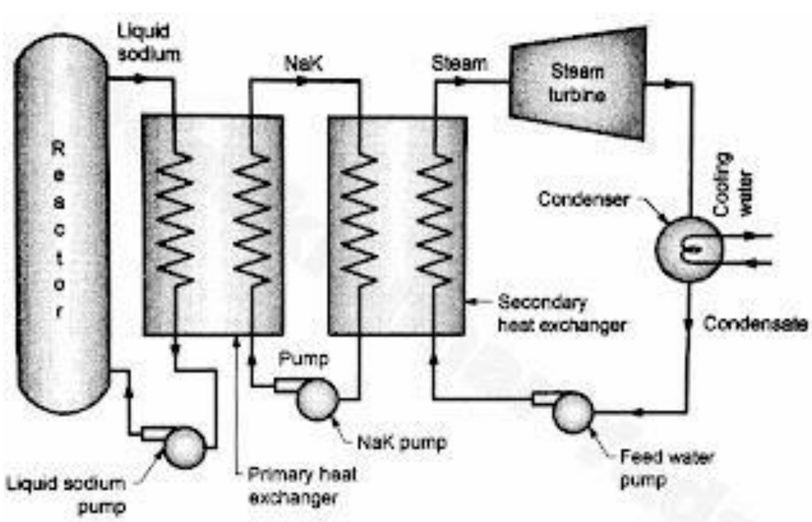
The moderator is in a large tank called a calandria, penetrated by several hundred horizontal pressure tubes which form channels for the fuel, cooled by a flow of heavy water under high pressure (about 100 times atmospheric pressure) in the primary cooling circuit, typically reaching 290°C. As in the PWR, the primary coolant generates steam in a secondary circuit to drive the turbines. The pressure tube design means that the reactor can be refuelled progressively without shutting down, by isolating individual pressure tubes from the cooling circuit. It is also less costly to build than designs with a large pressure vessel, but the tubes have not proved as durable.



A CANDU fuel assembly consists of a bundle of 37 half metre long fuel rods (ceramic fuel pellets in zircaloy tubes) plus a support structure, with 12 bundles lying end to end in a fuel channel. Control rods penetrate the calandria vertically, and a secondary shutdown system involves adding gadolinium to the moderator. The heavy water moderator circulating through the body of the calandria vessel also yields some heat (though this circuit is not shown on the diagram above).

Sodium Graphite Reactor:

1. Sodium graphite reactor is a typical liquid metal reactor. The arrangement of a sodium graphite reactor power plant is shown in Figure.
2. It uses graphite as the moderator and liquid sodium as coolant which can reach temperature of about 850°C at low pressure of only 7 bar. In the primary circuit the heat is absorbed by liquid sodium in the reactor.
3. The sodium becomes radioactive while it passes through the core and reacts chemically with water. Therefore, the heat absorbed by sodium is transferred to secondary coolant sodiun potassium (Nak) in the primary heat exchanger which in turn transfers the heat in the secondary heat exchanger called steam generator.
4. Water leaving the steam generator is converted into superheated steam upto temperature of 540°C. This steam is used for power generation in the steam plant circuit in the usual manner.
5. The reactor vessel, primary circuit and the primary heat exchanger have to be shielded from radiations. The liquid metal is required to be handled under the cover of an inert gas like helium to prevent contact with air while charging or draining in the primary and secondary heat exchangers.



Sodium Graphite Reactor

Advantages of Sodium Graphite Reactor :

1. High temperatures of steam can be obtained due to use of liquid sodium as coolant.
2. System need not be pressurized.
3. Thermal efficiency is high.

4. Cost of pressure vessel and piping system is reduced due to use of low pressures sodium in primary circuit.

Disadvantages of Sodium Graphite Reactor :

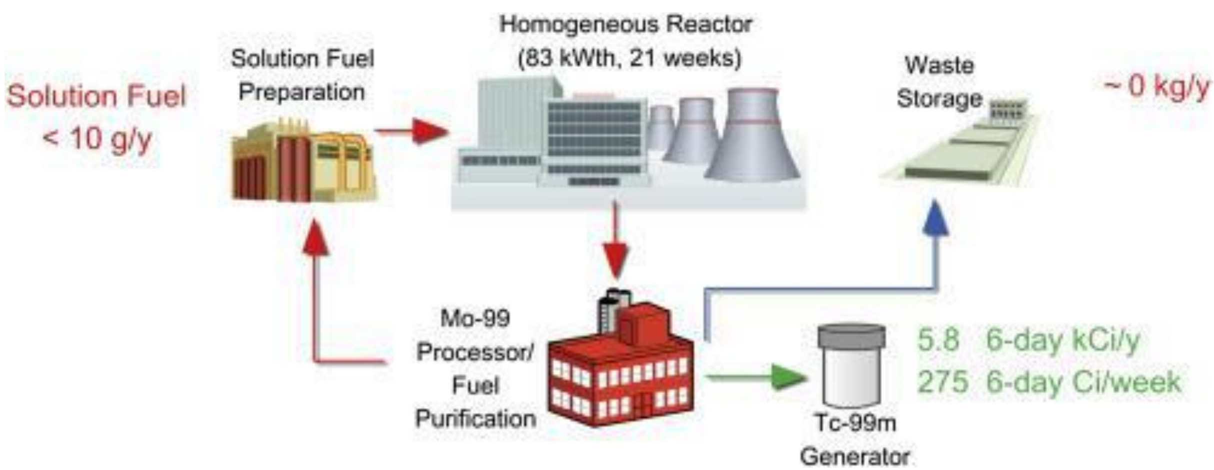
1. Sodium reacts violently with air and water.
2. Intermediate heat exchanger is required to separate radioactive sodium with water and steam.
3. Primary and secondary heat exchanger are needed to be shielded with concrete blocks against radiations.
4. Any leakage of sodium coolant is highly dangerous.

Fast breeder Reactor:

A Fast Breeder Reactor (FBR) is a nuclear reactor that uses fast neutron to generate more nuclear fuels than they consume while generating power, dramatically enhancing the efficiency of the use of resources. Nuclear fission by fast neutron causes the increase in neutrons generated.

Fast breeder reactor (FBR) which use fast (i.e.: unmoderated) neutrons to breed fissile plutonium and possibly higher transuranics from fertile uranium-238. The fast spectrum is flexible enough that it can also breed fissile uranium-233 from thorium, if desired.

Homogeneous Reactor: A nuclear reactor in which the fuel is distributed (as by being dissolved in a liquid) uniformly or approximately uniformly throughout the moderator material.

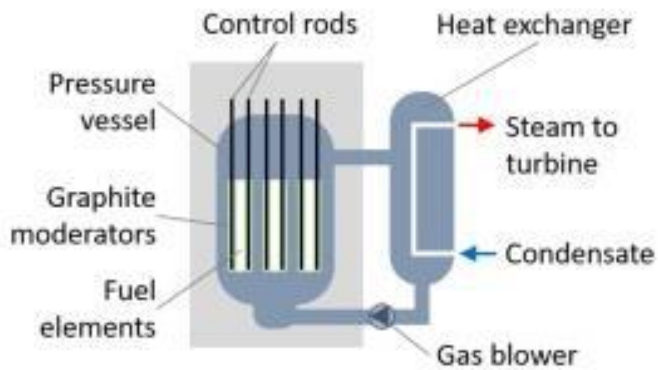


Gas Cooled Reactor: A gas cooled reactor (in short, GCR) is a nuclear reactor that works with graphite as a neutron moderator and a gas including carbon dioxide or helium in available designs as coolant. Although there are different types of reactor cooled by gas, the terms GCR and, to a lesser extent, gas cooled reactor is used specifically to refer to this reactor type.

The GCR could utilize natural uranium as fuel, and the countries that have developed them were able to produce their fuel without any dependence on other countries to supply enriched uranium. It was available at the time of their development in the 1950s only in the United States or the Soviet Union.
At present, gas cooled reactors account for about three percent of all reactors in commercial operations around the world. All of them are advanced carbon-dioxide gas cooled reactors in the UK that will be phased out by the mid-2020s.
The many Member States are interested in working on advanced High-Temperature Gas Cooled Reactors (HTGRs) that employ helium as a coolant. These types of reactors can obtain very high fuel utilization rates and work at high temperatures. They also generate process heat used in hydrogen production and low-temperature applications, including seawater desalination and district heating.

Gas Cooled Reactor Basics

- Gas cooled reactors utilize graphite as a neutron moderator and carbon dioxide as the coolant. With the three percent market share, all are installed in the United Kingdom. These reactors apply natural or somewhat enriched uranium as fuel.
- As shown in the following figure, carbon dioxide circulates inside the core, absorbs the heat from the fuel parts, and reaches 650 °C.
- It then flows to the heat exchangers located outside of the pressure vessel of the reactor concrete.
- These are of the gas-to-water heat exchanger types that use the once-through fundamental to boil the flowing water.
- The water is then applied in the conventional steam cycle.
- The once-through boiler operates based on the critical point of water. With an increase in pressure in the Rankine cycle, the saturation temperature corresponding to that pressure increases.
- Thus, as the pressure increases, the quantity of latent heat needed decreases. At a critical point, no latent heat is required, and therefore, the water directly evaporates into steam.
- The once-through boiler works at pressures above the critical water point pressure. Therefore, they are also called “supercritical boilers”



Schematic diagram of gas cooled reactor (Reference:

- In this design, to penetrate the moderator and control the reaction, boron control rods are utilized. In addition, there may be a secondary shutdown system that involves the injection of nitrogen into the coolant.
- However, in the second generation of the gas cooled reactors, the steam generators are installed inside the concrete pressure vessel, which needs a much larger structure and, therefore, more capital costs.

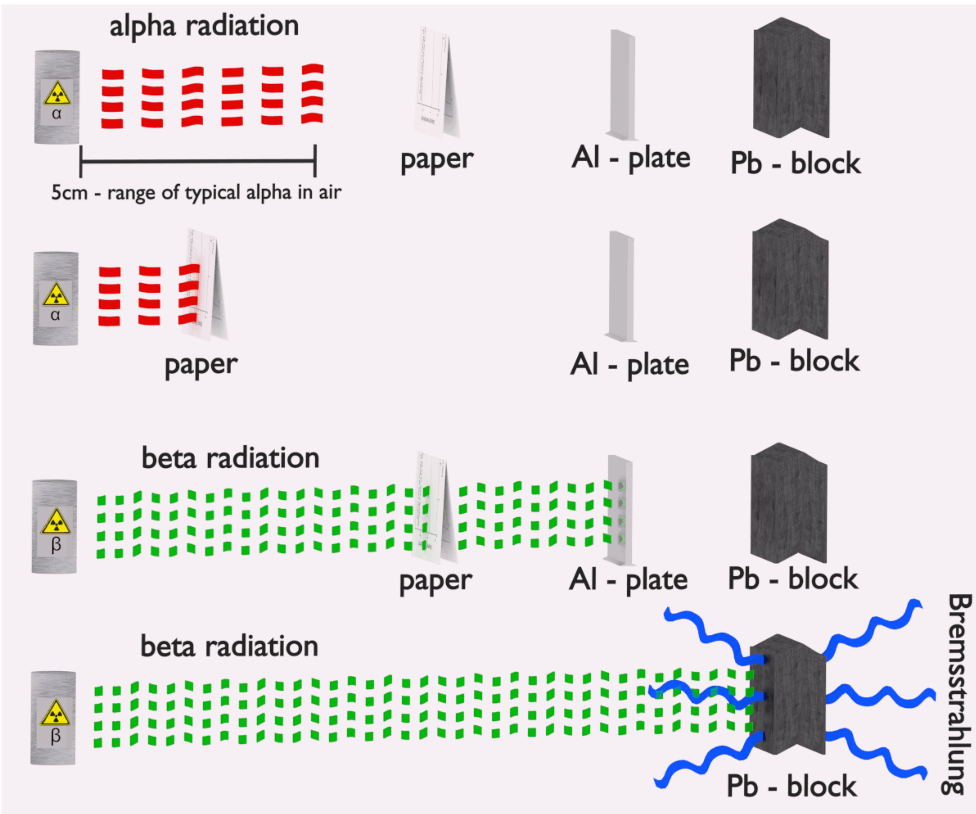
Advantages of Gas Cooled Reactors over Water Cooled Reactors

1. Gas cooled reactors present potential operational and safety advantages over water cooled reactors.
2. A principal operational motivation for working on this technology is enhanced energy conversion efficiency provided by a higher reactor operating temperature. For example, water cooled reactors have a possible maximum temperature limit of around 350°C, which allows a conversion efficiency (the ratio of output electricity to heat) of about 32–34%.
3. In comparison, a GCR can run at temperatures up to 800–850°C and yield a heat-to-electricity conversion efficiency of more than 40% using conventional steam turbine facilities or as high as 50% using a more advanced gas turbine apparatus.

Radiation Hazards and Shielding

Shielding of Ionizing Radiation:

Shielding of ionizing radiation means having some material between the source of radiation and you (or some device) that will absorb the radiation. Radiation shielding usually consists of barriers of lead, concrete, or water. Many materials can be used for radiation shielding, but there are many situations in radiation protection. It highly depends on the type of radiation to be shielded, its energy, and many other parameters. For example, even depleted uranium can be used as good protection from gamma radiation, but on the other hand, uranium is inappropriate shielding of neutron Radiation shielding means having some material between the source of radiation and you (or some device) that will absorb the radiation. The amount of shielding required, the type of material of shielding strongly depends on several factors. We are not talking about any optimization.



In fact, in some cases, inappropriate shielding may even worsen the radiation situation instead of protecting people from the ionizing radiation. Basic factors, which have to be considered during the proposal of radiation shielding, are:

- Type of the ionizing radiation to be shielded
- The energy spectrum of the ionizing radiation
- Length of exposure
- Distance from the source of the ionizing radiation
- Requirements on the attenuation of the ionizing radiation – ALARA or ALARP principles
- Design degree of freedom
- Other physical requirements (e.g.,, transparence in case of leaded glass screens)

Calculation of Shielded Dose Rate in Sieverts from Contaminated Surface

Assume a surface in which 1.0 Ci of 137Cs contaminates. Assume that this contaminant can be approximated by the point isotropic source, which contains 1.0 Ci of ^{137}Cs, with a half-life of 30.2 years. Note that the relationship between half-life and the amount of a radionuclide required to give an activity of one curie is shown below. This amount of material can be calculated using λ, which is the decay constant of certain nuclide:

$$N(atoms)\, x\, \lambda(s^{-1}) = 1\, Ci = 3.7\, x\, 10^{10}\, Bq$$

About 94.6 percent decays by beta emission to a metastable nuclear isomer of barium: barium-137m. The main photon peak of Ba-137m is **662 keV**. For this calculation, assume that all decays go through this channel.

Radioactive Waste Disposal:

- Radioactive wastes are stored so as to avoid any chance of radiation exposure to people, or any pollution.
- The radioactivity of the wastes decays with time, providing a strong incentive to store high-level waste for about 50 years before disposal.
- Disposal of low-level waste is straightforward and can be undertaken safely almost anywhere.
- Storage of used fuel is normally under water for at least five years and then often in dry storage.
- Deep geological disposal is widely agreed to be the best solution for final disposal of the most radioactive waste produced.

➢ Most low-level radioactive waste (LLW) is typically sent to land-based disposal immediately following its packaging for long-term management. This means that for the majority (~90% by volume) of all of the waste types produced by nuclear technologies, a satisfactory disposal means has been developed and is being implemented around the world.

➢ For used fuel designated as high-level radioactive waste (HLW), the first step is storage to allow decay of radioactivity and heat, making handling much safer. Storage of used fuel may be in ponds or dry casks, either at reactor sites or centrally. Beyond storage, many options have been investigated which seek to provide publicly acceptable, safe, and environmentally sound solutions to the final management of radioactive waste. The most widely favoured solution is deep geological disposal.

➢ The focus is on how and where to construct such facilities.

Used fuel that is not intended for direct disposal may instead be reprocessed in order to recycle the uranium and plutonium it contains. Some separated liquid HLW arises during reprocessing; this is vitrified in glass and stored pending final disposal.

Intermediate-level radioactive waste (ILW) that contains long-lived radioisotopes is also stored pending disposal in a geological repository. In the USA, defence-related transuranic (TRU) waste – which has similar levels of radioactivity to some ILW – is disposed of in the Waste Isolation Pilot Plant (WIPP) deep geological repository in New Mexico. A number of countries dispose of ILW containing short-lived radioisotopes in near-surface disposal facilities, as used for LLW disposal.

Storage ponds:

- Storage ponds at reactors, and those at centralized facilities such as CLAB in Sweden, are 7-12 metres deep to allow the racked fuel assemblies to be covered by several metres of water.
- The fuel assemblies are typically about 4 m long and standing on end. The multiple racks are made of metal with neutron absorbers incorporated in it.
- The circulating water both shields and cools the fuel. These pools are robust constructions made of thick reinforced concrete with steel liners.
- Ponds at reactors may be designed to hold all the used fuel for the life of the reactor, but usually the design assumes some removal of cooled fuel for reprocessing or to dry storage.

Dry storage

- Some storage of fuel assemblies which have been cooling in ponds for at least five years is in dry casks or vaults, typically with air circulation inside concrete shielding.
- Dry storage has been used at US nuclear power plants since 1986, and at least one-third of the total US used fuel is now in dry storage casks. Facilities are at most of the nuclear power plant sites (including some closed ones).
- As of the end of 2019, 3203 casks had been loaded at 72 interim spent fuel storage installations (ISFSIs) in the USA.
- Transfer from wet storage to dry casks at a power plant site may use special shielded transfer casks, which are less robust than those used for transport beyond the site.

Advantages of nuclear energy

1. Low-cost energy. Although building nuclear power plants has a high initial cost, it's relatively cheap to produce energy from them and they have low operating costs
2. Reliable.
3. Zero carbon emissions.
4. Promising future energy supply.
5. High energy density.

Disadvantages:

1. Nuclear reactions are very hard to control, as they are chain reactions and even a slight mistake can cause huge risks.
2. The elements used in the reaction are radioactive and the radiation can cause severe health issues like cancer and other genetical deformation.
3. Unfortunately, this is also used in nuclear weapons. An atomic bomb is based on nuclear fission reaction where the reaction is uncontrollable.
4. It was used two times in World War2 and causes the deaths of millions of people.

Nuclear fusion occurs inside the sun where two hydrogen atoms are combined to form one helium atom which in process produces huge amount of energy

Chemical and Nuclear reactions

Chemical reactions involve the combination or separation of whole atoms.

$$C + O_2 = CO_2$$

This reaction is accompanied by the release of about 4 electron volts (eV). An electron volt is a unit of energy in common use in nuclear engineering. 1 eV = 1.6021 × 10 $^{-19}$ joules (J) = 1.519 × 10 $^{-22}$ Btu (british thermal units) = 4.44 × 10^{-26} kWh. 1 million electron volts (1 MeV) = 106 eV.

In chemical reactions, each atom participates as a whole and retains its identity. The molecules change. The only effect is a sharing or exchanging of valence electrons. The nuclei are unaffected.

In chemical equations there are as many atoms of each participating element in the products (the right-hand side) as in the reactants (the left-hand side). Another example is one in which uranium dioxide (UO_2) is converted into uranium tetra fluoride (UF_4), called green salt, by heating it in an atmosphere of highly corrosive anhydrous (without water) hydrogen fluoride (HF), with water vapor (H_2O) appearing in the products.

$$UO_2 + 4HF = 2H_z\,O + UF_4$$

Water vapor is driven off and UF, is used to prepare gaseous uranium hexafloride (UF_6), which is used in the separation of the U^{235} and U^{238} isotopes of uranium by the gaseous diffusion method. (Fluorine has only one isotope, F^9 , and thus combi-nations of molecules of uranium and fluorine have molecular masses depending only on the uranium isotope.)

Both chemical and nuclear reactions are either exothermic or endothermic, that is, they either release or absorb energy. Because energy and mass are convertible, Eq. (*according to Einstein's law*),

$$\Delta E = \frac{1}{g_c} \Delta m c^2$$

(*where c is the speed of light in vacuum and g,. is the familiar engineering conversion factor. Equation (10.1) applies to all processes, physical, chemical, or nuclear, in which energy is released or absorbed. Energy is, however, classified as nuclear if it is associated with changes in the atomic nucleus*.)

chemical reactions involving energy do undergo a mass decrease in exothermic reactions and a mass increase in endothermic ones. However, the quantities of energy associated with a chemical reaction are very small compared with those of a nuclear reaction, and the mass that is lost or gained is minutely small. This is why we assume a preservation of mass in chemical reactions, undoubtedly an incorrect assumption but one that is sufficiently accurate for usual engineering calculations.

In nuclear reactions, the reactant nuclei do not show up in the products, instead we may find either isotopes of the reactants or other nuclei. In balancing nuclear equations it is necessary to see that the same, or equivalent, nucleons show up in the products as entered the reaction. For example, if K, L,

M, and N were chemical symbols, the corresponding nuclear equation might look like

$${}_{Z1}K^{A1} + {}_{Z2}L^{A2} \rightarrow {}_{Z3}M^{A3} + {}_{Z4}N^{A4}$$

To balance the following relationship must be satisfied.

$$Z_1 + Z_2 = Z_3 + Z_4$$

$$A_1 + A_2 = A_3 + A_4$$

Sometimes the symbols y or v are added to the products to indicate the emission of electromagnetic radiation or a neutrino, respectively. They have no effect on equation balance because both have zero Z and A, but they often carry large portions of the resulting energy.

Although the mass numbers are preserved in a nuclear reaction, the masses of the isotopes on both sides of the equation do not balance. Exothermic or endothermic energy is obtained when there is a reduction or an increase in mass from reactants to products, respectively.

Safety measures for nuclear power plants

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

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

(i) Fission of nuclei of nuclear fuels.

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

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

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

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

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

(iii) Waste water from nuclear power plant should be purified. The water purification plants must have a high efficiency of water purification and satisfy rigid requirements as regards the volume of radioactive wastes disposed to burial.

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

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

(vi) The safety system of the plant should be such as to enable safe shut down of the reactor whenever required. Engineered safety features are built into the station so that during normal operation as well as during a severe design basis accident the radiation dose at the exclusion zone boundary will be within permissible limits as per internationally accepted values. Adoption of a integral reactor vessel and end shield assemblies, two independent shut down systems, a high pressure emergency core cooling injection system and total double containment with suppression pool are some of the significant design improvements made in Narora Atomic Power Project (NAPP) design. With double containment NAPP will be able to withstand seismic shocks.

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

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

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

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

Power of nuclear reactor

Nuclear power comes from nuclear fission

Nuclear power plants heat water to produce steam. The steam is used to spin large turbines that generate electricity. Nuclear power plants use heat produced during nuclear fission to heat water.

In nuclear fission, atoms are split apart to form smaller atoms, releasing energy. Fission takes place inside the reactor of a nuclear power plant. At the center of the reactor is the core, which contains uranium fuel.

The uranium fuel is formed into ceramic pellets. Each ceramic pellet produces about the same amount of energy as 150 gallons of oil. These energy-rich pellets are stacked end-to-end in 12-foot metal fuel rods. A bundle of fuel rods, some with hundreds of rods, is called a fuel assembly. A reactor core contains many fuel assemblies. The heat produced during nuclear fission in the reactor core is used to boil water into steam, which turns the blades of a steam turbine. As the turbine blades turn, they drive generators that make electricity. Nuclear plants cool the steam back into water in a separate structure at the power plant called a cooling tower, or they use water from ponds, rivers, or the ocean. The cooled water is then reused to produce steam.

Nuclear power plants have generated about 20% of U.S. electricity since 1990

As of July 1, 2022, 92 nuclear reactors were operating at 54 nuclear power plants in 28 states. Thirty-two of the plants have two reactors, and three plants have three reactors. Nuclear power plants have supplied about 20% of total annual U.S. electricity since 1990. Learn more about the U.S. nuclear energy industry.

The United States generates more nuclear power than any other country

In 2020, 33 countries had commercial nuclear power plants, and in 17 of the countries, nuclear energy supplied at least 20% of their total annual electricity generation. The United States had the largest nuclear electricity generation capacity and generated more nuclear electricity than any other country. France, with the second-largest nuclear electricity generation capacity and second-highest nuclear electricity generation, had the largest share—about 69%—of total annual electricity generation from nuclear energy.

Top five nuclear electric generation capacity countries, 2020

Country	Nuclear electricity generation capacity (million kilowatts)	Nuclear electricity generation (billion kilowatthours)	Nuclear share of country's total electricity generation
United States	96.50	789.88	20%
France	61.37	379.50	69%
China	47.53	366.30	5%
Japan	31.68	43.00	5%
Russia	28.58	215.75	21%
Source: U.S. Energy Information Administration, International Energy Statistics, as of July 11, 2022			

Calculate Power of a Nuclear Reactor

Q1. The mass number of a nucleus is

(A) Always less than atomic number

(B) Always more than atomic number

(C) Equal to atomic number

(D) Some times more than and sometimes equal to atomic number.

Solution:
We know that the mass number of a nucleus represents the number of nucleons (neutrons + protons), and the atomic number represents the number of neutrons in the nucleus. So, when there are no neutrons in the nucleus, only then the atomic number equals the mass number. Hence, the correct option is (D).

Q2. In which of the following decays, the element does not change?

(A) β – decay (B) α – decay

(C) Positive– decay (D) γ – decay

Solution:

We know that γ ray has no charge and no mass. Hence, it is during the emission of γ ray that there is no change in atomic number or mass number. So, the correct option is (D).

Q3. In the reaction $_7N^{14}$ + $_2He^4$ —> $_8O^{17}$ + $_1H^1$ the minimum energy of the α-particle is

(A) 1.21 MeV (B) 1.62 MeV

(C) 1.89 MeV (D) 1.96 MeV.

(M_N = 14.00307 amu, M_{He} = 4.00260 amu and M_O = 16.99914 amu, M_H = 1.00783 amu and 1 amu = 931 MeV)

Solution:

The given reaction is $_7N^{14}$ + $_2He^4$ —> $_8O^{17}$ + $_1H^1$

We first calculate the total mass of reactants as well as products

Total mass of reactants = 18.00567 amu

Total mass of products = 18.00697 amu

Mass defect = 18.00697 – 18.00567 = 0.0013 amu

Energy (E) = 931 (0.0013) = 1.2103 MeV

Hence the correct option is (A).

Q4. In the carbon cycle of fusion

(A) Four $_1H^1$ fuse to form $_2He^4$ and two positrons

(B) Four $_1H^1$ fuse to form $_2He^4$ and two electrons

(C) Two $_1H^2$ fuse to form $_2He^4$

(D) Two $_1H^2$ fuse to form $_2He^4$ and two neutrons

Solution:

The carbon cycle of fusion is given by this equation

$4\,^1H^1$ —> $_2He^4$ + 2. $_{+1}e^0$ + Energy

Hence, it is clear that in this equation four $_1H^1$ fuse to form $_2He^4$ and two positrons. So, (A) is the correct option.

Q5. In each fission of U^{235}, 200 MeV of energy is released. If a reactor produces 100 MW power, then the rate of fission in it will be

(A) 3.125×10^{18} per minute

(B) 3.125×10^{17} per second

(C) 3.125×10^{17} per minute

(D) 3.125×10^{18} per second

Solution:

The energy released in every fission of U^{235} is given in the question. We know the formula P = nE/t.
Hence, substituting the values in this formula, we get
$n/t = P/E = 100\times10^{6} / 200[1.6\times10^{13}]$
$= 3.125 \times 10^{18}$ /sec
SO (D) is the correct option.

Q6. To generate a power of 3.2 MW, the number of fissions of U^{235} per minute is (Energy released per fission = 200 MeV, 1 eV = 1.6 ´ 10^{-19}J)

(A) 6×10^{18}¡ (B) 6×10^{17}
(C) 10^{17} (D) 6×10^{16}

Solution:
The power of reactor P = nE/t
Here, 'n' denotes the number of fissions,'t' denotes the time and 'E' is the energy released per fission.
$\therefore 3.2 \times 10^{6} = n(200\times10^{6})(1.6\times10^{-19}) / 60$
$\Rightarrow n = 6 \times 10^{18}$. This gives (A) as the correct option.

Q7. If in nuclear reactor using U^{235} as fuel, the power output is 4.8 MW, the number of fissions per second is (Energy released per fission of U^{235} = 200 MeV watts, e eV = 1.6 ´ 10^{-19} J)

(A) 1.5×10^{17} (B) 3×10^{19}
(C) 1.5×0^{25} (D) 3×10^{25}

Solution:
The power output is given to be 4.8 MW. This may be represented as:
$P = 4.8$ MW $= 4.8\times10^{6}$ W
The power of a nuclear reactor is given by the formula P = nE/t
$\therefore n/t = P/E = 4.8\times10^{6} / (200)(1.6\times10^{-13}) = 1.5 \times 10^{17}$
So this gives (A) as the correct option.