UNIT – III

NUCLEAR POWER PLANTS

1. Write a short notes on basics of Nuclear Engineering.

STRUCTURE OF AN ATOM:

- In 1803 John Dalton, attempting to explain the laws of chemical combination, propose his simple but incomplete atomic hypothesis. He postulated that all elements consists of indivisible minute particles of matter and atoms were different for different elements and preserved their identity in chemical reactions.
- In 1811 Amadeo Avo-gadro introduced the molecular theory based on the molecule, a particle of matter composed of a finite number of atoms. It is now known that the atoms are themselves composed of sub particles, common among atoms of all elements.
- An atom consists of a relatively heavy, positively charged nucleus and a number of much lighter negatively charged electrons that exist in various orbits around the nucleus. The nucleus, in turn, consists of sub particles, called nucleons.
- Nucleons at primarily of two kinds: the neutrons which are electrically neutral and the proton which are positively charged.
- The electric charge on the proton is equal in magnitude but opposite in sign to that on the electron.
- The atom as a whole is electrically neutral the number of protons equals the number of electrons in orbit. One atom may be transformed into another by losing or acquiring some of the above sub particles.
- The masses of the three primary atomic sub particles are

  Neutron mass *mn* = 1.008665 amu

  Proton mass *mP* = 1.007277 amu

  Electron mass *me* = 0.0005486 amu.

  amu = *atomic mass unit* = 1.66 × 10–27 kg, or 3.66 × 10–2 lb.
- These three particles are the primary building blocks of all atoms. Atoms differ in their mass because they contain varying numbers of them.

ISOTOPES:

- The number of protons have similar chemical and physical characteristics and differ mainly in their masses. They are called *isotopes*. For example, deuterium frequently called *heavy hydrogen* and it is an isotope of hydrogen.

ATOMIC NUMBER AND MASS NUMBER:

- The number of protons in the nucleus is called the atomic number. *It is denoted as Z*.
- The total number of nucleons in the nucleus is called the mass *number A*.

VALENCE ELECTRON AND VALENCE SHELL:

- Electrons that orbit in the outermost shell of an atom are called *valence electron*.
- The outermost shell is called the *valence shell*. Thus, hydrogen has one valence electron and its K shell is the valence shell, etc.

CRITICAL MASS:

- There is a threshold mass of a radioactive isotope at which the flux density of radioactive particles will sustain a chain reaction. If this reaction is uncontrolled the result is an atomic bomb explosion.

Types of Radiation	Atomic Weight	Charge
Alpha radiation (Helium nucleus)	4	+2
Beta radiation (Electron)	~0	– 1
Neutron	1	0
Gamma ray	~0	0

ALPHA PARTICLES(α particles):

- Alpha is quickly absorbed by matter because the particles have a large probability of collision with nuclei. Sources external to the human body cause radiation absorption within the thickness of the skin.
- Radiation from airborne particles in the lung are absorbed by surface membranes lining the lung.
- Alpha emitters ingested with food cause radiation absorption by the lining of the gut. The risk of genetic damage to adult organisms is very small because absorption takes place in surface cells.

BETA PARTICLES(β particles):

- Beta particles penetrate to the deepest parts of the body and can cause genetic damage and disrupt the function of cells anywhere in the body. Building walls and earthwork provide substantial shielding.

GAMMA PARTICLES(γ particles):

- Gamma has the greatest penetration due to their small cross-section.
- Gamma particles can pass through ordinary materials. Effective shielding requires blankets of lead. Gamma radiation is a danger to all cells in the body.

HALF LIFE(T):

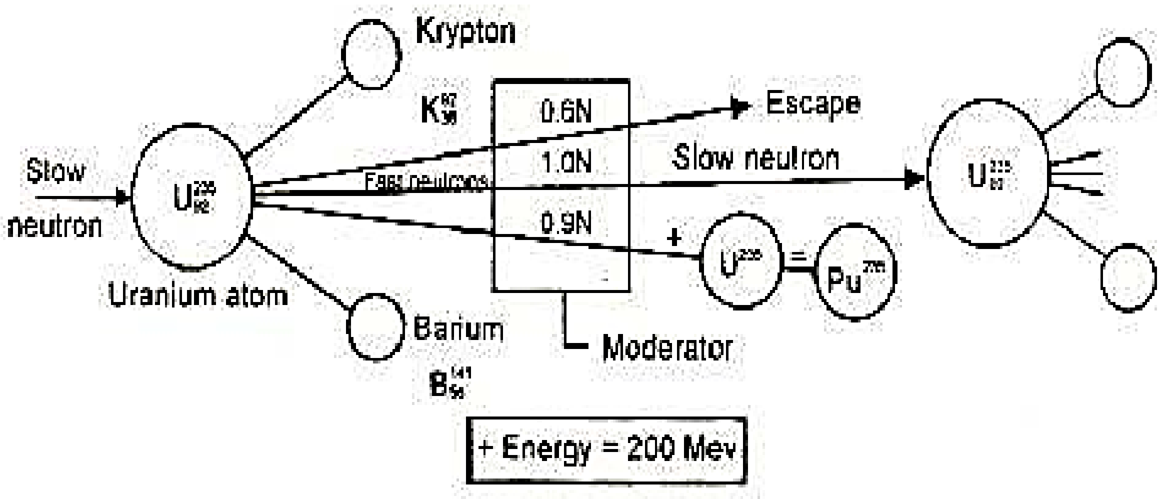
Time taken for half the atomic nuclei to spontaneously split is called as Half-life. The amount of nuclei decays exponentially

$$N = N_0 \exp(-t/T)$$

N = Amount of radioactive material, t = Elapsed time

N_0 = Initial amount

Fission energy:



Nuclear fission

- Nuclear energy is divided from splitting (or) fissioning of the nucleus of fissionable material like Uranium U-235.
- Uranium has several isotopes (Isotopes are atoms of the same element having different atomic masses) such as U-234, U-235 and U-238.
- Of the several isotopes, U-235 is the most unstable isotope, which is easily fissionable and hence used as fuel in an atomic reactor.

When a neutron enters the nucleus of an unstable U-235, the nucleus splits into two equal fragments (Krypton and Barium) and also releases 2.5 fast moving neutrons with a velocity of 1.5×10^{7} m/sec and along with this produces a large amount of energy, nearly 200 million electro-volts. This is called nuclear fission.

Chain reaction:

- The neutrons released during fission are very fast and can be made to initiate the fission of other nuclei of U-235, thus causing a chain reaction.
- When a large number of fission occurs, enormous amount of heat is generated, which is used to produce steam.
- The chain reaction under controlled conditions can release extremely large amount of energy causing "atomic explosion"

- Energy released in chain reaction, according to Einstein law is

$$\mathbf{E = mc^2}$$

Where, E = Energy liberated (J)
m= Mass (kg)
c = Velocity of light (3×10^{8} m/sec).

Out of 2.5 neutrons released in fission of each nucleus of U-235, one neutron is used to sustain the chain reaction about 0.9 neutron is captured by U-238 which gets converted into fissionable material Pu-239 and about 0.6 neutron is partially absorbed by control rod materials, coolant and moderator.

If thorium is used in the reactor core, it gets converted to fissionable material U-233.

Thorium 232 + Neutron → Uranium-233

Pr-239 and U-233 so produced are fissionable materials are called secondary fuels. They can be used as nuclear fuels. U-238 and Th-232 are called fertile materials.

Fusion energy:

Energy is produced in the sun and stars by continuous fusion reactions in which four nuclei of hydrogen fuse in a series of reactions involving other particles that continually appear and disappear in the course of the reaction, such as He^3, nitrogen, carbon, and other nuclei, but culminating in one nucleus of helium of two positrons.

$$4\ {}_1H \rightarrow {}_2He + 2\ {}_{+1}e$$

To cause fusion, it is necessary to accelerate the positively charged nuclei to high kinetic energies, in order to overcome electrical repulsive forces, by raising their temperature to hundreds of millions of degrees resulting in plasma. The plasma must be prevented from contacting the walls of the container, and must be confined for a period of time (of the order of a second) at a minimum density. Fusion reactions are called thermonuclear because very high temperatures are required to trigger and sustain them. Table lists the possible fusion reactions and the energies produced by them. n, p, D, and T are the symbols for the neutron, proton, deuterium (H2), and tritium (H3), respectively.

Number	Fusion reaction		Energy per reaction MeV
	Reactants	Products	
1	D + D	T + p D	4
2	+ D	He^3 + n T	3.2
3	+ D	He^4 + n	17.6
4	He^3 + D	He^4 + p	18.3

Many problems have to be solved before an artificially made fusion reactor becomes a reality.

2. Draw and explain block diagram of Nuclear power plant and write few advantages and disadvantage. (or) Explain the layout of Nuclear power plant with their component functions.

The Main components of nuclear power plants are:

i) Nuclear Reactor
ii) Steam generator
iii) Turbine
iv) Coolant pump and Feed pump
v) Generator(for converting mechanical energy into electrical energy)

i) Nuclear reactor:

- Nuclear reactor is a device designed to maintain a chain reaction producing a steady flow of neutrons generated by the fission of heavy nuclei.
- Heat is produced in the reactor due to nuclear fission of the fuel U235.
- The heat liberated in the reactor is taken up by the coolant circulating through the core.

Need of Shielding in Reactor:

The important sub components present in nuclear reactor are:

- ✓ Moderator
- ✓ Reflector
- ✓ Shielding
- ✓ Cladding
- ✓ Control rods
- ✓ Coolant

A) Moderator:

- In any nuclear chain reaction, the neutrons produced are fast moving neutrons.
- These are less effective for further fission reaction with U235 and they try to escape from the reactor.
- To reduce the speed of these neutrons must be reduced if their effectiveness is carrying out fission is to be increased.
- This is done by making these neutrons collide with lighter nuclei of other materials.
- Each collision causes loss of energy and thus the speed of neutrons is reduced. Such a material is called a 'Moderator'.
- The neutrons thus slowed down are easily captured by the fuel element at the chain reaction proceeds slowly.

B) Reflectors:

- Some of the neutrons produced during fission will be partly absorbed by the fuel elements, moderator, coolant and other materials.

- The remaining neutrons will try to escape from the reactor and will be lost.
- Such losses are minimized by surrounding the reactor core with a material called a reflector which will reflect the neutrons back to the core.
- They improve the neutron economy. (Examples: Graphite, Beryllium)

C) Shielding:

- The radiations due to nuclear fission in the reactor are very harmful to human life.
- It requires strong control to ensure that this radioactivity is not released into the atmosphere to avoid atmospheric pollution.
- A thick concrete shielding and a pressure vessel are provided to prevent the escape of these radiations to atmosphere.
- Tin, lead or steel is used as shielding material.

D) Cladding:

- In order to prevent the contamination of the coolant by fission products, the fuel element is covered with a protective coating. This is known as cladding.

E) Control rods:

- Control rods are used to control the reaction to prevent it from becoming violent.
- They control the reaction by absorbing neutrons.
- These rods are made of boron or cadmium.
- Whenever the reaction needs to be stopped, the rods are fully inserted and placed against their seats and when the reaction is to be started the rods are pulled out.

F) Coolant:

- The main purpose of the coolant in the reactor is to transfer the heat produced inside the reactor.
- The same heat carried by the coolant is used in the heat exchanger for further utilization in the power generation.

Some of the desirable properties of good coolant are listed below

- It must not absorb the neutrons.
- It must have high chemical and radiation stability
- It must be non-corrosive.
- It must have high boiling point (if liquid) and low melting point (if solid)
- It must be non-oxidizing and non-toxic.

The above-mentioned properties are essential to keep the reactor core in safe condition as well as for the better functioning of the content.

- It must have high density
- It must have low viscosity
- It must have high conductivity

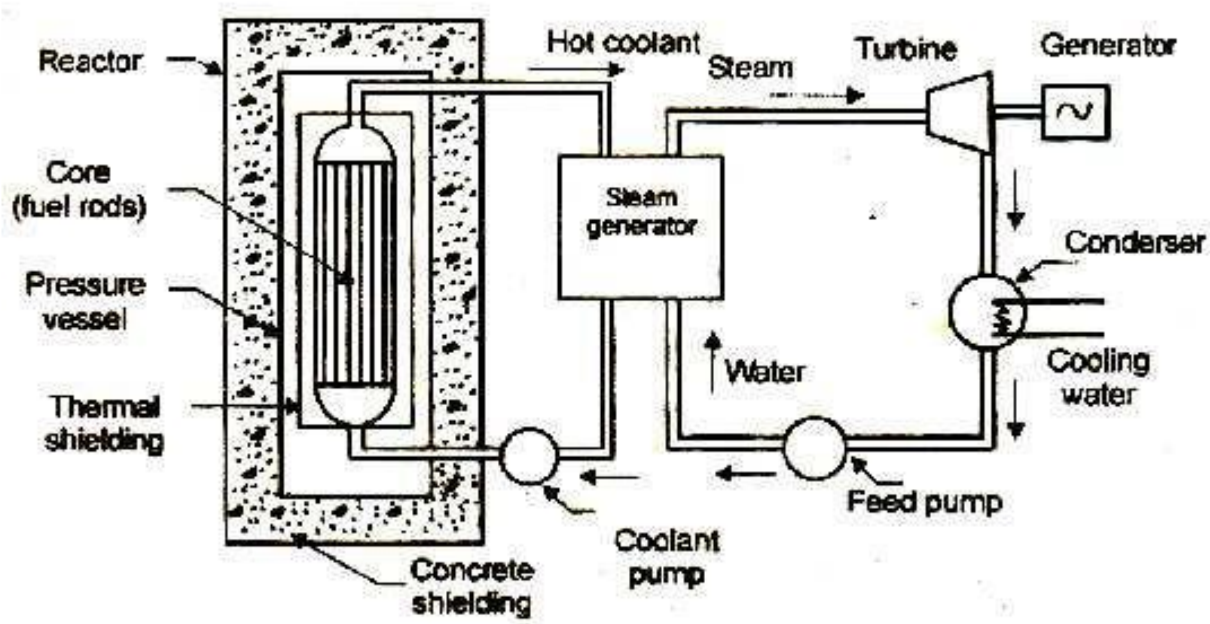
- It must have high specific heat.

These properties are essential for better heat transfer and low pumping power.

- The water, heavy water, gas (He, CO_2), a metal in liquid form (Na) and an organic liquid are used as coolants.
- The coolant not only carries large amounts of heat from the core but also keeps the fuel assemblies at a safe temperature to avoid their melting and destruction.

ii) Steam generator:

- The steam generator is fed with feed water which is converted into steam by the heat of the hot coolant.
- The purpose of the coolant is to transfer the heat generated in the reactor core and use it for steam generation.
- Ordinary water or heavy water is a common coolant.



Layout of Nuclear Power Plant

iii) Turbine and Generator:

- The steam produced in the steam generator is passed to the turbine and work is done by the expansion of steam in the turbine.
- The turbine rotates the generator and produces an electrical energy by its principle.

iv) Coolant pump and Feed pump:

- The steam from the turbine flows to the condenser where cooling water is circulated.
- Coolant pump and feed pump are provided to maintain the flow of coolant and feed water respectively.

Advantages of nuclear power plant:

- It can be easily adopted where water and coal resources are not available.
- The nuclear power plant requires very small quantity of fuel. Hence fuel transportation cost is less.
- Space requirement is less compared to other power plants of equal capacity.
- It is not affected by adverse weather conditions.
- Fuel storage facilities are not needed as in the case of the thermal power plant.
- Nuclear power plants will converse the fossils fuels (coal, petroleum) for other energy needs.
- Number of workmen required at nuclear plant is far less than thermal plant.
- It does not require large quantity of water.

Disadvantages of nuclear power plant:

- Radioactive wastes, if not disposed of carefully, have adverse effect on the health of workmen and the population surrounding the plant.
- It is not suitable for varying load condition.
- It requires well-trained personnel.
- It requires high initial cost compared to hydro or thermal power plants.

3. Explain in detail about Boiler Water Reactor. (or) Describe the construction and operation of BWR. (or) Explain any one type of light water nuclear reactor.

Introduction:

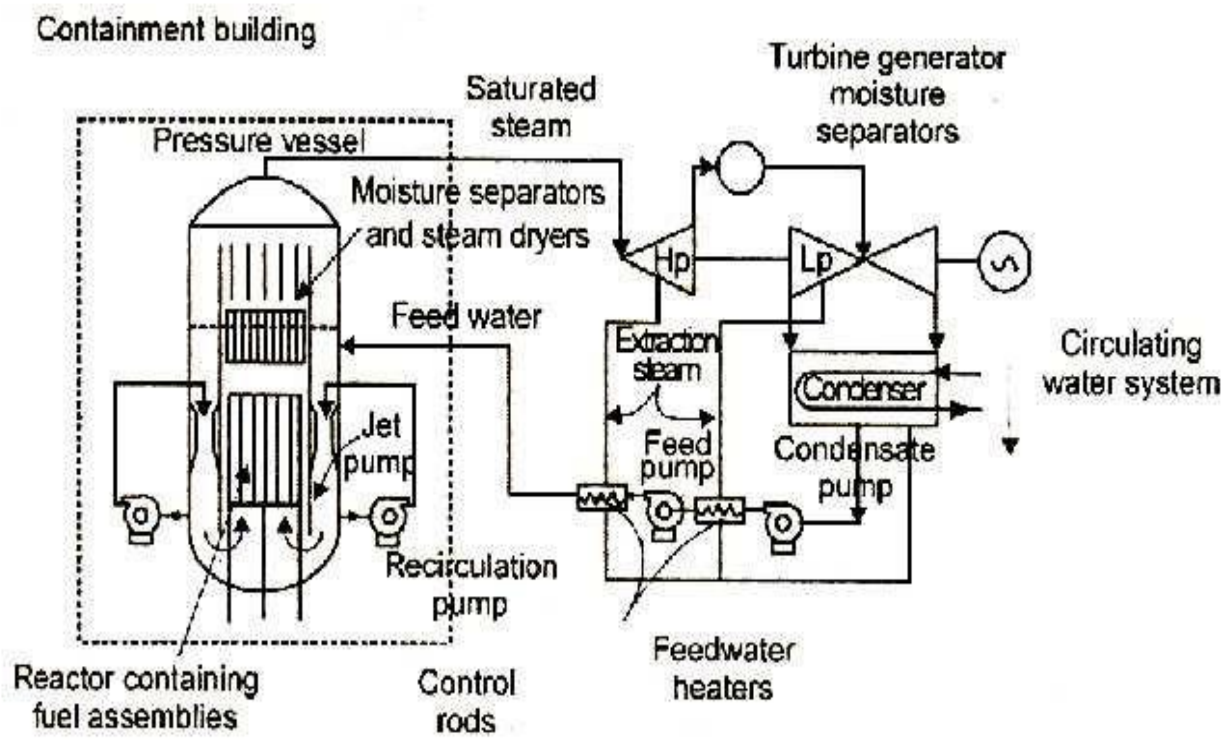
- The **Boiling Water Reactor** (**BWR**) is a type of light water nuclear reactor used for the generation of electrical power.
- It is the second most common type of electricity generating nuclear reactor after the pressurized water reactor (PWR).
- The purposes of the reactor vessel assembly are to:
  - ✓ House the reactor core
  - ✓ Serve as part of the reactor coolant pressure boundary
  - ✓ Support and align the fuel and control rods
  - ✓ Provide a flow path for circulation of coolant across the fuel
  - ✓ Remove moisture from the steam exiting the core, and
  - ✓ Provide a refloodable volume for a loss of coolant accident

Construction of BWR:

- The BWR reactor core consists of a large number of fuel rods housed in fuel assemblies in a nearly cylindrical arrangement.
- Each fuel assembly contains an 8×8 or 9×9 square array of 64 or 81 fuel rods (typically two of the fuel rods contain water rather than fuel) surrounded by a square Zircaloy channel box to ensure no coolant cross flow in the core.

- The fuel rods are similar to the PWR rods, although larger in diameter. Each fuel rod is a zirconium alloy- clad tube containing pellets of slightly enriched uranium dioxide (2% to 5% U-235) stacked end-to- end.
- The reactor is controlled by control rods housed in a cross-shaped, or cruciform, arrangement called a control element.
- The control elements enter from the bottom of the reactor and move in spaces between the fuel assemblies.
- The BWR reactor core is housed in a pressure vessel that is larger than that of a PWR.
- A typical BWR pressure vessel, which also houses the reactor core, moisture separators, and steam dryers, has a diameter of 6.4 m, with a height of 22 m.
- Since a BWR operators at a nominal pressure of 6.9 MPa, its pressure vessel is thinner that of a PWR.

Schematic Diagram:



Schematic diagram for boiling water reactor.

Operation (Working) of BWR:

- The fuel Uranium-235 is used as a fuel in the reactor to produce nuclear fission chain reaction.
- Light water which acts as the coolant and moderator.

- The coolant passes through the core where boiling takes place in the upper part of the core.
- The heat produced by the nuclear fission reaction is taken by the coolant into the steam generator.
- The steam generator(Boiler) transfers the hot water and some of the water is vapourized into the steam.
- The wet steam then passes through a bank of moisture separators and steam dryers in the upper part of the pressure vessel.
- The water that is not vaporized to steam is recirculated through the core with the entering feed water using two recirculation pumps coupled to jet pumps.
- The steam leaving the top of the pressure vessel is at saturated conditions of 7.2 MPa and 278◎C.
- The steam then expands through a turbine coupled to an electrical generator.
- After condensing of steam into liquid in the condenser, the liquid is returned to the reactors as feedwater.
- Prior to entering the reactor, the feedwater is preheated in several stages of feedwater heaters.
- The balance of plant systems (Example: Turbine generator, feedwater heaters) are similar for both PWR and BWRs.

Advantages of BWR:

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

Disadvantages of BWR:

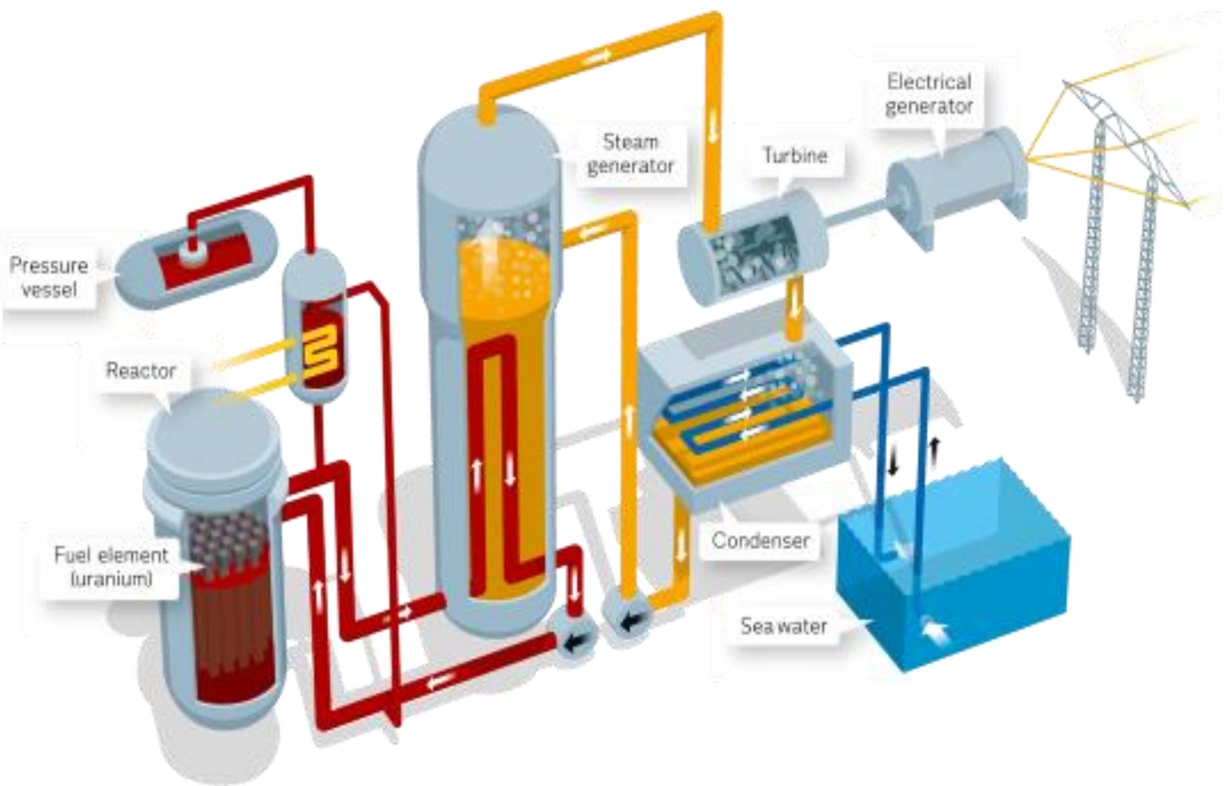
- Possibility of radioactive contamination in the turbine mechanism should there be any failure of fuel elements.
- More safety precautions are needed which are costly.
- Wastage of steam resulting in lowering of thermal efficiency on part load operation.
- Boiling limits power density only 3 to 5% by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

4. Explain in detail about Pressurized Water Reactor with its advantages and disadvantages. (or) Describe the construction and operation of PWR. (or) Explain any one type of light water nuclear reactor.

PWR Reactor Design(Construction):

Coolant:

- Light water is used as the primary coolant in a PWR.
- It enters the bottom of the reactor core at about 275 °C (530 °F) and is heated as it flows upwards through the reactor core to a temperature of about 315 °C (600 °F).
- The water remains liquid with the high temperature due to the high pressure in the primary coolant loop around 155 bar (15.5 MPa at 153 atm)
- Pressure in the primary circuit is maintained by a pressurizer, a separate vessel that is connected to the primary circuit and partially filled with water which is heated to the saturation temperature.
- To achieve a pressure of 155 bar, the pressurizer temperature is maintained at 345 40°C, which gives a sub-cooling margin of 30 °C.
- The coolant is pumped around the primary circuit by powerful pumps, which can consume upto 6 MW each.
- After picking up heat as it passes through the reactor core, the primary coolant transfers heat in a steam generator to water and evaporating the secondary coolant to saturated steam.



Schematic diagram for Pressurized Water Reactor

Moderator:

- Pressurized water reactors require the fast fission neutrons to be slowed down (a process called moderation or thermalization) in order to interact with the nuclear fuel and sustain the chain reaction.
- In PWRs the coolant water is used as a moderator by letting the neutrons undergo multiple collisions with light hydrogen atoms in the water, losing speed in the process.
- This "moderating" of neutrons will happen more often when the water is denser (more collisions will occur).
- The use of water as a moderator is an important safety feature of PWRs, as an increase in temperature may cause the water to turn to steam.
- Therefore, if reactivity increases beyond normal, the reduced moderation of neutrons will cause the chain reaction to slow down, producing less heat and makes PWR reactors very stable.

Fuel:

- After enrichment the uranium dioxide (UO_2) powder is fired in a high-temperature, sintering furnace to create hard, ceramic pellets of enriched uranium dioxide.
- The cylindrical pellets are then clad in a corrosion-resistant zirconium metal alloy Zircaloy which are backfilled with helium to aid heat conduction and detect leakages.
- Zircaloy is chosen because of its mechanical properties and its low absorption cross section.
- The finished fuel rods are grouped in fuel assemblies called fuel bundles that are used to build the core of the reactor.
- A typical PWR has fuel assemblies of 200 to 300 rods each and a large reactor is about 150–250 such assemblies with 80–100 tonnes of uranium in all.
- Generally, the fuel bundles consist of fuel rods bundled 14 × 14 to 17 × 17.
- A PWR produces on the order of 900 to 1,500 MW_e.
- PWR fuel bundles are about 4 meters in length.
- Refueling for most commercial PWRs is on an 18–24 month cycle.

Control Rods:

- Boron and control rods are used to maintain primary system temperature at the desired point.
- Boron readily absorbs neutrons and increasing or decreasing its concentration in the reactor coolant.

- An entire control system involving high pressure pumps is required to remove water from the high pressure primary loop and re-inject the water back in with differing concentrations of boric acid.
- The reactor control rods, inserted through the reactor vessel head directly into the fuel bundles, are moved for the following reasons:
  - ✓ To start up the reactor.
  - ✓ To shut down the primary nuclear reactions in the reactor.
  - ✓ To accommodate short term transients such as changes to load on the turbine.
- The control rods can also be used:
  - ✓ To compensate for nuclear poison inventory.
  - ✓ To compensate for nuclear fuel depletion.

Operation (Working) of PWR:

- The reactor have reactor vessel which contains water as coolant and uranium as Moderator.
- When the uranium atoms are splitting to produce nuclear fission chain reaction.
- The nuclear fission reaction produces fast moving neutrons and also some energy in the form of heat.
- Due to heat from nuclear reaction, the water is heated to 325°C.
- The high pressure inside the reactor is regulated by a pressure vessel, preventing the boiling of water.
- The hot water from the reactor is transferred to the steam generator which is a large heat exchanger.
- Steam is produced because the pressure is lower and steam is subsequently fed into the turbine.
- The pressure from the steam causes the turbine blades to rotate and the turbine operates a generator which generates electricity.
- The steam is then conveyed to a condenser which consists of a large number of small pipes.
- Sea water is pumped through pipes and condenses the steam into water again.
- The sea water is pumped back out to the sea again and is then around 10°C warmer than when it entered the condenser.
- The condensed water is pumped back from the steam generator into the reactor to be heated again.
- The water in the reactor thus circulates in a closed cycle so neither the steam generator water nor the cooled sea water comes into contact with the water in the reactor.

Advantages of PWR:

- PWR reactors are very stable due to their tendency to produce less power as temperatures increase.
- PWR turbine cycle loop is separate from the primary loop, so the water in the secondary loop is not contaminated by radioactive materials.
- When power is lost, the control rods immediately stop the primary nuclear reaction. The control rods are held by electromagnets and fall by gravity when current is lost.
- PWR technology is favoured by navy, the compact reactors fit well in nuclear submarines and other nuclear ships.

Disadvantages of PWR:

- The PWR design requires high strength piping and a heavy pressure vessel and hence increases construction cost.
- Additional high pressure components such as reactor coolant pumps, pressurizer, steam generators, etc. are also needed.
- Additional components increases the capital cost and complexity of a PWR power plant.
- The high temperature water coolant with boric acid can cause radioactive corrosion products to circulate in the primary coolant loop. This limits the lifetime of the reactor
- The requirement to enrich the uranium fuel for PWRs also presents a serious explosion risk.
- Water acts as a neutron moderator, it is not possible to build a fast neutron reactor with a PWR design.

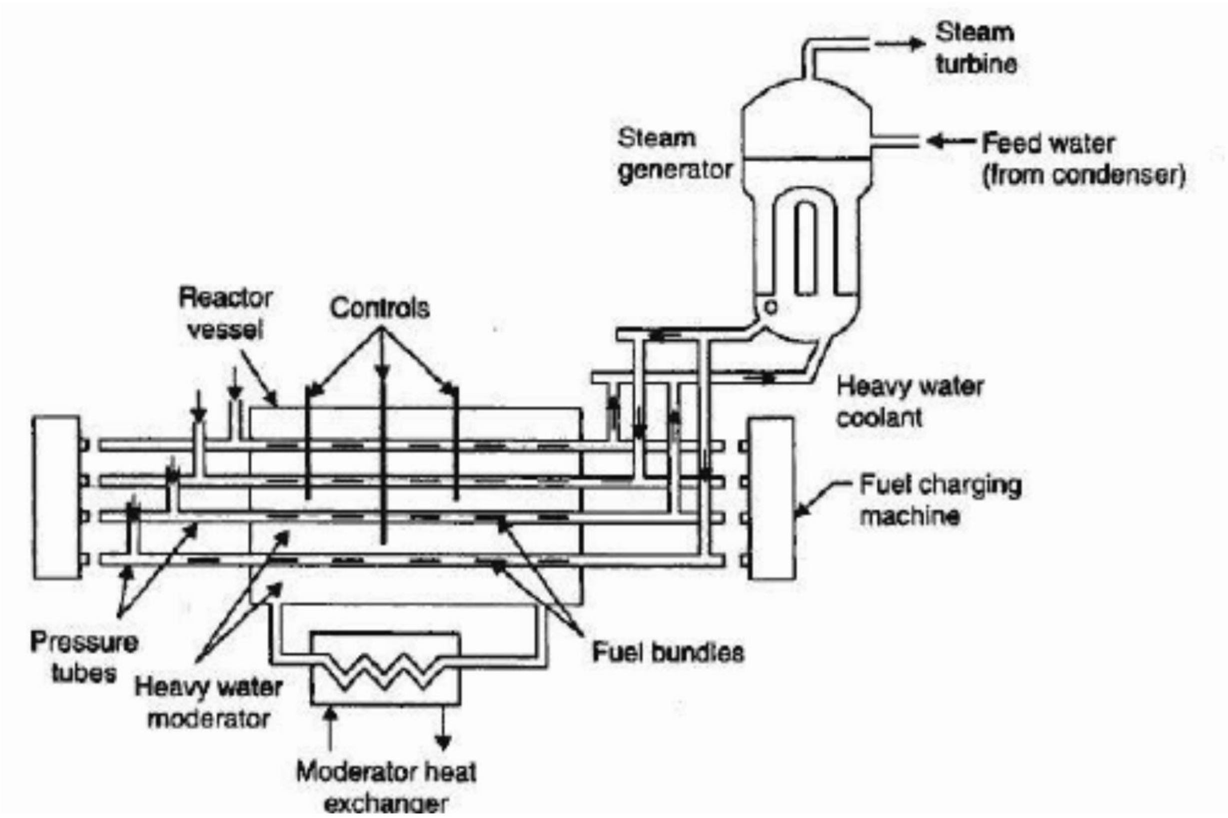
5. Explain in detail about CANada Deuterium Uranium Reactor with its advantages and disadvantages. (or) Describe the construction and operation of CANDU Reactor. (or) Explain the most preferable nuclear reactor used in Canada.

CANDU Reactor Components:

Reactor vessel and core:

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

- The high pressure (10 MPa) and high temperature (3700 C) coolant leaving the reactor core enters the steam generator.
- About 5% of fission heat is generated by fast neutrons escaping into the moderator, and this is removed by circulation through a separate heat exchanger.



Schematic diagram of CANDU Reactor

Fuel system:

- In a CANDU reactor the fuel is normal (i.e., unenriched) uranium oxide as small cylinder pellets.
- The pellets are packed in a corrosion resistance zirconium alloy tube, nearly 0.5 long and 1.3 cm diameter, to form a fuel rod.
- The relatively short rods are combined in bundles of 37 rods and 12 bundles are placed end to end in each pressure tube.
- The total mass of fuel in the core is about 97,000 kg.
- The CANDU reactor is unusual in that refueling is conducted while the reactor is operating.

Control and protection system:

- There are the various types of vertical control system incorporated in the CANDU reactor:
- A number of strong neutron absorber rods of cadmium which are used mainly for reactor shut-down and start-up.

- In addition to above there are other less strongly, absorbing rods to control power variations during reactor operation and to produce an approximately uniform heat (power) distribution throughout the core.
- In an emergency situation, the shut-down rods would immediately drop into the core, if necessary by the injection of a gadolinium nitrate solution into the moderator.

Steam system:

- The respective ends of the pressure tubes are all connected into inlet and outlet headers.
- The high temperature coolant leaving the reactor passes out the outlet header to a steam generator of the conventional inverted U-tube and is then pumped back into the reactor by way of the inlet header.
- Steam is generated at a temperature of about 265°C.
- There are two coolant outlet (and two inlet) headers, one at each end of the reactor vessel corresponding to the opposite directions of coolant flow through the core.
- Each inlet (and outlet header is connected to a separate steam generator and pump loop.
- A single pressurizer maintains an essentially constant coolant system pressure.
- The reactor vessel and the steam generator system are enclosed by a concrete containment structure.
- A water spray in the containment would condense the steam and reduce the pressure that would result from a large break in the coolant circuit.

Operation of CANDU reactor:

- The fuel Uranium-235 is used as a fuel in the reactor to produce nuclear fission chain reaction.
- The reactor have reactor vessel which contains heavy water as coolant and uranium as Moderator.
- When the uranium atoms are splitting to produce nuclear fission chain reaction.
- The nuclear fission reaction produces fast moving neutrons and also some energy in the form of heat.
- The heavy water which acts as a moderator slow down the fast moving neutrons and pull back the neutrons for the next nuclear fission reaction.
- Due to heat from nuclear reaction, the heavy water is heated to some high temperature.
- The hot water from the reactor is transferred to the steam generator which is a large heat exchanger.
- Steam is produced because the pressure is lower and steam is subsequently fed into the turbine.
- The pressure from the steam causes the turbine blades to rotate and the turbine operates a generator which generates electricity.

- The steam is then conveyed to a condenser which consists of a large number of small pipes.
- Sea water is pumped through the pipes and condenses the steam into water again.
- The sea water is pumped back out to the sea again and is then around 10°C warmer than when it entered the condenser.
- The condensed water is pumped back from the steam generator into the reactor to be heated again.

Advantages of CANDU reactor:

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

Disadvantages of CANDU reactor:

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

6. Draw and explain the Fast Breeder Reactor? (or) Describe the FBR with its coolant.

Introduction:

- A breeder reactor is a nuclear reactor capable of generating more fissile material than it consumes. These devices are able to breed (or create) more fissile fuel than they use from fertile material such as uranium-238 or thorium-232.
- Breeders were at first found attractive because their fuel economy was better than light water reactors,
- But the interest is declined after 1960s as more uranium reserves were found and new methods of uranium enrichment with reduced fuel costs.

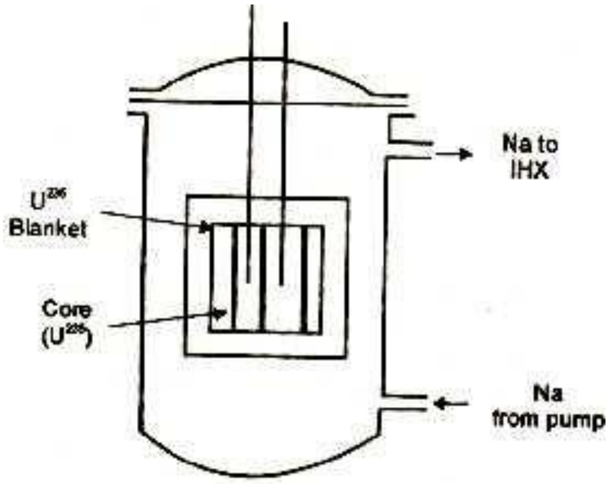
Types of Breeder Reactor:

A) Thermal Breeder:

- Thermal breeder reactor use thermal spectrum (moderated) neutrons to breed fissile uranium-233 from thorium (thorium fuel cycle).
- Due to the behavior of the various nuclear fuels, a thermal breeder is thought commercially feasible only with thorium fuel, which avoids the buildup of the heavier transuranics.

B) Fast Breeder Reactor:

- Fast breeder reactor **(**FBR) uses fast 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.
- It is mostly preferable because of fuel utilized is abundant in nature compared to thermal breeder used fuel.



Fast breeder reactor arrangement

Fast Breeder Reactor Design:

- In this reactor the core containing U235 is surrounded by a blanket (a layer of fertile material placed outside the core) of fertile material U238.
- Fast breeder reactor has no moderator to control the speed of chain reaction.
- The fast moving neutrons liberated due to fission of U-235 are absorbed by U-238 which gets converted into fissionable material Pu-239 which is capable of sustaining chain reaction.
- This reactor is important because it breeds fissionable material from fertile material U238 available in large quantities.
- Like sodium graphite nuclear reactor this reactor also uses two liquid metal coolant circuits.
- Liquid sodium is used as primary coolant when circulated through the tubes of intermediate heat exchange transfers its heat to secondary coolant sodium potassium alloy.
- The secondary coolant while flowing through the tubes of steam generator transfers its heat to feed water.
- Fast breeder reactors are better than conventional reactors both from the point of view of safety and thermal efficiency.
- The fast breeder reactor becomes inescapable in view of the massive reserves of thorium and the finite limits of its uranium resources.

Coolant for Fast Breeder reactor:

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

i) Liquid metal (Na or Na-K)
ii) Helium (He)
iii) Carbon dioxide(CO_2)

Sodium has the following advantages:

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

Operation of Breeder reactor:

- In this reactor the core containing the fuel as Uranium-235(U-235) is surrounded by a layer of fertile material Uranium-238(U-238).
- Sodium is used as coolant to transfer the heat from reactor to an intermediate heat exchanger(IHX).
- When nuclear fission reaction of U-235 takes place, the fast moving neutrons are liberated and also some energy is generated in the form of heat.
- The fast moving neutrons are absorbed by U-238 which gets converted into fissionable material Plutonium-239(Pu-239)
- When Pu-239 combines with the neutrons, it is capable of producing further nuclear chain reaction.
- The heat generated by the nuclear reaction is absorbed by the coolant(sodium).
- Sodium is boiled quickly due to its low boiling point and and the hot sodium is supplied to Heat exchanger.
- In the heat exchanger, the heat of sodium is transferred to the cool water present in the same heat exchanger.
- After the heat transfer, the cool sodium metal can be fed back into the reactor core through the feedpump.
- Some of the hot water in heat exchanger is vapourized into steam and steam is subsequently fed into the turbine.
- The pressurized steam causes the turbine blades to rotate and the turbine operates a generator which generates electricity.
- The steam is then conveyed to a condenser and condenses the steam into water again.
- The condensed water is pumped back from the steam generator into the reactor to be heated again.

Advantages of breeder reactor:

- A breeder reactor creates 30% more fuel than it consumes.
- Breeder reactors can even use the uranium waste from uranium processing plants.
- It reuses fuel for the expenses for mining, milling, and processing of uranium ore are minimized.

- This technology does not contribute to air pollution, except during the mining and processing of uranium ore.
- Breeder reactors can use a small core, which is important to sustain chain reactions.
- It can generate much more energy than traditional coal power plants.

Disadvantages of breeder reactor:

- Breeder reactors use highly enriched fuels which causes the danger of critical accidents.
- Breeder reactors are always working at a very high temperature and a fast pace.
- Low efficiency due to fissile material such as Plutonium.
- It requires liquified sodium or potassium metal as a coolant,
- The construction and operation is very costly.
- These reactors are complex to operate.

7. Explain in detail about Gas Cooled Reactor with its advantages and disadvantages. (or) Describe the construction and operation of GCR. (or) Explain the operation of nuclear reactor which uses carbon-dioxide as coolant.

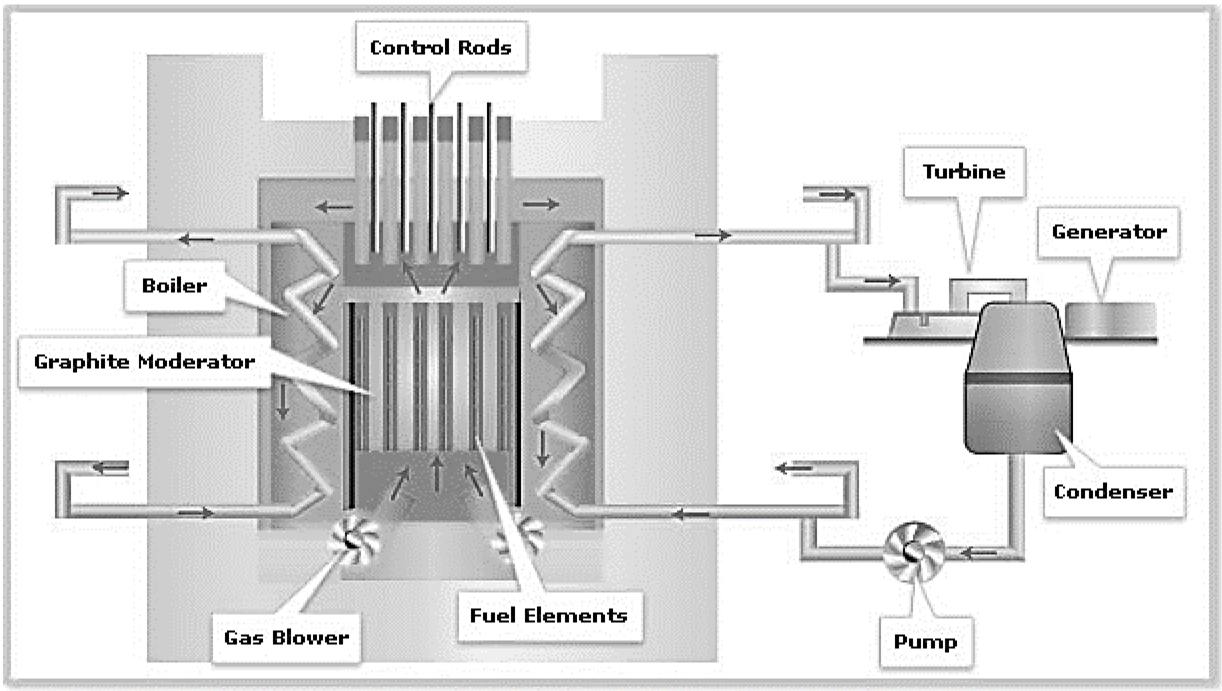
Introduction:

- The Gas Cooled Reactor was one of the original design reactor which uses the moderator is graphite and an Inert gas as coolant (e.g. helium or carbon dioxide).
- The advantage of the design is that the coolant can be heated to higher temperatures than water.
- As a result higher plant efficiency (40% or more) could be obtained compared to the water cooled design (33-34%).
- The older reactor design uses carbon dioxide gas circulating through the core (at a pressure of 1.6 MPa or 230 pounds) per square inch to remove the heat from the fuel elements.
- The fuel consists of natural uranium metal clad with an alloy of magnesium known as Magnox (thus the name for the reactor type).
- The newer Advanced Gas Cooled (AGR) Reactors use a slightly enriched uranium dioxide clad with stainless steel as moderator and Carbon dioxide gas is the coolant.

Operation (Working) of Gas Cooled Reactor:

- The reactor core consists of fuel element which is natural uranium metal and it is cladded by Magnox(an alloy of magnesium).
- Carbon-di-oxide is used as a coolant and graphite is used as moderator.
- When the uranium atoms are splitting to produce nuclear fission chain reaction.
- The nuclear fission reaction produces fast moving neutrons and also some energy in the form of heat.

- Carbon dioxide gas passed through the fuel channels absorbs the fission heat and also reduces the speed of neutrons.
- The hot carbon-di-oxide gas from the reactor is transferred to the Heat exchanger(steam generator).
- In the heat exchanger, the heat of CO_2 gas is transferred to the cool water present in the same heat exchanger.
- After heat transfer, the CO_2 gas is fed back into the reactor core through feedpump.
- Some of the hot water is vapourized into steam in the heat exchanger and steam is subsequently fed into the turbine.
- The pressurized steam causes the turbine blades to rotate and the turbine operates a generator which generates electricity.
- The steam is then conveyed to a condenser and condenses the steam into water.
- The condensed water is pumped back from the steam generator into the reactor to be heated again.



Schematic diagram for Gas Cooled Reactor based Power Plant

Gas Cooled reactor design:

Reactor core:

- The reactor moderator consists of a 16 sided stack of Graphite bricks.
- The graphite acts as moderator as well as provide necessary channels for fuel assembly, control rods and coolant flow.
- The shielding around the core is necessary to protect the surrounding steel work and boilers from neutrons.

- The shielding is provided by using more thickness of graphite moderator and also higher thickness steel is used for boiler design.
- The upper neutron shield consists of graphite and steel bricks.
- The lower shield is made up of graphite bricks which is placed on steel plates.
- For control the chain reaction of the neutrons with the fuel, control rods are inserted into the core.
- Under emergency conditions, nitrogen may be injected between the fuel assemblies to absorb neutrons.

Fuel:

- In a Gas Cooled Reactor design, the unit operates on fast neutrons and there is no moderator is needed to slow neutrons down.
- Apart from nuclear fuel such as uranium, other fuels can also be used.
- The most common is thorium, which absorbs a fast neutron and decays into Uranium 233.
- Gas Cooled Reactor designs have breeding properties because they can use fuel that is unsuitable in light water reactor designs and breed fuel.
- Because of these properties, once the initial loading of fuel has been applied into the reactor, the unit can go years without needing fuel.
- If these reactors are used for breeding, it is economical to remove the fuel and separate the generated fuel for future use.

Coolant:

- The gas used can be many different types, including carbon dioxide or helium.
- It must be composed of elements with low neutron capture cross sections to prevent induced radioactivity.
- The use of gas also removes the possibility of phase transition–induced explosions, such as in water-cooled reactor flashes to steam upon overheating or depressurization.
- The use of gas also allows for higher operating temperatures than are possible with other coolants increasing thermal efficiency,
- The gas coolant allows other non-mechanical applications of the energy such as the production of hydrogen fuel.

Advantages of Gas Cooled Reactor:

- If CO_2 is used as the cooling gas, it eliminates the possibility of explosion which is always present in water cooled reactors
- There is no need for cladding the metallic fuel which leads to simple fuel processing techniques.

- In this reactor design, the coolant can be heated to higher temperatures than water to achieve higher thermal efficiency.
- This reactor design is not susceptible to some types of accidents possible with water cooled reactors.

Disadvantages of Gas Cooled Reactor:

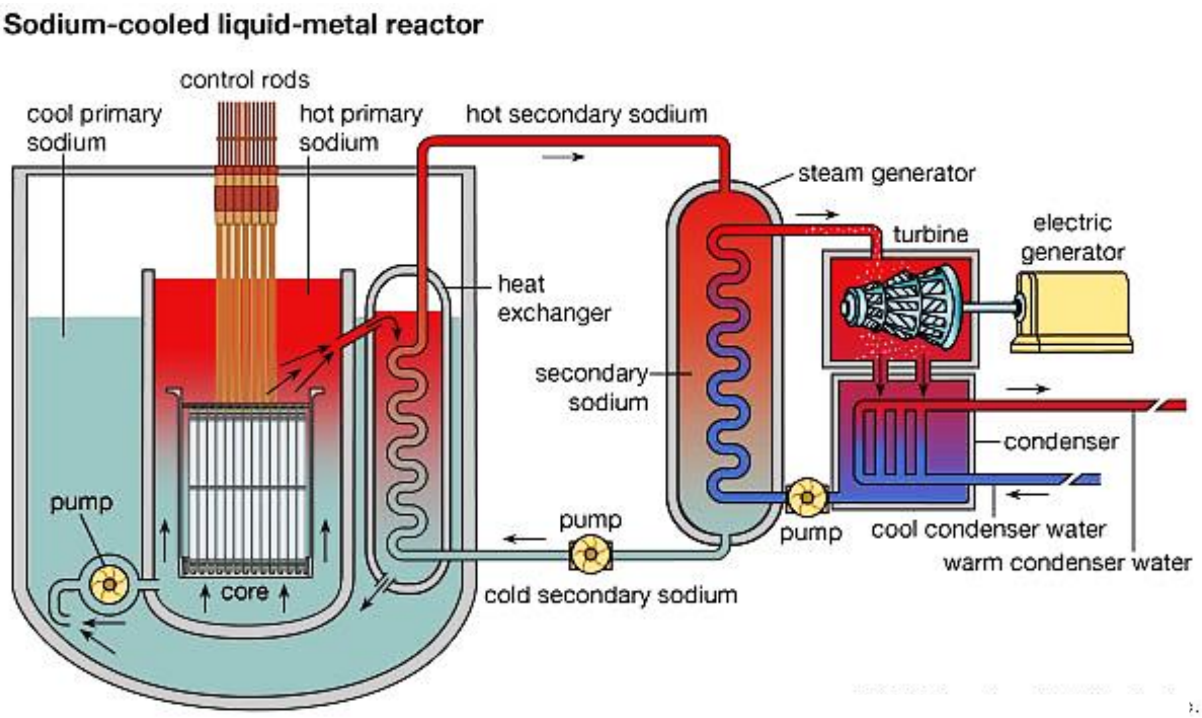
- The main drawback of these plants is there low power density
- This reactor design requires large size of the reactor for relatively smaller power requirements.
- When Helium is used as coolant, its low neutron absorbing capacity makes it unsuitable for load control.

8. Explain in detail about Liquid Metal Cooled Reactor with its advantages and disadvantages. (or) Describe the construction and operation of LMCR. (or) Explain the operation of nuclear reactor which uses Liquid Metal as coolant.

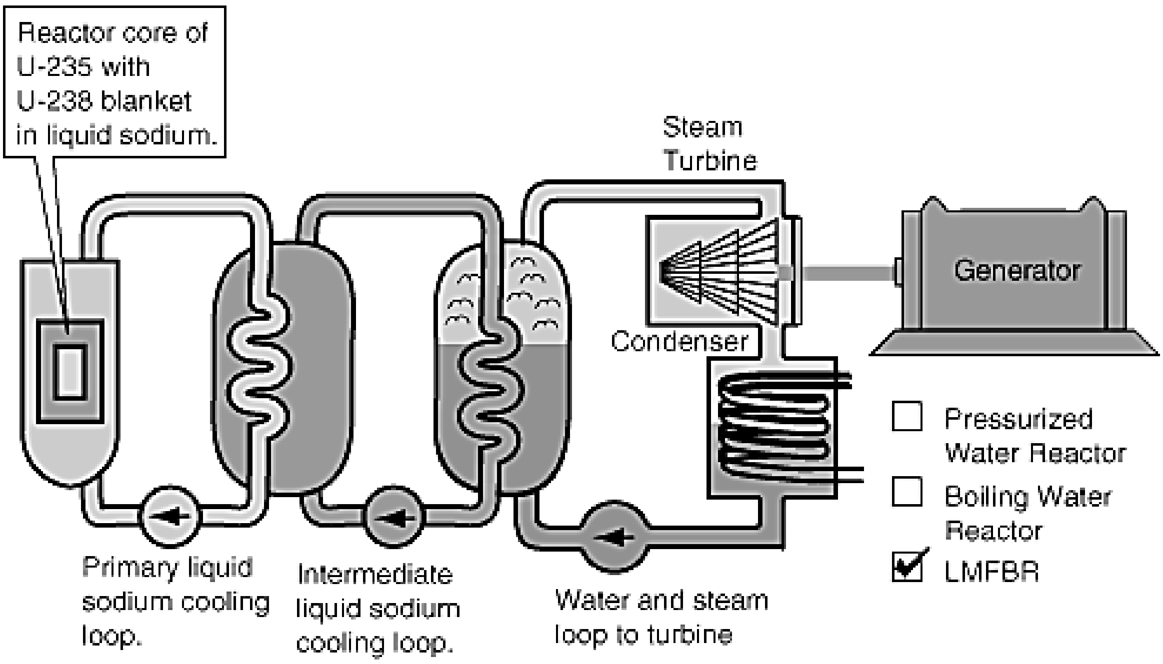
Liquid Metal Cooled Reactor:

Introduction:

- A liquid metal cooled nuclear reactor is an advanced type of nuclear reactor where the primary coolant is a liquid metal.
- The alternate names for liquid metal cooled reactor such as Liquid metal Fast Reactor or LMFR
- Liquid metal cooled reactors were first adapted for nuclear submarine use and also studied for power generation applications.
- Because the metal coolants have much higher density than the water used in most reactor design.
- The metal coolants remove heat more rapidly and allow much higher power density.
- This property of metal coolant is attractive in situations where small size and less weight is required like on ships and submarines.
- To improve cooling with water, most reactor designs are highly pressurized to raise the boiling point which presents safety and maintenance issues that liquid metal designs lack.
- Additionally, the high temperature of the liquid metal can be used to produce vapour at higher temperature than in a water cooled reactor leading to a higher thermodynamic efficiency



Schematic diagram of Pool type Liquid Metal Cooled Reactor Power Plant



Schematic diagram of Loop type Liquid Metal Cooled Reactor Power Plant

Liquid Metal Cooled Reactor Design:

- All liquid metal cooled reactors are fast neutron reactors, and most fast neutron reactors have been liquid metal cooled fast breeder reactors.

- The liquid metals used typically need good heat transfer characteristics. Some of the liquid metals used in nuclear reactor are:
  - ✓ Mercury
  - ✓ Sodium
  - ✓ Sodium Potassium
  - ✓ Lead
  - ✓ Tin
- Fast neutron reactor cores tend to generate a lot of heat in a small space when compared to other reactors.
- A low neutron absorption is desirable in any reactor coolant, but especially important for a fast reactor.
- The slower neutrons are more easily absorbed, the coolant should ideally have a low moderation of neutrons.
- It is also important that the coolant does not cause excessive corrosion of the structural materials and so it's melting and boiling points are suitable for the reactor operating temperature.
- Ideally the coolant should never boil as that would make it more likely to leak out of the system, resulting in a loss-of-coolant accident.
- Conversely, if the coolant can be prevented from boiling this allows the pressure in the cooling system to remain at neutral levels, and this dramatically reduces the probability of an accident.

Coolant Properties:

- If the pressurized water could be used for a fast reactor, it tends to slow down neutrons and absorb them.
- This limits the amount of water that can be allowed to flow through the reactor core, and since fast reactors have a high power density
- Water boiling point is also much lower than most metals so that the cooling system be kept at high pressure to effectively cool the core.

Liquid metal coolants		
Coolant	**Melting point**	**Boiling point**
Sodium	97.72 °C, (207.9 °F)	883 °C, (1621 °F)
NaK	−11 °C, (12 °F)	785 °C, (1445 °F)
Mercury	−38.83 °C, (−37.89 °F)	356.73 °C (674.11 °F)
Lead	327.46 °C, (621.43 °F)	1749 °C, (3180 °F)
Lead-bismuth eutectic	123.5 °C, (254.3 °F)	1670 °C, (3038 °F)
Tin	231.9 °C, (449.5 °F)	2602 °C, (4716 °F)

Operation of Liquid Metal cooled Reactor:

- The reactor have reactor vessel which contains sodium liquid metal as coolant and uranium as Fuel.
- When the uranium atoms are splitting to produce nuclear fission chain reaction.
- The nuclear fission reaction produces fast moving neutrons and also some energy in the form of heat.
- Due to heat from nuclear reaction, the sodium is heated in the reactor vessel quickly due to its low boiling point.
- The hot sodium from the reactor is transferred to the Heat exchanger(steam generator).
- In the heat exchanger, the heat of sodium is transferred to the cool water present in the same heat exchanger.
- After the heat transfer, the cool sodium metal can be fed back into the reactor core through the feedpump.
- Some of the hot water is vapourized into steam and steam is subsequently fed into the turbine.
- The pressurized steam causes the turbine blades to rotate and the turbine operates a generator which generates electricity.
- The steam is then conveyed to a condenser and condenses the steam into water again.
- The condensed water is pumped back from the steam generator into the reactor to be heated again.

Advantages of Liquid metal cooled reactor:

- This reactor design has a high fuel burn-up ratio.
- This reactors design does not corrode steel reactor vessel. The reactor design is very compact.
- It has a high power output for its size.
- Liquid metal-cooled reactors are not pressurized leading to simpler piping systems.
  The liquid metal coolant cannot turn to steam unlike water during a meltdown and making a steam explosion impossible.
- Some changes of this design can be used as breeder reactors.

Disadvantages of Liquid metal cooled reactor:

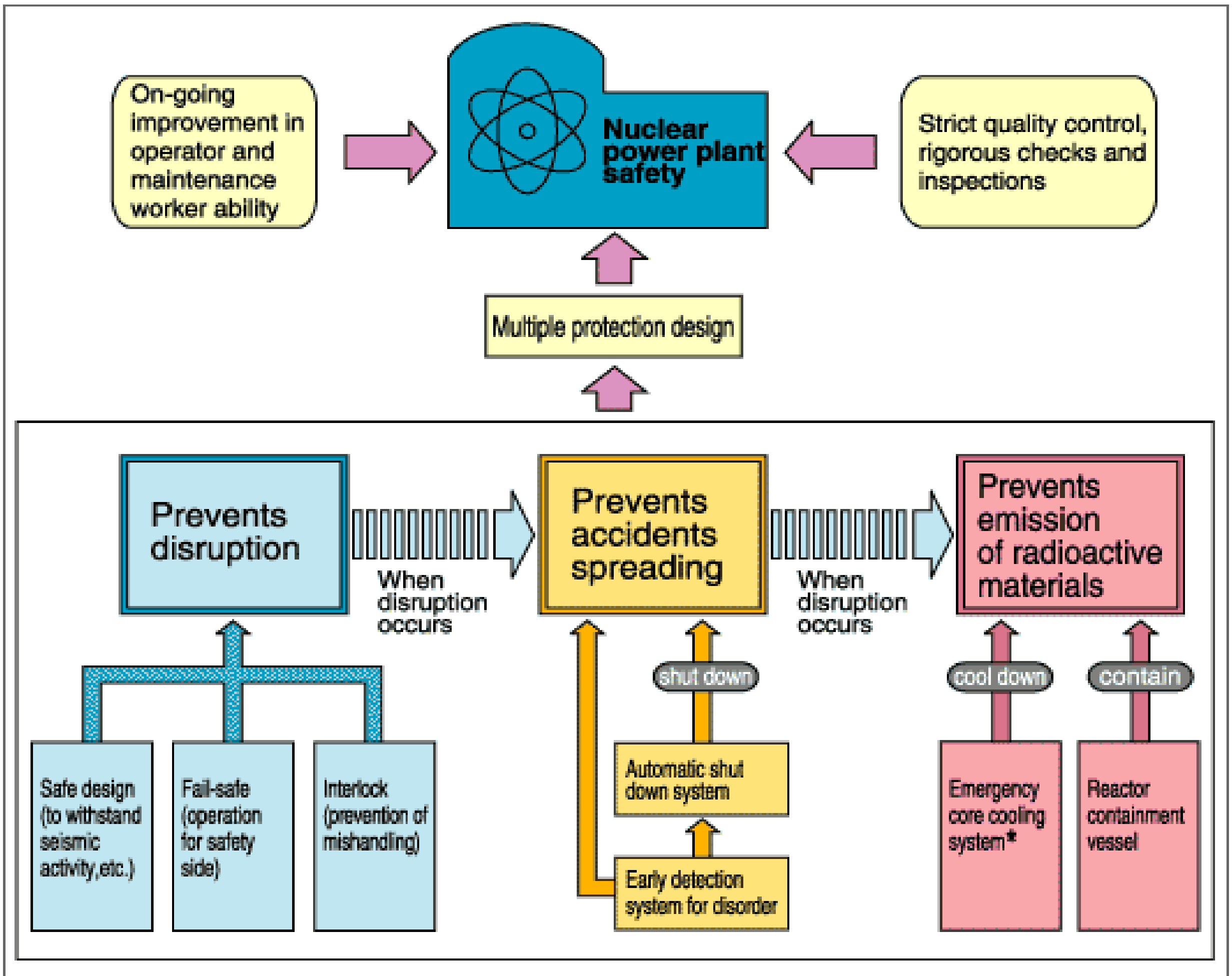
- The high temperature of the reactor could make the complex design.
- Sodium as coolant reacts violently with water and air.
- Cost is very high

9. Describe the need of safety measures in nuclear power plant and also explain in detail about the safety measures of nuclear power plant.

<u>**Need of safety measures:**</u>

- Nuclear power plants requires multiple safety measures which are designed on the assumption that they must ensure the safety of the neighboring communities.
- The safety measures should not have no adverse impacts on their health.
- Nuclear power plants are designed to prevent abnormal incidents from occurring.
- Even if abnormal incidents do occur, nuclear plants are also designed to prevent the potential spreading of abnormal incidents and leakage of radioactive materials around the surrounding environment.

Safety Features of Nuclear Plant Design



* Emergency Core Cooling System (ECCS): When an accident occurs, huge amounts of water will be automatically poured into a nuclear reactor to cool down nuclear fuel.

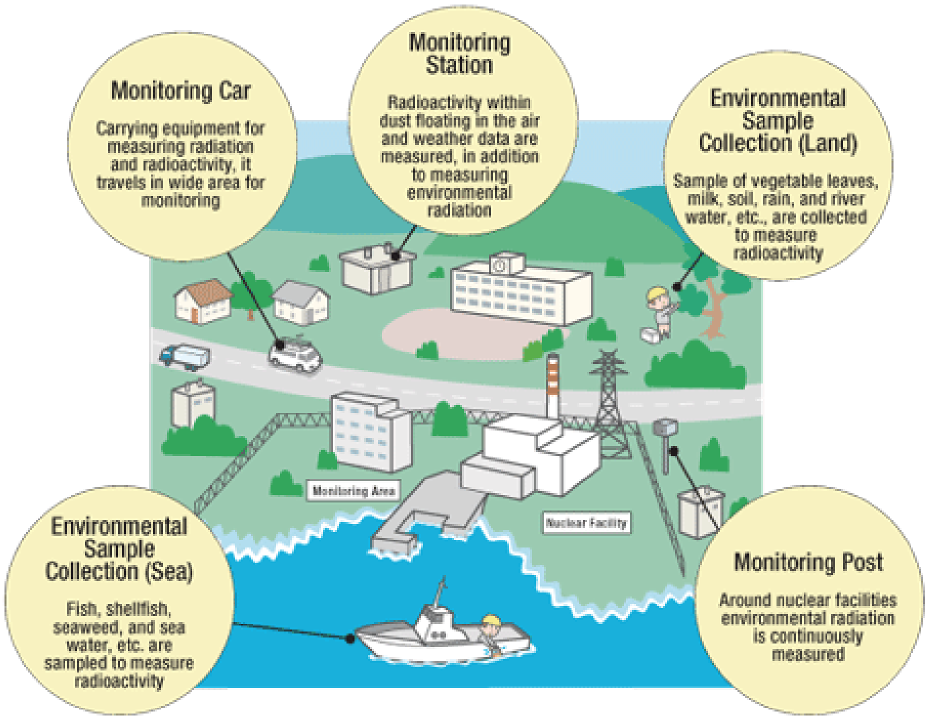
<u>**Environmental Radiation Monitoring measures:**</u>

- Nuclear operators monitor environmental radiation around their facility and radioactivity in environmental samples in order to confirm that there is no harmful effect on the surrounding environment.

- Local governments as well as utilities independently measure radiation dose in the air by radiation monitoring systems around nuclear power plants.
- In addition, they periodically collect seawater, soil and agricultural as well as sea products to measure and analyze them for radioactive material content and to ensure that power plants have no adverse impact on the surrounding environment.

- Measures to be put into action in order to ensure safety during unusual events can be summarized in the following three points:
  - ✓ To shut down operating reactors
  - ✓ To cool down reactors so as to remove heat from nuclear fuel
  - ✓ To neutralize the radioactive materials during such accidents

Environmental Radiation Monitoring around Nuclear Facilities



<u>Aseismic Measures:</u>

- Several safety measures against earthquakes are taken at all stages of design, construction of nuclear power plants.
  - ✓ Thorough Installation
  - ✓ Seismic design considering even an extremely rare earthquake
  - ✓ Detailed Analytical Evaluation
  - ✓ Confirmation of safety of bearing ground and surrounding slopes

Aseismic Measures Taken by Nuclear Power Plants

【8 key safety points】

Stages	Measures	Details
Assuring safety at the design stage	① Thorough investigation	Perform a detailed survey of active faults and past earthquakes at the site and its surrounding areas as well as the geology and geological structure of the site.
	② Seismic design considering even an extremely rare earthquake	Assure the seismic design to prevent safety-significant components and systems from losing their functions against ground motions both in the horizontal and vertical direction which are assumed to occur during the plant service life, even though the possibility is extremely low.
	③ Detailed analytical evaluation	Perform detailed analyses of possible complicated jolts to important buildings and components when a postulated earthquake hits the site using reliable computational codes to verify the seismic safety.
	④ Confirmation of safety of bearing ground and surrounding slopes	Perform tests and analyses to verify if the ground, on which the facilities important for seismic safety are to be built, has sufficient bearing resistance against earthquakes and confirm that assumed events accompanying an earthquake, such as the collapse of surrounding slopes, would not significantly influence the safety of reactor facilities.
	⑤ Confirmation of safety against tsunami	Performing detailed numerical simulations of a tsunami which is assumed to accompany an earthquake to confirm that it would not significantly influence the safety of the facilities.
Assuring safety at the construction and operation stages	⑥ Construction of a nuclear power plant on ground with sufficient bearing resistance	Build a nuclear power plant on ground that has a low amplitude of earthquake ground motion, sufficient bearing resistance, and no possibility of sliding or adverse subsidence.
	⑦ Automatic shutdown function	Install a system which can automatically shut the reactor immediately after jolts exceeding a certain level are detected.
	⑧ Demonstration of earthquake resistance and understanding of seismic limits using a shaking table and exciter	Demonstrate the earthquake resistance of nuclear facilities, understand the design margin and verify the validity of computational codes used in the maintenance and analysis of equipment functions by applying earthquake loads exceeding the design limit to the actual unit or a specimen equivalent to the actual unit by using a shaking table or exciter.

- ✓ Confirmation of safety of any other natural disaster such as storm, tsunami, etc.
- ✓ Construction of nuclear power plant on ground with bearing resistance
- ✓ Automatic shutdown function of reactor during accidents
- ✓ Demonstration of earthquake resistance and analyzing the seismic limits by shaking tables and exciter.