Catalog

BASICS OF NUCLEAR ENGINEERING

Cheap and abundant power is essential to the modern world in coming years. The rapid increase in industry and living standard of the people advance the pressure on conventional sources of power i.e. coal, oil and hydro. The resources of these fuels are becoming depleted in many countries, and thus there is a tendency to seek alternative sources of energy. Hydro-electric stations produce cheap power, but need a thermal backing to increase the firm capacity.

In a nuclear power station instead of a furnace, there is a nuclear reactor, in which heat is generated by splitting atoms of radioactive material under suitable conditions. This splitting or nuclear fission of materials like uranium (U), Plutonium (Up), has opened up a new source of power of great importance.

The heat produced due to fission of uranium and plutonium is used to heat water to generate steam which is used for running turbo generators.

A nuclear power plant differs from a conventional power plant only in the steam generating part. The schematic arrangement of a simple nuclear power plant using liquid coolant with and without heat exchanger is shown in Figure other type of nuclear power station will be considered latter.

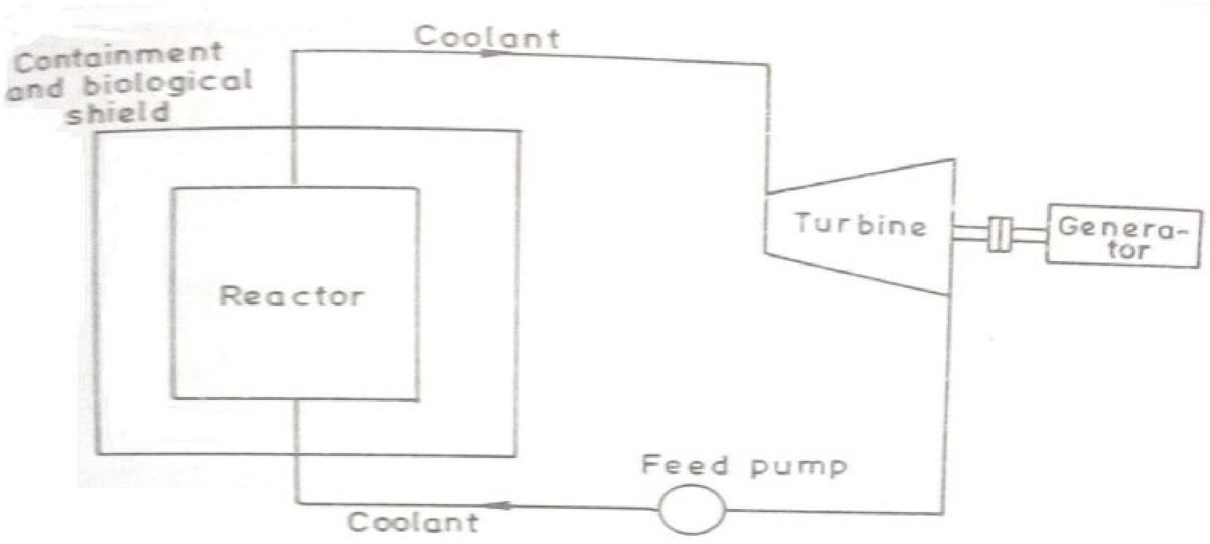
The main parts of a nuclear power station are the nuclear reactor and a heat exchanger, together with the familiar steam turbine, condenser and a generator. Heat is provided by fashioning or splitting of uranium atoms, in a reactor.

A cooling medium takes up this heat and deliver it to the heat exchanger, where steam for the turbine is raised. The reactor and heat exchanger are equivalent to the furnace and boiler in a conventional steam plant. When the uranium atoms split, there is radiation as well, so that the reactor and its cooling circuit must be heavily shielded against radiation hazards. The rest of the plant is similar to the ordinary steam plant.

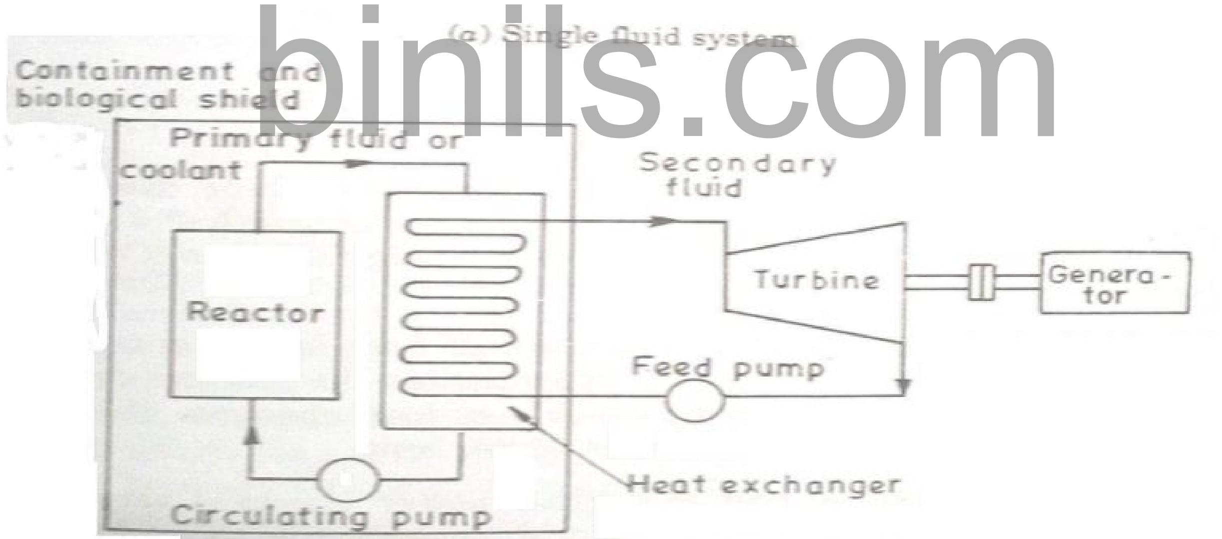
The steam generated in the heat exchanger is admitted to the turbine, and after work has been done by the expansion of steam through the turbine, the steam is condensed into the condensate in the condenser.

The condensate pump sends the condensate back to the heat exchanger, thus forming a closed feed system. The other auxiliaries are similar to those in a familiar steam station.

For economical use in a power system a nuclear power station generally has to be large, and where large units are justifiable, nuclear power stations are considered as alternatives to conventional stations.



(a) Single fluid system



(b) Dual-fluid nuclear power plant

simple nuclear power plant with and without heat exchanger

Advantages of nuclear power station compared to the conventional thermal power station

1. It reduces the demand for coal, oil and gas, the costs of which are tending to rise as the stocks become depleted. The amount of fuel used in the plant is small. Greater nuclear power production leads to conversion of coal oil etc.

2. Since the amount of fuel needed is small, there are no problems of fuel transportation, storage etc. It has been found that one kilogram me of uranium can produce, as much energy as can be produced by running 4500 tones of high trade coal.
3. Nuclear power plant requires less space compared to any other plant of the equivalent size.
4. Besides producing large amounts of power, the nuclear power plant can produce valuable fissile material, which is extracted when the fuel has to be renewed.
5. Bigger capacity of these plants in an additional advantage.
6. Nuclear plants create no smog, and are unaffected by adverse weather condition
7. Greater nuclear power production leads to conservation of coal, oil etc.

Limitations

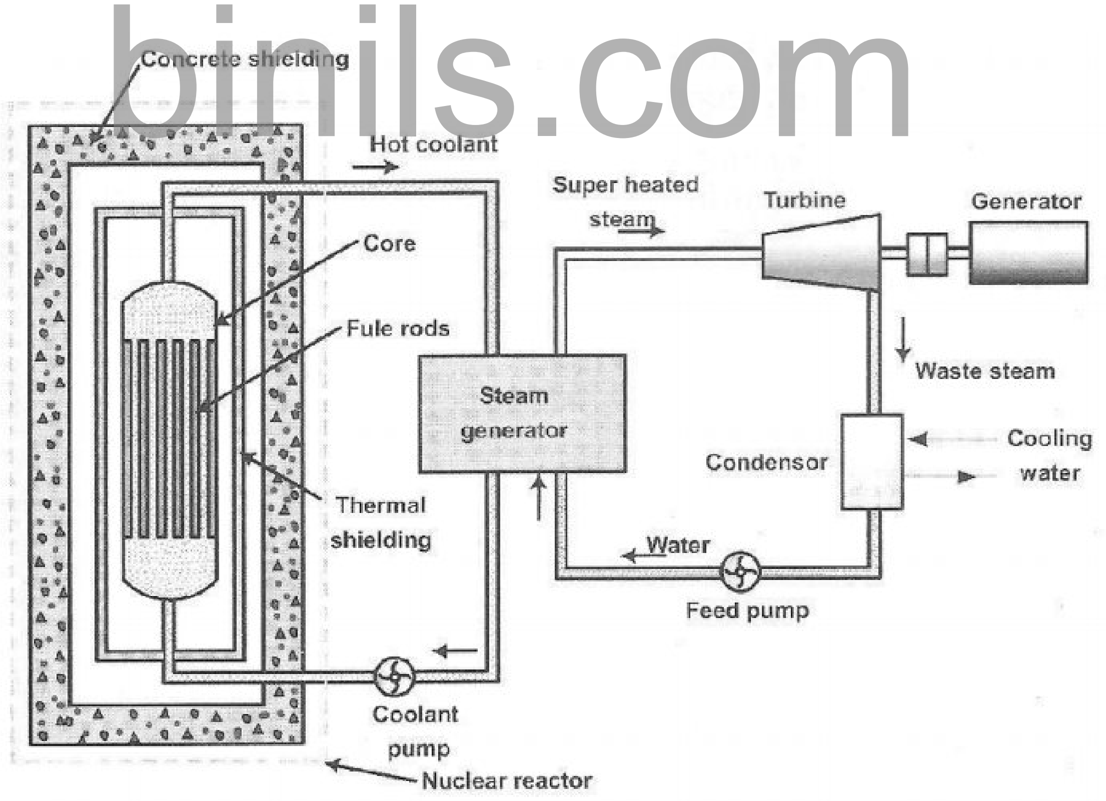
1. The nuclear power plants include danger of radioactivity, detrimental working conditions to health of workers, the problem of disposal of radioactive waste, high salaries of trained personnel etc.
2. Nuclear power plants can be used as base load plants. They are not suitable for variable load operation as the reactors cannot be easily controlled to respond quickly to load changes. They are used at a load factor of not less than 80 per cent.
3. The initial capital cost of nuclear power plant is very high only very few countries in the world possess the technology to manufacture nuclear reactors and nuclear fuel. Inspire of this, nuclear power is likely to supply greater and greater portion of future power needs of the world.

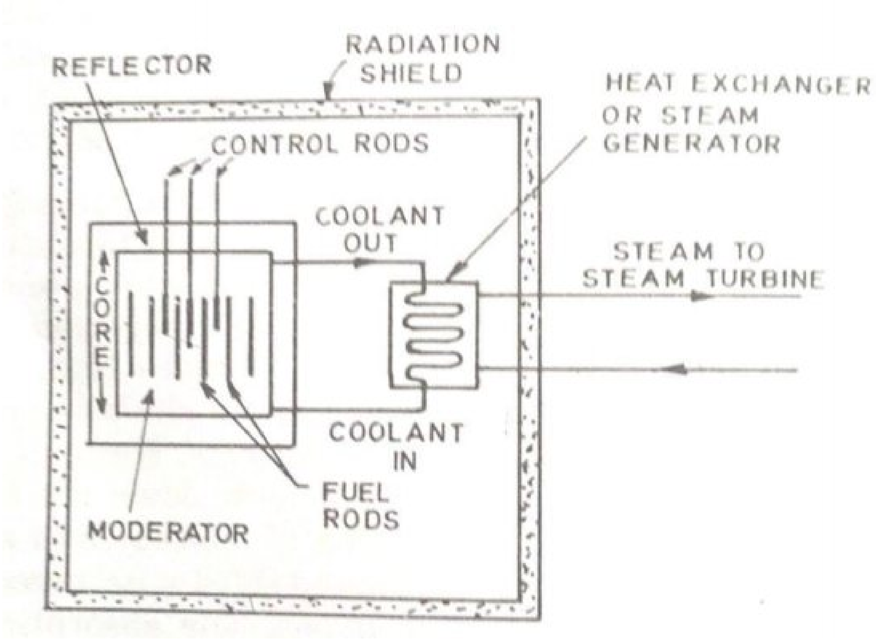
LAYOUT AND SUBSYSTEMS OF NUCLEAR POWER PLANTS

A nuclear reactor is basically a furnace where the fashioning of atoms can be controlled and the heat put to useful work. In a nuclear fission reactor, the conditions are such that fission energy is released at a controlled rate.

The fission energy is converted into heat in the reactor, and this heat is utilized to raise steam directly or indirectly. The steam then drives a turbine-generator to produce electricity in the conventional manner.

Figure shows the main components of a reactor. The location of fuel, moderator, control rods and coolant in a typical power reactor are shown. These components are enclosed in a pressure vessel. The coolant heated in passing by the fuel elements, flows through a heat exchanger where it turns water in a secondary circuit, into steam. The steam is then used to drive a turbine generator.





Basic components of a nuclear power reactor

Nuclear reactors may be used in addition to power generation for several purposes such as to produce heat for the thermoelectric power, process work or space heating to produce fissionable materials, radio isotopes, neutron etc.; to proper ships, submarines, aircrafts etc.; and for research testing and irradiation work.

A nuclear reactor consists of the following basic parts:

1. The **core** which is the part containing the fuel elements.
2. The **neutron moderator** which aids the fission process by slowing down the neutrons.
3. The **reflector** which scatters back neutrons escaping from the core.
4. **Controller's** means for controlling the rate of fission and consequently the power level of the reactor.
5. The **coolant** or the cooling system which removes the heat generated in the core.
6. The **radiation shield** which protects the operating personnel from radiations emitted during fission. Description of each of these components is given in the following paragraphs.

1. **Core**: fuel all reactors have a central core in which fissions occur and most of the fission energy appears as heat. The core contains the nuclear fuel consisting of a fissile species (i.e. uranium^{233}, uranium^{235} or plutonium^{239}) and usually a fertile material (i.e. thorium^{232} or uranium^{238}).

In some thermal reactors, the fuel is natural uranium with roughly 0.7 weight percent of uranium ^{235} and 99.3 percent of uranium^{238}. Most commercial power reactors a uranium fuel enriched to about 2.5 to 3 percent in uranium^{235}.

For a fast reactor a more highly enriched fuel is required. A typical fast reactor fuel might contain 15 to 20 percent of uranium^{235} or plutonium^{239}; the remainder is uranium^{238} to serve as fertile material.

The fuel elements are made of plates or rods of uranium metal or ceramic. The plates or rods are usually clad in a thin sheath of stainless steel, zirconium, or aluminum to provide corrosion resistance, retention of radioactivity and, in some cases, structural support. Space is provided between the individual fuel plates to allow for passage of the coolant.

2. **Core-moderator**

The moderator, commonly water or graphite, is dispersed between the fuel assemblies. It serves to slow down or moderate, the fast neutrons produced in fission. These lower velocities provide a better opportunity for the neutrons to cause further fission.

Fission neutrons escaping from the fuel rods at high velocity are slowed down as a result of collisions with moderator nuclei. The slow (approximately thermal) neutrons may then be absorbed generally in other fuel rods, and these cause fissions.

In this way, slow neutrons can maintain the fission chain. The actual energy (or speed) distribution of the neutrons causing most of the fissions is determined by the nature and proportions of the fuel and moderator, as well as by the temperature.

The best moderators are materials consisting of elements of low mass number, preferably with little or no tendency to capture neutrons. Ordinary water (H_2O) for example, is a common moderator; two of its three atoms are hydrogen with a mass number of unity.

The great majority of power reactors are of these types known as light-water reactors because these use ordinary (or light) water as the moderator.

In some power reactors, the moderator is deuterium oxide (D_2O), also heavy water; this is a form of water containing deuterium, the heavier, naturally occurring isotope of hydrogen with a mass number of two.

Such reactors are heavy water reactors. The only other moderator material used to any significant extent is graphite which is essentially pure carbon, with a mass number of 12.

3. **Control Rods**

The control rods are made of a neutron absorbing material and upon movement in or out of the core, vary the number of neutrons available to maintain the chain reaction. The rate of fashioning may thereby be controlled. The materials employed are those with high absorption cross sections, such as boron, cadmium, hafnium, silver and indium. The materials are formed into solid rods which may be withdrawn or inserted in the reactor core at selected points to raise or lower the effective multiplication factor.

For normal operation the multiplication constant must be maintained at unity. This will ensure the neutron flux is held at constant value. The control rods are moved in and out of channels in the core by control rod devices.

The diagram of a heterogeneous reactor in which reactivity is controlled by the movement of neutron absorbed rod is shown in Fig 3.3. To ensure even distribution of neutron flux it is necessary to employ large number of rods—the number generally exceeding hundred.

When rods are fully inserted, the neutron absorption will be maximum, K will be much less than 1 and reactor shut down. Generally the control rods divided into three categories. Shut off rods, coarse and fine regulation rods.

The shut off rods are normally kept out and are used for reducing the reactivity in the case of emergency. The regulation rods for starting and continuous control. The coarse control rods are for taking the reactor to the required power level after it has been started and for effecting large changes.

However the reactivity should not be changed at a dangerous rate. The fine control rods are for maintaining the reactor critical when running under normal conditions. They can adjust reactivity to a fine degree of accuracy.Control rods drives are hydraulic or electric motor driven; rack and pinion and screw drives are common.

4. Reflector

The main purpose of the reflector which surrounds the core is to decrease the loss of neutrons. It is another method of lowering the neutron leakage and improving the neutron economy by providing a reflector around the reactor core. Neutrons escaping from the core enter the reflector where many collide with reflector nuclei and are turned back into the core. The critical mass of fuel is then less, than it would be without a reflector; consequently the size and cost of the reflector are reduced.

A reflector material is one with a high neutron scattering cross section, a low absorption cross section, and a good slowing down ration, for the speed of escaping neutrons is likely to be slightly higher than thermal speed. In fact most of the materials that make good moderators such as graphite, light water and beryllium, also make good reflector materials.

In a fast reactor the reflector must be a material of high mass number to avoid slowing down the neutrons. The core is then surrounded by a layer (or blanket) consisting of uranium2^{38}, either as natural uranium or uranium that has been depleted in Uranium^{235} (Depleted Uranium is the residual material from the Uranium^{235} enrichment operation).

The uranium blanket acts as a reflector in returning some of the neutrons escaping from the core. However, an important purpose of the blanket is to serve as a fertile material; capture of neutrons by Uranium^{238} followed by two stages of beta particle emission, results in the formation of fissile Pu^{239}. In some fast reactors designs a stainless neutron reflector surrounds the fertile blanket.

5. Coolant

The heat generated in the fuel by fissions is removed by circulation of a coolant through the reactor core. The coolant transfers heat out of the reactor core is circulated either directly or indirectly as the thermodynamic medium for conversion of the heat energy to electrical energy.

As a direct cycle, the coolant, either steam or hot gas, drives a steam turbine or a gas turbine, respectively. This is a single cycle system, used in boiling water reactors (BWRs). A dual cycle can be installed in most of the gaseous or pressurized water reactors (PWRs).

In PWR, the pressure in the reactor vessel, which contains the core and coolant, is so high that the water does not boil. After passing through the core to remove fission heat, the high pressures water is pumped through the tubes in a heat exchanger and returned to the reactor vessels.

Heat is transferred from the reactor water to feed water at a lower pressure surrounding the steam generator tubes; because of lower pressure, the feed water boils and produces steam to drive the turbines. The exhaust steam from the turbines is condensed and returned as feed water to the steam generator.

A triple cycle has been postulated for liquid-metal coolant reactors in which an intermediate coolant is used between the primary (sodium) coolant and the final steam to prevent possible contact of the hot sodium and water. The primary coolant is circulated through annular spaces in the fuel elements themselves or in channels formed by adjacent fuel elements in the core.

Water cannot be used as coolant in fast reactors because of its moderating effect on neutron energy. Consequently, most current fast reactor designs are based on molten sodium as the coolant.

6. Radiation shielding or biological shielding

Shielding is necessary in order to protect the walls of the reactor vessel from radiation damage, and also to protect operating personnel from exposure to radiation. The first known as the internal or thermal shield is provided through steel lining, while the other called external or biological shield; is generally made of thick concrete (about1.8 to 2.4m) surrounding the reactor installation.

The components of a nuclear emission alpha and beta particles, neutrons and gamma rays vary in their energy and/or intensity and their ability to travel and penetrate material of these—only the fast neutrons and gamma rays present some serious difficulty in designing the reactor shielding, since alpha and beta particles can be stopped by a fraction of an cm. of solid substance, while thermal neutrons can be automatically guarded against with a shield thick enough to provide protection against fast neutrons and gamma rays, alpha particles cannot penetrate the skin.

However it is necessary to prevent spreading of alpha particles to environment to eliminate contamination. A sheet of paper is a sufficient shield against alpha particles. A beta particle is an electron emitted from a radioactive nucleus.

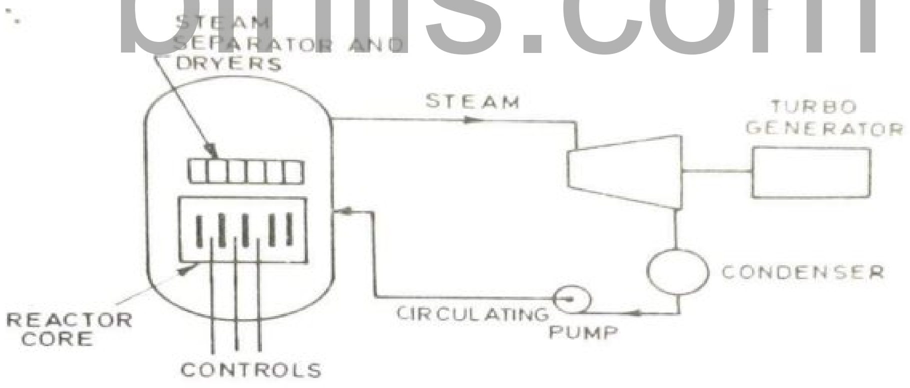
This particle can travel several meters in air but is unable to penetrate thick materials being easily stopped by a thin sheet of aluminum/lead/brick. Over exposure to beta particle can cause skin burns and repeated over exposure may result in malignant growths.

Boiling Water Reactor (BWR)

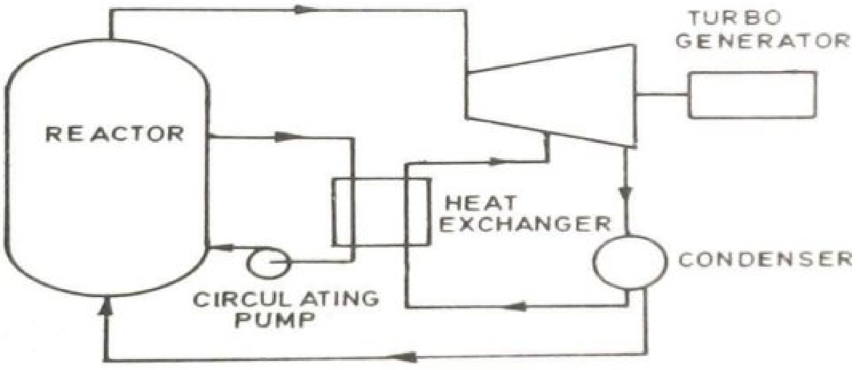
A thermal nuclear power reactor in which ordinary (or light) water is the moderator and coolant, as well as the neutron reflector. The system pressure is high, but not as high as in a pressurized water reactor, so that the water boils and steam is generated within the reactor core, so that the water boils and steam is generated within the reactor core.

In this plant cycle, also known as direct steam cycle, steam is produced in the reactor itself instead of in a heat exchanger. Since auxiliary power is reduced from 6% to 1% by elimination of the heat transfer circuit between reactor and steam generator, the overall plant efficiency increases with a BWR.

Boiling water reactor use enriched uranium as a fuel (enriched uranium contains more fissionable isotope U^{235} than the naturally occurring percentage 0.7%). The fuel rods contain small cylindrical pellets of uranium dioxide with an average initial enrichment of about 2.6% in $uranium^{235}$.



(a) Direct cycle boiling water reactor.



BWR cycles

Figure shows the arrangement of direct cycle boiling water reactor. The uranium elements are arranged in a particular lattice from inside a steel pressure vessel containing water. Fission heat is removed from the reactor by conversion of water to steam in the core. It is a direct cycle reactor.

The steam is generated in the reactor itself and this steam after passing through turbine and condenser returns to reactor. Feed water enters the reactor tank below to pass through the fuel elements in the core as coolant and also as moderator.

The control elements in a BWR have a cruciform cross section; each element had four blades containing stainless steel tubes filled with neutron poison (i.e., absorber) boron as boron carbide. The blades can move up and down in the spaces between the fuel assemblies with one control element between four assemblies in most cases. Some 180(or so) such elements are distributed evenly throughout the core.

The controls of a BWR are inserted from the bottom of the core, rather than the top as in other reactors. This is convenient, because the space above the core us occupied by steam-water separators and desirable because the neutron absorber at the bottom of the core can compensate for the steam bubbles formed bubbles formed higher up in the core.

As the coolant water flows upward through the core, it removes the fission heat from the fuel rods and boils. The wet steam enters a bank of water separators and then passes on to dryers in the upper part of the reactor vessel. The relatively dry steam then proceeds to turbine to generate electricity. The turbine condensate is returned to the reactor as feed water.

The various cycles used in BWR are:

(1) Natural circulation single cycle
(2) Forced circulation single cycle
(3) Forced circulation dual cycle

In the natural circulation, single, cycle, no pump is used to circulate the water through the reactor core and such a plant is best suited for capacity of 50—100MW. In the forced circulation plant the coolant is pumped through the core. This design is preferred in 100—1000MW size range.

In the dual cycle plant, part of the heat of circulation is used for generate additional low pressure steam for the turbine. A steam to steam heat exchanger is required which adds cost.

India's first nuclear power plant at Tarapur has two reactors (each 200MW capacity) of BWR type.

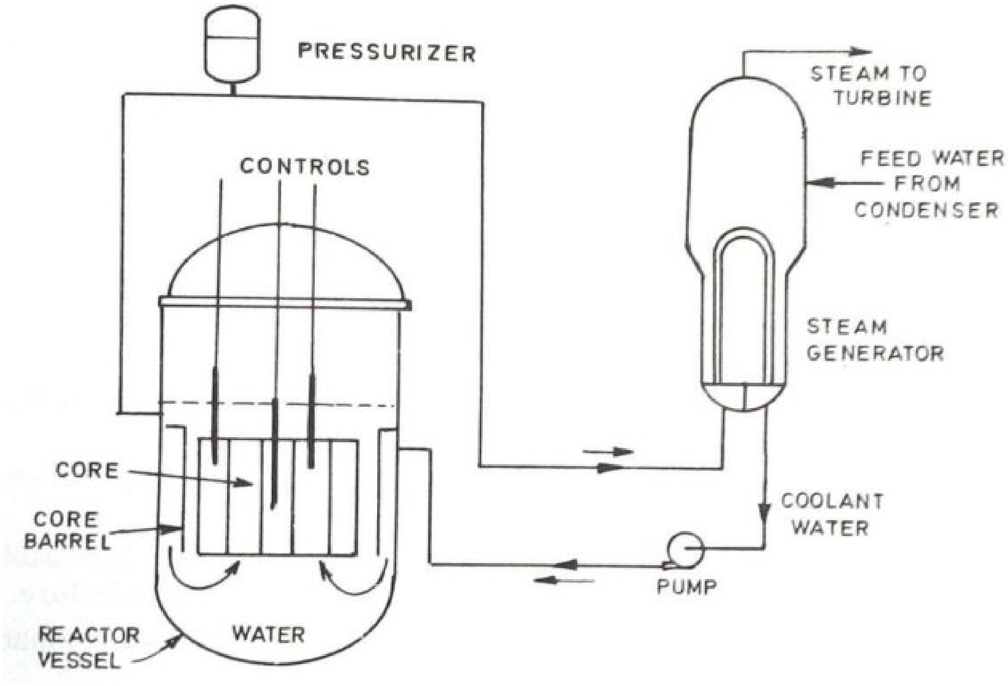
Advantages

1. Heat exchangers pump and auxiliaries equipment requirements are reduced or eliminated, resulting gain in thermal efficiency with reduction in cost.
2. The pressure inside the pressure vessel is not high so a thicker vessel is not required which further reduces cost, and simplifies containment problems,
3. It is more efficient cycle than the PWR since for a given containment pressure the outlet temperature of the steam is appreciably higher.
4. Thermal efficiency of BWR to about 30% as compared to 20-22% in PWR.
5. The metal temperature remains low for given output conditions.
6. The reactor is capable of promptly meeting the fluctuating load requirements.

Disadvantages

1. Possible carryover of radioactivity to steam equipment. There is possibility of radioactive contamination in the turbine mechanism. Turbines may require shielding.
2. On part load operation, there is wastage of steam resulting in lowering of thermal efficiency.
3. More elaborate safety precaution needed, which are costly.
4. More biological protection is required.

PRESSURIZED WATER REACTOR (PWR)



Pressurized-water reactor (PWR)

The PWR is a thermal reactor, generally using enriched fuel (uranium oxide) and depending on the type of moderator used clad with stainless steel or zirconium alloy and the pressure vessel is of steel. Light or heavy water may be used as the combined coolant cum moderator.

The pressure vessel and the heat exchanger are surrounded by a concrete shield. Heat exchanger is used to develop steam, the primary loop being formed by the coolant moderator.

The water under pressure is used as both the moderator and coolant. To prevent boiling of coolant in the core, it is maintained under pressure of 153 atm. (15.5MPa) (at this pressure water boils at 345˚ C).

As shown in Fig 3.5, a pump circulates water at high pressure round the core so that the water in the liquid state absorbs heat from the uranium and transfers it to the secondary loop, heat exchanger or boiler. After giving up some of its heat to boil water and produced steam in the steam generator, the high pressure water is pumped back into the reactor vessel.

It enters just above the core and flows down through the annular region called the down comer, between the core barrel and the pressure vessel wall. At the bottom of the core, the water reverses direction and flows upward through the core to remove the heat generated by fission.

The coolant steam pressure is maintained within a limited range by means of a pressurized connected between the reactor vessel and a steam generator. The pressurizer is a large cylindrical steel tank containing some 60% by volume of liquid water and 40% steam during steam operation.

A large PWR may have from two to four independent steam generators loops in parallel. Most steam generators consists of a large number of inverted U-shaped tubes enclosed in a casing called the shell. The high pressure, high temperature water from the reactor flows through the inside of the tubes, and heat is transferred to water at a lower pressure [75 atm (7.6MPa)] on the outside (shell side) of the tubes.

The water in the shell boils at the lower pressure and produced moist steam. Entrained moisture is separated in the upper part of the steam generator and steam at a temperature of about 290˚C proceeds to the turbine system. After passage through the steam generator tubes, the high pressure water is pumped back to the reactor vessel.

Coarse control of a PWR is achieved by the neutron poison (i.e. absorber) boron as boric acid, dissolved in the reactor water. The boron compensates for the extra fuel present initially, and this is used up during reactor operations, the basic acid concentration is decreased.

The controlled rods, referred to earlier, which can be moved in or out of the core, are used to start up the reactor and shut it down and for automatic fine adjustments during normal operation. Another used of the control rods is to make the heat (or power) distribution ad uniform as possible throughout the core. Completed insertion of the rods will always cause the reactor to shutdown.

Advantages

1. Steam supplied to the turbine is completely free from contamination
2. The reactor is compact in size as compared with some other type (such as gas cooled reactor GCR).
3. Light water is the cheapest coolant and moderator.
4. Cooling system is simple
5. Fission products remain contained in the reactor and are not circulated
6. High power density
7. Possibility of breeding plutonium by providing a blanket of U^{238}.

Limitations

1. High pressure requires a costly reactor vessel and leak proof primary coolant circuit.
2. High pressure and high temperature water at rapid flow rates increase corrosion an erosion problems.
3. Steam is produced at relatively low temperature and pressure and consequently needs super heating.

CANada Deuterium-Uranium reactor (CANDU)

A thermal nuclear power reactor in which heavy water (99.8% deuterium oxide D_2O) is the moderator and coolant as well as the neutron reflector. The CANDU reactor was developed (and is used extensively) in Canada, where a full scale commercial reactor of this type first started operation in 1967.

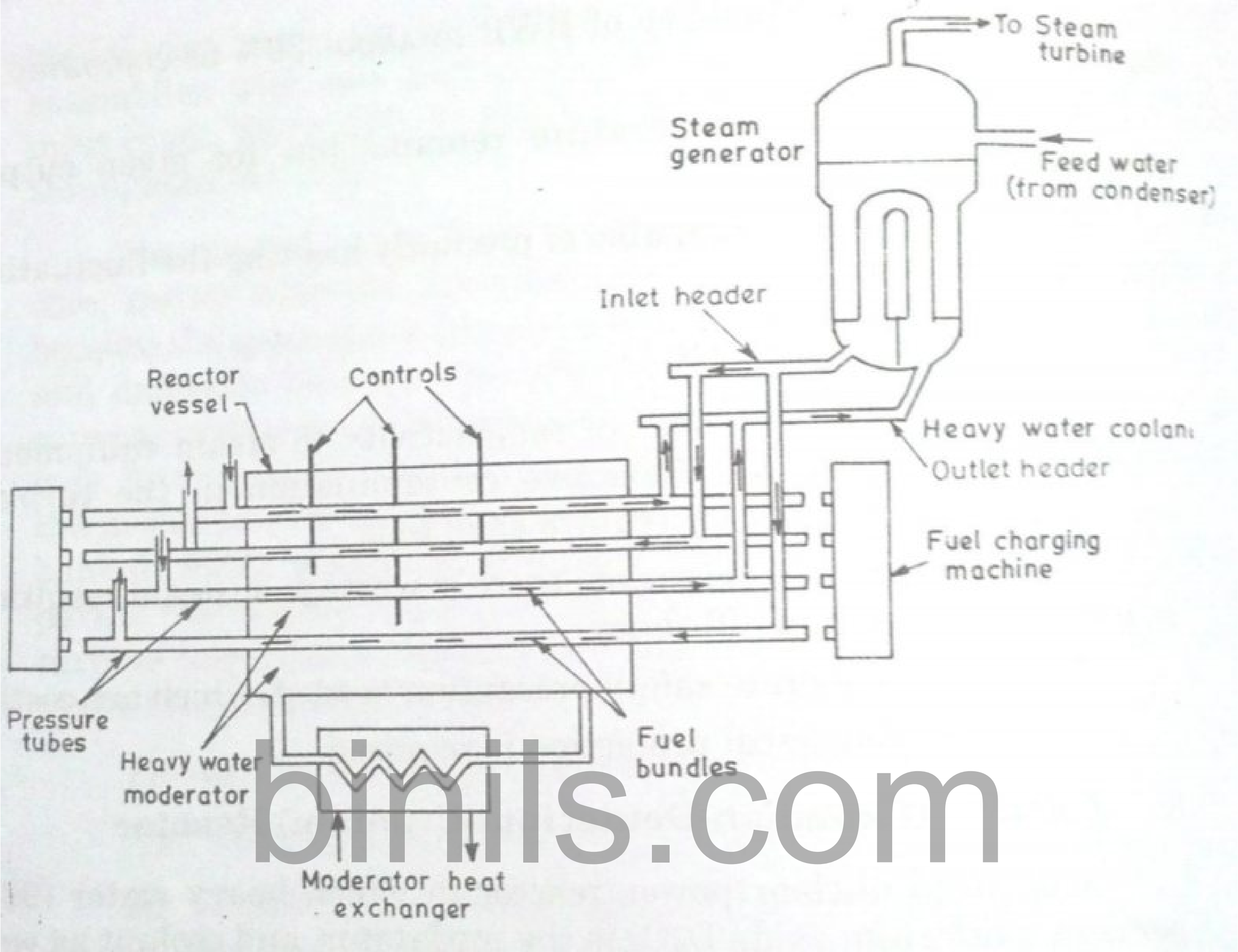
A few CANDU reactors are operating or under construction in some other countries. These reactors are more economical to those countries which do not produced enriched uranium, as the enrichment of uranium is very costly. In this type of reactors the natural uranium (0.7% U^{235}) is used as fuel and heavy water as moderator.

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

Consequently unlike the pressure vessel of a LWR, the CANDU reactor vessel, which contains the relatively cool heavy water moderator, does not have to withstand a high pressure. Only the heavy water coolant circuit has to be pressurized to inhibit boiling in the reactor core.

General Description

Reactor vessel and core: The arrangement of the different components of CANDU type reactor is shown in figure The reactor vessel is a steel cylinder with a horizontal axis. (Length and diameter of a typical cylinder are 6m x 8m respectively). The vessel is penetrated by some 380 horizontal channels called pressure tubes because they are designed to withstand a high internal pressure.



CANDU (Canadian Deuterium-Uranium) Reactor

The channels contain the fuel elements and the pressurized coolant flows along the channels and around the fuel elements to remove the heat generated by fission. Coolant flow is in the opposite directions in adjacent channels.

The high temperature (310˚C) and high pressure 100 atm (10Mpa) coolants leaving the reactor core enters the steam generator, as described below. Roughly 5% of the fission heat is generated by fast neutrons escaping into the moderator, and this is removed by circulation through a separate heat exchanger.

The fuel in the CANDU reactor is normal (i.e. unenriched) uranium oxide as small cylindrical pellets. The pellets are packed in corrosion—resistance zirconium alloy (zircaloy) tube, nearly 0.5m 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 to about 97,000 kg.

The CANDU reactor is unusual in that refueling (i.e. removal of spent fuel and replacement by fresh fuel) is conducted while the reactor is operating. A refueling machine inserts a fresh fuel bundle into one end at a horizontal pressure tube which is temporarily disconnected from the main coolant circuit.

A spent fuel bundle is thus displaced at the other end and is removed. This procedure is carried out, like the coolant flow, in opposite directions in adjacent channels.

Control and protection system. The CANDU reactor has several types of vertical control elements. T hey includes a number of strong neutron absorber (i.e. poison) rods of cadmium which are used mainly for reactor shutdown and start up.

In addition there is other less strongly, absorbing rods to control power variations heat (power) distribution throughout the core. In an emergency situation, the shut down rods would immediately drop into the core, followed if necessary by the injection of a gadolinium nitrate solution into the moderator (Gadolinium is a very strong absorber of thermal neutrons)

Steam System. The respective ends of the pressure tubes are all connected into inlet and outlet headers (manifolds). The high temperature coolant leaving the reactor passes out the outlet header to a steam generator of the conventional inverted U tube (as in pressurized water reactor) and is then pumped back to the reactor by way of the inlet header.

Steam is generated at a temperature of above 265˚C. There are two coolant outlet (and two inlet) headers, one at each end of the reactor vessel, corresponding to the opposite direction of coolant flow through the core. Each inlet (and outlet) header is connected to a separate steam generator and pump loop. A single pressurizer, of the type used in pressurized-water reactors, maintains an essentially constant coolant system pressure.

Safety features. A break in a single pressure tube would result in some loss of coolant, but the particular tube could be disconnected and reactor operation would proceed with the other tubes. A mere loss of coolant accident, with possible damage to the fuel and release of radioactive fission products would develop from a break in one of the coolant header or in the pipes to or from the steam generators.

An emergency core-cooling system would then supply additional coolant. The separate moderate system would also provide a substantial heat sink.

A concrete containment structure encloses the reactor vessel and the steam generator system. 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.

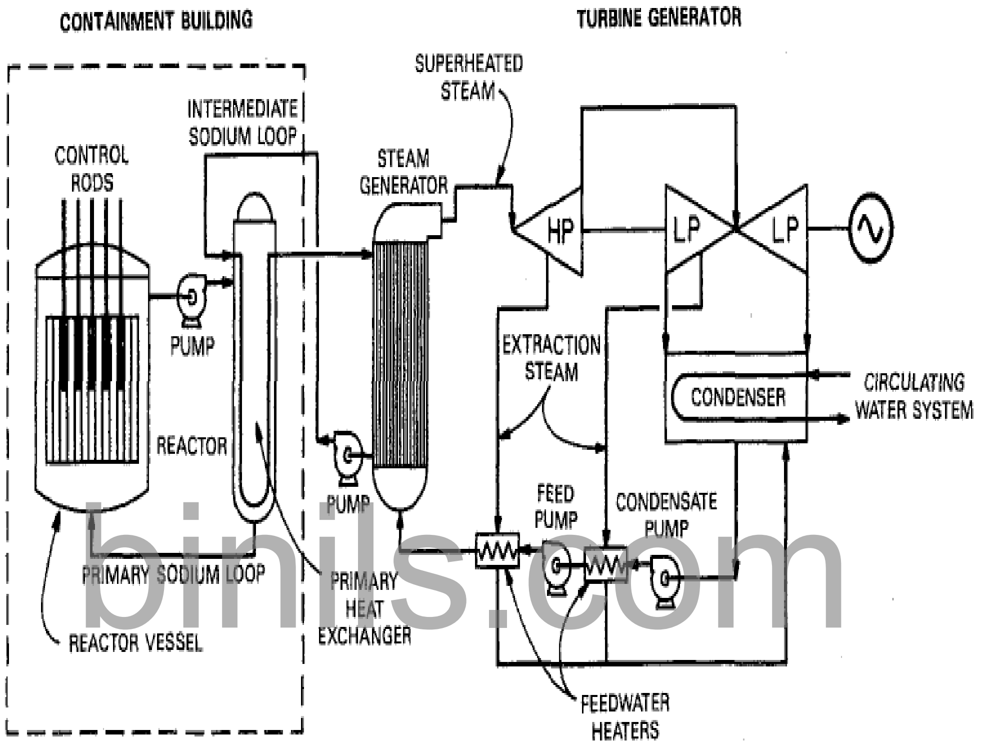
Advantages:

1. Enriched fuel is not required.
2. The reactor vessel does not have to withstand a high pressure as vessel of PWR and BWR. Only the heavy water coolant circuit (fuel tubes) has to be pressurized to inhibit boiling in the reactor core, therefore, the cost of the vessel is less?
3. The moderator can be kept at low temperature which increases its effectiveness in slowing down neutrons.
4. Heavy water is used as moderator, which has higher multiplication factor and low fuel consumption.
5. Site construction requires lesser time as compared with PWR and BWR.

Disadvantages

1. Heavy water is very costly
2. Leakage problems.
3. Very high standard of design, manufacture and maintenance are needed.
4. The reactor size is extremely large as power density is low as compared with PWR and BWR.

FAST BREEDER REACTOR



The breeder reactor has the capability of producing more fuel than it consumes through the breeding of uranium. The reactor core is surrounded by fertile material $^{238}_{92}U$, which Captures the neutrons not used for fashioning, and through a series of nuclear decays produces $^{239}_{94}P$, a fissile fuel.

Breeder reactors operate in the fast neutron energy range to take advantage of the higher number of neutrons produced take advantage of the higher number of neutrons produced per fission in uranium and plutonium fuel which result from the absorption of the high-energy neutrons.

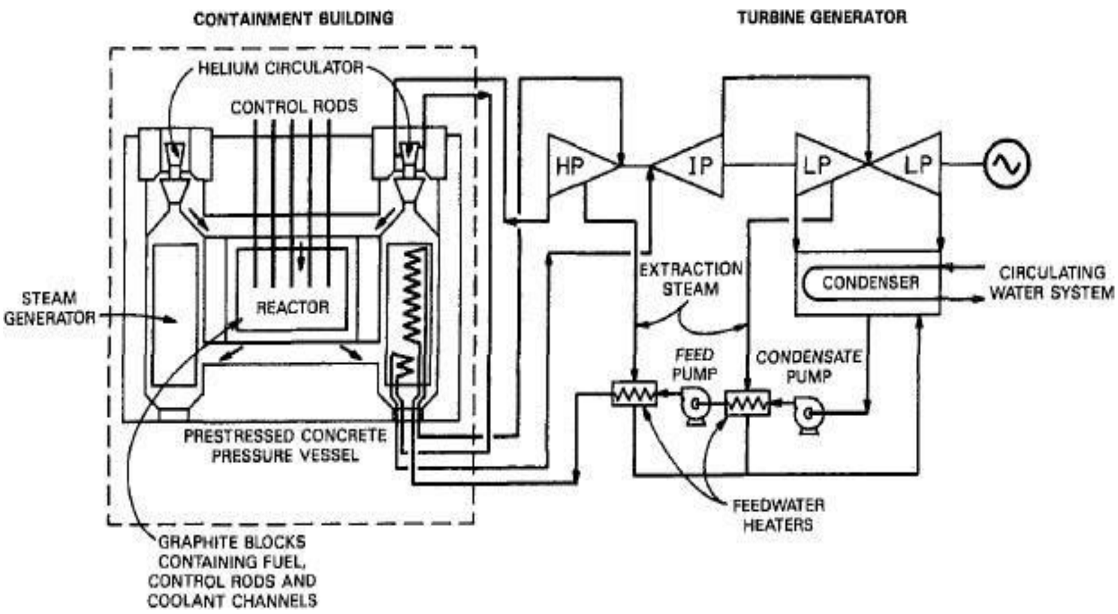
Breeder reactors can produce additional plutonium fuel to support several light water reactors, and thus have the potential to increase nuclear fuel reserves.

Figure shows a simplified schematic of a breeder reactor. Liquid sodium is used as the coolant to remove the reactor fission energy and transfer the energy to steam generators. Sodium is used because of its good heat transfer properties, low neutron moderating characteristics, and low operating pressures. Since liquid sodium becomes radioactive in passing through the reactor, a primary heat exchanger (sodium to sodium) is used to prevent leakage of radioactive sodium into the steam cycle.

An additional advantage of the primary heat exchanger is to prevent water getting into the nuclear core. The breeder core consists of a number of fuel assemblies of stainless steel fuel rods that are packed with pellets of ^{238}U dioxide and ^{239}Pu dioxide material.

The intermediate coolant passes to a steam generator (sodium to water exchanger) that produces superheated steam at 1,535 psig (10.6MPag), 906˚F (486˚C). Superheated steam expands through the high and low pressure section of the turbine generator, is condensed, and then returned to the sodium/water steam generator. The steam cycle is similar to a conventional steam cycle utilizing a 3,600 rpm non reheat turbine generator.

GAS COOLED REACTORS



Gas cooled reactor

The largest program involving commercial gas-cooled reactors (GCRs) was developed in England. The first series of GCRs used graphite as a moderator and carbon dioxide as the coolant. The reactor consisted of a large number of graphite blocks housed in a steel pressure vessel. Numerous channels ware drilled through the graphite blocks.

The channels either contained fuel elements or were used for control rod insertion. The fuel elements consisted of natural uranium metal clad with Magnox, an alloy of magnesium. Carbon dioxide passed through the fuel channels, removing the fission heat. The gas was then circulated to heat exchangers that produced steam, and then returned to the reactor.

The steam from the steam generators was expanded through a turbine generator, condensed, and returned to the steam generators. The Magnox series operated successfully but had low thermal efficiency and low fuel lifetime because of the low operating temperature (780˚F, 420˚C) and radiation damage limits due to the metallic uranium fuel. Later designs integrated the heat exchangers around the core inside the pressure vessel which consisted of a pre stressed concrete structure.

The advanced gas-cooled reactor (AGR) was developed to overcome the limitations of the Magnox except that the reactor fuel consisted of enriched uranium dioxide fuel pins clash with stainless steel and housed in fuel elements. Each fuel channel contained several fuel elements. Because of the high operating gas coolant temperature of 1,210˚F (654˚C) at the reactor outlet, superheat and reheat steam were produced.

High-temperature Gas-Cooled Reactors

The high-temperature gas-cooled reactor (HTGR) is an American design that produces a higher gas temperature, and thus, a higher steam temperature and higher thermal efficiencies than those of the LWR and HWR. Thermal efficiencies are similar to those for modern pulverized coal plants.

The HTGR, shown schematically in Fig 3.8, uses helium gas as the coolant and graphite as the neutron energy moderator. This reactor consists of hexagonal graphite blocks in which cylindrical fuel rods containing small spherical fuel particles of enriched uranium and thorium are housed within fuel holes interspersed with coolant holes for helium flow.

The graphite blocks are stacked vertically to form the reactor core. Helium flows through the graphite blocks, removing the fission hear, and then passes to one or more steam generators that produced superheated and reheated steam.

Superheated steam at 2400 psig(15.4Mpag), 950˚F(510˚C) is sent to a high-pressure turbine where the steam exhaust is then reheated in the steam generators at 550 psia (3.8MPa), 950˚F (510˚C) and sent back to the intermediate pressure turbine. The balance-of-plant systems (e.g., steam turbine generator, condensers, and feed water heaters) are very similar to those of a modern pulverized coal plant.

The graphite core, steam generators, and helium circulators are located in a pre stressed concrete pressure vessel. Control is provided by control rods of boron carbide, which enter from the top of the reactor core through channels in the graphite blocks.

SAFETY MEASURES FOR NUCLEAR POWER PLANTS

The radioactivity of the fission products which accumulate in the fuel during reactor operation has an important influence on the design of nuclear reactors of all types. Because radioactive material in the air or water constitutes a potential health hazard, special precautions are taken to ensure that any unavoidable releases to environmental during normal operation or at the lowest reasonably achievable levels. In addition so called "engineered safety features are provided to minimize the escape of radioactivity in the event of a severe malfunction.

The engineering safety features are designed to prevent or minimize the escape of radioactive fission products to the environment as the result of a severe transient that persists or develops after a reactor trip. Among the more important of these features are the emergency cores cooling system and the containment structure.

After a reactor is shutdown, either deliberately or as the result of an emergency, heat continues to be generated by radioactive decay of the fission products present in the fuel. For a reactor which has been operating for some time, the rate of decay heat regeneration after shutdown is initially about 7% of the full reactor heat power. This decreases with time but is still significant after several days.

Consequently, to avoid damage to the fuel by overheating, with the accompanying release of fission products, adequate cooling must be maintained for some time after the reactor is shutdown.

Safety considerations also dictate that the neutron detection and electronic gear by provided in duplicate such that, if one circuit fails, control can still be maintained. During normal operation the reactor control system must be able to maintain the power level at a constant value, change power level as load demand changes, and be able to handle short and long-term transients.

A variety of signals are used during steady-state operation to actuate control devices. Load demand, temperature, pressure, flow rate, and neutron flux signals are fed to appropriate discriminating and integrating circuits to provided the signals which adjust control rods, change moderator level, change fuel concentration, close or open valves, change motor speeds, etc. Either manual or automatic control can be used with a tendency toward greater reliance on automatic systems.

The use of safety devices, such as fuses to prevent overheating and relief valves to prevent over pressures, is common in industry. Safety devices on reactor differ in two important aspects—speed of action and range of operation.