Introduction to Nuclear Engineering. There is a common trend throughout the world to use nuclear energy as a source of power. This is because of the rapid depletion of conventional energy sources. Transportation network and large storage facility are not required which is one of the major hurdle in coal based thermal power plants. However, recently there is stiff opposition for the installation of nuclear plants due to a fear of radiation hazards.

Atomic Number, Mass Number and Isotope. The number of protons in an atom is known as *atomic number*. The total number of protons and neutrons in the nucleus of an atom is known as *mass number*. The difference between mass number and atomic number gives number of neutrons in an atom.

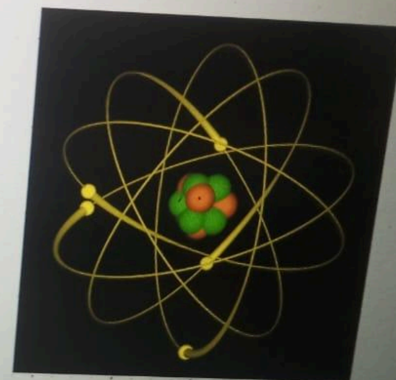
An element is distinguished by its atomic number. Some elements exist in more than one form, with the same atomic number but with different mass numbers. These are known as isotopes of an element. For example uranium exists in three isotopic forms ${}_{92}U^{233}$, ${}_{92}U^{235}$ and ${}_{92}U^{238}$.

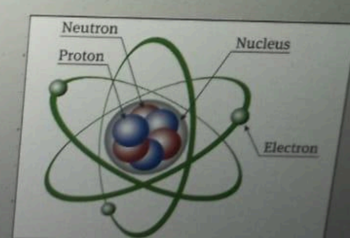
All the three have the same atomic number but different mass numbers.

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

Atomic Structure

- An atom consists of a positively charged nucleus surrounded by a number of negatively charged particles (electrons).
- The nucleus contains two types of particles, namely protons and neutrons.
- Number of electrons on the orbit are equal to the number of protons in a nucleus.
- Any addition of electrons to the neutral atom makes the atom negatively charged. Similarly any subtraction of electrons will make it positively charged. Such an atom is know as an ion and the process of charging the atom is known as ionization.





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Nuclear Reaction

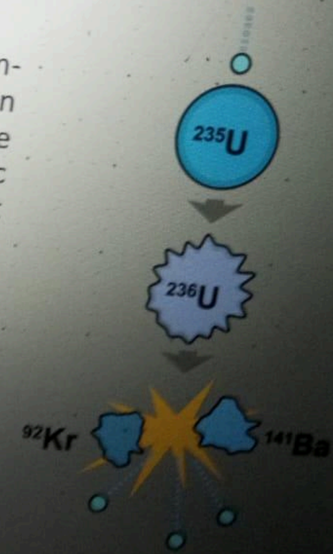
- A reaction that changes the number of protons or neutrons in the nucleus of an atom.
- There are several kind of nuclear reactions, including the fragmentation of large nuclei into smaller ones is termed as **nuclear fission.**
- Building up of small nuclei into large ones is termed as **nuclear fusion.**
- The changes began by collision with elementary particles or other nuclei.

Nuclear Fission

- **Nuclear fission** is either a nuclear reaction or a radioactive decay (also known as nuclear decay, radioactivity or nuclear radiation) process in which the nucleus of an atom splits into smaller parts (lighter nuclei). The fission process often produces free neutrons and gamma photons, and releases a very large amount of energy even by the energetic standards of radioactive decay.

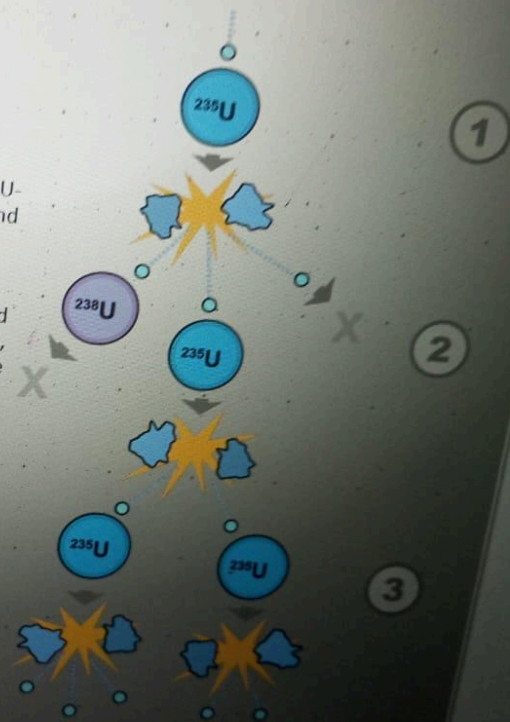
Nuclear Fission

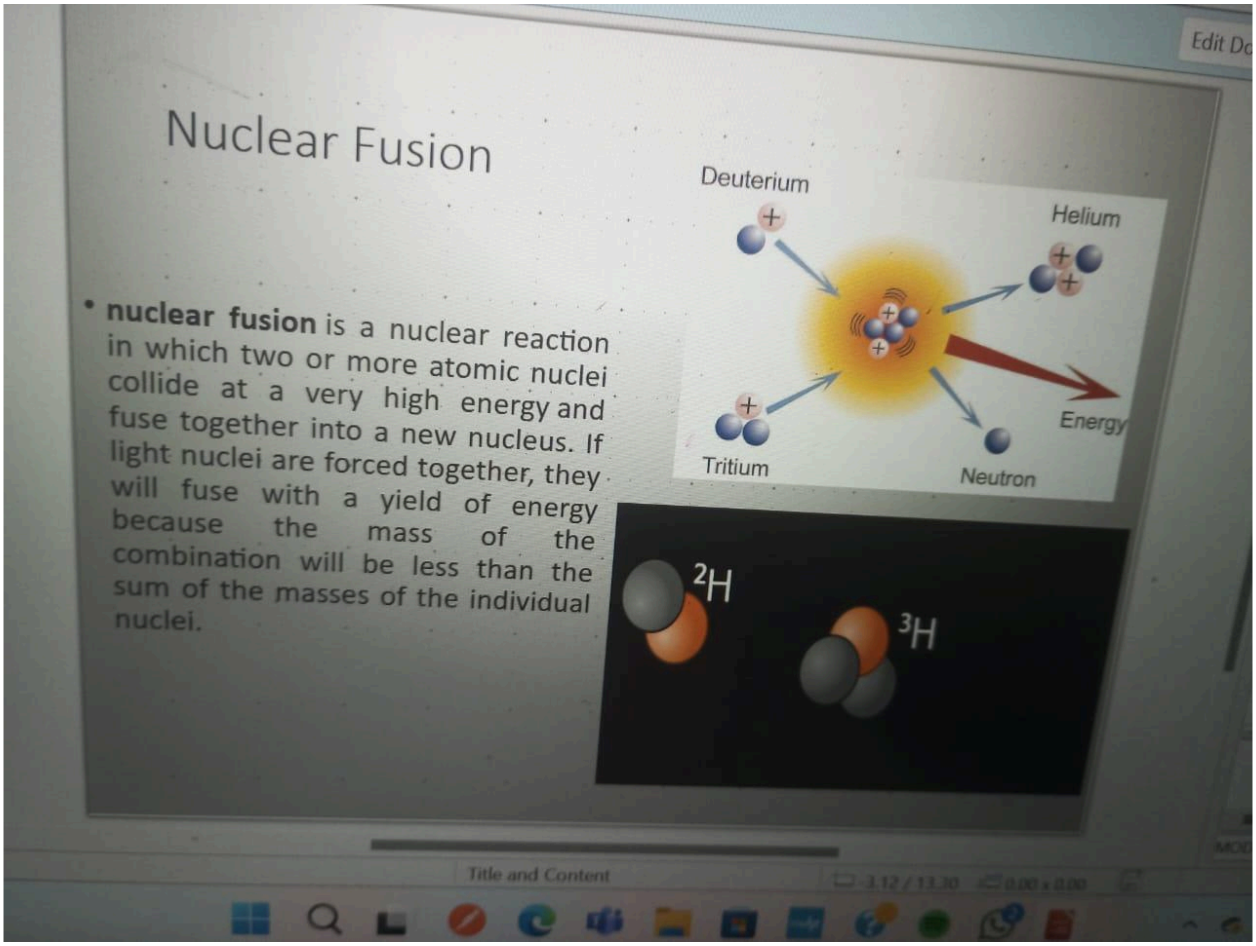
- A neutron is absorbed by a uranium-235 nucleus, turning it briefly into an excited uranium-236 nucleus, with the excitation energy provided by the kinetic energy of the neutron plus the forces that bind the neutron. The uranium-236, in turn, splits into fast-moving lighter elements (fission products) and releases a small amount of free neutrons. At the same time, one or more "prompt gamma rays" (not shown) are produced, as well.



Nuclear Fission Chain Reaction

- Natural uranium occurs in three isotopes, U-238, U-235 and U-234. isotope U- 235 is very easily and readily fissionable.
- A schematic nuclear fission chain reaction.
- 1. A uranium-235 atom absorbs a neutron and fissions into two new atoms (fission fragments), releasing two or three new neutrons and some binding energy.
- 2. Neutrons may be absorbed by an atom of uranium-238 and does not continue the reaction. Neutron may simply lost and does not collide with anything, also not continuing the reaction. However, the neutron does collide with an atom of uranium-235, which then fissions and releases two or three neutrons and some binding energy.
- 3. Again, neutrons collide with uranium-235 atoms, each of which fissions and releases between two or three neutrons, which can then continue the reaction.



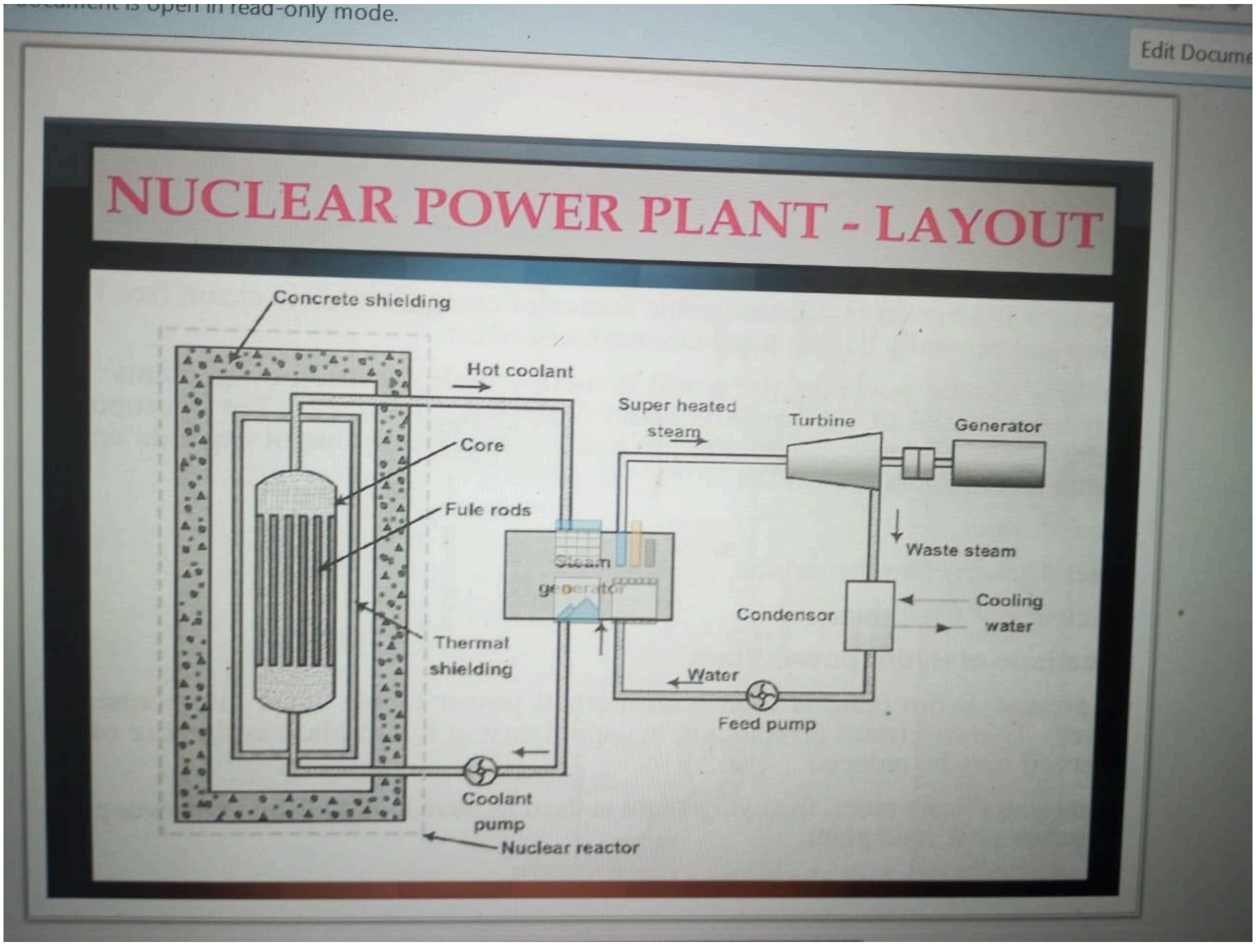


Nuclear Fuels used in Nuclear Power Plant

Following nuclear fuels are used in nuclear power plants:

1. Natural uranium
2. Enriched uranium
3. Thorium
4. Plutonium
5. U_{233}
6. Uranium oxide (UO_2)
7. Uranium carbide.

Working of Nuclear Power Plant with Layout



The simple construction of a nuclear power plant as shown in the figure. It consists of a nuclear reactor, coolant circulating pump, heat exchanger, feed pump, condenser, turbine and generator as shown in the line diagram of the nuclear power plant.

The heat is generated in a reactor by the fission reaction. The coolant in the primary circuit gets heated by absorbing the heat and enters into the heat exchanger. In a heat exchanger, the feed water is heated and converted into steam by the hot coolant by means of heat transfer.

The steam from the heat exchanger enters the turbine and the turbine is connected to the generator which generates power. The steam after doing the work enters into the condenser and converted into the water which is pumped again to the heat exchanger by the feed pump.

The hot coolant gets cooled in heat exchanger is recirculated into the reactor by a coolant circulating pump. This cycle is repeated for continuous generation of power. The generated power is supplied to the distribution line for consumers as shown in the line diagram.

Advantages:

Despite the higher initial cost of a nuclear plant, the lower fuel cost permits conservation of foreign exchange in the power sector. A large amount of energy can be released from a small mass of active material i.e. the complete fission of one kilo of uranium includes energy equivalent to 3100 tons of coal or 1700 tons of oil. Nearly 1012 tonnes of uranium and thorium is available in the earth crust. The other factors which are in favour of nuclear energy are:

1. Lower fuel cost.
2. Upgrades the local industry through the use of cheap electric energy.
3. Minimises the ecological effects of power generation.
4. It does not require any fuel transportation facilities.
5. It does not requires large storage facilities.
6. Develops national scientific capabilities through national nuclear research developments.
7. Improves the way of life and makes the people free from burdensome tasks which can be easily performed by electrical energy.
8. It has no combustion products and it is a clean source of power which does not contribute to air pollution

Disadvantages

- High capital investment.
- High maintenance cost.
- Radioactive wastes should be disposed of carefully.
- Skilled workers are required.
- It is not suitable for varying loads.

Difference between Nuclear Fusion and Fission

Nuclear Fission	Nuclear Fusion
1. Fission is the splitting of a large atom into two or more smaller ones.	1. Fusion is a fusing of two lighter atoms into a larger one.
2. This reaction does not normally occur in nature.	2. Fusion occurs in stars, such as Sun.

3. Fission produces many highly radioactive particles.	3. Few radioactive particles are produced by the fusion reaction.
4. The critical mass of the substance and high-speed neutrons are required.	4. High density, high-temperature environment is required.
5. Lower energy is released.	5. The energy released is 3 to 4 times greater than the energy released by fission.
6. It is used in nuclear power plants.	6. Used for bomb production.
7. Uranium is the main fuel.	7. Hydrogen isotopes are the main fuel.

Site Selection for Nuclear Power Plant:

Assessment of public safety results in greater concern for site selection for a Nuclear power plant. All the natural factors are taken into account like transport of radioactive material to the public during normal operating condition as well as highly unlikely event of an accident that would result in release of radioactive material to the environment.

The various factors that are taken into account while selecting the site for a nuclear power plant are:

1. Water availability

The site must be equipped with ample quantity of water as the plants require substantially greater quantity of cooling water, because of its higher turbine heat rate and feed water required for steam generation. Therefore, the site must be nearer to a river, reservoir, sea or ocean.

2. Distance from load centre

The power plant should be located near the load centre as this will reduce the cost of transmission line and also reduces transmission loss.

Note: The power plant is located near the load centre while meeting other requirements like reasonable land cost, adequate cooling water, away from population distribution, local zone restriction, accessibility for fuel shipment, etc.

3. Distance from populated area

The plant should be away from the population in order to avoid the radioactive hazard.

4. Transportation facilities

The site should be accessible by rail and road as heavy machinery are to be brought to the site during the installation and fuel during its operation.

5. Waste disposal

The waste of a nuclear power plant are very radioactive therefore sufficient space must be there to dispose the radioactive waste.

6. Cost of the land

Large area is required to built a nuclear power plant, therefore the land price should be reasonable.

7. Nature of land

The land should have good bearing capacity of about 1 MN/m^2 and must not come under earthquake prone zone. The land is studied for its past history of tremors and earthquake in order to design the plant that can withstand the severest earthquake.

8. Future extension

A choice for future extension of the plant should be made in order to meet the energy demand in future.

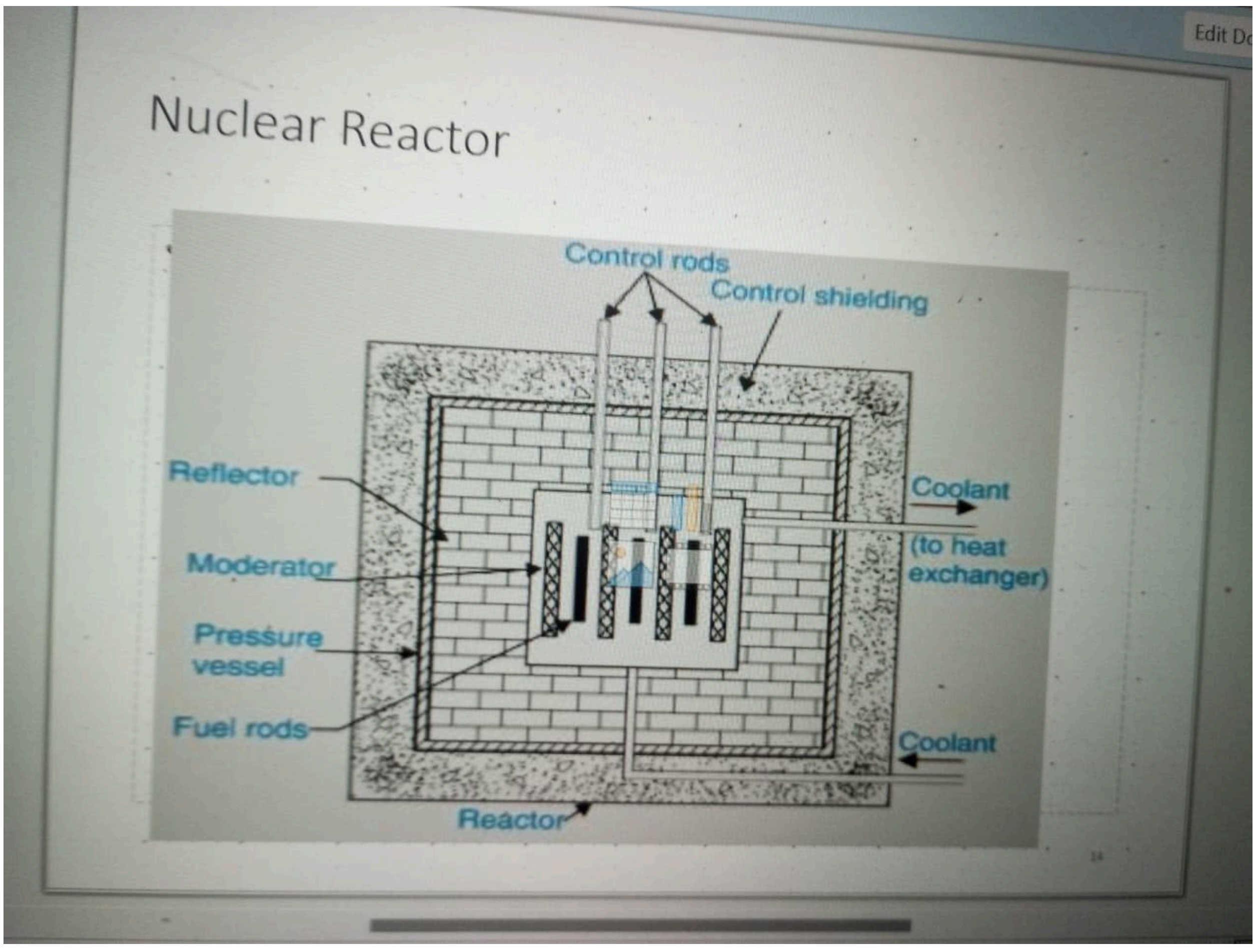
9. Availability of workforce

During construction of the plant enough labour is required. The labour should be available at the proposed site at cheap rate.

10. Size of the plant

The capacity of the plant decides the size of the plant, large plants require large area. Therefore the capacity of the plant also plays a vital role in the selection of site.

Components of Nuclear Reactor



A nuclear reactor is a device in which nuclear fission is controlled as a self-stabilizing chain reaction. In other words, it is a nuclear furnace which burns fuels like U235, U233 or Pu239 to produce the heat, neutrons and radio-isotopes as shown in the figure.

A nuclear reactor consists of the following:

1. Fuel rod
2. Moderator

3. Reflector
4. Coolant
5. Control rods
6. Shielding
7. Reactor vessel.

1. Fuel Rod

The fuels used in reactors are uranium, plutonium and thorium. Among the three uranium and its content are naturally available up to 70% to 90% in the uranium ore and the other two are formed in the nuclear reactor during the fission process.The fuel rods are used to produce the heat, neutrons and radio-isotopes.

2. Moderator

Its main function is to absorb the part of the kinetic energy of the neutrons. The neutrons collide directly with the moderator and thus reduces the kinetic energy of fast neutron to slow neutron. The light water, heavy water and graphite are the most common moderators used in reactors.The moderator is also used to increase the probability of reaction.

3. Reflector

Its main function is to reflect back the escaping neutrons back into the core from the surface of the core. A reflector is usually placed around the core. The neutrons produced in fission process can be absorbed by the fuel itself, a moderator, coolant, and some neutrons may escape from the core without absorption. To reduce the loss of neutrons, the reflector is placed around the core.

4. Coolant

The main function of coolant is to absorb a large amount of heat produced in the reactor. The heat carried by the coolant is used for power generation. If water is used as a coolant, it absorbs the heat and gets converted into steam for power generation.

5. Control Rods The control rods are used to :

- Start the reactor from the cold.
- For maintaining the chain reaction in a steady-state.
- To shut down the reactor automatically under emergency condition.

The control is necessary to prevent the melting of fuel rods and destruction of the reactor under emergency situation. Cadmium, boron or hafnium are commonly used as a control rod.

6. Shielding

A thermal shielding is provided through steel lining and external shield is be reactor installation to protect the operating provided with concrete surrounding the reactor installation to pro actor walls from radiation damage. personnel from exposure to radiations and reactor walls from radiation damage.

7. Reactor Vessel

It encloses the reactor core, reflector and shield. It also provides entrance and exit passage for coolant. The control rods are passed through a holder from the top of the vessel. The reactor vessel has to withstand a pressure of about 200 bar or more. The reactor core is placed at the bottom of the vessel.

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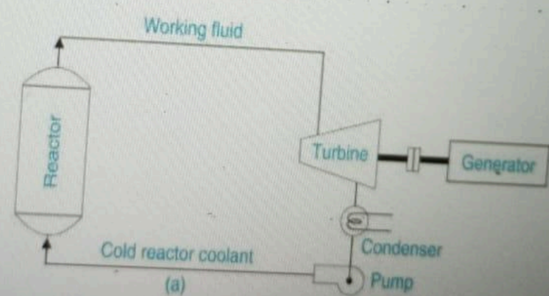
Heat

Circuits to utilize Nuclear Heat

- **Direct Circuit System**

  In this case, the fluid used for power generation is directly passed through the reactor core to absorb heat and then it is passed through the mechanical unit to convert heat energy to work. By passing water into reactor core steam can be generated and used directly to run the steam turbine and power plant works on Rankine Cycle.



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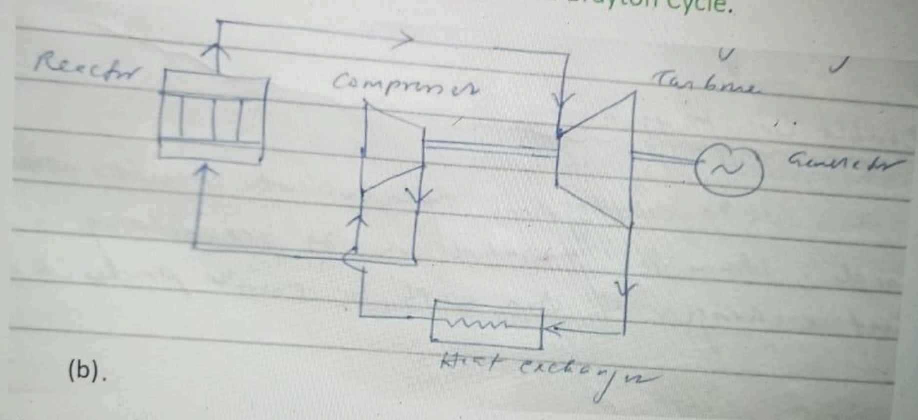
- Pressurized gas can be used to absorb heat and then used to turn gas turbine and power plant works on closed Brayton Cycle.



(b).

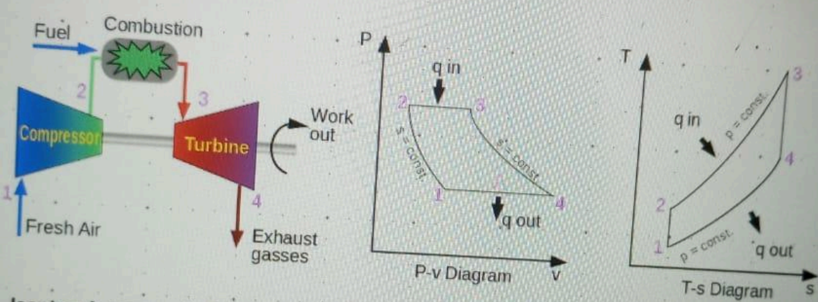
The fist circuit is used for boiling water reactor and the second circuit is used for gas cooled reactors.

Indirect Circuit System

a. Single Circuit System
b. Double Circuit System

Direct Circuit Gas Cooled Reactor

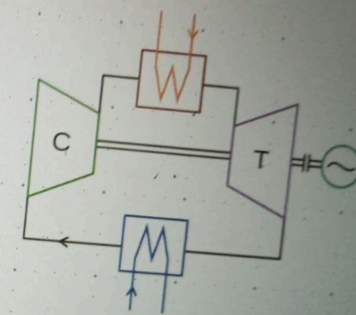
Brayton Cycle



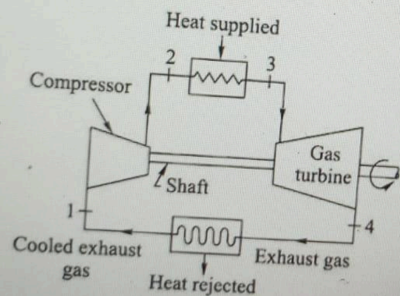
1. **Isentropic process (adiabatic process):** ambient air is drawn into the compressor, where it is pressurized. (i.e. compression)
2. **Isobaric process**: the compressed air then runs through a combustion chamber, where fuel is burned, heating that air—a constant-pressure process, since the chamber is open to flow in and out. (i.e. heat addition)
3. **Isentropic process (adiabatic process):** the heated, pressurized air then gives up its energy, expanding through a turbine (or series of turbines). Some of the work extracted by the turbine is used to drive the compressor. (i.e. expansion)
4. **Isobaric process**: heat rejection (in the atmosphere).

Closed Brayton Cycle

A closed Brayton cycle recirculates the working fluid; the air expelled from the turbine is reintroduced into the compressor, this cycle uses a heat exchanger to heat the working fluid instead of an internal combustion chamber. The closed Brayton cycle is used, for example, in closed-cycle gas turbine and space power generation.



C compressor and **T** turbine assembly
w high-temperature heat exchanger
ʍ low-temperature heat exchanger
~ mechanical load, e.g. electric generator



Closed gas turbine cycle

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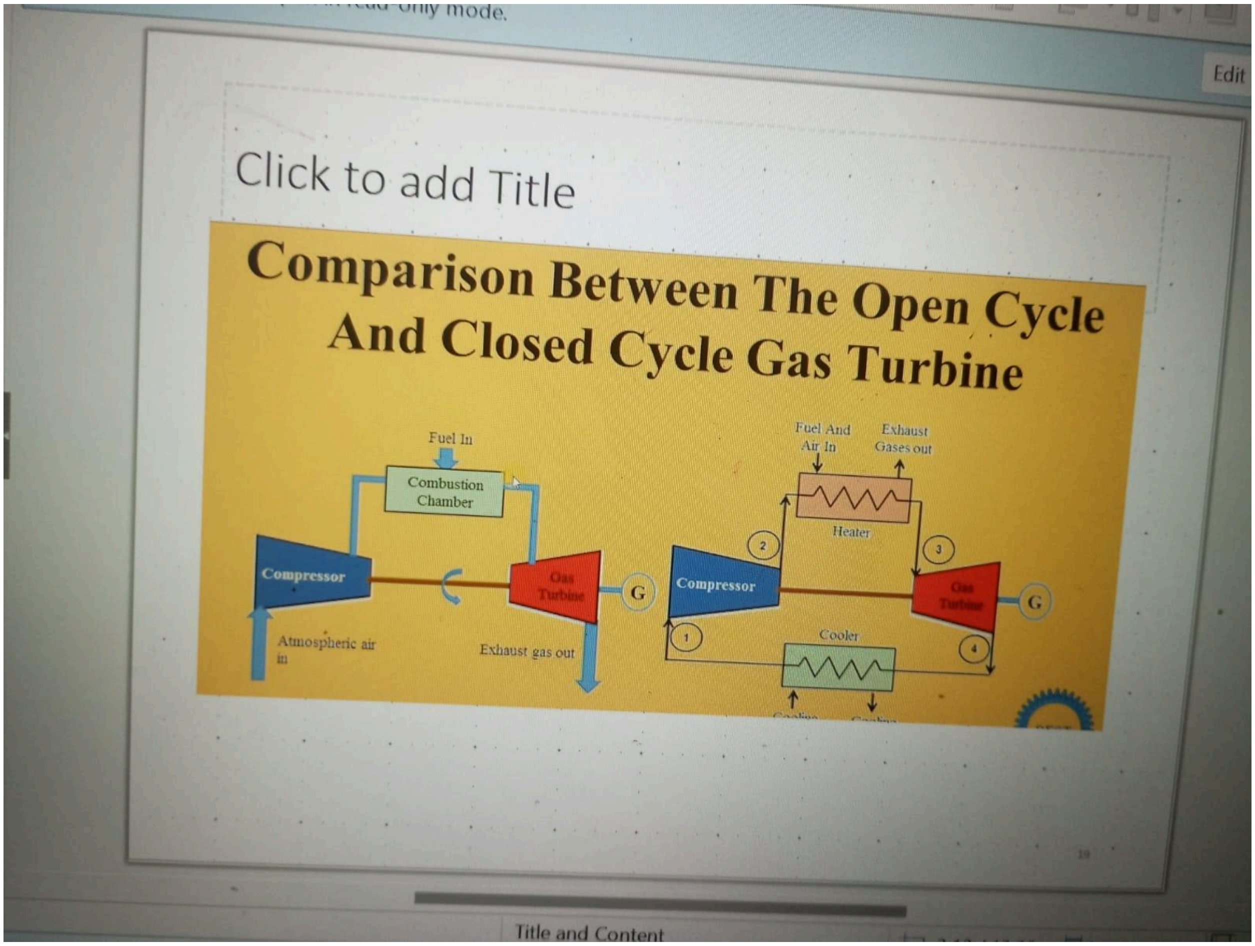

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Exhaust Gases out
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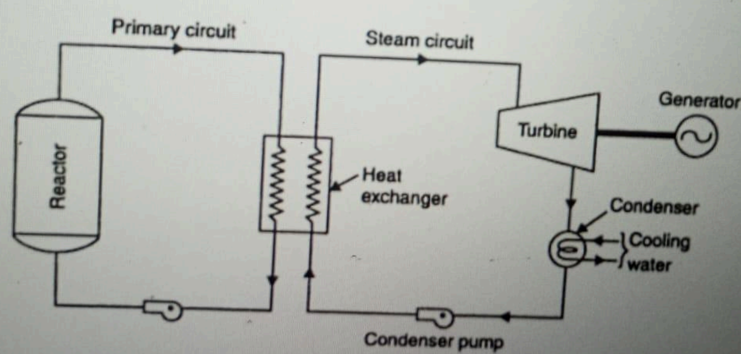
Indirect Circuit System

1. Single Circuit System

- In this system, the coolant passing through the reactor carries the heat generated and it is utilized for generating steam in the heat exchanger.
- In the primary circuit water or a gas can be used as the heat transfer medium. The steam generated is used for power production in a steam turbine.
- This is generally used in pressurized water reactor (PWR) or gas cooled reactor (GCR).



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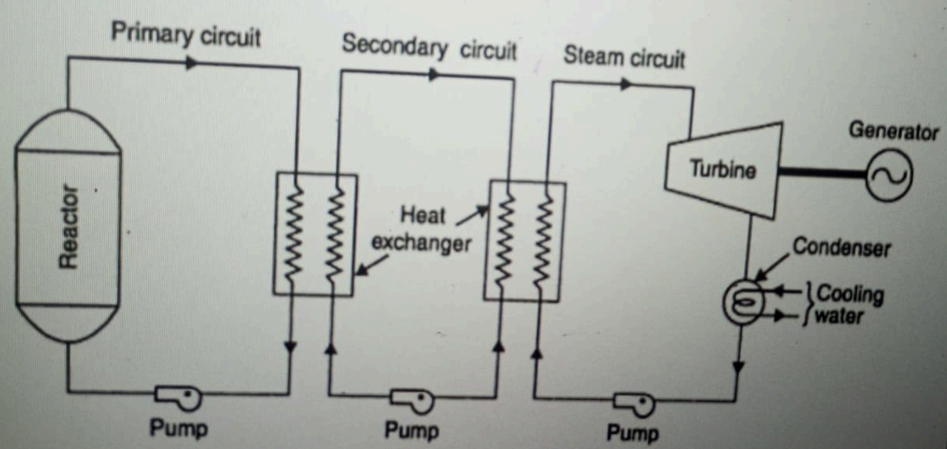
2. Double Circuit System

- In this system, two coolant circuit are used. Steam is generated in the secondary heat exchanger and then used for power production.
- This system is used in breeder reactor because radio-active intensity in the reactor is very high.



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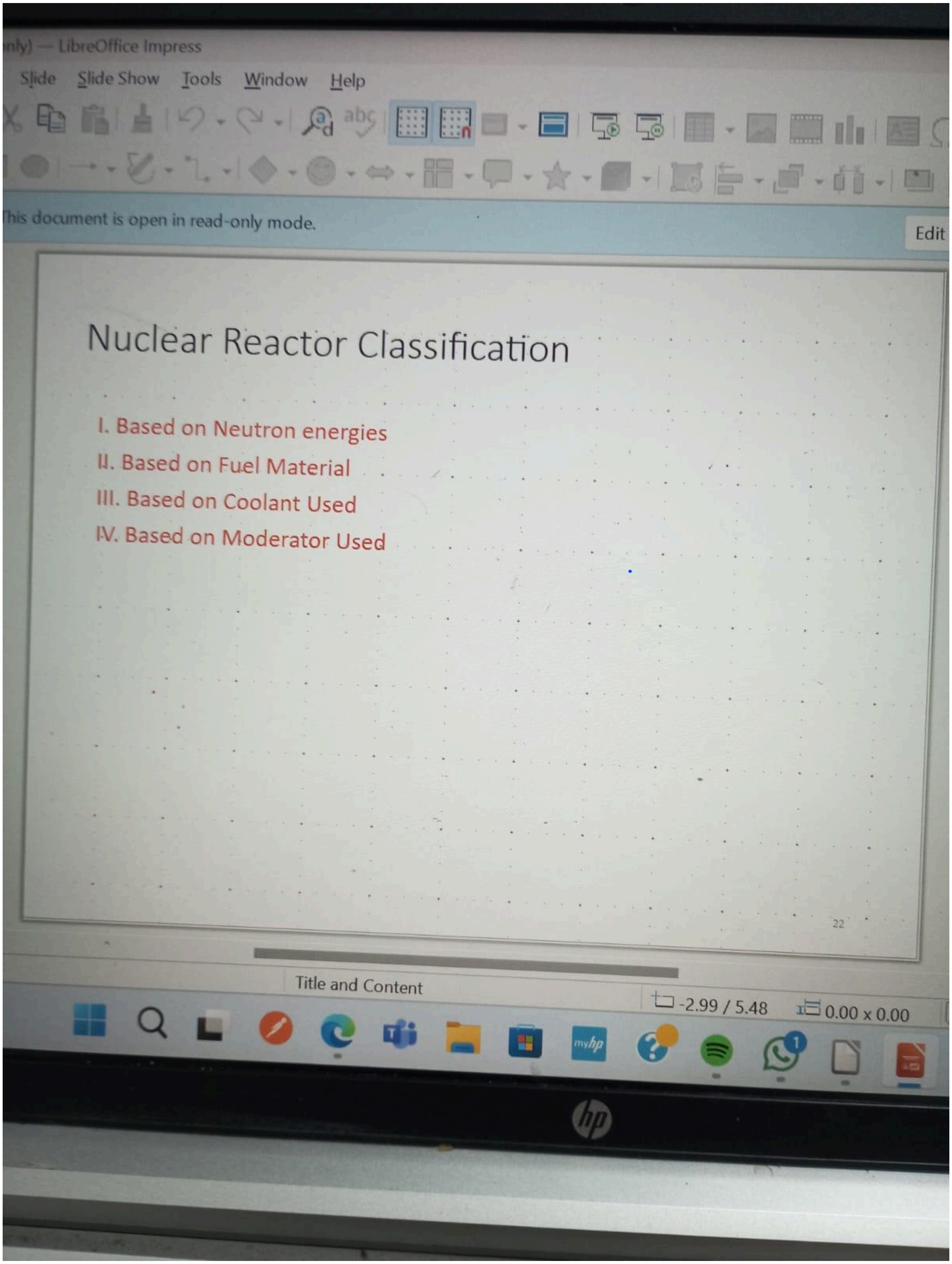
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Nuclear Reactor Classification
I. Based on Neutron energies
II. Based on Fuel Material
III. Based on Coolant Used
IV. Based on Moderator Used
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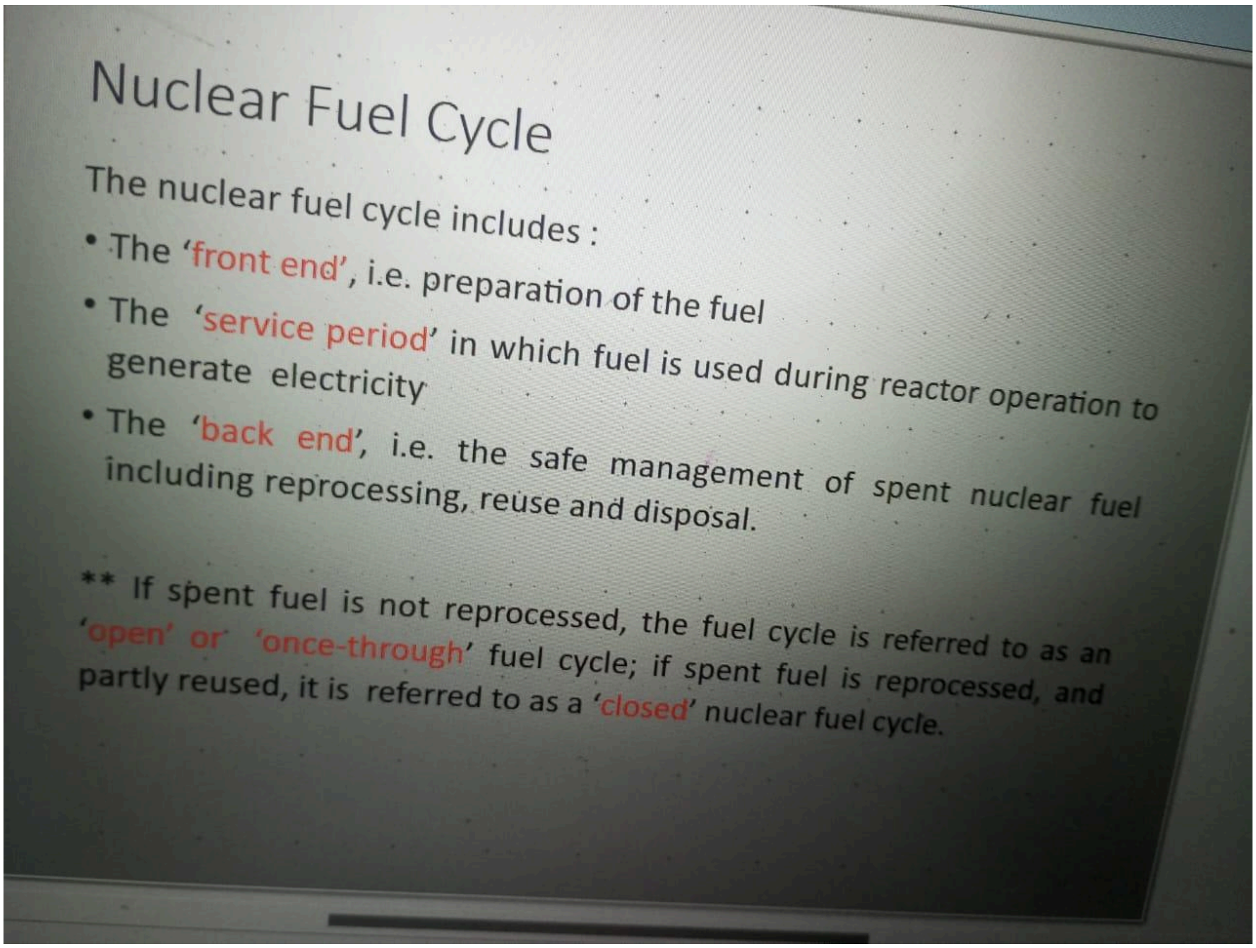
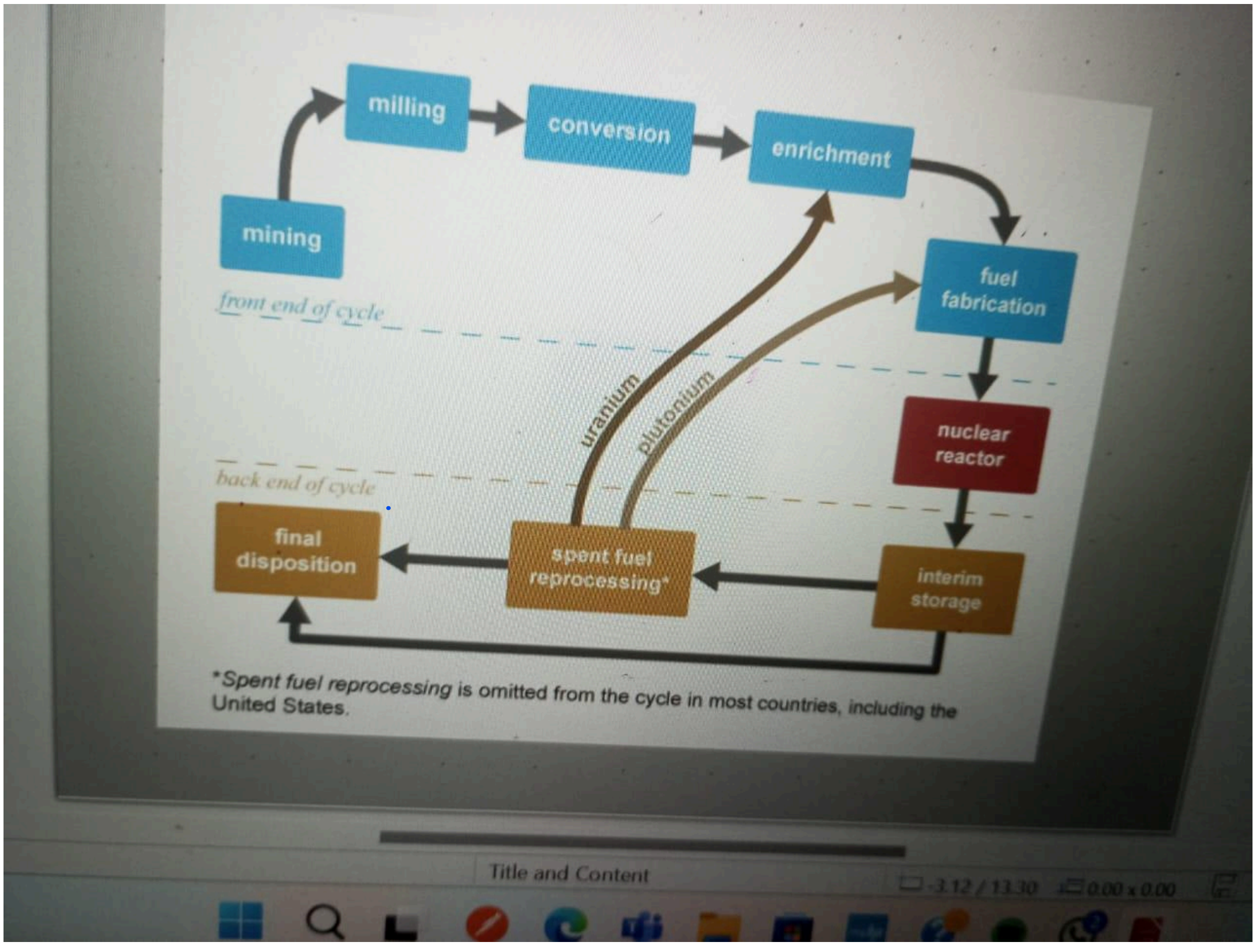
Water cooled reactors

Water cooled reactors are classified as ordinary water moderated reactor and heavy water moderated reactors.

- Ordinary water coolant and moderated reactors: the fuel used is enriched uranium and are further subdivided in
  - pressurised water reactor and
  - Boiling water reactors
- Heavy water coolant and moderated or CANDU type reactors: the natural uranium with heavy water as moderator is an alternative which can be used. This type of reactor is also known as CANDU-type as it was first introduced by CANADIAN engineers.

FUEL CYCLE


Nuclear Fuel Cycle
The nuclear fuel cycle includes :
• The 'front end', i.e. preparation of the fuel
• The 'service period' in which fuel is used during reactor operation to generate electricity
• The 'back end', i.e. the safe management of spent nuclear fuel including reprocessing, reuse and disposal.
** If spent fuel is not reprocessed, the fuel cycle is referred to as an 'open' or 'once-through' fuel cycle; if spent fuel is reprocessed, and partly reused, it is referred to as a 'closed' nuclear fuel cycle.



Conversion

For most types of reactors, the concentration of the fissile ^{235}U isotope in natural uranium must be enriched typically to between 3 percent and 5 percent. Natural uranium oxide from mines and processing plants is chemically converted into uranium hexafluoride (UF_6), a compound that when heated forms a gas that can be fed into enrichment plants. There are only three conversion facilities outside of Russia and China. These are located in the United States, Canada, and France.

Fuel Fabrication

Enriched UF6 is shipped to a fuel fabrication facility where it is heated back to a gas and chemically processed to uranium dioxide powder. The powder is pressed into ceramic pellets and sintered (baked) at a high temperature (over 2550 F).

The pellets are then encased in metal tubes to form fuel rods, which are arranged into a fuel assembly ready for introduction into a reactor. The dimensions of the fuel pellets and other components of the fuel assembly are precisely controlled to ensure consistency in the characteristics of the fuel. Nuclear fuel assemblies are specifically designed for particular types of reactors and are made to quality assurance specifications. The most common reactor, the pressurized-water reactor (PWR), contains 150-200 fuel assemblies, whereas the boiling-water reactor, the second most common reactor, contains 370-800 fuel assemblies.

In a fuel fabrication plant great care is taken with the size and shape of processing vessels to avoid criticality (a limited chain reaction releasing radiation). With low-enriched fuel criticality is most unlikely, but in plants handling special fuels for research reactors this is a vital consideration.

Waste Disposal

The Office of Nuclear Energy is responsible for ongoing research and development related to long-term disposition of spent nuclear fuel and high-level radioactive waste.

The mission of the Office of Spent Fuel and Waste Disposition (SFWD), which manages this work, is to protect people and the environment, now and in the future, by establishing an integrated system for storage, transportation, and disposal of the nation’s spent nuclear fuel and high-level radioactive waste.

Enrichment

The enrichment process separates gaseous uranium hexafluoride into two streams, one being enriched to the required level known as low-enriched uranium (LEU); the other stream is progressively depleted in ^{235}U and is called “tails," or simply depleted uranium.

Gas centrifuge technology using uranium hexafluoride gas as feed is the sole method of commercial enrichment.

This process uses the physical properties of molecules, specifically the 1 percent mass difference between the two uranium isotopes, to separate them. Another technology that can be used to enrich uranium is called laser enrichment. This technology has not been utilized at the commercial level and is undergoing technology development.

Used fuel and reprocessing

After time, the amount of usable fuel in the reactor will diminish due to heavy elements and other fission products being produced. After 18-36 months the fuel is removed from the reactor, however there is still potential for energy contained in it, with the amount depending on the type of reactor. This fuel is very hot and radioactive, so it is stored temporarily in a storage pool of water, which cools it and absorbs the radiation.

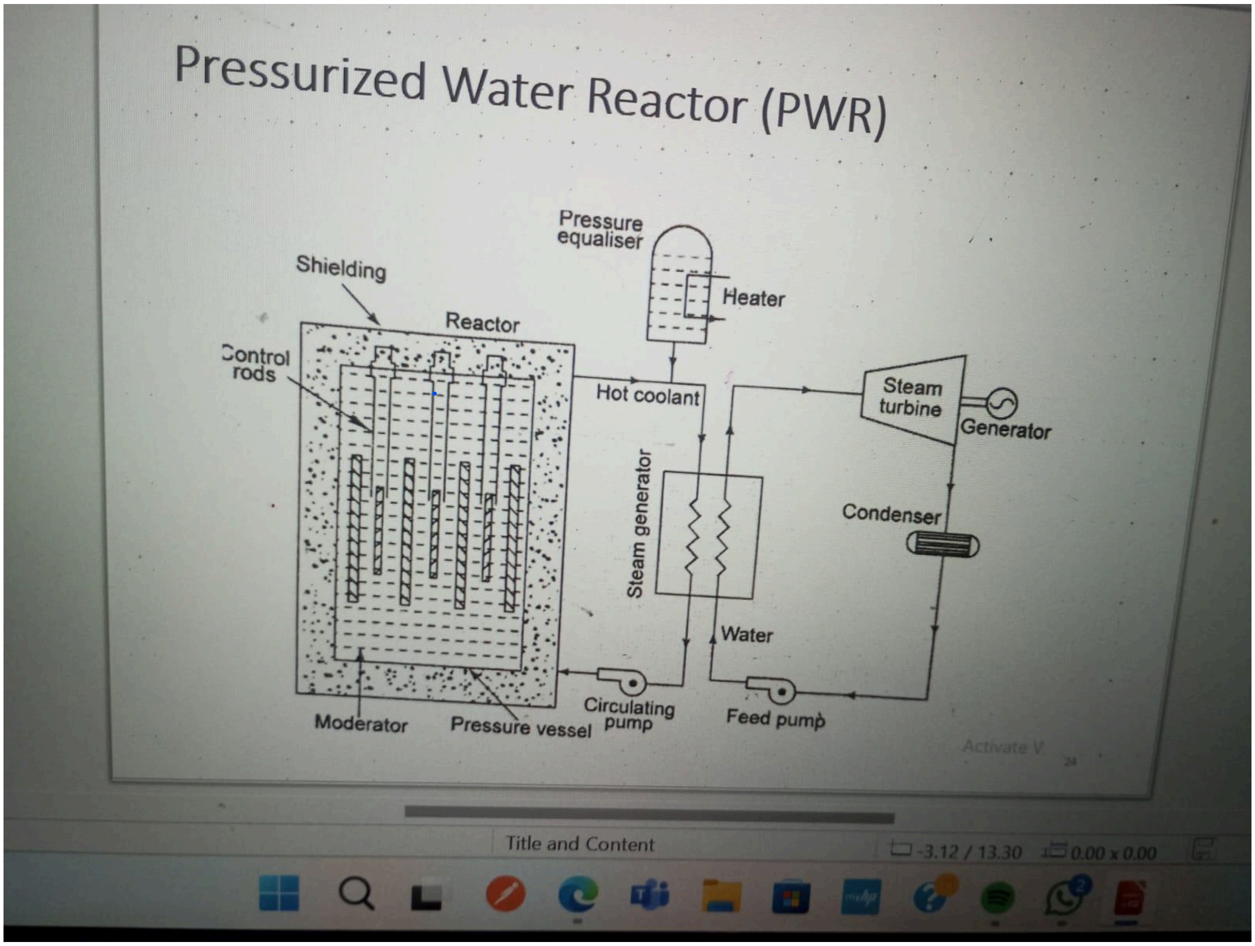
The fuel can then be reprocessed since it still has slightly more ^{235}U than found in nature (if the fuel comes from a light water reactor, a BWR or PWR). The plutonium can be made into a mixed oxide (MOX) fuel, in which uranium oxide is combined with plutonium oxide.[1] This is done by dissolving the fuel rods in a solution in order to obtain the separate materials.

Types of Reactors

The reactors can be classified into the following categories:

1. Depending on neutron energy:
    1. Fast reactors
    2. Thermal reactors or slow reactors
    3. Intermediate reactors.
2. Types of fuel used:
    1. U235 reactors
    2. U238 reactor
    3. Th22 reactor
3. Types of coolant used:
    1. Gas-cooled reactor
    2. Water-cooled reactor
    3. Liquid metal cooled reactor
4. Type of moderator used:
    1. Graphite reactor
    2. Beryllium reactor
    3. Water reactor
5. Type of core:
    1. Homogeneous reactor
    2. Heterogeneous reactor.

Pressurized water reactor (PWR)



A pressurized water reactor is a nuclear reactor in which the water flowing uses high pressure in the primary circuit to prevent it from boiling. Otherwise, the high temperature inside the reactor would convert the heat water into steam.It is currently the most widely used type of nuclear reactor in nuclear power plants worldwide in order to generate electric power. There are more than 230 nuclear reactors worldwide built up with this systemThe first purpose of the PWR model was to use it in a nuclear submarine.Pressurized water reactors (PWR) use enriched uranium as nuclear fuel.Along with boiling water reactors (BWR), the pressurized water reactor is a light water reactor.The pressurized water reactor (PWR) works in 4 steps:

- The reactor core within the reactor vessel generates heat through fission reactions.

- The high-pressure water from the primary circuit transports this thermal energy to a steam generator outside the pressure vessel.
- Inside the steam generator, the heat coming from the primary circuit converts the water from the secondary circuit into steam.
- The steam generated drives a turbine that produces electricity.

The pressurized water reactor PWR has converted nuclear energy from nuclear fuel into electrical energy during these four points. Then, the cycle begins again: the resulting steam is converted back into liquid water through a condenser. The condenser puts the secondary circuit in thermal contact with a tertiary course through which cold water circulates outside (seawater, rivers, lakes, etc.). Once the condenser has converted the steam into liquid water, it returns to the steam generator driven by a series of water pumps.

PWR reactor advantages:

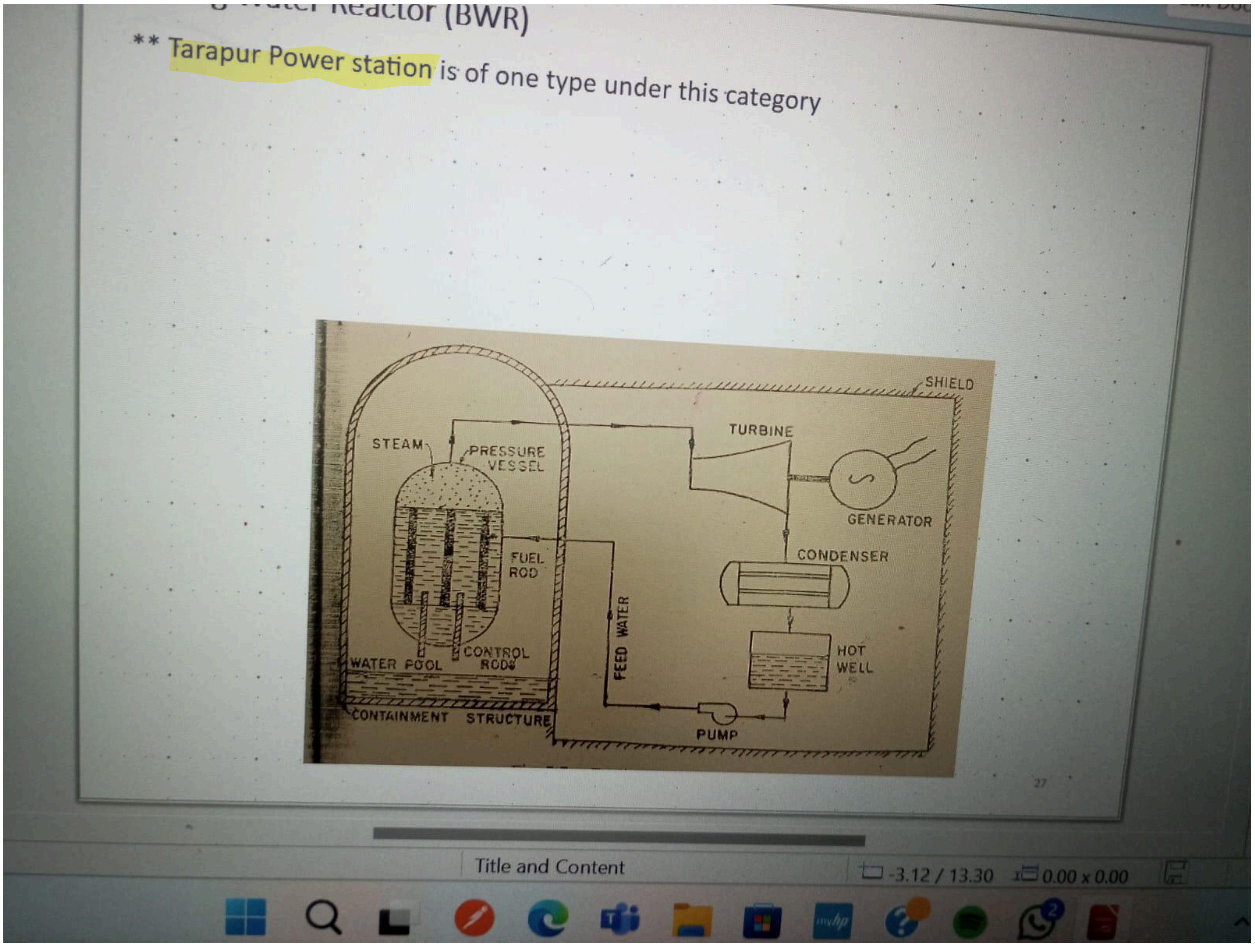
- PWR-type reactors are very stable due to their tendency to reduce their power when the temperature increases.
- PWRs can be operated with a core that contains less fissile material than is necessary to reach the prompt critical conditions with instantaneous neutrons. It reduces the possibility of the reactor having an uncontrolled power surge making it safer.
- PWRs can use ordinary water as a moderator instead of requiring heavy water.

PWR nuclear reactor disadvantages:

- The water in the primary cooling system must be highly pressurized to keep the water in the liquid phase. However, it increases construction costs and the risk of an accident with the loss of refrigerant from the primary system.
- PWRs cannot change spent fuel while they are operating.
- Hot water from the primary with dissolved boric acid is corrosive to stainless steel, causing corrosion products (which are radioactive) to circulate through the primary circuit. It limits the reactor’s useful life and requires unique systems for filtering corrosion products.
- Ordinary water is more absorbing of neutrons than heavy water. Therefore when using regular water as a moderator, it is necessary to use enriched uranium as fuel, which increases fuel cost.
- Since water acts as a neutron moderator, building a fast reactor with a PWR design is impossible.

Boiling Water Reactor (BWR)

The boiling water reactor (BWR) is the second most common type of nuclear reactor. There are about 94 operating BWRs in the world, which is 21% of all reactors.The fuel is very similar to the fuel of the PWR. Ceramic pellets are made of uranium enriched to 2.1%—2.6%. They are inserted into fuel rods that are assembled into fuel bundles 4 meters long. Each assembly resides in its own channel that rectifies the water coolant flow. The reactor is actually a steel pressure vessel about 10 meters high and the reactor core is 3.5 meters high and 4.5 meters in diameter. This reactor is refueled once a year during reactor shutdown when one-quarter to one-third of the fuel bundles is replaced.



Ordinary water is used as both the moderator and the coolant. The water boils directly inside the reactor. The design of the reactor core allows operation even if approximately 12%—15% of its top portion is filled with steam (however, with lower efficiency). Boiling water is also used for control purposes because steam bubbles are not a very good moderator compared to water and thus the fission reaction is attenuated. The water pressure is 7 MPa and its temperature is about 280 °C. The steam generated inside the reactor is dried and supplied directly to a turbine. This is a single-circuit power plant.

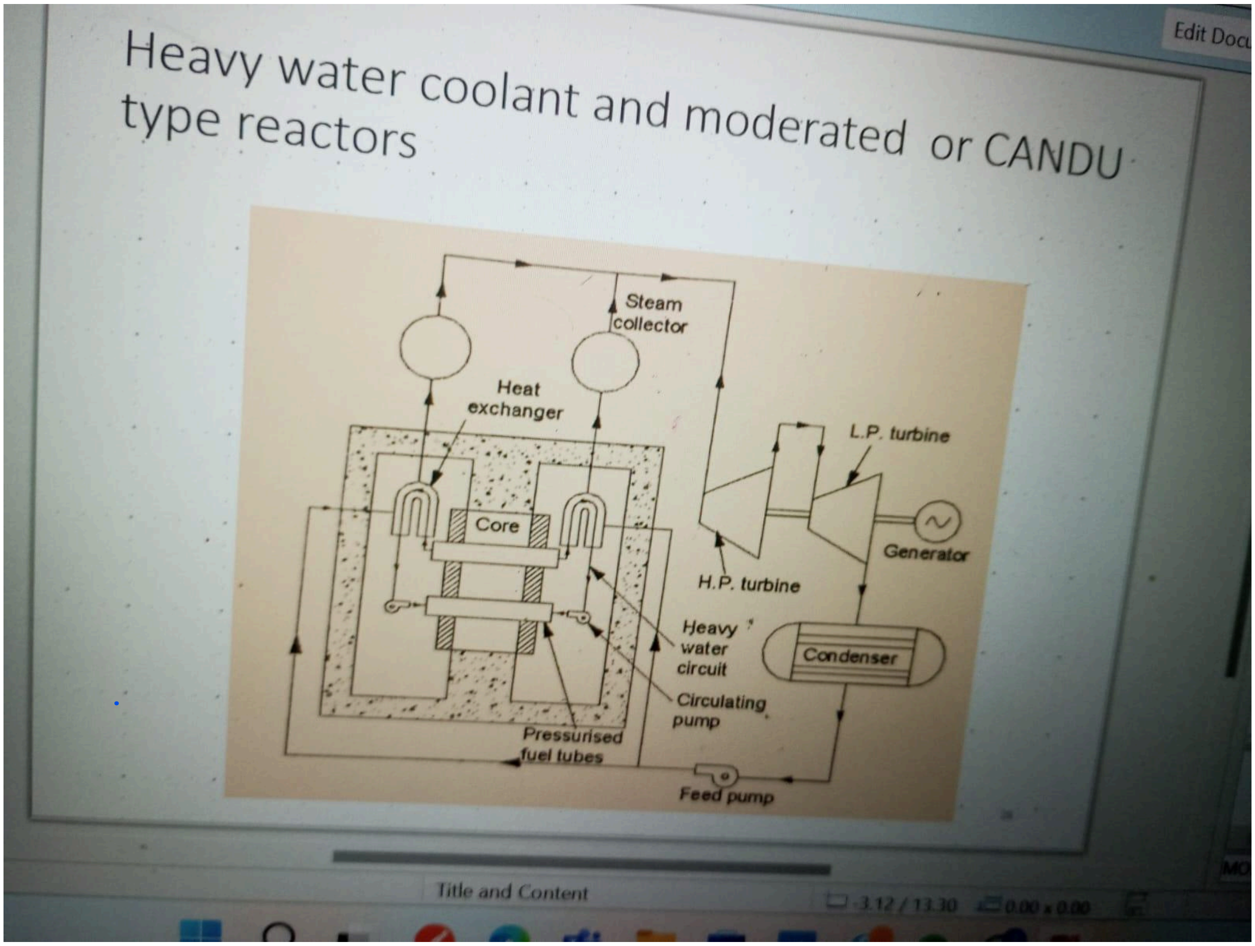
Advantages

1. The pressure inside the reactor vessel is much lower than PWR as water is allowed to boil inside the reactor. Hence, the reactor vessel is much lighter than PWR and reduces the cost of pressure vessel considerably.
2. Since the reactor does not require steam generator, pressurizer, circulating pump and piping's, the cost is further reduced.
3. Boiling water reactor is more stable than PWR.
4. Thermal efficiency of BWR plant is more than PWR plant.

Disadvantages

1. The BWR has negative power demand coefficient. i.e., when more power is demanded from the reactor, it may produce less.
2. The steam leaving the reactor is slightly radioactive and hence the turbine and the pipings should be properly shielded.
3. Since the boiling of water on the surface of the fuel is allowed, the 'burn out' of fuel is more.

Heavy water coolant and moderated or CANDU Reactor



A reactor developed and designed by Canadian is called **CANDU (CAN**adian **D**euterium **U**ranium) reactor.
It uses pressurized heavy water (which has 99.8% deuterium oxide) as a moderator and primary coolant. Natural Uranium is used as fuel for this reactor.
A Canadian Deuterium Uranium Pressurized Heavy Water power plant is shown in the figure.

Construction and Working of CANDU Reactor

- Natural uranium used as fuel is in the form of small cylinder pallets. These are packed in corrosion-resistant Zirconium alloy tubes of 0.5 cm long and 1.3 cm in diameter to form a fuel rod.
- These short rods are combined in 37 bundles of 37 rods and 12 bundles are placed end to end in each pressure tubes.
- This type of arrangement helps in refueling the reactor while in operation.
- The reactor vessel is a cylinder called *Calandria*. It is placed horizontally. It has pressure tubes penetrating the reactor vessel. The active core is about 6 m high and 7-8 m in diameter.

- In the primary circuit, the deuterium coolant enters the array of pressure tubes at 110 bar pressure and 260 degrees Celsius temperature. It flows through the fuel element and leaves the pressure tubes at about 370 degrees Celsius after absorbing the heat generated by the fission of fuel material.
- The coolant at 110 bar and 370 degrees leaving the reactor enters the steam power plant where the generated steam is used in the conventional steam power plants.
- Control rods are made up of *cadmium*. These control rods are used to start and shut down the reactor. In addition, there are other absorbing rods that are used to control the power output during reactor operation.

Advantages of CANDU Reactor :

1. Enriched fuel is not required.
2. The cost and time of construction are less.
3. It has a good neutron economy resulting in a good breeding ratio.
4. Heavy water is used as a moderator which has low fuel consumption.

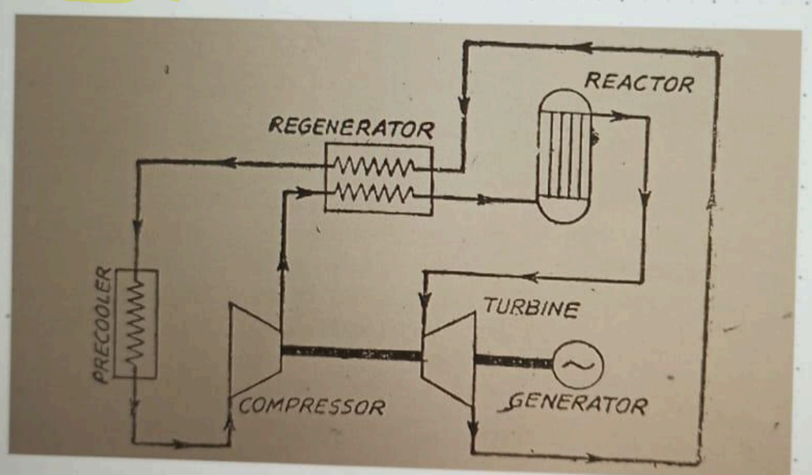
Disadvantages of CANDU Reactor :

1. Heavy water used as a moderator is costly.
2. A leakage problem may occur.
3. It has critical temperature limitations.
4. It requires has a standard of design, manufacture, and maintenance.
5. The size of the plant is large.

Gas cooled reactor

Direct Circuit Gas Cooled Reactor

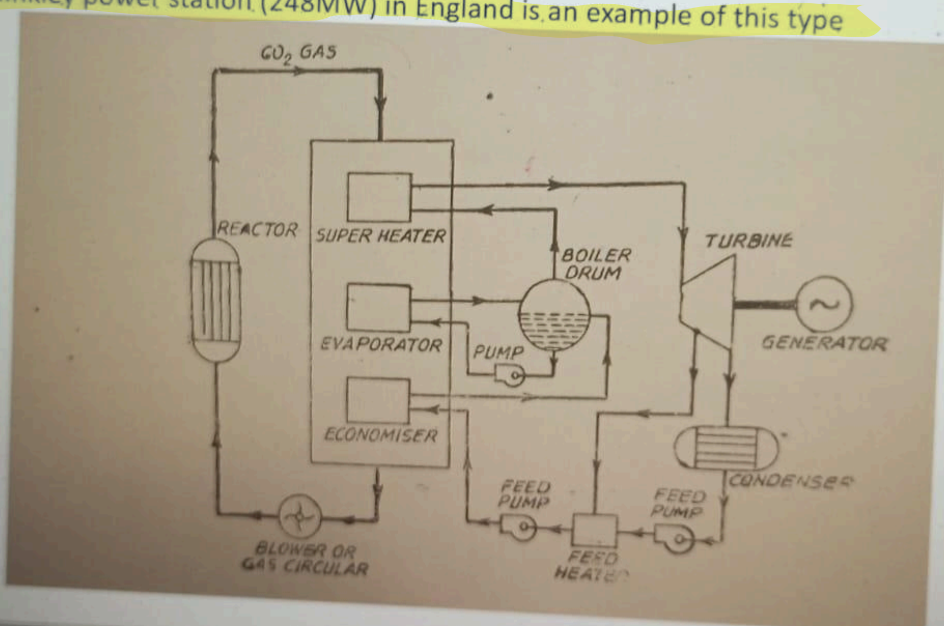
The high pressure and high temperature gas coming out of the reactor is directly fed to the gas turbine for power generation. This is similar to closed Brayton Cycle except the heat required to heat the fluid is generated in the reactor instead of in the combustion chamber



Indirect Circuit Gas Cooled Reactor

The gas is passed through the reactor to carry the heat generated by fission and the hot gas is further used for governing superheated steam.

**Hinkley power station (248MW) in England is an example of this type



Advantages

Gas-cooled nuclear reactors offer several significant advantages compared to other reactor designs, making them attractive for various applications:

- Higher thermal efficiency: Due to the use of an inert gas as a coolant, GCR reactors can operate at higher temperatures compared to water-cooled reactors, increasing thermal efficiency and power generation.
- Greater safety: The gases used as refrigerants in GCRs are non-corrosive and non-flammable, which contributes to a safer environment. Additionally, GCR reactor designs often include passive safety systems that can mitigate the effects of an accident.
- Less radioactive waste: GCR reactors typically produce less high-level radioactive waste compared to other designs, making them easier to manage and store long-term.
- Fuel flexibility: Gas-cooled reactors can use a variety of nuclear fuels, including enriched uranium, depleted uranium and plutonium, providing flexibility in fuel supply.
- Various applications: In addition to the generation of electrical energy, this type of reactor can be used in industrial applications, such as hydrogen production or water desalination.

Disadvantages

- Initial costs: Construction of GCR reactors can be expensive due to high-strength materials and design complexity.
- Operational Safety: Although GCR reactors have inherent safety features, radioactive waste management and operational safety remain critical concerns.
- Technological development: Despite advances in the design of gas-cooled nuclear reactors, additional technological development is still needed to reach their full potential and ensure safety.

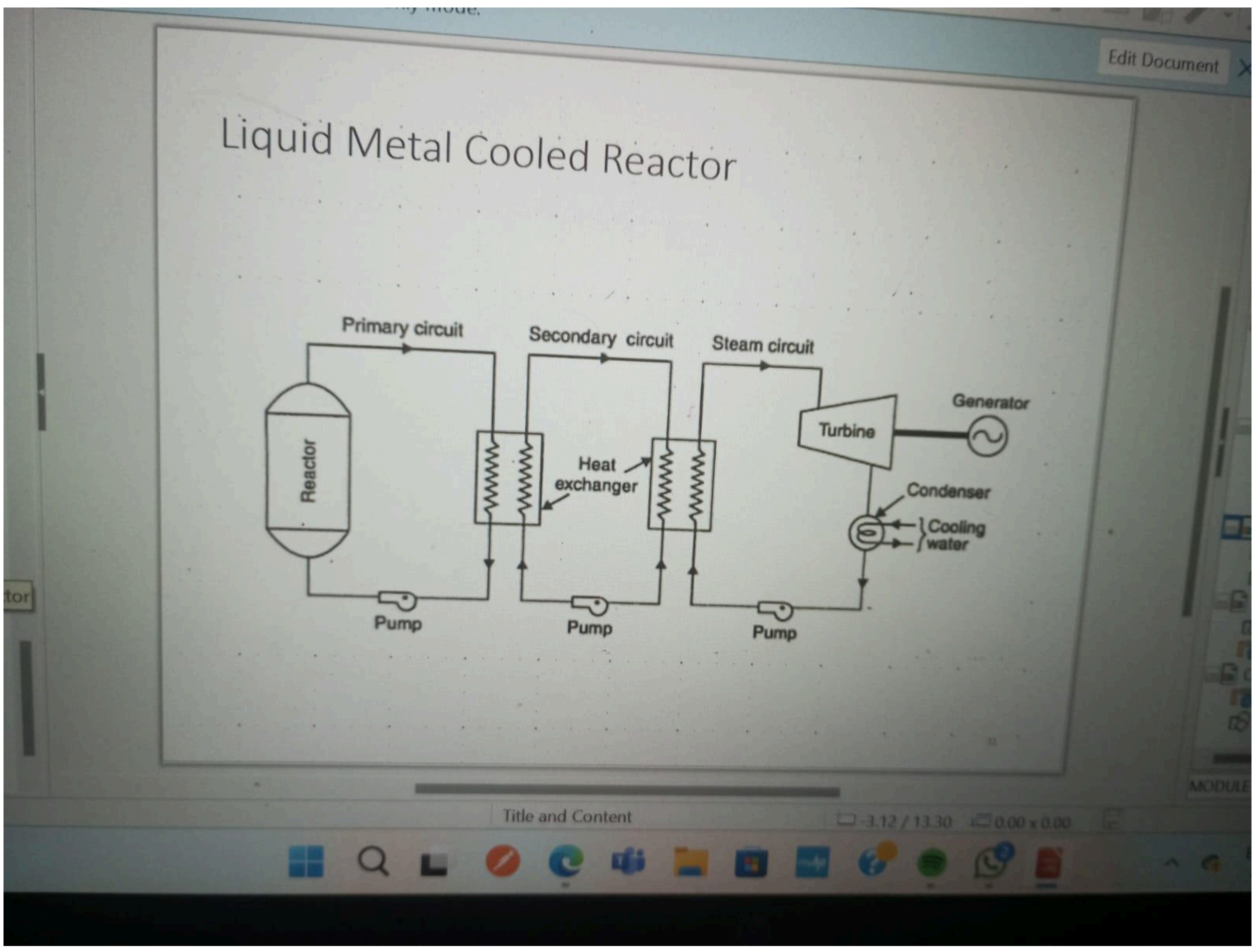
Liquid Metal Cooled Reactor (LMCR) – Working, Advantages & Disadvantages:

A liquid metal cooled reactor (LMCR) is an advanced type of nuclear reactor that uses a liquid metal as the primary coolant. The use of liquid metal has many advantages because the reactor need not to be kept under pressure and they allow high power density than the conventional coolant. The high temperature of the liquid metal is used to produce vapour at higher temperature leading to higher plant efficiency.

Sodium-Graphite Reactor (SGR) is a typical liquid metal cooled reactor that uses sodium as coolant and graphite as moderator.

Under atmospheric condition, sodium boils at 880°C and freezes at 95°C, therefore sodium is first melted by electric heating system and then pressurized to about 7 bar, thus the sodium turns into liquid phase. The liquid sodium is then circulated by the circulation pump.

The arrangement of a sodium graphite reactor (SGR) is shown in Fig. 3.12.



The reactor has two coolant loop. The primary loop contains liquid sodium which is circulated through the fuel core and it absorbs the heat liberated by the fission of fuel. The liquid sodium gets cooled in the heat exchanger and goes back to the reactor vessel. The secondary loop contains an alloy of sodium and potassium in liquid form. This liquid takes heat from the heat exchanger and then passes through a boiler.

Feed water from the condenser enters the boiler, the heated sodium potassium liquid passing through the tube gives heat to the water thus converting it into steam (superheated). Graphite is used as the moderator in this reactor.

Advantages of sodium graphite reactor:

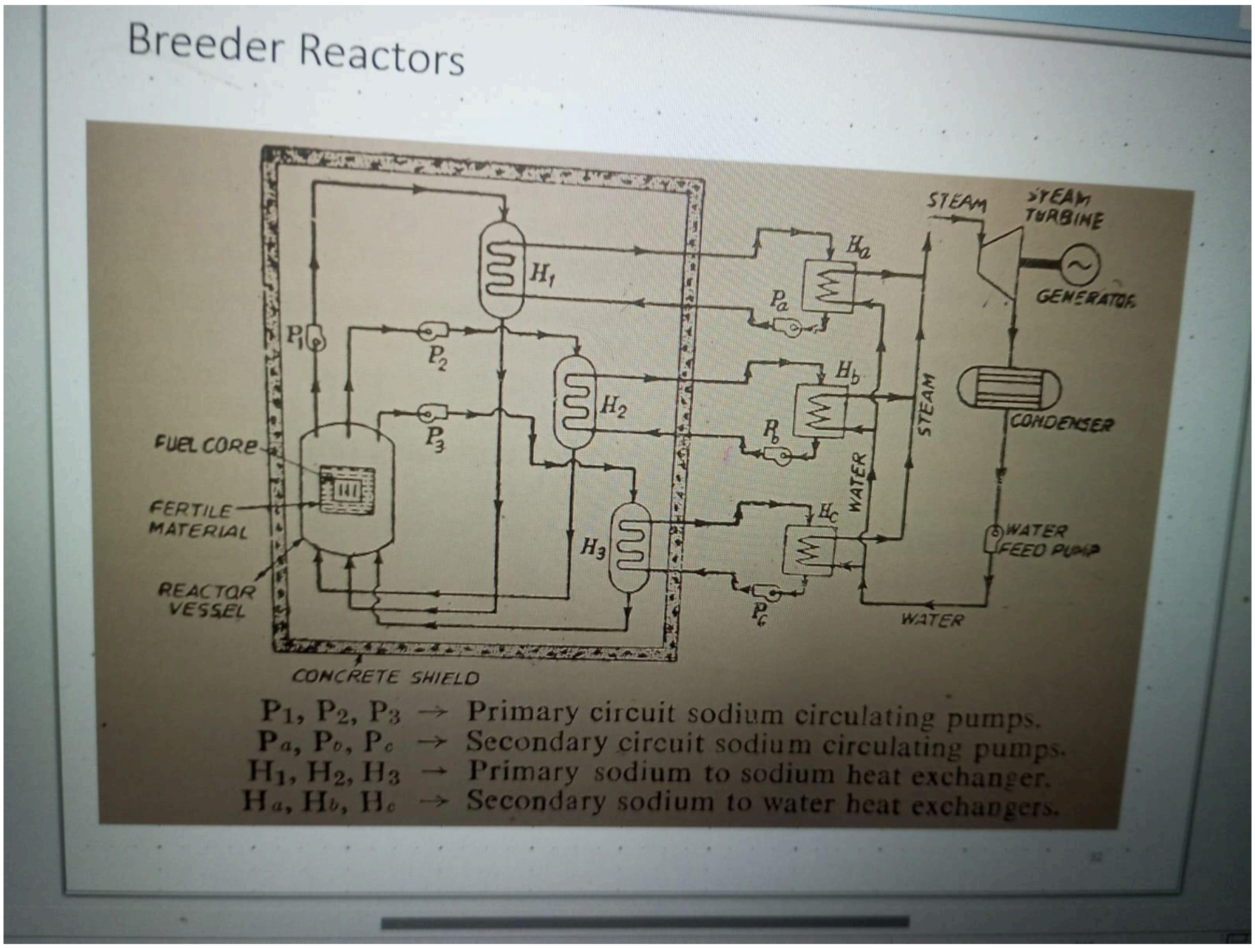
1. Thermal efficiency is high.
2. Coolant need not be pressurized.
3. Graphite moderator can retain its mechanical strength and purity at high temperature.
4. Production of superheated steam and excellent heat removal.

Disadvantage of sodium graphite reactor:

1. Sodium reacts violently with water and air.
2. Leakage of sodium is dangerous.
3. Leak proof heat exchanger must be used, which increases extra cost.
4. Difficulties in inspection and repair.

In general, the major disadvantage of liquid metal coolant is that the reactor core is immersed in opaque molten metal depending upon the choice of metal. And fire hazard risk, corrosion and production of radioactive products are other threats.

Fast Breeder Reactor (FBR) – Definition and Working Principle:



Breeding – The process of producing fissionable material from a fertile material such as Uranium 238 (U_{238}) and thorium 232 (Th_{232}) by neutron absorption is known as breeding.

In this Fast Breeder Reactor (FBR) system, the core containing U_{235} is surrounded by a blanket of ferrite material U_{238}. In this reactor, no moderator is used. The fast moving neutrons liberated due to fission of U_{235} are absorbed by U_{238} which gets converted fissionable material Pu_{239} which is capable of sustaining chain reaction. Thus, the reactor is very important because it breeds fissionable materials from fertile material U_{238} available in large quantities.

This reactor system uses two liquid metal coolant circuits. Liquid sodium is used as primary coolant when circulated through the tubes of Intermediate Heat Exchanger (IHX) and transfers its heat to secondary coolant sodium potassium alloy. The secondary coolant transfers its heat to feed water while flowing through the tubes of steam generator.

Considering safety and thermal efficiency, fast breeder reactors are better than conventional reactors.

The following coolants are commonly used for fast breeder reactors.

- Liquid metal (Na (or) NaK)
- Helium (He)
- Carbon dioxide.

Sodium has the following advantages.

1. Sodium has very low absorption cross-sectional area.
2. Sodium possesses good heat transfer properties at high temperature and low pressure.
3. Sodium does not react any of the structural materials used in primary circuit.

Advantages:

1. Heat developed per unit volume of core or per unit area of fuel surface is less.

2. Ease of control.

3. Greater inherent safety.

Disadvantages:

1. Severely limited choice of fuel from the point of view of neutron economy when fuel used is uranium.

2. Much larger size and weight of reactor per unit power.

3. More fissile material consumption than could be automatically replaced.

Fast breeder reactors can convert more fertile material to fissile material and therefore, net fuel consumption is much less. As a matter of fact more fissile material could be produced than would be consumed by it (fast breeder reactor).

Safety of nuclear power plant:

1. **Multiple Redundant Safety Systems**: Modern nuclear power plants have multiple backup systems to ensure continuous safety even if primary components fail.
2. **Robust Containment Structures**: The reactors are enclosed in thick, reinforced concrete containment buildings to prevent the release of radioactive material.
3. **Emergency Core Cooling Systems (ECCS)**: Multiple cooling systems are in place to maintain core temperature, preventing overheating or a meltdown.
4. **Passive Safety Features**: Many new reactors use passive safety features that rely on natural processes (e.g., gravity) to maintain safety, even during power outages.
5. **Automatic Control Rod Insertion**: Control rods automatically drop into the reactor core to halt the nuclear reaction if unsafe conditions are detected.
6. **Continuous Monitoring**: Nuclear reactors are equipped with numerous sensors and automated systems that continuously monitor temperature, pressure, and radiation levels.
7. **Strict Regulation and Oversight**: National and international agencies, such as the IAEA and NRC, provide rigorous regulations and oversight to ensure compliance with safety standards.
8. **Emergency Preparedness Plans**: Comprehensive plans are in place for plant personnel, local authorities, and surrounding communities to respond effectively to any emergency.
9. **Learning from Past Incidents**: Incidents like Chernobyl and Fukushima have led to improved design, safety culture, and regulatory measures to enhance the overall safety of nuclear power plants.
10. **Seismic and Natural Disaster Protection**: Modern nuclear plants are designed to withstand earthquakes, floods, and other natural disasters to reduce the risk of damage to critical systems.

Comparison of different nuclear power plants of about 500 MW capacity

Parameter	Water Cooled Reactors			Gas cooled Reactor (AGR)	Fast Breeder Reactor FBR
	PWR	BWR	CANDU		
Fuel material	UO_2 3%	UO_2 2·5%	UO_2 Natural	UO_2 2·5%	UO_2 15%
Can material	Zr	Zr	Zr	SS	SS
Coolent	H_2O	H_2O	D_2O	CO_2	Na
Coolent pressure (kgf/cm²)	150	70	95*	30	Zero
Coolent temperature inlet/outlet	275/300	275/285	250/290	300/700	400/[illegible]00
Moderator	H_2O	H_2O	D_2O	Graphite	None
Steam pressure (kgf/cm² and temperature	52 2[illegible]2°C	68 280°C	42 255°C	162 562°C	162 538°C
Thermal efficiency	33%	35%	30%	41%	43%
Reactor wall thickness in cm	20	15	0·6	3[illegible]0	1·5

*but in smaller tubes.