UNIT 3 NUCLEAR POWER PLANT

Structure

3.1 INTRODUCTION

Due to the high demand of electric power in all the fields, like industries, commercial, institutional and housings, etc. the shortage of electric power is becoming a big problem in day-to-day. It may be due to the technological development or need of the changing life styles of the human. In most of the summers all the cities and rural areas also facing the problem of power cuts, this is due to over burden of the power or usage of power is increasing day-by-day.

Electric power has become an important and essential resources, it is used for all the purposes. Without electric power, a single day cannot move further. Keeping in mind the above problem, the R & D of government departments are establishing different modes of power generation plants. Nuclear power plant is one of the mode of the power generation. In this unit, we study about the nuclear power plant.

Objectives

After studying this unit, you should be able to

- understand the nuclear reactions,
- know the nuclear materials,

- describe all types of nuclear reactors, and
- explain about the nuclear power station.

3.2 ATOMIC STRUCTURE OF MATTER

Atomic Structure

All atoms are composed of a central nucleus surrounded by a number of orbiting electrons – like planets orbiting the sun.

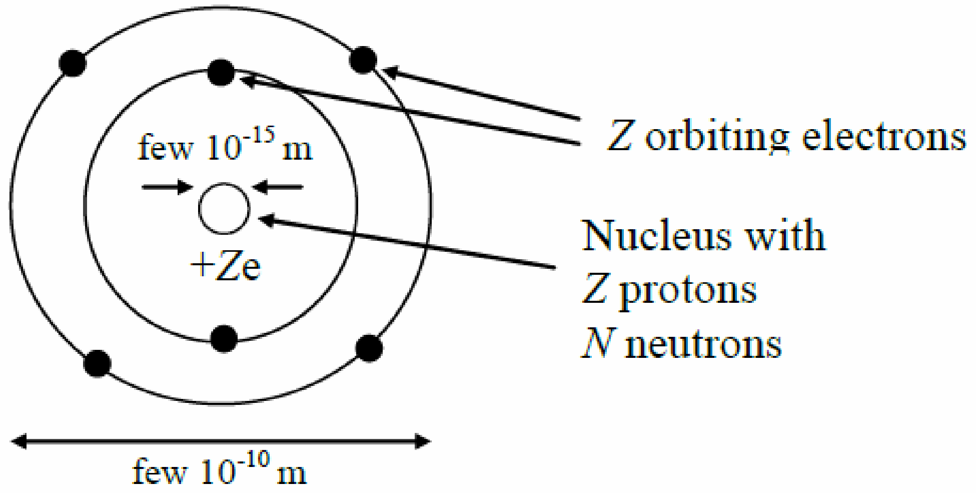


Figure 3.1 : Atomic Structure

A problem is that orbiting electrons would be accelerating and should radiate energy causing them to spiral into the nucleus.

Atomic Nomenclature

An atomic nucleus is the small heavy central part of an atom consisting of *A* nucleons : *Z* protons and *N* neutrons. *A* is referred to as the mass number and *Z* the atomic number. Nuclear size is measured in fermis (also called femtometres), where 1 fm = 10-15 m.

The basic properties of atomic constituents are as follows :

	Charge	**Mass (*u*)**	**Spin ($h/2\pi$)***	**Magnetic Moment ($J\ T^{-1}$)****
Proton	*e*	1.007276	1/2	1.411×10^{-26}
Neutron	*e*	1.008665	1/2	-9.66×10^{-27}
Electron	*e*	0.000549	1/2	9.28×10^{-24}

* $h = 6.626 \times 10^{-34}$ Js, is Planck's constant

** The unit *T* is the tesla – the SI unit of magnetic field.

Charge

Protons have a positive charge equal and opposite to that of the electron. Neutrons are uncharged. Thus a neutral atom (*A*, *Z*) contains *Z* electrons and can be written symbolically as ${}_{Z}^{A}X_{N}$.

Mass

Nuclear and atomic masses are expressed in atomic mass units (u) based on the definition that the mass of a neutral atom of ${}^{12}\mathrm{C}$ is exactly 12.000 u. (1 u = 1.6605×10^{-27} kg).

Spin

Each of the constituents has a spin 1/2 in units of $h/2$ and is an example of the class of particles of half-integer spin known as fermions. Fermions obey the Exclusion Principle, first enunciated by Wolfgang Pauli in 1925, which determines the way electrons can occupy atomic energy states. The same rule applies to nucleons in nuclei.

Magnetic Moment

Associated with the spin is a magnetic dipole moment. Compared with the magnetic moment of an electron, nuclear moments are very small. However, they play an important role in the theory of nuclear structure. It may be surprising that the uncharged neutron has a magnetic moment. This reflects the fact that it has an underlying quark sub-structure, consisting of charged components. An important application of nuclear moments, based on their behaviour in electromagnetic fields, is the technique of magnetic resonance imaging [MRI] or nuclear magnetic resonance.

An atom can be ionized by

losing one or more electrons and forming a positive ion (e.g. Fe^+, Cu^+)

gaining additional electrons and forming a negative ion (e.g. O^- , O^{--}).

Elements, Isotopes, Isotones and Isobars

The name of an element uniquely identifies the atomic number *Z*.

Element	**Atomic Number *Z***
Hydrogen	1
Helium	2
Lithium	3
Beryllium	4
Boron	5
Carbon	6
. . .	. . .
Uranium	92
Neptunium	93
Plutonium	94

Isotopes of an Element

Atoms whose nuclei have the same *Z* but different *N*. The electron structure and, the chemical properties of isotopes are similar.

For example, Carbon has three naturally occurring isotopes

$$^{12}_{6}C_6,\quad ^{13}_{6}C_7,\quad ^{14}_{6}C_8$$

Isotones

Nuclides with the same *N* and different *Z*.

Isobars

Nuclides with the same mass number *A*. It is usual to omit the *N* and *Z* subscripts from the symbolic representation and include only the mass number as superscript:

Forces Acting in Atoms and Nuclei

The electromagnetic force acts as an attractive force between electrons and the nucleus and as a repulsive force between protons inside the nucleus. Within the nucleus, a strong, short-range force holds nucleons together in close proximity to each other. There is also a very much weaker nuclear force, which gives rise to radioactivity. The gravitational force acts between objects with mass, but is only perceived when masses are large. It is totally negligible in its effect on the structure of atoms and nuclei.

3.3 ATOMIC NOMENCLATURE

All atoms are made up of three subatomic particles: the proton, neutron and electron. Each determines part of how we see an atom:

The number of protons in an atom determines its atomic number. This is the atoms “identity”: all atoms with one proton are hydrogen atoms, all atoms with two protons are helium atoms and so on. The atomic number (*Z*) is the same as the number of the element in the periodic table. The atomic number is denoted with a leading subscript: $_{2}$He refers to a helium atom with two protons.

The sum of the number of protons and neutrons together determines the atomic mass. The atomic mass is denoted with a leading superscript : $^{4}_{2}$He refers to a helium atom with 2 protons (subscript = atomic number) and 4 total neutrons and protons. Thus, it has two neutrons. Changing the number of neutrons in an atom creates an isotope of that atom: the atom identity stays the same, but the atomic mass changes. A helium atom with only one neutron would have the symbol $^{3}_{2}$He : helium-3 is an isotope of helium with two protons and (2 protons + 1 neutron) = 3 atomic mass

The electrons of an atom exist in a cloud around the nucleus. In a neutral atom there are as many electrons as there are protons. Adding or subtracting an electron creates an ion of that atom. This is denoted by placing a trailing superscript with the charge on the atomic symbol. For example, an atom of helium-3 that lost an electron would have a +1 charge and a symbol $^{3}_{2}\mathrm{He}^{+}$

To summarise :

Changing the No. of protons changes the element.

Changing the No. of neutrons changes the isotope of that element.

Changing the No. of electrons creates an ion of that element.

3.4 NUCLEAR BINDING ENERGY

Nuclei are made up of protons and neutron, but the mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it. The difference is a measure of the nuclear binding energy which holds the nucleus together.

The enormity of the nuclear binding energy can perhaps be better appreciated by comparing it to the binding energy of an electron in an atom. The comparison of the alpha particle binding energy with the binding energy of the electron in a hydrogen atom is shown below. The nuclear binding energies are on the order of a million times greater than the electron binding energies of atoms.

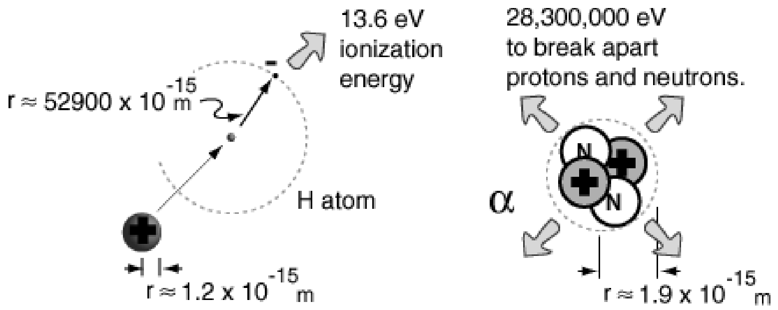


Figure 3.2 : Comparison of Atomic and Nuclear Scales and Binding Energy

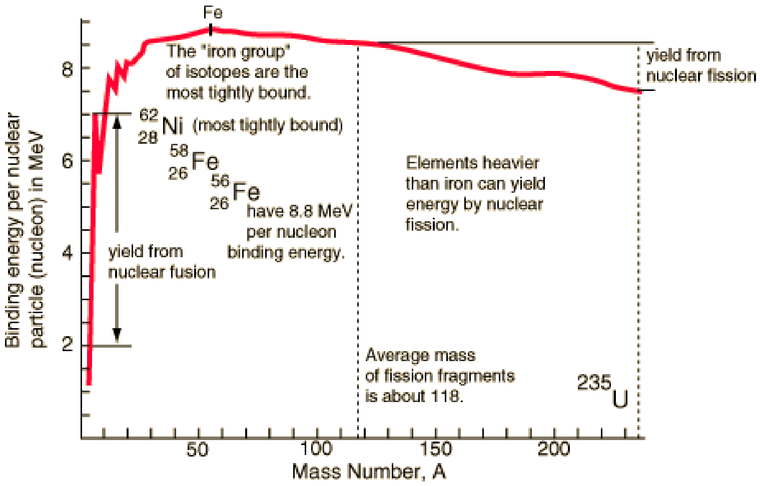


Figure 3.3 : Nuclear Binding Energy Curve

The binding energy curve is obtained by dividing the total nuclear binding energy by the number of nucleons. The fact that there is a peak in the binding energy curve in the region of stability near iron means that either the breakup of heavier nuclei (fission) or the combining of lighter nuclei (fusion) will yield nuclei which are more tightly bound (less mass per nucleon).

The binding energies of nucleons are in the range of millions of electron volts compared to tens of eV for atomic electrons. Whereas an atomic transition might emit a photon in the range of a few electron volts, perhaps in the visible light region, nuclear transitions can emit gamma-rays with quantum energies in the MeV range.

3.5 MASS DEFECT

The distance between theoretical calculated mass and experimentally measured mass of nucleus is called mass defect. It is denoted by Δm.

It can be calculated as follows :

Mass defect = (Theoretical calculated mass) – (measured mass of nucleus)

i.e. (sum of masses of protons and neutrons) – (measured mass of nucleus)

In nuclear reactions, the energy that must be radiated or otherwise removed as binding energy may be in the form of electromagnetic waves, such as gamma radiation, or as heat. Again, however, no mass deficit can in theory appear until this radiation has been emitted and is no longer part of the system.

The energy given off during either nuclear fusion or nuclear fission is the difference between the binding energies of the fuel and the fusion or fission products. In practice, this energy may also be calculated from the substantial mass differences between the fuel and products.

When the nucleons are grouped together to form a nucleus, they lose a small amount of mass, i.e. there is mass defect. This mass defect is released as (often radiant) energy according to the relation $E = mc^2$; thus, binding energy = mass defect * c^2. This energy holds the nucleons together and is known as binding energy. In fact, mass defect is a measure of the binding energy of the nucleus. The greater the mass defect, the greater is the binding energy of the nucleus.

3.6 NUCLEAR FISSION

When unstable heavy nuclei are bombarded with high energy neutrons, it splits into several smaller fragments. These fragments, or fission products, are about equal to half the original mass. This process is called Nuclear Fission. Two or three neutrons are also emitted.

The sum of the masses of these fragments is less than the original mass. This 'missing' mass (about 0.1 percent of the original mass) has been converted into energy. Fission can occur when a nucleus of a heavy atom captures a neutron, or it can happen spontaneously.

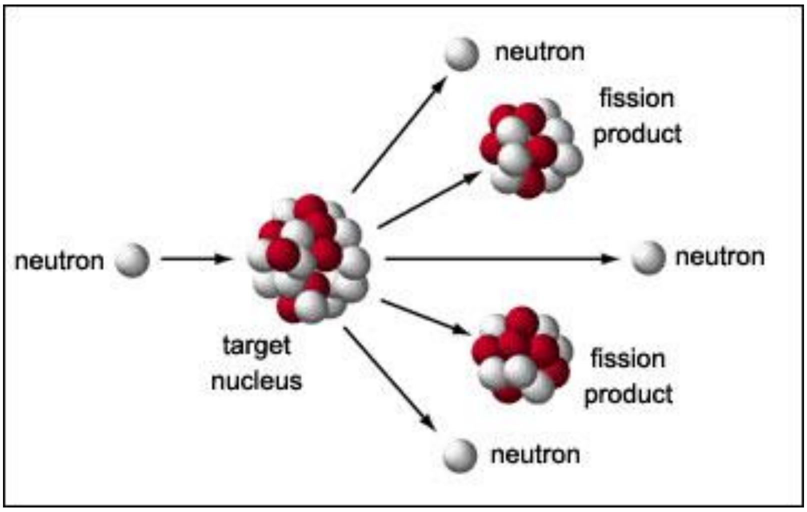


Figure 3.5 : Nuclear Fission

3.6.1 Controlled Nuclear Fission

To maintain a sustained controlled nuclear reaction, for every 2 or 3 neutrons released, only one must be allowed to strike another (uranium) nucleus. If this ratio is less than one then the reaction will die out; if it is greater than one it will grow uncontrolled (an atomic explosion). A neutron absorbing element must be present to control the amount of free neutrons in the reaction space. Most reactors are controlled by means of control rods that are made of a strongly neutron-absorbent material such as boron or cadmium.

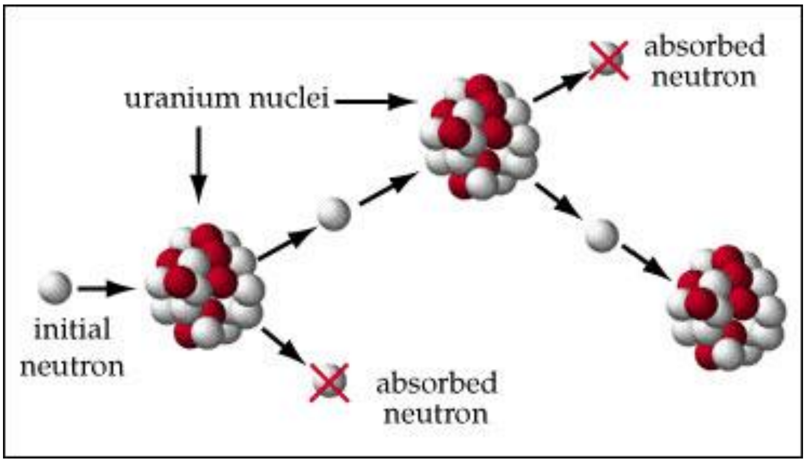


Figure 3.6 : Controlled Nuclear Fission

In addition to the need to capture neutrons, the neutrons often have too much kinetic energy. These fast neutrons are slowed through the use of a moderator such as heavy water and ordinary water. Some reactors use graphite as a moderator, but this design has several problems. Once the fast neutrons have been slowed, they are more likely to produce further nuclear fissions or be absorbed by the control rod.

3.6.2 Spontaneous Nuclear Fission

The spontaneous nuclear fission rate is the probability per second that a given atom will fission spontaneously – that is, without any external intervention. If a spontaneous fission occurs before the bomb is fully ready, it could fizzle. Plutonium 239 has a very high spontaneous fission rate compared to the spontaneous fission rate of uranium 235. Consideration of the spontaneous fission rate of each material is required when designing nuclear weapons.

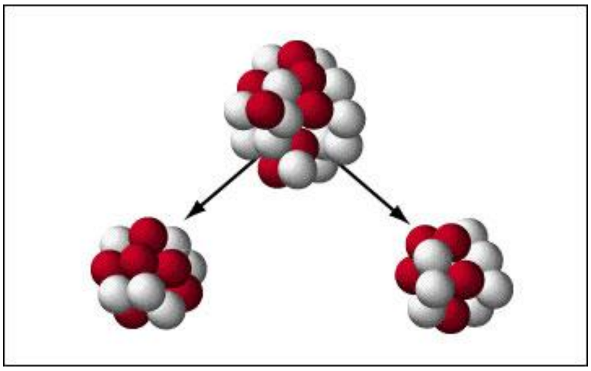


Figure 3.7 : Spontaneous Nuclear Fission

1.7 NUCLEAR FUSION

In nuclear physics and nuclear chemistry, nuclear fusion is the process by which multiple like-charged atomic nuclei join together to form a heavier nucleus. It is accompanied by the release or absorption of energy, which allows matter to enter a plasma state.

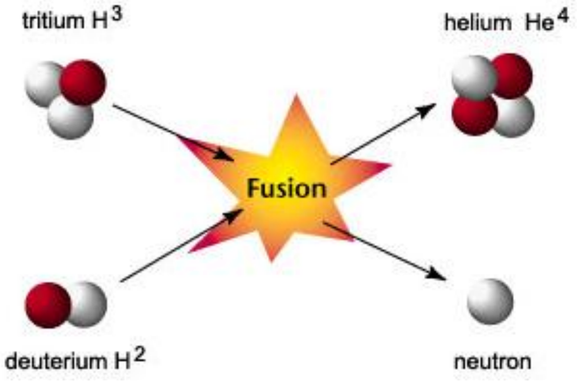


Figure 3.8 : Nuclear Fusion

The fusion of two nuclei with lower mass than iron (which, along with nickel, has the largest binding energy per nucleon) generally releases energy while the fusion of nuclei heavier than iron absorbs energy; vice-versa for the reverse process, nuclear fission.

Nuclear energy can also be released by fusion of two light elements (elements with low atomic numbers). The power that fuels the sun and the stars is nuclear fusion. In a hydrogen bomb, two isotopes of hydrogen, deuterium and tritium are fused to form a nucleus of helium and a neutron. This fusion releases 17.6 MeV of energy. Unlike nuclear fission, there is no limit on the amount of the fusion that can occur.

3.8 NUCLEAR REACTION

In nuclear physics, a nuclear reaction is the process in which two nuclei or nuclear particles collide to produce products different from the initial particles. In principle a reaction can involve more than three particles colliding, but because the probability of three or more nuclei to meet at the same time at the same place is much less than for two nuclei, such an event is exceptionally rare. While the transformation is spontaneous in the case of radioactive decay, it is initiated by a particle in the case of a nuclear reaction. If the particles collide and separate without changing, the process is called an elastic collision rather than a reaction.

In the symbolic Figure shown, ${}^{6}_{3}\mathrm{Li}$ and deuterium react to form the highly excited intermediate nucleus ${}^{8}_{4}\mathrm{Be}$ which then decays immediately into two alpha particles. Protons are symbolically represented by red spheres, and neutrons by blue spheres.

$${}^{6}_{3}\mathrm{Li} \quad + \quad {}^{2}_{1}\mathrm{H} \quad \rightarrow \quad {}^{4}_{2}\mathrm{He} \quad + \quad ?$$

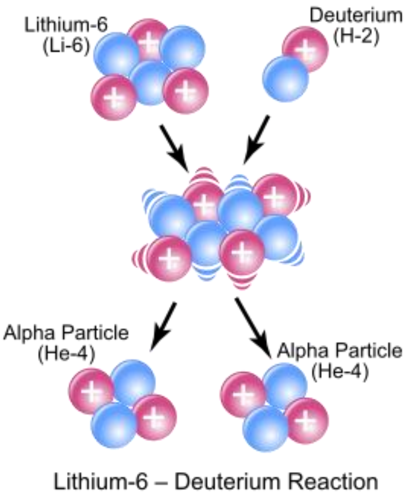


Figure 3.9 : Nuclear Reaction

To balance the equation above, the second nucleus to the right must have atomic number 2 and mass number 4; it is therefore also Helium-4. The complete equation therefore reads :

$$ {}^{6}_{3}\text{Li} \quad + \quad {}^{2}_{1}\text{H} \quad \rightarrow \quad {}^{4}_{2}\text{He} \quad + \quad {}^{4}_{2}\text{He} $$

or more simply :

$$ {}^{6}_{3}\text{Li} \quad + \quad {}^{2}_{1}\text{H} \quad \rightarrow \quad 2\,{}^{4}_{2}\text{He} $$

Nuclear power plants operate by precisely controlling the rate at which nuclear reactions occur, and that control is maintained through the use of several redundant layers of safety measures. Moreover, the materials in a nuclear reactor core and the uranium enrichment level make a nuclear explosion impossible, even if all safety measures failed. On the other hand, nuclear weapons are specifically engineered to produce a reaction that is so fast and intense it cannot be controlled after it has started. When properly designed, this uncontrolled reaction can lead to an explosive energy release.

3.9 NUCLEAR CHAIN REACTIONS

A nuclear chain reaction occurs when one nuclear reaction causes an average of one or more nuclear reactions, thus leading to a self-propagating number of these reactions. The specific nuclear reaction may be the fission of heavy isotopes (e.g. ^{235}U) or the fusion of light isotopes (e.g. ^{2}H and ^{3}H). The nuclear chain reaction is unique since it releases several million times more energy per reaction than any chemical reaction.

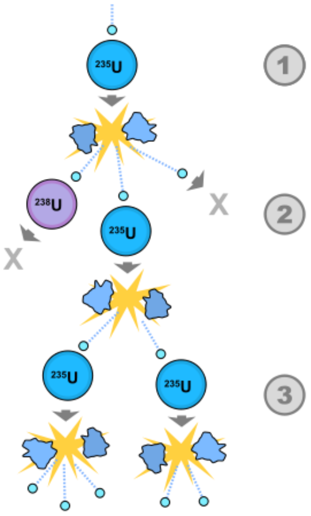


Figure 3.10 : Nuclear Chain Reactions

Table 3.1 : Comparison of Fusion and Fission Processes

Sl. No.	Fusion	Fission
1	Light elements fuse together with release of energy	Energy is released by the bombardment of heavy nuclear with neutrons. The nucleus splits into fragments of equal mass
2	Heavy mass will be converted in to energy	Light mass will be converted into energy
3	Amount of radioactive material consumed in a fusion process is very low	In fission process it is very high
4	Health hazard is very less	Health hazard is high due to higher radio active materials
5	Construction of controlled fusion reactors is very difficult	It is possible to construct self-sustained fission reactors and have positive energy release
6	Very very high temperature are required for fusion process (≥ 30 million degrees)	Manageable temperatures are obtained

3.10 FISSION CHAIN REACTION

Fission chain reactions occur because of interactions between neutrons and fissile isotopes (such as ^{235}U). The chain reaction requires both the release of neutrons from fissile isotopes undergoing nuclear fission and the subsequent absorption of some of these neutrons in fissile isotopes. When an atom undergoes nuclear fission, a few neutrons (the exact number depends on several factors) are ejected from the reaction. These free neutrons will then interact with the surrounding medium, and if more fissile fuel is present, some may be absorbed and cause more fissions. Thus, the cycle repeats to give a reaction that is self-sustaining.

A possible nuclear fission chain reaction :

(a) A uranium-235 atom absorbs a neutron, and fissions into two new atoms (fission fragments), releasing three new neutrons and a large amount of binding energy.

(b) One of those neutrons is absorbed by an atom of uranium-238, and does not continue the reaction. Another neutron leaves the system without being absorbed. However, one neutron does collide with an atom of uranium-235, which then fissions and releases two neutrons and more binding energy.

(c) Both of those neutrons collide with uranium-235 atoms, each of which fissions and releases a few neutrons, which can then continue the reaction.

Fusion Chain Reaction

In a more generalized sense, a nuclear fusion reaction can be considered a nuclear chain reaction: it occurs under extreme pressure and temperature conditions, which are maintained by the energy released in the fusion process.

Critical Mass

Although two to three neutrons are produced for every fission, not all of these neutrons are available for continuing the fission reaction. If the conditions are such that the neutrons are lost at a faster rate than they are formed by fission, the chain reaction will not be self-sustaining.

At the point where the chain reaction can become self-sustaining, this is referred to as critical mass.

In an atomic bomb, a mass of fissile material greater than the critical mass must be assembled instantaneously and held together for about a millionth of a second to permit the chain reaction to propagate before the bomb explodes

The amount of a fissionable material's critical mass depends on several factors; the shape of the material, its composition and density, and the level of purity.

A sphere has the minimum possible surface area for a given mass, and hence minimizes the leakage of neutrons. By surrounding the fissionable material with a suitable neutron “reflector”, the loss of neutrons can be reduced and the critical mass can be reduced.

3.11 TYPES OF NUCLEAR MATERIALS

(a) Special Nuclear Material consists of uranium-233 or uranium-235, enriched uranium, or plutonium.

(b) Source Material is natural uranium or thorium or depleted uranium that is not suitable for use as reactor fuel.

(c) Byproduct Material, in general, is nuclear material (other than special nuclear material) that is produced or made radioactive in a nuclear reactor. Byproduct material also includes the tailings and waste produced by extracting or concentrating uranium or thorium from an ore processed primarily for its source material content.

Nuclear fission fuels are classified as fertile or fissile by the behaviour or their nuclei in fission reactions

3.11.1 Fissile Material

Fissile materials are composed of atoms that can be split by neutrons in a self-sustaining chain-reaction to release enormous amounts of energy. In nuclear reactors, the fission process is controlled and the energy is harnessed to produce electricity. In nuclear weapons, the fission energy is released all at once to produce a violent explosion. The most important fissile materials for nuclear energy and nuclear weapons are an isotope of plutonium, plutonium-239, and an isotope of uranium, uranium-235. Uranium-235 occurs in nature.

3.11.2 Fertile Material

A material, which is not itself fissile (fissionable by thermal neutrons), that can be converted into a fissile material by irradiation in a reactor. There are two basic fertile materials: uranium-238 and thorium-232. When these fertile materials capture neutrons, they are converted into fissile plutonium-239 and uranium-233, respectively.

3.12 NUCLEAR POWER REACTORS

A nuclear reactor produces and controls the release of energy from splitting the atoms of elements such as uranium and plutonium. In a nuclear power reactor, the energy released from continuous fission of the atoms in the fuel as heat is used to make steam. The steam is used to drive the turbines which produce electricity (as in most fossil fuel plants).

There are several components common to most types of reactors:

Fuel

Usually pellets of uranium oxide (UO_2) arranged in tubes to form fuel rods. The rods are arranged into fuel assemblies in the reactor core.

Moderator

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

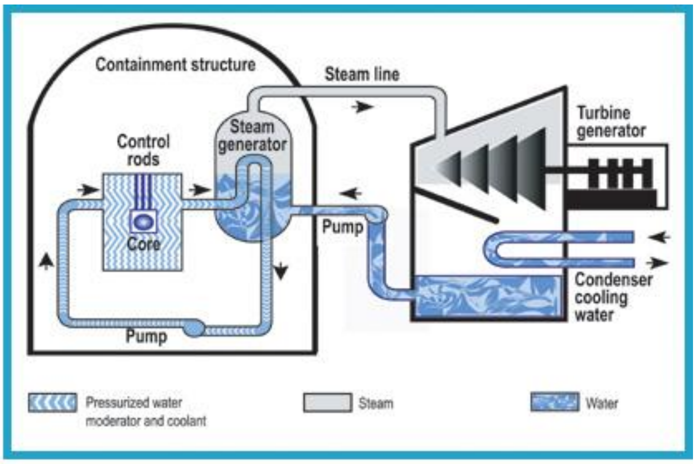
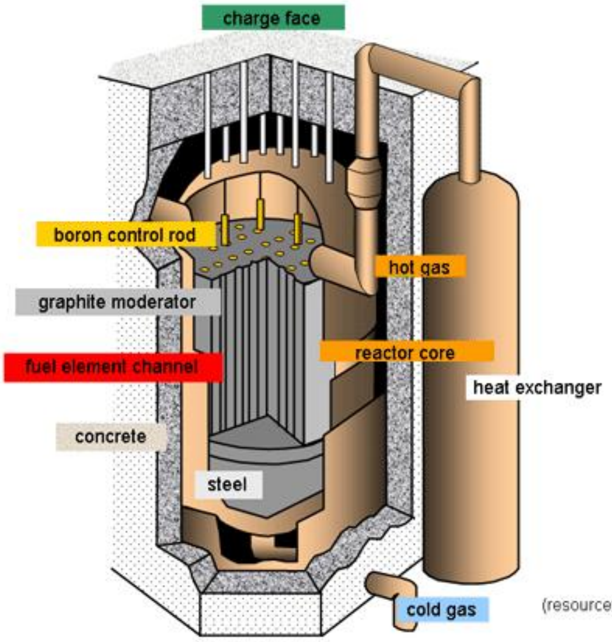


Figure 3.11 : Nuclear Power Plant

Control Rods

These are made with neutron-absorbing material such as cadmium, hafnium or boron, and are inserted or withdrawn from the core to control the rate of reaction, or to halt it. (Secondary shutdown systems involve adding other neutron absorbers, usually in the primary cooling system.)



(resourcefulphysics.org)

Figure 3.12 : Nuclear Reactor

Coolant

A liquid or gas circulating through the core so as to transfer the heat from it. In light water reactors the moderator functions also as coolant.

Pressure Vessel or Pressure Tubes

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

Steam Generator

Part of the cooling system where the heat from the reactor is used to make steam for the turbine.

Classification on the basis of different criteria :

On the Basis of Neutron Energy

(a) Fast Reactor: In these reactors, fission is effected by fast neutrons without any use of moderators.

(b) Thermal Reactors: In these reactors, fission is effected by fast neutrons are slowed down with the use of moderators. The slow neutrons are absorbed by the fissionable fuel and chain reaction is maintained.

On the Basis of Fuel Used

(a) Natural Fuel: In this reactor, natural Uranium is used as fuel and generally heavy water or graphite is used as moderator.

(b) Enriched Uranium: In this reactor, the Uranium used contains 5 to 10% U^{235} and ordinary water can be used as moderator.

On the Basis of Moderator Used

(a) Water moderated

(b) Heavy water moderated

(c) Graphite moderated

(d) Beryllium moderated.

On the Basis of Coolant Used

(a) Water cooled reactors

(b) Gas cooled reactors

(c) Liquid metal cooled reactors

(d) Organic liquid cooled reactors.

Classification by Use

(a) Electricity

Nuclear power plant.

(b) Propulsion

- (i) Nuclear marine propulsion.
- (ii) Various proposed forms of rocket propulsion.

(c) Other Uses of Heat

- (i) Desalination
- (ii) Heat for domestic and industrial heating
- (iii) Hydrogen production for use in a hydrogen economy

(d) Production Reactors for Transmutation of Elements

- (i) **Breeder Reactors :** Fast breeder reactors are capable of producing more fissile materials than they consume during the fission chain reaction (by converting fertile U-238 to Pu-239) which allows an operational fast reactor to generate more fissile material than it consumes. Thus, a breeder reactor, once running, can be re-fueled with natural or even depleted uranium.
- (ii) Creating various radioactive isotopes, such as americium for use in smoke detectors, and cobalt-60, molybdenum-99 and others, used for imaging and medical treatment.
- (iii) Production of materials for nuclear weapons such as weapons-grade plutonium.

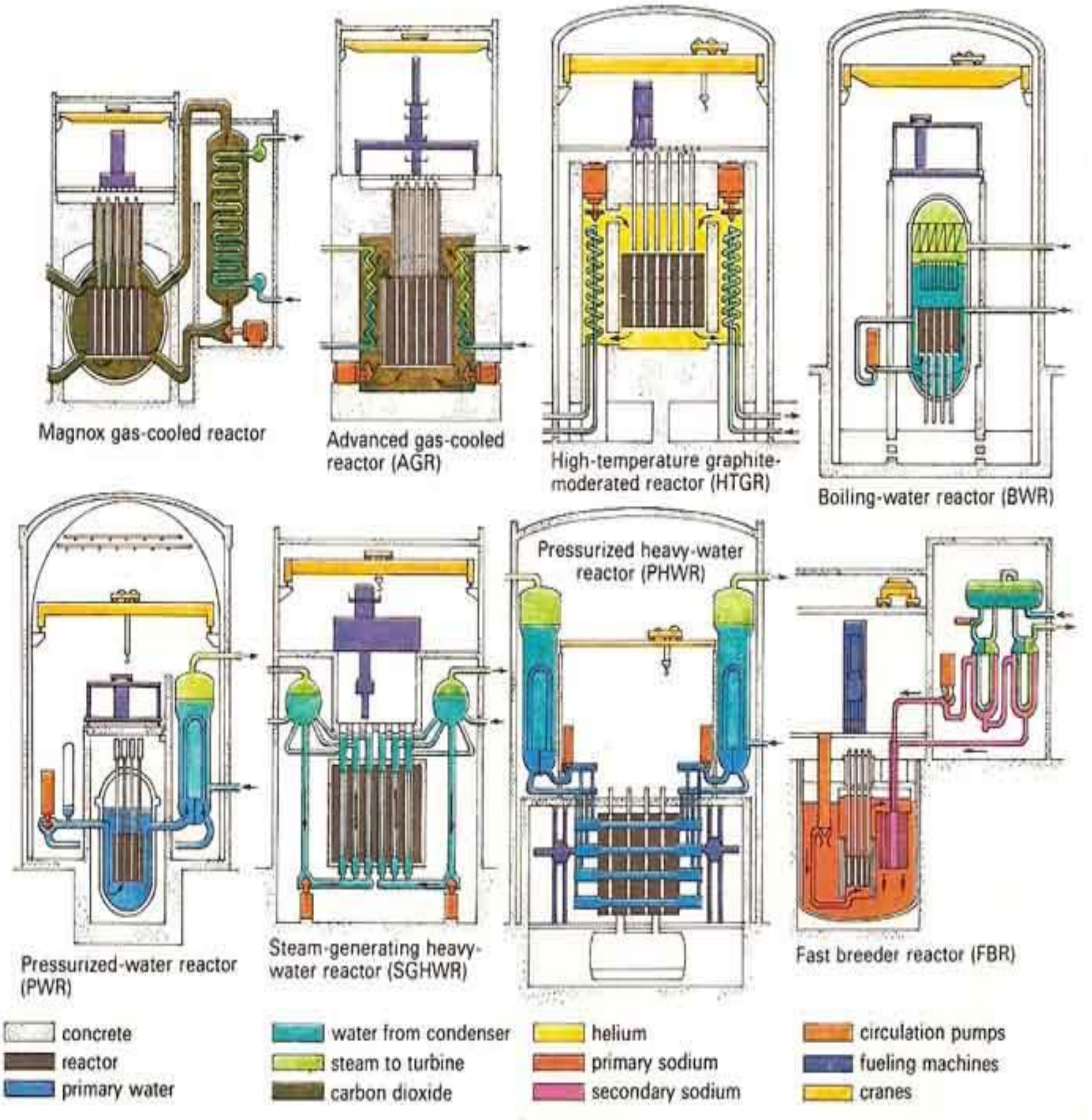


Figure 3.13 : Different types of Nuclear Reactors

(e) Providing a source of neutron radiation (for example with the pulsed Godiva device) and position radiation (e.g. neutron activation analysis and potassium-argon dating).

(f) **Research Reactor :** Typically reactors used for research and training, materials testing, or the production of radioisotopes for medicine and industry. These are much smaller than power reactors or those propelling ships, and many are on university campuses. There are about 280 such reactors operating, in 56 countries. Some operate with high-enriched uranium fuel, and international efforts are underway to substitute low-enriched fuel.

3.13 BOILING WATER REACTOR (BWR)

The BWR uses demineralized water (light water) as a coolant and neutron moderator. Heat is produced by nuclear fission in the reactor core, and this causes the cooling water to boil, producing steam. The steam is directly used to drive a turbine, after which is cooled in a condenser and converted back to liquid water. This water is then returned to the reactor core, completing the loop. The cooling water is maintained at about 75 atm (7.6 MPa) so that it boils in the core at about 285°C. In comparison, there is no significant boiling allowed in a PWR because of the high pressure maintained in its primary loop - approximately 158 atm (16 MPa, 2300 psi).

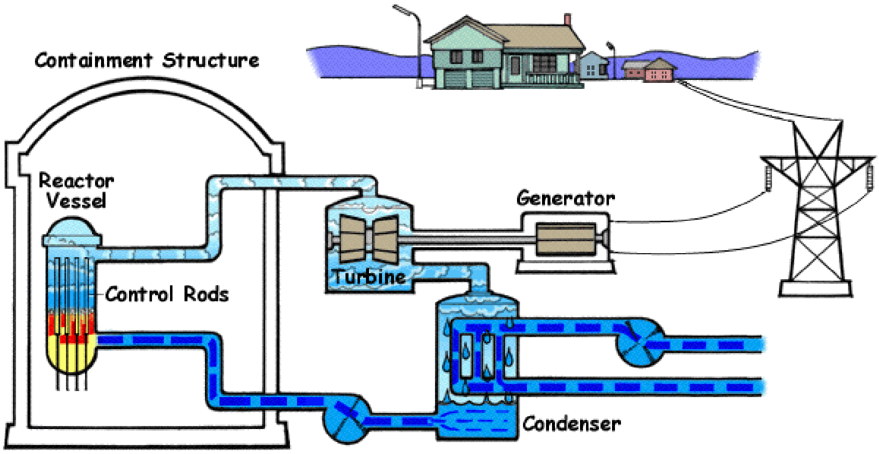


Figure 3.14 : Boiling Water Reactor

3.13.1 Description of Major Components and Systems

Feedwater

Steam exiting from the turbine flows into condensers located underneath the low pressure turbines where the steam is cooled and returned to the liquid state (condensate). The condensate is then pumped through feedwater heaters that raise its temperature using extraction steam from various turbine stages. Feedwater from the feedwater heaters enters the reactor pressure vessel (RPV) through nozzles high on the vessel, well above the top of the nuclear fuel assemblies (these nuclear fuel assemblies constitute the “core”) but below the water level.

The feedwater enters into the downcomer region and combines with water exiting the water separators. The feedwater sub cools the saturated water from the steam separators. This water now flows down the downcomer region, which is separated from the core by a tall shroud. The water then goes through either jet pumps or internal recirculation pumps that provide additional pumping power (hydraulic head). The water now makes a 180 degree turn and moves up through the lower core plate into the nuclear core where the fuel elements heat the water. Water exiting the fuel channels at the top guide is about 12 to 15% saturated steam (by mass), typical core flow may be 45,000,000 kg/hr (100,000,000 lb/hr) with 6,500,000 kg/hr (14,500,000 lb/hr) steam flow.

The heating from the core creates a thermal head that assists the recirculation pumps in recirculating the water inside of the RPV. A BWR can be designed with no recirculation pumps and rely entirely on the thermal head to recirculate the water inside of the RPV. The forced recirculation head from the recirculation pumps is very useful in controlling power, however. The thermal power level is easily varied by simply increasing or decreasing the forced recirculation flow through the recirculation pumps.

The two phase fluid (water and steam) above the core enters the riser area, which is the upper region contained inside of the shroud. The height of this region may be increased to increase the thermal natural recirculation pumping head. At the top of the riser area is the water separator. By swirling the two phase flow in cyclone separators, the steam is separated and rises upwards towards the steam dryer while the water remains behind and flows horizontally out into the downcomer region. In the downcomer region, it combines with the feedwater flow and the cycle repeats.

The saturated steam that rises above the separator is dried by a chevron dryer structure. The steam then exits the RPV through four main steam lines and goes to the turbine.

Control Systems

Reactor power is controlled via two methods: by inserting or withdrawing control rods and by changing the water flow through the reactor core.

Positioning (withdrawing or inserting) control rods is the normal method for controlling power when starting up a BWR. As control rods are withdrawn, neutron absorption decreases in the control material and increases in the fuel, so reactor power increases. As control rods are inserted, neutron absorption increases in the control material and decreases in the fuel, so reactor power decreases. Some early BWRs and the proposed ESBWR (Economic Simplified BWR) designs use only natural circulation with control rod positioning to control power from zero to 100% because they do not have reactor recirculation systems. Fine reactivity adjustment would be accomplished by modulating the recirculation flow of the reactor vessel.

Changing (increasing or decreasing) the flow of water through the core is the normal and convenient method for controlling power. When operating on the so-called “100% rod line”, power may be varied from approximately 30% to 100% of rated power by changing the reactor recirculation system flow by varying the speed of the recirculation pumps. As flow of water through the core is increased, steam bubbles (“voids”) are more quickly removed from the core, the amount of liquid water in the core increases, neutron moderation increases, more neutrons are slowed down to be absorbed by the fuel, and reactor power increases. As flow of water through the core is decreased, steam voids remain longer in the core, the amount of liquid water in the core decreases, neutron moderation decreases, fewer neutrons are slowed down to be absorbed by the fuel, and reactor power decreases.

Steam Turbines

Steam produced in the reactor core passes through steam separators and dryer plates above the core and then directly to the turbine, which is part of the reactor circuit. Because the water around the core of a reactor is always contaminated with traces of radionuclides, the turbine must be shielded during normal operation, and radiological protection must be provided during maintenance. The increased cost related to operation and maintenance of a BWR tends to balance the savings due to the simpler design and greater thermal efficiency of a BWR when compared with a PWR. Most of the radioactivity in the water is very short-lived (mostly N-16, with a 7-second half-life), so the turbine hall can be entered soon after the reactor is shut down.

Size

A modern BWR fuel assembly comprises 74 to 100 fuel rods, and there are up to approximately 800 assemblies in a reactor core, holding up to approximately 140 tonnes of uranium. The number of fuel assemblies in a specific reactor is based on considerations of desired reactor power output, reactor core size and reactor power density.

Safety Systems

The BWR reactor core continues to produce heat from radioactive decay after the fission reactions have stopped, making nuclear meltdown possible in the event that all safety systems have failed and the core does not receive coolant. Also a boiling-water reactor has a negative void coefficient, that is, the thermal output decreases as the proportion of steam to liquid water increases inside the reactor. However a sudden increase in BWR steam pressure (caused, for example, by a blockage of steam flow from the reactor) will result in a sudden decrease in the proportion of steam to liquid water inside the reactor. The increased ratio of water to steam will lead to increased neutron moderation, which in turn will cause an increase in the power output of the reactor. Because of this effect in BWRs, operating components and safety systems are designed to ensure that no credible, postulated failure can cause a pressure and power increase that exceeds the safety systems' capability to quickly shutdown the reactor before damage to the fuel or to components containing the reactor coolant.

In the event of an emergency that disables all the safety systems, each reactor is surrounded by a containment building consisting of 1.2-2.4 m of steel-reinforced, pre-stressed concrete designed to seal off the reactor from the environment.

Reactor Protection System (RPS)

The Reactor Protection System (RPS) is a system, computerized in later BWR models, that is designed to automatically, rapidly, and completely shut down and make safe the Nuclear Boiler System (NBS - the reactor pressure vessel, pumps, and water/steam piping within the containment) if some event occurs that could result in the reactor entering an unsafe operating condition. It does not require human intervention to operate.

If the reactor is at power or ascending to power (i.e. if the reactor is critical; the control rods are withdrawn to the point where the reactor generates more neutrons than it absorbs) there are safety-related contingencies that may arise that necessitate a rapid emergency shutdown of the reactor, or, in Western nuclear parlance, a "SCRAM". The SCRAM is a manually-triggered or automatically-triggered rapid insertion of all control rods into the reactor, which will take the reactor to decay heat power levels within tens of seconds. Since ~ 0.6% of neutrons are emitted from fission products ("delayed" neutrons), which are born seconds/minutes after fission, all fission can not be terminated instantaneously, but the fuel soon returns to decay heat power levels. Manual SCRAMs may be initiated by the reactor operators; while automatic SCRAMs are initiated upon :

(a) Low reactor water level indicative of :
  - loss of coolant accident (LOCA)
  - loss of proper feedwater (LOFW)

(b) High drywell (primary containment) pressure
  - indicative of potential loss of coolant accident

(c) Main Steam Isolation Valve Closure (MSIV)
  - indicative of potential main steam line break

(d) Turbine stop valve or turbine control valve closure
  - if turbine protection systems wish to cease admission of steam the Reactor SCRAM is in anticipation of a pressure transient that would increase reactivity (collapse boiling voids)
  - generator load rejection will also cause closure of turbine valves and SCRAM reactor

(e) Loss of Offsite Power (LOOP)
  - during normal operation, the reactor protection system (RPS) is powered by offsite power
    - ➢ loss of offsite power would open all relays in the RPS would open causing all SCRAM signals to come in redundantly
    - ➢ would also cause MSIV to close since RPS is fail safe; plant assumes a main steam break is coincident with loss of offsite power

(f) Radiation Monitor Trips

- Intermediate Range Monitor (IRM) Upscale
  - ➢ Prevents reactor from exceeding power level preset stages during startup without positive operator control.
- Average Power Range Monitor (APRM) Upscale
  - ➢ Prevents reactor from exceeding power level absolute maxima during operation or relative maxima prior to positive operator confirmation of end of startup.
- Average Power Range Monitor/Coolant Flow Thermal Trip
  - ➢ Prevents reactor from exceeding variable power levels without sufficient coolant flow for that level being present.

(g) High RPV Pressure

- Prevents excessive stress from pressure being placed on RPV and piping.
- Decreases reactivity to compensate for boiling void collapse due to high pressure.
- Prevents safety pressure relief valves from opening in drywell, resulting in HPCI and RCIC activation due to high drywell pressure, along with the potential creation of a mess.
- Serves as a backup for several other trips, like Turbine Trip and MSIV Closure.

Emergency Core Cooling System (ECCS)

While the RPS is designed to prevent contingencies from happening, the ECCS is designed to respond to contingencies if they do happen. The ECCS is a set of interrelated safety systems that are designed to protect the fuel within the reactor pressure vessel, which is referred to as the “reactor core”, from overheating. These systems accomplish this by maintaining reactor pressure vessel (RPV) cooling water level, or if that is impossible, by directly flooding the core with coolant.

These systems are of 3 major types :

High Pressure Systems

These are designed to protect the core by injecting large quantities of water into it to prevent the fuel from being uncovered by a decreasing water level. Generally used in cases with stuck-open safety valves, small breaks of auxiliary pipes, and particularly violent transients caused by turbine trip and MSIV closure.

Depressurization Systems

These systems are designed to reduce and maintain the level of pressure at a lower level. As pressure is reduced, steam condenses to liquid water, and this increases the core water level. If water level is still falling with partial depressurization and full high-pressure system functioning, full depressurization will occur to a much lower pressure level, where the next set of systems respond.

Low Pressure Systems

These systems are designed to function after the depressurization systems function. They have extremely large capacities compared to the high pressure systems and are supplied by multiple, redundant power sources. They will maintain any maintainable water level, and, in the event of a large pipe break of the worst type below the core that leads to temporary fuel rod “uncovery”, to rapidly mitigate that state prior to the fuel heating to the point where core damage could occur.

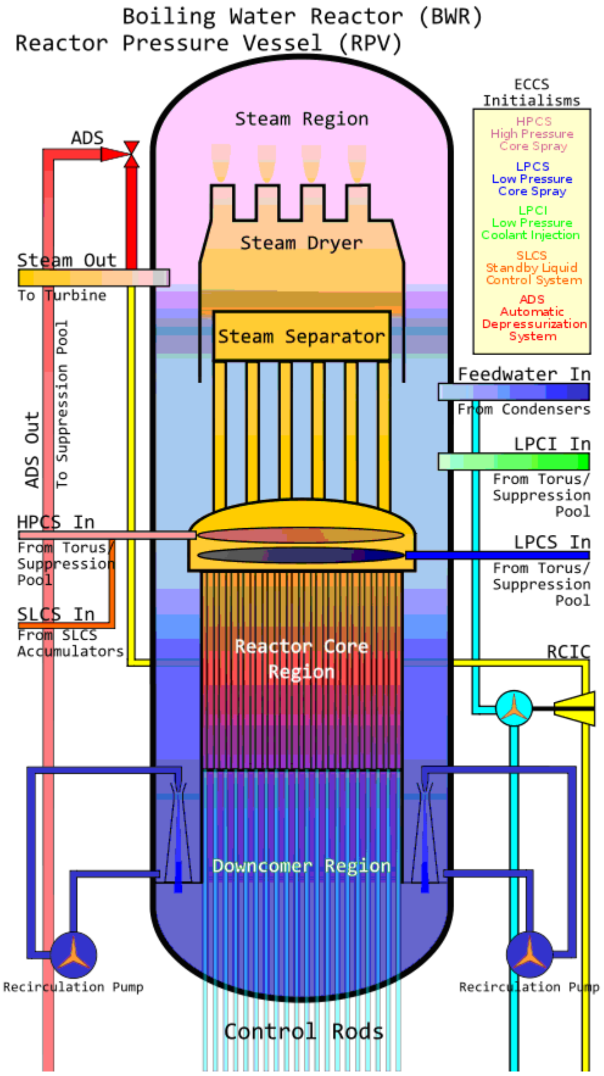


Figure 3.15 : Diagram of a Generic BWR Reactor Pressure Vessel

High Pressure Coolant Injection System (HPCI)

The High Pressure Coolant Injection System is the first line of defense in the Emergency Core Cooling System. HPCI is designed to inject substantial quantities of water into the reactor while it is at high pressure so as to prevent the activation of the ADS, CS, and LPCI systems. HPCI is powered by steam from the reactor, and takes approximately 10 seconds to spin up from an initiating signal, and can deliver approximately 19,000 L/min to the core at any core pressure above 6.8 atm. This is usually enough to keep water levels sufficient to avoid automatic depressurization except in a major contingency, such as a large break in the makeup water line.

Reactor Core Isolation Cooling System (RCIC)

The Reactor Core Isolation Cooling System is not a safety-related system proper, but is included because it can help to cool the reactor in the event of a contingency, and it has additional functionality in advanced versions of the BWR.

RCIC is designed to remove the residual heat of the fuel from the reactor once it has been shut down. It injects approximately 2,000 L/min into the reactor core for this purpose, at high pressure. It also takes less time to start than the HPCI system, approximately 5 seconds from an initiating signal.

Automatic Depressurization System (ADS)

The Automatic Depressurization System is not a part of the cooling system proper, but is an essential adjunct to the ECCS. It is designed to activate in the event that the RPV is retaining pressure, but RPV water level cannot be maintained using high pressure cooling alone, and low pressure cooling must be initiated. When ADS fires, it rapidly releases pressure from the RPV in the form of steam through pipes that are piped to below the water level in the suppression pool (the torus/wetwell), which is designed to condense the steam released by ADS or other safety valve activation into water), bringing the reactor vessel below 32 atm (3200 kPa, 465 psi), allowing the low pressure cooling systems (LPCS/LPCI/LPCF/GDCS), with extremely large comparative coolant injection capacities to be brought to bear on the reactor core.

Low Pressure Core Spray System (LPCS)

The Low Pressure Core Spray System is designed to suppress steam generated by a major contingency. As such, it prevents reactor vessel pressure from going above the point where LPCI and LPCS would be ineffective, which is above 32 atm (3200 kPa, 465 psi). It activates below that level, and delivers approximately 48,000 L/min (12,500 gpm) of water in a deluge from the top of the core.

Low Pressure Coolant Injection System (LPCI)

The Low Pressure Coolant Injection System is the “heavy artillery” in the ECCS. Consisting of 4 pumps driven by diesel engines, it is capable of injecting a mammoth 150,000 L/min of water into the core. It is capable of being brought to bear at reactor vessel pressures below 465 psi. Combined with the CS to keep steam pressure low, the LPCI can suppress nearly all contingencies by rapidly and completely flooding the core with coolant.

Classification of BWR :

(a) Advanced Boiling Water Reactor (ABWR)

(b) Simplified Boiling Water Reactor (SBWR)

(c) Economic Simplified Boiling Water Reactor (ESBWR)

3.13.2 Advantages and disadvantages of BWR

Advantages

- The reactor vessel and associated components operate at a substantially lower pressure.
- Pressure vessel is subject to significantly less irradiation and so does not become as brittle with age.
- Operates at a lower nuclear fuel temperature.
- Fewer components due to no steam generators and no pressurizer vessel. (Older BWRs have external recirculation loops, but even this piping is eliminated in modern BWRs, such as the ABWR.)
- Lower risk (probability) of a rupture causing loss of coolant and lower risk of a severe accident should such a rupture occur. This is due to fewer pipes, fewer large diameter pipes, fewer welds and no steam generator tubes.
- Measuring the water level in the pressure vessel is the same for both normal and emergency operations, which results in easy and intuitive assessment of emergency conditions.
- Can operate at lower core power density levels using natural circulation without forced flow.
- A BWR may be designed to operate using only natural circulation so that recirculation pumps are eliminated entirely. (The new ESBWR design uses natural circulation.)

- BWRs do not use boric acid to control fission burn-up, leading to less possibility of corrosion within the reactor vessel and piping. (Corrosion from boric acid must be carefully monitored in PWRs; it has been demonstrated that dangerous reactor vessel head corrosion can occur if the reactor vessel head is not properly maintained. Since BWRs do not utilize boric acid, these contingencies are eliminated.)
- The current fleet of BWRs have predictable, uniform designs that, while not completely standardized, generally are very similar to one another. The ABWR/ESBWR designs are completely standardized. Lack of standardization remains a problem with PWRs.
- BWRs are overrepresented in imports, if the importing nation doesn't have a nuclear navy. This may be due to the fact that BWRs are ideally suited for peaceful uses like power generation, process/industrial/district heating, and desalinization, due to low cost, simplicity, and safety focus, which come at the expense of larger size and slightly lower thermal efficiency.
    - Sweden is standardized mainly on BWRs.
    - Germany has a large number of BWRs, which are overrepresented in their national fleet compared to the US.
    - Mexico's only two reactors are BWRs.
    - Japan experimented with both PWRs and BWRs, but most builds as of late have been of BWRs, specifically ABWRs (though indigenous PWRs and a rumored indigenously-designed Japanese BWR may give GE a run for its money).
    - In the CEGB open competition in the early 1960s for a standard design for UK 2nd-generation power reactors, the PWR didn't even make it to the final round, which was a showdown between the BWR (preferred for its easily understood design as well as for being predictable and "boring") and the AGCR, a uniquely British design; the indigenous design won, possibly on technical merits, possibly due to the proximity of a general election.

Disadvantages

- Complex calculations for managing consumption of nuclear fuel during operation due to "two phase (water and steam) fluid flow" in the upper part of the core. This requires more instrumentation in the reactor core. The innovation of computers, however, makes this less of an issue.
- Much larger pressure vessel than for a PWR of similar power, with correspondingly higher cost. (However, the overall cost is reduced because a modern BWR has no main steam generators and associated piping).
- Contamination of the turbine by short-lived activation products. This means that shielding and access control around the steam turbine are required during normal operations due to the radiation levels arising from the steam entering directly from the reactor core.
- Control rods are inserted from below for current BWR designs. There are two available hydraulic power sources that can drive the control rods into the core for a BWR under emergency conditions. There is a dedicated high pressure hydraulic accumulator and also the pressure inside of the reactor pressure vessel available to each control rod. Either the dedicated accumulator (one per rod) or reactor pressure is capable of fully inserting each rod. Most other reactor types use top entry control rods that are held up in the withdrawn position by electromagnets, causing them to fall into the reactor by gravity if power is lost.

3.14 CANDU TYPE REACTOR

CANDU stands for "**CAN**ada **D**euterium **U**ranium".

It's a Canadian-designed power reactor of PHWR type (Pressurized Heavy Water Reactor) that uses heavy water (deuterium oxide) for moderator and coolant, and natural uranium for fuel.

CANDU-specific Features and Advantages

Use of Natural Uranium as a Fuel

- CANDU is the most efficient of all reactors in using uranium: it uses about 15% less uranium than a pressurized water reactor for each megawatt of electricity produced
- Use of natural uranium widens the source of supply and makes fuel fabrication easier. Most countries can manufacture the relatively inexpensive fuel
- There is no need for uranium enrichment facility
- Fuel reprocessing is not needed, so costs, facilities and waste disposal associated with reprocessing are avoided
- CANDU reactors can be fuelled with a number of other low-fissile content fuels, including spent fuel from light water reactors. This reduces dependency on uranium in the event of future supply shortages and price increases

Use of Heavy Water as a Moderator

- Heavy water (deuterium oxide) is highly efficient because of its low neutron absorption and affords the highest neutron economy of all commercial reactor systems. As a result chain reaction in the reactor is possible with natural uranium fuel
- Heavy water used in CANDU reactors is readily available. It can be produced locally, using proven technology. Heavy water lasts beyond the life of the plant and can be re-used

CANDU Reactor Core Design

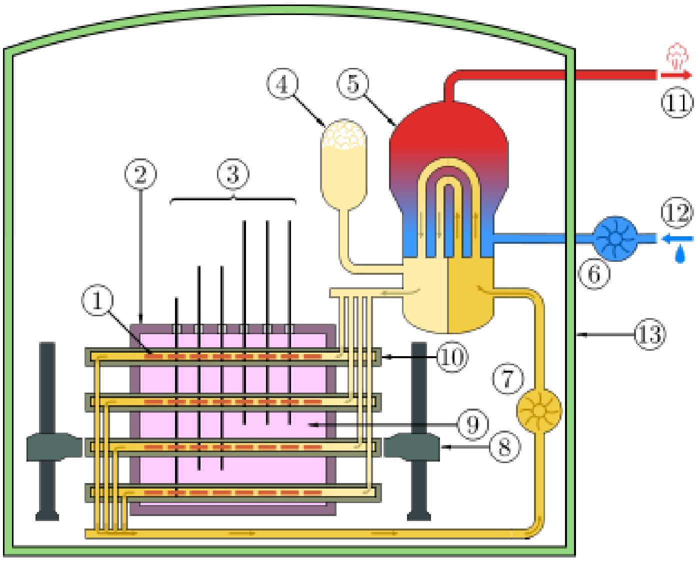
- Reactor core comprising small diameter fuel channels rather that one large pressure vessel.
- Allows on-power refueling – extremely high capability factors are possible.
- The moveable fuel bundles in the pressure tubes allow maximum burn-up of all the fuel in the reactor core.
- Extends life expectancy of the reactor because major core components like fuel channels are accessible for repairs when needed.

Design features

Schematic Diagram of a CANDU reactor: The primary loop is in yellow and orange, the secondary in blue and red. The cool heavy water in the calandria can be seen in pink, along with partially-inserted shutoff rods.

The CANDU reactor is conceptually similar to most light water reactors, although it differs in the details.

Fission reactions in the nuclear reactor core by heating a fluid, in this case heavy water is heated. This coolant is kept under high pressure to raise its boiling point and avoid significant steam formation in the core. The hot heavy water generated in this primary cooling loop is passed into a heat exchanger heating light water in the less-pressurized secondary cooling loop. This water turns to steam and powers a conventional turbine with an electrical generator attached to it. Any excess heat energy in the steam after flowing through the turbine is rejected into the environment in a variety of ways, most typically into a large body of cool water, such as a lake, river or ocean. Heat can also be disposed of using a cooling tower, but they are avoided whenever possible because they reduce the plant's efficiency. More recently-built CANDU plants, such as the Darlington Nuclear Generating Station near Toronto, Ontario, use a discharge-diffuser system that limits the thermal effects in the environment to within natural variations.



(1) Fuel bundle, (2) Calandria (Reactor Core), (3) Adjusters Rods, (4) Heavy Water Pressure Reservoir, (5) Steam Generator, (6) Light Water Pump, (7) Heavy Water Pump, (8) Fueling Machines, (9) Heavy Water Moderator, (10) Pressure Tube, (11) Steam going to Steam Turbine, (12) Cold Water Returning from Turbine, (13) Containment Building made of Reinforced Concrete

Figure 3.15 : CANDU Reactor

At the time of its design, Canada lacked the heavy industry to cast and machine the large, heavy steel pressure vessel used in most light water reactors. Instead, the pressure is contained in much smaller tubes, 10 cm diameter, that contains the fuel bundles. These smaller tubes are easier to fabricate than a large pressure vessel. In order to allow the neutrons to flow freely between the bundles, the tubes are made of zircaloy, which is highly transparent to neutrons. The zircaloy tubes are surrounded by a much larger low-pressure tank known as a calandria, which contains the majority of the moderator.

Canada also lacked access to uranium enrichment facilities, which were then extremely expensive to construct and operate. The CANDU was therefore designed to use natural uranium as its fuel, like the ZEEP reactor, the first Canadian reactor. Traditional designs using light water as a moderator will absorb too many neutrons to allow a chain reaction to occur in natural uranium due to the low density of active nuclei. Heavy water absorbs fewer neutrons than light water, allowing a high neutron economy that can sustain a chain reaction even in unenriched fuel. Also, the low temperature of the moderator (below the boiling point of water) reduces changes in the neutrons' speeds from collisions with the moving particles of the moderator ("neutron scattering"). The neutrons therefore are easier to keep near the optimum speed to cause fissioning; they have good spectral purity. At the same time, they are still somewhat scattered, giving an efficient range of neutron energies.

The large thermal mass of the moderator provides a significant heat sink that acts as an additional safety feature. If a fuel assembly were to overheat and deform within its fuel channel, the resulting change of geometry permits high heat transfer to the cool moderator, thus preventing the breach of the fuel channel, and the possibility of a meltdown. Furthermore, because of the use of natural uranium as fuel, this reactor cannot sustain a chain reaction if its original fuel channel geometry is altered in any significant manner.

In a traditional light water reactor (LWR) design, the entire reactor core is a single large pressure vessel containing the light water, which acts as moderator and coolant, and the fuel arranged in a series of long bundles running the length of the reactor core. To refuel such a reactor, it must be shut down, the pressure dropped, the lid removed, and a significant fraction of the core inventory, such as one-third, replaced in a batch procedure. The CANDU's calandria-based design allows individual fuel bundles to be removed without taking the reactor off-line, improving overall duty cycle or capacity factor. A pair of remotely-controlled fueling machines visits each end of an individual fuel string. One machine inserts new fuel while the other receives discharged fuel.

A lower ^{235}U density also generally implies that less of the fuel will be consumed before the fission rate drops too low to sustain criticality (due primarily to the relative depletion of ^{235}U compared with the build-up of parasitic fission products). However, through increased efficiency which, among other benefits, avoids the need for enriched uranium, CANDU reactors use about 30-40% less mined uranium than light-water reactors per unit of electrical energy produced.

Figure 3.16 : Two CANDU Fuel Bundles

A CANDU fuel assembly consists of a number of zircaloy tubes containing ceramic pellets of fuel arranged into a cylinder that fits within the fuel channel in the reactor. In older designs the assembly had 28 or 37 half-meter long fuel tubes with 12 such assemblies lying end to end in a fuel channel. The relatively new CANFLEX bundle has 43 tubes, with two pellet sizes. It is about 10 cm (four inches) in diameter, 0.5 m (20 inches) long and weighs about 20 kg (44 lb) and replaces the 37-tube bundle. It has been designed specifically to increase fuel performance by utilizing two different pellet diameters.

A number of distributed light-water compartments called liquid zone controllers help control the rate of fission. The liquid zone controllers absorb excess neutrons and slow the fission reaction in their regions of the reactor core.

CANDU reactors employ two independent, fast-acting safety shutdown systems. Shutoff rods penetrate the calandria vertically and lower into the core in the case of a safety-system trip. A secondary shutdown system involves injecting high-pressure gadolinium nitrate solution directly into the low-pressure moderator

Purpose of Using Heavy Water

The key to maintaining a nuclear reaction within a nuclear reactor is to use the neutrons being released during fission to stimulate fission in other nuclei. With careful control over the geometry and reaction rates, this can lead to a self-sustaining chain reaction, a state known as "criticality".

Natural uranium consists of a mixture of various isotopes, primarily ^{238}U and a much smaller amount (about 0.72% by weight) of ^{235}U. ^{238}U can only be fissioned by neutrons that are fairly energetic, about 1 MeV or above. No amount of ^{238}U can be made "critical", however, since it will tend to parasitically absorb more neutrons than it releases by the fission process. In other words, ^{238}U is not fissile. ^{235}U, on the other hand, can support a self-sustained chain reaction, but due to the low natural abundance of ^{235}U, natural uranium cannot achieve criticality by itself. The "trick" to making a working reactor is to slow some of the neutrons to the point where their probability of causing nuclear fission in ^{235}U increases to a level that permits a sustained chain reaction in the uranium as a whole. This requires the use of a neutron moderator, which absorbs some of the neutrons' kinetic energy, slowing them down to an energy comparable to the thermal energy of the moderator nuclei themselves (leading to the terminology of “thermal neutrons” and “thermal reactors”). During this slowing-down process it is beneficial to physically separate the neutrons from the uranium, since ^{238}U nuclei have an enormous parasitic affinity for neutrons in this intermediate energy range (a reaction known as “resonance” absorption). This is a fundamental reason for designing reactors with discrete solid fuel separated by moderator, rather than employing a more homogeneous mixture of the two materials.

Water makes an excellent moderator. The hydrogen atoms in the water molecules are very close in mass to a single neutron and thus have a potential for high energy transfer, similarly the collision of two billiard balls. However, in addition to being a good moderator, water is also fairly effective at absorbing neutrons. Using water as a moderator will absorb enough neutrons that there will be too few left over to react with the small amount of ^{235}U in natural uranium, again precluding criticality. So, light water reactors require fuel with an enhanced amount of ^{235}U in the uranium, that is, enriched uranium which generally contains between 3% and 5% ^{235}U by weight (the waste from this process is known as depleted uranium, consisting primarily of ^{238}U). In this enriched form there is enough ^{235}U to react with the water-moderated neutrons to maintain criticality.

One complication of this approach is the requirement to build uranium enrichment facilities which are generally expensive to build and operate. They also present a nuclear proliferation concern since the same systems used to enrich the ^{235}U can also be used to produce much more “pure” weapons-grade material (90% or more ^{235}U), suitable for making a nuclear bomb. Operators could reduce these issues by purchasing ready-made fuel assemblies from the reactor supplier and have the latter reprocess the spent fuel.

An alternative solution to the problem is to use a moderator that does not absorb neutrons as readily as water. In this case potentially all of the neutrons being released can be moderated and used in reactions with the ^{235}U, in which case there is enough ^{235}U in natural uranium to sustain criticality. One such moderator is heavy water, or deuterium-oxide. It reacts dynamically with the neutrons in a similar fashion to light water, albeit with less energy transfer on average given that heavy hydrogen, or deuterium, is about twice the mass of hydrogen. The advantage is that it already has the extra neutron that light water would normally tend to absorb, reducing the absorption rate.

The use of heavy water moderator is the key to the CANDU system, enabling the use of natural uranium as fuel (in the form of ceramic UO_2), which means that it can be operated without expensive uranium enrichment facilities. Additionally, the mechanical arrangement of the CANDU, which places most of the moderator at lower temperatures, is particularly efficient because the resulting thermal neutrons are “more thermal” than in traditional designs, where the moderator normally runs hot. This means that the CANDU is not only able to “burn” natural uranium and other fuels, but tends to do so more effectively as well.

Fuel Cycles

Range of possible CANDU Fuel Cycles : CANDU reactors can accept a variety of fuel types, including the used fuel from light-water reactors.

Compared with light water reactors, a heavy water design is “neutron rich”. This makes the CANDU design suitable for “burning” a number of alternative nuclear fuels. To date, the fuel to gain the most attention is mixed oxide fuel (MOX).

MOX is a mixture of natural uranium and plutonium, such as that extracted from former nuclear weapons. Currently, there is a worldwide surplus of plutonium due to the various agreements between the United States and the former Soviet Union to dismantle many of their warheads. However, the security of these supplies is a cause for concern. One way to address this security issue is by converting the warhead into fuel and burning the plutonium in a CANDU reactor.

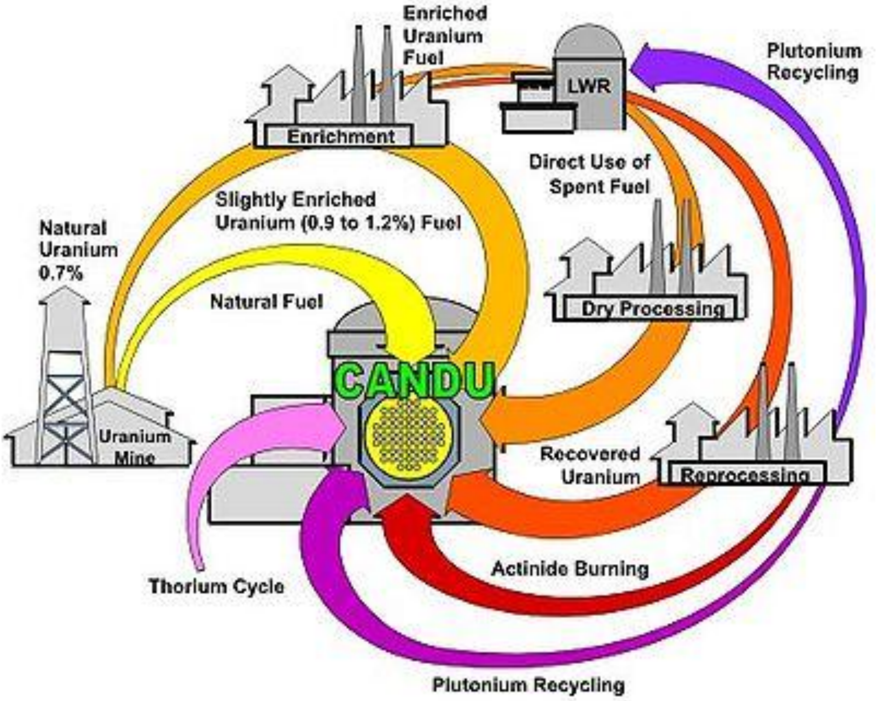


Figure 3.17 : Fuel Cycles

Plutonium can also be extracted from spent nuclear fuel reprocessing. While this consists usually of a mixture of isotopes that is not attractive for use in weapons, it can be used in a MOX formulation reducing the net amount of nuclear waste that has to be disposed of.

Plutonium isn’t the only fissile material in spent nuclear fuel that CANDU reactors can utilize. Because the CANDU reactor was designed to work with natural uranium, CANDU fuel can be manufactured from the used (depleted) uranium found in light water reactor (LWR) spent fuel. Typically this “Recovered Uranium” (RU) has a U-235 enrichment of around 0.9%, which makes it unusable to an LWR, but a rich source of fuel to a CANDU (natural uranium has a U-235 abundance of roughly 0.7%). It is estimated that a CANDU reactor can extract a further 30-40% energy from LWR fuel by recycling it in a CANDU reactor.

Recycling of LWR fuel does not necessarily need to involve a reprocessing step. Fuel cycle tests have also included the DUPIC fuel cycle, or direct use of spent PWR fuel in CANDU, where used fuel from a pressurized water reactor is packaged into a CANDU fuel bundle with only physical reprocessing (cut into pieces) but no chemical reprocessing. Again, where light-water reactors require the reactivity associated with enriched fuel, the DUPIC fuel cycle is possible in a CANDU reactor due to the neutron economy which allows for the low reactivity of natural uranium and used enriched fuel.

Several Inert-Matrix Fuels have been proposed for the CANDU design, which have the ability to “burn” plutonium and other actinides from spent nuclear fuel, much more efficiently than in MOX fuel. This is due to the “inert” nature of the fuel, so-called because it lacks uranium and thus does not create plutonium at the same time as it is being consumed.

CANDU reactors can also breed fuel from natural thorium, if uranium is unavailable.

The Engineering Approach

Like all engineered systems, the best way to understand and appreciate the CANDU reactor is to look at how it functions. Engineered systems are designed by functional decomposition, that is, they are broken down into subsystems based on a functional subgrouping, rather than by physical characteristics, etc. Examples would be the heat transport system of CANDU or the steering system of an automobile. We decompose the big problem (how to produce electrical energy, how to design a car, etc.) into progressively smaller, but interrelated problems (how to produce heat and how to convert the heat to electricity, or how to steer a car and how to stop a car, etc.). By breaking the big problem down into smaller and smaller problems, we systematically define problems that we can solve. These solved pieces, however, must be integrated back into a whole if we are to have a successful solution.

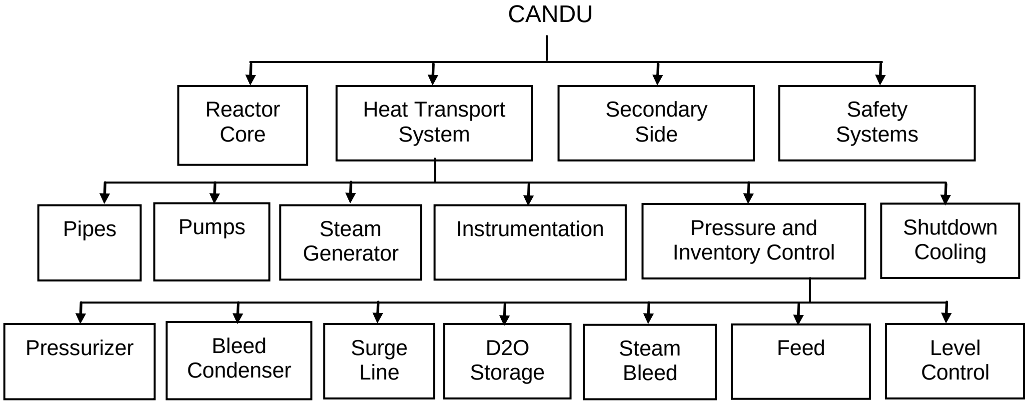


Figure 3.18 : Functional Decomposition

Implicit in such an approach is the question : "What does each subsystem have to do"? Thus the responsible engineer starts by asking "What are the functional requirements"? There are usually many ways to meet these functional requirements and it is the engineers job to find a workable solution that meets these requirements effectively meaning an optimum of efficiency, cost and safety, taking society and the environment well into account. Past experience usually plays a large role in engineered systems, but this is especially true for nuclear reactors because of the stringent quality assurance requirements and high safety standards. As a consequence, progress is more by systematic evolution.

Advantages of Nuclear Power Generation

(a) Nuclear power generation does emit relatively low amounts of carbon dioxide (CO_2). The emissions of green house gases and therefore the contribution of nuclear power plants to global warming is therefore relatively little.

(b) This technology is readily available; it does not have to be developed first.

(c) It is possible to generate a high amount of electrical energy in one single plant.

Disadvantages of Nuclear Power Generation

(a) The problem of radioactive waste is still an unsolved one. The waste from nuclear energy is extremely dangerous and it has to be carefully looked after for several thousand years.

(b) **High Risks :** Despite a generally high security standard, accidents can still happen. It is technically impossible to build a plant with 100% security. A small probability of failure will always last. The consequences of an accident would be absolutely devastating both for human being and for the nature. The more nuclear power plants are built, the higher is the probability of a disastrous failure somewhere in the world.

(c) Nuclear power plants as well as nuclear waste could be preferred targets for terrorist attacks.

(d) During the operation of nuclear power plants, radioactive waste is produced, which in turn can be used for the production of nuclear weapons.

(e) The energy source for nuclear energy is Uranium. Uranium is a scarce resource, its supply is estimated to last only for the next 30 to 60 years depending on the actual demand.

(f) The time frame needed for formalities, planning and building of a new nuclear power generation plant is in the range of 20 to 30 years in the western democracies. In other words: It is an illusion to build new nuclear power plants in a short time.

3.15 COMPARISON OF NUCLEAR POWER STATION WITH A STEAM POWER STATION

Nuclear power is one of the cheapest ways of producing electric power. The overall generation cost (cost/kWh) is less than all other electricity generation technologies. One can build a nuclear reactor to any place they want but a coal fired plant must be close to coal mines and one can only build a dam to a very specific place at a river basin. The cost of generation includes capital cost (very large for nuclear power plants and dams) including the interest paid for the load, operation and maintenance cost (similar for fossil fired plant and a nuclear power plant) and the fuel cost (nuclear has the cheapest fuel where as fossil fueled plants has the largest). Nuclear power plants use less land than other alternatives (Solar or wind need many times more land to generate similar power).

The exhaust gases from fossil fired plants contain CO_2 and there is no way to get rid of them. This gas is contributing to the temperature increase of the atmosphere. Coal has some degree of sulphur and when burned SO_2 is created. This gas causes acid rains. Some of the sulphur can be scrubbed from the coal while or after the combustion but it increases the cost of electricity. If the burners operate at high temperatures, like in gas turbines and diesel engines, nitrogen oxides are generated. This gas is one of the contributors of the ozone depletion in the atmosphere.

Ash from a fossil fired plant accumulates around the power plant as ash mountains and it contains toxic elements like cadmium and radioactive elements like uranium and thorium.

Nuclear power generates very little amount of highly radioactive waste. The toxicidity of this waste demises with time. After a very long time, the activity of the nuclear waste will be same as earth’s surface.

Nuclear power gives energy independence to a nation. Considering the strings attached to gas and petroleum sales in the international markets, nations that are not dependent of foreign energy resources have free hand in diplomacy.

3.16 HEALTH HAZARDS

About 80 percent of the public believes it is more dangerous to generate electricity from nuclear power than from coal. The enormous public misunderstanding about nuclear power may be largely attributed to :

(a) a widespread and exaggerated fear of radiation,

(b) a highly distorted picture of reactor accidents,

(c) grossly unjustified fears about disposal of radioactive waste, and

(d) failure to understand and quantify risk.

Radiation

How Dangerous Is Radiation?

Is being struck by a particle of radiation a terrible tragedy? No. Every person is struck by about a million particles of radiation every minute from natural sources. (The rate varies with geography and other factors.) This rate is hundreds of times greater than our exposure to radiation from the nuclear power industry. So is our average exposure to radiation from medical X-rays.

Although a single particle of radiation can cause cancer, the chance it will do so is only about one in 30 quadrillion. Hence, the million particles that strike us each minute have only one chance in 30 billion of causing a cancer. A human lifespan is about 40 million minutes; thus, all of the natural radiation to which we are exposed has about one chance in 700 of causing a cancer. Since our overall chance of dying from cancer is one in five, only one in 140 of all cancers may be due to natural radiation. The average exposure from a nuclear power plan to those who live closest to it is about 1 percent of the exposure to natural radiation; hence, if they live there for a lifetime, there is perhaps once chance in 70,000 (1/100th the chance from natural radiation and 1/14,000 the chance from all causes) that they will die of cancer as a result of exposure to its radiation.

Routine Emissions from the Nuclear Industry

In operation, nuclear power plants routinely release small quantities of radioactive gases and contaminants in water into the environment. More importantly, when reactor fuel is chemically reprocessed, more radioactive gases are released at the reprocessing plant. Extensive studies predict that, with current technology, routine releases of radiation due to operation of one large power plant for one year, including reprocessing, will cause 0.25 cancer deaths over the next 500 years. Since we are not reprocessing fuel now, effects of current operations are only about 20 percent of this. Available technologies can drastically reduce releases from reprocessing plants.

Reactor Accidents

Power plants include many levels of protection against radioactivity releases, based on a defense in depth design philosophy. For example, an accident could be initiated by a sudden rupture in the system, allowing the cooling water to escape. Levels of protection against this are :

(a) the highest quality standards on materials and equipment in which such a rupture might occur;

(b) elaborate inspection programs to detect flaws in the system using X-ray, ultrasonic, and visual techniques;

(c) Leak-detection systems (Normally a rupture starts out as a small crack, allowing water to leak out slowly. Such leaks would be detected by these systems and repaired before a rupture could occur);

(d) an emergency cooling system, which would rapidly replace the water lost in such a rupture accident, restoring cooling to the reactor fuel. (In this type of accident there are several different pumping systems, any one of which would provide sufficient water to avert a meltdown if all the other somehow failed.);

(e) The containment, a strong building in which the reactor is housed, which would normally hold the released radioactivity inside even if there were a meltdown.

Radioactive Waste

There are several types of radioactive waste generated by the nuclear industry, but we will concentrate largely on the two most important and potentially dangerous, high-level waste and radon.

High-level Waste

In a rationally planned and developed nuclear power program, spent reactor fuel would be shipped to a reprocessing plant to remove valuable components. The residue, containing nearly the entire radioactivity produced in the reactor, is called high-level waste. Following reprocessing, the waste can be converted into a rock-like form and buried deep underground in a carefully selected geological formation.

One important aspect of high-level waste disposal is the small quantities involved. The waste generated by one large nuclear power plant in one year and prepared for burial is about six cubic yards, roughly one truckload. This is two million times smaller by weight, and billion of times smaller by volume, than wastes from a coal plant. The electricity generated in a year sells for more than $400 million, so if only 1 percent of the sales price were diverted to waste disposal, $4 million might be spent to bury this one truckload of waste, enough to pay for very elaborate protective measures.

To understand the very long-term (millions of years) hazard, natural radioactivity in the ground is a good comparison. The ground is full of naturally radioactive materials. By adding nuclear waste to it, the totally radioactivity in the top 2,000 feet of US soil would increase by one part in ten million per plant-year. Moreover, the radioactivity in the ground (except perhaps very near the surface) does virtually no harm.

RADON

Another aspect of nuclear waste may involve important health impacts: the release of radon, a radioactive gas that naturally evolves from uranium. There has been some concern over increased releases of radon due to uranium mining and milling operations. These problems have now been substantially reduced by cleaning up those operations and covering the residues with several feet of soil. The health effects of this radon are several times larger than those from other nuclear wastes, such as the high-level waste discussed above, but they are still much smaller than the effects of coal-burning.

However, a far more important impact of the nuclear industry on radon is that by mining uranium out of the ground, we avert future radon emissions and thus avoid future health impacts. Most of the uranium is mined from deep underground, so one might think the radon could not escape. However, the ground surface is constantly eroding away, so eventually the uranium mined would have been near the surface, where it radon emissions could cause lung cancers. When these effects are calculated, the result is an eventual saving of 450 lives per plant-year operation. This saving is thousands of times larger than the lives calculated to be lost from radioactive waste. Also, coal burning releases small amounts of uranium into the environment, eventually causing 30 fatalities per plant-year through radon released.

3.17 SAFETY PRECAUTIONS

Treatment and Conditioning of Nuclear Wastes

Treatment and conditioning processes are used to convert radioactive waste materials into a form that is suitable for its subsequent management, such as transportation, storage and final disposal. The principal aims are to :

(a) Minimize the volume of waste requiring management via treatment processes.

(b) Reduce the potential hazard of the waste by conditioning it into a stable solid form that immobilizes it and provides containment to ensure that the waste can be safely handled during transportation, storage and final disposal.

It is important to note that, while treatment processes such as compaction and incineration reduce the volume of waste, the amount of radioactivity remains the same. As such, the radioactivity of the waste will become more concentrated as the volume is reduced.

Conditioning processes such as cementation and vitrification are used to convert waste into a stable solid form that is insoluble and will prevent dispersion to the surrounding environment. A systematic approach incorporates :

(a) Identifying a suitable matrix material – such as cement, bitumen, polymers or borosilicate glass - that will ensure stability of the radioactive materials for the period necessary. The type of waste being conditioned determines the choice of matrix material and packaging.

(b) Immobilizing the waste through mixing with the matrix material.

(c) Packaging the immobilized waste in, for example, metallic drums, metallic or concrete boxes or containers, copper canisters.

The choice of process used is dependent on the level of activity and the type (classification) of waste. Each country's nuclear waste management policy and its national regulations also influence the approach taken.

Incineration

Incineration of combustible wastes can be applied to both radioactive and other wastes. In the case of radioactive waste, it has been used for the treatment of low-level waste from nuclear power plants, fuel production facilities, research centers (such as biomedical research), medical sector and waste treatment facilities.

Following the segregation of combustible waste from non-combustible constituents, the waste is incinerated in a specially engineered kiln up to around 1000^oC. Any gases produced during incineration are treated and filtered prior to emission into the atmosphere and must conform to international standards and national emissions regulations.

Following incineration, the resulting ash, which contains the radionuclide’s, may require further conditioning prior to disposal such as cementation or bituminization. Compaction technology may also be used to further reduce the volume, if this is cost-effective. Volume reduction factors of up to around 100 are achieved, depending on the density of the waste.

Incineration technology is subject to public concern in many countries as local residents worry about what is being emitted into the atmosphere.
However, modern incineration systems have well engineered high technology processes designed to completely and efficiently burn the waste whilst producing minimum emissions.

The incineration of hazardous waste (e.g. waste oils, solvents) and non-hazardous waste (municipal waste, biomass, tyres and sewage sludge) is also practiced in many countries.

Compaction

Compaction is a mature, well-developed and reliable volume reduction technology that is used for processing mainly solid man-made low-level waste (LLW). Some countries (Germany, UK and USA) also use the technology for the volume reduction of man-made intermediate-level/transuranic waste. Compactors can range from low-force compaction systems (~ 5 tons or more) through to presses with a compaction force over 1000 tones, referred to as super compactors. Volume reduction factors are typically between 3 and 10, depending on the waste material being treated.

Figure 3.19 : Incineration

Low-force compaction is typically applied to the compression of bags of rubbish, in order to facilitate packaging for transport either to a waste treatment facility, where further compaction might be carried out, or to a storage/disposal facility. In the case of super compactors, in some applications, waste is sorted into combustible and non-combustible materials. Combustible waste is then incinerated whilst non-combustible waste is super compacted. In certain cases, incinerator ashes are also super compacted in order to achieve the maximum volume reduction.

Low-force compaction utilizes a hydraulic or pneumatic press to compress waste into a suitable container, such as a 200-litre drum. In the case of a super compactor, a large hydraulic press crushes the drum itself or other receptacle containing various forms of solid low- or intermediate-level waste. The drum or container is held in a mold during the compaction stroke of the super compactor, which minimizes the drum or container outer dimensions. The compressed drum is then stripped from the mold and the process is repeated. Two or more crushed drums, also referred to as pellets, are then sealed inside an over pack container for interim storage and/or final disposal.

A super compaction system may be mobile or stationary in concept, supplied as a basic system manually controlled, with a minimum of auxiliary equipment, to an elaborated computer controlled system which selects drums to be processed, measures weight and radiation levels, compresses the drums, places the crushed drums in over pack containers, seals the over packs, records the drums and over packs content via a computerized storage system.

Every year worldwide tens of thousands of drums are volume-reduced and stored, with waste generally being reduced in volume by up to a factor of 5.

Cementation

Cementation through the use of specially formulated grouts provides the means to immobilize radioactive material that is on solids and in various forms of sludge’s and precipitates/gels (flocks) or activated materials.

In general the solid wastes are placed into containers. The grout is then added into this container and allowed to set. The container with the monolithic block of concrete/waste is then suitable for storage and disposal.

Figure 3.20 : Compaction

Similarly in the case of sludge's and flocks, the waste is placed in a container and the grouting mix, in powder form, is added. The two are mixed inside the container and left to set leaving a similar type of product as in the case of solids, which can be disposed of in a similar way.

This process has been used for example in small oil drums and 500-litre containers for intermediate-level wastes and has been extended to ISO shipping containers for low-level waste materials.

The technology is being used in the immobilization of many toxic and hazardous wastes that arise outside the nuclear industry and has the potential to be used in many more cases.

Vitrification

The immobilisation of high-level waste (HLW) requires the formation of an insoluble, solid waste form that will remain stable for many thousands of years. In general borosilicate glass has been chosen as the medium for dealing with HLW. The stability of ancient glass for thousands of years highlights the suitability of borosilicate glass as a matrix material.

This type of process, referred to as vitrification, has also been extended for lower level wastes where the type of waste or the economics have been appropriate.

Most high-level wastes other than spent fuel itself arise in a liquid form from the reprocessing of spent fuel. To allow incorporation into the glass matrix this waste is initially calcined (dried) which turns it into a solid form. This product is then incorporated into molten glass in a stainless container and allowed to cool, giving a solid matrix. The containers are then welded closed and are ready for storage and final disposal.

Several other alternative ceramic processes have also been developed which also achieve the desired quality of product.

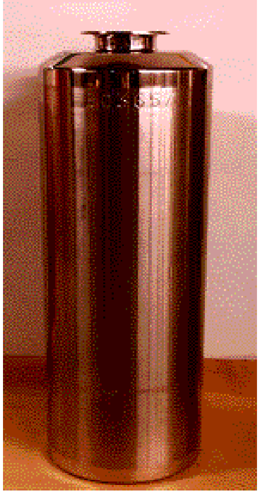


Figure 3.21 : Vitrification

In-situ vitrification has also been investigated as a means of 'fixing' activity in contaminated ground as well as creating a barrier to prevent further spread of contamination.

SAQ 1

(a) What do you mean by ‘Fission of Nuclear Fuel’?

(b) What is ‘nuclear fusion’? How does it differ from ‘nuclear fusion’?

(c) Describe the process of nuclear reaction.

(d) What is a nuclear reactor? How nuclear reactors are classified? Enumerate and explain essential components of nuclear reactor.

(e) Explain with help of neat diagram the construction and working of a nuclear power plant.

SAQ 2

(a) What is ‘Boiling Water Reactor’ (BWR)? Explain the major components of BWR.

(b) Describe the advantages and disadvantages of BWR.

(c) What is CANDU type nuclear reactor? Also explain the working principle.

(d) Compare the nuclear power station with steam power plant.

3.18 SUMMARY

Due to high demand of electricity, the need for establishing different types of power plant is increased. Nuclear power plant is one of the power generating mode. In this unit, we have learnt about nuclear fission and nuclear fusion. The nuclear chain reaction is unique since it releases several million times more energy per reaction than any chemical reaction. This unit also elaborated on the boiling water reactors (BWR), and is used for producing steam.

3.19 KEY WORDS

Nuclear Fission	:	The process of bombarding unstable heavy nuclear with high energy neutrons to produce several smaller fragments of fission products.
Nuclear Fusion	:	The process by which multiple like – charged atomic nuclei join together to form a heavier nucleus.
Nuclear Reaction	:	A nuclear reaction is the process in which two nuclei or nuclear particles collide to produce products different from the initial particles.

3.20 ANSWERS TO SAQs

Refer the preceding text for all the Answers to SAQs.