NUCLEAR ENERGY AS AN ALTERNATIVE SOURCE OF ENERGY

Nishtha Saxena¹,² and Monika Kamboj¹

1. Department of Chemistry, Amity School of Applied Sciences, Amity University
   Lucknow Campus, Lucknow-226010, (Uttar Pradesh) India
2. Department of Chemistry, Institute of Chemical Technology, Mumbai, Maharashtra-400019, India

ABSTRACT

Civil society is built on an energy resource. It is very essential for the survival of the modern world and it affects every aspect of life. To form steam from boiling water, nuclear power is a clean and efficient way. The steam generated turns turbines to produce electricity. In nuclear power, the radiation released into the environment is lesser as compared to any other major source of energy. Studies have been done that indicated that major industrial accidents are more destructive than the worst possible accident at a nuclear plant. Nuclear power is one of the few commercially tested sources of energy that is virtually free of greenhouse gas emissions. This automatically makes it of interest to climate change pundits. This article explores nuclear energy as an alternative source of energy and explains the process of nuclear fission, nuclear reactions, nuclear fuel, various nuclear reactor types, operations involved in nuclear reactors, the nuclear fuel cycle, the fueling of nuclear reactors, and fusion power.

Keywords: Nuclear, energy, fusion, fission, radiation, Nuclear reactor, Nuclear fuel

Introduction

In nuclear reactions, there is a release of a tremendous amount of nuclear energy which can be used productively to generate heat. The steam turbines in a nuclear power plant can make use of this released heat to produce electricity. This is called nuclear energy or nuclear power. There are various ways by which we can obtain nuclear power with the help of the nuclear fission process, nuclear fusion process, and nuclear decay process. In today’s world, the process of nuclear fission of uranium and plutonium is used to produce nuclear power which in turn is used for the production of electricity. Nowadays a lot of research is going on generating electricity from the nuclear fusion process. If we compare other energy sources, then nuclear power has one of the lowest levels of fatalities per unit of energy generated. The other energy sources which include coal, petroleum, natural gas, and hydroelectricity, are the reasons for the highest levels of mortality due to either air pollution or accidents. Nuclear energy is a safer, cleaner, and more sustainable energy source with zero carbon footprint. Nuclear fission is considered to be a dense source of energy as the amount of free energy present in nuclear fuel is tremendously high when compared to the amount of free energy that is present in chemical fuels like gasoline. However, the generation of nuclear waste is a problem as the products formed by nuclear fission are highly radioactive. The products formed by the nuclear fission process are more radioactive as compared to heavy
elements which are fissioned as fuel and they remain so for a significant amount of time which can give rise to nuclear waste problems. The other advantage of using nuclear energy as an alternative source of energy is that it can produce a large amount of electricity on less land whereas other energy sources may require a large amount of land. Because nuclear fuel is extremely dense, the amount of nuclear fuel used is also lesser. Nuclear power plants can operate at much higher capacity factors as compared to fossil fuels or renewable energy sources. Capacity factor can be defined as what percentage of time a power plant can produce energy. Nuclear power requires less maintenance and is designed in such a way that it can operate for a longer duration before refueling typically over 1.5 or 2 years. With the help of a comprehensive understanding of nuclear energy and the expansion of its technology through products such as SMR i.e. small modular reactors, nuclear energy is the next prominent energy source.

**Nuclear Fission**

Nuclear fission refers to the radioactive decay process in which an atom’s nucleus divides into two or more smaller lighter nuclei. There is the production of gamma photons along with the release of a very high amount of energy. In the process of induced fission reaction, the Uranium-235 nucleus absorbs a neutron and forms an excited Uranium-236 nucleus, with the excitation energy that is provided by the combination of forces that helps to bind the neutrons and the kinetic energy of the neutrons. The Uranium-236 further divides into fast-moving lighter elements i.e., barium and krypton, and additionally releases three free neutrons and gamma rays.

\[
^{235}_{92}U + ^1_{0}n \rightarrow ^{236}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^1_{0}n
\]

**Figure 1: Nuclear Fission Chain reaction**

In nuclear fission, the nuclei produced are of equivalent size with a mass ratio of approximately one or two. So, the fission process is a form of nuclear transformation. The release of huge amounts of energy during fission is because of the mass defect. It was observed that the summation of the mass of the individual neutron and the \(^{235}_{92}U\) was more when compared to the overall mass of the products resulting from fission. This loss of mass appears in the form of a massive amount of energy and so nuclear fission is a highly exothermic process. Einstein’s Mass-Energy relation

\[
E = mc^2.
\]
In the process of nuclear fission of $^{235}\text{U}$, the energy released is nearly 200MeV corresponding to an average mass defect of 0.22μ.

Nuclear Fuel

Nuclear fuels are isotopes of a particular element that can easily undergo nuclear fission. Heavy fissile actinide elements, which can sustain nuclear fission, can be utilized as nuclear fuels. Some of the most fissile nuclear fuels are $^{235}\text{U}$, and $^{239}\text{Pu}$. In nuclear fuels, nuclear fission is possible only when the nucleus absorbs a neutron and releases the excitation energy. The same process can be observed in fissionable isotopes like $^{238}\text{U}$, but they require additional energy which can be provided by fast neutrons.

1. Oxide Fuel

The fuel that is used for fission reactors is based on metal oxide. It is used because the melting point of oxide is much higher. Uranium dioxide can be used as oxide fuel and is prepared generally by heating uranyl nitrate that produces UO₃. UO₂ is formed by heating UO₃ with hydrogen.

$\text{UO}_2(\text{NO}_3)_2\cdot6\text{H}_2\text{O} \rightarrow \text{UO}_3 + \text{NO}_2$

Then the organic binder and UO₂ are mixed together and converted into pellets. Then for the sintering of the solid to take place, the pellets formed are kept under high-temperature conditions. Then it is converted into a dense solid with pores in it.

2. Mox Fuel

Mixed oxide also commonly known as Mox fuel is a mixture of two radioactive materials i.e., plutonium and uranium which is an excellent fuel material for light water reactors and also it is an alternative to low-enriched uranium fuel.

3. Metal Fuel

Metal fuels offer more advantages when compared to oxide fuel because they have higher heat conductivity but cannot withstand high temperatures like oxide fuel. Some metal fuels are alloys, whereas others are made entirely of uranium metal. Uranium zirconium, uranium aluminum, uranium molybdenum, and uranium silicon are some of the uranium alloys. Metal fuels are widely employed in liquid metal fast breeder reactors or water reactors.
4. TRIGA Fuel

Training Research Isotopes General Atomics (TRIGA) reactors use TRIGA fuel. Uranium Zirconium hydride (UZrH) is mostly used in these reactors. However, its reactivity decreases with an increase in the core temperature. These cores are susceptible to high leakage and if any excess neutrons are leaked from these cores, they can be used for research purposes.

5. Actinide Fuel

In a fast neutron reactor, when the uranium and plutonium capture the neutron then actinides are produced which are can be further used as fuel. Metal actinide fuel is an alloy of actinides, plutonium, zirconium, and uranium.

6. Non-Oxide Ceramic Fuel

Ceramic fuels have an advantage over oxide fuels because they have high melting points and heat conductivities.

7. Uranium Nitride

Uranium nitride has good thermal conductivity and a very high melting point. One disadvantage of the fuel is that $^{15}\text{N}$ is used which produces a large amount of $^{14}\text{C}$. The nitrogen required for the fuel is very expensive and so the process of pyroprocessing is used to recover $^{15}\text{N}$.

8. Uranium Carbide

Uranium carbide fuel is used in liquid metal fast reactors. It has a very high melting point and thermal conductivity. This fuel can also be used in GENERATION IV reactors such as the gas-cooled fast reactor because of the absence of oxygen in the fuel and its ability to complement a ceramic coating.

9. Liquid Fuel

The liquids which contain nuclear fuel in the dissolved form are liquid fuels. Liquid fuels have a great advantage because there is the possibility of virtually eliminating runaway reactor meltdown which further provides automatic load-following capability. This helps in the generation of electricity and can be used in high-temperature industrial heat applications. Liquid fuels release xenon gas which can absorb neutrons and can cause structural occlusions in solid fuel.
10. Molten Salts

When the nuclear fuel is directly dissolved in the molten salt coolant such fuels are called molten salt fuels. Molten salt fuels have applications in molten salt reactor experiments and liquid core reactor experiments. In the molten salt reactor, the liquid fuel used is a mixture of lithium, beryllium, thorium, and uranium fluorides.

11. Aqueous Solutions of Uranyl Salts

The solution of uranyl sulfate or other uranium salts in water is used in the aqueous homogeneous reactors.

Nuclear Reactors

A device that is used to start and control a fission nuclear chain reaction is called a nuclear reactor which is used to generate electricity. The principle behind this is that when the energy is released in the form of heat during a nuclear fission reaction, this heat is taken up by the water which is further pumped into the tubes of the heat exchanger. These tubes help in the generation of steam which turns an electric generator in order to produce electricity.
Operations involved in nuclear reactors:

1. Fission Process: -

In this process, we first take the atomic nucleus which is fissile like $^{235}\text{U}$ or $^{239}\text{Pu}$ which absorbs a neutron and further undergoes nuclear fission. The heavy nucleus of the isotope then splits into lighter nuclei and releases a huge amount of energy and free neutrons. Further, these free neutrons are captured by other atoms that are fissile and start further fission reactions which release more neutrons further and this phenomenon is called a nuclear chain reaction. Control rods that contain neutron poisons and neutron moderators can be used to control the nuclear chain reactions. Nuclear reactions are equipped with an automatic or manual system in order to shut down the fission process if it detects dangerous conditions.

2. Heat Generation:-

The heat can be generated in numerous ways-

1. When we obtain fission products then their kinetic energy gets converted into thermal energy and this takes place when there is a collision between nuclei with nearby atoms.
2. During the fission process some gamma rays are also produced which are absorbed by the reactor and gets converted into heat energy.
3. When the fission products undergo radioactive decay and some materials that are activated by neutron absorption also produce heat.

3. Cooling:-

Water, a gas, or a liquid metal, such as liquid sodium or liquid lead, or molten salt, is used as a coolant in nuclear reactors and is circulated in the reactor core. From the reactor core, the coolant absorbs the heat that is generated by the nuclear fission process and is used to generate steam.

4. Reactivity Control:-

In the reactor core, the rate of fission can be controlled by controlling the neutrons that induce further fission events. This can be done with the help of control rods and it is the fastest method. Control rods can easily absorb neutrons because they are made of neutron poisons. The coolant that is used in reactors can also be used as a neutron moderator. The function of the moderator is to convert the fast-moving neutrons into slow-moving thermal neutrons. Fast neutrons are less likely to trigger fission than thermal neutrons. Coolant in some reactors can sometimes function as control rods by absorbing neutrons.

If we want to increase the power output of these reactors then it can be done by heating
the coolant. During emergencies, nuclear reactors are shut down by automatic systems. In order to shut down the fission reactions, the automatic systems insert a large amount of boron in the form of boric acid. Another method of controlling fission reaction is poisoning by xenon or using the iodine pit. One of the fission products which is produced during the fission process is Xenon-135 can act as a neutron poison and shut downs the reactor by absorbing neutrons. We need to keep power levels high so that Xenon-135 does not accumulate and get destroyed by the absorption of neutrons. Another fission product produced during the fission process is Iodine-135 which continues to decay to new Xenon-135 even when the reactor is shut down. This makes the situation worse and starting the reactor again becomes difficult as Xenon-135 decays into Caesium-135. This is known as an iodine pit. The reactor can be started if it has the necessary extra reactivity capacity.

5. Electric Power Generation:-

During the fission process, a tremendous amount of heat is released which can be converted into usable energy. The heat released is used to boil water which produces pressurized steam. This steam is used to move a steam turbine which helps in the generation of electricity.

Types of Reactors: Reactors are classified on the basis of:

A) Type of nuclear reaction: -

The nuclear fuel used in most commercial reactors is uranium, plutonium, and sometimes thorium also. Depending on the neutron’s energy that is capable of sustaining the fission chain reaction, fission reactors can be classified as

Thermal Neutron Reactors:-

These are the most common types of nuclear reactors. Basically, in these reactors, thermal neutrons are used for the fission process. The neutron moderator materials slow down the neutrons until their neutron temperature is thermalized which means the kinetic energy of these neutrons becomes equivalent to the average kinetic energy of the surrounding particles. The coolant used in these reactors can also act as a moderator. The coolant used is usually high-pressurized water which helps in increasing the boiling point. These are surrounded by a reactor vessel, shield for radiation, containment building, and instrumentation to monitor and control the reactor.

1. Fast Neutron Reactors:-

These types of reactors use fast neutrons to cause fission reactions. A neutron moderator is not used in these types of reactors and instead, coolants that are less moderating are used. Highly fissile material is needed for these reactors to sustain a chain reaction because of the relatively lower probability of fission versus capture by U-238. The advantage of fast neutron reactors is that they produce less radioactive waste because
all the actinides become fissionable with fast-moving neutrons.

B) Moderator material used in thermal reactors:-

1. Graphite Moderated Reactors:-

These types of reactors use carbon as a neutron moderator. In these types of reactors, uranium is used as nuclear fuel. Some of the graphite-moderated reactors used in electricity generation are gas-cooled reactors like Magnox, UNGG reactor, Water cooled reactors, and High-temperatures cooled reactors.

2. Water Moderated Reactors:- They are sub-classified as:

- Heavy Water Moderated Reactors:-

The coolant and neutron moderator used in a pressurized heavy water reactor is heavy water. The fuel used in these types of reactors is natural uranium, and sometimes very low enriched uranium. In order to avoid boiling, the heavy water coolant is kept under pressure which allows it to reach higher temperature. These types of reactors do not require enriched fuel because of the heavy water used increases the neutron economy of the reactor as it has low absorption of neutrons.

- Light Water Moderated Reactors:-

These are the most common types of thermal reactors. The coolant and moderator used in these types of reactors is ordinary water. The density of the water decreases as the temperature is increased and this way fewer neutrons that are passing through it are slowed down. There are broadly three types of light water reactors, The Boiling Water Reactor, the Pressurized Water Reactor, and the Supercritical water reactor. The heat that is generated by fission in the boiling water reactor converts the water into steam. The steam produced drives the power-generating turbines. But the heat that is generated by the fission process in the pressurized water reactor is transferred into the secondary loop with the help of a heat exchanger. The generation of steam takes place in the secondary loop which drives the power-generating turbines. After steam flows through the turbines, it gets converted into water again in the condenser in both cases.

A soluble neutron absorber, usually boric acid is added in pressurized water reactor coolant which allows the extraction of control rods at the time of stationary power operation so as to ensure every power and distribution of flux over the entire core. Ordinary water can also be used as a coolant in the light water reactor. In a pressurized water reactor, water that will be used as a cooling system is separated physically from the water that will generate steam under pressure when water is boiled. But in a boiling water reactor, the water is boiled in the reactor core that is used for the steam turbines.

The most widely used fuel in light water reactors is Uranium-235. Sometimes
Uranium-238 is also used as a fuel in these reactors which contributes to the fission process by converting to Plutonium-239.

4. Light element moderated reactors:- They are of three types.

- Molten Salt Reactors:-

These types of reactors are moderated by light elements like lithium or beryllium which are present in the fuel or coolant matrix salts LiF and BeF₂. In these types of reactors, the coolant or the fuel used is a molten salt mixture. The special feature of molten salt reactors is that they operate at or close to atmospheric pressure. Another important feature of these reactors is that they do not produce fission gases which are dangerous and radioactive and are naturally absorbed into the molten salt. Another special feature of these reactors is high operating temperatures which provide electricity generation with high efficiency, there is the possibility of grid storage facilities and hydrogen production in an economical way. Molten salt reactors can be fast or thermal reactors. Unlike steam, fluoride salts that are used in these reactors dissolve poorly in water and so it does not form burnable hydrogen. Molten salts are not damaged by the neutron bombardment in the reactor core as in the case of steel and solid uranium oxide. The nuclear fuel cycles in the case of the molten salt reactor are cheaper because they can work even with slow neutrons. In these reactors, there is no need for the fabrication of fuel rods.

- Liquid Metal Cooled Reactors:-

In these types of reactors, the coolant used is a mixture of lead and bismuth and beryllium oxide can be used as a moderator. In these types of reactors, the coolant used is a liquid metal. The advantage of using metal coolants is that they remove heat more quickly and allow higher power density. The advantage of the high temperature of liquid metal is that it can produce vapor at higher temperatures as compared to water cooled reactor which increases the thermodynamic efficiency. Since liquid metals are electrically conducting in nature they can be moved by electromagnetic pumps too. These are the fast-neutron reactor. The first liquid metal-cooled nuclear reactor was Clementine which used mercury as a coolant. Another coolant that can be used in these types of reactors is sodium and a eutectic sodium-potassium alloy. The advantage of using them as a coolant is that they do not corrode steel and are easily compatible with nuclear fuels. Lead can also be used as a coolant because its properties make it an excellent coolant as it acts as a radiation shield against gamma rays and has good neutron properties. Another advantage of using lead as a coolant is that its higher boiling point provides safety advantages because the reactor can be efficiently cooled even if it reaches above-normal operating conditions.

- Organically Moderated Reactors:-
In these types of reactors, the coolant and moderators used are biphenyl and terphenyl. These types of reactors use organic fluid like polychlorinated biphenyl which can act as both a coolant and neutron moderator. The advantage of using organic fluids is that they are less corrosive to metals and so coolant pipes can also be built from normal carbon steel and not corrosion-resistant metals that are much more expensive. Organic fluids do not flash into gas so there is no need for containment building.

4. Gas Cooled Reactors:

In these types of reactors, the coolant used is gas. The most commonly used gas as a coolant is carbon dioxide. The other gases used are nitrogen and helium. These gases run through the heat exchanger in order to produce steam for steam turbines. In these types of reactors, the neutron moderator used is graphite. The fuel used in these types of reactors is natural uranium.

Nuclear Fuel Cycle

Most thermal reactors use enriched uranium or amixture of plutonium and uranium. The nuclear fuel cycle is the process of mining, processing, enrichment, usage, reprocessing, and disposal of uranium ore.

The ratio of fissionable U-235 isotope in natural uranium is found to be much less, so enriched fuel is required for the reactors. In the process of enrichment, the percentage of U-235 is increased and is generally done by means of diffusion by gas or centrifugation by gas. The enriched uranium is then converted into uranium dioxide powder and further converted into pellet form. Fuel rods are formed when the pellets formed are piled into tubes and then sealed. These fuel rods are then used in a nuclear reactor. In the fission process, mostly fissile U-235 and non-fissile U-238 are used. Thermal neutrons can easily cause fission in U-235. A thermal neutron can be defined as one which moves with the same speed as the atoms around it. The vibration of an atom is directly proportional to its absolute temperature. U-235 is fissionable by thermal neutrons when they move along with the same vibrational speed.

Pu-239 is another fuel formed when U-238 captures a fast-moving neutron. It can be used as a fuel in nuclear reactors because it is fissionable with thermal neutrons as well as fast neutrons. Thorium-232 is also a fertile material that can absorb both fast neutrons and thermal neutrons. This will change to Thorium-233 which further produces Protactinium-233 and Uranium-233 by the beta decay process. The Uranium-233 produced is used as a fuel. This cycle is called the Thorium fuel cycle.

Fuel Filling in Nuclear Reactors

Full power day is the term used to express the amount of energy that is present in nuclear fuel. It is the number of 24-hour periods in which a nuclear reactor is scheduled to run at maximum power to generate heat energy. In the reactor’s operating cycle, the number of full power days depends on the fissile Uranium-235
present at the initial stages of the cycle. The higher the amount of U-235 at the start of the cycle, the more full power days there will be. At the last stages of the operating cycle, the fuel present in some of the assemblies is spent. The spent fuel is then replaced with fresh fuel assemblies. Spent nuclear fuel is first removed from the reactor and then transferred to the onsite spent fuel pool. A large amount of water is present in the spent fuel pool that helps in lowering the temperature and shielding of spent nuclear fuel. Approximately after 5 years when the energy of the fuel decays, then it is transferred to dry shielded casks from the fuel pool where it can be stored for thousands of years safely. Then dry shielded casks are stored onsite in impervious concrete bunkers. An average onsite fuel storage facility, which is even less than a football field, may hold 30 years of used fuel. The term burnup can be defined as the amount of energy that can be extracted from nuclear fuel. It is measured in terms of heat energy produced per unit of fuel weight at initial stage.

**Fusion Power**

The generation of electricity by using heat produced by the nuclear fusion reaction is called fusion power. A heavier nucleus is formed when two lighter atomic nuclei combine together and release a tremendous amount of energy. This process is called fusion.

\[ ^2\text{H} + ^3\text{H} \rightarrow ^4\text{He} + ^1\text{n} \]

**Figure 3:** Nuclear Fusion

Fusion reactors are devices that are designed in order to harness the energy that is released during the fusion process. The requirements that are needed for the fusion process are fuel, pressure, a confined environment with sufficient temperature, and confinement time in order to create plasma so that the fusion process can occur. It helps in creating a comparison between the rates of energy that is produced by fusion reaction within fusion fuel to the rate of energy that is lost to the environment. When all these requirements are combined then they result in power producing system which is known as Lawson Criterion. Generally, hydrogen
isotopes like deuterium and tritium are used for fusion reactors. These isotopes react very easily and reach the Lawson Criterion requirements with less extreme conditions. The major challenge behind producing a successful design is that the fuel needs to be heated to tens of millions of degrees.

Nuclear fusion as a source of power has various advantages over the nuclear fission process. These include lesser nuclear waste, radioactivity reduced during operation, sufficient fuel supplies, and most importantly increased safety. It is difficult to produce the design in a practical and economical manner because of the necessary combination of temperature, pressure, and duration. Another problem that is faced is managing the neutrons that are released during the fission process which may degrade the materials that are required for the reaction chamber.

Conclusion

As the new technology is growing, more energy will be required and the current supply of energy will not be able to meet the upcoming demands. Now, renewable energy sources are unable to meet the growing demands and fossil fuels have a major role in polluting and contaminating the air and water making the world the most dangerous place to live in. These days clean and sustainable source of energy is needed that is also able to meet the needs of the world. In order to solve problems nationally and internationally then nuclear energy is the best solution.

Suggested Reading:

32. European Fusion Development Agreement, “Lawson’s Three Criteria”, EFDA, viewed 31/03/2021

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