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Environmental Impact of Nuclear Power Plant for Electricity Generation

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ABSTRACT:

Risk is an inherent aspect of all human activities, from personal choices to global operations, with nuclear power plants being no exception. This research assessed the environmental impact of nuclear power plants by conducting a synthesis analysis using a systematic literature review of data obtained from various studies. Drawing from 20 previous research articles, this study examines the key environmental risks associated with nuclear energy, including accidents, radioactive waste management, and their long-term effects on ecosystems and human health. While nuclear energy serves as a low-carbon alternative for electricity generation, it presents significant environmental challenges, particularly in the areas of waste disposal and contamination. The study also explores various mitigation strategies, such as advanced safety protocols, decontamination techniques, and improved waste management systems, that aim to minimize the environmental footprint of nuclear energy. The findings emphasize the critical need for continuous innovation and improvements in nuclear technology to ensure its environmental sustainability and safety.

Keywords: nuclear power plant, nuclear energy, reactors, electricity generation, environmental impact, greenhouse gas emissions

1. INTRODUCTION

1.1 BACKGROUND OF THE STUDY

When it comes to global warming, coal, oil and other traditional energy gaps, has become an urgent task to accelerate the change of the global energy structure, and the development of new energy has become a consistent energy strategic goal in the world. In recent years, the proportion of electricity generation from various renewable energy sources has gradually increased, but compared with various types of clean energy, nuclear energy has the advantages of good economic returns and high efficiency of investment and has developed extremely rapidly in the past decade[1]. Moreover, of all the presently known available sources of energy, nuclear energy has the capacity of producing a huge amounts of needed power within the available time frame. Nuclear power contributes roughly 11% of the overall global electricity production, making up approximately one-third of the total low-carbon electricity generated worldwide[2]. However, considerable economic and technical problems must to be solved before large-scale utilization of this source can become possible. Nuclear power facilities are responsible for the generation of radioactive waste, which is one of the most important environmental influences they have[3]. Spent fuel rods and other radioactive materials are produced by nuclear power plants. These products have to be managed and stored with extreme caution in order to avoid contaminating the surrounding habitat[4]. Nuclear power facilities not only generate radioactive waste but also require substantial quantities of water for cooling purpose. This can exert a substantial influence on local water supplies, especially in regions where water shortage is already a matter of concern[5]. There are 448 Nuclear Power Plants (NPPs) spread across 31 countries in 2015. Of these, the United States is the country with the most NPP owners at 99, followed by France with 58 NPP, Japan with 48 NPP, Russia with 35 NPP, and many other countries. Based on data from the same year, there were 60 nuclear power plants under construction in 16 countries, with 20 of them in China. Of the 16 countries that are building the nuclear power plant, there are two countries that will have the first nuclear power plant, namely Belarus and the United Arab Emirates[6].

According to figures published by the World Nuclear Association in August 2024, nuclear plants supplied 2602 TWh of power in 2023, up from 2545 TWh in 2022.

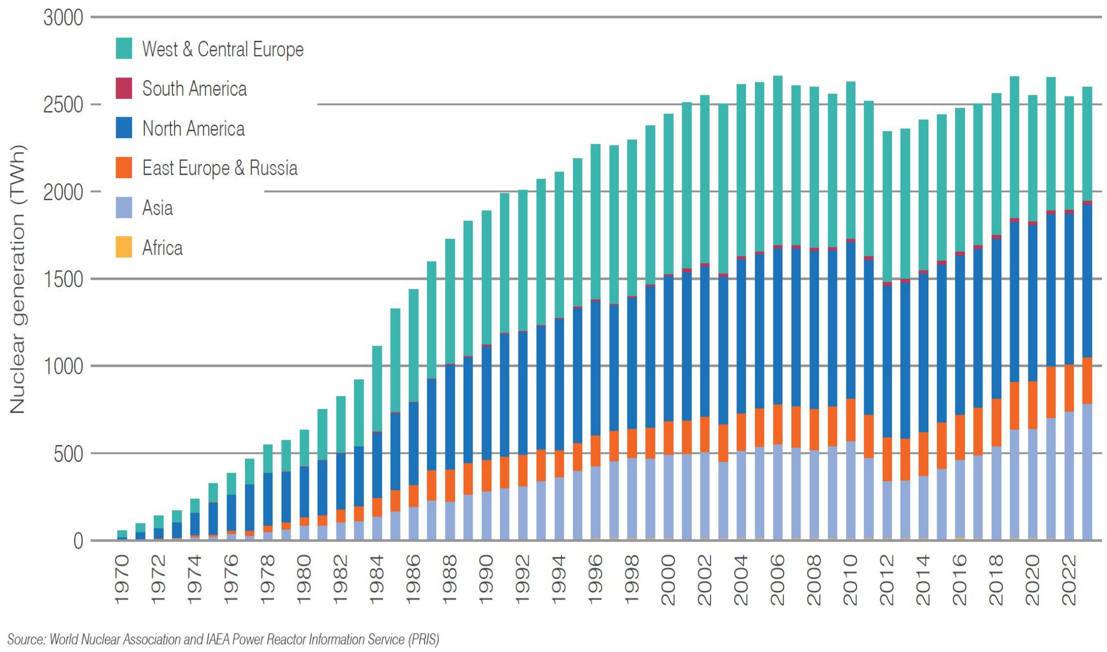

Figure 1: Nuclear electricity production 1970-2023 (source: World Nuclear Association)

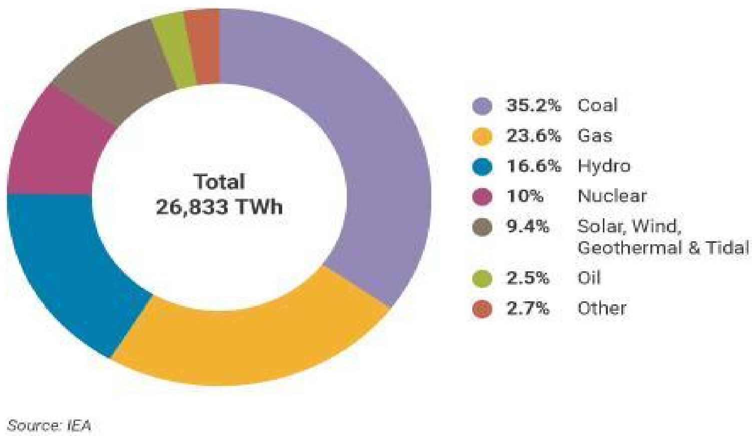

Figure 2: World electricity production by source 2020 (source: World Nuclear Association)

In 2023, at least 25% of the electricity produced in 14 countries came from nuclear sources. Nuclear energy supplies roughly half of the electricity in Hungary, Slovakia, and the Ukraine, but up to 70% of France's electricity comes from it. Over twenty-five percent of Japan's electricity was generated by nuclear power, and same percentage is predicted to reappear.

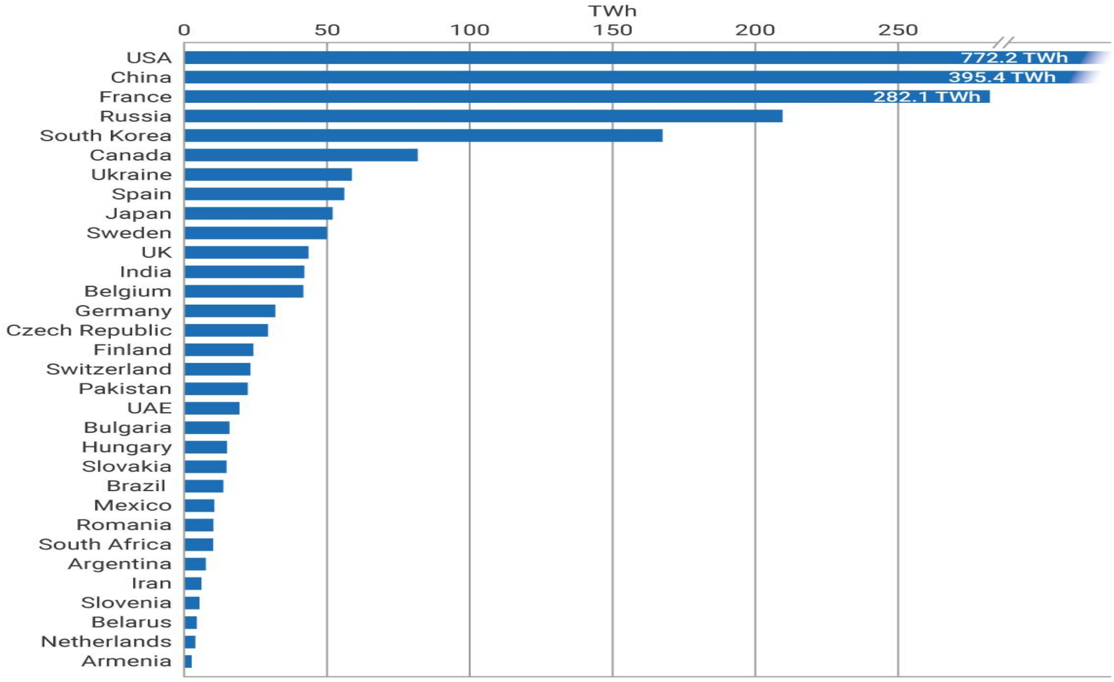

Figure 3: Nuclear generation by country 2023 (source*: World Nuclear Association).*

There is an obvious need for new generating capacity around the world, both to replace obsolete fossil fuel units, particularly coal-fired ones that produce significant amounts of carbon dioxide, and to satisfy increasing demand for electricity in various countries. In 2022, fossil fuels accounted for 61% of all energy generation. The share of fossil fuels in power generation has not changed substantially over the previous 15 years or so, despite the significant encouragement and expansion of unreliable renewable electricity sources in recent years[7].

1.2 STATEMENT OF THE PROBLEM

Using the energy that is released from nuclear fission or fusion reactions, nuclear power plants are able to generate electricity. A substantial amount of electricity may be generated from a relatively small amount of fuel, which is a quality that differentiates them from other types of energy sources. The potential for accidents in a disposal of radioactive waste, and the mining of uranium are being cited as key downsides by those who are opposed to the proposal. The environmental impact of nuclear power for the generation of electricity will be investigated in this study, which will also investigate the opportunities and challenges presented by this technology.

1.3 RESEARCH QUESTION

The research will be guided through the following question:

1. What are the greenhouse gas emissions from nuclear power plants?

2. What are the risks of radioactive waste from nuclear power plants?

3. What are the environmental consequences of nuclear accidents?

4. How does the environmental impact of nuclear power plants compare to other sources of electricity generation, such as fossil fuels and renewable energy sources?

1.4 RESEARCH JUSTIFICATION

the study on the environmental impact of nuclear power plants for generating electricity brings attention to several significant issues, such as the handling of radioactive waste, the utilization of water, the destruction of habitats, and the release of greenhouse gases. It is obvious that careful investigation is required to evaluate the whole range of environmental effects connected to nuclear energy generation, regardless of the claims of some activists that nuclear power could slow down climate change by reducing carbon emissions. The research will also discuss the ethical aspects that must be taken into account when doing research on the impact that nuclear power plants have on the environment. Through this research, the potential for injury to human and the environment will be significantly reduced to a minimum. There will be accountability and transparency in the way that the research is carried out. Research will be used to inform the nuclear power policy and decision-making. It is also planned to distribute the findings of the research through a different channels, including public presentations and scholarly publications.

1.5 AIM AND OBJECTIVES

1.5.1 Aim

The aim of this research is to assess environmental impact of nuclear power plant for electricity generation

1.5.2 Objectives

The specific objectives of the study are as follows:

- Gather and evaluate data about the emissions of greenhouse gases, the use of water, and the generation of radioactive waste by nuclear power plants.
- Conduct a literature review on the effects that nuclear accidents have on the surrounding ecosystem.
- To determine the environmental standards and norms that are applicable to nuclear power plants or facilities.

2. LITERATURE REVIEW

2.1 Overview Of Nuclear Power Plant

A nuclear power plant is a facility that uses nuclear reactions to generate electricity. The fuel used in a nuclear power plant consists of enriched uranium oxide pellets, which are organized into fuel rods and then joined into fuel assemblies. The fuel assemblies in the reactor core undergo nuclear fission processes, resulting in the release of heat. It consists of a nuclear reactor (i.e heat chamber) which produces heat through nuclear fission, and a steam turbine which converts the heat into electricity. The nuclear reactor uses uranium or plutonium as fuel and generates a controlled chain reaction to produce heat. This heat is then used to produce steam and the heat produced turn the turbines connected to generators to produce electricity[8].

Nuclear power is the only possible replacement of the fast exhausting fossil fuels through its rate of growth has been disappointingly slow than what was expected. Initial delays were associated with establishing operational reliability and high cost of commercialization of nuclear power[9].

The unit cost per kilowatt-hour for nuclear power are now comparable to or lower than unit costs for other sources in most parts of the world[10]. And also the countries that depend on oil but do not have their own can reduce the import of oil when the nuclear power plant is constructed. Nuclear power plant is composed with the components and the abridgment of the components are listed here. The reactor vessel, it contains the nuclear reactor core and is the heart of a nuclear power plant, because is the place where a controlled nuclear fission processes occur. It is made up of a steel cylinder with strong walls that can tolerate high temperatures and pressures without losing its ability to protect the reactor core. Control rods work in the reactor core to regulate the speed of nuclear fission processes. These rods have the ability to absorb neutrons. Operators have the ability to regulate the heat production and power output of the reactor by adjusting the position of the control rods. These rods are essential for ensuring the stability of the nuclear reaction. The coolant system is a fluid that flows within the reactor core, absorbing the thermal energy emitted by the nuclear processes. Subsequently, the high-temperature coolant is circulated to a heat exchanger, where it converts it's thermal energy to water in a separate circuit. Water, heavy water, and liquid sodium are the most prevalent types of coolants. Water is the predominant coolant owing to its widespread availability and cost-effectiveness. The steam generator functions as a heat exchanger, facilitating the transfer of heat from the coolant to water in a distinct loop. The thermal energy in the secondary loop undergoes a phase change, transforming the hot water into steam, which subsequently propels the turbine. The turbine is a rotating machine that converts the high-pressure steam into mechanical energy. The turbine is connected to a generator through a shaft. As the turbine spins, it rotates the generator's rotor, generating electricity and then after driving the turbine, the steam is cooled and condensed back into water in a condenser. The cooled water is then pumped back to the steam generator to complete the cycle[11].

The Main Control Room (MCR) of a nuclear power plant is the most important part of the facility. It is a place that has been precisely planned and is equipped with the finest technology. It is in this room that highly qualified operators are responsible for coordinating the complex processes that generate electricity from nuclear fission occurring in the nuclear reactor. Within this control center, a dedicated team of operators, which normally involves between three to five personnel depending on the size and complexity of the plant, bears the task of supervising the operation of the plant, ensuring that it is safe, and maintaining its reliable operation. As the central command station, the MCR is responsible for giving operators with a full picture of the plant's systems and activities. This is accomplished through the utilization of a network of specialized instrumentation and control panels. These displays give immediate information on reactor status, turbine operations, coolant flows, and other critical parameters, enabling operators to identify and respond to any possible changes or abnormalities promptly and effectively. The role of the MCR operators extends far beyond mere monitoring. They constantly assess the plant's performance, analyzing trends and patterns to detect subtle changes that could signal impending issues. Additionally, they engage in meticulous planning and coordination, ensuring that maintenance activities, equipment inspections, and other routine procedures are carried out seamlessly without disrupting the plant's continuous operation. So also, the MCR operators' responsibilities encompass a wide spectrum of expertise, requiring a blend of technical proficiency, critical thinking skills, and unwavering vigilance. They must possess a deep understanding of nuclear power plant principles, reactor dynamics, and safety protocols, while simultaneously demonstrating the ability to analyze complex data, make timely decisions, and maintain composure under pressure. The MCR is a testament to the intricate interplay of technology and human expertise that underpins the safe and efficient operation of nuclear power plants. It stands as a symbol of the dedication and expertise of nuclear power plant operators, who play a vital role in ensuring that this clean and reliable energy source continues to power our world[12].

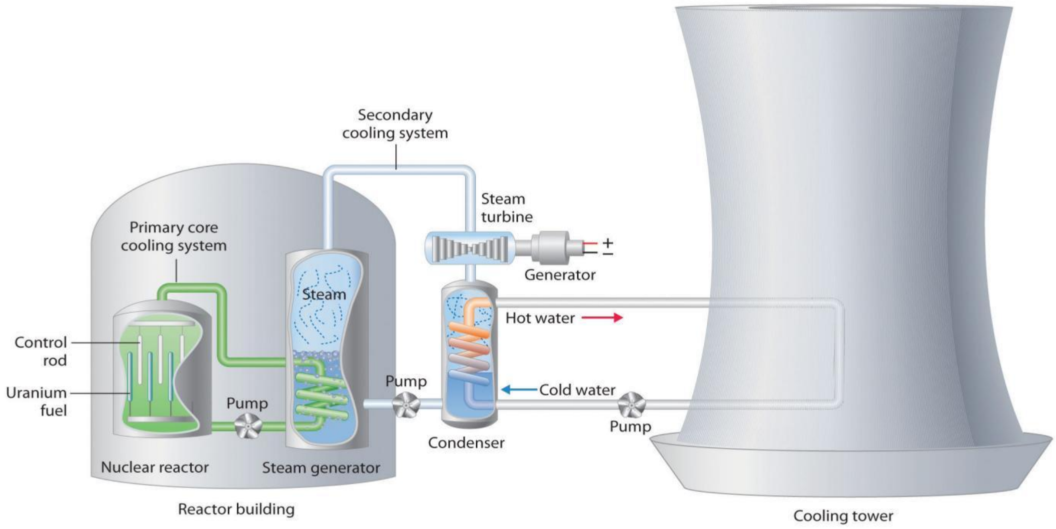

Figure 4. A Systematic diagram of working condition of nuclear power plant Source: Nuclear Power- Using Fission to Generate Electricity. (2021, January 19)

The fuel rods are made of a corrosion-resistant alloy that encases the partially enriched uranium fuel; controlled fission of 235U in the fuel produces heat. Water surrounds the fuel rods and moderates the kinetic energy of the neutrons, slowing them to increase the probability that they will induce fission. Control rods that contain elements such as boron, cadmium, or hafnium—which are very effective at absorbing neutrons—are used to control the rate of the fission reaction. A heat exchanger is used to boil water in a secondary cooling system, creating steam to drive the turbine and produce electricity. The large hyperbolic cooling tower, which is the most visible portion of the facility, condenses the steam in the secondary cooling circuit; it is often located at some distance from the actual reactor[13].

Even though nuclear energy has various advantages,also there are disadvantages or risks from using nuclear energy itself. There have been two fatal accidents caused by nuclear power plants, namely the Chernobyl tragedy in 1986 and the Fukushima tragedy in 2011[14].

The Chernobyl tragedy in 1986 had a significant impact on the environment. Based on research results, it is estimated that in 2005 there were 7,000 cases of thyroid cancer in groups of people exposed to radioactive radiation from the Chernobyl tragedy[15].Apart from that, the tragedy which was mainly caused by very minimal safety standards at the local and national level resulted in the evacuation and relocation of around 300,000 citizens of the Soviet Union. Contamination from the Chernobyl tragedy had an impact on the forestry sector which affected plant growth in various forests in the Soviet Union and Northern Europe and increased the potential for forest fires in these areas. Meanwhile, various freshwater ecosystems in both Western Europe and the Soviet Union experienced high levels of contamination for several years since the tragedy occurred[16].

As reported that Japan is the country with the third largest number of nuclear power plants in the world in 2015, the energy production produced by nuclear power plants is among the lowest in the world due to the Fukushima tragedy. NPP contributed 31% of the total energy mix in Japan in February 2011 and then dropped to 0% in May 2012 for thorough inspection and checking[17]. Research also shows that freshwater biota in Fukushima is exposed to severe pollution and the greater the exposure of animals, the greater the level of radionuclide pollution[18]. Various radionuclide contents are found in various types of fish and this can be spread mainly by migratory animal species such as tuna.

Apart from the risk of a nuclear power plant disaster which can endanger the environment and the people around the nuclear power plant, the waste of nuclear fuel can be a risk to the environment and society. The waste fuel used in the operation of a nuclear power plant requires a high level of management in its processing. Based on data for 2010, it is estimated that there are 250,000 tons of nuclear fuel waste that require permanent disposal. Permanent disposal sites are increasingly important because the waste has a high level of radioactivity for up to one million years[19].

However, a place for storing or disposing of nuclear waste cannot be used as a long-term solution, mainly because of the space needed and the increasing use of nuclear energy. There is a need for careful planning, direction, and funding to create a sustainable and permanent solution to addressing the problem of nuclear fuel waste[20].

Based on the background and literature review described, one would be interested in studying the dilemma that occurs regarding the advantages or advantages that can be generated by nuclear energy with the risks or disasters that can occur from nuclear energy itself.

2.2 Nuclear processes

According to nuclear particle experiments, the total mass of a nucleus (m_{nuc}) is less than the sum of the masses of its constituent nucleons (protons and neutrons). The mass difference, or mass defect, is given by

$|\Delta m| = Zm_p + (A - Z)m_n - m_{nuc}$

Where Zm_p is the total mass of the protons, $(A - Z)m_n$ is the total mass of the neutrons, and m_{nuc} is the mass of the nucleus.

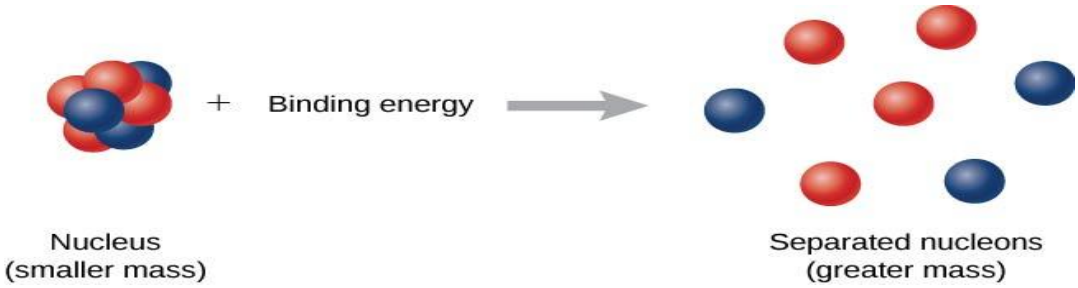

Figure 5: Binding energy

The binding energy is the energy required to break a nucleus into its constituent protons and neutrons. A system of separated nucleons has a greater mass than a system of bound nucleons[21]. Each nucleus, consisting of protons and neutrons (collectively known as nucleons), has an associated binding energy. A graph of binding energy per nucleon is shown in the graph below. The total binding energy of a nucleus is the energy released when a nucleus is assembled from individual nucleons; the greater the energy release, the lower the potential energy of the nucleus, so higher binding energy in the graph represents greater stability. When one nucleus is converted to another or others of higher binding energy, whether that be through a natural radioactive process or through an artificially induced process, the difference in the total binding energies of the nuclei is released as kinetic energy of the particles produced and gamma rays. This energy can be harnessed through traditional methods, e.g. by heating water to generate steam to drive a turbine, and so electricity can be produced[22].

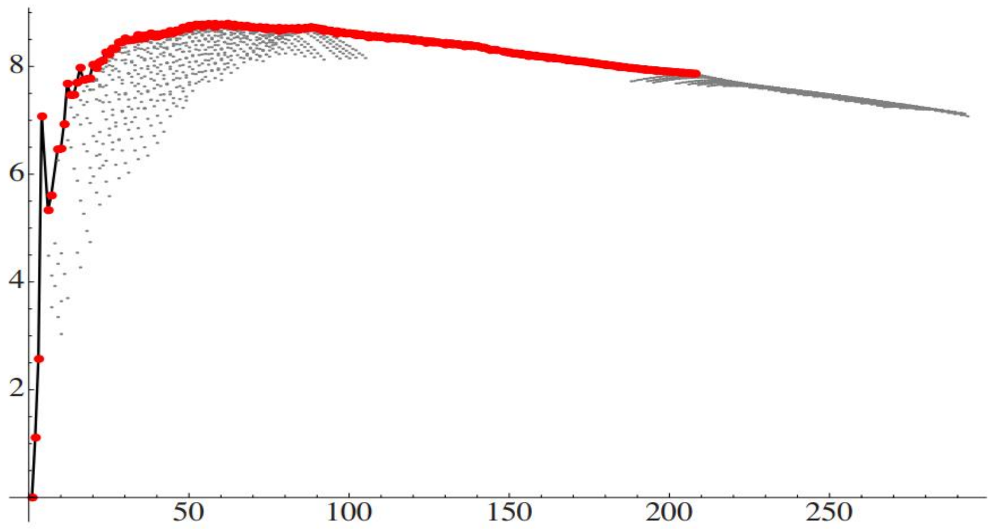

Figure 6: Binding energy per nucleon n (B/A in MeV vs. A) of stables nuclides (Red) and unstable nuclides (Gray). (CC BY-NC-ND; Paola Cappellaro)[23]

2.2.1 Nuclear Fission

Fission is a case of (n, f) reaction, a special case of transmutation reaction. Uranium is the most important nuclear fuel. The natural uranium contains about 0.7% U^{235}, 99.3% U^{238}, and a trace amount of U^{234}. Here, we discuss the neutron-induced nuclear fission, which is perhaps the most significant nuclear reaction. When a slow (thermal) neutron gets absorbed by a $5U^{235}$ atom, it leads to the formation of an unstable radionuclide U^{236}, which acts like an unstable oscillating droplet, immediately followed by the creation of two smaller atoms known as fission fragments (not necessarily of equal mass). About 2.5 neutrons on average are also released per fission reaction of U^{235}.An average energy of 193.5MeV is liberated. A bulk of the energy (160 MeV or 83%)is carried out by the fission fragments, while the rest by the emitted neutrons, gamma rays, and eventual radioactive decay of fission products. Fission fragments rarely move more than 0.0127 mm from the fission point and most of the kinetic energy is transformed to heat in the process. As all of these newly formed particles (mostly fission fragments) collide with the atoms in the surroundings, the kinetic energy is converted to heat.The fission reaction of U^{235} can occur in 30 different ways leading to the possibility of 60 different kinds of fission fragments. A generally accepted equation for a fission reaction is given below:

U_{92}^{235}+n_0^1 → Kr_{36}^{92}+Ba_{56}^{142}+$2n_0^1$+Energy,

which represents the fission of one U^{235} atom by a thermal neutron resulting into the fission products (Kr and Ba) with an average release of two neutrons and an average amount of energy (see above). It is clear from the atomic masses of the reactant and products, that a small amount of mass is converted into an equivalent energy following Einstein's famous equation $E = MC^2$.

U^{235} is the one and only naturally occurring radioisotope (fissile atom) in which fission can be induced by thermal neutrons. There are two other fissile atoms (Pu^{239} and U^{235}) that are not naturally occurring. They are created during the neutron absorption reactions of U^{238} andTh^{232} respectively. Each event consists of (n, γ) reactions followed by beta decays. Examples are shown below:

U_{92}^{238}+n_0^1→ $U_{92}^{239} + \gamma$ ………………………………………1

$U_{92}^{238} \rightarrow Np_{93}^{239}$+$\beta^-$, $t_{1/2}$=23.5min……………………….2

$Np_{93}^{239} \rightarrow Pu_{94}^{239}$+$\beta^-$, $t_{1/2}$=23.5 days……………………….3

Th_{90}^{232}+n_0^1 → $Th_{90}^{233} + \gamma$……………………………………………4

$Th_{90}^{233} \rightarrow Pa_{91}^{233}$+$\beta^-$, $t_{1/2}$=22.4min……………………..5

$Pa_{91}^{233} \rightarrow U_{92}^{233}$+$\beta^-$, $t_{1/2}$=27.0 days………………………………6

The concept of the "breeder" reactors is based on the preceding nuclear reactions, and U^{238} and Th^{232} are known as "fertile" atoms. Heavy radioisotopes such as Th^{232},U^{238}, and Np^{237} can also undergo neutron-induced fission, however, only by fast neutrons with energy in excess of 1 MeV. That is why these radionuclides are sometimes referred to as "fissionable"[24]. U-235 fission can produce a nuclear chain reaction. In a compound consisting of many U-235 nuclei, neutrons in the decay of one U-235 nucleus can initiate the fission of additional U-235 nuclei (Figure 7 below). This chain reaction can proceed in a controlled manner, as in a nuclear reactor at a power plant, or proceed uncontrollably, as in an explosion.

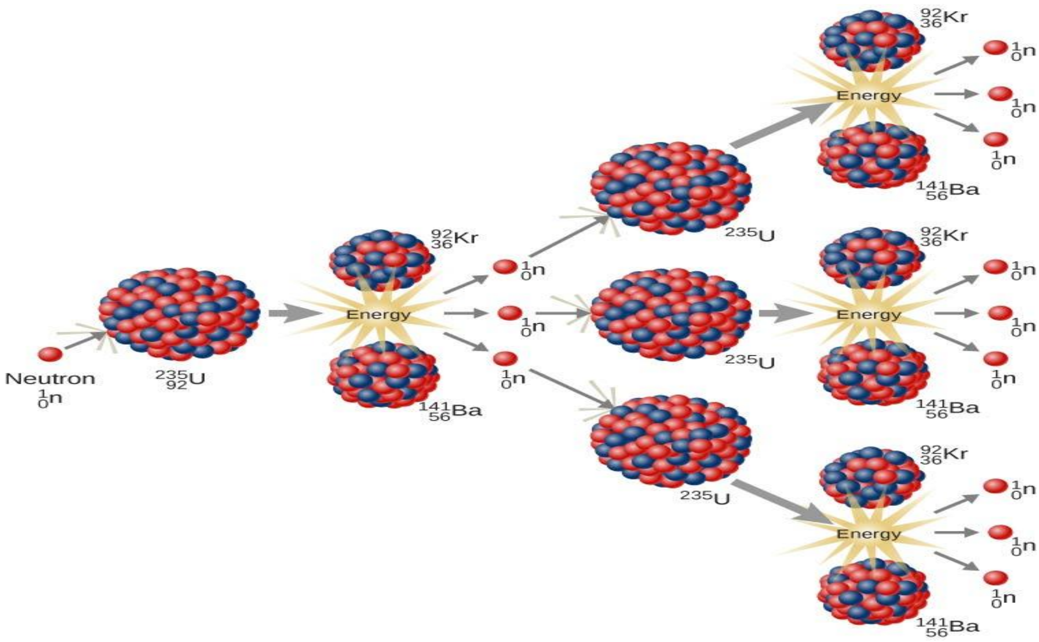

Figure 7: In a U-235 fission chain reaction, the fission of the m nucleus produces high-energy neutrons that go on to split more nuclei. The energy released in this process can be used to produce electricity[25].

2.3 Nuclear Reactor

A nuclear reactor is a device used to initiate and control a fission nuclear chain reaction or nuclear fusion reactions. Nuclear reactors are used at nuclear power plants for electricity generation and in nuclear marine propulsion. Heat from nuclear fission is passed to a working fluid (water or gas), which in turn runs through steam turbines.These either drive a ship's propellers or turn electrical generators' shafts. Nuclear generated steam in principle can be used for industrial process heat or for district heating. Some reactors are used to produce isotopes for medical and industrial use, or for production of weapons-grade plutonium. As of 2022, the International Atomic Energy Agency reports there are 422 nuclear power reactors and 223 nuclear research reactors in operation around the world[26].

A nuclear reactor produces and controls the release of energy from splitting the atoms of certain elements. In a nuclear power reactor, the energy released is used as heat to make steam to generate electricity[27].

2.3.1 Types Of Nuclear Reactor

The common types of nuclear reactors that are employed for power generation are as follows:

2.3.2 Pressurized water reactor (PWR)

A pressurized water reactor (PWR) constitutes the large majority of the world's nuclear power plants (with notable exceptions being the UK, Japan and Canada). Pressurized water reactor (PWR) have water in a primary circuit and generate steam in a secondary circuit. PWRs also operate with UO2 as the fuel and H2O as the moderator as well as the coolant. The reactor core in a large PWR comprises of 150 to 200 fuel assemblies, or more. The fuel assemblies of the PWR are comprised of a 14 × 14 to 17 × 17 square array of fuel pins or up to 331 hexagonal fuel pins. In the PWRs, there is no metal fuel channel as the single-phase primary fluid (water) operated better than the BWR's boiling coolant. The water in the primary loop is maintained as a liquid under high pressure and enters the steel reactor vessel containing the core through inlet nozzles. The water flows downward along the inner vessel wall and flows up through the fuel assemblies gathering heat energy, and exits through the outlet nozzle as a liquid. The heat energy from the primary loop is extracted by the steam generators (secondary circuit) that convert the water into steam. The reactivity control is implemented through neutron-controlling fuel rods (made of boron carbide-filled pins) and soluble neutron poison boric acid. The steam-water mixture that leaves from the top of the secondary circuit enters the stages of moisture separation. The steam line then directs the steam to turn the turbine generator to produce electricity.

In a PWR, the primary coolant (water) is pumped under high pressure to the reactor core where it is heated by the energy released by the fission of atoms. The heated, high pressure water then flows to a steam generator, where it transfers its thermal energy to lower pressure water of a secondary system where steam is generated. The steam then drives turbines, which spin an electric generator. In contrast to a boiling water reactor (BWR), pressure in the primary coolant loop prevents the water from boiling within the reactor. All light-water reactors use ordinary water as both coolant and neutron moderator. Most use anywhere from two to four vertically mounted steam generators; VVER reactors use horizontal steam generators.[27]

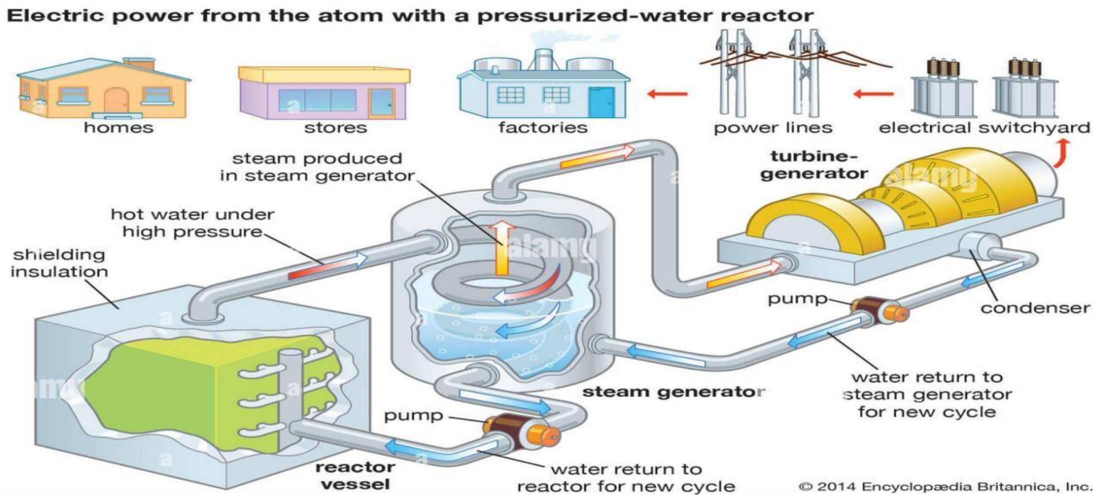

Figure 8: Pressurized water reactor diagram

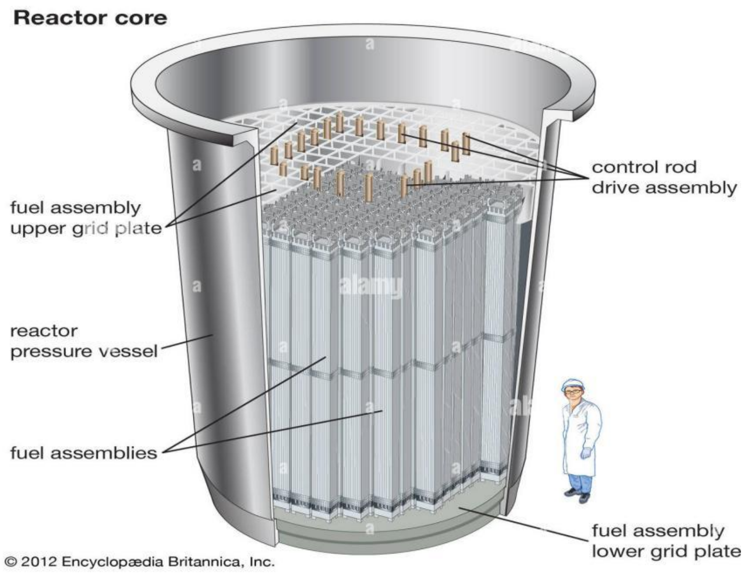

Figure 9: Pressurized-water reactor core

figure 5 and 6 are sourced from Encyclopedia britannica inc., january 2014)[28]

2.3.3 Boiling water reactor (BWR)

A boiling water reactor (BWR) is a type of light water nuclear reactor used for the generation of electrical power. It is the second most common type of electricity-generating nuclear reactor after the pressurized water reactor (PWR), which is also a type of light water nuclear reactor.

BWRs are a single-loop system that makes steam in the primary circuit itself above the reactor core. BWRs generally operate using uranium dioxide (UO2) as the fuel and water (H2O) as the moderator as well as the coolant. The reactor core in a BWR comprises of up to 800 fuel assemblies or more. The fuel assemblies of the BWR are comprised of a 7 × 7 to 10 × 10 square array of fuel pins, surrounded by a metal fuel channel that prevent the movement of steam-water mixture between the fuel assemblies, thereby ensuring adequate cooling of the fuel assemblies. The feedwater (pumped into the steel reactor vessel containing the core) is converted to steam as a result of the heat generated by fission chain reactions occurring within the fuel pins. The reactivity control is implemented through a combination of neutron-controlling fuel rods (made of boron carbide-filled pins) and coolant flow adjustment. The steam-water mixture that leaves from the top of the core enters the stage of moisture separation where the water droplets are removed before the steam is allowed to enter the steam line. The steam line then directs the steam to turn the turbine generator to produce electricity.

The main difference between a BWR and PWR is that in a BWR, the reactor core heats water, which turns to steam and then drives a steam turbine. In a PWR, the reactor core heats water, which does not boil. This hot water then exchanges heat with a lower pressure system, which turns water into steam that drives the turbine. The BWR was developed by the Argonne National Laboratory and General Electric (GE) in the mid-1950s. The main present manufacturer is GE Hitachi Nuclear Energy, which specializes in the design and construction of this type of reactor[29].

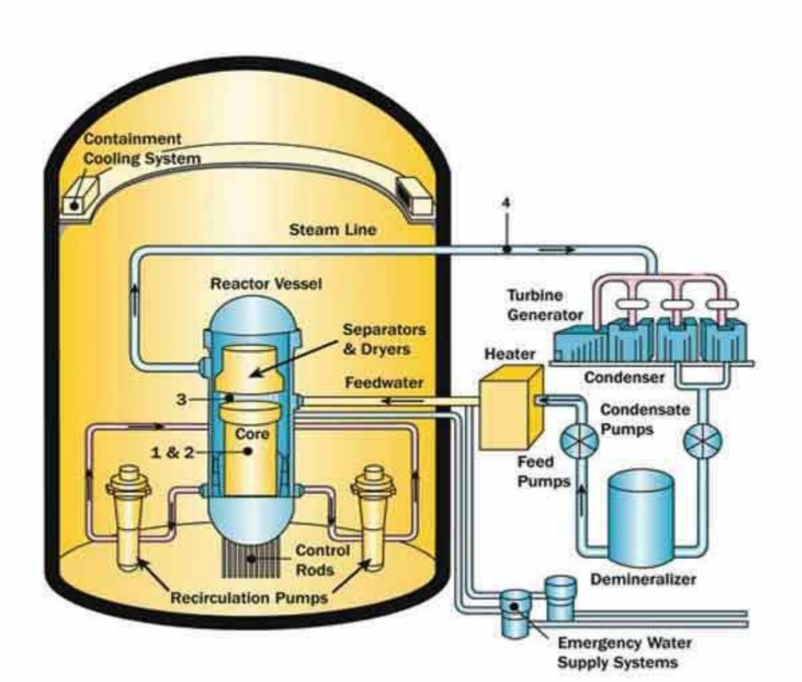

Figure 10. Scheme of typical Boiling Water Reactor (BWR) NPP (courtesy of NRC USA): General basic features-1) thermal neutron spectrum; 2) uranium-dioxide (UO 2) fuel; 3) fuel enrichment about 3%; 4) direct cycle with steam separator (steam generator and pressurizer are eliminated), i.e., single-flow circuit (single loop); 5) RPV with vertical fuel rods (elements) assembled in bundle strings cooled with upward flow of light water (water and water-steam mixture); 6) reactor coolant, moderator and power-cycle working fluid are the same fluid; 7) reactor coolant outlet parameters: Pressure about 7 MPa and saturation temperature at this pressure is about 286°C; and 8) power cycle-subcritical-pressure regenerative Rankine steam-turbine cycle with steam reheat[30].

2.3.4 Heavy-water-moderated reactor (HWR)

Heavy-water-moderated reactors are also a two-loop system like PWRs with the exception that heavy water (in primary loop) transfers the heat to water (in secondary loop) for generation of steam. The HWRs operate with CO_2 as the fuel and heavy water/deuterium oxide (D_2O) as the moderator as well as the coolant. The Canadian Deuterium-Uranium (CANDU) reactor is the signature representative of HWRs. The pressurized heavy water (PHW) CANDU also contains a two-loop system, like the PWRs, with the primary PHW loop transferring the heat to a loop of ordinary water for steam production. The primary fluid, i.e., the PHW is distributed among the pressure tubes that pass through a large Calandria vessel that contains a separate heavy water moderator. The coolant is collected in two separate loops. The fuel assemblies of the HWRs are comprised of uranium dioxide fuel pellets clad in zirconium. The reactivity control is accomplished through online fueling (a machine-based technique that enables changing the fuel of a nuclear reactor, while the reactor is critical) that is required to compensate for low reactivity inherent in natural uranium. The steam-water mixture that leaves from the top of the secondary circuit enters the stage of moisture separation for segregation of steam, which is passed in to the steam line to finally turn the turbine generator for producing electricity[31].

Figure 11: Scheme of CANDU-6 reactor (PHWR) NPP (courtesy of AECL): General basic features-1) thermal-neutron spectrum; 2) natural uranium-dioxide (UO_2) fuel; 3) fuel enrichment about 0.7%; 4) indirect cycle with steam generator (also, a pressurizer required (not shown)), i.e., double-flow circuit (double loop); 5) pressure-channel design: Calandria vessel with horizontal fuel channels (see Fig. 10c); 6) reactor coolant and moderator separated, but both are heavy water; 7) reactor coolant outlet parameters: Pressure about 9.9 MPa and temperature close to saturation (310°C); 8) on-line refuelling; and 9) power cycle-sub critical-pressure regenerative Rankine steam-turbine cycle with steam reheat (working fluid light water, turbine steam inlet parameters: Saturation pressure of ~4.6 MPa and saturation temperature of 259°C)[32].

2.3.5 Gas-cooled reactor (GCR)

A GCR is cooled by a gas. The gas absorbs heat from the reactor; this hot coolant then can be used either directly as the working fluid of a combustion turbine to generate electricity or indirectly to generate steam. There are two different types of GCR. One type utilizes both natural- and enriched-uranium fuels with CO2 as coolant and graphite as moderator. Another one uses enriched fuels, helium as coolant, and heavy water as moderator.

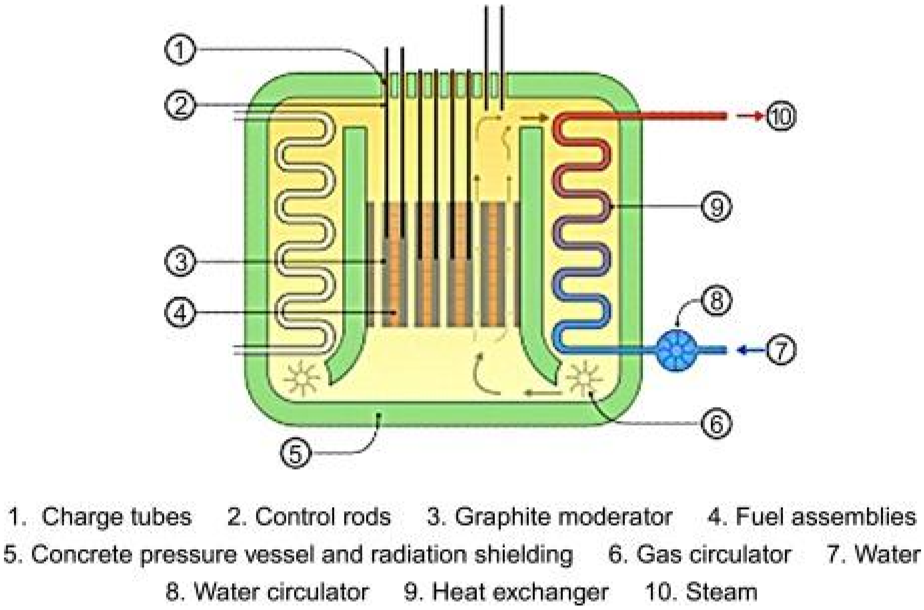

Figure 12: Sectional view of a typical gas-cooled reactor.

Source: From Fig. B.4, P 557. D.K. Sarkar, Thermal Power Plant–Design and Operation, 2015, Elsevier; Amsterdam, Netherlands[33].

2.3.6 Advanced Gas Cooled Reactor

The AGR is a commercial thermal reactor that consists of uranium oxide fuel pellets core in stainless-steel cladding within graphite blocks. The carbon dioxide acts as a coolant while graphite as a moderator. The achievable temperature of the coolant at the reactor output during normal operation is around 650℃, which can be driven up to 750℃ with new designs of further technological developments. The carbon dioxide circulates through the core at 4.3 MPa. However, in the future design and implementation, there is a potential to increase the operating pressure in order to couple it with a direct cycle supercritical CO_2 power conversion system. This coupled system can consequently enable high-efficiency and economic hydrogen production through steam electrolysis at medium temperatures[34].

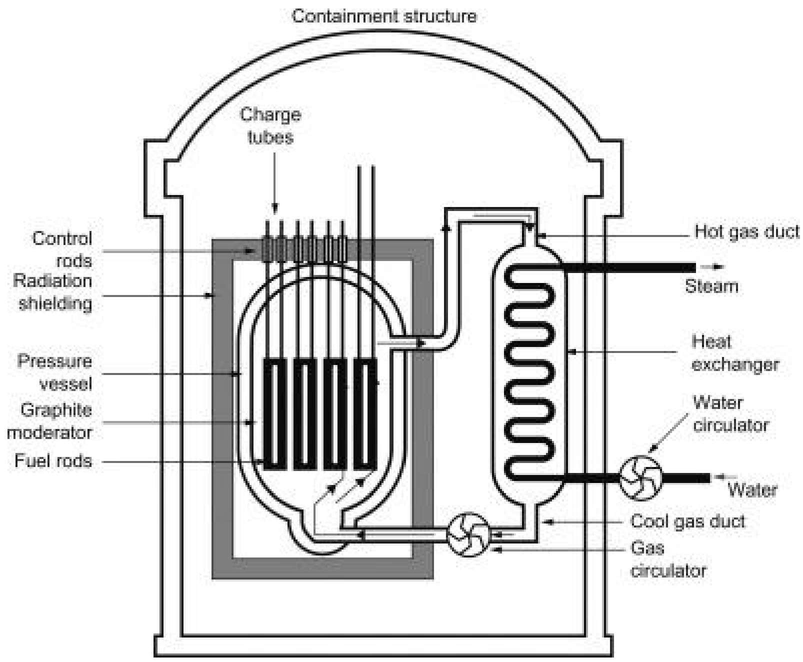

Figure 13:A schematic of an AGR

The advantage of the AGR is that higher temperatures in the core can potentially provide for a higher efficiency of power generation[35].

2.3.7 Light Water Graphite Reactor (LWGR)

LWGR is a group which representative construction is RBMK reactor - Reaktor Bolszoj Moszcznosti Kanalnyj. It is boiling water reactor, light water cooled and with graphite as moderator. This design was developed from army construction to pluton production. It is pressure tube and single circuit reactor. Steam is generated directly in the reactor and separated in steam drums (Fig. 14 below). Water used in RBMK is radioactively contaminated. Reactor should be shielded up as BWR is. The function of the graphite moderator is to slow down the neutrons produced during nuclear fission so that they can more easily collide with other uranium atoms and sustain the nuclear chain reaction. The coolant, usually ordinary water, removes the heat generated by the fission reactions and carries it away from the reactor core to drive steam turbines that generate electricity[36].

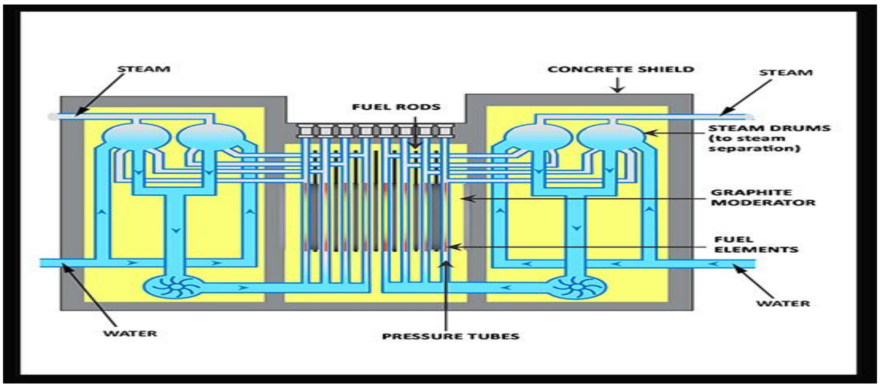

Figure 14. Schematic diagram of LWGR/RMBK construction

Source: "Power Reactors - Characteristics. 2010 WNA Pocket Guide", World Nuclear Association, July 2010[37]

2.4 Nuclear fuel cycle

Nuclear fuel is the fuel that is used in a nuclear reactor to sustain a nuclear chain reaction. These fuels are fissile, and the most common nuclear fuels are the radioactive metals uranium-235 and plutonium-239. All processes involved in obtaining, refining, and using this fuel make up a cycle known as the nuclear fuel cycle[38].. Uranium-235 is used as a fuel in different concentrations. Some reactors, such as the CANDU reactor, can use natural uranium with uranium-235 concentrations of only 0.7%, while other reactors require the uranium to be slightly enriched to levels of 3% to 5%. Plutonium-239 is produced and used in reactors (specifically fast breeder reactors) that contain significant amounts of uranium-238. It can also be recycled and used as a fuel in thermal reactors. Current research is being done to investigate how thorium-232 can be used as a fuel.

The uranium fuel is manufactured into small fuel pellets and are packed into fuel rods and surrounded by cladding to avoid leaking into the coolant. These fuel rods are assembled into a fuel bundle, as seen below. There can be hundreds of fuel bundles in a nuclear reactor, meaning there can be tens of thousands of fuel rods[39].

Figure 15. An enriched nuclear fuel pellet (Wikimedia Commons. (June 17, 2015). *Fuel Pellet*

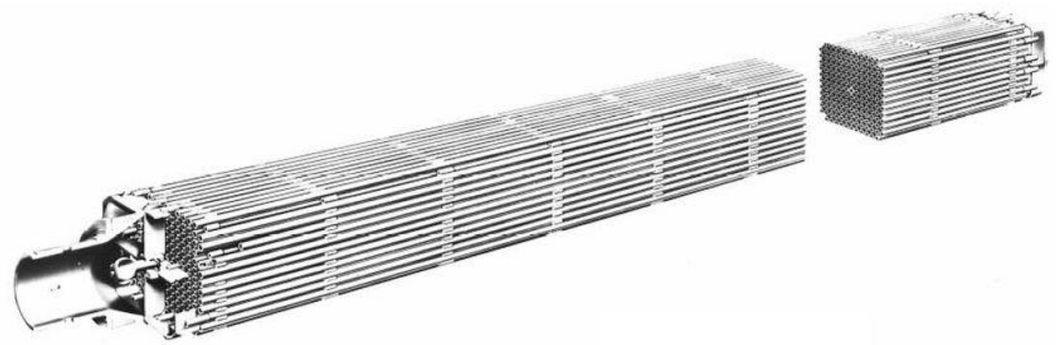

Figure 16: These assemblies are used in boiling and pressurized water reactors, and are packed into the core to produce heat in a nuclear reaction[40].

2.5 Nuclear reactor's lifespan

According to Emmerechts, Raetzke, and Okra (2011), nuclear power plants are typically designed to operate for 30 to 40 years. Between 2010 and 2020 a large number of nuclear power plants in the world and in The Organization for Economic Co-operation and Development (OECD) member countries, in particular, will reach their 30th or 40th anniversary. As of June 2011, out of 440 nuclear power plants operating in the world, approximately 81% had been in operation for more than 20 years and about 35% for more than 30 years.

In most countries with nuclear reactors older than 30 or 40 years, it was decided to continue operating individual plants beyond this initial time frame for which they were licensed or designed (hereinafter referred to as “long-term operation” or “continued operation”). In other countries, where nuclear reactors are approaching the 30/40-year threshold, discussions have started to do the same. Countries in general allow nuclear reactors to continue operating beyond the period that was initially envisaged, permitting a total lifetime of 50 to 60 years, as long as they can be operated safely. The 30th or 40th anniversary is not an “expiry date” from a technical point of view. The design lifetime means that, at the time of licensing, it was demonstrated that the major components would be able to function safely for 30 or 40 years[41].

3. Methodology

3.1 Materials

A comprehensive analysis was conducted on the environmental impact of nuclear power plants for electricity generation by examining a substantial body of recent scientific literature. This literature encompasses a broad spectrum of studies focusing on various factors influencing the environmental effects of nuclear power. The selected research articles and studies were carefully reviewed for their methodological rigor, data quality, and relevance to the topic.

3.2 Methods

This study uses a descriptive qualitative research method with synthesis analysis. Synthesis analysis is used to look at issues regarding the impact of nuclear energy on the environment and make conclusions from a variety of different perspectives . There are several criteria regarding previous studies used in this study. The inclusion criteria of the research used by the authors are articles that discuss the impact of nuclear energy on the environment, as well as articles that use statistical or empirical data to answer research questions. Exclusion criteria from this study were articles that did not address the impact of nuclear energy on the environment and articles that did not use statistical or empirical data to answer research questions[42].

Previous studies examining the environmental impact of nuclear energy were derived from various academic literature sources. As for the research time frame, the researcher is looking for is research from 2015 to 2021. There are several keywords used by researchers in searching for previous research such as "the impact of nuclear energy on the environment", "the impact of nuclear energy in the Chernobyl tragedy", "the impact nuclear energy in the Fukushima tragedy”, and “the impact of nuclear fuel waste on the environment”. In this study, there are several hypotheses regarding the impact of nuclear energy on the environment, some of these hypotheses are:

- Null Hypothesis: Nuclear energy does not affect the environment.

This implies that the use of nuclear energy does not produce any measurable or significant environmental changes, such as pollution or ecological disturbances.

- Alternative Hypothesis: Nuclear energy affects the environment.

This suggests that nuclear energy does contribute to environmental changes, possibly through radioactive waste, heat emissions, or risks associated with nuclear accidents, which may negatively impact ecosystems or human health.

4. Results Presentation

Based on the explanation that has been made before, twenty previous studies are utilized as references for the synthesis analysis. Various previous studies that discussed the impact of nuclear on the environment are then discussed descriptively in order to obtain results regarding these issues.

4.1 Literature Description

Table 1. Literature Description

No.	Name of the Researcher and Year of Research	Research Title	The Scope of The research	Research Purposes	Research Methods
1	Imanaka et al.,2015	Comparison of the Accident Process, Radioactivity Release and Ground Contamination between Chernobyl and Fukushima-1	Chernobyl City and Fukushima City	What is the Comparison between the accident process And the impact of radiation between the Chernobyl tragedy and Fukushima?	Quantitative regression Dependent variable: accident process and radiation contamination Independent variable: Nuclear radiation at Fukushima and Chernobyl
2	Shimura et al.,2015	Public Health Activities for Mitigation of Radiation Exposure sand Risk Communication Challenges after the Fukushima Nuclear Accident	Fukushima City	What steps in the public health sector were used to mitigate the threat of radiation after the Fukushima tragedy in 2011?	Explanative qualitative
3	Aliyu et al., 2015	An Overview of Current Knowledge Concerning the Health and Consequence of the Fukushima Daiichi Nuclear Power Plant (FDNPP) Accident	Fukushima City	What impact did the Fukushima tragedy have on the surrounding environment?	Descriptive quantitative Dependent variable: environment and health Independent variable: nuclear radiation
4	McCombie & Jefferson, 2016	Renewable and Nuclear Electricity: Comparison of Environmental Impacts	Country	What is the comparison between nuclear energy and other renewable energy regarding the resulting impact on the environment?	Quantitative regression Dependent variable: environment Independent variables: nuclear and renewable energy
5	Vayssier, 2016	Severe Accident Management Guidance: Lessons Still to be Learned after Fukushima – The Need for an Industrial Standard	Fukushima City	What are the weaknesses of the nuclear reactor disaster guide (SAMG) and how to overcome these weaknesses?	Descriptive quantitative Dependent variable: nuclear reactor disaster guide Independent variable: Fukushima nuclear power plant accident
6	Hirose, 2016	Fukushima Daiichi Nuclear Plant Accident: Atmospheric and	Fukushima City	What impact did the Fukushima tragedy have on the atmosphere and	Quantitative regression Dependent variable: atmospheric and oceanic Independent

		Oceanic Impacts over the Five Years		oceans around the Fukushima area?	variable: nuclear radiation
7	Steinhauser & Saey, 2016	137Cs in the Meat of Wild Boars: A Comparison of the Impacts of Chernobyl and Fukushima	Chernobyl city and Fukushima city	How does the impact of the Chernobyl and Fukushima tragedies compare to the level of wild boar contamination in the two regions?	Quantitative regression Dependent variable: wild boar species Independent variable: nuclear radiation at Chernobyl and Fukushima
8	Bonzom et al.,2016	Effects of Radionuclide Contamination on Leaf Litter Decomposition in the Chernobyl Exclusion Zone	Chernobyl City	Analyzing the impact of radioactive contamination on the Decomposition process of leaf litter in the Chernobyl exclusion area	Quantitative regression Dependent Variable: leaf litter Independent variable: nuclear radiation
9	Beresford et al.,2016	Thirty Years after the Chernobyl accident:What lessons have we Learned?	Chernobyl City	To analyze how the science of radioecology is used for repairs after the Chernobyl tragedy	Descriptive Qualitative
10	Richter, 2017	Energopolitics and Nuclear Waste: Containing the Threat of Radioactivity	Community	What is the justification for accepting a community group for nuclear fuel waste?	Descriptive qualitative
11	Cotton, 2018	Environmental Justice as Scalar Parity: Lessons from Nuclear Waste Management	Country	Does the nuclear fuel processing infrastructure planning system consider environmental justice?	Explanative qualitative
12	Ramana, 2018	Technical and Social Problems of Nuclear Waste	Country	What are the challenges sand solutions for handling nuclear fuel waste, especially high-level fuel waste?	Qualitative descriptive

13	Uyba et al., 2018	Comparative Analysis of the Countermeasures Taken to Mitigate Exposure of the Public to Radioiodine following the Chernobyl and Fukushima Accidents: Lessons from both accidents	Chernobyl city and Fukushima city	How do the mitigation measures taken at Chernobyl and Fukushima compare to the public's exposure to thyroid radiation?	Qualitative comparative analysis
14	Omar-Nazir etal., 2018	Long-term Effects of Ionizing Radiation after the Chernobyl Accident: Possible Contribution of Historic Dose	Chernobyl City	How does the impact of the radiation produced by the Chernobyl tragedy compare to bird species at the time of the tragedy with bird species today?	Quantitative regression Dependent variable: bird species Independent variable: nuclear radiation
15	Lerebours et al.,2018	Impact of Environmental Radiation on the Health and Reproductive Status of Fish from Chernobyl	Chernobyl City	How will the Chernobyl tragedy affect the health of fish species in Chernobyl and the surrounding area?	Quantitative Regression Dependent Variable: fish species Independent Variable: nuclear radiation
16	Kharecha & Sato, 2019	Implications of Energy and CO2 Emission Changes in Japan and Germany after the Fukushima Accident	Fukushima City	What impact did the Fukushima tragedy have on *CO2*emission levels in Japan and Germany after the tragedy?	Quantitative regression Dependent variable: *CO2* emission levels in Japan and Germany Independent variable: Fukushima nuclear power plant accident
17	Mahmood et al., 2020	The Role of NuclearEnergy in the Correction of Environmental Pollution: Evidence from Pakistan	Country	Did nuclear energy produce *CO2* emissions in Pakistan in 1973-2017?	Descriptive quantitative Dependent variable: *CO2* emissions Independent variable: nuclear energy
18	(Onda et al., 2020)	Radionuclides from the Fukushima Daiichi Nuclear Power Plant in Terrestrial Systems	Fukushima City	What impact did the Fukushima tragedy, especially the outpouring of radionuclides, have on the surrounding environment?	Quantitative regression Dependent variable: environment of the Fukushima region Independent variable: nuclear radiation

19	Beresford et al.,2020	Field Effect Studies in The Chernobyl Exclusion Zone: Lessons to be Learned	Chernobyl City	What are the long term effects of radiation exposure on the environment in the Chernobyl Exclusion Zone?	Quantitative regression Dependent variable: environment in the Chernobyl Exclusion Zone Independent variable: nuclear radiation
20	Antwis et al., 2021	Impacts of Radiation Exposure on the Bacterial and Fungal Microbiome of Smal Mammals in the Chernobyl Exclusion Zone	Chernobyl City	What impact did the Chernobyl tragedy radionuclide radiation have on mammalsin the Chernobyl exclusion zone?	Quantitative regression Dependent variable: mammal species Independent variable: nuclear radiation

Based on the results of 20 studies conducted from 2015 to 2021, it showed that most of the research uses case study objects for nuclear power plant accidents in Chernobyl and Fukushima. The impact of nuclear on the environment itself is represented in various objects such as animals, plants, humans, oceans, air, and CO2 emissions. Most of the research uses quantitative regression methods by obtaining data through direct observation to obtain accurate data. Apart from that, several studies use a comparative approach, especially to compare the situation that occurred after the Chernobyl tragedy with Fukushima

4.2 Findings

Table 2. Research Results

No.	Environment Object	Research Impact	Research Recommendation
1	Animal	Various animal species such as fish, birds, significantly mammals affected by the nuclear and wild boar were power plant accidents in Chernobyl and Fukushima. Nuclear radiation causes disruption to the health system of various animal species.	Periodic carried out surveillance is routinely on animal species in the area where the nuclear power plant accident occurred.
2	Plant	The nuclear power plant accidents in Fukushima and Chernobyl had a significant impact on plants in the two regions. There are various disturbances in the growth system until the death of various types of plants.	Routine control measures are taken in contaminated areas. Apart from that, decontamination efforts are carried out in areas affected by radiation.
3	Human	Nuclear power plant accidents have a significant impact on humans such as population displacement and cancer. Other long-term effects on human health often emerge after the accident.	Various steps such as regular monitoring and decontamination are carried out for the people affected by the nuclear power plant accident.
4	Marine	Although the Chernobyl nuclear power plant accident did not have an impact on the ocean, the Fukushima nuclear power plant accident did have a radiation impact on the surrounding ocean area.	Various mitigation measures have been taken, such as monitoring and decontamination measures to minimize radiation exposure to fish biota and waters around the Fukushima area.

5	Air	Nuclear radiation spread in the air and atmosphere after the nuclear power plant accidents at Chernobyl and Fukushima. The spread of the radiation resulted in contamination and radioactive content in various areas other than the accident area.	Various decontamination and cleaning steps are carried out to prevent more radiation exposure to the air.
6	CO_2 Emission	Nuclear energy can make a significant contribution to reducing CO_2 emissions globally. The operational life of a nuclear power plant, which is relatively long, in the range of 40 to 60 years, makes nuclear energy a substitution option for fossil energy.	There is aneed for collaboration between stakeholders to ensure that the PLTN construction has qualified safety standards to prevent accidents.

5. Discussion And Conclusion

5.1. Nuclear Impact on Environmental Damage

Based on the findings of researchers regarding previous studies discussing the impact of nuclear energy on the environment, 14 out of 20 studies explained that nuclear energy has a negative impact on the environment. 1 out of 20 studies explained that nuclear energy has a positive impact on the environment, and 5 studies focused on other factors such as society and disaster guidance in terms of the impact of nuclear energy on the environment. Of the 14 studies that discussed the negative impacts of nuclear energy on the environment, 5 of them explained the mitigation measures taken while the other 9 only presented data regarding the negative impacts of nuclear energy on the environment. 6 out of 20 studies used the Chernobyl tragedy case study as the research focus, 15 Previous studies discussing the impact of nuclear power plant accidents on the environment in Chernobyl and Fukushima explained in depth the environmental damage caused by nuclear. The nuclear power plant accidents in Fukushima and Chernobyl had a significant impact on both living things around the accident area and the environment itself in the short and long term. Apart from that, nuclear fuel waste requires special attention because nuclear fuel waste that is not managed effectively can damage the environment and the people living around the waste.

5.2. Mitigation Policy to Overcome Negative Impacts of Nuclear on the Environment

When viewed collectively and based on case studies and the focus used by previous researchers, nuclear energy has a negative impact on the environment. However, these negative impacts already have several mitigation measures that can be taken or used to prevent similar incidents from occurring in the future. Various mitigation efforts have been carried out, including decontamination and cleaning efforts carried out after the accident at the Chernobyl Nuclear Power Plant to mitigate its impact on the environment. Long-term health checks are also carried out for people living around the Chernobyl area to treat people exposed to radiation. Mitigation carried out after the Fukushima tragedy is the evacuation and closing of various areas to prevent radiation exposure to the people in the area.

The synthesis analysis in this study focuses on the impact of nuclear energy on the environment, drawing from a comprehensive review of previous research. The studies analyzed explore both the negative and positive environmental impacts of nuclear energy, while also considering other factors such as the social and community aspects related to nuclear fuel waste management. Some of the research remains inconclusive, as it examines broader issues beyond direct environmental effects. This highlights the need for further investigation into nuclear energy's environmental impact from various perspectives and more thorough analysis of these inconclusive areas.

5.3 Conclusion

Based on the results of synthesis analysis that has been carried out from previous studies, especially regarding the Chernobyl, Fukushima, and nuclear fuel waste, there are various important findings. Various previous studies have explained that nuclear power plant accidents can have a significant impact on the environment, especially various species of living things caused by radiation contamination. Nuclear energy can also make a significant contribution to reducing CO2 emissions globally. The operational age of nuclear power plants which can last 40 to 60 years makes nuclear power plants one of the alternatives to replace fossil energy.

Apart from that, there are limitations to this study, mainly due to research that focuses on certain case studies thereby limiting the generalizability of these findings. This conclusion requires attention and further research as a reference material for making nuclear power plants. The author here suggests further research discussing security and mitigation that was carried out after the Chernobyl and Fukushima tragedies and nuclear fuel waste. To develop knowledge in the field of nuclear energy, interdisciplinary collaboration is needed between researchers, policy makers, and stakeholders to develop effective strategies to improve the security system of nuclear power plants and the processing of nuclear fuel waste.

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