OPEN ACCESS
Saudi Journal of Engineering and Technology
Abbreviated Key Title: Saudi J Eng Technol
ISSN 2415-6272 (Print) |ISSN 2415-6264 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Review Article

Nuclear Power Reactor- An Overview

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DOI: 10.36348/sjet.2023.v08i07.001 | **Received:** 28.05.2023 | **Accepted:** 01.07.2023 | **Published:** 04.07.2023

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Abstract

Nuclear energy is the second-highest producer of carbon-free electricity after hydropower. Currently, nuclear energy is generated from fission- where the nuclei of an atom split into several parts; however, research on the energy generation from fusion is ongoing. Nuclear reactors are termed as heart of this process. This paper reviews the major nuclear reactor involved in these reactors' power generation and working and provides a broader aspect of the GEN-IV reactor.

Keywords: Nuclear energy, Electricity, Reactor, Uranium.

INTRODUCTION

The International Atomic Energy Agency defines nuclear energy as the energy released from the nucleus. The nucleus is a core of an atom made of protons and neutrons. This can be produced either by fission – when nuclei of an atom split into several parts or by fusion – when nuclei fuse. Currently, electrical energy is produced by fission, and fusion is under development [1].

A report by International Energy Agency (IEA) states that nuclear power is the second-largest source of low-carbon electricity today after hydropower. In advanced economies, nuclear was the largest source of low-carbon electricity, providing 18% of the supply in 2018. Yet nuclear is quickly losing ground. While 11.2 GW of new nuclear capacity was connected to power grids globally in 2018 – the highest total since 1990 – these additions were concentrated in China and Russia. Nuclear power has avoided about 55 Gt of CO_2 emissions over the past 50 years, nearly equal to 2 years of global energy-related CO_2 emissions. However, despite the contribution from nuclear and the rapid growth in renewables, energy-related CO_2 emissions hit a record high in 2018 as electricity demand growth outpaced increases in low-carbon power [2].

A nuclear reactor is the heart of a nuclear power plant. Their main job is to house and control the nuclear fission heat generated from this is used to spin the turbine to create electricity. Currently, more than 440 commercial reactors are operational around the globe, with 92 alone in the U.S.A [4].

CLASSIFICATION OF NUCLEAR REACTOR [5]

The operating nuclear reactors can be classified on a technology basis as follows:

1. Pressurized water reactors (PWR, approx. 68.8%)
2. Boiling water reactors (BWR, approx. 9.5%)
3. Pressurized heavy water reactor (PHWR/CANDU, approx. 6.5%)
4. Light Water Graphite Reactor (Reaktor Bolshoy Moshchnosti Kanalniy and EGP) (approx. 2.7%)
5. Advanced Gas-Cooled Reactor
6. Sodium-cooled fast breeders
7. GEN-IV Reactors

Since the 1950s, the development of nuclear technology has progressed rapidly with significant improvements. One distinguishes at this moment four reactor generations from GEN-I to GEN-IV. Fig. 15 depicts the reactor generations from the prototype GEN-I reactors to the revolutionary GEN-IV reactors.

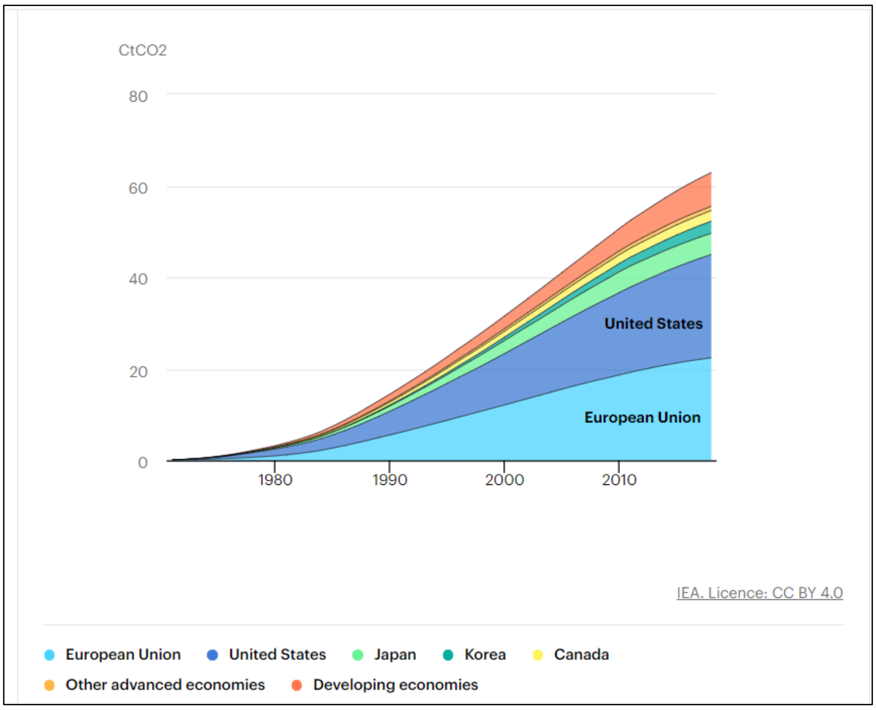

Figure 1: Cumulative CO_2 emission avoided by global nuclear power in selected countries, 1971-2018 [3]

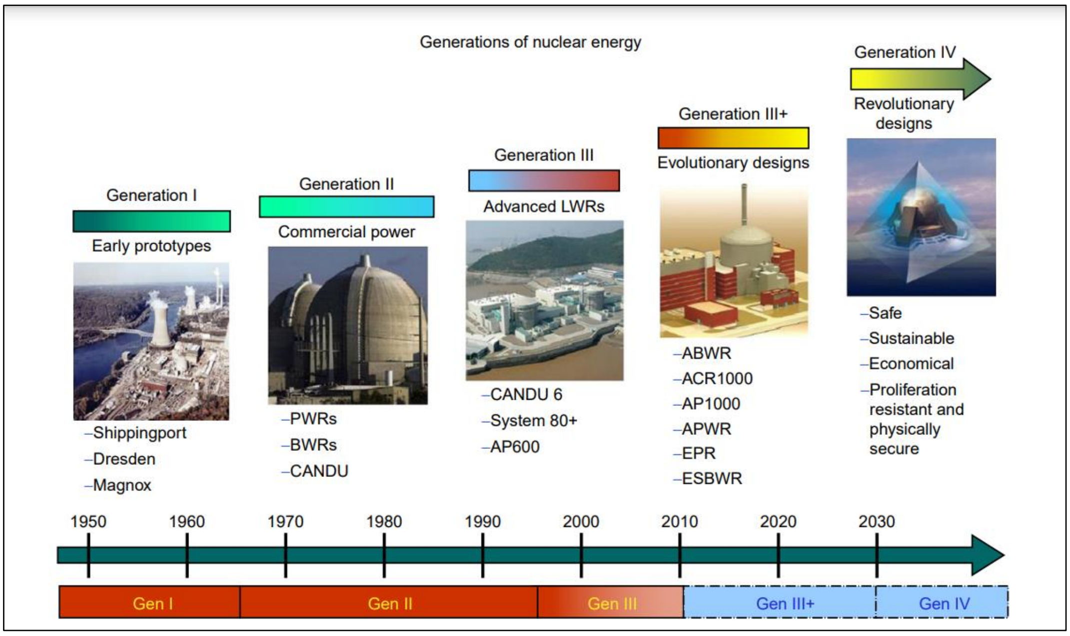

Figure 2: Progress of nuclear technology from generation I to IV (GEN I–IV) reactors [5]

PRESSURIZED WATER REACTOR

Most used reactors in the world. A PWR is divided into primary and secondary coolant circuits [5]. Cooling water is kept in a primary coolant under pressure to avoid boiling. The heat from the primary coolant is transferred to the secondary coolant circuit via the heat exchanger. The water in this second system can boil and generate steam to drive the turbine [7]. Most commercial terrestrial nuclear power plants are PLWR type with 3% to 5% enrichment grades. The weight of the fuel assembly for a PWR is typically approx. 650 kg and contains approx. 320 kg uranium in the form of UO_2 pellets. The nuclear reactor, the pressurizer, and the steam generator are placed in a reinforced steel–concrete building, a so-called containment building with a wall thickness of approx. 1 m. The containment building is built airtight and kept at 300–600 Pa under pressure to avoid radiation leaks leakage into the atmosphere [5]. Here the reactor vessel is subjected to high temperature and high pressure, so the construction material should withstand the entire lifetime of >60 years, which is expected from GEN III+ reactors [5,7]. A typical PWR has a generating capacity of 1000 MW. The efficiency is around 33% [7].

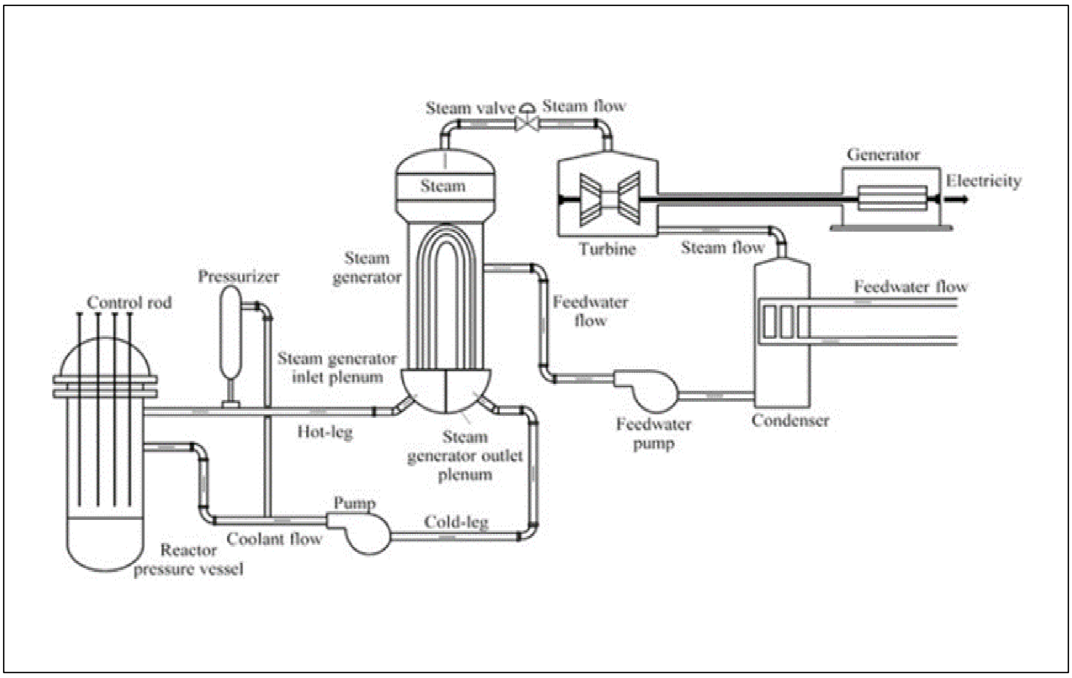

Figure 3: Schematic of a pressurized water reactor [9]

BOILING WATER REACTOR

BWR is a single-loop reactor [8]. In this, the water is boiled under the pressure of 75atm, raising the boiling point to 285°C. The generated steam is used to drive the steam turbine. The used steam is condensed and recycled back to the reactor core [7]. The key advantages of BWR are that they have a simple structure, Higher thermal efficiency because of higher steam temperature, and easier load follow-up. The reactor building contains only the reactor vessel as a main component and Lower investment. [5-6] It uses fuel as UO_2 pellets [5]. This fuel is placed into the reactor as uranium-oxide pellets in zirconium-alloy tubes. There may be as much as 140 tonnes of fuel in 75,000 fuel rods. Refueling a BWR involves removing the top of the reactor. The core is kept underwater, with the water shielding operators from radioactivity. Boron control rods enter the core from beneath the reactor [7]. In this, steam is exposed to the core, and some radioactive contamination is observed in the turbines, making them short-life reactors [7]. BWRs have capacities of up to 1400 MW and an efficiency of around 33% [7].

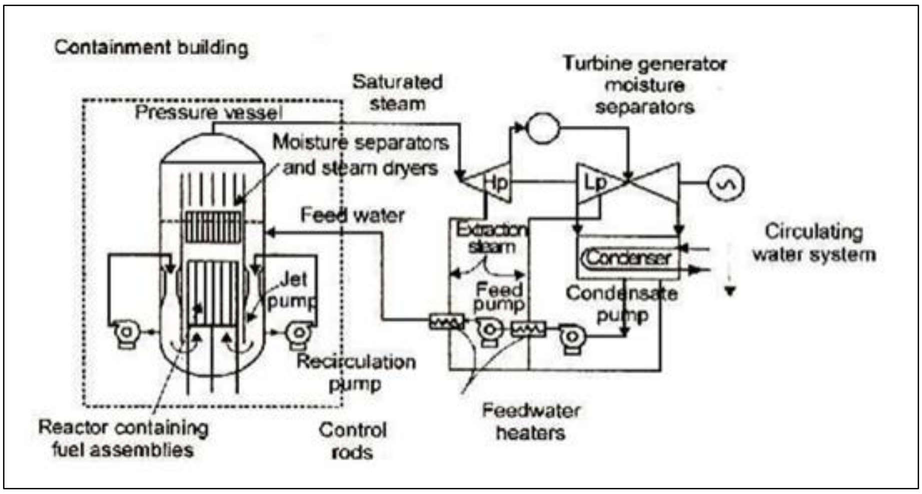

Figure 4: Schematic of a boiling water reactor
(https://www.brainkart.com/article/Construction-and-working-principle-of-Boiling-Water-Reactor-%28BWR%29_5587/)

CANADA DEUTERIUM-URANIUM REACTORS

Canada developed this reactor and used heavy water as a mordent and cooler. Heavy water is a form of water in which the two normal hydrogen atoms have been replaced with two of the isotopic form—deuterium. Each deuterium atom weighs twice as much as a normal hydrogen atom, hence the name heavy water. Heavy water occurs in small quantities in natural water. Heavy water is much more expensive than light water, but it has the advantage that it absorbs fewer neutrons than normal water. Therefore, it is possible to sustain a nuclear reaction without the need to enrich the uranium fuel [7]. The reactor building contains the reactor vessel with core and moderator, the loading and discharging machines on both sides of the core, and the steam generator [6].

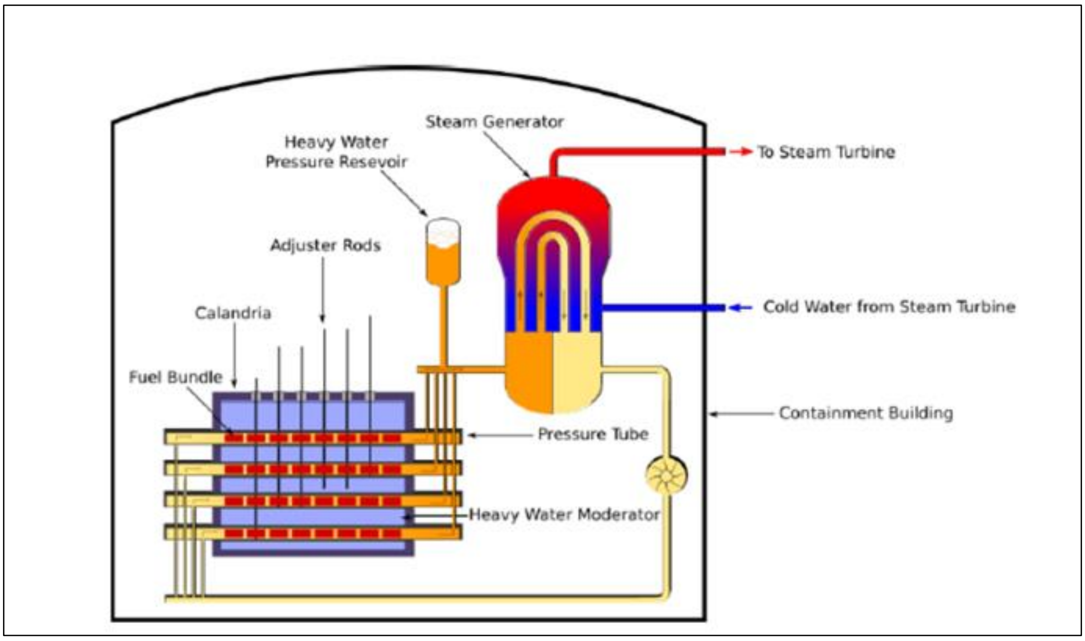

Figure 5: General view of a Canada deuterium uranium nuclear power plant [10]

Fig. 6 depicts the cross-sectional view of a fuel channel containing the pressure tube, fuel rods, and coolant. The pressure and calandria tubes are separated through a gap to ensure an effective heat barrier between the D_2O moderator at low temperatures and the D_2O coolant at high temperatures. The gap is filled with CO_2 gas. The calandria tubes are made of zircalloy-2 and embedded in the moderator. The main moderator volume/mass is beyond the calandria tubes. Separating the coolant at high-temperature pressure from the moderator at low-temperature pressure is one of the essential differences between CANDU reactors and other operating reactors.

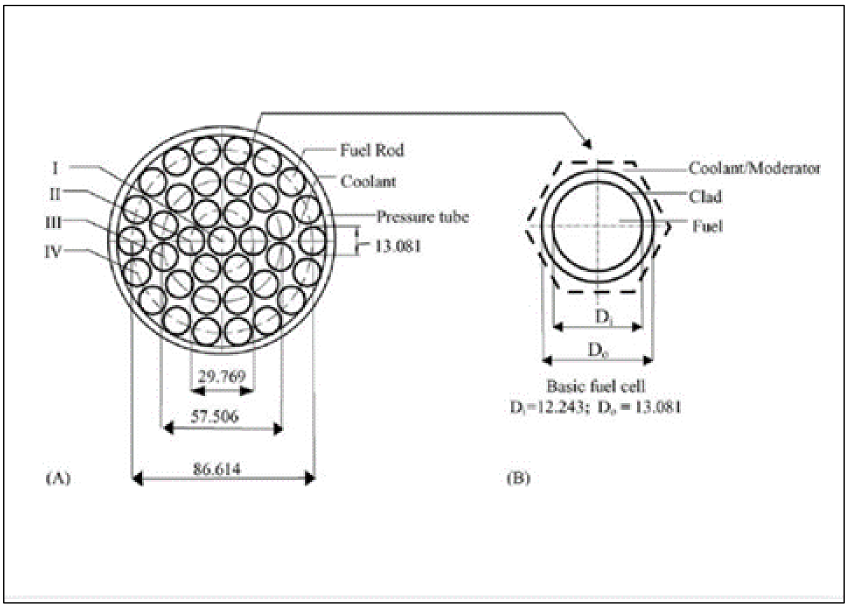

Figure 6: Cross-sectional view of the fuel bundle (dimensions in mm) [8]

Fig. 7 depicts the picture of a fuel bundle [9]. One fuel bundle is ~50 cm long, has a diameter of ~10 cm, and weighs ~20 kg. The nuclear heat is generated in pressure tubes in the fuel bundle region and transferred with D_2O coolant to the power conversion system outside the reactor building. Zirconium has a very small thermal neutron absorption cross-section and constitutes the main structural material in the core. Pressure tubes are made of Zr–Nb. D_2O coolant enters the tubes at 266°C and leaves at 310°C at a pressure of ~10 MPa [6].

Figure 7: Canada deuterium uranium fuel bundle
(https://cna.ca/reactors-and-smrs/nuclear-fuel/)

Usually, 380–480 fuel channels making the reactor core are arranged in square geometry in a horizontal reactor vessel, called a calandria vessel, shown in Fig. 8. The reactor vessel is filled with a D_2O moderator at a low temperature (< 71°C) and ~100 kPa pressure. The calandria vessel is not exposed to high temperatures or pressures and hence has a thickness of 2.86 cm and is made simply of ASTM 304L steel. A high-quality refractory steel alloy is not needed. Fitting the reactor vessel with several meters of diameter at atmospheric pressure with a few centimeters of wall thickness requires only modest technology. Reactor coolant flows through the pressure tube, where the fuel rods are placed in fuel bundles. In Fig. 8, one can recognize the pressure tubes from one side of the reactor vessel. Under the on-power condition, the fresh fuel bundles are pushed into the reactor through the pressure tubes with a special loading machine from one side, while the depleted fuel bundles are discharged from the other side. On-power uploading and discharging lead to a high plant operation factor of the CANDU reactor [6].

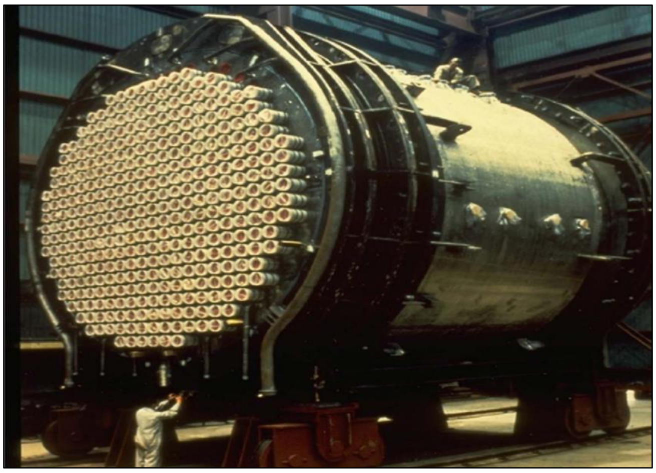

Figure 8: A view of the calandria vessel of a Canada deuterium uranium reactor [6]

LIGHT WATER GRAPHITE REACTOR (Reaktor Bolshoy Moshchnosti Kanalniy and EGP)

It is a pressurized water reactor [5] that was developed from plutonium production reactors [6]. The main distinction from other commercial reactors is the implication of individual fuel channels. It is a graphite-moderated reactor [5]. It consists of a vertical pressure tube of length 7m running through a graphite moderator and is cooled by the water, which is allowed to boil at 290°C in the core. The fuel used is low-enriched uranium (LEU) oxide made of fuel assemblies 3.5 m long. With moderation mainly due to the fixed graphite, excess boiling reduces the cooling and neutron absorption without inhibiting the fission reaction. A positive feedback problem can arise, so they have never been built outside the Soviet Union [6].

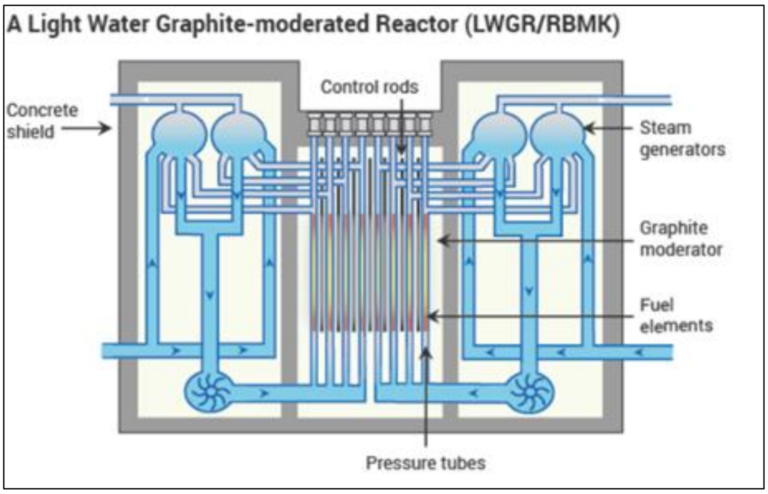

Figure 9: A Soviet-designed light water/graphite moderated reactor
(https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/appendices/rbmk-reactors.aspx)

ADVANCED GAS-COOLED REACTORS

The Magnox reactor developed early generation AGR in England as graphite moderated and CO_2 cooled. The secondary coolant is water. Fuel was natural uranium in metallic form. Hence, the steam pressure and temperatures were low, and the plant efficiency was modest. The second generation of British gas-cooled reactors uses graphite moderators and CO_2 as the primary coolant. The fuel is uranium oxide pellets in stainless steel tubes, enriched to 2.5%–3.5%. The CO_2 coolant is heated to 650°C at a pressure of 40 atm, producing superheated steam at approximately a temperature. 600°C in the steam generator located inside the concrete and steel pressure vessel. Such high steam temperatures allow reaching thermodynamic conversion efficiencies of approx. 41%. Fig. 10 shows the main components of an advanced gas-cooled reactor [5].

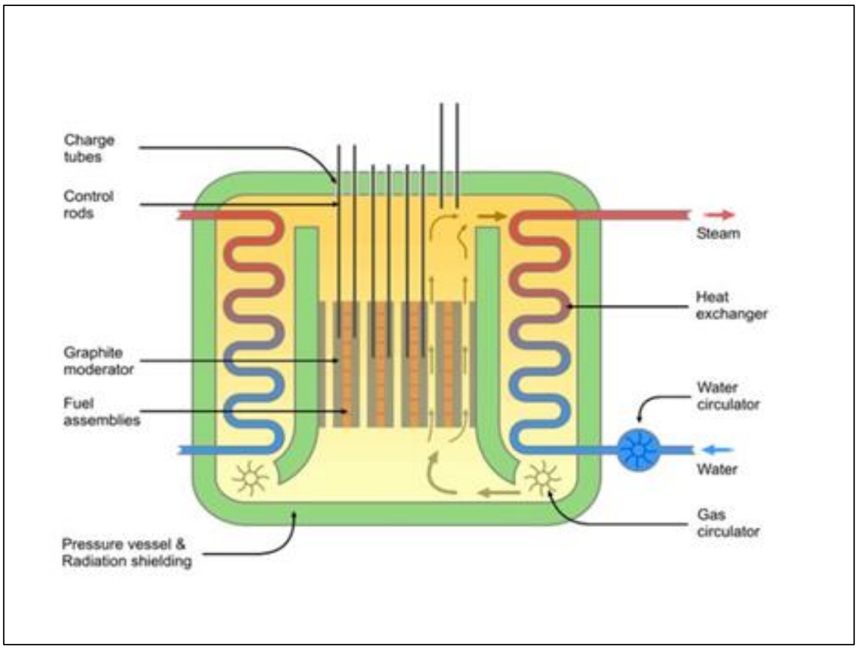

Figure 10: An advanced gas-cooled reactor (AGR) [12]

SODIUM-COOLED FAST BREEDERS

Breeder reactors are those whose fuel-to-product consumption ratio exceeds 1.0. Sodium-cooled FBs have been connected to the grid for about 60 years with great expectation to have a significant share in the world energy market after the 1980s. However, their electricity cost is still about double the LWRs; hence, they must be commercially competitive. Also, the actual doubling time of FBs is much longer than postulated initially (approx. 50 years). Notwithstanding, FB technology is the sole established one to use the waste uranium resources by converting the main isotope ^{238}U to the new fuel ^{239}Pu. LWRs can use only about 1% of uranium with plutonium recycles. Another significant feature of fast reactors is their suitability to operate as "burners." Water-cooled nuclear power plants produce substantial quantities of nuclear waste as minor actinides (MAs) with long half-life times and high-level α-radioactivity. FBs can efficiently burn the MA and have energy from this nuisance of nuclear waste [5].

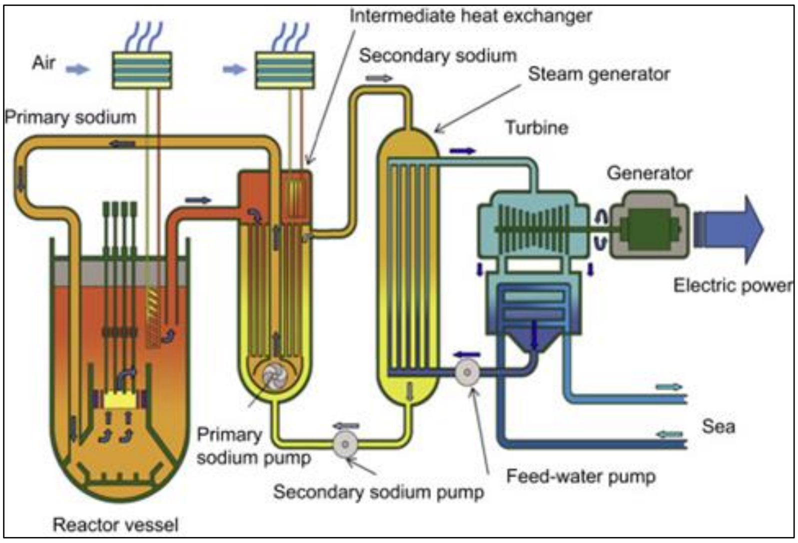

Figure 11: Sodium-cooled fast breeders
(https://en.wikipedia.org/wiki/Sodium-cooled_fast_reactor)

GEN-IV REACTORS

GEN-IV Reactors are being developed to address current generation nuclear power plants' sustainability, safety, economics, and proliferation resistance. Currently, GEN-IV reactors are very high-temperature reactors (VHTR), the SFR, the LFR, the gas-cooled fast reactor (GFR), and reactors with the potential to be fast or thermal, the molten salt reactor (MSR) and supercritical water-cooled reactor (SCWR). Among these SFRs and VHTRs are the most developed. In most of these reactors, the constrain of knowledge and cost exist also, and their development could be improved due to unabated fossil fuel power stations [8].

Very high-temperature reactor

A VHTR is a graphite-moderated, helium-cooled thermal reactor that aims to produce an outlet temperature of >1000°C for process heat application. Several low-temperature versions of VHTRs have been tested, like Dragon, HTTR, and HTR-10, and have the lowest barriers to commercial deployment of all Generation IV reactors. Their designs incorporate high-temperature limits and particulate fuel dispersed in the graphite moderator, making a robust fuel with sizeable thermal inertia. This imparts high levels of intrinsic safety. HTRs have never been coupled for heat applications, and the current technology cannot reach the targeted operating temperatures needed for process heat. However, achievable temperatures of around 900°C are currently helpful for several applications, for instance, the chemical industry [8].

Liquid metal-cooled fast reactor

LFR and SFR use uranium resources by breeding plutonium and operating it in a closed fuel cycle. The main goal is to use Uranium sustainability. There is also a particular interest in LMCFRs due to their potential to reduce the lifetime and radiotoxicity of nuclear waste through the fission of long-lived nuclear waste component Designs have very small cores and high fissile content compared with LWRs, with metal coolants and no moderator. The metal coolants were favourable since they have high thermal conductivity, allowing for enhanced cooling via natural convection. Furthermore, vapor pressures, which permit reactors to operate at close to atmospheric pressure, help prevent significant coolant losses in the event of leaks.

However, liquid metal also causes issues such as sodium fires with SFRs and corrosion with LFRs. SFRs are the most developed commercial fast reactor, with significant international experience, operating several large-scale demonstrators (e.g., BN-6,00 and SuperPhenix). However, current SFRs are economically uncompetitive and require more experience and development. LFRs have only been deployed in the USSR navy, with the nearest commercial prototype, MYRRHA, under development in Europe [5]. Lead coolants are compatible with water and air, which is an advantage over sodium, removing the issue of sodium fires. However, MYRRHA and other near-term LFR designs have limited operating temperatures due to corrosion issues and will require significant development materials and components [8].

Gas-cooled fast reactors

The GFR is the least developed fast reactor option, using a helium coolant and operating at high temperatures and pressure. Unlike LMFRs, it has the added advantage of high outlet temperatures and has the potential to be a more sustainable, long-term alternative to the VHTR. Its current deployment is restricted by the need to develop materials to survive the harsh, in-core environment. A near-term prototype, ALLEGRO, is being designed with a reduced operating temperature and using existing materials. Additionally, the gas coolant in a GFR has low thermal inertia and is under high pressure. Therefore, it cannot 'pool' or dissipate heat like a liquid metal coolant. This requires unique safety designs to cool the core of a GFR in a loss of coolant accident and the event of a loss of onsite power [8].

Molten Salt Reactor

MSRs differ significantly from the other reactor types, as the fuel is liquid. This enables highly parasitic fission products to be removed from the fuel during operation (online reprocessing), permitting the reactor to run more efficiently than solid-fuelled systems. MSRs can, in principle, operate up to very high temperatures due to the molten salts having very high boiling points. However, they are likely to operate at much lower temperatures, given current material understanding. Liquid fuel also gives rise to problems in terms of material behavior, the development of online reprocessing technology, and robust components (such as pumps and heat exchangers) which can operate and be inspected in high radiation environments. The system's uniqueness also significantly complicates licensing as there is relatively little experience. Most experience comes from a small-scale prototype (the MSRE) in the United States of America, which operated for around 1.5 effective full-power years. This makes MSRs a long-term goal [8].

Supercritical water-cooled reactor

The SCWR extends current water-cooled reactor technology but operates at significantly higher pressures and temperatures. The coolant is in a single phase, which permits a few expensive system components to be eliminated (such as steam generators and dryers). At the same time, the higher temperature allows for greater thermal efficiency and, therefore, a more competitive system. However, there are significant gaps in our understanding of supercritical water's chemistry, thermal hydraulics, and the behavior of materials exposed to this coolant in a neutron field [8].

CONCLUSION

Nuclear energy can play a crucial role in meeting the growing global demand for electricity while reducing CO_2 emissions. The GEN-IV reactors are more rigorously targeting sustainability, safety, and economics. This paper provides the bigger picture of all the major commercial reactors, which will help the policymakers and stakeholders to be informed about these reactors.

Conflict of interest

The author declares that there is no conflict of interest.

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