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Engr. Najam Waheed

Engr. Najam Waheed obtained his Bachelor's Degree from University of Engineering & Technology, Lahore in Civil Engineering. He has over thirty years of multifaceted professional experience leading and pursuing development and engineering projects which includes planning, project management, preparation of technical reports and contract documents. He is well-versed in various national and international codes, regulation, quality standards and their implementation. He worked on various prestigious and technically complex projects.

Engr. Najam Waheed has been a Council Member of Pakistan Engineering Congress for more than two decades. He has been an active member of the Congress serving as Secretary, Joint Secretary, Treasurer, and convener of all important Committees of the Congress, and was elected as the President of the Pakistan Engineering Congress in December 2021. His vision has been manifested in an digital transformation of the Congress's services and has laid a strong foundation for future growth and developments of Engineers Communities.

His dedication to engineering development and the Pakistan Engineering Congress played a significant role in developing effective synergies with important professional bodies in the country, which would significantly contribute to engineer's professional competence in a challenging environment of disruptive technologies and sustainable development.



Engr. Najam Waheed
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Paper No.819

NUCLEAR POWER GENERATION TECHNOLOGY: CONCEPTS, EVOLUTION, AND ITS ROLE IN A SUSTAINABLE ENERGY SUPPLY SYSTEM

Dr. Noor Jamal,
Mr. Mansoor Hassan Khan Lodhi

NUCLEAR POWER GENERATION TECHNOLOGY: CONCEPTS, EVOLUTION, AND ITS ROLE IN A SUSTAINABLE ENERGY SUPPLY SYSTEM

By:

Dr. Noor Jamal[1], Mr. Mansoor Hassan Khan Lodhi[1]

Abstract

Nuclear power plants (NPPs) operate much the same way that other thermal steam power plants (SPPs) do, to generate electricity. The major difference is the source of thermal energy for steam generation, that spins turbine(s), coupled with a generator. Since its inception in the early 1950s, nuclear energy is recognized as an important source of commercial energy supply for sustainable development. Consequently, many developed countries-initiated efforts to develop nuclear power technology and today, there are several variants/types of nuclear power reactors.

These variants are being evolved, aimed at enhancing and improvement of NPP technology and its safe operation. Currently, in the world, most of the under construction commercial NPP are Generation-III and are mostly Pressurized Water Reactor (PWR) by technology type. Likewise, more than two-third out of the total 442 operational NPPs are PWR.

In Pakistan, all five operational (2,430 MWe) and one under-construction (1,100 MWe) nuclear reactors are PWR type. In these, one operational (1,100 MWe) and the one under-construction (1,100 MWe) are Generation-III (i.e., latest generation). These NPPs of the country operate under International Atomic Energy Agency (IAEA) safeguards and periodically review by the World Association of Nuclear Operators (WANO) to maintain rigorous safety standards. Locally, the implementation of these standards is assured by the government through Pakistan Nuclear Regulatory Authority (PNRA). Established in 2001 through an act, PNRA is a statutory body that functions independently, with 24/7 presence of their experts at the Country's NPPs. Since 1971, Pakistan total nuclear generation is 111 billion kWh, that has avoided more than 69 million $CO_{2\text{-eq}}$ greenhouse gases (GHG) emissions in the country.

1. Introduction

Historically, the development of modern power system is rooted in the invention of steam engine in 1769. Using abundantly available coal, this invention triggered the development of large-scale industry by replacing humane and animal muscular power (Caineng & al., 2016). The industrial growth and scientific research/inventions of almost 100 years helped in developing the world first direct current (DC) power plant in 1875 in France. This plant was based upon steam engine and dynamo. In 1884, alternating current (AC) generator was invented, that triggered the initiatives of hydropower plant technology. Till 1900, hydropower plant had marked several milestones[2]. Thus, by the time, coal and hydropower had been established as source of energy for electricity generation (Power Magzine, 2007).

Later, the technology development aided in the exploration of mass scale oil and gas resources. Compared to coal, these two resources were expensive and were used for

[1] Applied Systems Analysis Division, PAEC

[2] In Pakistan (as a part of United India by the time), 1 MWe hydropower plant near Renala Khurd was built in 1923 by Sir Ganga Ram

powering automobiles[3]. But later, their production cost reduced by virtue of scale of economy and turned into options for power generation. During this period, steam turbine was also being developed, and General Electric (GE) made the world first 500 kWe and 5 MWe steam turbine in 1901 and 1903, respectively. With the passage of time, steam turbine size (capacity) and efficiency improved (Power Magzine, 2007). In the late 1940s, nuclear energy emerged as a new energy option for power generation. Relatively clean and densest energy contents within fuel made the nuclear energy an attractive power generation option, particularly in industrial countries. They embarked individually upon development of nuclear reactor technology for power generation. Consequently, different variants of nuclear reactor technology emerged, that prevailed in the next 20-25 years across the globe. Today, nuclear energy meets around 10% of the world electricity requirements.

This paper presents the concept of nuclear power reactor technology & its operation and discusses variants of the nuclear reactor technology. The paper likewise highlights the development of the technology and management approach to ensure safety of NPP operation. In the later sections, the paper briefly presents information regarding NPP current status around the world as well as in Pakistan and highlights the technology recognized role in a sustainable development of energy system.

2. Advent of Nuclear Energy

In 1954, Russia's APS-1 Obninsk[4] of 6Mwe capacity was the world first nuclear reactor that supplied electricity to the Country's grid system. Almost two years later, in 1956, two nuclear reactors[5] - each of 60 MWe - in the UK were connected to the country grid system. The USA first nuclear reactor 68 MWe Shipping-port[6] - came online by the end of 1957. It is noteworthy that the NPPs of all these three countries were based upon different concepts of NPP technology. By the late 1960s, nuclear energy was well established power generation option in Europe (including Russia) and the USA. However, during 1970s and 1980s, nuclear power generation capacity expanded most rapidly in the developed countries (see Figure-2) and prevailed in many developing countries, including Pakistan (IAEA (c), 2021). Pakistan first NPP – KANUPP 137 MWe - was commissioned in 1971 and its commercial operation started the next year.

[3] In 1886, the invention of internal combustion engine triggered the initiatives of automobile industry

[4] The reactor produced electricity till 1959 and was based on Russian Light Water Graphite moderated Reactor (LWGR) technology, discussed later in the paper

[5] These two reactors were Gas Cooled Reactor (GCR) and is discussed later in the paper

[6] The USA first reactor was Pressurized Water Reactor (PWR), that is to be discussed later in the paper

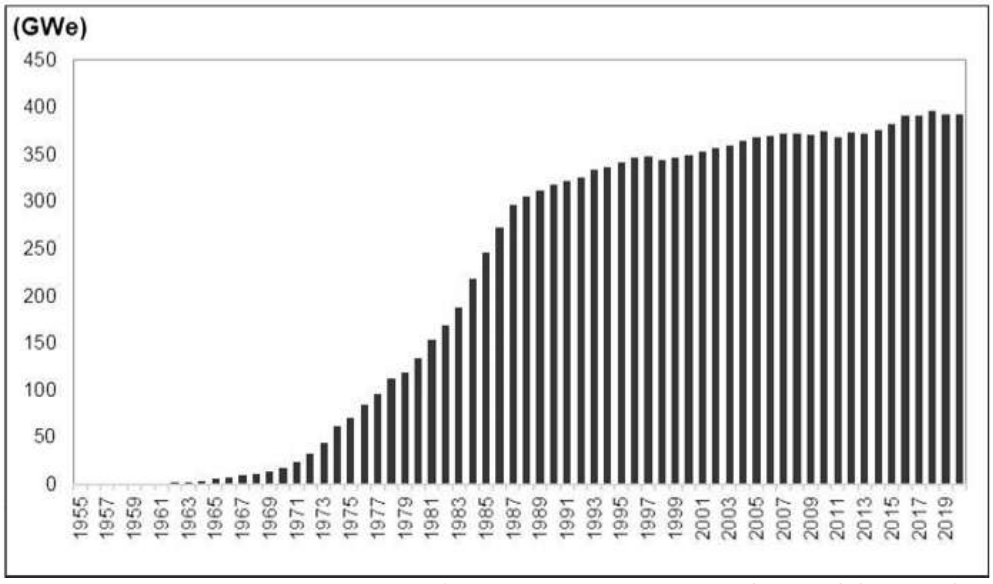


Figure-1: World Installed NPP Capacity by Year 2020 (IAEA (c), 2021)

3. NPP Basic Concepts

In case of both SPP and NPP, steam is produced to spin turbine(s) that is coupled with a generator through a shaft to generate electricity. However, in case of NPP, the heat (i.e., energy) source to produce the steam is nuclear fuel (i.e., uranium) instead of fossil fuel. Compared to fossil fuel, the energy density of nuclear fuel is substantially high. This fuel, as a whole, with some other auxiliaries is termed as the reactor core of an NPP. The reactor core is kept in a steel or steel reinforced concrete confinement, depends upon technology variant and accordingly termed as reactor pressure vessel, calendria or just confinement. Reactor core occupies a fraction of the vessel volume and the rest of the vessel is occupied/filled by moderator and primary coolant.

In a nuclear reactor core (i.e. nuclear fuel), a sustainable fission reaction takes place to produce thermal energy (i.e., heat). The production of thermal energy is proportional to the fission reaction rate, and this rate is controlled through chemicals, employed in the form of solid rods and liquid. In a fission reaction, a neutron enters (or is absorbed by) the nucleus of fissionable atom isotope (e.g., U-235), that split the atom into two atoms of light elements[7] (e.g., U-235 into Kr-89, Ba-144). Each fission/splitting process generates thermal energy (i.e., heat) of about 200 MeV (3.2044e-11 Joule) as well as 2-3 neutrons. For a sustainable chain fission reaction, one of these neutrons must enter into the nucleolus of target atom (U-235). In almost all currently operating reactor types, slowing down of these neutrons to a certain energy level is required to maximize the probability of fission reaction. This slowing down of neutrons is achieved through a medium, called moderator of the reactor (The Open University, 2019).

Ideally, the moderator should not absorb neutrons. However, all the three well-established moderator medium – light water, heavy water, and graphite – absorb fraction of the neutrons. These mediums can be ranked by least neutron absorption (i.e., efficient moderator) as; heavy water, graphite, and light water. Consequently, when needed, the ratio of fissionable isotopes (e.g., U-235) must be increased in the reactor fuel to compensate for the neutron absorption. Naturally, the ratio of this isotope in the reactor fuel is only 0.7% and is sufficient to be used as fuel with heavy

[7] The light element further decay into other elements

water as moderator. In the case of the other two moderator medium, the isotope U235 percentage is increased during fuel fabrication process, generally 3.0% to 4.0% (The Open University, 2019), (Hewitt & Collier, 1997).

NPP primary coolant is in fluid[8] form (e.g., water, gas, etc.,), that transports heat from the reactor core to heat exchanger (HX)[9]. The HX is like a boiler - filled with water - but having internal tubes grid/arrangement. When the hot primary coolant from the reactor core/vessel passes through these tubes of the HX, the heat transfers to the HX filled water, that boils and converts into steam. Consequently, the primary coolant temperature drops and this relatively cold coolant is pumped back into the vessel, thus forming a closed loop. This closed loop is called primary loop of the NPP (The Open University, 2019), (Hewitt & Collier, 1997).

The difference in the designs of nuclear reactor is mainly due to the arrangement as well as choice of moderator and coolant. Obviously, these choices affect the fuel enrichment requirements as mentioned earlier. Additionally, differences can be found in the mechanism of thermal energy transportation from reactor core. In the following section, these differences in the well-known reactor designs are briefly elaborated.

4. NPP Technology Variants

4.1 Pressurized Water Reactor (PWR)

Pressurized Water Reactor (PWR) technology was initially developed by the USA. Currently, in addition to the USA, China, France, South Korea, and Russia are the lead developers of PWR based NPP. In the current total operating reactors across the globe, more than 73% share by capacity belongs to PWR technology that operates in 28 different countries. Pakistan's all five operational nuclear reactors and the under-construction one are PWR. In the installed PWR capacity across the globe, the leading shareholders are France, the USA and China with share around 22%, 21%, and 17%, respectively. In the under-construction nuclear reactors, around 88% capacity is PWR, that is being constructed in 19-different countries (IAEA (c), 2021) (IAEA, 2020).

In PWR, the primary loop (including pressure vessel) is filled by light water (i.e., common water), that functions as moderator as well as coolant, and the fuel is obviously enriched. For a sustainable fission reaction, the primary loop is highly pressurized typically 15-16 MPa - to avoid any steam or bubble formation at the operating temperature of 300^{o} C and is, therefore, called PWR. A schematic diagram of a typical PWR is presented in Figure-2 (Hewitt & Collier, 1997) (CAMECO, 2017); (WNA, 2021).

[8] Depends upon technology type, the fluid can be gas, water, or even molten metal or salt at the working temperature

[9] In Boiling Water Reactor (BWR) case, coolant water converts into steam directly within reactor vessel and required no HX

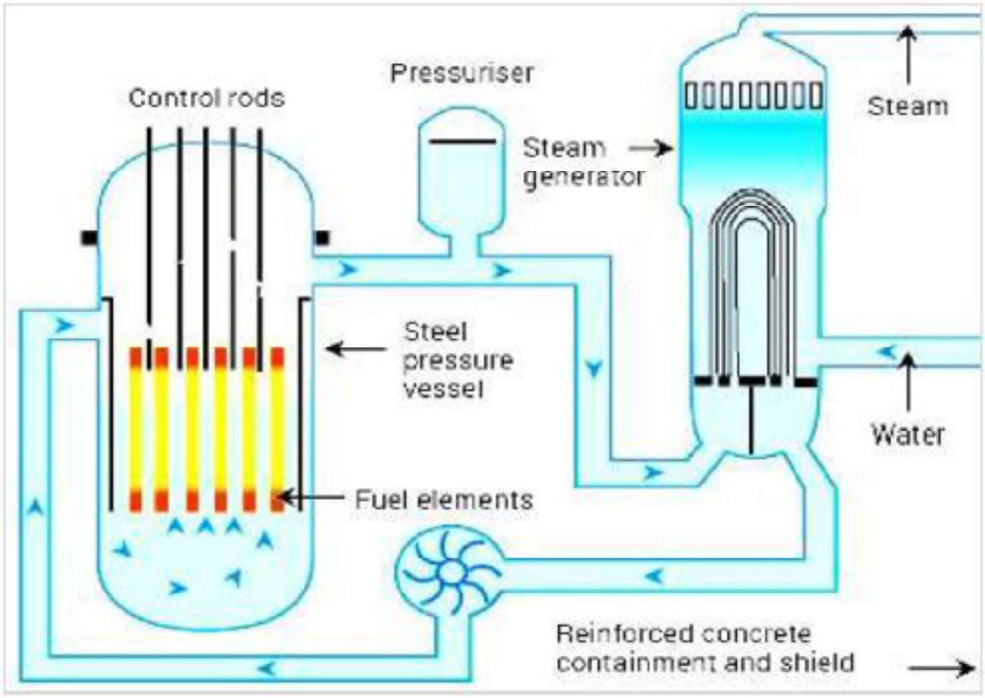


Figure-2: Schematic of Pressurized Water Reactor (PWR) Nuclear Island

4.2 Boiling Water Reactor (BWR)

In addition to PWR, the USA early efforts also resulted in the development of Boiling Water Reactor (BWR) technology. Currently, the USA has the highest number (i.e., 31) of BWR reactors followed by Japan (i.e., 17 reactors). However, regarding future development, the efforts by Japan are most significant and they are the only country constructing new BWRs (2x1326.5 MWe) capacity. In the current operating reactor in the world, the share of BWR by capacity is around 16% that operates in 09-different countries (IAEA (c), 2021); (Hewitt & Collier, 1997).

In BWR, like PWR, light water is used both as moderator and as coolant, with enriched fuel. However, BWR operates at around 7 MPa pressure, consequently, 12%-15% of the total water in the vessel is converted into steam at typical operating temperature of 285^{o} C. The steam exists in the top part of the vessel, that is treated for moisture separation before channelling to steam turbine for spinning. This approach of the design eliminated the requirement of HX (Figure-3). However, to compensate for the boiled water, the reactor core (i.e., fuel) and vessel volume are to be more than PWR (CAMECO, 2017); (WNA, 2021); (Hewitt & Collier, 1997).

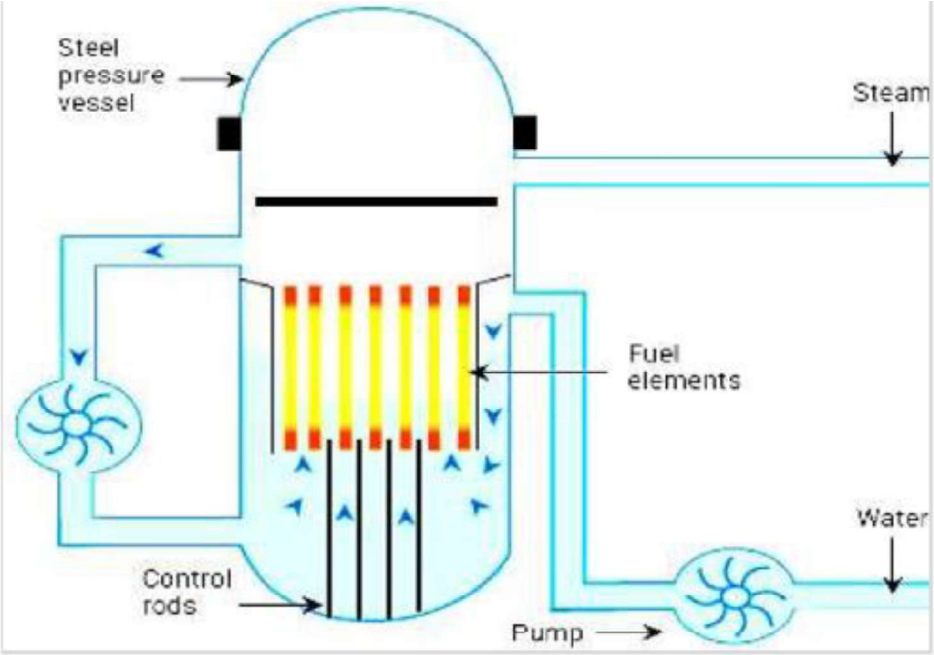


Figure-3: Schematic of Boiling Water Reactor (BWR) Nuclear Island (WNA, 2021)

4.3 Pressurized Heavy Water Reactor (PHWR)

The USA and Sweden were the countries, that initiated the early efforts of Pressurized Heavy Water Reactor (PHWR) development. However, the real development of this technology belongs to Canada, that has developed CANDU-6, a Generation-III[10] PHWR. Recently, India also claimed 100% indigenous capability of PHWR design and construction, but this yet to be demonstrated/confirmed. In the existing operation reactors, PHWR share is around 6% by capacity, with highest capacity share in Canada (~58%) and India (~16%). Currently, India's four under-construction PHWRs are the world only under-construction PHWR (IAEA, 2020).

Pakistan's first NPP - Karachi Nuclear Power Plant (KANUPP) - was also based upon PHWR technology. This plant was commissioned in 1971 and permanently shut down in August 2021 for decommissioning.

In the case of PHWR, the vertical vessel is replaced with a horizontal drum like structure, called Calandria. The Calandria encapsulates dozens of channels for holding nuclear fuel, giving advantage of online fueling i.e., inserting new fuel bundle and removing/collecting the used one. The rest of the calendria volume is filled of heavy water to moderate neutrons. Commonly, the reactor coolant is also heavy water but of low grade by purification. Therefore, without mixing with the moderator, the coolant passes through annular - formed over each fuel channel - to transport heat from the reactor. The heavy water moderator as well as coolant allow to use natural uranium as fuel i.e., required no enrichment for a sustainable fission reaction. Typically, PHWR coolant pressure at reactor exit is 9-10 MPa and temperature is 310° C. In the following (Figure-4), a typical PHWR schematic diagram is presented for more clarification (CAMECO, 2017); (WNA, 2021); (Hewitt & Collier, 1997).

[10] The Generations are discussed later in the paper

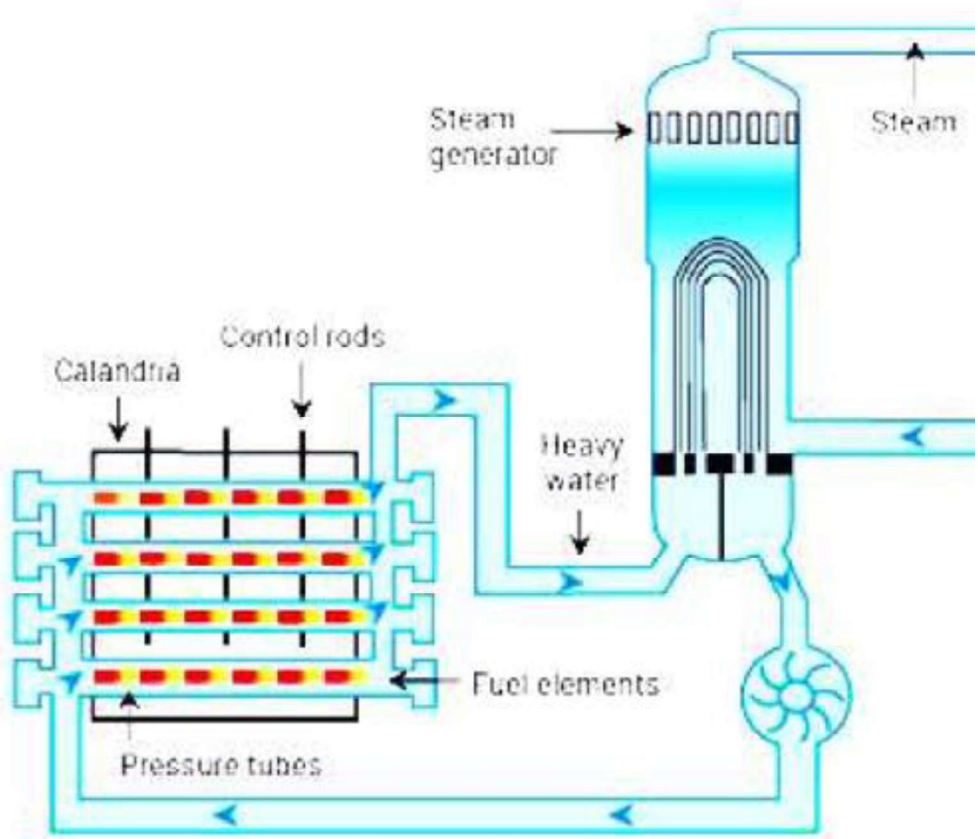


Figure-4: Schematic of a Typical Pressurized Heavy Water Reactor (PHWR) Nuclear Island (WNA, 2021)

4.4 Gas Cooled Reactor (GCR)

The UK initiated the development of Gas Cooled Reactor (GCR) in early 1950s, and currently all operational GCRs (i.e., 14) are in the UK. This operational capacity makes less than 2% of the world operating NPP capacity. However, many countries including Japan, China, etc., are working on the advanced version of the GCR technology. China recently connected the country high temperature gas cooled reactor (HTGR) based NPP to the national grid for demonstration of the technology. This NPP is consisted of 2x100 MWe unit of the HTGR (IAEA, 2020); (CNNC, 2021).

In this type of reactors, solid graphite is used as moderator and gas as coolant. Since graphite is solid, therefore, compartments and channels are formed within the graphite volume for fuel placement and gas flow. The gas is typically carbon-dioxide or helium, that removes heat generated by the reactor core (i.e., within fuel) and transports it to the HX for steam production (Figure-5). Since GCR coolant (i.e., gas) is superheated, therefore, it operates at extremely high temperature (450-600^{o} C). The coolant temperature of the future advanced version of the technology (i.e., HTGR) is expected to be around 850^{o}C (CAMECO, 2017); (WNA, 2021); (Hewitt & Collier, 1997).

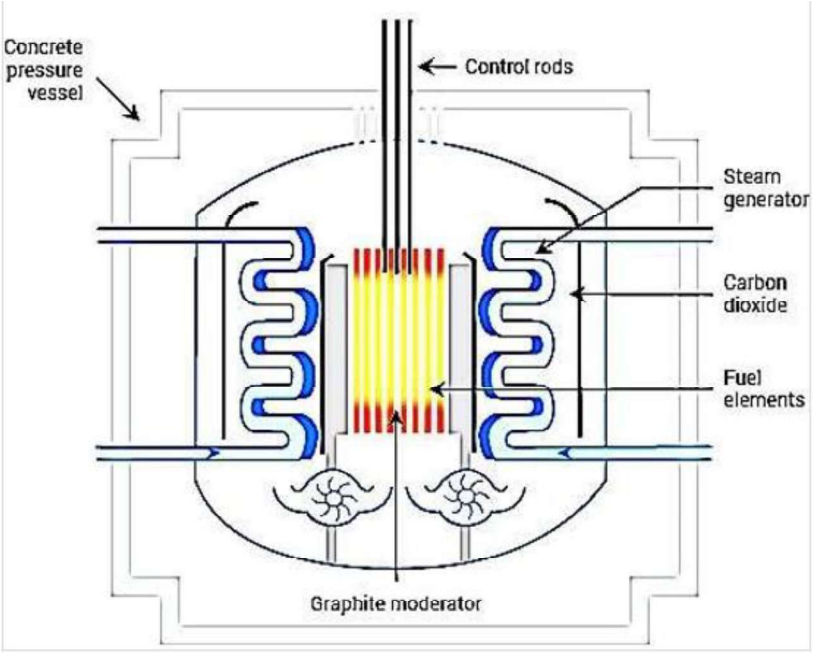


Figure-5: Schematic of a Typical Gas Cooled Reactor (GCR) Nuclear Island (WNA, 2021)

4.4 Light Water Graphite Reactor (LWGR)

LWGR was developed by the former USSR and had been built only in Russia or in USSR former states. Outside Russia (i.e., USSR), the technology did not receive much consideration. The existing operational 12-LWGR are in Russia, that constitute around 2% of the world NPP capacity.

In this type of reactor, the moderator is graphite and long pressure tubes pass throug it for fuel placement and water (light water) flow as shown in Figure-6. The operating pressure of the LWGR is around 7 MPa and temperature is 290^{o}C, that permits partial boiling of the water as in BWR (Hewitt & Collier, 1997).

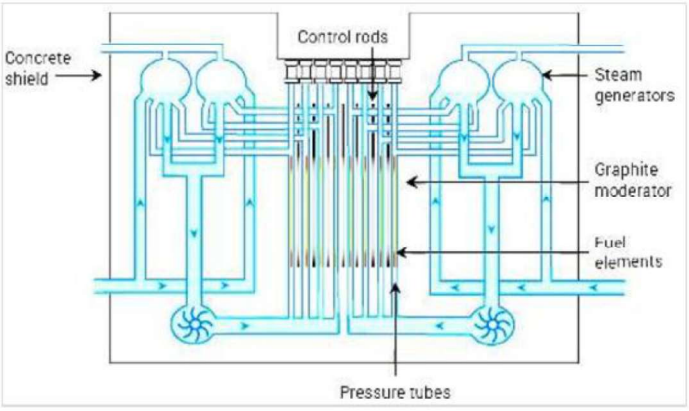


Figure-6: Schematic of a Typical Gas Cooled Reactor (GCR) Nuclear Island, (WNA, 2021)

4.5 Fast Breeder Reactor (FBR)

In addition to above, the fast reactor breeder reactor is another well-known design category of the nuclear reactor. The design is well-proven and has been demonstrated in many countries, however, the high construction and

operating/maintenance costs are major hurdles to commercialize the design. Russia's two fast fast reactors of total 1,380 MWe capacity, are only commercially operated reactors in the world, with China's 25 Mwe demonstration FBR (WNA, 2021); (Hewitt & Collier, 1997).

For comparison, shares of different reactor technologies in the total operating 413.7 GW capacity are presented in the following (Figure-7).

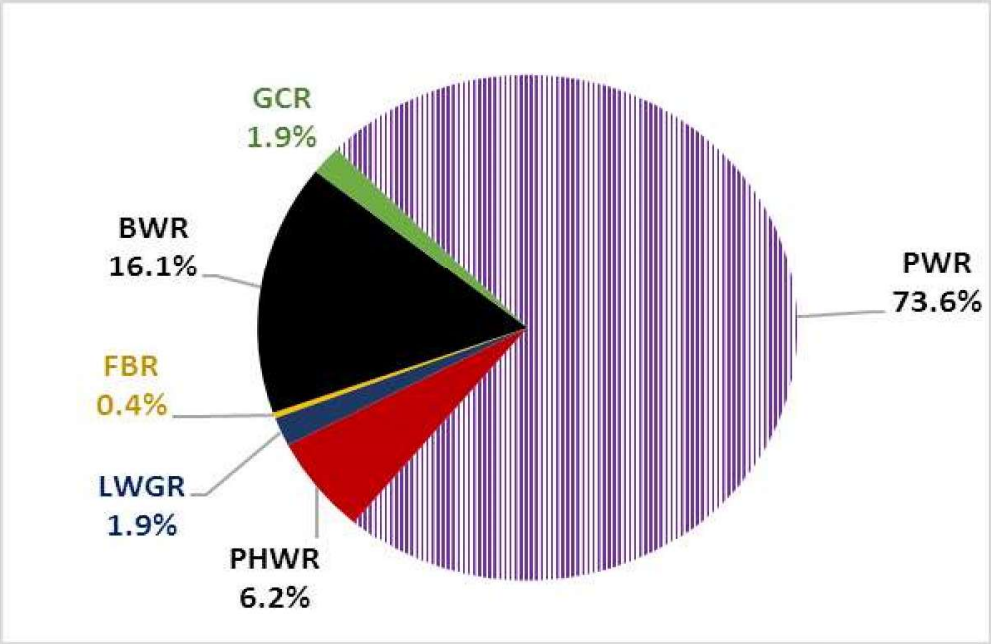


Figure-7: Share of Different Reactor Type in the Installed NPP Capacity (IAEA (c), 2021)

5. Evolution of NPP Technology

All variants of NPP technology perpetually improve and evolve with aim of enhancing performance, safety, and economics. For convenience, this enhancement in the technology is classified and each class is termed as Generation. Currently, Generation-III technology is commercially available for development and Generation-IV technology is in the early phase of design. Since the installation of NPPs and improvement/enhancement in the technology continue side by side, therefore, temporal-overlapping of different generations can be found in the installed capacity across the world. In the following, different Generation of the technology are briefly presented.

5.1 Generation-I

Generation-I (Gen-I) of nuclear power technology included early (1950s) prototype reactors, that were developed in Europe and in the USA. These prototype nuclear reactors were derivatives of the reactors, that were designed and developed for military purposes (e.g., submarine propulsion). Relatively small in size[11], these demonstration reactors had no or limited arrangements (i.e., dedicated systems) for a safe commercial operation (i.e., electricity generation) (Goldberg & Rosner) (Haas, Mez, & Ajanovic, 2019).

[11] The size of Gen-I most reactors ranges 5 MWe to 70 MWe. However, few later installed reactors of the generation in the USA and the UK were quiet big one

Consequently, most reactors of the Gen-I technology served to generation electricity for some period (i.e., 5-25 years) and Gen-II reactors started to replace them in 1960s. However, the UK's Wylfa-1 Gen-I reactor continued electricity production until recent. This reactor of 530 MWe (i.e., GCR) was permanently shutdown in

2019, after operating for almost 50-years. Pakistan's KANUPP-I of 137 MWe is categorized by some experts as Gen-I technology. However, the plant had relatively better arrangements and dedicated safety systems. KANUPP-I is permanently shut down in August 2021 after almost 50 years of operation (Goldberg & Rosner) (Haas, Mez, & Ajanovic, 2019).

5.2 Generation-II and China's Generation-II Plus

Gen-II reactors were designed and developed specifically for commercial use. Therefore, these reactors have more arrangements and design features for a safe operation. The safety systems of these reactors sense any abnormal condition – whether internal (e.g., pressure, temperature, etc.,) or external situation (e.g., seismic activity, grid fluctuation, etc.,) - and if any such condition comes about, the reactor shut down automatically. For the safe shutdown, dedicated active safety systems are installed. To implement the concept of defense in-depth, these systems are redundant as well as diverse in their function (Goldberg & Rosner) (Haas, Mez, & Ajanovic, 2019).

Gen-II started to prevail in 1960s and dominate the NPP new-builds market across the globe until recent (i.e., 2010 or even later). In 2000, China added up some safety features of Generation-III in their Generation-II reactors, that resulted in Generation II+ version of the technology (NEI-Magzine, 2013). The same Generation II+ reactors were then exported to Pakistan, that operate at Chashma Nuclear Power Generation Station (CNPGS).

Typically, the capacity of these reactor ranges from few hundreds up to 1,600 MWe. In most cases, the design life of Gen-II reactors is 40-year that can be extended. In the USA, life extension up to 40-year of some Gen-II reactors is planned. Today, more than 98.0% of the world installed nuclear power capacity is Gen-II or Gen-II plus (Goldberg & Rosner) (Haas, Mez, & Ajanovic, 2019).

5.3 Generation-III

The design of Gen-III reactor technology emerged in the late 1980s and most of these designs are evolutionary i.e., developed from Gen-II design. Among others, the prominent improvements in this new generation of the reactor technology are following (Goldberg & Rosner) (Haas, Mez, & Ajanovic, 2019);

i) Gen-III reactor design incorporated passive safety systems/features i.e., reactor does not require active controls or operator intervention to mitigate the impacts of any abnormal event. These systems work automatically under all conditions using gravity, fluid buoyant forces, and natural convection.

ii) Reactor containment is double in most designs, that increased the containment strength and helped in the implementation of the above-mentioned passive safety system.

iii) The design life of Gen-III reactors is 60-year, that improved the plant economics.

iv) In some designs of the generation, standardization and modularization in the design of Gen-III reactors is conceived, that help in licensing and construction of the plant.

Currently, only few reactors of the generation are in operation, that included Pakistan's 1,100 Mwe KANUPP-2 (K-2) plant. However, around 35 Gen-III reactors - including Paki -3 (K-3) - are worldwide under construction (IAEA, 2020); (Haas, Mez, & Ajanovic, 2019).

In addition to above, the concept of Small Modular Reactor (SMR) is also under development. The SMR designs have incorporated safety features of Gen-III technology, and aimed to achieve the following objectives (IAEA (d), 2020):

- Construction of the NPP as modules in a factory, that are to be installed in sequence. This will improve construction quality and will reduce construction time, resulting in improvement of the NPP economics.
- Construction of different size (i.e., capacity) NPP, by installing multiple SMR, that shares different systems and resources. The flexibility in size will facilitate to adjust the NPP capacity according grid system size.
- The smaller size and construction efficiency will lead to easier financing, even for developing countries.
- To use nuclear energy for power generation as well as industrial application, including hydrogen production, desalination, etc.

NuScale Power, a private US firm, has designed an SMR, and based upon that design, an NPP is currently under development in the USA. This NPP will be consisted of 06 to 12 SMR, each of 60 MW capacity.

5.4 Generation-IV

Gen-IV covers a range of different design concepts to further improve nuclear reactors safety & economics, reduce waste, and make the technology proliferation resistant. In the year 2000, Generation-IV International Forum (GIF) was formed, that consisted of 14-member countries, including the USA. Out of some 100 conceptual designs, the GIF has selected six of them for research and development (R&D). These designs are mostly revolutionary and required substantial crosscutting R&D. Therefore, it will take years, if not decades for the Gen-IV reactors to be available on commercial basis (Goldberg & Rosner) (Haas, Mez, & Ajanovic, 2019).

6. IAEA, WANO Role in Maintaining Safety of NPPs

The International Atomic Energy Agency (IAEA) was established in 1957 and the same year, Pakistan became member of the IAEA. The IAEA functions under the umbrella of United Nations (UN) as the focal point for development/ expansion and peaceful use of nuclear power & radiation in the world. For this purpose, the IAEA assists member states and provides services in the form of trainings, knowledge sharing, technology transfer, and expansion planning. The IAEA also provides guidelines and standards regarding each phase of NPP development and operation i.e., from site selection till de-commissioning. Pakistan comply these guidelines and apply the standards through internal monitoring and verification mechanism. Nevertheless, Pakistan Nuclear Regulatory Authority (PNRA) – established in 2001- is the sole independent authority to validate and certify the implementation of these standards in Pakistan. Therefore, as a regulatory authority, PNRA is involved in the process of NPP development, operation, and decommissioning (PNRA, 2021) (IAEA(b), 2021).

Pakistan is also member of the World Association of Nuclear Operator (WANO), that was established in 1989 to maximize NPP safe and reliable operation by working

together. WANO is independent of any government or regulatory influence. For the safe and reliable operation of NPP around the world, they do independent assessment, share information, and emulate best practices across the member states. WANO main services included (WANO, 2021);

i) In-depth Peer Review of member state NPPs operation by external experts, at four-year frequency, with a follow up after two years.

ii) Performance Analysis by collecting and analyzing operating experience, particularly data related to an event, that is shared among member states.

iii) Member Support Programme, that is carried out at the request of member state.

iv) New Unit Assistance, that support an NPP during project phase and its transition from project phase to safe and reliable operation.

7. Nuclear Energy: World and Pakistan Outlook

Nuclear power has been an important part of the world as well as Pakistan power system. Currently, around 442 nuclear reactors are operating in 32 different countries, including Pakistan as shown below (Figure-8). In the year 2020, the share of nuclear energy in the world total electricity generation was 10%[12], with highest share in the national electricity generation of France. In Pakistan's power system, the contribution of nuclear energy in electricity supply during 2020 was around 7.0%. This share is expected to grow further up to 11.0% in the next year - as K-2 (i.e., 1,100 MWe) has started commercial operation in May, 2021 (IAEA (c), 2021).

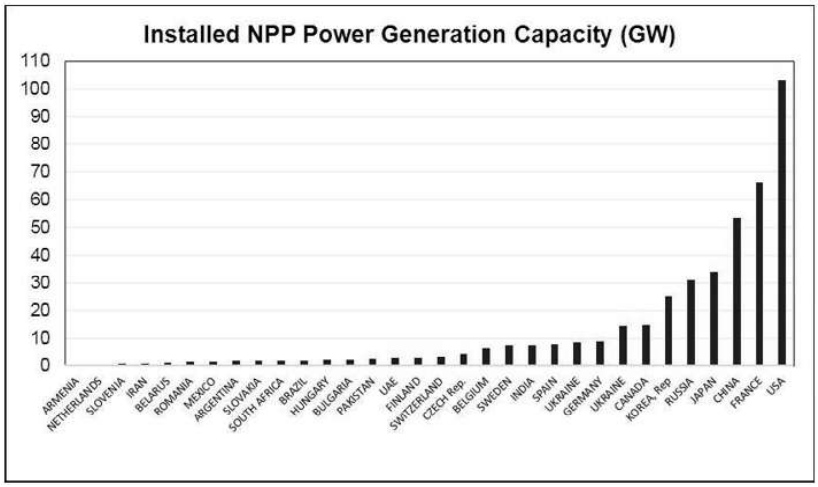


Figure-8: Installed NPP Power Generation Capacity (GW) in Different Countries (IAEA (c), 2021)

In addition, around 59 GW nuclear capacity is under-construction. In this total, more than 50% is in Asia, that included Pakistan's 1,100 MWK-3 NPP.

8. Identified Future Role of Nuclear Energy

8.1 Firm Base Load Supply Option

Nuclear power fuel cost and variable operating cost is the least among all thermal power generation option. Therefore, an NPP is generally designed to operate as base-load plant and once fuelled, it operates for 14 - 18 months non-stop. This constant

[12] The total generation is around 25 trillion kWh

continuous supply increases the power supply system reliability. In addition, it helps in stabilizing the supply system prices as the share of fuel price is less than 15% in the cost of generation. Among others, these two attributes are essential for economic growth, particularly large-scale industry expansion. Like any developing country, a perpetual and significant economic growth potential is foreseen in the case of Pakistan. Hence, the country will require substantial and sustainable firm base-load supply, that can be guaranteed through development of nuclear power capacity expansion.

8.2 Climate Change Mitigation

Climate change owing to anthropogenic greenhouse gases (GHG) emission is a known challenge. Currently, the total annual anthropogenic GHG emission is more than 50 billion tonnes CO_2 equivalent and expected to grow by more than 20% by 2050 (IPCC, 2021); (University of Michigan, 2021). In this annual GHG emission, 65%75% comes from burning of fossil fuel for energy (including ~25% of electricity sector) production (United Nations, 2015). According to IPCC (2021), the energy related emissions should be neutralized by 2050 to avoid rise in the earth surface mean temperature by 1.5° C above pre-industrial (1850-1900) temperature by the end of this century. In other case, there will be proportional severe impacts of climate change in the form of; long warm weather, rapid glacier melting, irregular rainy seasons, flood, drought, etc., that will be hard to cope, particularly by developing countries.

Nuclear energy is a recognized energy generation option to achieve the sector GHG emission neutrality. Therefore, IPCC as well as other well-known organizations included nuclear power in almost all prospective solutions for handling the climate change. In 2050, therefore, nuclear power is expected to be doubled as of current capacity (IAEA, 2020).

Since Pakistan is among the 10 most prone countries, that are facing the severity of climate change, therefore, the country has always supported the international efforts of GHG emission mitigation. In this regard, in 2016, Pakistan ratified the Paris Agreement of GHG emission mitigation. For effective mitigation, therefore, nuclear power will be essential for the country to reduce the country energy sector GHG emissions, that currently constitutes around 45% of the Country's total around 490 million tonne $CO_{2\text{-eq}}$ emissions (GoP, 2021). Since 1971, nuclear energy has avoided 69 million tonne $CO_{2\text{-eq}}$ GHG emissions, that are equivalent to burning of around 28.7 million tonne coal in an open field.

8.3 Security of Energy Supply

Security of energy supply is essential for a sustainable energy system. Since nuclear fuel contains densest contents of energy as mentioned earlier, therefore, any disruption of fuel supply resulting from international politics or other issue - does not affect an NPP operation for months, even years. Once fueled, a nuclear reactor can operate more than 18 months as mentioned above. In addition, fuel for two years can be stored conveniently without extra cost.

9. Conclusion

NPP is well-proven power generation technology and several variants of the technology are available in the world. The technology is being evolved for the last 70-years, aiming to improve operational safety and economics. Currently, 442 nuclear reactors are operating in the world, mostly PWR designs of Gen-II. However,

Pakistan's nuclear reactors at Chashma Nuclear Power Generation Station (CNPGS) reactors are Generation II+ (i.e., plus) PWR, and the recently commissioned K-2 and the under-construction K-3 are Gen-III PWR. Gen-III designs are relatively safer that use natural convection, buoyancy, and gravity to perform the safety operation, without humane intervention.

Nuclear power contributes well in the energy supply system of several developed and emerging developing countries. In the world, the share of nuclear energy in the energy supply system is 10% and an increase in the capacity of the nuclear reactor is acknowledged to handle the climate change issue and for a reliable power supply.

In Pakistan, nuclear energy has been part of the Country's power system from 1971, and its current share is more than 9%.

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