



न्यूक्लियर पावर कॉर्पोरेशन ऑफ इंडिया लिमिटेड
Nuclear Power Corporation of India Limited

NUCLEAR POWER CORPORATION OF INDIA LIMITED
(A GOVT. OF INDIA ENTERPRISE)

A Brief Introduction to Light Water Reactors



Kudankulam Nuclear Power Plant – 1&2

**Directorate of
Corporate Planning and Corporate Communication**

INTRODUCTION

Light Water Reactors (LWRs) are the most popular among all types of nuclear reactors in the world. At present, 379 out of 441 power reactors under operation and 45 out of 51 new reactors under construction are LWR. There are two major variants of LWR namely, Pressurised Water Reactor (PWR) and Boiling Water Reactor (BWR). Reactor types which are in use other than LWR are Pressurised Heavy Water Reactor (PHWR), Fast Breeder Reactor (FBR), Gas Cooled, Graphite Moderated Reactors (GCR), High Temperature Gas Cooled Reactors (HTGR) and Light Water Cooled, Graphite Moderated (RBMK type Russian Reactor - LWGR). The distinguished feature of LWR with respect to other types of reactor is that light water (ordinary water) is used as both reactor coolant and moderator. Table-1 provides the details of installed capacity of different reactor designs.

Table 1: Total Number of Operational Reactors: 441

Reactor Type	Reactor Type Descriptive Name	No. of Reactors	Total Net Electrical Capacity (MW)
BWR	Boiling Light-Water Cooled and Moderated Reactor	61	61849
FBR	Fast Breeder Reactor	3	1400
GCR	Gas Cooled, Graphite Moderated Reactor	10	5650
HTGCR	High Temperature Gas Cooled Reactor	1	200
LWGR	Light-Water Cooled, Graphite Moderated Reactor	12	8358
PHWR	Pressurized Heavy-Water Moderated and Cooled Reactor	48	24404
PWR	Pressurized Light-Water Moderated and Cooled Reactor	306	291681
Total		441	393542

(Source: IAEA PRIS database as on April 06, 2022)

LIGHT WATER REACTORS

1. PRESSURIZED WATER REACTORS

Pressurized Water Reactors (PWRs) use light water at high pressure (to prevent boiling in the reactor core) as coolant as well as neutron moderator. Compared to heavy water, light water as moderator has a higher tendency to capture neutrons, so natural uranium, with its low fissile content (0.71% of U^{235}), is insufficient for sustaining a nuclear fission chain reaction with light water as moderator. Hence PWRs use slightly enriched uranium (3 to 5% U^{235} content) as fuel.

Two coolant cycles (primary and secondary coolant cycles, with water used as coolant for both cycles) are used in a pressurized water reactor. The primary coolant is circulated through the core in order to remove the heat generated by nuclear fission. In the steam generator, primary coolant transfers heat to the secondary coolant. Primary coolant passes through large number of tubes in steam generator, while the secondary coolant flows through the shell side of the steam generators and evaporates to pressurized steam. Notably, this transfer of heat takes place without mixing the two fluids, as they belong to two isolated loops. This avoids direct contact of secondary coolant with radioactive primary coolant and prevents secondary water from becoming radioactive.

From there, the steam reaches the turbine, where it rotates high-pressure and low-pressure turbines which, in turn, rotate an electric generator to generate electricity. This generated electricity is evacuated from the station through a switchyard connected to transmission lines. The spent steam is condensed in a condenser and the resulting secondary water is pumped out of the condenser with a series of pumps, reheated, and pumped back to the steam generator.

A vacuum is maintained at the turbine outlet to cause the pressure to drop across the turbine. This enables maximum extraction of energy from the steam. Before being fed into the steam generators, the condensed steam (referred to as feedwater) is preheated, which not only enhances the cycle efficiency, but also minimizes thermal shock at the steam generators.

The primary coolant loop contains Reactor Pressure Vessel (RPV), Pressurizer, Steam Generator and Coolant pump. Reactor Pressure Vessel (RPV) consists of core, water and control rods. A schematic of Typical PWR type reactor plant is given in Figure 1.

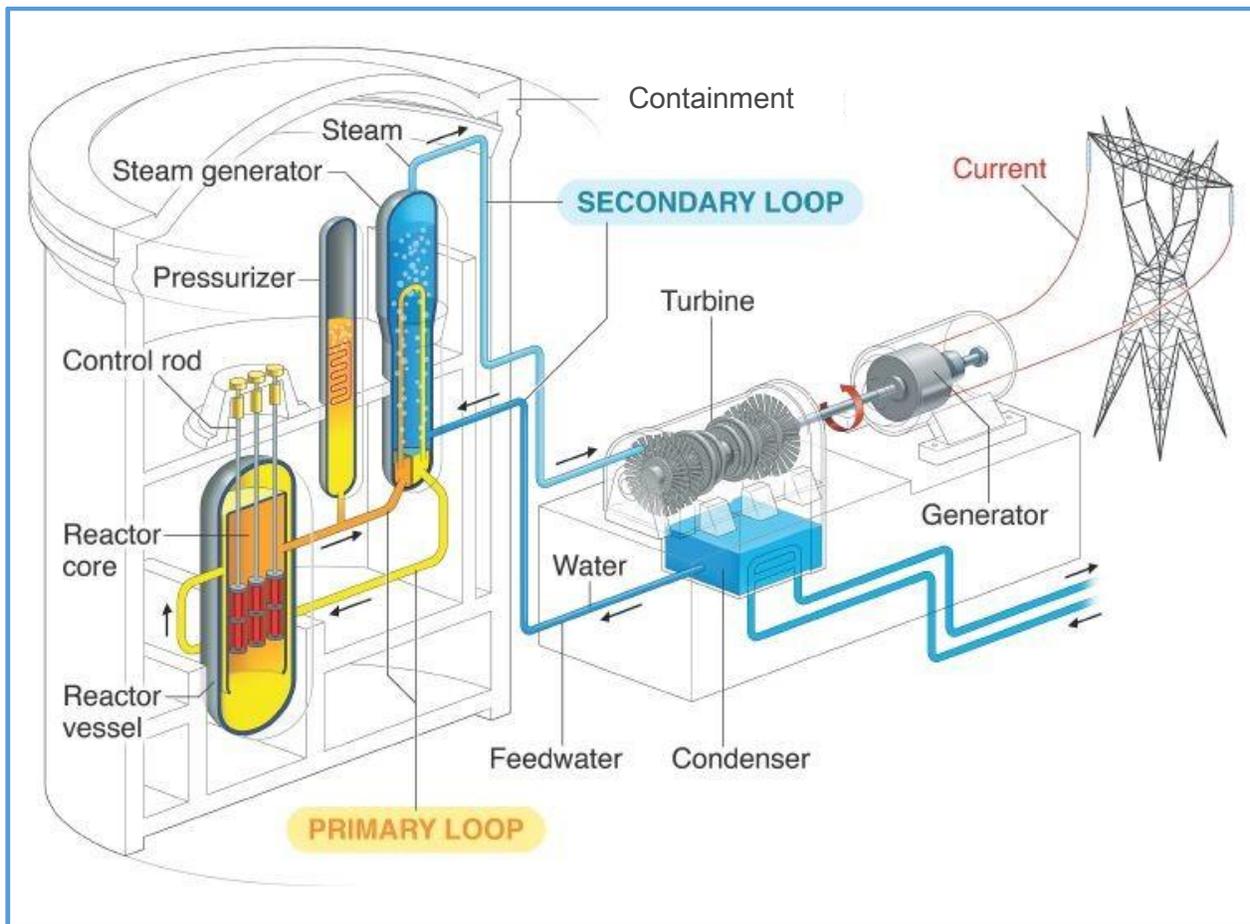


Figure 1: A schematic of a typical PWR

REACTOR PRESSURE VESSEL:

Reactor Pressure Vessel (RPV) is the heart of a nuclear power plant. RPV is a thick cylindrical vessel made of alloy steel. It houses reactor internals, fuel assemblies, the control rods and a host of other mechanisms and connections. Light water, which is the coolant, enters and exits through the coolant inlet (called cold leg) and outlet, (called outlet) respectively. The coolant entering through the cold leg is directed downwards and enters the core barrel through the perforations in the flow distribution plate welded to the bottom of RPV. The coolant circulates through the reactor core and absorbs the heat in the core produced by fission chain reaction taking place in the nuclear fuel, and then this hot coolant moves out through hot leg. From here, the hot coolant reaches steam generators through main coolant pipelines (MCP).

COOLANT

The fission heat generated by the nuclear fuel is absorbed by the light water used as the primary coolant circulating through the reactor core. Under pressure, the hot coolant water in the primary coolant loop is prevented from boiling. This allows relatively more heat to be carried per volume of coolant.

PRESSURIZER

A pressurizer, like its name suggests, maintains pressure in the primary circuit. It is a separate cylindrical vessel that is connected to the hot leg of primary circuit and is partially filled with water. Submerged heaters located in the pressurizer heat the coolant to the desired temperature whenever pressure reduces in reactor coolant system. If pressure in the system increases, the spray line releases cold water, which turns the steam in the pressuriser into water and reduces the pressure. Pressure transients in the primary coolant system are controlled automatically through use of automatic heaters and water spray, as per the requirement.

REACTOR COOLANT PUMP

The reactor coolant pump, which is a vertical-type single-stage pump, circulates coolant in the primary circuit. The hot coolant of the primary circuit transfers heat to water in a lower pressure secondary circuit in steam generators as explained earlier, evaporating the secondary coolant to steam. Thereafter, this cooled primary coolant is sent back to the reactor vessel through these re-circulating reactor coolant pumps, to be heated again by the fission heat of the nuclear fuel. A flywheel is provided at the top for extending the coast down of the pump at so as to ensure adequate coolant to a reactor core even at a power loss. By coasting down time, we mean the time taken by the rotating pump to come from full speed to the rest position which increases by providing a flywheel and hence time for initial core cooling in the event of a power loss.

STEAM GENERATOR

Steam generator is a heat exchanger inside which heat is transferred from the primary circuit to the secondary circuit. Heated water from reactor vessel travels through main coolant pipes to the steam generator. Primary side water passes through tubes surrounded by secondary water flowing through the shell. Dry saturated steam exits the steam generator through main steam lines and reaches the turbine. Primary coolant, after transferring heat to the secondary coolant, is returned to the reactor vessel allowing it to be reheated.

Two design solutions have been adopted for the steam generators worldwide. Design with tube bundle arranged vertically and design with tube bundle arranged horizontally. Vertical U-tube type steam generators are used in western PWRs and horizontal steam generators are used in the VVER type reactors.

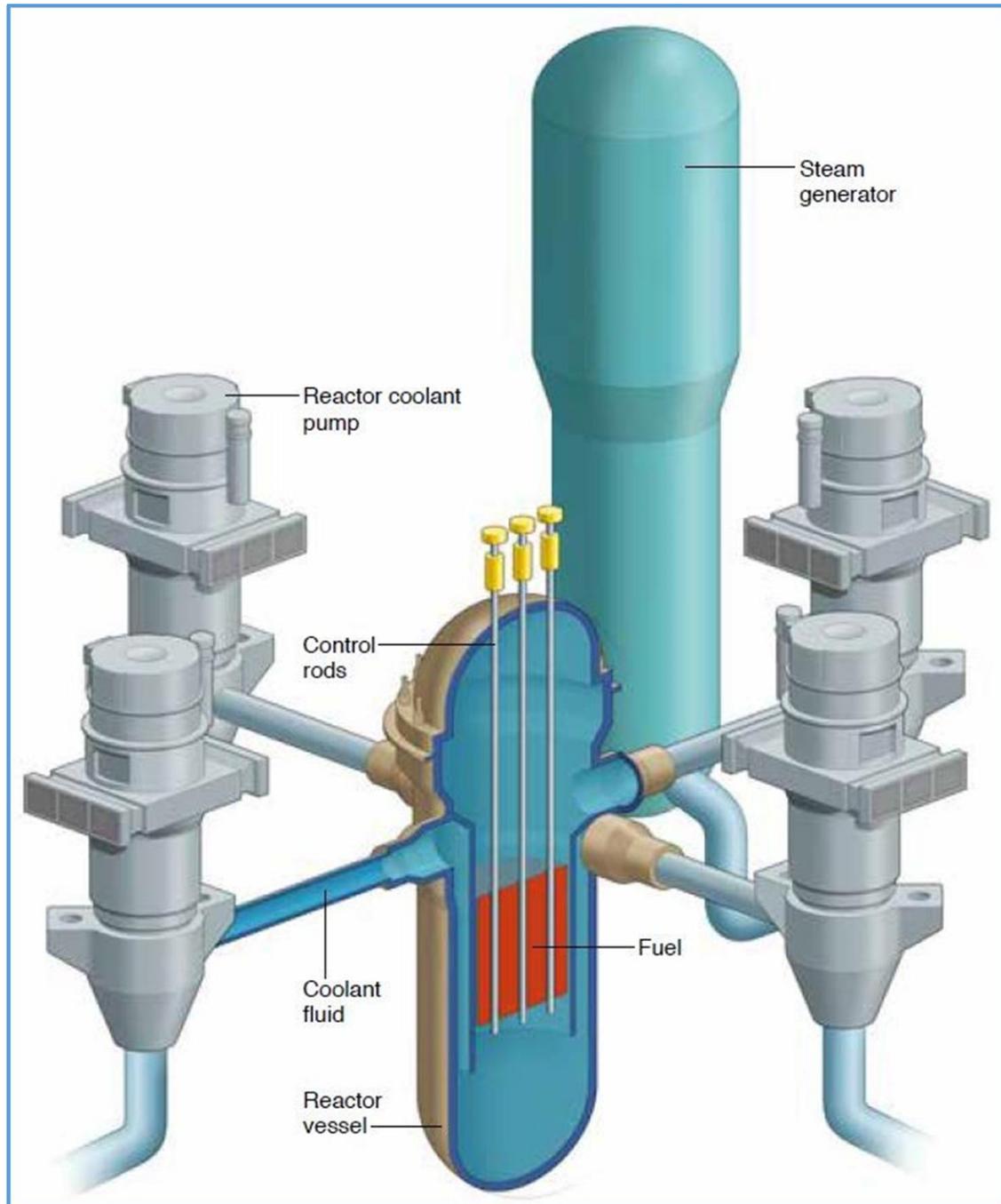


Figure 2 Components of Nuclear Steam Supply System

FUEL

PWRs use cylindrical sintered ceramic fuel pellets made of slightly enriched uranium dioxide (UO_2). The pellets are arranged inside zirconium metal alloy (Zircaloy) rods. Zirconium alloy is chosen for fabricating fuel rods because of its mechanical properties, corrosion-resistance and low neutron absorption property. Fuel rods are grouped in fuel assemblies that are placed in the core of the reactor. A typical PWR has fuel assemblies of 200 to 300 rods each, and a large reactor would have about 150–250 such assemblies with 80–100 tonnes of uranium in all (Figure-2).

Upon gradual depletion of fissile content, fuel assemblies need to be replaced with fresh ones. PWRs have a typical refuelling cycle of 12 to 24 months. During each such refuelling, approximately one third of the reactor core is replaced.



Figure 2: A typical fuel assembly of PWR

REACTOR CONTROL

Reactivity – the rate of chain reaction – in the reactor core is maintained using control rods and also by adjusting the boron concentration in the primary coolant. Boron, being a neutron absorber, is also used to control reaction rate in the core. This is achieved by adding or diluting boric acid dissolved in the primary coolant. Higher Boron concentration leads to greater number of neutrons to be absorbed, leaving fewer neutrons to take part in the fission chain reaction, thus reducing the rate of fission chain reaction, and vice versa. High pressure pumps are used to inject borated water in the high pressure primary loop with differing concentrations of boric acid to maintain desired reactivity in the core.

Control rods, which are made of neutron-absorbing material such as Cadmium, Hafnium or Boron, use the same principle with different mechanical mode to control reactivity in the core. Control rods are placed at strategic location at the reactor head and they are moved in and out to varying degrees amid fuel rods, in order to control reactivity in the core to the desired level to either reduce power or to shutdown the reactor.

SAFETY FEATURES IN PWRS

PWR reactor technology has evolved over several decades. So, while the basic principles remain the same, successive evolutionary reactor designs have brought improvements that have made the reactors safer.

The latest PWRs incorporate unique combination of 'active' and 'passive' safety systems, taking the safety paradigm to an even higher level. Active safety systems provide robust safety function immediately in case of an unlikely scenario of emergency. Complementary to the active systems, the passive safety systems work even in station blackout conditions, that is, even if there is a total unavailability of electricity to the plant. This is possible because passive safety systems do not require electrical power to function, but rely on the unfailing natural principles such as gravity, inertia/conservation of momentum, pressure differential, convection, etc.

There are multiple safety systems to handle postulated accidents. Some of the important safety systems in modern PWRs include:

- Emergency core-cooling system (ECCS)
- Containment Spray System
- Passive Heat Removal System (PHRS)
- Containment isolation systems
- Hydrogen Recombiners
- Core Catcher

2. BOILING WATER REACTORS (BWRs)

Another type of LWR is the **Boiling Water Reactor (BWR)**. Globally, it is the second-most common type of nuclear power reactor after the pressurized water reactors. A BWR differs from a PWR in the fact that the coolant pressure is maintained such that water starts boiling while passing through the core. In a BWR, steam generated in the core is used directly to drive a steam turbine. This steam is then condensed and pumped into the reactor vessel with feed water pumps.

Unlike PWR, BWR does not have a separate secondary circuit. The coolant passing over fuel rods, picks up fission heat and boils, producing steam. The water-steam fluid enters

the riser area above the reactor core. A moisture separator located at the top of the riser area swirls the two-phase flow in cyclone separators, where the steam is separated. The steam rises upwards towards the steam dryer. Eventually, this dry saturated steam exits the Reactor Vessel through main steam lines and reaches the turbine. The steam drives the turbine. The exhausted steam from the turbine is directed into condensers, where the steam is cooled down to water, which is then pumped to the reactor vessel through feed water heaters that raise its temperature using extraction steam from various stages of the turbine. A schematic of Typical BWR type reactor plant is given in Figure 3.

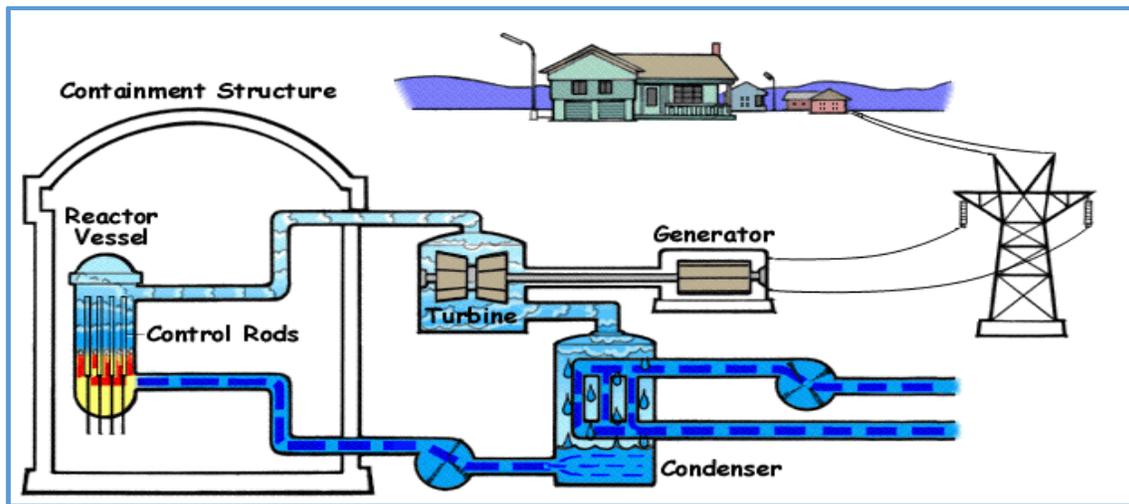


Figure 3: A typical Schematic of Boiling water reactor

CONTROL SYSTEMS

The BWR is controlled by blades entering from the bottom of the reactor vessel. The blades are usually of cruciform cross section and fit in between the fuel boxes surrounding the fuel elements. The fuel elements often contain burnable poison (e.g. Gd_2O_3). Because of the boiling in the reactor, boric acid cannot be used for reactivity control; however, it is provided as an extra emergency shutdown feature. The control blades contain boron carbide rods or powder placed in channels in the stainless steel blade-wings. One of the inherent safety feature of the BWR type of reactors is the negative temperature coefficients both for fuel and moderator, and also negative void coefficient. This means that the bubble formation (*void*) along the fuel pins reduces the reactivity. It is therefore a common practice to control the reactor power by the main coolant circulation pumps; increased circulation initially reduces the voids (and fuel temperature) thereby increasing power production until the previous void fraction has been almost restored at a slightly higher average fuel temperature.

STEAM TURBINES

Unlike a PWR, there are no primary and secondary coolant loops in a BWR. Thus, the same steam which is produced in the reactor core by coming in contact with the fuel rods is the one that drives the turbines. BWRs use high-pressure as well as low-pressure steam turbines. Saturated steam from the reactor is used for driving a high-pressure turbine. Thereafter, the high-pressure turbine exhaust passes through a steam reheater, which superheats the steam and directs it to drive the low-pressure turbines. The exhaust of the low-pressure turbines is sent to the main condenser, which condenses the steam into water, which is then pumped back to the reactor.

REFUELLING SYSTEMS

The number of fuel assemblies in a specific reactor is determined based on reactor core size, desired reactor power output and reactor power density. There are 74 to 100 fuel rods in each fuel assembly, while the reactor core itself is made up of up to 800 assemblies approximately.

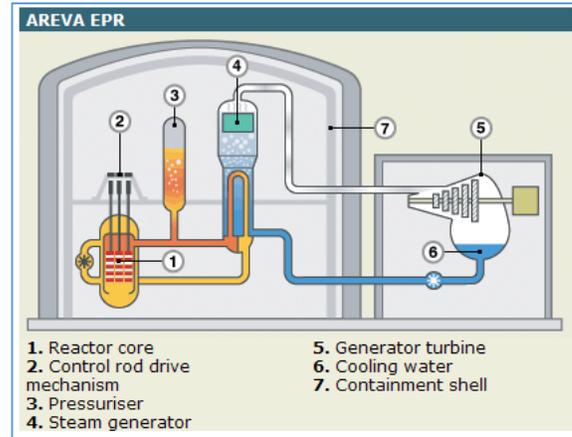
BWRs require refuelling every 18 to 24 month. During such a refuelling outage, about one-third of fuel assemblies are replaced. The remaining fuel assemblies are shuffled to new core locations. This helps maximize the efficiency and power produced in the subsequent fuel cycle.

NEW GENERATION LWRs

These light water reactor plants considered for implementation are based on advanced nuclear technology with the objectives of higher safety, technology diversity, and maximized nuclear electrical capacity. Recent developments in the reactor technology includes application of advanced safety features i.e. active and passive safety systems to enhance the safety. Passive safety systems use natural driving forces such as pressure, gravity, natural circulation, and convection to perform their intended function. The passive safety systems make the reactor to maintain the core and containment cooling for a designated time without any external AC power in case of eventualities. In such case, these passive safety systems are able to prevent core damage and ensure core cooling and containment for a designated time without the need of any external power supply. The advancement in technology also lead towards achieving the goal of higher design life of the reactors, higher availability, lower waste generation, lower predicted core damage frequency, lower large release frequency, lesser occupational radiation exposure as well as simplified operation and maintenance aspects of the plant. Some of the new design LWRs are described below.

1. EPR

EPR (Evolutionary Power Reactor) is a third-generation PWR type reactor design that has evolved from the combined efforts of AREVA NP (formerly Framatome ANP) of France and Siemens of Germany, based on the French N4 and the German KONVOI reactors. This reactor design is capable of achieving around 1,650 MWe of net power output with a thermal efficiency of 36%. The EPR has four independent, redundant safety train and a thick double-wall containment enclosing the reactor.

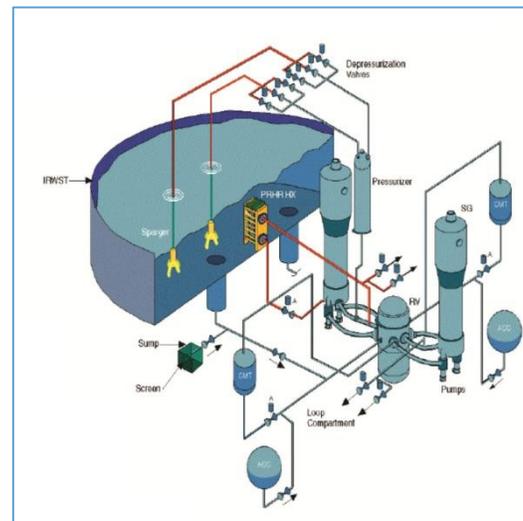


Among the advanced new features that it incorporates is the Ex-vessel Core Catcher concept to mitigate a postulated core melt accident. The standardised EPR design also allows load-following design adaptations. It means the output power can be changed according to the demand of the grid without the need of shutting down the reactor in case of low demands from the grid.

The first EPR Units came online at Taishan in China, where unit 1 became the first EPR to enter commercial operation in December 2018. In Europe, EPRs are currently under construction in France and the UK: Flamanville 3, currently expected to start up in 2023 with commercial operation in 2024; and two units at Hinkley Point C, currently stated for commercial operation in 2026 (unit 1) and 2027 (unit 2). OLKILUOTO-3 in Finland was connected to the grid on March 12, 2022.

2. AP1000

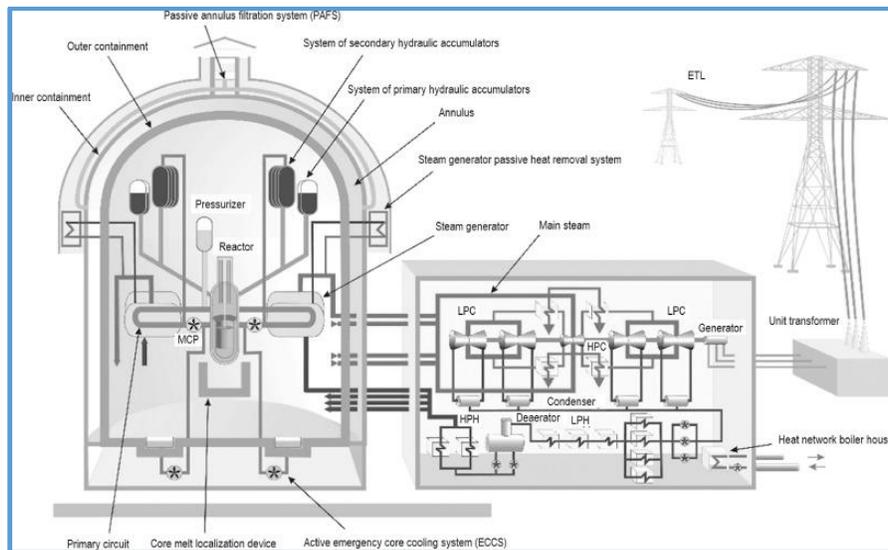
Advanced Passive 1000 (AP1000) is a Generation III+ PWR designed by Westinghouse. In contrast to a more widely prevalent four-loop design, AP1000 is a two-loop reactor. This design has evolved from the AP600 reactor, with an improved reactor containment isolation and improved safety margins. Notably, the design of AP1000 aims at simplification, right from construction techniques to overall safety systems as well as control and instrumentation. It harbours several innovative passive safety features such as passive residual heat removal system and a passive containment cooling system comprising of primary containment made of steel. In unlikely event of a severe accident, this reactor design employs in-vessel retention scheme to retain a



molten core inside the reactor pressure vessel with sufficient external cooling by passive means. With a gross power rating of 3415 MWth, the reactor has a gross electrical power output of 1250 MWe.

Sanmen-1 was the world's first AP-1000 to start up and entered commercial operation on September 21, 2018. Next Unit-1 of Haying Plant began commercial operation on October 22, 2018. Sanmen-2 and Haying-2 attained commercial operation in November 2018 and January 2019 respectively. All these four reactors are located in China. KANUPP-3 is ACP-1000 reactor model which was connected to the grid on March 04, 2022 but is yet to be commercial. Vogtle-3&4 are two AP-1000 reactors which are under construction in USA.

3. VVERs



Vodo-Vodyanoi Energetichesky Reaktor (Water-Water Power Reactor) or simply VVER is a series of pressurised water reactor design originally developed in the erstwhile Soviet Union, and now Russian Federation. The larger VVER-1000 developed after 1975 and is a four-loop system. It adopts the basic Russian design of model V-320 with advanced safety features. Latest models of VVER-1000 reactors (e.g. V-412 model in Kudankulam, India) have external crucible-type core-catcher for retaining molten corium inside the containment building in case of postulated severe accident scenario.

The VVER-1200 is a generation III+ reactor - an evolution of the VVER-1000 with increased power output to about 1200 MWe (gross) and providing additional passive safety features. This generation III+ reactor has four coolant loops, 163 fuel assemblies, and are rated at 3200 MWth with gross thermal efficiency of 37.5%, with extensive use of passive safety features as well as double containment shell for the reactor building. VVER-1200 reactor (Novovoronezh II-1, Russia) has entered into commercial operation in 2017.

Presently, VVER type of reactors are in operation in Russian Federation, Ukraine, Hungary, Finland, Czech Republic, Slovakia, Bulgaria, China, Belarus, Iran and India. Countries where VVER reactors are presently under construction include India, Bangladesh, China, Russian Federation, Slovakia, Ukraine and Turkey. Also some countries are planning to construct VVER Reactors include Finland, Iran, Egypt, Jordan and Turkey.

Role of Light Water Reactors in Indian Nuclear Power Programme

India has steadfastly seen nuclear power as an important element in its energy strategy and critical to achieve India's objective of clean energy, security and diversity in supply. India's indigenous power programme is primarily based on PHWRs using the natural uranium as fuel and heavy water as the moderator and coolant.

The very first nuclear power reactor to be built in India was a BWR at Tarapur, Maharashtra in collaboration with USA which was a turnkey project with General Electric (GE), USA. The Indian nuclear power programme envisaged by DAE from late eighties considered large scale addition to the capacity by adopting through international collaboration large power reactors of light water reactor type.

In line with this, two reactors KKNPP 1&2 (2X1000 MW) set up in cooperation with Russian Federation are in operation. Units 3 to 6 (KKNPP 3&4 – 2X1000 MW and KKNPP 5&6 – 2X1000 MW) are under construction. Discussions are in progress to arrive at project proposals in respect of reactors to be set up in cooperation with France at Jaitapur, Maharashtra and with the USA at Kovvada in Andhra Pradesh.

The light water reactors plants considered for implementation are based on advanced technology with higher level of safety, longer design life and efficiency. These reactors are designed as per the safety codes of the country of origin and are required to be fully compliant with Indian regulatory requirements.

Conclusion:

The Light Water Reactors form an integral part of the Indian Nuclear Power Program as an additionality to the indigenous and unique three stage power program being adopted by India. This has been done to meet the power demand of the country by a clean and a green source of power supply. Adding power by means of these light water nuclear power reactors will also contribute to India's Intended Nationally Determined Contributions (INDC) for working towards climate justice.

Nuclear Power Plants & Sites in India



Capacity In Operation (6780 MW)

Capacity Under Construction (8200 MW)

*Out of these units, RAPS-1 (100 MW) is owned by the DAE and managed by NPCIL



Published by:

Directorate of Corporate Planning & Corporate Communication (CP&CC)

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