The status of nuclear power development in India

B. C. Pathak[1], C. P. Kaushik[2,3], K. N. Vyas[4] and R. B. Grover[3,*]

[1]Nuclear Power Corporation of India Limited, Mumbai 400 094, India
[2]Bhabha Atomic Research Centre, Mumbai 400 085, India
[3]Homi Bhabha National Institute, Mumbai 400 094, India
[4]Department of Atomic Energy, Mumbai 400 001, India

Considering the energy resource profile in the country, Homi Bhabha underscored the need for the development of atomic energy, advocated the pursuit of a closed fuel cycle and selected the reactor system to be adopted by India for large-scale deployment. Following the vision outlined by him, India selected pressurized heavy water reactors (PHWRs) of smaller capacity (i.e. 220 MW plants) for large-scale commercial deployment of nuclear energy. Over time, the country developed expertise in this technology with the construction of several 220 MW plants and then raised the capacity to 540 MW. This experience, expertise and indigenization have led to the development of a state-of-the-art 700 MW PHWR, and India is now set to install several such reactors along with light water reactors in technical collaboration with foreign vendors, to increase the nuclear-installed base in the country. Technologies to reprocess spent nuclear fuel and manage high-level waste have also been developed and deployed. This article presents a brief outline of the present status of nuclear power development in India.

Keywords: Atomic energy, fuel cycle, heavy water reactors, nuclear power.

Introduction

AFTER establishing the Department of Atomic Energy (DAE) in India, one of the first tasks taken up by the then leadership was to delineate the role of atomic power in the country's electricity mix[1]. Energy resources available in India were surveyed and interestingly, they included solar energy, though it was recognized that the technology for using it economically had not yet been developed. An important conclusion was that the energy potential of uranium and thorium was many times that of the conventional energy resources and the way forward was to pursue a closed fuel cycle[2]. To realize the vision outlined by Homi Bhabha, it was necessary to develop several technologies and establish a sound institutional framework. While the development of an institutional framework based on the blueprint prepared by Bhabha has been summarized elsewhere[3], this article outlines the present status of the development and deployment of technologies for generating nuclear electricity.

Bhabha formulated a general plan for the development of atomic energy in 1954 and, since then the world has come to realize that carbon level in the atmosphere is rising and influencing the global climate. This has increased the importance of deploying low-carbon technologies in the energy sector and also in industries where fossil fuels are used as fuel or as molecules/feedstock. For example, coal is used in steel-making both for its energy content and as a reducing agent. To reduce carbon emissions, the use of fossil fuels in energy generation and directly in the industry needs to be eliminated or reduced drastically so that the vision of net-zero by 2070, announced by our Prime Minister, Narendra Modi at COP-26 can be realized. This calls for setting a target for energy availability, for use as energy, and to produce the molecules and feedstock for use in industry to replace fossil fuels, and all this from low-carbon sources, i.e. hydro, nuclear, solar and wind. Next, we examine what all this involves.

Setting a target for energy availability in India

Forecasting energy growth and modelling energy systems are complex tasks. Both involve too many assumptions. While they provide information about possible trends, results vary lot depending on the assumptions. The assumptions and results represent the ideological or philosophical leanings of the modelling group. Energy professionals, in general, are advocating a transition to a low-carbon energy mix to address the imperative of climate change. This will involve the electrification of several sectors and increase the electricity demand. However, studies concerning electricity growth are forecasting electricity demand that is not consistent with their advocacy for electrification. To quote two examples, studies have been done by the International Energy Agency (IEA) and the Council on Energy, Environment and Water. Ahluwalia and Patel[4] have commented on gross underestimation of the elasticity of energy consumption with respect to gross domestic product, particularly by IEA.

*For correspondence. (e-mail: rbgrover@hbni.ac.in)

Having announced that India will reach net-zero by 2070, the country should also decide on a target for electricity generation in 2070 and possible pathways to reach that target. For deciding a target for energy generation, two different approaches, i.e. top–down and bottom–up are followed[5].

Bottom–up approaches are developed based on the concept of decent living energy and involve too many assumptions. It is better to follow the simpler top–down approach as the assumptions involved are fewer. Top–down approaches involve making human development index (HDI) versus per capita energy per annum plots. Energy could be in the form of total primary energy, total final consumption (TFC) or electricity supply. Grover[5] had earlier come up with a target for electricity generation based on an HDI versus electricity generation per capita per annum and commented that the target so arrived at is on the lower side because of expected structural changes in the energy sector aimed at transition to a low-carbon energy mix. The Government of India (GoI) has announced the target of achieving net-zero by 2070, and estimates for a revised target have now been made. Based on an HDI versus TFC plot (Figure 1), Bhattacharyya *et al.*[6] concluded that to get an HDI of 0.9, India must aim to provide a TFC of about 75 GJ per capita per annum. This number comes down to about 45–50 GJ per capita per annum as energy efficiency improves and electrification of end-use services takes place, but is significantly above the present per capita per annum TFC of 19.3 GJ. India faces twin challenges as it has to increase the availability of energy several fold and at the same time make structural changes in the energy mix to achieve the target of net-zero.

The next step is to provide the needed TFC to citizens in a manner that makes it possible to achieve the target of net-zero. Converting TFC to electricity requirements is an involved process. For some services like light transport, there will be an improvement in efficiency as electric motors are more efficient than internal combustion engines, whereas for heavy-duty transport where it might become necessary to use hydrogen or fuel derived from hydrogen such as ammonia, the efficiency of energy use will fall as it would involve the production of hydrogen by electrolysis and its use in internal combustion engines or fuel cells. At present, water electrolysis using low-carbon electricity is the only techno-commercial mature option for producing low-carbon hydrogen. This can change when high-temperature nuclear reactors or solar thermal processes, or some altogether new technologies are developed. To minimize and ultimately eliminate the use of fossil fuels in industries such as steel, cement and fertilizers, one would need electricity as well as hydrogen (as a molecule/feedstock and also as a source of energy). Additionally, there are industries where complete elimination of the use of fossil fuels might not be possible, and for such industries, one will have to continue to use fossil fuels along with energy-intensive carbon capture technologies.

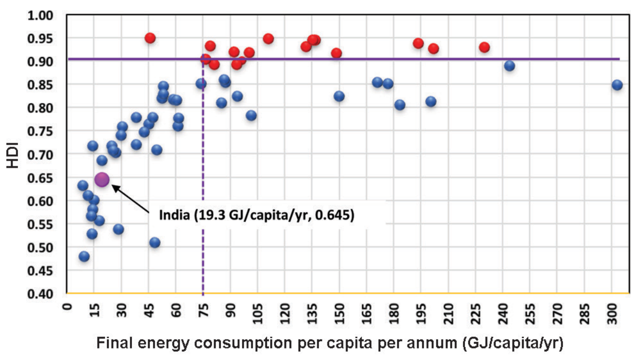


Figure 1. Human development index (HDI) as a function of total final consumption for the year 2019 (data from IEA for energy, UNDP for HDI and UNDESA for the population)[6]. Note: All countries, except Hong Kong, with HDI above 0.9 have total final energy commission above 75 GJ per capita per annum (75 GJ = 20,833 kWh). Hong Kong has a service economy and already has a high degree of electrification.

After the announcement of the net-zero target year, energy system modellers are building scenarios and estimates hover between 15,500 and 18,000 kWh per capita per annum[6]. One can take this number to be 16,000 kWh per capita per annum for planning purposes. Current estimates suggest that in 2070 the population of India will be around 1.5 billion; this translates into a total generation of 24,000 TWh. It will be used as electricity and also for the generation of hydrogen. To put this number in perspective, it may be recalled that the total generation in India in 2020–21 was about 1600 TWh. Irrespective of the kilowatt hour per capita per annum to be made available in the country, one can certainly mention that the energy mix has to be diverse with nuclear as a significant component.

The pathway to reach the target generation needs meticulous planning. An approach that is not based on detailed optimization exercise can lock in assets and make energy unaffordable for the consumers. A detailed study by MIT, USA, concludes that economics calls for nuclear to be a significant part of the energy mix[7].

The nuclear power programme started in India with the construction of two boiling water reactors at Tarapur, Maharashtra. These units, commissioned in 1969, were turnkey projects from M/s General Electric (GE), USA, and were set up to obtain experience in the operation and maintenance of nuclear power plants (NPPs) and to demonstrate the technical viability of operating them in the Indian grid. However, for large-scale deployment, it was decided to set up pressurized heavy water reactors (PHWRs). The factors that contributed to the selection of PHWRs included the following[8]:

- Use of natural uranium as fuel (i.e. development of fuel-enrichment facilities was not required).
- High neutron economy (resulting in the low requirement of natural uranium).

- An efficient producer of plutonium (required for the fast reactor programme).
- Possibility of developing technology for the production of heavy water within the country.
- Possibility of fabricating all the equipment within the country, as PHWRs do not have a high-pressure reactor vessel.

The PHWR programme was begun with the cooperation of Canada by setting up two 220 MW units. Starting from this beginning and achieving complete indigenization, India has quickly arrived at a pioneering position in PHWR technology. The indigenization includes manufacturing and construction by the Indian industry. India is not endowed with large deposits of uranium, but after the Nuclear Suppliers Group amended its guidelines for international trade, uranium availability is no longer an issue[9]. In parallel, efforts to explore uranium in the country were intensified and have led to about a threefold augmentation of domestic uranium resources since 2005. Kain *et al.*[10] provide more details about the intensification of domestic exploration efforts.

At present, India is operating 18 units of PHWRs (consisting of 16 units of 220 MW and two units of 540 MW) and six PHWRs (of 700 MW) are under construction. GoI has accorded administrative approval and financial sanction for the construction of ten 700 MW PHWRs in fleet-mode. To rapidly ramp up nuclear-installed capacity, light water reactors are also being set up in collaboration with other countries. Two units of pressurized water reactors have already been set up and four more are under construction.

To understand the basics, research reactors and research facilities were first set up and they helped in adopting a science-based approach for the nuclear power programme. For the operation of nuclear reactors, the front-end and back-end fuel-cycle activities are important and are being pursued. Uranium mining, fuel fabrication and heavy water production comprise front-end activities, and facilities were set up in India at the beginning of the programme itself. Spent-fuel reprocessing and waste management comprise back-end facilities. In this article, we explain the maturity level achieved in the design and construction of PHWRs and the associated back-end activities of the nuclear fuel cycle. Other articles in this Special Section describe the front-end facilities.

Evolution of PHWRs and the present status

220 MW PHWRs

The first two PHWR units at the Rajasthan Atomic Power Station (RAPS) were based on a similar reactor at Douglas Point, Canada. In addition to design, Canada also provided all the main equipment for the first unit, whereas India contributed to the construction, installation and commissioning. For the second unit, import content was reduced considerably. Due to the Peaceful Nuclear Explosion in 1974, Canada withdrew support and India completed the remainder of the design, construction and commissioning. The rating was changed to 200 MW nominal power output based on operational experience in the Indian environmental conditions.

Starting from the next PHWR station, i.e. Madras Atomic Power Station (MAPS), indigenization of PHWR technology began in real earnest. The physics and engineering design of these units were reoptimized by DAE to provide about 10% higher power than the earlier units. Few other design changes were also introduced in the MAPS units; notably, partial double containment and the concept of suppression pool for vapour suppression to limit the containment peak pressure during a loss of coolant accident and closed loop for the process cooling water system to avoid any possibility of radioactivity release to the water body. To accelerate implementation of the PHWR programme, the design was standardized while retaining the unit capacity at 220 MW. The twin units at Narora Atomic Power Station (NAPS) were the first set of indigenously designed, standardized 220 MW PHWRs. As the design of a NPP has to keep up with the regulatory requirements, evolution of technology, operational feedback, etc. the standardized design of 220 MW PHWR units included major design changes and improvements. One prime aim of the changes made in the standardized 220 MW units was that the concepts of the systems developed should be extendable for larger capacity units in the future. These included two fast-acting, independent and fail-safe reactor shutdown systems, with additional systems to ensure long-term sub-criticality during a plant shutdown. The moderator level control mechanism in RAPS-1 and 2 and MAPS-1 and 2 for raising and lowering reactor power was replaced by shim rods. Double containment with the outer containment fully enveloping the inner one and with a pressure suppression pool was provided. The reactor was engineered to be full-tank calandria with a water-filled calandria vault, an integral end shield and calandria. Subsequently, many more 220 MW PHWR units were constructed with the same configuration and some design alterations to benefit from the evolution in equipment manufacturing and civil construction techniques, advances in control and instrumentation (C&I), etc. All this was done based on extensive computational studies of the reactor physics design, modelling of engineering systems, development and testing of components and subsystems, and the design of a new system; wherever needed, academic institutions and Indian industry were involved.

540 MW PHWRs

To realize the economy of scale, the design of 540 MW PHWR was taken up simultaneously with the 220 MW units, and two such units are operating at Tarapur Atomic Power Station (TAPS). These units, extended from the proven standardized 220 MW design, have a larger reactor core size and thereby increased fissile material in the core. The diameter of the pressure tubes was increased to accommodate larger-diameter fuel bundles consisting of 37 fuel pins instead of 19 fuel-pin bundles used in the 220 MW units. Also, the number of fuel bundles in the coolant channel was increased from 10 in the 220 MW to 12 in the 540 MW units. The number of coolant channels was also increased from 306 to 392. This necessitated changes in the design of the reactor control and shutdown systems. A large reactor core is neutronically loosely coupled (i.e. effect of neutron flux change in one part in the core is not sensed in the other parts). This required dividing the core into several control zones (Figure 2), which are monitored and controlled individually for zonal power control and in unison for bulk power control[8,11]. Considerable reactor physics studies and physical model testing were conducted to firm up this additional feature. In the 540 MW PHWRs, the first shutdown system (consisting of mechanical shutoff rods), was essentially similar to that of the 220 MW units, though the number of shutoff rods was increased from 14 to 28. The second shutdown system in the 540 MW PHWRs was changed to injecting gadolinium nitrate, which is a poison for neutrons, directly into the moderator (Figure 3).

Improved operating performance of PHWRs

With continuous improvements in design, preventive maintenance, operational practices, procedures and learnings from our own and as well as international exposure, training, upgradation in general, etc. the number of trips/shutdowns had reduced to 1.9 outages/unit/yr in 2020–21 from 11.4 outages/unit/yr in 1992–93. This resulted in increased availability factors of the units comparable to the international level.

Several PHWR units have continuously operated for more than a year (Figure 4). Out of 10 longest running NPPs in the world, 4 are from India. RAPS-5 set the record of continuous operation for 765 days; RAPS-3 continuously operated for 777 days, NAPS-2 for 852 days and KGS-1 continuously operated for 962 days pushing the performance bar higher and higher.

The entire journey of nuclear power capacity enhancement was not without challenges like en-masse coolant channel replacement, en-masse feeder replacement, en-masse boiler hair-pin replacement, domestic fuel crisis, etc. These challenges were not only dealt with successfully, but with the experience and lessons learnt, expertise has been strengthened further in handling similar situations.

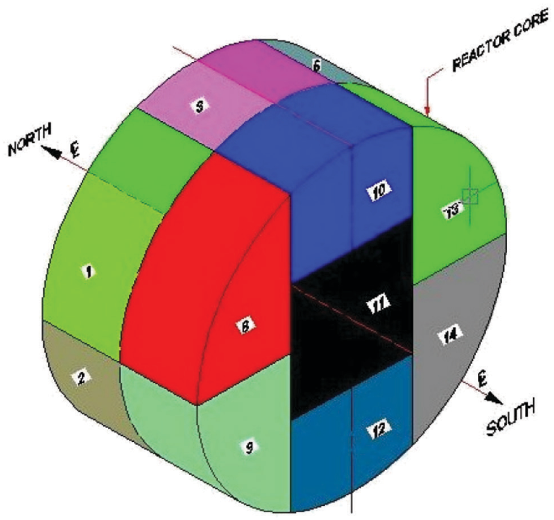


Figure 2. Fourteen reactor zones with the respective zone control compartments in 540 and 700 MW PHWRs (schematic).

Increasing the power to 700 MW to achieve economy of scale

To further optimize the cost of electricity through economy of scale, 700 MW PHWR units were designed, keeping the same reactor core as in the 540 MW units. The first 700 MW PHWR unit at Kakrapar Atomic Power Station (KAPS) was synchronized with the grid on 10 January 2021. One more unit at KAPS and two units each at RAPS and Gorakhpur Haryana Anu Vidyut Pariyojna are under construction. Administrative approval and financial sanctions of GoI have been accorded for 10 more 700 MW units, which are being taken up in fleet mode. Thus, the total capacity addition envisaged through 700 MW PHWRs is 11, 200 MW.

As mentioned above, the core design of the 700 MW units is the same as that of the 540 MW units, but the energy extracted is uprated 25% by allowing partial boiling (above ~85% full power) to the extent of 2–3% quality at the exit of the coolant channels. The increase in nominal maximum channel power from 5.5 to 6.5 MW contributes 18% more power output and an additional 7% is achieved by modified burnup zones for achieving higher flux flattening. The 700 MW reactor core is designed to produce 2290 MW of fission power and 2166 MW of thermal power to the coolant compared to 1830 MW of fission power and 1730 MW of thermal power to the coolant in the 540 MW PHWRs. All the features and systems required for a larger core of 540 MW are common to the 700 MW PHWRs as well.

Due to low excess reactivity in PHWRs where natural uranium is used as fuel, on-power refuelling is required to be done almost daily in the channels of the reactors. A long, continuous run of PHWRs requires this refuelling system to be highly reliable. To meet the higher refuelling requirement in 700 MW units over previous reactors, the

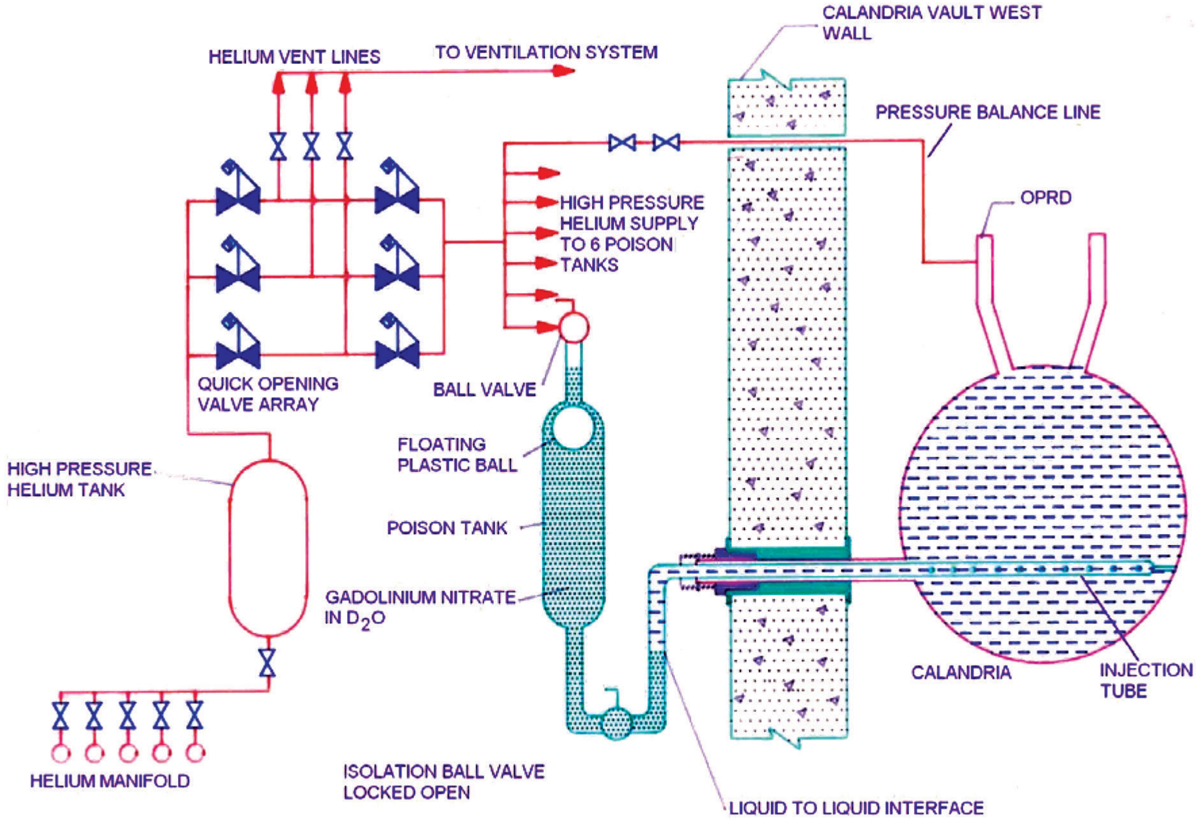
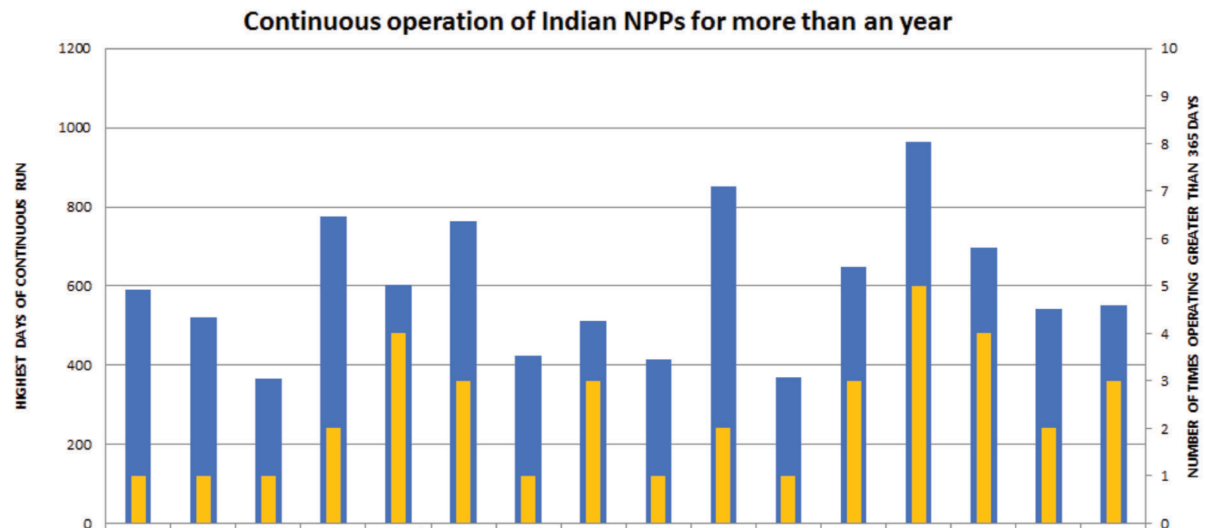


Figure 3. Second shutdown system of 540 and 700 MW PHWRs (schematic).



	TAPS-2	TAPS-3	TAPS-4	RAPS-3	RAPS-4*	RAPS-5	RAPS-6	MAPS-2	NAPS-1	NAPS-2	KAPS-1	KAPS-2	KGS-1	KGS-2	KGS-3	KGS-4
Highest run	590	522	365	777	602	765	423	513	414	852	370	647	963	698	541	550
No. of Times	1	1	1	2	4	3	1	3	1	2	1	3	5	4	2	3

*Continue to operate

Figure 4. Performance of Indian PHWRs (updated up to November 2021).

fuel transfer system (both for fresh fuel loading and discharging spent fuel) has been redesigned to keep operation and maintenance needs at a reasonable level. A low-pressure light water equipment, i.e. mobile transfer machine (MTM), has been introduced to carry out new fuel as well as spent fuel transfer operations (Figure 5). It is common to both the fuelling machines. Transfer of irradiated fuel from the reactor building (RB) to the spent fuel storage bay (SFSB) is accomplished through a short-length discharge port, connecting RB and SFSB. For housing and movement of MTM, a fuel transfer tunnel made up of super-heavy-density concrete is provided inside RB.

With development in technology, C&I for such complex plants has seen a total change. The use of indicating metres, strip-chart recorders and alarm windows had increased equipment density on the control panels. The increased equipment density was making it difficult for operators to focus attention, and these have been long since abandoned for a variety of reasons. One is the fast obsolescence of technology devices used earlier. Finding one-to-one replacement of vital parts for normal maintenance became impossible with time. The R&D units of DAE and Electronics Corporation of India Ltd, have kept pace with new technological options to develop newer approaches in C&I, computerization and hardware. For example, state-of-the-art new features have been incorporated in the design of 700 MW C&I architecture. Systems are grouped function-wise. Alarm function, logic control, process control and assimilation of functions about the process are combined. Each group is provided with its operator interface. The main control room is designed with ergonomic considerations to ease the sensory impact on operators and thus reduce the probability of human errors. Seated operation is introduced and hence, many of the controls from the main control panel are replaced with soft commands from the operator interface. Large video screens are provided in the main control room for viewing operational parameters simultaneously by the entire crew in the room. Hardware modules are standardized to reduce the variety of hardware and the inventory of spares. To take care of obsolescence, hardware modules are developed with the latest components, and forward and backward compatibility is ensured. At the same time, layout ensures physical separation of hardware for protection to address common cause failure. Software is modularized for uniform and quick development and to reduce the efforts required in V&V.

Figure 5. Mobile transfer machine for fuel transfer in 700 MW PHWRs.

Safety of Indian PHWRs

In NPPs, safety is the prime consideration; beginning from the siting stage it continues during design, construction, operation and eventually decommissioning. In the design and operation of NPPs the principle of defence-in-depth is followed, which is akin to the Swiss cheese model used in other safety-critical industries. According to this principle, any undesirable event is to be prevented by strengths built into the design of the plant, including its control and protection systems. Further, if prevention is not successful in a rare case, then the plant should have additional designed safety systems to mitigate the consequences of the event within acceptable limits. This practice is followed in all PHWRs and in this process, design-specific events of varying severity are postulated at the design stage and systems are introduced to safely handle the events. As part of the defence-in-depth approach, multiple systems are provided for each of the identified safety functions, one backing the other. Integral to the defence-in-depth approach is envisaging that the situation can go beyond the capability of the ‘designed’ safety systems; therefore, providing backup systems, additional means and procedures to safely handle such unlikely events has been the practice of regulatory requirements in India. As the severity of the postulated event increases, its consequences will be higher; requiring a very high order of reliability from the associated safety systems to make all postulated accident scenarios acceptable from the point of overall risk. It is ensured by design that the dose release even for the most severe postulated events is at a level at which deterministically no adverse health effects are expected.

While the above is a general description of the safety design of NPPs and has been followed for all operating and under-construction PHWRs, each design has some peculiar inherent safety characteristics and some vulnerabilities, which are addressed by providing appropriate systems or provisions. For example, in PHWRs the shutdown function is required to be robust and for this, the reactor is provided with two independent and diverse shutdown systems, each individually capable of safely terminating any uncontrollable transient from any operating state of the reactor. Each shutdown system is provided with independent instrumentation to capture any change in the identified plant parameters, to initiate reactor trip (cessation of fission reaction). Based on analysis of the postulated events, all PHWRs are provided with appropriate trip parameters. In 700 MW PHWRs, where a certain amount of boiling in channels has been introduced, new protection in the form of regional overpower trip is provided on both shutdown systems to ensure that local power remains within limits at all times, thereby maintaining fuel safety. All postulated transients or events do not require reactor tripping; slower power control is adequate for such events. In PHWRs, this power control is achieved by a system which is independent of reactor shutdown systems.

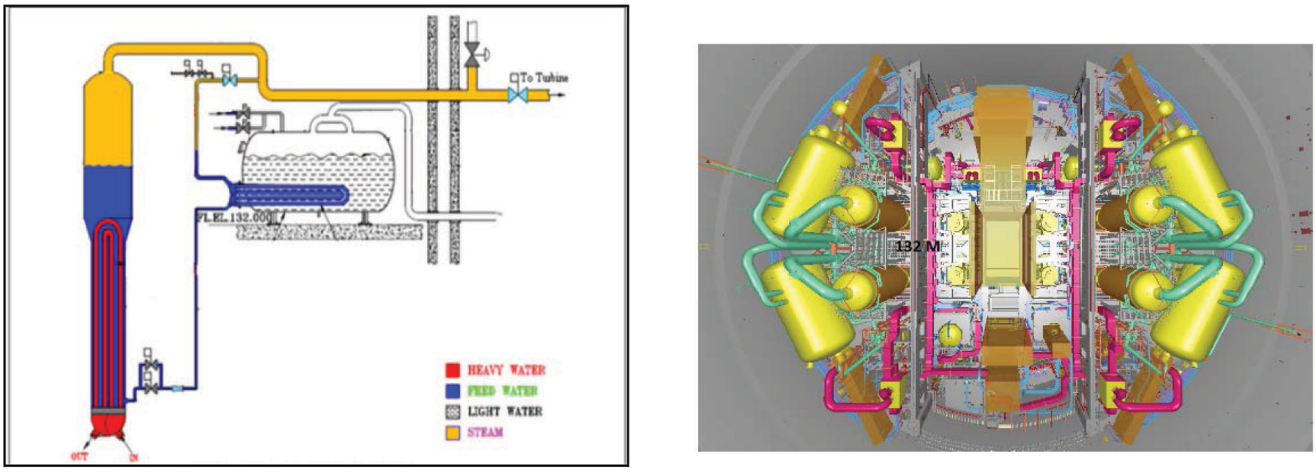


Figure 6. Schematic of passive decay heat removal system (700 MW PHWRs).

After shutting down the reactor, decay heat needs to be removed from the nuclear fuel, which keeps on reducing (decaying) with time. For removing this decay heat, just by density difference, without any pump for coolant circulation (natural circulation or thermo-syphoning), a unique feature is available in the PHWR layout, wherein steam generators located at higher elevation provide sink for the heat from the fuel located at a lower elevation. To reduce coolant temperature, close to the cooling water temperature, one more system relying on forced circulation of the coolant is available in all PHWRs. In 700 MWe PHWRs, this system is designed to be valved in at full pressure and temperature of the coolant system, whereas in earlier units, it was possible to valve in this system only after cooling down to 150°C by steam generators.

NPPs are equipped with multiple number of emergency diesel generators (EDGs), which backup the grid power for use by safety systems. In 700 MW units for example, 4 × 100% capacity EDGs are provided.

In design, one of the postulated events is considering that both the grid and the provided EDGs are not available. In such a situation, referred to as station blackout, the previously described feature of thermo-syphoning comes into action to remove the decay heat of fuel in PHWRs. During station blackout, the normal systems to supply makeup water lost gradually due to steam generation in the steam generators are not available due to postulated loss of power supplies. This event has been well catered to from inception in PHWRs by providing water to the secondary side of steam generators by diesel-operated pumps, which do not depend on station power supplies. In 700 MW PHWRs, in addition to this feature of diesel-driven pumps, a passive decay heat removal system capable of removing decay heat for 8 h is also introduced (Figure 6). This system removes decay heat by preserving water inventory in steam generators. It also works on the principle of natural circulation and does not require any motive power to function once the system is taken into service. Beyond 8 h, the heat sink in the system can be augmented by pumps that do not rely on station power.

Voiding in the coolant channels in PHWRs (due to postulated event of loss of coolant inventory from the closed primary coolant loop, transferring fission energy from fuel to steam generators) introduces positive reactivity, which manifests as an increase of reactor power for a short time till the fast-acting shutdown systems act to shut down the reactor. A system (known as the emergency core cooling system) is engineered to continue core cooling even in this case. For larger PHWRs (e.g. 540 MW), to limit the amount of voiding in such a case, the primary heat transport system is divided into two vertical halves. Each of these loops, arranged in a 'figure of 8' configuration, consists of two circulating pumps and two steam generators along with the required headers and feeders. In 700 MW PHWRs, interleaving of feeders is adopted, wherein two PHT loops feed alternate channels, in contrast to distribution in two vertical halves in the 540 MW design (Figure 7). Globally first, this arrangement is aimed at minimizing the positive void coefficient of reactivity by uniformly distributing coolant voids resulting from a postulated loss of coolant event.

The double containment as used in the standardized 220 and 540 MW units along with associated engineered safety features provide effective confinement of releases. Based on radiological impact assessment, it is conservatively assessed that for postulated severe events, with containment remaining intact, there may not be a requirement for the displacement of the neighbouring population even in an extreme emergency. The design of double containment adopted in the 700 MW units is primarily identical to the earlier units with the addition of a steel liner on the inner walls along with certain new engineered features as required for a larger plant, like a spray system for condensing steam formed during a postulated pipe break event.

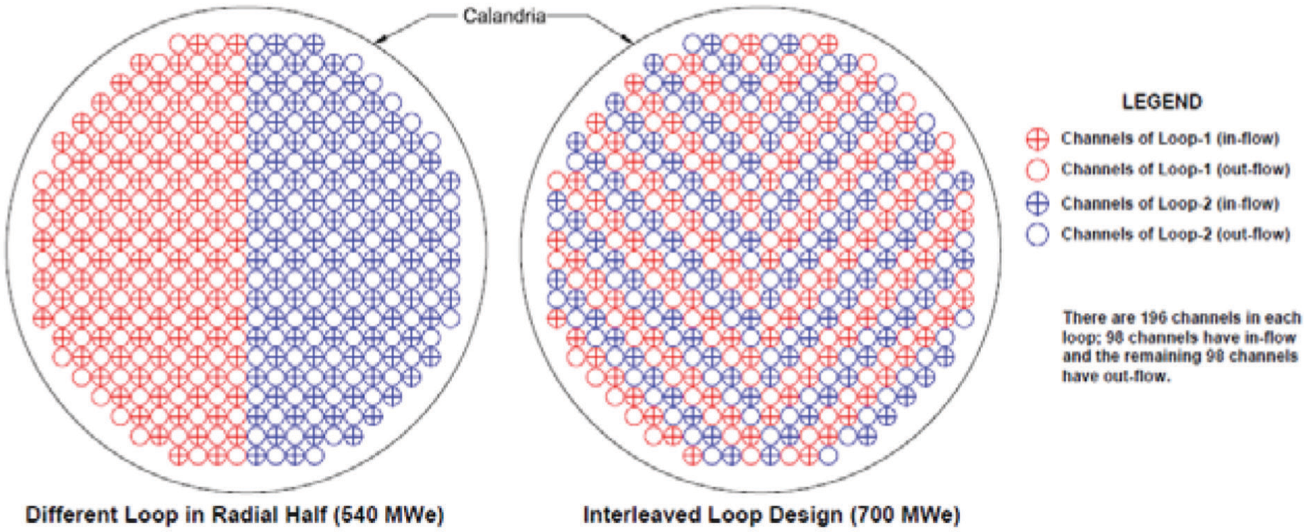


Figure 7. Two loops of the main coolant system in 540 and 700 MW PHWRs.

Also, factory-built and qualified, indigenous electrical penetration assemblies have been installed, which are special cable-sealing arrangements for the passage of power and control cables from and to the RB providing a barrier against the release of radioactivity to the environment. These features have led to marked confidence in the leak tightness of the containment.

A feature that is inherently available in the PHWR design is that the reactor core is always surrounded by a large quantity of water maintained at a low temperature. This helps in absorbing decay heat and delaying the progression of accident in case designed cooling systems are not available.

The prominent lesson from accidents at the Fukushima Daiichi NPP in Japan is that external events of high magnitude have the potential of making on-site systems and facilities unavailable. Following a review of this event, existing provisions in the Indian NPPs have been strengthened further and new features added where necessary, considering that no designed power sources and on-site water sources are available in such an eventuality. These provisions, known as hook-up points, outside the RB can be used to supply water from any suitable/additional on-site source, including using mobile pumps or fire tenders. Water inventory, adequate to remove decay heat for a minimum of seven days, is always stored in seismically qualified structures at the site. For PHWRs, this provision is over and above those available to inject water to the identified systems through the on-site pumps, which do not require station power supplies for their operation. Air-cooled diesel generator (DG) sets, which can be operated without any auxiliary support are provided for the management of total loss of off-site and on-site power supplies for extended periods. These DG sets can supply power to instrumentation for monitoring plant parameters and emergency lighting. The output rating of these DG sets is designed to cater to operating a small-capacity pump for transferring water, if required, under such conditions.

PHWRs are now provided with passive catalytic (hydrogen) recombiner devices, strategically located inside the RB to help in limiting hydrogen concentration, which is expected to be generated as a result of metal–water reaction between zircaloy and steam under high-temperature conditions; this may be one of the postulated severe events.

Containments have been designed, constructed and proof-tested for highest pressures expected inside in a severe event estimated in design analysis using conservative approaches. However, to reduce containment pressure in any unforeseen condition, and thereby maintain the integrity of the containment, containment filtered venting system is provided in PHWRs.

To aid in accident management, new systems, like hydrogen and steam concentration monitoring system and severe accident parameters monitoring system are provided in PHWRs.

The back-end of the nuclear fuel cycle

Reprocessing of spent nuclear fuel

As stated earlier, because of its nuclear fuel resource profile, India has opted to pursue a closed fuel cycle. Plutonium recovered by reprocessing the spent nuclear fuel (SNF) from thermal reactors will be used as fuel in fast breeder reactors. A prototype fast breeder reactor is under commissioning at Kalpakkam and uses MOX (mixed oxides of plutonium and depleted uranium) fuel. To fully utilize the energy potential of fissile material and also fertile material, multiple recycling is envisaged, i.e. SNF from fast reactors will also be reprocessed and plutonium recycled as fuel. Besides utilizing the full energy potential of fissile and fertile materials, the pursuit of a closed fuel cycle also aids nuclear waste management. It opens up additional possibilities: recovery of the long-lived minor actinides by partitioning of high-level waste for subsequent transmutation in specially designed reactors and recovery of valuable radionuclide for use in societal applications. As a result of the recovery of minor actinides and other radionuclides, the footprint of the geological repository and the time frame required for geological isolation of waste are significantly reduced.

When India entered the domain of reprocessing, PUREX (an acronym for plutonium uranium reduction and extraction), a solvent extraction process for reprocessing SNF had already been developed. PUREX has been the workhorse of fuel reprocessing for the last few decades and no other process developed before or after can equal its versatility[12].

PUREX uses 30% tributyl phosphate in pure *n*-dodecane as an organic solvent and this was adopted in India as well. The first reprocessing plant in India, i.e. the plutonium plant, was commissioned in 1965 at Bhabha Atomic Research Center (BARC), Trombay and it is still under operation for the reprocessing of research reactor SNF. Based on experience obtained from the plant, reprocessing of SNF from PHWRs was initiated in the early seventies by building and operating a power reactor fuel reprocessing plant (PREFRE-I) at Tarapur[13–15]. Subsequently, a reprocessing plant at Kalpakkam (KARP) and another at Tarapur (PREFRE-II) were built and are under operation for reprocessing of PHWR SNF. Recently, an additional plant (KARP-II) has been commissioned for PHWR SNF reprocessing at Kalpakkam. PREFRE-I has now been shut down after successful completion of its operating life fulfilling the design intentions and rest of the plants are under operation. India has mastered the technology of reprocessing SNF arising from thermal reactors, both research such as Dhruva, and power reactors such as PHWRs. The plutonium recovered has been utilized for the fabrication of MOX fuel for the upcoming PFBR. The management of high-level waste generated from reprocessing is being carried out safely and effectively as described in the subsequent section.

Over the years, indigenous developments have resulted in several improvizations in the process flow sheet to improve recovery, separation efficiency and thus product (U and Pu) quality. Recent developments have focused on the head-end system, and remotization to improve the availability of the system, enhance throughput and minimize personal exposure. As a result, the performance of reprocessing facilities has been satisfactory and has demonstrated the highest level of safety. As the nuclear-installed capacity is likely to be increased multifold, the need for reprocessing SNF will also increase. Utilizing the vast experience in the field of spent fuel reprocessing, a large-capacity integrated nuclear recycle plant is under construction at Tarapur[16].

In parallel with reprocessing SNF from thermal reactors, reprocessing of fast reactor fuel has been done in pilot plants. A plant to reprocess SNF arising from PFBR is under construction at Kalpakkam to close the fast reactor fuel cycle and pave the way for multiple recycling of SNF.

Radioactive waste management

DAE has given utmost importance to the safe management of radioactive waste since the inception of the nuclear power programme. Waste-volume minimization and near-zero discharge of radioactivity have always been central principles of radioactive waste management to protect people, environment and future generations from the harmful effects of radiation. Based on basic strategies involving delay and decay, dilute and disperse, recycle and reuse, and concentrate and contain, entire radioactive waste management plans and practices have been developed and implemented.

As mentioned earlier, the pursuit of a closed fuel cycle reduces the volume and long-term radiotoxicity of waste needing disposal. Safe and effective management of high-level liquid waste (HLLW) generated during the reprocessing of SNF is an important and decisive aspect for the selection of closed fuel cycle. HLLW contains more than 99% of radioactivity present in SNF. Conventionally, HLLW is immobilized in an inert glass matrix by a vitrification process to reduce the waste volume and isolate the radionuclide from the environment. Vitrified HLLW is stored in a passive air-cooled vault for removal of decay heat for a few decades before its disposal in a geological disposal facility (GDF). The GDF is likely to be constructed in a stable granitic host rock well below the surface. However, because of small nuclear power installed capacity in India and the pursuit of a closed fuel cycle along with partitioning of waste, GDF is not an immediate requirement for India. For example, when PHWRs having a total capacity of 1000 MW are operated for 25 years, only 187.5 tonnes of vitrified waste (470 waste packages of 150 litre capacity, each containing 400 kg of vitrified waste) will be generated, which will require to be disposed of in a GDF. With the deployment of partitioning technology, the amount of vitrified waste, requiring eventual disposal in a GDF, will be further reduced by more than an order of magnitude.

The first vitrification facility for HLLW, i.e. the waste immobilization plant (WIP), was built in the early 1990s at Tarapur based on induction heated metallic melter (IHMM) for converting HLLW generated from PREFRE-I into a glass matrix. With experience gained from WIP, Tarapur, another IHMM-based vitrification plant was commissioned at Trombay in 2002 and is still under operation to treat HLLW generated from reprocessing research reactor SNF. Limited throughput of IHMM being a constraint,

Figure 8. Actinide separation demonstration facility, Tarapur.

Figure 9. Solvent extraction system, Trombay.

a higher capacity Joule heated ceramic melter (JHCM) was developed and has been successfully deployed at the Advanced Vitrification System, Tarapur. WIP, Kalpakkam has been commissioned for the management of HLLW using JHCM in 2017. Combining all these plants, more than 500 vitrification operations have been carried out safely, showcasing the capabilities of the country in the field of vitrification of HLLW. India is among few countries in the world that have mastered vitrification technology at an industrial scale[17].

Efforts are continuing for further minimization of the waste volume and thus, the need for a GDF. R&D in the field of the partitioning of HLLW is being undertaken to achieve the same. Due to consistent efforts in the development of novel extractants as well as processes, a solvent extraction-based Actinide Separation Demonstration Facility (ASDF) was commissioned at Tarapur (Figure 8) in 2014, aiming to partition minor actinides from HLLW. This is the first and only engineering scale facility in the world for partitioning of minor actinides from HLLW and has been designed to treat a few tens of thousands of litres of HLLW.

Based on the successful operation of ASDF, Tarapur, another engineering-scale solvent extraction-based partitioning system at WIP, Trombay was built and commissioned in 2015 for the separation of radioactive components from inactive components for value recovery and waste volume minimization (Figure 9). Utilizing this solvent extraction system, recovery of many valuable fission products such as ^{137}Cs, ^{90}Sr, ^{106}Ru, etc. has been demonstrated in bulk amounts from HLLW at WIP, Trombay, for use in various societal applications[18,19].

Besides the management of HLLW, intermediate-level liquid waste (ILLW) generated from reprocessing facilities is also treated effectively using radionuclide specific ion exchange resins at the waste management facilities of Trombay, Tarapur, and Kalpakkam. Low-level liquid waste (LLLW) generated from all the fuel-cycle facilities is treated before discharge to the environment. Chemical treatment is the oldest process under operation at various radioactive waste management sites to obtain good decontamination factors for bulk removal of radioactivity before the discharge of effluents to the environment. R&D is being continued to develop membrane-based novel technologies for the treatment of large volumes of LLLW to obtain better decontamination factors and to discharge minimal radioactivity, realizing the concept of a 'near-zero discharge of radioactivity'.

Low- and intermediate-level radioactive solid wastes are generated from all the fuel-cycle facilities. Various treatment methodologies such as compaction, incineration and melt-densification have been deployed based on the nature of radioactive solid waste to reduce the volume before its disposal in a near surface disposal facility (NSDF). Recently, a plasma-based incineration system has been developed at Trombay to treat the bulk amount of polymeric waste for obtaining a better volume reduction factor without the generation of toxic gases. The treated radioactive solid waste is finally disposed off in a suitably engineered NSDF. The NSDFs are designed based on a multi-barrier concept to retard the migration of radionuclides to the environment. Engineering of barriers is done based on the nature and category of waste to be disposed of in the NSDF. Presently, about eight NSDFs are under operation in the country for disposal of low- and intermediate-level radioactive solid waste after suitable treatment, as required. These NSDFs are planned to have surveillance for 300 years after closure to monitor the migration of radionuclides, if any. More than 60 years of experience in the disposal of solid waste in NSDF enhances confidence in its design and construction for the safe disposal of radioactive solid waste.

Concluding remarks

Pooled together, Indian NPPs operated by the Nuclear Corporation of India Limited (NPCIL) have logged about 570 years (as of May 2022) of safe operation. Nuclear safety is a moving target and therefore NPPs have to keep abreast with the current safety standards. For this purpose, Indian NPPs undergo periodic safety reviews (every 10 years) and implementable safety enhancements are incorporated to ensure compliance with the most recent safety standards. In addition to continual safety improvements, Indian NPPs undergo review following any major event at other NPPs (international as well as national). In the past, such reviews have been carried out following events at TMI-2, Chernobyl, Fukushima NPPs, and also in Indian NPPs (like TG fire in NAPS-1, external flooding in KAPS and MAPS-1 and 2). To illustrate the application of this continual enhancement of safety, the oldest NPP units in India, i.e. TAPS units 1 and 2 with the distinction of completing 50 years of operation; have been provided with measures to strengthen containment safety.

The operating experience feedback programme ensures that all such retrofitted safety improvements become part of design for upcoming NPPs. The latest PHWR design (700 MW) has all these modifications included. In addition to all the standard features of PHWRs, this design incorporates several first-of-a-kind features to further strengthen the fulfilment of fundamental safety functions. This together with the inherent safety features of PHWRs enhance the safety of the 700 MW design, which is reflected by at least an order better core damage frequency (for internal events at full power) compared to other PHWR designs in the country.

India has been successful in designing and constructing spent-fuel reprocessing plants, fabrication of plutonium-bearing fuel for fast reactors and waste management facilities. The success achieved in the partitioning of high-level waste arising from reprocessing plants reduces the volume of nuclear waste to be disposed of in a GDF and thereby obviates the need for a GDF by several decades.

The following distinguishing features make the 700 MW PHWR worthy of being replicated to enhance nuclear-installed capacity in India:

- Improved layout features such as interleaving of feeders to improve safety.
- Advanced control systems.
- Introduction of a MTM to handle higher fuelling requirements.
- Improved containment features, including a steel lining that eliminates the need for evacuation even in an extreme emergency.
- Incorporation of systems to handle severe events postulated as part of the design.

To increase capacity addition through these units, the measures incorporated include standardized layout and design leaving re-engineering and qualification limited to site-specific inputs; standardization of safety analysis and procurement specifications and adoption of bulk procurement for multiple units. Experience indicates that it will be possible for NPCIL to construct 700 MW PHWRs at Rs 15 crores per MW – a globally competitive cost. Considering the competitive cost and advanced safety features, and the fact that more than 95% of equipment and components are manufactured in India, several 700 MW PHWRs should be constructed to achieve the target of a net-zero energy mix by 2070.

Meeting India's development aspirations is dependent on significant growth in energy consumption and a simultaneous shift to low-carbon energy systems. Estimates of energy generation potential from solar, wind, small and large hydro are way below the projected final energy requirements of 24,000 TWh for a net-zero and highly developed India. Therefore, there is need for a significant increase in nuclear power installed capacity.

A panoramic view that accounts for the cost of generation, cost and stability of the transmission and distribution system, security of supply, risk of unserved demand, and the presence of an indigenous supply chain, needs to be taken for arriving at an optimal energy mix. The policies of GoI (for financing the projects, purchase obligations by (electricity) Distribution Companies (DISCOMs), interstate transmission charges, etc.) should provide a level playing field for all low-carbon technologies. Several countries in Europe are struggling with increasing electricity tariffs due to the increased penetration of intermittent renewables against the promise of free energy from the wind and the sun. A level playing field for and accounting system costs associated with all low-carbon technologies will result in an energy mix determined by constraints of various technology options and provide energy to Indian citizens at competitive prices.

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