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Small Modular Reactors in Indian Power Generation – Perspective & Prospects

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Abstract:- The Indian government has made public its intent for decommissioning its coal-fired plants (CFPs) in the coming years, leading to elimination of all SFPs by the year 2070. As CFPs at present generate about 73 % of its electricity production, alternate power generators have to be planned urgently. The main alternate sources to fill this shortfall appear to be solar and nuclear. Solar power is useful in meeting agriculture and domestic demands, but is limited to vicinities. Major claims have been made for installation of nuclear power plants of indigenous design and manufacture. However, their rates of completion have been found wanting. Efforts have been made for importing nuclear power plant units of large sizes (1000 MWe or more). However, their locations are limited due to stringent siting requirements. In this scenario, the role of Small Modular Reactor units (300 MWe or less) and designed to be located at sites of decommissioned Coal Fired Plants close to population centres becomes prominent. In this paper, the benefits and drawbacks of advanced Small Modular Reactor units are presented.

***Keywords**:- Small Modular Reactors, Renewal Energy, Coal Fired Plants, BWRs, PWRs.*

I. INTRODUCTION

Indian electric power generations as per Ministry of Power for FY-2022-23 is the following:

- There are 273 coal-fired power plants (CFPs) with generation of around 204 GWe. Of these, 81 are set to be replaced in coming 4 years by Renewable Energy (RE) plants. In the table below, the power from carbon includes power from burning of lignite, gas and oil.
- The official target is to install REs with 175 MWe generation capacity and phase out all CFPs by 2070. Each CFP has a design life of 25 to 40 years.
- Current installed capacities and annual generations statistics are as follows:

Table 1 the power from carbon includes power from burning of lignite

FUEL	Cap. MWe	Cap. %	Gen. BUe	Gen. %
Carbon	210395	49.7 %	1078444	73.45 %
Gas	24824	6.1 %	36143	2.46 %
Hydro	51786	12.6 %	162163	11.04 %
Wind-RE	41930	10.2 %	68640	4.67 %
Solar-RE	63302	15.1 %	73483	5.0 %
Nuclear	6780	1.7 %	47019	3.20 %
TOTAL	410.339	100 %	1468155	100 %

Our total installed capacity is 410.339 GWe and our total production is 1468155 BUs in 2022. Our overall load factor is around 41 %. In addition, Transmission & Distribution losses are 22 %.

If nuclear power plants have to meet even a part of the shortfall in generation of 204 GWe in four years and even greater shortfall due to decommissioning of coal fired power plants (CFPs) in the longer haul, nuclear power plants must be installed urgently in order to remain relevant.

Our atomic energy department (DAE) have projected their growth of nuclear power on several occasions [1]. However, these projections have not met their targets as can be seen below;

Our targets for nuclear power development have been made several times from 2004 to 2018. These targets announced in 2011 from 63 GWe by 2032 were revised 2018 to 25 GWe by 2031.

In April 2007 the government gave approval for the first four of eight planned 700 MWe PHWR units: Site works at Kakrapar for first 700 Mwe unit were completed by August 2010. First concrete was cleared for Kakrapar 3&4 was in November 2010 and March 2011 respectively, after Atomic [1].Energy Regulatory Board (AERB) approval. The AERB approved Rajasthan 7&8 in August 2010, and site works then began. Construction was then expected to take 66 months to commercial operation. However, to date the first 700 MWe unit is still under commissioning since July 2020.

The 500 MWe Prototype Fast Breeder Reactor (PFBR) started construction in 2004 at Kalpakkam near Madras. It was expected to start up about the end of 2010 and produce power in 2011, but this schedule is delayed significantly. In 2014, 1750 tonnes of sodium coolant was delivered. With construction completed, in June 2015 Bhavini PFBR was "awaiting clearance from the AERB for sodium charging, fuel loading, reactor criticality and then stepping up power generation." In March 2020 the government said that commissioning would be in December 2021. More than two years later there is no news of end of commissioning and production of commercial power.

II. ASSUMPTIONS AND LIMITATIONS

From the foregoing paragraphs, it is evident that targets of installed nuclear power plants of indigenous designs rated at 700 MWe capacity have slipped by a decade or more. Our fleet of indigenous FBRs rated at 500 MWe may be realised even later, in the distant future.

There have been some external factors that may have caused these slippages. We had been under sanctions for import of nuclear power technology since 1994. This may have adversely affected our progress in developing our PHWRs and FBRs.

Hence we adopted the strategy of importing PWRs of large capacities (1000 MWe per unit or more) from overseas suppliers Russia, France and perhaps USA. These units would generate around 32 GWe from new 22 units, and should be available in another 10 years or so.

In this study, it is suggested that we supplement our imported reactors with numbers of SMRs of generation capacity of around 300 MWe each. It is assumed that technical resources and funds for these plants, including their enriched fuels for their lifetimes of 60 years would be available.

III. SUGGESTED STRATEGY FOR INCREASING OUR NUCLEAR POWER CAPACITY

In light of the central government's decision to cut coal-fired plants (CFPs) power generation and to replace the old CFPs by other means, the field had opened for nuclear power to fill the void. Presently, this void has been assigned largely to Renewable Energy (RE) plants, notably solar. However, solar power is limited to daylight hours and cannot meet large loads such as evening loads.

While it is possible to build power collectors such as hydraulic or battery accumulators for REs, such storage means would increase the power cost by a factor of four or more [2]. As the capacity factor of REs is just about 15 % as can be seen from Table-1, they may not be able to meet all the grid loads that they are exposed to. Generally, the daily load variation ranges from 20 % to 60 % from 7 am. to 9 am. And from 35 % to 100 % from 10 am. to 7 pm. in industrial conditions [2]. There may not be enough surplus generation during daylight hours to warrant electric storage collectors for REs for catering to heavy loads such as industry and transport.

By the same reckoning, even if 175 GWe of REs are installed as projected, they may not replace more than 45 GWe to 50 GWe of power deficit from demobilised CFRs.

However, RE (solar) units for domestic power consumption are very attractive options in that these panels, mounted on building roof-tops or open grounds, yield low-cost power since they do not suffer from major collection, transmission or distribution losses. Since Indian domestic and agriculture consumption is around 20 % and 18 % respectively, RE is ideally suited to meet this need.

Nuclear power plants of large capacities (1000 MWe or more per unit) should be installed at coastal sites which are not near large industrial or population centres. This is evident from the decision to install in addition, 28 units at coastal sites and capable of generating 32 GWe by advanced PWR plants from Russia, France and USA. Since these are of demonstrated designs and performances, they could be in operation in about 10 to 15 years from now. Our indigenous 700 MWe units would supplement the power production from large capacity NPPs as and when they come on line. These large capacity plants would be useful for base-load operations on our electric grids. Such a large power rated plant generally require a large footprint on the ground in shape of actual plant area, a 1.5 km. exclusion area, a low population area of 15 km. around the plant for emergency response. Hence, their location close to population centres is not advisable. These massive power units require large amounts of cooling water, both sea water and fresh water. The coastal plants have access to sea water. These plants also have their own desalination plants for fresh water supply.

To cater to changing loads, Small Modular Reactors (SMR) are considered suitable. Modern SMRs are designed to limit their stored radio-activity, and design their containment and emergency control systems so that they do not cause emergency conditions beyond 1.5 km. even under accident conditions. These are part of requirements for Generation III+ (Gen.III+) to generation IV (Gen.IV).

SMRs can be handy in replacing CFRs in situ since the existing grids and switch-yards could be used for SMRs too. Further, since most CFR units are in the range 250 MWe to 500 MWe per unit, they could be replaced on the same locations for installing SMRs. Since CFRs have large areas around them in the form of ash fields and unfit for habitation or agriculture, these ash fields could form the exclusion zones around the SMRs without impacting the local flora, fauna or human habitation [2].

Several SMR designs are in consideration world-wide. These include BWRs, PWRs, gas cooled reactors, Molten Salt Reactors (MSRs) and metallic fuelled Fast Breeder Reactors. Their ratings range from 30 MWe to 300 MWe each. Power reactors rated beyond 300 MWe are not considered SMRs.

Some BWRs and PWRs of SMR category are under manufacturing, construction or commissioning globally. We should consider importing suitable BWRs and PWRs of SMR type rated at around 300 MWe per unit initially. These should be of Gen. III+ or better. There are reliable manufacturers of standard power generation equipment in the range of 170 MWe to 300 MWe per unit. Hence, only the nuclear pressure vessels and their internals would need to be imported initially, and balance of plant equipment could be made indigenously. We should try to indigenise their entire manufacture as we gain experience with their performance. Such SMRs should be located at the sites of demobilised CFRs which are generally close to industrial and population centres.

In this study the comparative benefits and drawbacks of SMR-BWRs and SMR-PWRs are presented. The earlier BWRs and PWRs have similar designs but of Gen. III in operation. These earlier generation units had been rated from 1000 MWe to 1350 MWe. Table 2 summarizes the major design features of standard BWRs, PWRs, and SMR-BWR and SMR-PWR.

Two modern designs of SMRs, namely SMR-BWR and SMR-PWR are seen as viable options for future SMRs. The SMR-BWRs are characterised by large pressure vessels to accommodate emergency heat sinks for the reactor in case the generated steam cannot be condensed in normal heat sinks.

Early generation BWRs operated in natural circulation at Humboldt Bay in US, at Dodewaard in Holland, and KLT-40S in Russia, with rated powers ranging from 50 MWe to 65 MWe, providing confidence in viability of their concepts. So designing and manufacturing SMR-BWRs of 300 MWe is feasible. However, these units would need upgradation of their safety features to conform to Gen. III+ requirements. Such safety features are installed on current large power BWRs. The terrible accidents at Fukushima BWRs in 2011 in Japan have cast doubts on safety of BWRs in general. These accidents triggered by a massive earthquake, caused extensive steam voiding in the reactor cores, leading to generation of hydrogen and oxygen [3]. It has to be proved by design and if necessary, by experiments, that such accidents would never occur in SMR-BWRs.

Modern SMR-PWR designs also have large pressure vessels to accommodate the internal steam generators and pressurizers a apart from accommodating huge emergency heat sinks. Threse pressure vessels also contain integral steam generators of the Once Thru Steam Generator (OTGS) type .and reactor circulation pumps.

We do not have any such fore-runners of PWRs with integral pressurizers or steam generators in their pressure vessels. All existing power PWRs have external mush-room shaped steam generators, except those on Three Mile Island (TMI) PWRs. Those TMI-PWRs were stopped after the 1979 accident where it was believed that their OTGS type steam generators provided insufficient stored heat sink capacity for emergency cooling of the reactor. This weakness led to generation of excessive amounts of hydrogen in the TMI reactor. It has to be proved by design and if necessary, experiments that such accidents never occur in SMR-PWRs.

Modern high power BWRs and PWRs of Gen. III have incorporated improvements to prevent such horrific accidents such as Three Mile Island PWR, Fukushima BWRs and a few incidents of lesser impact that have occurred so far. However, in view of the vast amounts of their contained radio-activity and consequent decay heat generation even after reactor shut-down, such large power reactor units are located far from population or industrial centres as also from rivers and lakes. These power reactor units have emergency response regions of around 15 km. around the sites.

SMRs are characterized by their ability to maintain safe conditions in emergencies over prolonged periods of time. Their redundant systems are designed for reactor shutdown, reactor cooling and containment cooling in emergency conditions for prolonged periods of time without the need for emergency response in the public domain.

Two different designs, a SMR-BWR named BWRx-300 by Hitachi and General Electric rated at 290 MWe, and the other a SMR-PWR named NUWARDS by EDF-CEA of France, rated at 2X170 MWe twin unit design have been compared with features of standard high power PWRs and BWR. Details of SMRs are available [4]. These units have been designed by well-known designers and manufacturers of established large power BWRs and PWRs respectively. In this study, the pros and cons of using such designs of SMRs are described, compared and summarized in Table 2.

Table 2 the salient features of SMR-BWR, SMR-PWR

PARAMETER and unit	**Gen. III-BWR**	**Gen. III-PWR**	**SMR-BWR**	**SMR-PWR**
Reactor Power MWth/MWe	3990/1438	4450/1650	840/290	2*540/2*170
Conversion efficiency %	36 %	37 %	34.5 %	31.5 %
Reactor pressure, MPa	7	15.9	7	15.5
Steam pressure, MPa	7	7	7	4.5
Input fuel enrichment %	Around 5 %	Around 5 %	Around 5 %	Around 5 %
Dischrg. fuel burnup, GWD/T	Around 4.5	Around 4.5	Around 4.5	Around 4.5
Operating fuel cycle, months	15-18	15-18	24 months	24 months
Reactor coolant means	pumps	pumps	Nat. circ.	pumps
Reactor Control Devices	CRDs	CRDs	CRD, FMCRD	CRD, FMCRD
Back-up reactivity control	Boron inject	Boron inject	Boron inject	Boron inject
Reactor power regulation	Flow control	CRDs, Boron	FMCRDs	FMCRDs
Emerg. Containment cooling	Water spray	Water spray	passive	passive
Core power density, MWt/m^3	49	89	Around 45	Around 45
SBO Coping Time, w/out LOCA	A few days	a few days	7 Days	3 or more days
SBO Coping Time with LOCA	1 day	1 day	3 days	3 days
Footprint area on ground	4 sq.-km.	4 sq.-km.	8400 sq.-m.	3550 sq.-m.

Table 2 shows the salient features of SMR-BWR, SMR-PWR as compared with standard BWRs and PWRs. To amplify the stated features, the following clarifications are offered:

- The reactivity control devices in SMR units are Control Rod Drives with large discrete steps in normal movement and quick insertion in emergency shut-down situations.

The FMCRD devices have, in addition, fine movements to respond to normal power changes;

- The SMR-BWR and SMR-PWR do not have boron addition for power control. The boron injection is a back-up system to the normal scram feature of their CRDs;
- The emergency cooling of the reactor core as well as of the containment are achieved by emergency cooling in external water pools. The SMR-BWR has one such pool for the reactor cooling, and another pool (spent fuel pond) for cooling the containment, both by thermo-syphon; The SMR-PWR has an external pool for emergency reactor cooling by thermo-syphon, and a water basin around the containment shell for cooling by conduction;
- All the reactor types in Table 2 have load-following ability from 50 % to 100 % power. However, the standard BWRs and PWRs cannot match the required power escalation rate beyond 90 % power due to fuel pellet-clad interaction concerns. SMR-BWR and SMR-PWR, with their lower power density should be able to meet the required power ramp-up rates;
- The steam cycle conversion rate at 31.5 % of SMR-PWR would require rechecking. Its steam generators operate at 4.5 MPa. In comparison, the PHWR steam generators operate at 5 MPa, but with conversion efficiency at 28 % or 29 %.
- Standard PWRs and BWRs as also SMR-PWR use around 6 % of their electric output as house load. Roughly half of it, namely 3 %, goes into reactor recirculation pumps. Since SMR-BWR works on natural circulation, its house load should come to around 3 % only. Hence, its net electric output would be enhanced by around 3 %. By the same reckoning, its warm-up rate, being dependent on fission heat, would be much slower than that of others.

IV. CONCLUSIONS AND RECOMMENDATIONS

- There is imperative need to augment our rate of nuclear power creation to avoid a future crisis in power generation. We need to focus on SMRs for inland urban sites where coal fired plants (CLPs) are getting decommissioned and cannot be replaced by solar power;
- We must examine very critically the risks and hazards of available SMRs. As brought out earlier, both SMR-BWR and SMR-PWR have some safety concerns. These have to be addressed in depth before relying on those SMRs;
- We must plan to indigenise manufacture of major components of the selected SMRs since large numbers of those SMRs will be required in the mid-term future;
- In installing numerous SMRs as replacements for SFPs in urban areas, we must limit the storage of spent fuel at site and arrange for its removal and reprocessing. The risks of storage of spent fuel containers as seen at the Zaporizzya site in the open, near the war zone of Ukraine are horrifying. This is a generic observation for all of our nuclear plants.

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