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《Special Review》

Indian Nuclear Programme: Achievements and Prospects*

Dr. Raja Ramanna
Formerly Chairman, Atomic Energy Commission and Secretary,
Department of Atomic Energy, Government of India
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I. Introduction

The potential of nuclear energy for economic development of our country was foreseen by Homi Bhabha the founder of the Indian nuclear programme as early as 1944 even before its awesome power was first demonstrated to the world. It was not long before Bhabha recognised the unique situation of India as far as nuclear fuel resources was concerned namely that while our commercially exploitable uranium reserves were relatively modest at $<$50, 000 tons, that of thorium deposits were enormous at over 300, 000 tons. Accordingly he conceived of a three stage strategy for our nuclear power programme with remarkable foresight which is described later in the paper. Even at the outset one of our primary goals was set as the achievement of self sufficiency in harnessing atomic power. Ambitious plans were therefore laid out for the establishment of the relevant industrial infrastructure for the manufacture of all the major components of nuclear power stations indigenously. Today India is among the select few (less than ten) countries in the world which have the total capability to design, construct, commission & operate nuclear power stations entirely on its own. This paper reviews the achievements of the Indian nuclear programme over the past four decades and projects its prospects into the early years of the next century.

II. Three Stage Strategy and Choice of Reactor Types

The strategy proposed for the development of nuclear energy in India envisages installation of natural uranium fuelled thermal reactors in the first instance to generate electricity and produce large quantities of plutonium. The second stage contemplates plutonium fuelled fast breeder reactors to produce electricity and more plutonium as well as U-233 from the thorium blankets surrounding the Pu fuelled core. The third stage is to comprise of breeders/ advanced converters optimised to operate on the Th/U-233 cycle.

The first task was to select the type of thermal reactor which would best suit our needs. A choice had to be made between the following three types of reactors: (a) The natural uranium graphite gas cooled reactor; (b) Enriched uranium fuelled LWR and (c) Natural uranium fuelled pressurised heavy water PHWR type of reactor. Our preliminary studies had indicated that the last of these namely the PHWR would

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be most appropriate for the conditions prevalent in India for the following reasons: (i) Its use of our scarce uranium resources would be most efficient; (ii) The natural uranium fuel could be manufactured indigenously and (iii) It would produce large quantities of plutoinum which could beffectively used for starting fast breeder reactors.

III. Tarapur: India's First Nuclear Power Station

During the late fifties even as various alternatives were being debated, a global tender was invited for setting up India's first nuclear power station at Tarapur, 80km north of Bombay. It turned out that the offer from General Electric Company of USA for a 2-unit (200MWe each) BWR station was the cheapest. Even though this type of reactor did not fit in with our long term three stage strategy, the Government nonetheless decided to purchase the Tarapur reactors[2] on a turn-key basis from GE in order to bring the benefits of nuclear power to the country as early as possible and to give an opportunity to Indian scientists and engineers to gain experience in building and operating a nuclear power station in an Indian environment-particularly in our relatively small electrical grid systems. Tarapur became operational in 1969 and has played a key role ever since in training manpower for our future programme and providing very valuable inplant experience especially in equipment maintenance problems under high radiation field conditions.

IV. PHWR: The Workhorse of the Indian Nuclear Programme

As already mentioned the heavy water moderated natural uranium fuelled horizontal pressure tube reactor concept developed in Canada was selected as the most suitable reactor type for our programme.[3] In 1961 a heavy water moderated research reactor CIRUS designed with Canadian help became operational at the Bhabha Atomic Research Centre (BARC), Trombay. This played a very useful role in training manpower in the operation of heavy water moderated reactors. By the mid 60s construction of our first 220MWe PHWR type power station RAPS-I had commenced at Kota[4] in Rajasthan. The design of RAPS-I reactor was very similar to that at Douglas Point, the first Canadian PHWR reactor. The major equipment for RAPS-I reactor was imported from Canada. However even at that time significant efforts were launched for the indigenisation of the subsequent PHWR units. This gave an opportunity for many industries in India to take up manufacture of sophisticated equipment for the first time. RAPS-I reactor was commissioned in 1972. But in 1974 following our Peaceful Nuclear Experiment the Canadians withdrew all cooperation in the nuclear field with India and banned the export of nuclear components to us. This gave an unexpected jolt to our power programme at that time, delaying the commissioning of RAPS-II. But in retrospect it was perhaps a blessing in disguise as it forced us to speed up the process of indigenisation and identify manufacturers for all major nuclear components within the country. RAPS-II commenced commercial operation in 1981.

The operational experience with the RAPS reactors since then has been extremely useful in checking out various sub-systems and has provided very valuable data for improving the design of the subsequent PHWR units. In the initial period many difficulties were encountered with the RAPS reactors. The recurrent occurrence of turbine failure was rather unexpected considering that turbines are normally looked upon as conventional equipment (these turbines were manufactured in Canada and not in India). RAPS-I also experienced a number of trips due to grid induced disturbances. However the most serious problem with the RAPS-I unit has been the development of cracks in the end shield resulting in its being shut down for many years. A series of attempts have been made over the years to repair this including a novel chemical technique of plugging. The most recent efforts appear to have been somewhat successful and our safety authorities have just accorded cleara nce for resumption of operation of RAPS-I at 50% capacity. In comparison RAPS-II has performed consistently well during the last few years; in 1986 it had an uninterrupted operation of 163 days. The performance in 1987 has so far been equally impressive.

The experience with the RAPS units both as regards construction and operation has played a significant role in the commissioning of the two 235MWe PHWR units MAPS-I & II at Kalpakkam, 40km south of the city of Madras. The MAPS reactors are the first of the totally indigenous PHWR units. MAPS-I which was synchronised into the grid in July 1983 and MAPS-II which became operational in 1986 mark the coming of age of the Indian atomic energy programme. The construction of a half a kilometer long tunnel under the sea bed, for the first time in the country, to draw silt free sea water for cooling the power plant is a typical example of how the nuclear programe in the country has given Indian engineers the opportunity to tackle complex technical problems.

The design of the next two units presently under construction at Narora(near Delhi) posed an additional and challenging problem since Narora is situated in a seismic zone. Consequently an earthquake proof design had to be carried out not only for the buildings but for all the nuclear equipment also. Besides, the Narora units also incorporate several new design features that are expected to be useful for extrapolating to 500MWe PHWR reactors of the future. The first of the Narora reactors is scheduled to become operational in 1988.

Construction of two more such units has already been started at Kakrapar in Gujarat. With this the total installed nuclear capacity by the early 90s would be nearly 2, 300 MWe. The PHWR reactor concept has thus become firmly established as the workhorse of the 1st stage of the Indian nuclear programme. A 15 year plan has therefore been prepared for the installation of 10, 000MWe of PHWRs to constitute about 8~10% of our total electricity output by the year 2000.[5] This ambitious programme calls for setting up 12 more units of the standardised 235MWe type and 10 reactors of 500 MWe capacity. The design for the latter is almost complete and the first 500MWe PHWR reactor can be expected to become operational by 1995. The 15 year master plan covers in detail every aspect necessary to ensure its speedy implementation such as financial outlays, industrial involvement, infrastructure requirement and manpower planning.

At this point it is worth making a few remarks on the economics of nuclear power in the Indian context. The capital cost of nuclear power plants in India has increased from Rs 1, 600/KW for Tarapur through Rs 5, 000/KW for the Kalpakkam units to the current estimated cost of Rs 14, 000/KW(US$ 1, 100/KW) which is about 25% higher than that of conventional fossil fuel thermal power stations. As for the cost of power generated the concept of break-even distance has been in vogue since the fifties when it was first estimated that the cost of nuclear power would be comparable to that of thermal power generated about 800Km away from coal mines. Today however it has been found that even right at the pit head the cost of electricity from both types of plants is comparable.

V. R & D Support from BARC and Infrastructural Facilities

The Indian nuclear programme could not have made any headway but for the R & D support provided by the Bhabha Atomic Research Centre (BARC) at Trombay. With a staff strength of 14,000 of which over 3,000 are professional scientists and engineers, BARC is possibly the biggest nuclear research centre in the world today. The R & D activities of BARC span all facets of the nuclear fuel cycle, both front end and back end, applications of isotopes in agriculture & industry and encompasses all branches of scientific endeavour. Besides the four operational research/experimental reactors, Trombay also houses the R & D activities associated with the fuel fabrication, fuel reprocessing, and waste management/immobilization. A pilot plant for chemically seperating plutonium from the irradiated uranium metal rods discharged from the CIRUS reactor was commissioned over two decades ago. A small scale facility has also been established to seperate U-233 from irradiated thorium rods. But perhaps one of the most important activities of BARC is the Training School which has provided the vital manpower input to the entire nuclear programme by recruiting every year about 150 to 200 of the best science & engineering graduates form the Indian Universities and giving them one year advanced oriented course. The fact that the lectures and laboratory training are provided by actively working scientists/engineers has been responsible for the high quality of the trained manpower entering into the scientific pool implementing the atomic energy programme.

As mentioned earlier self reliance has been a byword of the Indian nuclear programme right from the inception. Accordingly infrastructural facilities has been set up for the manufacture of all specialised components such as uranium fuel, heavy water, electronics control systems etc. within the umbrella of the Department of Atomic Energy. These include the Indian Rare Earths Ltd. (IRE), Uranium Corporation of India Ltd. (UCIL), Nuclear Fuel Complex (NFC), Electronics Corporation of India Ltd. (ECIL) and 8 heavy water plants at various sites in the country. The manufacture of Conventional equipment like steam generators, turbines and alternators are carried out in various public and private sector companies in the country.

VI. Fast Breeder Programme

It was recognised early that a nuclear power programme based solely on the natural uranium fuelled PHWR cycle cannot meet our growing electricity requirements into the next century. The second stage of our nuclear programme therefore calls for the development of fast breeder reactors using the plutonium generated in the first generation PHWRs. With a view to establish the technological base for liquid metal cooled fast breeder reactors (LMFBR) a second research centre now known as the Indira Gandhi Centre for Atomic Research (IGCAR), wholly devoted to this objective has been set up at Kalpakkam. An important milestone was crossed at IGCAR in October 1985 when the 15 MWe fast breeder test reactor (FBTR)[6] attained criticality for the first time. Although its design is based on that of the French fast reactor RAPSODIE, unlike RAPSODIE which uses oxide fuel, FBTR is fuelled with plutonium-uranium carbide fuel fabricated entirely indigenously. India is the only country in the world to go in directly for advanced carbide fuel. The motivation for this bold choice is the fact that the doubling time of fast breeder reactors fuelled with PuO2-UO2 is too long(>30 years) to be of any relevance to our long term needs. If nuclear power is to constitute any meaningful fraction of our electricity demands in the next century then it is clear that the doubling time of our fast breeder reactor has to be 15 years. Detailed studies have indicated that advanced Pu-U carbide fuelled LMFBRs have the potentiality to give such short doubling times[7]. Even as practical experience is accumlated in the operation of a sodium cooled fast reactor FBTR, detailed design work has commenced on s 500 MWe Prototype Fast Breeder Reactor (PFBR) scheduled for operation by the end of this century.

VII. Research on the Thorium/U-233 Cycle

As per the three stage strategy discussed earlier, the exploitation of the energy potential of our vast thorium reserves is envisaged mainly for the third and final stage when adequate inventories of fissile Pu-239 and U-233 would have been built up with the help of fast breeder reactors. However, R & D work is already being carried out, albeit at a low key, to master the technology of the Th/U-233 cycle[8]. Even as early as the mid 50s when the design of the CIRUS research reactor was being frozen provision was made for introducing a ring of air cooled thorium rods around the periphery of the core. This step has been responsible for giving the needed for setting up various pilot plants and prototype facilities related to the thorium cycle right from thorium fuel fabrication to the reprocessing and chemical seperation of U-233. With the U-233 so produced a low critical mass (400g of U-233) zeor energy solution reactor experiment PURNIMA II[9] was carried out at BARC, Trombay during 1984~86. Presently a U-233 fuelled 30KW tank type neutron source reactor[9] is nearing completion at Kalpakkam. Besides thorium fuel bundles have also been irradiated in the Madras atomic power reactor during its start up for power flattening purposes. In addition plutonium enriched thorium fuel rods are currently undergoing irradiation tests at a test loop in the CIRUS research reactor.

One of the potential advantages of the Th/U-233 cycle-surprisingly not widely known is the much smaller quantum (by a factor of 3 or 4 orders of magnitude) of long lived actinide waste nuclides such as Np, Am, Cm, Cf etc. generated in this cycle as compared to the U-235/U-238/Pu-239 cycle. This comes about because as many as 7 or 8 successive neutron captures are needed to reach mass number of 240 in the Th-232/U-233 cycle whereas in the U-238/Pu-239 cycle only one or two neutron captures are sufficient. Over the years this attractive feature of the Th/U-233 cycle got suppressed in literature primarily because of the extensive studies of this topic carried out by Prof. Pigford & his student Yang[10] of the University of California in 1978 on U-235 fuelled thorium-HTGRs. Our recent analysis[11] of the problem clearly shows that were U-233 to be used as the fissile component instead of 93% enriched U-235, the quantum of long lived actinide waste generated would indeed be significantly less.

VIII. The Emerging Option of Fusion Breeders

Recent developments in the area of thermonuclear fusion research have opened up the prospects of scientific breakeven being achieved by the end of the 80s. Physicists have always been fascinated by the possibility of using fusion reactors as a neutron source for fissile fuel breeding[12]. In this context the development since 1980 of the fission suppressed blanket con-

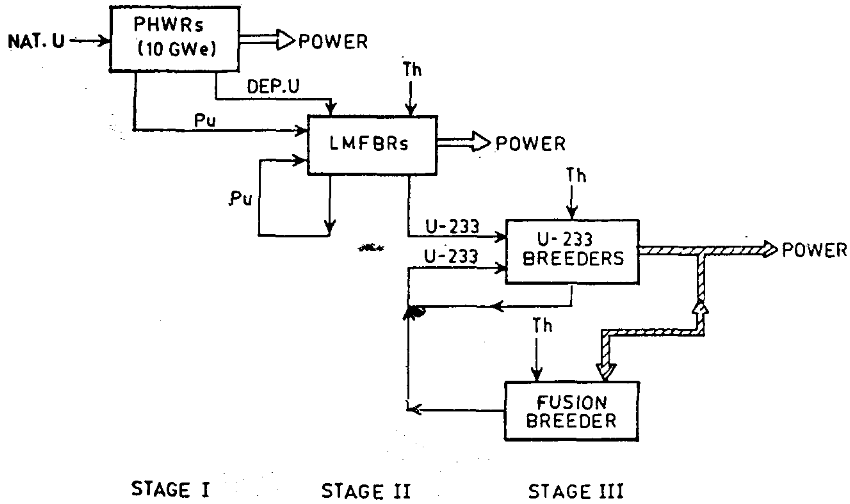

Fig. 1. Modified Three Stage Strategy for Nuclear Power in India.

cept[13,14] in many laboratories holds great promise. In this type of blanket the design is optimised to maximise U-233 production and minimise energy deposition, with the help of neutron multipliers based on (n, 2n) reactions in beryllium or lead.

Our recent studies have shown that even a few sub-Lawson fusion breeders set up around the year 2020 can play a very crucial role in our nuclear programe[15]. Availability of such fusion breeders can significantly ease the design constraints imposed on our fast breeder reactors. For example if there is a conflicting design choice to be made between reactor safety and breeding performance we can now lay greater emphasis on safety characteristics rather than on breeding gain. Cladding thickness and sodium void coefficients are typical examples of design parameters that could influence breeding gain and safety characteristics in conflicting directions. Experimental and theoretical investigations are underway at BARC to study the neutronic characteristics of various fusion blanket configurations. We are pinning high hopes on the prospects of fusion breeders for converting thorium directly into U-233, and thereby leading to the early adoption of the Th/U-233 cycle in the next century. Fig. 1 depicts the three stage strategy modified to take into account the possible role of fusion breeders in our nuclear programme.

IX, Summary and Conclusion

The Indian nuclear programme is poised to establish 10, 000 MWe capacity of PHWR by the turn of the century constituting the first phase of our long term three stage programme. Necessary R & D infrastructural manufacturing facilities have been established in the country in all aspects of the fuel cycle towards this end. The recent commissioning of the fast breeder test reactor at Kalpakkam marks the begining of our efforts to master fast breeder technology which would be needed early in the next century to help achieve a rapid growth rate of nuclear capacity. Meanwhile work on various aspects of the thorium fuel cycle has also commenced. We are keenly following world wide developments in the area of thermonuclear fusion since fusion breeders could help us exploit our thorium resources much earlier than originally envisaged.

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