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INDIA'S THREE-STAGE NUCLEAR POWER PROGRAMME: A BRIEF REVIEW IN 2025

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Abstract: Nuclear power provides a stable and reliable source of energy that can reduce dependence on fossil fuels. Nuclear power is capable of providing large scale base load electricity. India's Nuclear programme has led to the development of indigenous technologies and highly skilled manpower. It helps diversify India's energy mix, reducing vulnerability to international fuel price shocks. In this paper the author tries to give an up to date account of India's three stage Nuclear programme.

Introduction:

Recently (4^{th} March, 2024), the Indian Prime Minister was present in the start of the process of core-loading the indigenous prototype fast breeder reactor (PFBR) at the Madras Atomic Power Station in Kalpakkam, Tamil Nadu, India. Core loading refers to the process of placing nuclear fuel assemblies into the reactor's core. This is a historic milestone because although the Prime minister stayed for barely 45 minutes, this event takes India into the second stage of India's three stage nuclear programme. India's Nuclear programme is a highly sophisticated and ambitious programme which is supposed to lead India to a state of complete energy independence and self-sufficiency for centuries. This programme is ambitious in the sense that India is planning to use Thorium as the fuel for long run production of electricity. Though it is somewhat easy to generate electricity from Uranium but India has only limited Uranium reserve. India has only around 1-2% of global Uranium reserve, but one of the largest shares of global thorium reserve (~ 25%). But difficulty is that Thorium cannot be used directly as fuel as it is not a fissile material. But Thorium can be converted into Uranium-233 within a breeder reactor which is a fissile material. Moreover India has a plan to utilize the reactor byproducts in the subsequent stage and thereby managing nuclear wastes whereas most of the developed countries are using only Uranium as nuclear fuel for electricity generation and reactor byproducts are being thrown in safe custody as garbage without any intension of reprocessing except for partly utilizing in weapons production. India holds the world's largest reserves of Thorium in beach sands along the coasts of Kerala, Tamil Nadu and Odisha. Thorium is extracted from monazite, a mineral found in beaches. India's nuclear program is designed to utilize Thorium in its third stage, leveraging its potential for sustainable and efficient energy production for next centuries. In the first stage, India uses Pressurised Heavy Water Reactor (PHWR) and natural uranium which contains mostly Uranium-238 and Uranium-235. Uranium-235 is fissile. Nuclear reactions produce Plutonium-239 and energy. In the second stage, India will use Pu-239 together with U-238 in the Prototype Fast Breeder Reactor (PFBR) to produce U-233, Pu-239 and energy. Here Thorium will be used as blanket. In the third stage Pu-239 will be used along with Th-232 in breeder reactors to produce U-233 and energy.

Methodology:

To prepare this paper the author adopts the systematic literature review process. Books, websites and research papers were thoroughly studied.

History of the India's Nuclear programme:

In India research in Nuclear Physics began in 1945 with the establishment of the Tata Institute of Fundamental Research in Bombay. The Atomic Energy Act was passed in Parliament in 1948 soon after the country gained independence and set forth India's objective for the development and utilization of atomic Energy for peaceful purposes. In 1950s, Dr. Homi Bhabha, the well known physicist was the pioneer of India's three-stage nuclear power programme. Dr. Bhabha summarized the rationale for the three-stage approach as follows:

"The total reserves of thorium in India amount to over 500000 tons in the readily extractable form, while the known reserves of uranium are less than a tenth of this. The aim of long range atomic power programme in India must therefore to base the nuclear power generation as soon as possible on thorium rather than uranium….The first generation of atomic power stations based on natural uranium can only be used to start off an atomic power programme…..The Plutonium produced by the first generation power stations can be used in a second generation of power stations designed to produce electric power and convert Thorium into

U-233 or depleted uranium into more plutonium with breeding gain …. The second generation of power stations may be regarded as an intermediate step for the breeder power stations of the third generation all of which would produce more U-233 than they burn in the course of producing power.”

In November 1954, Bhabha presented the three-stage plan for national development at the conference on “Development of Atomic Energy for Peaceful Purposes” where then India’s Prime Minister Jawaharlal Nehru was also present. In 1954 Government established the Department of Atomic Energy with the sole responsibility for all Nuclear activities in the country. Until now the work of Atomic Energy Commission was restricted to the survey of radioactive materials, setting up plans for processing monazite and limited research activity in the area of electronics, methods of chemical analysis of minerals and the recovery of valuable elements from available minerals. In 1954, a multidisciplinary centre for research and development was set up in Trombay near Bombay which is now known as Bhabha Atomic Research Centre (BARC).Then the first major project of the centre was undertaken, namely, the building of a pool-type reactor. This reactor, named APSARA, became critical by 1956. It was the only reactor at that time in Asia, outside the Soviet Union. The fuel elements were imported from United Kingdom and all its equipments were designed and built within our country. In 1956, CIRUS, a 40 MW natural uranium heavy water moderated research reactor with Canadian collaboration was decided to build and it became critical in 1960. The CIRUS reactor continues to be in operation to this day using fuel produced at the Trombay plant and heavy water from the facility we set up at Nangal in Northern India. However, it was only in 1958 the Indian Government formally adopted the three-stage plan. Indian Government recognized that Thorium was a source that could provide power to the Indian people for the long term. In the decade 1956-66 we embarked on a wide variety of technological activities such as uranium extraction and purification, fuel fabrication, reactor control and instrumentation, research reactor construction, radioisotope separation, radiation medicine and vacuum technology. In 1961 we commenced work for setting up a processing plant at the BARC completely on our own and without any foreign collaboration. The plant was successfully commissioned in 1964. The decade 1966-76 saw the introduction of nuclear power in India. India’s first nuclear power station at Tarapur, near Bombay, consisted of two boiling water reactors (BWR), each of about 200MWe capacity, which went into operation in 1969. This project was awarded to General Electric of the USA on the basis of global tender. The involvement of Indian personnel was, however substantially huge. About the same time we also decided to install a heavy-water power station at Kota in the state of rajasthan consisting oftwo 220 MWe reactors. In this case it was a collaborative venture with Canada. India retained the responsibility for construction and installation activities while Canada undertook to supply the design and major equipment. The first unit of the Rajasthan station has been in operation since 1975. The 2005 Indo-US Nuclear Deal and the NSG waiver have created many hitherto unexplored alternatives for the success of the three-stage nuclear power programme. India published highest numbers of research papers in the world in each of the years from 2002 to 2006. As of April 2025, India has 25 nuclear reactors in operation in 8 nuclear power plants with a total installed capacity of 8880 MWe. Nuclear power is contributing 3% of total power generation in India. 11 more reactors are under construction and many are planned.

The three stage nuclear programme of India:

Let us now elaborate the three stages of the India’s nuclear programme.

Stage I – Pressurised Heavy Water Reactor

In the first stage natural uranium is used as fuel to produce electricity and Plutonium-239 is obtained as byproduct. The natural uranium is 0.711% uranium-235, 99.284% uranium-238 and a trace of uranium-234. Uranium-235 is only fissile and uranium-238 is not fissile but can be converted in a reactor to the fissile isotope plutonium-239.. India had the most efficient reactor design in terms of uranium utilization and the existing Indian infrastructure in 1960s allowed for quick adoption of the PHWR technology. Heavy water is used as moderator and coolant. The reason behind is that heavy water doesn’t absorb neutrons as compared to light water and reduces the speed of fast neutrons which is necessary for chain reaction to sustain. Enriched uranium can also be used as fuel for better efficiency but uranium enrichment is expensive. India correctly calculated that it would be easier to create heavy water production facilities than uranium enrichment facilities. Since the programme began, India has developed a series of sequentially larger PHWRs under IPHWR series derived from Canadian supplied reactors. The IPHWR series consists of three designs of 220MWe, 540MWe and 700MWe capacity. Almost the entire existing base of Indian nuclear power (4780MWe) is composed of first stage PHWRs of the IPHWR series, with the exception of the two Boiling water Reactor (BWR) units at Tarapur.

Stage II – Fast Breeder Reactor

In this stage the Fast Breeder Reactors (FBR) would use Plutonium-239 Uranium mixed oxide (MOX) fuel made from plutonium-239, recovered by reprocessing spent fuel from the first stage and natural uranium. In second stage Pl-239 undergoes fission to produce energy while the U-238 transmutes to additional Pl-239. Thus it breeds more fuel than it consumes. Thorium can be introduced as a blanket material in the reactor and transmuted to Uranium-233 for use in the third stage. Doubling time refers to the time required to extract as output, double the amount of fissile fuel, which was fed as input into the breeder reactors. It uses liquid sodium a highly reactive substance as coolant in two circuits.

Stage III – Advanced Nuclear Power Systems

The main aim of the third stage of nuclear programme is to get a sustainable nuclear fuel cycle. The advanced nuclear system will be made to use a combination of Thorium and uranium-233.Therefore, the vast thorium of India would be exploited and uranium -233 derived from second stage will also be exploited. It will also be a breeder reactor only..

Why was the stage II (PFBR) delayed?

The design of the Prototype Fast Breeder Reactor (PFBR) at Kalpakkam was done by Indira Gandhi Centre for Atomic Research (IGCAR). Bharatiya Nabhikiya Vidyut Nigam Ltd (Bhavini), a public sector company under the Department of Atomic Energy (DAE) has been given the responsibility to build the fast breeder reactors in India.

Sanctions against India's 'smiling buddha' nuclear test forced the use of a mixed carbide fuel over enriched uranium (which France was to deliver). By the time the Indian government started the PFBR in 2003, most people who worked on the FBTR were also nearing or had retired. Bhavini had improperly handled the purchase of several PFBR components by becoming overly reliant on the NPCIL. Other causes of delay included technical difficulties with the reactor coolant.

Challenges Ahead:

1. The 2011 Fukushima Daiichi disaster shifted public opinion worldwide against nuclear power, slowing work on new facilities.
2. Today, the tariff for solar electricity is under Rs 2.5/kWh wheras nuclear electricity costs around Rs 4/kWh.
3. The FBRs are harder to handle than other reactor designs. The thorium fuel cycle produces caesium-137, actinium-227, radium-224, radium-228 and thorium-230 which are all radioactive in ways that complicate their handling and storage.

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