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EVOLUTION OF THE INDIAN NUCLEAR POWER PROGRAM

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■ **Abstract** Presently, India occupies a leading place among Asian nations in the indigenous design, development, construction, and operation of nuclear power reactors. Nuclear power generation in India is based on a three-stage plan to eventually make use of the abundant national resources of thorium, through the use of fast breeder reactors. To achieve this long-range goal, India had to necessarily start with setting up heavy water–moderated, natural uranium–fueled power reactors to produce the plutonium required for the subsequent stages. But, as a result of India's nuclear weapon test in 1974, the developed nations imposed a comprehensive ban on the export of nuclear materials and technology to India, and these sanctions are still in force. This article outlines the steps followed by India to successfully counter these sanctions over the last 25 years and presents a critical evaluation of the potential problems and prospects of nuclear power in India.

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INTRODUCTION

India is the only developing nation to have indigenously developed, demonstrated, and deployed a wide range of scientific capabilities and technologies in the civilian aspects of nuclear science and technology. Though the country's original intention was to use these only for peaceful applications, India found itself at the center of world attention after 1974 when it first demonstrated its strengths through the development and testing of a nuclear weapon. The international reprobation and subsequent technology sanctions directed at India since then have succeeded in slowing down its nuclear efforts only temporarily. India's fundamental resolve to establish a world-class nuclear science and technology base in the country and to proceed with the development of civilian and military applications of nuclear energy has since been reinforced over the years. The long-range planning for and steady implementation of an indigenous nuclear power program is a clear demonstration of this determination.

This article traces the growth of the Indian nuclear power program in detail, from its early forays into setting up three imported power reactors to its relatively later entry into fast breeder reactor technologies. The first half of this article describes the steps taken to build the required facilities and expertise in the country. These include the exploration, mining, and processing of nuclear ores and the setting up of a modern nuclear science and technology complex at Trombay. The early interactions with the United States and Canada through which India built its first set of large reactors are also discussed. The article takes the reader through India's entry into the nuclear weapons club in 1974, the technology sanctions and international isolation it suffered due to this, and the national strategies pursued in countering this technology-denial regime.

The second half of the article discusses the triumphs and tribulations of the nuclear power program over the two decades that followed the imposition of sanctions. This includes India's successful efforts in setting up seven power reactors on its own during this period, while incorporating design improvements in successive stations. The final sections of the article include the Indian achievements to date in designing and developing advanced heavy water reactors and liquid metal–cooled, fast breeder reactors for the power program. While giving credit for the wide-ranging technological strengths that the Indian nuclear establishment has gained, the author has also focused on the not-so-laudable status of nuclear safety in the mid-1990s. However, an evaluation of the more recent data on modifications and repairs made in the Indian nuclear plants is also included, which shows that the safety status has indeed improved since the 1993–1996 period. The article comments on some of the general criticism leveled against the program and concludes with a general outline of the future course that this program might traverse.

This article is intended as an objective analysis of the Indian nuclear program, and it is not meant for making a case for or against nuclear power in India. No in-depth analysis of the economics of nuclear power in India is attempted, due to a lack of realistic cost data on many aspects of this program and for the sake of brevity of this article. The author's close association with the Indian nuclear program as an insider and his first-hand experience with western and Indian nuclear technologies over the years have helped in making the appraisal given in this paper. It is only incidental that this close examination of the evolution of the Indian nuclear power program concurrently brings out the futility of imposing international technology sanctions on a determined and competent nation like India.

INCEPTION OF THE NUCLEAR PROGRAM

Creation of Apex Organizations

Ever since India emerged as an independent nation in 1947, nuclear science and technology have occupied leading places among the country's development sectors. The strong rapport between India's first Prime Minister, Jawaharlal Nehru, and Dr. Homi Bhabha, the architect of the nation's nuclear program, helped avert bureaucratic interferences in establishing the manpower and facilities for the program. In 1945, the Tata Trust had already formed the Tata Institute of Fundamental Research (TIFR), with Bhabha as its director, to initiate basic research in nuclear sciences. Soon after independence, the Constituent Assembly passed the Indian Atomic Energy Act in 1948, under which the Atomic Energy Commission (AEC) was constituted the same year. Under the AEC, the Department of Atomic Energy (DAE) was created in 1954 to serve as the apex executive agency of the government in this field with the overall guidance of the AEC, and it has since been responsible for all civilian and military nuclear activities in India.

The Three-Stage Nuclear Power Program

The major fossil fuel resource domestically available to India is its proven coal deposits of about 75 billion tonnes. In addition, the country has nuclear ores from which a total of about 78,000 tonnes of uranium metal and about 518,000 tonnes of thorium metal can be extracted (1). If the entire uranium resources are first used in natural uranium–fueled pressurized heavy water reactors (PHWRs), it is estimated (1) that about 420 gigawatt electric-years (GWe-yrs) of electricity can be produced. The resulting depleted uranium and separated plutonium from these PHWRs, if used in fast breeder reactors (FBRs), could generate an additional 54,000 GWe-yrs of electricity. In these FBRs, production of uranium-233 (U233) can also be achieved by loading thorium assemblies in their blanket and low-power zones. Eventually by transitioning to generations of Th-U233 fueled breeder reactors, India should be able to produce an additional 358,000 GWe-yrs of electricity (1). Thus, even at an installed nuclear power capacity of 500–600 GWe, the country's nuclear resources will be able to sustain its electricity generation needs far beyond the extinction of its coal deposits.

It is evident from the historical development of the Indian nuclear program that generating electricity was indeed the primary focus of the program, if not the only one, up until the late 1960s. In his Presidential address to the 1954 United Nations Conference on Peaceful Uses of Atomic Energy, Bhabha outlined a three-stage plan for establishing nuclear power generation in India. Recognizing the limited resources of natural uranium and the abundant availability of thorium in the country, Bhabha and his colleagues selected a strategy of setting up heavy water–moderated, natural uranium-fueled, PHWRs for electricity generation in the first stage, with the production of plutonium as a by-product. As mentioned earlier, the second stage would comprise fast breeder reactors fueled with this plutonium along with depleted uranium, to produce U233 in their thorium-loaded blanket region. The third stage of the power program would employ fast breeders fueled with thorium and the U233 produced initially from the second stage. Ultimately, the third-stage breeder reactors would produce more fissile material than they burn while providing electricity, thus ensuring the sustainability of nuclear power for several decades to come.

Bhabha's mid-1950 plan involved technologies that were then only in the distant horizon, and it was proposed well before the first commercial nuclear power reactor was built anywhere in the world. The strong capabilities in chemistry and chemical engineering that the country possessed by the 1960s, as against the relatively weaker base in mechanical engineering sciences and production technology at the time, could also have prompted India to prefer the indigenous development of heavy water production and plutonium extraction rather than the uranium enrichment process via the centrifuge process.

INITIAL SUPPORT FACILITIES

Early Production of Nuclear Materials

From the beginning, the Indian program paid priority attention to the indigenous production of nuclear materials. The Rare Minerals Survey Unit was established in 1949 to conduct exploration work for mineral ores of uranium, thorium, zirconium, and other essential materials within the country. This work is being continued over the years by the Atomic Minerals Directorate of the DAE and the Indian Rare Earths Limited (IREL), which was started in 1950. The IREL, together with a thorium metal plant, which went into operation in 1955 at Trombay in western India, started supplying thorium compounds and rare metals for the program. The exploratory mining for uranium ore started about the same time in the eastern state of Bihar. In later years, these efforts came under the Uranium Corporation of India Limited (UCIL), which was set up in 1967 to carry out mining, milling, and initial processing of uranium ores. A uranium metal plant was also set up in Trombay in the mid-1950s, where nuclear-grade uranium ingots were produced by 1959. A pilot-scale fuel element fabrication plant established in Trombay was used to produce the first set of ten natural uranium fuel elements by February 1960, for use in the CIRUS reactor. Further discussion of material development activities carried out in the later years can be found below.

The Bhabha Atomic Research Center

In 1957, India started setting up a large nuclear science and technology complex at Trombay, which was renamed in 1967 as the Bhabha Atomic Research Center (BARC). Today, BARC houses a number of modern research laboratories and pilot plants, covering almost all basic and applied sciences as well as an array of impressive engineering and technology development facilities. These include two large research reactors of 40 and 100 megawatts-thermal (MWt) rating and a few smaller reactors used for physics studies.

Over the past decades, BARC has pioneered almost all the research, development, and demonstration activities needed for establishing the national PHWR program. One such important contribution has been in the field of radioactive waste management. As in other countries, India also treats low- and intermediate-level wastes in eco-friendly ways, while the small quantity of high-level waste so far produced has been immobilized in glass matrix through vitrification. A pilot plant to immobilize highly active waste has been operational in Tarapur for several years now. The vitrification process developed in BARC, using sodium borosilicate glass matrix with some modifiers, has been adopted for this plant as well as the two larger waste management plants currently being set up in Trombay and Kalpakkam. Vitrified waste is stored in a specially designed solid storage surveillance facility, where it will remain for about 30 years before ultimate disposal in deep geological formations. Studies for setting up such eventual repository sites are under way in the eastern part of the country.

Ever since its creation, BARC has steadily expanded its activities and facilities and consolidated its strengths in every subarea of the nuclear fuel cycle. Unofficial figures put the total employment in this center at about 17,000 in 2001, of which about 7,500 are scientists and engineers. By any international standard, BARC today is a world-class nuclear science and technology development center and perhaps one of the best of its kind in Asia.

Thermal Research Reactors

Along with establishing a national base for nuclear materials, the DAE was also acquiring capabilities in the design, construction, and operation of nuclear reactors. The initial reactors to come up were the thermal research reactors. The smaller among these were used for zero-power and low-power reactor physics studies, verification of neutron cross-sections, and developing instrumentation systems. The larger ones were primarily for conducting in-reactor engineering loop experiments and for the production of a variety of radioisotopes.

The first research reactor to be set up in 1956 at BARC was a light water–moderated swimming pool unit of 1.0 MWt rating, called APSARA, which is still in operation. A second, larger research reactor called CIRUS was built jointly by India and Canada through an intergovernmental agreement under the Colombo Plan. This heavy water-moderated 40 MWt reactor commenced operation in July 1960, using heavy water supplied by the United States. Even as the CIRUS Project was being negotiated with Canada, BARC scientists were designing a plant for recovering plutonium from the spent fuel in CIRUS. The construction of this indigenous reprocessing plant began in 1961, and it was commissioned in 1965, which made India one of the very few nonnuclear weapon states to develop and master this difficult technology. In later years, India indigenously designed and built a 100 MWt heavy water-moderated reactor called DHRUVA, which was commissioned in BARC in 1985. CIRUS and DHRUVA still continue to serve the Indian military program as major producers of weapons-grade plutonium, besides producing radioisotopes for medical and industrial purposes.

EARLY POWER REACTORS

Tarapur Atomic Power Station

The first international cooperation that helped India in the nuclear field came in the early 1950s through the opportunity offered to train its scientists and engineers in the United States. This was followed by an expression of interest by Bhabha in extending the Indo-U. S. cooperation to include the potential supply of U.S. power reactors to India. It was clear that the Indian interest was prompted by the desire to introduce nuclear power generation in the country as early as possible and to obtain the best financial terms from the United States, rather than by its preference for the light-water reactor (LWR) systems. India eventually obtained a credit of $80 million for the two General Electric boiling water reactors (BWRs) it bought, at a low annual interest rate of 0.75% and a repayment schedule of 40 years (2). The construction of these 210 megawatts-electrical (MWe) reactors started in October 1964, and they commenced commercial operation in October 1969 to become one of the first few power reactors to operate anywhere in the world. These units were set up at the Tarapur Atomic Power Station (TAPS-1 and 2) in the western state of Maharashtra, about 100 miles north of Bombay. In 1985, the TAPS reactors had to be derated permanently from a power level of 210 MWe to 160 MWe because of the inoperability of all its secondary steam generators, in which extensive tube cracks had developed.

Rajasthan Atomic Power Station

Bhabha had also initiated discussions on nuclear power reactors with Canada at about the same time he was negotiating with the United States. In the area of heavy-water reactor technology, India had already benefited from the Indo-Canadian cooperation on the CIRUS Project. This interaction, coupled with the fact that heavy water reactors formed the first stage of the Bhabha plan, led to discussions on initiating an Indo-Canadian program on nuclear power. In April 1964, India and Canada agreed to set up a 200 MWe PHWR power station in the Rajasthan state of India. Design of the reactor and the supply of all critical equipment were the responsibility of the Canadians. The design adopted for India was a replica of the one Canadians used earlier in their Douglas Point reactor, though no operational feedback from this reference reactor was available to the designers at that time. Many of the problems that the Indians had to later face in their Rajasthan and Madras stations can be attributed to the use of this premature Canadian technology.

The system integration tasks for the Rajasthan Atomic Power Station-1 (RAPS-1) were jointly carried out, and the construction and commissioning of the plant were mainly done by the Indians, under Canadian guidance. The Indian engineers who were trained in Canada on reactor operation and maintenance took charge of the plant afterwards. RAPS-1 went into commercial operation in November 1972. Two years after the agreement to build the first reactor unit, Canada and India agreed in December 1966 to set up a second similar reactor (RAPS-2) at the same site. Midway through this cooperation on the second unit, India conducted its nuclear weapon test, and Canada retaliated by abruptly withdrawing from this program.

THE 1974 NUCLEAR WEAPON TEST

Sidestepping to Nuclear Weapons

In May 1974 India conducted an underground nuclear explosion, which was essentially the country's first attempt at testing a nuclear weapon. India, a nation that started out with the sole intention of using nuclear energy for peaceful purposes, had its own compelling reasons for going nuclear. Prominent among these were the inequities India perceived in the then-emerging nuclear non-proliferation regime, with the Non-Proliferation Treaty (NPT) of 1970 having given a specially elevated status to five nuclear-weapon states, including China. Nuclear weapons thus became the new currency of power and prestige among nations, which relegated many otherwise capable nations like India to a permanent secondary status. India found this unacceptable, refused to join the NPT, and decided to chart out its own course.

International Reactions to the Indian Test

The sharp reaction to the nuclear test from Canada and the United States was more than the Indian decision makers had anticipated. Within four days of the test, Canadians froze all assistance to India for the RAPS nuclear units and insisted on comprehensive International Atomic Energy Agency (IAEA) safeguards on all Indian nuclear facilities. India was unwilling to comply with this, and eventually Canada terminated all its nuclear cooperation, in May 1976. Since 1974, the supply of most of the crucial components and equipment for the RAPS-2 reactor was withheld, and India was left to complete this project on its own.

The United States also felt the need to react strongly to what they interpreted as India's defiance and challenge of the nuclear non-proliferation regime, which was then being shaped under U.S. leadership. A group of twenty nations, already functioning as the Zangger Committee, introduced a "trigger list" of items that all member states agreed not to export, unless the receiving state agreed to accept IAEA safeguards on the facilities for which they were meant. Not satisfied with this, the U.S. took the initiative to form the Nuclear Suppliers Group (NSG) in the mid-1970s, which agreed to impose restrictions on an extensive list of additional items. The post-1992 restrictions of the NSG also included the stipulation that any country receiving nuclear materials must agree to accept IAEA safeguards on all its facilities. Furthermore, prompted mainly by the Indian weapon test of 1974, the U.S. Congress enacted the Nuclear Non-Proliferation Act (NNPA) in 1978, mandating that the U.S. shall not export nuclear-related supplies to any country that does not agree for IAEA safeguards on all its nuclear activities. In addition, the NNPA bans exports to any nonnuclear weapon state that has exploded a nuclear device, a stipulation specifically aimed at India.

Following the enactment of the NNPA, the United States withdrew from its obligation to supply enriched uranium fuel for the Tarapur reactors because India was unwilling to agree for IAEA full-scope safeguards on all Indian nuclear facilities. The U.S. government also barred the General Electric Company from exporting the contracted spare parts to India and from providing any technical assistance for the TAPS reactors. After the United States withdrew, France agreed to supply the fuel for some time. But, after the 1992 NSG restrictions came into force, the French stopped supplying nuclear fuel for TAPS. China stepped in at that time to assist India with fuel supply because it was not a member of the NSG.

However, following India's nuclear weapon tests in May 1998, China indicated its unwillingness to supply any more fuel. In 2001, Russia and India reached an agreement (3) under which Russia guaranteed the enriched uranium supply for TAPS, and the first fuel shipment has reached India (4). The United States strongly objected to this agreement (5), but Russia affirmed that it was unwilling to alter the agreement with India. In the meantime, India developed and tested irradiation of a few fuel subassemblies containing mixed oxides of uranium and plutonium (MOX) in TAPS, with the intention to partially replace the enriched uranium fuel in these reactors with MOX.

STRUGGLING THROUGH SANCTIONS

The DAE Reorganizes its Strategy

Under the nuclear denial regime imposed on India since 1974, it is unable to import raw materials, components, equipment, and technology that are directly or indirectly required for its nuclear facilities. In the mid-1970s, India's key industrial sectors and its science and technology institutions were still in their nascent stages of development, and they were unable to immediately step in and assist the DAE in rapidly indigenizing their program. And yet, the decade that followed witnessed an unprecedented demonstration of cooperation and excellence from both the nuclear establishment and the national industries.

The activities on the design and construction of nuclear power plants within the DAE were originally entrusted to its Power Projects Engineering Division (PPED), created in June 1967. In 1984 the PPED was merged with a newly formed Nuclear Power Board, which functioned for three years with more comprehensive responsibilities. As the program grew, the DAE decided in September 1987 to consolidate all power sector activities under the purview of a newly constituted public sector company within the department, called the Nuclear Power Corporation of India Limited (NPCIL). NPCIL continues to have the total responsibility for the Indian nuclear power sector, under the control of the DAE.

The DAE has been conducting a world-class one-year training program in nuclear science and engineering since 1957 at the BARC Training School, which currently admits about 200 engineering and science graduates every year. The forty-fifth batch of trainees from this program will be graduating in 2002, bringing the total number trained so far to nearly 8,000. Because of this, the DAE did not consider promoting the establishment of independent academic programs in nuclear sciences and engineering within the Indian Institutes of Technology (IITs) or the universities in the earlier years. This policy appears to be changing; the DAE decided in the mid-1990s to set up a swimming-pool, low-power research reactor at the Andhra University and funded nuclear-safety related research projects at some of the IITs and Indian universities.

In the post-1974 period, all reactor design and development work was taken up within the DAE itself, drawing heavily upon the abilities of the already trained personnel and the experience base of those who had participated in the earlier reactor projects. The immediate necessity was to design and fabricate the components and equipment for RAPS-2 and the other PHWR units on which construction work had already started. Over the next two decades, all the PHWR system components and subsystems denied through the sanctions were designed and produced indigenously, with neither external technological assistance nor import of special materials (6, 7). The focus on self-reliance that the Indian program had from the outset helped India to confidently address and surmount the problems.

Involvement of Indian Industries

The design, development, and manufacturing responsibility for the power plant equipment was taken up mainly by the industries on their own because these were similar to the items they were delivering for the conventional thermal power stations in the country (6). In doing this, industries made use of the technological collaborations established at that time with reputable foreign companies for manufacturing a variety of power plant equipment in India. Because these secondary system components did not fall in the category of nuclear equipment, their production under the then-existing contractual arrangements with foreign collaborators was not affected by the restrictions of the post-1974 export restrictions.

Some of the key primary system equipment for the PHWR stations, as well as the fast breeder program in later years, was designed and fabricated by Bharat Heavy Electricals Limited (BHEL), a major government-owned power sector manufacturing company, which employs almost 65,000 people spread over its five manufacturing divisions. Soon after 1974, the Corporate Research and Development (R&D) Division of BHEL was entrusted with the central coordination role for all crucial supplies from the company to the DAE nuclear installations. The author served as the general manager in charge of BHEL's R&D Division and oversaw this effort from 1976–1986. In addition to BHEL, a few of the major private sector manufacturing companies, such as Larsen & Toubro and Godrej Industries, also took on major responsibilities for supplies.

EMERGING FROM THE SANCTIONS

Madras Atomic Power Station

While the Rajasthan Power Station was under construction, the PPED of the DAE was designing a twin-reactor station to be built at the Madras Atomic Power Station (MAPS-1 & 2), in south India. Basically, the MAPS reactors were very similar to the RAPS units, except that the DAE scientists made a few notable improvements. Indian physicists successfully redesigned the Canadian core in RAPS-1 to obtain 220 MWe (gross) output instead of the 200 MWe (gross) in RAPS-1, through better flattening of the neutron flux distribution (8). The Indian metallurgists developed and used an improved stainless steel alloy for fabricating the reactor end shields because the cracking of the RAPS-1 end shields due to irradiation embrittlement resulted from the choice of a wrong material by the Canadians. The MAPS-1 unit eventually began commercial operation in January 1984, and MAPS-2 began in March 1986. Prior to this, RAPS-2 was completed and put into commercial operation in April 1981.

In the early years of operation, both reactors at MAPS experienced structural failures of the moderator manifold within their calandrias, which resulted in the subsequent need to reverse the flow in their moderator circuits. As a safety precaution, both MAPS-1 & 2 were derated thereafter to a power level of 170 MWe (9). Current plans are to repair this deficiency during the next long shutdown of each unit, so that the original power rating can be restored.

Well before the MAPS reactors came on-line, PPED engineers started evaluating all equipment and systems in the RAPS and MAPS designs, with a view to substantially redesign many of them. The difficulties experienced in the early operation and maintenance of RAPS-1, the limitations in the infrastructure and manufacturing capacity within the country, and the desire to incorporate some of the then openly available information on emerging concepts in nuclear plant design were the primary motivations behind this evaluation.

Narora Atomic Power Station

Based on the evaluation of the earlier reactors, the PPED engineers completed the design of the 2 × 220 MWe Narora Atomic Power Station (NAPS-1 & 2). Among the changes made were certain improvements on reactor safety, which were absent in the Canadian design (8). Two high-pressure stages were added to the emergency core cooling system at Narora because the analysis of the hypothetical loss-of-coolant accident showed that the Canadian concept of coolant injection at a lower pressure could result in overheating and even local melting of the core. In addition, the Indian design incorporated two independent and diverse active shut-down systems and a third level passive system that depended on gravity to add a borated solution into the core for use in case all power supplies to the station are lost, which would cause a prolonged station blackout. Such an event indeed happened in March 1993, during a devastating fire incident at NAPS-1, and the injection of the borated solution ensured that secondary criticality of the core did not occur during the long total power blackout. Furthermore, several new equipment and subsystem designs were also introduced for the first time in NAPS, including U-tube steam generators in place of the complicated Canadian units used in RAPS. Eventually, NAPS-1 was brought into commercial operation by January 1991 and NAPS-2 by July 1992.

Kakrapar Atomic Power Station

Yet another serious deficiency of the original Canadian design at RAPS-1 & 2 could not be corrected until India set up the Kakrapar Atomic Power Station (KAPS-1 & 2) in the western part of the country. Canadians had selected zircaloy-2 as the material for the coolant channel pressure tubes in their Douglas Point Station, as well as in RAPS-1 & 2. Analyses done after the catastrophic pressure tube rupture in 1984 in their Pickering Station showed that zircaloy-2 is prone to irradiation-induced creep deformation, which could lead to local blister formation and eventual tube rupture (9). Choice of niobium-stabilized zircaloy as the construction material for the pressure tubes was proposed as the solution to this problem. But, neither this new alloy nor the metallurgical and production processes for it were made available to India. Therefore, the metallurgists at BARC and the engineers at the Nuclear Fuel Complex had to collaborate and indigenously produce such tubes. In the meantime, the DAE took a deliberate decision to proceed with the projects in hand, using pressure tubes made out of basic zircaloy-2, in the interest of avoiding project delays. The first unit to use the improved tube material in its initial construction was the KAPS-2 reactor. This meant that en masse retubing of all seven PHWRs built prior to KAPS-2 has to be done before each unit completes eight full-power years of operation.

KAPS-1 was put into commercial operation in May 1993. When KAPS-2 reached a similar status in May 1995, the Indian 220 MWe (gross) PHWR system was deemed to have reached its full maturity. KAPS-2 is indeed a much improved reactor system compared to the Canadian RAPS-1, which was the only PHWR unit India had at the time all international cooperation was cut off. Among its other achievements, India had by 1995 also established eight heavy water production plants in the country, which made it self-sufficient in this key input for the PHWR program.

Kaiga Station and Extension of RAPS

At the end of the more than 20 years of determined efforts, the Indian nuclear power program finally emerged from the shadows of international sanctions, which were aimed principally to prevent India from reaching this capability level. As the program was nearing this accomplishment, more enthusiasm was evident on the part of the government in sanctioning further 220 MWe PHWR stations and in supporting advanced reactor projects for the future. Actions taken in this regard led to the setting up of the 2 × 220 MWe Kaiga Atomic Power Station (KGS-1 & 2) and two further reactors of similar rating at Rajasthan (RAPS-3 & 4). These four reactors also reached commercial operation between March and December 2000. Table 1 gives a list of Indian nuclear power reactors currently in operation or under construction.

ADVANCED PHWR DESIGNS

The 540 MWe PHWRs

In the mid-1980s, DAE started looking into two different concepts for the next generation of heavy water power reactors. The first was the extension of the 220 MWe (gross) design to a 540 MWe (gross) rating, and the second was a heavy water–moderated, boiling light-water cooled advanced reactor for thorium utilization.

TABLE 1 Indian nuclear power reactors

Reactor	Type	Gross rating (MWe)	Designed by	Status	Initial operation
TAPS-1	BWR	160	United States	Operational	1969
TAPS-2	BWR	160	United States	Operational	1969
RAPS-1	PHWR	150	Canada	Operational	1972
RAPS-2	PHWR	200	Canada/India	Operational	1981
MAPS-1	PHWR	170	India	Operational	1984
MAPS-2	PHWR	170	India	Operational	1986
NAPS-1	PHWR	220	India	Operational	1991
NAPS-2	PHWR	220	India	Operational	1992
KAPS-1	PHWR	220	India	Operational	1993
KAPS-2	PHWR	220	India	Operational	1995
RAPS-3	PHWR	220	India	Operational	2000
RAPS-4	PHWR	220	India	Operational	2000
KGS-1	PHWR	220	India	Operational	2000
KGS-2	PHWR	220	India	Operational	2000
TAPS-4	PHWR	540	India	In construction	2005
TAPS-3	PHWR	540	India	In construction	2006
KKS-1	LWR	1000	Russia	In construction	2007
KKS-2	LWR	1000	Russia	In construction	2008

By 1985, unlike in the very early years, several load centers in India grew to be sufficiently large consumers of electricity, and the introduction of PHWRs of larger rating became increasingly viable and economical. Conventional thermal power units already exceeded the 500 MWe unit size by then, and the interconnected transmission grid was also capable of handling large power flows. Encouraged by the success of indigenizing the 220 MWe system, the BARC and NPCIL engineers therefore jointly initiated the design of a 540 MWe PHWR, which, like its precursor, is of horizontal pressure-tube design, fueled with natural uranium oxide elements and moderated and cooled by heavy water (10). The reactor is provided with two fast-acting, physically separate shut-down systems that rely on diverse principles. The first of these involve the insertion of cadmium neutron absorber rods, and the second consists of injecting a gadolinium nitrate solution into the moderator region to cause shut down. The global and local power control of the reactor is achieved through a liquid zone control system, which uses light water as neutron absorber. In 1999 the government gave financial sanction for setting up the 2 × 540 MWe TAPS-3 & 4 units at Tarapur, and civil construction works have been progressing since then. The scheduled criticality date for the TAPS-4 unit is October 2005, and for TAPS-3 it is July 2006 (11).

Advanced Heavy Water Reactor

In July 2001 India announced its intention to build an advanced heavy water reactor (AHWR) of 750 MW (thermal) rating, with construction to begin in 2004 and commercial operation by 2011 (12). The detailed design of this reactor is in the late stages of completion, and the experimental validation of certain new concepts is presently being done. The AHWR is a vertical tube reactor, which can be refueled at power and cooled by boiling light water under natural circulation (13). Complex equipment such as steam generators and primary pumps are thus eliminated in the design. The physics design of the core aims at maximizing the use of its thorium-based fuel and at achieving a slightly negative void coefficient of reactivity. These objectives are reached through the use of mixed oxides of plutonium and thorium in some of the fuel pins in each fuel cluster, with mixed oxides of thorium and uranium-233 in the remaining pins, and by the use of a heterogeneous moderator consisting of amorphous carbon and heavy water. The reactor relies on a passive emergency cooling system, based on water supplied from a gravity-driven pool, which can keep the reactor cooled continuously for three days without operator intervention.

Several features of the AHWR could lend itself to a reduction in both the per-megawatt capital cost and the construction time, when compared to the 220 MWe PHWR. Because the reactor will produce as much U233 as it consumes, with 75% of the total power coming from the thorium fuel, the AHWR will serve as an initial vehicle for utilizing thorium, while awaiting the third stage of the power plan based on thorium-U233 fast breeder reactors to be established.

FAST BREEDER REACTOR PROGRAM

Fast Breeder Test Reactor (FBTR)

In order to concentrate on the development of fast breeder reactors, the DAE set up a separate center at Kalpakkam in south India in 1969, which is presently known as the Indira Gandhi Center for Atomic Research (IGCAR). IGCAR has grown and become a dedicated fast reactor technology development center, with a total employment of 2,400 scientists, engineers, and supporting staff.

In 1968, India and France initiated discussions on setting up a fast breeder test reactor (FBTR) at Kalpakkam, as a cooperative effort. The choice was to build a 40 MWt, 13.2 MWe loop-type sodium-cooled reactor, modeled after the French research reactor RAPSODIE (Fortissimo). Though the design of the FBTR was partially provided by the French, this reactor was only in its early stages of construction in 1974 when France withdrew from the project in view of India's nuclear weapon test.

Detailed design and fabrication of many of the critical equipment and subsystems of the FBTR, therefore, had to be done in India. IGCAR and the national industries came together in this task, much the same way the unfinished tasks on

RAPS-2 were being carried forward at that time. With the much higher operational temperatures involved in the FBTR, the complexity of equipment, and the critical choices of materials, the completion of this reactor, in the absence of any foreign technical assistance and import of materials and equipment, presented a formidable challenge to the nuclear establishment. It is, therefore, no surprise that it took more than 11 years of coordinated national effort before the FBTR could reach first criticality in October 1985.

Soon after the FBTR was brought to criticality in 1985, it was shut down for repairs, following an inadvertent fuel-handling mishap. The tools and tackles needed to remotely carry out this repair work had to be designed and made within the country. After repairs, the reactor was brought back into operation in 1989, and until 1992 it was operated at a power level of 1.0 MWt. By March 1993 the power was raised in steps to 10.5 MWt. Since then, the power level has been increased only to about 14 MWt because of a limited core size, which is restricted by the amount of plutonium made available to this program.

Fast Reactor Fuels and Special Alloys

Over the past three decades, Indian scientists and engineers have been developing alternate fuels and reactor materials needed for the fast reactor program (14). The reprocessing technology for separating uranium-233 (U233) from thorium bundles irradiated in the CIRUS reactor was taken up in the late 1960s, and the first batch of nuclear-grade U233 was produced at BARC in September 1970. Based on the studies at BARC, a modified pilot reprocessing plant was built, and it is currently under commissioning. This plant will be operated to reprocess the first few irradiated cores from the FBTR and to gather data and operational experience that can then be used in completing the fast reactor fuel reprocessing plant, which is also currently under construction.

Contrary to the French practice, Indians decided to fuel the FBTR with 316 SS-clad mixed plutonium-uranium (Pu-U) carbide because of its better thermal performance, the potential for higher breeding ratio, and the requirement of a lower plutonium inventory for the initial loading, when compared to a mixed oxide fuel. Within BARC, such fuel elements for the FBTR were fabricated by 1984. By December 2001, this fuel charge reached a burn-up of 88,000 megawatt-day (MWd) per tonne without any clad failure, and its burn-up is expected to cross 100,000 MWd/tonne during 2002 (15, 16; S.B. Bhoje, personal communication). In the meantime, Indian metallurgists have also fabricated mixed Pu-U mononitride as well as metallic fuel in the form of a uranium-plutonium-zirconium (U-Pu-Zr) alloy, as alternate standby fuels for future fast reactors (17). All of these fuels, along with the well-understood Pu-U mixed oxide, are being test-fabricated and irradiated in the FBTR for performance evaluation.

For the development of the special nonfuel materials required for the fast reactor program, IGCAR joined hands with the Steel Authority of India and the Special Alloys Production Plant of the defense department. Some of the materials already developed and tested through this collaboration include type 316LN and 304LN austenitic stainless steels for structurals, a titanium-stabilized stainless steel called Alloy-D9 for fuel cladding and hexagonal cans, and a modified 9Cr-1Mo ferritic steel for steam generators.

Prototype Fast Breeder Reactor

Soon after commissioning the FBTR in 1985, IGCAR engineers embarked on the conceptual design of a 500 MWe prototype fast breeder reactor (PFBR), which is a sodium-cooled, pool-type reactor with two secondary loops and four steam generators in each loop. The reactor is designed for a minimum operational life of 45 years. Initially, the plan is to fuel the PFBR with mixed Pu-U oxide, keeping the option open to use other fuels in future breeders. Though India has gained some experience with the mixed-carbide fuel in the FBTR, this fuel needs to be further optimized for a higher linear heat-rate and a lower clad-fuel gap. Besides, the extensive experience already gained with the mixed-oxide fuel in India makes it a more appropriate candidate fuel for the first series of fast breeder reactors. As for reactor safety, the measures provided in the PFBR include two diverse shutdown systems, two independent decay-heat removal systems, a core-catcher that can handle the melting of up to seven subassemblies, and a rectangular reactor containment building (18).

Several liquid-sodium loops are being operated at IGCAR to assist in the development of PFBR instrumentation systems and for performance testing of control rod drive mechanisms and other subsystems. The prototype control and safety rod mechanisms, fuel transfer machine, full-size sectors of the main reactor vessel, inner vessel, roof slab, etc. have been manufactured and are being tested. Hydraulic testing of scale models of the primary circuit have been used in finalizing the design, along with tests for heat-exchanger hydraulics and flow-induced vibration. A full-scale prototype pump testing facility has also been set up in association with the industry.

The detailed design of the PFBR has now been completed and, in some cases, designs for some of the key equipment and components have been transferred from IGCAR to the major manufacturing industries in the country to start trial production. The Atomic Energy Regulatory Board (AERB) has already approved a site adjacent to the MAPS-1 & 2 units for setting up the PFBR and is reviewing the design of the reactor system to accord regulatory clearance. The civil works at the PFBR site were scheduled to begin during the second half of 2002, and the reactor system will be commissioned in 2008 (19).

NUCLEAR SAFETY STATUS

Organization of Safety Regulation

Until 1972, the DAE did not have a separately identifiable organization or personnel for conducting the safety review of their nuclear installations. In February 1972, DAE constituted an internal Safety Review Committee (SRC) to maintain safety oversight of DAE facilities. The SRC, however, did not qualify as an independent agency because it was formed from within the DAE itself.

In November 1983, the AERB of the Government of India was set up through an executive order of the secretary of DAE. The AERB's original charter was to oversee and enforce safety in all nuclear operations, including those within the DAE and also those among the national industrial and medical users of radiation. This was modified in April 2000 to exclude all BARC facilities from AERB's oversight, which followed the declaration of BARC as a nuclear weapons laboratory. The AERB chairman reports to the Atomic Energy Commission (AEC), which is also headed by the secretary of DAE who has ultimate responsibility for the DAE installations. The chairman of the NPCIL is also a member of the AEC, thereby indirectly exercising administrative powers over the AERB, which is supposed to independently enforce safety in the NPCIL plants. In addition, the AERB has very few qualified staff of its own, and about 95% of the technical personnel in AERB safety committees are officials of the DAE whose services are made available on a case-to-case basis for conducting the reviews of their own installations. The perception is that such dependency could be easily exploited by the DAE management to influence the AERB's evaluations and decisions.

The author was a member of the AERB from June 1990 to June 1993 and the chairman of the AERB from June 1993 to June 1996. During the latter period, he was also unanimously elected in June 1994 to serve as the chairman of the IAEA's 16-nation Drafting Committee for the Convention on Nuclear Safety, which subsequently came into force that month. India was one of the first countries to join this Convention in September 1994. Article 8 of the Convention calls for an effective separation of the functions of the country's nuclear regulatory agency from any other body or organization concerned with the promotion or utilization of nuclear energy. The present setup of the AERB, as subservient to the DAE, clearly violates this article of the Convention to which India is a signatory (9, 20).

Safety in DAE Installations: Mid-1995 Status

Much has been published in the open literature (9, 20) regarding the poor safety status in the DAE nuclear facilities, as it existed in June 1996 when the author's association with the AERB ended, and therefore the details of these deficiencies and their importance are not elaborated in this paper. Both after the Three Mile Island accident in the United States and the subsequent Chernobyl accident in the Soviet Union, DAE carried out high-level internal evaluations of the safety of their installations. These resulted in two separate top-secret reports, one in 1979 and the other in 1987, which identified the then-existing crucial deficiencies that required urgent rectification. The AERB investigations of the devastating fire that occurred in the NAPS-1 unit in March 1993 and the collapse of the inner containment dome at the Kaiga-1 unit in May 1994 also brought out several serious lacunae, which then existed in DAE's overall approach to safety management. The AERB therefore decided in 1995 to initiate a comprehensive evaluation of the safety status of all DAE nuclear installations so that necessary corrective actions could be identified and implemented in a timely manner. The comprehensive findings of this evaluation were brought out in the 1995 AERB document on the Safety Issues in DAE Installations.

The deficiencies detailed in the AERB report were generally classified into a few categories (9). These included certain serious deficiencies in the emergency core cooling systems in some of the operating power reactors. There were also some nuclear installations in which certain primary system components or internals were either cracked or structurally weakened over the years, needing repairs or replacement. A group of further defects involved the reactor instrumentation and protection systems, which had degraded the reliability and safety of the reactors. There were also instances of prolonged and continuous leakages from buried pipelines carrying highly radioactive waste fluids or weaknesses of design and construction in steel tanks containing very large quantities of such fluids.

A disproportionate number of these serious deficiencies were found in the four reactors of Canadian and U.S. origin, which were built early in the program and subsequently abandoned by their developers after the 1974 technology sanctions were imposed on India. In contrast, the more recent reactors of Indian design and construction at Kakrapar and Kaiga had very few or no serious defects at all. However, a matter of concern was that, among the 134 specific issues included for corrective action in this report, there were some identified in the DAE's own evaluations of 1979 and 1987 as items requiring urgent attention, and these had not been acted upon even in 1995.

The AERB report was subsequently reviewed and accepted by the AEC at their February 1996 meeting when the AEC directed the DAE to initiate prompt action to implement all recommendations made in the report. The non-DAE members of the AEC felt it was imperative to take this decision, and they were influential in enforcing it.

Safety Improvements During 1996–2001

Since June 1996, the DAE and NPCIL have been paying more systematic attention to safety and performance issues. Available information on the safety-related corrective actions taken in the past five years leads one to surmise that the safety of the Indian nuclear power stations has definitely improved since the time the AERB's 1995 report was approved by the government. The decisive steps taken by the AERB during 1993–1996, when this regulatory organization did exercise its statutory obligations, appear to have brought about the intended corrective impact on the program.

According to a recent communication from AERB Secretary K.S. Parthasarathy to the author, 119 out of the 134 safety issues are reported to have been completely resolved. The AERB communication does not, however, state which of the high-priority issues are still among the unattended ones, nor does it clarify any details of the already resolved issues. There is, however, some information available from the NPCIL on notable modifications and improvements they have made since 1996. For example, the en masse coolant channel replacement and the retrofitting of a high-pressure emergency core cooling system in the RAPS-2 reactor were completed, and the reactor was brought back to full power operation in June 1998 (22). Preparations are now being made for similar upgrades in both the MAPS-1 and RAPS-1 reactors. The RAPS-1 reactor was shut down in 1994 because of a serious leakage of radioactive heavy water through the over-pressure relief device in its moderator system. This was repaired in 1997, and the reactor was brought back to a higher power level of 150 MWe (23). Similarly, the essential inspection of the core shrouds in TAPS-1 & 2 was done in 1996–1997 to verify their structural integrity (24). The deficiencies in the emergency power supply systems in TAPS-1 & 2 and RAPS-2 were rectified in 1998–1999, to substantially reduce the chances of a total power outage in these units (25). India's first nuclear power plant simulator at the Nuclear Training Center at RAPS was upgraded with state-of-the-art technology systems and recommissioned in October 1999 (26). Four-week training programs for PHWR operations personnel are now conducted regularly at this facility. In recent years, NPCIL also brought about changes in their management and quality control practices, which have contributed to the substantial improvement in the annual capacity factors of the stations, and these changes have also helped improve the safety of the installations.

Lastly, the NPCIL, with its rapidly improving performance, has lately been receptive to international interactions wherever useful. International peer review teams from the World Association of Nuclear Operators (WANO) have conducted evaluations of KAPS-1 & 2 in 1998 and NAPS-1 & 2 in 2000. As a WANO member, the NPCIL has also sent its senior engineers to participate in similar reviews of foreign stations, to jointly conduct training programs with WANO and the IAEA, and to help the IAEA in their technical assistance programs. The U.S. Nuclear Regulatory Commission (U.S. NRC) is also in the process of reviving a safety-related cooperative program with the AERB, which was temporarily suspended after the Indian weapon tests in 1998.

Although the safety status in the nuclear installations appears to have indeed improved in recent years, the DAE and the NPCIL must realize that their best conceived plans for expanding the nuclear power sector could be derailed overnight if a serious nuclear accident occurs in India. To this end, it would be wise for the DAE to relinquish its direct control of the AERB and enable it to act as an independent and competent regulatory body serving the nation's overall interest.

CRITICISM OF THE INDIAN PROGRAM

The Choice, Rating, and Performance of Reactors

Over the years, there have been several criticisms leveled against the Indian nuclear program, both by international analysts and from within the country. In his authoritative book titled *India's Nuclear Bomb* (2), George Perkovich seriously questioned the wisdom of Bhabha's plan for establishing nuclear power generation in the country. According to Perkovich, India's investment in nuclear power in the 1950s and beyond represented a major diversion of capital into a relatively unproductive area of economic development. This conclusion is reached from a few other premises of his, which are also worth examining. Perkovich claims that the Indian choice of the 220 MWe rating for the initial set of power reactors proved to be a major economic handicap because it ignored the economy of scale obtainable at the 500–600 MWe unit size. Yet another comment of his relates to the approximately 40% average load factor at which Indian nuclear plants operated through the mid-1990s, as against the 80% figure which Bhabha used while making his optimistic cost projections. Perkovich also points out that the choice of heavy water-reactor technology was an uneconomical one for India, given its higher capital costs in comparison to light-water reactors using enriched uranium fuel. Lastly, he mentions that Bhabha and Nehru were alarmed by India's lack of natural uranium resources and were seduced by the theoretical lure of using plutonium-breeding reactors to transform India's abundant thorium reserves into an unending source of cheap electricity. It is helpful to address these comments of Perkovich because they represent the general criticism leveled by many others as well.

Viewed in the context of the present performance of the Indian nuclear power program, the above comments have much less validity than in the past. The average annual capacity factor of the Indian nuclear plants in the 1998–2000 period was 75%, 80%, and 82.5%, respectively, in consecutive years (27), and it has already surpassed Bhabha's original assumption of 80%. As for the choice of a low power rating for the initial reactors, it should be noted that when the program started in the late 1960s there were no power reactor units with ratings higher than about 210 MWe (gross) anywhere in the world. Also, before India could stabilize its first 200 MWe RAPS-1 unit, the country came under international sanctions in 1974. Under those circumstances, it was a wise decision for India to stay with the 220 MWe size while indigenously implementing the technological corrections and improvements on the Canadian design at RAPS-1, before proceeding to the higher rating of 540 MWe.

Besides Perkovich, other critics like Tongia & Arunachalam (28) and Ramana (29) also seriously questioned the advisability and viability of the Indian fast breeder reactor program aimed at thorium utilization. The DAE organizations adequately rebutted these criticisms in their subsequent publications (30, 31). Tongia and Arunachalam (28) used very pessimistic assumptions for several key parameters on which their eventual conclusions depend. For the Pu-U238 breeders, they rightly concluded that the average plant capacity factor (PLF) achievable by Indian PHWRs is the parameter that has the maximum influence in determining the fissile material doubling times in the initial set of fast breeders. The authors parametrically varied the PLF of PHWRs only between 40% and 75%, to draw their erroneous conclusions, whereas by 2002 the Indian PHWRs reached an average annual PLF of 82.6%, much above the median value used in this study. For the eventual stage of Th-U233 breeders, Ref (28) concludes that fissile material losses during reprocessing have the dominant influence and, in this case, a range of 1% to 3% losses were assumed in the study. Here again, currently, the reprocessing plants seem to be achieving closer to 1.5% losses (16) rather than a value near 3%. Various other assumptions of the Tongia & Arunachalam paper (28) were similarly slanted toward a pessimistic performance of the Indian program, when they are compared to the ground realities of recent years (30, 31). And, finally, the recommendation of the authors that "India should consider entering into long-term agreements with other countries, with appropriate policy innovations, for importing uranium" is a naïve one, to say the least. It is tantamount to implying that India should consider signing the NPT as a nonnuclear weapon state party, thereby freeing itself from the restrictions imposed through the NNPA and NSG, and thus qualify itself to buy uranium from the world market. This is precisely the position that India has been unwilling to accept for almost the last three decades, and there is no reason to believe that the country is now willing to change this position and seek import of nuclear fuel under inequitable terms.

Recent indications from the DAE organizations provide current estimates for the short- and long-term growth plans for nuclear power in India (1, 16, 31). These still conform to Bhabha's original vision, with the second stage of Pu-U238 breeders now envisaged in two consecutive phases, the first with fissile material doubling times of 30 years or more and the second phase consisting of improved designs with expected doubling times in the range of 12–15 years. The use of domestic resources of natural uranium in PHWRs will enable the setting up of about 10–12 GWe of nuclear power capacity in the first stage. The depleted uranium from part of these reactors along with the separated Pu from the spent fuel will be used to set up about 25 GWe of additional capacity through the first phase Pu-U238 breeders (of Bhabha's second stage) with admittedly longer doubling times, as noted above. However, the growth of this generation of breeders will not be limited by their poorer breeding characteristics but by the speed with which PHWRs will be set up and their spent fuel reprocessed. By the time this phase is over, the program hopes to be ready with an improved second phase Pu-U238 breeder (of Bhabha's second stage), with much lower doubling time, through using a fuel other than the mixed oxide, with higher theoretical fuel density and capable of burn-ups in excess of 100,000 MWd/tonne, reduced clad thickness, etc. This phase will continue to use depleted uranium and reprocessed Pu from the PHWRs but will increasingly introduce thorium into the fuel cycle in the blanket and low-power zones to produce U233. In this phase, the growth of nuclear power is expected to be faster, and the total gross installed capacity can be brought over decades to a level of 400–500 GWe. By then, a transition can be achieved to a full Th-U233 cycle with the third-stage breeders, which Bhabha foresaw in the mid-1950s. Nuclear power can be generated at a level of 500 GWe or higher for several decades to come through this stage, using the immense thorium resources available in India.

Economics of Nuclear Power in India

It is true that, during the past five decades since India started implementing the Bhabha plan, the DAE has never published any comprehensive analysis of the economics of nuclear power in India. Without access to data on the hidden and indirect subsidies provided by the government for fuel fabrication, heavy water production, spent-fuel reprocessing, and waste management, it is hard to work out the real costs of nuclear power to the taxpayer from openly available bits of information. The DAE, on its part, is perhaps being intentionally vague and evasive because they know that a realistic, conventional costing will show nuclear electricity to be still more expensive than its alternatives, though the gap could possibly be narrowing with time. But, analysts who are critical of the government's financing of the nuclear power program often overlook the immense financial resources the taxpayers have already invested over the past five decades in this endeavor. Much of this expense cannot be associated with the nuclear weapons infrastructure but is directly attributable to the civilian nuclear power program. Now that these past investments are finally beginning to show some promising returns, abandoning the program or not actively encouraging its growth does not make any sense from an overall economic point of view.

Those who criticize Bhabha for introducing his three-stage power plan in 1954 and his promise of cheap nuclear power should note the 1954 remarks of Lewis Strauss, the then chairman of the U.S. AEC, that " our children will enjoy in their homes electrical energy (from nuclear sources) too cheap to meter " (32). Official studies within the U.S. administration at that time were pessimistic about the economic viability of nuclear power, in contrast to public statements of Strauss (33). In the United States, nuclear power got an early footing in the 1960s only because of government subsidies, of not having to make costly safety improvements, and through a deliberate decision of reactor manufacturers to internally absorb heavy losses in the interest of attracting potential customers. In the 1970–1990 period, when most of the subsidies were withdrawn and the U.S. NRC started imposing the mandatory post-Three Mile Island safety modifications, manufacturers were also unwilling to suffer losses, and the consequence was a substantial rise in the cost of nuclear power. As for the poor performance of the Indian plants in earlier days, statistics show that similar low performance was also characteristic of the early U.S. plants. The average capacity factor of all U.S. nuclear plants was only 57.6% in 1980 and 68.0% in 1990, before rising to 86.8% in 1999 (34). The Indian plants also went through a similar phase of lower capacity factors before reaching a figure of 82.5% in 2000.

It is, therefore, clear that the general strategies used by Bhabha's successors and the Indian government to promote nuclear power were not very different from those used by Strauss and the U.S. industries two decades earlier. The similarities in approaches and experiences of the United States and India are understandable because both countries were developing these technologies on their own, the former by virtue of being the lone pioneer in the field and the latter being compelled to pioneer its way through the adversities of an externally imposed international isolation.

The Rationale for the Indian Program

Critics of the Indian nuclear power program also fail to see that the end objectives of cost-competitive nuclear electricity and nuclear weapons have been only secondary to India's larger and more fundamental desire to establish world-class capabilities in nuclear science and technology within the country. Given the heritage and past history of the country and the inherent strengths of its intellectuals, visionaries like Bhabha and Nehru valued the importance of establishing such capabilities and laid the foundation for their growth. The field of nuclear power generation encompassed almost all areas of science and technology and was therefore a natural choice to serve as a targeted objective around which a multitude of indigenous capabilities could be developed. Viewed from this vantage point, many of the otherwise perplexing decisions of the Indian nuclear establishment are understandable as essential and interrelated elements of a strategy for resolutely adhering to the course charted out by Bhabha and Nehru for the nuclear program. The fervor for indigenous technology development and a reluctance to accept charitable pieces of technical assistance occasionally offered by the western nations under conditionality have helped stimulate and nourish the local expertise. The selection of a three-stage power development program based on PHWRs and LMFBRs was the only one that suited the national availability of nuclear fuel resources and was seen as the backbone of a long-term energy security policy and a self-reliant technology program. Even before sanctions were imposed, the Indian nuclear scientists were already tuned to the inevitable need for self-reliance, and therefore, facing the challenges of international isolation did not come as a severe shock or hardship to them. Finally, the DAE is deliberately evasive in discussing the true costs of nuclear power and is reluctant to allow the AERB to function as an independent regulator, primarily because of its fear that an open debate of the economics and safety of nuclear power in India at this stage might stunt the DAE's ambitious plans for growth. The serious lack of transparency that the DAE displays, even in civilian operations, is also for protection against the perceived opposition to its programs.

Western analysts do not often realize that the nuclear establishment in India, which handles both the civilian and military aspects of nuclear power, is a very powerful entity with direct access to the highest levels of government. Its recommendations on policy and projects are often unquestioned by decision makers, and the establishment has its own rationale why their present policies are the right ones. But, in spite of all the criticism and the roadblocks placed on its path, by 2002 India has built ten PHWRs of indigenous design and is operating them at an average annual capacity factor of about 83%, has two 540 MWe PHWRs of indigenous design under construction, and a robust fast reactor development program under execution, besides having an accelerated growth plan in place. One has to attribute these achievements entirely to the vision of Bhabha and Nehru, the tenacity of their successors in staying the course against all adversities, and the spirited efforts of thousands of competent scientists and engineers in the Indian nuclear establishment and industries.

FUTURE OF THE INDIAN PROGRAM

Facing a Potential Financial Shortage

In the beginning of 2002, it is evident that the future growth of nuclear power in India will not be limited by the availability of suitable technologies or manufacturing facilities in the country but could only be slowed down owing to the lack of adequate financial resources for investment in this sector. Given the importance of the nuclear endeavor, the government can be expected to provide some funds to this program at all times, but such inputs may not dramatically increase in the coming years because of competing demands on public money from other key sectors. It would therefore be imperative for the DAE and the NPCIL to increasingly generate revenues from their own plants to supplement the limited public funds they are likely to receive. This has been a strong motivation behind the recent improvements in plant capacity factors and safety in the NPCIL installations.

The nuclear establishment is also wooing the Indian financial sector and the major private industries to invest in nuclear projects, as part owners of future plants. Because building up a larger installed capacity rapidly would mean accelerated revenues for the NPCIL and the DAE, they have been interested lately in setting up a few imported reactors. But, it is clear that India would be interested in such imports only if they are made available with financial credit at low interest rates and a stretched out repayment schedule, which is the case with the purchase of power reactors from Russia.

Import of Russian VVER Reactors

In importing nuclear reactors, the provisions of the NPT, NSG, and the NNPA will certainly come in India's way. In spite of these obstacles and the strong protests from the United States, the Russian government has recently agreed to set up two 1000 MWe VVER-392 reactors, with substantially improved safety features, at Kudankulam in southern India. The first intergovernmental agreement between India and Russia on this project dates back to 1988, but it has undergone some changes over the years. According to the latest plan, Russia will supply the design and critical equipment and guarantee the lifetime supply of enriched uranium fuel for these light water–moderated pressurized water reactors (LWRs). Russians will supply 90% of the total equipment and also provide 54% of the credit at 4% annual interest, repayable in 14 equal annual installments starting one year from the commissioning date (35). The NPCIL will undertake the construction and commissioning of the reactors under Russian supervision and subsequently take charge of the plant operations. Construction work at the site started last year, and the Kudankulam-1 & 2 units (KKS-1 & 2) are expected to commence operation by December 2007 and December 2008, respectively.

According to the Indo-Russian agreement, India will reprocess the spent fuel from these reactors and retain the plutonium inventory, while maintaining IAEA safeguards on the reactors and its associated fuel reprocessing plant. According to the chairman of the Indian AEC, the agreement also has provisions for Russia to supply four additional VVER reactors in the future (36).

A criticism often heard about the import of light-water reactors (LWRs) is that this is inconsistent with Bhabha's three-stage plan for nuclear power, based on PHWRs and fast breeder reactors (FBRs). But, as the DAE often clarifies, the import of large LWRs is primarily for rapidly increasing the installed nuclear capacity base of the NPCIL and not for introducing LWR technology in the country. A larger power base will enable the NPCIL to substantially increase its net profits and these, along with the collateral finances they could then raise from banking institutions and private sector investors, will be reinvested in the indigenous plan for building PHWRs and FBRs.

Nuclear Power Program in 2020

Currently, the total installed capacity for electricity generation in India is about 102,000 MWe, of which only 2,770 MWe comes from nuclear power. The 2 × 540 MWe PHWR units at Tarapur (TAPS-3 & 4) are currently under construction, and they will be commissioned by 2006. Later on, the 2 × 1000 MWe VVER reactors at Kudankulam (KKS-1 & 2) are expected to be commissioned by 2008. Recent reports confirm that the government has also approved the addition of 2 × 220 MWe PHWRs at Rajasthan (RAPS-5 & 6) and 2 × 220 MWe units at Kaiga (KGS-3 & 4), with construction to begin later in 2002, and the reactors to be commissioned by 2007 (11, 37). In addition, it is realistic to assume that the first PFBR will be operating at full power by 2010. As per these firm plans, India should attain a total nuclear power capacity of 7,230 MWe (gross) by 2010 (38).

Between 2010 and 2020, India is likely to build four more 220 MWe PHWRs, ten units of 540 MWe PHWRs, three more 500 MWe FBRs, and six more 1000 MWe LWRs. This will represent an addition of 13,780 MWe (gross) to the nuclear power capacity over the second decade of this century. The LWRs added will most likely be of Russian VVER design because Russia has already agreed in principle to sell these additional reactors to India, despite the restrictions imposed by the NSG (36, 39). It is also likely that the two BWR units at Tarapur and the PHWR unit at RAPS-1 will be shut down permanently well before that time, causing a decrement in installed capacity by 470 MWe (gross). Therefore, the net addition to nuclear power during the 2010 to 2020 period will be 13,310 MWe.

Thus, by 2020, the Indian nuclear power program would have most likely established a total capacity of 20,540 MWe. This independent estimate coincidentally comes close to the announced DAE plan for reaching 20,000 MWe by 2020 (40). Then the total electricity generation in the country would reach a level of about

250,000 MWe, in which the contribution of nuclear power would be about 8%. The total power reactor population will consist of 31 PHWRs, 4 FBRs, and 8 LWRs, totaling 43 reactors. Of these, 35 will be indigenously developed reactors, and the remaining 8 will be imported LWRs. By then, Bhabha's vision of an indigenous nuclear power program will be well on its way to fuller realization, despite the delays inflicted by the proponents of the nuclear non-proliferation regime, because of the Indian resolve not to succumb to its pressures.

India's indigenous capabilities in the PHWR technology have presently reached a level where the country is in a position to confidently export such reactors, especially to the developing countries who are interested in setting up nuclear power plants or research reactors. However, given the conflicts with the western nations in the nuclear arena, including India's nonadherence to the NPT, it is certain that India will face significant roadblocks if it were to attempt nuclear exports at present. The removal of these difficulties through an equitable normalization of nuclear relations between India and the rest of the world is, therefore, certainly in the overall global interest.

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