Indigenous Fast Breeder Reactors: Key to Long Term Energy Security

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Preamble

Energy plays a key role for India's transformation to a developed nation. India aspires to achieve net zero emission target by 2070, with nuclear energy being a major contributor, as it is clean, green, safe, economical and sustainable form of energy. In order to effectively utilize the available resources and to attain self reliance, the great visionary Dr. Homi J. Bhabha, conceived the three stages of Indian Nuclear Power programme (NPP). India has mastered the first stage of NPP including construction, commissioning and operation of Pressurized Heavy Water Reactors (PHWRs) and is in the demonstration phase of the second stage with the commissioning of Prototype Fast Breeder Reactor (PFBR). FBTR was commissioned in 1985 and has almost completed four decades of successful operation. PFBR is in an advanced stage of commissioning and expected to go critical very soon. This chapter traces the genesis of Fast Reactor Programme in India, highlights the growth of the various aspects of the second stage of NPP, showcases the milestones of Fast Breeder Test Reactor (FBTR) and Kalpakkam Mini reactor (KAMINI) over the years, societal applications of FBTR towards production of radiopharmaceuticals and the way forward for the future in Fast Reactor Programmes.

Introduction

Dr. Homi J. Bhabha, the founding father of Indian Atomic Energy programme, highlighted the indispensability of nuclear energy, initially as a supplement to, and later as a substitute for, fossil fuel based power generation, when he made the famous statement: `No power is costlier than no power'. Realizing the limited reserves of natural uranium and abundant reserves of thorium in India, the visionary chalked out the "three stage nuclear programme" which is being pursued by the Department of Atomic Energy (DAE).

The three-stage programme envisages utilization of natural uranium in the first stage as fuel in Pressurised Heavy Water Reactors (PHWR), which generates electricity and plutonium. Fast Breeder Reactors (FBRs) utilise the spent fuel from the first stage(depleted uranium) and plutonium to produce electricity and breed more plutonium, to fuel more reactors in the second stage. The third stage will include thermal reactors to utilise the vast thorium resources in the country along with uranium or plutonium. This sequential three-stage programme is based on a closed fuel cycle, wherein the fuel for third stage will be based on U-233 which will be obtained by processing irradiated thoria blankets of second stage.

The three stages have important fuel cycle linkages. The closed fuel cycle multiplies the energy potential of the fuel and greatly reduces the quantity of waste generated. Thus, the three-stage nuclear power programme would ensure that the nuclear energy will make a significant contribution to the vast energy demands of our country on a sustainable basis, through the effective utilization of available resources.

Evolution of FBR Programme

The seed for the Fast Reactor Programme in India was sown by forming Fast Reactor Section under Reactor Engineering Division at Bhabha Atomic Research Centre (BARC) in 1968, soon after the visit of Dr. Vikram Sarabhai to the site of Rapsodie, a French Fast Reactor. After pursuing detailed theoretical studies on design options, coolants and their combinations, breeding ratio with possibility of commercial deployment, it was concluded that sodium cooled Fast Reactors will be the best choice in the Indian context. In order to accelerate the Fast Reactor Programme, Dr. Vikram Sarabhai, the then Chairman took a decision to collaborate with a country having experience in the design, construction and operation of FBRs.

At that time, France was having a focused Fast Reactor Programme, hence bilateral agreement was signed between French Atomic Energy Commission (CEA) and Department of Atomic Energy (DAE) for the transfer of specific FBR technologies, to set up a Fast Breeder Test Reactor (FBTR) in India. The responsibility of construction of FBTR, a first-of-its kind reactor, was with India, according to the Indo-French agreement. Following the signing of the bilateral agreement, a design team with engineers, scientists and draftsmen, led by Shri S. R. Paranjpe, was deputed to the Cadarache Nuclear Centre in France in 1969. The team worked for over 15 months and completed the preliminary design. Indian Engineers were also trained in various aspects of component manufacturing and reactor operation.

The objective of establishing FBTR was to:

- Demonstrate the feasibility of a sodium cooled fast breeder reactor equipped with steam generator and turbine.

- Provide a test bed for the irradiation of fuels, blanket and structural materials with particular reference to the development of high-performance fuel
- Serve as a facility for the development of sodium technology,
- Provide the basis for gaining experience in the fuel cycle aspects of fast reactor programme.
- Assist in developing a core team of personnel having expertise in design, construction and operation of FBRs and
- To gain information related to the possible utilization of thorium in fast reactors.

Establishment of Reactor Research Centre [RRC]

In order to accelerate the Fast Reactor Programme in India, Dr. Vikram Sarabhai, formed the RRC at Kalpakkam on April 30, 1971 through an executive order. RRC was established with the clear mission of advancing Fast Breeder Reactor science and technology in the country for commercial use. He also played a pivotal role in developing a roadmap for interdisciplinary research across reactor physics, engineering, materials, chemistry, reprocessing, safety, instrumentation, and other related fields. To support the project at Kalpakkam, a team of 50 engineers and technicians was transferred from BARC to the then RRC in June 1971.

Establishment of various laboratories at RRC

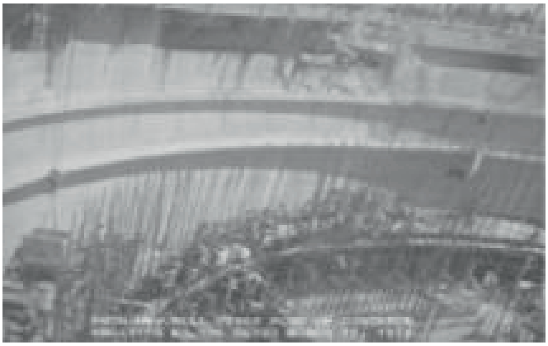
Along with the construction of FBTR, additional laboratories and facilities necessary for supporting and advancing Fast reactor Technology emerged. Sodium loops were set up for training the personnel in sodium handling and for testing of the components and instruments in sodium. Water loops were set up for thermal hydraulic studies, testing of components, etc. A facility for purifying commercial grade sodium to reactor grade was set up. The road map laid by Dr. Vikram Sarabhai took shape and as a result Radiochemistry Laboratory, Reprocessing Development Laboratory, Central Design Office, Central Workshop, Safety Research laboratory, Materials Science Laboratory, Radiometallurgy Laboratory, Materials Development Laboratory, Computer Centre and Electronics Instrumentation Laboratory, were established. FBTR served as a catalyst for the overall growth of the Centre.

Fast Breeder Test Reactor

The administrative approval and financial sanction orders for setting up of FBTR at RRC, Kalpakkam were conveyed on September 30, 1971. The project Report of FBTR was prepared and the civil construction of FBTR began with the first ground breaking on January 31, 1972.

Rock Breaking activity at Fast Breeder Test Reactor construction site

The civil construction progressed and the first pour of concrete was carried out on March 13, 1974.



RCB Wall concreting on February 25, 1975
(RCB) first pour of concrete on March 13, 1974

Reactor Containment Building

By May 1977, civil construction of all the buildings was completed.

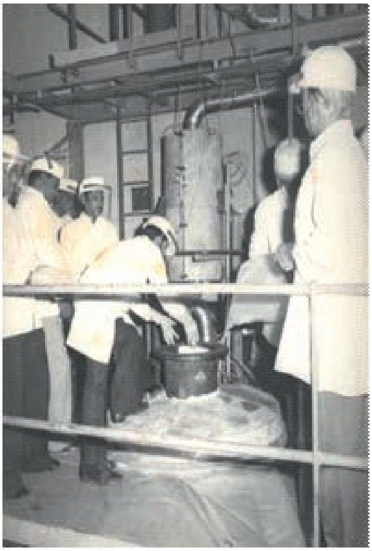
FBTR after completion of civil construction, 1977

This was followed by the arrival of various components, which were being fabricated in the shop floors of industries spread all over India. Except the raw materials for Nuclear Steam Supply System (NSSS), borated graphite, one control rod drive mechanism, one sodium pump, grid plate, bellow sealed valves and sodium instrumentation, all other components were made in India.

Rapsodie used MOX fuel with 30% PuO_2 and 70% UO_2 with the latter enriched to 85% U-235. India was unable to import the enriched fuel due to embargo. As an alternate option, it was proposed to go in for a MOX fuel with natural uranium and more plutonium. Studies on this fuel indicated poor performance and hence it was proposed to use enriched uranium. To overcome the challenges in enrichment, carbide fuel option was explored. Subsequently, a bold decision was taken by Dr. Raja Ramanna, then Chairman of the Council of the Centre, to go in for a plutonium rich carbide fuel as the driver fuel for the first core of FBTR. It was decided to redesign the core for carbide fuel with minimum plutonium inventory, as the technology for reprocessing of carbide fuel was not available then.

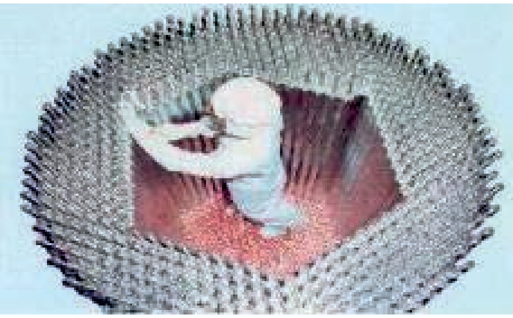
Most of the non-nuclear and auxiliary systems had been commissioned before the arrival of the components of the nuclear systems at FBTR site. During this period, the 500-kWsodium loop was commissioned at Reactor Engineering Laboratory.


500 kW Loop- First Sodium facility at IGCAR


First Sodium Charging in melter tank for sodium purification for FBTR

Testing of Intermediate Heat Exchanger, performance testing of EM pumps was carried out. Flow meter calibration loop was commissioned and all the Flow meters were calibrated. Continuous level sensors were calibrated in Continuous Level Probe Calibration loop. 150 tons of sodium required for FBTR was procured from Indian manufacturers, charged in tanks, purified and transported to FBTR. Secondary sodium system was commissioned, during the period from May 1984 to April, 1985. The project team steered by Shri N. Srinivasan, Shri N.L. Char and later by Shri C.V. Sundaram, successfully took the FBTR to completion.

Fuel pins of composition $Pu_{0.7}U_{0.3}C$ containing controlled amount of M_2C_3,were fabricated by BARC and were available at site by April 1985. The fuel pins were assembled into subassemblies at FBTR by a team from Nuclear Fuel Complex (NFC). The subassemblies were loaded in the core and the primary system was filled with sodium in July 1985.

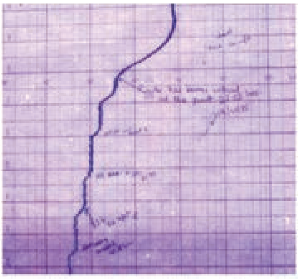


Core loading was done manually in 1985

The count-down for criticality began with the start of loading of fuel subassemblies on October 02, 1985. FBTR went critical on October 18, 1985, with a small carbide core of 22 fuel subassemblies rated for 10.5 MWt, catapulting India into the select few countries with fast reactors. Dr. Raja Ramanna, the then Chairman, AEC was personally present at the console to witness the first criticality. Dr. Raja Ramanna's presence on the historical moment was particularly most fitting, as he had played a crucial role in nurturing and guiding the programs. It was a joyous and proud moment for thousands of DAE personnel spread across India.

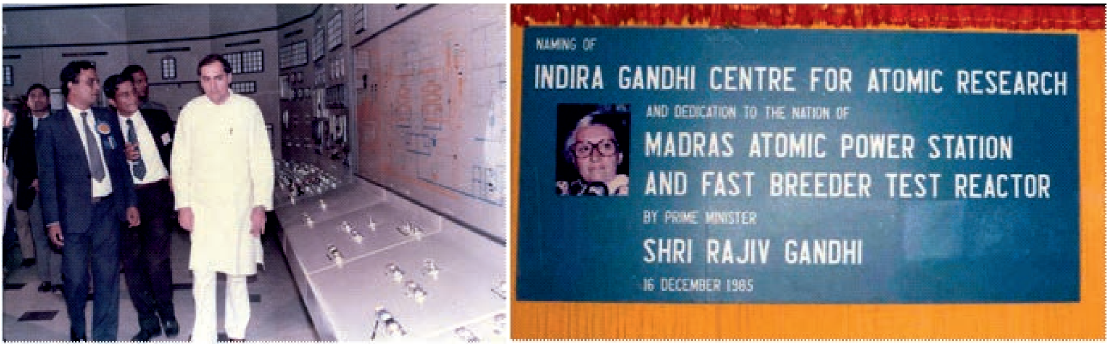
All eyes on Kalpakkam

FBTR goes critical



Dr. Raja Ramanna, Dr. M. R. Srinivasan, Shri C.V. Sundaram at FBTR witnessing first criticality

On December 16, 1985, the then Honorable Prime Minister of India (Late) Shri Rajiv Gandhi visited Reactor Research Centre and renamed it as Indira Gandhi Centre for Atomic Research. The day also marked another historic event: the dedication of the Madras Atomic Power Station and the Fast Breeder Test Reactor to the nation.



Shri Rajiv Gandhi the then Honorable Prime Minister at FBTR on December 16, 1985

As the steam generators were not available at that time, FBTR was operated at low power with steam generator bypassed. Low power experiments were conducted during this period. The fuel handling incident in May 1987 delayed the commissioning process, but this was subsequently overcame and the reactor was back on stream in May 1989. The intervening time was gainfully utilized for connecting the steam generators to the secondary sodium circuits and commissioning the steam generator leak detection system. The power was progressively raised in a phased manner from 1 MWt in 1991 to 10.5 MWt in 1993. One Mark-I subassembly was discharged in May 1996 with a burn-up of 25GWd/t. In 1996, to further increase the reactor power, Mark-II subassemblies with a lower Pu content ($Pu_{0.55}U_{0.45}C$) were gradually introduced around the Mark-I. After conducting high-power physics and engineering experiments, the power was increased to 11.5 MWt, and the turbo generator was successfully synchronized to the grid for the first time in July 1997.

In addition to serving as a self-driven irradiation facility for the Pu-rich monocarbide fuel, the reactor was also used to study the irradiation creep behavior of Zr-Nb alloy, which was developed indigenously for the PHWR program during 1998-99. Later, the fuel reached a burn-up of 50 GWd/t in April 1999 and 100 GWd/t in September 2002.

In July, 2006 FBTR fuel reached a burn-up of 155 GWd/t without any clad failure, which was a world record for burn-up of Pu rich carbide fuel. This coincided with Twenty years of successful operation of FBTR. A Commemoration function was organized to celebrate twenty years of successful operation of FBTR on July 18, 2006.

Veterans of Project, Operation& Maintenance Team
(*On the occasion of 20 successful years of FBTR operation*)

As a step towards closing of fuel cycle, reprocessing of carbide fuel was initiated and the reprocessing of FBTR fuel with burn-up of 155GWd/t was successfully demonstrated in the year 2008. This was an important milestone as the reprocessing of high plutonium bearing carbide fuel with such a high burn-up was demonstrated for the first time in the world. In 2010, fuel cycle was successfully closed with the loading of the fuel containing plutonium obtained from spent fuel discharged from FBTR and reprocessed in **CO**mpact **R**eprocessing facility for **A**dvanced Fuels in **L**ead cells (CORAL) Facility.

Dr. A.P.J. Abdul Kalam, Former President of India and a doyen of Science and Technology visited our Centre on 24 April, 2008

FBTR completed 25 years of successful operation without major incidents in 2010, an important milestone in demonstrating the technological viability of fast spectrum reactors. Also in 2010, test fuel bundle of PFBR reached the original target burn-up of 100 GWd/t.

Fukushima incident occurred in 2011. Post-Fukushima, the emphasis was on maintaining reactor safety even in the event of a station black out. Towards this, an extensive retrofitting programme was carried out to protect the plant against the external events such as flood, Tsunami & earthquakes.

In 2011, metal fuel irradiation studies commenced and natural U-6%Zr sodium bonded metal fuel slugs were supplied by BARC, fuel pin fabrication and irradiation were carried out at IGCAR.

The reactor power was further progressively raised from 27.3MWt to 32MWt during successive irradiation campaigns with turbo generator synchronized to the grid generating 7 MWe power.

In order to raise the reactor power to its designated rated power of 40 MWt, studies on the conceptualizing of the core configuration were initiated in 2018. It was envisaged to introduce four B_4C poison subassemblies in the second ring in addition to the Mark –I and Mark – II subassemblies. Also, in order to extend the life span of FBTR grid plate, introduction of tungsten carbide shield subassemblies to increase the axial shielding against fast neutron, was recommended.

FBTR achieved its target power of 40 MWt for the first time in its history at 17.30 hrs on March 7, 2022. FBTR was operated successfully at the design capacity of 40 MWt for three consecutive power campaigns achieving cumulative operation of 250 Effective Full Power Days. Subsequently FBTR has been relicensed for further operation up to June 2028.

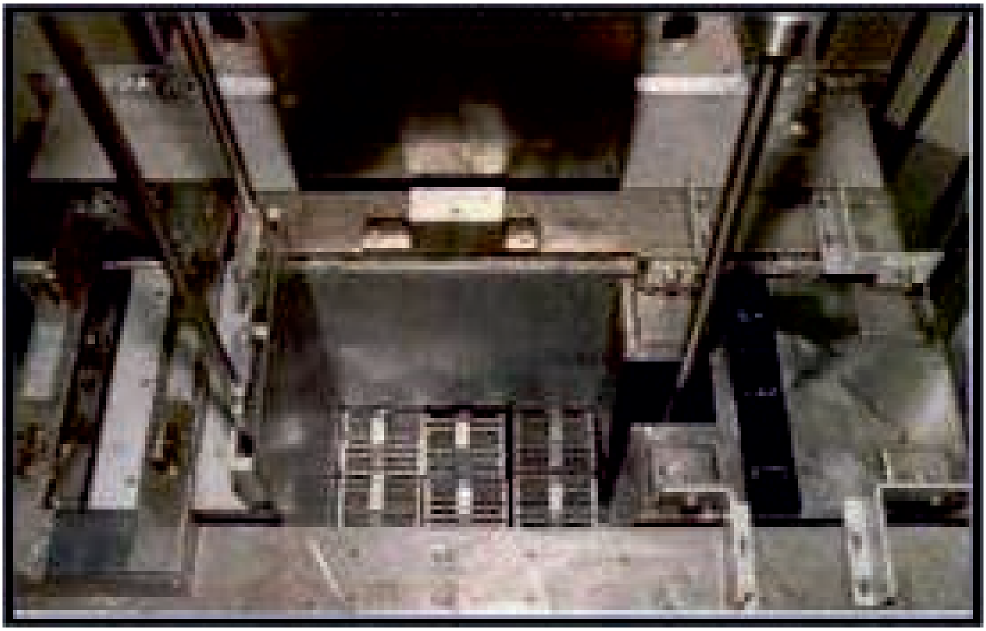
Fast Breeder Test Reactor

Over the years, the reactor systems, sodium systems, control rod drive mechanisms, and other safety-related and auxiliary systems of the FBTR have demonstrated satisfactory performance. At present, FBTR serves as an irradiation facility for fuels and structural materials, while also supporting challenging experiments designed to improve the safety of future FBRs.

FBTR has also contributed for many mission-based programmes including testing of High Temperature Fission Chambers of PFBR, irradiation experiments on metallic fuel pins of different composition such as enriched U-6%Zr sodium bonded metal fuel, sphere-pac MOX fuel pins of PFBR, experimental MOX fuel pins containing 45% PuO_2, experimental pins containing TRISO (Tri-structural Isotropic) coated particle type fuel and disc specimens of Compact High Temperature Reactor (CHTR) structural material (Nb-1%Zr-0.1%C).

FBTR also serves as cradle for training human resource for operation and maintenance of fast reactors.

KAMINI (Kalpakkam Mini reactor)



Top view of KAMINI

KAMINI is a unique reactor in the world to have ^{233}U as the driver fuel, designed and built jointly by BARC and IGCAR. It is a light water moderated/cooled and beryllium oxide reflected low power research reactor designed to operate at a nominal power of 30 kW.

This reactor is employed for neutron radiography of irradiated FBTR fuel, activation analysis, and radiation physics research. It operates as a neutron source, delivering a flux of 10^{12} n/cm^2/s at the core center. KAMINI has been used for neutron radiography of pyro devices intended for space applications, as well as for testing neutron detectors. High-temperature fission chambers (HTFC), developed for the PFBR, have also been tested in KAMINI. Additionally, KAMINI functions as a national facility for neutron radiography of both radioactive and non-radioactive objects, as well as for neutron activation analysis of a wide range of samples received from various institutions.

Experimental Facilities in Support of FBR Programme

In order to validate the reactor design, several full scale and scaled down experimental facilities using sodium and as well as water medium were established. The Large Component Test Rig was commissioned in 1994 to conduct full-scale testing of critical PFBR reactor components. Heat and mass transfer studies in the cover gas were performed, and experiments were conducted on circumferential temperature asymmetry and sodium aerosol deposition in the vertical annuli of the top shields. Additionally, temperature distribution studies were carried out for the PFBR roof slab model and the control plug model. In addition to the above experiments, full scale testing of prototypes of Control Safety Rod Drive Mechanisms, Diverse Safety Rod Drive Mechanisms (DSRDM) full scale testing of PFBR Fuel Handling machines viz. Inclined Fuel Transfer Machine (Full Size) & In Vessel-Fuel transfer machine-Transfer Arm & Failed Fuel Location Module of PFBR, testing of Under sodium ultrasonic scanner, calibration of permanent magnet flow meters, level probes, Sodium Aerosol Detectors, Eddy Current Flow sensor for PFBR, cyclic and endurance testing of gripper and translation bellows designed for Control rod Drive Mechanisms of FBTR were carried out in sodium. Performance testing of model gate valve and shield plug of PFBR was carried out.

Large Component Test Rig

Steam Generator Test Facility

5.5 MWt Steam Generator Test Facility (SGTF) was set up during the year 2000 with a view to reduce conservatism in design for future FBR steam generators (SG) and arrive at an economic design. This facility simulates the operating parameters of PFBR. SGTF has been effectively utilized for estimation of SG heat transfer area margin, SG thermal hydraulic instability studies, Endurance test of steam generator, testing of SG under transient conditions, development of acoustic leak detection system, operation of SG with plugged tube condition, assessing the adequacy of SG tube support against flow induced vibration, development and testing of eddy current inspection tool for ISI in SG. Sodium Water Reaction Test Rig was commissioned in 2001 and has been used for micro steam leak studies in sodium heated SG and is being used to get further data on material wastage due to small/larger leaks. The rig has also been useful to evaluate the performance of different Hydrogen sensors in sodium and argon cover gas.

The development of electrochemical meters for monitoring hydrogen, carbon and oxygen in sodium has been a major achievement. In particular, the development of the Electrochemical Hydrogen Meter (ECHM) to detect water steam leak in the steam generator at the incipient stage has been one of the significant contributions. The in-house developed robust ECHM can measure a change in ~ 10 ppb of hydrogen in sodium in a background of around 50 ppb. The excellent performance of the ECHM has provided us confidence to introduce the same as one of the steam generator tube leak detection systems in the PFBR.

In-Sodium Fatigue loop & Creep loop were established in 2003 to study the mechanical properties of PFBR component materials specimens under the influence of flowing sodium like low cycle fatigue, creep fatigue interaction tests, pin-on-disc tribological experiments, thermal striping experiments, creep and creep rupture experiments. LEENA Facility commissioned in 2007, was used for qualifying the leak detector layout for different sizes of pipelines for PFBR, by simulating actual sodium leak. SADHANA Sodium facility, a 1:22 scale model sodium facility commissioned in 2009, has been used to study the thermal hydraulic behavior of Safety Grade Decay Heat Removal System (SGDHRS) of PFBR. Estimation of heat transport capability, steady state and transient response of the SGDHRS during various emergency operating conditions were experimentally validated in this facility. Thermal Shock Test Facility was commissioned in 2011, for cold thermal shock studies on the dissimilar weld joints in the DSRDM electromagnet. Sodium Facility for Component Testing commissioned in 2019, has been utilized for performance testing of Annular Linear Induction Pumps of 50 and 170 m^3/h capacity for PFBR and other developmental activities in sodium technology.

Many water facilities like 1/4th, 5/8th models of PFBR were established to study thermal-hydraulic performance aspects of components where amenability of sodium testing was not possible. Sodium Technology Complex with a large sodium facility to carry out testing of components for FBR-1&2 is being commissioned.

Prototype Fast Breeder Reactor (PFBR)

Following the successful performance of the FBTR and the experience gained in its design and construction, DAE decided to proceed with the launch of the Prototype Fast Breeder Reactor (PFBR). Towards this, DAE established a steering Group to plan the PFBR, in December 1979. Based on the recommendation of the steering Group, a PFBR Working Group was constituted to decide the significant design options, including the power rating. The Working Group recommended a prototype reactor with a capacity of 500 MWe, utilizing oxide fuel and consisting of four primary loops, each with four primary pumps and eight sodium-to-sodium heat exchangers to transfer nuclear heat from the primary to the secondary heat transport loops. These loops would feed a total of thirty-six steam generators, nine per loop. As this design represented an attempt to develop such a large plant indigenously, it was decided to seek a design review from a peer group. Based on the recommendations of the peer group, the design was modified and a thorough design review was carried out by a senior level committee set up by DAE, in the year 1992/1993. The design was optimized during 1994-2002, a techno-economic design with only two coolant loops was finalised and Detailed Project Report (DPR) was submitted to the Department in 2002 for consideration of financial sanction. In October 2002, the Atomic Energy Commission approved the construction of PFBR. In September 2003, administrative approval and financial sanction was granted by the Government of India.

IGCAR initiated and successfully completed the Research & Development needed for design validation, as well as the design and engineering of the reactor. This also included the development of technologies for materials and components manufacturing, pre-project activities, securing all necessary statutory clearances, and overseeing the construction and integrated commissioning of the PFBR.

Since the compact plant layout significantly impacts both safety and economy, the concept of an interconnected building for the nuclear island was adopted. The nuclear island includes the safety-related buildings, such as the Reactor Containment building, steam generator building, fuel building, radioactive waste building, control building, and electrical building, all connected to form a unified structure.

In order to reduce construction time, the excavation work for nuclear island was planned as a pre-project activity, which commenced with "Ground Breaking Function" on August 18, 2003. A public sector company "Bharatiya Nabhikiya Vidyut Nigam Limited (BHAVINI)", was established under DAE with the mandate of procurement, construction, commissioning and operation of prototype Fast Breeder Reactor (PFBR). Construction of PFBR commenced in the year 2004.

A major milestone in the construction of PFBR, was the successful erection of the safety vessel in the reactor vault, on June 24, 2008. This Safety vessel is the third largest thin vessel, successfully erected for FBR (worldwide). The successful erection symbolizes the indigenous, design, fabrication and challenging erection capabilities. IGCAR has collaborated closely with BHAVINI in the manufacture of critical components, such as the grid plate and core support structure. These components have been manufactured with exceptional precision and quality. In the subsequent years, the construction of PFBR progressed steadily, with lowering of main vessel in reactor vault in 2009, erection of thermal baffle in 2010 and integration of roof slab with main vessel in 2011. The civil construction of nuclear island connected building was completed in 2013.

Lowering of Safety Vessel in reactor vault

Protoype Fast Breeder Reactor (PFBR) 500 MWe

In the meantime, 1600 tons of sodium were received as 18 tons consignments from M/s Metaux Speciaux, France and the sodium was transferred into the sodium tanks at PFBR. In 2016, an in-service inspection vehicle (DISHA) was developed to inspect the dissimilar welds of the roof slab using visual and ultrasonic examination techniques. After the construction, manufacturing, and erection of all PFBR systems and components were completed, the commissioning of individual systems and the integrated commissioning were undertaken. As a step towards sodium filling, four Annual Linear Induction Pumps of capacity 170 m^3 /hour were manufactured in-house, in 2021.

After completing all the pre-requisite activities and obtaining regulatory clearance, sodium filling in Main Vessel commenced on August 10, 2023 and filling of 1150 tons of sodium was completed successfully by August 15, 2023. This was followed by the historic milestone of initiation of "core loading" on March 04, 2024, in the presence of Honorable Prime Minister, Shri Narendra Modi.

Commencement of core loading on March 04, 2024, in the presence of Honorable Prime Minister, Shri Narendra Modi

The core of PFBR has MOX fuel with two enrichment zones of 21% and 28% PuO_2. The fuel pin consists of annular fuel pellets encapsulated by D9 steel clad with helium present in between. The fuel pins are packed in compact triangular pitch, which are grouped together to form a fuel subassembly. The maximum linear power is 450 W/cm and maximum fuel burn-up is 100GWd/t. The core includes two rows of blanket subassemblies surrounding the inner and outer fuel regions and twelve absorber rods arranged in two rings—nine control and safety rods and three diverse safety rods. Two independent shutdown systems ensure reactor safety, capable of shutting down the reactor within 1 second even if one system fails.

The design of reactor with sodium as coolant involves calls for a three-loop design – primary radioactive sodium loop, secondary non-radioactive sodium loop and tertiary water loop. The Intermediate heat exchanger for sodium-to-sodium heat transfer and Steam Generator for sodium-to-water heat transfer were designed in IGCAR. The development of tube-to-tube sheet welding with a spigot joint configuration resulted in achieving 100% radiography of the joints, thereby minimizing the possibility of sodium-water reaction. Sodium being liquid with high boiling point, the reactor system need not be pressurized. Since the pressure is low, the sodium pumps were designed with free-surface levels capable of operating over wide range of operating speeds.

The design of fuel handling components and reactor control systems involves challenging requirements like precision, compactness, reliability, operation in sodium / sodium aerosol, etc. The components required for handling fresh fuel subassembly, spent fuel subassembly, special handling flasks for handling pumps & intermediate heat exchangers were designed in-house at IGCAR. The design of in-core handling of subassembly by Transfer Arm and Inclined Fuel Transfer machine were complex in nature and extensively tested in-house before deployment at PFBR.

Design of safety critical systems and components of sodium cooled fast reactors was done in order to meet the safety limits specified by the design international codes. The compact, long and slender design of components results in several challenges, which include seismic qualification and flow induced vibration. Study of reactor vessel damage during core disruptive accident, stability analysis of secondary and primary sodium pumps and seismic analysis for reactor core of PFBR were carried out which are complex and challenging in nature. Since liquid sodium has large heat transfer coefficient, the structural components undergo severe thermal transients which are life limiting factors. Computational Fluid Dynamics analyses were also carried out to study flow induced vibration, thermal stripping, etc.

FBR-1&2

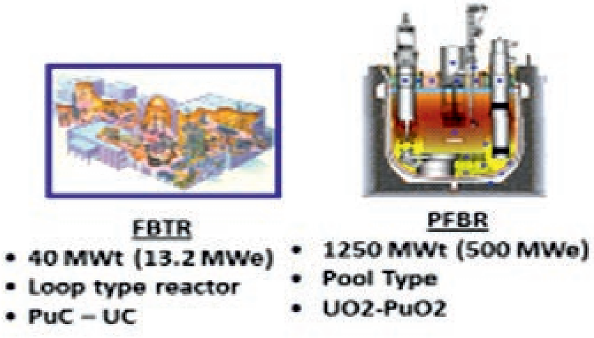
The large size power reactors in FBRs hold the key in obtaining economically competitive power generation. In this context, FBR-1 & 2 were initially envisaged as 600 MWe twin unit concept with minor changes in core structure, main vessel size, improved void coefficient, improved breeding gain, etc.

Consequent to detailed discussions held with BHAVINI, the power rating of FBR-1 & 2 is revised to 500 MWe in order to preserve the experience of PFBR and to standardize the design of the 500 MWe reactor with MOX Fuel. Thus, FBR-1&2 are envisaged to have the same design as that of PFBR with bare minimum changes.

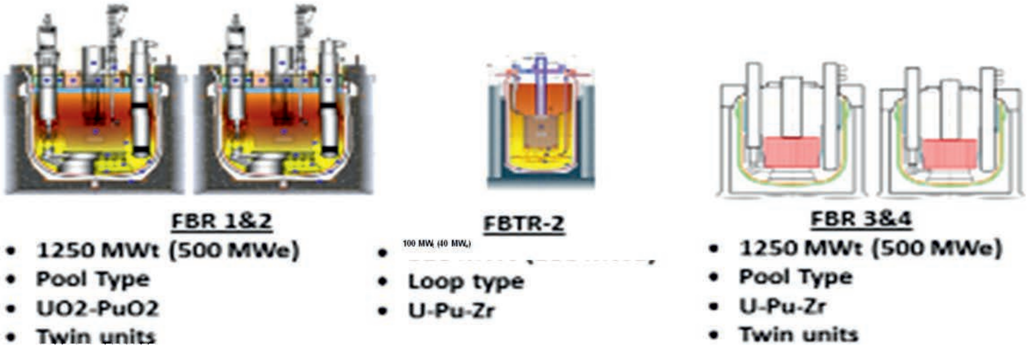
FBR Unit-1 & Unit-2 are proposed to be constructed on the South side of PFBR. The proposed reactor buildings will be similar to PFBR in order to retain the existing design to the maximum extent possible. All other facilities are proposed to be shared between two FBR units.

Way Forward

The way forward for the FBR program will take two main tracks. In the first track, continuation and maturing of the fast reactor technology in the form of deploying two more reactors with MOX fuel namely FBR-1&2 which will be primarily carried out by BHAVINI with the necessary design support from IGCAR. In the second track, to realize the necessity of lower doubling time for faster nuclear potential growth, demonstration of the metal fuel cycle is being pursued by IGCAR. The program consists of design, construction and operation metal fuel test reactor (FBTR-2), fabrication of the metal fuel, post irradiation examination and validation of the fuel performance, pyro-processing of the metal fuel and closing the fuel cycle. The fuel subassembly and pin design selected for FBTR-2 will be such that it can be directly deployed in the future 500/1000 MWe metal fueled reactors. In this regard, FBTR-2 is designed initially with hybrid core concept with proven carbide fuel as driver fuel and full-scale metal fuel subassembly irradiation at the centre of the core. After successful verification of the metal fuel performance, the FBTR-2 will be converted fully to metal fuel to study the core safety aspects of the full metal core. Parallel to the reactor program, front end and back-end programs will be deployed. After successful demonstration of the FBTR-2 with integrated metal fuel cycle, FBR-3&4 will be deployed with metal fuel core for shorter doubling times. The FBR-3&4 will have reactor technology from FBR-1&2 and fuel technology from FBTR-2. This would pave the way for successful development of FBR technology in the coming years to realize the nuclear energy growth in the country.



Snapshots of FBTR- PFBR



Snapshots of FBR1&2 – FBTR-2 – FBR3&4

Societal applications

Technologies developed for FBR also have many spin-offs which have societal application in various domains. One of the spin-offs is production of radiopharmaceuticals.

Metastatic bone pain is the most common pain syndrome in cancer patients, affecting up to 70% of those with prostate and breast cancer, and up to 30% of patients with lung, bladder, and thyroid cancers. In addition to pain, patients may experience complications such as skeletal fractures, hypercalcemia, and spinal cord or nerve root compression, all of which can impair mobility and disrupt sleep, significantly reducing quality of life. The management of bone pain includes analgesics, radiotherapy, radiofrequency (RF) ablation, hormones, chemotherapy, and surgery. Radiotherapy often employs bone-seeking isotopes like phosphorus (32,33P) and strontium (^{89}Sr).

Strontium is an element that behaves biologically like calcium. Sr-89 chloride selectively localizes in bone, especially in areas where bone cells are rapidly dividing (such as areas with bone metastases that are causing the pain). It remains in the bone for longer duration and provides pain relief. The efficacy of the treatment is maximized as the radiation emitted is absorbed almost completely within this area.. The usual therapeutic dose is 148 MBq (4 mCi). The compound is marketed under the brand name “Metastron” in USA and Canada and is presently being imported at a cost of about Rs.4 lakhs per dose.

To ensure increased availability and complete import substitution, the feasibility of producing ^{89}Sr in FBTR, Kalpakkam by irradiation of yttria and the separation of ^{89}Sr from irradiated yttria have been successfully demonstrated.

Production of ^{89}Sr Radiopharmaceuticals in Fast Reactor has been accomplished in laboratory scale by irradiating yttria pellets. Preparation of target yttria pellets, dissolution of high-density pellets, purification of Sr from Y has been standardized. Four trial irradiations of the target yttria pellets in FBTR and radiochemical processing of the irradiated pellets to get the pure source of ^{89}Sr using the hot cell facilities were carried out. Flow Sheet for the production of $^{89}SrCl_2$ has been finalized.

This chemically purified ^{89}Sr source satisfied the various radiopharmaceutical quality control protocols including biological as validated by Radiopharmaceutical Division (RPhD), BARC, Mumbai. Further studies are under progress.

Timeline snapshot

Date	Milestone
1971	Reactor Research Centre Established
September 30, 1971	Administrative approval and financial sanction for setting up of FBTR at RRC, Kalpakkam
January 31, 1972	The civil construction of FBTR began
March 13, 1974	First pour of concrete at FBTR
May 1977	Completion of FBTR civil construction
October 18, 1985	FBTR First Criticality
October 29, 1996	KAMINI First Criticality
July, 1997	Turbo Generator Synchronized to Grid
September 17, 1997	KAMINI power raised to 30 kWt
September, 2002	MK-I fuel reached a burn-up of 100GWd/t
September, 2003	Administrative approval and financial sanction for construction of PFBR
July, 2006	MK-I fuel reached a burn-up of 155GWd/t
June 24, 2008	Erection of PFBR safety vessel in reactor vault
2010	FBTR Fuel cycle successfully closed
March 7, 2022	FBTR achieved its target power of 40 MWt for the first time in its history
March 04, 2024	Initiation of PFBR core loading
October 18, 2025	FBTR clocks 40 years

Summary

As India is striving towards Viksit Bharath by 2047 and aims to realize net-zero emission by 2070, viable, sustainable, long-term, low-carbon energy options are being explored in the forefront. Nuclear energy is one of the major options and has a critical role in achieving this transformation.

India has a comprehensive three stage Nuclear Power Programme (NPP), devised by the great visionary Dr. Homi J. Bhabha for the long-term energy security of the nation. In realizing his vision, the first stage of NPP, on indigenous construction, commissioning and operation of Pressurized Heavy Water Reactors (PHWRs) has been successfully accomplished and attained a good level of maturity. The successful launch of the first stage has enabled us to embark on the fast reactor programme which is the second stage of NPP. Fast Reactors with closed fuel cycle are in the centre stage of the nuclear programmes to achieve energy sustainability. The success of the three-stage programme is centred on the Fast Reactor Programme which started with the successful commissioning of FBTR. The successful performance and the expertise gained in the commissioning & operation of FBTR, has enabled to launch the 500 MWe PFBR. Many experimental facilities and laboratories were established to verify and validate the design of PFBR which is now in the integrated stage of advanced commissioning. PFBR will serve as the launch pad for FBR 1 & 2. Commercial operation of Fast Breeder Reactors will lead to the third stage of the nuclear power programme. The challenges posed at various stages in the advancement of the fast reactor power programme, have been overcome and paved way for atmanirbharata or indigenization in different spheres of nuclear science and technology.