ADVANCED TECHNOLOGY DEVELOPMENT

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THE ADVANCED TECHNOLOGY DEVELOPMENT vertical sets out a comprehensive roadmap for advancing India's self-reliance in nuclear and related technologies to strengthen national energy security and technological independence. It prioritizes the development of indigenous cryogenic systems to support superconducting accelerators, scaling up to 4000 W at 2 K, which will reduce dependence on imported refrigeration technology. The hydrogen mission emphasizes innovation in green hydrogen production through electrochemical and thermochemical routes, efficient storage techniques, and safety management measures aimed at achieving the 2070 net-zero target. For fast breeder reactors, initiatives focus on domestic production of critical components, development of remote inspection systems, and creation of large-scale testing facilities to ensure operational reliability. Parallelly, research into advanced semiconductor and superconducting radiation detectors supports nuclear safety, healthcare diagnostics, and non-destructive industrial testing. It also outlines breakthroughs in portable accelerator and cryo-cooler technologies and the indigenization of high-power RF systems essential for energy-efficient, compact accelerators. Collectively, these programs align with the 'Aatmanirbhar Bharat' vision and aim to position India as a global leader in sustainable nuclear innovation and advanced energy technologies.

Hydrogen Technologies

Alkaline Water-based Electrolyser: Indigenization of the Alkaline Water-based Electrolyser (AWE) manufacturing technology has been successfully achieved and consistently tested across capacities ranging from 20 NLph to 1,00,000 NLph. An Alkaline Water Electrolyzer of 0.5 MW capacity, with a hydrogen production rate of 100 Nm^3/hr, has been developed and deployed at Cochin International Airport Limited (CIAL), Kochi, in collaboration with Bharat Petroleum Corporation Limited (BPCL) for establishing a green hydrogen fueling station. his stands as the only indigenous cell module technology in India utilizing domestically sourced components under the “Make in India” initiative. The system operates efficiently at a pressure of 10 bar, achieving hydrogen purity greater than 99.5% and an electrical energy efficiency exceeding 72% at maximum capacity. Further scaling has led to the successful design, development, and testing of a prototype 1 MW stack with a hydrogen production capacity of 200 Nm^3/hr. The Alkaline Water Electrolyzers are compact, bipolar plate, filter-press type units. This indigenous technology holds significant market potential for large-scale green hydrogen production, with industrial implementation planned through technology transfer mechanisms.

Laboratory hydrogen generator using AWE Tech: A Plug-in type Laboratory alkaline water electrolyser system was designed & fabricated using compact high integrity cylindrical cell. This system is designed for producing high-purity hydrogen onsite without any moving part. It was operated successfully for more than 100 hours, up to 20 NLPH Hydrogen production rate at 4 bar pressure and more than 99.9% purity at the cell stack outlet.

Indigenous diaphragm to replace asbestos in AWEs: Commercial-scale (2 m diameter, the largest available in the International market) Polysulfone-Zircona mixed-matrix membrane-diaphragm based on BARC-developed technology was launched in GH2INDIA EXPO 2025 in August, 2025. The indigenous diaphragm is going to replace asbestos and other imported separators in alkaline water electrolyser, which is going to be a key player in National Green Hydrogen Mission (NGHM) of Government of India.

PEM Electrolyser Development: The development of indigenous Proton Exchange Membrane (PEM) Electrolyser up to 50 NLph Hydrogen production capacity is completed and demonstrated the performance with more than 80%

Alkaline Water Electrolyser Plant installed at CIAL, Kochi.

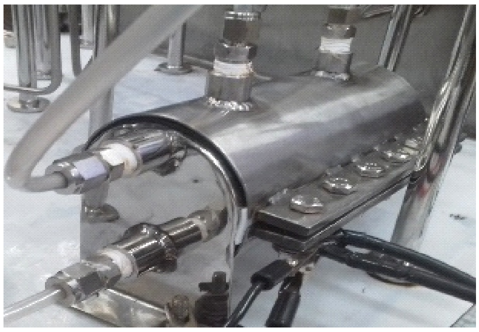
energy efficiency. One such system was fabricated and tested using indigenously developed PEM electrolyser for pure water Electrolysis, with oxygen side pressurization for conversion of D_2O^{18} to H_2O^{18}.

Copper-Chlorine Thermochemical Cycle: Under the "Nuclear Energy Mission for Viksit Bharat", a first-of-its-kind Copper-Chlorine (Cu-Cl) thermochemical cycle integrated pilot-scale facility has been demonstrated for hydrogen production. This facility, with a design capacity of 150 NL/h, recorded a cumulative operation of 225 hours - being the highest operational duration achieved globally for any thermochemical cycle. Expedited demonstration and scale-up activities are being actively pursued for nuclear hydrogen production. Key initiatives include: Demonstrating coupling of the Cu-Cl cycle with the Fast Breeder Test Reactor (FBTR); Setting up a 3000 NL/h prototype facility; and Designing a Cu-Cl cycle system integrated with a proposed 5 MWth HTGCR for nuclear hydrogen generation.

Iodine-Sulphur Process: The Iodine-Sulphur (I–S) process involves sequential reactions for water splitting, the first reaction is Bunsen Reaction where water reacts with SO_2 and I_2 at approximately 80°C in an exothermic process, producing sulphuric acid (SA) and hydriodic acid (HI). In the Sulphuric Acid Decomposition step where SA decomposes endothermically at around 850°C, yielding O_2 and SO_2. In the Hydriodic Acid Decomposition step, HI decomposes endothermically at about 450°C, producing H_2 and I_2.

After successful demonstration of the I–S process in a metallic system at 150 NLph, the process has been scaled up twenty-fold to 3 Nm³/h capacity. The design of the scaled-up facility is complete, and tendering activities are in the advanced stage. This activity was undertaken in collaboration with the Heavy Water Board (HWB). Documentation for statutory clearances, including the Preliminary Safety Analysis Report and Design Basis Report, has been completed and submitted for AERB approval through HWB.

Modified Iodine-Sulphur Process: In the modified Iodine-Sulphur process, sulphuric acid is not decomposed but is instead retained as a valuable co-product, produced simultaneously with hydrogen. SO_2 is generated via combustion of sulphur, and serves both as a reactant and an energy source for the process.



Cell for laboratory H_2 generator.

A 100 kmol/hr hydrogen production facility based on the modified I–S process has been designed in collaboration with a private vendor under the Atal Incubation Scheme. Preparation of a Detailed Project Report for coupling this modified process with a Gas-Cooled Reactor (GCR) is currently in progress.

Iodine-Hydrogen Sulphide (I-H_2S) Process: As a spin off to Iodine-Sulphur process, a new process to utilize H2S (a harmful refinery by product typically treated using claus process) is envisaged and successfully demonstrated in lab scale. This technology is now being advanced towards bench scale deployment along with refinery/private vendor, enabling cleaner hydrogen generation and conversion of a polluting waste stream into an energy resource.

In this process, H_2S reacts with iodine in the presence of water, forming hydriodic acid (HI) and solid sulphur. The sulphur is separated, and HI is fed into a decomposer to produce hydrogen and iodine. Feasibility studies have also been conducted using dimethylformamide in both glass and metallic reactors. A detailed study is planned to investigate the reaction of iodine with H_2S in an organic phase, aimed at generating comprehensive kinetic data for process optimization.

Hybrid-Sulphur Process: The Hybrid-Sulphur (HyS) process is a two-step water-splitting mechanism for hydrogen production. BARC has designed and commissioned a closed-loop HyS Process Engineering Facility with a capacity of 5 NLph hydrogen generation. Currently, a multi-stack Sulphur Dioxide Electrolysis cell is being fabricated, which will be installed and commissioned in the next phase of development.

Membrane Reactor Technology for High-yield Hydrogen Production: Indian patent on membrane reactor (MR) technology for enhanced HI decomposition (from ~22 % to ~95 % at 450°C; 2 bar) in I-S thermochemical process has been granted and know-how is transferred for commercialization. The technology is modified and extended to enhance H_2 production/recovery from waste gas stream containing NH_3 and H_2S. NH_3 to H_2 conversion of ~95% (500°C and 1 bar; against 80%) and H_2S to H_2 conversion of ~80% (1000°C, 1 bar; against 20%) was achieved using MR. This know-how is being commercialized to augment on-demand in situ high-purity hydrogen (≥99.9%) production through ammonia cracking, and production of MLD quantity of hydrogen & recovery of sulfur through treatment of industrial waste gas stream.

Development of Turbo-Molecular Pumps

Turbo-molecular Pump AnuTurbo-400: The AnuTurbo-400 system represents a high-performance, indigenously developed turbo-molecular pump designed for reliable and efficient vacuum generation. The ANU TURBO architecture integrates several critical subsystems to ensure high-speed operation and long-term consistency. Its rotor assembly comprises a precision-engineered rotating shaft and impeller, featuring multiple compression stages. The impeller has been entirely designed and fabricated in-house using additive manufacturing, aligning with a patent filed by BARC. Operating at a rotational speed of 24,000 rpm, the shaft incorporates rotors supported by both passive and active magnetic bearings, along with a BLDC motor drive. The system employs two radial active magnetic bearings positioned at each end of the shaft to control radial vibrations, complemented by a central thrust active magnetic bearing to counter axial vibrations. These are further stabilized by passive permanent magnets. For additional safety, mechanical backup bearings are included to protect the system against accidental shocks, sudden air ingress, or power failures, though they remain disengaged during normal operation.

AnuTurbo-400 System.

The system can operate reliably at temperatures up to 85°C, making it suitable for demanding and aggressive application environments. The electronic subsystems follow a modular design philosophy, facilitating ease of maintenance and upgrades. A dedicated user interface enables comprehensive monitoring, diagnostics, and control of the entire pumping system.

The pump has successfully undergone rigorous performance and endurance testing under laboratory conditions, followed by field trials at several constituent units of DAE.

The AnuTurbo-400 is suited for a wide range of advanced vacuum applications, including leak detection, mass spectrometry, electron microscopy, particle accelerators, electron beam welding among others.

High Performance Vacuum Pump: The AnuTurbo-80 high performance vacuum pump is an advanced multi-stage axial-flow turbomolecular pump integrating a unique combination of rotating and static blades. Its impeller, developed in-house using additive manufacturing based on a BARC-filed patent, ensures superior efficiency. Driven by a high-speed indigenously developed BLDC motor operating up to 36,000 rpm with an integrated sensor-less controller, the system employs precision ball-bearing support and fully in-house–designed components for vacuum integrity, housing, and rotor dynamics. Tested to 30,000 rpm, it achieves a compression ratio above 10,000 and an ultimate vacuum of 8.8×10^{-6} mbar. The pump finds applications in mass spectrometry, electron microscopy, plasma technology, nanotechnology, and high-energy physics. Its upcoming version, AnuTurbo-80R3, aims for a compression ratio beyond 100,000 and an ultimate vacuum of 10^{-7} mbar, featuring improved impellers, isolated bearings with temperature monitoring, a high-torque BLDC motor, and built-in air cooling for enhanced reliability.

HPGE based Radiation Detectors: HPGe detectors are favored for high-resolution gamma and X-ray spectroscopy due to their excellent electron-hole pair generation efficiency, high atomic number, and superior energy resolution compared to other detectors. These detectors operate by detecting high-energy photons (100 keV to 10 MeV) interacting with electrons in germanium through photoelectric effect, Compton scattering, and pair production. A planar HPGe detector is typically constructed using p-type crystals with electrical contacts formed by lithium diffusion (n-contact) and boron implantation (p-contact), with the detector functioning upon application of reverse bias voltage to create a depletion region for charge collection.

The critical process of producing ultra-pure germanium crystals via zone refining and Czochralski crystal growth techniques helps in reducing impurities and defects, essential for achieving the high resolution. Crystal characterization techniques such as Hall measurements, X-ray diffraction, and lifetime measurements are employed for quality assurance.

Significant emphasis is placed on development of radiation detectors in BARC, covering chemical processing, fabrication of electrical contacts, surface passivation by RF sputtering, and cryostat design for cooling detectors to liquid N_2 temperatures (90-100 K), essential to reduce thermal noise. Both n-type and p-type HPGe detectors were fabricated and tested, exhibiting low leakage currents (<100 pA) and excellent energy resolution (FWHM of ~1.5 keV at 662 keV).

A fully indigenous technology chain for the production of HPGe detectors in BARC, encompassing raw material processing to high-resolution gamma spectroscopy instrumentation, meeting DAE requirements has been envisioned with ongoing efforts to scale detector volume and improve resolution. This makes India self-reliant in a critical area of nuclear technology.

PIXEL Detector for Particle Radiation Detection: PIXEL-type Particle Radiation Detector have been fabricated, using in-house/locally grown high purity prime grade silicon wafers. Detectors have been produced at a PSU's foundry facility, as per BARC technology and tested using laboratory alpha sources such as Americium-241 and Thorium-229. It has shown similar resolution and sensitivity, as compared to the best commercial detectors available in the market.

Fabricated HPGE diode.

CFD Modelling & Development of Codes with GUI for Chemical Engg. Processes, Equipment: A continuum pseudo-fluid CFD model has been developed and validated for simulation of dense grain flows. CFD modelling has been used to simulate two-phase flow in half cells of alkaline water electrolyzers (AWEs) of different sizes. The results were used in an in-house code to quantify the flow distribution in the stacks of AWEs. Codes with GUI (ANUSim modules) were developed for simulating solute transport through liquid membrane immobilized in hollow fiber contactor, and for population balance modelling for estimating drop size in stirred liquid-liquid dispersions.

Technology Development for FBR Applications

Retrieval of Tilting Rail from PFBR under Sodium-filled Conditions: BARC has successfully retrieved a dislodged tilting rail from the Transfer Fuel Handling System of the PFBR under sodium-filled conditions. This complex operation required the development of a specialized machine equipped with force and position feedback mechanisms at the reactor top to extract the rail from the Inclined Fuel Transfer Machine (IFTM). The complete cycle - from conceptualization to deployment - was accomplished in a record period of 4.5 months. Removal of the rail was a pre-requisite to resume the long-pending fuel loading activities in the PFBR.

The Inclined Fuel Transfer Machine (IFTM), an ex-vessel handling system in the Transfer Bay (TTBR), facilitates transfer of core sub-assemblies between the In-Vessel Transfer Position (IVTP) and the Ex-Vessel Transfer Position (EVTP). After in-vessel cooling, irradiated sub-assemblies are moved into a sodium-filled transfer pot (TP), positioned at the IVTP of the IFTM, via a transfer arm.

The TP is lifted by a hoisting mechanism mounted atop the Rotatable Shield Leg (RSL), utilizing a chain and sprocket system. During lifting, the TP transitions from an inclination of 17° to 31° through the tilting rail system as it enters the Primary Tilting Mechanism (PTM). At the 31° position, the tilting rails serve a dual purpose - providing the required angular transition and acting as load-bearing members when the TP is stationed at the IVTP.

Following completion of blanket sub-assembly loading in the reactor core, and prior to initiating initial fuel loading (IFL), difficulties arose when the TP could not be lowered to its bottommost position at the IVTP. Subsequent ultrasonic testing under sodium conditions revealed that one of the 31° tilting rails had become dislodged from its mounting brackets. This condition is only possible if all sixteen fixing bolts securing the rail have failed, allowing it to slide down.

The machine with its Argon flask after removal from core.

Development of Rail Retrieval Machine: Before advancing further with fuel loading in PFBR, it was decided to remove the dislodged tilting rail from the PTM. The design, conceptualization, and manufacturing responsibilities for this task were assigned to BARC.

BARC developed a purely mechanical manipulator capable of operating under sodium at temperatures up to 220°C without the need for sodium draining. The manipulator is operated remotely using mechanical shafts from the reactor top, maintaining effective sealing to prevent sodium vapor and aerosol escape. The machine was designed using available in-house materials. Fabrication primarily employed waterjet cutting techniques to circumvent slower milling and lathe operations. Functional checks were integrated to detect dimensional errors & tolerance stack-ups, thereby eliminating the need for exhaustive component-level inspections. These design & fabrication optimizations enabled completion of the machine within 4.5 months using in-house workshop facilities.

Rail Retrieval Operation: Dry trials were conducted at BHAVINI using a dummy PTM (IFTM) to validate the manipulator's performance. The actual retrieval of the dislodged tilting rail from the reactor was executed on 6 September 2025 without draining the sodium, while maintaining a core temperature of 180°C. The blind operation was completed smoothly, with all force and position feedbacks responding accurately and reliably.

Advanced Technology, Computing & Secured Quantum Communication: BARC has prioritized the integration of modern computational techniques within nuclear research, focusing on High-Performance and Cloud Computing, Scientific Visualization, Machine Learning, Mass Storage, Information Security, and Advanced Database Systems. These initiatives support BARC's scientific research community through state-of-the-art computing, visualization, and storage infrastructure. The Mod Lab Computer Centre , established in 1977 to host a BESM-6 mainframe, has evolved significantly to accommodate a Petaflop-scale supercomputing facility, enhanced networking, and large-capacity storage. A 15-petabyte mass storage system has been deployed, managed by an indigenously developed storage management software - SANMAN. Administrative modernization includes the complete digitization of the DPS purchase workflow, replacing physical files. To align BARC's infrastructure with emerging AI and Quantum technologies, R&D efforts are underway. Fabrication & room-temperature characterization of Al/AlO_x/Al Josephson Junction devices have been completed, with cryogenic studies planned next. In applied AI research, a Treatment Planning System and an AI-assisted Segmentation Suite for Radiotherapy have been developed to optimize cancer treatment parameters. A GPU-accelerated beta version deployed at TMC, Mumbai, achieved 90% segmentation accuracy with a 10-second prediction time per organ.

Additionally, an on-premise AI-driven drug discovery platform, 'SANJEEVANI', leveraging open-source AI frameworks, has been developed for centralized computational infrastructure. Parallel studies are examining Quantum Key Distribution (QKD) protocols using open-source quantum network simulators on the BARC network, marking significant progress towards secure quantum-era communication and computation capabilities.

Safe & Secure Systems for Nuclear Facilities: Control and Instrumentation (C&I) systems constitute the operational core of nuclear facilities, ensuring reliability, maintainability, and scalability through indigenous development. The existing hardware-based Alarm Annunciation System of FBTR has been upgraded to a modern configuration using the TPLC-32 platform integrated with the Distributed Plant Information and Supervisory Control System. The upgraded AAS consists of seven nodes, each comprising dual hot-standby TPLC-32 subsystems. Dual-redundant alarm servers and operator consoles based on DPISCS manage alarm visualization and archival via a redundant Ethernet network.

A Distributed Control System (DCS) for the INRP has been jointly developed with M/s. ECIL, Hyderabad, based on the indigenously built safe and secure NUCON-C PLC platform. The complete DCS for Reprocessing Blocks-1 and 2 at INRP-Tarapur has been manufactured, tested, and deployed. Parallel-plate gamma-compensated ionization chambers featuring advanced boron coating (developed in BARC) exhibit strong adhesion, thermal stability up to 600°C, ±5% signal linearity, and a gamma compensation ratio of ~7.4%.

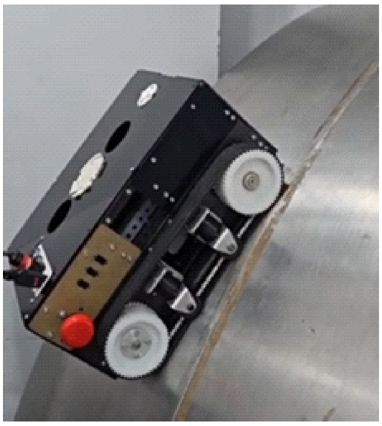
Upgraded MLCC and 15 PetaByte Storage Facility.

Indigenous instrumentation advances include an inline flow-through ultrasonic sensor with embedded thermocouple for isotopic purity analysis of heavy water (0-100% D_2O, 27-50°C), validated in simulated conditions. The Agglomeration Onset Detection System, employing attractor comparison for real-time “S parameter” estimation, now functions as an early-warning system at INRP-K. Similarly, an ultrasonic ammonium nitrate concentration monitoring system integrated with SCADA was developed and field-tested successfully.

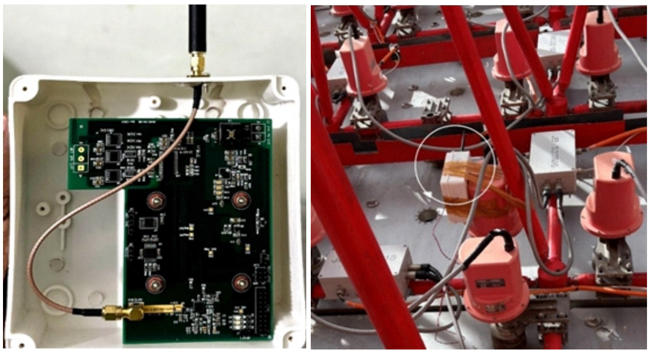
Further developments include FPGA-based neutron assay electronics for MOX quantification, ultrasonic pulsation monitoring for uranium extraction optimization, and C&I architectures for next-generation reactors including IPR, HTGR, and BSMR. Reactor safety innovations include real-time loose-part monitoring algorithms and an AI-based image processing system for estimating drop size distribution in solvent extraction, enhancing analytical precision and operational safety.

Development of Tools and Techniques for Inspection of Critical Facilities: For assessing Tube-to-Tube Sheet (TTS) weld joints in heat exchangers and steam generators, an indigenous automated software analyzes batches of radiographic images to evaluate and categorize weld quality. In the domain of in-service inspections, negative-pressure adhesion-based robotic crawlers have been designed for examining stainless steel and nonmagnetic structures, operating on curved and vertical surfaces. To ensure reliability in ultrasonic measurements, an automated ultrasonic immersion probe characterization system standardizes beam parameters such as focal length, beam width, and axis alignment. Additionally, a fully indigenous 8-channel ultrasonic and eddy current inspection system, integrated with data recording, flaw characterization, and analysis software, has been successfully implemented for reactor pressure vessel inspections in boiling water reactors.

C&I, Processing & Computation Systems for Applications in Frontiers of Basic Research: Modern sensor and instrumentation technologies form the core of several Mega Science projects. The Giant Meterwave Radio Telescope serves as a premier astronomical facility, where its servo system ensures precise tracking of celestial objects using command inputs from the Central Station. A key upgrade features an optimal Linear Quadratic Gaussian (LQG) controller, implemented for the first time in India, in large telescopes at the GMRT's C04 unit resulting in a 3-fold disturbance attenuation over conventional systems. For the Major Atmospheric Cherenkov Experiment (MACE), Wireless Actuator Controller (WAC) and Mirror Alignment Central Hub (MACH) electronics were developed to actively correct mirror alignment against gravity-induced deflections, with successful field trials completed. Additionally, a 32-channel neutron counting DAQ system for HARL in Gulmarg, and an indigenous 8-channel, 500 MSPS digitizer with FPGA-based architecture for high-energy physics applications were developed.



Robotic crawlers designed for examining stainless steel and nonmagnetic structures.



The Wireless Actuator Control for deployment in MACE Telescope Facility.

Physical and Cyber Security Systems: A major focus has been the advancement of ICS systems through sensor development. Photodiodes measuring 30 mm × 4 mm × 0.3 mm were designed and fabricated for ICS detector modules. Fifty integrated modules, each comprising 16 detector arrays with front-end electronics, were successfully tested. Additionally, progress has been made in developing a muon-based passive detection system for high-Z material identification. A prototype with 1 metre long drift tube detectors demonstrated good performance, exhibiting insulation resistance above 10^{13} Ω, stability up to 5 bar pressure, and a helium leak rate below 10^{-8} bar·L/sec, achieving approximately 85% muon detection efficiency.

In cybersecurity, Post-Quantum Cryptography (PQC) based VPN appliances have been developed to secure data communication against potential quantum-era threats. For enhanced physical security, a Bluetooth Low Energy (BLE) object and visitor tracking system integrated with RFID has been deployed across multiple facilities, including the BARC campus. Cyber threat analysis has been strengthened through a Security Information and Event Management (SIEM) system now operational at BARC Trombay, BARC Tarapur, and AERB. A Cyber Threat Intelligence Information Integration and Exchange System automates threat data acquisition and dissemination for proactive mitigation.

To ensure information integrity, the Generative AI Threat Elimination System (GAITE) was developed to monitor sensitive code uploads to AI platforms. A Dynamic User-Specific Digital Watermarking technology enables secure tracking of unauthorized video distribution. Additionally, 3D modeling and virtual-environment applications have been introduced for security training and scenario simulations, including a virtual walkthrough of high-security areas like Anushakti Nagar. A standalone encrypted application ensures protected access to these digital environments.