REACTORS PROGRAMME

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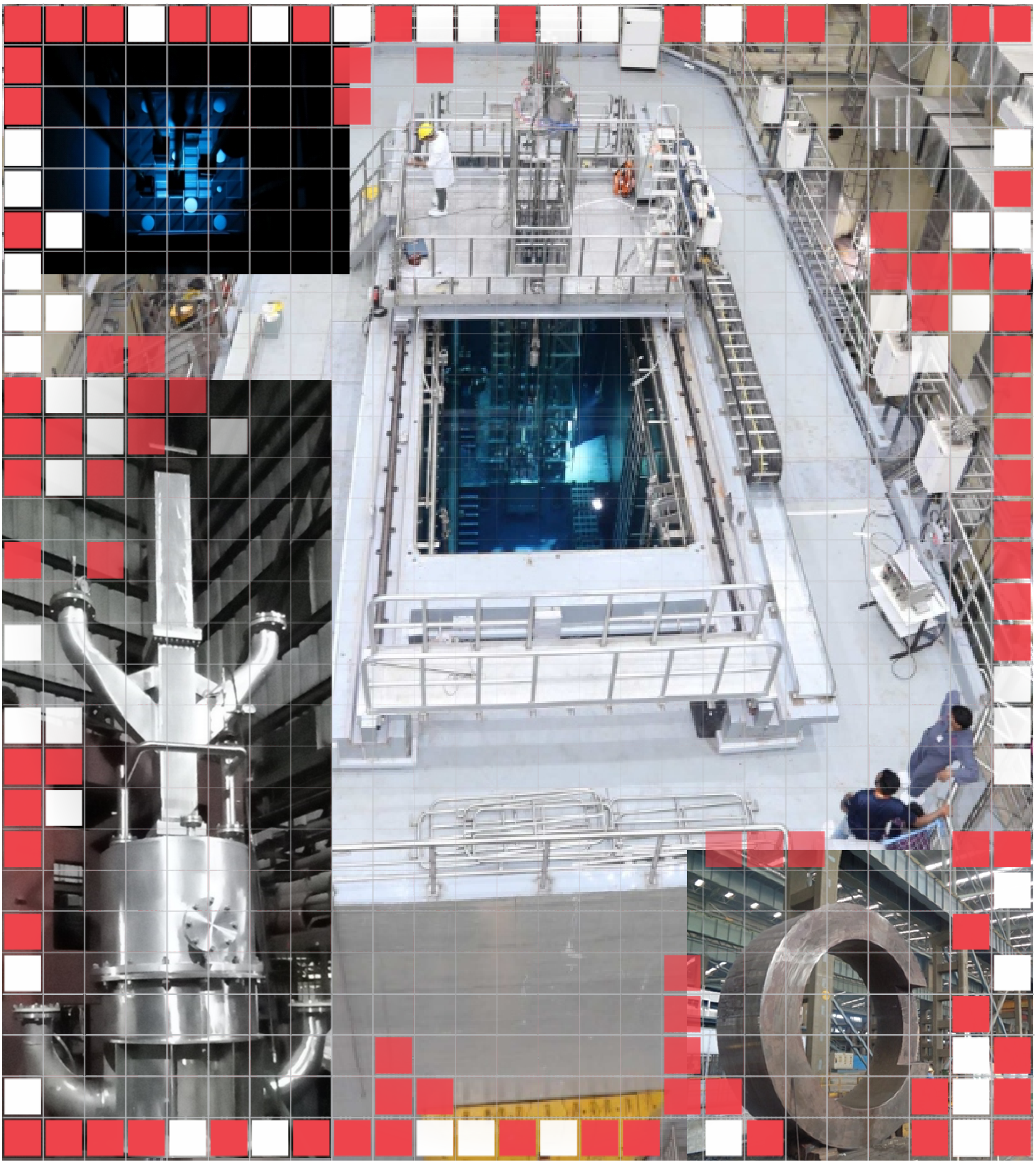
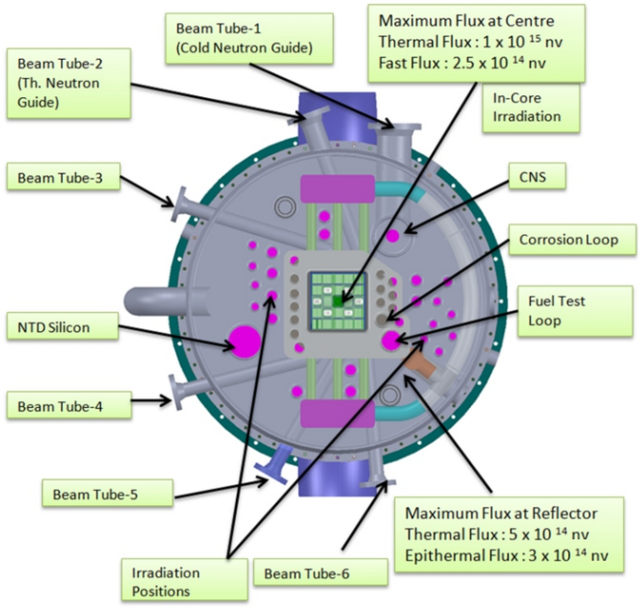


THE REACTORS PROGRAMME

is the core mission of the DAE's 'Vision 2047', advancing India's self-reliance in critical technologies, and energy security while augmenting its leadership in global nuclear technology landscape. Its flagship initiatives encompass the design, development, construction, and commissioning of research and developmental reactors, aligned with the multi-stage nuclear power programme. In the run up to the Amrit Kaal (Year 2047), the programme emphasizes greater indigenization, advanced R&D, and sustainability, with major developmental activities planned at premier research centres.

New Reactors

High Flux Research Reactor: A standout activity in the domain of reactors is the High Flux Research Reactor (HFRR) - a pool-type compact research reactor coming up at BARC Visakhapatnam. It is designed to yield high neutron flux in the order of 10^{15} n/cm^2/s (peak) and operates at a nominal power of 40 MWth. The advanced nuclear research facilities planned at HFRR include cold neutron sources, corrosion studies, radioisotope production, and advanced testing of nuclear fuels and materials, which are considered a boon to both academia and industry. Envisioned as a centralized national facility for neutron beam research and neutron transmutation doping (NTD) of silicon, feasibility studies for commercial-scale NTD production of silicon is under active evaluation. Once fully operational, HFRR will serve as a national facility for neutron beam research with advanced facilities and instruments for both DAE and non-DAE users.



Salient features of HFRR.

High Temperature Gas Cooled Reactor: India's pioneering development of High Temperature Reactor technology represents a major milestone toward realizing the national vision of 'Atmanirbhar Bharat' (self-reliant India). It advances energy independence, industrial competitiveness, and environmental sustainability through indigenous nuclear innovation. As a lead step, the 5 MWth High Temperature Gas Cooled Reactor (HTGCR), developed indigenously by BARC, is designed to deliver high-grade process heat suitable for clean hydrogen production - a decisive step in decarbonizing core industrial sectors and reducing dependence on imported fossil fuels.

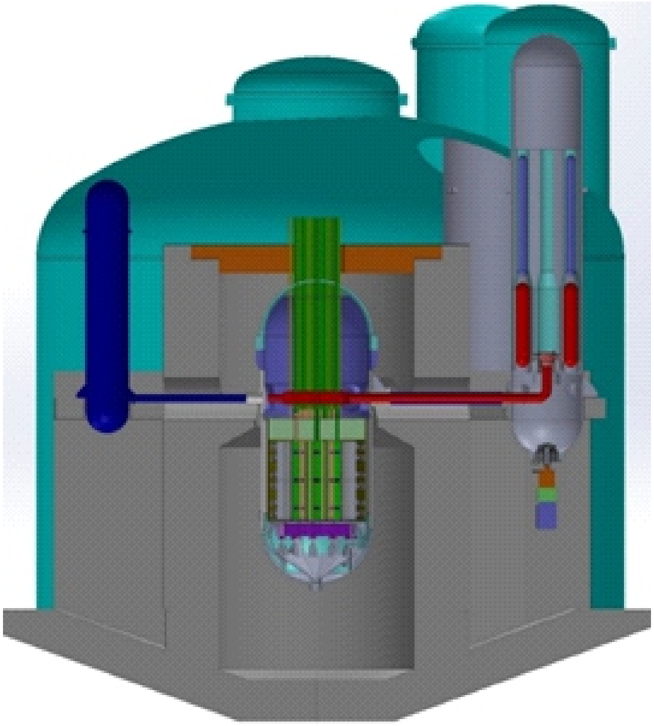
The High Flux Research Reactor will have advanced research facilities such as cold neutron source and corrosion test loop, a first-of-a-kind facilities in India's research reactor landscape. It will also have a provision for production of neutron transmutation doped (NTD) silicon; supports development of new nuclear materials for advanced reactors.

India's HTGCR, being developed by BARC, uses advanced physics simulation tools combining Monte Carlo (PATMOC) and deterministic (ARCH) codes. These provide co-dependent optimization of fuel cluster configuration, thermal-hydraulic feedback, and neutron economy. The design ensures extended core life - approximately 4 full power years - with adequate excess reactivity and redundant safety systems. The compact core, about 2 meters in diameter, contains 21 fuel channels and 28 reactivity control devices comprising three types of control rods and two diverse, fast-acting shutdown systems. This configuration provides strong reactivity management and operational reliability. Slightly enriched uranium dioxide (UO_2) serves as fuel, moderated and reflected by high-density, near-isotropic graphite. The average thermal neutron flux is approximately 1.44×10^{13} n/cm^2/s, producing a core power density of 1.1 kW/litre. The reactor's inherent safety is reinforced by negative reactivity coefficients, ensuring self-stabilizing performance across its operational life. Control rod worth is stringently managed to guarantee safe reactivity control under all conditions.

The fuel cluster design follows a physics–thermal hydraulics coupled methodology. It uses pin-type fuel assemblies consisting of cylindrical UO_2 pellets clad in austenitic steel for corrosion resistance and mechanical strength. The pellets measure 12.2 mm in diameter with a 1:1 length-to-diameter ratio, while the pellet–clad radial gap is precisely maintained at 0.12 mm to accommodate differential thermal expansion. Each cluster hosts 24 pins - nine in the inner ring and fifteen in the outer - secured centrally to prevent bowing (or stress deformation). Vertically arranged assemblies are linked via tie rods and enclosed within double graphite sleeves and static gas gaps that limit both heat loss and neutron leakage. To ensure structural soundness and thermal performance, engineering test loops are planned for fuel experimentation, focusing on thermomechanical reliability, flow-induced vibration effects, and endurance under full-spectrum service conditions. These validation programs are integral to qualifying the fuel design for long-term, high-temperature operation.

The HTGCR core comprises precision-machined graphite blocks - octagonal and rectangular - designed to securely accommodate fuel channels and reactivity control devices. The blocks are assembled using spigot rings and dowel pins, with interlocking keys preventing rotational displacement. To withstand both seismic loads and irradiation-driven dimensional changes, a temperature-compensated core restraint mechanism maintains geometric stability under dynamic conditions. The re-entrant flow core configuration enhances cooling efficiency by circulating the primary coolant through annular passages that lower graphite temperature before re-entering the fuel channels. The cooled graphite contributes to efficient moderation and structural longevity. Hot coolant emerges from the core at 650^{0}C, transferring energy to the heat utilization system for process applications. The graphite assembly is housed within a robust core barrel supported on a diagrid, enclosed by thermal and neutron shields made from low-alloy steel for durability and radiation protection.

The HTGCR focuses on efficient process heat delivery for hydrogen generation. The Heat Utilization System (HUS) integrates chemical reactors within primary heat exchangers, optimizing the Copper–Chlorine (Cu–Cl) thermochemical cycle. The Primary Heat Transport (PHT) system has two redundant CO_2-cooled loops, each capable of removing up to 2.5 MW of thermal energy. During operation, most heat supports hydrogen production, while the Secondary Cooling System (SCS) handles surplus heat through atmospheric cooling towers. The system operates within metallic containment, ensuring radiation-tight boundaries, and exhaust air is filtered using HEPA systems for environmental protection. Passive and active safety mechanisms reinforce reliability: the Passive Decay Heat Removal System (PDHRS) disperses residual heat via natural circulation, and the Emergency Core Cooling System (ECCS) addresses loss-of-coolant conditions. Dual, fast-acting reactor protection systems respond automatically to abnormal reactivity changes, ensuring defense-in-depth safety.



The Engineered Safety Features placed inside a metal containment of HTGCR.

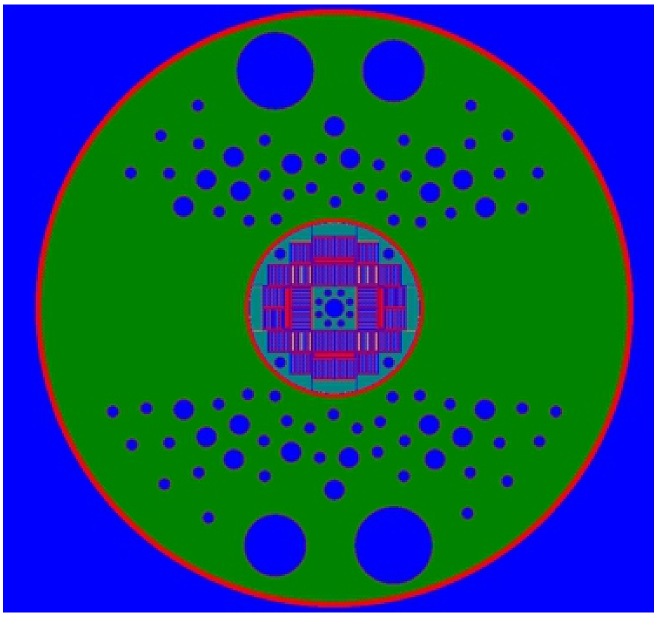
A first-of-a-kind coupling technology is being evolved for HTGCR which integrates the nuclear reactor with a chemical plant employing Copper-Chlorine cycle for H_2 production. Successful demonstration of clean H_2 production using nuclear energy will be an important step towards industry decarbonisation.

Isotope Production Reactor: The Isotope Production Reactor (IR)is a high-flux, 40 MW open-pool type reactor designed primarily for large-scale radioisotope production, especially for nuclear medicine. Planned for commissioning at BARC Visakhapatnam, it will be built in Engineering, Procurement and Construction mode, beginning in 2027 and expected to commence operations by 2034. The project supports India's goal of self-reliance in medical isotope supply, unlocking exports, and advanced healthcare infrastructure.

The facility will produce high-specific-activity isotopes such as 192Ir, 99Mo, 60Co, 177Lu, 131I, 153Sm, 166Ho, 188W and 90Y in addition to production of specialized isotopes, such as Pu-238, Ni-63 and NTD-Si, for deployment in programmes of high national importance. With an estimated annual output of 0.8 million curies (MCi). Besides medical use, some isotopes will serve strategic national programs.

The reactor uses low-enriched uranium (LEU) in the form of U_3Si_2 fuel and employs light water as coolant and moderator. The core houses 28 plate-type fuel assemblies surrounded by beryllium reflectors and a central beryllium trap to enhance neutron flux. Around the core is a heavy-water reflector tank, supported by a cylindrical inlet plenum that distributes coolant water evenly. The coolant flows upward through the core, carrying away fission heat, and exits through outlet nozzles to the heat-removal systems.

Most irradiation positions are located in the reflector region, providing large irradiation volumes. Target materials are sealed in aluminum capsules and irradiated in tray rods inserted into these locations. After irradiation, manipulators in hot cells retrieve the capsules and transfer them in shielded casks to the isotope processing facility.


The core of Isotope Production Reactor.

The nuclear island consists of the reactor building, auxiliary buildings, service structures, and a 75 m exhaust stack for safely venting gaseous effluents. The reactor operates roughly 280 days per year, with refueling performed during shutdowns; about one-third of the core is replaced per cycle. Spent fuel is stored underwater in a connected storage bay.

Heat is removed via the Primary Heat Transport System, which maintains sufficient flow to prevent boiling. Backup shutdown cooling pumps ensure core cooling during loss-of-coolant accidents. In blackout scenarios, natural circulation through dedicated valves sustains passive heat removal. Long-term cooling is provided by diesel-backed pool-water systems.

The Isotope Production Reactor is designed to produce high specific-activity and specialized isotopes such as 99Mo, 60Co, 177Lu, 131I, 153Sm, 166Ho, 90Y with significant healthcare applications.

Two independent shutdown systems guarantee safety: Primary System equipped with six control-cum-shut-off rods operated from above and the Secondary System equipped with four emergency rods with a heavy-water dump component operated from below.

Overall, the Isotope Reactor integrates robust safety, efficient heat removal, and specialized isotope production capabilities to serve both medical and strategic sectors.

Advanced Purified Reactor Vessel Alloy (APURVA): The Pressurised Water Reactor (PWR) based Nuclear Power Plant (NPP) necessitates the development of large, high-purity, low-alloy steel (LAS) forgings for the fabrication of the Reactor Pressure Vessel (RPV) - the plant's most critical component. The RPV for India's PWR program is a ~12 m long vessel with an outer diameter of about 5 m, designed to withstand temperatures around 320^0C and pressures of approximately 16 MPa over a 60-year service life under intense radiation exposure.

Developing such robust RPV forgings posed major challenges, including achieving large section thicknesses with uniform mechanical properties, controlling microstructure and chemical composition, ensuring excellent weldability, and preventing hydrogen-induced micro-cracks. Addressing these challenges required development of indigenous technology through extensive research and industrial collaboration.

To realize this capability, a program was initiated in BARC in partnership with Ranchi based Heavy Engineering Corporation Ltd to develop low alloy steel (LAS) forgings. Subsequently, efforts with L&T Special Steels and Heavy Forging Pvt. Ltd., Hazira, focused on scaling up to industrial production of heavy-section forgings. Metallurgical parameters - melting chemistry, forging practices, and heat-treatment protocols - were optimized through rigorous R&D work. Three prototype shell forgings with internal diameters ranging from 3.8 m to 4.2 m and thicknesses of 340 mm, 550 mm, and 750 mm were produced successively, simulating various RPV sections such as nozzle belts and flanges. Comprehensive metallurgical and mechanical testing confirmed uniform through-thickness properties and structural soundness. Impurity control was achieved at parts per million levels, including hydrogen content below 1 ppm. The developed special-grade steel was designated "**A**dvanced **Pu**rified **R**eactor **V**essel **A**lloy", or APURVA.

The manufacturing process utilized a controlled melting and refining route to achieve superior purity and chemistry. Specially selected steel scrap and direct reduced iron (DRI) were melted in a 100-ton Electric Arc Furnace (EAF), refined and alloyed in a 110-ton Ladle Furnace (LF), and degassed in a 110-ton Vacuum Degassing (VD) unit under ultra-low vacuum (<1.0 torr) to remove hydrogen. Two 100-ton degassed heats were sequentially cast in a 208-ton mold within a Vacuum Ingot Casting (VIC) setup, also under <1.0 torr conditions. The resulting ingots underwent extensive forging, heat treatment, machining, and inspection.

Key R&D areas focused on: Optimization of chemical composition and process parameters for each forging thickness; Control of impurities and gaseous elements (H, N, O); Determination of optimal quenching rates and validation of heat treatment cycles and Extensive material characterization and qualification testing.

A novel laboratory-scale physical simulation technique developed at BARC enabled fine-tuning of heat-treatment cycles specific to each section. Over 300 trials involving around 3000 test samples were executed before industrial implementation. The validated forgings were then examined for ultrasonic integrity, mechanical strength, fracture toughness, fatigue performance, thermal endurance, and weldability using samples extracted from multiple orientations and elevations.

APURVA replica of 750 mm thick ring forging erected in BARC Trombay.

Development of APURVA signifies the achievement of significant technological milestone in LWR technology. It stands as a testament to BARC's unwavering commitment to achieving self-reliance in critical technologies.

The qualification included 100% ultrasonic scanning, through-thickness mechanical testing, post-quench and temper (QT) evaluations, directional mechanical tests (axial, tangential, radial), low-cycle fatigue and fracture toughness tests conforming to ASME standards, temper embrittlement (step cooling) tests under ASME Section IIA SA-542 requirements, and weldability assessments via Tekkon Y-Groove and Varestraint methods. All results exceeded acceptance norms with considerable margins.

The project concluded successfully, establishing indigenous expertise in manufacturing high-thickness RPV class forgings. The domestically developed APURVA steel now supports production of RPVs, steam generators, and other pressure-boundary components for water-cooled reactors operating up to 350^{0}C.

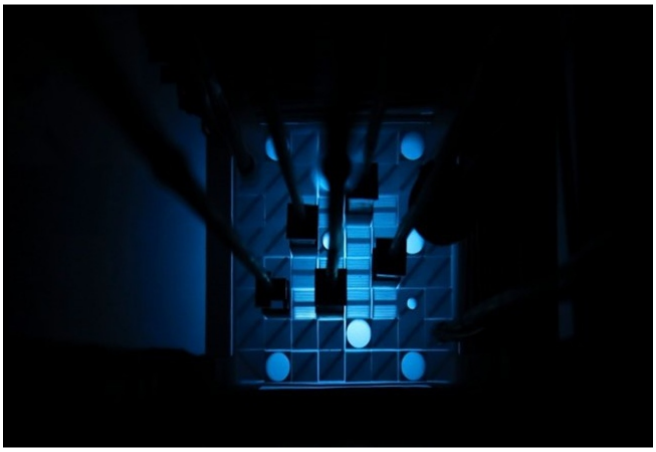
A significant milestone in India's pursuit of nuclear self-reliance was marked by the Atomic Energy Commission's in-principle approval of the Bharat Small Modular Reactor BSMR-200, an entirely indigenous medium-sized PWR project jointly executed by BARC and NPCIL, employing APURVA forgings for its RPV.

The APURVA monument installed at BARC's Trombay campus, created from prototype forgings of 340 mm, 550 mm, and 750 mm thickness, symbolizes India's technological advancement toward Aatmanirbhar Bharat in the Amrit Kaal era.

Operation and Utilization of Research Reactors: During the year, research reactors Apsara-U and Dhruva operated with high safety and reliability, supporting medical, agricultural, and industrial isotope production, fundamental research, material testing, and studies for future power reactor programs. The Critical Facility (CF) was operated to cater to research community requirements.

The Apsara-U reactor achieved rated 2 Mwth power with ~92% availability, supporting research and radioisotope production. Indigenous uranium silicide dispersion fuel demonstrated robustness beyond 55,000 MWD/Te burn-up.

Sixteen cans in tray rods were irradiated and 78 samples processed via Neutron Activation Analysis (NAA). Preparations for fission molybdenum production progressed, including qualification of tray rod assemblies and safety clearance, with trial irradiation planned. Material characterization samples were routinely irradiated; a single crystal alignment facility is under commissioning in a beam tube.



Apsara-U Reactor Core.

Irradiation experiments included natural uranium specimens for fission gas distribution, swelling, and creep studies; Invar alloy used in calandria supports; and dissimilar material joints for cryogenic applications. A facility for Neutron Transmutation Doping (NTD) of silicon ingots (4"–8" diameter, 10" length) is under design for installation in Apsara-U.

The Dhruva reactor operated with ~80% availability. Annual plant radiation dose was the lowest since commissioning. Production included 410 medical and industrial radioisotopes and 44 NAA samples. Fission molybdenum targets were irradiated as required. Seventy-two plates were delivered to the Fission Moly Processing Plant. An on-power irradiation facility was designed and tested, enabling target handling without reactor downtime.

An on-power irradiation facility for fission moly was designed & tested for deployment in the operations of Dhruva. The facility will enhance the production of fission moly as the loading/unloading of targets for irradiation will be done without affecting the reactor's regular operation.

Instrumentation upgrades included differential temperature monitoring of 130 failed-fuel detection tubes, continuous shut-off rod position monitoring, and a new radiation data acquisition system. Seawater supply reliability improved through year-round desilting and design of a new intake system. The Dhruva's coolant header pressure was enhanced via procurement of a fourth auxiliary pump (XCP-4), tested and pending commissioning.

A laser-based positioning system for Fuelling Machine-A was installed, with performance testing in progress. Security enhancements included upgrading the Perimeter Intrusion Detection System (PIDS).

The Critical Facility was operated on 67 occasions, supporting detector testing and activation of large samples for NAA.

Thirty-eight nuclear detectors and 36 samples with 11 foils were activated, matching predicted reactivity values. Integral experiments with molten salt reactor fuel salt at various core locations validated theoretical estimates for MSR development.