The Small mighty!

Research Reactors in BARC

History, Development & Utilization

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Research Reactors (RRs) are central to the development of nuclear science and technology programme for societal benefits. BARC has a long history of more than 65 years in designing, constructing and safely operating RRs of various type and size. Systematic ageing programme have been put in vogue to refurbish and extend the life of RR. The article describes in brief the history of RR at Mumbai, BARC, their progressive development and various aspects of utilization for societal benefits.

Research reactors (RRs) in BARC have been the forerunners for the nuclear energy programme of the country. They are primarily meant to provide neutron source for research and applications in healthcare, neutron imaging, neutron activation studies, neutron scattering experiments etc. Generally, any upcoming technologies are proven in a RR before their implementation in commercial power reactors. RRs are generally simpler and smaller than power reactors with power level varying from zero power (like Critical Facility for AHWR) to few hundreds of MW (like Dhruva), and generally operate at low temperature. They use far less amount of fuel than a power reactor, but their fuel may require Uranium with much higher enrichment like that in Apsara-U. They may have a very high power density in the core, requiring special design features. Being flexible, RRs are best suited for testing nuclear fuels of various reactor types, studying the safety margins for nuclear fuel, and developing accident tolerant and proliferation resistant fuel for future reactors.

Unlike power reactors having standardized design, different RRs have distinct designs and operating modes. A common design is a pool type reactor like Apsara, where the core is a cluster of fuel elements housed in a large pool of water. In a tank type reactor like Dhruva and Cirus, core is contained in a closed vessel as in the power reactors. In tank-in-pool type reactor, the core is enclosed in a tank which is in turn located in a pool of water. Most of the RR cores have channels to locate materials for irradiation experiments. In addition, beam tubes which penetrate the reactor vessel, pool and shielding provide neutron and gamma beams for experimental use in reactor hall or adjoining guide tube laboratory.

Around the world, a total of 818 research reactors have been built so far, out of these 443 have been decommissioned and 224 reactors are in operation. Russian Federation has the highest number of operational RRs (63), followed by USA with 42 reactors, China with17 and France 10.

The very first research reactor of Asia, named Apsara, was commissioned in BARC in the year 1956. It was a 1MW, swimming pool type reactor fuelled with enriched uranium–aluminium alloy clad with aluminium. The reactor core was housed in a stainless steel lined pool of 8.4 m long, 2.9 m wide and 8 m deep, filled with demineralized light water. The core, suspended from a movable trolley, could be parked at three positions to facilitate wide range of experiments at beam tubes, thermal column and a shielding corner in addition to the in-core irradiation. It produced an average neutron flux of 10^{12} n/cm^2/sec.

Apsara enabled the Indian scientists and engineers to understand the complexities and intricacies of operating a nuclear reactor safely. Simplicity of this reactor design had made it very popular among the researchers. Various experiments could be planned and carried out with relative ease, as the reactor core was easily accessible and movable. The thermal column and the shielding corner facilities in the reactor made it very versatile for carrying out experiments. Facility for irradiation of targets with fast neutron alone was also available in Apsara. In a span of around 50 years, the reactor had been instrumental in carrying out advanced studies in the field of neutron physics, fission physics, radio chemistry, biology, irradiation techniques and R & D work on reactor technology. Neutron activation analysis technique developed with Apsara found wide applications in chemistry, archaeology and forensic sciences. Various shielding experiments to verify the design adequacy of shield configurations used in reactors such as Dhruva, PHWRs, 500 MW_e Prototype Fast Breeder Reactor etc had been carried out in the shielding corner of Apsara. The reactor was shut down for good in the year 2009.

Subsequent to the experience with Apsara, need for high power research reactors which cater to the additional requirements of radioisotope production, irradiation facilities etc. was felt. This led to the construction of a high flux and high power research reactor known as Canada India Reactor (CIR). This reactor, built with the help of AECL, Canada, was similar to Canadian NRX reactor, but with few changes based on the location and requirement. CIR was later renamed as Cirus by Dr. Bhabha. It was a vertical tank type 40 MW_{th} reactor. The reactor was natural uranium fuelled, heavy water moderated, graphite reflected and light water cooled. It produced a flux of 6.5 x 10^{13} n/cm^2/sec.

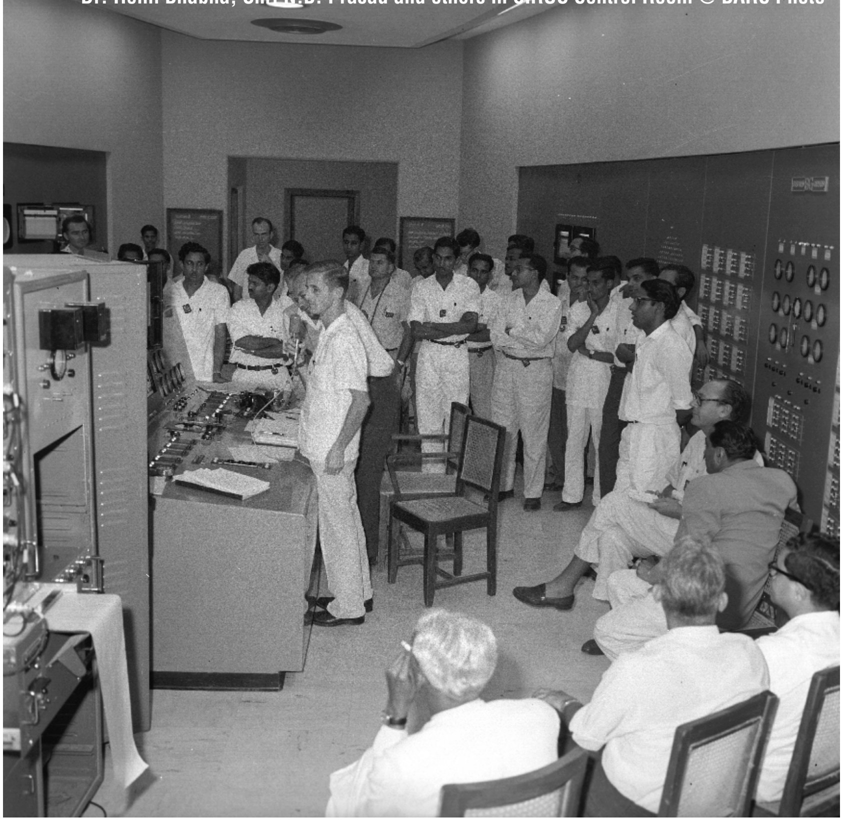
Cirus became the work horse of the nuclear energy program, as it provided larger irradiation volume at larger flux. Cirus reactor was solely catering to the country's radioisotopes requirements till Dhruva became operational in 1985. The reactor had a pneumatic carrier facility, where short term irradiations can be carried out. This facility was extensively used for activation analysis, for determining trace quantities of materials in a given sample. The reactor had also been used for silicon doping experiments, much needed for electronics industry. Cirus had a set of six self-serve units, in which on-power irradiation of 30 samples can be done simultaneously, for production of short-lived isotopes.

In order to utilize and develop Thorium fuel technology, irradiation of thorium was started in graphite reflector region of Cirus very early. The first charge of fuel for Kamini reactor was produced by irradiating thorium in Cirus. An in-pile Pressurized Water Loop (PWL) of 400 kW heat removal capacity operating at a pressure of 115 kg/cm^2 and temperature of 260°C was available at Cirus which was a valuable facility for test irradiation of power reactor fuel and materials. Utilizing this facility, development of MOX fuel for Tarapur BWR fuel program was taken up. This facility was also utilized for validating various design assumptions and analysis by carrying out test irradiations and later examining the fuel. Irradiation of various structural materials of the power reactors such as end shield and Zircaloy pressure tubes of PHWRs etc. were carried out at Cirus PWL. These experiments built the confidence for designing and operating power reactors.

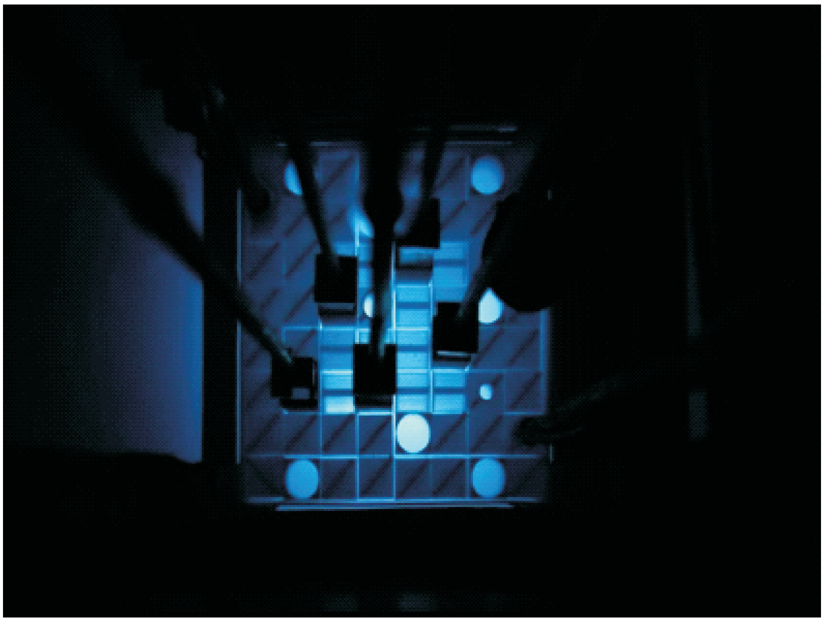
In those days Cirus and Apsara became centres of excellence in nuclear education. People who got early experience in operating these reactors, later grew to lead various nuclear projects and programs. After four decades of successful operation, detailed ageing studies were carried out in Cirus, which indicated possibility of substantial life enhancement by carrying out refurbishment of identified systems, structures and components. Refurbishment of the reactor was taken up during1997 to 2002. Along with, this major safety upgrades were also carried out to meet present safety standards. After operating the reactor for another 8 years, it was permanently shut down on 31st December, 2010 to honour the Civil Nuclear Deal.

During the early seventies, strong need was felt to build a research reactor with further higher neutron flux to meet the growing demand of radio-isotope production and advanced research in basic sciences and engineering. Accordingly, a high flux research reactor of 100 MW_{th} capacity was designed,

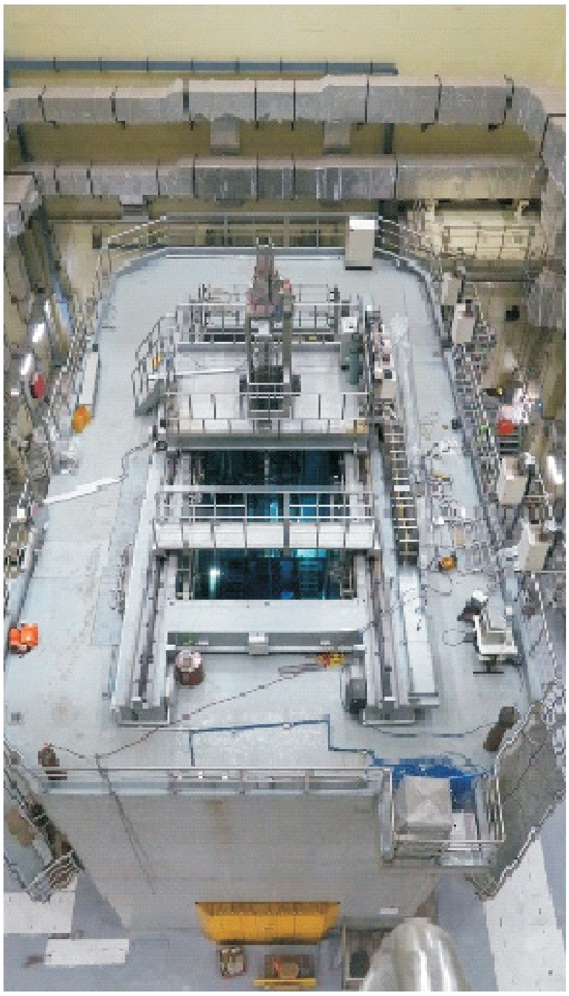
Dr. Homi Bhabha, Shri N.B. Prasad and others in CIRUS Control Room @ BARC Photo



Apsara-U Facility



Cherenkov Radiation during Power Operation



Reactor Pool Top

constructed and commissioned indigenously. Originally named the R-5, and subsequently renamed as Dhruva by the then President of India Dr. Gyani Zail Singh, this reactor first went critical on 8 August 1985.

Dhruva is a 100 MW_{th} reactor with metallic natural uranium as fuel, heavy water as moderator, coolant and reflector, giving a maximum thermal neutron flux of 1.8 x 10^{14} n/cm^2/ sec. Many of the reactor structure designs were a forerunner; to be adopted for the standardized Indian PHWR being designed at that time. Manufacturing of the reactor vessel which is over 7 meters in height, 3.72 meters in diameter and weighing about 30 tons was taken up in the central workshop of BARC. Many evolving technologies such as plasma arc cutting of thick (50 mm) stainless steel plates, precision welding and electron beam welding etc. were developed and successfully employed for the fabrication of reactor vessel. Fabrication of the 300 mm diameter beam hole re-entrant cans for the use in neutron beam research posed another big challenge. A cold rolling facility was set up at MIDHANI Hyderabad where the zircaloy-2 plates were cold rolled to the requisite uniform thickness. Technology for electron beam welding of zircaloy-2 plates in a glove box under argon atmosphere was developed in DRDL Hyderabad. Development of rolled joints for 300 mm diameter between SS and zircaloy-2 beam tubes was a major developmental activity. Designing of the re-fuelling machine for safe and reliable operation was another challenging work. The machine carrying fuel assemblies was to make a leak tight joint with the coolant channel and continue cooling of the fuel during transit. For this the fuelling machine, having lead shielding and weighing over 300 Tons is to be aligned with the channel with in an accuracy of ± 0.25 mm.

The design, construction, commissioning and operation of Dhruva have been a completely indigenous effort. In addition to the engineers and scientists of BARC, several governmental institutions and public sector and private industrial organizations in the country have participated in the above, meeting very stringent requirements. This high flux reactor which was designed, constructed and commissioned entirely indigenously reflects the country's resolve to achieve self-reliance in nuclear technology. For last 35 years Dhruva has been extensively utilised for engineering and beam tube research, testing of equipment and material and large scale production of isotopes.

Apsara-U is an upgraded version of the Apsara reactor, with 2 MW rated power. Here the reactor core is replaced with Low Enriched Uranium (LEU) in the form of U_3Si_2 dispersed in aluminium matrix as fuel to meet the international requirement. The core is surrounded by two layers of beryllium oxide reflectors. The reactor core is suspended from a movable trolley and can be parked at three reactor core positions inside the pool like the old Apsara reactor. The maximum thermal neutron flux is enhanced to 6.1×1013 n/cm^2/s in the core region and maximum thermal neutron flux in reflector region is increased to 4.4×1013 n/cm^2/s. Maximum fast neutron flux is 1.3×1013 n/cm^2/s. The higher neutron flux facilitates production of isotopes for applications in the field of medicine, industry and agriculture. The Apsara-U also provides enhanced facilities for beam tube research, neutron activation analysis, neutron radiography, neutron detector development & testing, biological irradiations, shielding experiments and training of scientists and engineers.

All the systems and components of Apsara-U are designed and manufactured to meet enhanced power level for better utilization of the reactor adhering to the latest safety codes and standards. The direction of primary coolant flow through the core has been made downward to avoid mixing of radioactive water directly with the reactor pool. The water from core outlet is sent through a delay tank to reduce the radiation field in the process equipment room to a reasonably low value, and the major short-lived activities are allowed to die down before the water is circulated back to the reactor pool. Additionally, a hot water layer is provided on the top of the pool water, which reduces the radiation field at the pool top to acceptably low values. Emergency power supply is provided for all the safety related equipment for the reactor.

Apsara-U reactor core is mounted on a 140 mm thick aluminium grid plate having 64 lattice positions arranged in 8 x 8 square array with a lattice pitch of 79.7 mm. The central 4 x 4 lattice positions of the core are loaded with fuel assemblies and are surrounded by two layers of BeO reflector assemblies. The core has two types of fuel assemblies, viz. Standard Fuel Assembly (SFA) with 17 fuel bearing plates, and Control Fuel Assembly (CFA) with 12 fuel bearing plates. Various types of reflector assemblies are designed to satisfy the requirements of positioning of various components in the reflector region such as fine control rod, irradiation positions, fission counters, thermocouple in addition to reflecting the neutrons towards the core standard BeO reflector assemblies.

The reactor power is controlled by means of two Control-cum-Shut-Off Rods (CFA-CSRs) and one Fine Control Rod (FCR). The shutdown of the reactor is also achieved by the CSRs. In addition, two Shut-Off Rods (SORs) are also provided to shut down the reactor. The CSRs and SORs are located inside control fuel assemblies. Twin fork type control element has been developed using Hafnium plates to cater to the control and shut down requirements.

In order to ensure the fuel safety, the coolant velocity has been so chosen that for the hottest standard and control fuel assembly and shut-off rod assembly, the fuel meat and clad temperatures do not exceed the prescribed limits. Accordingly, the primary coolant flow has been augmented with secondary flow to meet the high heat removal requirement. A natural circulation valve is developed to meet the requirements of core cooling in case forced circulation is not available due to failure of the primary coolant pump.

Research Reactors offer a diverse range of applications such as neutron beam research for material studies and non-destructive examination, neutron activation analysis to measure very small quantities of an element, radioisotope production for medical and industrial use, neutron irradiation of fuel and structural materials for advanced nuclear power plants, neutron transmutation doping of silicon, etc. Besides, RRs have contributed significantly in education and training of operators, maintenance staff, radiation protection and regulatory personnel, students and researchers.

Neutron Beam Research

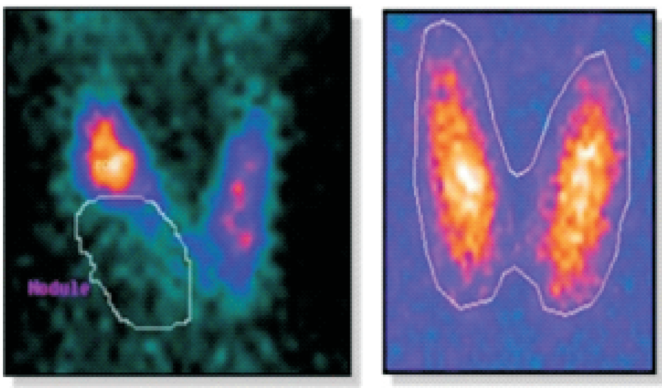
The internal structures of matter at microscopic and atomic levels are very important to understand as they determine macroscopic properties of a material including how they react. The short range strong interaction of neutron with matter and its inherent magnetic moment makes neutron scattering a unique probe to analyse solid and condensed fluid matter. An important advantage of neutron over other forms of radiation is that neutron, being neutral in charge, can penetrate the bulk of materials. The incident monochromatic neutrons are scattered without a change in their energy i.e. elastic scattering which informs about the arrangement of atoms in materials. When the neutrons undergo inelastic scattering i.e. a change in their energy during scattering, they can yield information about the dynamics of atoms. By performing neutron scattering, biologists understand proteins essential for the functioning of brain; how bones mineralise during development or how they repair or decay with age. Physicist can create more powerful magnet that could be of use in accelerators or levitated transport. Chemist improves batteries and fuel cell. Material scientist can improve steel for use in aircraft, nuclear reactor and many other challenging applications.

Radioisotope Production and Applications

A stable material can be made radioactive by bombarding it with neutrons in a reactor. The radioisotopes, thus produced, can be widely used for societal benefits especially in industry and medicine.

Radioisotopes are now considered indispensable in the diagnosis of a variety of diseases and also in therapy. In diagnosis, two types of techniques are employed, the first one being the in-vivo techniques, where the patient is administered a radio-pharmaceutical either orally or intravenously. The distribution of the injected radio-pharmaceuticals in different organs/metabolic pathways is studied from outside the body by using a suitable radiation detector such as gamma camera. Such techniques provide images of the organ function. Thus the procedure not only provides anatomical information but also the more important functional information about the organ.

Neutron Transmutation Doping (NTD)-Si, which is the process of creating non-radioactive dopant atom from the host Si atoms by thermal neutron irradiation and its subsequent radioactive decay, has been used extensively in manufacturing of



Thyroid Images using ^{99m}Tc
Normal scan (left) and an abnormal scan (right)with poor uptake in the left lobe, due to nodules

Buddha relic (original)

Neutron Tomography of Buddha relic: Wax remnants on surface due to bronze casting process were detected (last)

high power semiconductor devices. The quality of NTD-Si, both from the viewpoints of dopant concentration and homogeneity has been found superior to the quality of doped silicon produced by conventional methods.

To summarize, our research reactors have made tremendous contributions to almost all facets of science and technology. However, one of the bigger technological challenges is to refurbish them, not only to meet present day safety requirements and technology standards, but also to enhance their useful life. In this regard, a systematic ageing programme is required to be established at an early stage of reactor operation. Dhruva has already completed more than 35 years and it has been decided to refurbish the reactor for long term operation of at least 20-25 years. Main challenges involve safety evaluation and upgrades, remote handling techniques for inspection of inaccessible components etc. The expertise gained during refurbishment of Cirus would help in implementing this ambitious programme in a long way.