Research Reactors in India

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Preamble

Research Reactors have been the back bone of the nuclear industry. They have provided a valuable support in development of the Indian Nuclear Power Program in many ways, viz. testing of materials, fuel, equipment, shielding experiments, validation of codes etc. During the course of construction of these reactors lot of new technologies were developed which turned out to be the fore runners for use in power reactors. In addition to the above these, reactors have also provided lot of societal benefits by way of radioisotope production. This paper highlights the history of development of Research Reactors and their role in nuclear industry.

Historical Perspective

On December 2nd, 1942, something incredible happened at the squash courts of the University of Chicago. Enrico Fermi, the Italian born Physicist demonstrated, to the world, the feasibility of extracting controlled energy from self-sustaining neutron chain reaction. Shortly thereafter, as early as in 1944, even before India attained independence, Dr Homi Bhabha was already formulating the strategy for setting up a nuclear research programme in India.

In line with his vision, one of the earliest decisions he took was to build research reactors (RR) of different types. Each of these rapidly accelerated the understanding of the complex issues involved in the control of nuclear chain reaction. The design of reactors involves high levels of optimisation of geometry, fuel design, safety, material selection, irradiation behaviour of fuel and structural materials. These could be mastered only by building test reactors, which use different types of fuels, structural materials, coolants etc. Toward this end, several research reactors were systematically designed and built during different stages of the programme. The first of these reactors was a swimming pool type of reactor, aptly christened “APSARA” – the celestial nymph by Pandit Nehru himself. The basic design of the reactor was frozen in July 1955 and Indian scientists and engineers completed the construction in just over a year. With APSARA, India became the first Asian country outside the erstwhile Soviet Union, to have designed and built its own nuclear reactor.

The next crucial step involved the planning of larger reactors having much higher neutron flux and power than what was available at APSARA. This plan materialised in 1960 with the building of CIRUS, a high power (40MWt) research reactor. This reactor, then known as the Canada India Reactor or CIR for short, was built in collaboration with Canada. These early gains catapulted India into an ambitious nuclear program. CIRUS and APSARA have provided the necessary confidence and expertise for design and safe operation of many nuclear reactors in the country.

In early 1961, a zero energy critical facility named ZERLINA (Zero Energy Reactor for Lattice Investigations and New Assemblies) was built, for studying various geometrical aspects (lattice parameters) of a reactor fuelled with natural uranium and moderated with heavy water.

The three stage programme calls for building plutonium based reactors in the second stage. Therefore, the next logical step was to build a critical facility, which used plutonium as fuel. Such a test reactor was built in 1972 and was named PURNIMA (Plutonium Reactor for Neutronic Investigations in Multiplying Assemblies). This reactor was intended for studying the behaviour of plutonium fuel in a pulsed fast reactor (PFR). Following this, a critical facility called PURNIMA-2 was designed, with a solution containing 400 g of uranyl nitrate serving as the fuel for this facility. It attained criticality in 1984.

In the early seventies, a need was felt for a research reactor having even larger neutron flux and irradiation volumes than CIRUS, for meeting the growing requirements for radioisotopes and research. This culminated in building of a totally indigenous 100 MWt research reactor, having the highest flux in Asia at that time. It attained criticality in August 1985 and was named DHRUVA.

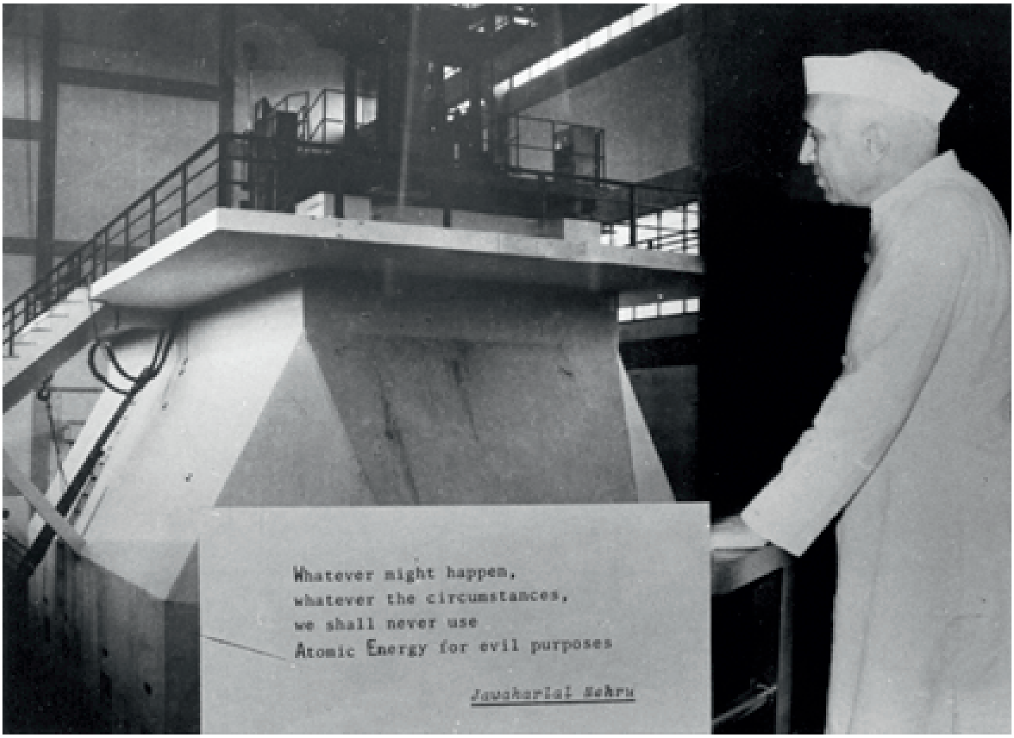
Research Reactors – Salient Features

Research Reactors have been the back bone of the nuclear energy program. They have supported the program in many ways, viz. testing of materials, fuel, equipment, shielding experiments, validation of codes etc. During the course of construction of these reactors several new technologies were developed which turned out to be the forerunners for use in power reactors. In addition to the above, these reactors have also provided lot of societal benefits by way of radioisotope production.

Research reactors are primarily meant to provide neutron source for research and applications in healthcare, neutron imaging, neutron activation studies, neutron scattering etc. Generally, any upcoming technologies are proven in a RR before their implementation in commercial power reactors. RRs are generally simpler and smaller than commercial power reactors with power level varying from zero power to few hundreds of MW, and generally operate at a low temperature. They use much less amount of fuel than a power reactor, but their fuel may require uranium with much higher enrichment (U-235). They may have a very high power density in the core. Being flexible, RRs are best suited for testing of nuclear fuels of various reactor types, studying the safety margins of nuclear fuel, and developing accident tolerant and proliferation resistant fuels for future reactors. Unlike power reactors having standardised 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.

APSARA

The very first research reactor of Asia, named Apsara, was commissioned in BARC (then AEET) in the year 1956. It was a 1MW, swimming pool type reactor fueled 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. The maximum thermal neutron flux available in the reactor was 10^{13}n/cm^2/s. 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 only fast neutron 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. Neutron radiography has also been carried out in Apsara, which has been used for components of space programme. Various shielding experiments to verify the design adequacy of shield configurations used in reactors such as Dhruva, PHWRs, 500MW Prototype Fast Breeder Reactor etc. had been carried out in the shielding corner of Apsara. The reactor was shut down permanently in the year 2009.



Apsara- The First Research Reactor of Asia at BARC

CIRUS

Subsequent to the experience with Apsara, a need for high power research reactors which would 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 MWt reactor. The reactor was natural uranium fueled, heavy water moderated, graphite reflected and light water cooled. It produced a flux of 6.5 x 10^{13}n/cm^2/s. 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 in1985. The reactor had a pneumatic carrier facility, where short term irradiations could 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 sixself-serve units, in which on-power irradiation of 30 samples could 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 thefuel. Irradiation of various structural materials of the power reactors such as end shield and Zircaloy pressure tubes of PHWRs etc. were carried out at CIRS PWL. These experiments built the confidence for designing and operating power reactors.

In those days, CIRUS and Apsara became centers 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

Research Reactor Cirus at BARC

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 honor the Civil Nuclear Deal.

DHRUVA

During the early seventies, strong need was felt to build are search 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 highflux research reactor of 100 MW capacity was designed, 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_t reactor with metallic natural uranium as fuel, heavy water as moderator, coolant and reflector, giving a maximum thermal neutron flux of $1.8 \times 10^{14} n/cm^2/s$. 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 beamwelding 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-2beam tubes was a major developmental activity. Designing of there-fueling 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 fueling machine, having lead shielding and weighing over 300 Tons, is to be aligned with the channel within an accuracy of ± 0.25 mm.

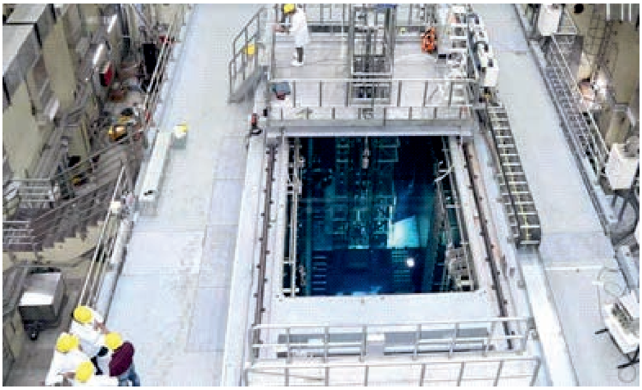
Research Reactor Dhruva at BARC

The design, construction, commissioning and operation of Dhruva has been a completely indigenous effort. In addition to the engineers and scientists of BARC, several government 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 more than 36 years, Dhruva has been extensively utilized for engineering and beam tube research, testing of equipment and material and large scale production of isotopes.

APSARA-U

Apsara-U is an upgraded version of the Apsara reactor, with 2MW 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 6.1×10^{13} n/cm^2/s in the core region and maximum thermal neutron flux in reflector region is increased to 4.4×10^{13} n/cm^2 /s. Maximum fast neutron flux is 1.3×10^{13} 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.

Apsara-U reactor core is mounted on a 140 mm thick aluminium grid plate having 64 lattice positions arranged in 8 x 8square array with a lattice pitch of 79.7 mm. The central 4 x 4lattice 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 standard BeO reflector assemblies, reflecting the neutrons towards the core.

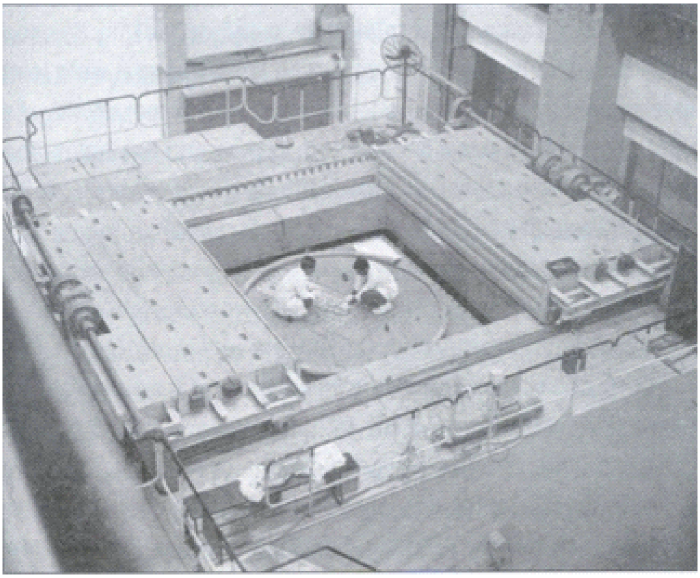


Reactor Pool of Apsara-U Research Reactor at BARC

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.

ZERLINA

Zerlina was the third reactor to be built in India and was a totally indigenous facility. This reactor was built for the purpose of studying various core geometries. The geometric arrangements of the fuel elements in the core, called the lattice has a significant bearing on the physics of reactors. At the time of embarking on a large power programme, there was a need for an experimental reactor in which different types of lattices could be assembled with ease. This would help evaluate their reactor physics characteristics and develop satisfactory computer coded for the design of both research and power reactors. Zerlina was made critical on January 14, 1961. All the measurements for Dhruva reactor lattice physics were carried out in Zerlina. This facility was also used for many experiments where computational modelling of neutron absorbing / producing assemblies is difficult. Zerlina played an important role in development of measurement techniques, inter-calibration of neutron activation foils of alloys and standardisation of counting set-ups. All these aimed at improving measurement accuracies. Zerlina played a key role in evaluating various design parameters and some of the components of Dhruva, like reactor instrumentation and start-up systems. The reactor core characteristics of MAPS reactor and various instruments, including safety related systems developed for India's nuclear programme by different agencies were also evaluated in Zerlina. Zerlina was decommissioned in 1983, as it was felt that a lattice experiment facility was no longer needed.



Zero Energy Reactor for Lattice Investigations and New Assemblies – Zerlina at BARC

Purnima Series of Reactors

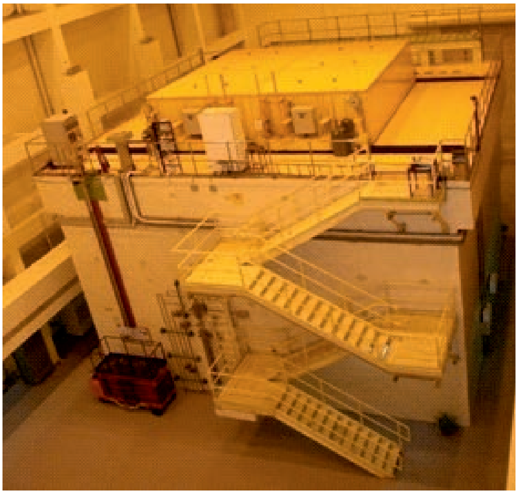
The second and third stage of nuclear programme entails the construction of fast breeder reactors which use plutonium and thermal reactors using U-233 respectively. The Purnima series of reactors were built for gaining experience in designing such reactors. Purnima was designed as a zero-energy fast research reactor. It attained criticality on May 18, 1972. Later called as Purnima-1, the reactor was extensively used for carrying out detailed studies on fast reactor neutronics. The core of Purnima was dismantled after carrying out all planned experiments. The infrastructure developed for this reactor was later used to house the subsequent Purnima series of reactors.

After completion of Purnima-1, a ^{233}U uranyl nitrate solution fueled beryllium oxide reflected zero energy thermal reactor called Purnima-2 was set up. This reactor attained criticality on 10 May 1984. A major objective of this reactor was to perfect the technique of carrying out criticality experiments. Purnima-2 made a significant contribution toward development of ^{233}U fueled reactors. The reactor was shut down in 1986.

Purnima-3 was built and used as a test bed and zero energy critical facility to study the core of KAMINI (Kalpakkam Mini) reactor. In this reactor, ^{233}U-Al alloy (20%) flat plate type fuel subassemblies and beryllium oxide reflectors clad with aluminium/zircaloy were used. The reactor was made critical on April 29, 1992. Experiments were performed to study various core-reflector configurations of interest to Kamini reactor. The core of Purnima-3 was dismantled and the fuel was transferred to Kamini reactor in 1996.

Critical Facility

For conducting lattice physics experiments for validating Advanced Heavy Water Reactor (AHWR) design parameters, a 400 W reactor called Critical Facility was commissioned in 2008.



AHWR-Critical Facility at BARC

Core of AHWR-Critical Facility

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 analyze 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 mineralize 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 nuclear 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 radiopharmaceutical 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 Activation Analysis

Neutron activation analysis is an important technique to determine elements at major, minor and trace concentration levels in samples of wide variety accurately and precisely. It is a sensitive and selective technique capable of quick detecting and quantifying multiple elements even from a small sample. The sample is subjected to neutron irradiation in a reactor facility and later the characteristic gamma radiation emitted by the activated nuclei is detected to identify trace elements in ppb range. The techniques are used in environmental and life science, forensic science, material science, quantification of elements in a mineral ore sample and archaeology. A large number of case exhibits (transmission wires, bullet materials) referred to from various central/state forensic laboratories, have been examined to give an opinion about source correspondences/commonness of origin. Determination of toxic trace element such as Chromium, Mercury in food materials and Arsenic in potable water have been carried out. Several rock samples, including meteoric sample have also been examined for their Rare Earth Element concentrations.

Neutron Imaging and its applications

Neutron imaging as a non-destructive testing method can be used for a broad spectrum of industrial/scientific applications. When a beam of neutrons passes through a sample, it leaves the image of the sample on a detector. The neutron interacts with nuclei of the atoms that compose the sample and the absorption and scattering properties of neutron make it possible to create the image. It can even produce image of lighter element like hydrogen. The neutron imaging technique finds application in fault detection in the engineering components, distribution of hydrogen, boron and cadmium in metals, water transport in soil/plant/fuel cell, study of cultural artefacts for preservation and restoration, real time neutron radiography is also used for flow visualization of two phase flow.

Neutron Transmutation Doping (NTD)-Si

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 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.

Conclusion

Materials used for the nuclear energy programme are very different than those used for general engineering purpose since the nuclear properties exhibited by them play an important role in their selection. Irradiation behavior of any material is a very complex phenomenon and its testing in appropriate reactor environment is very important to understand its characteristics. Everything that goes into a power reactor is appropriately tested in a research reactor, qualified and only then it is allowed to be used in a power reactor. Research Reactors have played a pivotal role for the development of the Nuclear Energy programme in the country.

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