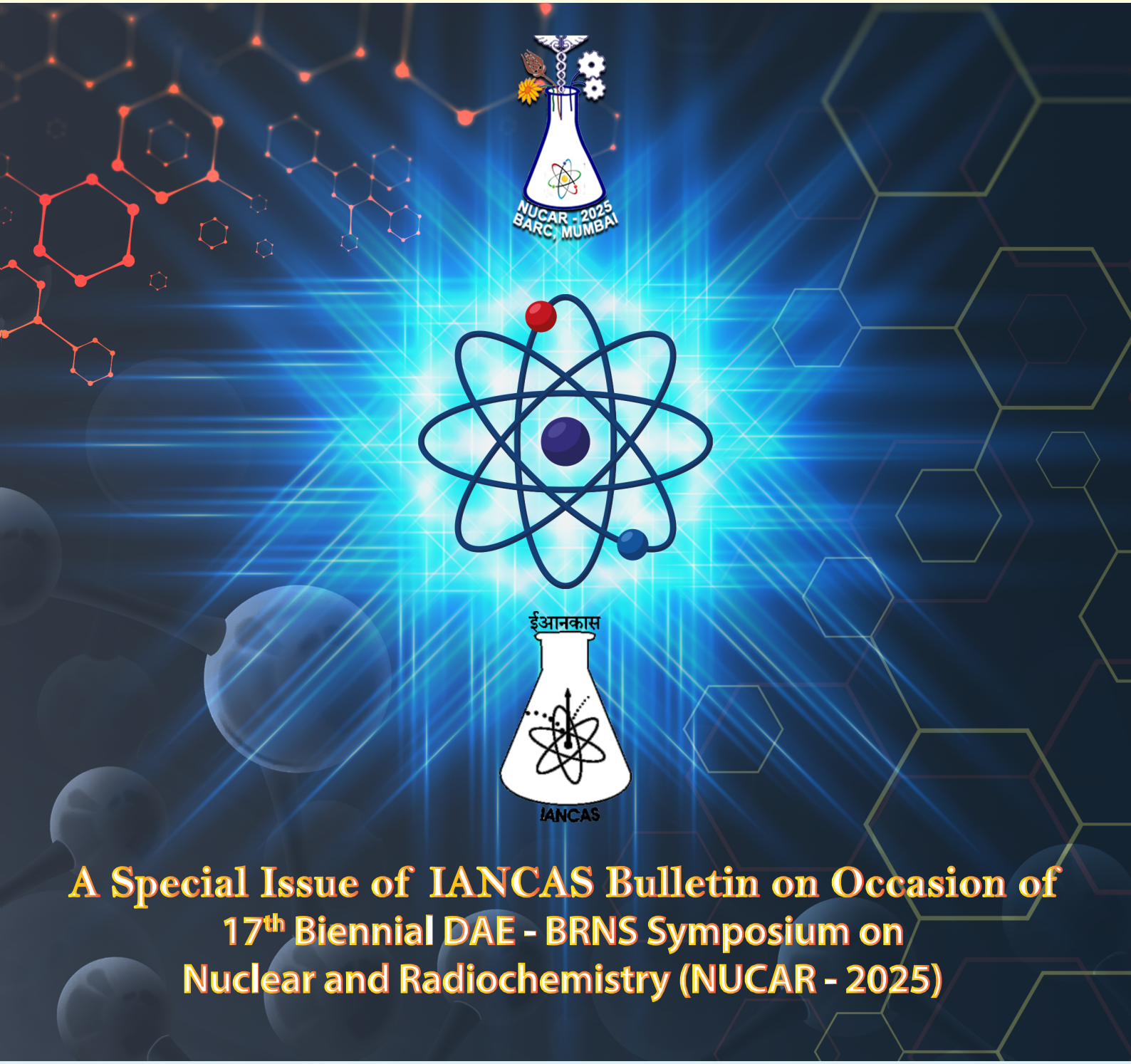
Souvenir

DAE / BARC Research Reactors and Accelerator Facilities for Research, Development and Societal Applications



A Special Issue of IANCAS Bulletin on Occasion of
17th Biennial DAE - BRNS Symposium on
Nuclear and Radiochemistry (NUCAR - 2025)

Organized by

Bhabha Atomic Research Centre, Mumbai
Indian Association of Nuclear Chemists and Allied Scientists (IANCAS)

भारी पानी बोर्ड, मुंबई
परमाणु ऊर्जा विभाग
Heavy Water Board, Mumbai
Department of Atomic Energy

प्रौद्योगिकीय संपदा के माध्यम से राष्ट्र का गौरवान्वयन
Creating Pride for the Nation through Technological Wealth

नाभिकीय एवं विशेष ग्रेड का भारी पानी
Nuclear & Special Grade Heavy Water

पोटैशियम धातु Potassium Metal

ड्यूटेरियम गैस Deuterium Gas

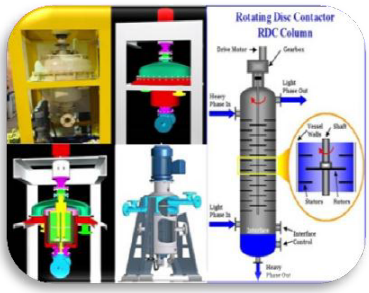
एनएमआर विलायक NMR Solvents
($CDCl_3$; Acetone-d6; DMSO-d6; Acetonitrile-d3 etc.)

बोरॉन-10&11 Boron-10&11

नाभिकीय ग्रेड सोडियम
Nuclear Grade Sodium

निष्कर्षण धातुकर्म हेतु विलायक
Solvents for Extractive Metallurgy

स्वास्थ्य सेवा हेतु सामग्री
Materials for Healthcare
(पीईटी स्कॅनिंग हेतु ऑक्सीजन-18 जल ^{18}O Water for PET Scanning; कैंसर के उपचार हेतु ड्यूटेरियम क्षीण जल Deuterium Depleted Water for Cancer Care)



नए उपकरण, पदार्थों और प्रकियाओं का विकास तथा अभियांत्रिकी सेवाएं
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Souvenir

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Organized by

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at

DAE Convention Centre, Anushaktinagar, Mumbai – 400 094

Editors

R. Acharya, Archana Mukherjee, S. A. Ansari and S. K. Rakshit

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Preface

This special bulletin is designed to provide accessible and comprehensive information to researchers working in DAE facilities, with the aim of fostering collaboration and enhancing the utilization of available facilities. The issue features 15 contributed articles detailing various reactor and accelerator facilities, along with the types of research and societal applications they support.

Articles focusing on reactor facilities provide insights into the Dhruva and Apsara-U reactors, as well as critical facility dedicated to research activities. These are followed by contributions on the utilization of reactors for neutron scattering experiments, the production of radioisotopes for healthcare, and the application of radioisotope techniques for optimizing industrial processes and improving product quality. One article highlights the KAMINI reactor at Kalpakkam, emphasizing its use in characterization studies and neutron activation analysis. In addition to reactor facilities, this issue also features various accelerator facilities within the DAE that support a wide range of activities. These include Cyclotron Facility at RMC, Mumbai, which focuses on the production of medically important radionuclides for clinical applications. Details of the BARC-TIFR Pelletron Linac Facility (PLF), FOTIA, Ion Beam Analysis Facilities at the Institute of Physics, Bhubaneswar, and the 3 MV Tandem Accelerator Facility at NCCCM-BARC, Hyderabad are also provided.

A dedicated article by the DAE Task Force highlights the collaborative potential of research reactors, ion-beam accelerators, and materials research facilities at BARC, encouraging joint initiatives both within DAE units and with academic institutions. The issue also includes an overview of the services provided by the commercial wing of DAE—Board of Radiation and Isotope Technology (BRIT) for societal applications of radiation and radioisotopes. Finally, the role of the Board of Research in Nuclear Sciences (BRNS) is outlined, showcasing its continued support for nuclear science and technology advancement through extramural research funding. This bulletin represents an effort to strengthen collaborations among research groups across India in the pursuit of excellence in nuclear science and technology. We extend our sincere thanks to all contributors for providing such valuable insights. We hope this information will be widely shared and utilized by DAE researchers and the broader academic community.

Editors
R. Acharya
Archana Mukherjee
Seraj A. Ansari
S. K. Rakshit

About IANCAS

Indian Association of Nuclear Chemists and Allied Scientist (IANCAS) was founded in 1981 with an objective of popularizing Nuclear and Radiochemistry, Applications of Radioisotopes, and Nuclear Techniques among the scientific community in India. For this purpose, IANCAS is continuously organizing seminars, workshops and publishing periodic thematic Bulletins focused on fundamentals of Nuclear and Radiochemistry and applications of radioisotopes in education, research, agriculture, medicine and industry. At present, IANCAS has 2023 life members from different Indian institutes and universities. With active participations of the life-members, IANCAS has become one of the popular associations for popularizing the subject of Nuclear and Radiochemistry across the country.

IANCAS through its various outreach programs motivate the young researchers and scientists to apply Nuclear and Radiochemistry based methods in their respective research field. In addition, IANCAS life-members through IANCAS activities motivate students to pursue a career in the field of Nuclear Science. For the promotion of Nuclear Science among the researchers, IANCAS has instituted three awards; (i) Dr. M. V. Ramaniah Memorial Award (ii) Dr. Tarun Dutta Memorial Award, and (iii) Prof. H. J. Arnikar best thesis Award. All these three Awards are conferred annually. Dr. M. V. Ramaniah Memorial Award is conferred to an outstanding scientist for the significant contributions in the field of Nuclear and Radiochemistry during his/her lifetime. Dr. Tarun Dutta Memorial Award is given to a scientist (below 45 years age) having significant contributions in the field of Nuclear and Radiochemistry including the applications of radioisotopes. Prof. H. J. Arnikar best thesis Award is given for the PhD thesis focused on Nuclear and Radiochemistry and application of radioisotopes etc. In addition, IANCAS has instituted Dr. K.S. Venkateswarlu Memorial Endowment Lecture which is biannually bestowed during NUCAR symposium to the scientists / academics in recognition of their contributions in the area of water chemistry & related field.

IANCAS publishes thematic Bulletins on the topics directly related to the Nuclear Science and Technology with the financial support from BRNS, DAE. These Bulletins are distributed free to all IANCAS life-members, and are made freely available at IANCAS website (www.iancas.org.in) for download. The association's popular book on "Fundamentals of Nuclear and Radiochemistry" is widely sought amongst the academia, researchers and students from DAE and Universities.

Information about the workshops, Awards and various other activities of IANCAS are available on the website (www.iancas.org.in). All the publications of IANCAS including Bulletins and books are also available at the website.

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IANCAS

How to Become a Member of IANCAS?

Join IANCAS and help in popularizing the subject of Nuclear and Radiochemistry. Life Membership of IANCAS is open and can be obtained by applying online and payment of a nominal Membership Fees of Rs. 1000/-

To become a member, please visit the IANCAS website:

https://www.iancas.org.in/join-iancas.php

Fill the online application form and pay the membership fee online by NEFT (Bank details are available on website). Members can also deposit membership fees in cash to any SBI Brach with the bank details given below.

Bank: State Bank of India
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IFSC Code (For NEFT): SBIN0001268

In the online application, attach a recent passport size photograph and the transaction receipt (online of offline) and submit.

On submission of the online form, a confirmation e-mail will be sent to the applicant. After scrutinizing the details of the applicant, Life-Membership Number will be issued and will be communicated to the applicant by e-mail.

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17th Biennial DAE-BRNS Symposium on Nuclear and Radiochemistry (NUCAR-2025)
DAE Convention Centre, Anushaktinagar, Mumbai – 400094
April 23-26, 2025.

Technical Programme

Day 1: Wednesday, April 23, 2025	
08:00- 09:30	**Registration**
09:30-10:30	**Inaugural Function**
10.30-11.00	**Inauguration of Exhibition Stalls and High Tea**
Session 1: (11:00 to 13:00)	
Session Chair: Dr.V.Venugopal &Co-Chair: Dr. A.V.R. Reddy	
IT-1	***Fabrication of Fast Reactor Fuels and their Characterization*** *Amri tPrakash, BARC, Mumbai.*
IT-2	***Research and Development of Microsphere based Fuels for Advanced Reactor Concept*** *Rajesh V. Pai, BARC, Mumbai.*
IT-3	***Development of Solvents for Nuclear Fuel Cycle*** *C. V. S. Brahmananda Rao, IGCAR, Kalpakkam.*
IT-4	***New Methodologies and Substrates for the Assay of Actinides using NuclearRadiations*** *Rahul Tripathi, BARC, Mumbai.*
Lunch (13:00 – 14:00)	
Session 2 (14:00 to 16:00) **Poster Presentation** **A2, A3, A5, A7, B1, B2, B3, B4, B5, B6, B7** **C1, C2, C3, C4, C6, C7, C8, C9, C10, C11, C13, C14, C15** **D1, D2, D3, D4, D5, D7, D8** **E1, E2, E3, E4, E5, E6, E7, E8, E9, E10** **F1, F2, F3, F4, F5, F6, F7, F8, F9, F10, F11, F12, F13, F14, F39** **G1,G2, G3, G4, G5, G6, G7, G8, G9, G10,** **G11, G12, G13, G14, G15, G16, G17, G18** **I1, I2, I3, I5, I6, I7, I18**	
Session 3: (16:00 to 18:00)	
Session Chair: Dr. K.L. Ramakumar & Co-Chair: Dr.Y. Balaji Rao	
ISP-1	***Direct Solid Sampling of Nuclear Materials for Chemical Quality Assurance – An Advanced ETV-ICP-OES Application*** *S.B. Deb, BARC, Mumbai.*
ISP-2	***Development of Ion Chromatography as an Analytical Tool in the Nuclear Material Fabrication process at Nuclear Fuel Complex*** *Shehanaz Bano, Nuclear Fuel Complex, Hyderabad.*
ISP-3	***Radiation Detection using Scintillators for Multiple Applications*** *LiviuMatei, MSAG, Fisk University, USA.*
Oral Presentations	**A-1, B-9, D-23, F-31,I-4, H-1**
19.00 onwards	**Dinner**

Day 2: Thursday, April 24, 2025	
Session 4 (9:30 to 10:30)	
Session Chair: Dr.S.K. Aggarwal& Co-Chair: Dr. A.C. Bhasikuttan	
IT-5	***High-Precision Mass Spectrometry Methods for Environmental Radionuclide Analysis*** *NobertKavasi, Fukushima Institute for Research, Education and Innovation (F-REI), Japan*
IT-6	***Isotopic Separations at Heavy Water Board*** *Ajit R. Dusane, Heavy Water Board, Mumbai.*
Tea Break (10:30– 11:00)	
Session 5 (11:00 to 13:00)	
Dr. M. V. Ramaniah Book Release & IANCAS Award Ceremony	
Lunch (13:00 – 14:00)	
Session 6 (14:00 to 16:00) **Poster Presentation** **A8, A10, A11, A12** **B8, B10, B11, B12, B13, B14, B15** **C16, C17, C18, C19, C21, C22, C23, C24, C25, C26, C27, C29, C30,C35** **D9, D10, D11, D13, D14, D15, D16** **E11, E12, E13, E14, E15, E16, E17, E18, E19, E20** **F15, F16, F17, F18, F19, F21, F22, F23, F24, F25, F26, F27, F28, F30** **G19, G20, G21, G22, G23, G24, G25, G26, G27, G28, G29, G30, G31, G32, G34, G35, G36, G37** **H2** **I8, I9, I10, I11, I12, I13**	
Session 7 (16:00 to 18:00)	
Session Chair: Dr. B.S. Tomar & Dr. C.N. Patra	
IT-7	***The Approaches to Design the Ligands for Separation of f-elements*** *V. G. Petrov, Lomonosov Moscow State University, Russia.*
Oral Presentations	**A-4, A-6, C-5, C-12, C-20,D-6, D-12, D-24, G-33**
18.00-19.30	**Presentations by IANCAS Awardees**
19.30 onwards	**Dinner by IANCAS**

Day 3: Friday, April 25, 2025	
Session 8 (9:30 to 11:00)	
Session Chair: Dr. P. K. Mohapatra & Co-Chair: Dr. P.A. Hassan	
IT- 8	***Production and Applications of Radioisotopes at RIKEN RI Beam Factory– Search for New Elements through Therapy of Cancer*** *H. Haba, Nishina Center for Accelerator-Based Science, RIKEN, Japan.*
IT-9	***Physics Safety and Utilization Aspects of Research Reactors*** *Tej Singh, BARC, Mumbai.*
IT-10	***Climate Change Impacts on Global Water Resources – Role of Nuclear Techniques*** *Chidambaram S., Kuwait Institute for Scientific Research, Kuwait.*
Tea Break (11:00 – 11:30)	
Session 9 (11:30 to 13:00)	
Session Chair: Dr. P.K. Pujari & Co-Chair: Dr. Smeer Durani	
IT-11	***Delayed Molecular Hydrogen Production in Portlandite Under Irradiation: Reaction Mechanisms and Consequences for the Storage of Radioactive Waste*** *Sophie Le Caer, Université Paris-Saclay, France.*
ISP-4	***Calibration Free Laser Ablation Molecular Isotopic Spectrometry – A New Outlook to the Isotopic Composition Determination of Boron*** *Arnab Sarkar, BARC, Mumbai.*
ISP-5	***Dynamics of Neck-Rupture in Nuclear Fission using Particle Emission as a Probe*** *Y. K. Gupta, BARC, Mumbai.*
ISP-6	***Nuclear Instrumentation and Application of AI*** *P. P. Shete, BARC, Mumbai.*
Lunch (13:00 – 14:00)	
Session 10 (14:00 to 16:30)	
Session Chair: Dr. A.R. Joshi & Co-Chair: Dr. Umesh Kumar	
	Presentation by Exhibitors
Oral Presentations	**A-9, C-28, D-20, F-20, F-29, G-54, G-57**
Session 11 (16:30 to 18:00) **Poster Presentation** **A13, A14, A15, A16, A17** **B16, B17, B18, B19, B20, B21, B22** **C31, C32, C33, C34, C36, C37, C38, C39, C40, C41, C42, C43** **D17, D18, D19, D21, D22, D25, D26** **E21, E22, E23, E24, E25, E26, E27, E28, E29, E30** **F32, F33, F34, F35, F36, F37, F38, F40, F41, F42, F43, F44, F45, F46** **G38, G39, G40, G41, G42, G43, G44, G45, G46, G47, G48, G49, G50, G51, G52, G53, G55, G56** **H3, H4** **I14, I15, I16, I17, I19, I20**	
19.30 onwards	**Dinner**

Day 4: Saturday, 26 April, 2025	
Session 12 (9:30 to 11:00)	
Session Chair: Dr. N. Sivaraman & Shri M.K. Saxena	
IT-12	***Back End Fuel Cycle- Status and Current Trends*** *Madhuri Shetty, BARC, Mumbai.*
IT-13	***Recent Advances in Nuclear Waste Management Practices in India*** *D. Banerjee, BARC, Mumbai.*
IT-14	***Advanced Materials for Selective Capture and Removal of Radionuclides in Nuclear Waste Management*** *Debajit Sarma, IIT Patna, Patna*
Tea Break (11:00 – 11:30)	
Session 13 (11:30 to 13:00)	
Session Chair: Dr. S. Kannan & Dr. Amrit Prakash	
IT-15	***Development of Fluoride based Salts for Molten Salt Reactor*** *S. C. Parida, BARC, Mumbai.*
ISP- 7	***Molten Salt-based Electrochemical De-oxidation of Uranium and Thorium Oxides*** *R. Kumaresan, IGCAR, Kalpakkam.*
ISP- 8	***Fissile Zone Identification System(FIZIDS)*** *K. Sundararajan, IGCAR, Kalpakkam.*
ISP- 9	***Development of Potentiometric Sensors for Lanthanides and Actinides*** *Bholanath Mahanty, BARC, Mumbai.*
Lunch (13:00 – 14:00)	
Session 14 (14:00 to 15:30)	
Session Chair: Prof. V.K. Manchanda & Dr. Y.K. Bhardwaj	
IT -16	***Regulatory Clearance and Hot Commissioning Experience of DFRP*** *K.Rajan, IGCAR, Kalpakkam.*
ISP-10	***Recent Advances in Industrial Applications of Radiotracers for Process Optimization in Glass Production and Waste Water Treatment*** *Jayashree Biswal, BARC, Mumbai.*
ISP-11	***Medical Cyclotrons: An Essential Need for Cancer Management*** *M. R. A. Pillai, Ex- BARC, Mumbai*
ISP-12	***Radiolabeled Somatostat in Analogs for Diagnosis and Therapy of Neuroendocrine Cancers: In-house Synthesis, Quality Control and Preliminary Clinical Investigation*** *V. Kusum Vats, BARC, Mumbai.*
15.30 to 17.00: Panel Discussion and Valedictory Function	

Contents

Experimental and Irradiation Facilities at Dhruva Research Reactor

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Introduction

The availability of high flux of neutrons in the research reactors facilitate basic and applied research in the field of chemistry, physics and biology, production of radioisotopes for application in the fields of medicine, agriculture and industry; irradiation and testing of reactor materials and nuclear fuels; neutron radiography and neutron activation analysis. Research reactors have played a vital role in the development of nuclear technology in our country. Research reactor Dhruva is fulfilling all such requirements of researchers.

Brief History of Research Reactor Program of BARC

The Indian nuclear program started with the building of a 1 MW_{th} pool type research reactor "Apsara' in the year 1956 at Bhabha Atomic Research Centre (BARC). A 40 MW_{th} reactor 'Cirus' and a low power test reactor 'Zerlina' for physics studies of future reactors were subsequently set-up during 1960 and 1961 respectively. Apsara &Cirus was utilized in a number of ways during its 50 years of safe operation and is presently under the process of decommissioning. Another facility called Zerlina reactor was constructed and later decommissioned after carrying out required reactor physics studies related to Natural Uranium fuel and HW moderator. Towards this, construction and commissioning of Purnima series of reactors were undertaken during the period 1970-1992, to study the reactor systems based on Plutonium and Uranium-233 and various aspects of Thorium utilization. After required experimental studies these reactors were decommissioned. Research Reactor Dhruva was successfully commissioned in year 1985 through totally indigenous efforts. Dhruva is presently a workhorse for utilizing technologies related with high neutron flux. To optimize and confirm the physics design parameters of such an Advanced Heavy Water Reactor (AHWR) a 'Critical Facility' for lattice investigations was commissioned in BARC in year 2007. The facility is being widely utilized for Physics experiments, detector testing and irradiation of samples of irregular shape and larger sizes. Simple design of Apsara reactor, its vast utilization and its aging related issues called for construction of similar facility with some enhanced features as per operating experience with the old reactor. Accordingly, Apsara-U (U stands for upgraded) was designed and commissioned in the year 2018. The new reactor with increased flux is now ready for all challenges in terms of its utilization.

Present status of Research Reactors at Trombay

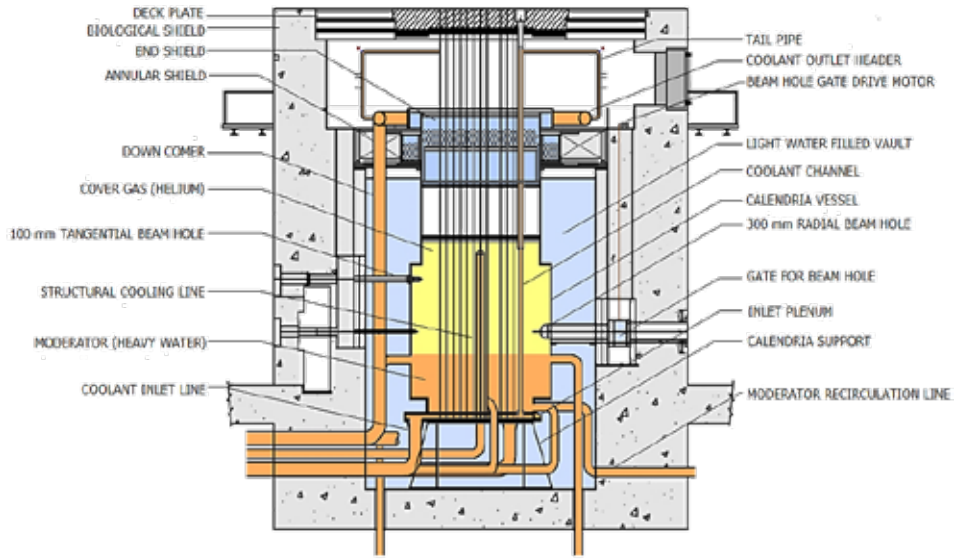
Presently research reactor Dhruva, Apsara (U) and Critical Facility at Trombay complex are operational and meeting demands of a number of researchers in field of basic sciences & material testing. Apsara (U) and Dhruva have additional challenge to meet supply of radioisotopes for medical and industrial use. Important design aspects, facilities and utilization of these reactors have been explained below.

The Research reactor DHRUVA

Dhruva is a 100 MW_{th} research reactor using natural metallic Uranium fuel and heavy water as

coolant, moderator and reflector. Maximum thermal neutron flux available at the rated power is 2.0 x 10^{14} n/cm^2/sec. There are a total of 146 lattice positions in the reactor vessel, out of which normally 128 positions are used for loading the fuel assemblies and 9 positions contain the cadmium shut-off rod. The remaining positions are used for isotope production and experimental facilities.

In last 35 years of operation, Dhruva has been extensively used for basic research in neutron beam technology, radio -isotope production and neutron activation analysis. Besides such utilization, some of the fuel and other in-core positions have also been used for carrying out certain specific engineering experiments for material and special fuel testing. Reactor has been also been utilized for man power training in the field of nuclear technology.



General arrangement of Dhruva Reactor

Special features of Dhruva reactor

For the prospective of Dhruva utilization, most important feature of the research reactor is its large core size, high thermal neutron flux (Max 2×10^{14} n/cm^2/sec), availability of excess reactivity in the core and feasibility of installation of experimental assemblies in any coolant channel. High neutron flux not only facilitates production of isotopes of higher specific activity in bulk, but also results in high neutron flux in beam tubes(~10^9 n/cm2/sec at pile face) for neutron beam utilization. Excess core reactivity permits a verity & bulk of material irradiation in the core. Each of the coolant channels in Dhruva is instrumented. Thus, any experimental assembly (with similar geometry of Dhruva fuel assembly and meeting specific safety requirement) can be installed in any fuel channel for material testing, special fuel irradiation or isotope production. Coolants flow though such experimental assemblies can be suitably controlled to meet thermal-hydraulics requirements and to limit vibration.

Irradiation facilities at Dhruva

Isotope Tray Rod

These provide facility for producing fairly large quantities of radioisotopes after appropriate period of irradiation at high flux levels. There are two tray rods for regular isotope production. Each tray rod can handle 90 capsules containing targets enclosed in cold weld standard aluminium Can (capsules of 22 mm diameter and 42 mm height). Three numbers of such aluminium containers are kept around the central rod to form a tier. Each tray rod assembly has 30 such tiers. The tube has a window in front of each tier. The central rod can be rotated to bring any of the three tiers for capsule removal and reloading fresh capsules in a shielded cell called tray rod Facility (TRF) with master slave manipulator. The tray rods are heavy water cooled. The demand for production of radio isotopes is to be met on a weekly basis. Earlier, for loading and unloading of samples to and from the tray rod, the reactor had to be shut down. To reduce the frequency of reactor shut downs on this account, further development work was carried out to enable the tray rod operations with reactor operating at high power. Regular irradiation in on-power tray rod was started at H-07 pile position since 1999. A second on-power tray rod was installed in K-09 pile position with provision for irradiation of Xenon gas in August 2008. To meet the bulk demand of radioisotopes of higher half-life, additional isotope tray rods in fuel position (commonly called as off power tray rod) and Slug rods were also installed in to Dhruva core time to time. These tray rod /Slug rod are meant for long term (months to years) irradiation of target material and are handled during main coolant pumps in off condition only. The designs of such tray rods are similar to standard tray section to accommodate standard aluminium capsule for irradiation as in case of On-power tray rod. Slug rods can have specific design to accommodate slugs of target material (e.g. cobalt pencils) and coolant path. These assemblies can be installed in any coolant channel after certain modification in processing circuit of flow and temperature instrumentation as flow requirement for such assemblies are lesser as compare to channel containing standard fuel assemblies.

In past a number of tray rods in Fuel position and slug rods (such as Cobalt slug rods, antimony rods, Zircaloy rods etc) were installed in pile on specific requirements. A vast number of radioisotopes for application in healthcare, industries, agriculture and research are produced in Dhruva. Refer annexure-1 showing detail of important isotopes produced in Dhruva. For medical applications, presently, Dhruva is producing radioisotopes for meeting 40-50% demand of I-131 (annual production ~1200-1500 Ci), 10-15% demand of Mo-99 (annual production ~1000 Ci), 75-80% demand of Lu-177 (annual production ~500Ci) and 100% demand of Sm-153 (annual production~250-300 Ci) and I-125 (annual production 20-25 Ci) of our country.

Pneumatic Carrier Facility (PCF)

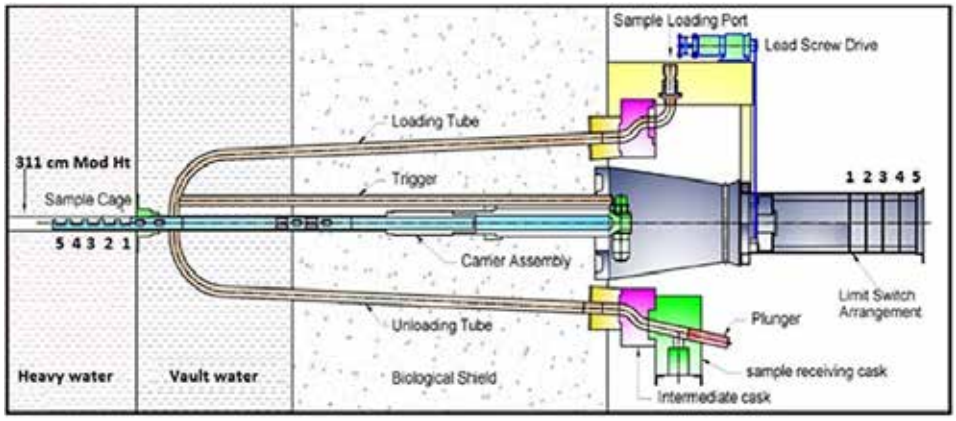
The facility is specially meant for the irradiation of short-lived samples which require minimum transit time between the completion of irradiation and counting. This facility has provision for shooting the sample into the core for irradiation and receiving back the same from a laboratory located outside reactor building. In this facility, the samples are encapsulated in 25 mm diameter and 38 mm long ethylene propylene capsules and are pneumatically transported to a carrier rod in the reactor from the fume hood located in attached laboratory. Samples are received back in the same fume hood after the required period of irradiation. Irradiation of samples is fully automated. The facility provides a neutron flux of the order of 5×10^{13} n/cm^2/sec at the irradiation location at a reactor power of 50 MW. The facility is mainly used for neutron activation analysis. This technique provides not only rapid quantitative simultaneous analysis

down to ppb level or below but also provides critical validation support to other techniques. The growth and success have been mainly due to the availability of research reactors with high neutron flux and to the advances in high neutron spectrometry systems. A wide variety of samples were irradiated in PCF for application in material sciences, environmental and life sciences, forensic science and archaeology. PCF has also been used for determination of uranium by solid-state nuclear track detector (SSNTD) using fission track analysis (FTA).

Self-Serve Facility

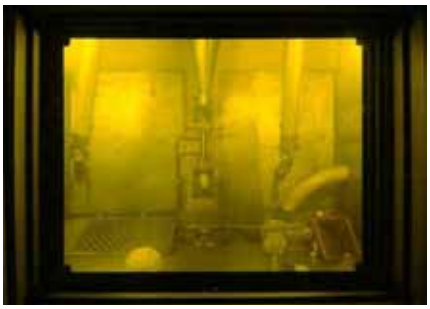
Self-serve facility is meant for producing smaller quantity of radioisotopes at relatively lower flux levels and for irradiation of samples with intermediate half-life for NAA. This irradiation can be carried out without affecting the reactor operation for a pre-determined time and is ideally suited for the production of short-lived radioisotopes. The irradiation period may be of few hours to couple of days as per user's requirement. The Self-Serve unit is located at upper through tubes. At present one of Self-Serve unit is operational and being utilized for samples irradiation. The Self-Serve unit has five irradiation locations in reflector region of the Core. An Aluminium capsule containing target material is enclosed inside a spherical ball as shown in figure. The ball is rolled into the irradiation location under gravity and at the end of irradiation the ball is rolled out into a lead shielded flask. Refer diagram below showing setup of Self-Serve unit for sample movement. Further extraction and handling of sample is carried out in the tray rod facility hot cell. The facility provides a neutron flux of the order of 5 x 10^{12} n/cm^2.sec at the irradiation location. Presently, three irradiated position of Self Serve-2 is being used for irradiation of Capsules. A number of rock and glass samples has been irradiated in Self-Serve for NAA.

SELF SERVE BALL WITH CAPSULE



Tray Rod facility (TRF)

For loading and unloading of isotope capsules from tray rod, a hot cell (commonly called tray rod facility) has been provided in Dhruva. It can handle a maximum activity of 2x10^5 Ci of Cobalt-60. The cell is equipped with through-the-wall type master slave manipulator (MSM) having slave arm in hot cell and master arm in the control station.



Radiation Shielding Window

Neutron Beam Holes in Dhruva

A large number of horizontal beam hole facilities have been provided in Dhruva reactor for neutron beam experiments as also for sample irradiations. Such beam neutrons are used in a variety of ways by means of sophisticated on-line computer-controlled instruments to

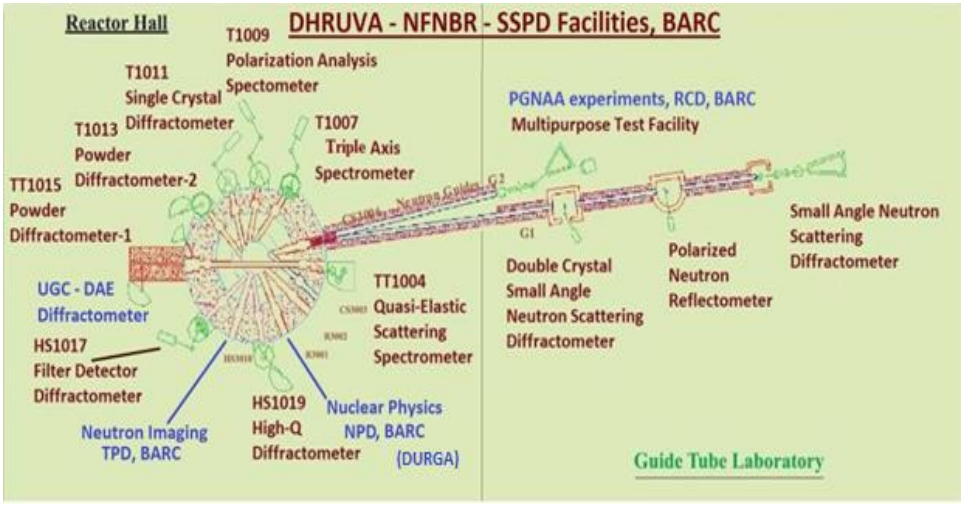
- Basic research related to Atomic physics, chemistry, material science etc.
- To determine characteristics pertaining to crystalline, magnetic structures, nature of atomic motions,
- Investigate materials for engineering, metallurgical, chemical, biological behaviour
- Nuclear fission and Decay investigations
- Neutron radiography.

In Dhruva, the following beam holes have been provided for experimenters:

- Four 100 mm diameter tangential beam holes
- Four 100 mm diameter radial beam holes
- Two 300 mm diameter radial beam holes
- Two through-tubes of 100 mm diameter providing four experimental ports.
- One 300 mm diameter beam hole, originally designed for installation of a cold neutron source, with a rectangular satellite port for installation of neutron guides.
- One 300 mm diameter beam hole originally designed for installation of a hot neutron source with a provision of two 100 mm diameter satellite ports for beam extraction.

The provision of tangential beam holes and through tubes for neutron beams are new features, built into the experimental facilities at Dhruva. Tangential beam holes provide better neutron to core gamma discrimination which is helpful to conduct experiments using neutron beam with reduced gamma flux from core. 100mm beam holes are used by for Solid state physics experiments related to neutron scattering using instrumented setup near pile face. The flux at pile face at 100MW_{th} operation is 10^9 n/cm^2/sec.

In the figure various beam tubes and their utilization by the researchers has been shown.



Special facilities have been setup at 300 mm diameter beam holes to utilize them for specific purpose. Presently facilities for neutron imaging and fission spectrum studies have been installed at 300 mm beam holes. It has also been planned to commission new facilities in these beam

holes such as intense Positron Radiography and facility to measure residual stress using Neutron scattering techniques. Each beam hole assembly is provided with two gates for shielding. The inner gate, located inside the biological shield and electrically operated, is used to open or close the neutron beam entering the experimental area. The outer gate is meant for shielding, whenever the beam hole is being utilized for irradiation of samples.

Neutron Beam research

Facilities available for utilizing 100 mm beam lines for basic research

There are four neutron scattering facilities at the tangential beam lines, three at the ends of the through tube, two at the radial beam lines and three instruments in the guide laboratory. Six diffractometers, (two small angle neutron scattering facilities, and one neutron reflectometer) help to study structures of magnetic materials, ferroelectrics, soft matter, nanomaterials, amorphous compounds, glasses, thin films, multilayer's, as a function of composition and/or temperature, pressure, and magnetic field. Three neutron spectrometers facilitate the study of excitations (lattice vibrations, molecular/ magnetic/ diffusive) in materials (crystalline, soft matter, nanomaterials).

Guide tube Laboratory

Cold neutron beams can be transported using guides, to the laboratory located adjacent to the reactor building for conducting experiments in low gamma and neutron back ground condition. Two neutron guide tubes G1 and G2 (length: 21 m and 35 m, radius of curvature: 1916 m and 3452 m, characteristic wavelength: 3.0 Å and 2.2 Å respectively) transport neutron beams in to Guide-Tube Laboratory from the reactor hall. Average flux at the breaks, provided on the guides to accommodate various instruments, is ~ 10^7 n/cm2/sec.

UGC-DAE CSR facility

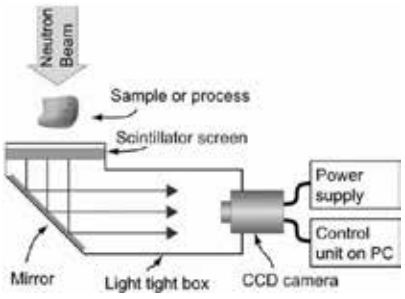
UGC-DAE consortium for Scientific research (CSR) facilitates utilization of the Nation facility for neutron beam research (NFNBR) at Dhruva reactor by scientists and students from Universities and various academic institutions across the country. CSR scientists have developed and installed neutron powder diffractometer along with a unique sample environment for carrying out neutron diffraction experiments at low temperatures and high magnetic field. The setup has been installed at beam hole of lower through tube the reactor. The diffractometer is mainly used for characterization of novel magnetic materials.

Experimental Hutch

Utilization of 300 mm beam Holes

Thermal neutron imaging at beam hole HS-**3018**

Techniques such as radiography or tomography are very useful tools for various scientific investigations and industrial applications. Neutron radiography is complementary to X-ray radiography, as neutrons interact with nucleus as compared to X-ray interaction with orbital electrons. A neutron imaging beam-line has been designed and developed at 100 MWth



Dhruva research reactor for neutron imaging applications such as radiography, tomography and phase contrast imaging. Combinations of sapphire and bismuth single crystals have been used as thermal neutron filter/gamma absorber at the input of a specially designed collimator to maximize thermal neutron to gamma ratio. The maximum beam size of neutrons has been restricted to ~120 mm diameter at the sample position. A cadmium ratio of ~250 with *L/D* ratio of 160 and the thermal neutron flux is ~4×107 n/cm2/sec at the sample position. Non-destructive radiography/ tomography experiments on hydrogen concentration in Zr-alloy, aluminium foam; ceramic metal seals etc. have been carried out on this beam line.

DURGA for Fission spectrum studies at beam hole R-3001

Dhruva Utilization in Research using Gamma Array (DURGA) is a unique facility in the country to carry out prompt-gamma coincidence spectroscopy measurement using thermal neutron beam of Dhruva at beam hole R-3001. A unique facility in the country for nuclear structure studies of neutron-rich nuclei following thermal neutron induced fission reactions and Capture Gamma Spectroscopy (CGS). In the present configuration, the hybrid gamma detector array consists of six Compton-suppressed high-purity clover Ge detectors and an equal number of $LaBr_3$(Ce) fast Scintillators. The heart of the DURGA facility is a state-of-the-art, trigger less data acquisition system. Prompt and decay spectroscopy of neutron-rich fission fragment nuclei is one of the main research objectives of this facility. Apart from this, the facility is used heavily in studying Capture Gamma Spectroscopy (CGS). From application point of view, investigation of nuclear isomers and fuel cycles of actinides, relevant to reactor operation/designing, are planned to be carried out.

Testing of Neutron detectors

Neutron detectors of various types and sensitivities are developed by Electronics Division of BARC and ECIL Hyderabad. Before these detectors can be used for various reactor regulation or protection systems and they have to be tested for their performance under simulated conditions. One of the Dhruva beam holes has been utilized for accelerated life testing of newly developed ion chambers. 3 pitch Inconel SPNDs used in Indian PHWR were also tested in one of beam hole of Dhruva. Spare positions of Ion chamber baskets of Dhruva are also being utilized for checking performance of detectors of new design.

In-core Material irradiation and experimental fuel testing

Irradiation of Zircaloy calandria tube samples

For Calandria tubes (CT) of Indian PHWR, to evaluate the relative irradiation performance of seamless Zircaloy calandria tubes vis-a-vis seam welded Zircaloy calandria tubes, a specially made assembly called Zircaloy slug rod was irradiated in Fuel channel position in Dhruva. The assembly consists of various samples of zircalloy fabricated though different fabrication routes which were test irradiated in Dhruva reactor to study their comparative In-pile growth behavior. These studies along with subsequent studies done at FBTR for higher fluence, resulted in finalization of manufacturing route for the PHWR Calandria tubes.

Irradiation of Thoria assembly

A number of Thoria assemblies were irradiated in fuel positions of Dhruva. The irradiation program had helped in generating first-hand experience of Thorium-based fuel cycle, especially in U-233 production, and contamination level of U-232 in U-233.

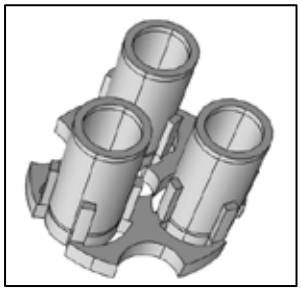
Antimony rod irradiation for Start-up source in power reactors

Antimony Pins for Sb-Be start-up source are being irradiated in Dhruva as per requirement of Power reactors of NPCIL

9.0 Additional enhancements for meeting current demand of radioisotopes

9.1 Irradiation of Cobalt-60

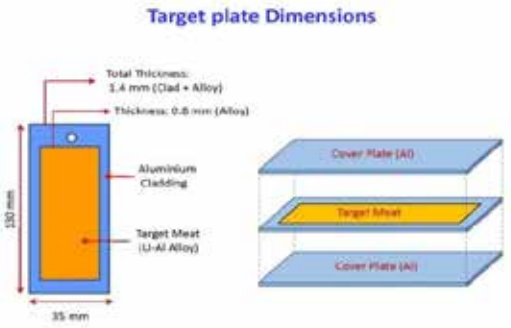
In order to meet the increasing demand for low specific activity of Co-60, for supply of Gamma Chambers and Blood Irradiator to various users in countries and abroad, Nickel plated Cobalt-59 slugs of 36 gm each in standard Al-cans are being irradiated in off power tray rod in the reactor. For meeting requirement of Co-60 of very high specific activity (>200 Ci/gm), beads of Co are being irradiated in a specially made zircaloy capsule in new Adjuster rod of Dhruva. These capsules are designed to confine 10 gms of Cobalt pellets of 1 mm diameters and 1 mm height in its annuals space. The shape of capsule is such that it ready to use in Tele-therapy source and same need not to be cut to extract out pallets of cobalt. Capsules has been loaded in to a specially made tray section of the Adjuster rod of Dhruva shown in figure. 45 capsules can be loaded in to the tray section of the adjuster rod.



Zr capsules in Adjuster Rod Tray section

M**oly-99 Production by Fission Molly**

Nuclear fission is the most widespread method to produce Mo-99 of very high specific activity. A preliminary analysis for production of fission moly in Dhruva reactor has been carried out with LEU-Al alloy as target material. The proposed Fission Moly target consists of a rectangular fuel meat plate of dimension 114 mm (Long) x 30 mm (Wide) x 0.8 mm (Thick) and clad of 0.3 mm thickness. The target fuel meat is UAl3 produced from dispersion of UAl2 in Aluminium-1S matrix. The cladding material of the fuel meat is Al. The targets is being loaded in to containers and same are being further loaded and irradiated in a specially designed and tray rod assembly installed in a regular fuel Channel position. At rated operation of Dhruva Reactor, with 12 Target plates, Total activity of Mo-99 after pre calibration time (~8 days) can be as high as 300Ci. Irradiation of such LEU targets has been started on regular basis in Dhruva.



Special Experiments

Validation of Thermal Hydraulic codes with instrumented fuel rod

The steady state and transient temperature of Dhruva fuel pin clad were evaluated theoretically using different thermal hydraulic models and codes. In order to validate the design, an instrumented fuel assembly was fabricated and irradiated at Dhruva to measure temperature of

fuel pin clad during steady state and transients. Instrumented fuel assembly was similar to the regular fuel assembly of Dhruva. Five thermocouples were fixed at predicted hot spot elevations on four outer pins and one central fuel pin of the assembly. The steady state and rate of change of clad temperature of fuel pin clad were monitored during reactor operation and power changes. A flow coast down experiment was conducted at high reactor power by tripping all main coolant pumps simultaneously. The results matched reasonably well with the results obtained by COBRA-IV-I.

Neutron Noise Measurement

Establishing applicability of neutron noise measurement technique for diagnostics of in-core components for heavy water reactors a specially designed assembly consisting of five neutron sensors with integral cable assembly, mounted at different elevations was installed in one of the vertical experimental positions in reactor core. The AC component of the signal was electrically separated and recorded simultaneously with vibration signal tapped by accelerometers mounted on nearby core structure extensions. The recorded signal was analysed by FFT analyser. Prominent distinct frequency peaks could be identified both in the AC output of the neutron sensors of the special assembly and the mechanical vibration of in-core structures. This experiment indicated that neutron noise could be effectively utilized as an early diagnostic technique for in-core components in heavy water reactors.

Man Power Training

During the last 35 years a large number of Engineers, Scientists, operators and technicians have been trained at Dhruva reactor. This trained manpower is contributing to our nuclear programs in various capacities.

Conclusion

The research reactors in BARC have provided valuable operating experiences of over 100 reactor-years. The insight gained in construction and operation of research reactors like Dhruva has played a significant role in developing India in all respects related to our nuclear program. The various irradiation and experimental facilities in Dhruva have been well utilized and help in achieving new heights in production of radioisotopes and material testing.

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A Glimpse of Neutron Scattering Facilities at Dhruva Reactor

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Introduction

Neutron scattering is an essential tool for characterization of structure and dynamics in condensed matter that encompasses a wide spectrum of multidisciplinary research. Penetrating power inside materials, simultaneous sensing capabilities of both light and heavy atoms, comparable wavelength (/energy) to the atomic length scale (/basic excitations) in materials, magnetic sensibility etc. have made thermal neutron a unique probe for characterization of materials. A variety of materials including ceramics, biological, soft matter, nuclear, pharmaceuticals, engineering, etc. are being routinely investigated by neutrons, aiming to design novel materials for societal applications in the domains including spintronics/electronics, quantum technology, energy harvesting and storage, pharmaceuticals, drug delivery and cosmetics, water treatment, nuclear waste management. In this article a few recent research highlights based on the neutron scattering facilities in Dhruva is provided.

Unlike x-ray photons with a similar wavelength, that interacts with the electron-cloud surrounding the nucleus, neutrons interact primarily with the nucleus. This makes neutron very sensitive to light atoms like hydrogen, which are difficult to detect using x-rays. Neutrons can also distinguish between the neighbouring atoms of the periodic table like iron, cobalt, and nickel. Scattering and absorption cross sections of neutron vary widely among the isotopes of an element and thus neutron can distinguish between the isotopes. Neutrons have a magnetic moment, which allows them to interact with the atomic magnetic moments through dipole–dipole interaction. Therefore, neutrons can be used to investigate microscopic magnetic structures.

Today, the neutron scattering activity in India is mainly centred around the indigenously built Dhruva reactor (a medium flux, natural Uranium, heavy water moderated, heavy water-cooled reactor; max thermal power 100 MW, max central thermal neutron flux $\sim 1.8 \times 10^{14}$ neutrons/cm^2/s) and it serves as the National Facility for Neutron Beam Research (https://nssi.org.in/pdfs-files/NFNBR-Brochure-2024.pdf).

The National Facility for Neutron Beam Research (NFNBR), Dhruva contains eleven beamlines developed by Solid State Physics Division (SSPD). The facilities developed, maintained and operated by SSPD, BARC are i) Triple Axis Spectrometer ii) Polarized Neutron Spectrometer, iii) Single Crystal Diffractometer, iv) Powder Diffractometer I, v)Powder Diffractometer II, vi) Time of Flight Spectrometer, vii) High Q Diffractometer, viii) Double Crystal Based Medium-resolution Small-Angle Neutron Scattering (MSANS) facility, ix) Polarised Neutron Reflectometer, x) Small Angle Neutron Scattering (SANS) Instrument, and xi) Multipurpose test facility.

These facilities attract a strong national user base of over 200 groups from universities and other academic institutions. At present this is one of a kind of facility in the entire country. Some details of the facilities, the research areas they cater to, the instrument responsible, and some representative publications, are given below.

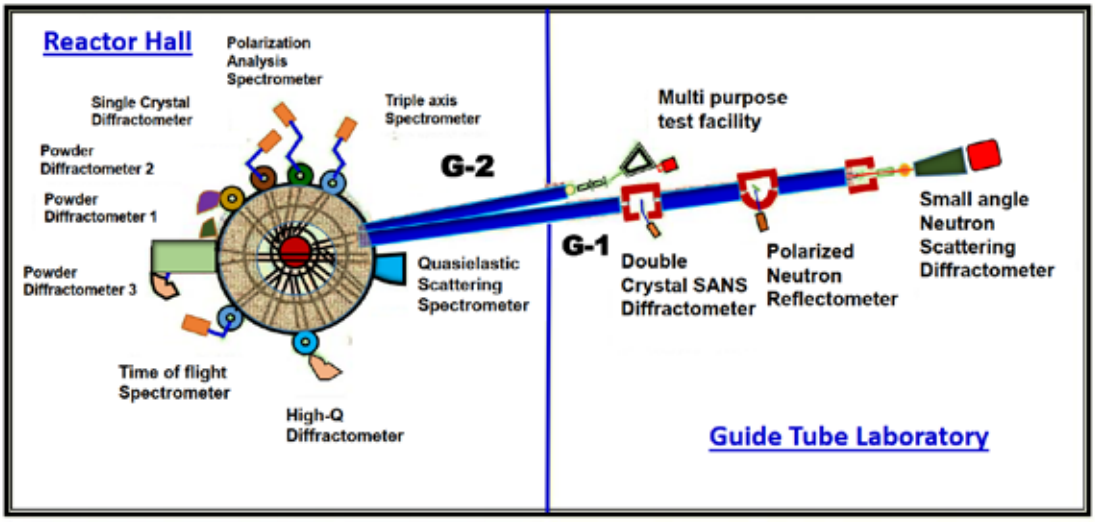

Fig. 1. Layout of the neutron scattering facilities at Dhruva reactor.

Fig. 1. Some photographs of different neutron scattering instruments at Dhruva reactor

The neutron scattering activities can be divided into three sub categories, namely i) Structure in advanced functional and magnetic materials, including thin films and multilayers, ii) Mesoscopic structure and interaction in soft matter and nanostructured materials, and iii) Periodic dynamics in materials.

Structure in advanced functional and magnetic materials

Neutron scattering is an invaluable tool to provide information about the atomic-scale structure of materials. Neutron diffraction can be used for the investigation of crystalline, hybrid nanostructured materials, and to determine the static structure factor of gases, liquids or amorphous materials. The available facilities for carrying out Neutron diffraction are:

Sr.	Facility (Name, and Parameters)	Research Area	Representative publications	Contact Persons
1.	Single Crystal Diffractometer Optimum sample size: 3 mm × 3 mm × 3 mm	Study of high precision 3D structure of materials	1. R. R. Choudhury et al., Bull. Mater. Sci. 44 (2021) 108. 2. R. Chitra et al., Journal of Molecular Structure 1267 (2022) 133550.	Dr R Chitra rchitra@barc.gov.in Dr Rajul R Choudhury rajul@barc.gov.in
2.	High Q Diffractometer Sample requirements: Powder sample 1-2.5 cc (Volume) or pellet of 6-8 mm diameter and height 4.5 cm	Study of short and intermediate range order in glasses, liquids and disordered crystals	1. Manjunath T. Nayak et al., Silicon, 14 (2022) 10337. 2. Amandeep Kaur et al., Phys. Chem. Glasses: Eur. J. Glass Sci. Technol. B 61 (2020) 27. 3. Ranjan Mittal, et. al, Phys. Rev. B 105 (2022) 104106.	Sourabh Wajhal swajhal@barc.gov.in Dr S K Mishra skmsspd@barc.gov.in P S R Krishna glass@barc.gov.in
3.	Powder Diffractometer I Sample requirements: Powder sample (2-5 g) or pellet of 10 mm diameter and height 6 cm	Study of magnetic ordering/ phases in polycrystalline magnetic materials	1. S. K. Kuila et al., Inorg. Chem. 2025 64 (2025) 1798-1807. 2. M. K. Singh et al., Phys. Rev. B 109, 174401 (2024). 3. D. Garg et al., Phys. Rev. B 110, 104401 (2024).	Dr Anup Kumar Bera akbera@barc.gov.in Dr Amit Kumar amitkr@barc.gov.in Dr Anil Jain ajain@barc.gov.in
4.	Powder Diffractometer II Sample requirements: Powder sample 1- 2.5 cc (Volume) or pellet of 6-8 mm diameter and height 4.5 cm	Delineation of chemical and magnetic structure phase diagrams of poly-crystalline materials	1. S Wajhal et al., Journal of Alloys and Compounds 1021 (2025) 17965. 2. A. Jain et al., Phys. Rev. B 110 (2024) 224415. 3. D. Chakrabartty, ACS Nano, 19, 3614-3623 (2025).	Dr S K Mishra skmsspd@barc.gov.in Sourabh Wajhal swajhal@barc.gov.in A B Shinde abshinde@barc.gov.in
5.	Polarized Neutron Spectrometer Sample requirements: Powder sample (2 g) or pellet of 5-6 mm diameter and height 15 mm	Study of 1.Size/magnetization of magnetic domains or clusters at mesoscopic length scales 2. Magnetic correlations	1. A. Chatterjee et al., J. Appl. Phys. 134 (2023) 104103. 2. Deepak et al., Phys. Rev. Materials 5 (2021) 124402. 3. R.N. Bhowmik et al., J. Magn. Magn. Mater. 588 (2023) 171412.	Dr Amit Kumar amitkr@barc.gov.in Dr Anil Jain ajain@barc.gov.in Kuldeep S Chikara kchikara@barc.gov.in

Mesoscopic structure and interaction in soft matter and nanostructured materials

Soft matter and nanostructured materials possess structures at the mesoscopic level, which is between the microscopic and macroscopic scales. Small Angle Neutron Scattering (SANS) is a powerful technique for studying the shape, size distribution of mesoscopic structure, interactions between structures, and morphology of their complexes in soft matter and nanomaterials. In addition, neutron reflectometry is used to study of morphology of thin films heterostructures. The facilities for carrying out SANS and neutron reflectometry are:

Sr.	Facility (Name, and Parameters)	Research Area	Representative publications	Contact Persons
1.	Small Angle Neutron Scattering (SANS) Instrument Sample size: Larger than 15 mm (H) × 10 mm (W) × 1 mm (T) (Approximately 2 ml in volume for liquids and 1 g for solids)	Determination of the structure and interactions at nanometre length scales in systems	1. Sugam Kumar and Vinod K. Aswal, Soft Matter 20, 5553-5563 (2024). 2. R. Laishram et al., J. Am. Chem. Soc. 144 (25), 11306-11315 (2022). 3. A. Sikder et al., Angewandte Chemie 131 (6), 1620 (2019).	Dr Debes Ray debes@barc.gov.in Dr Sugam Kumar sugam@barc.gov.in Dr Sohrab Abbas abbas@barc.gov.in
2.	Double Crystal Based Small- Angle Neutron Scattering (SANS) instrument Minimum required sample size: Larger than 15 mm (H) × 15 mm (W) × 2 mm (T)	Mesoscopic structure in synthesized and naturally occurring materials	1. Ashish Singh, Carbon Trends 19 (2025) 100468. 2. D. Sen et al., Microporous and Mesoporous Materials 323 (2021) 111234. 3. A. Das et al., Langmuir 38 (2022) 3832.	Dr Avik Das avikd@barc.gov.in Dr J. Bahadur, jbahadur@barc.gov.in Dr Debasis Sen, debasis@barc.gov.in
3.	Polarised Neutron Reflectometer Sample size: More than 20 mm × 20 mm	Structural and magnetic characterization of thin film and multilayer samples	1. Preeti Negi et al., Journal of Magnetism and Magnetic Materials 581 (2023) 170941. 2. Debarati Bhattacharya et al., Applied Surface Science 572 (2022) 151300. 3. Surendra Singh et al., Journal of Applied Physics, 137, 065301 (2025).	Dr Surendra Singh, surendra@barc.gov.in Dr D. Bhattacharya, debarati@barc.gov.in Dr Harsh Bhatt, harshbhatt@barc.gov.in

Periodic dynamics in materials

Neutrons can gain or lose energy as they interact with the material, providing information about the energy levels of atomic vibrations and molecular motions. Inelastic neutron scattering (INS) studies the energy exchanged between the neutron and the material, revealing information about the vibrations and other dynamic processes. Neutron spectrometers are used to measure the energy and momentum transferred during neutron scattering, providing detailed information about the material's dynamics. The facilities for INS are:

Sr.	Facility (Name, and Parameters)	Research Area	Representative publications	Contact Persons
1.	Triple Axis neutron Spectrometer Sample requirements: Powder sample (10-15 g) or pellet of 20 mm diameter and height 3-4 cm, single crystal 8-10 cc volume	Measurements of phonon dispersion curves, phonon density of states, and crystal field excitations	1. S.P. Kandare et al., Journal of Physics and Chemistry of Solids 150 (2021) 109819. 2. Prabhatasree Goel et al., Front. Chem. 6 (2018) 331. 3. Prabhatasree Goel et al., J. Appl. Phys. 125 (2019) 205106.	Dr Ranjan Mittal rmittal@barc.gov.in Dr Prabhatasree Goel knp@barc.gov.in Dr M K Gupta, mayankg@barc.gov.in
2.	Time of flight neutron Spectrometer Sample requirements: Powder sample (10-15 g) or pellet of 20 mm diameter and height 3-4 cm	Allows measurement of the scattering function in (Q, E) space	Mala N. Rao et al., Proc. Solid State Phys. Symposium 55 (2021) 358.	Dr Mala N Rao mala@barc.gov.in

Conclusions

In brief, owing to the special attributes of neutrons, neutron scattering technique is unique and it provides the crucial information on structure and dynamics in materials. A strong and focused neutron-based research, encompassing interdisciplinary fields, is being carried out at Dhruva reactor, Bhabha Atomic Research Centre, and is based on the indigenously developed facilities at the Dhruva reactor involving single crystal diffraction, powder diffraction, small-angle scattering, high Q diffraction, reflectivity, in-elastic and quasi-elastic scattering. A wide variety of technologically relevant materials, including ceramics, alloys, glass, magnetic, biological, granular materials, nanostructured materials are being investigated using these facilities. Under NFNBR, a large number of user communities from universities and institutes, all over the country, use these facilities apart from the dedicated in-house research.

Experimental & Irradiation Facilities at Apsara-U Research Reactor

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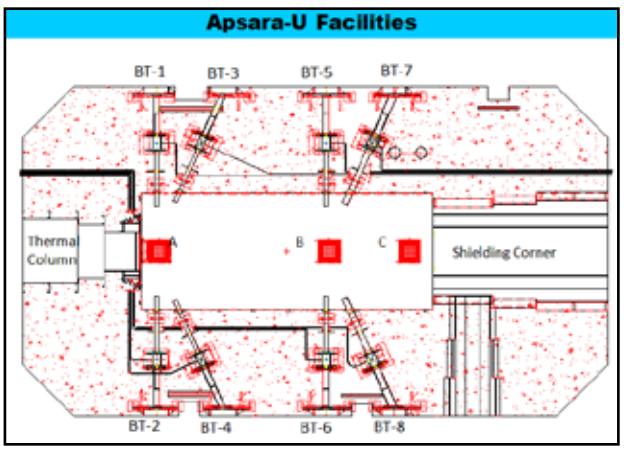
APSARA-U

Apsara-U is a 2 MWth pool type research reactor, made critical on 10th September 2018. The reactor has a maximum thermal neutron flux of 6.1×10^{13} n/cm^2/sec and fast neutron flux of 1.4×10^{13} n/cm^2/sec. It uses indigenously developed low enriched uranium; plate type fuel made of Uranium Silicide dispersed in aluminum matrix. Light water is used as moderator and coolant and Beryllium Oxide as a reflector. The core is cooled by forced circulation of de-mineralized water while shutdown cooling is through natural circulation of coolant. A one meter thick thermally stratified layer of hot water at about 5^0C temperature more than the bulk pool water temperature is maintained at the top of bulk water. It helps to keep the pool top radiation field practically negligible. This is first of a kind system for a reactor in India.

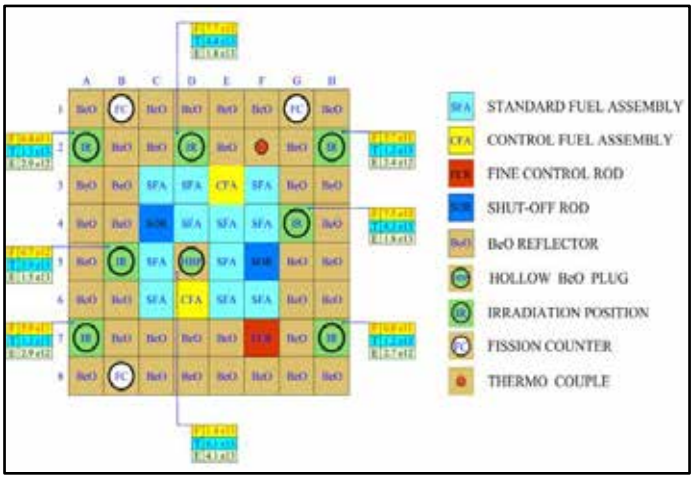
Apsara-U Reactor Core

Facilities at Apsara-U



- Apsara-U is a versatile facility with flexibility of operating the reactor at three different positions A, B & C in the reactor pool, with easy access to the core; facilitating different experiments.
- There are eight beam tubes in position A and B of reactor core, where experimental facilities are being set up by researchers. These include facilities for neutron imaging and depth profile of different materials, prompt gamma neutron activation analysis, single-crystal alignment and neutron detector testing etc.
- Thermal column located at position A will be used for testing of various types of neutrons and gamma detectors as well as for neutron activation analysis. Graphite blocks are stacked in Thermal Column. It has 5 experimental holes, where maximum thermal neutron flux varies from 1.0×10^8 to 1.0×10^9 n/cm^2/sec (Cadmium ratio > 2000).

- Shielding experimental facility is located at position C with neutron flux ~10^{10} n/cm^2/sec, where shielding designs can be validated by carrying out experiments over wide energy ranges.
- Apart from the experimental facilities available in the periphery of the core, in-core and out-of-core irradiation positions for research and irradiation are provided at Apsara-U. The reactor core has 1 in-core position at central location for long term and short-term irradiation of target materials. In addition, 7 irradiation positions in BeO reflector region are provided for long term and short-term irradiation of target materials. Maximum 110 samples can be irradiated at a time in reactor core.
- Special tray Rod assemblies are provided in the reactor for production of radioisotopes. Each tray Rod can accommodate 15 capsules of target material.



Core Configuration with flux level

Neutron Imaging Facility

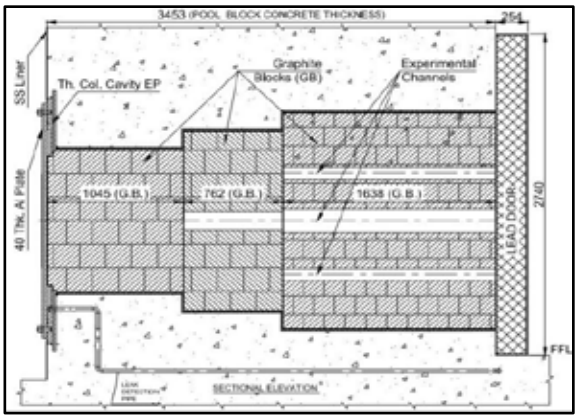
Utilization of Apsara-U

- The reactor is operated on a 24 x 7 basis and mainly utilized for production of radio isotopes. High specific activity Cu-64 in no-carrier added form was developed from Zn-64 by irradiation, which is a very promising isotope with its application in theranostics. After extensive trials, it has been approved for human use by regulator. Major radio isotope produced utilizing Apsara-U reactor are ^{64}Cu, ^{99}Mo, ^{153}Sm, ^{156}Ho etc. Titanium-47 sample

was irradiated for production of an emerging theranostics radioisotope ^{47}Sc. ^{47}Sc has excellent potential for use in personalized cancer management as can be simultaneously used for treatment and monitoring treatment response.

- It offers fast neutron flux (> 1 MeV) of about 1.4×10^{13} n/cm^2/sec, which can be utilized for material irradiation studies.
- Short duration irradiation of samples for material characterization using Neutron Activation Analysis is started as per requirement of researchers.
- A neutron imaging and neutron depth profile experiment facility was installed and commissioned at BT-7 by TPD. Shielding efficacy was verified at 2 MW power. Neutron images of few specimens were taken by TPD at 2 MW power. Feasibility study of Neutron Depth Profiling (NDP) in this experimental set-up was also carried out. Results were found to be very encouraging. This facility is being efficiently used for testing of detectors and research work.
- Installation of a neutron detector test facility at BT-8 and a single-crystal alignment facility at BT-6 by SSPD has been initiated.
- PGNAA facility at BT-5 has been initiated.
- Feasibility of neutron transmutation doping of silicon (NTD-Si) is being explored in Apsara-U. A suitable irradiation location was explored. Measurement of neutron flux profile at the proposed location was carried out by irradiation of gold foils and copper wires mounted on a silicon ingot, at 600 kW power. A number of trial irradiations with small size silicon samples were successfully carried out to gather practical experience in various stages of the doping of silicon. An irradiation set-up is being designed and fabricated for producing NTD-Si at Apsara-U.
- Production of fission molly using fuel mini-plates and using fuel as the target is underway. Integrated trial for handling fission moly tray rod with dummy targets in core and tray rod facility is successfully completed. Safety committee clearance for fission moly production in Apsara-U is underway.

Shielding Experimental Facility



Thermal Column Sectional View

Experimental and Irradiation Facilities at Critical Facility Reactor of BARC

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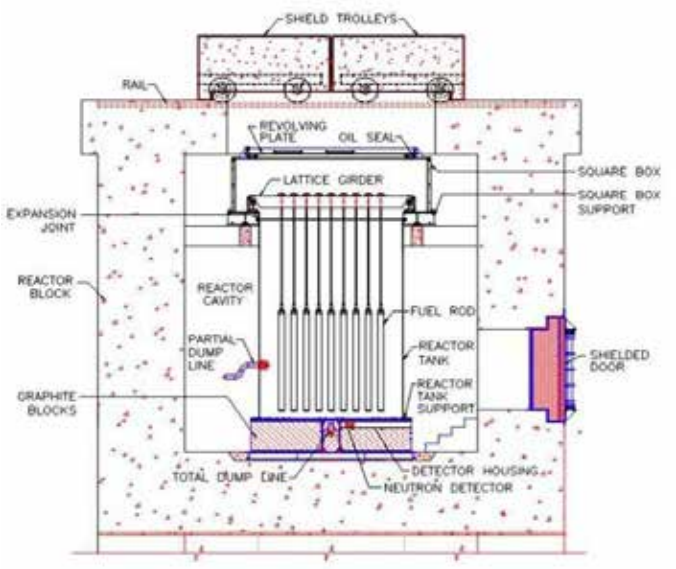
CRITICAL FACILITY

Critical Facility (CF) is a low power reactor built as a part of the over-all technology development program to validate the physics design of the thorium based Advanced Heavy Water Reactor (AHWR). Salient design features of the reactor are:

- Nominal Power : 100 Watt.
- Thermal Neutron Flux : ~ 10^8 n/cm^2/sec.
- Reactor Tank :Vertical, cylindrical made of Al
- Tank Dimentions : 330 cm Φ, 500 cm ht.
- Lattice pitch : Variable (minimum 215 mm)
- Moderator : Heavy water
- Shutdown system : 6 Cadmium shut-off rods & Moderator Dump

Facilities at CF:

Although the main objective of AHWR-CF is for conducting experiments and validating the physics design parameters of AHWR, the reactor has facilities in graphite reflector for sample irradiation, testing of neutron detectors etc.



- The graphite reflectors at the bottom of the reactor houses two cuboidal shape positions for activation of various samples. The cuboidal positions have dimension of 150 cm × 10 cm × 10 cm. Thus, a large space is available for irradiation of irregular samples having bigger size. Maximum thermal neutron flux at irradiation position is 5 × 10^7 n/cm^2/sec. Installation and removal of the samples is manual and activated sample can be availed within short time after activation for subsequent analysis.
- The graphite reflectors placed beneath the reactor tank has facilities for testing of neutron detectors and also to activate samples (Soil, geological rock, biological sample and metallic alloys) for neutron activation analysis (NAA). Both, the calibration of the neutron detectors and NAA are ongoing activities carried out almost on routine basis.
- Large size samples (up to 500 g) after packing in polythene can be activated in graphite reflector position. Higher masses of the samples (1 to 500 g) are used to obviate the error due to inhomogeneous distribution of analytes in small sub samples.

Utilization of CF

The reactor is being utilized for validating the physics design parameters of AHWR Type Fuel. Reactor Physics Design Division (RPDD) in coordination with Reactor Engineering Division (RED) has carried out various experiments both in the standard reference core and extended core (by installation of six additional fuel cluster in standard core). Following is a list of important experiments carried out in the Critical Facility.

Reactor Physics Studies

- Reactor power calibration by absolute flux measurement by activation method.
- Axial flux distribution measurements on the central fuel cluster.
- Gold Cadmium-ratio measurement at infinite dilution.
- Measurement of level coefficient of reactivity of standard reference core by positive period method.
- Fine structure neutron flux measurement inside the central lattice cell of standard reference core.
- Gamma scanning of Natural. Uranium and thorium pin irradiated at central location of E5 cluster in reference core.
- Critical height measurement with various types of experimental clusters, [NU, ThO_2] Mixed Pin, Th-Pu (1%) Six Pin Cluster, Th-LEU Six Pin MOX Cluster.
- Measurement of the Moderator Temperature Coefficient of Reactivity (MTCR).
- Measurement of Westcott neutron spectrum parameters in reference core of AHWR-Critical Facility, using Lu and Cu foils.
- Axial, thermal and epithermal flux profile measurement inside (NU-ThO_2-NU) sandwich Cluster.
- Photo-neutron decay studies in standard reference core
- Commissioning of Online Flux Mapping System of AHWR-CF.
- Sub-criticality measurement using neutron noise method.
- Void coefficient with one (Th-1%Pu) MOX cluster in the extended reference core using water and HDPE as coolant simulating various voiding conditions.

Detector Testing:

- On an average nearly 30 neutron detectors were tested annually.
- Various types of neutron detectors like Fission chamber, Boron lined proportional counters, Helium-3 Detectors, Gamma compensated Ionization chamber, Micro fission Chamber, Transmission line fission chamber, Uncompensated Ionization chambers, Pre-start up equipment for Project-B with B-10 Proportional counters for different reactors were tested in CF. The testing of the detectors involves:
- Checking of the discriminator bias characteristics, HV characteristics, linearity of the flux measurement range, neutron sensitivity, gamma discrimination, long term count rate stability and response time etc.
- Repeatability of detector response, measurement of count rate loss at high flux
- Performance checking immediately after exposure to high fluence & at high flux etc.

CF is mainly used for characterizing the detector performances of pulse detectors as the maximum flux at the detector location is of the order of 2×10^7. For DC detectors, the full

measurement range may not be covered due to limited neutron flux at these locations. The DC detectors are checked for their response and initial signal calibration characterization.

Sample Irradiation for neutron activation analysis

Around 150 assorted samples were activated yearly in the graphite reflector. Large and irregular shape samples are being irradiated for neutron activation analysis in Graphite reflector region at bottom of the reactor.

Special Campaign at CF

Besides the above-mentioned experiments, following are a few important activities/experiments conducted in CF:

- Effectiveness of Hafnium absorber plates developed by ChED was checked.
- Criticality experiment was performed with graphite moderator at core center which would be used for testing of MSR fuel salt.
- Worth measurement of Hafnium absorber section of SOR and CSR for new Apsara-U reactor before installation in the Apsara-U reactor.
- Activation of DM water, dye and absorbent used in DP testing of welded joints for analysis of Chlorine and Br-82.
- Measurement of fission products of Uranium Silicide, type of fuel used in Apsara-U reactor.
- Sensitivity checking of modified critical accident dosimeter badge.
- Activation of medicine samples to see radiation damage on the medicine carried by astronauts during long term space missions.
- Activation of articles for special cores for testing and commissioning of the axial& integral gamma scanner and establish the procedural steps for bulk gamma scanning of the activated articles are such cores.

Conclusions

The research reactor has provided valuable operating experiences of over 15 years. The insight gained in construction and operation of the reactor has played a significant role in developing India in various aspects related to our nuclear program. The various irradiation and experimental facilities in the reactor are well utilized and helps in achieving new heights in production of radioisotopes and material testing.

Production of Radioisotopes for Human Healthcare Using Research Reactors

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Introduction

Production of radioisotopes for societal applications using research reactors at Bhabha Atomic Research Centre (BARC) has come a long way since its inception in late 50's immediately after the commissioning of Apsara reactor. In the initial stage, targets such as tellurium metal powder, elemental sulphur, sodium carbonate etc. were irradiated for production of ^{131}I, ^{32}P and ^{24}Na, respectively. Irradiation assemblies were handled in a special shielded cell at Apsara hall where the target capsules were removed and transported in lead shielding containers to Cadell Road laboratories for further processing. Availability of CIRUS reactor and establishment of Radiological Group of Laboratories (RLG) at Trombay in the 60's provided a major boost to radioisotope production in India at a commercial scale. Large-scale production of a large number of useful radioisotopes, particularly ^{99}Mo as the parent radioisotope of ^{99m}Tc was initiated. While parallel launch of ^{99m}Tc and imaging device (Hal Anger's camera) in early 60's revolutionized diagnostic imaging, the early pioneers of radioisotope programme of BARC (then AEET) rose to the occasion by providing a practical source of ^{99m}Tc from ^{99}Mo produced in Trombay reactors within a few years of the discovery of ^{99}Mo/^{99m}Tc generator at Brookhaven National laboratory. The generator system based on solvent (methyl ethyl ketone) extraction and was popularly known as 'Trombay ^{99}Mo/^{99m}Tc Cow' or simply 'Trombay Cow'. Commissioning of DHRUVA research reactor in 1985 was an important milestone in the development and implementation of indigenous nuclear technology in the field of radioisotope production, which resulted in significant augmentation of production capacity.

Radioisotope production and the subsequent radiochemical processing and separation techniques are continuously evolving and and its application is being demonstrated in several important areas of public interest, such as healthcare, agriculture, food preservation, industrial process monitoring/trouble shooting, research, environment monitoring etc. Many of the 1st generation reactor-produced radioisotopes such as ^{24}Na, $^{57/58}$Co, ^{51}Cr, ^{203}Hg and ^{32}P have mostly lost their utility, while some of those particularly ^{131}I continue to be of significant relevance currently too.

Production, radiochemical processing and deployment radioisotopes for human healthcare constitutes an important activity at Radiopharmaceuticals Division (RPhD), BARC. Radiochemicals Section, RPhD shoulders the responsibility for the steady availability of reactor produced radioisotopes in suitable radiochemical formulation required for variety of uses in nuclear medicine. This article explores the current landscape and future outlook of the production, radiochemical processing, and purification of medically useful radioisotopes using Dhruva and Apsara-U research reactor at BARC, Trombay campus.

Production of radioisotopes utilizing Dhruva reactor for nuclear medicine

Radioisotopes are produced by thermal neutron activation of suitable target chemicals from few days to several weeks and sometime upto months at neutron flux in the range of 1.8×10^{13} n.cm^{-2}.s^{-1} to 1.8×10^{14} n.cm^{-2}.s^{-1}. Measured amounts of target material are weighed and sealed in

standard aluminum irradiation capsules (22 mm outer diameter, 46 mm height), as shown in **Figure-1** for MoO_3 target. Certain precious target materials, particularly isotopically enriched targets are first encapsulated in quartz ampoules which are placed inside the irradiation containers. The amount of target, duration of irradiation and position of target in the tray rod are decided based on detailed optimization depending on the total activity as well specific activity requirement for individual radioisotopes.

Figure-1. Encapsulation of MoO_3 target in standard 1S aluminum irradiation container

Presently, irradiations for radioisotope production are carried out in tray rods (K-09 and H-07) dedicated for radioisotope production in Dhruva. Apart from these, U-Al alloy targets are irradiated in special irradiation facility. **Table-1** lists the medically useful radioisotopes currently produced in Dhruva research reactor along with target chemicals, nuclear reactions involved in their production and the end use of the individual radioisotope.

In the following sections, we discuss the production routes and radiochemical processing/separation methodologies of a few selected radioisotopes, namely ^{99}Mo, ^{131}I and ^{177}Lu in more detail. These are the 3 major reactor-produced radioisotopes which dominates nuclear medicine market globally as well as in India.

Table-1. List of medically useful radionuclides produced in Dhruva reactor

Isotopes	**Target**	**Nuclear reaction**	**Cross Section (σ_{th})**	**Quantity and frequency**	**Use**
Routinely produced for commercial deployment					
^{99}Mo	MoO_3 (Natural, 24.4% ^{98}Mo	$^{98}Mo(n,\gamma)^{99}Mo \xrightarrow{\beta^-} {}^{99m}Tc$	0.135 b (0.7 b resonance integral)	0.74-1.48 TBq (20-40 Ci) per batch - Weekly	^{99m}Tc - in diagnostic imaging (SPECT)
^{131}I	TeO_2 (Natural, 34.5% ^{130}Te)	$^{130}Te(n,\gamma)^{131}Te \xrightarrow{\beta^-} {}^{131}I$	0.29 b	1.11-1.85 TBq (30-50) Ci per batch - Weekly	Imaging and therapy of thyroid disorder and other oncological condiations

^{177}Lu	$Lu(NO_3)_3$ (Enriched, >80% ^{176}Lu)	$^{176}Lu(n,\gamma)^{177}Lu$	2090 b	1.850 TBq (50 Ci) per batch - Weekly	Targeted radionuclide therapy
^{153}Sm	Sm_2O_3 (Enriched, >98% ^{152}Sm)	$^{152}Sm(n,\gamma)^{153}Sm$	206 b	111-185 GBq (3-5 Ci) per batch - Monthly	Pain palliation due to bone metastases
^{125}I	Xe gas (Enriched, 10% in ^{124}Xe)	$^{124}Xe(n,\gamma)^{125}Xe \xrightarrow{EC} {}^{125}I$	165 b	111-185 GBq (3-5 Ci) per batch - Quarterly	Brachytherapy of occular and prostate cancer
For research, development and demonstration purpose					
^{166}Ho	Ho_2O_3 (Natural, 100% ^{165}Ho)	$^{165}Ho(n,\gamma)^{166}Ho$	66 b	18.5-185 GBq (0.5-5 Ci) per batch - As per requirement	Cancer therapy and treatment of arthritis
^{90}Y	Y_2O_3 (Natural, 100% ^{89}Y)	$^{89}Y(n,\gamma)\,^{90}Y$	1.28 b	(7.4-18.5 GBq) 0.2-0.5 Ci per batch - As per requirement	Cancer therapy and treatment of arthritis
^{177}Lu (NCA)	Yb_2O_3 (Enriched, >96% ^{176}Yb)	$^{176}Yb(n,\gamma)^{177}Yb \xrightarrow{\beta^-} {}^{177}Lu$	2.85 b	~37 GBq (~1 Ci) per batch - As per requirement	Targeted radionuclide therapy
^{99}Mo (HSA)	U-Al alloy (Low enriched U)	$^{235}U(n,f)^{99}Mo \xrightarrow{\beta^-} {}^{99m}Tc$	583 b, 6.1% fission yield	5.55 TBq (150 Ci) per batch - Trial	^{99m}Tc - in diagnostic imaging (SPECT)

Molybdenum-99 by direct (n,γ) route

Molybdenum-99 is the parent radionuclide for ^{99m}Tc ($T_{1/2}$ = 6.02 h and E_γ = 140 keV), which is estimated to be used in about 30 million medical diagnoses annually throughout the world and is considered as the workhorse of nuclear medicine procedures. Availability of ^{99m}Tc for preparation of diagnostic radiopharmaceuticals is ensured in the form of ^{99}Mo/^{99m}Tc generator system from which ^{99m}Tc is separated under aseptic conditions. For last several decades, indigenous production of ^{99}Mo is being carried out by thermal neutron activation of natural MoO_3 target and 0.74-1.48 TBq (20-40 Ci) of ^{99}Mo is processed and supplied weekly from our laboratory for nuclear medicine applications. The neutron irradiated target is dissolved in NaOH in presence of H_2O_2 and supplied as [^{99}Mo]$NaMoO_4$ as the parent radiochemical for ^{99m}Tc. The specific activity of ^{99}Mo obtained is about 22.2-29.6 GBq/g (600-800 mCi/g) of Mo. Large-scale regular production of ^{99}Mo with the mentioned specific activity have resulted its successful utilization in preparation of 14.8 GBq (400 mCi) ^{99}Mo/^{99m}Tc gel generators (Geltech) at Board of Radiation and Isotope Technology (BRIT).

Iodine-131

Iodine-131 in the form of [^{131}I]NaI solution is extensively used in the diagnosis and treatment of thyroid disorders including differentiated thyroid cancer. Iodine-131 decays by emission of both β^--particles with a maximum energy of 0.61 MeV and γ photons [principal γ photon energy 364 keV (81%)]. The 8.04 day half-life is logistically favorable for shipment of ^{131}I radiopharmaceuticals to places far away from the reactors. With expanding areas of applications and growing interest in the use of [^{131}I]I-labeled radiopharmaceuticals, the domestic demands of ^{131}I has increased several folds over the last decade. In the quest for an effective method for large-scale routine production of ^{131}I to cater the increasing domestic requirements, our focus shifted toward dry distillation technology, drawn by its advantageous characteristic. The dry distillation technology developed at BARC is facile, robust, efficient, easily up-scalable, generates minimum amount of radioactive waste and cost-effective. Briefly, the procedure involves the heating of neutron irradiated high purity TeO_2 target at 740° C (just above the melting point of TeO_2), purging the ^{131}I released using an inactive carrier gas and trapping it in NaOH solution containing Na_2SO_3 to obtain ^{131}I as radiochemically pure [^{131}I]NaI solution [1]. This method has been successfully used for the routine production of 1.11-1.85 TBq (30-50 Ci) of ^{131}I in a batch throughout the year. Iodine-131 produced is utilized for the preparation of [^{131}I]MIBG, [^{131}I]NaI therapeutic capsules and other [^{131}I]I-labeled biomolecules apart from its regular use as orally administered doses of [^{131}I]NaI solution.

Lutetium-177

Lutetium-177 decays to stable ^{177}Hf with a half-life of 6.65 d by emission of β^- particles having E_{max} of 497 keV (78.6%), 384 keV (9.1%) and 176 keV (12.2%). The emission of low-energy gamma photons [E_γ = 113 keV (6.6%), 208 keV (11%)] enable imaging and therapy with the same radiolabeled preparation and allow dosimetry to be performed before and during treatment as well. Two different strategies, namely, (i) direct thermal neutron activation of enriched (in ^{176}Lu) lutetium target and (ii) thermal neutron activation enriched (in ^{176}Yb) ytterbium target leading to the formation of ^{177}Lu from the β^- decay of the short-lived activation product ^{177}Yb ($T_{½}$ = 1.9 h) could be utilized to produce ^{177}Lu [2]. The direct (n,γ) route offers large-scale ^{177}Lu production with specific activity adequate for targeted tumor therapy in nuclear reactors having thermal neutron flux of ~1.2×10^{14} n.cm^{-2}.s^{-1} or higher using enriched target (at least 75% or more in ^{176}Lu). This is the least intricate route to access ^{177}Lu in the desired chemical form with minimum generation of radioactive waste, apart from being inexpensive [2]. In order to tap the potential of (n,γ)^{177}Lu production method for application of ^{177}Lu in the preparation of receptor-specific therapeutic radiopharmaceuticals, we have worked on feasibility of producing ^{177}Lu in adequate specific activity and in requisite purity by careful optimization of the irradiation parameters [3]. Radiopharmaceuticals Division is currently supplying around 1.85 TBq (50 Ci) of radiopharmaceutical grade [^{177}Lu]$LuCl_3$ solution every week to the leading nuclear medicine centers across India. The specific activity of indigenously produced ^{177}Lu available every week at nuclear medicine clinics in India is around ~740 GBq/mg (20 Ci/mg), considering the decay loss of 48 h during transit [2,3]. The different steps involved in large-scale production and radiochemical processing of clinical grade [^{177}Lu]$LuCl_3$ formulation is pictorially presented in **Figure-2**.

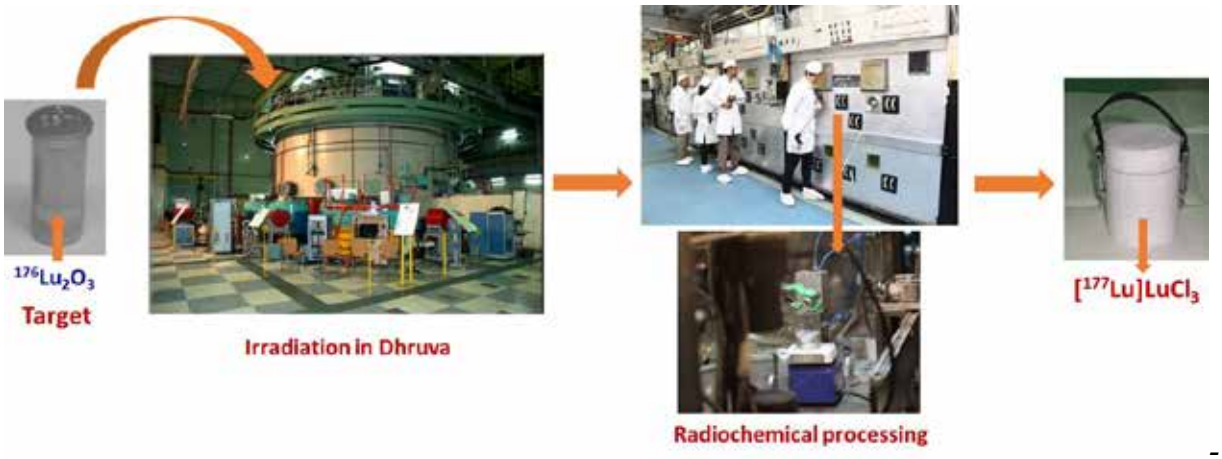

Figure-2. Indigenous production of clinical grade $[^{177}Lu]LuCl_3$

No-carrier-added (NCA) ^{177}Lu produced via ^{176}Yb(n,γ)^{177}Tb $\xrightarrow{\beta^-}$ ^{177}Lu route is becoming increasingly popular in the practice of targeted radionuclide tumor therapy. An electrochemical separation procedure based on selective electro-amalgamation of Yb and purification procedure based on deposition of ^{177}Lu on a platinum electrode was developed by our group to obtain NCA ^{177}Lu in a clinically usable form [4]. Overall yield of the radiochemical separation and purification process developed was > 70% and it was reproducible in multiple batches. The effective specific activity of NCA ^{177}Lu was ~3.0 TBq/mg (~80 Ci/mg). The feasibility of recovery of enriched (in ^{176}Yb) target in chemical form suitable for reuse in the production of a fresh batch of NCA ^{177}Lu was demonstrated, which makes the process economically viable.

Production of ^{64}Cu utilizing Apsara-U reactor

Copper-64 ($T_{½}$ = 12.7 h) is an intrinsically theranostic radioisotope because of its unique nuclear decay characteristics: it decays via electron capture (44 %), β^+ emission (17 %, 0.655 MeV), and β^- emission (39%, 0.573 MeV). Electron capture also leads to the release of Auger electrons, which is an added advantage in its use for therapy. Despite excellent attributes, this unique radioisotope could never carve a niche for itself in routine clinical practices, mainly, due to its insufficient commercial availability at an affordable price. Over the last few years, there is a renewed interest towards the use of this radioisotope. This is particularly because of the improvement in supply logistics of this radioisotope and identification of simple $[^{64}Cu]CuCl_2$ as a cost-effective radiopharmaceutical for cancer theranostics. With an aim towards achieving widespread and cost-effective availability of this radioisotope for the benefit of cancer patients in our country, Radiopharmaceuticals Division, BARC has explored the feasibility of its indigenous production in NCA form by irradiation of natural ZnO target inside the core of the newly commissioned Apsara-U reactor via ^{64}Zn(n,p)^{64}Cu reaction. The relatively high fast neutron flux available in Apsara-U is utilized for this purpose as ^{64}Zn(n,p)^{64}Cu has a threshold energy of 1.9 MeV. An efficient radiochemical separation procedure based on solvent extraction of ^{64}Cu as dithizonate complex was developed. The overall yield of ^{64}Cu after the separation process was > 85% and it could be obtained with an effective specific activity of ~11.1 GBq/mg (300 mCi/μg) and > 99.9% radionuclidic purity [5].

Future Prospective

In addition to the routine production of several well-established radionuclides currently utilized in nuclear medicine, extensive research and development efforts are actively underway to explore, optimize, and standardize the production routes and radiochemical separation protocols of a growing number of novel and emerging radioisotopes (e.g. ^{47}Sc, ^{161}Tb, ^{169}Yb) at Radiopharmaceuticals Division, BARC. These efforts aim to enhance the efficacy and precision of cancer diagnosis and therapy, particularly within the rapidly evolving field of targeted radionuclide therapy and theranostics. The focus is on developing isotopes with superior physical and biological characteristic that can significantly improve outcomes in the management of various malignancies.

Acknowledgement

The authors sincerely thank Dr. Y. K. Bhardwaj, Associate Director, Radiochemistry and Isotope Group, BARC for his encouragement support. Radioisotope production is an on-going program and many have contributed to the success of the programme over many years. The authors sincerely thank all the yester year and current staff members of Radiopharmaceutical Division and Reactor Group of BARC, who have contributed to this important activity of the Department.

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Application of Radioisotope Techniques for Process Optimization and Improvement of Product Quality in Industrial Process Plants

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Introduction

Over the years various radioisotope-based techniques have been successfully developed by Isotope & Radiation Application Division of Bhabha Atomic research Centre and applied in industry for trouble shooting and process optimization thereby benefitting Indian industry. In addition to this several R&D projects have been executed in collaboration with industry and academic institutes for development of new radioisotope-based techniques. In radiotracer techniques, the radioactive material in a suitable physico-chemical form similar to that of the process material is injected into the system at the inlet and its passage is monitored along the system at strategically selected locations using radiation detectors. The tracer concentration obtained as a function of time at detection locations is plotted and information about occurrence of malfunctions, if any and hydrodynamic behaviour of the process equipment are drawn. Dhruva research reactor, Bhabha Atomic Research Centre, Mumbai is continuously utilized since nearly four decades for production of a variety of radioisotopes for a number of industrial applications in India. Over the years, the reactor produced radioisotopes used for industrial applications include, ^{82}Br, ^{140}La, ^{198}Au, ^{131}I, ^{99m}Tc, ^{46}Sc, ^{79}Kr (as radiotracer) and ^{137}Cs, ^{60}Co, ^{192}Ir (as sealed source). Applications of radiotracer techniques for residence time distribution (RTD) measurements of process plants are demonstrated in various complex industrial flow systems such as, Pilot-scale coal gasifier, Glass production unit, cross flow reactor, Paper and Pulp Digester. The RTD measurement enabled in identification of malfunctions such as leak, scaling, dead volume, bypassing, channeling, radial mal-distribution and mean residence time, holdup and axial dispersion of the process material in industrial systems. RTD measurements helped in optimization of the process, improvement in process efficiency and product quality.

Radioisotopes produced by utilizing a particle accelerator, such as, pelletron or cyclotron are applied in a special area known as Thin Layer Activation technique (TLA). TLA technique has been developed to monitor and quantify wear and corrosion rate of various metallic components. The technique has been applied to measure wear rate of automobile gears, evaluation of anti-wear additive to lubricants, corrosion monitoring of carbon steel in hydrocarbon processing environment and assessment of inhibition property of different molecules for acid corrosion of steel and bronze. TLA is a highly sensitive and accurate technique for wear and corrosion monitoring of metallic components.

In India, Board of Radiation and Isotope Technology (BRIT), Department of Atomic Energy supplies radioisotope products and radiation equipment while the Isotope and Radiation Application Division, Bhabha Atomic Research Centre undertakes R&D programmes for advanced applications and offers professional service to meet the country's demand in various fields of applications. Some of the applications of radioisotopes carried out in India are described below.

Leak detection

This is probably the most widespread use of radiotracers in industrial troubleshooting with highest benefit to cost ratio. A leak is an undesirable interconnection between isolated parts of a system or between two systems and is suspected if there is any abnormal behavior of a system, such as loss of pressure, contamination of product or loss of process efficiency. A leak in a system can occur due to an unintended crack, corrosion or porosity, hole in an enveloping wall, loosening of bolts/joints and cracking of gaskets. After suspecting a leak(s) in a system, it is essential to confirm and identify the leaking system(s) at the earliest to avoid deterioration of product quality, loss of process efficiency, risk in safety and environmental hazards.

Radiotracer techniques are widely used for leak detection in buried pipelines and industrial systems. The design of a leak detection test in a buried pipeline depends upon case to case basis. Location of actual leak position is a little more complicated as the monitoring procedure needs to be designed to suit each specific application. However, in an industrial system such as heat exchanger or condenser the detection of leak, if any, is unambiguously achieved by injecting the radiotracer in the part suspected to be leaking and monitoring the tracer in the suspected part. A typical arrangement for leak detection in heat exchanger is shown in Fig.1. Care should be taken to inject adequate adequate quantity of the radiotracer so that the lowest suspected leak rate will result in the detection of radiotracer. Otherwise, the non-detection of the radiotracer is much easier for interpretation on any leak.

Flow rate measurement

The knowledge of flow rates of solids, liquids and gases is an essential requirement in industry. Usually suitable flow meters are installed to measure the flow rates of the phases in industrial plants but there are certain situations where neither flow meters nor any conventional techniques can be used. Radiotracer techniques are well-established and routinely used techniques for flow rate measurements in industrial systems, particularly in situations where there is need to calibrate the installed flow meters, highly accurate measurements are needed and conventional techniques cannot be applied. Two different methods i.e. pulse velocity and radiotracer dilution methods exist for flow rate measurements of flow rates in industrial and hydrological systems. The principal of the pulse velocity is shown in Fig.1. The pulse velocity method is usually applied to pipelines or systems with well-defined cross-sections. The method involves instantaneous injection of a suitable radiotracer into the system and measuring its concentration at two downstream locations separated by a distance d. The mean transit time ($\bar{t}$) between the two pulses is determined and linear velocity (v) of the radiotracer pulse is obtained. The linear velocity is multiplied by the cross-sectional area (A) to obtain flow rate (Q) of the flowing phase. Thus:

$$Q = \frac{d}{\bar{t}}.A = v.A \qquad (1)$$

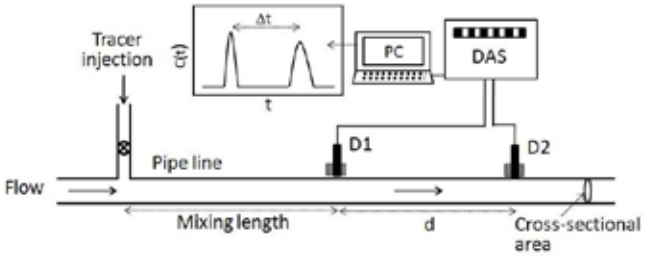

Fig. 1. Principle of pulse velocity method

The principle of the dilution technique is shown in Fig. 2. In dilution technique, a tracer solution of known concentration (C_1) is injected into the flow stream at a constant rate (Q_1) for a particular duration of time. Samples are collected from a sufficiently downstream location, where the tracer is completely mixed within the flow. The tracer concentration (C_2) in the collected samples is measured. The discharge rate (Q_2) of the flow stream is calculated by following tracer balance equation:

$$Q_1C_1 = (Q_2 + Q_1)C_2 \qquad (2)$$

Since, $Q_2 >>> Q_1$, the above equation can be written as:

$$Q_2 = Q_1 \frac{C_1}{C_2} \qquad (3)$$

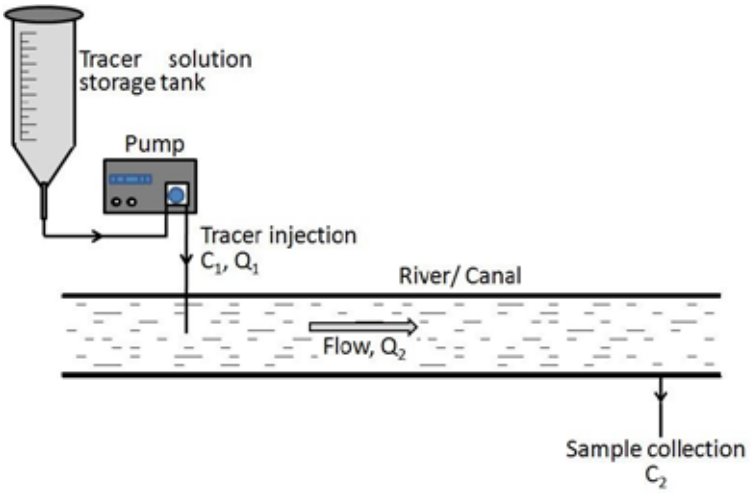

Fig. 2. Principle of radiotracer dilution method

An important advantage of radiotracer dilution method is that it is independent of dimension of the test section and thus is suitable for measurement of flows in irregular containments such as canals, open channels, rivers and streams. Errors in the measurements arise mainly due to incompleteness of mixing of radiotracer, variation in the injection rate (Q_1) of the tracer and error in measurement in counting of C_1 and C_2.

Residence time distribution measurement

A group of fluid elements entering a flow system at a particular time may take different paths through the system and consequently take different times to exit the system. The distribution of these times is called the residence time distribution (RTD). RTD is an important characteristic of continuous flow systems and provides vital information about hydrodynamic behavior of the system. Radiotracer techniques are commonly used for measurement of RTD of process material in industrial flow systems. A typical experimental setup for RTD measurement is shown in Fig.3. A suitable radiotracer is instantaneously injected into the system at the inlet and monitored at the outlet of the system using collimated scintillation detector connected to a data acquisition system set to record radiotracer concentration at a preset time interval. The measured radiotracer concentration is normalized and is called RTD (E(t)) of the process fluid. Thus:

$$E(t) = \frac{C(t)}{\int_0^t C(t)dt} \qquad (4)$$

and $$\int_0^t E(t)dt = 1 \qquad (5)$$

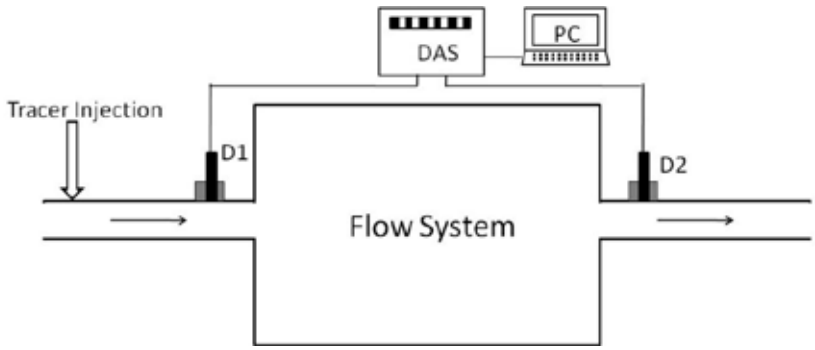

Fig. 3. A typical experimental setup for measurement of residence time distribution

From the measured RTD curve, the information about flow anomalies is obtained and mean residence time (MRT) is estimated. The measured RTD curve is modeled using suitable mathematical models and degree of axial mixing is quantified and performance of the system is evaluated. Tanks-in-series and axial dispersion models are two simple, widely used ones to simulate RTD measurements in industrial flow systems.

Mixing/blending time measurement

Radiotracer techniques are widely used to measure the mixing times in pilot scale as well as in large-scale batch systems in a variety of industries. The techniques involve the introduction of a suitable tracer into the system along with one of the components of the mix and monitor the concentration of the tracer either continuously ("*in situ*") using radiation detectors placed at one or more than locations or take samples from a single location at regular intervals. Another approach, which is statistically more representative of the process, is to take large number of samples from different locations possibly at short time intervals. In this case the average concentration of a given group of samples is determined and the standard deviation (σ) is calculated. From the calculated values of σ, a plot of σ versus t is plotted and adequate mixing is deemed to have been achieved when σ becomes constant. The standard deviation of a set of n data points is given as:

$$\sigma = \sqrt{\frac{\left(C_i(t_i) - \overline{C_0}(t_0)\right)^2}{(n-1)}} \qquad (6)$$

Where, $C_i(t_i)$ and $\overline{C}_0(t_0)$ are tracer concentration at time t_i and mean tracer concentration, respectively.

Wear and corrosion studies

Loss of material from surfaces i.e. wears and corrosion of metallic, polymeric components is a common problem in industry and various technological areas. The loss of material is primarily due to mechanical, chemical and electrical phenomena. Measurement and quantification of wear and corrosion is often desired for quality control and assessment of reliability and durability of various mechanical parts and tools. The conventional techniques such as gravimetery, micrometery, profilography, replica method etc. are used for wear and corrosion measurements in industry but these techniques have poor accuracy, low sensitivity, cumbersome to use as the component need to be dismantled or removed for each measurement and cannot be applied in all situations due to non-accessibility. During seventies a radiotracer technique called Thin Layer Activation (TLA) technique was developed which overcomes the drawbacks of conventional techniques. The TLA technique is highly sensitive (0.1 ± 0.01 mm thickness wear or corrosion and 1 μg to 1 ng mass loss), can be used for online monitoring, accurate, easy to use, does not require elaborate safety measures, can be applied in case of commonly used materials (iron, cadmium, zinc, iridium, platinum, silver, tin, palladium, lead, tantalum), adaptable in various situations and can be used for localized measurements. The techniques is widely used in many countries to measure wear, corrosion in various industries such as automobile industry, power plants, process industry, oil and petroleum refineries and in many high technology areas.

The technique employs irradiation of a target material or component by a beam of charged particles (proton beam of energy 9-13 Mev, deuteron, ^{3}He and ^{4}He of energy 10–30 MeV) in a accelerator and to produce a suitable radioisotope in thin surface layer (10-300 μm) of the material. Specially designed zigs are used for mounting the targets for irradiation. The produced radioisotope depends upon elemental composition of the irradiated target. If an iron target is irradiated with a proton beam of energy 12-13 MeV, ^{56}Fe(p,n)^{56}Co nuclear reaction takes place producing ^{56}Co radioisotope. ^{56}Co has a half-life of 77.3 days and emits gamma rays of energy 847 KeV. The half-life and energy of the gamma rays are suitable for wear/corrosion studies. The irradiated component is subjected to mechanical or chemical degradation such as wear, corrosion and any loss of material from the surface is measured by measuring radioactivity of the produced radioisotope. Either the residual radioactivity in the component or in debris is measured. NaI(Tl) scintillation detector coupled with a single channel analyzer or HPGe detector coupled with a multichannel analyzer (MCA) is used for measurement of activity in TLA. The residual activity in the component is measured with time and plotted. From the slope of the plotted curve and a calibration curve, the wear rate can be obtained.

Radioactive particle tracking (RPT) technique

In the RPT technique, a single gamma emitting radioactive particle is used as a marker of the phase whose velocity fields are to be mapped. In case of liquid phase tracking in a system, the particle should be as smaller as possible in diameter and neutrally buoyant, whereas in case of solid phase tracking the particle should have same size, shape and density as the solid phase. The suitably designed single radioactive particle is introduced into the process system and its movement inside the system is monitored using an array of scintillation detectors mounted strategically around the system. The intensity of radiation is continuously acquired for a preset time interval over a predefined time period. A calibration is performed by keeping the particle at various specified locations inside the system and noting the intensities recorded by the mounted detectors. Calibration is performed prior to the measurement at actual operating condition at which the flow fields are to be mapped. The instantaneous positions of the particle as a function

of time and space are calculated using the calibration and acquired data. From the instantaneous position of the particle of time and space (Lagrangian trace), instantaneous velocity time series of the fluid element is obtained. The instantaneous velocity time series is used to obtain a number of flow quantities such as time-averaged velocity fields, turbulent shear stresses, kinetic energy of fluctuations, dispersion coefficients, Hurst exponents, residence time distributions (RTD), diffusivity tensor, trajectory length distributions (TLD), circulation patterns, return time distributions, etc. of the tracked phase are obtained.

Sediment transport investigations

Harbour development programme or a river valley project requires complete understanding of the movement of sediment either on sea bed or river bed or in suspension. Radiotracer techniques have been routinely used to evaluate parameters such as direction of movement, velocity and quantity of bedload transport are used in many countries for over three decades. The procedure involves preparation of a radioactive particulate tracer having similar physicochemical properties as the bed material, injection of the tracer at the desired point, tracking of the tracer with underwater nuclear detectors and finally interpretation of iso-activity contours to evaluate the parameters mentioned above. Two kinds of tracer preparations are in common use. In first method, the tracer is prepared by incorporating an active element like scandium or iridium in glass, ground the glass and mix the different grain size fractions to have the grain size distribution as the bed material of interest and activate the powder in a nuclear reactor to produce the radiotracer (incorporating Scandium-46 or Irridium-192). In second method, which is usually used in short duration studies, needs careful treatment of the surfaces of the grains to obtain good labeling of radioactive material. Most of the radiotracer investigations are aimed at:

- examining the suitability of the existing dumping ground for dredged silt.
- selection of a suitable dumping ground for new projects
- examining the suitability of alignments of proposed navigation channels
- Pollution studies in coastal areas

In India about more than 80 large-scale sediment transport investigations have been carried out covering in all major ports over last four decades.

Conclusions

India has advanced facilities and adequate expertise for applications of radioisotopes in industry. The radioisotope technology is well developed and services have been routinely provided to Indian industry for troubleshooting, process diagnosis and optimization on commercial basis. Different institutes or industries can be benefited by application of state of the art radioisotope based techniques by approaching to the Head of Institute of Bhabha Atomic research Centre, Mumbai.

Characterization Studies and Neutron Activation Analysis at KAMINI Reactor, Kalpakkam, INDIA

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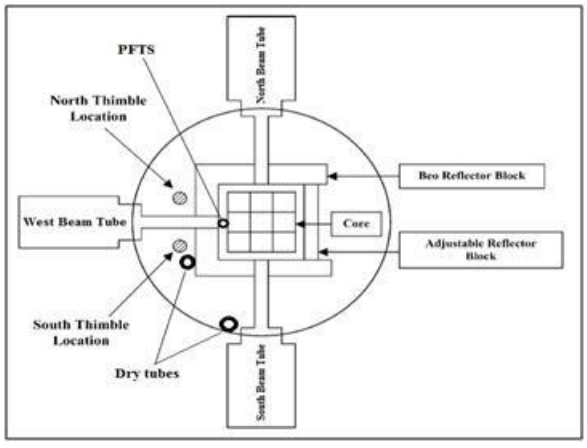
Abstract
The Kalpakkam Mini (KAMINI) reactor, operated at the Indira Gandhi Centre for Atomic Research (IGCAR) in Kalpakkam, is the only operating pool-type reactor in the world fuelled with ^{233}U and Al alloy. This paper presents a comprehensive characterization of its irradiation sites, including detailed neutron flux profiles, neutron energy spectra, spectrum parameters, and neutron temperature, with parameter validation using certified reference materials from IAEA and NIST to ensure high accuracy and reliability. The versatile irradiation capabilities of the KAMINI reactor have enabled the successful neutron activation analysis (NAA) of samples spanning diverse fields—ranging from forensic and archaeological artefacts to biological tissues, reactor components, food, pharmaceuticals, and environmental sediments. Various quantification methods like relative, k_0 -NAA and k_0 -IMNAA, were standardized and employed for precise multi-element quantification. Notably, a novel methodology rooted in the k_0 -NAA using Westcott formalism was standardized at KAMINI to account for the activation of non-1/*v* nuclides—marking the first such achievement in India. This advancement significantly enhances the reactor's analytical capabilities. The paper highlights the role of KAMINI as a national facility for advanced research, offering insights into reactor physics and broad-spectrum elemental analysis.

1. Introduction

KAMINI is a 30 kW research reactor fueled with ^{233}U–Al alloy and moderated by demineralized light water. It utilizes Beryllium oxide as a reflector and Cadmium as an absorber material in the safety control plates. With a peak core-centre flux of approximately 10^{12} n/cm²/s, the reactor supports neutron radiography, neutron activation analysis (NAA), radiation physics studies, large sample irradiations, and neutron detector testing. The facility features three beam tubes-two designated for neutron radiography (north and south) and one for radiation physics and material irradiation (west)-along with two thimble (North and South) irradiation sites at the core reflector boundary for small samples. Additionally, two aluminum dry tubes (DT1 and DT2) were designed to test neutron detectors and are being explored for the feasibility of conducting LSNAA. DT1, with a diameter of ~76 mm, is located 35 cm from the core centre, while DT2, with a diameter of ~110 mm, is situated 90 cm from the core centre adjacent to the south beam tube (Fig.1). A dedicated irradiation site adjacent to the



core, equipped with a pneumatically operated fast sample transfer system (PFTS), facilitates the study of both short-lived and long-lived isotopes by enabling rapid sample transfer (up to 1 g in a polypropylene container) during reactor operation without shutdown.

This paper details the characterization of various irradiation locations at KAMINI, covering neutron flux profiles, neutron energy spectrum, irradiation location based parameters-sub-cadmium to epithermal neutron flux ratio (*f*), epi-thermal neutron flux shape factor (α), epithermal index (r), and Maxwellian neutron temperature (T_n) and key NAA experiments.

2. Characterization studies of irradiation locations at KAMINI reactor:

2.1. Pneumatic Fast Transfer System:

Characterization of an irradiation location is crucial for evaluating experimental results involving material irradiation. Neutron spectrum at the PFTS position of the KAMINI reactor at 20 kW power was characterized using foil irradiation method [1]. Several foils with high purity (Au, Ti, Ni, In, Mo, Fe, Co & Al) and Y_2O_3 powder, sensitive to different neutron energy ranges, were irradiated. The irradiated foils were analysed by high-resolution gamma spectrometry using an HPGe detector coupled to an APTEC MCA. The spectra were converted to a readable format using an in-house developed VB program, and spectrum analysis was performed with peak-fit PHAST software to obtain peak areas. Saturation activity per nuclide and nuclear reaction rates were calculated, and the neutron spectrum at the PFTS position was evaluated using a 175-group vitamin-J structure with point flux tally. The Least Square Minimization approach was applied to unfold the neutron spectrum at the irradiation location. The integral flux at 20 kW power was found to be 6.01E+11 n/cm²/s.

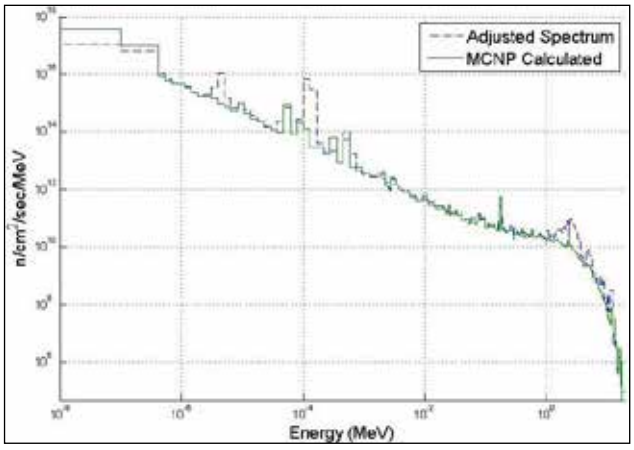


Figure 2. Neutron spectrum at PFTS of KAMINI reactor

In addition, the PFTS position was characterized according to the Høgdahl convention in k_0 -NAA, determining α and *f* values. The α value was determined using various methods, including the bare, Cd-ratio and Cd-cover approaches, with dual and multi-monitors such as Au, Zr and Zn. The *f* value was determined using Cd-ratio method with Au and Zr monitors. Bare and Cd-covered samples were irradiated at 20 kW power in the PFTS position for 30 minutes and 6 hours, respectively. Reference materials (50–100 mg) were irradiated alongside the comparator Au for 5 minutes and 5 hours to validate the k_0-NAA method. Activity measurements were performed using a 30% relative efficiency HPGe detector and activation products from gold (^{198}Au), zirconium (^{95}Zr and ^{97}Zr) and zinc (^{65}Zn) were used to calculate α and *f* values. The α values from different approaches ranged from -0.0386 to -0.0440 (average: -0.0406 ± 0.0025), indicating a hard neutron spectrum at the PFTS position [2]. The average *f*-value was 25.1 ± 0.4, suggesting that the neutron flux consists of approximately 96% thermal neutrons and 4% epithermal neutrons at the PFTS position. The elemental concentrations obtained using the newly characterized parameters for the reference materials were in good agreement with certified values, with Z-scores at the 95% confidence level within ±2, validates the methodology and ensures the accuracy and reliability.

2.2. West Beam Tube and Thimble Positions:

A cavity for the LSNAA facility is situated at the west beam port beneath heavy shielding blocks. This cavity offers a sample volume of 220 mm (length) × 170 mm (breadth) × 270 mm (height). To accommodate this space, a custom Perspex box was fabricated to securely hold the sample container. The spatial flux distribution inside this volume was obtained by irradiating gold foils at the vertices and the centre of the box and the flux at the vertices was found to vary between 1.14E+7 and 2.0E+7 $n.cm^{-2}.s^{-1}$, while the flux at the centre was 4.0E+7 $n.cm^{-2}.s^{-1}$. The f value was found to be 140, it was obtained by irradiating a thin foil of Indium with and without cadmium cover at the centre of the sample box. Similarly, the neutron flux, f values of north and south thimble positions were 1.1E+10, 232 and 3.6E+8, 252 respectively.

2.3. Dry Tubes (DT1 and DT2):

Dry tubes are sufficiently large and characterization of these positions towards the determination of neutron flux, f and α is a mandatory requirement to carry out the IM-NAA experiments. The axial flux profile was obtained for the DT-1 & 2 and observed that the maximum neutron flux in DT-1 was (1.02 ± 0.02) E+10 cm^{-2} s^{-1} at 368 mm and (4.90 ± 0.30) E+7 cm^{-2} s^{-1} at 300 mm for DT-2, with their measured positions from its bottom. The f value for DT-1 at this location of maximum neutron-flux was found to be144 ±7 indicating the presence of thermal neutrons component being more than 99%. The α value of DT-1 was found to be -0.289 ± 0.010 indicating the existence of a hard epithermal neutron spectrum. Similarly, the average f value was found to be 115 ± 6 at a distance of 67 mm from the bottom of the DT-2. For validation, an IAEA CRM SL-1 was analyzed by IM-NAA method and the associated elemental concentrations were determined and found to be in good agreement with that of the certified values. The deviations were within ±5% and the Z-score was found to be ±1 for most of the elements.

2.4. Standardization of Westcott Formalism in PFTS, KAMINI

Westcott formalism in k_0 -NAA was standardized at the PFTS irradiation channel of the KAMINI reactor to accommodate non-1/v nuclides. The key neutron spectrum parameters like Modified Spectral Index $r_0\sqrt{T_n/T_0}$) and Westcott factor $g_{Lu}(T_n)$ were determined and found to be 0.037 ± 0.001 and 1.8939 ± 0.0130, respectively. These values were obtained by measuring the activity of (n,γ) reaction products from nuclides exhibiting both 1/v behaviour (^{197}Au, ^{94}Zr, and ^{58}Fe) and non-1/v behaviour (^{176}Lu). The obtained $g_{Lu}(T_n)$ value was used to determine the neutron temperature (T_n) and found to be 47.2 ± 0.8°C, which was further validated by fitting the thermal neutron spectrum computed using MCNP. The neutron temperature obtained from the Maxwellian fit was found to be within ±5% of the experimental value, confirming the accuracy of the reactor modelling by MCNP. The Westcott parameters were further validated through the analysis of reference materials, reinforcing the reliability of the characterization [3].

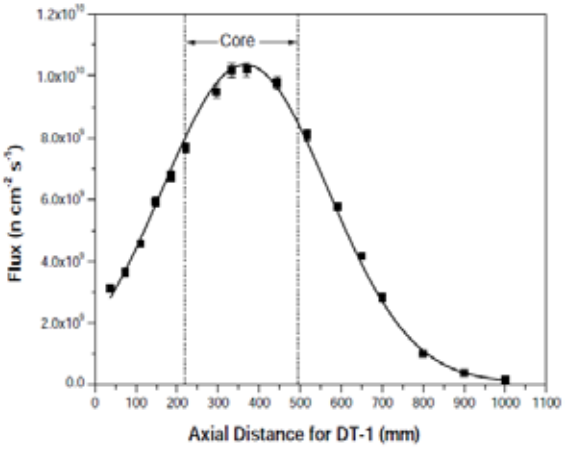


Figure 3 Variation of neutron flux along the vertical axis of DT-1

Table 1. Irradiation locations, neutron flux, and sample requirements at KAMINI reactor

S.No.	Irradiation location	Flux ($n.cm^{-2}.s^{-1}$)	Allowed sample & max. amount	
			Solid	Liquid
1	PFTS	$6.1x10^{11}$	Maximum 1 g	Not allowed
2	North Thimble	$1.1x10^{10}$	25 g	~10 mL
3	South Thimble	$3.6x10^{08}$	25 g	~10 mL
4	West Beam Tube	$6.0x10^{07}$	Vol.(mm) 250 x 300 x 250	~1 L
5	DT1	$1.0x10^{10}$	Tube diameter ~75 mm	Not allowed
6	DT2	$4.6x10^{07}$	Tube diameter ~103 mm	Not allowed

3. Neutron Activation Analysis at KAMINI reactor

3.1. Nuclear Materials:

In fast reactors, activated corrosion products like ^{54}Mn, ^{58}Co, ^{60}Co, ^{65}Zn and fission products such as ^{134}Cs and ^{137}Cs are generated and released into the coolant, leading to an activity burden and necessitating the use of high radiation shielding. To reduce this effect, radionuclide traps using materials like metal foams are employed to capture radionuclides from liquid sodium. Nickel foam samples were equilibrated with sodium and Mn for varying durations (100–1000 hours at 400°C) and analyzed for Mn concentration, which ranged from 0.4% to 2.4%. Similar studies were conducted with Zn and Cu-foam equilibrated with sodium and Hg under different conditions, and their reproducibility was analyzed [4].

Ceramic insulation materials, such as spacers and tapes used in reactors exposed to high temperatures (around 300°C), were analyzed by INAA. These materials are crucial for shielding thermal and electrical energy, enhancing durability. Identifying isotopes produced during reactor operation is important for radiological safety. The results showed varying concentrations of elements like arsenic (As), cerium (Ce), chromium (Cr), and lanthanum (La), with differences observed between the tape and spacer samples. INAA proved to be an effective non-destructive technique for determining multiple elements in these materials, essential for radiation safety.

The analysis of platinum (Pt) in silica-supported platinum (Pt/SiO2) catalysts, used in nuclear plants for processes such as U(VI) reduction and hydrazine destruction during nuclear fuel reprocessing, was conducted using INAA. Traditional methods like Atomic Absorption Spectroscopy and Inductively Coupled Plasma Optical Emission Spectroscopy are cumbersome and require sample dissolution. INAA, however, provided a non-destructive and reliable way to accurately estimate Pt content in catalysts, ensuring quality and accountability in nuclear applications.

Estimating titanium (Ti) and nickel (Ni) in D9 and T91 alloys using NAA is challenging due to short half-lives of activation products and intense Compton background from ^{56}Mn gamma emissions. The k_0-NAA method is typically used for quantifying elements via (n,γ) reactions, but its application to (n,p) reactions is underexplored. The k_0-NAA method was extended to (n,p) reactions on Ti and Ni using gamma energies from $^{47}Ti(n,p)^{47}Sc$ and $^{58}Ni(n,p)^{58}Co$. Parameters like k_f-factors, fast-to-epithermal neutron flux ratio, and h-factor were evaluated and validated with a reference material. Results confirm the method's accuracy for precise elemental analysis in advanced alloys.

3.2. Archaeological Artifacts:

Ancient pottery samples were analyzed for elemental content by irradiating them alongside the IAEA SL-1 multi-element comparator for 1 and 6 hours at the PFTS position of the KAMINI

reactor. The irradiated samples were counted over two months using a vertical HPGe detector, and elemental concentrations were calculated using the relative method of NAA. An in-house developed VB program employed to calculate the concentrations of elements such as K, Sc, Cr, Mn, Fe, Co, Zn, Cs, La, Ce, Sm, Eu, Hf and Th were determined.

As part of a restoration project for a South Indian palace, the gold leaf embellishments on pillars in the Public and Private Durbar Halls and Kalyana Mandapam were analyzed. Gold foil preparation involved flattening a gold ingot into foil less than 25 μm thick through a cold-working process. Samples, including foils, stickers, and flakes, were collected and analyzed using INAA to estimate gold content. Although INAA provided accurate gold estimates, some gold was lost during sample collection, and thus, only qualitative results were used for assessing the gold work.

3.3. Medical Applications:

^{89}Sr is widely used in nuclear medicine for bone pain palliation treatment and is produced by irradiating a yttria target material in the FBTR through the reaction ^{89}Y(n,p)^{89}Sr. High-purity Y_2O_3 is employed as the target material for irradiation. Therefore, understanding the impurity profile of Y_2O_3 is crucial for identifying potential radioisotopic impurities produced during the irradiation process and for purifying the ^{89}Sr source. The sample was irradiated and then dissolved in HNO_3. Cation exchange chromatography was used to separate Y, reducing the high Bremsstrahlung background from ^{90}Y. Lanthanide impurities were quantified by gamma spectrometry using an HPGe detector. The RNAA method was applied to quantify rare earth impurities in the target material for ^{89}Sr production.

Ti-Mo alloys, particularly Ti-xMo (x=1, 7, 15, 25 wt%), are ideal for biomedical implants due to their excellent strength-to-weight ratio, corrosion resistance, and biocompatibility. The alloys were analyzed for Ti and Mo contents, as well as impurities. Samples were irradiated for 5 minutes at 10 kW to measure ^{51}Ti, followed by a 2-hour irradiation at 20 kW to measure ^{99}Mo and impurities. Gamma spectrometry was used to calculate the elemental concentrations. The amounts of Ti and Mo were within the expected range and tungsten impurity was detected at ppm levels.

An elemental profile analysis of the Ayurvedic anti-diabetic formulation Nishakatakadi decoction and its constituent herbs was performed using EDXRF and INAA methods. Major elements like Na, K, Mg, Al, S, P, Ca, and minor elements such as Ti, Mn, Fe, Co, Cu, Zn, Rb, and trace elements including Sr, Br, La, Sm, W, and Pb were quantified. Twelve elements were identified in various herbs through INAA. This elemental profile serves as a unique fingerprint for the herbal formulation, aiding in quality assurance and the standardization of Ayurvedic medicines [5].

3.4. Food and Environmental samples:

Under the UGC DAE CSIR program, a project titled “Quantification of Aluminium in Food Samples by NAA” is being investigated by Biju Patnaik University of Technology, Cuttack, Odisha. Approximately 40 food samples were irradiated at the PFTS position of the KAMINI reactor and immediately counted for ^{28}Al (2.24 min) at Nuclear Chemistry lab of KAMINI lab. The Al content was calculated after blank correction. Additionally, the samples were analyzed using the PIGE technique, though INAA was found to be simpler and required minimal sample size for accurate Al concentration determination [6].

India, being a major producer of fly ash due to its coal-based thermal power plants, requires effective elemental characterization for safe disposal and utilization. The k_0-IMNAA method was employed for elemental analysis of fly ash, allowing precise determination of major, minor, and trace elements [7].

The k_0-method of INAA was also used to analyze beach rock samples from the Southeast Coast of Tamil Nadu. Short (5 min) and long (5 h) irradiations were performed, and SRM 1646a Estuarine Sediment was analyzed for comparison. The study showed good agreement between measured and certified values, demonstrating INAA's effectiveness in multi-elemental analysis of geological samples, including rare earth elements.

3.5. Forensic Samples:

Nail samples from Forensic Sciences Department, Chennai, were received for As determination. NAA was carried out using some trail samples collected from our colleagues to obtain the minimum detection limit and sensitivity of Arsenic in nail samples and internal standard addition method was also carried out to confirm the accuracy. Similarly the real samples were also analysed and reported for further case study.

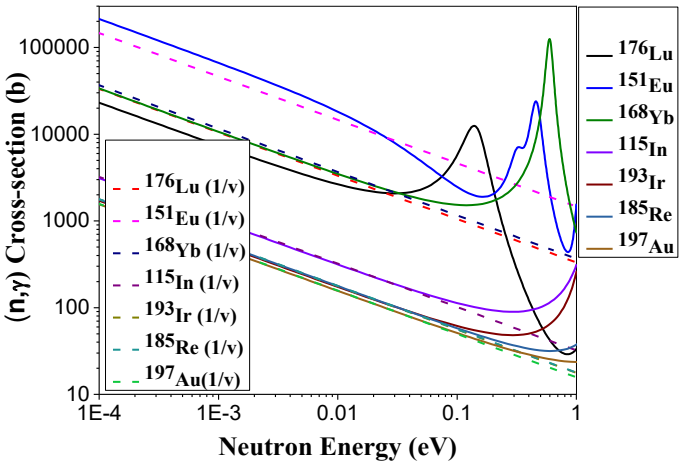


Figure 4 Variation of capture cross-section for non-1/v nuclides with

3.6. Assay of non-1/v nuclide using k_0-NAA:

This study investigates the impact of the Westcott g-factor on the concentration of elements such as In, Ir, Re, Yb, Eu, and Lu**,** determined via (n,γ) reactions using k_0 -based NAA [8]. These elements have thermal neutron capture cross-sections that deviate from the conventional 1/*v* behaviours. The g-factor for non-1/v nuclides was calculated using the characterized neutron temperature (T_n) at the PFTS channel of the KAMINI reactor. A g(T_n) vs T_n correlation (0–100 °C) was established using the ENDF/B-VIII.0 data, processed with NJOY21 modules RECONR and BROADR. The g-factor's effect on concentration was most significant for Lu (81%) and minimal for Re (0.2%) (^{185}Re).

3.7. Assay of alloy samples using k_0-NAA

Various alloy samples, including SS 316, D9, and T91, were irradiated at the PFTS location of the KAMINI reactor. The elemental concentrations in these samples were determined using both k_0 -NAA and k_0 -IMNAA. A standard-less analytical methodology was developed and successfully applied to determine the elemental composition of these complex alloy matrices, eliminating the need for conventional standards [9].

4. INAA Training

To demonstrate NAA to students from training school, relative method of NAA, determination of half-life and k_0-method are being conducted.

5. Conclusions:

The KAMINI reactor plays a key role in determining the elemental composition of samples across various matrices using non-destructive NAA method. It has applications in nuclear science, archaeology, environmental studies, forensics and medicine, providing precise trace element measurements and contamination monitoring. The reactor also aids in developing new methodologies, such as the Høgdahl and Westcott formalism, and non-1/v nuclide determinations. Characterizing irradiation positions is essential for NAA adoption, and it provides a test bed to train researchers and advancing nuclear science and analytical chemistry techniques.

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Contact details of the official responsible for utilizing the KAMINI reactor: Requests for utilizing the KAMINI reactor to carry out NAA of samples from educational institutions, R&D facilities and industries shall be sent to Dr. G.V.S. Ashok Kumar, Head, Nuclear Chemistry Section, Materials Chemistry & Metal Fuel Cycle Group, Indira Gandhi Cenrte for Atomic Research, Kalpakkam – 603102, Tamil Nadu, India. E-mail: gvs@igcar.gov.in.

The Medically Important Radionuclides from Cyclotron Facility and Their Clinical Deployment: An Overview from India and World Perspective

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The invention of the cyclotron traces back to the early 1930s, when it was developed by Ernest Lawrence through his research in Nuclear Physics. By the late 1930s, its potential in the field of medicine emerged after Phosphorous-32, was employed to treat a leukaemia patient. Ground breaking advancement came in the mid-1970s with the synthesis of Fluorine-18 Fluorodeoxyglucose (^{18}F-FDG) which enabled the imaging of cellular glucose metabolism. This discovery not only spurred the development of compact, high-energy cyclotrons for medical use, but also paved the way for positron emission tomography (PET), a widely used imaging modality. Today, cyclotrons play a pivotal role in diagnostics (PET scans), cancer therapy, and research, transforming the landscape of Nuclear Medicine & Clinical Oncology.

In India, the establishment of the first medical cyclotron and PET imaging facility in 2002 at the Radiation Medicine Centre (RMC), Mumbai, by DAE-BARC marked the dawn of PET-based molecular imaging in the country. Over the past decade, the number of medical cyclotrons has increased significantly due to the rising demand for short-lived PET isotopes and the expansion of the field of theranostics (Nuclear medicine imaging and therapy). Newer compact cyclotron designs have lowered the cost of production. In 1983, The International Atomic Energy Agency (IAEA) compiled a comprehensive list of global Database of Cyclotrons for Radionuclide Production. As per the current list, there approximately 1,300 operational cyclotron facilities which are dedicated to production of medical radioisotopes worldwide (1).
According to the energy of the particle accelerated and their utility, cyclotrons can be broadly divided into 3 categories as illustrated in Table 1.

Cyclotrons are essential in the production of the short lived medically relevant radioisotopes used in diagnostic imaging, i.e. PET and SPECT imaging. These isotopes are typically generated by bombarding stable target materials with accelerated protons or deuterons. Small medical cyclotrons (SMCs) are compact accelerators designed for proton energies below 20 MeV. These systems are predominantly installed in hospitals, universities, and small-scale industrial radionuclide production facilities. While most SMCs accelerate protons exclusively, some models can also accelerate deuterons at half the proton energy. Many hospitals across the country operate their in-house cyclotrons for production and synthesis of these radionuclides and for academic research.

Medical Cyclotron Facility: Indian Perspective

As of 2024, India has 25 medical cyclotron facilities operated by various government and private institutions across the country, with accelerated proton energy ranging from 11MeV to 30MeV. The medical cyclotron at the Radiation Medicine Centre (RMC, BARC), Mumbai is a 16.5 MeV cyclotron housed at the Tata Memorial Hospital Annexe Building basement at Parel Mumbai, that is primarily used to produce PET emitter ^{18}F and ^{18}F based radiopharmaceuticals required

for PET imaging, i.e ^{18}F-FDG, Sodium Fluoride-18 (^{18}F-NaF) and Fluoroethyltyrosine (^{18}F-FET).

^{18}F-FDG is the most widely used radiopharmaceutical for PET imaging worldwide as well as India, whose versatility and diagnostic accuracy has revolutionised the field of imaging. It is a glucose analogue labelled with the positron-emitting isotope fluorine-18 (half-life: 110 minutes). ^{18}F-FDG accumulates in metabolically active tissues, particularly cancer cells, which exhibit increased glucose uptake. This makes it invaluable in oncological diagnosis in terms of tumour detection, staging, and treatment monitoring (Figure-1). It also plays a major role in various non-oncology fields as well, such as cardiology for assessment of myocardial viability (e.g. following myocardial infarction coupled with myocardial perfusion imaging), neurology for assessing brain metabolism (e.g. in dementia), and in infection and inflammation imaging (Figure-2 and Figure-3) including investigating 'Fever of Unknown Origin' (FUO). FUO is characterized by a prolonged fever (>3 weeks) that remains undiagnosed despite a thorough evaluation. It poses a diagnostic challenge due to its diverse potential causes, including infections, malignancies, autoimmune diseases, as well as other rare conditions.^{18}F-FDG PET/CT is a powerful second-line tool in FUO, substantially improving diagnostic sensitivity and accuracy and reducing unnecessary invasive procedures, especially when conventional tests fail to identify the cause of prolonged fever.

Another medically relevant PET radiopharmaceutical produced at the medical cyclotron facility at the RMC is ^{18}F-NaF, a PET tracer used primarily for bone imaging. When injected intravenously, ^{18}F-NaF rapidly distributes in the bloodstream and binds to hydroxyapatite crystals in bone, especially in areas of increased osteoblastic activity. This makes it highly sensitive for detecting bone metastases, fractures, and metabolic bone disorders. Compared to the conventional bone scan (with ^{99m}Tc-MDP based SPECT imaging) ^{18}F-NaF PET-CT offers superior spatial resolution, faster imaging (scanning within 1 hour), and higher target-to-background ratios. It is especially valuable in oncology: prostate, breast, and lung cancer staging and also in the presence of osteolytic metastasis such as in thyroid carcinomas (as illustrated in Figure-4) and also in orthopedics for evaluating bone trauma or infection.

Another important ^{18}F-based radiotracer is ^{18}F-Fluoroethyl-L-tyrosine (^{18}F-FET). It is an amino acid analogue, which is transported across the cell membrane via L-amino acid transporter. The disadvantage of ^{18}F-FDG is its normal physiological uptake seen in the brain tissue, which precludes it use in diagnosis of brain tumours. ^{18}F-FET shows high uptake in cancer cells in contrast to healthy cells, which makes it favourable in diagnosis of primary brain tumours (gliomas). There are various other ^{18}F-based radiotracers that are used in day-to-day clinical practice across the world, such as ^{18}F-Fluorodopa, ^{18}F-PSMA-1007, ^{18}F-Flurocholine, ^{18}F-Florbetaben, etc**.** The short half-life of ^{18}F requires on-site or nearby production.

Gallium-68 (^{68}Ga) is another versatile PET radionuclide with unique advantages. Its 68-minute half-life makes it ideal for same-day imaging, while its generator-based production (from ^{68}Ge/^{68}Ga systems) eliminates reliance on cyclotrons, enabling widespread clinical use due to in-house production.

It can be also produced by the Medical Cyclotron facility as is done routinely at the Variable Energy Cyclotron Centre (VECC) facility at Kolkata by proton irradiation of solid Zinc-68 target (^{68}Zn(p,n)^{68}Ga) and is supplied to the nearby hospitals by BRIT, Kolkata. However, owing to the short half-life of ^{68}Ga, the supply of cyclotron produced ^{68}Ga-radiopharmaceutical is limited in the Kolkata region only.

The primary strength ^{68}Ga lies in peptide-based PET imaging through bifunctional chelates and is well-established in the clinical parlance. When chelated to targeting vectors (e.g., DOTA-TATE, PSMA-11), it finds widespread use in diagnosis of oncological as well non-oncological diseases (Figure-5 and Figure-6). A major advantage of ^{68}Ga is that its coordination chemistry applies to the development of Lutetium-177 (^{177}Lu)-labelled theranostic agents. Recently, there has been a surge in the discovery and use of ^{68}Ga based new and novel tracers for research and clinical purposes.

In the context of India, the primary problem faced for large-scale utilisation of ^{68}Ga is the limited availability of the parent isotope - Germanium-68. While India has some resources, it currently does not have a robust domestic production capability for ^{68}Ge/^{68}Ga generators, and relies heavily on import, which is both expensive and leads to significant time lag. The demand for ^{68}Ga-based tracers is anticipated to rise steeply in the future.

Increase in demand for indigenous production has led to the development of alternative approaches to produce Germanium-68. The most noteworthy contribution is from VECC and BRIT, Kolkata who have jointly produced ^{68}Ge in India from indigenously developed Ga-Ni alloy electroplated target using 30 MeV Medical Cyclotron (^{69}Ga (p, 2n)^{68}Ge). The target was preliminarily irradiated for 80 hours (4000 μAh) continuously with 28 MeV proton energy. It is expected to produce export level of ^{68}Ge for the preparation of the ^{68}Ge/^{68}Ga generator, thereby reducing the dependence on the imported generator systems.

Medical Radioisotopes at the DAE Cyclotrons at Variable Energy Cyclotron Centre at Kolkata (VECC):

The Variable Energy Cyclotron Centre (VECC), established by BARC in Kolkata in 1969, operates three cyclotrons: A) K-130 cyclotron (Room temperature cyclotron) for delivering light ion beams (proton, alpha etc.) for experiment purposes. B) K-500 (Superconducting cyclotron) for supplying a variety of ion beams to the experiments at cyclotron facility and C) CYCLONE-30—a dedicated 30 MeV negative hydrogen ion medical cyclotron facility, which became operational in 2018. The extracted beam energy is adjustable from 15 MeV up to 30 MeV. The facility features five beamlines: One PET-dedicated line, two SPECT-dedicated lines and two R&D lines.

Currently this facility, along with BRIT produces radioisotopes and radiopharmaceuticals for healthcare institutions across Eastern India region. Since 2020, it has commercially supplied ^{18}FDG and in the subsequent years, various other tracer such as ^{18}F-NaF (for bone scanning), Gallium-68-PSMA (for diagnosis of prostate cancer) and Ga-68-DOTATATE (for diagnosis of endocrine cancer) have been produced. Besides these PET tracers, certain SPECT diagnostic agents are produced via CYCLONE-30. Thallium-201-Chloride was successfully produced for the first time in India in 2021 for cardiac studies (for cardiac ischemia and viability assessment). Also, Gallium-67-citrate radiopharmaceutical (for infection imaging) was successfully produced on experimental basis. Another gamma emitting radioisotope which plays a crucial role in diagnostic nuclear medicine is Iodine-123 (^{123}I). Currently, thyroid uptake and imaging studies, as well as diagnostic scans for advanced or metastatic neural crest cell derived tumours are performed with low dose of Iodine-131 (^{131}I) based agents i.e ^{131}I-NaI and ^{131}I-mIBG. The beta emission of ^{131}I makes it an ideal candidate for treatment but not for diagnosis. Iodine-123 (^{123}I) is a pure gamma-emitter so it can be administered at higher dose leading to superior quality SPECT images. Also, its relatively shorter half-life (13.2 h vs. 8 d) leads to reduced patient exposure with minimal safety concerns. Due to its ideal nuclear properties, ^{123}I finds ubiquitous

applications across multiple specialities- thyroid studies, neurology, cardiology and in oncology for metastatic neural crest cell derived tumours, i.e Neuroblastoma, Phaeochromocytoma / Paraganglioma

Producing ^{123}I is a technologically challenging process. The successful domestic production of ^{123}I at VECC, Kolkata in 2023 marked a pivotal milestone in Nuclear Medicine in India. Production of Astatine-211 (^{211}At) is also underway. ^{211}At is a promising alpha emitter for targeted alpha therapy with ^{211}At meta-astatobenzylguanidine (^{211}At- MABG) that can be used for the treatment of metastatic/advanced neural crest cell derived tumours. ^{18}F and ^{68}Ga form the cornerstone of PET imaging but there are also few other long-lived PET radioisotopes that are produced via cyclotron which find their application in medical field, for e.g. ^{89}Zr, ^{124}I, ^{64}Cu. These long lives radioisotopes are primarily used in immunePET imaging and long-term biodistribution studies. Their long half-life matches slow antibody kinetics better than short-lived isotopes. Key positron emitting radioisotopes and SPECT radioisotopes along with their routes of production are enlisted in Table-2 and Table-3 respectively. The global surge in cyclotron facilities and Nuclear Medicine research has played a transformative role in healthcare. New facilities will expand access to advanced diagnostics (PET/SPECT) and targeted therapies, particularly in oncology, addressing both urban and rural healthcare disparities. This progress positions the country to lead in affordable, sustainable, and cutting-edge Nuclear Medicine solutions for improved patient outcomes nationwide.

TABLE 1: Distinction of Cyclotron Types

CLASSIFICATION	ENERGY RANGE	TYPICAL LOCATION
SMALL MEDICAL CYCLOTRON	< 20 MeV	- hospitals - universities - local commercial plants
INTERMEDIATE ENERGY CYCLOTRON	20-35 MeV	- regional commercial plants - research institutes
HIGH ENERGY CYCLOTRON	>35MeV	- research institutes - cancer proton therapy centers

TABLE 2: Key Positron-Emitting Radioisotopes & their Production in Medical Cyclotron Facility

Isotope	Half-Life	Nuclear Reaction	Energy Range (MeV)	Target Material	Common PET tracers	Clinical Use
Fluorine-18 (^{18}F)	110 min	$^{18}O(p, n)\ ^{18}F$	11-17	$H_2{}^{18}O$ (enriched water)	^{18}FDG, ^{18}F-NaF, ^{18}FET	-Oncology: Imaging tumour metabolism -Regional brain and cardiac metabolism -Bone scan
Carbon-11 (^{11}C)	20.3 min	$^{14}N(p,\alpha)^{11}C$	11-17	N_2 gas (+ O_2 or H_2)	^{11}C-Choline, ^{11}C-Methionine	-Amino acid metabolism -Prostate cancer -Brain tumours -Parathyroid adenoma
Nitrogen-13 (^{13}N)	9.97 min	$^{16}O(p,\alpha)^{13}N$ $^{12}C(p, n)\ ^{13}N$	19 11	$H_2{}^{16}O$ (water)	^{13}N-Ammonia	Myocardial blood flow and perfusion
Oxygen-15 (^{15}O)	2.03 min	$^{15}N(p, n)\ ^{15}O$ $^{14}N(d, n)\ ^{15}O$ $^{16}O(p, pn)\ ^{15}O$	11 6 >26	N_2 gas (+ O_2)	^{15}O-Water	Myocardial blood flow and perfusion
Copper-64 (^{64}Cu)	12.7 h	$^{64}Ni(p,n)^{64}Cu$ $^{64}Ni(d,2n)^{64}Cu$	10-15	Enriched ^{64}Ni	^{64}Cu-ATSM ^{64}Cu-DOTATATE	-Imaging tumour hypoxia -Somatostatin receptor positive tumours: NET -ImmunoPET
Strontium-82 (^{82}Sr)	25 d	$^{85}Rb(p, 4n)^{82}Sr$	50-100	Natural ^{85}Rb	$^{82}Sr/^{82}Rb$ generator system	Myocardial blood flow and perfusion
Zirconium-89 (^{89}Zr)	78.4 h	$^{89}Y(p,n)^{89}Zr$ $^{89}Y(d,2n)^{89}Zr$	11-13 12-18	Enriched ^{89}Y	^{89}Zr-mAb	ImmunoPET by labelling with antibodies
Iodine-124 (^{124}I)	4.18 d	$^{124}Te(p,n)^{124}I$ $^{124}Te(d,2n)^{124}I$	10-20	Enriched ^{124}Te	^{124}I-mAb ^{124}I-NaI	-ImmunoPET by labelling with antibodies -Thyroid cancer
Gallium-68 (^{68}Ga)	67.7 min	$^{68}Zn(p,n)^{68}Ga$	11-14	Enriched ^{68}Zn solid	^{68}Ga-DOTATATE, ^{68}Ga-PSMA	-Somatostatin receptor positive tumours: NET -Prostate cancer
Germanium-68 (^{68}Ge)	270.8 d	$^{69}Ga(p, 2n)^{68}Ge$ $^{nat}Ga(p,xn)^{68}Ge$	30	Enriched gallium metal Gallium-Nickel alloys	$^{68}Ge/^{68}Ga$ generator system	Same as ^{68}Ga

TABLE 3: Key SPECT Radioisotopes Produced in Cyclotron

Isotope	Half-Life	Nuclear Reaction	Energy Range (MeV)	Target Material	SPECT tracer	Clinical Use
Iodine-123 (^{123}I)	13.2 h	^{124}Te(p, 2n)^{123}I ^{124}Xe(p,pn)^{123}Xe→^{123}I	26–20	Highly enriched ^{124}Te	^{123}I-NaI	Thyroid uptake and imaging, myocardial imaging
Gallium-67 (^{67}Ga)	3.26 d	^{68}Zn(p, 2n)^{67}Ga	20-28	Enriched ^{68}Zn	^{67}Ga	Infection and inflammation imaging
Thallium-201 (^{201}Tl)	73.06 h	^{203}Tl(p, 3n)^{201}Pb → ^{201}Tl	19-30	Enriched ^{203}Tl	^{201}Tl	Myocardial perfusion and viability imaging
Indium-111 (^{111}In)	2.83 d	^{111}Cd(p, n)^{111}In ^{112}Cd(p, 2n)^{111}In	10-18 20-25	Natural cadmium, Enriched ^{112}Cd or natural silver	^{111}In-DTPA ^{111}In-Octreotide ^{111}In-mAb	Cisternography NET imaging ImmunoSPECT
Technetium-99m (^{99m}Tc)	6.01 h	^{100}Mo(p,2n)^{99m}Tc	15-25	Enriched ^{99}Mo	"Workhorse of Nuclear Medicine": Multiple tracers used for gamma imaging and SPECT imaging	

TABLE 4: Key Therapeutic Radioisotopes Produced in Cyclotron

Isotope	Half-Life	Nuclear Reaction	Energy Range (MeV)	Target Material	Therapy radionuclide	Clinical Use
Astatine-211 (^{211}At)	7.2 h	^{209}Bi(α, 2n)^{211}At	28-35	High purity bismuth metal	^{211}At-mABG	Treatment of neural crest cell derived tumours
Copper-67 (^{67}Cu)	61.8 h	^{67}Zn(p,n)^{67}Ga → ^{67}Cu ^{70}Zn(p, α)^{67}Cu	12-16 30 MeV	Enriched zinc	Theranostic pair of ^{64}Cu	
Rhenium-186 (^{186}Re)	3.72 d	^{186}W(p,n)^{186}Re	12-18	Enriched tungsten	^{186}Re-HEDP ^{186}Re-sulfide	-Bone pain palliation -Radiosynoviorthesis

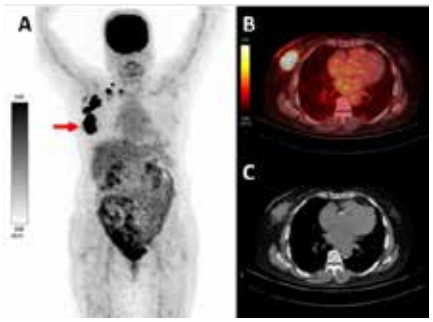

FIGURE 1: 58-year-old lady, with Carcinoma right breast- Invasive ductal carcinoma, triple negative underwent staging ^{18}FDG PET/CT. Intense ^{18}FDG uptake is seen in a right breast lesion (red arrow) and other satellite lesions with few right axillary and right cervical lymph nodes.

A: Maximum intensity projection (MIP) image, **B,C:** Fused axial PET/CT and CT image.

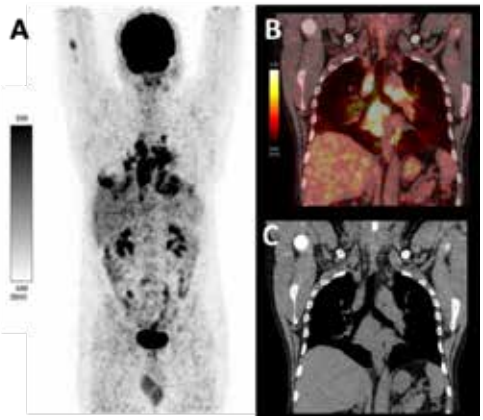

FIGURE 2: 39-year-old man, with history of dry cough and breathlessness on exertion, with Serum ACE level: 80.39 U/L was diagnosed with sarcoidosis. He was referred for ^{18}FDG PET/CT to evaluate the disease extent.
^{18}FDG PET/CT showed intense ^{18}FDG uptake in multiple enlarged bilateral mediastinal lymph nodes, which is a classical finding of pulmonary sarcoidosis.

A: Maximum intensity projection (MIP) image, **B,C:** Fused coronal PET/CT and CT image

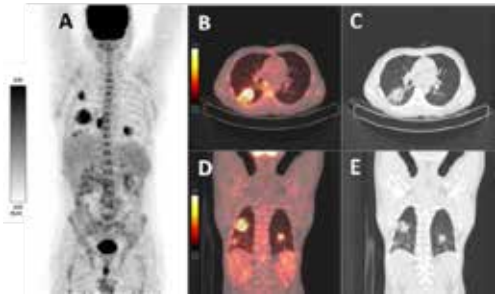

FIGURE 3: A 40-year-old man, with history of low-grade fever with chills and cough with sputum production- suspected pulmonary tuberculosis.
^{18}FDG PET/CT showing intense ^{18}FDG uptake in multiple cavitating consolidatory lesions in bilateral lung and small ^{18}FDG avid enlarged mediastinal lymph nodes.

A: Maximum intensity projection (MIP) image, **B,C**: Fused axial PET/CT and CT image. **C,D:** Fused coronal PET/CT and CT image.

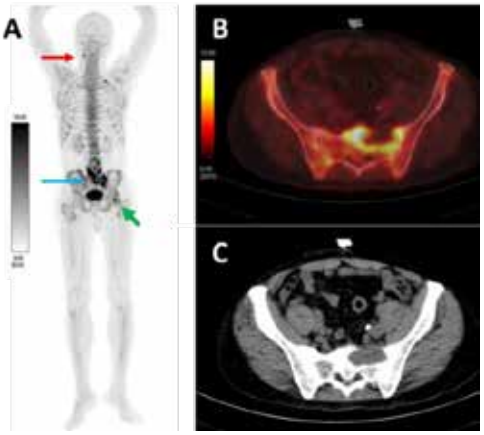

FIGURE 4: A 60-year-old man, case of differentiated thyroid carcinoma with skeletal metastasis under ^{18}F-NaF bone PET-CT which shows multiple tracer concentrating lytic lesions in the right mandible (red arrow), ribs, lower lumbar vertebra, sacrum (blue arrow) and left femur (green arrow).

A: MIP image **B,C:** Fused PET/CT and CT image showing lytic lesion in the sacrum with a soft tissue component.

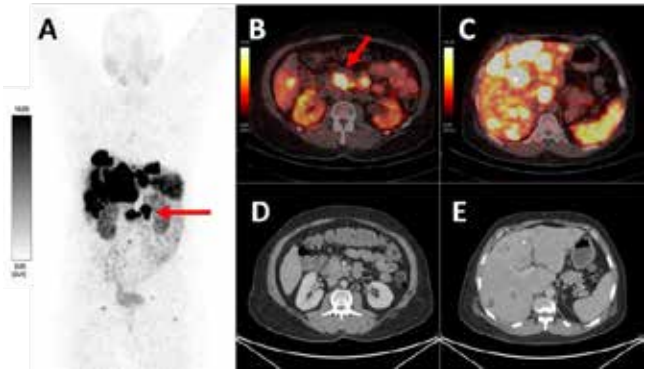

FIGURE 5: A 56-year-old man, with grade II Neuroendocrine tumour of the pancreas with liver metastasis. ^{68}Ga-DOTATATE scan showing high grade SSTR expressing pancreatic body lesion (red arrow) and multiple arterially enhancing liver lesions with high grade SSTR expression**.**

A: ^{68}Ga-DOTATATE MIP B,C**:** Fused axial PET/CT images, **D,E:** Axial contrast enhanced CT images.

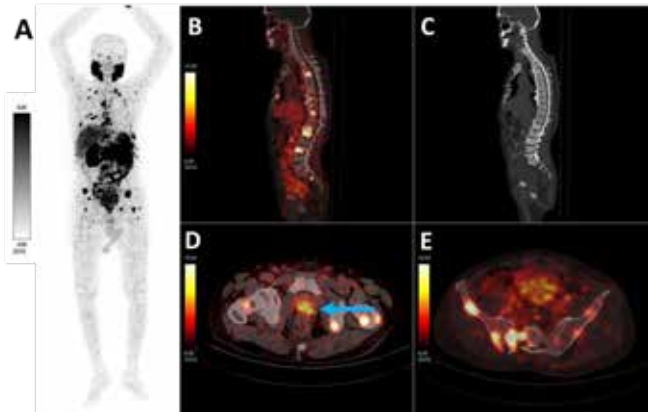

FIGURE 6: A 68-year-old man with Adenocarcinoma prostate (Gleasons score 4+4=8), with Sr. PSA level >100 ng/ml, for staging PSMA PET/CT. ^{68}Ga-PSMA-11 PET/CT shows high PSMA expressing lesion in the prostate (blue arrow), pelvic and abdominal lymph nodes and multiple sclerotic skeletal lesions.

A: MIP image, **B,C:** Fused sagittal PET/CT and CT images, **D,E:** Fused axial PET/CT images showing prostate lesion (blue arrow).

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BARC-TIFR Pelletron Linac Facility (PLF)

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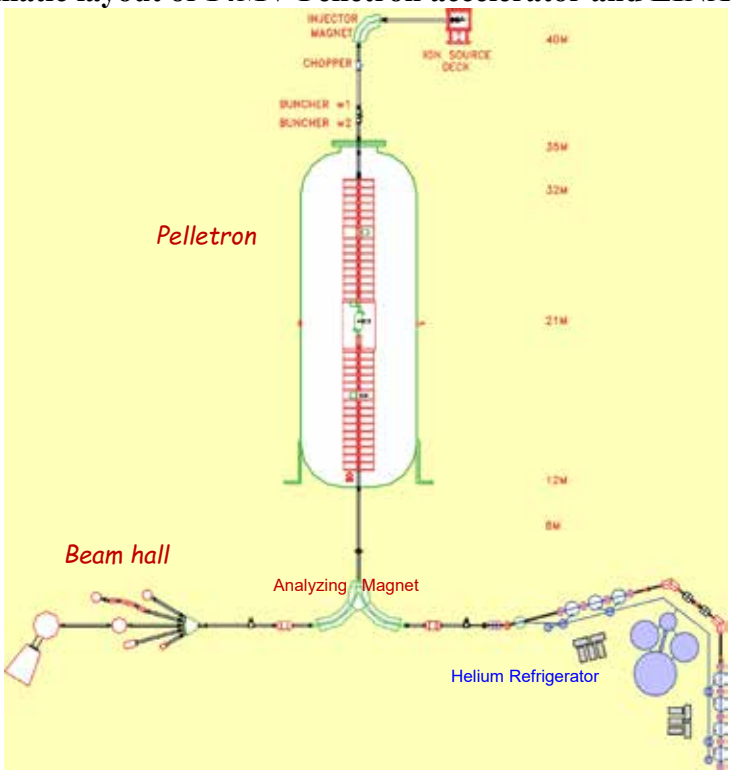
Summary of the facility

The Pelletron-Linac facility, set up as a collaborative project between BARC and TIFR, located at TIFR campus, Mumbai, has been a major centre for the heavy ion accelerator-based research in India. The accelerator facility consists of a 14UD Pelletron with LINAC booster. The Pelletron accelerator was formally inaugurated on 30th December 1988 and marked an important milestone in nuclear physics research in India. The Pelletron accelerator has been operating round-the-clock delivering more than 45 different ion species from proton to Iodine. The accelerator is mainly used for basic research in the fields of nuclear, atomic and condensed matter physics as well as material science. Over the years, a number of developmental activities have been initiated resulting in enhancement of overall performance and uptime of the accelerator and also enabling variety of application-oriented programmes including, accelerator-based mass spectrometry, production of large-scale track-etch membranes, radioisotopes production, low flux protons irradiation damage studies and secondary neutron production for cross section measurement etc. The developmental activities involve, replacement of voltage grading based on corona needles by resistances, installation of a new terminal potential stabilizer, introduction of recirculation terminal gas stripper system, development of negative ion beams for a wide range of ion species, a double harmonic drift buncher in the low energy injection path and integration of Linux based control & monitoring system. The facility was augmented with the indigenously developed superconducting LINAC booster to enhance the energy of the beams available from Pelletron accelerator. The phase I of LINAC booster was commissioned on 22nd September 2002 and the facility was dedicated to users on 28th November 2007 after the completion of the phase II. The LINAC booster consists of seven liquid helium cryostat modules, each housing four lead coated (2 μm) copper quarter wave resonators (QWR). The cavities are designed to operate at 150 MHz with an optimum acceptance at a velocity corresponding to beta=0.1. Most of the critical components of the LINAC booster have been designed, developed and fabricated indigenously. A variety of state-of-the-art experimental facilities have been developed at this centre to pursue frontier research in nuclear, atomic, condensed matter and multidisciplinary areas. Experimental facilities are attached to dedicated beam lines installed in Cascade beam hall for Pelletron energies and two Linac beam halls I & II for both Pelletron and Linac boosted energies. While a majority of the researchers at this facility are from BARC and TIFR, the experimental community includes scientists and students from other research centers and universities within India and abroad. About 165 Ph.D. theses and 825 publications in international referred journals have resulted from the research activities at the PLF. These include 19 publications in Physics Review Letter and 21 in other Letter journals.

A Schematic layout of 14MV Pelletron accelerator and LINAC Booster



Technical Specifications:

Pelletron Accelerator

Type of Machine	DC Electrostatic Tandem Accelerator
Max Terminal Voltage	14 Million Volt
Type of Beams	Proton to Heavy Ion
Max Mass	^{127}I (accelerated so far)
Voltage Stability	+/- 1 kV
Proton Energy Range	8.0 MeV to 28 MeV
Alpha Particle Energy Range	12.0 MeV to 42 MeV
Acceptance Test values (Proton Current)	3.0 µA at 8.0 MeV 5.0 µA at 28.0 MeV
Acceptance Test Values (Alpha Particle Current)	2 µA at 42.0 MeV
Acceptance Test Values (Chlorine Current)	100 pnA at 14.0 MV Terminal
Applications	Nuclear & Atomic Physics, radiochemistry, Material Science, Accelerator Mass Spectrometry and Industrial applications.
Radiation Type	Instantaneous X-rays, Gamma and Neutrons.

LINAC Booster:

Type of machine	Superconducting RF linear Accelerator
Accelerating Structure	Quarter Wave Resonator
Superconductor	Lead
Operating Temperature	4.2 K
Operating Frequency	150 MHz
Input velocity range (β=v/c)	0.07 – 0.14
Optimal input velocity (β_{opt})	0.1
Mass range accelerated	12 - 80
Design output energy	14 MV per charge state

Main Instrumentation for Nuclear Physics Experiments:

i. Clover Detector Array for discrete gamma ray spectroscopy with auxiliary detectors
ii. 150cm dia Scattering Chamber, with two independently rotatable arms permitting detector rotation and target ladder adjustment from remote without beam interruption using Programmable Logic Controller, for charged particle spectroscopy and fission studies
iii. BaF_2/$LaBr_3$ array for high energy gamma ray studies with BGO/NaI(Tl) multiplicity filter
iv. Charged Particle Array based on Si pad (Delta-E) and CsI(E) detectors
v. Neutron Detectors Array of 18 Liquid Scintillation detectors and Annular parallel plate avalanche counter having 12 segmented signal read out with angular coverage from 5 degree to 11 degree, for Time of Flight Technique based compound nucleus residue tagging
vi. MWPC and Si-strip detectors for angular distribution measurements of particles
vii. Electron spectrometer and X ray detector for atomic physics studies with gas and foil targets
viii. Irradiation setups
ix. High current proton and secondary neutron irradiation facility
x. Low background offline counting facility

Main Fields of Nuclear Research:

i. Nuclear reactions (elastic, inelastic, transfer, fusion and fission reactions)
ii. Nuclear structure & spectroscopy
iii. Nuclear data generation relevant to nuclear reactors as well as IAEA coordinated research programs on advanced nuclear reactors and nuclear astrophysics
iv. Elemental analysis using PIGE (Particle Induced Gamma Emission)

Main Fields of Other Research:

i. Atomic & Cluster physics
ii. Condensed Matter Physics &Material Science
iii. Radiochemical studies
iv. Accelerator mass spectrometry, production of track-etch membranes
v. Low flux secondary neutron production for irradiation studies

vi. Low flux proton irradiation damage studies relevant to space bound devices, materials and yield improvement in wheat & rice seeds
vii. Application of thin layer activation technique for wear and corrosion rate measurement.

Future Developments:
1) High voltage upgrade of Pelletron tandem accelerator to sustain operation up to 14 MV by replacing the existing accelerating tubes with new generation high gradient accelerating tubes in phased manner without significantly affecting user utilization.
2) Fabrication and installation of low beta niobium cavities in the first module of Superconducting LINAC Booster to enhance the mass range of accelerated ions. Development of digital LLRF control for the superconducting cavities.

User Community:
Bhabha Atomic Research Center (Mumbai)
Tata Institute of Fundamental Research (Mumbai)
Inter University Accelerator Center (New Delhi)
Variable Energy Cyclotron Center (Kolkata)
Saha Institute of Nuclear Physics (Kolkata)
UGC-DAE Consortium for Scientific Research (Kolkata)
University of Mumbai (Mumbai)
University of Calcutta (Kolkata)
Indian Institute of Technology (Roorkee)
Indian Institute of Technology (Bombay)
Indian Institute of Technology (Kharagpur)
Viswabharati University (Santiniketan)
Panjab University (Chandigarh)
Banaras Hindu University (Varanasi)
Delhi University (New Delhi)
Andhra University (Vishkhapatnam)
University of Kashmir (Srinagar)
Guru Ghasidas University (Bilaspur)
Bengal Engineering and Science University (Kolkata)
Center for Excellence in Basic Sciences (Mumbai)
Sambalpur University (Sambalpur)
Institute of Physics (Bhubaneswar)
MS University (Baroda)
Allahabad University (Allahabad)
Guru Nanak Dev University (Amritsar)
Notre Dame University (Notre Dame, USA).

Location: TIFR, Homi Bhabha Road, Navy Nagar, Colaba, Mumbai-400005
Tel: +91-22-22782318 (PLF-TIFR Control Room) & +91-22-25593450
Webpage: http://www.tifr.res.in/~pell/pelletron/index.php
C**ontact Person** (User Liaison, PLF): Dr. Sanjoy Pal
Phone: +91-22-22782454/ +91 -22-22782318
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Folded Tandem Ion Accelerator (FOTIA) at BARC

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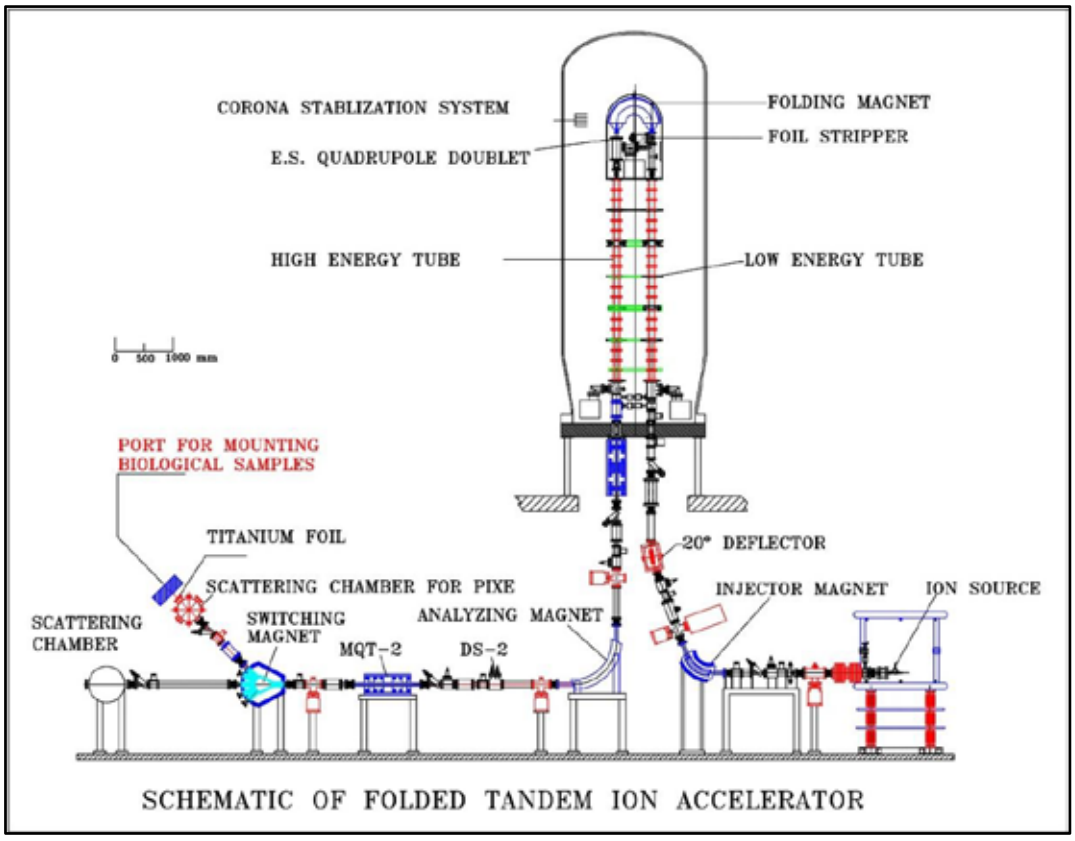
The Facility

The 5.5 MV Van de Graaff accelerator at BARC, Trombay has been converted into a 6 MV Folded Tandem Ion Accelerator (FOTIA). FOTIA is a unique variety of tandem accelerator built within the structure of a single-ended Van-de-Graaff accelerator. Two acceleration tubes are placed side by side rather than end-to-end as in the conventional tandem, and a 180° magnet inside the high voltage terminal guides the beam between the tubes.

During 2000 initial commissioning of the accelerator has been done with N_2+CO_2 insulating gas. After achieving a high voltage of 3.4 MV, carbon beams have been accelerated up to terminal voltages of 3.1 MV. The accelerated beams were characterized by measuring the Rutherford Back Scattering from Gold targets. The long term voltage stability of better than 5 kV was obtained during these measurements. The N_2+CO_2 mixture is replaced by SF_6 gas in order to get 6 MV on the terminal.



SCHEMATIC OF FOLDED TANDEM ION ACCELERATOR

Since then it is in operation and has been used both for basic and applied research. The facility has been delivering variety of ion beams for last twenty five years reliably for performing

various kinds of experiments and contributed immensely to various programs of DAE, ISRO and universities. External PIGE facility using low energy proton beam from FOTIA has been utilized for Boron-10 Isotope content determination in B4C samples on commercial basis. FOTIA has three operational beam lines where experiments like PIXE, PIGE, RBS, material irradiation, Prompt Neutron Fission studies and radiation biology experiments are carried out.

FOTIA Specifications

Type of Machine	DC Electrostatic Tandem Accelerator
Terminal Voltage	6 MV
Voltage Stability	± 2 kV
Beam Energy Range	Up to 5 MeV for Proton Up to 66 MeV (Ca^{10+}) for heavy ions.
Type of Beams	H^{+1} to Ca^{10+}
Maximum Beam current	Proton: 200 nA Heavy ions: < 100 nA
Radiation Type	Instantaneous X-rays, Gamma and Neutrons.
Insulating Gas	SF_6 at 90 psig
Applications	Nuclear & Atomic Physics Material Science PIXE, PIGE, RBS Radiation Biology Prompt Fission Studies

Beam details

Beam Species	Max. Energy	Max. current/Intensity
^{7}Li, ^{12}C, ^{16}O and ^{19}F and other heavy ion beams upto A=40	66 MeV	< 100 nA
Proton	Upto 5 MeV	200 nA
Neutron	Below 5 MeV using ^{7}Li(p,n) and ^{9}Be(p,n)	10^{6}-10^{7} n/sec/cm^{2}

Principle of Operation

The SNICS ion source is located at the ground floor, which generates negative ions that are initially accelerated to low energies in a short horizontal section. These low energy negative ions are then bent through using a 70^{o} injector magnet followed by a 20^{o} electrostatic deflector into the vertical accelerating column. In the first stage, the negative ions are accelerated towards the

positively charged high voltage terminal situated at the top of the accelerator. The accelerated negative ions pass through a thin carbon foil stripper. The fast moving ions lose electrons while passing through the stripper and acquire positive charges. The average positive charge of the ion depends upon the type of the ion and its energy. The resulting positive ions now get bent through 180^{o} by the magnet placed inside the terminal and then enter the second or high energy stage of acceleration where the high positive voltage of the terminal acts repulsively on the positive ions. The final energy of the ions which have acquired a positive charge of n units will be (n+1) eV, where V is the terminal voltage. The accelerated ions coming out of the high energy accelerating tube are focused by a magnetic quadrupole triplet and then analysed by the 90^{o} dipole magnet, located on the ground floor. The analysed beam is then guided to different experimental beam lines through the quadrupole triplets and the switching magnet.

SNICS Ion Source

FOTIA Terminal

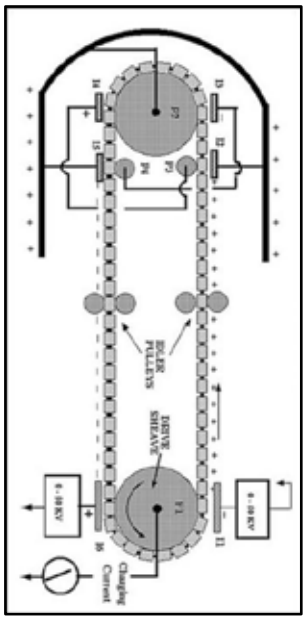
Accelerator Column Structure

90^{o} Analysing Magnet

Pellet Charging System (High Voltage system)

The charging system in FOTIA utilizes a chain of alternate metal cylinders (pellets) joined by nylon links. The chain is rotated by an induction motor at 600 RPM. The pellets are steel cylinders of 3.2 cm diameter and 3.2 cm height. The charging is done by electrostatic induction and the maximum charging current is more than 50μA. This continuous transport of charge

results in the buildup of high voltage at the terminal. The voltage gradient in the high voltage column and accelerating tube is achieved by HV resistor chain. The column has 18 gaps in each module, while the accelerating tube has 33 gaps.



Pellet Charging System

High Voltage Grading System

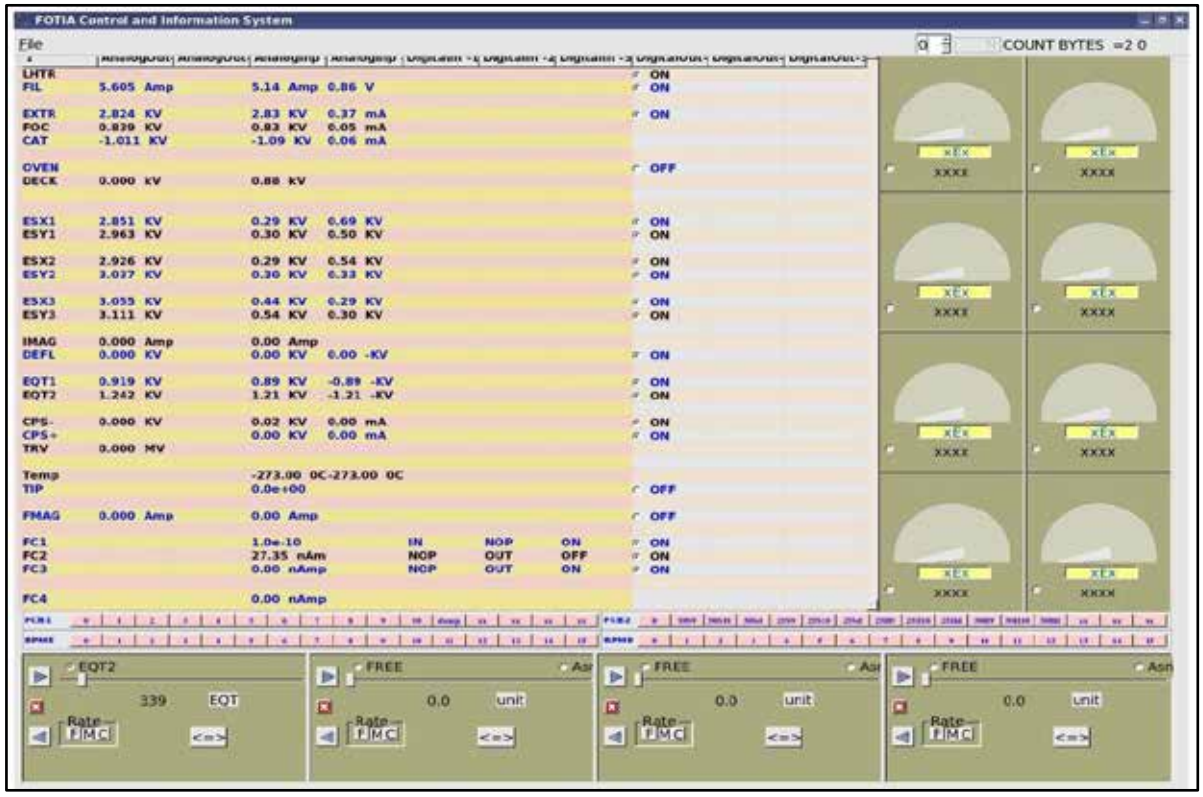
Ultra High Vacuum System

In FOTIA, the ions extracted from the SNICS-II negative ion source have to travel a distance of nearly 35 meters before they reach the experimental target. Since the charge exchange cross sections for heavy ions are very large it is necessary to minimize the residual gas pressure and maintain ultra-high vacuum (UHV) in the accelerator tubes and rest of the beam transport system of the accelerator.

The UHV is also required to reduce the loss of beam intensity and spread in energy of the ion beams due to collisions of the ions with the residual gas molecules present due to poor vacuum. A distributed pumping system having eight pumping stations maintain UHV in the whole accelerator. A vacuum of $1x10^{-8}$ Torr is routinely achieved throughout the accelerator beam path.

FOTIA Control & Information System

The accelerator is controlled by a PC based control system, which is designed as a network of PCs with a front-end interface using CAMAC instrumentation. All the PCs use Linux operating system. GUI is designed using QT framework for better user interface and controls. The system is designed to control and monitor the parameters like current and voltage applied to various components, the status control, the status read of the instruments, the quality of the beam, etc. Communication of the parameters in the high voltage areas (located in terminal and ion source deck) to the CAMAC instruments is through the fibre optic telemetry system. The system uses a voltage-to-light & light-to-voltage technique to communicate through point-to-point plastic fibre optic cables. A Terminal Voltage Stabilization system developed in-house achieves good voltage stability of ±2 kV at terminal voltage of 6 MV.

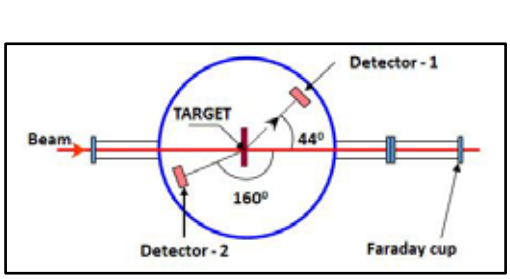


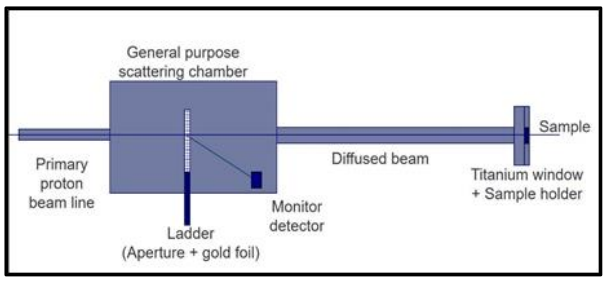
Graphical User Interface of FOTIA Control & Information System

FOTIA Beam Lines

Three experimental beam lines are operational in FOTIA beam hall. The beam coming out of the analysing magnet can be delivered to any of these beam lines by means of a switching magnet.

1. **0^O beam line** is a general purpose beam line having a general purpose scattering chamber dedicated for conducting RBS, material science and irradiation type experiments.





Left: Experimental setup for Rutherford Back Scattering Experiments,
Right: Experimental setup for Irradiation Experiments

2. **25^O – Hill side beam line** is a dedicated beam line for following nuclear physics studies.
   - Fast neutron induced fission of actinides and minor-actinides
   - Cross section data measurements of Materials relevant to GEN-IV reactors / ADS Radioisotope production.

Left: Experimental setup at 25^{o} Hill-Side Line.
Right: Experimental setup at 25^{o} Sea-Side Line

25^{O} – Sea side beam line is a dedicated beam line for PIXE, PIGE, External PIGE type experiments and in-situ current normalized PIGE method for low Z elements.

Conclusion

FOTIA facility has been delivering variety of ion beams for last twenty five years reliably for performing various kinds of experiments and contributed immensely to various programs of DAE and other research institutes and universities.

Some of the major experiments carried out at FOTIA facility are Quantification of low Z elements in geological samples using External PIGE, Irradiation of IPG glasses, PFNGS Measurement in Neutron induced fission on Neptunium, Irradiation of alkali halide glasses, Depth profiling of phosphorous in polymer sheet sample, Quantification of ^{18}O isotope in liquid water samples by external PIGE using current normalization, Measurement of prompt fission gamma in the fast neutron induced fission of ^{232}Th, Quantification of Boron & its isotopic composition in Boron compounds and ceramic materials using external PIGE & Thick target gamma ray yield & low Z element detection by External PIGE.

FOTIA is one of the safest accelerators in operation and received safety shield for three consecutive years earlier. Many of the FOTIA practices are recommended by ULSC-PA to other accelerator facilities to adopt, which is an indication of very high safety standard of FOTIA.

Ion Beam Analysis Facilities at Institute of Physics, Bhubaneswar

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The Ion Beam Analysis (IBA) facilities located at the Institute of Physics (IOP), Bhubaneswar, India are mainly equipped with two essential instruments that play a crucial role in the field of ion beam research. The first one is the NEC model 9SDH-2 Tandem Pelletron accelerator. This sophisticated device is designed to generate positive ion beams with energy levels that can be tuned a wide range of energies within a range of 1 to 12 MeV. Notably, the 9SDH-2 tandem Pelletron accelerator features a maximum terminal voltage of 3 MV, which can be adjusted to any value between 0.5 MV and 3.0 MV. This tunability allows researchers to optimize the accelerator's output based on the specific type of ion being utilized and the energy requirements of their experiments. The second one is a 40 KV low-energy negative ion implanter which is capable of producing different type of negative ion beams with energy between 20 and 40 keV.

3.0 MV 9SDH-2 Tandem Pelletron Accelerator

The Pelletron accelerator at IOP is equipped with two distinct negative ion sources: Alphatross (rf source) and Multi-Cathode Source of negative ion by cesium sputtering (MC-SNICS). Alphatross is exclusively used for the production of negative helium ions (He^-), whereas MC-SNICS is designed to generate different other negative ions. The ion beams that are commonly used at IOP facility include hydrogen (H), helium (He), lithium (Li), carbon (C), silicon (Si), copper (Cu), silver (Ag), and gold (Au) etc. These negative ions, possessing an energy of 55 keV, are injected into the Pelletron accelerator (Figure 1). These negative ions inside the accelerator tube experience electron loss due to collisions with argon gas, which leads to their conversion into positive high-energy ions beams. The ion beam currents that are focused on the target or samples, typically of several nanoAmps.

Figure 1. Pelletron Accelerator at IOP

Ion Beam Analysis Techniques at IOP

The IOP accelerator facility serves as a crucial resource for a variety of research problems that require the application of ion beam analysis (IBA) techniques. These techniques encompass a range of methodologies, including Rutherford backscattering spectrometry (RBS), which is employed to analyze the composition and structure of materials at the atomic level (Figure 2).

Ion-channeling is another technique utilized within this facility, allowing researchers to investigate the arrangement of atoms in crystalline materials by observing the behavior of ions as they traverse through the lattice.

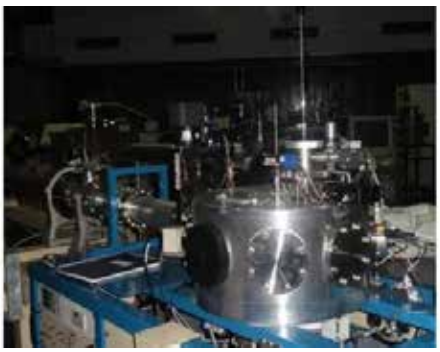

Figure 2. Rutherford Back Scattering Beam Line with experimental chamber, set up for RBS, Ion Channeling & Elastic Recoil Detection Analysis (ERDA).

Furthermore, Proton-Induced X-Ray Emission (PIXE), is a method employed, to ascertain the elemental analysis of materials (Figure 3). The process involves exposing a material to energetic proton beam, which leads to atomic interactions that emit electromagnetic radiation in the x-ray range of the spectrum, characteristic of specific elements. PIXE is a highly effective and non-destructive analytical technique that is routinely utilized at IOP by many users such as medical practitioner, geologists, archaeologists, art conservators, and various other professionals to address the research related to condensed matter physics, health, environment and materials science. Simillarly, Particle-induced gamma-ray emission (PIGE) spectroscopy is a specialized technique within the realm of nuclear reaction analysis. It is categorized as one of the thin-film analytical methods employed in ion beam analysis. This technique involves the interaction of energetic particles, such as protons or alpha particles, with a target material, leading to the emission of gamma rays. The emitted gamma rays provide valuable information about the elemental composition and distribution of elements within thin films similar to PIXE. PIGE spectroscopy is particularly advantageous for its sensitivity to light elements and its ability to analyze materials without significant damage, making it a powerful tool in various fields, including materials science, semiconductor research, and environmental studies.

Figure 3. Proton Induced X-ray Emission (PIXE)/ Particle-induced Gamma-ray Emission (PIGE) Line with experimental chamber, Facility for: PIXE/PIGE, Scattering & Nuclear Reaction Analysis (NRA).

In addition to these IBA techniques, the accelerator facility also plays a vital role in supporting research that involves ion implantation and irradiation (Figure 4). Ion implantation is a process used to introduce ions into a material, thereby modifying its physical and chemical properties, which is particularly important in semiconductor fabrication and materials science. Similarly, ion irradiation involves exposing materials to ion beams to study their effects on material properties, such as radiation damage and defect formation. Collectively, these capabilities make the accelerator facility an indispensable asset for advancing knowledge in various scientific fields, including materials science, physics, and engineering.

Figure 4. Implantation beam Line, Facility for Ion Implantation & Ion Irradiation

Low Energy Ion Implanter

The IBA facilities at IOP is also equipped with a 40 KV low-energy negative ion implanter (Figure 5). This device is capable of producing different types of negative ion beams that operate within an energy range of 20 to 40 keV. The beam line essentially consists of a negative ion source, an accelerating column, focusing devices such as electrostatic quadruples, an analyzer magnet for selecting the particular ion beam as well as transporting in a particular direction and finally, an ion implantation chamber. The facility is equipped with a sputter base negative ion source namely SNICS source (Source of negative ion by cesium sputtering) for generating negative ion beams. The optimized ion beam spot size can be varied from 5 mm x 5 mm to 10 mm x 10 mm. An electrostatic scanner placed in front of the target/sample, allows a uniform ion implantation. The facility is in regular operation for ion implantation purposes especially for material science experiments.

Figure 3. Low energy negative ion implanter

Other facilities at IOP

Additionally, the UGC-DAE Consortium for Scientific Research has recently inaugurated the Bhubaneswar Node of UGC-DAE CSR at the Institute of Physics (IOP), which will provide access to state-of-the-art facilities at IOP Bhubaneswar. IOP is equipped with many advanced experimental facilities dedicated to research in condensed matter physics and materials science. Below are some of the experimental facilities available at IOP:

i) 200 keV Transmission Electron Microscope (Jeol, Ultra high resolution),
ii) 2 – 30 keV Field Emission Gun based Secondary Electron Microscope with FIB attachment,
iii) UHV–STM (Omicrom MBE system),
iv) Scanning Probe Microscopes (VEECO-make),
v) High-precision Atomic Force Microscope (Asylum Research-make),
vi) X-Ray photoelctron Spectroscopy,
vii) He-Cd laser (Kimon Koha-make) based Photoluminescence System (Edinburgh Instruments-make),
viii) UV-VIS-NIR Spectrophotometer (Shimadzu-make),
ix) UHV e-beam evaporation DC/RF magnetron sputtering (Excel Instruments-make coupled with Advanced Energy-make pulsed DC and RF power supplies),
x) Molecular Beam Epitaxy (MBE) with RHEED, STM,
xi) Powder Diffractometer (Bruker-make), High-resolution XRD system with reciprocal space mapping (Bruker-make),
xii) SQUID–VSM based MPMS System (Quantum Design-make),
xiii) Pulsed laser deposition unit, and
xiv) Micro-Raman spectrometer

Conclusions

Overall, IOP house a diverse range of ion beam analysis techniques, leading to notable progress in materials science, semiconductor studies, and numerous other applications. The collective resources available at IOP provide a robust platform for cutting-edge research and experimentation in ion beam technology, along with advancements in condensed matter physics and materials science research.

3 MV Tandem Accelerator facility at NCCCM-BARC, Hyderabad

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NCCCM-BARC, Hyderabad has a 3 MV Tandem Accelerator facility which was installed in the year 1995. Since its installation, the facility has been extensively utilised for compositional characterisation and depth profiling of different elements in the surface and near surface regions of the materials using Ion Beam Analytical Techniques. Over the past 30 years this facility is augmented with different experimental beam lines and associated subsystems like, scattering chambers, collimators, vacuum ports etc, to carry out (a) Rutherford Backscattering Spectrometry (RBS), (b) Elastic Recoil Detection Analysis (c) Particle Induced Gamma Emission Spectroscopy (PIGE) (d) Nuclear Resonance Reaction Analysis (NRRA) (e) Particle Induced X-ray Emission Spectroscopy (PIXE) and (f) Coincidence Ion Beam Analysis facility. The facility has been used in the development of methodologies for determination and depth profiling of light elements (H, B, C, N, O, F, Al, Mg, etc) and analysis of multi-layer coatings. Further, the above techniques are extensively used for measuring composition and thickness of the multilayer coatings, interfacial stability and are also used to determine diffusion coefficients. The analysis is carried out by detecting prompt radiations (γ, protons, α particles etc) from nuclear reactions/scattering induced by energetic ion beams produced from the accelerator. The figure below shows the injector assembly, accelrator tank and experimental end stations.

Injector assembly and T-shape tank

Experimental end stations

The 3MV Tandem accelerator system is has three major sub-systems (a) Injector assembly (b) Accelerator (c) Experimental end stations.

Injector assembly consists of (a) two negative ion sources namely Duoplasmatron source for generation of H^- and He^- ions and Sputter ion source for generation of negative ions of H, Li, C, N, F, Cu, Ni etc. (b) focusing elements for optimum beam transmission (c) 90° bending magnet for negative ion beam injection into the accelerator.

Accelerator encompasses (a) accelerating column (b) Terminal consisting of nitrogen gas based stripper assembly (c) Cockcroft Walton type high voltage generation unit (d) high pressure tank holding insulating SF_6 gas up to a pressure of 7 bar and (e) Switching/analyzing magnet ($\pm 15^{\circ}$ and $\pm 30^{\circ}$ ports) .

The experimental end-stations consists of various beam lines, collimators, scattering chambers, vacuum pumps/gauges, 4- axis sample manipulator, electron suppressor for proper charge integration, forming a Faraday cup assembly, detector for detection/measurement of charged particles, X-rays and γ-rays.

The facility is equipped to carry-out IBA on vacuum compatible solid samples of size up to 25 mm × 25mm (Ideal dimension). These solid samples are mounted on 4-axis sample manipulators and placed inside the scattering chamber. For detecting prompt reaction products, the scattering chambers are equipped with Silicon Surface Barrier detectors (SSBD) for charge particle detection, High Purity Germanium (HPGe) and Bismuth Germanium Oxide (BGO)detectors for γ-ray detection, and Si(Li) detector for X-ray detection. For processing the signals from the detectors various electronic modules such as pre-amplifiers, Spectroscopy amplifiers, PC- based Multichannel Analyser are in place. It is worth mentioning that the facility is equipped with four channel, high speed (100MS/s) digitizer which enables simultaneous detection of signal from four different detectors and has the ability to carry out coincidence/correlated measurements.

The figure below shows an experimental setup for carrying out nuclear reaction analysis using multiple detectors.

This 3 MV Tandem accelerator facility has been catering to various DAE units, National Institutes (ISRO, DMRL, DRDO etc), Academic Institutes (IITs, Universities etc) and industries for compositional analysis of materials using IBA techniques.

Person to contact for beam time/ collaboration:
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Research Reactor, Ion-Beam Accelerator and Materials Research Facilities of BARC for Collaborative Research Work within DAE and with Universities/Academic Institutes

R. Acharya[1], A.K. Gupta[2], Mala Rao[3], A. K. Arya[4], P.D. Babu[5]

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Various BARC Facilities for University/Academic Institutes Collaboration through UGC-DAE-CSR, Mumbai Centre: since 2021.

Sr.	Facilities and Associated Techniques
1.	Neutron scattering and imaging studies utilizing neutron beam at research reactors.
2.	BARC-TIFR Pelletron-LINAC facility for Nuclear Physics Research
3.	Folded Tandem Ion Accelerator (FOTIA) and LEHIPA facilities for ion beam studies
4.	Electron beam Accelerators, Pulsed neutron source and Pulsed electromagnetic systems and high impact (Ballistic) studies
5.	Neutron irradiation facilities for applications utilizing research reactors of BARC
6.	Nuclear and radio-analytical (NAA, IBA, XRF) and spectroscopy facilities for chemical characterization and Positron Annihilation Spectroscopy for materials characterization.
7.	Materials Science facilities for microstructural and surface investigations using TEM, SEM, EPMA, ESCA, 3DAP, XRD and Raman techniques, mechanical testing of materials, etc.
8.	SAXS, Ferroelectric, Piezoelectric and Pyroelectric Analyzer, Rheometer, Confocal microscope, High Temperature thermo-dilatometer

UGC-DAE Consortium for Scientific Research: UGC DAE CSR (https://www.csr.res.in/): Centre Director of each unit can be contacted as per the Webpage address/contacts: UGC-DAE Consortium for Scientific Research (formerly known as IUC-DAEF), was created in the year 1990. The broad objective of Consortium is developing competence and promoting research in front line areas of science and technology in Indian Universities by providing institutional framework for optimum utilization of major research facilities established by the Department of Atomic Energy such as Synchrotron Radiation Sources at, RRCAT Indore; Reactor and Accelerator Facilities at BARC Mumbai; VECC at Kolkata (node at IOP, Bhubaneswar) and facilities at IGCAR, Kalpakkam.

Neutron scattering and complimentary facilities: Neutron scattering facilities under National facility for neutron beam research (NFNBR) and other complimentary facilitates can be accessed through UGC-DAE Consortium for scientific research. The details of facilities under NFNBR can be found on https://nssi.org.in/pdfs-files/NFNBR-Brochure-2024.pdf. Broad features and facilities are listed below.

Nuclear & Radioanalytical Techniques
Utilizing Nuclear Research Reactor and Particle Accelerator

1. Neutron Based Activation Techniques

Neutron Activation Analysis (NAA)

NAA applications: Major, minor and trace elements (Na to U) in geological, biological/food, environmental (soil, sediment, coal, coal fly ash), archeological, industrial and forensic samples, materials Sciences (alloys, ceramics, glasses). In addition to total elemental concentrations, speciation studies of trace elements (like As, Cr, Iodine etc.) are feasible.

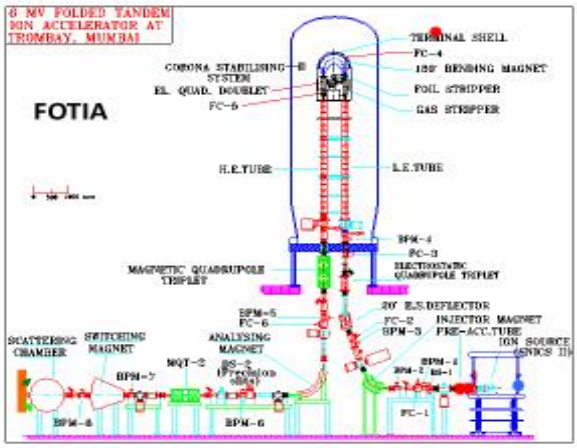
2. Ion Beam Analysis (IBA) Techniques

Particle Induced Gamma-ray Emission (PIGE) :Using proton beam from tandem accelerator – low Z elements (Li, B, F, Na, Al, Mg, Si, P and Ti quantification) in all types of samples including alloys, ceramics, glasses as well as Total B and its Isotopic Composition ($^{10}B/^{11}B$ atom ratio) in boron based copounds (Boric Acid), ceramics like B_4C / refractory materials (di & hexa borides).

Particle Induced X-ray Emission (PIXE) – All elements from K to U quantification possible like ED-XRF with lower matrix effect. Applications to many fields including archaeology, forensic, environmental samples.

NAA using Dhruva (PCF & SS facility) and Apsara-U reactors for multielement determination. PIGE/ External PIGE using Proton beam (in air) at FOTIA and NCCCM, BARC for Low Z elements, and Boron Isotopic composition.

Experimental Facilities at Folded Tandem Ion Accelerator (FOTIA)



Setup for fast neutron induced fission studies of actinides

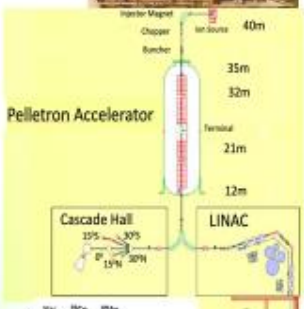
General purpose Scattering Chamber Schematic of RBS setup

PIXE Facility :
Scattering Chamber & Si(Li) detector

BARC-TIFR Pelletron Linac Facility (PLF)

The 14MV Pelletron Accelerator, has been serving as a work-horse for heavy ion accelerator based research for more than three decades since its commissioning, delivering wide range of beams, catering to diverse users within and outside DAE

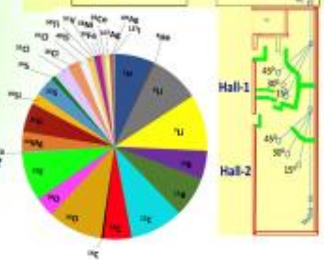
- Experimental Facilities for
  - Nuclear physics
  - Atomic physics
  - Condensed matter physics & material science
  - Production of track-etch membranes
  - Low flux Proton irradiation damage studies
  - Accelerator Mass Spectrometry
- Users
  - BARC, TIFR, SINP & VECC
  - DRDO, ISRO, Universities and other research institutions



Neutron production & radiopharmaceutical applications

HI induced-mutation studies in grains

Track Etched Membrane production setup



Utilization of BARC facilities for R&D work via Institute to Institute collaboration or via UGC DAR CSR Projects (3 years Projects) and One-Time Visit for experimental work utilizing BARC facilities with UGC DAE CSR support.

- Write /Email to Concerned Division and Contact Scientist (Get from Large Scale Facilities of BARC from UGC DAE CSR Mumbai Centre Web Portal from web page www.csr.res.in)
- Always give your full address with contact details and your CV/Biodata/Area of Research/Facility to Use/Technique to Use

- Contact Scientist will get permission from concerned Office/Division Head, will let you know about the availability of facility and his and her availability
- You may then approach UGC DAE CSR Mumbai Centre for financial support (TA/Local hospitality) as per the UGC-DAE CSR rules.

Look for details of BARC Large Scale facilities & contact scientists under Mumbai Centre

Acknowledgments

We sincerely thank Chairman, AEC, and Director, BARC for their support. Thanks are due to Director, UGC-DAE-CSR, and Directors of Materials Group and MRG of BARC for their encouragement. We sincerely thank Associate Directors of RC&I Group, Reactor Group, Physics Group, Chemistry Group and BTDG. We also thank Heads of different Divisions of BARC (ROD, IADD, RCD, FCD, ACD, SSPD and ChD) for their support & encouragement for enhanced utilization of BARC facilities.

Societal Applications of Radiations & Radioisotopes – BRIT Scenario

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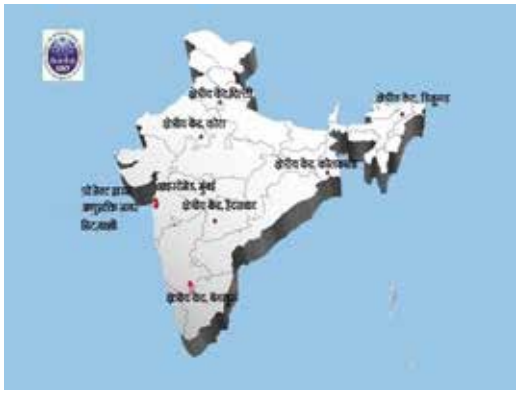
Preamble

Board of Radiation and Isotope Technology (BRIT), an Industrial Unit of Department of Atomic Energy (DAE), Government of India was established on March 01, 1989. BRIT's focus on harnessing the benefits of radioisotope applications and radiation technology across industry, healthcare, research and agricultural sectors continues to create a visible impact by fulfilling societal needs through its various commercial ventures all over India.

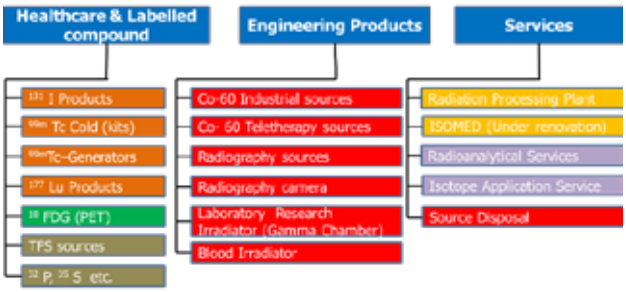
BRIT provides a broad portfolio of products in the form of Radiopharmaceuticals, Labelled Compound and Nucleotides, Sealed Radiation Sources, Gamma Chambers, Blood Irradiators and Radiography Exposure Devices. BRIT also offers Isotope Application services, Radioanalytical services, Calibration and Dosimetry services and Radiation Processing Services besides Project Consultancy services for setting up Radiation Processing Plants in the private sector.



BRIT has a wide geographic coverage with head quarter in Navi Mumbai and major operations centres in Navi Mumbai, Mumbai, Rawatbhata (Kota) (RAPPCOF at RAPS site, dedicated to Cobalt-60 recovery and processing), and Kolkata (at the Cyclone-30 medical cyclotron facility at VECC, dedicated to production of positron emitter radioisotopes) as well as four regional laboratories located at Bengaluru, Delhi, Dibrugarh and Hyderabad.

The vision of Board of Radiation and Isotope Technology (BRIT) is to empower India through Technology, creation of more wealth and providing better quality life to its citizens. This is to be achieved by making India energy independent, contributing to provision of sufficient, safe and nutritious food and better health care to our people through development and deployment of radiation technologies and their applications.

BRIT -Three Verticals



BRIT is providing various products and services, which are covered under three verticals (1) Healthcare & Labelled Compounds, (2) Engineering Products, and (3) Services.

1) **Healthcare & Labelled Compounds:** Various products supplied in healthcare covers range of Radiopharmaceuticals and related products that includes:

a. ^{131}I based Products – Used for Diagnostic & Therapeutics purposes
b. ^{99}Mo-^{99m}Tc Generator – Used for elution of ^{99m}Tc used for SPECT based diagnostic applications
c. ^{99m}Tc Cold Kits – Used for diagnostic application with ^{99m}Tc
d. ^{177}Lu Products – Used for Therapeutics & pain palliation applications
e. ^{18}F products – Used for PET diagnostics applications

Other than these BRIT also supplies various Radio-chemicals and RIA (Radio Immuno Assay) Kits. BRIT has developed state-of-the-art methods and standardized procedures for the synthesis, purification and quality control /quality assurance of labelled compounds and biomolecules. As Carbon and Hydrogen are fundamental components of all organic compounds, they can be replaced with their isotopes (Carbon-14 and Other Isotopic labelled compound) without altering their chemical properties. These compounds can be detected and quantified with high sensitivity at nanomolar levels of concentration thus making them the favoured choice for biological research.

This includes ^{14}C and ^{35}S based labelled compounds, Special Illuminators, Deuterated NMR Solvents, custom synthesis etc.

2) Engineering Products:

BRIT supplies various radioactive sources and equipment which are used in industry in the field of NDT, gamma radiation processing, Radiation teletherapy applications, research etc. These products and equipment includes:

a. Co-60 Irradiator Sources – used in Gamma Irradiation Facilities used for irradiation of food products, sterilisation of medical products etc.
b. Co-60 Teletherapy Sources – used in Radiation Teletherapy Machine for cancer treatment
c. Radiography Exposure Devices and Radiography Sources – Used in Industries for NDT applications. Ir-192 and Co-60 sources are supplied.
d. Lab Irradiators – Supplied with Co-60 and Cs-137 based isotopes to be used for research applications
e. Blood Irradiators- Supplied with Co-60 and Cs-137 based isotopes to be used for blood irradiation applications

Other than these BRIT also supplies various Reference and Custom made sources, Nucleonic Guage sources, sources for brachytherapy applications, dosimeters, dosimetry system, electrochemical cells, biological indicators etc.

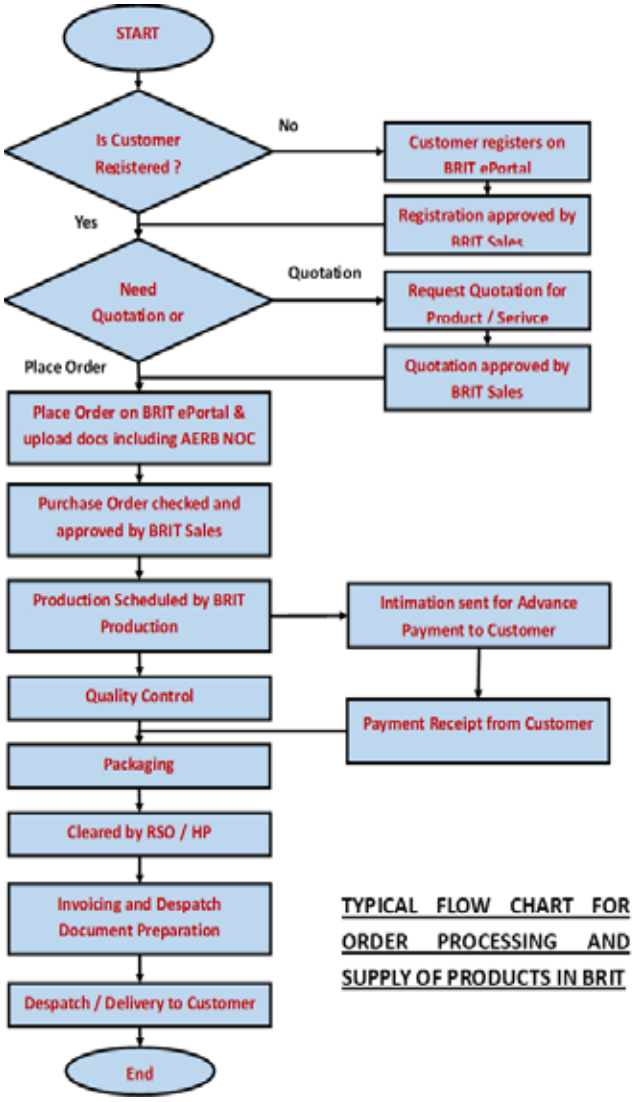
3) Services:

BRIT provides various radiation and radioisotope-based services which includes:

a. Gamma Radiation Processing Services – provided through Radiation Processing Plant in Vashi and ISOMED plant at south site BARC.
b. Radioanalytical services – for testing and certification of radioactivity content in food products, water samples, steel samples and environmental samples etc.
c. Isotope applications services – having application in Oil refineries & petrochemical plants, Onshore & offshore oil production wells, Heavy engineering, Construction & manufacturing units, Thermal power plants, Dam, ports & harbours etc.

d. Dosimetry Services – for commissioning and re commissioning dosimetry services are provided for radiation processing plants for sterilisation of medical products and for food irradiation applications
e. Consultancy Services - through MoU with interested entrepreneurs for setting up Gamma Radiation Processing Plants in Private/Public Sector
f. Calibration services – for Portable Radiation Monitoring Instruments

How to Procure –Procedure:



TYPICAL FLOW CHART FOR ORDER PROCESSING AND SUPPLY OF PRODUCTS IN BRIT

Web Links:

- BRIT has website available at https://www.britatom.gov.in which provides information on various products and services supplied.
- Orders are processed through BRIT ePortal available at https://eportal.britatom.gov.in

Important Contacts for Sales & Marketing:

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022 68687482-87, 7253, 7254
022 27887702-07, 7253, 7254

References:

1. https://www.britatom.gov.in

BRNS: Advancing Nuclear Science and Technology Through Extramural Research Funding

Hemant P. Agnihotri, S. Khan, Ajay Kumar, Gopika Vinod*

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The Board of Research in Nuclear Sciences (BRNS) is an advisory body of Department of Atomic Energy (DAE), which is established to promote advancing scientific research through extramural funding. BRNS has been instrumental in driving innovation across universities, academic institutions and national laboratories. Its mandate is to leverage the expertise of researchers nationwide, enabling them to contribute significantly to the DAE's strategic goals and the broader scientific landscape in the collaborative mode. Thereby generate a large pool of qualified and skilled human resources to cater to the needs of the department in the time to come. BRNS has a long history, starting before India's independence as the Atomic Energy Committee, the first government agency to fund research outside of government institutions. This Committee was formed in the year 1945 under the aegis of Council of Scientific Research (CSIR). It was renamed as Atomic Research Committee in (ARC) in 1947, which subsequently became Board of Research in Atomic Energy (BRAE) under the Atomic Energy Commission formed during 1947-48. Following this, the BRAE was again renamed as Board of Research in Nuclear Sciences (BRNS) in the year 1955. In the year 1998, BRNS was restructured with an independent BRNS secretariat. In October 2018, BRNS was reconstituted to better align its activities with the strategic nine visions of the DAE.

The Department of Atomic Energy (DAE) was formed in August 1954 and primary mandate of DAE is the production of safe and economical nuclear power, using indigenous uranium and thorium resources. Towards this end, DAE is involved in developing, in stages, pressurized heavy water reactors, fast breeder reactors and reactors using thorium with associated fuel cycle facilities. DAE also builds research reactors for production of radioisotopes and carries out programmes on isotope and radiation technology applications in medicine, agriculture and industry. DAE develops advanced technology in areas such as accelerators, lasers, control and instrumentation, computers, biotechnology, information technology and materials technology and also encourages technology transfers to other users and industry. DAE supports basic research in nuclear energy and related frontier areas of science. Thus, the key objective of BRNS is to encourage, support and promote scientific research in areas of relevance to the mandate of DAE in research groups outside DAE to derive benefits from their expertise.
Research areas relevance to the mandate of DAE are categorized into nine themes:

i) **First Stage of Indian Nuclear Power Programme (NPP):** Mechanical and thermal engineering of present and evolving nuclear reactors, Probabilistic & Deterministic Safety Analyses, Health Physics, Development and Validation of Computer Codes, Reactor Physics & Nuclear Data, Seismic Design, Construction Technologies, Equipment Design and Prototyping, Heavy water-related technologies.

ii) **Uranium, Rare metals & Nuclear Structural Materials (URM):** Mineral Exploration and Processing, Mining Technologies, Beach sand minerals, Separation Science, Chemical &

mechanical processing of nuclear materials, Nuclear fuel & structural materials, Radiation damage, Non-destructive testing.

iii) **2nd stage of Indian Nuclear Power Programme Fast Reactor & Back End Fuel cycle (FRR):** Mechanism and equipment for FBR, FBR safety, Development of materials and associated technologies for future FBRs, Material Irradiation and In-service inspection for FBRs, Sodium Experiments, Sensors & instrumentation development, Reprocessing and Waste management technologies for thermal and fast reactor fuel cycle.

iv) **Health Care (HLC):** Cancer Research, Radiopharmaceuticals for diagnostics & therapy, Development of Cancer Drugs, Research on Tuberculosis, Drug-resistant tuberculosis, Drug discovery and drug delivery, Genetics, Medical Cyclotron, Radiotherapy units.

v) **Food Security (FOS):** Nuclear Agriculture, Mutation breeding for seed development, Bio-pesticide, Preservation of agriculture products, seafood, meat & ready to eat/cooked food, Management of agriculture waste, Bio-composting.

vi) **Water and Waste Management (WWM):** Water Purification and Desalination, Membrane-based and nano-composite filters. Environmental Studies, Effluent Treatment, Isotope Hydrology, Management of municipal dry & wet waste, Integrated water & waste management.

vii) **Mega Science Schemes (MSS):** Nuclear Fusion, High Energy and Particle Physics, Cryogenics, Charged particle accelerators, Gravitational wave, Astronomy including gamma ray astronomy, Neutrino physics & Observatory.

viii) **Basic Research and Science Education (BRE):** High Energy and Nuclear Physics, Condensed Matter, Crystal Growth and Nano Materials, Characterization of Materials by Neutron and Synchrotron Radiation, Interface between Physics, Chemistry, Biology and Engineering, Radiochemistry, Radiation and Photochemistry, Cell and Molecular Biology, Radiation Biology, Science Education.

ix) **Directed Research (DIR):** Accelerators, Lasers, Electronics, Nano and microelectronic devices, VLSI, Detectors & Sensors, Scientific Instruments, Computer Science, Cyber Security, Robotics, Process and Medical Instrumentation, Energy Conversion and Storage, Cyber-physical system, Internet of Things (IOT).

BRNS technically & financially supports research projects under following four different categories:

i) **Relevant Research Projects (RRP):** BRNS supports high quality research & development programmes of relevance to DAE. Scientists / Engineers working in universities, academic/ research institutions of higher learning, having a regular position in government recognized universities, academic/ research institutions ONLY are eligible to apply. Researchers associated with government recognized incubation centre and DSIR (Department of Scientific and Industrial Research) recognized R&D organizations of Private Industry can also be considered for funding. Scientists / Engineers should have a minimum 5 years active service left in the institute and should be a full time faculty and on regular payroll of the

institute. Key achievement of RRP accomplished last year with outstanding outcomes was *Fabrication of Li4SiO4 pebbles with optimized strength and porosity by Extrusion-Spherodization* from Institute of Plasma Research, Gandhinagar along with NIT Rourkela.

ii) **Co-ordinated research projects (CRP):** It's a joint programme of supporting R&D for priority areas of DAE activities. In this scheme, Principal Collaborator from DAE units prepares a research project proposal consisting of 3 to 4 sub project proposals involving Co-PCs corresponding to each sub-project. Various researchers across the country submit their application as Principal Investigator (PI) against these proposals.
Typical example is on-going CRP of the Chemical Engineering Division, BARC Mumbai, in collaboration with IIT BHU, IIT Guwahati, and IIT Jammu, which focuses on Decoding Flow Physics of Elevated Temperature Fluidized Bed Reactors Using Radiotracers. The project includes the following sub-projects (SP):
SP-1: Study of Solid Hydrodynamics in an Elevated Temperature Gas-Solid Fluidized Bed with Secondary Gas Injection through Side Wall Pneumatic Nozzles. (IIT BHU)
SP-2: Investigation of Solid Flow in an Elevated Temperature Fluidized Bed with Decomposing and Non-Decomposing Liquid Injection through Side Wall Pneumatic Nozzles. (IIT Guwahati)
SP-3: Study on Two and Three-Phase Fluidized Beds: Hydrodynamic and Machine Learning (ML) based Computational Fluid Dynamics (CFD) Investigations. (IIT Jammu)

In last five years, BRNS has sanctioned 354 projects throughout the country, figure 1 shows the state-wise distribution of these research projects.

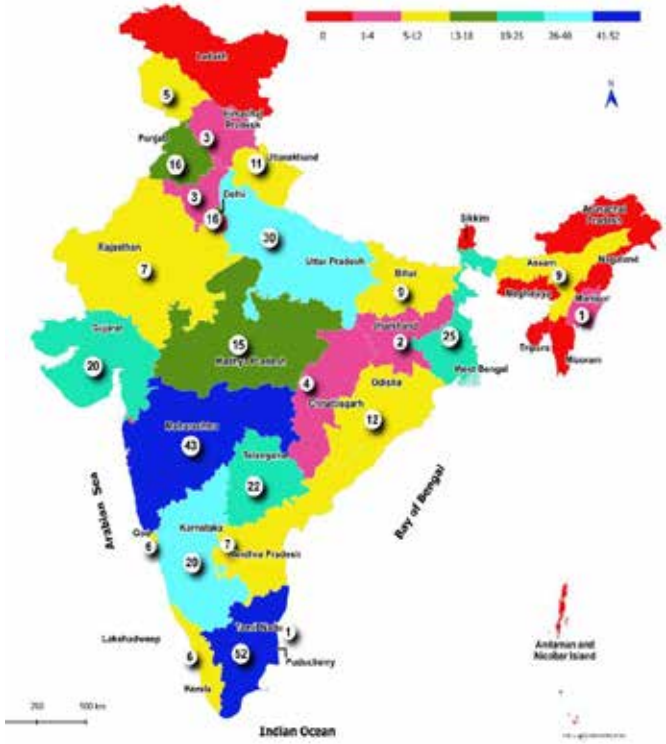

Figure (1): State-wise distribution of research projects sanctioned during F.Y. 2019-24 by BRNS.

iii) **Young Scientist Research Project (YSRP):** The main objective of the scheme is to encourage young scientists in the initial years of settling down in their career. Young scientists are provided with the necessary grants for research in setting up their first laboratories. This scheme is applicable to only scientists below the age of 35 years and can apply for it throughout the year but would be awarded twice a year.

iv) **MoUs / Mega projects:** BRNS provides funding for high value research projects under Memorandums of Understanding (MoUs) among academic /research institutions outside DAE and DAE institutions on major thrust areas of DAE interests. Such MoUs are generally entered into with academic / research centre outside DAE, when a major facility needs to be created for carrying out some of the important DAE activities. These centres are often National Centres where the facilities are accessible to the nationwide users.

At present under Mega project/MoU, there is National Facility for Atom Probe Tomography (NFAPT) at IIT Madras. NFAPT houses the state of art atom probe tomography (APT), latest cutting edge technology "Local Electrode Atom Probe (LEAP5000 XR)" along with "Helios Dual Beam Scanning Electron Microscope with Focused Ion Beam (FIB)" for LEAP sample preparation, which are showed in figure 2. This enhances the nation's materials research and development by enabling atomic-level 3D characterization. The facility operates round-the-clock and hands on training programmes and workshops are being conducted regularly for the benefit of research scholars and young researchers. It is being utilised by several government and private institutes (academic and industries) on payment basis along with partner institutes (including IITs and DAE) using the allotted time slots for the instruments.

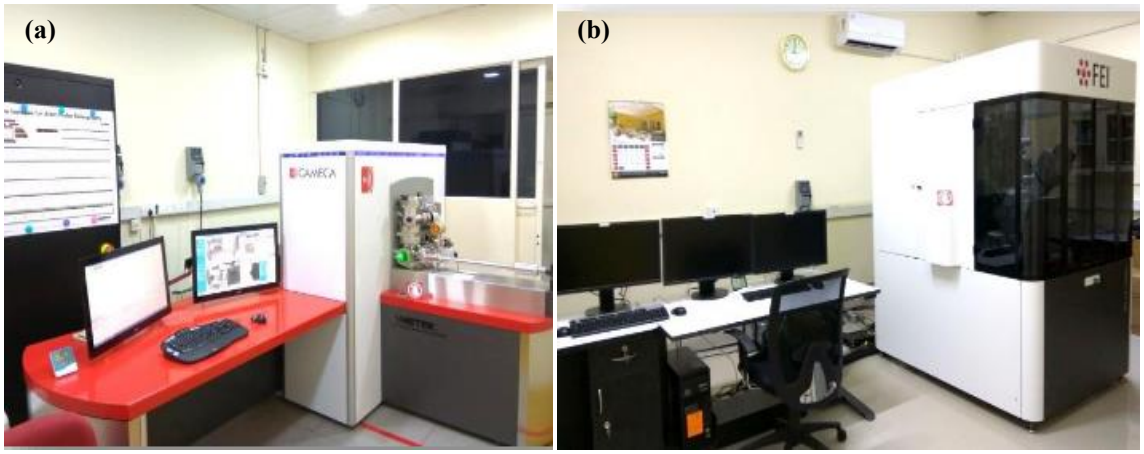

Figure (2) shows the (a) LEAP 5000 XR, and (b) Focused Ion Beam Facility.

Besides funding research projects, BRNS provides financial assistance to organize symposia/conferences/workshops on topics of relevance to the DAE programmes. BRNS is giving full financial assistance to the events organised by DAE institutes and partial financial assistance to symposia / conferences / workshops, organised by non-DAE academic and research Institutes across India. Figure 3 shows the state-wise distribution of financial assistance to symposia in F.Y. 2023-24.

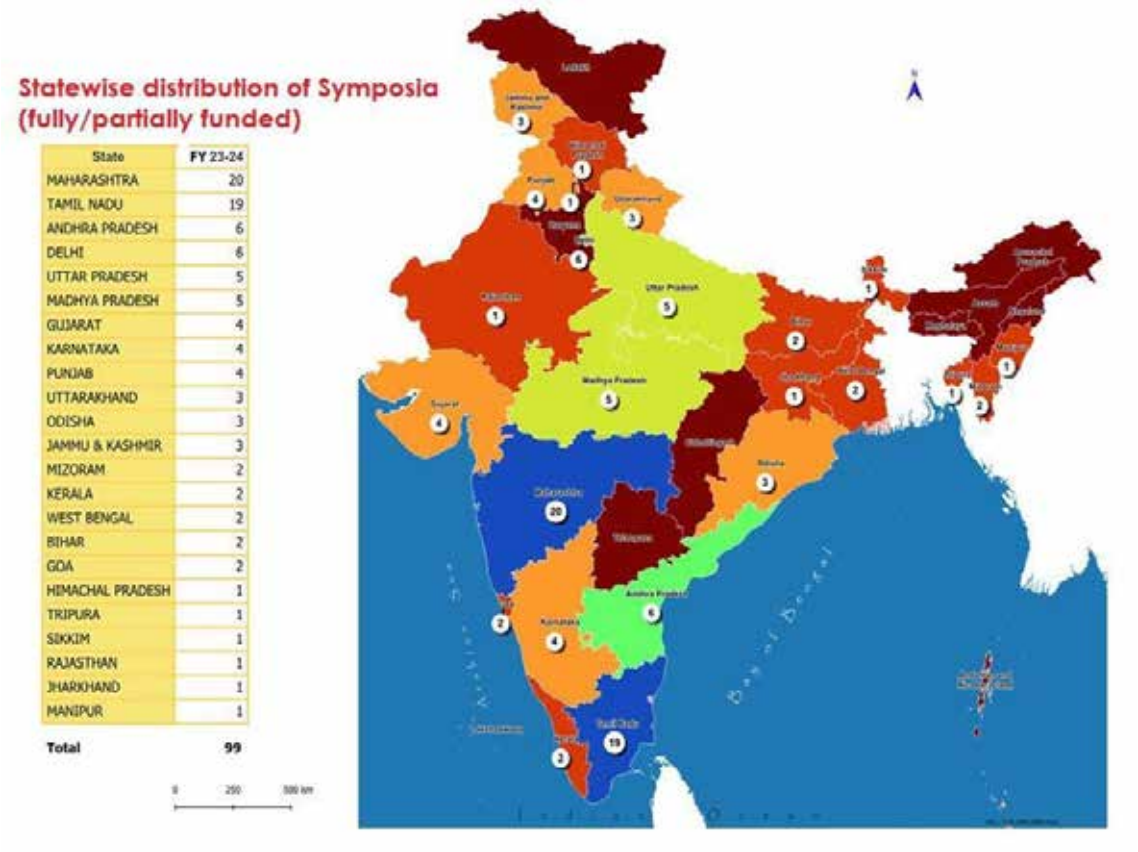

Figure (3): State-wise distribution of financial assistance to symposia in F.Y. 2023-24.

The Indian scientific community is invited to join in advancing nuclear science and technology. For more information, please visit the BRNS website at **https://brns.res.in/** or write to us at **helpdesk.brns@barc.gov.in** and **brns.symp@barc.gov.in**.

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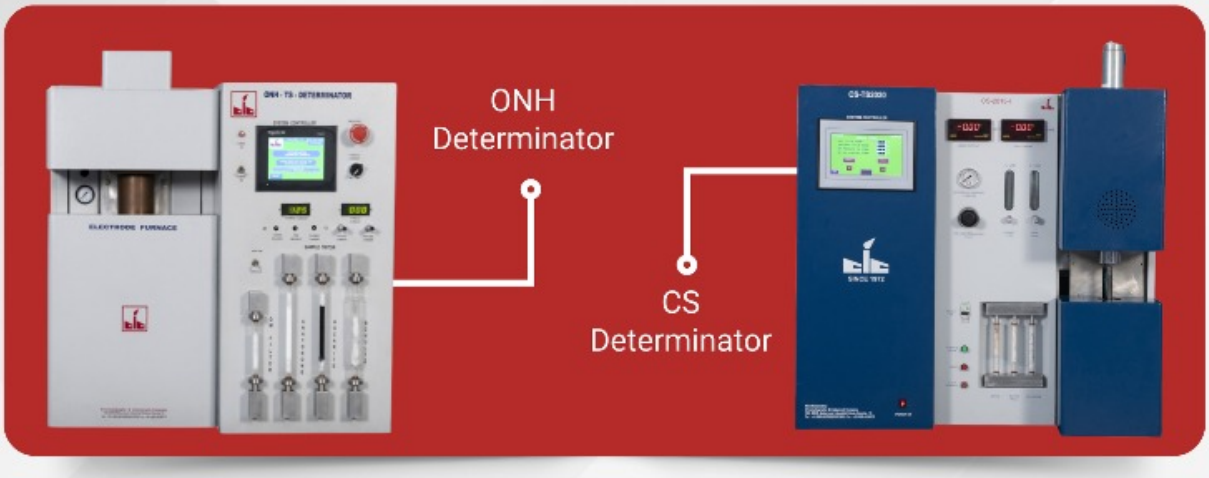

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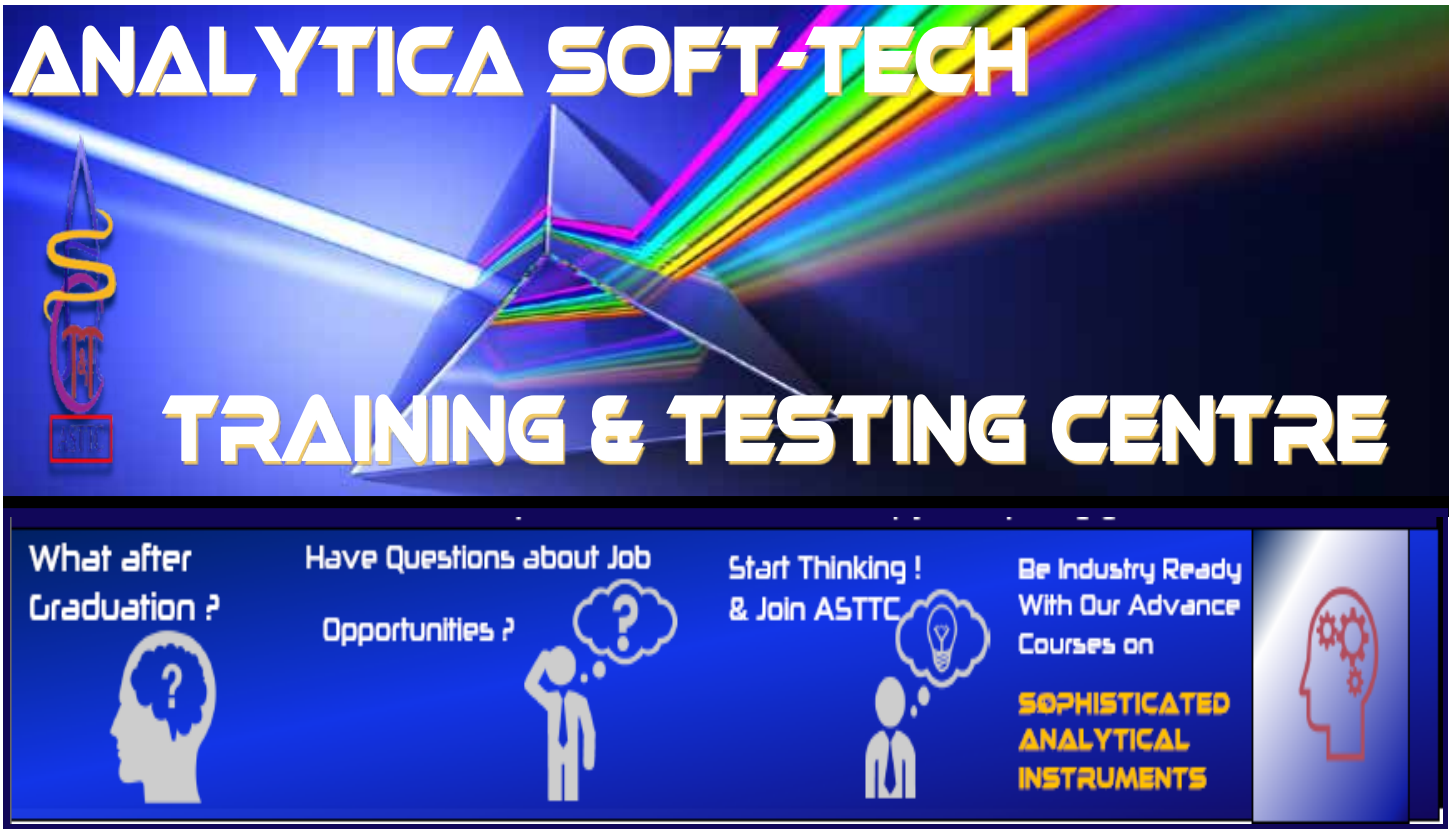

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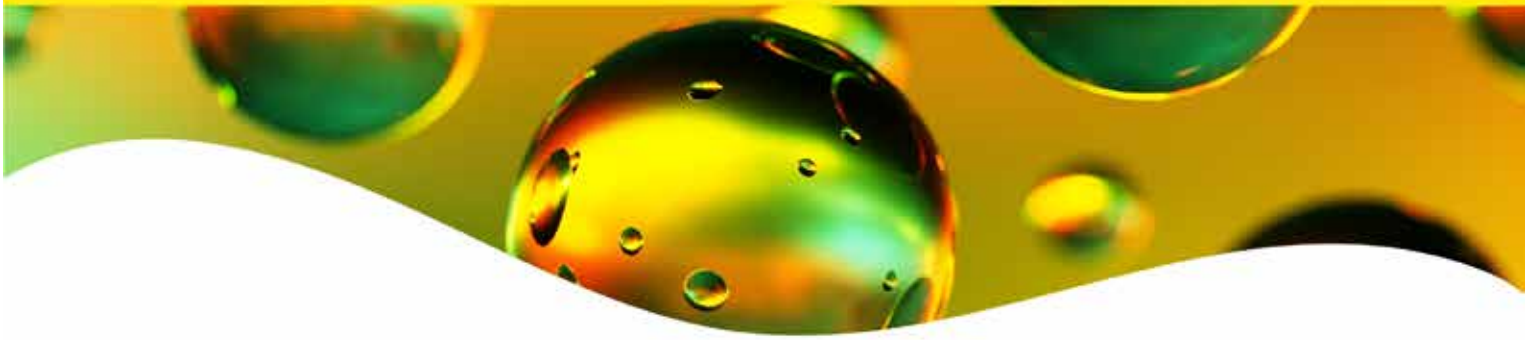

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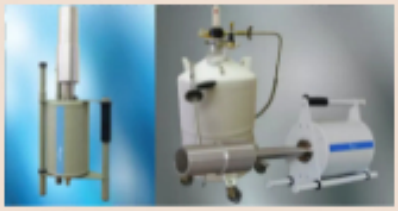
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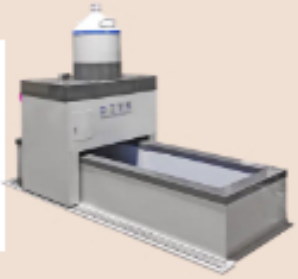
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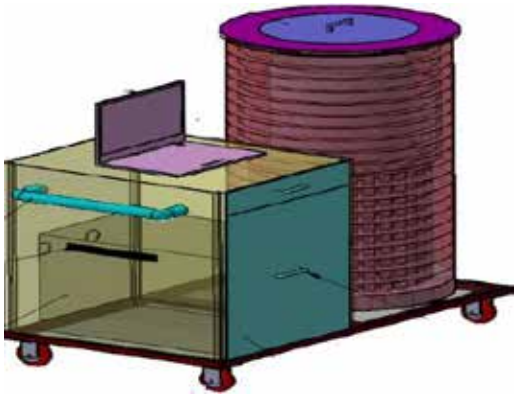

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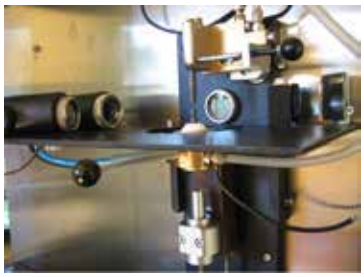

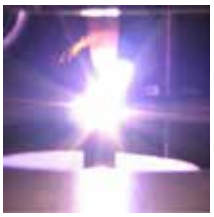

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The system DCA-302 is an autarkical excitation unit for the adaption to different emission spectrometers by a flexible UV-quartz-fiber-optic. The DC-Arc system features

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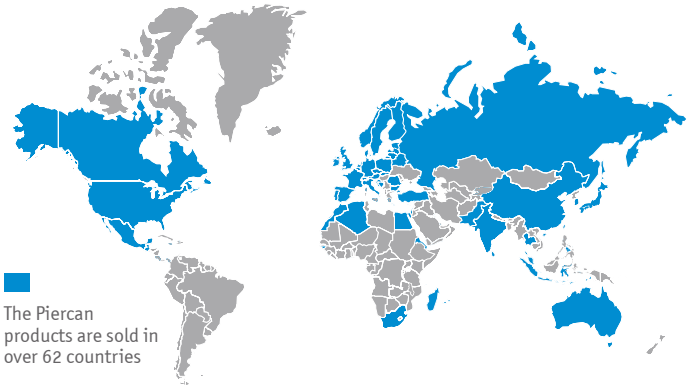

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ATOMIC ENERGY REGULATORY BOARD
www.aerb.gov.in

Mission:
To ensure that the use of ionising radiation and nuclear energy in India does not cause undue risk to the health of people and the environment.

AERB has the mandate to enforce radiation safety rules promulgated under the Atomic Energy Act, 1962 in the country, primarily Atomic Energy (Radiation Protection) Rules, 2004 and Atomic Energy (Safe Disposal of Radioactive Wastes) Rules, 1987.

- Atomic Energy Act, 1962 also empowers AERB with administration of Factories Act 1948, including enforcement of its provisions, appointment of inspection staff in the installations of Department of Atomic Energy (DAE), under its purview, for industrial safety.
- National Disaster Management Plan-2016 of India mandated AERB for preparing national plan for nuclear and radiological emergencies.
- AERB is entrusted with the responsibility to notify 'Nuclear Incidents' under the Civil Liability for Nuclear Damage Act, 2010.

- **AERB's Jurisdiction**
- AERB regulates nuclear fuel cycle facilities, right from exploration, mining, milling, fuel fabrication, nuclear power production, fast breeder reactor fuel fabrication as well as associated facilities (e.g. Heavy Water Plants
- Research Reactors
- Two research reactors: KAMINI (Kalpakkam Mini) reactor and Fast Breeder Test Reactor (FBTR) located at Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam are under AERB's regulatory purview.).
- Radiation Facilities
  AERB regulates large spectrum of facilities involved in the handling and application of radiation sources starting from small dental X-ray machine to high intensity radiation processing facilities.
- Transport of Radioactive material and Waste Management

Regulatory and Safety Functions

- *Safety Policies and Regulatory Documents:* AERB develops safety policies and regulatory documents for nuclear, radiation and industrial safety for facilities & activities under its purview.
- *Safety Review and Assessment:* AERB conducts safety review and assessment of facilities and activities under its purview.
- *Licensing:* AERB grant licenses to various facilities and activities after ensuring compliance with the specified requirements.
- *Regulatory Inspections:* AERB conducts regulatory inspections to ensure compliance of regulatory requirement, statutory norms and safety requirements.
- *Enforcement:* AERB enforces appropriate regulatory actions depending upon nature of non-compliance to regulatory requirements.
- *Emergency Preparedness and Monitoring:* AERB reviews facility specific emergency preparedness plan. AERB has set-up Nuclear and Radiological Emergency Monitoring Centre (NREMC) at its headquarters for monitoring and independent assessment of response action during nuclear or radiological emergency.
- *Safety Research & Analysis:* AERB conducts independent research to supplement regulatory review and assessment activities through its Safety Research Institute (SRI), Kalpakkam.
- *Public Communication and Safety Promotion:* AERB keeps public informed on major issues of safety significance. Towards this, AERB conducts safety promotional and public outreach activities.
- *National and International Coordination:* AERB maintains liaison with statutory bodies and other agencies in the country as well as abroad regarding nuclear and radiological safety.
- *Regulatory Peer Reviews:* AERB participates and invites peer review of regulatory services with a view to share experience and improvement in regulatory approaches.

Strengths of AERB: Independent Regulatory Decisions, Transparency and Competency

Safety Infrastructure

- AERB has implemented web-based Licensing system, e-LORA for Radiation facilities of the country.
- AERB has established its own Safety Research Institute (SRI) at Kalpakkam
- AERB has established Regional Regulatory Centres (RRCs) in Delhi, Kolkata and Chennai
- Integrated Management System(IMS) which integrates all its processes and activities into one framework

Radioisotopes & Radiation Technology in
Healthcare, Industry, Agriculture & Research

PRODUCTS

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RADIATION SOURCES	•	RADIOGRAPHY ^{192}Ir, ^{60}Co
	•	TELETHERAPY ^{60}Co
	•	NUCLEONIC GAUGES ^{60}Co
	•	Ru - 106 (FOR OCULAR CANCER)
	•	CO- 60 FOR IRRADIATOR SOURCES
RADIOCHEMICALS	•	^{82}Br, ^{46}Sc, ^{203}Hg AND OTHERS
LABELLED COMPOUNDS	•	^{32}P – NUCLEOTIDES
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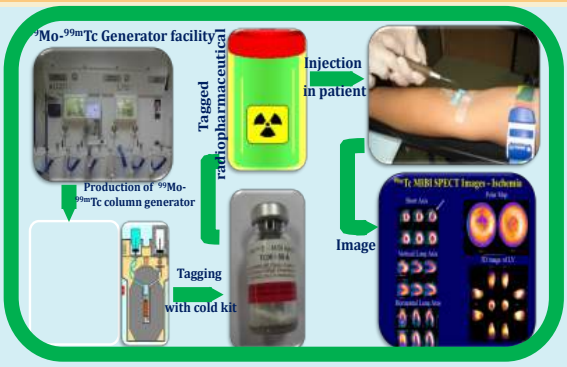

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