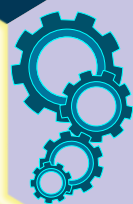
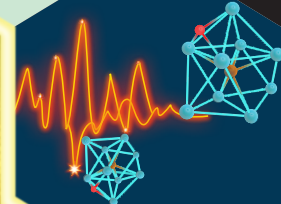
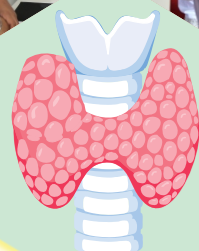


भाभा परमाणु अनुसंधान केंद्र का आधिकारिक द्विमासिक प्रकाशन
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बहु-आयामी नाभिकीय विज्ञान एवं
प्रौद्योगिकी से जीवन समृद्ध बनाना
Enriching Lives with
Multi-dimensional Nuclear S&T



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The front cover artwork showcases BARC's multidisciplinary research programs and their directed applications cutting across healthcare, medicine, and industry, alongside capacity building initiatives — all aimed at positively impacting citizens' lives. In the background, under a night-sky visual effect, are BARC's foundational facilities in Trombay - the Dhruva and CIRUS reactors and the Modular Laboratories.

बहु-विषयकता को बढ़ावा देता नाभिकीय क्षेत्र

संपादक
का संदेश

भा भा परमाणु अनुसंधान (भा.प.अ.) केंद्र न्यूज़लेटर के इस नवीन संस्करण की इस यात्रा में अपने वैज्ञानिक समुदाय के पाठकों का स्वागत करते हुए हमें अपार हर्ष की अनुभूति हो रही है। यह संस्करण, भापअ केंद्र में नाभिकीय विज्ञान एवं प्रौद्योगिकी की दीर्घाकार होती सीमाओं में नूतन विकास एवं नवोन्मेषी प्रौद्योगिकीय प्रगति के विविध आयामों को प्रस्तुत करता है। पिछले अंक में, विकास की जारी गतिविधियों एवं उच्च-तीव्रता प्रोटॉन रेखीय त्वरक (लीनॉक) के भावी विकास यात्रा की झलक प्रस्तुत की गई। वैज्ञानिक एवं प्रौद्योगिकीय प्रगति पर ध्यान केंद्रित करते हुए, वर्तमान संस्करण में चयनित विकास कार्यों को संग्रहित किया गया है जो केंद्र की बहु-विषयक अनुसंधान क्षमताओं और प्रगत विज्ञान को राष्ट्रीय एवं सामाजिक सरोकार के अनुप्रयोगों में बदलने की इसकी प्रतिबद्धता को दर्शाता है।

वर्ष 2026 के पहले कुछ महीनों में राष्ट्रीय विज्ञान दिवस (एनएसडी) और राष्ट्रीय प्रौद्योगिकी दिवस (एनटीडी) जैसी कई गतिविधियाँ उल्लेखनीय हैं। रेडियो-रासायनिक एवं आइसोटोप वर्ग ने भापअ केंद्र में कई अन्य वर्गों के साथ संयुक्त तत्वावधान में दिनांक 28 फरवरी से 2 मार्च तक, एनएसडी का आयोजन किया तथा सैकड़ों उत्साही छात्रों एवं आगंतुकों के साथ परस्पर संवाद किया। यह सिलसिला मई के महीने में एनटीडी के आयोजन के साथ जारी रहा, जो भारत की प्रौद्योगिक उपलब्धियों और प्रौद्योगिकीय आत्मनिर्भरता तथा वैश्विक नेतृत्व की दिशा में इसकी निरंतर यात्रा का स्मरण करती है। न्यूज़लेटर के इस अंक में भा.प.अ. केंद्र के इन दो प्रमुख आयोजनों से संबंधित वैज्ञानिक भावना, गतिविधियों एवं प्रमुख विशेषताओं को शामिल किया गया है। नाभिकीय ऊर्जा अनुसंधान को आगे बढ़ाने के अपने मूल जनादेश से परे, परमाणु ऊर्जा विभाग (प.ऊ.वि.) संस्थान प्रौद्योगिकियों को सुनिश्चित सामाजिक प्रभाव के साथ वितरित करने के उद्देश्य से बहु-विषयक अनुसंधान के एक व्यापक स्पेक्ट्रम को बढ़ावा देना जारी रखा है।

स्वास्थ्य देखभाल सर्वाधिक महत्वपूर्ण क्षेत्रों में से एक का प्रतिनिधित्व करती है जिसमें इन वैज्ञानिक प्रगति का सीधा उपयोग हो रहा है। उचित ही, “चिकित्सा में रेडियोआइसोटोप” विषय एनएसडी और एनटीडी दोनों कार्यक्रमों का एक मुख्य केंद्र रहा। इस विषय को ध्यान में रखते हुए वर्तमान अंक में, भा.प.अ. केंद्र में रेडियोआइसोटोप-आधारित निदान एवं चिकित्सा, रेडियोभेषजिक और युवा जन-सामान्य में कैंसर का शीघ्र पता लगाने और जांच के दृष्टिकोण में हाल ही के विकास पर केंद्रित किया गया है। ये प्रयास जीवन की गुणवत्ता बढ़ाने हेतु बेहतर नैदानिक एवं चिकित्सीय क्षमताओं के लिए स्वास्थ्य सेवा अनुप्रयोगों में नाभिकीय विज्ञान के उद्ग्रहण को दर्शाते हैं।

भा.प.अ. केंद्र में बहु-विषयक अनुसंधान की व्यापकता को प्रतिबिंबित करते हुए, इस संस्करण में नई खाद्य प्रौद्योगिकियों को समर्थ बनाने वाले प्रमुख प्रणाली संविरोधन, उच्च-शक्ति अवरक्त लेसर प्रौद्योगिकी और जल में चयनात्मक थोरियम का पता लगाने के लिए एक अतिसंवेदनशील प्रतिदीप्त संवेदक के विकास पर लेख शामिल हैं। समग्र रूप से, इस संस्करण में शामिल किए गए लेख वैज्ञानिक नवाचार, प्रौद्योगिकीय आत्मनिर्भरता एवं सामाजिक अनुप्रयोगों में भारत की क्षमताओं को मजबूत करते हुए नाभिकीय विज्ञान एवं संबद्ध प्रौद्योगिकियों की सीमाओं का विस्तार करने में भा.प.अ. केंद्र के निरंतर प्रयासों को उजागर करते हैं।

हम, इस संस्करण को समय पर प्रकाशित किए जाने में सकारात्मक भूमिका निभाने वाले सभी लेखकों, समीक समुदाय, प्रकाशन दल और प्रत्यक्ष अथवा परोक्ष रूप से सहयोग प्रदान करने वालों के प्रति आभार प्रकट करते हैं।

श्री मनोज सिंह

उत्कृष्ट वैज्ञानिक

अध्यक्ष, वैज्ञानिक सूचना संसाधन प्रभाग एवं
संपादक, भा.प.अ. केंद्र समाचार पत्र

The Mounting Multidisciplinarity of Nuclear Sphere

EDITOR'S
message

We are pleased to welcome our scientific community of readers to another edition of the BARC Newsletter, which presents a diverse spectrum of recent developments and emerging technological advances from the expanding frontiers of nuclear science & technology at BARC. The preceding issue provided an overview of the ongoing developmental activities and future roadmap of the High-Intensity Proton Linear Accelerator (LINAC). Continuing this focus on scientific and technological progress, the present issue brings together selected developments that reflect the Centre's multidisciplinary research capabilities and its commitment to translating advanced science into applications of national and societal relevance.

The first few months of 2026 were marked by a series of activities like National Science Day (NSD) and National Technology Day (NTD). From 28 February to 2 March, Radiochemistry & Isotope Group, along with several other groups at BARC organised NSD and interacted with hundreds of enthusiastic students and visitors. This momentum continued with the observance of NTD in May, commemorating India's technological achievements and its continuing journey towards technological self-reliance and global leadership. The scientific spirit, activities, and key impressions from these two flagship events of BARC are captured in this issue of the Newsletter.

Beyond its core mandate of advancing nuclear energy research, the Department of Atomic Energy (DAE) institutes continue to foster a broad spectrum of multidisciplinary research aimed at delivering technologies with tangible societal impact.

Healthcare represents one of the most significant domains in which these scientific advances are finding direct applications. Appropriately, the theme "Radioisotopes in Medicine" formed a central focus of both the NSD and NTD programmes. In keeping with this theme, the present issue highlights recent developments at BARC in radioisotope-based diagnostics and therapy, radiopharmaceuticals, and approaches for the early detection and screening of cancer among young populations. These efforts illustrate the translation of nuclear science into healthcare applications for improved diagnostic & therapeutic capabilities for enhancing quality of life.

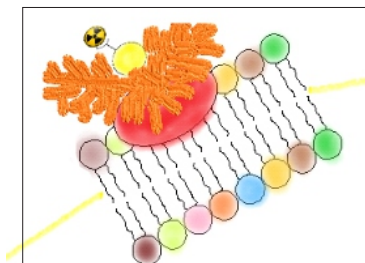
Further reflecting the breadth of multidisciplinary research at BARC, this issue features articles on major system refurbishments supporting new food technologies, high-power infrared laser technology, and the development of an ultrasensitive fluorescent sensor for selective thorium detection in water. Collectively, the contributions featured in this issue highlight BARC's continuing efforts to expand the frontiers of nuclear science and allied technologies while strengthening India's capabilities in scientific innovation, technological self-reliance, and societal applications.

We thank the all authors, community of reviewers, publication team and others for their positive role in bringing out this issue in a timely manner.

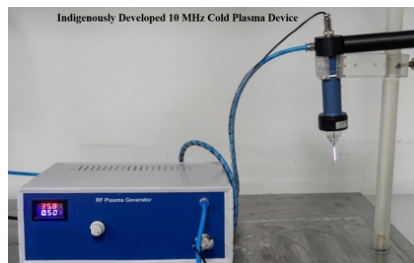
Mr. Manoj Singh

Outstanding Scientist
Head, Scientific Information Resource Division &
Editor, BARC Newsletter

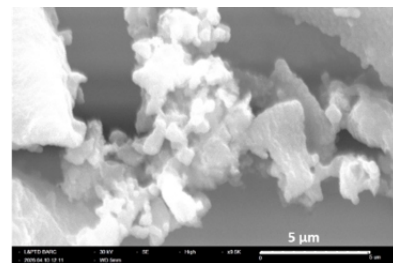
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Molecular targeting with radiolabelled ligands for imaging and therapy.



Indigenously Developed 10 MHz Cold Plasma Device.



SEM image of Carbonated Apatite(CA) 700.

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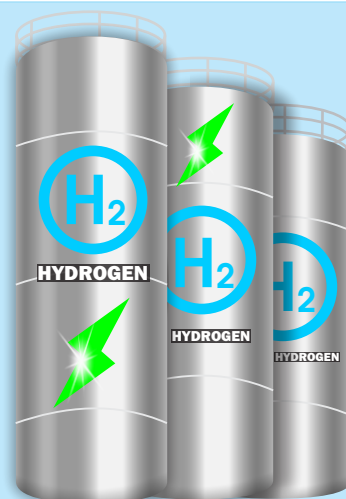
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1

भारत की पहली खाद्य किरणन अनुसंधान एवं विकास सुविधा का प्रौद्योगिकीय-आधुनिकीकरण – भा.प.अ. केंद्र में खाद्य पैकेज किरणक

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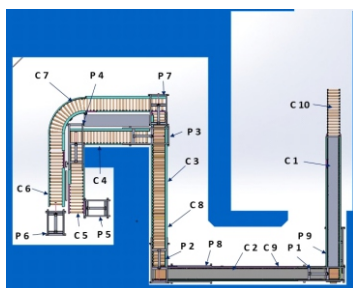
¹सुदूर प्रहस्तन एवं रोबोटिक्स प्रभाग, भाभा परमाणु अनुसंधान केंद्र, ट्राम्बे, मुंबई-400085, भारत

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सारांश



आधुनिक खाद्य पैकेज किरणक की उत्पाद प्रहस्तन प्रणाली में संवाहक और कर्षक का लेआउट।

खाद्य पैकेज किरणक (एफपीई) भारत की पहली प्रायोगिक कोबाल्ट 60 आधारित गामा विकिरण प्रसंस्करण सुविधा है। इसे एटॉमिक एनर्जी ऑफ कनाडा लिमिटेड द्वारा अभिकल्पित किया गया और वर्ष 1967 में परमाणु ऊर्जा प्रतिष्ठान, ट्राम्बे द्वारा कमीशन किया गया। इसकी स्थापना के बाद से ही इस बहुउद्देशीय सुविधा का उपयोग खाद्य उत्पादों की एक विस्तृत श्रृंखला के लिए गामा विकिरण का उपयोग करते हुए अनुसंधान एवं विकास गतिविधियों हेतु लगातार किया जा रहा है, ताकि अंकुरित मूलों (जैसे प्याज़) एवं कंदों (जैसे आलू), अनाज तथा दालों में कीटाणुशोधन, मछली तथा मांस से व्याधिजनक रोगाणुओं के उन्मूलन के साथ-साथ मसालों में सूक्ष्मजीव निर्जमीकरण सहित वांछित उद्देश्यों को प्राप्त किया जा सके। इसके अतिरिक्त, इस सुविधा का उपयोग विभागीय हित के विभिन्न पदार्थों एवं घटकों के विकिरण अनुक्रिया अध्ययन के लिए भी किया गया। इसके कमीशनन और कालप्रभावन के बाद से पांच दशकों से अधिक समय तक निरंतर उपयोग के कारण, उत्पाद/स्रोत प्रहस्तन प्रणाली में बार-बार गड़बड़ी/टूट-फूट होना चिंता का विषय बन गया है। कल-पुर्जों की उपलब्धता विशेषकर नियंत्रण प्रणाली हेतु एक अन्य चुनौती रही है जो रिले लॉजिक पर आधारित है। इन समस्याओं को दूर करने के लिए वर्ष 2020 में संयंत्र का पूर्ण उन्नयन किया गया। सिविल संरचना को छोड़कर, सभी उप-प्रणालियों, जैसे उत्पाद प्रहस्तन, स्रोत की आवाजाही और नियंत्रण को बदल दिया गया है, परिणामस्वरूप, खाद्य पैकेज किरणक का प्रौद्योगिकीय-आधुनिकीकरण हुआ है। उन्नत सुविधा ने वर्ष 2022 में पुनः प्रचालन आरंभ किया। इस लेख में, इस कार्य का संक्षिप्त विवरण एवं महत्वपूर्ण विशेषताओं को प्रस्तुत किया गया है।

1

Techno-modernization of India's First Food Irradiation R&D Facility - Food Package Irradiator (FPI) at BARC

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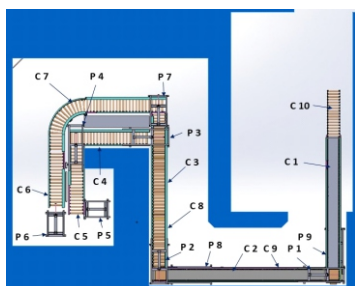
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ABSTRACT



The layout of the conveyors and pushers in the product handling system of the modernized FPI.

The Food Package Irradiator (FPI) is India's first pilot Cobalt 60 based gamma radiation processing facility. It was designed by Atomic Energy of Canada Limited and commissioned in the year 1967 by Atomic Energy Establishment, Trombay. This multipurpose facility has been continuously utilized since its inception for R&D activities using gamma radiation for a wide range of food products to achieve the desired objectives ranging from sprout inhibition of bulbs (e.g. onion) and tubers (e.g. potato), insect disinfestation in cereals and pulses, elimination of pathogenic microbes from fish and meat as well as microbial decontamination in spices. In addition, this facility has also been used for radiation response studies of various materials and components of the departmental interest. Due to continuous usage for over five decades since its commissioning and ageing, frequent disruptions/breakdowns in the product/source handling system became matter of concern. Availability of spares, particularly for the control system which was based on relay logic, was another challenge. Complete upgradation of the plant was taken up in 2020 to overcome these issues. Except the civil structure, all the subsystems, viz. product handling, source movement and controls have been replaced, resulting in the techno-modernization of Food Package Irradiator. The upgraded facility resumed the operation in 2022. This article presents an overview of this work and important features in brief.

KEYWORDS: Food Package Irradiator (FPI), Bulbs, Tubers

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Introduction

Food irradiation in India has been undertaken for preservation of food for safety, security and international trade. Based on the product profile and suitability there are different types of irradiators, such as gamma, electron beam, and X-ray systems. Gamma irradiator provides deep penetration and uniform dose distribution but involves handling radioactive materials with stringent safety requirements. In contrast, electron beam irradiator offers high process rate and lower regulatory hurdles but may struggle with thicker products, whereas X-ray irradiator has issue of conversion efficiency.

Food Package Irradiator (FPI), a Co-60 based gamma irradiator, was setup in the year 1967 at Food Irradiation Project Laboratory (FIPLy), current Food Technology Division in Bhabha Atomic Research Centre, Trombay, Mumbai. The original plant was a gift from Atomic Energy of Canada Ltd., a token of friendship to Dr. Homi Jehangir Bhabha, the founder of India's atomic energy program, from his rowing teammate at Cambridge, Dr. W.B. Lewis, later the chairman of the Canadian Atomic Energy Program. The plant utilizes gamma radiation from Co-60 source with a maximum allowable activity of 100 kCi. It is a multipurpose facility where a wide range of food commodities can be processed for R&D purpose in the dose range of 30 Gy to 25 kGy. This facility houses split source frame for variable dose rates and therefore suitable to deliver desired dose in wider spectrum. FPI, BARC has been remained the work horse since its commissioning for food irradiation research, allied R&D activities and services in India. The facility is the first Category IV food irradiation plant in India. Category IV irradiator has wet storage system for the radiation source which is made movable for radiation processing. At present (till February 2026) there are 32 commercial food irradiation facilities are operational across the country. Success in R&D at FPI, BARC has resulted in development of the scaled-up version of these gamma irradiators for food processing.

Scope of Techno-modernization

Because of more than five decades of utilization, various components of the facility have been deteriorated leading to difficulties in smooth plant operation. Unavailability of spare parts was another problem in plant operation and maintenance. Additionally, limited technical details were available without much elaboration. Efforts were made to reconstruct the detailed design of the existing mechanical and civil structures in order to assess the possibility of technical upgradation of the systems. Based on the information and operational experience the upgradation of the facility was planned without altering existing civil structures. The major scope includes a) Replacement of the old product handling system with upgraded design, b) Replacement of the entire source drive systems including source lifting mechanism, and c) Up-gradation of control system by replacing relay-based logic with PLC-SCADA-HMI interface.

Overall Requirements of an Industrial Irradiator

An irradiation facility should have the following basic components, a) a radiation source (radionuclide or machine source), (b) biological shield, (c) a product handling system, (d) control system, and (e) dosimetry laboratory. The facility must

be equipped with adequate source shielding to protect personnel and the environment from radiation exposure. This typically involves thick layers of lead or concrete. In case of Category IV irradiator, demineralized water of adequate column depth is used as a shielding for source during storage. The water also serves as a medium for heat dissipation.

Design Features of an Irradiator to Ensure Safety

System is required to be designed for safe and efficient handling of gamma radiation sources. This includes secure storage, easy replacement, and proper shielding. It is ensured that the design provides uniform irradiation of products. This often involves precise positioning systems and consistent source-to-product distances. Automation system is required for product handling, irradiation cycles and monitoring tool to enhance efficiency and reduce human error. System is designed for safe and efficient loading and unloading of products to be irradiated. This may involve conveyors, robotic arms, or other handling mechanisms. Easy access to all components is required for routine maintenance and repairs which includes source replacement and shielding inspections. Materials, components which can easily withstand radiation are used inside radiation cell.

The design features of irradiation facility are made to prevent unauthorized or accidental access to the irradiation cell. This includes locked doors, interlock systems, and controlled entry points. Emergency stop systems and alarms should be incorporated, along with SOPs (Standard Operating Procedures) for handling radiation emergencies. The facility must be equipped with radiation monitoring systems to detect and measure radiation levels, ensuring safe radiological environment. During operation of the facility, the trained and authorized operators should use personnel monitoring dosimeters and radiation survey meters. Facility is required to be designed and operated as per the national safety standards and regulations issued by the BARC Safety Council and Atomic Energy Regulatory Board (AERB) in India. In general, national safety standards are well aligned with International one particularly in terms of safe operation of radiation facilities. All necessary licenses and permits need to be obtained for the use and handling of radioactive materials. Comprehensive records of safety procedures, radiation surveys, maintenance, and training need to be documented.

Comprehensive training for all the involved personnel on the operation of the irradiator, safety protocols, and emergency procedures are required to be provided to ensure operational safety. Standard Operating Procedures (SOPs) for all aspects of irradiator operation, maintenance, and emergency response should be available and required to be implemented. The design and construction of an irradiation facility influence the dose delivery to the products. The optimized design is therefore of paramount importance to ensure adequate dose delivery. The major objectives to be considered during design of an irradiation facility are the dose uniformity in the irradiated product, efficient energy utilization and cost effectiveness.

System Description

Prior to delving into the specifications of the techno-modernization of FPI design, it is essential to outline the

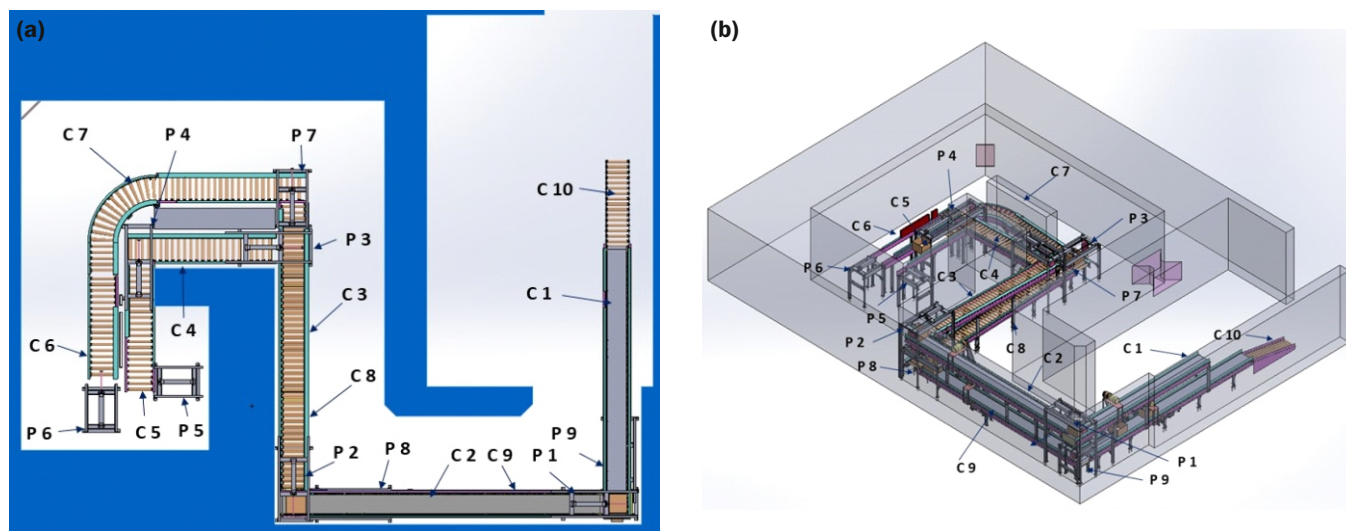


Fig.1: a) Plan view and b) Isometric view (3D model) of the conveyors (C) and pushers (P) of the Product Handling System of the modernized Food Package Irradiator (FPI), FTD.

overarching design requirements that ensure efficient and safe operation of the facility. The modernization of the irradiation facility must incorporate robust safety features, including adequate shielding to protect operators and the environment from radiation exposure. The mechanical design needs to facilitate seamless product handling while adhering to strict dose uniformity standards. Key requirements include a layout that minimizes radiation exposure to sensitive components and personnel, as well as the use of materials capable of withstanding high radiation levels. Moreover, the system must allow for easy maintenance and access to critical components without compromising safety. Ergonomic considerations are also vital, ensuring that product loading and unloading can be performed comfortably and efficiently. In addition, the design must comply with national and international safety regulations, ensuring that all operational aspects prioritize operator safety while maintaining adequate dose delivery and reliability in irradiation processes. These foundational requirements guide the development of the two major sub-systems: the mechanical system, which includes the product handling and source drive systems, and the electrical and control system, which governs the operational integrity and safety of the entire setup.

Modernization in Product Handling System

A new product handling system was introduced replacing the old conveyors. There were ten conveyors and nine pushers. Electrical actuators were used to run the conveyors. Pneumatic pushers were used to transfer product boxes from one conveyor to next conveyor after satisfying interlocks. It was a roller and belt/chain arrangement which was moved by geared motors. Conveyors 1, 2, 9, 10 were close to control room and these were belt conveyors. Belt conveyors gave smooth and noise less operation. Overall noise level in control room was reduced significantly in comparison with the earlier setup. However, other conveyors, near the source were exposed to higher radiation level. As belts cannot withstand high radiation, metallic roller conveyors were used near source. Before

selecting the belt material, radiation test was carried out on different belt samples. There were total eight number of motors and nine pneumatic cylinders. Product boxes, made of aluminium of size 13"X13"X9" have tare weight of 3.0 kg. These boxes were used to carry products/samples intended for radiation processing. The layout (plan view) of the conveyors and pushers in the product handling system is presented in Fig.1a. Fig.1b illustrates an isometric view of the 3D model, showcasing all the conveyors and pushers integrated into the system. As a part of the operational procedure, the product boxes are loaded manually on belt conveyor-1 at the loading station. Boxes move from one conveyor to another conveyor and finally reach inside irradiation cell. After getting required radiation exposure, these boxes come out from irradiation cell through various conveyors. Boxes are unloaded from conveyor-10 manually at the unloading station.

Modernization in Source Drive System

The modernized FPI has now been equipped with a sophisticated source & source drive system designed for optimal performance. The designed capacity of the facility is to house maximum source activity of 100 kCi and the loading after refurbishment of the facility was of 89 kCi as on November 29, 2022. There are two source racks that can accommodate up to 34 source pencils (W-91 type). The source is stored in a water pool of 5 m deep, lined with ceramic glazed tiles. The source handling system facilitates the movement of source pencils stored in two racks submerged in water. Sources are raised to operating level and lowered back to its safe underwater storage position with the help of the source frame driving unit. Water levels are monitored at various stages to ensure operational safety and efficiency.

The modernized source driving unit comprised of pneumatic cylinders, wire ropes, multiple pulleys and source frames. Multiple pulley arrangements had replaced long pneumatic cylinders of stroke length of 5.5 meter, reducing to 1.4 meter. Stainless steel wire rope of diameter 4 mm was used in the source handling system replacing the older rope of

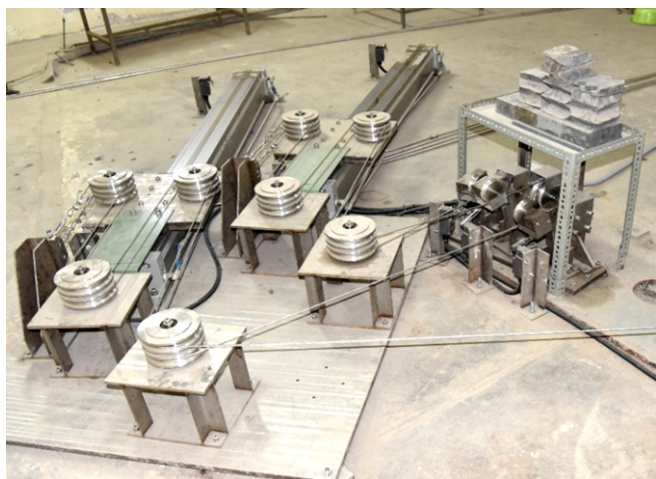


Fig.2: Layout of cylinders, pulleys of source drive system installed at the cell roof of the modernized FPI.

diameter 2.5 meter. Source frames were connected to wire rope using qualified swaged socket. Driving unit was installed at the rooftop of irradiation cell. In order to take the lifting ropes to the cell, four existing openings at the roof were utilized. Two guide ropes were kept unaltered to guide each source frame during vertical movement. Pneumatic cylinders were employed in this facility due to the lighter weight of the source frame. Loose wire protection systems were employed to detect and signal any rope failure or loosening. The layout of cylinders, pulleys of source drive system is shown in Fig.2.

Source Replenishment

The Standard Operating Procedure for the replenishment of Co60 source pencils in the FPI involves collaboration among several agencies. Food Technology Division (FTD) is the user of the facility and responsible to execute the source replenishment exercise with necessary approvals. After the refurbishment of the facility the structural integrity of the source storage pool was assessed by the Structural Integrity Committee (SIC), BARC for the first time since commissioning ensuring safe storage of source. Board of Radiation and Isotope Technology (BRIT) was engaged in source handling operations, and Health Physics Division (HPD), BARC provided the safety coverage during the source replenishment activity. Initially, the water level in the source storage pool was lowered by 200 mm to facilitate accommodation of the source storage and shipping cask (BLC- 100) followed by the removal of the fencing around the pool. The source unloading process included careful lowering of the source cage to the bottom of the pool, removal of the necessary drain plugs and bolts from the shipping container, and transfer of the source pencils into isolated source cages meticulously following their serial numbers. The shipping container was sealed and secured. It was hoisted above the pool for drainage followed by a thorough radiation leakage assessment. The loading operation mirrored this process, starting with the introduction of a source cask into the irradiator room and ensuring proper placement of the new pencils according to the activity distribution design finalized using Monte Carlo based radiation transport code to achieve



Fig.3: Control room with control panel and SCADA panel of modernized FPI.

desired dose uniformity into the irradiated products. Final steps involved securing the pencils, performing radiation measurements, and transferring the shipping container to BRIT custody.

Modernization in Electrical and Control System

The modernized FPI is now featured with the electrical and control system encompasses motors, sensors and a PLC-based control system with HMI and SCADA operator terminal. Conventional 3-phase, 415 Volts, 50 Hz induction motors power all the drives. Pneumatic cylinders were used for pushing operation. Electromechanical limit switches were installed to sense position and sequence operations. Off-the-shelf PLC and HMI components were deployed for control and safety interlocks implementation. End-limit positions sensed by limit switches/sensors were installed to display and utilize for process interlocks. Two-position, five-port solenoid valves were used to control the operation of each cylinder. Radiation-resistant cables capable of withstanding 200 Mrad were utilized for signal and power transmission within the irradiation cell. Control room with control panel and SCADA panel is shown in Fig.3.

Plant Operation

The Standard Operating Procedure was prepared to start the modernized facility in Auto Mode with source providing a systematic approach to ensure safe and efficient operation. The procedure includes a) powering on the MCB and the main panel, b) initiating the compressor and checking pneumatic systems, c) activating all the radiation area monitors in Control room, d) starting the ozone exhaust blowers, and e) verification to ensure proper functionality of all the interlocks. The SCADA PC is then powered on, and the SIMATIC WinCC software starts automatically. Provision for manual launching was also provided depending on the situational need. After logging in, the operators can set the operation switch to manual mode, reset the SCADA panel to clear previous data, and switches to Auto mode. In addition, essential features were incorporated such as a) selection of source combinations, b) performance of

search operation, and c) confirmation of the completion of the auto cycle. Upon finishing all the cycles, the provision was made to lower the source to its shielded position. Finally, the session can be concluded by exiting from the SCADA interface ensuring that all the protocols were followed for operational integrity and safety.

In the event of a power failure, the feature of auto-lowering of the source frame to water pool with conveyor system stop was incorporated. The design also ensured that the remaining cycle can proceed as long as the UPS is operational and supply power to the PLC and SCADA CPU.

Commissioning Dosimetry and Radiation Surveillance

The efficient upgradation of the facility was assessed by carrying out detailed dosimetry exercises to ensure desired dose delivery to the food commodity. The alignment of the exposed position of the source frame with the product box was assessed by the vertical placement of the dosimeters (Fricke and Ceri Cerous) inside the product box filled with rice as a medium. The variation in the absorbed dose between top and the bottom dosimeters was within $\pm 5\%$ ensuring acceptable source and product alignment. In order to obtain the entire dose profile inside the product box with food commodity, dose mapping with all possible source and product box configurations was carried out. The dose rates for small, large and total source configuration were measured as 5.84 Gy/min, 3.12 kGy/h, and 3.47 kGy/h with improved dose uniformity ratio (DUR) of 1.36, 1.27, and 1.30, respectively. The transit doses at Dmin and Dmax positions were also measured. A variation in the transit dose was observed in the range of 9.6 to

28.6 Gy/transit depending on the source and product box geometries.

In order to evaluate the radiological safety of the modernized FPI, a thorough radiation surveillance was carried out in all the areas of the facility such as control room, maze portals, cell roof with source exposed or shielded conditions as per the standard procedures. The radiation levels at all the occupied areas were well within the permissible limit of 1 $\mu\text{Sv/h}$.

Conclusion

It has been a challenging task to operate an old facility such as Food Package Irradiator, FTD, BARC complying with the safety requirements evolved with time. The facility has now been modernized by replacing all the mechanical, electrical, electronics and logic controls meeting all the present safety guidelines. The operation of the modernized facility has now become easy and ageing related breakdowns have been eliminated. Systematic preventive maintenances are in place to ensure smooth and safe operation of the facility. The facility has now been deployed for R&D exposures of various food and other commodities of departmental interest for regular utilization since 2022.

Acknowledgement

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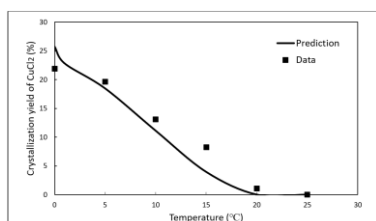
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हाइड्रोजन उत्पादन के लिए Cu-Cl ताप रासायनिक चक्र के क्रिस्टलीकरण चरण का अनुकरण करने हेतु ग्राफिकल यूजर इंटरफेस के साथ एक कोड का विकास

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सारांश



2 M CuCl₂, 8 M HCl के विद्युत विश्लेषक फ्रीड हेतु अलग-अलग इलेक्ट्रोलाइटिक रूपांतरण के लिए CuCl₂ का क्रिस्टलीकरण उत्पाद। क्रिस्टलीकरण तापमान 10⁰ C; — संभावित, ■ प्रयोगात्मक डेटा।

परमाणु ऊर्जा स्रोत के साथ ताप-रासायनिक Cu-Cl चक्र ग्रीनहाउस गैसों के उत्सर्जन के बिना H₂ उत्पादन हेतु एक आश्चर्य प्रक्रम है। क्रिस्टलीकरण भुक्तशेष विद्युत विश्लेषक विलयन से CuCl₂ क्रिस्टल को अलग करने के लिए इस चक्र के संचालन में से एक है। उन स्थितियों की सीमित सीमा के कारण जिनके तहत यह क्रिस्टलीकरण होता है, हर भुक्तशेष विलयन से ठंडा होने पर वांछित क्रिस्टल नहीं मिल सकते हैं। CuCl₂ क्रिस्टल संवृत्त तरीके से एक निरंतर चक्रीय प्रक्रिया हेतु आवश्यक हैं, इसलिए क्रिस्टलीकरण की सीमा पर भावी प्रचालन के लिए लाभदायक हैं। यहाँ, एक ग्राफिकल यूजर इंटरफेस (जीयूआई) के साथ एक कोड (पायथन 3 में) विकसित किया गया है विभिन्न पैरामीट्रिक स्थितियों के अंतर्गत क्रिस्टलीकरण प्रक्रिया के विलयन द्रव्यमान संतुलन का उपयोग करते हुए CuCl₂ के उत्पादन की संभावना तापमान, HCl सांद्रता, इलेक्ट्रोलाइटिक रूपांतरण, और विद्युत विश्लेषक भरण CuCl सांद्रण जैसी उत्पादन की संभावना व्यक्त की गई है। इस उद्देश्य के लिए कोड में घुलनशीलता सहसंबंध अंतर्निहित हैं। जीयूआई प्रदत्त विद्युत विश्लेषक भुक्तशेष विलयन के लिए वांछित क्रिस्टलीकरण की सीमा की संभावना व्यक्त करने में उपयोगी है। इस अध्ययन में किया गया कार्य, जिससे क्रिस्टलीकरण उत्पादन की संभावना व्यक्त होती है, बंद-लूप ताप-रासायनिक Cu-Cl चक्र के प्रचालन में बहुत लाभदायक है।

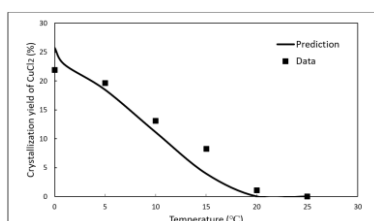
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Development of a Code with a Graphical User Interface to Simulate the Crystallization Step of the Cu-Cl Thermochemical Cycle for Hydrogen Production

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ABSTRACT



Crystallization yield of CuCl₂ for varying temperatures for 70% converted electrolyser feed of 2 M CuCl in 8 M HCl; — Prediction, ■ Experimental data.

The thermochemical Cu-Cl cycle coupled with a nuclear energy source is a promising process for H₂ generation without emission of greenhouse gases. Crystallization is one of the operations of this cycle for the separation of CuCl₂ crystals from the spent electrolyser solution. Due to the limited range of conditions under which this crystallization occurs, not every spent solution may yield the desired crystals upon cooling. As CuCl₂ crystals are necessary for a sustained cyclic process in a closed manner, predictions on the extent of crystallization are beneficial for the operation. Here, a code with a graphical user interface (GUI) has been developed (in Python 3.0) to predict the yield of CuCl₂ crystallization under different parametric conditions, viz., temperature, HCl concentration, electrolytic conversion, and electrolyser feed CuCl concentration, using the solute mass balance of the crystallization process. Solubility correlations are embedded in the code for this purpose. The GUI is useful for predicting the extent of desired crystallization for a given electrolyser spent solution. The work carried out in this study, leading to the prediction of crystallization yield, is very much beneficial in the operation of the closed-loop thermochemical Cu-Cl cycle.

KEYWORDS: Cu-Cl thermochemical cycle, Crystallization, Graphical user interface

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Introduction

Hydrogen, having a high energy density of 40 kWh/kg, is the fuel of the future because it does not emit greenhouse gases while burning. Conventional methods of hydrogen generation via fossil fuels lead to massive greenhouse gas (GHG) emissions ($\sim 11 \text{ kg CO}_2/\text{kg H}_2$) [1]. GHG emissions have become a vital issue, in view of the current scenario of global warming and its associated disadvantages to life. Alternatively, H_2 can also be produced through water splitting using electrical/ thermal energy [2].

Thermolysis and Electrolysis of water, based on the single-step decomposition of water, can produce hydrogen. Thermolysis of water, using heat for the decomposition of water, requires a very high temperature ($>2000^\circ\text{C}$) and is thus found impractical. Electrolysis of water is a promising process, but it uses energy in terms of electricity, which is comparatively expensive.

On the other hand, thermochemical cycles for hydrogen production use heat for the decomposition of water in multiple steps arranged in a closed loop. Thermochemical cycles use a sequence of chemical reactions for splitting water and thus adequately reducing the temperature requirement. Here, low-grade industrial waste heat can be utilised for heating requirements. These cycles can be coupled with a nuclear reactor to obtain heat and electricity [3]. Among these cycles, the Copper-Chlorine (Cu-Cl) cycle has a comparatively lower heat grade requirement ($\approx 550^\circ\text{C}$) [4-5]. The 4-step thermochemical Cu-Cl cycle is selected here because of its reduced equipment, lower heat requirement, and good energy efficiency [6-7].

In a 4-step Cu-Cl cycle, electrolysis, crystallization, hydrolysis, and thermolysis steps are used to attain closed-loop

breaking of water into hydrogen and oxygen (Fig.1). It uses energy both in the form of heat and electricity, and thus makes it a hybrid thermochemical cycle. The electrolysis step takes considerable less energy in the form of electricity, while the rest of the steps take energy in the form of heat only.

In the electrolysis step, the electrolyser produces H_2 gas at the cathode and converts Cu(I) into Cu(II) at the anode (Eq.1). As a result of the oxidation reaction at the anode, CuCl is partially converted to CuCl_2 , having around 50% to 75% of CuCl oxidation. Because of partial oxidation, the spent electrolyser solution consists of an aqueous solution of CuCl_2 (cupric chloride), CuCl (cuprous chloride), and HCl . This spent solution becomes feed to the crystallizer for the separation of CuCl_2 from the aqueous solution (Eq.2).

The CuCl_2 crystals, obtained from the crystallizer, are sent to hydrolysis reactor and its reaction with the steam produces copper oxychloride (Cu_2OCl_2) along with the HCl (Eq.3). Now in thermolysis reactor, Cu_2OCl_2 is decomposed resulting in molten CuCl along with generation of the oxygen (Eq.4). This molten CuCl is cooled and then dissolved in HCl for preparation of the anolyte solution of the electrolyzer. The HCl for dissolution is obtained from a hydrolysis reaction. Thus, all chemicals are recycled in a closed manner [8] (Fig.1) with net generation of hydrogen and oxygen from the splitting of water using multiple steps.

Electrolysis:	$2\text{CuCl (aq)} + 2\text{HCl (aq)} \leftrightarrow 2\text{CuCl}_2 \text{ (aq)} + \text{H}_2 \text{ (g)}$	$\sim 80^\circ\text{C}$	(1)
Crystallization:	$2\text{CuCl}_2 \text{ (aq)} \leftrightarrow 2\text{CuCl}_2 \text{ (s)}$	$\sim 10^\circ\text{C}$	(2)
Hydrolysis:	$2\text{CuCl}_2 \text{ (s)} + \text{H}_2\text{O (g)} \leftrightarrow \text{Cu}_2\text{OCl}_2 \text{ (s)} + 2\text{HCl (g)}$	$\sim 350^\circ\text{C}$	(3)
Thermolysis:	$\text{Cu}_2\text{OCl}_2 \text{ (s)} \leftrightarrow 2\text{CuCl (l)} + \frac{1}{2} \text{O}_2 \text{ (g)}$	$\sim 500^\circ\text{C}$	(4)

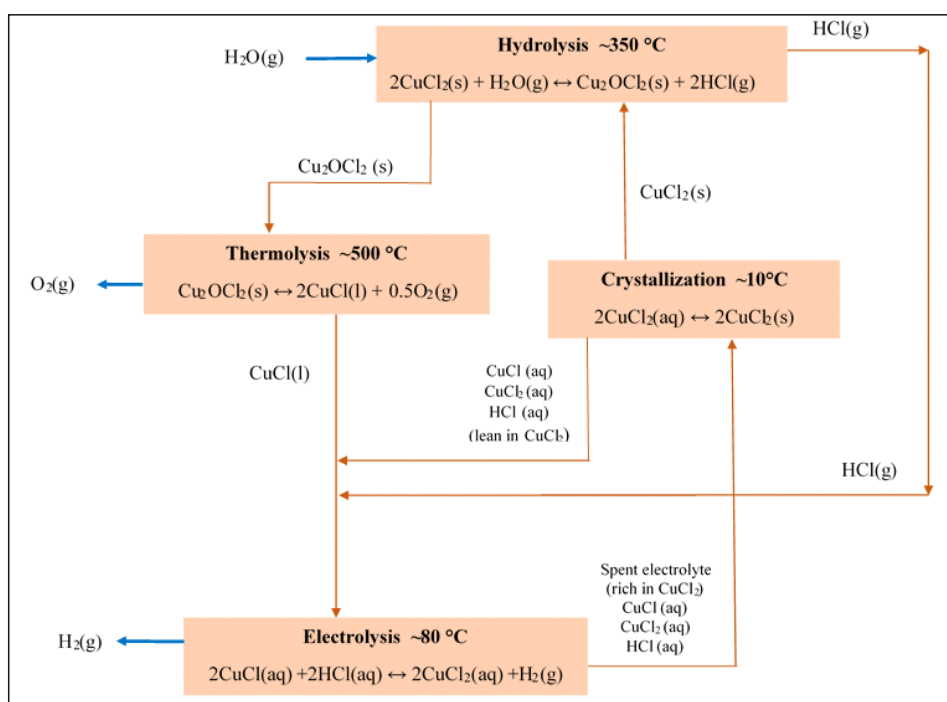


Fig.1: Cu-Cl thermochemical cycle for hydrogen production.

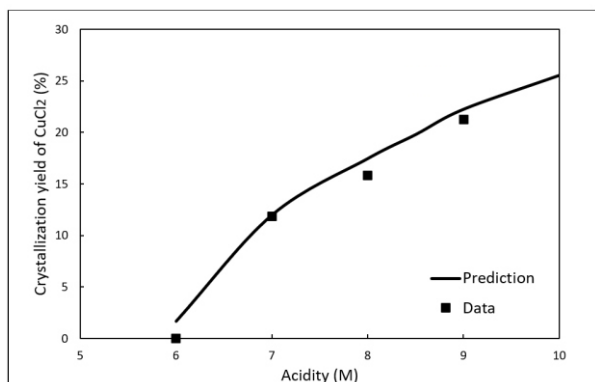


Fig.2: Crystallization yield of CuCl₂ for varying HCl concentration in the electrolyser feed for 75% conversion. CuCl concentration in the feed is 2 M and crystallization temperature is 10 °C;
 — Prediction, ■ Experimental data.

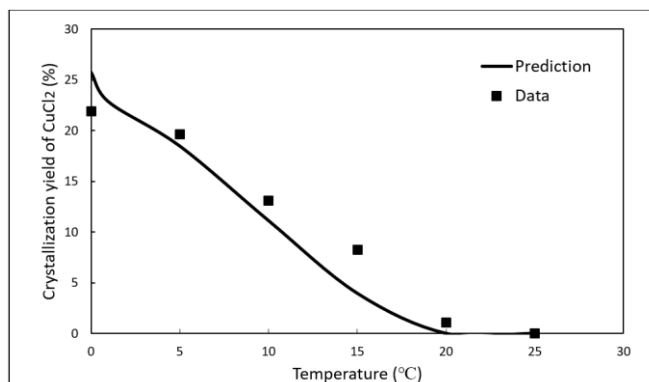


Fig.3: Crystallization yield of CuCl₂ for varying temperatures for 70% converted electrolyser feed of 2 M CuCl in 8 M HCl;
 — Prediction, ■ Experimental data.

The composition of the spent solution from the electrolyser may change due to variation in the electrolyser feed composition and its operating conditions, viz., flow rate and temperature. This spent solution becomes feed for the crystallizer, where a super-saturation state is attained by cooling the feed solution. CuCl₂ solubility continuously decreases with increasing HCl concentration [9-10]. On the other hand, CuCl solubility continuously increases with increasing HCl concentration [9]. Thus, there is an intermediate acidity range in which selective crystallization of CuCl₂ is viable. The rate and the yield of crystallization of CuCl₂ are also affected by HCl concentration [10].

Due to a particular range of conditions under which crystallization of CuCl₂ takes place, every feed solution may not give crystals, irrespective of the crystallization temperature. For sustained operation of the cycle, it is required to have a prior idea of the extent of crystallization for a given feed solution before the physical run. Accordingly, in the present work, a code with a graphical user interface (GUI) is developed for the prediction of crystallization yield for different parametric conditions, viz., temperature, HCl concentration, electrolytic conversion, and electrolyser feed CuCl concentration for the operational range of interest. Values of crystal yield obtained

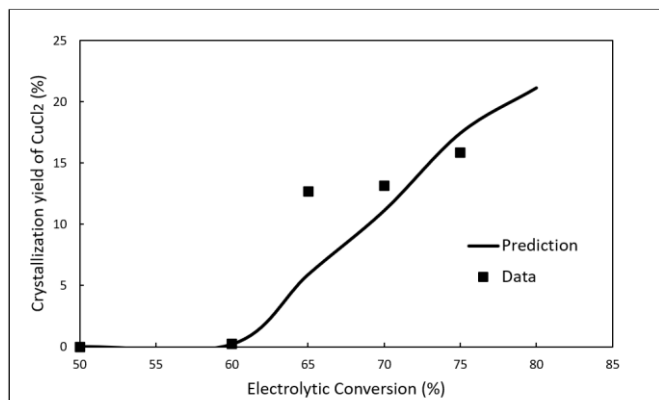


Fig.4: Crystallization yield of CuCl₂ for varying electrolytic conversion for electrolyser feed of 2 M CuCl, 8 M HCl. Crystallization temperature 10 °C;
 — Prediction, ■ Experimental data.

through GUI code, at different parametric conditions, are beneficial for the smooth operation of the CuCl cycle.

Methods

The developed GUI code (written in Python 3.0 interpreter) predicts the yield of CuCl and CuCl₂ crystallization, for varying operational parameters using solute mass balance equations of the crystallization process and solubility data, assuming equilibrium conditions and no evaporation. The operating time of crystallization is optimised (through batch experiments) to around 2 hours, as the major part of CuCl₂ is crystallised during this period. Also, this leads to manageable batch time in scaled-up units. However, nearly complete crystallization to achieve equilibrium may take longer than that. This is consistent with that reported [10,11]. Crystallization experiments are conducted at a temperature ≤ 10 °C; at such low temperatures, HCl vapour pressure is also quite low [12], leading to a low possibility of evaporation of HCl. Input parameters of the code are crystallization temperature, feed acidity, electrolytic conversion, electrolyser feed CuCl concentration, feed volume, HCl molarity and its specific gravity. Solubility data of CuCl and CuCl₂ are obtained from the literature [9-10], regressed with the *LAB Fit Curve Fitting Software* [13], and correlations for solubility (of CuCl and CuCl₂) are obtained with HCl concentration and temperature as the independent variables. These solubility correlations are incorporated in the code to estimate the solubility of CuCl and CuCl₂ for a given temperature and HCl concentration. The GUI displays solubilities along with the yields for given user inputs. Validation of the code is done with the generated experimental data. Details of experiments and generated data are presented in the earlier work [14].

Results and Discussion

Comparison of predicted yields of crystallization with observed yields for different parameters is presented in Fig.2, 3, and 4. These figures show the variation of predicted and observed yields with HCl concentration, temperature, and electrolytic conversion, respectively. Observed yields are found from batch crystallization experiments using a synthetic electrolyser spent solution of varying composition. The batch time for experiments was 2 hours. The average deviation between the yields predicted by the developed code (y_{Pred}) and

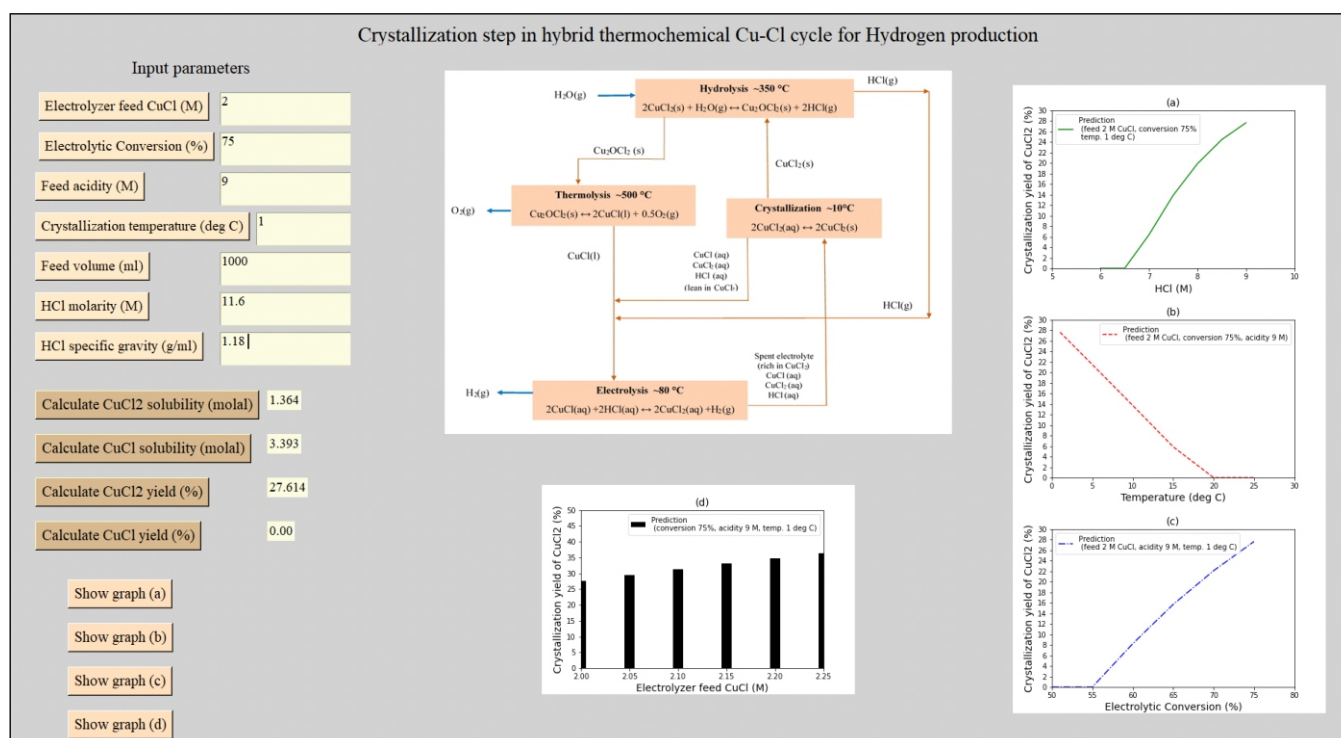


Fig.5: Screenshot of the developed graphical user interface (GUI) of the code for predicting the yield of crystallization of CuCl₂ in the thermochemical Cu-Cl cycle.

experimentally measured yields from generated data (y_{Expt}) is around 17%. The deviation between the model prediction and the data is calculated as,

$$\text{Deviation}(\%) = \frac{100}{p} \sum_{m=1}^p \left(\frac{|y_{\text{Expt},m} - y_{\text{Pred},m}|}{y_{\text{Expt},m}} \right) \quad (5)$$

Where p stands for the number of data points, and y represents data values of yield.

Yield is evaluated by Eq.6,

$$\text{Yield} = 100 \times \frac{\text{Crystals of CuCl}_2 \text{ (mole)}}{\text{CuCl}_2 \text{ in simulated solution (mole)}} \quad (6)$$

Effect of HCl concentration

HCl acts as a crystallising agent for the system. Crystallization of CuCl₂ is facilitated by the presence of HCl. Data is generated with an increase in feed HCl concentration at electrolytic conversion of 75% & a crystallization temperature of 10 °C. Fig.2 shows the comparison of the predicted yield of CuCl₂ crystals with the experimental yield for varying HCl concentration. Yield is observed to be increasing with an increase in HCl concentration. This goes in accordance with the solubility of CuCl₂, which decreases with an increase in HCl concentration [10]. The presence of CuCl in the spent solution may bring further reduction in the solubility of CuCl₂ because of the common ion effect. Yield as high as ~ 22% is predicted at the typical maximum acidity expected (9 M), which compares well with the experimentally measured yield of ~ 21%. It may also be noted that at 6 M HCl, no crystal formation is observed for the given conversion and temperature.

Effect of crystallization temperature

Crystallization is favoured by lower temperatures as solubility decreases with the decrease in temperature. Data is generated for a temperature range of 0 °C to 25 °C, and observations are shown in Fig.3 along with the predicted values of crystallization yield. Yield is found to be increasing with the decrease in the crystallization temperature, because of the decrease in solubility with decreasing temperature. It may be noted from Fig.3 that, at 25 °C, yield is predicted to be zero for a given solution composition, which agrees well with the experimental data. Fig.3 also shows that a yield as high as > 25% is predicted at 0 °C for 70% electrolytic conversion. For the feed solution of 50% converted electrolyser feed of 2 M CuCl in 8 M HCl, at 0 °C, the code predicts crystallization yield as zero, which is found close to the experimentally measured yield of around 0.03%.

Effect of electrolytic conversion

Data were obtained using synthetic spent solutions of electrolyser of different electrolytic conversions as feed, to observe the effect of electrolytic conversion on the crystallization of CuCl₂. HCl concentration is taken as 8 M, and crystallization temperature is kept fixed at 10 °C. Results are presented in Fig.4 along with the predicted values of yield for the same conditions. It has been observed that both predicted and observed yield values are increasing with the increase in the conversion. This is because increasing conversion leads to increased CuCl₂ concentration in the crystallizer feed and, consequently, increased driving force for crystallization. Also, with an increase in the concentration, the metastable zone width (MSZW) of crystallization decreases [15], which leads to

increased nucleation. For lower conversions, such as 50% and 60%, the predicted yield is zero, which matches the zero yield found in experiments at these conversions. For the feed solution of 80% converted electrolyser feed of 2 M CuCl in 8 M HCl, at 1°C, the predicted yield is found as 25.21%, which appears in line with the experimental data.

Fig.5 shows the screenshot of the graphical user interface (GUI) developed for the prediction of crystallization yields. The upper left frame of the GUI has tabs for providing user *input parameters*. The middle left frame contains the tabs for calculating *solubilities and yields*. After the input parameters have been specified by the user, the GUI code runs in the background and provides the crystallization yield values of CuCl and CuCl₂, on pressing the respective tab. The code also provides the solubilities estimated through inbuilt correlations at a given temperature and acidity. The lower left frame contains the tabs *show graph*, pressing which displays the results in a graphical form, both on the right side and the middle side of the GUI. The CuCl₂ yield values, from the crystallization step, obtained from the solution of the model equations for the typical operational range of acidity, temperature, electrolytic conversion, and electrolyser feed CuCl concentration, are shown graphically in the developed GUI.

Conclusion

The thermochemical Cu-Cl cycle is a promising process for hydrogen generation. Crystallization is one of the four steps of this closed-loop cycle. As not every crystalliser feed solution yields desired crystals on cooling, it is required to assess the extent of crystallization of CuCl₂ crystals from a given spent electrolyte solution, for efficient looping of the cycle. The composition of the spent electrolyte solution may change due to variation in the electrolyser feed composition and its operating conditions. In this work, a code with a GUI has been developed to predict the yield of crystallization. The GUI provides the tabs for input parameters to be supplied by the user. The model equations are solved in the background, and the yield of crystallization of CuCl and CuCl₂ for varying compositions of the spent solution is predicted and displayed. The code is capable of predicting the yield of crystals for a given temperature, HCl concentration, electrolytic conversion, and feed concentration in the operational range of interest. Predicted values of crystal yield are displayed graphically at different parametric conditions for the range of operation. Validation of the code is done with the generated experimental data. The work carried out in this study, leading to the prediction of crystallization yield, is important for the design and scale-up of the crystallization step as well as development of simulator for the thermochemical Cu-Cl cycle for hydrogen production.

Acknowledgement

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3

सिंटरन के निशान की जांच हेतु कार्बोनेटेड हाइड्रॉक्सीपेटाइट पर टेराहर्ट्ज-रमन स्पेक्ट्रमदर्शी

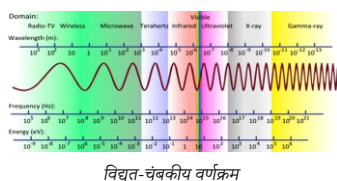
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सारांश



टेराहर्ट्ज-रमन स्पेक्ट्रमदर्शी (टीएचजेड-रमन) एक प्रगत घूर्णन-कंपन स्पेक्ट्रमदर्शी तकनीक है जो संरचनात्मक एवं आण्विक उपस्थिति के प्रमाण (अंगुल-छाप) प्रदान कर सकती है। इस कार्य का उद्देश्य रासायनिक रूप से संश्लेषित कार्बोनेटेड एपेटाइट, एक अस्थि खनिज अनुहार, का उच्च तापमान 400, 600, 700 और 800 °C पर सिंटर कर अभिलक्षण करना था। इसकी विशेषता 400 °C (सीए-400) पर THz-रमन शीर्ष तीव्रता में एक महत्वपूर्ण वृद्धि शिथिल बंध जल और हाइड्रॉक्सिल समूहों को हटाने से उत्पन्न संरचनात्मक पुनर्गठन है। मध्यवर्ती तापमान (600-700 °C) पर, कम तीव्रता और चरम विस्तार कार्बोनेट की कमी, आंशिक अपघटन एवं जालक पुनर्संरचना को इंगित करता है। 800 °C पर, टेराहर्ट्ज क्षेत्र (<200 cm⁻¹) में अतिरिक्त कंपन विशेषताओं का उद्भव बेहतर क्रिस्टलीकरण और संभावित प्रावस्था परिवर्तन का संकेत देता है। ध्यातव्य है कि, Ca-O कंपन मोड (O-Ca-O) विशेष रूप से टेराहर्ट्ज क्षेत्र में देखे गए और पारंपरिक रमन वर्णक्रमीय सीमा में अनुपस्थित थे, जो निम्न आवृत्ति जालक कंपन के प्रग्रहण में टेराहर्ट्ज-रमन स्पेक्ट्रमदर्शी के महत्व को उजागर करते हैं।

3

Terahertz-Raman Spectroscopy on Carbonated Hydroxyapatite to Investigate the Signature of Sintering

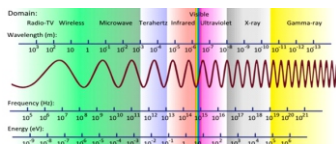
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ABSTRACT



Electromagnetic spectrum

Terahertz-Raman spectroscopy (THz-Raman) is an advanced rotational-vibrational spectroscopic technique which can provide structural and molecular fingerprints. This work was aimed to characterize chemically synthesized carbonated apatite, a bone mimicking mineral, sintered at elevated temperatures 400, 600, 700 and 800 °C. A significant enhancement in the THz-Raman peak intensity at 400 °C is attributed to structural reorganization arising from the removal of loosely bound water and hydroxyl groups. At intermediate temperatures (600-700 °C), reduced intensity and peak broadening indicate carbonate loss, partial decomposition and lattice restructuring. At 800 °C, the emergence of additional vibrational features in terahertz region (< 200 cm⁻¹) indicates improved crystallinity and possible phase transformation. Notably, Ca-O vibrational modes (O-Ca-O) were observed exclusively in the terahertz region and were absent in the conventional Raman spectral range, highlighting the significance of terahertz-Raman spectroscopy in capturing low-frequency lattice vibrations.

KEYWORDS: THz-Raman spectroscopy, Rotational-vibrational energy levels, Carbonated apatite, Bone mineral

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Introduction

Material characterization is of immense significance as it provides an insight into the chemical composition and structural arrangement of the materials which gives further information about bonding, purity, defects, mechanical, biological, thermal, and optical properties. Characteristic information prior to development helps in optimizing design and processing, saving significant time and resources. A range of techniques such as Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy, X-ray Photoelectron Spectroscopy, and Transmission Electron Microscopy are already in use for this purpose. Among them, Raman spectroscopy is a widely used and a powerful analytical technique based on the inelastic scattering of light, arising from changes in the polarizability of molecules. It provides a unique molecular fingerprint of materials. In this process, the energy of the incident photons, when they get scattered from molecules, undergoes a shift. When the photons lose energy during this interaction, it is termed a Stokes shift, whereas when they gain energy, it is referred to as an anti-Stokes shift (Fig.1a) [1]. Raman spectroscopy can also be used to study phase transition, vibrational rotational modes, glass transition and relaxation processes [2]. A conventional Raman spectrometer is associated with molecular vibration in a spectral range from 200 cm^{-1} to 4000 cm^{-1} and Raman signal in the range of 500 cm^{-1} to 1500 cm^{-1} provides chemical fingerprint of the molecules [3]. In last few decades, Raman spectroscopy at low wavenumbers ($< 200\text{ cm}^{-1}$), also known as Terahertz Raman spectroscopy (THz-Raman), has added an advancement in the analysis technique by providing structural fingerprint of the molecules and gained relevance in the research, Fig.1b [4]. THz-Raman spectroscopy has been used as an advanced vibrational-rotational spectroscopy approach in the range of $\sim 0.1 - 10\text{ THz}$ or $3-300\text{ cm}^{-1}$ to probe low-frequency molecular vibrations correspond to hydrogen bonding, lattice vibrations, intermolecular interactions, or phonons that are often invisible in the conventional Raman or IR spectra [5]. The ability to safely and remotely detect unknown materials is an advantage of

THz-Raman spectroscopy that is responsible for its wide popularity. Many explosives and hazardous chemicals have strong transition $< 6\text{ THz}$ (200 cm^{-1}) regime. Carriere et al. used THz-Raman to fingerprint different polymorphic forms of Carbamazepine with same chemical composition and Ammonium Nitrate, the material commonly used in explosives [6]. Singh et al. used THz-Raman spectroscopy to identify five common nitrogen based high energy organic compounds [7]. Zhang et al. reported THz-Raman spectra of graphite flaks and single walled carbon nanotubes [8]. Carpinteri et al. studied mechanical vibration of crystalline lysozyme enzyme in THz-Raman range [9].

Apatite is the primary mineral component of biological hard tissues such as bones and teeth and is extremely important in biomaterials and biomedical engineering [10]. It is a group of calcium phosphate minerals with general formula $\text{Ca}_{10}(\text{PO}_4)_6(\text{X})_2$ where X can be -OH, -Cl, -F, C etc. Apatite possess hexagonal lattice where phosphate group (PO_4^{3-}) form a tetrahedral structure and calcium ion occupy two distinct crystallographic positions designated as Ca (I) and Ca (II) sites, as shown with blue and red colour, respectively in Fig.1c [11]. Carbonated apatite (CA) which is chemically more similar to natural bone is a modified form in which carbonated ion (CO_3^{2-}) gets substituted into crystal lattice of hydroxyapatite [$\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$: (HAP)] and alters the physical and chemical properties of the lattice [12]. The CA when sintered to elevated temperature can undergo significant chemical and structural changes due to the thermal instability of carbonate group. Since, selective laser sintering of CA is employed for scaffold fabrication utilized as implant materials, study of its temperature dependent properties is of great significance.

In this work CA was synthesized by chemical method and characterized using SEM, EDS (energy dispersive x-ray spectroscopy), XRD and Raman spectroscopy. The CA powder was sintered at various elevated temperatures and its corresponding morphology was studied using SEM. Temperature dependent change in THz-Raman spectra were reported in the range of 0.6 cm^{-1} to 3000 cm^{-1} .

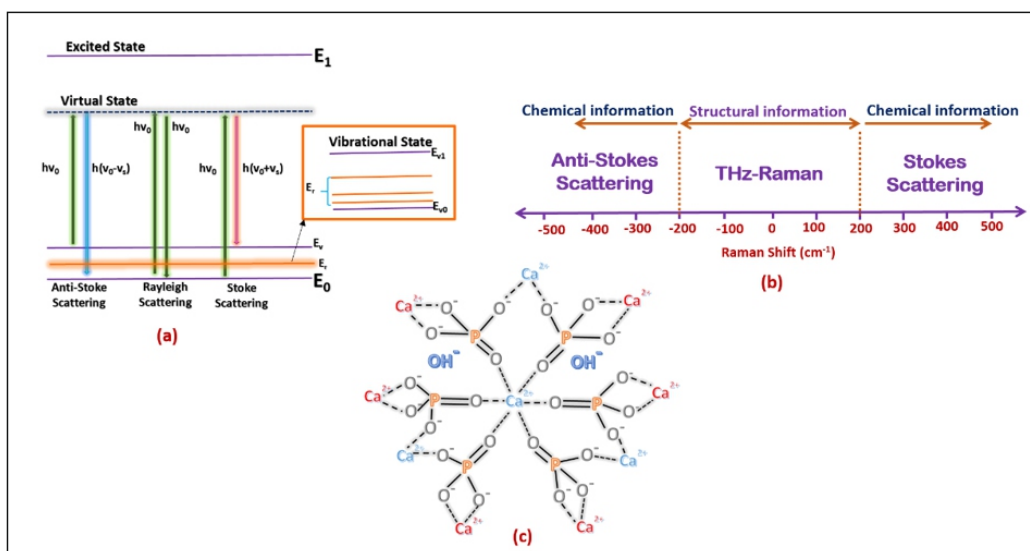


Fig.1: Illustration of typical (a) vibrational and rotation level of a molecule, (b) Terahertz and Raman spectrum range and (c) molecular structure of apatite.

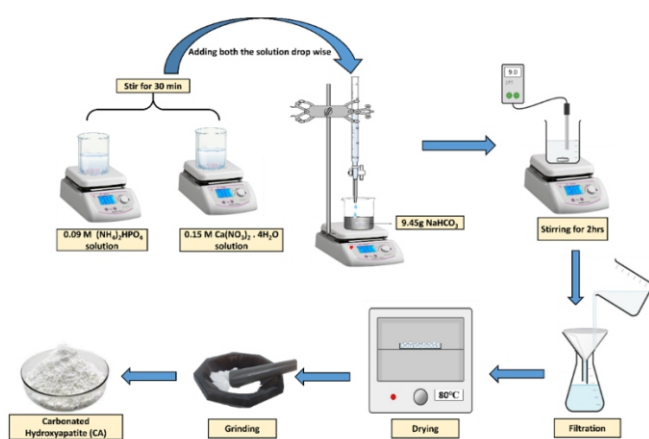


Fig.2: Illustration the steps for synthesis of CA.

Experiment

For synthesis of CA, about 9.45 g of NaHCO_3 was added to 250 ml of distilled water heated at 60°C placed on a magnetic stirrer to prepare bicarbonate mixture. Separately, about 8.85 g of 0.15 M of $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ in 250 ml of DI water and 2.97 g of 0.09 M of $(\text{NH}_4)_2\text{HPO}_4$ in 250 ml of DI water were stirred for 30 min. These two solutions were added into the bicarbonate mixture drop wise. The pH of the mixture was adjusted and maintained at 9 by adding ammonium hydroxide solution. The reaction mixture was continuously agitated at 1000 rpm and 60°C for 2 h. The precipitates was then washed three times with mixture of distilled water and 5% ethanol [13]. The residue was then dried at 80°C for 24 h in an oven and ground to a fine powder to obtain CA. A schematic diagram illustrating the steps of CA synthesis is shown in Fig. 2. For THz-Raman characteristics, CA powder was sintered at elevated temperature of 400°C , 600°C , 700°C and 800°C and sintered samples were termed as CA-400, CA-600, CA-700 and CA-800, respectively. Morphology of CA samples was studied using SEM (S&C 4500 M) and THz-Raman characterization was done in the range of 0.6 cm^{-1} to 3300 cm^{-1} (0.018 to 89 THz) using IndiRAM CTR300C Confocal Micro Raman/PL Spectrometer.

Results and Discussion

Fig.3a shows SEM image of as synthesized CA in which nanostructured powder is clearly visible. In EDS analysis shown in Fig.3b, detection of carbon along with Ca and P without additional impurity confirmed success of carbonation. Raman spectra of as synthesized CA and HAP (for the sake of comparison) are shown in Fig.3c. One can notice that the characteristic peak of HAP at 960 cm^{-1} corresponding to PO_4^{3-} stretching diminished and sharp an intense peak at 1090 cm^{-1} was observed in case of CA. This peak at 1090 cm^{-1} corresponds to the ν_1 symmetric stretching mode of CO_3^{2-} ions in CA [14, 15]. This indicated that PO_4^{3-} in HAP lattice was replaced by CO_3^{2-} molecules during the process of carbonization and this is called B-type substitution. Another possible replacement is -OH site in HAP by CO_3^{2-} and that is called A-type substitution [12]. Most of the biological apatites are of B-type CA. Fig.3d shows the XRD data that exhibit typical

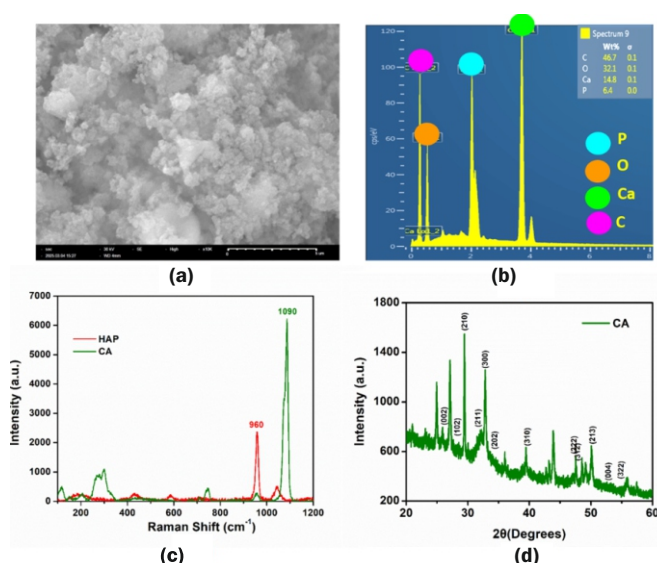


Fig.3: (a) SEM image (b) EDS analysis of as synthesized CA, (c) Raman spectra of HAP and CA (d) XRD of as synthesized CA.

diffraction peaks at 25.8° , 28.1° , 29.4° , 31.9° , 32.9° , 34.0° , 39.5° , 47.5° , 48.5° , 50.05° , 53.1° , and 55.9° corresponding to (002), (102), (210), (211), (112), (300), (202), (310), (222), (312), (213), (004), and (322) planes of CA respectively (JCPDS 09-0432) [16].

Figs.4a-4d show the SEM images of sintered CA powder where temperature dependent change in morphology is clearly visible. Fig.4e shows the THz-Raman spectra of as synthesized and sintered CA samples. In Raman band from 400 cm^{-1} to 1300 cm^{-1} , the characteristic peak of CA the characteristic peak of CA showed a significant increment for CA-400. This could be because at 400°C removal of loosely bound water, hydroxyl group and surface impurity induced structural reorganization and improved detectability of carbonated group [17]. Further, possibility of crystalline order of apatite lattice at this temperature may have enhanced the efficiency of Raman scattering. For CA-600, there is a possibility of carbonated group decomposing and release of CO_2 gas from the lattice structure. This resulted in the reduction of Raman peak intensity at 1090 cm^{-1} . As carbonate content reduces in the structure, the lattice shift towards stoichiometric HAP and therefore, the characteristic peak of PO_4^{3-} stretching of HAP was observed 960 cm^{-1} . On further sintering to $700\text{--}800^\circ\text{C}$, significant decomposition resulted in alteration of Ca/P ratio of apatite and phase transition to β -tricalcium phosphate (β -TCP) [17]. The defects generated during carbonated substitution get removed during sintering at these high temperature and generate more ordered structure [18].

A significant temperature dependent behavior was observed for CA in THz-Raman band ($1\text{--}10\text{ THz}$ or $0\text{--}333\text{ cm}^{-1}$) which correspond to phonon vibrations that arise due to collective motion of atoms in the crystal lattice (Fig.4e). As synthesized CA that is characterized by broad bands at 3.4 THz , 4.53 THz , 5.13 THz , 6.12 THz , 8.00 THz and 8.97 THz indicates poor crystallinity and structural disorder. The CA-400, exhibited two significantly intense sharp peaks centered around

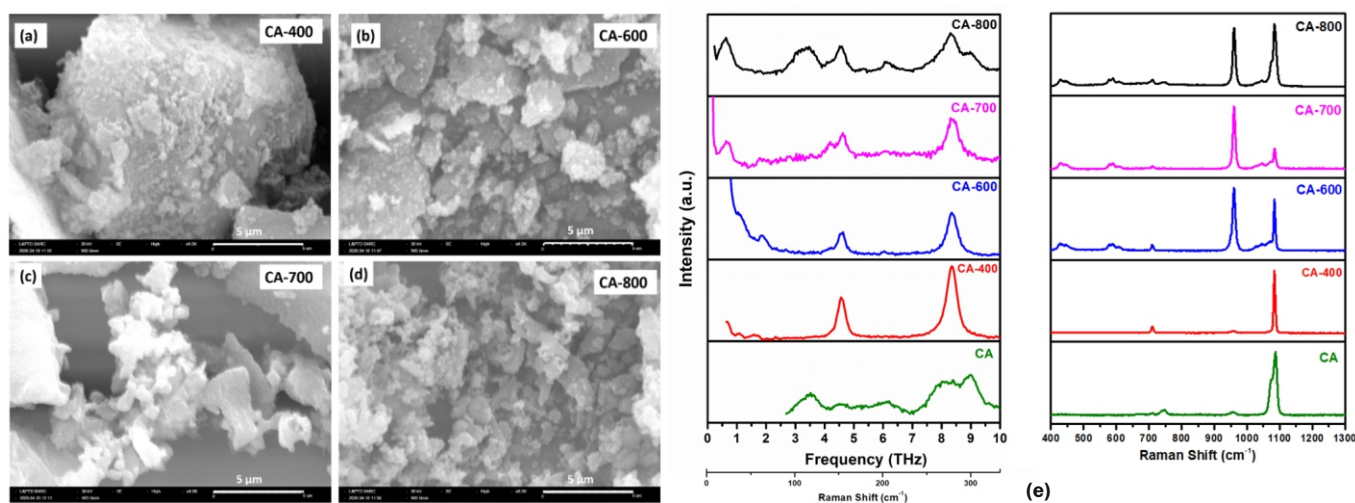


Fig.4: SEM images of (a) CA-400, (b) CA-600, (c) CA-700, (d) CA-800 and (e) THz-Raman spectra of CA, CA-400, CA-600, CA-700 and CA-800.

4.56 THz and 8.33 THz along with low intense peaks at 1.08 THz, 1.59 THz, 2.02 THz, and 2.32 THz. In the intermediate temperatures (600-700°C), reduction in peak intensity and peak broadening indicated structural modification due to loss of carbonated group, decomposition and restructuring. Here the observed THz-Raman bands were at 1.06 THz, 1.85 THz, 2.64 THz, 4.56 THz and 8.33 THz. At 800°C, additional vibrational features appeared in the THz-Raman spectrum, indicated possible phase transformation and modification in lattice dynamics [19]. Surface phonons contributes strongly in low-frequency Raman signals results in bond splitting and appearance of new peaks. It has been reported that the THz-Raman peaks detected $< 2 \text{ THz}$ ($< 70 \text{ cm}^{-1}$) corresponds to translational vibration motion of Ca^{2+} ions. Peaks between 2-6 THz ($70\text{-}200 \text{ cm}^{-1}$) corresponds to librational (restricted rotational) modes of PO_4 and CO_3 groups. And, the peaks between 6- 10 THz are low energy optical vibration of O-Ca-O bending [20].

Conclusion

The CA powder was successfully synthesized via a simple in-house chemical technique. Superior quality and purity of CA powder was confirmed from EDS, Raman and XRD. The signature of sintering (400–800°C) was systematically investigated using THz-Raman spectroscopy in both the terahertz (0–10 THz) & conventional Raman (400–1300 cm^{-1}) regime. The terahertz regime revealed collective translational and librational motions of Ca^{2+} ions and PO_4/CO_3 units, which are not accessible in the conventional Raman range. Carbonate substitution-induced lattice disorder was evident from peak broadening in the THz spectra for CA-600 and CA-700, providing direct insight into structural dynamics and substitution mechanisms. With increasing sintering temperature, progressive decarbonation, and enhanced crystallinity, were observed. These findings demonstrate that terahertz-Raman spectroscopy serves as a powerful complementary tool for probing low-frequency lattice vibrations and offers enhanced sensitivity for identifying structural evolution in apatite systems.

Acknowledgment

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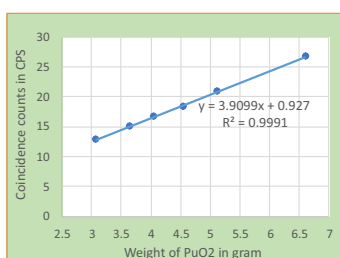
एनडब्ल्यूसीसी प्रणाली हेतु एक स्वदेशी एफपीजीए-आधारित संपात गणना मॉड्यूल का विकास

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सारांश



सीपीएस बनाम PuO_2 Wt. में संयोग की गणना।
(एफपीजीए आधारित)

(U, Pu)O₂ मिश्रित ऑक्साइड (MOX) मिश्रित पाउडर में, प्लूटोनियम की मात्रा का निर्धारण न्यूट्रॉन वेल कोइनसिडेन्स काउंटर (एनडब्ल्यूसीसी) तकनीक का उपयोग करके प्रक्रम नियंत्रण विधियों द्वारा किया जाता है। मौजूदा प्रणाली ने पारंपरिक इलेक्ट्रॉनिक्स को नियोजित किया, जो रखरखाव और संगतता में सीमा संतुलन बनाता है। चूंकि ऐसी प्रणालियाँ निर्यात नियंत्रण के तहत प्रतिबंधित हैं और भारत में व्यावसायिक रूप से अनुपलब्ध हैं, इसलिए विभाग की निष्क्रिय न्यूट्रॉन आमापन गतिविधियों को समर्थ बनाने के लिए स्वदेशी विकास अत्यंत आवश्यक है। इसे प्राप्त करने के लिए, भापअ केंद्र, मुंबई में इलेक्ट्रॉनिक्स प्रभाग ने एक स्व-स्थाने फील्ड प्रोग्रामेबल गेट ऐरे (एफपीजीए) आधारित संयोग मॉड्यूल विकसित किया। इसमें संबद्ध सिग्नल प्रक्रम इलेक्ट्रॉनिक्स एवं डाटा अधिप्राप्ति, चाक्षुषीकरण एवं पैरामीटर विन्यास के लिए एक ग्राफिकल यूजर इंटरफेस है, जो एफएफ, आईएनआरपी(ओ), तारापुर में समान परिस्थितियों के तहत पारंपरिक प्रणाली के साथ-साथ भावी अनुसंधान हेतु अग्रसर करता है, मॉड्यूल ने बेहतर स्थिरता और गणना की सटीकता का प्रदर्शन करते हुए, 0.997 से 0.999 तक सहसंबंध मान (R^2) प्राप्त किया। यह कार्य निरंतर न्यूट्रॉन संयोग माप के लिए जारी रखे जाने योग्य, पूर्णतः स्वदेशी समाधान प्रदान करता है।

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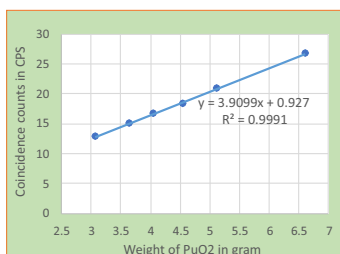
Development of an Indigenous FPGA-Based Coincidence Counting Module for NWCC System

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ABSTRACT



Coincidence counts in CPS Vs PuO_2 Wt. (FPGA Based)

In (U, Pu) O Mixed Oxide (MOX) blended powder, plutonium content is determined by process control methods using the Neutron Well Coincidence Counter (NWCC) technique. The existing system employed legacy electronics, posing limitations in maintainability and compatibility. Because such systems are restricted under export controls and commercially unavailable in India, indigenous development is absolutely essential to support the Department passive neutron assay activities. To address this, the Electronics Division at BARC, Mumbai, developed an in-house Field Programmable Gate Array (FPGA) based coincidence module. It features associated signal processing electronics and a graphical user interface for data acquisition, visualization, and parameter configuration, enhancing flexibility for future research. Tested alongside the legacy system under identical conditions at F.F., INRP(O), Tarapur, the module demonstrated improved stability and counting accuracy, achieving correlation values (R^2) from 0.997 to 0.999. This work provides a maintainable, fully indigenous solution for sustained neutron coincidence measurements.

KEYWORDS: FPGA, Gate Array, NWCC, Neutron Well, Coincidence Counter, Electronics, HDPE, Software, IC, Module

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Introduction

Quantitative analysis of Plutonium is an essential task in MOX fuel fabrication. Passive neutron coincidence counting is a well-established nondestructive assay technique used for estimating plutonium content in MOX fuel fabrication and safeguards applications [1]. Conventional chemical analysis methods, although precise, are slow, require elaborate sampling procedures, and generate α -active liquid waste, making them unsuitable for routine large scale operations. Earlier studies at BARC have demonstrated that NWCC, provide fast, reliable, and waste-free verification of PuO₂ enrichment in MOX fuel blends as well as in recycled materials such as Clean Rejected Oxide (CRO) powder and Dirty Rejected Oxide (DRO) powder [2]. NWCC distinguishes spontaneous fission neutrons from random (α, n) neutrons by analysing their time correlation. In plutonium-bearing MOX powders, spontaneous fission from even-even isotopes (mainly ²³⁸Pu, ²⁴⁰Pu, ²⁴²Pu) provides correlated events, while (α, n) neutrons from oxygen contribute an uncorrelated background [1]. Earlier work at BARC Tarapur established NWCC as a practical tool for verifying PuO₂ content across a wide range of sample sizes and demonstrated strong agreement with chemical methods for MOX pellets [2]. For detect coincidence event, different types of coincidence detection circuits have been described by Ensslin et al., who demonstrated that shift-register-based systems significantly reduce system dead time [1]. NWCC systems subsequently relied on shift-register-based electronics, first conceptualized by Boehnel et al. [1,3]. The electronic circuitry was further developed by Stephens et al. [4] and later improved by Swansen et al. [5,6] and Lambert et al. [7]. The shift-register concept enabled a substantial reduction in coincidence dead time and allowed measurements at higher count rates.

The design by Swansen et al. provided selectable gate widths (8-128 μ s) and pre-delays (1-32 μ s), enabling reliable operation at total count rates of several hundred kHz. Similar systems were also developed and optimized at BARC by S. P. Dange et al. and S. C. Kapoor et al., incorporating a fixed 8 μ s delay and two selectable gate widths of 64 μ s and 128 μ s [8,9]. However, these systems were implemented using discrete electronic components, many of which are now obsolete and no longer commercially available, creating challenges for long-term maintenance and reproducibility. In addition, the available gate widths were restricted to discrete values that are multiples of 2ⁿ, limiting optimization for different detector geometries and measurement conditions. Furthermore, the Real + Accidental (R + A) and Accidental (A) outputs obtained from the scalers do not represent true event counts, as the circuitry generates a single TTL pulse only when the accumulator exceeds a fixed threshold of ten counts.

To overcome these limitations, an FPGA-based coincidence counting module with associated signal-processing electronics was developed in-house at Electronics Division, BARC. The system was tested in parallel with the existing setup at F.F., INRP(O), Tarapur, under identical conditions. The developed system provides a flexible and maintainable indigenous solution compatible with established NWCC practices and can be extended for applications such as multiplicity counting and safeguards.

Overview of Existing System

The current system installed at F.F., INRP(O) was developed by the Radiochemistry Division, BARC, Mumbai, in 1993. The development and optimization details of this system are described in [8,9]. The block diagram of the system is shown in Figure 1. The system consists of the following units:

Detector Assembly: It is made up of 16 He-3 counters (50 cm length; 2.54 cm diameter and filled with He-3 at 4 Atm. pressure) arranged in single concentric array within the moderator housing of High-Density Polyethylene (HDPE).

Pre Amplifier: A single charge-sensitive preamplifier has been used for both high voltage biasing and amplification of the signal received from the detector assembly.

Amplifier: A single width Nuclear Instrumentation Module (NIM) Spectroscopy amplifier having variable gain (1 to 1000).

Coincidence Unit: The coincidence unit is a double width NIM module based on shift-register logic for neutron coincidence counting. Input pulses from the amplifier are discriminated into standard logic pulses and synchronized with the system clock for processing. A fix pre-delay is introduced using an 8-bit shift register to accommodate detector and amplifier recovery time and to avoid bias between the real-plus-accidental (R+A) and accidental (ACC) gates. The prompt R+A gate is implemented using a 64-bit shift register, providing selectable gate widths of 64 μ s or 128 μ s. Coincidence events within the R+A and ACC gates are continuously monitored using an up-down counter, which tracks the number of pulses present in the gate at any instant.

The counter output is processed through binary adders, converted to BCD format using binary-to-BCD converters, and accumulated in register latches. A fixed long delay of 1024 μ s between R+A and ACC sampling is generated using cascaded 64-bit shift registers. Each input pulse independently generates its own R+A and ACC sampling gates, eliminating the need to wait for gate closure and resulting in very low system dead time. This architecture allows operation at counting rates of several kilohertz. An underflow detection circuit provides fault indication, while the accumulated R+A and ACC counts are displayed using LED-based readouts.

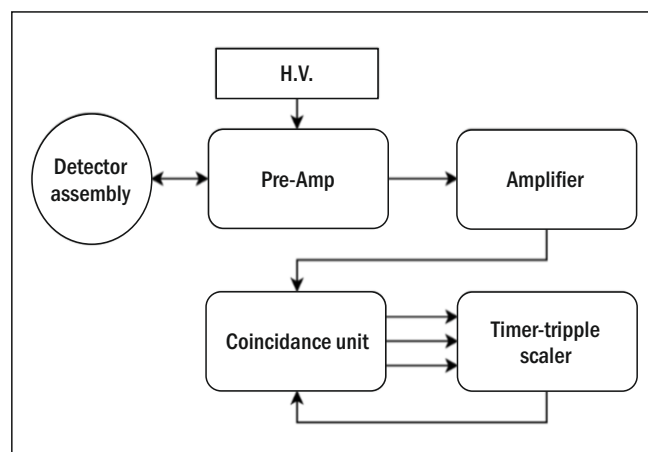


Fig.1: Block diagram of NWCC system.

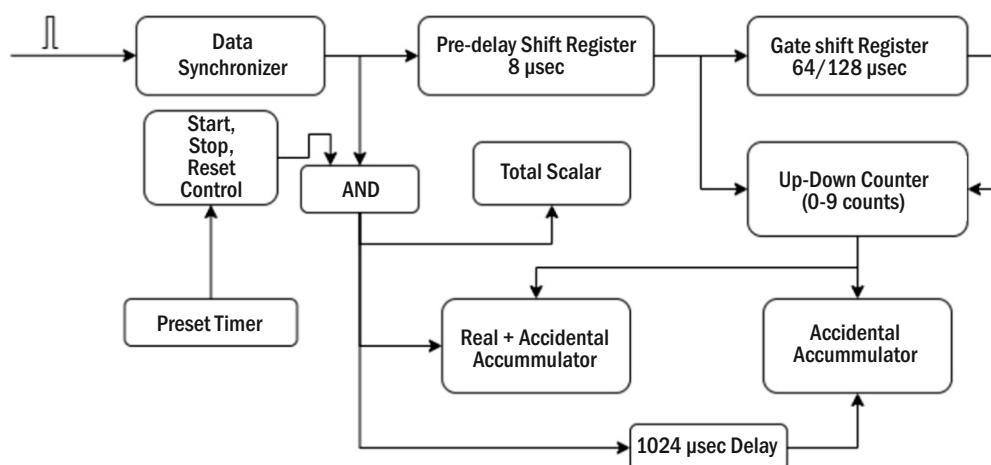


Fig.2: Block diagram of coincidence counter.

Details of FPGA based NWCC System

Electronics Division, BARC, had undertaken the development of the new portable and compact NWCC system based on the requirements of Fuel Fabrication Division, Nuclear Recycle Board, BARC, Tarapur and have delivered two NWCC units along with associated low noise charge sensitive pre-amplifiers (CSPA) for the He-3 Neutron well detector assembly.

One complete NWCC system consists of HDPE well with 16 detector assembly, CSPA (mounted very close to the detector assembly) and a compact and portable (25 cm X

30 cm X 15 cm) NWCC module comprising a variable HV supply, a variable gain spectroscopy amplifier, a discriminator logic, CSPA supply for external CSPA. A 1.5 KV, 1.3 mA HV supply is used for biasing multiple He-3 detectors in the detector assembly with a FPGA based programmable HV control logic with a voltage setting resolution of 1V in 1500V, a high count rate (maximum 200K CPS) FPGA based coincidence counter, and an Ethernet interface for data exchange with the command and control PC running the NWCC analysis software. The new NWCC system being portable and operating on 230V AC mains mitigates the need for large and heavy specialized supply bins used with the earlier NIM based NWCC system.

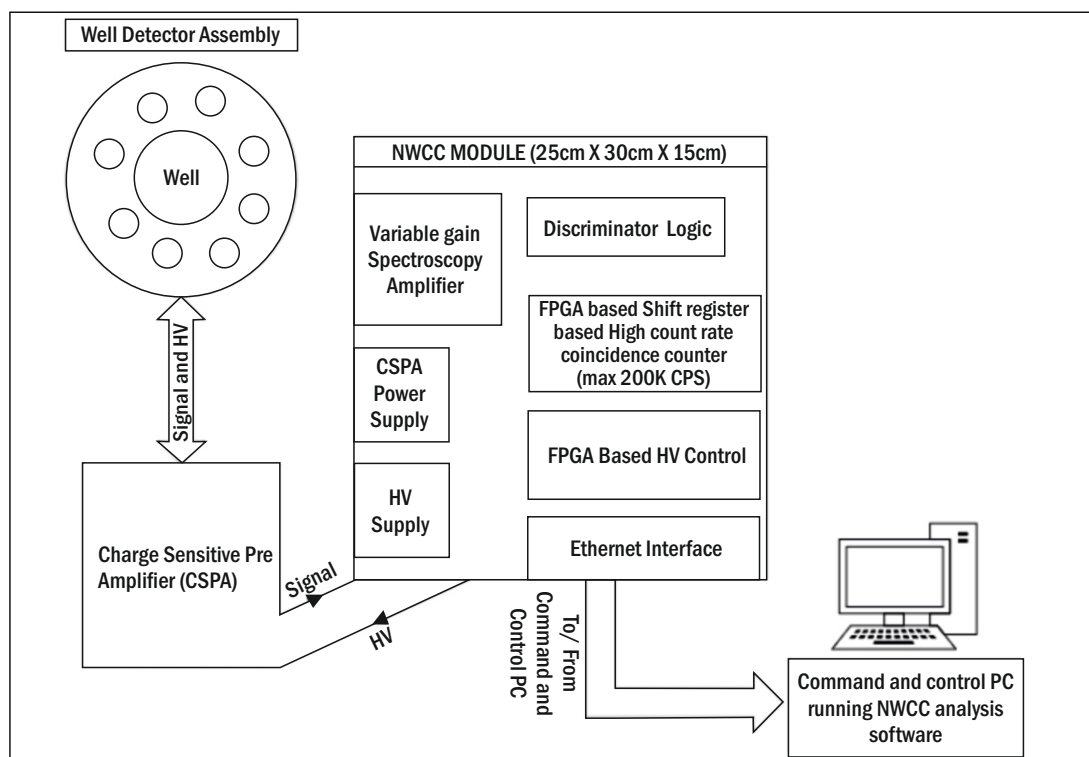


Fig.3: Block Diagram of the complete FPGA based NWCC System.

The technical specifications of the various electronic sub-modules of the NWCC system are as follows.

(A) Charge Sensitive Pre Amplifier (CSPA):

- (a) **Charge Sensitivity** (Si equivalent): Nominally 45 mV/MeV.
- (b) **Rise Time**: < 10 ns at 0 pF
- (c) **Input**: Accepts positive or negative charge input from detector.
- (d) **Bias**: Accepts detector bias from bias supply generated at NWCC module and applies it to detector through the input connector, maximum ± 1500 V, 1.3 mA
- (e) **Power**: Input power through 2-meter power cable from 9 pin D type connector in shaping amplifier in the NWCC module.

(B) Spectroscopy Amplifier:

- (a) **Gain Range**: Continuously adjustable from 10 to 500.
- (b) **Pulse Shape**: Unipolar Gaussian pulse shape at the output.
- (c) **Shaping Time**: 1 μ sec (Fixed).

(C) Discriminator Logic:

- (a) **Lower Level Discriminator (LLD)**: Variable LLD level from 0V to 6V settable with a voltage setting resolution of 50 mV in the range.
- (b) **Upper Level Discriminator (ULD)**: Variable ULD level from 0V to 10V settable with a voltage setting resolution of 50 mV in the range.

(D) Programmable High Voltage:

- (a) **Output Range**: 0 V to 1500 V with a voltage setting resolution on 1V (controlled by PC over Ethernet via FPGA based HV control algorithm)
- (b) **Maximum Current range**: 1.3 mA.
- (c) **Interface**: Connected to the Pre-amplifier via a 1-meter long Safe High Voltage (SHV) cable.

(E) FPGA based Coincidence Counter: The coincidence logic has been implemented in the FPGA through HDL based firmware development, following the coincidence algorithm described in [3]. Since the logic is realized using HDL, all operational parameters (Pre-delay, gate width, long delay) and functional features of the coincidence system are fully configurable and can be adapted for various passive neutron

assay applications within the department with only minor modifications to the firmware. For the INRP(O) system, which employs 16, He-3 detectors arranged in a well-type geometry, the coincidence logic has been configured with the following parameters:

- (a) **Pre-Delay**: Variable pre-delay time settable from 1 μ sec to 32 μ sec with a setting resolution of 1 μ sec.
- (b) **Gate Width**: Variable gate width settable from 8 μ sec to 128 μ sec with a setting resolution of 8 μ sec (i.e. 8, 16, 24, 32112, 120, 128).
- (c) **Maximum Count Rate**: 200K counts per second.

(F) NWCC Analysis Software (Running on PC):

- (a) The software provides command and control GUI on a PC for data acquisition from NWCC system hardware and for setting various hardware parameters over Ethernet.
- (b) The software also allows the user to automate preprogrammed acquisition runs for a preprogrammed duration using the automation module in the software.
- (c) The software can also generate regression plots from the data acquired from multiple samples and can compute the R^2 value.

Experiment and Results

To validate the performance of the FPGA based Coincidence Counting Module, an experimental setup was configured. A single preamplifier and spectroscopy amplifier was used to ensure identical input signal conditions for both coincidence counting units under comparison. The output of the spectroscopy amplifier was split into two identical signal paths. Each path was fed simultaneously to the FPGA based coincidence module and the reference coincidence module.

Identical operating parameters were configured in both coincidence modules:

- **Pre-delay**: 8 μ s
- **Gate width**: 128 μ s
- **Threshold**: 2.5 V

A standard PuO₂ source was used for testing. The mass of the PuO₂ source ranged from 3 g to 6.6 g. For each mass value, measurements were carried out for 100 seconds, and five repetitions were performed. The average real coincidence

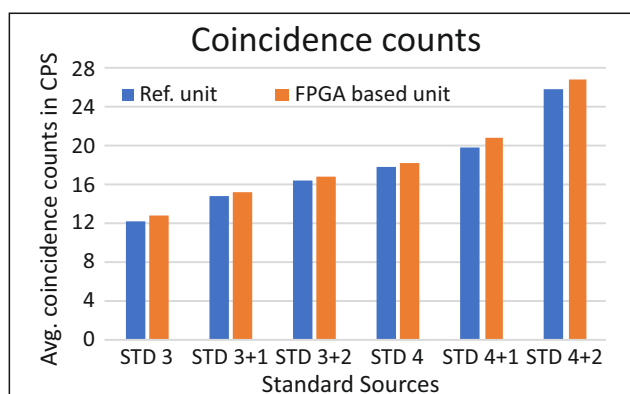


Fig.4: Coincidence counts for Ref. and FPGA based unit with diff. std.

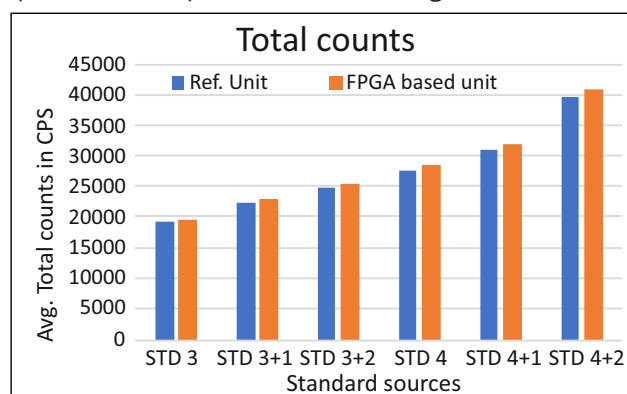


Fig.5: Total counts for Ref. and FPGA based unit with diff. std.

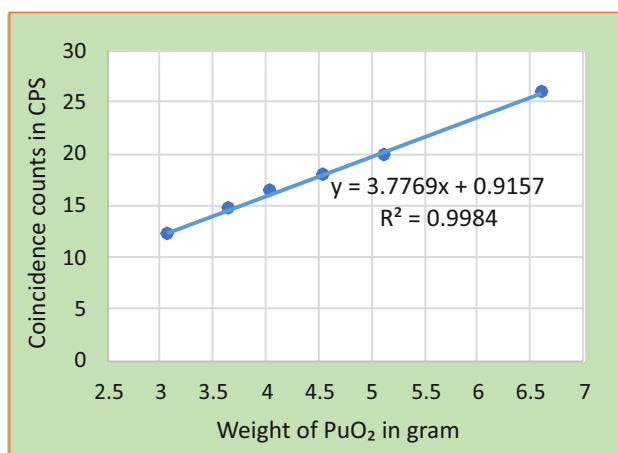


Fig.6: Coincidence counts in CPS Vs PuO₂ Wt. (Ref. unit).

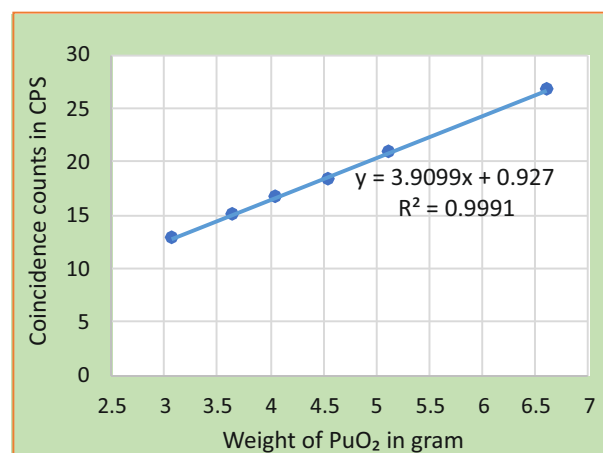


Fig.7: Coincidence counts in CPS Vs PuO₂ Wt. (Ref. unit).

counts and total counts were calculated for both modules. The details are presented in figure 4 and 5.

Figures 6 and 7 show the relationship between source mass and coincidence counts for the reference module and the FPGA-based module, respectively. The linear regression analysis yielded an R^2 value of 0.9984 for the reference module and 0.9991 for the FPGA based module.

Conclusion

This comparative study confirms that discrete IC based coincidence module can be effectively replaced by the proposed FPGA based module. The FPGA implementation offers greater flexibility, allowing parameters such as gate width and pre-delay to be modified through software without hardware changes, making it suitable for future research applications. The obtained R^2 values of 0.9984 for the existing system and 0.9991 for the FPGA based system confirm the good correlation and reliable performance of the developed module.

Future Scope and Possibilities

The FPGA-based design enables modification of well geometry and flexible adjustment of gate width and pre-delay without changing the overall electronic system. This allows optimization of the coincidence window for different detector configurations and sample conditions. The improved timing control enhances discrimination between real and accidental events, resulting in better accuracy. The programmable architecture ensures long-term adaptability.

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The authors would like to thank Mrs. Suparna Sodaye, Scientific Officer/H and her team from RCD, BARC for helping the developers test the electronics in with their neutron well coincidence counter during development phase. The authors would like to thank Chemical Quality Control Section of F.F. for providing the standard source and related details required for testing of the FPGA-based NWCC system. The authors also extend their sincere gratitude to Maintenance Section, FF for providing necessary help & support during comprehensive testing of the system.

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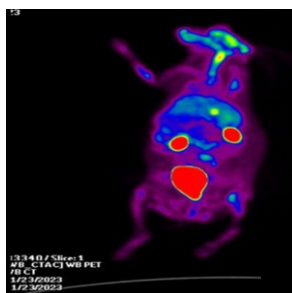
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5

नए रेडियो-भेषजिकों के पूर्व-नैदानिक विकास में प्रमुख तकनीकी बाधाएं : एक परिप्रेक्ष्य

योगिता शेते एवं संदीप बसु

विकिरण चिकित्सा केंद्र, भाभा परमाणु अनुसंधान केंद्र, टाटा स्मारक केंद्र एनेक्स बिल्डिंग, परेल, मुंबई-400012, भारत



खरगोश में जैव वितरण प्रतिबिंब विशिष्ट क्षेत्रों में उच्च तीव्रता वाले उद्ग्रहण का चित्रण।

सारांश

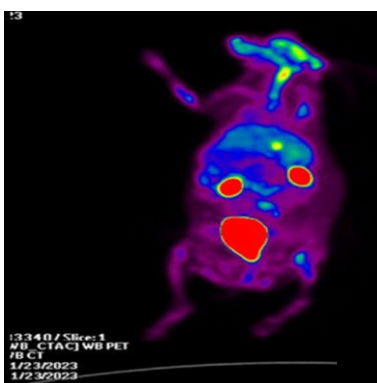
नए रेडियो-भेषजिक विकास एवं विस्तार में, नैदानिक संरक्षा मानव अनुप्रयोग के लिए मौलिक है। नैदानिक या चिकित्सीय उपयोग के लिए रेडियो-भेषजिक के पूर्व-नैदानिक विकास के चरणों में जीवशाला में जानवरों का उपयोग करके जोखिम मूल्यांकन एक महत्वपूर्ण कदम है। पशु अध्ययन रेडियो-भेषजिक विकास की आधारशिला है, जो 'कट एंड काउंट' डाटा एकत्र करने के लिए एक पारंपरिक विधि के रूप में कार्य करता है। वैज्ञानिक समुदायों ने दुनिया भर में पशु कल्याण और पशु प्रयोगों के लिए 3 (R) आर सिद्धांत को अपनाया है। इसलिए, पशु मॉडलों की वाइवो/जीवस्थ जैव वितरण और भेषज-गुणगतिकी समझ में दिनचर्या का उपयोग करके नए रेडियो-भेषजिक के परीक्षण को अपनाया गया है। नए रेडियो-भेषजिक विकसित करते समय पशु शरीर विज्ञान और प्रयोगात्मक अभिकल्पन का मौलिक ज्ञान आवश्यक है, क्योंकि यह ज्ञान प्रजातियों, उपभेदों, लिंग और उपयोग किए गए जानवरों की कुल संख्या के चयन का औचित्य प्रदान करता है। इस रिपोर्ट में, हमने सामाजिक लाभ के लिए वैज्ञानिक परिणाम सुनिश्चित करने हेतु नैतिक दिशानिर्देशों का पालन करते हुए, नई रेडियो-भेषजिक के विकास में बाधाओं को दूर करने के लिए अपनाई जाने वाली व्यावहारिक चुनौतियों और उनके समाधानों का उल्लेख करने का प्रयास किया।

5

Key Technical Barriers in Pre-clinical Development of New Radiopharmaceuticals: A Perspective

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Biodistribution imaging in rabbit displaying high-intensity uptake in specific regions.

ABSTRACT

In the new radiopharmaceutical development and expansion, the clinical safety is fundamental for human application. Risk assessment by using laboratory animals is a crucial step in the phases of pre-clinical development of radiopharmaceuticals either for diagnostic or therapeutic use. Animal studies are a cornerstone of radiopharmaceutical development, where 'cut and count' acts as a traditional method for gathering data. The scientific communities have embraced the animal welfare and 3Rs principle for animal experiments worldwide. Therefore, testing of new radiopharmaceuticals by using routine in vivo biodistribution & pharmacokinetic understanding of animal models have been adopted. Fundamental knowledge of animal physiology and experimental design is essential when developing new radiopharmaceuticals, as this knowledge justifies the selection of the species, strains, sex, and total number of animals used. In this report, we endeavoured to address the practical challenges and their solutions to be implemented to overcome the barriers in the development of new radiopharmaceuticals, while adhering to ethical guidelines to ensure scientific outcomes for societal benefit.

KEYWORDS: Nuclear medicine imaging, Laboratory animals, Radiopharmaceuticals

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Introduction

Biomedical and pharmaceutical research relies extensively upon the use of laboratory mice, wistar rats, Guinea pigs, and rabbits (Shete et al., 2024). Administering investigational agents such as novel drug formulations, antibodies, and radiopharmaceuticals allows researchers to determine vital pharmacokinetic and toxicological data necessary for successful clinical translation (Turner et al, 2011).

The Radiation Medicine Centre, BARC, Parel, is a pioneer institute in radioisotopic treatment in India. Although 1963 marked the beginning of preclinical radiopharmaceutical testing in animals, specific guidelines for handling radioactivity in this context were initially underdeveloped. Subsequently, the Atomic Energy Regulatory Board was established to regulate the safety and use of these materials. The AERB (Atomic Energy Regulatory Board) and International Atomic Energy Agency (IAEA), have established guidelines for optimizing medical radiation exposure and setting safety standards for human patients. The evaluation of preclinical animal studies in radiopharmaceutical development hinges on three main factors, translational relevance to human application, the physicochemical properties of the agent, and the specific study objectives (Korde et al., 2022). The persistent advancement of radioactive tracers is imperative to address the complex demands of modern health challenges. As a result, non-clinical testing of radiopharmaceuticals has experienced a threefold increase, leading to a surge in animal usage.

Radiopharmaceutical studies aim to ensure safe clinical use through the evaluation of in-vivo behaviour. Essential nonclinical studies must be performed to define target engagement, non-target organ uptake, and biodistribution, ensuring safe administration (Baldrick, 2021., Korde et al. 2022). Various factors, including species-specific variations, difference in metabolic pathways or protein expressions, administration routes, distress, method of evaluation and anesthesia, influence experimental outcome, often resulting in failed clinical trials. A literature survey highlights that improper consideration of these factors contributes to significant delays in translating preclinical findings to human applications. (Andes et al., 2002, Namdari et al., 2021, Mukherjee et al., 2022, Mizuo et al., 2023).

Globally new guidelines have been established, stating that the use of animals in experiments must adhere to the 3Rs principle of Replacement, Reduction, and Refinement (CCSEA, 2018, Kousholt et al., 2023). Furthermore, the IAEA preclinical testing guidelines (2023) emphasize that the '3Rs' principle must be followed in accordance with national guidelines. In biodistribution studies, the principles of reduction and refinement can be achieved by utilizing advanced imaging techniques and modifying evaluation methods.

Despite significant scientific progress, regulatory frameworks for preclinical radiopharmaceutical animal testing have failed to evolve, adhering instead to protocols established several decades ago. Consequently, a comprehensive revision of the Radiopharmaceutical Committee (RPC) regulations

governing preclinical studies for radiopharmaceuticals is required.

We herein outline the essential technical considerations for in vivo radiopharmaceutical studies, covering the various component such as anesthesia, dosing, animal model selection, and appropriate evaluation method to obtain biodistribution data.

To achieve better scientific outcomes from the animal experiments, it is necessary to integrate fundamental knowledge of existing animal species and refine procedures, which leads to improvements in both scientific research and animal welfare.

Technical Hurdles

Routes of administrations

An objective of the animal experiments, the route of administration is defined in preclinical models by: (i) the properties of the compound, (ii) nature of the formulation and (iii) routes of human application. Different routes of administrations like intravenous, intramuscular, Subcutaneous, intraperitoneal and intradermal, intrathoracic, intranasal, intracerebral and topical used in animals. The most commonly employed routes of administration for preclinical test substances are intravenous, subcutaneous, intraperitoneal (Shimizu, 2004). Administration methods for radiopharmaceuticals are tailored to their physicochemical properties and experimental findings. Precise intravenous administration is crucial for the success of many preclinical radiopharmaceutical studies (Vines, et al., 2011). However, radiopharmaceutical was also tested by subcutaneous, retro-orbital, intraperitoneal administrations are also examined by investigators in preclinical studies of radiopharmaceuticals (Schiffer, et al., 2007, Fueger et al., 2006).

The administration route in animal research is usually kept consistent with that used in humans, while the specific dose of the test radiopharmaceutical is adjusted according to the intended application. While in majority the preferred route of administration for radiopharmaceutical is intravenous route, there are few exceptions like (a) Iodine-131 is given by oral route, and the same for the Technetium-99m for gastric emptying study, while (b) inhalation route is adopted for radiolabeled gases used in lung studies include xenon-133, Krypton-81m (Clerc et al., 2017).

Administering radiopharmaceuticals via the fragile lateral tail veins of conscious mice is a technically demanding procedure due to the small, delicate nature of the vessels (Nanni et al., 2007). The small diameter of the lateral tail vein often leads to vessel damage and blockage when repeated injections are attempted (Shimizu., 2004). These difficulties not only complicate subsequent intravenous access but also cause pain and distress, impacting the animal's welfare and altering normal physiological parameters. Consequently, this can affect group behaviour and introduce variability in the biodistribution data, compromising study integrity (Vines, 2011, NIH guideline, 2019).

Handling stress is a major factor influencing vein accessibility in rodent models. Untrained personnel, excessive

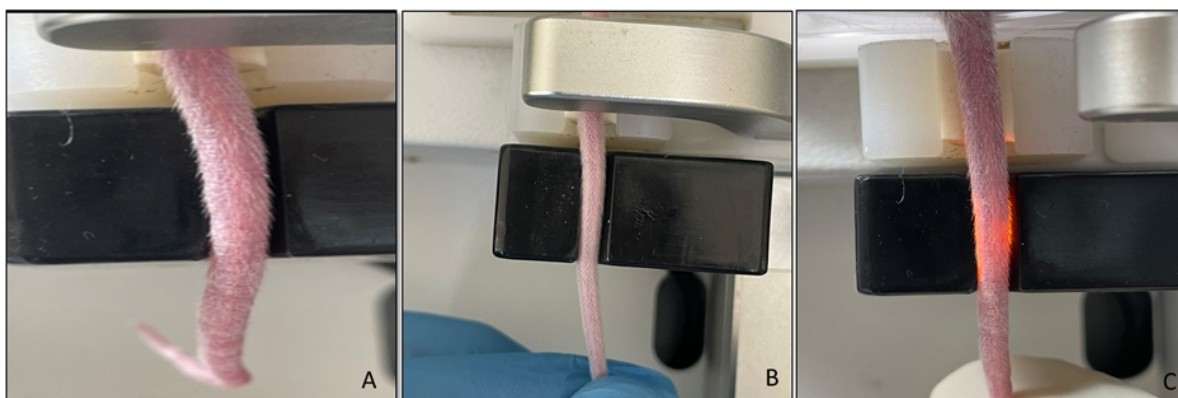


Fig.1: Intravenous administration of radiopharmaceuticals via mouse tail vein in preclinical testing: A. Tail vein in normal condition, B. After 30 minutes in a 37°C warming chamber, the tail vein showed improved visibility compared to normal conditions, C. The combined use of warming and a tail vein light illuminator improves vascular visibility in BALB/c mice.

handling, and environmental noise can trigger stress in mice and rats. This leads to increased aggression, fear-based freezing, and significant peripheral vasoconstriction, creating substantial challenges for successful, intravenous injections (Kim et al., 2019, Kiyatkin et al., 2021).

Radiotracers are frequently administered into the interstitium rather than accurate intravenously, negatively affecting preclinical research outcomes. The frequency and severity of these mistakes, even with experienced staff, are often underestimated, serving as a critical limiting factor for data quality in small rodent PET-CT imaging studies (Groman et al., 2004). Radiopharmaceutical biodistribution and PET quantification in mice are significantly influenced by injection technique, leading to discrepancies in percent uptake values in mice (Vines et al., 2011).

Apart from this, the radioactivity handler person gets the unnecessary exposure when manipulating the tail vein for radiopharmaceutical injection in the animals (Vines, 2011).

To overcome such problems, animal handlers should receive comprehensive training in effective handling techniques to minimize stress and distress in animals. A proper way of handling animals reduces aggression and enhances their normal physiological state, which in turn helps ensure the accuracy of intravenous injections.

To prepare the tail for improved visibility and promote vasodilation, consideration can be made for using a heating lamp, warming chamber, immersing it in warm water, or utilizing a specialized platform with a heating element (Shimizu., 2004) (Fig.1, 2, 3 and 4).

While the tail vein is the conventional route for intravenous injections in small rodents, scientific literature recommends several alternative, highly accessible blood vessels to improve injection accuracy and success rates. These alternatives include the dorsal metatarsal vein of the hind limb, the saphenous vein, the external jugular vein, and the retro-orbital plexus (Wang et al., 2022).

To enhance the accuracy of nonclinical data in radiopharmaceutical studies and better mimic common human administration routes, appropriate intravenous injection techniques in small animals must be considered, even if these routes are not routinely employed in standard laboratory practices.

Selection of animal species

The selection of an appropriate animal model is a key factor defining research outcomes, with the optimal choice depending heavily on the study's specific objectives. Proper species selection based on the therapeutic or diagnostic

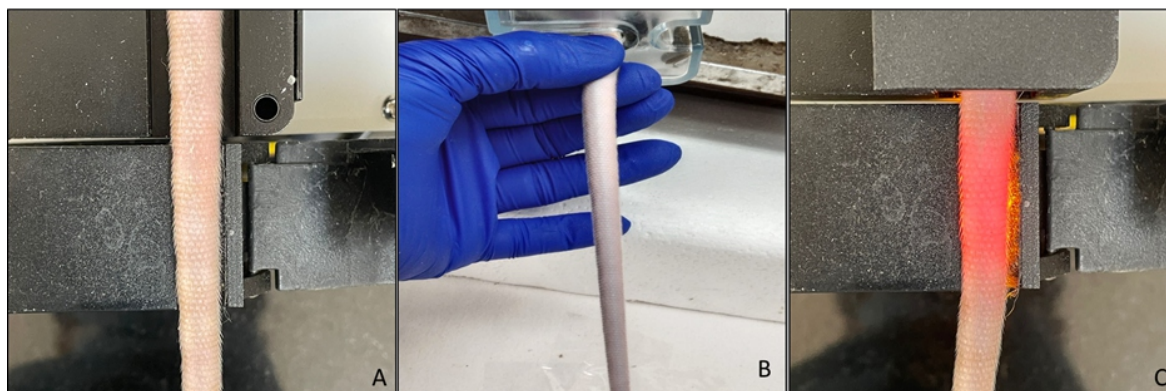


Fig.2: Intravenous administration of radiopharmaceuticals via Rat tail vein in preclinical testing: A. Rat tail vein in normal condition, B. After 30 minutes in a 37°C warming chamber, the tail vein showed improved visibility compared to normal conditions, C. The combined use of warming and a tail vein light illuminator improves vascular visibility in wistar rat.

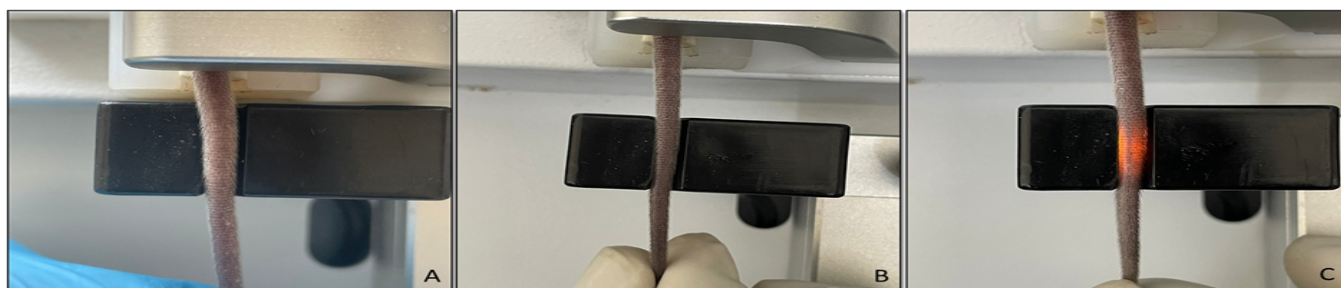


Fig.3: Intravenous administration of radiopharmaceuticals via C57Bl/6 mice tail vein in preclinical testing: A. Black mice tail vein in normal condition, B. After 30 minutes in a 37°C warming chamber, the tail vein showed improved visibility compared to normal conditions, C. The combined use of warming and a tail vein light illuminator improves vascular visibility in black mice.

application of radiopharmaceuticals is essential for enhancing the translation of animal data to humans (Alstrup et al., 2021, Fowler et al., 2001).

Animal species in nonclinical studies are chosen for their similarity to humans in anatomy, physiology, and metabolism specifically, “Absorption, Distribution, Metabolism, and Excretion” (ADME). This selection ensures that cross-reactivity and pharmacological responses are relevant for human clinical application (Namdari et al., 2022, Mizuo et al., 2023).

Generally, mice and rats are the most commonly used animal models for radiopharmaceutical studies, often requiring a large number of animals to be sacrificed to generate biodistribution data for each time point. Beyond these two, other species are also being explored for testing the same radiopharmaceuticals and for various other studies (Alstrup et al., 2021, Lambrecht, 2012, Kuntner et al., 2011, Maitz et al., 2024), (Fig.5).

The primary objective in radiopharmaceutical studies is to ensure human safety by providing safe administration, preventing systemic reactions, identifying target and non-target organs, and determining retention and excretion times. There are no clear, universal guidelines for species selection in nonclinical safety assessments. The Japanese guidelines recommend that non-clinical regulatory toxicology studies be conducted in two species (one rodent and one non-rodent) with proper justification. (Stonerook, 2015., Namdari et al., 2022). However, the IAEA guideline (2023) suggested

radiopharmaceutical evaluation in both sexes in a single animal species is sufficient, unless the planned indication is gender-specific.

General toxicology typically utilizes small rodents and non-rodent species, however, these models are often restricted in dynamic scanning applications due to limited blood volume, rapid induction of hypothermia, smaller body size and poor tolerance to anesthesia (Krinke., 2000). Comparing multiple tracers in a single animal is difficult, necessitating the use of more rodent animals across different groups. Unfortunately, this conflicts with the 3Rs, the reduction replacement and refinement principle. Additionally, the limited spatial resolution of PET and SPECT scanners, relative to the small anatomy of mice and rats, challenges the recognition of detailed anatomical structures (Stadelmann et al., 2015). As per the IAEA, guideline 2021, Hematology, serum biochemistry test should also include along with biodistribution and dosimetry studies. Due to the limited blood volume in mice and rats, sufficient samples cannot be frequently obtained for the required tests to meet the guideline.

A non-rodent or larger animal models facilitate in-depth experimentation and the utilization of human clinical PET scanners. Due to their substantial body size and blood volume, these models are ideal for dynamic studies, with prolonged anesthesia facilitating longitudinal comparisons of multiple tracers in a single subject (Alstrup et al., 2009). As an intermediate-sized model, the rabbit offers a superior platform for radiopharmaceutical evaluation, providing clear visualization of major organ systems including the brain, heart, lungs, liver, kidneys, thyroid, and lymph nodes along with detailed skeletal mapping. Rabbits are a suitable translational model for nuclear imaging, as PET and SPECT data acquired with human-equivalent protocols show strong similarity to human results (Duranthon et al., 2012, Gebhardt et al., 2025, Shete et al., 2025).

Considering the current scenario, small rodents have multiple limitations and translating radiopharmaceutical data from animals to humans requires careful consideration and data obtained from rats and mice should be cautiously interpreted (IAEC, 2023).

To advance radiopharmaceutical evaluation, we must incorporate non-rodent models like rabbits, ferrets, and dogs. Rabbits are particularly advantageous, offering a superior balance of technical feasibility, manageable laboratory

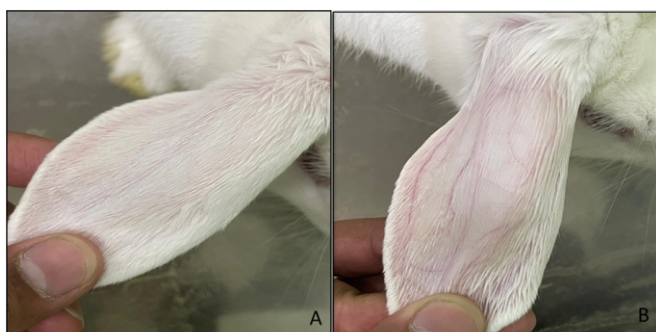


Fig.4: Intravenous administration of radiopharmaceuticals via New Zealand White Rabbit Ear vein in preclinical testing: A. Rabbit marginal and central ear vein easily seen in normal condition, B. Simple tap and alcohol rub for few minutes increase more clear visible ear vein in normal condition in Rabbit.

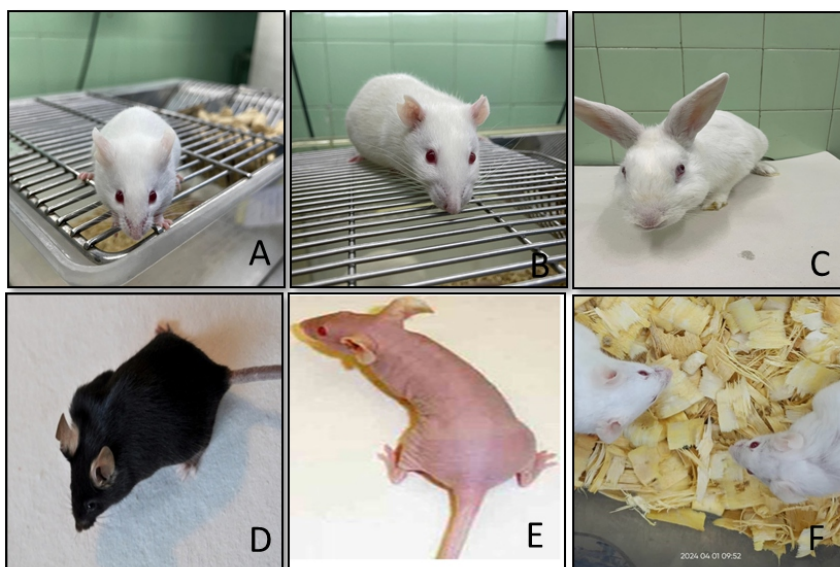


Fig.5: Different Animal Species Utilized for Radiopharmaceutical Development in non-clinical testing in Radiation Medicine centre Animal House Facility, Parel. A. BALB/c mice, B. Wistar Rats, C. New Zealand White Rabbit, D. C57Bl/6 mice, E. Nude mice, F. Severe Combined Immunodeficiency(SCID) mice.

housing, and straightforward experimental handling of radioactive agents. These large animal models bridge the gap between preclinical studies and human application by improving model accuracy. Compared to smaller rodents, rabbits provide superior experimental options, such as convenient auricular vein access for serial administration and blood sampling with reduced stress. Performance of different haematology and biochemistry tests per the international radiopharmaceutical guidelines, 2023. Their size and physiology also make them ideal for long-term, anesthetized imaging and simplified physical dosimetry studies. Additionally, the use of rabbits enables strict adherence to the ALARA principle for radioactivity handlers during radiopharmaceutical injection, imaging, dosimetry as well as meeting the 3Rs principle as per the (CCSEA, guideline, 2018, Shete et al., 2025).

Evaluation of system

To ensure ethical compliance and high-quality data, nonclinical testing of radiopharmaceuticals is shifting from traditional, terminal tissue analysis to advanced, non-invasive imaging modalities like micro-PET-CT and micro-SPECT-CT. These technologies allow for longitudinal in-vivo tracking within the same animal, reducing the total animal count while enhancing data accuracy. Adapting these methodologies is essential to refine the current procedures, minimize error and align with the highest standards of animal welfare (Klein et al., 2007) (Fig.6).

Dose

The required dose of radiopharmaceuticals varies based on several factors, including the study application, formulation, radioisotope half-life, and experimental duration. While human diagnostic dosages are strictly defined, there are no universally established guidelines for preclinical animal studies in India. Generally, intravenous injections for PET-CT or SPECT-CT

imaging in rats and mice range between 100-500 μ Ci (microcuries), though some studies report successful imaging with doses as low as 50 μ Ci, depending on the isotope, system sensitivity, and desired image quality. For rabbits, recommended activity ranges from 3–5 mCi for SPECT-CT and 1–2 mCi for PET-CT (Shete et al., 2024). When imaging rabbits, higher activity concentrations in smaller organs are preferred to improve visibility across extended time points for particular study.

Ethical Consideration and Dosimetry

Accurately predicting human radiation toxicity from small animal data is still difficult due to significant differences, such as faster metabolism and higher dose requirements in rodents. The situation is further complicated by the need for large animal numbers to accurately trace RP clearance. Given this scenario, an ideal experimental model must provide, in a single study, complete data on biodistribution, excretion, and detailed target and non-target organ kinetics. To improve ethical standards in preclinical studies, focusing on a few large animal models rather than hundreds of small rodents is preferred for studying biodistribution (Kiani et al., 2022, Shete et al., 2025).

Regulatory Approvals

Pre-clinical studies involving radioactivity in animals necessitate two key approvals in India, IAEC approval for animal experimentation (under CPCSEA) and, for radioactive material usage, licensure of laboratory premises by the AERB. Researchers must adhere to the ethical guidelines prescribed in the IAEC proposal, though it is important to note that no fixed dose limits for radioactive administration in animals are prescribed in any of the committees. Before granting approval, the IAEC must rigorously review the scientific justification, the criticality of using animal models, and the appropriateness of the chosen species.

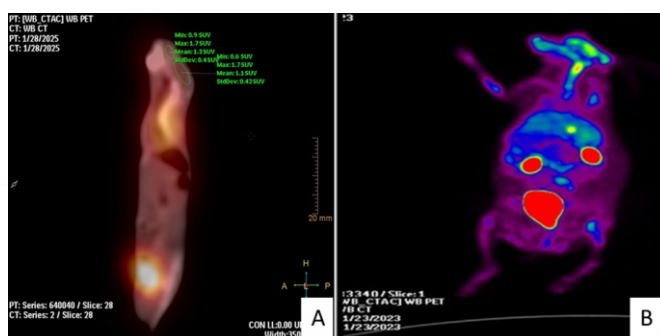


Fig.6: PET-CT Imaging in Mice and Rabbit with Fludeoxyglucose F18(18F-FDG) radiopharmaceutical comparative analysis: A. Although mice whole-body imaging showed specific uptake in the hot region, compartmental analysis was challenging to distinguish, B: Biodistribution imaging in the rabbit displayed high-intensity uptake in specific regions, enabling compartmental kinetic modeling across various tissues.

Radioactive waste handling and contamination control

Preclinical studies often generate significant amounts of solid and liquid radioactive waste. Following standard safety procedures, the 'delay and decay' method is an effective solution for managing contaminated surgical instruments, cotton plugs, absorbent sheets, and dissection materials. Generation of liquid waste should be strictly minimized or avoided. The second most important approach to radioactive waste management is confinement within designated areas. This will also ensure the restricted access and safe handling. Minimizing waste volume improves safety and operational efficiency. To ensure radioactive biomedical safety, the local Radiation Safety Officer must monitor all waste and disposal is authorized only upon approval, following standard procedures.

Conclusion

Preclinical animal data is a mandatory requirement by radiopharmaceutical regulatory authorities for approval of new radiopharmaceuticals, therefore, animal experiments have evolved as an essential part of the nonclinical study phase. However, adherence and commitment to the 3Rs principles (Replacement, Reduction, and Refinement) must be prioritized before its approval by the scientific community. Periodic revision of preclinical radiopharmaceutical guidelines is essential to adapt to new scientific developments. Preclinical studies must balance the pursuit of scientific goals with a rigorous commitment to animal welfare.

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6

तनु कोलॉइडी निलंबनों के प्रक्रमण हेतु स्वदेशी स्पर्श-रेखीय प्रवाह निस्यंदन प्रणाली का विकास

मीनू प्राशर और कुलवंत सिंह

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प्रयोगशाला-स्तर की स्पर्शरेखीय प्रवाह निस्यंदन (टीएफएफ) प्रणाली को भा.प.अ. केंद्र द्वारा स्व-विकसित किया गया

सारांश

कुशल अनुप्रवाह सांद्रण एवं तनु कोलॉइडी निलंबनों के शुद्धिकरण के लिए एक स्वदेशी, पूर्णतः स्वचालित स्पर्शरेखीय प्रवाह निस्यंदन (टीएफएफ) प्रणाली विकसित की गई। 0.1m² और पीएलसी/एचएमआई-आधारित स्वचालन के प्रभावी निस्यंदन क्षेत्र के साथ 10 kDa पॉलीइथरसल्फोन खोखला-तंतु झिल्ली मॉड्यूल से युक्त, प्लेटफॉर्म का उपयोग प्रयोगशाला संश्लेषित एल्युमिनोसिलिकेट नैनोपार्टिकल निलंबन के 4 L को संसाधित करने के लिए किया गया। 0.2 बार के ट्रांसमेम्ब्रेन दबाव पर, प्रणाली ने 500 mL तक आठ गुना आयतन की कमी हासिल की। 15 चक्रों में, बाद के डायफिल्ट्रेशन ने अवशिष्ट Na⁺ और Cl⁻ आयनों को हटा दिया, जैसा कि वास्तविक समय पारगम्य चालकता एवं एक्स-रे विवर्तन विश्लेषण में कमी से पुष्टि हुई है। ये परिणाम नैनो-पदार्थ प्रक्रम के लिए एक स्केलेबल और पर्यावरण के अनुकूल प्लेटफॉर्म को प्रदर्शित करते हैं।

6

Development of an Indigenous Tangential Flow Filtration System for the Processing of Dilute Colloidal Suspensions

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Indigenously developed laboratory scale TFF system

ABSTRACT

An indigenous, fully automated tangential flow filtration (TFF) system was developed for the efficient downstream concentration and purification of dilute colloidal suspensions. Equipped with a 10 kDa polyethersulfone hollow-fibre membrane module with an effective filtration area of 0.1m² and PLC/HMI-based automation, the platform was used to process 4L of a laboratory synthesized aluminosilicate nanoparticle suspension. At a transmembrane pressure of 0.2 bar, the system achieved an eight fold volume reduction to 500mL. Subsequent diafiltration over 15 cycles removed residual Na⁺ and Cl⁻ ions, as confirmed by the decrease in real-time permeate conductivity and X-ray diffraction analysis. These results demonstrate a scalable and eco-friendly platform for nanomaterial processing.

KEYWORDS: Tangential flow filtration, Colloidal suspension, Hollow-fibre

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Introduction

Advanced inorganic nanomaterials play an increasingly important role in clean energy, environmental remediation, catalysis, and biomedical technologies [1–3]. Many of these materials are synthesized as dilute colloidal suspensions, making efficient concentration and purification essential for obtaining high-quality products and enabling their large-scale utilization. To address this technological challenge, we designed an indigenous Tangential Flow Filtration (TFF) system for the fully automated post-synthesis processing of dilute colloidal suspensions. The integrated platform combines concentration and constant-volume diafiltration with automated process monitoring and control, providing an efficient and scalable processing.

Unlike conventional purification techniques such as sedimentation, dead-end filtration, and dialysis, TFF employs continuous tangential flow across the membrane surface, minimizing membrane fouling while enabling rapid removal of dissolved impurities and concentration of the product. TFF is well established in biopharmaceutical processing [4,5] and protein purification [6]. By extending it to advanced inorganic nanomaterials [7], the developed TFF setup provides a completely indigenous energy-efficient, eco-friendly, and resource-conserving separation strategy for dilute inorganic colloidal suspensions with high processing rates, reduced water consumption, and chemical-free operation, aligned with India's vision for sustainable materials development.

In this work, we demonstrate the performance of the indigenously designed, fully automated TFF system using a laboratory-synthesized colloidal suspension of aluminosilicate nanoparticles. The system achieved rapid volumetric concentration, effective removal of residual synthesis salts (Na^+ and Cl^-), and recovery of high-purity nanoparticles, demonstrating its potential as a scalable downstream processing for advanced nanomaterials.

Experimental Set-Up

An indigenous integrated Tangential Flow Filtration system was designed and commissioned for the concentration and purification of dilute colloidal suspensions. The major components of the set-up are:

● **Feed/Retentate Reservoir:** A 5L stainless-steel reservoir serves as the unified feed and retentate vessel for continuous suspension recirculation. It is directly mounted on a precision digital load cell (± 1 g resolution) to obtain real-time mass measurements and volumetric feedback during the concentration and diafiltration.

● **Recirculation & Buffer Pumps:** The suspension is circulated through the main feed line using a variable-speed peristaltic pump fitted with low-shear silicone tubing. A secondary peristaltic pump is also integrated into the fluid circuit to add buffer to the retentate vessel during diafiltration cycles.

● **Membrane Module:** The membrane-based separation is achieved using a polyethersulfone (PES) hollow-fibre membrane module with a molecular-weight cut-off (MWCO) of 10 kDa. The module has a total effective filtration area of 0.1m².

● **Pressure Control & Temperature Monitoring:** The operating transmembrane pressure (TMP) is regulated using a stainless-steel needle backpressure valve installed downstream of the retentate outlet. The permeate line is kept completely open ($P_{\text{permeate}} = 0$ bar) to allow atmospheric discharge during filtration. An inline temperature indicator is installed on the retentate return line to monitor fluid heating during continuous recirculation.

● **Pressure Transducers:** Digital piezoresistive pressure sensors are positioned at the feed inlet (P_{Feed}) and retentate outlet ($P_{\text{Retentate}}$) to continuously monitor hydraulic pressure and calculate TMP according to the equation below:

$$\text{TMP} = \frac{(P_{\text{Feed}} + P_{\text{Retentate}})}{2} - P_{\text{permeate}} \dots\dots\dots(1)$$

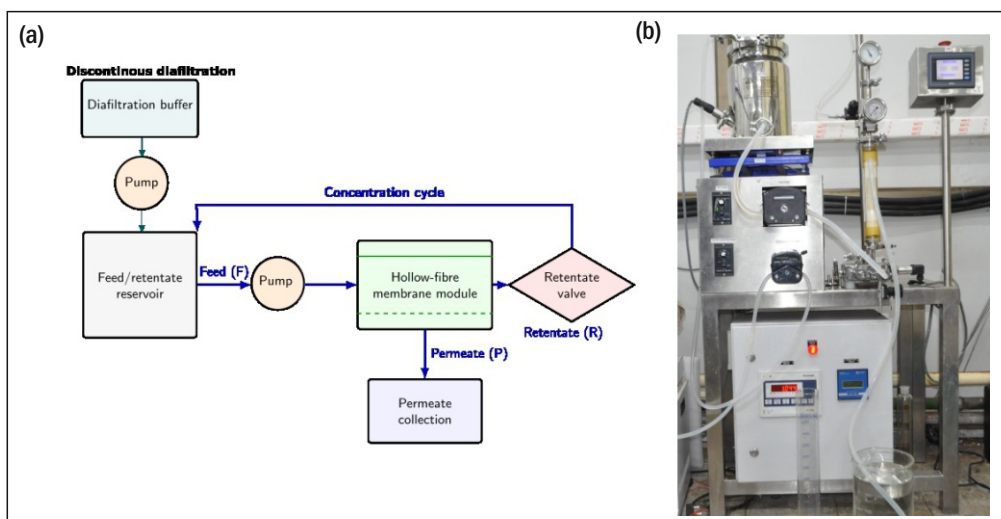


Fig.1: (a) Process-flow schematic of the TFF system showing the feed/retentate reservoir, recirculation pump, hollow-fibre membrane module, retentate cycle, permeate collection, and buffer addition for diafiltration, (b) Photograph of the indigenously developed laboratory scale TFF system with its feed/retentate reservoir, pumps, membrane module, pressure monitoring instruments, and HMI-based control panel.

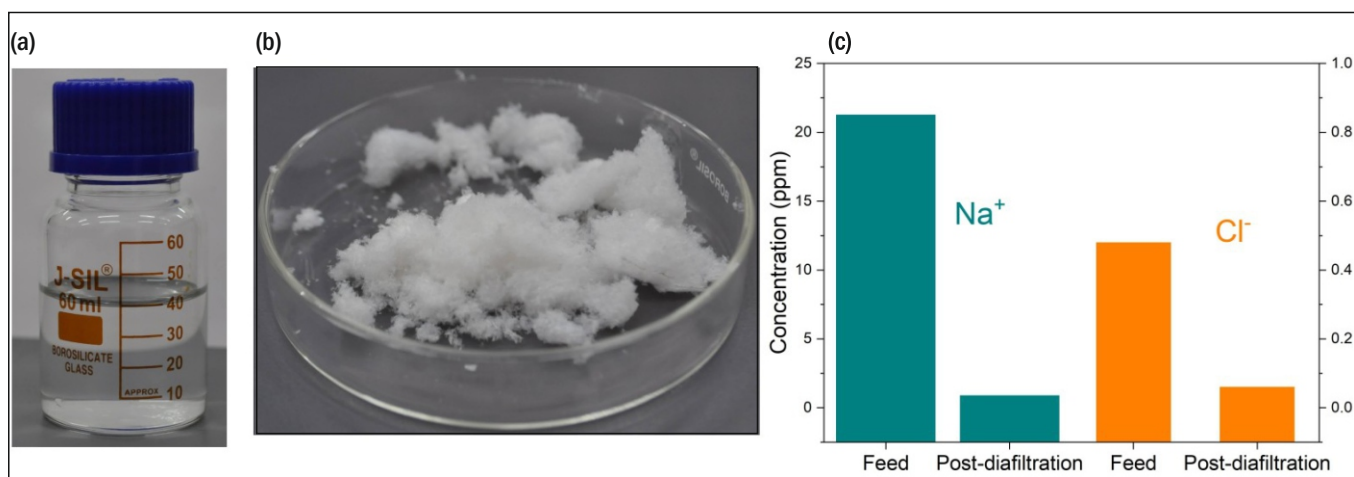


Fig.2: (a) As-synthesized aluminosilicate colloidal suspension (b) white, fluffy powder obtained after freeze-drying the diafiltered suspension. (c) Concentrations of residual Na⁺ and Cl⁻ in the initial feed and the post-diafiltration retentate, demonstrating substantial removal of soluble ionic impurities.

●**Inline Analytical Probes:** A conductivity cell is inserted directly into the feed tank to continuously track ionic strength and impurity washout in real time.

●**HMI/PLC Control System:** A programmable logic controller (PLC) interfaced with a touch screen human-machine interface (HMI) automates recirculation pump control, discontinuous diafiltration buffer addition, conductivity monitoring, and high-pressure safety alarm.

Fig.1(a) depicts the schematic flow paths and operating modes of our TFF assembly, while Fig.1(b) shows the actual system equipped with a 10 kDa hollow-fibre membrane module. During concentration, the feed pump circulates colloidal suspension from the feed/retentate reservoir and delivers it through the feed line (F) to the membrane module. At a given transmembrane pressure (TMP), the solvent and low-molecular-weight impurities are forced through the membrane pores into the permeate (P) stream, while the retained nanoparticles pass through the retentate (R) line and recirculated to the reservoir. In the set-up, diafiltration is

operated in a discontinuous mode. During the diafiltration (purification) stage, buffer pump adds a volume of fresh buffer equal to the retentate volume (V), to make total volume 2V. The feed pump then concentrates the volume to remove permeate until the suspension returned to its baseline volume V, thereby completing one diafiltration cycle (1 DV). This sequence is repeated in an auto mode for N cycles, till the desired purification level is achieved.

Experimental Results

To demonstrate the purification efficiency of the developed TFF system, an inorganic aluminosilicate colloidal suspension synthesized in laboratory and used as the model feed. The as-synthesized opalescent suspension (pH = 3.0), hereafter referred to as the Feed, (shown in Fig.2(a)), is a stable colloidal suspension with zeta potential of +42 mV. During TFF process, the feed volume of 4 L is first concentrated to 500 mL (volume concentration factor = 8) and then 15 discontinuous diafiltration cycles were performed at TMP = 0.2 bar. This concentrated and diafiltered retentate upon freeze-drying yields

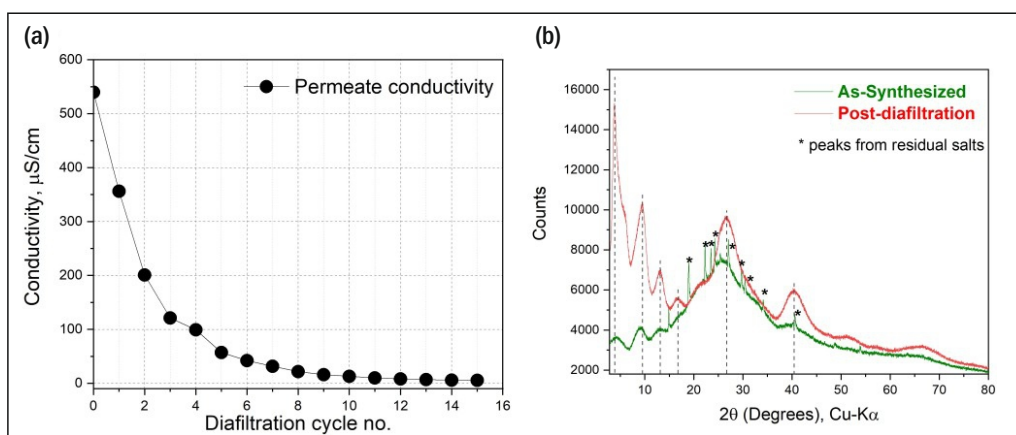


Fig.3: (a) Variation in permeate conductivity with diafiltration cycle number, showing the progressive removal of dissolved ionic species, (b) Powder XRD patterns of the as-synthesized and post-diafiltration retentate (powder samples obtained after freeze-drying the suspensions). The disappearance of sharp reflections associated with residual salt phases (indicated by asterisk (*)) in the post-diafiltered sample indicates high purity final product.

final white, fluffy, cotton-like material (Fig.2(b)), with mass concentration of nearly 1 gL^{-1} . Fig.2(c) compares the residual Na^+ and Cl^- concentrations in the initial feed and final retentate, demonstrating near-complete removal of these ionic species. As shown in Fig.3(a), the rapid decrease in the permeate conductivity up to first 8 diafiltration cycles and subsequent saturation, confirming the rapid removal of soluble ionic species. Fig.3(b) shows the comparison between the powder X-ray diffraction (XRD) patterns of freeze-dried samples obtained from the concentrated feed before diafiltration and from the final retentate after 15 diafiltration cycles. Disappearance of the sharp reflections associated with residual salt phases after diafiltration and enhanced broad reflections from the purified product validates the successful purification step.

Conclusion

An indigenous, fully automated Tangential Flow Filtration system was successfully designed, developed and commissioned for the scalable concentration and purification of dilute colloidal suspensions. During batch processing of an aluminosilicate nanoparticle suspension, the feed volume was successfully concentrated eightfold from 4 L to 500 mL, with near-complete removal of residual Na^+ and Cl^- ions over 15 diafiltration cycles. The PLC/HMI-based control system enabled precise, real-time monitoring of process hydraulics and impurity washout. Through this work, a robust and modular indigenous platform for the high-purity downstream processing of advanced functional nanomaterials at larger operational scales is established.

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युवतियों की थायरॉइड स्क्रीनिंग

सतत नाभिकीय चिकित्सा-आधारित कार्यक्रम का सार्वजनिक स्वास्थ्य प्रभाव

Thyroid Screening Among Young Women

Public Health Impact of a Sustained Nuclear Medicine-Led Program

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Thyroid disorders represent a major endocrine health concern in India, with hypothyroidism and subclinical hypothyroidism occurring more frequently than in many Western countries, emphasizing the need for early detection and preventive screening strategies among vulnerable populations such as young women. This study aimed to evaluate the feasibility and impact of thyroid screening camps conducted as part of a Nuclear Medicine outreach initiative for young adult females. Screening camps were organized at educational institutions and community centres involving participants aged 18–25 years. After informed consent, demographic details, clinical history, and symptoms suggestive of thyroid dysfunction were documented. Blood samples were collected for biochemical investigations including thyroid-

stimulating hormone (TSH), thyroxine (T4), anti-thyroid peroxidase antibodies (anti-TPO), vitamin D, vitamin B12, and other relevant parameters where applicable. Participants also received counseling regarding thyroid health, nutrition, lifestyle factors, and the importance of early diagnosis. Individuals with abnormal findings were referred for further medical evaluation and management. The initiative improved awareness regarding thyroid disorders and enabled identification of previously undetected thyroid dysfunction and associated biochemical abnormalities. Community-based thyroid screening programs may serve as an effective strategy for awareness generation, early diagnosis, referral, and future epidemiological and translational research activities.

Introduction

Thyroid disorders are among the most common endocrine diseases worldwide and represent a major public health concern in India. Epidemiological studies have reported a comparatively higher prevalence of hypothyroidism and subclinical hypothyroidism in the Indian population than in many Western countries. In India, the prevalence of hypothyroidism and subclinical hypothyroidism has been estimated to be approximately 10.95% and 8.02%, respectively, while lower prevalence rates have generally been reported in the United States and Europe [1,2]. Hyperthyroidism and subclinical hyperthyroidism, although less common, also contribute significantly to endocrine morbidity. The increasing burden of thyroid dysfunction in India highlights the need for greater awareness, early diagnosis, and community-based screening initiatives, particularly among vulnerable populations such as young women [1].

Young women between 18 and 25 years of age represent a particularly vulnerable group because this period is associated with important hormonal, metabolic, and reproductive transitions. In addition, nutritional deficiencies and limited healthcare accessibility continue to contribute to thyroid dysfunction in several rural and semi-urban regions of Maharashtra despite nationwide iodization programs. Many thyroid abnormalities during early adulthood remain undiagnosed because symptoms such as fatigue, weight fluctuations, menstrual irregularities, anxiety, hair loss, and poor concentration are often nonspecific and attributed to lifestyle-related stress [3].

The consequences of undetected thyroid dysfunction extend beyond individual health. Hypothyroidism and autoimmune thyroid disease may adversely affect fertility, pregnancy outcomes, fetal neurodevelopment, and long-term metabolic health. Early identification and timely intervention are therefore important not only for improving quality of life but also for safeguarding future maternal and child health [4].

Recognizing this public health need, the "Thyroid Disorders and Immunoassay Development" (TDID) Section at Radiation Medicine Centre (RMC) has initiated thyroid screening and awareness camps targeting young women in educational institutions and underserved communities. These outreach activities integrate the scientific strengths of nuclear medicine with preventive healthcare strategies, thereby transforming laboratory expertise into direct societal benefit [Fig.1].



Fig.1: Blood collection team during the "Thyroid Screening Camp".

Thyroid Disorders Among Young Women: A Growing Public Health Concern

Thyroid disorders disproportionately affect women, with studies from India reporting a significantly higher prevalence among females compared to males. Hypothyroidism, subclinical hypothyroidism, autoimmune thyroiditis, and iodine deficiency-related goiter are increasingly being detected in adolescents and young adults. Several Indian campus-based studies have reported thyroid dysfunction rates ranging from 7% to 13% among apparently healthy young women, indicating that a substantial proportion of cases remain clinically silent [5].

The vulnerability of young women arises from multiple interacting factors. Nutritional deficiencies such as inadequate iodine, iron, selenium, vitamin D, and vitamin B12 intake may impair thyroid hormone synthesis and metabolism. Hormonal fluctuations associated with puberty, menstrual cycles, and reproductive maturation further influence thyroid physiology. In rural settings, poor awareness regarding thyroid symptoms, delayed healthcare access, and financial constraints contribute to underdiagnosis [6].

Subclinical hypothyroidism deserves particular attention because affected individuals may appear healthy despite biochemical abnormalities. If left untreated, these conditions can gradually progress to overt hypothyroidism and contribute to obesity, dyslipidemia, menstrual disturbances, infertility, polycystic ovarian syndrome (PCOS), depression, and cardiovascular complications. Importantly, thyroid dysfunction during pregnancy is associated with miscarriage, preterm delivery, low birth weight, and impaired cognitive development in children [7].

These concerns highlight the urgent need for early screening programs specifically designed for young women before the onset of pregnancy and major reproductive complications.

Nuclear Medicine and the Role of Radioimmunoassay in Thyroid Diagnostics

Nuclear medicine has played a transformative role in thyroid disease diagnosis and management for several decades. Among its most significant contributions is the development of highly sensitive immunoassay techniques such as Radioimmunoassay (RIA) and Immunoradiometric Assay (IRMA), which enable precise quantification of thyroid hormones and related biomarkers [Fig.2].

The RIA Services of TDID Section at RMC routinely performs RIA and IRMA-based investigations for thyroid hormones, autoimmune markers and tumor marker including, thyroxine (T4), thyroid-stimulating hormone (TSH), free thyroxine (FT4), anti-thyroid peroxidase antibodies (anti-TPO) and thyroglobulin (Tg) [8, 9, 10, 11]. These assays are particularly valuable for detecting early and subclinical thyroid dysfunction, where hormone changes may be subtle and difficult to identify through conventional screening approaches.

RIA-based methodologies offer several advantages in resource-limited settings:

- *High analytical sensitivity and specificity*
- *Reliable detection of low hormone concentrations*

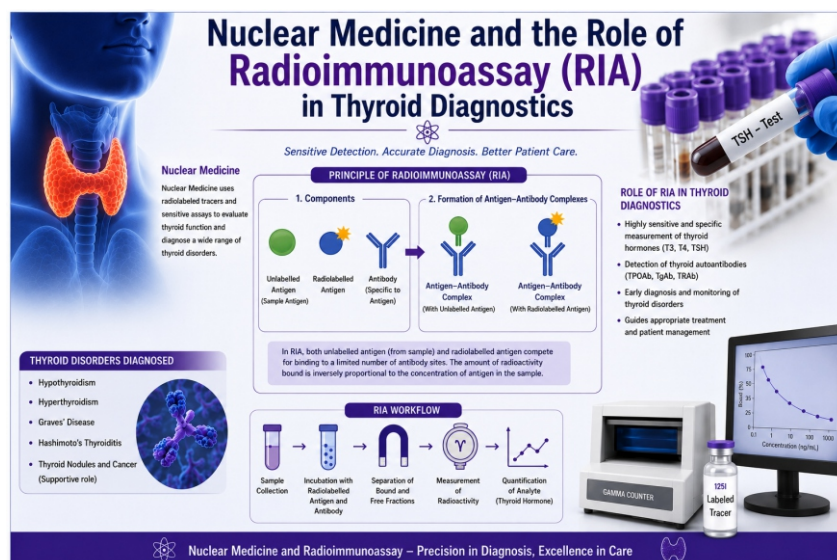


Fig.2: Role of radioimmunoassay in thyroid diagnostics.

- Cost-effective large-scale population screening
- Standardized performance for epidemiological studies
- Suitability for autoimmune thyroid disease assessment

The department has also contributed to indigenous kit development, reducing dependency on imported diagnostic systems while promoting self-reliance in nuclear medicine technology [10, 11]. Research activities within the laboratory include studies on thyroid autoimmunity, iodine metabolism, biomarker development, thyroid cancer monitoring, and genetic factors influencing thyroid disorders [12].

Collaborations with Academic Institutions

Through collaborations with academic institutions such as Department of Foods and Nutrition, The Maharaja Sayajirao University of Baroda, India [13, 14]; Department of Food Science and Nutrition, SNDT University, Mumbai [12], Guru Nanak College of Arts, Science & Commerce (Autonomous) and Guru Nanak Institute of Management Studies, Mumbai [Fig.3]; the department has extended its expertise beyond laboratory diagnostics into public health outreach and awareness generation. To date, we have successfully collected approximately 300 samples through



Fig.3a: College student volunteers providing blood samples during the "Thyroid Screening Camp"

these screening camps, with a target enrolment of nearly 1000 participants.

Design and Implementation of Thyroid Screening Camps

The thyroid screening initiative was conceptualized as a community-oriented preventive healthcare program aimed at identifying hidden thyroid dysfunction among young women. The outreach strategy combines biochemical screening, health education, nutritional awareness, and epidemiological research within a single integrated framework.

Target Population

The thyroid screening camp primarily focusses on asymptomatic young women without a prior diagnosis of thyroid disease or other major systemic disorders, aged 18–25 years, studying in colleges and universities, as well as young women residing in rural Maharashtra. This age group was selected because thyroid disorders during early adulthood often remain asymptomatic yet significantly influence future reproductive and metabolic health.

Screening Protocol

The core screening investigation includes serum TSH estimation using sensitive RIA-based assays. Individuals with abnormal TSH values, particularly those exceeding the predefined cutoff levels (>5.2 IU/mL), are advised further evaluation using:

- Free thyroxine (Ft4)
- Total T4
- Anti-TPO antibodies

To provide a more holistic health assessment, additional biochemical investigations may include:

- Vitamins: Vitamin B12, Vitamin B9 (Folate), Vitamin D
- Fertility hormones: Estradiol, FSH, LH, Progesterone, Prolactin
- Biochemical tests: Blood Glucose (HbA1C), Complete

बहु-आयामी नाभिकीय विज्ञान एवं प्रौद्योगिकी से जीवन समृद्ध बनाना ENRICHING LIVES WITH MULTI-DIMENSIONAL NUCLEAR S&T

Blood Count (CBC), Kidney Function Tests (KFT), Lipid Profile, Liver Function Tests (LFT), Serum Calcium.

This integrated approach helps identify metabolic and nutritional factors commonly associated with thyroid dysfunction.

Awareness and Educational Activities

Each camp incorporates educational sessions conducted by senior scientists, clinicians, and technical experts from RMC. These sessions typically include:

- Basic thyroid gland physiology
- Common symptoms of thyroid disorders
- Importance of iodine nutrition
- Lifestyle and dietary guidance
- Reproductive implications of thyroid dysfunction
- Role of nuclear medicine in diagnosis and monitoring

Such educational interventions help dispel myths associated with thyroid disorders and encourage timely medical consultation.

Ethical and Research Components

All screening activities are conducted in accordance with Institutional Ethics Committee guidelines following appropriate informed consent procedures. Participants identified with abnormal clinical or biochemical findings are referred for further medical evaluation and management. Blood samples collected during the screening camps may also be preserved for future research studies investigating genetic polymorphisms and molecular biomarkers associated with thyroid disorders. These may include analysis of deiodinase gene variants, particularly DIO2 Thr92Ala polymorphisms, which are involved in the peripheral conversion of thyroxine (T4) to the biologically active hormone triiodothyronine (T3). Alterations in DIO2 Thr92Ala activity have been implicated in thyroid hormone homeostasis, susceptibility to

hypothyroidism, metabolic dysfunction, impaired response to levothyroxine therapy, and inter-individual variability in thyroid hormone metabolism [15].

Societal Impact of Nuclear Medicine Outreach

The thyroid screening initiative demonstrates how nuclear medicine can directly contribute to preventive healthcare and community welfare. Traditionally perceived as a highly specialized hospital-based discipline, nuclear medicine is increasingly expanding its role into public health, awareness generation, and early disease detection.

Early Diagnosis and Prevention

One of the most significant impacts of the program is the identification of asymptomatic and subclinical thyroid disorders before the development of major complications. Early diagnosis allows timely initiation of treatment and lifestyle modifications, thereby preventing long-term endocrine and reproductive consequences.

Empowerment Through Awareness

The educational component of the camps empowers young women to recognize symptoms, seek medical advice, and understand the importance of nutritional health. Increased awareness also helps reduce stigma and misconceptions surrounding hormonal disorders and reproductive health issues.

Strengthening Public Health Data

The screening initiative provides valuable epidemiological data on thyroid disorders, nutritional deficiencies, and autoimmune markers among young Indian women aged 18–25 years. Such data are important for understanding regional disease patterns, identifying vulnerable populations, and estimating the burden of undiagnosed thyroid dysfunction in the community. The findings may support the development of targeted screening strategies, improve healthcare resource allocation, guide preventive health programs, and contribute to evidence-based public health policies aimed at improving long-term endocrine and reproductive health outcomes.

Promoting Indigenous Diagnostic Capability

The use of indigenous technologies (RIA/IRMA) developed within the department highlights the importance of self-reliance in medical diagnostics. Affordable, locally developed assays enable large-scale screening while reducing dependence on imported technologies, thereby aligning with national healthcare and scientific development goals.

Bridging Laboratory Science and Community Healthcare

The program exemplifies translational healthcare, where advanced laboratory technologies are directly utilized for societal benefit. By extending diagnostic expertise into educational institutions and rural communities, the department has successfully bridged the gap between scientific research and real-world healthcare needs.

Integrating Thyroid Screening with Broader Women's Health

An important strength of the initiative is its multidisciplinary and holistic approach. Thyroid dysfunction



Fig.3b: College student volunteers providing blood samples during the "Thyroid Screening Camp"

बहु-आयामी नाभिकीय विज्ञान एवं प्रौद्योगिकी से जीवन समृद्ध बनाना ENRICHING LIVES WITH MULTI-DIMENSIONAL NUCLEAR S&T



Fig.3c: College student volunteers providing blood samples during the "Thyroid Screening Camp"

rarely exists in isolation and is often associated with nutritional, metabolic, and reproductive abnormalities. Therefore, the camps incorporate broader health assessments to provide comprehensive preventive care.

Nutritional Deficiencies and Thyroid Function

Deficiencies of iron, selenium, vitamin D, and vitamin B12 are increasingly recognized as contributors to thyroid dysfunction and autoimmune thyroiditis. Assessing these parameters alongside thyroid hormone levels allows better understanding of disease patterns and facilitates targeted nutritional counseling.

Reproductive and Metabolic Health

Thyroid disorders significantly affect menstrual regularity, ovulation, fertility, and pregnancy outcomes. By integrating reproductive hormone evaluation and metabolic profiling, the camps help identify young women at risk for PCOS, infertility, obesity, and metabolic syndrome.

Mental and Academic Well-being

Undiagnosed hypothyroidism may contribute to fatigue, impaired concentration, mood disturbances, and reduced academic performance among students. Early identification and treatment may therefore positively influence psychological well-being and educational productivity.

Operational Challenges and Future Opportunities

Despite its promising outcomes, large-scale thyroid screening in rural and semi-urban regions presents several logistical and social challenges:

- Limited healthcare infrastructure in remote areas
- Transportation and sample handling difficulties
- Inadequate public awareness regarding thyroid disorders
- Fear and stigma associated with hormonal diseases
- Financial and manpower constraints for repeated outreach programs

However, the department's infrastructure, including gamma counters, trained technical personnel, and

established immunoassay laboratories, enables efficient processing of large sample volumes. Mobile outreach models and collaborations with colleges, public health centers, and community organizations further strengthen implementation capacity.

Future Directions

The department aims to significantly expand the screening initiative over the coming years through:

- Collaboration with primary healthcare centers
- World Thyroid Day awareness campaigns
- Integration with women's health programs
- Development of regional thyroid health databases
- Genetic and molecular epidemiological studies

By 2027, the initiative aims to screen about 1000 young women while generating valuable data to guide future preventive strategies and policy recommendations.

Conclusion

The thyroid screening and awareness initiative undertaken by RMC represents an important example of how nuclear medicine can extend beyond hospital-based diagnostics into meaningful community healthcare outreach. Through the application of sensitive RIA and IRMA technologies, preventive screening strategies, and educational programs, the initiative addresses a significant yet often underrecognized health concern among young women.

The program has demonstrated the feasibility and effectiveness of conducting community-based endocrine health screening, facilitating the early identification of previously undiagnosed thyroid dysfunction and associated biochemical abnormalities while simultaneously improving awareness regarding thyroid health, nutrition, reproductive well-being, and preventive healthcare practices.

The encouraging participation observed during the screening camps reflects the growing acceptance and need for such outreach initiatives. Furthermore, the integration of indigenous diagnostic technologies with epidemiological and translational research provides valuable opportunities for future investigations involving molecular biomarkers and genetic susceptibility factors associated with thyroid disorders. By transforming scientific expertise into accessible healthcare services, the initiative contributes toward healthier future generations, improved maternal and child health, and greater public awareness of endocrine disorders. Overall, this outreach effort highlights the peaceful and humanitarian applications of nuclear science and its significant potential to improve public health and community well-being.

Acknowledgement

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नाभिकीय चिकित्सा में रिसेप्टर-लक्षित थैरेनोस्टिक्स: वर्तमान स्थिति एवं संभावित भावी नैदानिक अनुप्रयोग

Receptor Targeted Theranostics in Nuclear Medicine: Current Status & Potential Future Clinical Applications

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Modern health care is moving towards precision through significant development of theranostic radiopharmaceuticals for cancer diagnosis and therapy. Nuclear medicine stands out distinctly due to its ability to provide precise functional and physiological details regarding a disease like cancer. This significant benchmark is not possible without the substantial contribution of nuclear sciences. It is a field where the gift of nuclear technology is translated into medical tools for imaging and targeted treatment at the molecular level. At the Radiation Medicine Centre, BARC, an amalgamation of basic nuclear sciences and clinical nuclear medicine, is enabling precision cancer care with the help of receptor-targeted radiopharmaceuticals (Fig.1).

Diseased cells, especially cancer cells, overexpress receptors that can act as molecular targets. The receptor-targeted radiopharmaceuticals are specifically designed for binding to these selective targets at the molecular level. The highly sensitive molecular imaging, like PET/CT and SPECT/CT, can be performed when these targeting molecules are labeled with suitable radioisotopes like [a] Gallium-68 (⁶⁸Ga) & Fluorine-18 (¹⁸F) for PET, and [b] Technetium-99m (^{99m}Tc) & Indium-111 (¹¹¹In) for SPECT. Additionally, same molecular target when radiolabelled with radionuclide like Lutetium-177 (¹⁷⁷Lu) (beta emitter) & Actinium-225 (²²⁵Ac) (Alpha emitter) can deliver therapeutic effect to tumor sites. This approach of clinical diagnosis, treatment, and monitoring of diseases using related radio pharmaceuticals enables personalized patient management and is popularly known as theranostics (Fig.2).

Somatostatin Receptor Radionuclide Therapy (PRRT) for the Treatment of Neuroendocrine Tumors

Peptide receptor radionuclide therapy (PRRT) for the treatment of neuroendocrine tumors (NET) is one of the significant benchmarks in receptor targeted theranostics. In this strategy, the somatostatin receptor expression can be visualized through PET/SPECT by radiolabeling somatostatin analog peptide, and this information can be used to plan targeted therapy using therapeutic radionuclides like Lutetium-177 (beta emitter), Actinium-225 (Alpha emitter).

PRRT delivers radiation selectively to tumor cells, thereby minimizing exposure to the surrounding healthy cells. The radionuclide selection can be done according to the tumor size, and disease status.

A large number of patients with advanced or metastatic neuroendocrine tumors have significantly benefitted from PRRT at the Radiation Medicine Centre (RMC), utilizing both indigenous and imported ¹⁷⁷Lu and ²²⁵Ac. More than 10,000 successful PRRTs have been administered at the Centre over last 16 years and is committed to serving many more in the future (Fig.3).

PSMA targeted Radioligand Therapy (PRLT) in Metastatic Castrate Resistant Prostate Cancer

PRRT paved the path for prostate-specific membrane antigen (PSMA)-targeted theranostics, which improved prostate cancer management at the RMC significantly. The prostate specific membrane antigen (PSMA) is overexpressed in prostate cancer. Radiopharmaceutical targeting PSMA enables PET imaging for the spread of disease and targeted therapy for advanced metastatic prostate cancer patient (Fig.4).



Fig.1: Translation of Nuclear science & technology to Clinical Nuclear Medicine showing the pathway from radioisotope production to patient care.

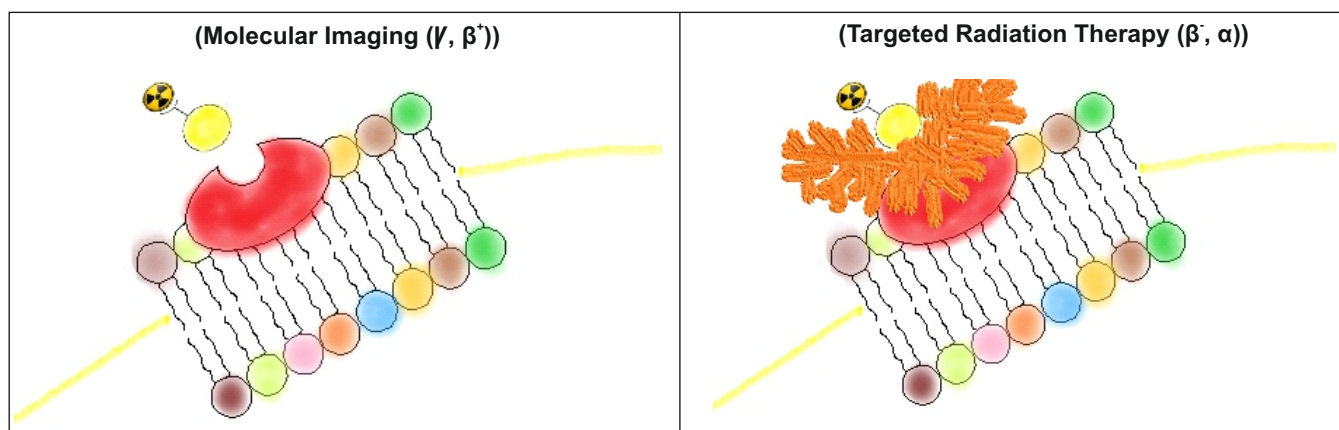


Fig.2: Diagrammatic representation of principle of receptor-targeted theranostics illustrating molecular targeting with radiolabelled ligands for imaging and therapy.

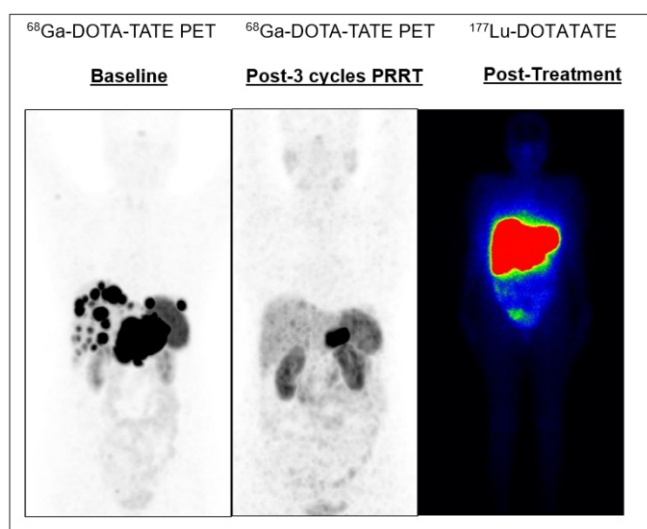


Fig.3: Somatostatin receptor based ^{68}Ga -DOTA-TATE PET and targeted PRRT in a patient of metastatic neuroendocrine tumor showing excellent response to PRRT. The ^{177}Lu -DOTATATE post-treatment planar gamma camera image (right column) showing intense uptake of therapeutic dose in tumour tissue.

FAPI-targeted Radioligand Therapy

Currently, fibroblast activation protein inhibitors (FAPI) based radio pharmaceuticals are proving to be promising agents targeting cancer-associated fibroblasts in the tumor microenvironment. FAPI-based radiopharmaceuticals represent an expanding frontier in nuclear medicine theranostics by targeting a wide range of tumor type (Fig.5).

Image-based Dosimetry in Nuclear Medicine Theranostics

Advanced imaging systems and quantitative techniques that support diagnosis and therapy planning are strong pillars of modern nuclear medicine. They play a crucial role in molecular imaging and therapy undertaken by the state-of-art imaging facility such as PET/CT and SPECT/CT with receptors targeted radiopharmaceuticals.

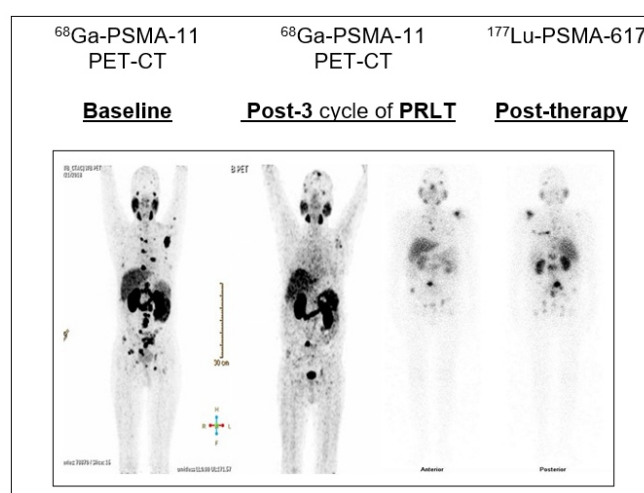


Fig.4: PSMA PET imaging demonstrating metastatic prostate cancer, enabling targeted radionuclide therapy with ^{177}Lu -PSMA-617 and showing excellent treatment response in a patient of Metastatic Castrate Resistant Prostate Carcinoma.

In addition to the sensitive detection of disease with radiopharmaceutical distribution and post-radionuclide therapy evaluation, the personalized treatment planning with improved safety and effectiveness of the radionuclide therapy is achieved by dosimetric studies. Dosimetry enables radiation dose estimation to the tumor lesions and normal organs (Fig.6).

A true interdisciplinary effort has led to the development and clinical translation of receptor-targeted theranostics. Multiple diverse domains of nuclear sciences and biomedical research have contributed to this success, beginning with the production of medical radioisotopes using nuclear technology, and the design of receptor-targeted molecules is achieved by advanced molecular labeling and radiopharmaceutical chemistry. Once designed, they are synthesized and subsequently labeled in specialized hospital radiopharmacy. The clinical translation of these radiopharmaceuticals is done through molecular imaging and targeted radionuclide therapy

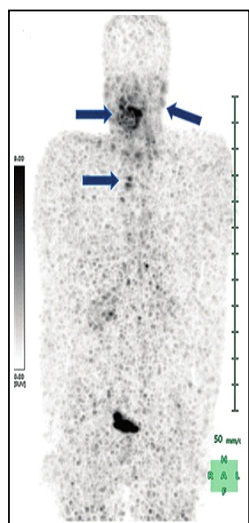


Fig.5: ^{68}Ga -FAPI-4 PET imaging showing uptake by the cancer-associated fibroblasts within the tumor microenvironment.



Fig.6: Image Based Dosimetry for dose estimation of patient treated with ^{177}Lu -FAPI- 2286.

in Nuclear Medicine. The Radiation Medicine Centre stands out uniquely by integrating nuclear physics, chemistry, biology, and clinical medicine, and thereby contributing to advancing precision health care.

The Radiation Medicine Centre, with its pioneering and high-volume extensive clinical and theranostic services to patients with neuroendocrine tumors and prostate cancer by means of PRRT and PSMA-based PRLT respectively, continuously strives to contribute significantly to the development of receptor based National level Theranostics in Nuclear medicine. Exploring emerging tracers such as FAPI is an advanced step towards this end. Such efforts significantly improve the quality of life of many cancer patients of the country.

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एआईई संवेदक का उपयोग करते हुए ट्रेस थोरियम (IV) हेतु सरल क्यूवेट-आधारित प्रतिदीप्ति विवरण

थोरियम के लिए जल-विलेय प्रतिदीप्ति संवेदक

Simple Cuvette-Based Fluorescence Readout for Trace Thorium(IV) Using an AIE Sensor

Water-Soluble Fluorescence Sensor for Thorium

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Thorium (Th) is a naturally occurring element of strategic relevance to India's nuclear energy programme, therefore, accurate Th(IV) detection in water underpins radiation surveillance, environmental stewardship, public health assurance, and the safe, sustainable utilisation of thorium within the Department of Atomic Energy's initiatives. While techniques such as ICP-MS provide excellent sensitivity, they are infrastructure-intensive and less suited to rapid, on-site screening.

In our newly published study, we report a dicarboxylated tetraphenylethylene probe (TPE-DCA) that enables selective, "turn-on" detection of Th⁴⁺ directly in 100% water via aggregation-induced emission (AIE). TPE-DCA is weakly emissive when molecularly dispersed. Upon Th⁴⁺ coordination to its carboxylate groups, charge neutralization and coordination-driven cross-linking trigger aggregation, restrict intramolecular motion, and switch the fluorescence "on". This produces an ≈ 180 -fold emission enhancement at 490 nm. The sensor operates near neutral pH (≈ 5 –6) and achieves a detection limit of 11 nM (≈ 3 ppb), well below the WHO guideline value for drinking water (245 ppb).

The probe shows negligible interference from competing ions, including lanthanides and uranium, and performs robustly in tap water, lake water, and undiluted seawater. Mechanistic validation using steady-state and time-resolved fluorescence, UV-vis absorption, FTIR, dynamic light scattering, SEM-EDS, and DFT calculations confirms Th-carboxylate coordination and nanoscale aggregate formation. Overall, this water-only AIE platform provides a simple, field-relevant strategy for routine thorium monitoring and a transferable design principle for actinide sensing in complex aqueous matrices. Because the response is a clean fluorescence turn-on in a cuvette-friendly format, it is readily compatible with compact fluorimeters or mini-spectrometers for on-site screening.

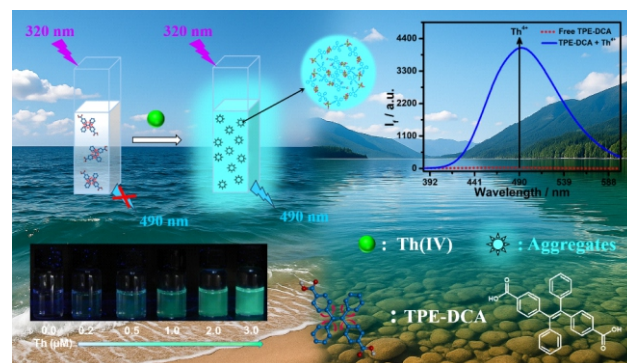


Figure: Schematic representation of Th(IV)-induced aggregation of TPE-DCA and the molecular structure of TPE-DCA (Small, 2025, DOI: 10.1002/smll.202508399).

Reference:

M. Ghosh, S. S. Kadlag, K. K. Swain, A. Ghosh, A. K. Sahu, P. K. Singh*, "Bright and Selective: A Dicarboxylate-Functionalized AIE Sensor for Th⁴⁺ in 100% Water with a Sub-ppm Level Sensitivity", Small (2025), DOI: 10.1002/smll.202508399.

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Research Highlights

10 मि.मी. की दूरी पर गैर-संपर्क जीवाणु निष्क्रियता की जांच प्लाज़्मा औषधी के लिए एक स्वदेशी शीत प्लाज़्मा उपकरण का उपयोग करके Investigation of Non-Contact Bacterial Inactivation at 10 mm Distance

Using an Indigenous Cold Plasma Device for Plasma Medicine

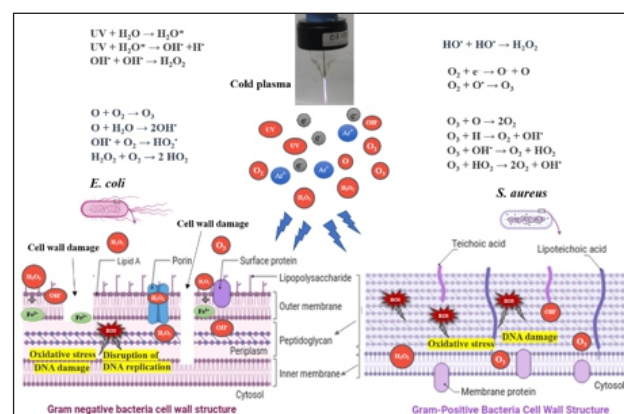
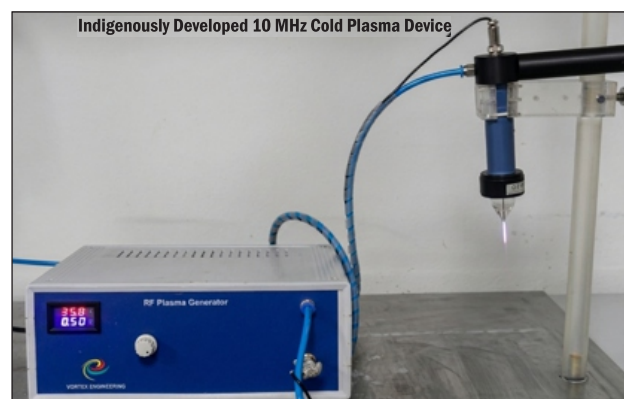
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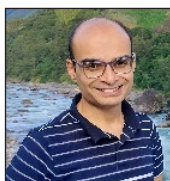
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Cold atmospheric pressure plasma (CAPP) is a promising antimicrobial technology, though its bactericidal mechanisms are not yet fully understood. An indigenous Tesla coil-based CAPP device was developed from first principles and evaluated against Gram-positive *Staphylococcus aureus* (*S. aureus*) and Gram-negative *Escherichia coli* (*E. coli*) using Ar, Ar-O₂, Ar-N₂, and Ar-dry air (3:1) gas compositions at a 10 mm treatment distance. Optical emission spectroscopy identified key bactericidal species including OH (~309 nm), N SPS (~337 nm), and OI (~777.4 nm), while electron microscopy confirmed plasma-induced cellular damage. Spectroscopic analysis quantified H₂O₂, OH radicals, UV radiation, and O₃. This work is recently published results (Vacuum 239 (2025) 114393) showed that pure Ar plasma, possessing the highest electron temperature and density, generated maximum H₂O₂ and UV radiation, achieving complete inactivation of both bacterial strains at 10 mm distance. The study further revealed greater resistance of *E. coli* due to its protective outer membrane, while H₂O₂ was found to play a crucial role in bacterial inactivation through oxidative stress and intracellular OH generation via the Fenton reaction. Efficient non-contact sterilization at 10 mm highlights its strong potential for remote sterilization and biomedical applications, enabling treatment without thermal or electrical discomfort while offering significant advantages for maintaining sterile environments in healthcare and industry.



About the author...



Dr. Rajib Kar is a Scientific Officer-G at the Laser & Plasma Technology Division, Bhabha Atomic Research Centre (BARC). His research focuses on non-thermal plasma applications, diagnostics, and development of novel atmospheric pressure plasma systems. His areas of interest include plasma medicine, plasma synthesis of carbon nanostructures, cold plasma-based decontamination, and plasma diagnostics using electrical probes and spectroscopy. He has published 93 research papers in reputed international journals and conferences, contributed book chapters for Elsevier, Springer, and BARC-SIRD publications, and serves as a reviewer for several international journals. His work has also led to technology transfer of a Cold Plasma Sterilization Device and the Indigenous Cold Atmospheric Pressure Plasma System: 10 MHz (ICAPPS-10) for scientific and industrial applications.



India Assumes Chairmanship for 2026

Dr. Tirumalesh Keesari and SIRD Editorial Team

India assumed the Chairmanship of the International Atomic Energy Agency's (IAEA) Regional Cooperative Agreement (RCA) for 2026, reaffirming its longstanding commitment to strengthening regional cooperation in the peaceful applications of nuclear science and technology. The Chairmanship was formally handed over by the outgoing Chair, Fiji, during the 48th Meeting of National Representatives (NRM) of the IAEA-RCA Programme, hosted by the Department of Atomic Energy (DAE), Government of India, in Navi Mumbai from May 19-22, 2026.

The meeting brought together National Representatives, scientists, technical experts, and officials from all 22 RCA Member States across the Asia-Pacific region. In a first-of-its-kind move, representatives from the African Regional Cooperative Agreement (AFRA) and the Forum for Nuclear Cooperation in Asia (FNCA) also participated, providing an important platform for wider scientific dialogue and enhanced inter-regional collaboration. Discussions focused on current and future RCA initiatives in healthcare, nuclear agriculture and food technology, water resource management, radiation technologies, environmental sustainability, and human resource development.

Addressing the inaugural session, Mr. Vivek Bhasin, Director, Bhabha Atomic Research Centre, highlighted India's achievements in applying nuclear science and technology for societal and industrial development, particularly in healthcare, agriculture, radiation processing, water management, and environmental protection. Mr. Rajeev Keswani, Head, Nuclear Controls & Planning Wing, DAE, underscored the importance of regional scientific cooperation in addressing shared developmental challenges and reaffirmed India's

commitment to collaborative progress across the Asia-Pacific.

As the incoming RCA Chair and India's National Representative, Mr. P. K. Sharma outlined priorities for the year ahead, including strengthening the regional cooperation framework, advancing new project proposals, supporting the activities of the RCA Regional Office, and preparing for the 70th IAEA General Conference. Welcoming the delegates, Shri Sampathkumar Raghunathan, National Liaison Officer (NLO), reflected India's tradition of hospitality through the ethos of Atithi Devo Bhava.

A key outcome of the meeting was the consideration of fourteen concept proposals for the 2028-29 RCA programme cycle. Recommendations of the RCA Technical Advisory Panel (TAP) were presented by Dr. K. Tirumalesh, Scientific Officer-H, Isotope and Radiation Application Division, BARC who served as TAP Lead and was commended for guiding the panel towards a shared consensus.

Delegates also visited the Advanced Centre for Treatment, Research and Education in Cancer (ACTREC), where Dr. Ajit Kumar Mohanty, Chairman, Atomic Energy Commission and Secretary, DAE, presented commemorative mementoes reflecting India's cultural heritage. The programme included an exhibition on the non-power applications of nuclear technology and a visit to the Chhatrapati Shivaji Maharaj Vastu Sangrahalaya in Mumbai.

Guided by the vision of Vishwa Bandhu Bharat and the theme India by Your Side, India's RCA Chairmanship reflects its commitment to fostering regional partnerships and advancing sustainable development through the peaceful applications of nuclear science and technology.

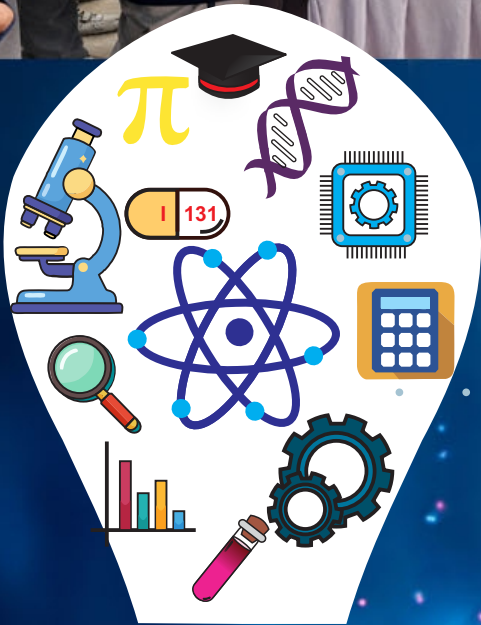
Radioisotopes Medicine Healthcare Students take Centre stage @ NSD & NTD 2026



The Bhabha Atomic Research Centre (BARC) showcased its research and development in radioisotopes during the National Science Day (26-28 February) and National Technology Day (11-13 May) celebrations, themed 'Radioisotopes in Medicine'. The events introduced students to the role of radioisotopes in affordable diagnosis and treatment to meet India's growing healthcare needs. The contributions of BARC to radioisotope production and radiopharmaceutical development was highlighted during the programs. DAE remains India's largest supplier of radiopharmaceuticals for disease diagnosis and therapy.



Held at the Central Complex Auditorium, Trombay, and the DAE Convention Centre, Anushakti Nagar, the programmes engaged 600-700 students daily through lectures, exhibitions, quizzes, audio-visual presentations, and guided tours to facilities. Dr. Sudeep Gupta, Director of Tata Memorial Centre, and Prof. Dr. Ravindra Dattatray Kulkarni, Vice Chancellor of the University of Mumbai, were the chief guests for the National Science Day and National Technology Day programmes, respectively. The Radiochemistry and Isotope Group (RC&IG) coordinated the events with support from other science, technology, and engineering groups at BARC.



NUCLEAR R&D Tech Spin-offs

Bhabha Atomic Research Centre (BARC) continues to foster industry collaboration by transferring emerging nuclear spin-off technologies and associated know-how besides stimulating rural entrepreneurship. The Centre is also accelerating efforts to incubate deep-tech startups in high-priority domains critical to sustained economic growth.



Technology Streamlining & Transfer

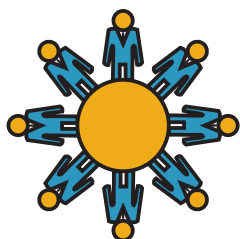


BARC continued to streamline indigenous technologies for public and industrial applications by introducing new innovations with applications in agriculture, advanced technology, metallurgy, quality assurance, healthcare, and nutrition. During the review period (May-June 2026), one new technology was placed in the public domain:



Probiotic Condiments (Spicy Green Coconut, Sweet & Sour Dates) (AB68FTD): This plant-based, ready-to-eat probiotic technology provides a convenient, dairy-free alternative to conventional probiotic products. Designed to promote gastrointestinal health and overall well-being, the technology combines traditional Indian condiments with functional nutrition, offering industry an innovative value-added product for commercialization.

Incubation & Startup Ecosystem



AIC BARC Anushakti Foundation, supported by the Atal Innovation Mission (AIM), continued to strengthen the deep-tech innovation ecosystem through startup incubation, technology commercialization, and industry engagement. As co-organizer of the Research

Scholars' Summit on Employment, Entrepreneurship & Startup Opportunities, AIC ANUSHAKTI showcased BARC's lab-to-land tech translation initiatives and incubation programmes while facilitating interactions among researchers, startups, industry, and academia.

As part of the DAE Incubators' Alliance, AIC ANUSHAKTI supported the launch of TECHATHON 2.0, a national-level deep-tech innovation challenge promoting mentoring, incubation, and commercialization of promising technologies.

The incubation ecosystem was further strengthened through approval of incubation policies, onboarding of new deep-tech startups, and constitution of a task force for publication of new BARC technologies. During the Technology Transfer & Incubation Ceremony held on 24 June 2026, 14 technology transfer agreements and 2 incubation agreements were signed, while the successful incubation of M/s. Gir Gau Krushi Jatan Sansthan, Rajkot, for commercialization of NISARGRUNA-based products was also recognized.

AIC ANUSHAKTI further expanded its outreach through strategic engagements with Atal Innovation Mission, participation in national innovation programmes, and presentations before Department of Atomic Energy leadership on strengthening technology translation and the DAE incubation ecosystem.

Rural Tech Entrepreneurship



AKRUTI Kendras continued to promote rural entrepreneurship and sustainable livelihoods through awareness programmes, tech demonstrations, skill development, and institutional collaborations. During the

review period, students, entrepreneurs, SHGs, government officials, and industry representatives participated in exposure visits, workshops, and training programmes on DAE-BARC technologies, including food processing, food preservation, and Rapid Bio-Composting.

On the occasion of World Environment Day, AKRUTI Kendra in Tarapur organized the Sustainability Entrepreneurs' Felicitation Ceremony, recognizing entrepreneurs who successfully adopted BARC technologies for sustainable livelihood generation. During the Technology Transfer Ceremony on 24 June 2026, entrepreneurs showcased commercially launched products based on licensed BARC technologies, including Foldable Solar Dryer, Ready-to-Eat Fruit Cubes, Low-GI High-Fibre Wheat Flour, Gluten-Free Multigrain Pre-mix Atta, Rapid Compost, Soil Testing Kit, and Jamun Strips.

AKRUTI Kendra-MGU strengthened academic outreach through internship programmes, institutional visits, and entrepreneurship lectures for university students, while AKRUTI Kendra-BLDEASSM showcased BARC technologies at the 2nd Vision Karnataka Exhibition, reaching over 5,000 visitors and receiving an award for excellence in technology dissemination and promotion.



① हिंदी कार्यशाला - उद्घाटन समारोह में उपस्थित अतिथिगण, वैज्ञानिक अधिकारीगण एवं हिंदी अनुभाग के पदाधिकारीगण। ② परमाणु विज्ञान प्रकाशन समिति - डॉ. ए.के. दुरेजा, सह निदेशक, के.एम.जी. की अध्यक्षता में आयोजित बैठक में उपस्थित सदस्यगण। ③ राजभाषा आंतरिक निरीक्षण - लेखा प्रभाग की समीक्षा बैठक में उपस्थित अध्यक्ष, एस.आई.आर.डी., संयुक्त नियंत्रक (वित्त एवं लेखा), निरीक्षण समिति के सदस्यगण और लेखा प्रभाग के अधिकारीगण। ④ परमाणु विज्ञान प्रकाशन समिति - डॉ. ए.के. दुरेजा, सह निदेशक, के.एम.जी. की अध्यक्षता में आयोजित बैठक में उपस्थित सदस्यगण।

भाषा परमाणु अनुसंधान (भा.प.अ.) केंद्र, मुंबई में राजभाषा के प्रभावी कार्यान्वयन के अंतर्गत मई - जून, 2026 के दौरान निम्नवत गतिविधियां आयोजित की गईं:-

राजभाषा कार्यान्वयन समिति की बैठक - दिनांक 29 जून, 2026 को निदेशक, भा.प.अ. केंद्र की अध्यक्षता में राजभाषा कार्यान्वयन समिति (OLIC) की बैठक का आयोजन किया गया। इस बैठक में, जनवरी-मार्च, 2026 की तिमाही के दौरान केंद्र में राजभाषा के कार्यान्वयन में हुई प्रगति की समीक्षा की गई, कार्यान्वयन के विभिन्न पहलुओं पर विचार-विमर्श किया गया और तदनुसार, निर्णय लिए गए।

‘परमाणु विज्ञान’ पत्रिका प्रकाशन समिति की बैठकें - डॉ. आदर्श कुमार दुरेजा, सह निदेशक, ज्ञान प्रबंधन वर्ग की अध्यक्षता में, केंद्र की हिंदी वैज्ञानिक पत्रिका ‘परमाणु विज्ञान’ के द्वितीय अंक के प्रकाशनार्थ “संपादकीय समिति” की बैठकें क्रमशः दिनांक 13/05/2026 और दिनांक 01/06/2026 को आयोजित की गईं। इन बैठकों में केंद्र और परमाणु ऊर्जा विभाग (प.ऊ.वि.) की विभिन्न इकाइयों से प्राप्त लेखों पर चर्चा कर पत्रिका के विषयगत संतुलन को बनाए रखने के अंतर्गत लेखों को अनंतिम रूप से सूचीबद्ध किया गया।

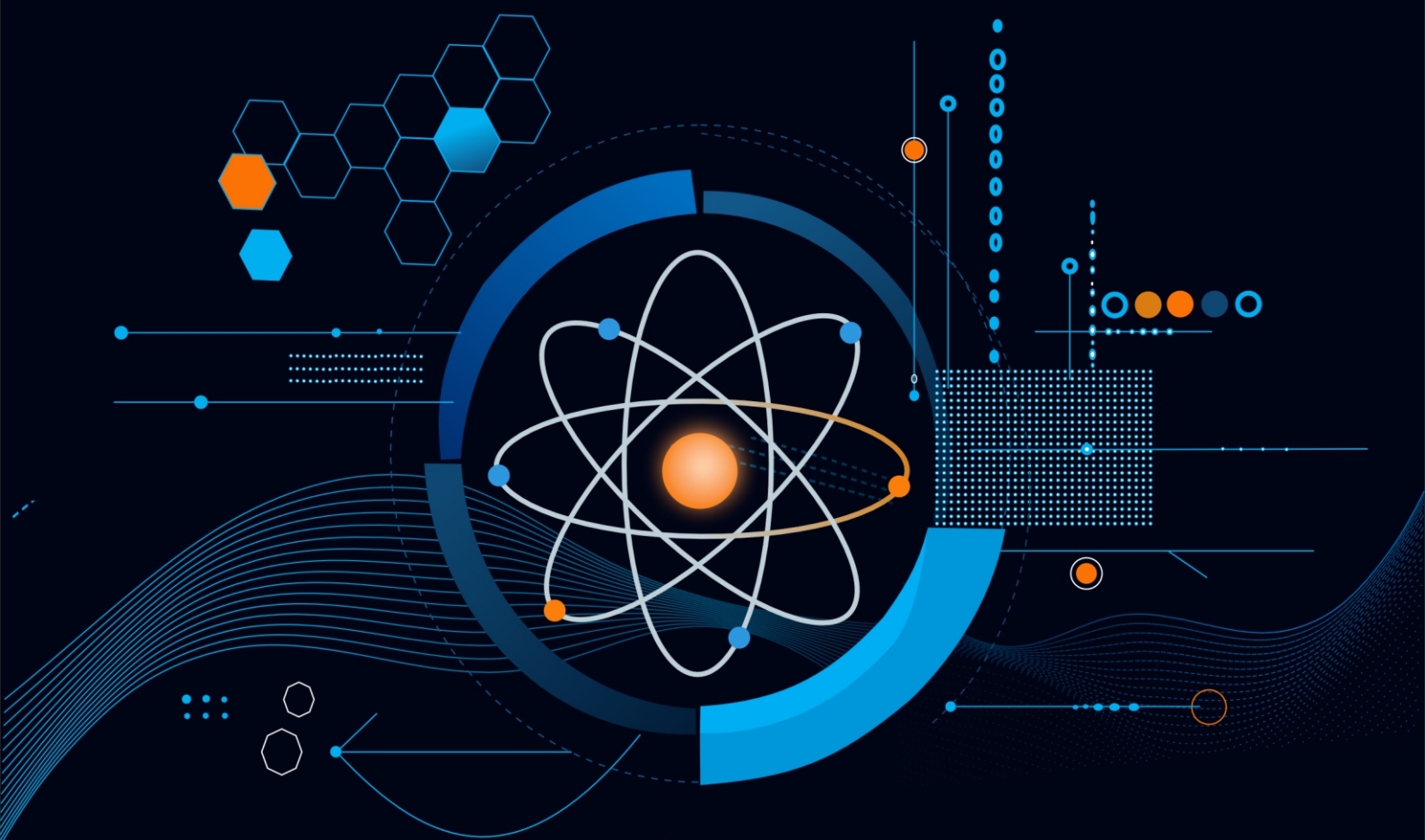
आंतरिक राजभाषा निरीक्षणोपरांत समीक्षा बैठकें - श्री मनोज सिंह, अध्यक्ष, एसआईआरडी एवं अध्यक्ष, आंतरिक राजभाषा निरीक्षण समिति, भा.प.अ. केंद्र की अध्यक्षता में गठित आंतरिक राजभाषा निरीक्षण समितियों (04) द्वारा प्रशासन, लेखा एवं सुरक्षा प्रभागों के कुल 67 अनुभागों में हिंदी के कार्यान्वयन की स्थिति का प्रत्यक्ष जायजा लिया गया। तदोपरांत, दिनांक 22/05/2025 को मुख्य सुरक्षा अधिकारी के नेतृत्व में सुरक्षा प्रभाग के अधिकारियों के साथ

और दिनांक 25/05/2026 को संयुक्त नियंत्रक (वित्त एवं लेखा) के नेतृत्व में लेखा प्रभाग के अधिकारियों के साथ उनके प्रभागों में राजभाषा के प्रभावी कार्यान्वयन की दिशा में सुधारात्मक उपाय किए जाने पर चर्चा की गई। समीक्षा बैठकों के पश्चात, भा.प.अ. केंद्र में सक्षम प्राधिकारी के अनुमोदन से निरीक्षण समितियों द्वारा प्रस्तुत रिपोर्टों के आधार पर संबंधित प्रभागों को अनुपालन रिपोर्टें प्रेषित की गईं।

हिंदी कार्यशाला का आयोजन - दिनांक 12/06/2026 को केंद्र में विभिन्न प्रभागों में कार्यरत वैज्ञानिक अधिकारियों के लिए एक पूर्ण दिवसीय हिंदी कार्यशाला का आयोजन किया गया। इस कार्यशाला में भाग लेने वाले 38 वैज्ञानिक अधिकारियों को संघ सरकार की राजभाषा नीति/नियम के अतिरिक्त, अभ्यास सहित हिंदी में टिप्पण एवं आलेखन, कंप्यूटर पर हिंदी टंकण, प.ऊ.वि. की प्रोत्साहन योजना (अटॉलिस) और केंद्रीय कर्मचारियों हेतु ‘आचरण नियमावली’ आदि विषयों की जानकारी प्रदान की गई।

नराकास बैठक में भापअ केंद्र का प्रतिनिधित्व - दिनांक 17 जून, 2026 को आयोजित नगर राजभाषा कार्यान्वयन समिति (नराकास), नवी मुंबई की छमाही बैठक में, श्री डी. श्रीनिवास राव, मुख्य प्रशासनिक अधिकारी और श्री सैयद इरफान अली, उप निदेशक (राजभाषा) ने केंद्र की ओर से प्रतिनिधित्व किया।

नराकास, ठाणे की प्रतियोगिता में केंद्र से प्रतिभागिता - केंद्र में राजभाषा के प्रचार-प्रसार के अंतर्गत नराकास, ठाणे द्वारा आयोजित हिंदी निबंध प्रतियोगिता जिसका विषय “संयुक्त परिवार” में भाग लेने हेतु भा.प.अ. केंद्र के पदाधिकारियों को प्रोत्साहित किया गया।



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