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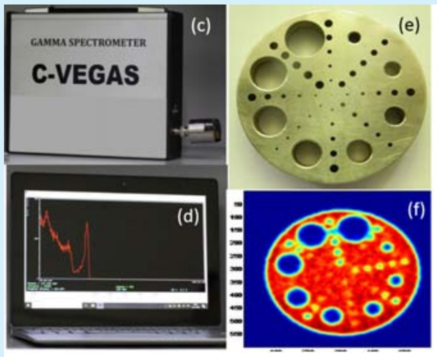

INDIRA GANDHI CENTRE FOR ATOMIC RESEARCH
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Editor's Desk

Dear Reader

Greetings

It is my pleasant privilege to forward the latest issue of IGC Newsletter (Volume 142, January 2025, Issue 4). I thank my team for their timely inputs, cooperation, and support in bringing out this issue.

The technical article of this issue "Development of AI Model for Reactivity Estimation Under Stochastic Noise" is by Mr. Rahul Raj and Colleagues from EIG, IGCAR.

Young Officer's Forum features articles on Role of Second Stage Program in Meeting Net Zero Target by Shri. S. Aravindan, Pyroprocessing of Metal Fuels - Present Status and Future Directions by Shri Sourabh Agarwal, Partitioning and Transmutation of Minor Actinides by Dr. Jammu Ravi, Materials Research and Development towards Metallic Fuel Fast Breeder Reactors by Shri Ashish Kolhatkar.

The IGCAR Lectures series articles on Single Crystals for Radiation Detectors, Imaging and Transducer Applications by Dr. S Ganesamoorthy, Design & Development of Customized and Innovative Sensors for FBR program by Shri M. Sivarama Krishna, Experimental Sodium Facilities & Sodium Handling Experiences at FRTG by Shri S. Chandra Mouli, Corrosion Issues of Materials in Fast Reactor and Reprocessing Environments by Dr. S. Ningshen, Distributed Digital Control System for PFBR by Shri A. Shanmugam, Development of Solvents for Nuclear Fuel Cycle by Prof. C. V.S. Brahmanada Rao are included in this Newsletter.

In the back cover, we have Blue Tiger butterfly found in IGCAR-campus.

The Editorial Committee would like to thank all the contributors. We look forward to receiving constructive suggestions from readers towards improving the IGC Newsletter content.

We express our deepest gratitude to Director IGCAR for his keen interest and guidance.

Shri J. Rajan
With best wishes and regards
Chairman, Editorial Committee, IGC Newsletter and
Head, Scientific Information & Networking Division, IGCAR

New Year 2025 Message

Shri C. G. Karhadkar
Distingushed Scientist & Director, IGCAR

Dear Colleagues,

It gives me a great pleasure in wishing all the colleagues of Indira Gandhi Centre for Atomic Research, General Services Organization and their families, a very happy, prosperous, healthy and blissful New Year 2025 and Season's Greetings for Pongal festival. As we enter the New Year, we need to take stock of all-round accomplishments, identify the challenges at the forefront and focus on making the year ahead professionally fulfilling and rewarding.

The Fast Breeder Test Reactor which is the flagship reactor of the second stage of our nuclear power programme, was operated at its design power level of 40 MWt. The total operating time of the reactor during 33rd irradiation campaign was 2664 hours and the total electrical energy generated was 15.49 million units. Subsequently, the preparatory works for the upcoming 34th irradiation campaign has commenced. The upper part and silicon bellow of one of the Control Rod Drive Mechanism has been successfully replaced. As a step forward towards achieving net zero emission, feasibility study on "Green Hydrogen Production" by a combined team of experts from BARC and IGCAR has been completed. Work towards establishing, a pilot-scale demonstration facility for hydrogen production is being initiated.

The Prototype Fast Breeder Reactor (PFBR) at BHAVINI is in an advanced stage of integrated commissioning and IGCAR continues to provide all necessary technical support. Many colleagues from various groups of IGCAR are working in synergy with BHAVINI team for the commissioning activities. Towards commissioning of PFBR, the modifications required in PFBR subassemblies have been successfully completed on time without any rejection. The NDE inspection module of the DISHA - V2 in-service inspection vehicle for inspecting the dissimilar weld between the main vessel and the roof slab of PFBR, has been successfully completed both at the room temperature and high temperature (120^0 C) qualification on a 1:1 mock-up facility. Also, detailed thermal modeling of Biological Shield Cooling System of PFBR has been carried out using CFD code to compare the predicted temperature distribution against plant data.

A conceptual design summary note has been prepared for a dedicated Metal Fuel Test Reactor; FBTR-II (100MWt) for launching it around 2035 to 2037. As, FBTR has got a limited residual life of around 12-15 calendar years (or ~ 6 EFPY), FBTR-II will serve as a replacement for FBTR. Detailed design of FBTR-II is in progress. With the establishment of FBTR-II, India will continue to have a fast neutron spectrum research reactor. Further, inventory calculations and estimation of actinide and fission product activity for FBTR-II have been done using ORIGEN2 code.

The U233 fuelled Kalpakkam Mini Reactor (KAMINI) is continuing its successful operation for testing of various neutron detectors, Neutron Activation Analysis (NAA), Neutron radiography of fresh & irradiated fuels and Shielding experiments. We embarked on the year 2024, with the dedication of indigenously developed Demonstration fast reactor Fuel Reprocessing Plant (DFRP) to the Nation by Honorable Prime Minister Shri Narendra Modi on January 02, 2024. Also, the plant was hot commissioned, and the first batch of 20 pins of FBTR spent fuel with burn-up of 155 GWd/t has been successfully processed. The recovered strategic material was dedicated to the nation in the presence of Dr. Ajit Kumar Mohanty, Chairman AEC and Secretary DAE. The experience gained from the hot Commissioning run has provided us a wealth of knowledge towards further optimization of the process and in establishing the parameters for taking up regular industrial scale processing. Subsequently, the second campaign for processing of 40 pins of FBTR spent fuel with 155 GWd/t burn-up, has been completed and the recovered material is converted into final product form by reconversion process at DFRP. COmpact Reprocessing facility for Advanced fuels in Lead shielded cells (CORAL), the only facility currently operating in the world for reprocessing high burn-up carbide fuels, has successfully completed 66 campaigns. At CORAL, preparatory works for commencing the 67th reprocessing campaign is under progress. The facility continues to process spent fuel from FBTR, achieving high decontamination and recovery rates and has been re-licensed by AERB until 2028.

As regards to the metallic fuels development programme, The ‘Sub-assembly level Metal Fuel Fabrication Facility’ was inaugurated by Dr. Ajit Kumar Mohanty, Chairman, AEC & Secretary, DAE on May 28, 2024 in the presence of Dr. B.Venkatraman, the then Director, IGCAR. The notable features of the facility are: it can produce one sodium bonded metal fuel pin per day, and fabricate 1.0 meter long fuel pins for sub assembly level irradiation in FBTR. On the same day, another new experimental facility for demonstration of pyro-processing operations using U-Pu-Zr alloy in maximum 250 g per batch was also inaugurated by Chairman, AEC.

Pertaining to indigenous materials and process development, we have successfully integrated for the first time, Digital Image Correlation (DIC) technique with small punch experiments for online monitoring of the strains and identifying the location of instability during deformation. We have also successfully demonstrated the In-house development of PyG coatings on engineering scale HDG components (1to5 kg) for pyrochemical reprocessing and Gen-IV reactor applications. Also, a 2-ton capacity electric overhead travelling (EOT) crane used for transfer of radioactive materials in the Radiometallurgy hot cells has been remotely repaired and put back to operation. It is a matter of pride that patents were granted for IGCAR inventions titled, "Leak Tight Flange and Gasket assembly for Instrumentation /Power Cables for Chemical and Radiochemical Facility”. This technology has also been transferred to a start-up from the neighborhood specializing in mechatronics. The technologies of ‘High Efficiency Particulate Filter (HEPA) Test Rig technology’, and ‘The Pulsating Sensor based Conductivity Meter technology’ developed under "Atma Nirbhar Bharat" programmes of IGCAR have been successfully transferred to start-up companies. To align with our Nation's key missions of Atmanirbhar Bharat and Viksit Bharat-2047, the DAE Incubation Centre of IGCAR functioning since October, 2020 has been registered as an Atal Incubation Centre with the name "AIC-IGCAR-FAST Foundation" on October 08, 2024 and as a ‘Section-8 Company’ under Companies Act, 2013. This company, registered with Ministry of Corporate Affairs, will be a fully Government owned non-profit private company supported by Atal Innovation Mission (AIM) of Niti Aayog and patronized by DAE and IGCAR (host institution).

On the societal front, towards production of radiopharmaceuticals, two batches of Strontium-89 radiopharmaceutical have been produced and sent to BRIT, Mumbai for bio-distribution studies. As regards to safety, environment and health, a Fission Product Noble Gas (FPNG) monitor has been installed in one of the predominant wind sectors of Kalpakkam site and commissioned, for providing real-time data on the presence of radioactive gases and their concentrations in atmospheric environment. It is proposed to integrate this system with the Online Nuclear Emergency Response System (ONERS) towards real-time monitoring and to distinguish radionuclide releases in case of accidental conditions for emergency response application. A Mid-Tropospheric Wind Profiler has also been installed and commissioned by IGCAR in association with ISRO Telemetry, Tracking and Command Network (ISTRAC), for Atmospheric Studies, Weather forecasting and Nuclear Emergency Decision support system applications. Detector elements have been developed successfully with energy resolution of 4% for 662 keV gamma radiation from 137Cs source based on single-crystals of CdZnTe grown at IGCAR and incorporated into a portable and wireless enabled Gamma Spectrometer for field testing in radiological laboratories and tested for computed tomography. Two New GIC-5000 Gamma Chambers have been installed and commissioned at IGCAR, Kalpakkam for meeting the research requirements of gamma irradiation for industrial, medical and agricultural products. One old GIC 5000 Gamma Chamber has been decommissioned and sent back to BRIT, Vashi.

On the human resources development front, twenty young trained Scientist and Engineers (OCES-2023, 18th Batch) have successfully completed their orientation programme at BARC Training School at IGCAR and were placed in various units of DAE. I am pleased to note that our Centre has been offering projects and internship opportunities to young postgraduate students as part of their academic programme, encouraging them to explore research in the frontier areas of science and technology. Our centre is also actively contributing to green initiatives. As part of Swachhata Hi Seva – 2024 celebrations, a tree plantation campaign was organised under the theme ‘Ek Pedh Maa Ke Naam’. Around 2500 ethnic, flowering and fruit bearing trees were planted within a period of 11 days by the employees of IGCAR covering an area of around 60,000 Sq. meters within DAE campus. This, created awareness amongst employees on green cover development towards reversing land degradation and improving the environment.

Continuing the commitment towards neighborhood community welfare, Inauguration and handing over of the Ultra filtration Membrane-based Point-of-Use Water Purifiers (5000 nos. of units) & 1000 LPH Community RO Water Purification Systems (3 nos. of units) deployed at Kunnathur, Kadambadi & Manamai Villages, Tamil Nadu to the heads of surrounding villages of Kalpakkam was held on February 07, 2024 at IGCAR. These Technologies were designed and developed by BARC, as a part of Swachhata Pakhwada initiative towards taking forward the DAE technologies for the benefit of the neighborhood.

Swachhata Pakhwada was observed in IGCAR, Kalpakkam for a fortnight from February, 16-29, 2024, with the objective of intense focus on the issues and practices of swachhata. Apart from cleaning activities, weeding of records and material from offices at IGCAR, a plethora of activities were additionally carried out such as: E-waste collection for disposal, and books collection for distribution to the needy. Tree plantation drive was organised in Anupuram Township engaging AECS School children and more than 100 saplings were planted; Cleanliness Drive was conducted in Government High School at Suradimangalam, Chengalpattu by cleaning and painting the School building. I am delighted to share that IGCAR, Kalpakkam has secured third rank in Swatchhta Pakhwada 2024 from DAE. It is with immense pride that our Centre celebrated its Foundation Day on April 30, 2024, marking a significant milestone in its journey. Shri Vivek Bhasin, Distinguished Scientist and Director, Bhabha Atomic Research Centre, Mumbai, graced the occasion as the chief guest. Dr. U. Kamachi Mudali, Vice- Chancellor, Homi Bhabha National Institute (HBNI) and Dr. Sanjay Kumar Jha, Chairman and Managing Director, Mishra Dhatu Nigam Limited (MIDHANI), were the guests of honour. On this significant day, Shri Vivek Bhasin, flagged off the commencement of the "Pilot scale production of radioisotopes (90Y, 32P) for the benefit of the society". A series of vision satellite theme meetings were conducted from April 15-26, 2024 by each group of IGCAR, as part of the IGCAR foundation day celebrations. Many Superannuated colleagues, including former Group Directors, associate directors, and division heads, were invited for the celebrations. Their insights and suggestions on the programmes of the centre and on the way forward were sought, leading to fruitful discussions and valuable interactions that benefited the younger colleagues.

In the current year, as part of the celebration of the Platinum Jubilee year of DAE, special industrial visit to IGCAR is organized on the Tuesday of every week for students from schools near Kalpakkam and Chennai areas. The programme includes visit to FBTR, RFG, labs at MCMFCG and Library, interactive session on educational and career opportunities at DAE, quiz competition, special address by senior official and prize distribution to the winners of quiz competition. Since August 2024, 16 schools with a total of 726 students & 36 teachers have visited IGCAR as part of this outreach programme. Also 38 colleges have participated in Industrial visit to IGCAR with 1542 students and 100 faculty, from different parts of south India during this year. About 727 persons from different spheres of general public, NGO's, VIPs, State/ Central Goverment Officials have also visited IGCAR as special visitors. IGC lecture series commenced from July 2024 and is being organized twice a month on 2nd and 4th Wednesdays, with two talks on diverse topics aiming to bring out the achievements, challenges overcome, plan and preparedness to meet the Amrit Kaal vision targets of IGCAR. Ten editions of the lecture series have been completed with twenty talks delivered, the recording of these talks have been stored in a digital repository for future reference.

GSO has achieved a significant milestone, marking a paradigm shift in the landscape of Anupuram Township with the addition of new tower blocks. The efforts put in by employees of GSO in maintaining the townships serene, green and clean is commendable. The Medical Group, has enhanced its services with better amenities and continues to provide excellent health care services to the residents of the townships.

I greatly acknowledge the painstaking efforts of principals, teachers and, staff all the Kendriya Vidayalayas and Atomic Energy Central Schools within our township premises, towards providing quality education to the students, in a holistic manner. I am pleased to see that students from all five schools have excelled in the board exams, achieving outstanding results. Teachers' day celebration was organized for the principals, teachers, and staff members from three Atomic Energy Central Schools, two Kendriya Vidyalayas, and Kindergarten Schools of Kalpakkam & Anupuram townships on September 5, 2024. The teachers and staff members completing 25 years of service and those retiring this year were felicitated, during Teachers' Day celebration. The Administration and Accounts departments of IGCAR and GSO have consistently provided exemplary services, offering guidance and support in the successful execution of all programmes.

Towards the way forward in 2025, apart from the other R&D and regular activities at the various groups of IGCAR and GSO, our focus would continue to be providing support for the integrated commissioning activities of PFBR such as initial Fuel Loading, subsequent First Approach to Criticality and progressive power operation. Our aim would be to continue operation of FBTR at 40 MWt by extending its service life through lower axial shielding with indigenously produced WC pellets for carrying out irradiation of advanced FBR structural materials and fuels, exploration on producing green hydrogen by setting up the demonstration facility and continue further campaigns at DFRP for the reprocessing of spent fuel from FBTR. We would also operate the 1 m fuel pin fabrication facility towards casting U-Pu-Zr metal fuel along with electro-refining facility, advance with respect to the production of the radioisotopes P-32 and Y-90 at FBTR. We would also take forward the AIC-IGCAR-FAST foundation activities to the next level and successfully complete the planned commitments for the platinum jubilee celebrations of our DAE.

These achievements have been made possible through the tireless and dedicated efforts of all our colleagues and I look forward to your continued support and cooperation for a productive and professionally fulfilling future ensuring sustained growth in all our activities in the coming year 2025.

Shri C. G. Karhadkar
Distinguished Scientist & Director, IGCAR

Mr. Rahul Raj completed his B.Tech in Electronics and Communication Engineering from the Muzaffarpur Institute of Technology, Bihar, and joined the Department of Atomic Energy (DAE) through the 65th batch of the BARC Mumbai Training School in 2021. In 2023, he joined the DDCSD, EIG, IGCAR. He earned his M.Tech in Nuclear Engineering from Homi Bhabha National Institute (HBNI) in 2024. Currently, he works as a Scientific Officer-C, with research interests in artificial intelligence, machine learning, and 3D development.

Technical Article

Development of AI Model for Reactivity Estimation Under Stochastic Noise

1. Introduction

Fast breeder reactors (FBRs) are a class of nuclear reactors that generate more fissile material than they consume, positioning them as a crucial component of nuclear energy production. However, the inherently dynamic behavior of FBRs presents significant challenges for reactor control and safety management. As a result, precise and timely estimation of reactivity changes is essential to ensure the safe and efficient operation of these reactors.

Traditionally, reactivity in FBRs is determined by monitoring changes in reactor power through the solution of inverse point kinetics equations, which incorporate six groups of delayed neutrons. This conventional approach is deterministic in nature, relying on predefined mathematical formulations. In contrast, Machine Learning (ML) models offer a data-driven alternative for reactivity estimation, potentially providing greater flexibility by learning from historical data.

Among ML techniques, deep neural networks (DNNs)—specifically Long Short-Term Memory (LSTM) networks—have shown promise, yielding lower prediction errors compared to traditional methods. To train these models, neutron concentration vs. reactivity datasets are generated using input reactivity values ranging from +20 pcm to -20 pcm. The datasets encompass three types of reactivity inputs: step reactivity, ramp reactivity, and sinusoidal reactivity.

The generated datasets are employed to train multiple ML models, followed by performance evaluation using random test datasets. The models are assessed under both noisy and noise-free conditions to gauge their robustness. This comparative analysis aims to explore the feasibility of ML-based reactivity estimation as a complement or alternative to the conventional inverse point kinetics approach.

2. Implementation of PKE

The Point Kinetics Equation (PKE) is employed to generate neutron concentration versus reactivity datasets, which serve as the foundation for training machine learning models. These datasets are produced by implementing custom Python code. Key input parameters for dataset generation include reactivity, initial neutron concentration, reactor characteristics, sampling time, and total simulation time. The generated output consists of neutron concentration data over time.

The PKE comprises a system of differential equations. To numerically solve these equations, the odeint function from the scipy.integrate library is utilized. The following differential equations, which constitute the PKE model, are applied to simulate neutron concentration as a function of reactivity:

$$\frac{dn}{dt} = k.(\rho-\beta).\frac{n}{l} + \sum_{i=1}^{6} \lambda_i.C_i$$

$$\frac{dC_i}{dt} = k.\beta_i.\frac{n}{l} - \lambda_i.C_i$$

where:

n(t) is the neutron population.

ρ(t) is the reactivity.

β is the delayed neutron fraction.

k is neutron multiplication factor.

L is prompt neutron lifetime

λi is the decay constant for the i-th group of delayed neutron precursors.

Ci(t) is the population of the i-th group of delayed neutron precursors.

βi is the delayed neutron fraction for the i-th group of precursors.

3. Generation of training data sets

The datasets are generated with neutron concentration versus reactivity values, sampled at 10 ms intervals. Due to the time-dependent nature of the Point Kinetics Equation (PKE), it is utilized for generating these training datasets. These datasets are subsequently used to train the system with various Machine Learning (ML) models, facilitating data-driven reactivity estimation.

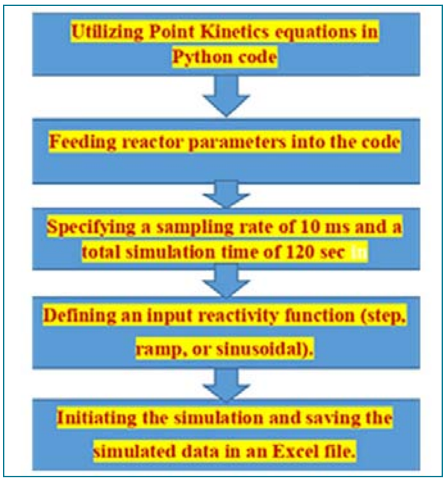

Figure 1. Flowchart represents data set generation process

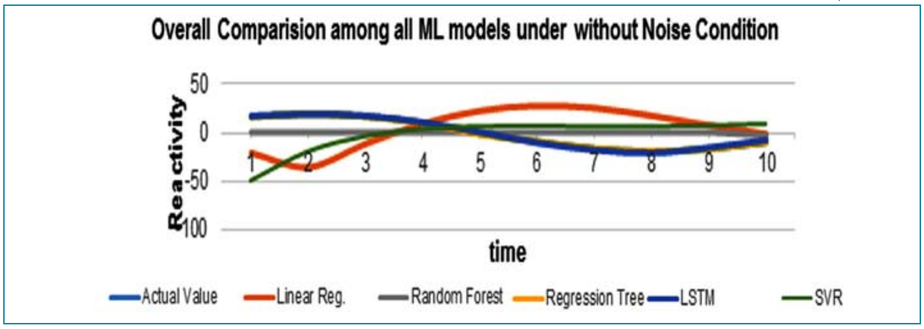

Figure 2. Test output of different ML models under no noise conditions

Figure 1 illustrates the steps involved in the process of generating the training datasets. The following types of reactivity inputs are employed:

- Ramp reactivity with varying slopes.
- Step reactivity with different step values.
- Sinusoidal reactivity with varying time periods.

4. Training with different ML models using generated data sets

Machine Learning (ML), a branch of artificial intelligence, leverages datasets to develop algorithms that identify underlying patterns. These algorithms can make predictions on new, similar data without the need for explicit programming for each task. In this study, various ML models are employed for training, including Linear Regression, Regression Tree, Support Vector Regressor (SVR), and Random Forest. Additionally, the Long Short-Term Memory (LSTM) model, a type of deep neural network, is used to enhance performance. The selection of these models is informed by a literature review of prior research studies.

The ML models are implemented using Python programming. Upon completing the training, the Mean Squared Error (MSE) metric is used to evaluate the system's performance. The MSE measures the deviation between predicted and actual values, with higher MSE values indicating lower prediction accuracy, thereby deeming the model unsuitable for practical use. An 80:20 split is applied to the dataset, where 80% is allocated for training and 20% for testing.

After training, the system undergoes testing with random datasets of normalized neutron flux. These datasets serve as input to the trained models to predict reactivity values. The predicted reactivity values

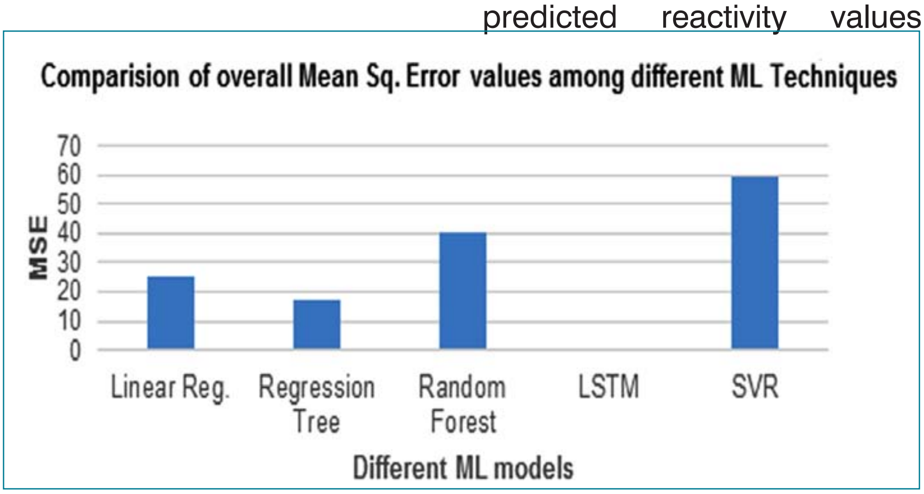

Figure 3. Bar graph of MSE values of different ML models under no noise noise conditions

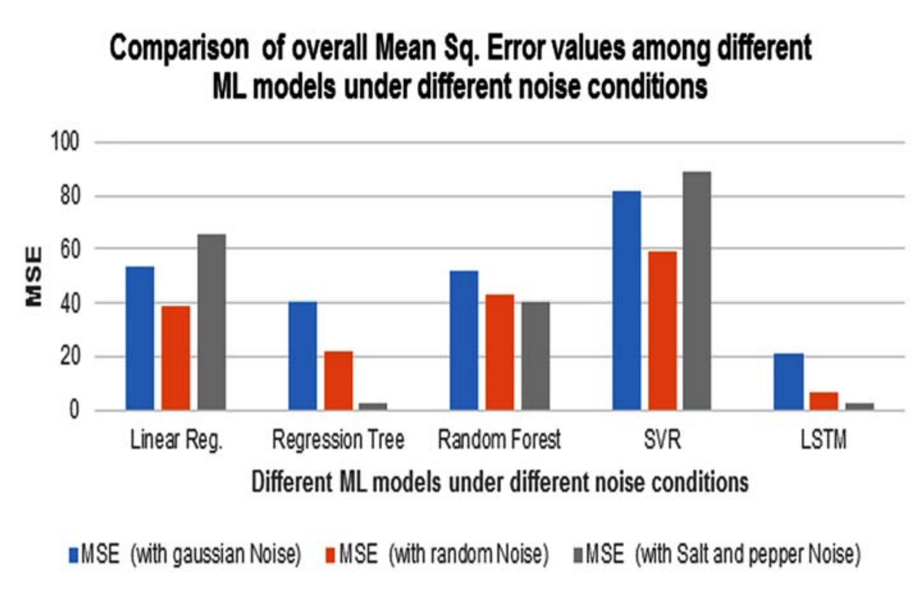

Figure 4. Plot of all MSE under different ML models (under different noises)

are then compared with the actual reactivity values (the corresponding values of the input neutron flux) to assess the model's accuracy.

5. Performance of different ML models with without noise datasets

The performance of the trained ML models is analyzed based on the results from the test datasets and the MSE values. Figure 2 presents a graph illustrating the deviations between predicted and actual reactivity values for the different ML models. Table 1 summarizes the overall MSE values for each ML model, with a corresponding graphical representation provided in Figure 3.

Table 1. MSE values of different ML models under no noise conditions

Sl. no	ML model	MSE
1	Linear Regression.	24.974
2	Regression Tree	17.215
3	Random Forest	40.379
4	LSTM	0.665
5	SVR	59.393

6. Performance of different ML models under noisy datasets

In this study, noise is introduced into the training datasets to evaluate the robustness of various ML models. The noise is simulated programmatically and superimposed on the original training datasets. The types of noise applied include Gaussian noise, random noise, and Salt & Pepper (SP) noise. The performance of the trained ML models is analyzed under these different noise conditions by comparing their Mean Squared Error (MSE) values. Table 2 presents the overall MSE values for each ML model under the various noise conditions, and the corresponding graphical representation is provided in figure 4.

In noise-free conditions, the LSTM model demonstrates favorable accuracy, achieving an MSE value of 0.66538 (Table 1). The Regression Tree model ranks second, though with a significantly higher MSE value of 17.21572 (Table 1). In noisy conditions, specifically under Salt-and-Pepper noise, both the Regression Tree and LSTM models exhibit the lowest MSE values, with 2.650 and 2.466, respectively (Table 2).

Thus, in the absence of noise, the LSTM model emerges as a reliable choice for predicting reactivity. Under noisy conditions, the Regression Tree and LSTM models perform well, particularly under Salt-and-Pepper noise, making both acceptable models for reactivity estimation.

Table 2. Combination of all MSE under different ML models (under different noise)

Sl. no	ML model	MSE (with gaussian Noise)	MSE (with random Noise)	MSE (with Salt and pepper Noise)
1	Linear Reg.	53.21789	38.78075	65.676
2	Regression Tree	40.71614	22.34780	2.650
3	Random Forest	51.80953	43.06870	40.526
4	SVR	81.54263	59.27	88.737
5	LSTM	20.86253	6.3654	2.466

Young Officer's Forum Lecture 1

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Role of Second Stage Program in Meeting Net Zero Target

India has set a goal to become a developed nation by 2047, during which the estimated per capita annual electricity consumption is expected to reach approximately 6,700 kWh - five times the current level of ~1200 kWh. The industrial revolution and the resulting greenhouse gas (GHG) emissions have been major contributors to global warming, and currently, India ranks as the third-largest emitter of GHGs. The primary contribution of India's CO_2 emissions comes from sectors such as power (53%), industry (24%), and transport (13%). Within the power sector, approximately 75% of CO_2 emissions stem from coal-powered plants. At COP26 climate meet in 2021, India pledged to achieve "Net Zero" by 2070. Net Zero is a condition where emissions released into the atmosphere must be balanced by those removed.

A study was conducted to explore strategies for increasing power generation while achieving Net Zero by 2070 and it was found that, to meet the electricity target while maintaining lower power generation costs, India's nuclear energy capacity would need to be ~ 250 gigawatts (GWe) by 2070. Currently, India has an installed nuclear power generation capacity of 8.18 GWe from 24 reactors. Out of them, 16 reactors with a combined capacity of 5.8 GWe are under the IAEA safeguards. Hence, about 70% of India's nuclear power comes from fuel imported majorly from Kazakhstan (60%) and Canada (39%). India's unique position of being the only country with known nuclear weapons that is not a signatory to the Non-Proliferation Treaty (NPT) but still participating in global nuclear trade could also expose it to geopolitical supply risks, potentially affecting its growth.

India has limited uranium reserves and about one-fourth of the world's thorium reserves. However, natural uranium contains only a small fissile fraction (0.7% U-235), and thorium is fertile. India's first stage nuclear program consists of PHWRs using natural uranium. The spent fuel has small fraction of Pu-239, a fissile nuclei which is converted from fertile U-238. The conversion of fertile nuclei to fissile nuclei is effective when the neutron yield per neutron absorbed in a fissile nucleus (η) is more than 2.

The Fast Breeder Reactors (FBRs) of second stage nuclear program play a crucial role in this scenario. Pu-239 has the highest neutron yield in the fast neutron energy spectrum (~ 100 keV). Therefore, when Pu-239 is used in the core of a fast reactor with blankets made of depleted uranium and/or thorium, it accelerates the conversion of U-238 to Pu-239 and/or Th-232 to U-233 respectively, effectively producing more fuel than it consumes, thus acting as a breeder. A typical 500 MWe FBR using oxide and metallic fuel is estimated to achieve a reactor doubling time (time required for producing fissile mass equal to its initial inventory) of about 65 and 14 years respectively. Hence, to meet the pace of India's energy growth with available resources, the most viable path is to use metallic-fuel-based FBRs.

In addition to decarbonizing the power sector, it is equally important to address emissions in the industrial and transportation sectors. Hydrogen is emerging as a promising alternative fuel. While there are several methods for producing hydrogen, one of the most economically viable and energy-efficient approaches is the thermo-chemical water splitting process. Among them, the Copper-Chlorine cycle stands out as it requires heat source at ~500°C. The Sodium-Cooled FBRs are an ideal candidate for hydrogen production as their operating temperature is in this range.

To summarize, FBRs offer several advantages like higher efficiency, low pressure operation, flexibility of hydrogen production, etc. FBRs provide a valuable pathway to utilize India's uranium & thorium resources and they can also serve as "nuclear waste burners".

Decarbonization is crucial for India's sustainable development and nuclear energy plays a vital role. The second stage of India's nuclear program is key to ensure an Atmanirbhar Bharat (self-reliant India) by improving uranium utilization and unlocking the potential of thorium, while also contributing to the decarbonization of the energy sector through hydrogen production. Let's work together to accelerate decarbonization efforts and secure a cleaner, greener future for generations to come.

Shri Sourabh Agarwal
Materials Chemistry & Metal Fuel Cycle Group
Indira Gandhi Centre for Atomic Research, Kalpakkam
Tamil Nadu
India

Young Officer's Forum Lecture 2

Pyroprocessing of Metal Fuels-Present Status and Future Directions

The rapid expansion of India's Fast Breeder Reactor (FBR) program is essential for utilizing the country's vast thorium reserve. This expansion requires the use of metal fuels in FBRs due to their high breeding ratio and shorter doubling time. Also, to lower down overall doubling time reprocessing of metallic fuels using pyroprocessing is most suitable because it can easily manage short cooled high burnup fuel. Pyroprocessing or pyrochemical reprocessing is a non- aqueous high temperature reprocessing method and molten salt electrorefining based pyroprocessing is most suitable for metal fuels. In molten salt electrorefining separation of actinides from fission products is based on the thermodynamic stabilities of their chlorides and the equipment where it execute is called as Electrorefiner. An Electrorefiner comprises an anode and a cathode immersed in a molten eutectic mixture of LiCl &KCl. Spent fuel is placed in the anode basket, and a solid cathode is inserted initially. The most stable chlorides, those of Alkali Metals (AM), Alkali Earth Metals (AEM), and Rare Earth (RE) fission products (FP), easily exit the anode and dissolve in the electrolyte. Conversely, the less stable Noble Metal (NM) FP chlorides and cladding materials remain in the anode basket. Actinide chlorides, with intermediate stability, dissolve at the anode and deposit at the cathode when a potential is applied. Initially, only uranium deposits on the solid cathode, but once the plutonium-to-uranium concentration ratio in the electrolyte exceeds by approximately four, the solid cathode is replaced by a liquid cadmium cathode. This allows U, Pu, and Minor Actinides to co-deposit. In summary, actinides are separated from noble metal FPs at the anode and from AM, AEM, and RE FPs at the cathode.

For over three decades, IGCAR has been developing pyroprocessing techniques. Initially, efforts focused on handling LiCl-KCl eutectic, designing equipment, and preparing uranium alloys, gaining skills in glove box purity and induction melting. In the second decade, facilities for processing uranium in small batches were established, leading to research on other process steps and plutonium-based alloys. The Pyro Process R&D Facility (PPRDF) was developed to demonstrate electrorefining and cathode processing of U-Zr alloy in larger batches with remote handling.

In the third decade, significant progress was made, including large-scale experiments with salt and uranium alloys. Achievements included vacuum distillation and melting of uranium dendrites and electrorefining experiments on U-Pu-Zr alloys. PPRDF was commissioned with advanced systems like a high-temperature Electrorefiner and vacuum distillation chamber.

Post-2020, focus shifted to electrorefining uranium in larger batches and setting up a new facility for electrorefining U-Pu-Zr alloy. Future developments aim to ensure comprehensive experience with all process steps, emphasizing the importance of spent salt purification and immobilizing fission products. A used salt treatment facility (USTF) will demonstrate these processes.

Efforts on waste treatment are ongoing, with laboratory-scale activities and engineering-scale demonstrations planned. After proving all process and waste treatment steps, a hot-cell facility will be designed and constructed to demonstrate pyrochemical reprocessing of irradiated ternary U-Pu-Zr alloy fuel from the FBTR reactor. Eventually, a full-scale pyroprocessing plant will be developed, followed by facilities for commercial metal fuel fast reactors.

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Young Officer's Forum Lecture 3

Partitioning and Transmutation of Minor Actinides

The spent nuclear fuels contain small amounts of actinides such as americium, curium and neptunium, and are considered as minor actinides. The uranium and plutonium present in the spent nuclear fuel are recovered by the PUREX process. The aqueous waste generated in the PUREX process is known as high-level waste (HLW). The radiotoxicity associated with HLW is due to the presence of minor actinides. Conventionally, HLW is disposed in deep geological repositories after vitrification into immovable matrix. Long half-lives and higher decay heats (For example, specific heats of ^{241}Am and ^{244}Cm are 0.11 and 2.84 w/g respectively) are responsible for the increased depths and volumes of the deep geological repositories, and demands the long-term surveillance. Alternatively, the partitioning (P) of minor actinides from HLW followed by transmutation (T) into stable/short-lived products, P&T strategy, is more economically viable option for the safe management of HLW.

Among the minor actinides, the neptunium exists in multiple oxidation states in nitric acid medium similar to plutonium and exhibits varied extraction tendency. The inter-convertible nature of neptunium ions is being exploited to divert the neptunium to plutonium stream in the reprocessing plants by adjusting the process conditions appropriately. As neptunium would undergo either fission or converted to plutonium in the fast reactor, there is no harm in routing neptunium to plutonium. Thus, the diversion of neptunium to plutonium stream resolves the long-term radiotoxicity issues associated with neptunium. On the other hand, americium and curium exhibit trivalent oxidation state similar to lanthanides. The concentration of trivalent lanthanides in HLW is much higher than trivalent actinides, and the chemistry of both trivalent lanthanides and actinides is very similar. In view of this, the selective separation of trivalent actinides from HLW is a highly challenging task. Rigorous R&D activities are being conducted all over the world to develop a separation procedure for the selective removal of minor actinides from HLW. However, till date, the separation procedures are immature to be adopted in industrial scale separation plants. Therefore, minor actinide partitioning from HLW is envisioned to carry out in two separation cycles. First one involves the co-extraction of trivalent lanthanides and actinides from the bulk of the fission products followed by mutual separation in the next cycle. Numerous solvents and separation procedures were proposed for the co-extraction of trivalent f-ions from HLW. Among them, diglycolamide (DGA) class of extractants are receiving much attention worldwide. However, most DGAs studied, for the co-extraction of trivalent actinides and lanthanides from HLW form undesirable third phase during the course of extraction. Moreover, the DGAs co-extract other unwanted metal ions like Zr(IV), Y(III), Sr(II) etc. These limitations are more clearly seen in the case of separations from HLW of fast reactor originated than that of PHWR originated due to high burn-ups. Considering all these challenges, advanced unsymmetrical diglycolamides that does not form any third phase during the separation of trivalent f-ions were synthesized and tested using simulated HLW of both PHWR fuel and fast reactor fuels.

In addition, procedures are developed for the mutual separation of lanthanides and actinides using completely incinerable dilgycolamic acid based solvents. The separated actinide fraction devoid of lanthanides is envisaged to be transmuted in fast reactors. Considering the experience in the operation of spent nuclear reprocessing plants and fast reactors, and their co-location, Kalpakkam DAE campus is most ideal location to set-up a facility for the trivalent actinide separation from HLW.

Young Officer's Forum Lecture 4

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Materials Research and Development towards Metallic Fuel Fast Breeder Reactors

The selection and development of core and structural materials play a vital role in ensuring the safety, operational efficiency, and cost-effectiveness of fast breeder reactors (FBRs). Research in advanced materials directly supports India's goal of achieving net-zero emissions by 2070 through commercial metallic-fueled fast reactors.

Fast reactor components face severe neutron irradiation and high temperatures, particularly fuel pin cladding (operating at 400–650°C) and subassembly wrappers (operating at 400–600°C). These components are evaluated based on the accumulated neutron damage expressed as displacement per atom (dpa).

Initially, austenitic stainless steels like SS304 and SS316 were used but were limited by unacceptable void swelling at neutron damage levels of ~60 dpa. To address this, 15Ni-15Cr steels with optimized titanium content, known as alloy D9, were developed and qualified through test irradiations in FBTR. These steels, used in PFBR with 20% cold working, withstand neutron damage up to 80 dpa. Further, development of a Indian Fast Reactor Advanced Clad (IFAC) steel, designed for damage levels up to 100–120 dpa by optimizing silicon and phosphorus content has been completed and test irradiation in FBTR is under progress. IFAC steels are proposed to be introduced in future cores of PFBR.

Beyond the aforementioned dpa levels, austenitic stainless steels become unsuitable due to swelling and associated embrittlement. Ferritic-Martensitic (FM) steels containing 9-18% chromium have demonstrated irradiation stability up to 200 dpa with minimal swelling, though their creep strength limits their application to 600°C. Oxide Dispersion Strengthened (ODS) alloys, incorporating yttria nano-particles, address this limitation by enabling operating temperatures above 650°C and irradiation stability beyond 150 dpa. However, 9Cr- ODS has drawbacks due to higher dissolution rates in nitric acid used in aqueous reprocessing. While 18Cr ODS has significantly lower dissolution rates, development of clad tubes longer than 1.0m is challenging due to difficulties in texture control during processing. MMG has currently taken up the development of 13-14Cr ODS cladding in collaboration with ARCI, MIDHANI and NFC and establishing its fabricability, out-of-pile properties, welding procedures and its irradiation performance.

As part of the R&D on metal fuel program, experimental fuel pins of binary and ternary alloys (Nat.U-6Zr, 14.5EnU-6Zr, Nat.U-19Pu-6Zr and 19EnU-23Pu-6Zr) with T91 (modified 9Cr-1Mo) as cladding are under irradiation in FBTR, followed with their performance assessment in hot cell facility. Similarly, advanced alloys such as IFAC-1, T9 (9Cr-1Mo), 9Cr-ODS, RAFM etc. in the form of pre-fabricated specimens are under irradiation in FBTR. With life of FBTR limited to 10-12y from now, the conceptual design of a test reactor (FBTR-2) with hybrid core of carbide and metal fuels has been initiated. As clad inner wall temperature is ~650°C for metal fuel pins of FBTR-2, T92 (T91 modified by tungsten, reduced Mo) is chosen for cladding, while alloy D9 is proposed for carbide fuel cladding and T9 is considered as wrapper material. Evaluation of the processing methods, mechanical properties, welding procedures, and irradiation performance is being taken up for qualifying T92 steel. Materials proven in FBTR-2 will support the development of commercial FBR 3&4 which are metallic-fueled reactors. Ongoing research also focuses on material development with improved properties such as SS316LN (0.12N) and modified 9Cr-1Mo steels to extend the reactor life beyond 40 years.

Emerging areas of research include adoption of advanced welding process and scaling up for component applications, development of novel shielding materials to improve reactor safety, Ceramic coatings for reactor and reprocessing applications, Enhanced prediction models for thermo-physical properties and diffusion behavior in fuel-clad systems and development of temperature-sensitive materials for absorber rods and fusible plugs.

Post-irradiation examination (PIE) is a vital link in the material development program to qualify material performance under reactor conditions. PIE facilities are being upgraded with advanced characterization tools, including customized Scanning Electron Microscopy (SEM) interfaced with glove box, X Ray Diffraction and Transmission Electron Microscopy (TEM) for quantifying the highly localized chemical and metallurgical damages of fuel- clad. It is also proposed to incorporate laser flash diffusivity for thermo-physical property estimation, retained fission gas analysis, and microanalysis using LIBS (Laser-Induced Breakdown Spectroscopy). It is envisaged to construct a new hot cell facility with advanced remote handling and characterization capabilities for PIE of 5.3m long fuel assemblies and 3.4m long fuel pins of FBTR-2.

The material development road map aligns with India's broader vision for sustainable nuclear energy systems, ensuring high efficiency, safety, and minimal environmental impact. These efforts are pivotal for realizing commercial metallic-fueled fast breeder reactors and supporting India's Net Zero Target by 2070.

Lecture Series - 1

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Single Crystals for Radiation Detectors, Imaging and Transducer Applications

Research and development of materials used as sensors and detectors have played a vital role in the technological advancement of nuclear reactors. Radiation detectors also form the heart of a radiation monitoring system in reprocessing facilities. Therefore, indigenous development and deployment of detector element for different ionizing radiation is utmost important if India wants to achieve self-sufficiency with respect to radiation monitoring devices used in nuclear facilities. Currently, active research is being carried out globally on the development of CdZnTe (CZT) based gamma-ray detectors. Apart from radiation detectors, transducers and sensors are also widely used to monitor various parameters in nuclear reactor environment. For example, the thermal expansion of fuel pins and cladding materials, which are immersed in liquid metal are being monitored by piezo-electric materials. Lead Zinc Niobate – Lead Titanate ($0.91Pb(Zn_{1/3}Nb_{2/3})O_3$-$0.09PbTiO_3$) (PZN-PT) single crystals can be used up to 180°C as active material in surface acoustic wave (SAW) devices for detecting the thermal expansion of cladding materials assisted by wave guides due to its high piezo electric coefficient. Similarly, β-Ga_2O_3 is used as sensor for power electronics and is also a potential candidate for neutron detector application. The major challenges impeding the growth of device grade single crystals of these materials are: poor thermal conductivity in CZT, incongruent melting in PZN-PT and high volatility of β-Ga_2O_3 that results in non-stoichiometry and polycrystallinity. These challenges necessitate novel and advanced growth methodologies. Single crystal growth facilities such as Travelling Heater Method (THM), Czochralski method, Bridgman method, Optical Floating Zone (OFZ) method and high temperature solution growth method, sensor fabricaton and device testing facilities have been established, some of which are discussed here.

1. Portable and wireless CdZnTe based gamma-ray spectrometer

CZT detectors occupy an important niche between cryogenically cooled HPGe and scintillation detectors. CZT detectors exhibit a resolution of about 1% or lower for the 662 keV ^{137}Cs with efficiency matching that of scintillators. Its wide bandgap (~1.57 eV), high atomic number, high resistivity (~10^{10} Ω-cm) and high electron mobility-lifetime product ($\mu\tau$~5×10^{-3} cm^2/V) makes it an ideal candidate for room temperature radiation detection. CZT detectors find application in a number of areas of nuclear fuel cycle, portable devices for security applications and medical as

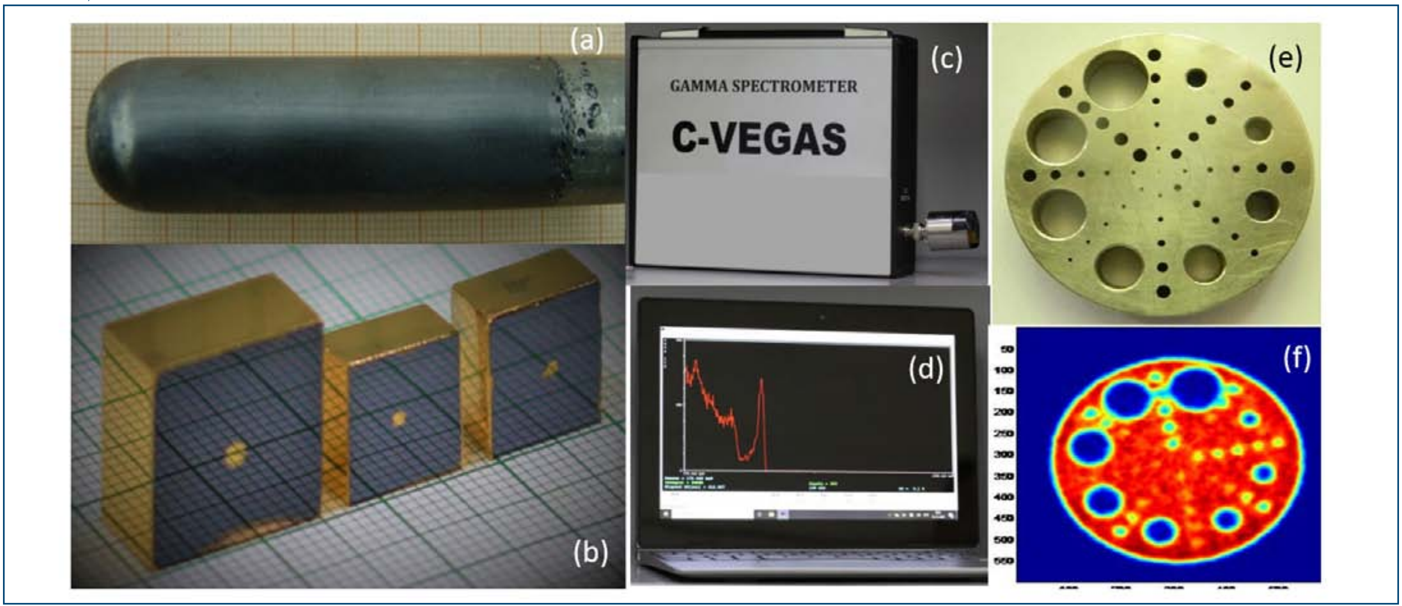

Figure 1: (a) THM grown CZT crystal; (b) Gold coated quasi-hemispherical detector element; (c) Portable and wireless CZT-Variable Energy Gamma Spectrometer (C-VEGAS), (d) Acquired gamma spectrum, (e) Stainless steel phantom and (f) CT image of SS recorded using ^{137}Cs

well as industrial imaging. Due to the poor thermal conductivity of CZT, crystals of CZT are grown by in-house THM, which consists of two-zone furnace for growth and annealing, precision translation (1-5mm/day), rotation (1-10rpm) along with load cell capable of measuring 0.01gm variation. In THM the molten solution consisting of CZT solute and excess Te as solvent is made to migrate through a solid source material (CZT) by the slow movement of the charge relative to the heater. Solute CZT crystallizes while the excess Te solvent is transported to the top. The ratio of CZT to Te within the solution determines its melting point, and the growth temperature is in the range of 850 – 950 ^{0}C. A typical grown CZT single crystal is shown Fig.1a. The wafers from the crystal boule were cut, lapped, polished, chemical etched and passivated. Then, gold electrodes were deposited on the wafer by an electroless process. A detector with a quasi-hemispherical electrode was prepared by electroding the five sides of the cuboidal CZT crystal of 10×10×5 mm^3 dimension, as shown in Fig.1b. A portable and wireless CdZnTe- Variable Energy Gamma Spectrometer named C-VEGAS was assembled and is shown in Fig.1c. It houses a commercial battery bank, Wi-Fi tethering device, preamplifier, MCA, and high voltage modules. The spectrum acquisition and

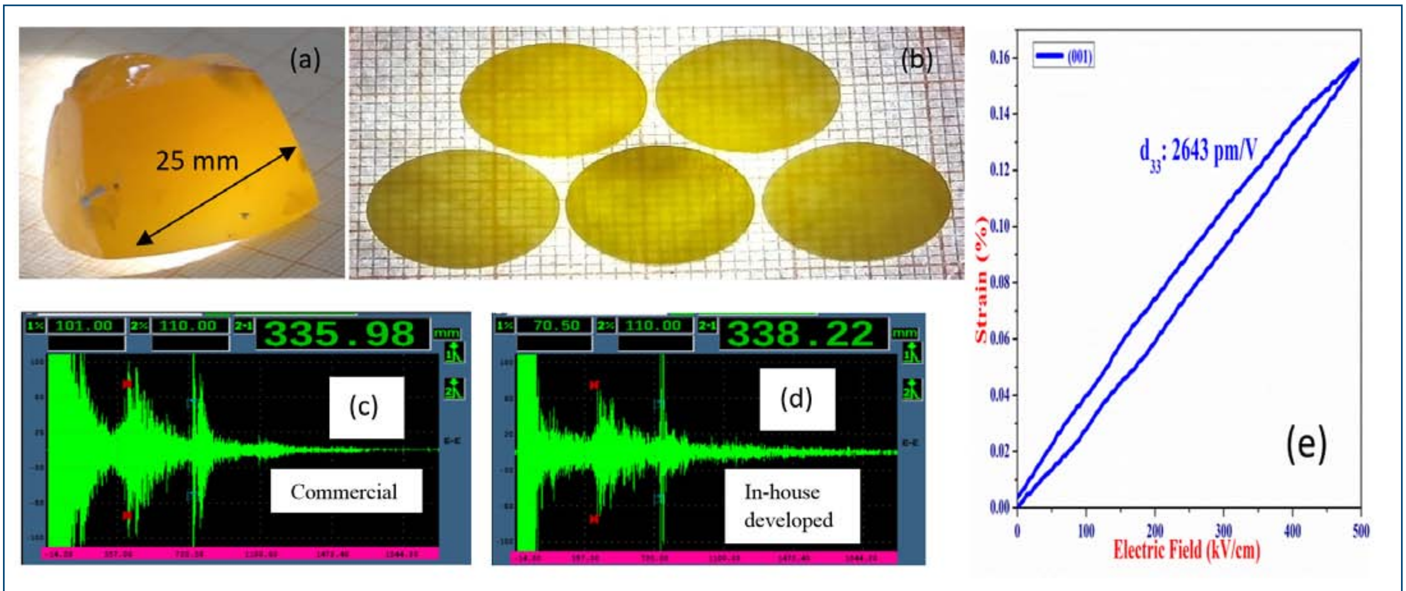

Figure 2: (a) As grown PZN-PT crystal, (b) Cut and polished PZN-PT elements, (c) Acoustic spectrum recorded in Olympus Epoch 650 on commercial element; (d) SAW transducer fabricated on in-house grown PZN-PT crystal and (e) Strain curve

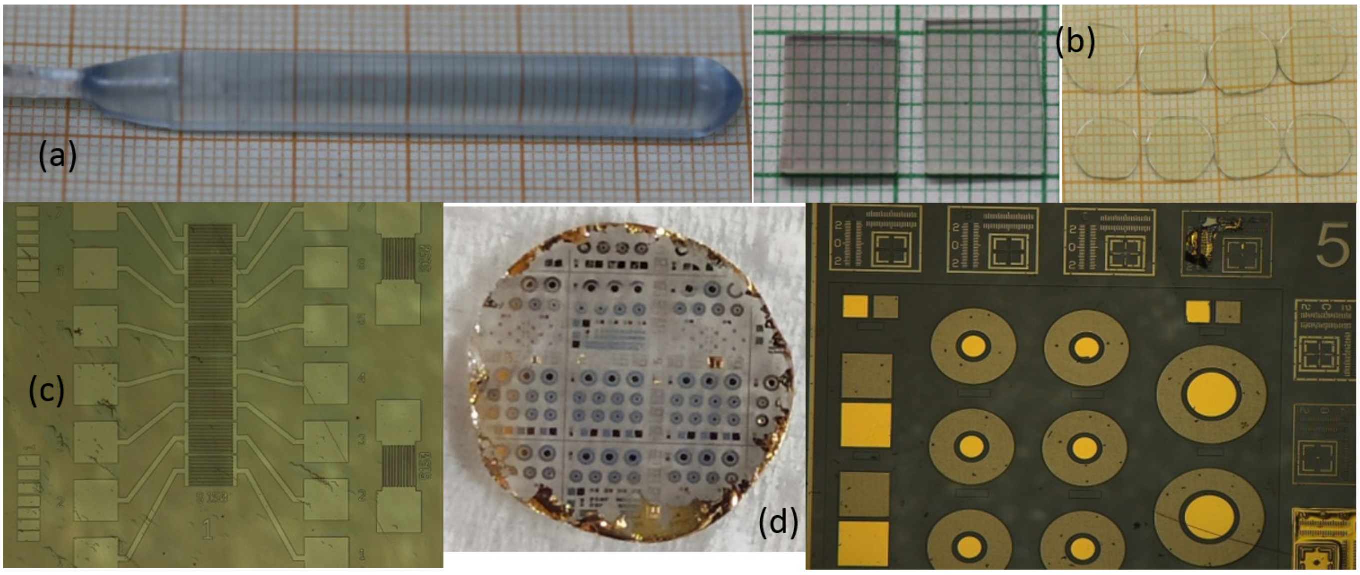

Figure 3: (a) β-Ga_2O_3 single crystal grown in OFZ; (b) Large area (010) and (100) substrates; (c) Optical image of 1x8 linear MSM array for UV detector and (d) Schottky barrier diodes

control were accomplished using the Wi-Fi connection between the tablet PC and spectrometer. Spectrum is recorded using digital signal processing at 1μs shaping time and 0.7 sec flattop time. The detector was positively biased at 1200 V. Photo peak of ^{137}Cs was resolved with an energy resolution of 4 % (Fig.1d). Computed tomography (CT) on the developed CZT detector was validated by imaging a stainless steel (SS) phantom (Fig.1e). Reconstructed image can resolve holes up to 500 micron (Fig.1f).

2. Growth of large size piezo-electric single crystals for transducer applications

Crystals of (PZN-PT), poled along [001] shows anomalously large electro-mechanical coupling factor (k_{33}>0.9%); high piezo coefficients (d_{33}<2000 pm/V); low coercive field (Ec~5 kV/cm) and a high dielectric constant (KT>5000), in comparison to PZT ceramics which possess only about 0.7%, of the same properties 400 pC/N, 30 kV/cm & 4000 respectively. It's Young's modulus is 70-80% lower than ceramic PZT. PZN-PT finds wide applications in nondestructive evaluation, medical ultrasound imaging, and underwater acoustics. Since PZN-PT melts in-congruently, crystal growth was implemented through a novel bottom cooling high temperature solution growth process so that number of spontaneous nucleation would be effectively controlled leading to large dimension crystal. As grown crystals display natural facets (Fig.2a). The cut and polished elements suitable for transducer fabrication are shown in Fig.2b. SAW transducer has been made with a poled (001) oriented crystal. Electro-acoustic parameters were tested at a frequency and voltage of 2.8 MHz and 400 V. The transducer was able to produce two echoes, one corresponding to the weldment of the waveguide to the metal base and the other corresponding to the length of the water vessel in the direction of propagation of the wave. The acoustic spectrum produced by the in-house developed SAW device (Fig.2d) matches well with the spectrum produced by the commercially available probe (Fig.2c). Electric field dependent unipolar strain of poled PZN-PT depict longitudinal piezoelectric coefficient (d_{33}) ~2600 pm/V (Fig.2e).

3. Growth of β-Ga_2O_3 single crystals by OFZ technique

β-Ga_2O_3 has a wide bandgap of 4.8 eV with transparency up to 260 nm finds applications in fabrication of light- emitting diodes, Schottky barrier diodes, neutron detector and field-effect transistors. β-Ga_2O_3 melts congruently at about 1820°C and single crystals were grown using a four mirror halogen lamp based OFZ system. As grown single crystal is shown in Fig.3a. Cut and one side polished substrates for photodetector and Schottky barrier devices are shown in Fig.3b. UV-Photodetectors (Fig.3c) and Schottky barrier diode (Fig.3d) fabricated in collaboration with CeNSE, IISc, Bangalore are shown in Fig. 3c and 3d respectively.

Lecture Series - 2

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Design & Development of Customized and Innovative Sensors for FBR program

DAE Kalpakkam complex is a multi unit site consisting of R&D organizations for nuclear research, power reactors of three stages of Indian nuclear program and various associated units. Thus, it requires many sensors and instruments to monitor various parameters in various utilities' processes, to ensure that all the installations are running safe with ease of maintenance and operation. To achieve this objective, at SISD, several innovative sensors and electronic systems were designed, developed in-house and deployed throughout the site.

Customized sensors and systems are developed to keep pace with ever changing requirements and challenges in the technology. The indigenous design, development of customized sensors and electronics make DAE Kalpakkam complex self reliant to the extent possible. The division does multi disciplinary research, design, development, supply and service support of application specific custom made sensors and unique processes, based on requirement from various nuclear facilities. In the absence of suitable indigenous commercially of the shelf sensors at affordable prices, sensors are designed inhouse with the moto of Standardization with Simplification and with complete documentation.

Some of the sensors/ systems designed in house and supplied to PFBR are as given below

> CSRDM dashpot oil level sensor for CSRDM's

> Conductivity sensors for condensate polishing unit and DM plant

> pH meter sensors for condensate polishing unit and DM plant

> MV-SV differential pressure sensor

> Software for estimating criticality

Nearly 100 sensors are designed, developed and supplied to utilities and labs such as FBTR, RDTG, RDL, CEG, CWMF, ESG, FRTG, MSG, RPG, KAMINI, ESL, DFRP, WSCD, SRI, MAPS & KAPS.

As a spin off, in the process of developing the sensors, ~25 international journal papers are published.

Technology of conductivity meter is transferred to the following firms in the last three years.

> M/S Serve XL Enterprises, Bengaluru

> Rajasthan based M/S Himalayan water Science Private Limited

> Mumbai based M/S Lablink company

> M/S Tech Source Solutions, Bengaluru,

pH meter is also offered for technology transfer

Oil level sensors are offered for incubation to M/S Krithy labs Chennai MSME and it is in the advanced stage of completion, for prototyping for their petroleum level measurement application in ~30000 trucks.

Turbidity meter is also offered for incubation.

Following sensors are going to be offered for incubation in the coming quarter.

> Guard tour monitoring system

> Lube oil quality meter
> Portable IoT power meter

Prototype Hardwired sensors developed for FBR's and other utilities are (Technology readiness varies from 5-9)

> Self powered passive temperature monitor for SGDHR,
> Piping snubber displacement and oil leak sensor
> Field tunable digital panel meter
> DSRDM drop time and time estimate system
> Void sensors for sodium
> Catchpot oil level sensor
> Dashpot oil level sensor
> Pressure transmitter,
> NaOH very high molarity portable sensor
> Wireless sensor for radiation monitoring

Micro controller based sensors:

> Transformer oil monitoring device
> I&C for gas sensors
> Sensor for fuel pin integrity checking
> Ovality meter
> Water level fluctuation sensor and analysis system
> Void fraction sensor
> Aumatic titrator
> Wear debris monitoring instrument
> Lubricant oil quality monitoring instrument
> Level probe and interface sensor for pyro processing plant
> Sensors for reprocessing applications

Prototype Sensors/systems are also developed for societal applications as given below.

> Portable 4g wireless power meter
> Spirometer
> Portable HW meter for checking adulteration of milk, petrol/diesel
> Sensors and interface units for Wireless monitoring of conductivity, pH, temperature & TDS in water sumps and reservoirs in IGCAR.
> Proof of concept experiments for the inherently safe, portable, passive, stationary-moving-flying micro SMRs

W.r.t. the sensor development program, the future activities are planned as given below

> Prototype instruments shall be tested in field environment and to be qualified for type tests to commission in reactor
> All the matured and related technologies need to be transferred and incubated with potential firms, to take them to wider usage in the industry.
> Development of new sensors and HW systems to replace the bought out and software based systems to avoid V&V in FBR's.
> Taking potential requirements in FBR's that need to be taken up where there is no sufficient support from industry in terms of documentation and software, especially for the bought out products.

Development of following sensors with HW electronics is in the pipe line:

> GM tube electronics
> T/C seven segment display
> High conductivity sensor
> Na level sensor electronics
> T/C lemo wireless connector
> OFC leak sensor
> OFC dashpot level sensor
> Analog PID controller
> fA current source/meter
> Rotary encoder
> Neutron detector and reconfiguration of Neutron flux monitoring system for PFBR
> Vernier power display meter
> HW Scalar timer for pulse counting
> Fire alarm sensor & panel
> Automatic RFID card detection and access control with built in Biometric sensor

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Lecture Series - 3

Experimental Sodium Facilities & Sodium Handling Experiences at FRTG

Introduction:

Fast reactors use liquid sodium as the coolant due to its favourable neutronic and thermal properties. Since the early 1970s, the Fast Reactor Technology Group (FRTG) is active in various areas related to sodium technology. This includes the design, erection, commissioning, and operation of sodium facilities for basic and applied engineering studies. The group operates as many as 13 sodium loops. In order to validate the reactor design, several full scale and scaled down experimental facilities using sodium are established and operated. Brief details about the experimental sodium facilities in operation at FRTG, activities carried out in these experimental facilities and sodium handling activities are mentioned below.

Fig.1: Steam Generator Test Facility

Experimental Sodium Facilities:

500 kW loop the first sodium loop was commissioned and testing of Intermediate Heat Exchanger, performance testing of EM pumps was carried out. Separate loops were operated for calibration of flow and level sensors for FBTR. Large Component Test Rig was operated for full scale testing of critical components of PFBR. Heat & mass transfer studies in cover gas, circumferential temperature asymmetry, sodium aerosol deposition in top shield, temperature distribution studies for PFBR roof slab model and control plug model etc. were carried out. Full scale testing of prototype Control Safety Rod Drive Mechanisms [CSRDM], Diverse Safety Rod Drive Mechanisms (DSRDM), testing of actual PR&PTM of IFTM, Transfer Arm, Failed Fuel Location Module, Under sodium ultrasonic scanner of PFBR were also carried out. Calibration of permanent magnet flowmeters, level probes and Eddy Current Flow sensor for PFBR, cyclic

Figure 2: LCTR pipe line sodium leak

and endurance testing of gripper and translation bellows designed for CRDM of FBTR were also carried out in sodium. 5.5 MWt Steam Generator Test Facility[Fig.1] which simulates the operating parameters of steam generator of PFBR was operated for estimation of SG heat transfer area margin, thermal hydraulic instability studies, testing under transient conditions and finally endurance test was completed. Sodium Water Reaction Test Rig was operated for steam injection studies into sodium with Steam Generator tube material specimens and has been used to generate data on material wastage due to small leaks. The facility has also been useful to evaluate the performance of different types of hydrogen sensors in sodium and argon. In-Sodium Fatigue & Creep loops were operated to study the mechanical properties of PFBR component materials specimens under the influence of flowing sodium like low cycle fatigue, creep fatigue interaction tests, creep and creep rupture. LEENA Facility was operated for qualifying the leak detector layout for different sizes of pipelines for PFBR, by simulating actual sodium leak. SADHANA Sodium facility, a 1:22 scale model sodium facility was operated to study the thermal hydraulic behaviour of SGDHR of PFBR. Estimation of heat transport capability, steady state and transient response of the SGDHR during various emergency operating conditions were experimentally validated in this facility. Thermal Shock Test Facility was operated for cold thermal shock studies on the dissimilar weld joints in the DSRDM electromagnet and qualification. Sodium Facility for Component Testing has been operated for performance testing of ALIP of 50 and 170 m3/h capacity for PFBR and for testing of frozen seal valves. Sodium Technology Complex [STC] a new building with a new sodium facility is being commissioned at IGCAR northern site. Sodium Charging in the storage tank of STC is under progress. Testing of integrated cold trap, frozen seal valve, in-sodium pressure sensor, Ex-vessel sensor etc., are other experimental activities carried out for FBR-1 & 2. Around twenty eight sodium leak incidents have occurred during the last 30 years of operation of the sodium facilities. Most of the leak incidents have been eye openers for the improvement in the safety features of the facilities.

Figure 3: Sodium Cleaning of ALIP for PFBR

Corrosion studies on AISI 316 L(N) SS material samples exposed to hot sodium, metallurgical studies on AISI 316 L(N)SS specimens exposed to sodium fire, effect of iron content on self-welding characteristics of NI-Cr-B hard face coated AISI 316 L(N) SS in sodium and studies on structural materials exposed to high temperature sodium in the presence of nitrogen gas have been carried out..

Sodium Aerosol Studies:

Experimental studies on the suitability of Sodium Aerosol Detection system for its functioning in nitrogen atmosphere, aerosol dispersion studies in open air for determination of ground level mass concentration, mass size distribution & chemical speciation were carried out.

Experiences in Sodium Transportation: 150 tonnes of sodium required for FBTR and 100 tonnes of reactor grade sodium for Large Component Test Rig were transported safely from Vadodara. 18 tonnes of sodium required for Steam Generator Test Facility was transported by ship from France and shifted from Chennai port to IGCAR. 6 tonnes of sodium manufactured indigenously by Heavy Water Plant Facility, Vadodara was transported safely by road to IGCAR.

Experiences in Sodium Cleaning & Disposal: Sodium cleaning experiences have been gained during the many years of operating of sodium facilities. Some of the recent important activities are cleaning of 170 m3/h Annular Linear Induction Pumps [Fig.3], FFLM, Intermediate Heat Exchanger [IHX] etc., for BHAVINI.

Sodium Fire related experiments: Class-D based Sodium fire extinguishing powder was tested on large sodium fires [50 kg] and qualified for sodium systems. As part of studies related to automation of sodium fire extinguishing, temperature profile above a sodium pool fire was experimentally evaluated.

Personnel Safety & First Aid during sodium handling: Handling of sodium requires necessary precautions with respect to the personnel safety. In case of sodium fall on body or eyes written procedures are established and being followed with respect to first aid and further treatment.

Summary:

This write up gives brief details about various experimental sodium facilities and the activities completed. In addition details of other experimental activities, sodium cleaning experiences, sodium leak incidents, sodium fire handling and experiences, sodium aerosol studies and experiences, personnel safety and first aid in case of sodium related injuries are covered in this write up.

Lecture Series - 4

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Corrosion Issues of Materials in Fast Reactor and Reprocessing Environments

The major issues that limit the service life of components in nuclear reactors and reprocessing plants is corrosion. Components of nuclear power plants are normally designed with the objective of zero-incident failures. However, reactors and reprocessing plant materials suffered failures through corrosion, costing huge economic losses in shutdown, repair, inspection and replacements of structural components. Corrosion Science and Technology Division (CSTD) at IGCAR has established an active and extensive R&D Programme to develop advanced materials, coatings and testing, evaluating and monitoring technologies for Fast Breeder Reactors (FBRs) and associated Reprocessing Plant. The mandate of CSTD is to provide R&D support for the FBRs and associated fuel cycles, research and development activities focusing on the development of high-temperature structural and advanced materials and novel durable coatings for corrosion protection as well as assessing the corrosion performance in different environments like: high temperature flowing molten sodium, molten chloride and fluoride salts and lead (Pb-Li & LBE), steam-water, seawater, nitric acid and molten chloride environments, aqueous media containing chloride or other halide ions, MIC and bioorganisms, concrete corrosion, steam oxidation, etc. In addition, CSTD is involved in basic R&D for corrosion mitigation and monitoring through in-house activities and collaborations with academic and research institutions and provides consultancy and services with respect to material selection, corrosion allowance, corrosion protection, failure analysis and life assessment of components.

The following are some of the key areas that have been actively pursued over the past few years to address the corrosion issues of materials used in fast reactor and reprocessing plants: (a) Materials and Coatings Development for FBRs: Development of high-performance ceramic coatings designed for molten salts and uranium melting applications. Advanced super hydrophobic, self-healing, graphene-based coating technologies are explored to mitigate microbiologically influenced corrosion. Research also includes the study of liquid metal corrosion (molten Pb and LBE) on candidate materials such as P91 and 316LN SS, as well as coatings like Fe/Al-based coatings. Sodium corrosion studies are also conducted, focusing on the performance of structural materials like 316LN SS and modified 9Cr-1Mo steel exposed to flowing sodium in a bi-metallic loop for 50,000 hours at 525°C, and environmental assisted cracking (EAC) and localized corrosion (pitting, crevice and IGC) & EAC (SCC, HE & CF) of type 304L and 316LN SS and its weldments. (b) Aqueous Reprocessing Materials: Efforts in this area include the generation of wear and tribo-corrosion data for reprocessing materials such as 304L SS and its weld metal, along with Ti-Gr2. Long-term corrosion data is also being collected for materials like FRFCF 304L SS, NAG SS, CP-Ti, Zr, and Ti alloys, and weldment under simulated reprocessing environments. Newer corrosion resistant alloys of metallic glasses and medium and high entropy alloys based on Ti/Zr for applications in nitric acid are also being explored. (c) Molten Salts Corrosion and Pyrochemical Reprocessing Work: This includes the qualification of candidate materials and ceramic coatings for use in molten salts during pyroprocessing applications. Research is also focused on the chemical vapour deposition (CVD) of pyrolytic graphite coatings on high-density graphite (HDG) components, uranium melting crucibles, cathode mould release, and anodes, all critical for pyrochemical reprocessing. (d) Other Developments and Projects: Major works include the development of environment-friendly chemical formulations and processes for steam generator materials. Additionally, efforts are focused on high-performance concrete for nuclear power plants in coastal regions, as well as polymer composite and super hydrophobic coatings designed for corrosion-resistant service water pipes, and the development of innovative biocides and bio-dispersant formulations aimed at MIC control and improving the efficiency and longevity of service water systems. Other activities also include AUSC-related project work on the fireside corrosion and steam side oxidation of candidate alloy materials (304HCu, 617M, Sanicro-25, 740H, etc) for AUSC plants.

A well-known quote about corrosion states, "Rust Never Rests," highlighting the relentless nature of this challenge and the necessity for ongoing research and innovation. The future road map focuses on the development of advanced materials and coatings for critical components, comprehensive long-term corrosion evaluations, accelerated corrosion testing, robust corrosion monitoring systems and innovative solutions for corrosion. Specifically, the focus will be on developing self-healing ceramic thermal barrier coatings, corrosion-resistant materials for molten lead reactors and Gen-IV systems, and conducting high-temperature corrosion studies in molten FLiNaK and FLiBe salts for next-generation reactors. Additionally, efforts will include the development of indigenous probes for long-term data collection in nitric acid, molten salts, and lead environments, as well as developing life prediction models for environment-assisted cracking and oxidation in reactor materials. The road map also includes advancing cleaning processes for steam generator tubes, omniphobic self-healing coatings for ferrous and non-ferrous materials, and the development of bulk metallic glasses and refractory high-entropy alloys for extreme conditions. Furthermore, non-conventional biofilm and MIC control methods will be explored. Through these activities, the safety, efficiency, and sustainability of components used in FBRs and associated reprocessing plants will be ensured, further contributing significantly to the advancement of nuclear technology and its sustainable integration into the energy landscape.

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Lecture Series - 5

Distributed Digital Control System for PFBR

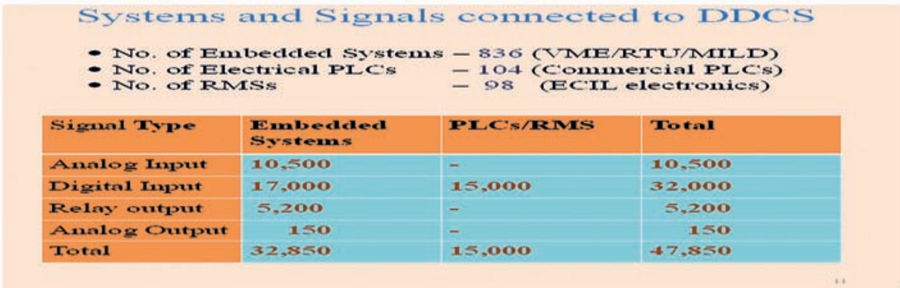
Introduction

Distributed Digital Control System (DDCS) is the design architecture adopted for Instrumentation & Control (I & C) of PFBR. DDCS is implemented using three-tier architecture wherein bottom tier consists of control nodes, middle tier comprises of process computers and top tier constitutes of display stations. The control nodes are geographically distributed and networked together with process computer and display stations.

Constituents of DDCS and their purpose:

DDCS is defined as the constituent of all nodes interconnected through Ethernet network of the plant and the network components. There are three broad categories of nodes connected in the DDCS network namely control nodes, process computer and display stations:

Control nodes: These are the digital I&C systems dedicated for monitoring/control of one or more specific processes. They include VME bus based RTC systems, RTU based systems, PLCs and sensors provided with network connectivity. These nodes perform distributed functions of the DDCS.



Systems and Signals connected to DDCS

- No. of Embedded Systems – 836 (VME/RTU/MILD)
- No. of Electrical PLCs – 104 (Commercial PLCs)
- No. of RMSs – 98 (ECIL electronics)

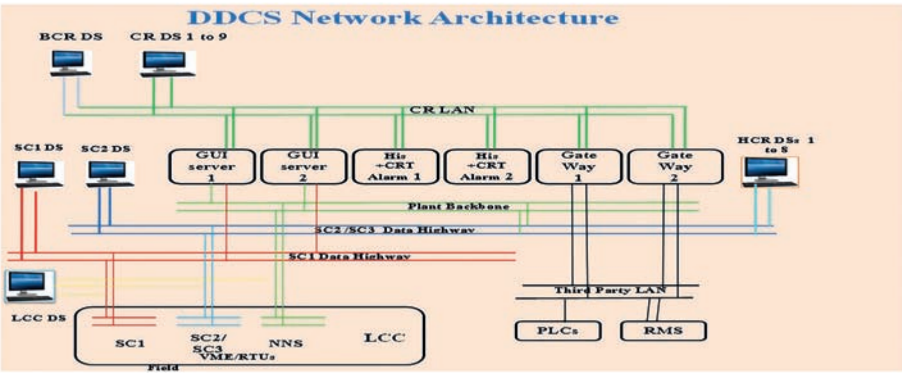
Signal Type	Embedded Systems	PLCs/RMS	Total
Analog Input	10,500	-	10,500
Digital Input	17,000	15,000	32,000
Relay output	5,200	-	5,200
Analog Output	150	-	150
Total	32,850	15,000	47,850

Process computer: Set of Fault tolerant servers meant for performing centralized functions in the DDCS network. Typical functions include facilitating information exchange between control nodes, generation and transmission of alarm signals, sending configurable parameters to control nodes, performing certain computational functions, logging of plant data and serving data required for GUI to operators.

Display Stations: These are the computers meant for providing GUI for the operators to interface with various other nodes of the DDCS network. These are distributed in CR, HCR, BCR, LCCs and in LCP.

Salient Features:

- Provision to view the plant data in various display formats
- Provision to operate the plant by issuing soft commands from process mimic displays of the display stations
- Provision to change the set points of the different process logics from display stations
- Provision to log the plant data
- Provision to generate soft alarms in chronological order
- Computer Guided mode of operation for Fuel Handling Machines to ensure the sequence of operation
- Connecting the third party systems in a secure manner to the plant control network.



Lecture Series - 6

Prof. C.V.S. Brahmananda Rao
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Development of Solvents for Nuclear Fuel Cycle

Tri-n-butyl phosphate (TBP) in n-alkane diluent medium (typically 1.1M of extractant in diluent) was utilized as a solvent for various separation processes in nuclear technology. However, the experience gained in the last seven decades has brought out a few drawbacks of TBP during reprocessing of fast reactor fuels. The major drawbacks of TBP include third phase formation (splitting of organic phase into two) with tetravalent metal ions like Pu(IV), higher aqueous solubility, radiation degradation etc. Several extractants have been investigated in our laboratory towards identification of an alternate extractant to TBP in various stages of nuclear fuel cycle.

Separation of U(VI) and Th(IV) from Rare Earths, RE(III) in nitric acid media with solutions of tri-iso-amyl phosphate (TiAP) in n-dodecane has been studied by batch extraction in cross-current mode to evaluate the feasibility of employing TiAP as an extractant for monazite ore processing. Solvent extraction studies were carried out with solutions containing Zr(IV), Hf(IV) and Ti(IV) with TBP and TiAP based solvents. A feed slurry containing Zr, Hf and Ti with concentrations of 82, 2.4 and 0.21 g/L, respectively in 4.5 M HNO_3 was employed. The third phase formation behaviour with Zr was examined using 1.1 and 1.47M TiAP and TBP solutions in n-Dodecane (n-DD) with different A/O ratios (aqueous by organic). Cross-current experiments were carried with zirconium feed slurry using 1.47M TiAP/n-DD with 1:3 A/O ratio. The extraction of Zr(IV), Hf(IV) and Ti(IV) was found to be about 89.8, 23.8 and 21.5%, respectively in the case of 1.1M TiAP/n-DD after four successive contacts. These studies will pave way for the development of flow sheets for separation of Zr from Hf and Ti using TiAP based solvent with high throughputs.

The development of phosphate based solvents for nuclear fuel cycle led to several studies with TiAP to qualify this solvent for various applications. Separation of U(VI) and Pu(IV) from Am(III) and lanthanides with 1.1M TiAP/HNP solvent using an ejector mixer-settler has been demonstrated. Aqueous reprocessing of metallic alloy fuels was also demonstrated. Another class of alternate solvents are phosphonates which exist in two variants, H-phosphonates and dialkylalkyl phosphonates. Large quantity of sulphate and phosphate bearing waste gets generated during analysis of U and Pu by potentiometric methods. Conventional TBP based solvent cannot be employed for recovery of U and Pu from sulphate and phosphate waste as it possess low distribution ratios in this medium. H-phosphonates are vital for recovery of actinides from highly complexing medium such as sulphuric acid and phosphoric acid. Several dialkyl H-phosphonates were examined for recovery of U and Pu from actual acidic waste solutions and these H-phosphonates have high D values for U, Pu and Am compared to TBP. Another class of phosphonates i.e. dialkylalkyl phosphonates were examined for recovery of palladium from high level waste. These dialkylalkyl phosphonates exhibit higher D values for Pd compared to TBP indicating that these solvents can be employed for recovery of Pd from high level waste. A new class of compounds, phosphoramide based solvents were prepared and characterised. Various hexa alkyl phosphoramides were synthesized by condensation reaction between $POCl_3$ and dialkyl amines. These molecules were thoroughly characterized by different techniques and various physico-chemical properties were measured and extraction behaviour of actinides were examined under various conditions. It has been identified that phosphoramides has high distribution ratios for Pu, high decontamination factors and possess low aqueous solubility compared to TBP. Alternate solvents were developed for processing of U/Th feed solutions for their separation using tri-sec-butyl phosphate (TsBP) with high throughput and better separation factors.

In addition to the experimental studies outlined earlier, systematic theoretical investigations were carried to understand the behaviour of actinide extraction and to support experimental ligand design for actinide separation and recovery. However, the application of theoretical calculations to actinide complexes poses challenges, which can be addressed through the use of appropriate methodologies. As an initial step, studies were carried out to identify the geometric and electronic structures of various complexes formed during extraction based on the stoichiometric equations. The energetics of metal-ligand interactions were derived and calculated. The data showed one-to-one correlation between experimentally established distribution ratios and theoretically derived complexation energies. This hypothesis was tested on more than 90 ligands and metal complexes, and was found to be a useful index for predicting ligand selectivity. For instance, the computationally predicted selectivity of ligands such as dicyclopentyl H-phosphonate, dicyclohexyl H-Phosphonate, and dimenthyl H-Phosphonate was later successfully corroborated with experimental distribution ratios.

Greenery development as a part of the Swachhata-Hi-Seva 2024 celebration

September 17- October 2nd , 2024

As part of Swachhata Hi Seva – 2024 celebrations, a tree plantation campaign was organized by IGCAR under the theme 'EkPedhMaaKeNaam' as suggested by Hon'ble Prime Minister to plant trees as a mark of love and respect for one's own Mother and for protecting and preserving Mother Earth. Around 2500 numbers of Ethinc Avenue, flowering and fruit-bearing trees were planted

Shri C. G. Karhadkar along with his colleagues during tree plantation

during the campaign spanning an area of around 60,000 sq. meters over 11 days by involving all the employees of IGCAR. This program helped to create awareness about cleanliness and greenery development. This campaign helps to ameliorate land degradation and also to create a shelter for the local birds and animals thereby enriching the biodiversity within the campus. This generated an interest and awareness among the employees in greenery development, protection of the environment, and the significance of sustainable development goals. For the first time, a plantation campaign covering 2500 saplings in a 60,000 sq meter area in a record short time of 11 days was done with the active participation of all the employees. As part of this campaign, 15 types of fruit-bearing trees(Custard apple, Wood apple, Jamun, Water apple, Star fruit, Orange, Table orange, Guava, Chiku, Tamarind, Jackfruit, Coconut, and Badam etc.), 15 different types of avenue and flowering plants (Cannonball, Tree tulip, Rosy trumpet, Red Silk Cotton, Alstonia (devil's tree), Punnai (oil-nut tree), Pride of India, (Koelreuteriapaniculata), Kadamba, Indian tulip, Spanish cherry, Red sandalwood, Manoranjitha, Arjuna tree, Neem tree, Pungam (Pongamiapinata), and Rudraksha tree), and some medicinal and ornamental plants were planted in the DFO plantation area, adjacent to Gamma Garden, and in the Air Force Camp area, located on the western side of the KKM gate.

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Awards & Honours

- Prof. (Dr.) M. Vasudevan, AD, MDTG, MMG has been awarded the G.D. Birla Gold Medal from Indian Institute of Metals for the year 2024.

- Dr. Diptimayee Samantaray, Head, HMTS, HMTD, MDTG, MMG has been awarded the Homi Bhabha Science and Technology Maanpatra for the year 2024 for her outstanding contributions in the field of Power Plant Material Manufacturing Technology and Development.

Best Paper/Poster Award

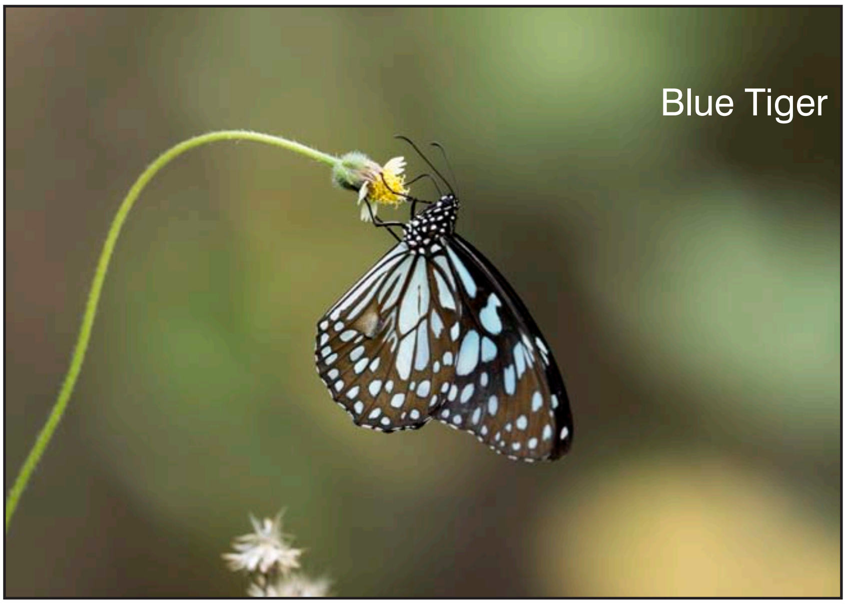
- Shri A. D. Arun has been awarded the "Analytical Methods Poster Presentation Prize", for the paper titled "An indigenous automatic titrator using pulsating sensors for diverse applications in trace level chemical analysis" by the Royal society of Chemistry, at CAMC 2024 - Conference organized by AMD, Hyderabad, India, held during 20-22nd November 2024.

- Dr. Sangeetha Jayakumar received the TPSI Founder President's Award for the Best Oral presentation at the International Conference on Materials and Thermophysical Properties (ICMTP) held during 21-23rd Nov. 2024 for the paper titled "Comparative study of the dosimetric parameters of multifiller nanocomposites for Lead-free diagnostic X-ray shielding" by Sangeetha Jayakumar, B.B. Lahiri, Arup Dasgupta.

- T. N. Prasanthi received ESAB India Award 2024 by the Indian Institute of Welding for best paper across all categories presented in Proc. 6th Inter. Congress: Advancement through sustainable and green welding 22nd-24th January 2024, Bangalore International Exhibition Centre, Bengaluru (IC-2024), IC-2024 for the paper titled "Interdiffusion studies in additive manufactured Ni-based hardfacing alloy coatings on austenitic stainless steel" by T. N. Prasanthi, C.P. Paul, C. Sudha.

- Shri K Krishna Chaitanya, Shri P Ettiyappan, Shri K Murugan, Shri P Chenthilkumar, Shri D Suresh and Shri P Azhagesan from Quality Assurance Division(QAD), SQRMG, IGCAR received "Par Excellence Award" in the 38th National Convention on Quality Concepts (NCQC 2024) conducted by Quality Circle Forum of India (QCFI) during 27th - 30th December, 2024 at IIITM, Gwalior, Madhya Pradesh.

Bio-diversity @ DAE Campus, Kalpakkam



Blue Tiger

Blue Tiger is a small butterfly with wide wings. It has a wingspan of 90 to 100 millimeters, with the males being smaller than the females. The upper side of the wing is dark brown to black and patterned with bluish-white, semi-transparent spots and lines.

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