GAS-COOLED REACTOR
ADVANCED REACTOR TECHNOLOGIES PROGRAM

07-16-2024

Robust bullet-time tagging and tracking system based on computer vision for individual ex-core TRISO-fueled pebble identification

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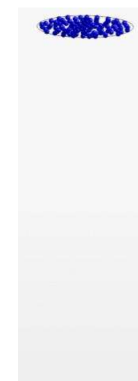
Motivation and Objectives

- **Motivation:** The motivation behind this proposal stems from the need to enhance the safety, efficiency, and reliability of high-temperature gas-cooled pebble bed reactors (PBRs)
- **Overall objective and challenge :** The project aims to develop and validate a novel, robust bullet-time tagging and tracking system using computer vision techniques for identifying TRISO-fueled pebbles and determining their transit times in-situ. This system addresses challenges of high temperature, radiation resistance, and economic feasibility. In commercial applications, it will measure pebble burnup to ensure pebbles do not exceed their end-of-life limits. Accurate burnup measurement is critical as it relates to the pebbles' residence time within the reactor core, impacting fuel utilization and safety. Prolonged residence can lead to irradiation, thermal damage, and fission product release, highlighting the importance of precise tracking and timely removal..
- **Objectives:**

1. Develop a high-temperature and radiation-resistant method for patterning Ultra-High Temperature Ceramic (UHTC) on graphite pebble.
2. Design a high-survivability camera array to capture images under extreme conditions.
3. Create a rapid and robust image processing and recognition methodology for practical application.
4. Adapt the cold flow pebble bed system for 6 cm diameter tagged pebbles and the new camera system.
5. Implement and integrate non-invasive Residence Time Distribution (RTD) and Radioactive Particle Tracking (RPT) techniques to validate the system.
6. Refine and adjust the image processing system using proven RTD/RPT techniques.
7. Assess the abrasion resistance of the tagged graphite pebbles over prolonged operation.
8. Evaluate the feasibility of implementing the developed system under real high-temperature and accident conditions in pebble bed reactors.



Simulation for the PBR Geometry

Tasks of the Project

Task 1. Developing, examining and assessing various methods of robust and economic pattern of Ultra-High Temperature Ceramic (UHTC) embedding or coating flush mounted on the pebbles surface

Task 2. Developing the optimal high-speed camera array with high survivability under high temperature and radiation

Task 3. Developing robust and rapid methodology of image processing and recognition system

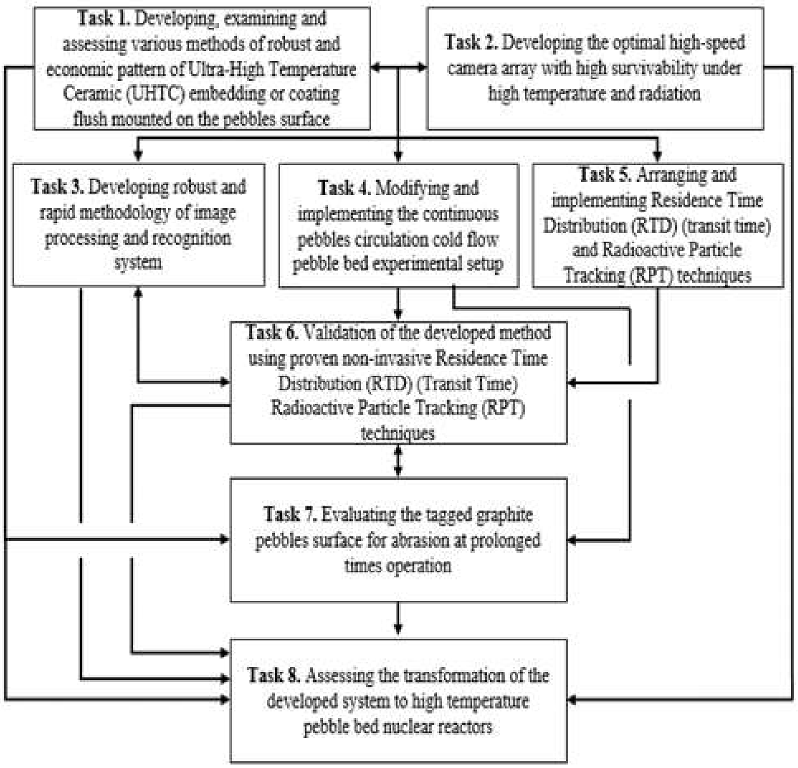
Task 4. Modifying and implementing the continuous pebbles circulation cold flow pebble bed experimental setup

Task 5. Arranging and implementing Residence Time Distribution (RTD) (transit time) and Radioactive Particle Tracking (RPT) techniques

Task 6. Validation of the developed method using proven non-invasive Residence Time Distribution (RTD) (Transit Time) Radioactive Particle Tracking (RPT) techniques

Task 7. Evaluating the tagged graphite pebbles surface for abrasion at prolonged times operation

Task 8. Assessing the transformation of the developed system to high temperature pebble bed nuclear reactors



Task 1 Selection of an Ultra-High Temperature Ceramic (UHTC) Pattern

Task 1 involved two main steps:

1. Selection of appropriate pattern type that can be easily processed and accurately recognized by the developed image recognition algorithm.
2. Exploring, testing, and assessing a feasible embedding, coating, or tagging method to pattern the 6.0 cm graphite pebbles with the thermal ultra-high temperature ceramic Ink (CERAMACOAT 503-VFG-C).

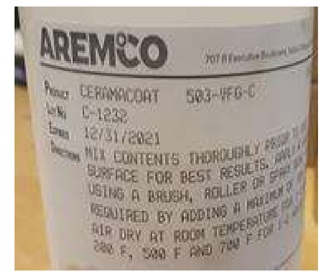
Pattern Selection Criteria

- The pattern should be salient, clear, and easily identified by the image recognition algorithm.
- The pattern should withstand abrasion during normal and high temperature conditions.
- The pattern should be produced with a practical and economical technique.

Task 1 Selection of an Ultra-High Temperature Ceramic (UHTC) Pattern

Up-to-date accomplishments / Carving Method

6.0 cm Graphite pebbles carved using Model Mazak VTC-20B and tagged with ceramic patterns



503-VFG-C-White

Single part, alumina-filled, water-dispersed, phosphate-bonded, highly abrasion and corrosion resistant sealer for applications to 3000 ºF (1650 ºC)

Task 1 Selected Early Attempts

Investigating and finding a patterning methodology using a pad printer

6.0 cm Graphite pebbles tagged with ceramic patterns

Pad printer

Task 1 Selected Early Attempts

Implementing Heat Treatment

- Early results of the ceramic ink-based patterns indicated weak adhesion between the deposited ceramic ink and the graphite surface. The patterns were prone to scuffing and deformation.
- We found that the treatment of the ceramic patterns after depositing them on the graphite surface increased the adhesion property and resulted in stable and brighter patterns.
- Therefore, we included a treatment step for applying ceramic patterns

Ceramic Patterns on graphite pebbles **(a)** Without treatment **(b)** With treatment

Task 1 Selected Early Attempts

Type of Pebbles & Patterning Methods Attempted

- ❖ Wooden balls of 6.0 cm were utilized during the first year of the project.
- ❖ The manufacturing of 6.0 cm graphite pebbles was delayed due to the pandemic.
- ❖ We selected and bought small printing machines.
- ❖ Several pattern types were explored, produced, and tested, including:
  - PostNet Barcode
  - QR Code
  - Random Pattern
  - Shapes
- ❖ It was concluded that these patterns were not suitable and subsequently discarded.
- ❖ Different patterns were then tested, including numerical patterns.

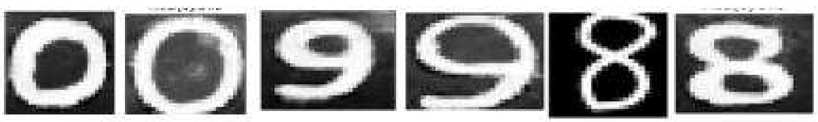
Selected Previous Patterning Methods and Printers

12

Task 1 Selected Early Attempts

Additional Selected Previous Patterning Methods

- Several patterning methods, including stencil and brush spray, paint pen, and pad printing, were tested to tag graphite pebbles with 3–4-digit numbers using the thermal ultra-high temperature ceramic ink (CERAMACOAT 503-VFG-C)
- The patterns obtained from the stencil and brush spray, and paint pen were insufficient as the generated number could not be reproduced precisely



Paint pen

Brush spray

13

Task 2. Developing the optimal high-speed camera array with high survivability under high temperature and radiation

- The bullet-time photography system of two high-speed radiation-resistant cameras has been achieved after various tested configurations.

- This camera array obtains the best images. It provides the minimum number of cameras with sufficient images of the pebble for identification.

- Therefore, two new high-speed cameras have been purchased; one placed at the inlet and one at the exit of the pebble bed to record the movement of pebbles as they enter and leave the bed.

- These new cameras, **Panasonic 4K Ultra HD Video Camera Camcorder HC-VX981K**, have a frame rate of **240 fps**, allowing for high-precision capture patterns on the pebbles.

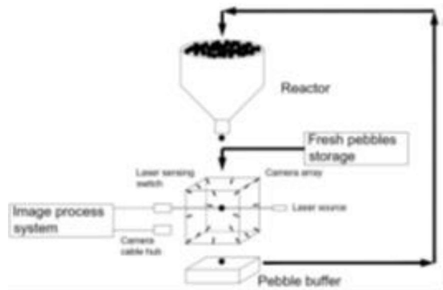
Task 2. Selected Early Attempts

Different array combinations to assess the image quality have been investigated:

- ***Trial 1:*** The first method consists of forming a cubic anthropomorphic in order to fix 8 cameras in the corners. The problem with this method was that the images were blurry due to the flashlight of the opposite camera.
- ***Trial 2:*** An arrangement of cameras to photograph the spheres, which is a tetrahedron structure with four cameras located at each corner, has been determined after different trials.
- ***Trial 3:*** An arrangement of cameras to photograph the spheres, which is two cameras mounted on the auger and operated by a laser.
- ***Trial 4:*** A new advanced methodology to track the pebbles, uses the screw mechanism to move the pebbles upward, and the patterns can be recognized in real-time by a camera following the moving path of the pebbles.

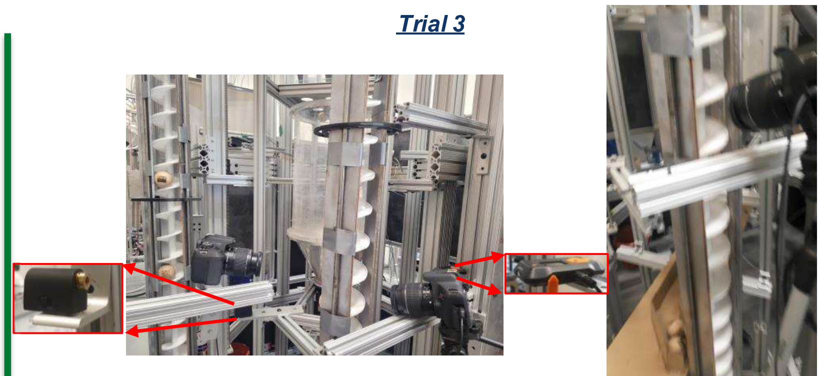
Task 2. Selected Early Attempts

Trial 1



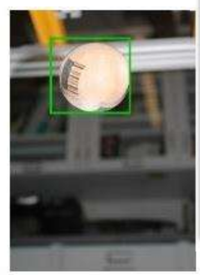
Camera setup directions and shielding glass box of bullet-time tagging and tracking system

Trial 3



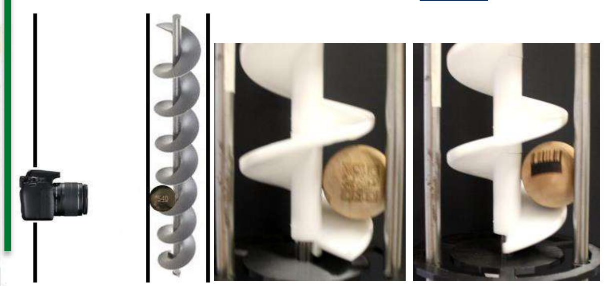
Trial 2

Canon EOS REBEL T7 Camera with a frame rate of 60 fps

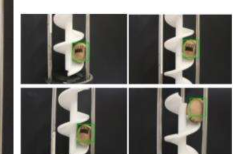


Barcode detection for falling pebbles

Trial 4



Online Object Recognition



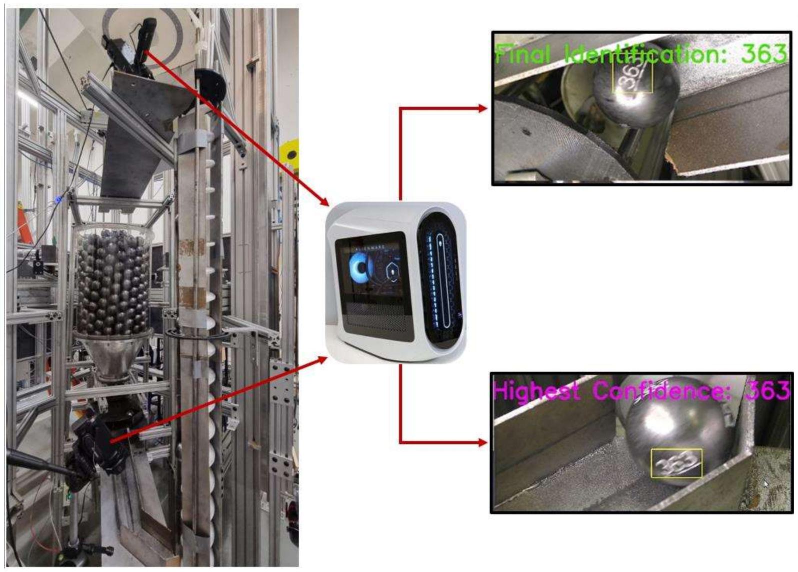
Barcode detection for moving pebbles

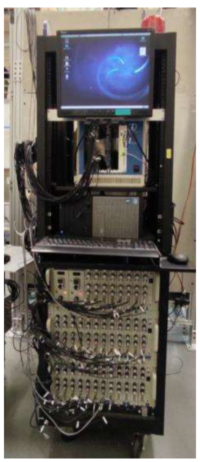
Task 3. Developing robust and rapid methodology of image processing and recognition system

- Problem Statement:
  - Build a robust model capable of identifying the digits on each ex-core TRISO-fueled pebble as they enter and exit the nuclear reactor core to calculate their respective residence time.
- Current Status:
  - Since pebbles are a spherical object that are also in motion, there are problems such as motion blur, rotations, and warped or cut-off digits that make it difficult to identify the numbers painted on.
  - We have made use of deep learning models to solve these issues and maintain a high accuracy even if there may be a distorted image.
  - We created a live system using multithreading that can actively identify pebbles from both the entrance and exit of the core (inlet/outlet) and calculate the residence time
- Goal:
  - Our current task is to expand the current algorithm to identify higher number of digits and / or different patterns.

Task 3. Developing robust and rapid methodology of image processing and recognition system

Up-to-date accomplishments / Our system to calculate and validate the residence time of the pebbles





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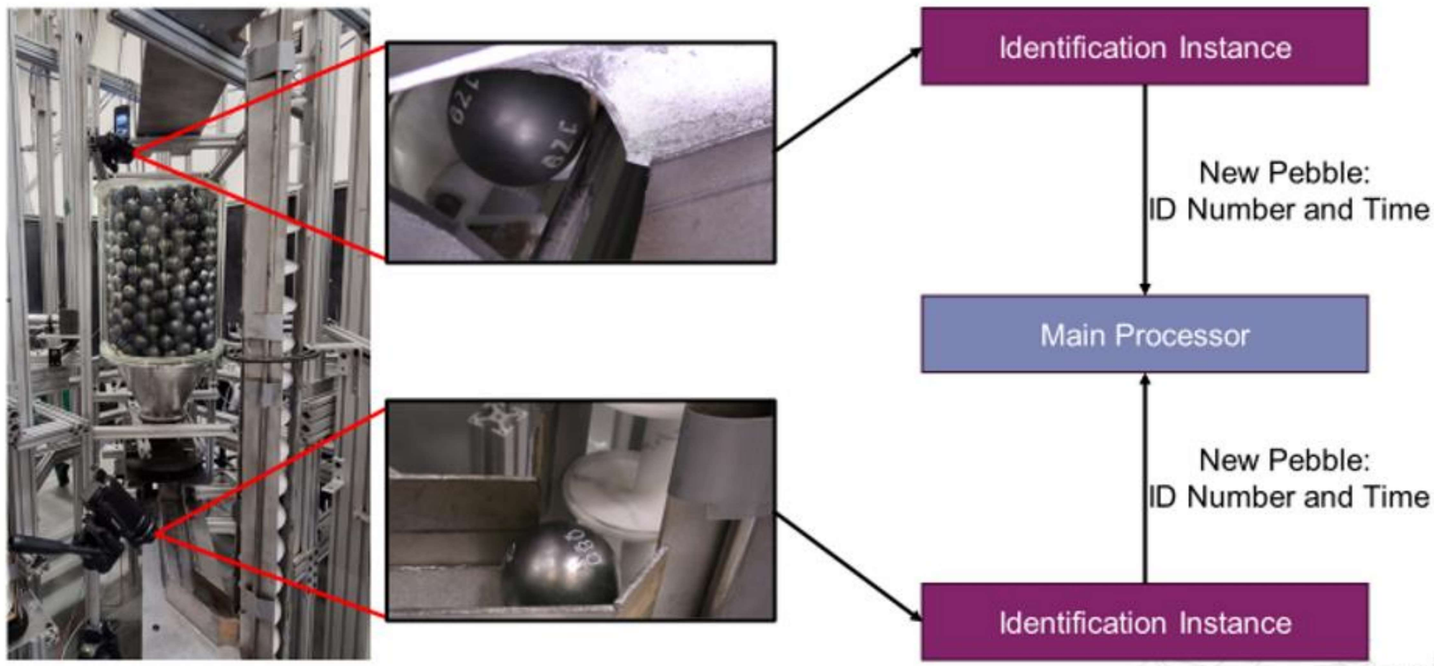
Validation of the Bullet-time Tracking System
using the RTD Technique

Task 3. Developing robust and rapid methodology of image processing and recognition system

Up-to-date accomplishments /We were able to identify pebbles twice as they rolled to the inlet and as they rolled from the outlet to calculate the residence time



Task 3. Developing robust and rapid methodology of image processing and recognition system

Identification Instance Pipeline

Suppose we have the video stream of either the inlet or outlet of the core that records pebbles rolling by, and we must identify them.

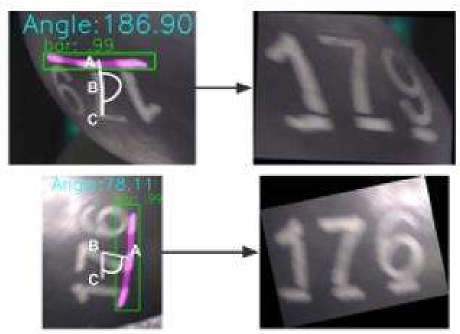
Digit Area Detection → Digit Area Orientation Alignment → Digit Recognition

Digit Area Detection

- Lots of unwanted background information in frame.
- Developed model to extract digit areas even under glare.

Digit Area Orientation Alignment

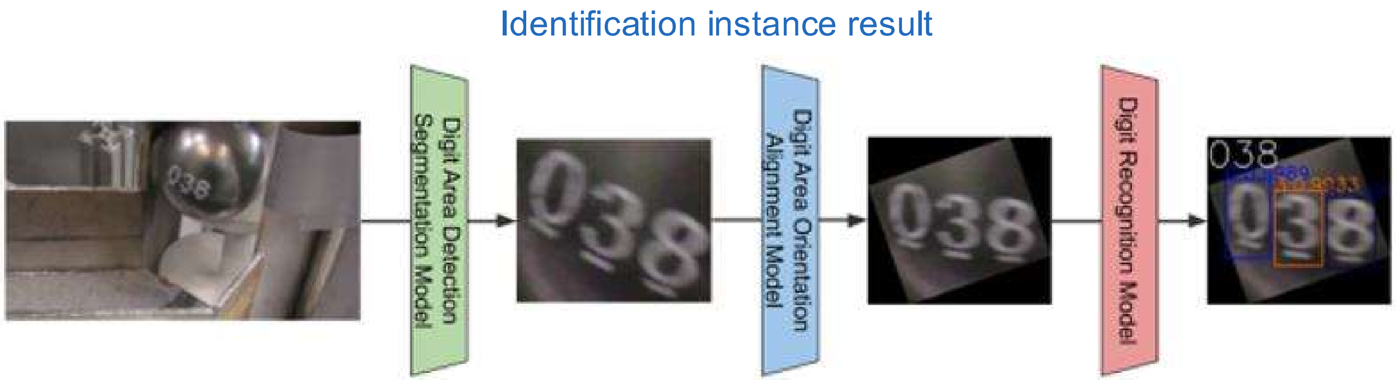
- Cannot guarantee digit areas will be horizontally aligned.
- Developed model to detect bars underneath digits and orient using an angle calculation.



Digit Recognition

- Need to recognize digits to obtain a classification.
- Can accumulate classifications over multiple frames and use a voting score for final identification.

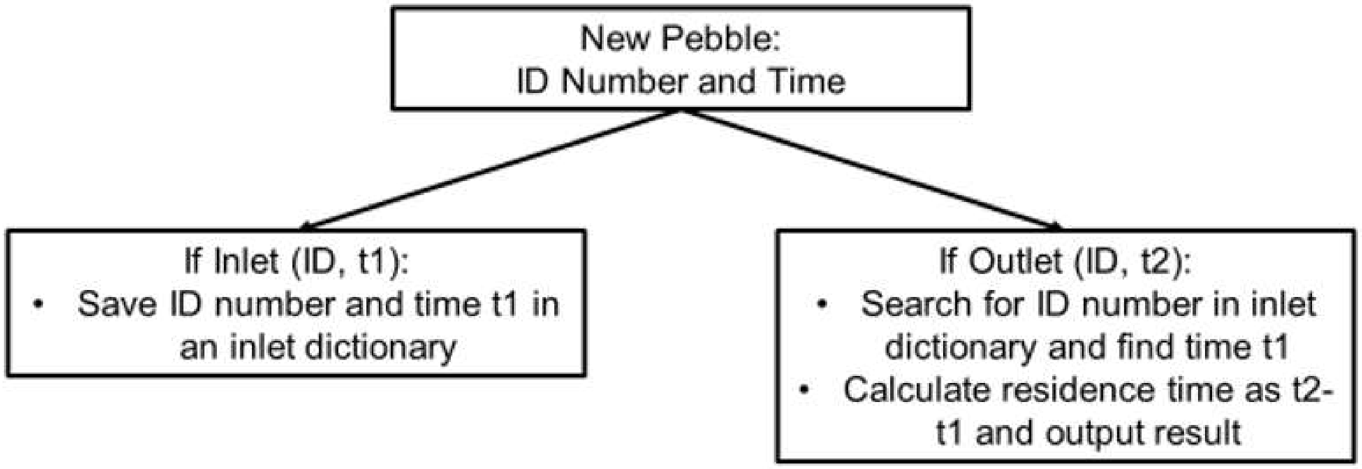
Task 3. Developing robust and rapid methodology of image processing and recognition system



Video	Pebble Identification	Individual Digit Recognition
Inlet Video (Individual Pebbles)	42/43 (97.67)	744/755 (98.54)
Outlet Video (Individual Pebbles)	42/47 (89.36)	814/849 (95.88)

Task 3. Developing robust and rapid methodology of image processing and recognition system

Main processor



Task 3. Developing robust and rapid methodology of image processing and recognition system

Save to inlet dictionary

Find ID in inlet dictionary and calculate Residence Time = t2-t1 = 916.15 – 91.05 = 825.1s or 13:45m

Inlet Dictionary: (empty)

Inlet Dictionary:
(ID: 229, t: 91.05s)

…..
(other pebbles roll by)

Inlet Dictionary:
(ID: 229, t: 91.05s)
(ID: 347, t: 121.81s)
(ID: 412, t: 898.23s)

Inlet Dictionary:
(ID: 347, t: 121.81s)
(ID: 412, t: 898.23s)

time (s)
0 sec

(ID: 229, t: 91.05s)

(ID: 229, t: 916.15s)

Inlet View (slowed down for observation)

…..

Outlet View (slowed down for observation)

Task 4. Modifying and implementing the continuous pebbles circulation cold flow pebble bed experimental setup

Up-to-date accomplishments

- A new unique separate effect cold-flow experimental pebble bed setup featuring continuous recirculation of 6.0 cm graphite pebbles has been designed, developed, tested and employed for developing the bullet tagging and tracking system
- Continuous recirculation of 6.0 cm graphite pebbles with a unique compact screw mechanism system
- One-Pebble at a time discharge mode
- Control over pebbles exit flow rate without jamming
- Both camera arrays for bullet tagging and tracking system, advanced radioactive particle tracking (RPT) technique, and a Radioisotope based Residence Time Distribution (RTD) technique for validation can be mounted on the setup.

Task 4. Selected Early Attempts

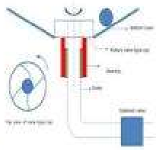
After careful assessment of the time and cost required to make these modifications, the team determined that it would be more efficient to develop a new setup while still maintaining the key features of the existing setup, such as one-by-one pebble discharge mode without jamming, having control of the pebbles' exit flow rate, and most importantly continuous recirculation of the pebbles.

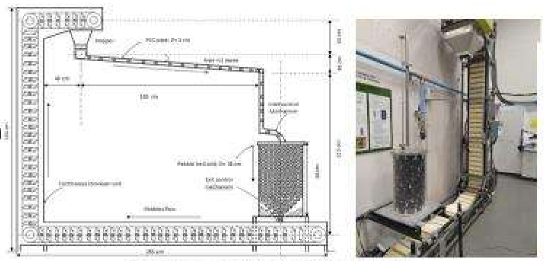
Previous Setup to be Modified

- In the early stage of the project, significant effort and time were invested on modifying the existing pebble recirculation setup to accommodate the use of 6.0 cm graphite pebbles.

The major components of the existed setup that required modification:

- Vessel
- Pebble extraction device
- Conveyer
- Pebble inlet piping and mechanism





Schematic and photos of the old setup

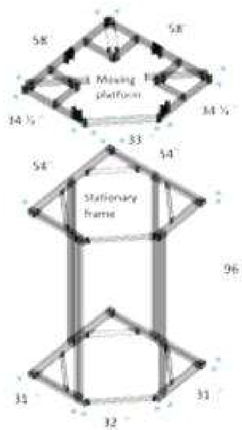
Pebble extraction device

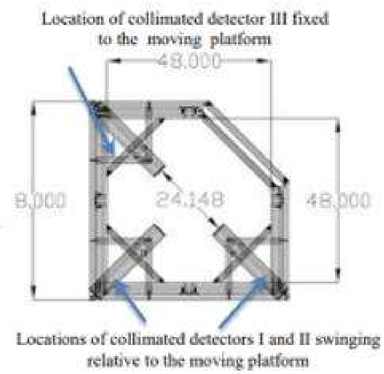
18

Task 4. Selected Early Attempts

❖ Design and development of a new continuous pebble experimental setup for the 6.0 cm graphite pebbles

1. Support structure frame with fixed and moving platforms for the RPT, RTD, and Camera Systems around the setup.



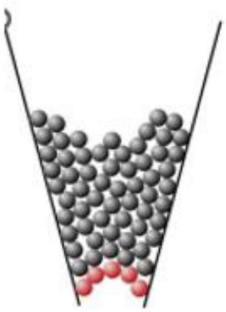


Schematic and photos of the support structure

Task 4. Selected Early Attempts

2. Developing, designing, and in-house manufacturing of a pebble extraction device without jamming

- The purpose is to extract the pebbles one at a time and to prevent pebbles from jamming above the discharge opening.
- The device consists of two fins that rotate slowly and are installed at the discharge opening.
- The device is driven externally through sprockets and chains.



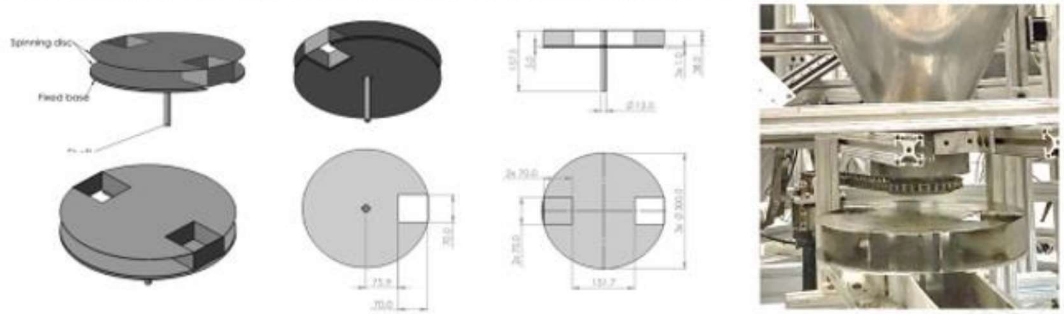
Pebble arching\jamming illustration

Schematics and Photos of the pebble extraction device

Task 4. Selected Early Attempts

3. Developing, designing, and in-house manufacturing pebble discharge control valve

- The purpose is to regulate pebble discharge rate
- The control valve is a disc spinning above a fixed flat base. The spinning disc has two openings that are slightly larger than the size of a pebble and 180° apart from each other. The flat base has one opening of similar size, leading to a route directed to the conveyor.
- The control valve is positioned below the opening of the bed cone.
- The control valve is driven by a stepper motor, and its rotation is controlled by a programmable electronic chip



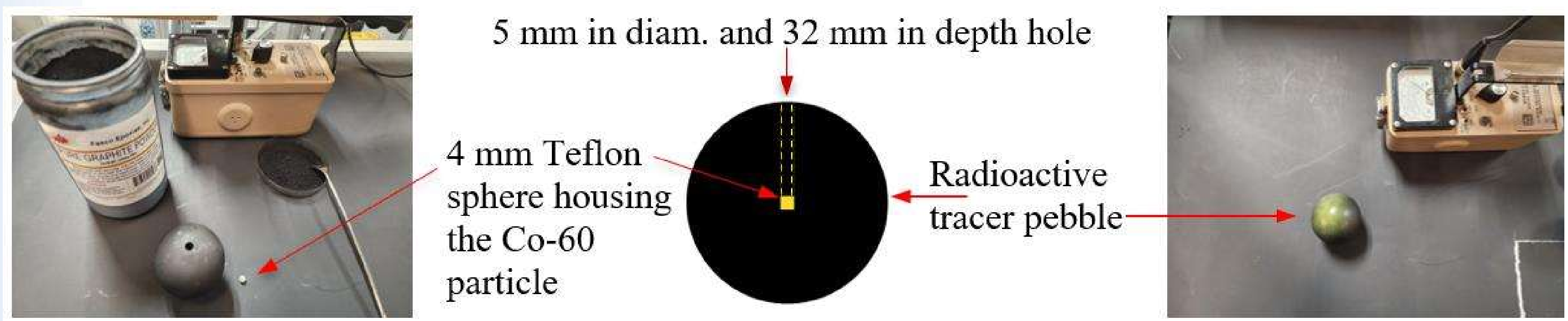
Schematics and Photos of the pebble discharge rate control valve

Task 5. Arranging and implementing Residence Time Distribution (RTD) (transit time) and Radioactive Particle Tracking (RPT) Techniques

- A radioisotope-based Residence Time Distribution (RTD) measurement technique has been developed and installed on the setup to measure the transit time simultaneously with the tagging and tracking system to validate the developed technique of the bullet-time tagging, and tracking system.
- A Dynamic Radioactive Particle Tracking (DRPT) has been developed and installed around the pebble bed to investigate pebble flow and to validate the developed technique of the bullet-time tagging, and tracking system.
- A radioactive tracer pebble of the same size and density as those constituting the pebble bed was prepared in-house and used to perform the RTD, and DRPT Techniques.

Task 5. Arranging and implementing Residence Time Distribution (RTD) (transit time) and Radioactive Particle Tracking (RPT) Techniques

- A radioisotope-based RTD and DRPT techniques are not off-the-shelf techniques. They involve numerous steps before, during, and after the experiments to obtain useful information; among these steps is the radioactive tracer particle preparation.
- A radioactive tracer pebble of the same size and density as those constituting the pebble bed was prepared in-house.
- A Co-60 radioisotope particle with an initial activity of 500µCi, was enclosed and sealed in a 4 mm Teflon and positioned at the center of a graphite pebble.



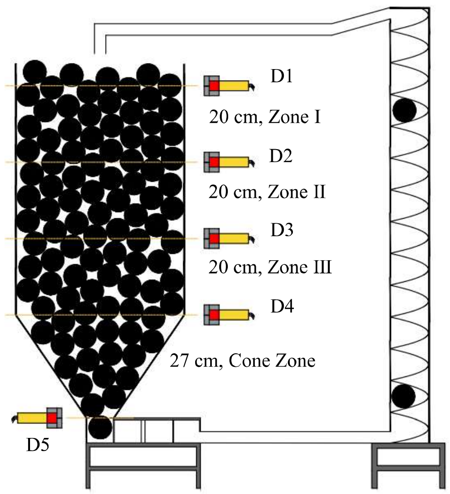
Schematic and Photos of the Tracer Pebble

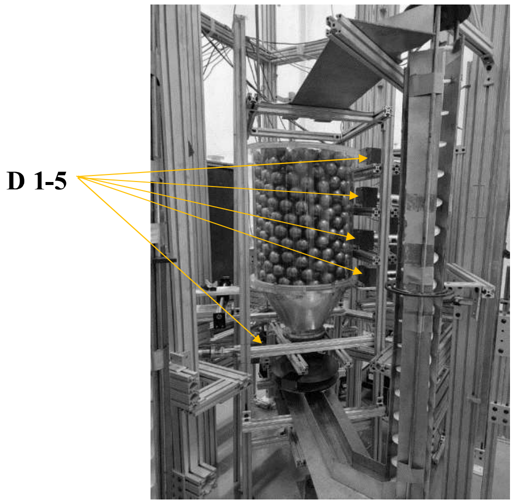
Task 5. Arranging and implementing Residence Time Distribution (RTD) (transit time) and Radioactive Particle Tracking (RPT) Techniques

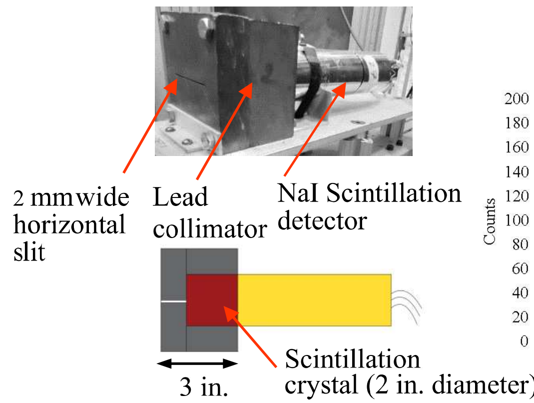
- The developed RTD technique uses a set of five collimated Sodium Iodide (NaI) detectors arranged long the height of the bed to track the photon counts of a radioactive tracer pebble.
- Detectors 1 and 5 are placed at the inlet and outlet of the pebble and their location is alighted with the camera system to simultaneously measure the over all residence time by the RTD and developed the tagging and tracking system.
- The remaining three detectors are arranged along the cylindrical section and used to obtain zonal residence time data.

Schematic and Photos of the Tracer Pebble

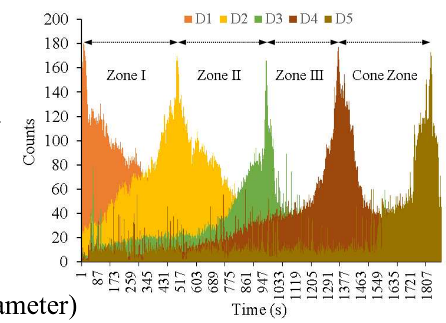
Task 5. Arranging and implementing Residence Time Distribution (RTD) (transit time) and Radioactive Particle Tracking (RPT) Techniques



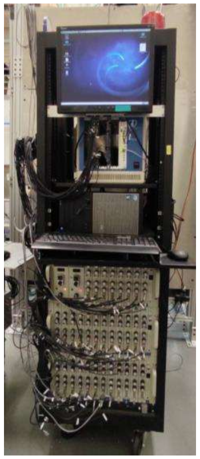




Collimated Detector



Counts Received by Detectors

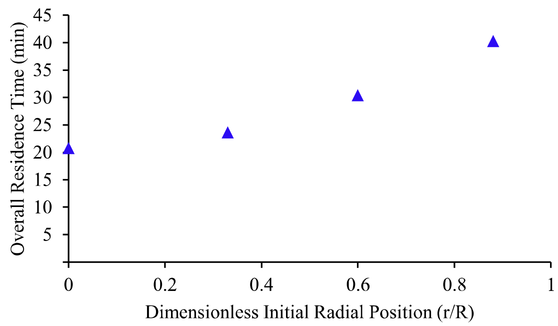


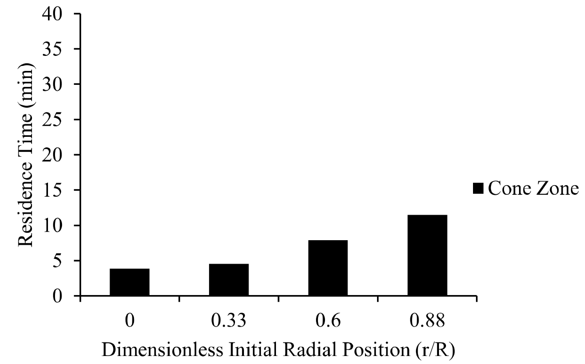
DAQ

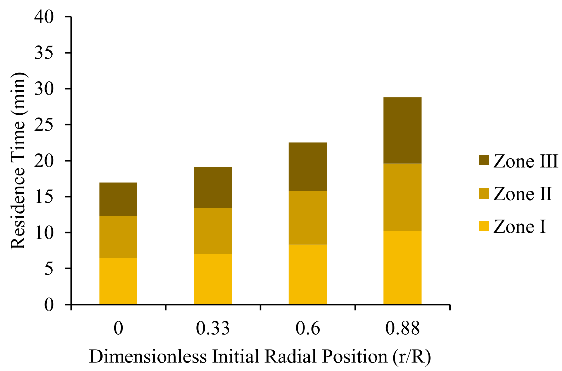
Schematic and photo showing the location of the Detectors

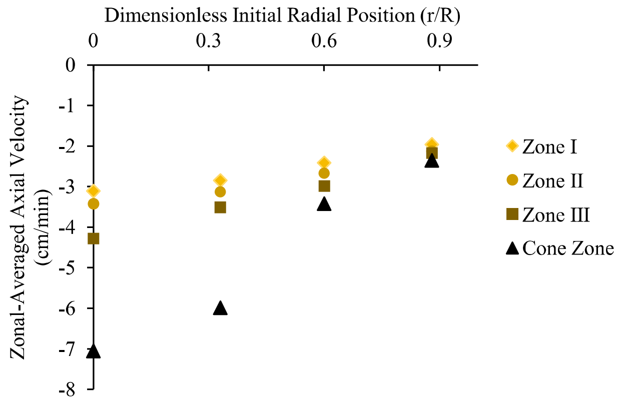
Schematic and Photos of the Tracer Pebble

Task 5. Sample result

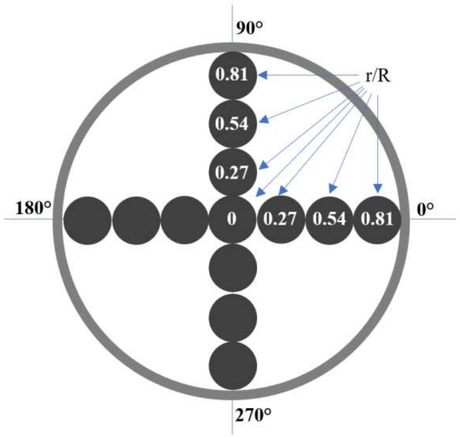








Task 6. Validation of the developed method using proven non-invasive Residence Time Distribution (RTD) (Transit Time) Radioactive Particle Tracking (RPT) techniques



Measurement locations: radial and angular positions in the experimental setup

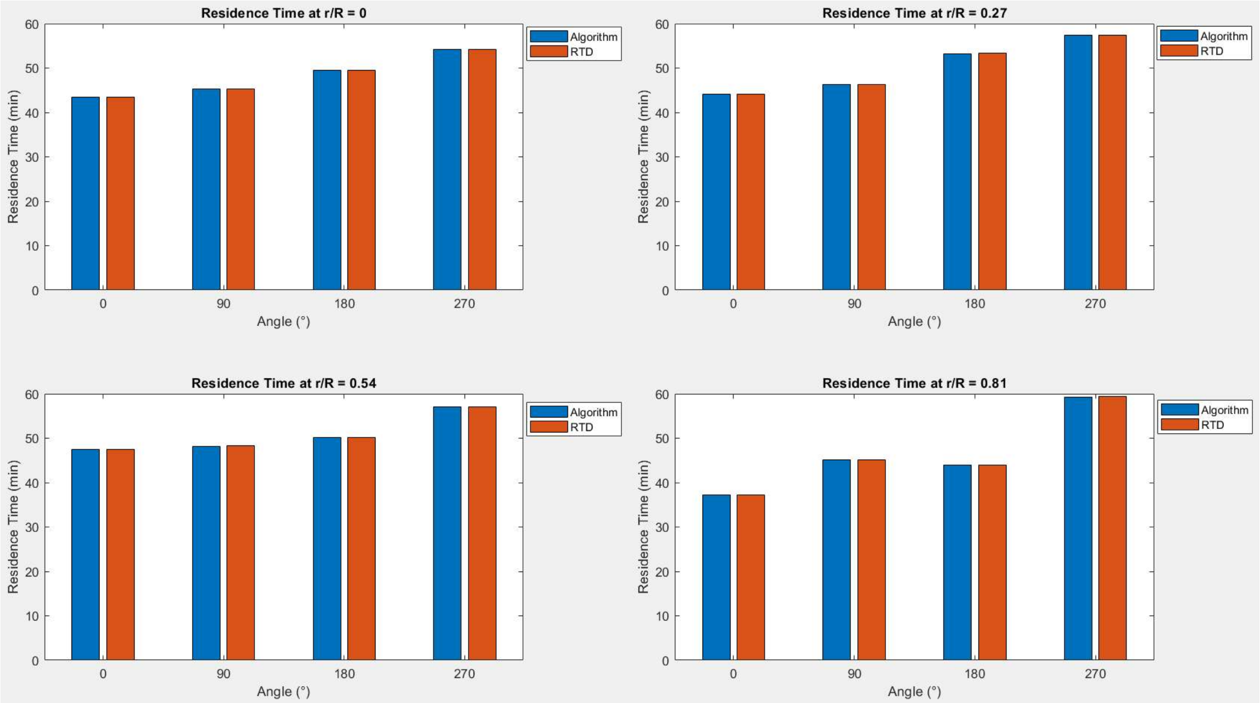
Overall residence time results obtained from algorithm detection

	r/R = 0	r/R = 0.27	r/R = 0.54	r/R = 0.81
Angle 0°	43min41sec	45min27sec	49min52sec	54min27sec
Angle 90°	44min07sec	46min34sec	53min25sec	57min37sec
Angle 180°	47min41sec	48min22sec	50min15sec	57min07sec
Angle 270°	37min23sec	45min20sec	44min00sec	59min29sec

Overall residence time results obtained from the RTD technique

	r/R = 0	r/R = 0.27	r/R = 0.54	r/R = 0.81
Angle 0°	43min38sec	45min28sec	49min50sec	54min25sec
Angle 90°	44min10sec	46min31sec	53min29sec	57min36sec
Angle 180°	47min40sec	48min25sec	50min20sec	57min10sec
Angle 270°	37min26sec	45min17sec	44min02sec	59min33sec

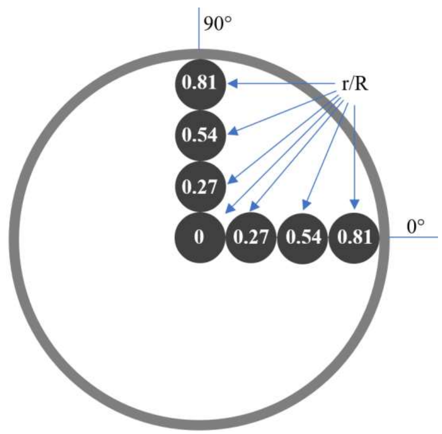
Task 6. Validation of the developed method using proven non-invasive Residence Time Distribution (RTD) (Transit Time) Radioactive Particle Tracking (RPT) techniques



Overall residence times at each r/R ratio and angle for both the algorithm and RTD data

Task 6. Validation of the developed method using proven non-invasive Residence Time Distribution (RTD) (Transit Time) Radioactive Particle Tracking (RPT) techniques

Studying the trajectory of the pebbles at various locations in Pebble Bed Nuclear Reactors using Advanced Dynamic Radioactive Particle Tracking Technique



1- Discharge Rate of **3.12 seconds**
2- Discharge Rate of **8.57 seconds**

Measurement locations: radial and angular positions in the experimental setup

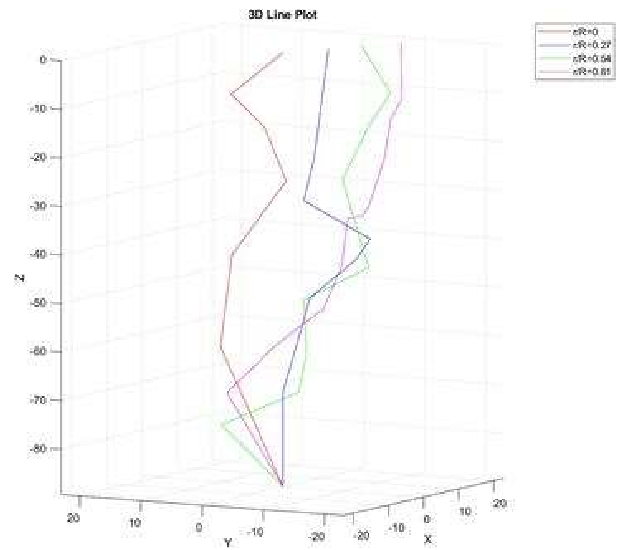
Task 6. Validation of the developed method using proven non-invasive Residence Time Distribution (RTD) (Transit Time) Radioactive Particle Tracking (RPT) techniques

Studying the trajectory of the pebbles at various locations in Pebble Bed Nuclear Reactors using Advanced Dynamic Radioactive Particle Tracking Technique

1- Angular Position at **0º**, Discharge Rate of **3.12 seconds**

Tracer trajectory length values for different initial seeding positions

	Tracer initial seed position Dimensionless radial position (r/R)			
	0	0.27	0.54	0.81
Trajectory length (in cm)	101.96	106.42	125.59	109.66
% increase with respect to the shortest trajectory length	-	4.38	23.18	7.56



Three-dimensional tracer trajectories at 0° and a discharge rate of 3.12 seconds

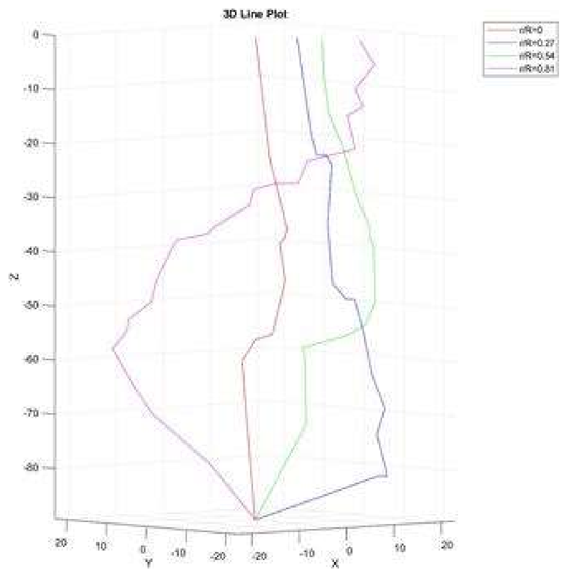
Task 6. Validation of the developed method using proven non-invasive Residence Time Distribution (RTD) (Transit Time) Radioactive Particle Tracking (RPT) techniques

Studying the trajectory of the pebbles at various locations in Pebble Bed Nuclear Reactors using Advanced Dynamic Radioactive Particle Tracking Technique

2- Angular Position at **0º**, Discharge Rate of **8.57 seconds**

Tracer trajectory length values for different initial seeding positions

	Tracer initial seed position Dimensionless radial position (r/R)			
	0	0.27	0.54	0.81
Trajectory length (in cm)	99.33	115.88	112.45	152.43
% increase with respect to the shortest trajectory length	-	16.66	13.21	53.46



Three-dimensional tracer trajectories at 0° and a discharge rate of 8.57 seconds

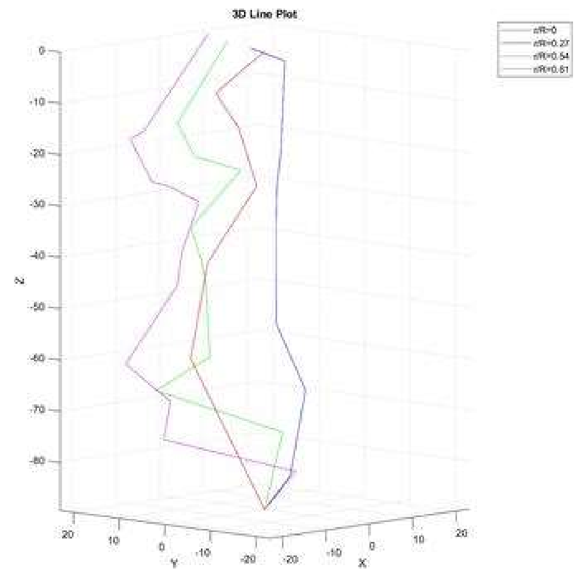
Task 6. Validation of the developed method using proven non-invasive Residence Time Distribution (RTD) (Transit Time) Radioactive Particle Tracking (RPT) techniques

Studying the trajectory of the pebbles at various locations in Pebble Bed Nuclear Reactors using Advanced Dynamic Radioactive Particle Tracking Technique

3- Angular Position at **90º**, Discharge Rate of **3.12 seconds**

Tracer trajectory length values for different initial seeding positions

	Tracer initial seed position Dimensionless radial position (r/R)			
	0	0.27	0.54	0.81
Trajectory length (in cm)	101.96	116.51	133.39	146.65
% increase with respect to the shortest trajectory length	-	14.27	30.83	43.84



Three-dimensional tracer trajectories at 90° and a discharge rate of 3.12 seconds

Linda and Bipin Doshi Department of Chemical and Biochemical Engineering

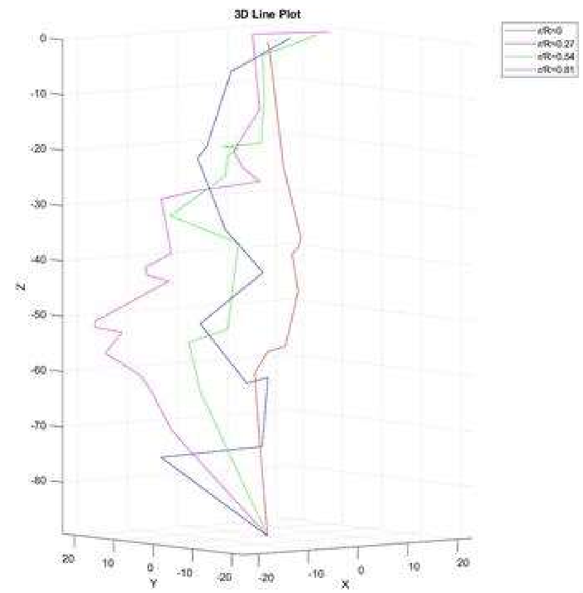
Task 6. Validation of the developed method using proven non-invasive Residence Time Distribution (RTD) (Transit Time) Radioactive Particle Tracking (RPT) techniques

Studying the trajectory of the pebbles at various locations in Pebble Bed Nuclear Reactors using Advanced Dynamic Radioactive Particle Tracking Technique

4- Angular Position at **90º**, Discharge Rate of **8.57 seconds**

Tracer trajectory length values for different initial seeding positions

	Tracer initial seed position Dimensionless radial position (r/R)			
	0	0.27	0.54	0.81
Trajectory length (in cm)	99.33	148.98	139.69	163.30
% increase with respect to the shortest trajectory length	-	49.98	40.63	64.40

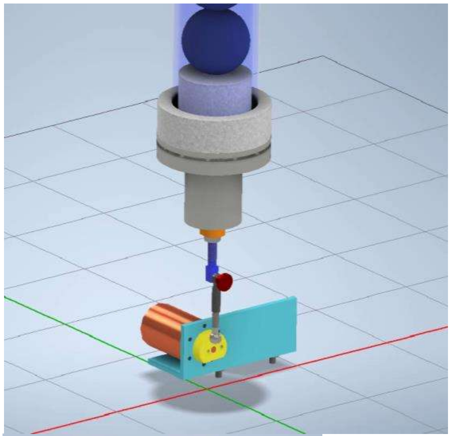


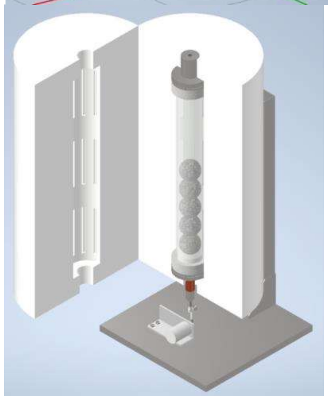
Three-dimensional tracer trajectories at 90° and a discharge rate of 8.57 seconds

Task 7. Evaluating the tagged graphite pebbles surface for abrasion at prolonged times operation

Up-to-date accomplishments

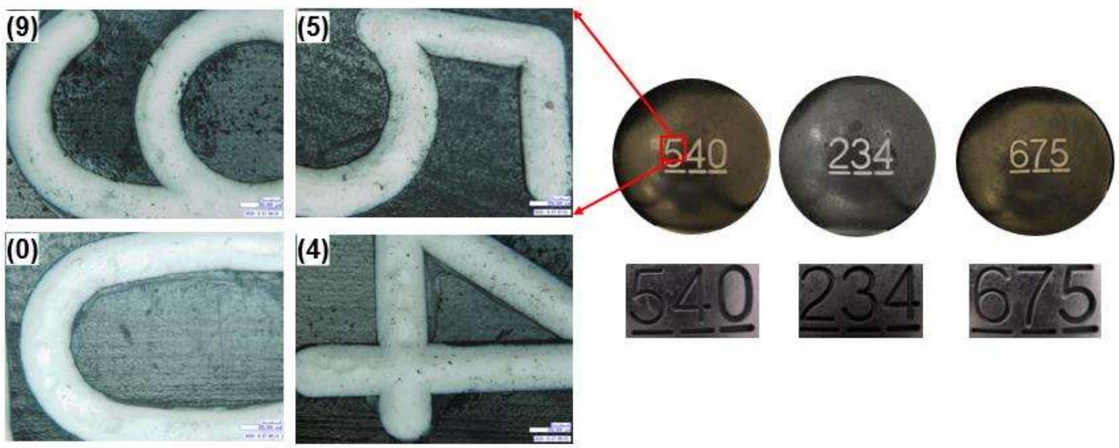
A new advanced heating abrasion setup has been designed to assess the feasibility and durability of our adopted patterning methodology. The setup consists of five graphite balls, mimicking the pebble bed reactor's motion, to evaluate the patterns' resistance to abrasion and friction under high temperatures (~1200 °C), integrated into a Carbolite EZS-3G 12/600B tube furnace, the setup allows controlled testing for precise insights into the coatings' performance under real conditions as per Task 8.





Task 7. Evaluating the tagged graphite pebbles surface for abrasion at prolonged times operation

Up-to-date accomplishments



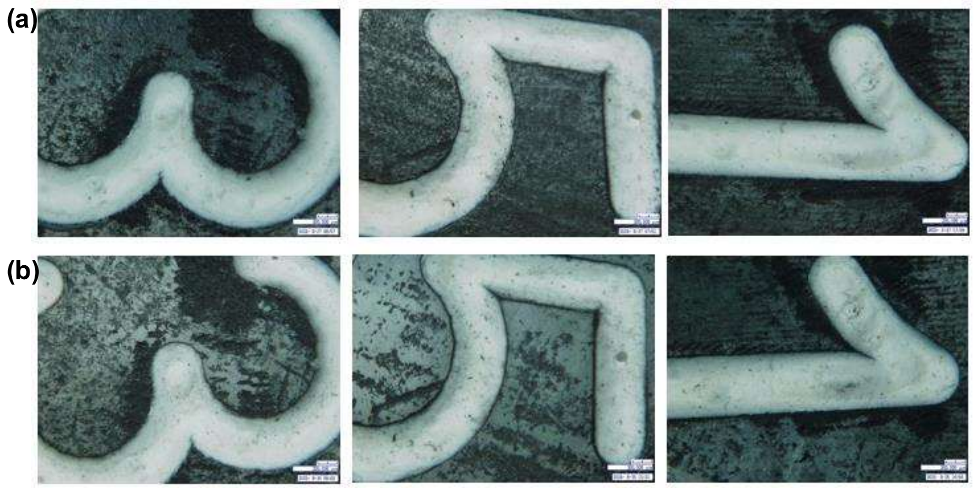
Images of the surface of the carved graphite pebbles using Hirox Microscope Examination

Hirox Hi-Scope Advanced KH-3000 microscope

Task 7. Evaluating the tagged graphite pebbles surface for abrasion at prolonged times operation

Up-to-date accomplishments

Comparative visuals of pebbles pre- and post-abrasion test without thermal exposure, captured via Panasonic camera

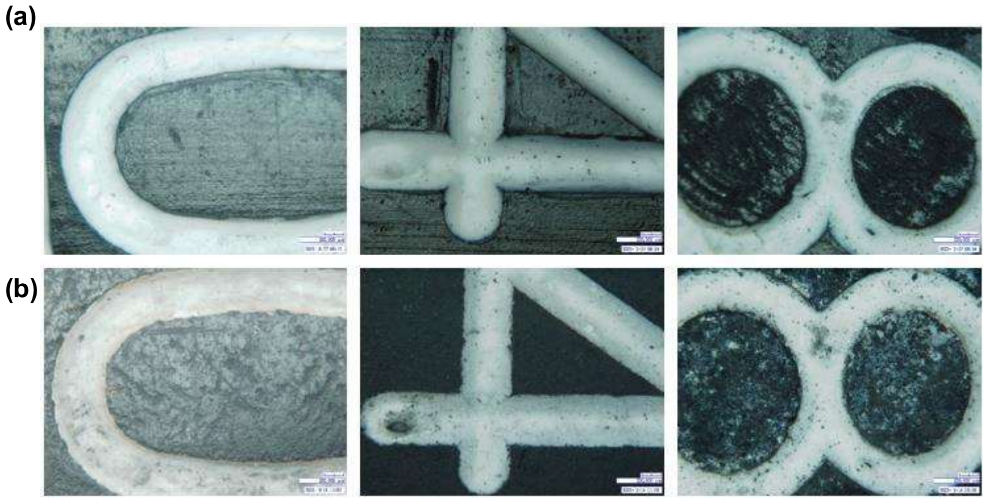


Microscopic Examination of Pebbles Before **(a)** and After **(b)** Abrasion Testing Without Thermal Exposure, Imaged with the Hirox Microscope

Task 7. Evaluating the tagged graphite pebbles surface for abrasion at prolonged times operation

Up-to-date accomplishments

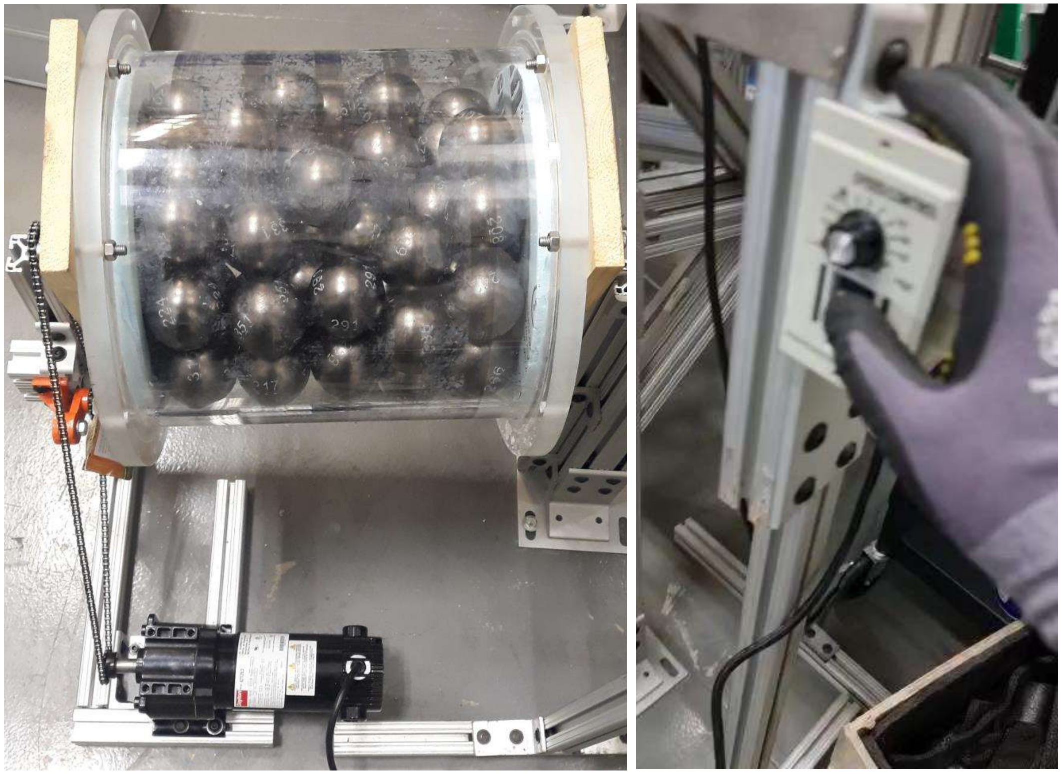
Comparative visuals of pebbles pre- and post-abrasion test with thermal exposure, captured via Panasonic camera



Microscopic Examination of Pebbles Before **(a)** and After **(b)** Abrasion Testing With Thermal Exposure, Imaged with the Hirox Microscope

Task 7. Selected Early Attempts

- Design and build a unique cold flow system that will be continuously operated for a long time
- Ensure that the adopted patterning/coating methodology (Task 1) is feasible and that the produced patterns withstand abrasion and friction for prolonged times of operation and recirculation.



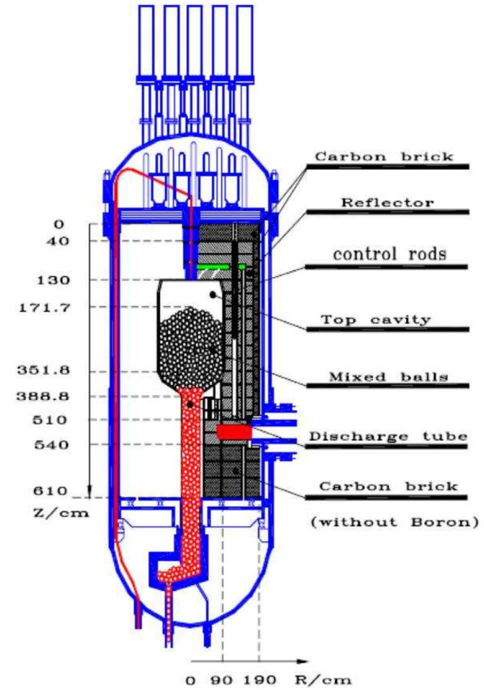
Abrasion Setup

Task 8. Assessing the transformation of the developed system to high temperature pebble bed nuclear reactors

- The developed tagging and tracking system will be assessed for transformation to be implemented on real pebble bed nuclear reactors under normal and accident conditions with close involvement of our industrial and national laboratory partners.

- We are currently in the final phase of conducting experiments to Analyze heat transfer at high temperatures inside the reactor.

- We are planning to expand the study by Design and conduct experiments to validate the system in a high-temperature environment. This might involve building a small-scale high-temperature test reactor.



Scheme of the Chinese pebble bed reactor (HTR-10)
Ding et al.,(2021)

Milestones and deliverables

1. System for determination of pebble transit time and identification
2. Ultra-High Temperature Ceramic (UHTC) coating or embedding methodology
3. optimum high-speed camera array with high
4. Methodology of image processing and recognition system
5. Well-developed and validated system package for pebble tagging and tracking with protocols and recommendation for transformation to real pebble beds.

Accomplishments

- A deliverable has been submitted to the DOE regarding **Task 2** ‘’Developing the optimal high-speed camera array with high survivability under high temperature and radiation’’.
- A deliverable has been submitted to the DOE regarding **Task 3** ‘’Developing robust and rapid methodology of image processing and recognition system’’.
- A deliverable has been submitted to the DOE regarding **Task 4** ‘’Modifying and implementing the continuous pebbles circulation cold flow pebble bed experimental setup’’.
- A deliverable has been submitted to the DOE regarding **Task 5** ‘’Arranging and implementing Residence Time Distribution (RTD) (transit time) and Radioactive Particle Tracking (RPT) Techniques’’.

On-going work

- Carving Technique Validation: Adopted a robust, high-temperature resistant carving methodology for graphite pebbles, which showed exceptional resilience in high-temperature tests and maintained integrity. Preliminary results from non-invasive radioisotope tests indicate promising durability and reliability, validating the effectiveness of the carving method for pebble bed reactors.

- Tracer Pebble Dynamics Validation: Conducted experiments with 600 patterned graphite pebbles to validate the dynamics of a uniquely tagged radioactive tracer pebble at different radial positions. Results showed consistent residence times from both algorithm detection and RTD techniques, confirming the algorithm’s reliability and effectiveness for real-time monitoring in pebble bed reactors. Theses results will be delivered soon to the DOE.

- Carved Pebble Durability Validation: Conducted rigorous validation experiments with carved patterned pebbles under the weight of 600 overlying pebbles using the RTD technique. Preliminary findings show the patterns remained intact, demonstrating the carving technique's durability and effectiveness for real-world reactor conditions, supporting further development of our tracking system. Theses results will be delivered soon to the DOE.

Future work

- Redesign the experimental setup to handle elevated temperatures and pressures, ensuring the seamless integration of the camera array system and tagging mechanisms. Implement structural reinforcements and thermal management solutions.

- Adapt and integrate the non-invasive Residence Time Distribution (RTD) and Radioactive Particle Tracking (RPT) techniques for validation in high-temperature, high-pressure environments.

- Calibrate the RTD and RPT systems to maintain accuracy and reliability under extreme conditions. Conduct parallel validation experiments to compare the performance of the new system with established benchmarks.

- Engage with experts to refine the system for practical application, ensuring compliance with industry standards and safety regulations. Develop comprehensive implementation guidelines and training programs for operational personnel.

- By transitioning to a high-temperature, high-pressure pebble bed reactor, we aim to validate and enhance our advanced RPT technique, camera array system, and image recognition algorithms. This comprehensive approach will ensure that our system meets the stringent demands of real-world reactor conditions, paving the way for significant advancements in the monitoring and management of pebble bed reactors.

Presentation(s)/ Communication(s)/ Poster(s)...

- **AIChE Annual Meeting (2023).** "Developing Robust and Rapid Methodology of Image Processing System for Individual Ex-Core TRISO-Fueled Pebble Recognition." *(Communication)*
- **Laufer Energy Symposium: Energy Economics-Global Trends in Technology and Policy (2023). "**Development of Pebbles Tagging and Validation and Investigating Hydrodynamics of Pebble Bed Reactors." *(Poster)*
- **URECA Celebration: the annual SB campus-wide undergraduate research symposium (2023).** "Robust TRISO-fueled Pebble Identification Utilizing Computer Vision and Deep Learning Techniques." *(Poster)*
- Presentation for **Gale and Wayne Laufer Endowed Energy Chair 2021** under the theme **(October 28, 2021):** "Alternative and Conventional Energy Selected Recent Advances."
- **4th International Conference on Advances in Radioactive Isotope Science (ARIS)** ***June 4-9, 2023*****:** Design and Development of a Radioisotope-Based Technique to Investigate Residence Time Distribution in a Cold-Flow Experimental Pebble Bed Reactor.
- **American Nuclear Society, 20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20)** ***August 20-25, 2023*****: "**Design and Development of Continuous Pebble Recirculation Experimental Setup to Investigate Residence Time Distribution and Axial Pebble Velocity in Pebble Bed-Type HTGRs.

Paper(s)

- **WACV (2024).** "Robust TRISO-fueled Pebble Identification by Digit Recognition." *(Submitted)*
- **American Nuclear Society, 20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20)** ***August 20-25, 2023*****: "**Design and Development of Continuous Pebble Recirculation Experimental Setup to Investigate Residence Time Distribution and Axial Pebble Velocity in Pebble Bed-Type HTGRs." *(Submitted)*

Website(s)

https://web.mst.edu/~aldahhanm/components/grants/grants.html

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Thank you

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