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

DOE ART Gas-Cooled Reactor (GCR) Review Meeting
Virtual Meeting
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Students and Collaborators

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- Josh Cogliati (Idaho National Laboratory)
- David Cislo (Framatome Inc)
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Students & Coworkers

- Jihane Mendil (Missouri S&T) 10/2020 - Present
- Abdullah Alzubaidi (Missouri S&T) 01/2023 - Present
- Ahmed Jasim (Missouri S&T) 01/2022 – Present
- Zeyad Zeitoun (Missouri S&T) 03/2021 – 11/2021
- Binbin Qi (Missouri S&T) 10/2020 – 03/2021
- Omar Farid (Missouri S&T) 10/2020 – 06/2021
- Liang Han (Stony Brook University) 10/2020 - 06/2022
- Zuhui Wang (Stony Brook University) 10/2020 - 12/2022
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Overall objectives

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

(1) Developing and validating a proven novel bullet-time tagging

(2) Tracking system that is unique, robust, transformative, high temperature, and radiation resistant based on computer vision techniques for individual TRISO-fueled pebble identification and in-situ transit time determination for ex-core evaluation.

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

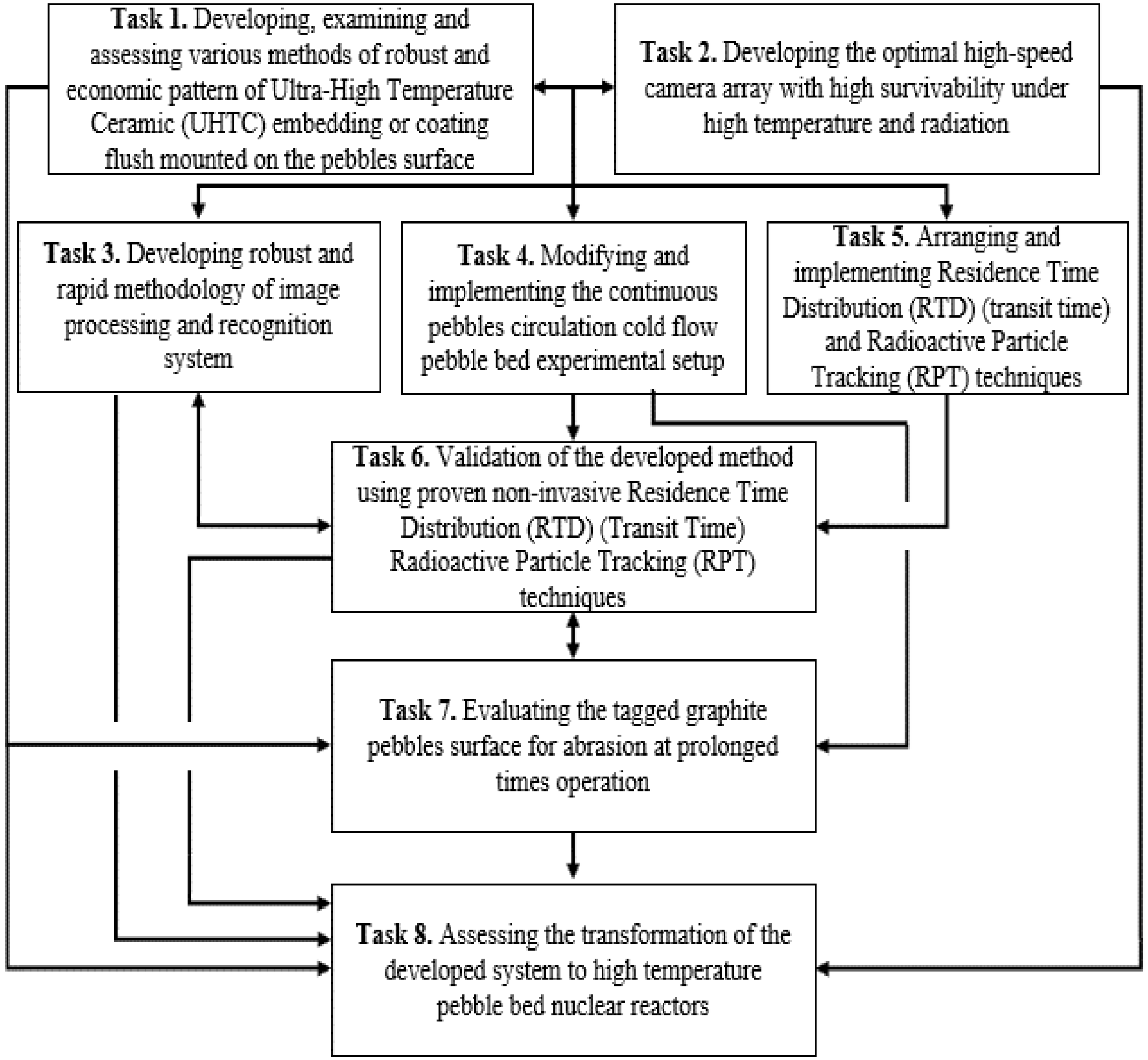
Task 4. Modifying and implementing the continuous pebbles circulation cold flow pebble bed experimental setup

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. 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 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.

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Task 1. Up-to-date Accomplishments

- Searching and finding ceramic ink
- Investigating and finding a patterning methodology and searching for a proper machine
- Printing 600 graphite pebbles with each pebble has been patterned on six sides.
- The patterns are uniform and can be identified with the image recognition algorithm.

Example

6.0 cm Graphite pebbles carved and tagged with ceramic patterns

Task 1. Up-to-date Accomplishments

Investigating and finding a patterning methodology using a pad printer

6.0 cm Graphite pebbles tagged with ceramic patterns

Pad printer

Task 1. Up-to-date Accomplishments

- 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

(a)

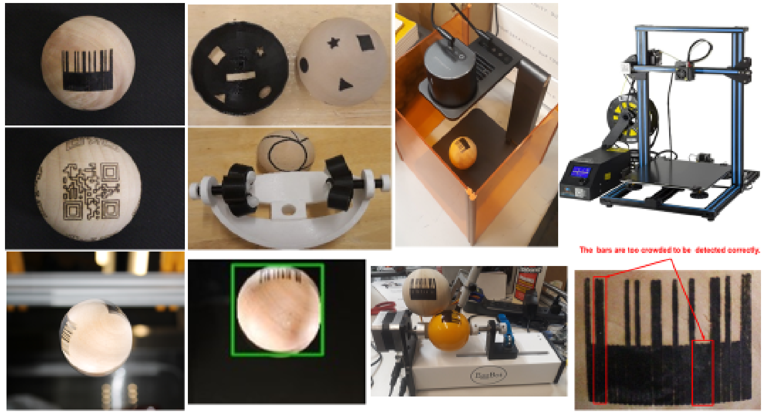
(b)

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

Task 1. Selected Early Attempts and Efforts That Were Made to Reach the up-to-date Accomplishments

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

Additional Selected Previous Patterning Methods

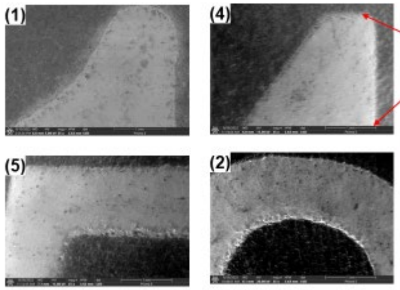
- Several patterning methods, including stencil and brush spray, paint pen, and pad printing, were tested to tag graphite pebbles with 3–4-digit numbers using the thermal ultra-high temperature ceramic ink (CERAMACOAT 503-VFG-C)
- The patterns obtained from the stencil and brush spray, and paint pen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

Paint pen

Brush spray

Task 1. Future Work

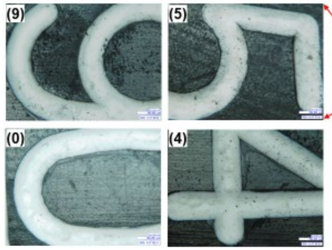
Quantitative assessments of the integrity and stability of the ceramic patterns on the graphite pebbles using a Scanning Electron Microscope (SEM) and Hirox Microscope Examinations.



Images of the surface of the patterned graphite balls using Scanning Electron Microscope (SEM) Examination

Task 1. Future Work

Quantitative assessments of the integrity and stability of the ceramic patterns



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

Hirox Microscope

Task 2. Up-to-date Accomplishments

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 and Efforts That Were Made to Reach the up-to-date Accomplishments

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

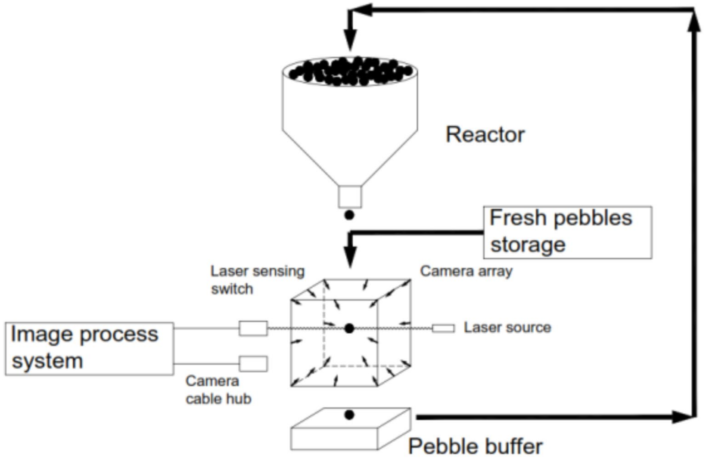
- ***Trial 1:*** The first method consists of forming a cubic anthropomorphic in order to fix 8 cameras in the corners. The problem with this method was that the images were blurry due to the flashlight of the opposite camera.

- ***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.

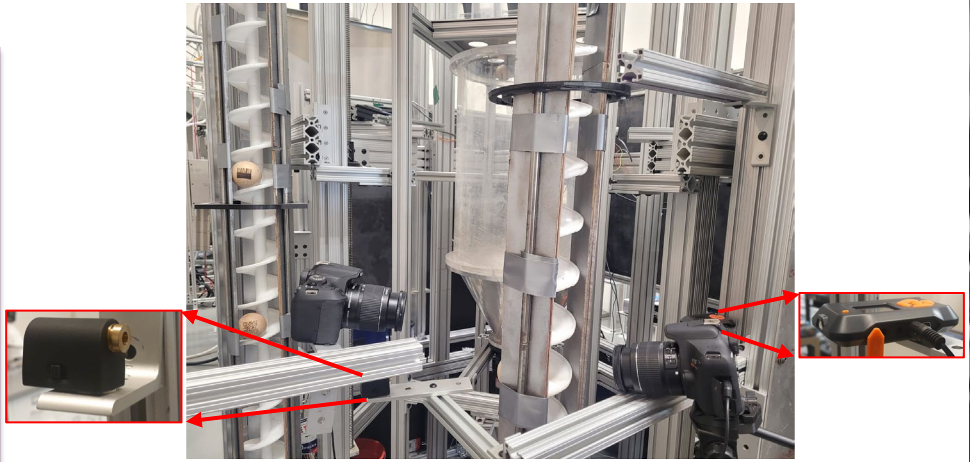
- ***Trial 4:*** A new advanced methodology to track the pebbles, uses the screw mechanism to move the pebbles upward, and the patterns can be recognized in real-time by a camera following the moving path of the pebbles.

Trial 1: Initial cubic anthropomorphic setup with 8 corner cameras resulted in blurry images due to flashlight interference.



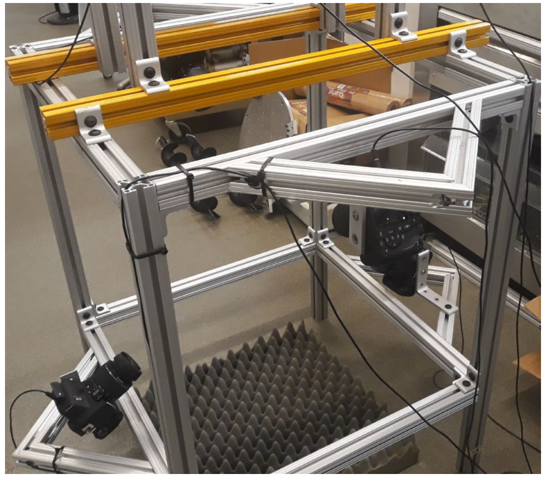
Camera setup directions and shielding glass box of bullet-time tagging and tracking system

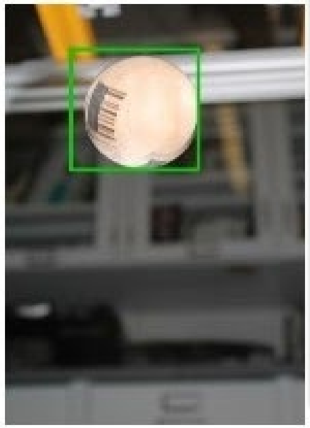
Trial 3: Auger-mounted camera arrangement with laser operation.



Trial 2: Tetrahedron camera arrangement selected after extensive experimentation.

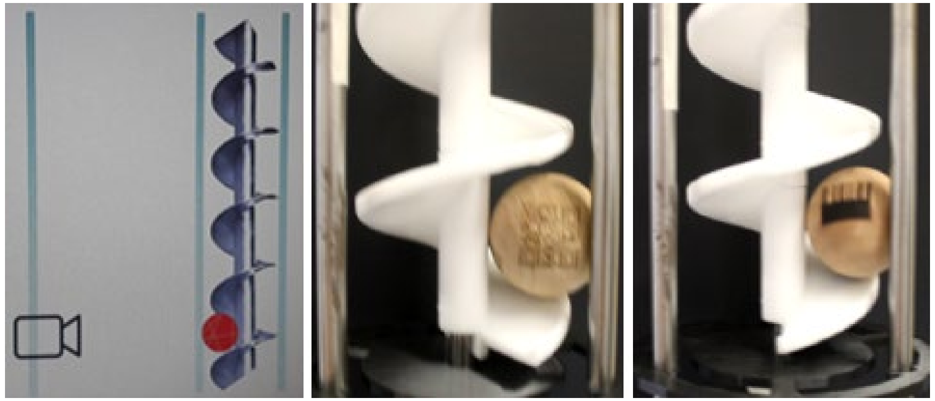
Canon EOS REBEL T7 Camera with a frame rate of 60 fps



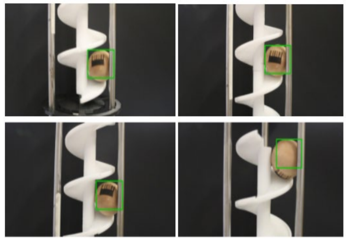


Barcode detection for falling pebbles

Trial 4: Real-time pattern recognition with a camera mounted on the new screw design for pebble movement.



Online Object Recognition



Barcode detection for moving pebbles

Task 2. Future work

- A deliverable has been submitted.

- The design and the structure of the camera arrangement are refined and adjusted based on the outcomes and results of the patterning recognition (Task 3) and the performance of the new pebble bed separate effect set-up of Task 4.

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

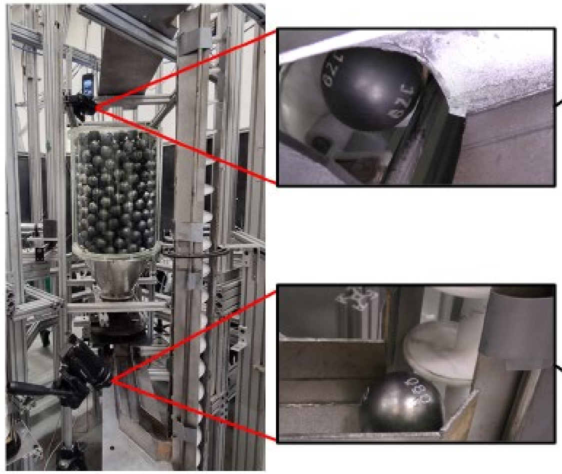
Project Overview

- Problem Statement:
  - We are to 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.
- Goal:
  - Our current task is to create 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.

Residence Time Calculation Set-Up

- We want to be able to identify pebbles twice: as they roll to the inlet and as they roll from the outlet to calculate the residence time.



Identification Instance

New Pebble:
ID Number and Time

Main Processor

New Pebble:
ID Number and Time

Identification Instance

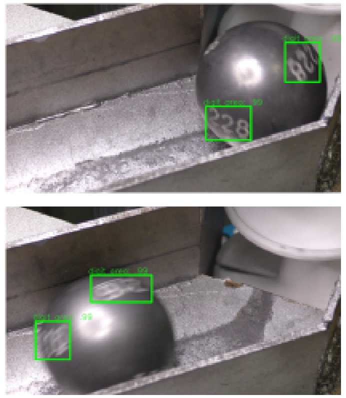
Identification Instance Pipeline

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

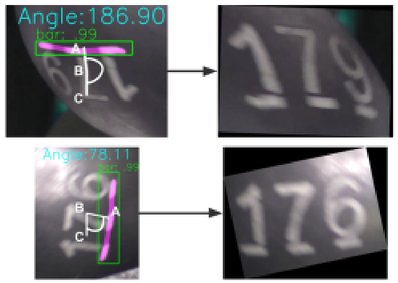
Digit Area Detection

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



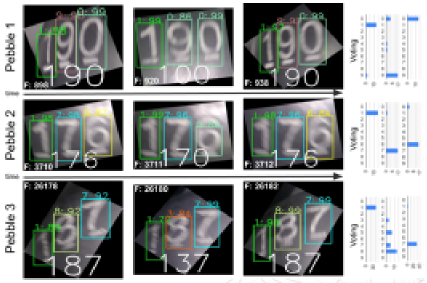
Digit Area Orientation Alignment

- 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.



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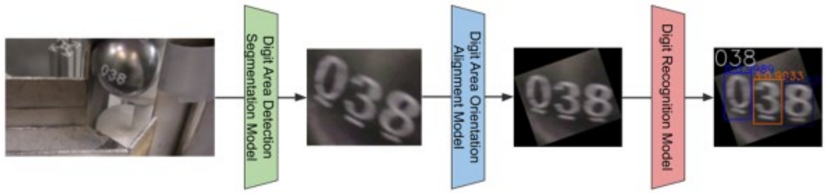
Identification Instance Results



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)

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Main Processor

New Pebble:
ID Number and Time

If Inlet (ID, t1):
- Save ID number and time t1 in an inlet dictionary

If Outlet (ID, t2):
- Search for ID number in inlet dictionary and find time t1
- Calculate residence time as t2-t1 and output result

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Example

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)

0s

(ID: 229, t: 91.05s)

(ID: 229, t: 916.15s)

Inlet View (slowed down for observation)

…..

Outlet View (slowed down for observation)

Residence Time Calculation Results and Further Work

- For the 47 pebbles identified in the outlet, there was a corresponding entry in the inlet dictionary for 34 of them meaning a 72.34% accuracy rate.
- One issue is pebbles being too close to each other as seen here:

(Slowed down view)

A slight buffer is being used in between pebbles so that they do not overlap each other like this.

- Most missed pebbles are due to incorrect pebble identifications happening in either the inlet or outlet view due to similar digits being confused (like 1 and 7 or 5 and 6).
- To combat this, we are working on creating a matching system for incorrectly identified pebbles so that their residence times can be calculated (ex: 127 matches most closely to 121).

Task 4. Up-to-date Accomplishments

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

- ❖ 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

Main Features

- ➢ 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.

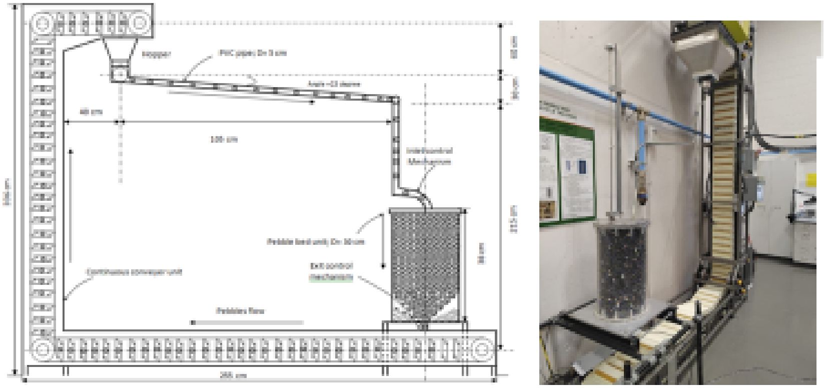
Task 4. Selected Early Attempts and Efforts That Were Made to Reach the up-to-date Accomplishments

Previous Setup to be Modified

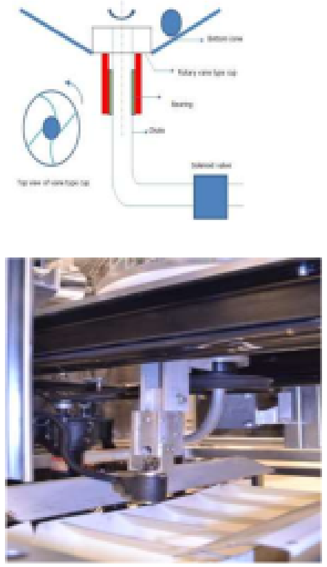
❖ In the early stage of the project, significant effort and time were invested on modifying the existing pebble recirculation setup to accommodate the use of 6.0 cm graphite pebbles.

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



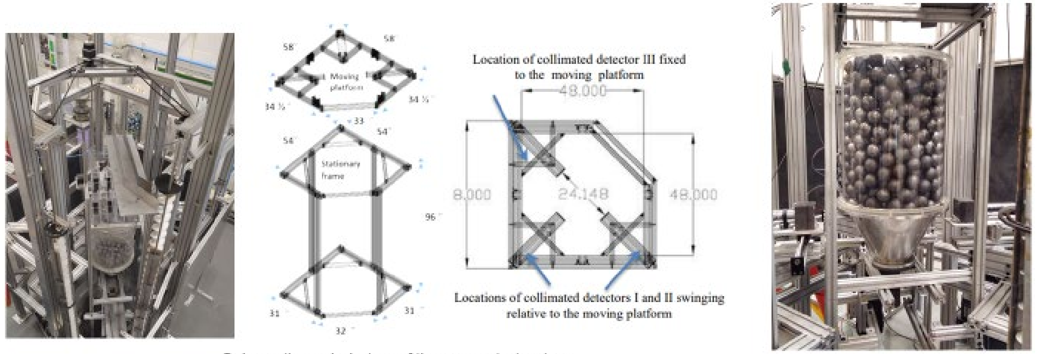
Pebble extraction device

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.

Steps of the Development of the New Setup

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

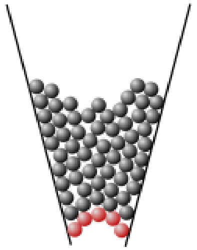
1. Support structure frame with fixed and moving platforms for the RPT, RTD, and Camera Systems around the setup.



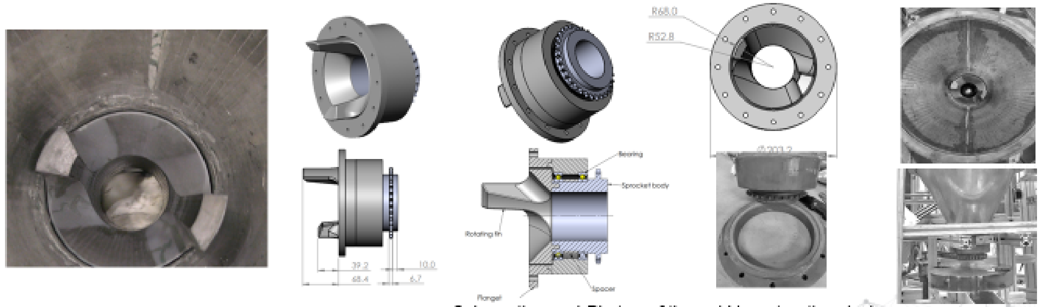
Schematic and photos of the support structure

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.



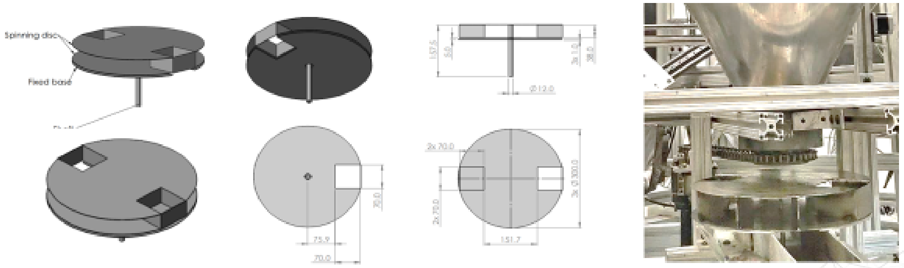
Pebble arching\jamming illustration



Schematics and Photos of the pebble extraction device

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

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ADVANCED REACTOR TECHNOLOGIES

Task 4. Current and Future Work

- A deliverable has been submitted.
- The setup is deployed, and we are extracting the needed data and information.
- This setup will be used as a novel, robust bullet-time tagging, and tracking system based on computer vision techniques that are reliably validated and that have been investigated for tagging and tracking each pebble.

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

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Task 5. Up-to-date Accomplishments

- 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.

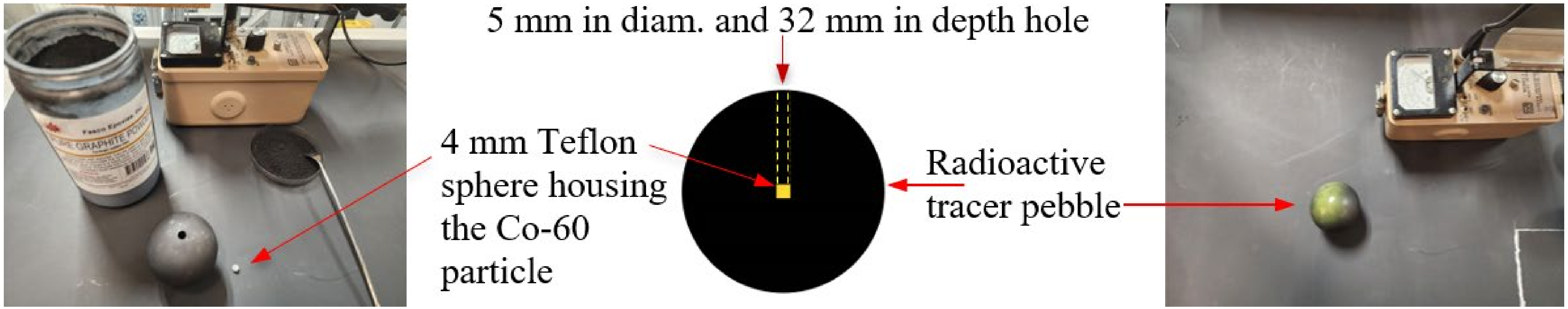
- A Dynamic Radioactive Particle Tracking (DRPT) has been developed and installed around the pebble bed to investigate pebble flow and to validate the developed technique of the bullet-time tagging, and tracking system.

- 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.

- 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.

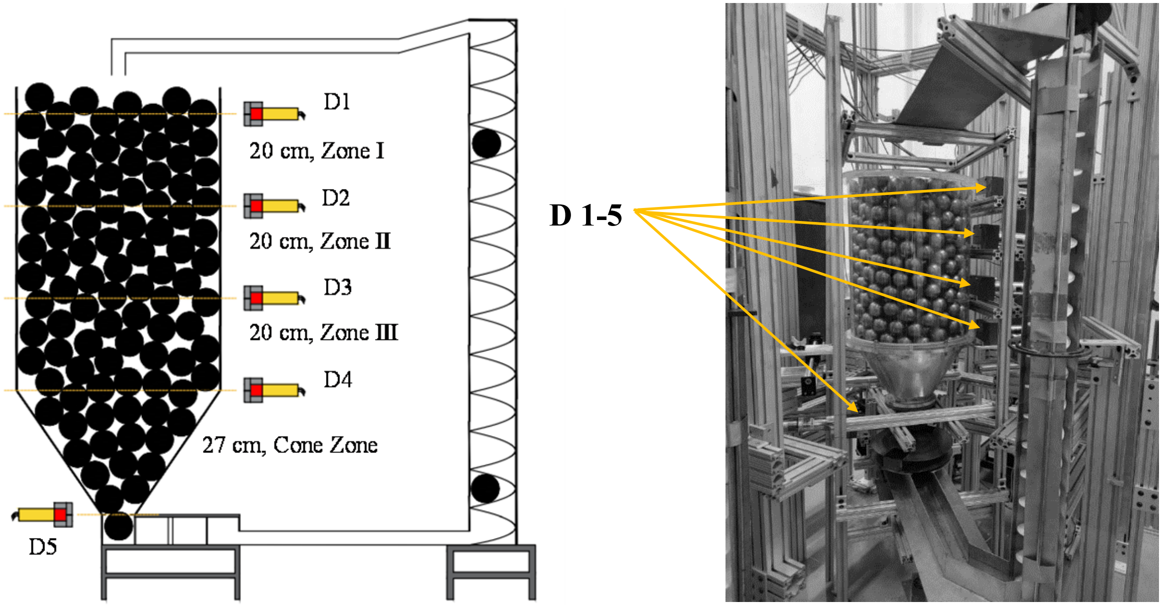


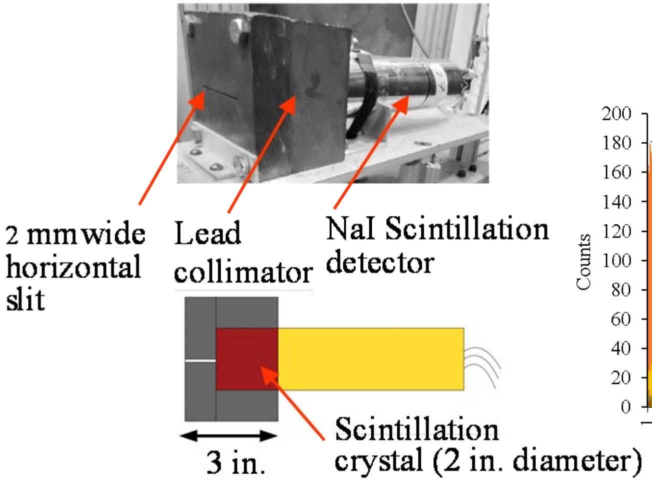
Schematic and Photos of the Tracer Pebble

- 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.

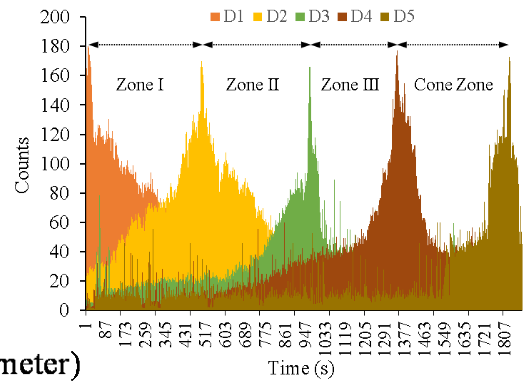
- Detectors 1 and 5 are placed at the inlet and outlet of the pebble and their location is alighted with the camera system to simultaneously measure the over all residence time by the RTD and developed the tagging and tracking system.

- The remaining three detectors are arranged along the cylindrical section and used to obtain zonal residence time data.

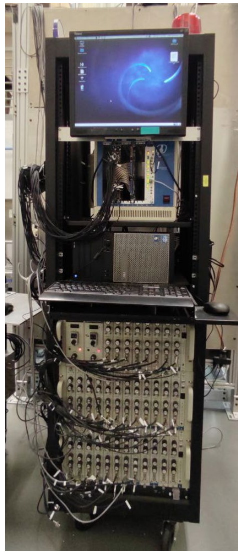




Collimated Detector



Counts Received by Detectors



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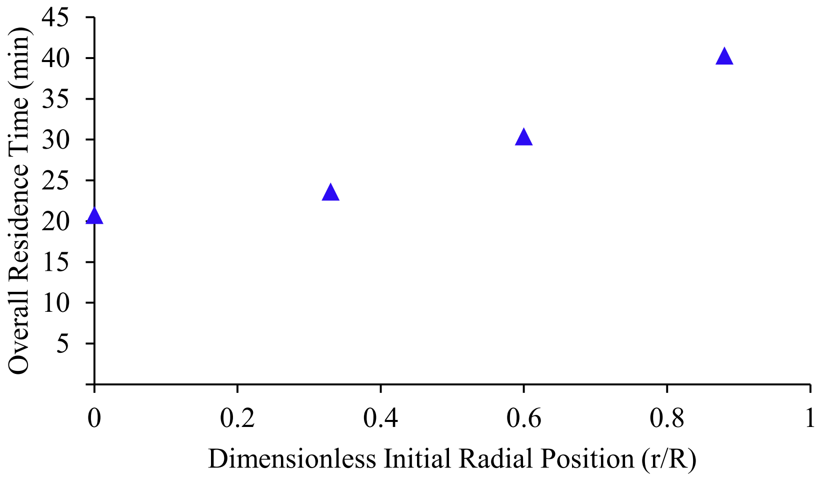
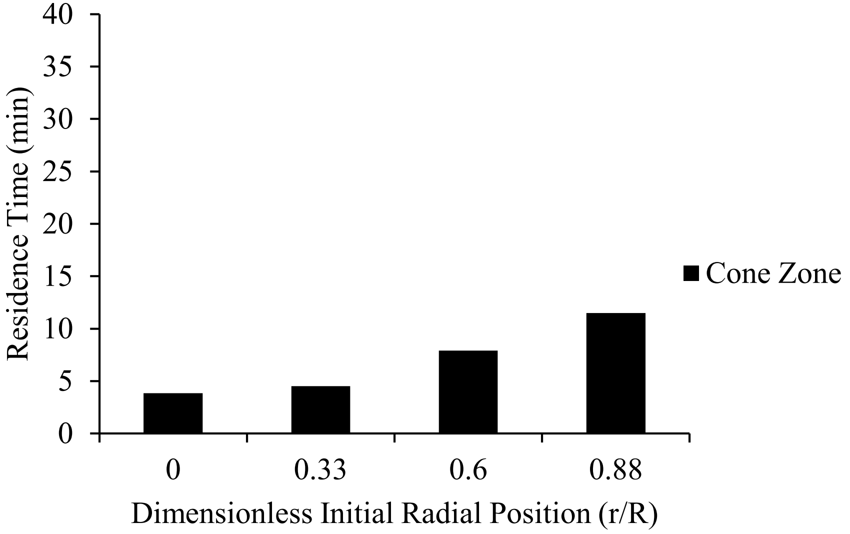
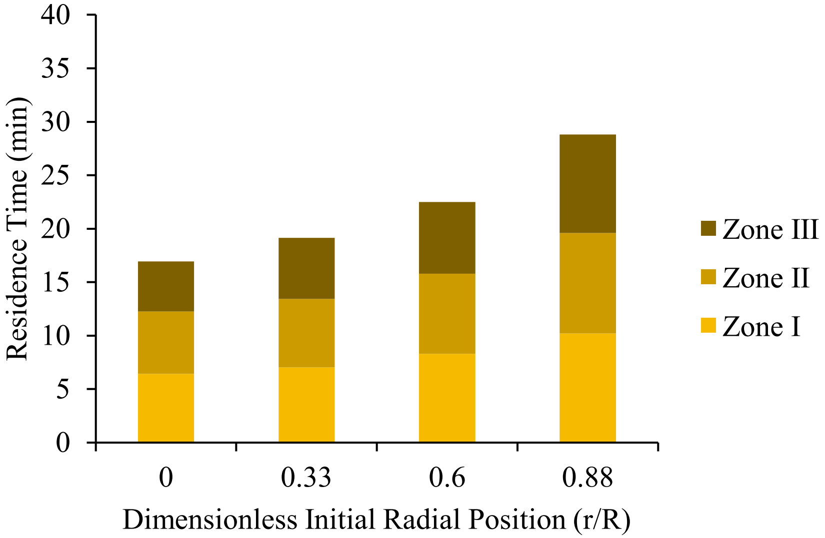
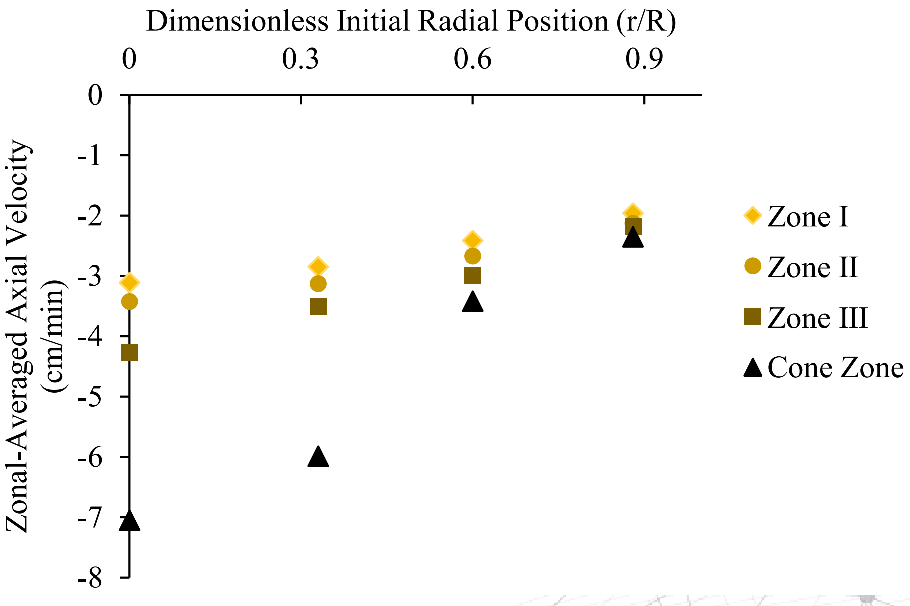
Schematic and photo showing the location of the Detectors

Task 5. Sample Results Obtained by the Radioisotopes Based RTD Technique





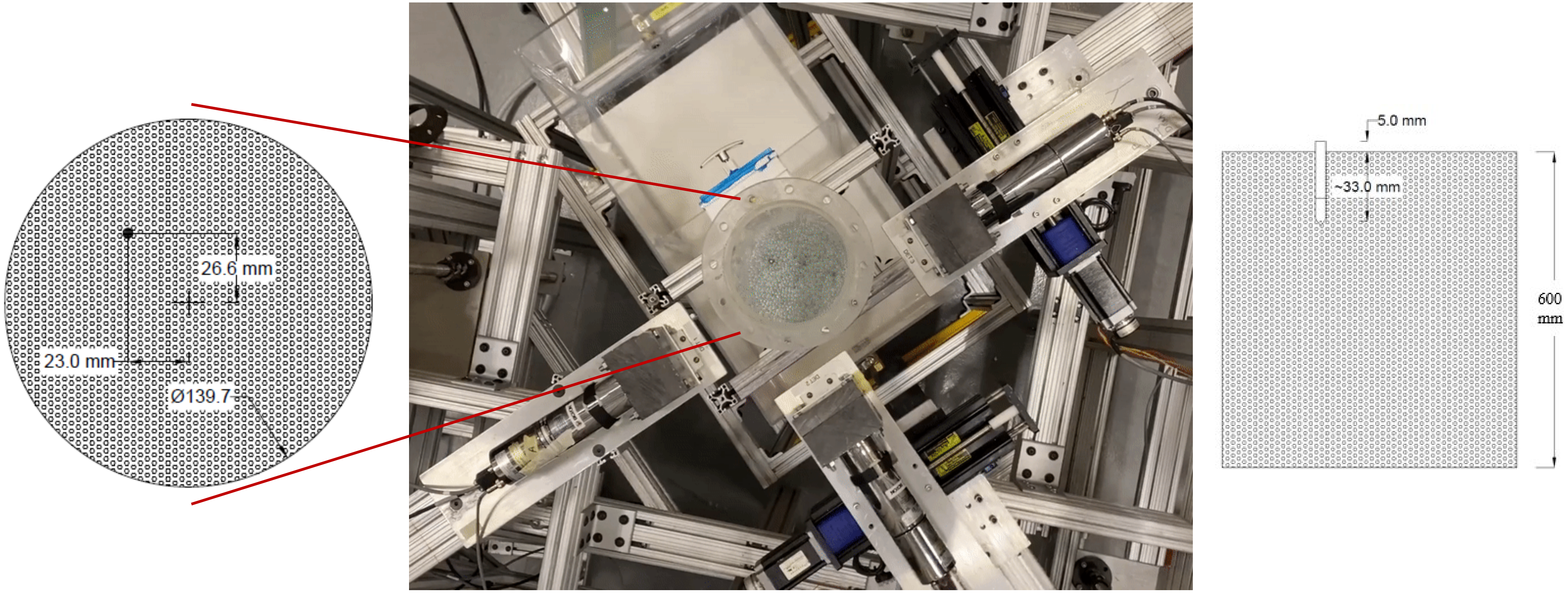




Task 5. Future work

- The Dynamic Radioactive Particle Tracking (DRPT) Technique is currently being implemented to provide information about three-dimensional pebbles trajectory, velocity, overall and local residence time distribution, and other related solids flow dynamic parameters in a non-invasive manner.

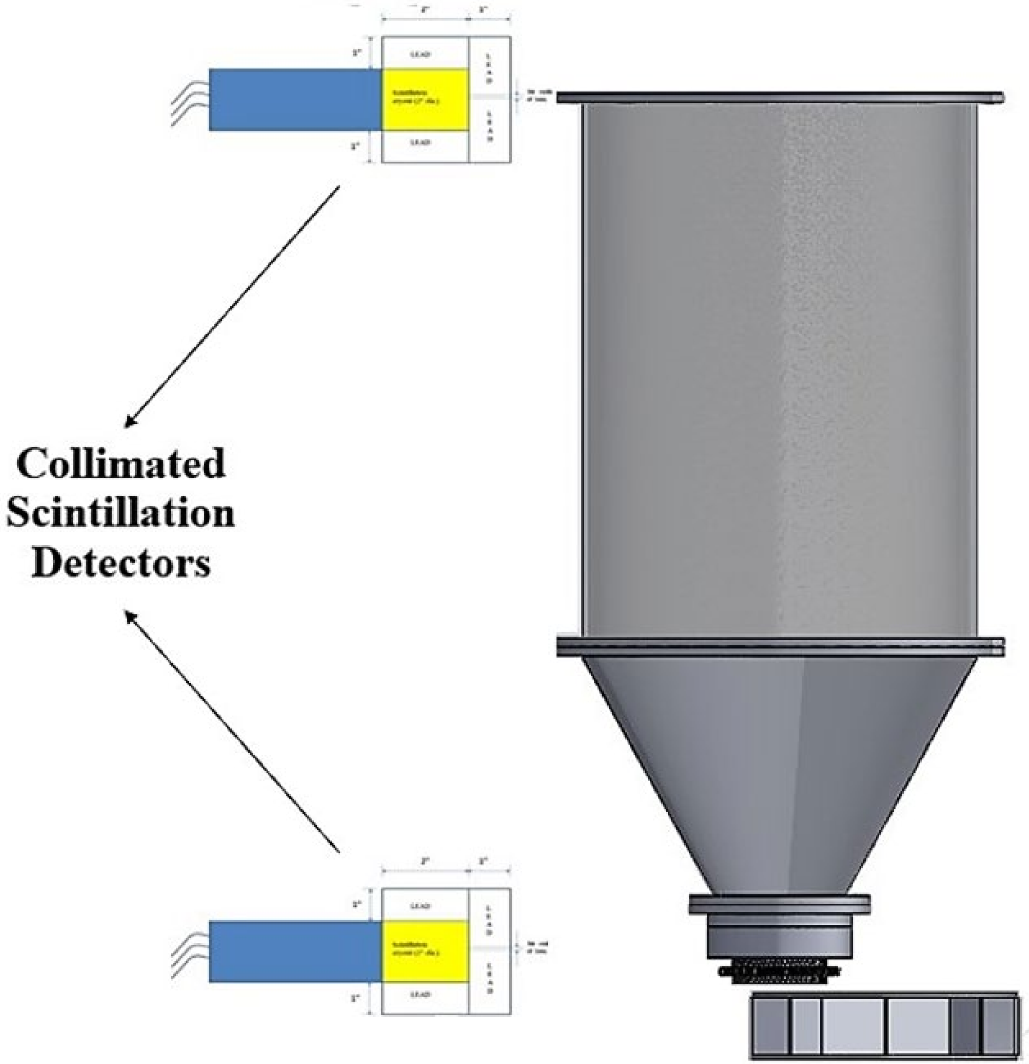
- However, implementing DRPT around continuous pebbles recirculation experimental set-up is more involved, challenging, and time-consuming. It demands carrying out numerous tasks before, during, and after DRPT experiments to obtain reliable information.



Dynamic Radioactive Particle Tracking System (DRPT)

Task 5. Future work

Continuing the Work and Investigation on Radioisotopes Based RTD

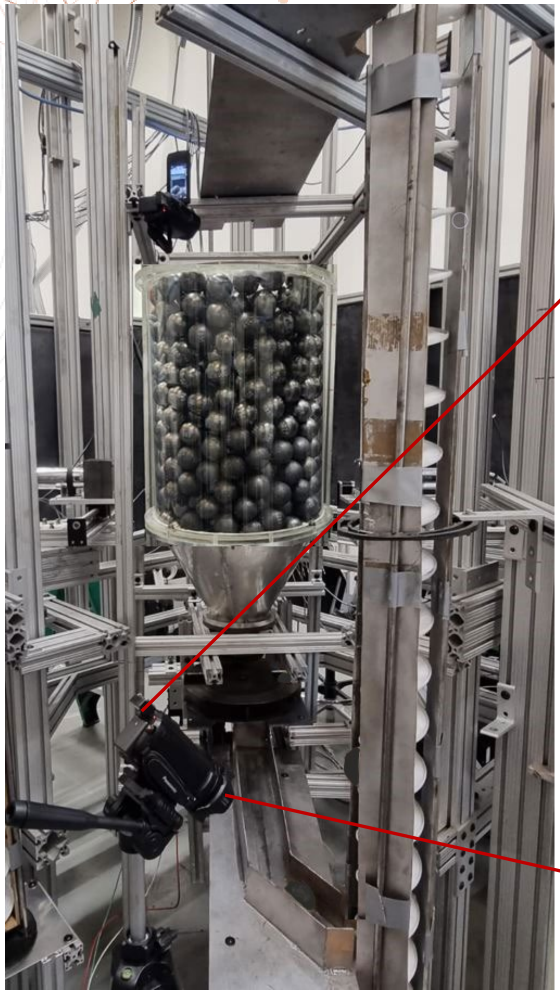


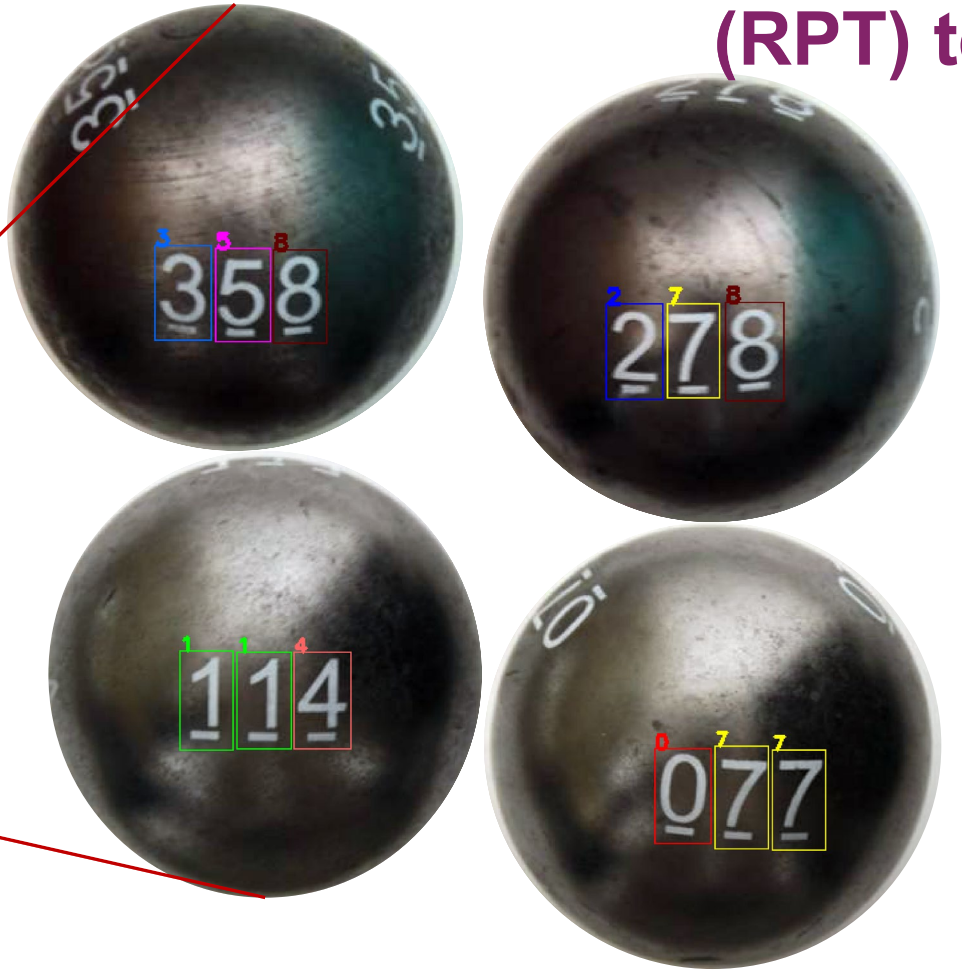
RTD set-up

Integrating the Camera Array System, Pattern Recognition Algorithm, and Radioisotopes Based RTD, DRPT, or RPT Techniques to implement online pattern recognition to measure pebbles' transit time and validate it non-invasively as per Task 6.

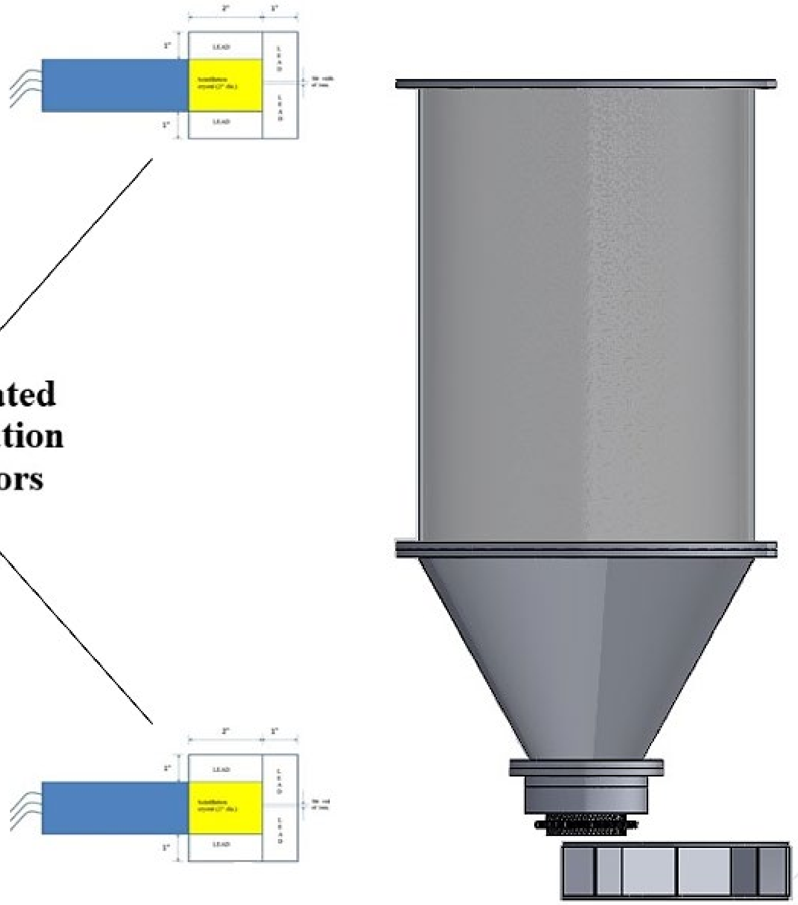
Task 6. Future work

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





Validation of the bullet-time tagging and tracking system using the RTD Technique

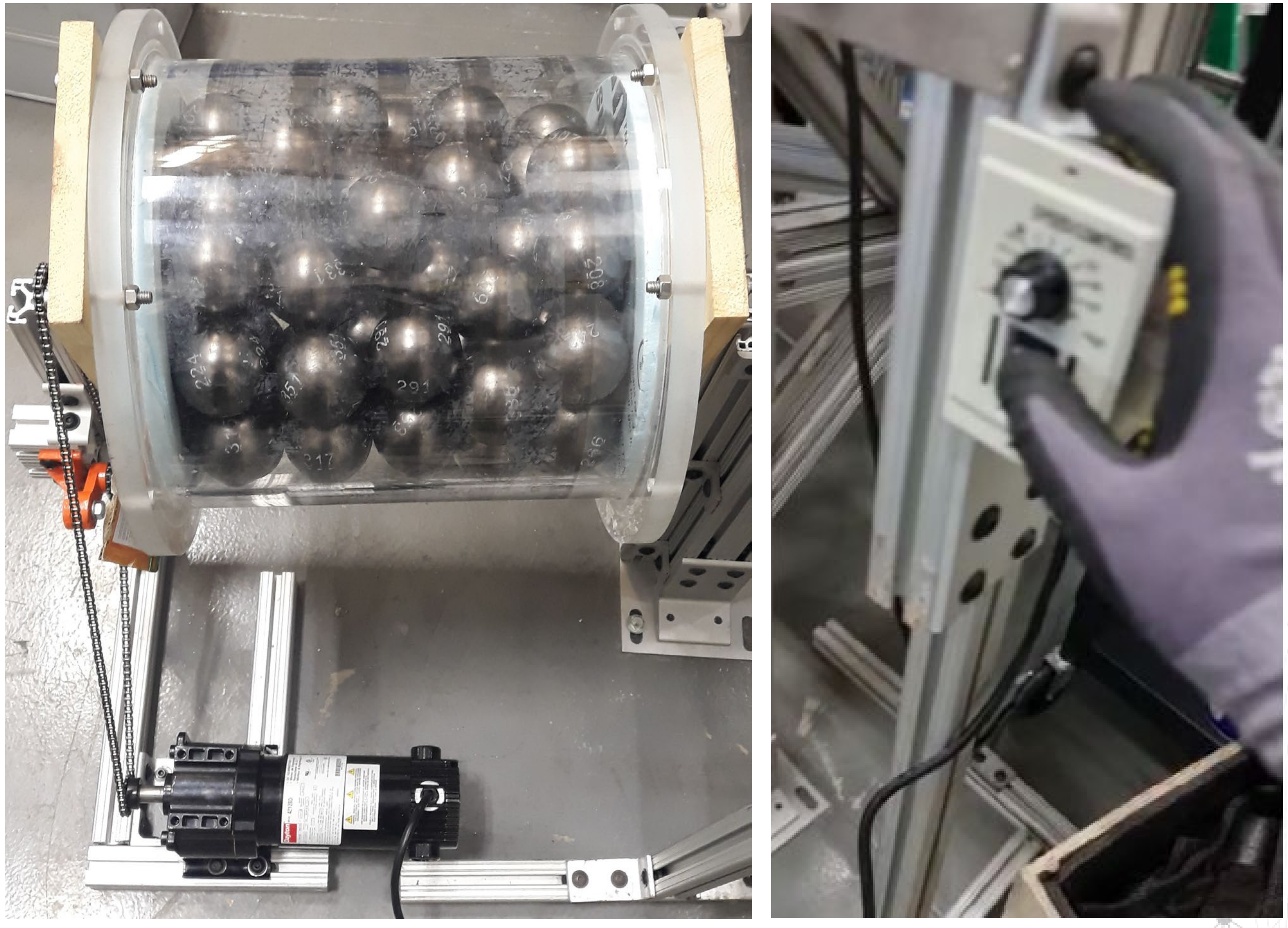


Task 7. Evaluating the tagged graphite pebbles surface for abrasion at prolonged times operation

Task 7. Up-to-date Accomplishments

- Designing and building a new 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.

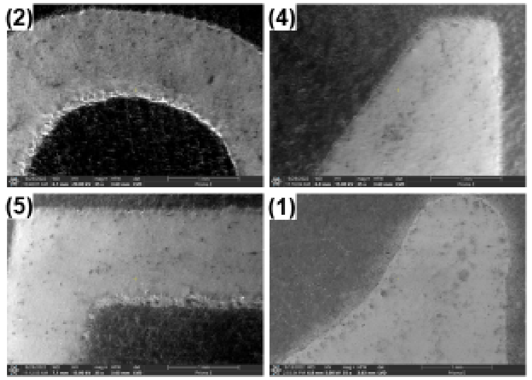


Abrasion Setup

Task 7. Future work

Task 7. Future work

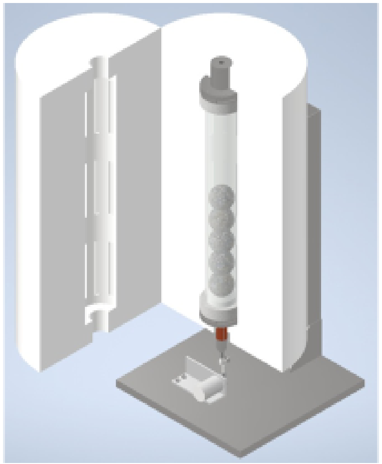
- The abrasion test unit will be operated for a selected number of patterned pebbles for long periods depending on the results.
- The ceramic patterns on the selected graphite pebbles' surfaces will be tested **before** and **after** the experiments for the integrity of the patterns using the Scanning Electron Microscope (SEM) technique.

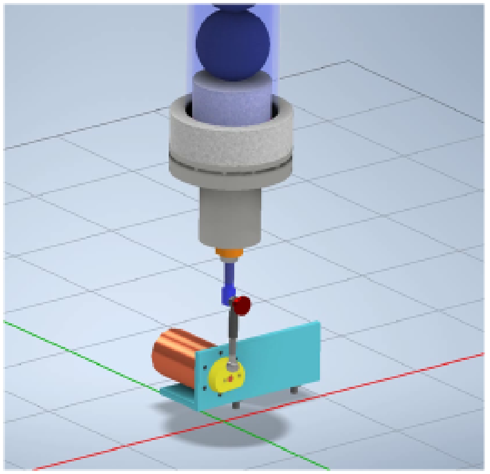


Images of the surface of the patterned graphite balls using SEM Examination

Task 7. Future work

A new advanced heating abrasion setup is 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.





Carbolite EZS-3G 12/600B tube furnace

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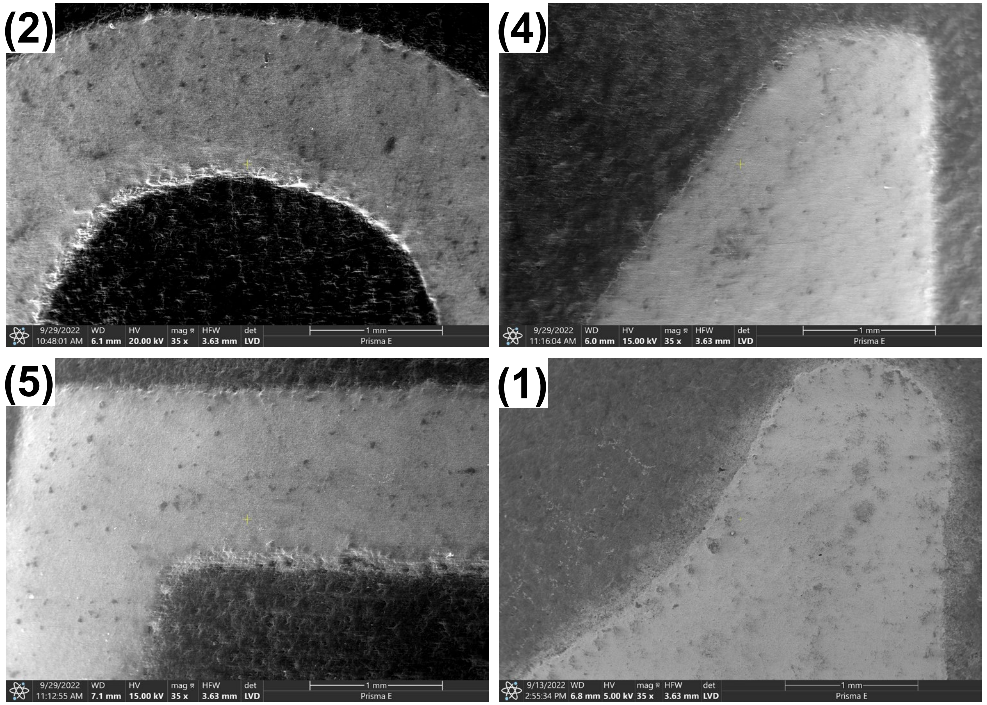

Images of the surface of the patterned graphite balls using SEM Examination

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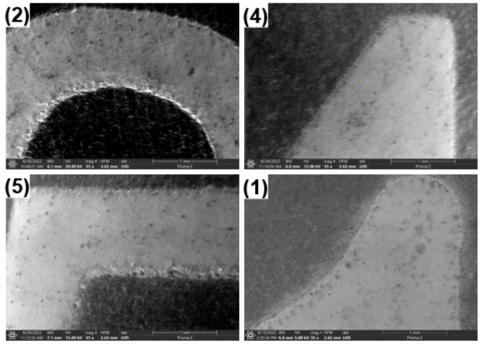
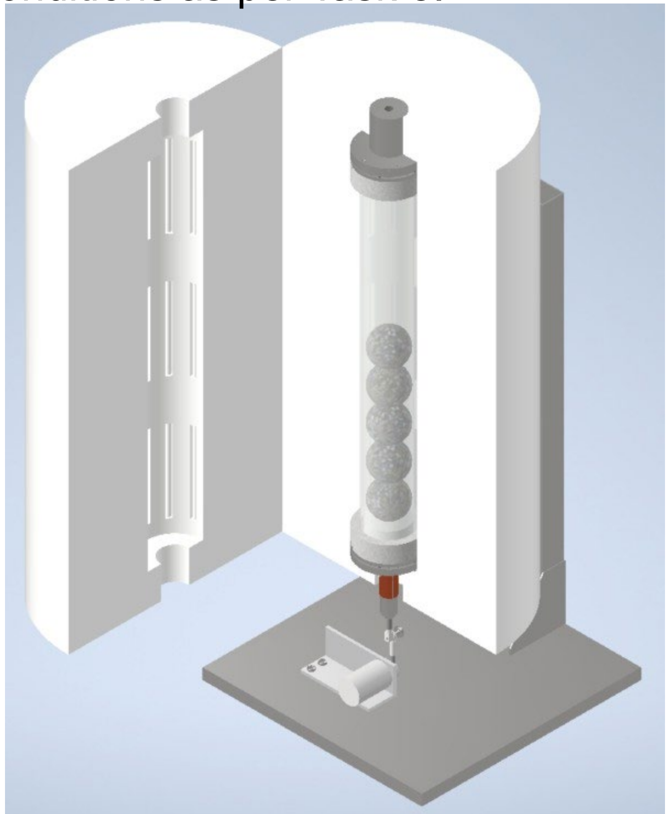
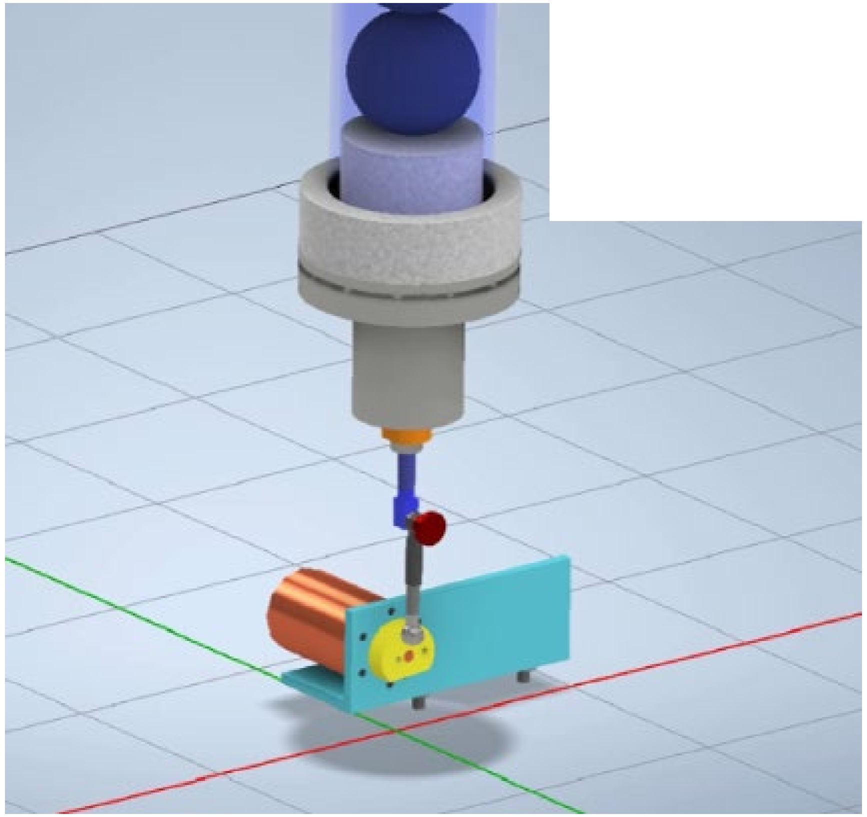


Images of the surface of the patterned graphite balls using SEM Examination

32





Carbolite EZS-3G 12/600B tube furnace

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

Products

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)

MISSOURI S&T University of Science & Technology

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

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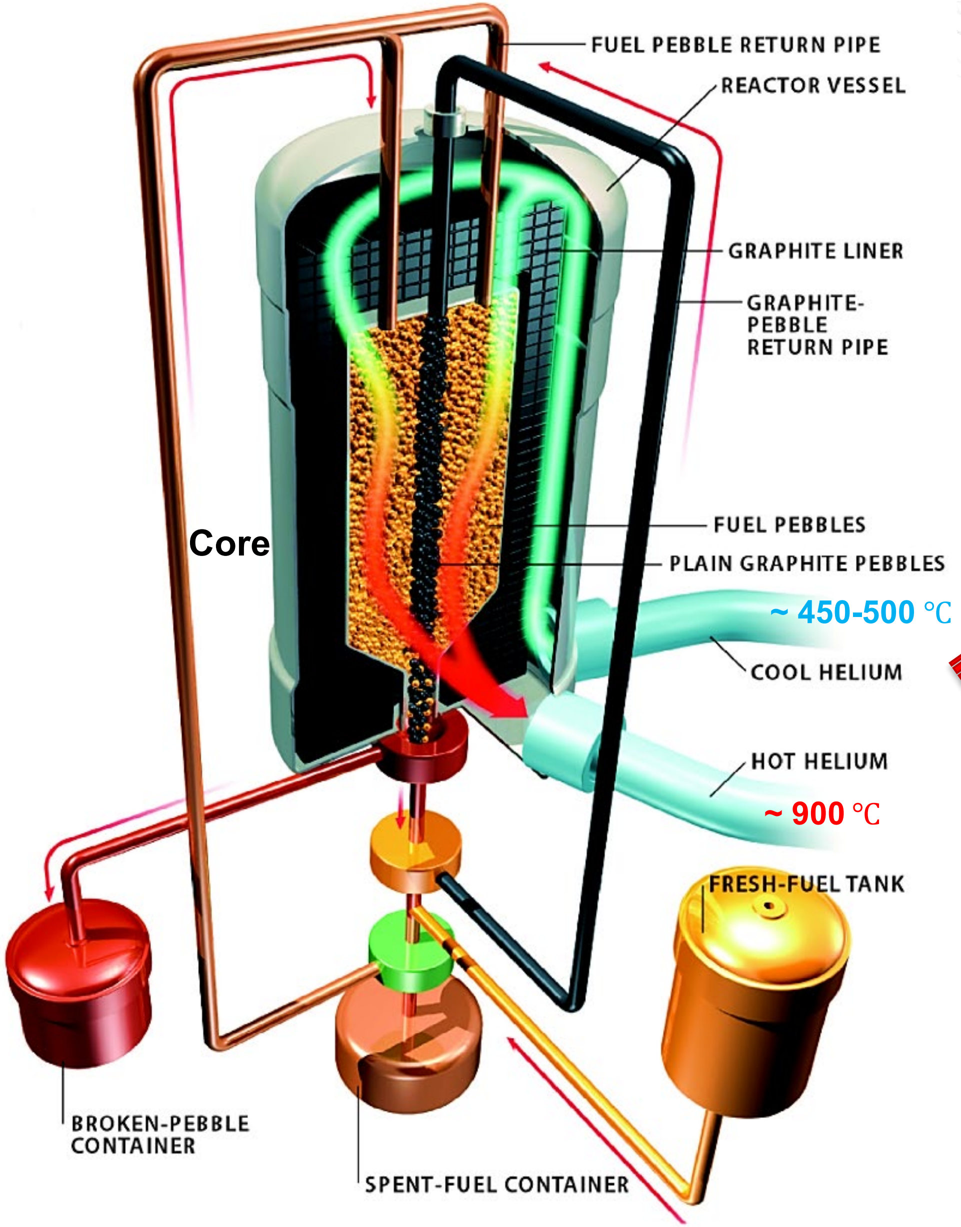
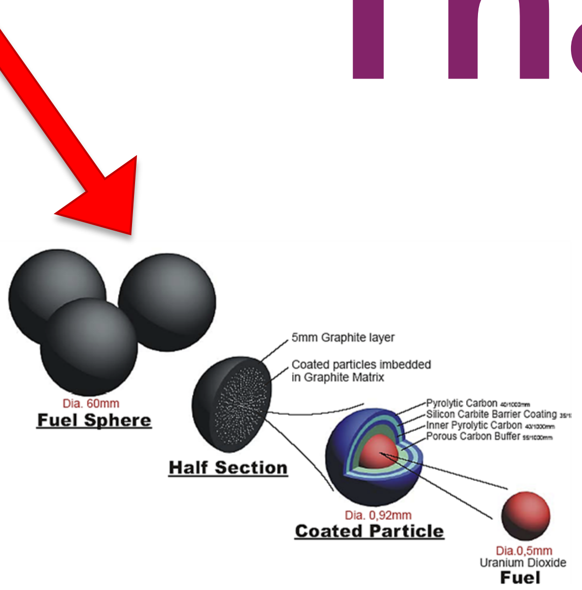
- Zeyad Zeitoun (Ph.D. Student)
- Omar Farid (Former Ph.D.)

- Roshan Kenia (BS) (roshan.kenia@stonybrook.edu)
- Liang Han (Former Postdoc)
- Zuhui Wang (Former Ph.D.)





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Stony Brook University

Thank you

ART Advanced Reactor Technologies