International Conference on Applications of Radiation Science and Technology

24-28 April 2017
IAEA Headquarters

Experimental Study of Pebble Flow Dynamics in a Pebble Bed Modular (PBMR) Using Radioactive Particle Tracking (RPT) Technique

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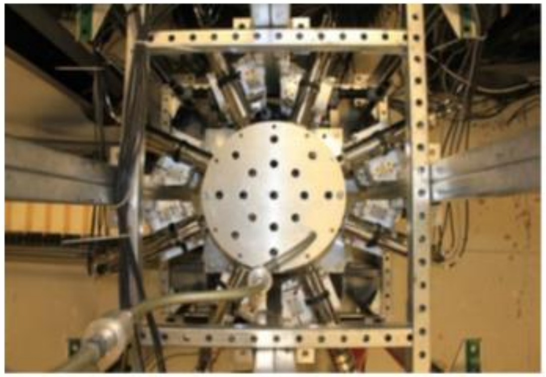
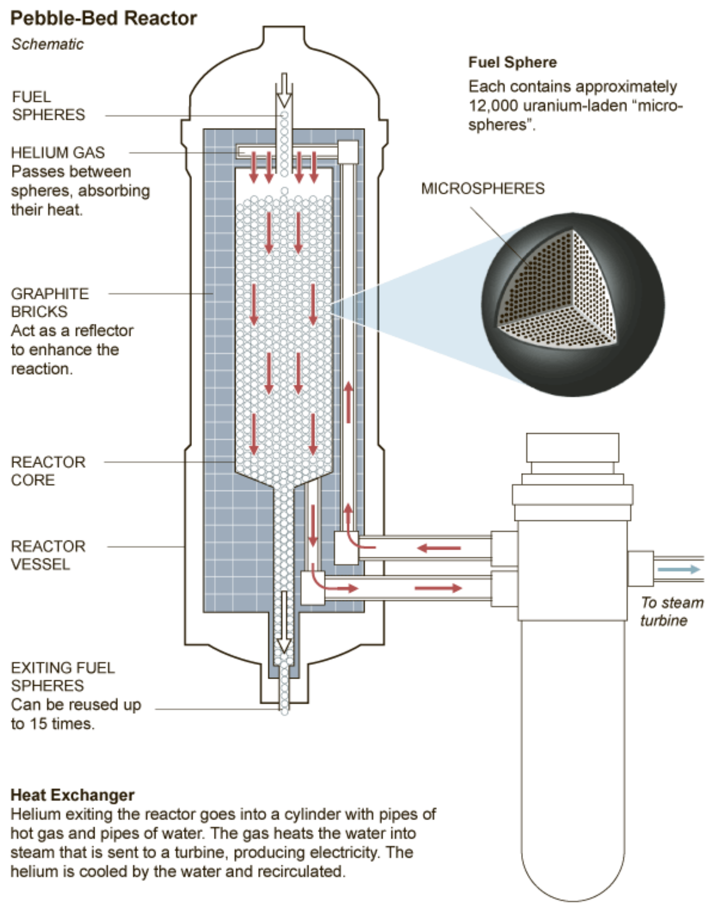


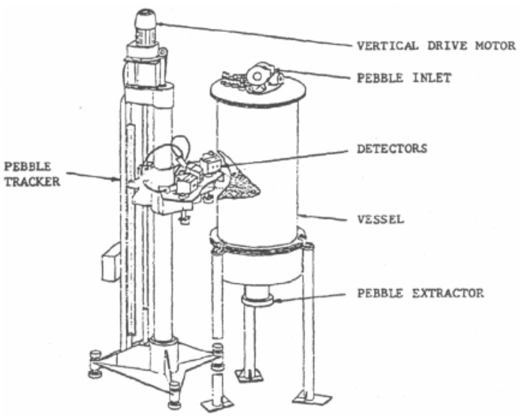

Pebble bed reactor- Gen IV Concept

- Pebbles are in continuous recirculation
- **Online refueling** – elimination of shut down requirements and **Higher burn-up**
- Higher outlet temp. (~900-1000°C) and passive safety features
- Inert helium coolant
- Attractive for:
  - Co-generation
  - Process heat applications
  - Hydrogen production
  - Water desalination
- Attractive due to passive safety, high thermal efficiency, high burn-up



Ref. http://farm6.staticflickr.com

Previous Limitations of Experimental Studies



3-D Model- Limited tracking using RPT

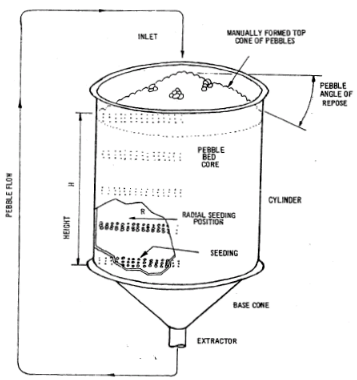


FIGURE 1. SKETCH OF PEBBLE BED NUCLEAR REACTOR SHOWING FULLY SEEDED PEBBLE BED

Gatt's work, 1973*

Half Model – Visual tracking

Motorized removal device ~120 pebbles per min

M.I.T. experimental study , 2004&

- Pebble trajectories are in a streamlined manner
- 2-D half model- easy for visual tracking, suffers from **wall effect**
- 3-D model Draining-stopping-tracking –draining (MIT study)
- Flow rate variation has a little effect on the flow profile
- Missing
  - Recirculation exp. Set-up
  - Use of advanced flow imaging techniques
  - Coupled exp. study with DEM based simulations
  - Continuous tracking

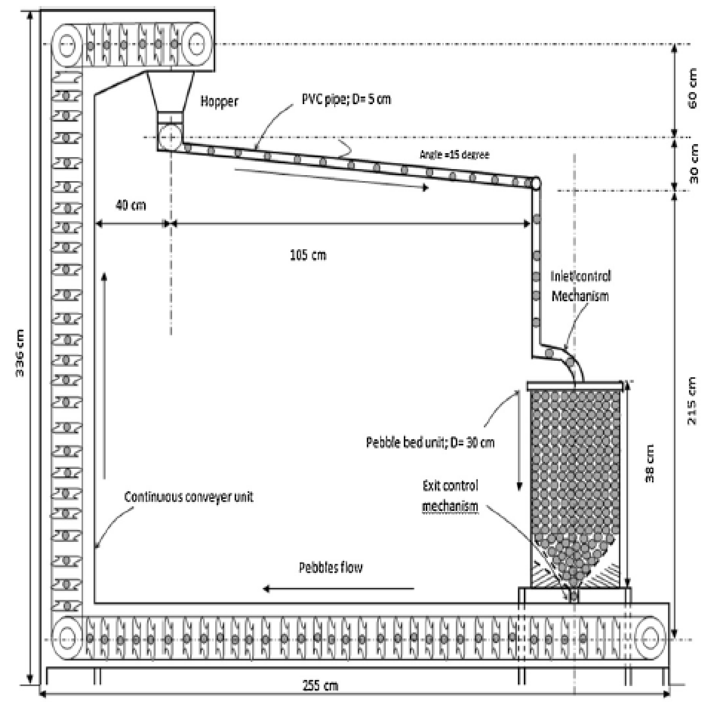
* Gatt, F.C., 1973, Flow of spheres and near spheres in cylindrical vessels, part IV, AEC, Lucas Heights.

& A.C. Kadak and M.Z. Bazant, 2004, Pebble flow experiments for pebble bed reactors, 2nd International Topical meeting on High Temperature Reactor Technology, Beijing, China.

Overall Objectives

- Design and development of **continuous pebbles recirculation exp. set-up** (that mimics PBR operation)
- Implementing RPT technique around it and provide benchmark data about
    - Pebbles flow path in 3-D & velocities
    - Overall & zonal residence time

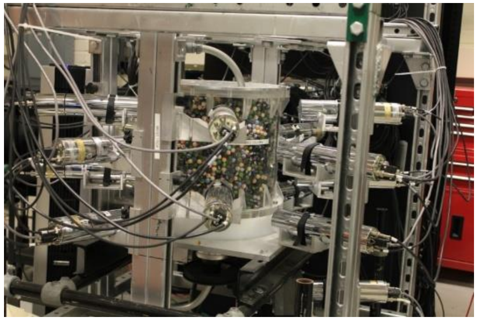
Continuous Pebble Recirculation Experimental Set-up

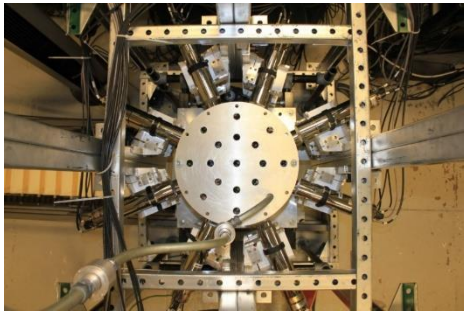


Radioactive Particle Tracking (RPT)

- ❑ Useful in characterization of 3-D flow fields of **dense and opaque** multiphase systems
- ❑ ***RPT Tracer***
  - ❑ Co-60 particle
  - ❑ Dynamically similar

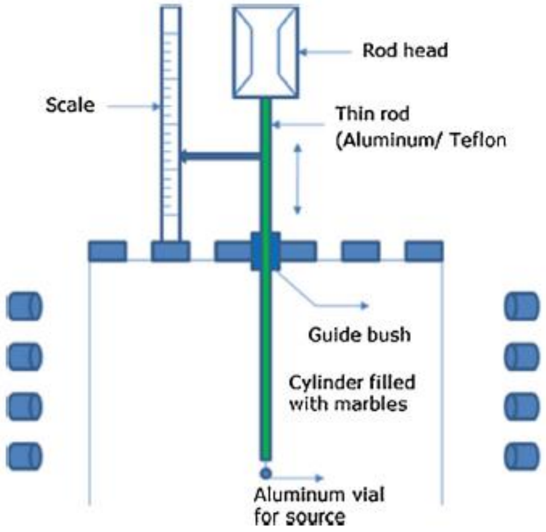
RPT tracer

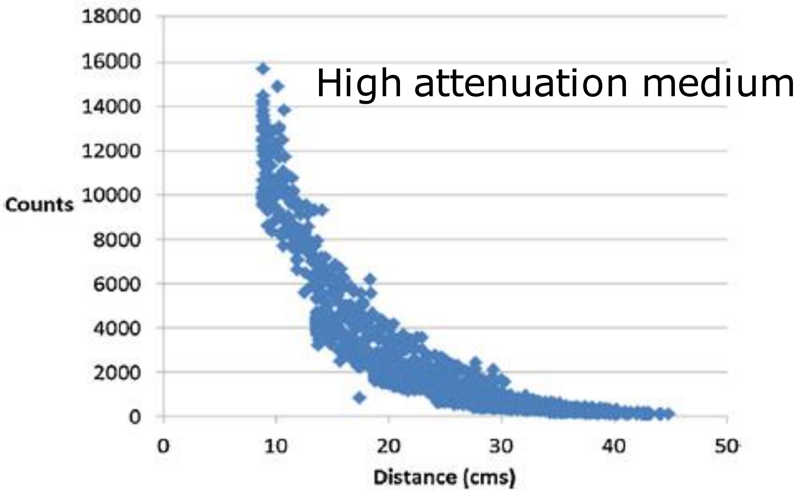




RPT Technique

RPT Calibration





RPT detector calibration curve for PBMR study.

RPT Position Reconstruction Algorithm

- Problem of finding unknown tracer position is reduced to matching the counts data received in all the detectors to the counts data information recorded for a known calibration position
- Cross-correlation based search for locating tracer particle location (finding the cross-correlation coefficient)

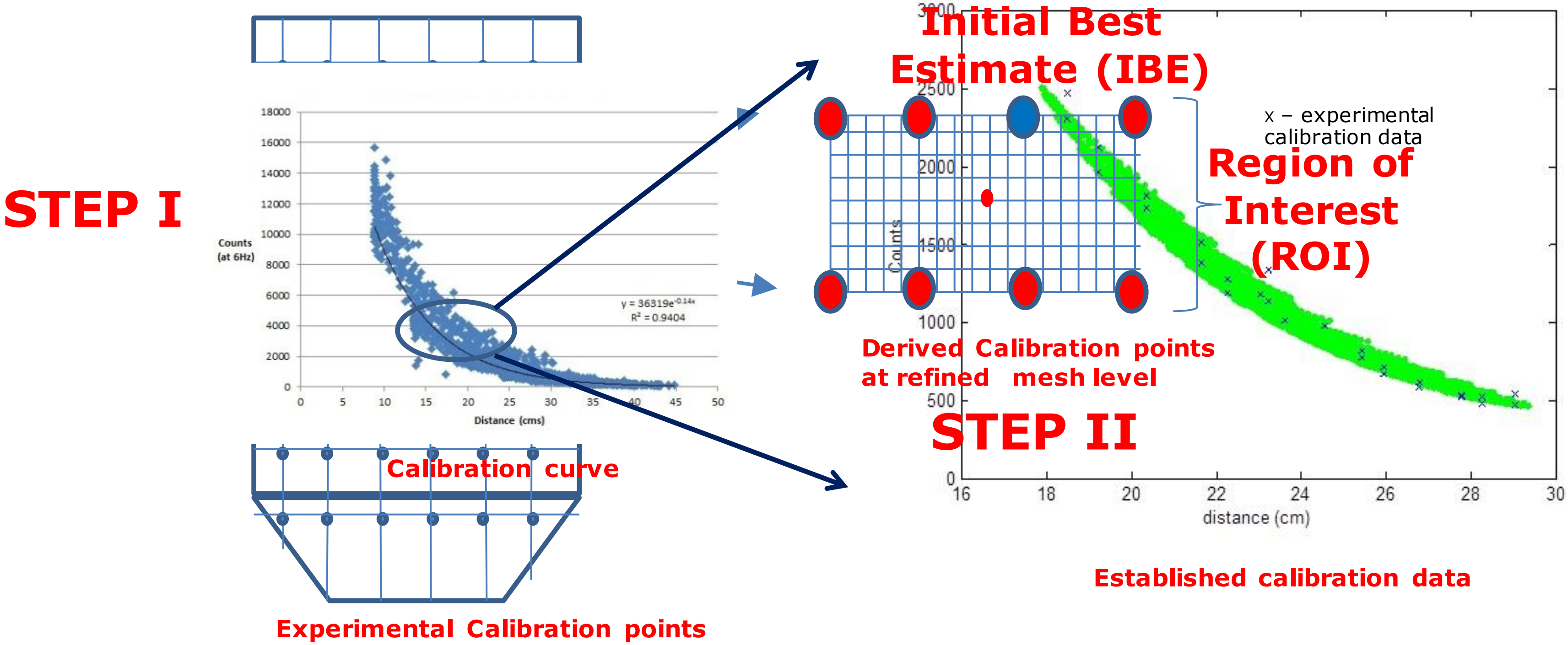
$$R_{run,calib_k}(0) = \sum_{i=1}^{N_d} \frac{C_{calib\ (i)}}{\sum_{j=1}^{N_d} C^2_{calib\ (j)}} \cdot \frac{C_{run\ (i)}}{\sum_{j=1}^{N_d} C^2_{run\ (j)}}$$

- Semi-empirical model relating the counts (C) to the position of the emitting tracer particle –accounts for the geometry as well as attenuating medium effects

$$C = \underbrace{\frac{k_1}{d^2}}_{1} \cdot \underbrace{\exp\left(-k_2\, d_x - k_3\, d_y - k_4\, d_z\right)}_{2} \underbrace{1 - \exp(-\mu_d\, k_5)}_{3}$$

Term 1 corresponding to inverse square law , k1 proportional to solid angle
Term 2 corresponding to attenuation characteristics of heterogeneous medium between tracer and detector
Term 3 corresponds to detector efficiency

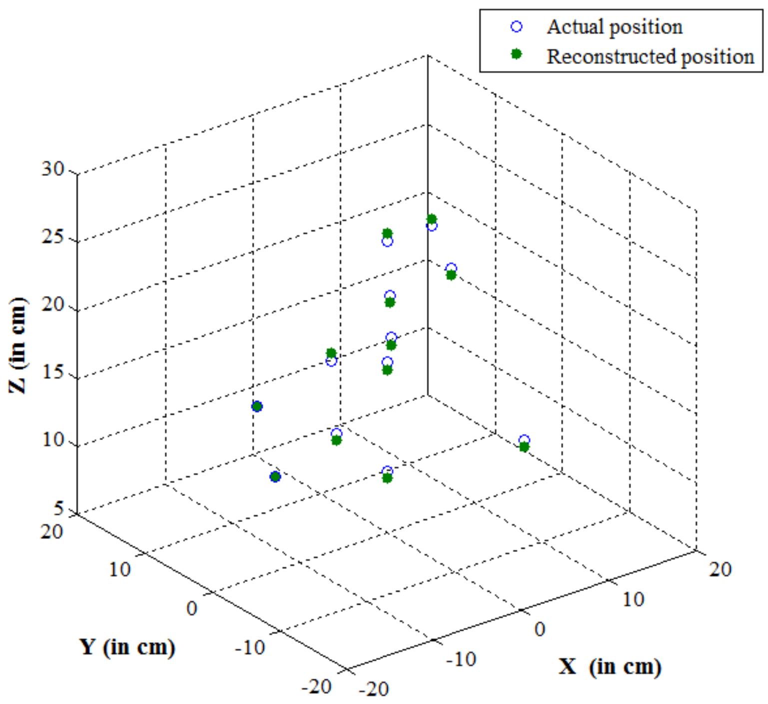
RPT Position Reconstruction Algorithm – 2 steps



- **Step I** – Finding maximum of $R_{run,calib_k}(0)$ for each data series and finding ROI from the whole domain- finding IBE point and then finding neighboring points around it
- **Step II** – Using semi-empirical model to derive additional calibration data for carrying out step I again for ROI found in step I

ROI : region of interest
$\mathbf{R_{run,calib_k}(0)}$: normalized cross-correlation coefficient
IBE : initial best estimate with maximum of $R_{run,calib_k}(0)$

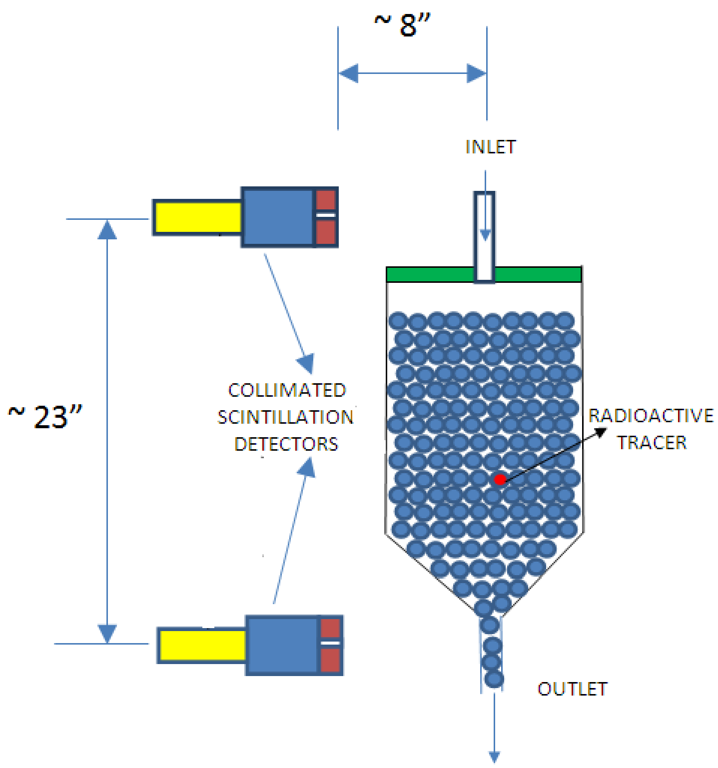
RPT Position Reconstruction Algorithm -Validation



- Finer mesh points are established for next cross-correlation based search (Δr=10mm,$\Delta\theta$=15°, Δz=5mm)
- Cross-correlation based search convergence criterion of $1 - R_{run,calib_k}(0) \leq 0.005$
- Validation - by treating some calibration points as unknown position data and carrying out 2-step cross-correlation based position search
- Reconstruction error ~ 5 mm
- Mostly, error in z-direction

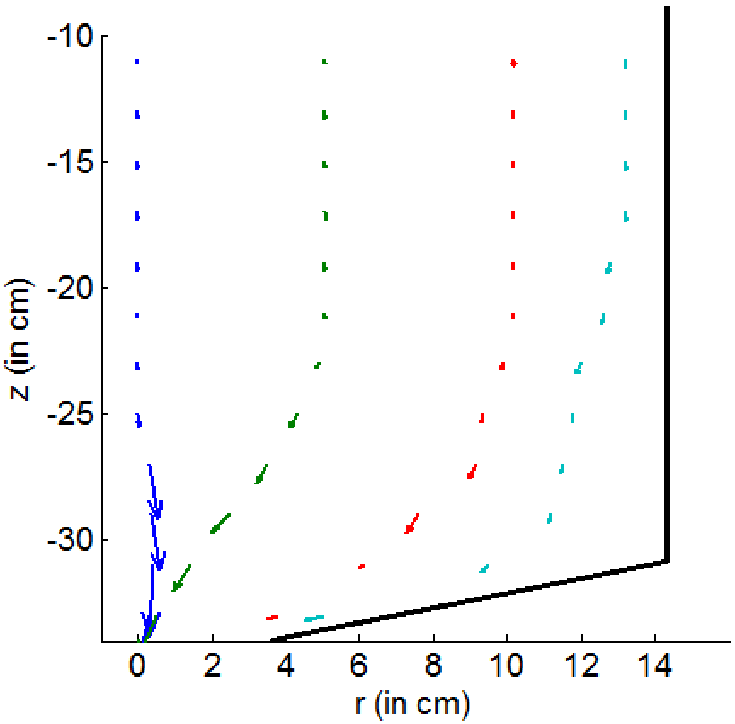
$R_{run,calib_k}(0)$: normalized cross-correlation coefficient

Overall Residence Time set-up

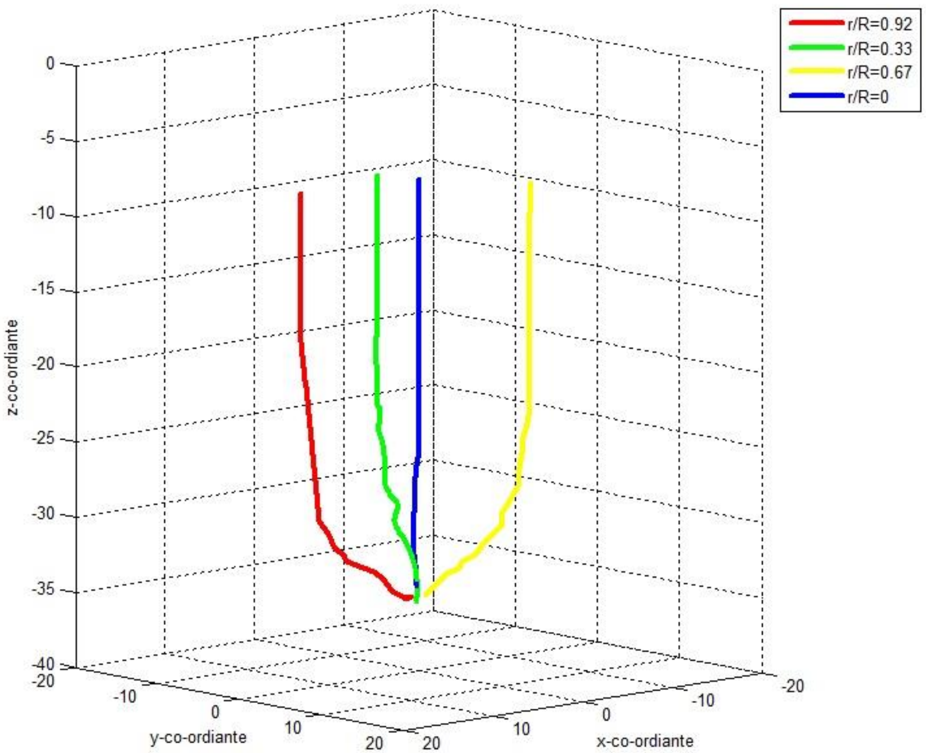


- A set-up involving two collimated detectors around the continuous pebbles recirculation experimental set-up
- Uses radioisotope based tracer mimicking pebbles dynamics
- Measures overall residence time in a non-invasive manner
- Detector collimators with horizontal slits
- When the tracer is in the plane of horizontal slit, maximum counts will be recorded –Principle of operation

Trajectories and Velocity Vector Plots



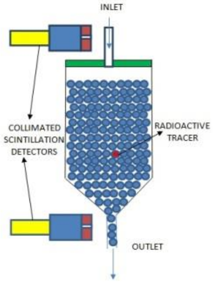
Velocity vector plot



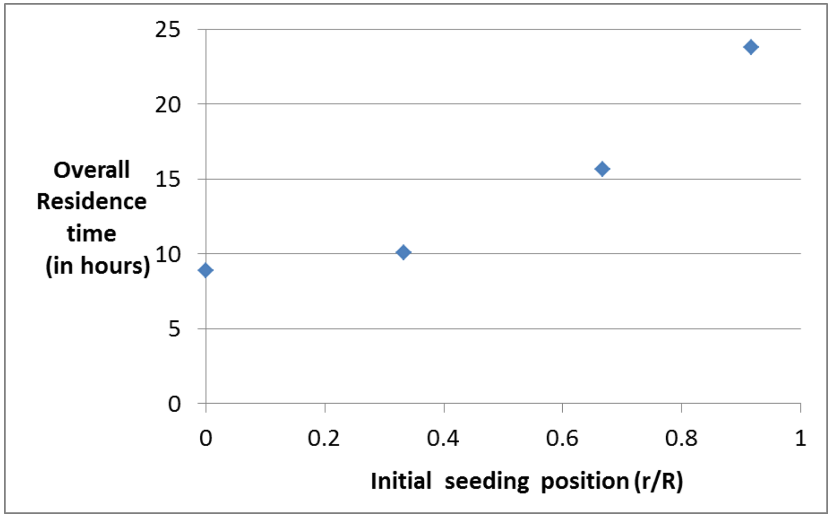
in cm

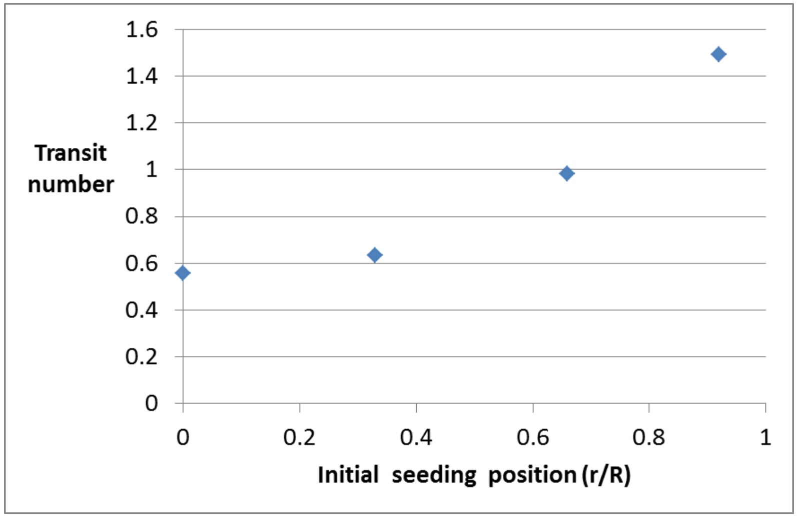
Trajectories in 3-D

- ❑ **Velocity of tracer increases as it moves towards exit opening**
- ❑ **Velocity is highest at the center and lowest near the wall**
- ❑ **Plug-type flow in upper region and converging flow in lower region**



Overall Residence Time



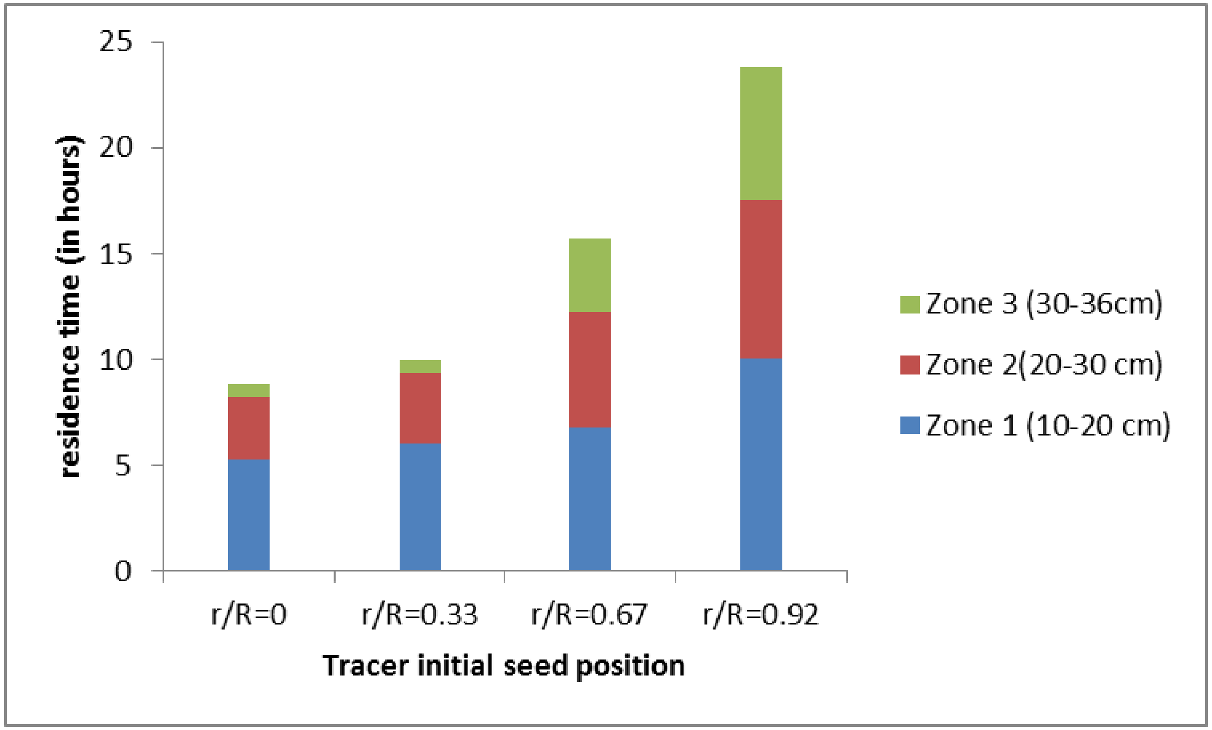


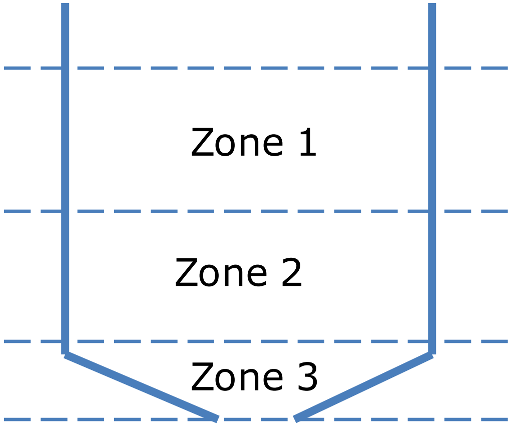
- $$\textbf{Transit number} = \frac{\text{No.of pebbles recirculated between the seeding of the tracer and it's exit}}{\text{total number of pebbles in the bed}}$$

- Overall Residence time/ Transit number increases at a slower rate while moving away from the center , whereas it increases at a higher rate close to wall.

***Ref.** Gatt, F.C., 1973, Flow of spheres and near spheres in cylindrical vessels , part IV, Australian Energy commission, Lucas Heights.

Zone-wise Residence Time Results

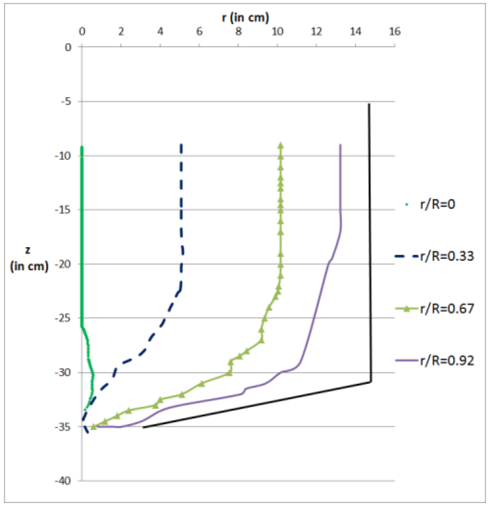


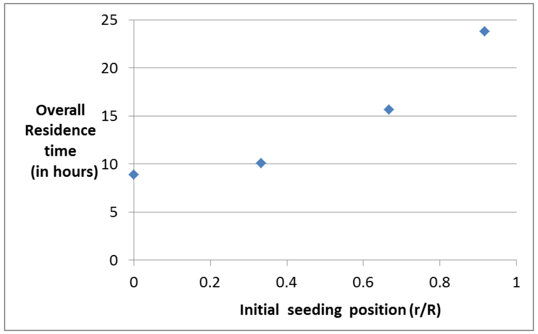


Zonal residence time decreases from zone 1 to 2 and further from zone 2 to 3 for all seed positions

Overall Average Speed Results

	Tracer initial seed position			
	Dimensionless radial position (r/R)			
	0	0.33	0.67	0.92
Trajectory length (in cm)	26.74	29.23	32.4	35.44
Overall residence time (in hours)	8.86	10.1	15.67	23.77
Tracer average velocity (in cm/hour)	3.02	2.89	2.07	1.49



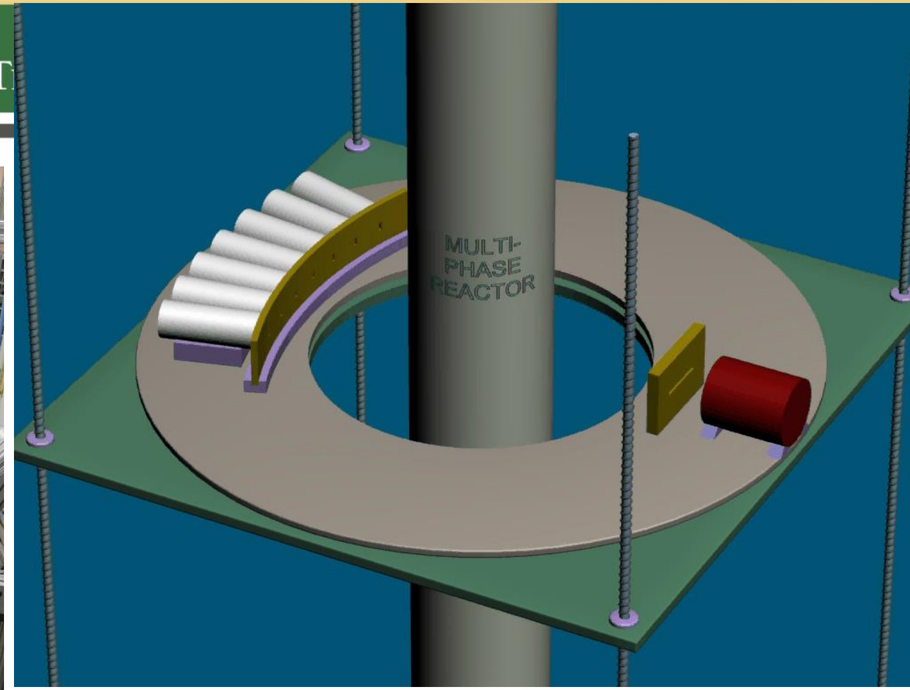


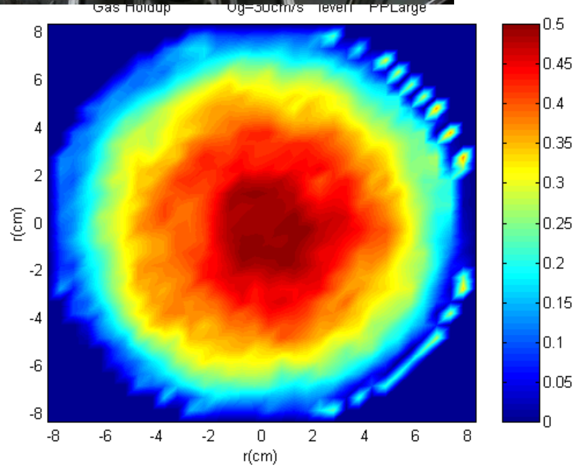
Overall average speed decreases from the center towards the wall

Computed Tomography (CT)

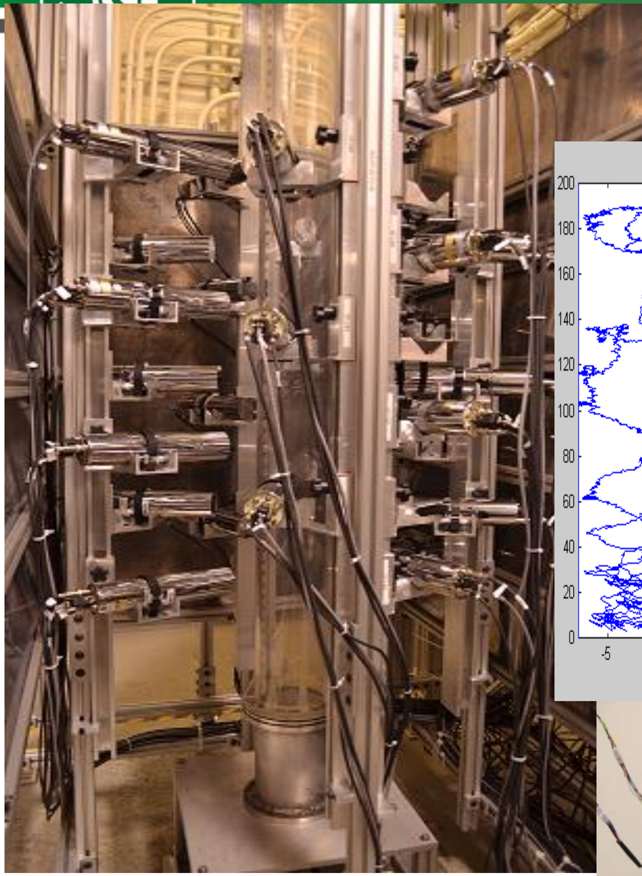
For Phase Distribution

M

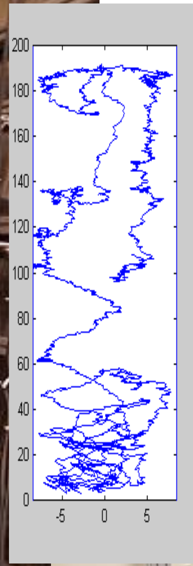


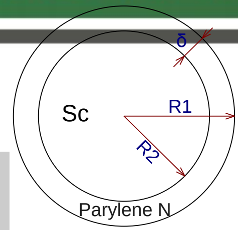


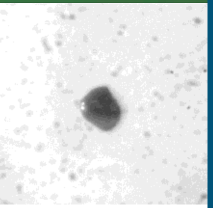
Radioactive Particle Tracking (RPT)



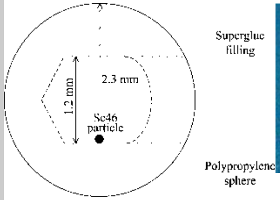
Picture of RPT



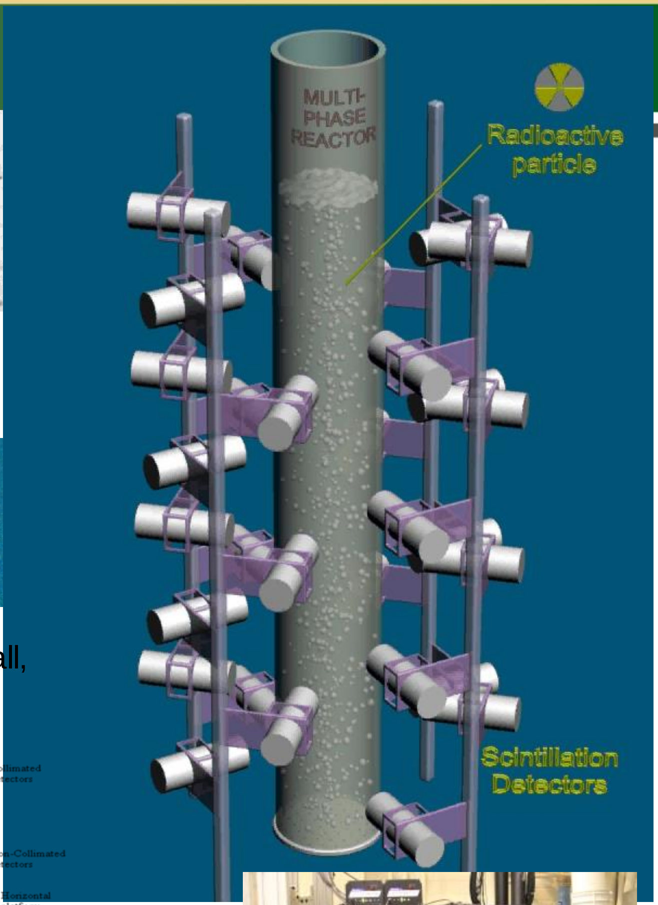


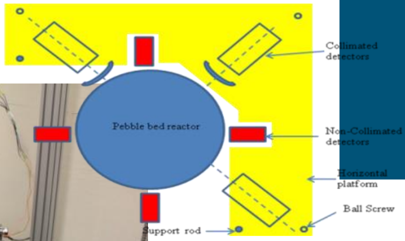


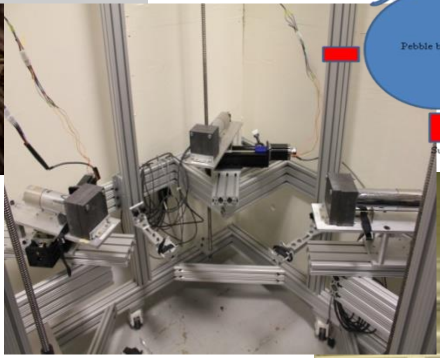
Sc^{46} particle coated with parylene-N, tracking solids

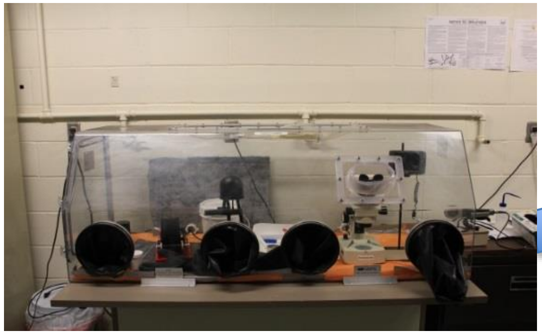


Sc^{46} particle in polypropylene ball, tracking liquid







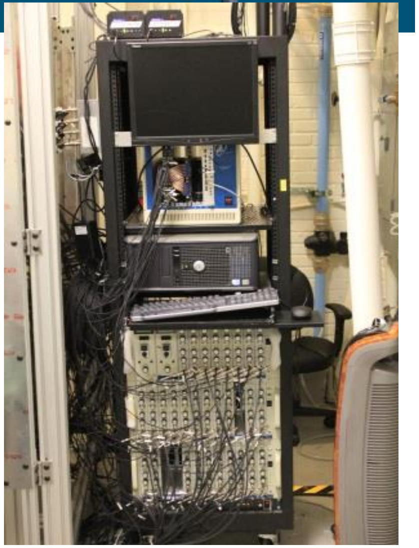


In Situ

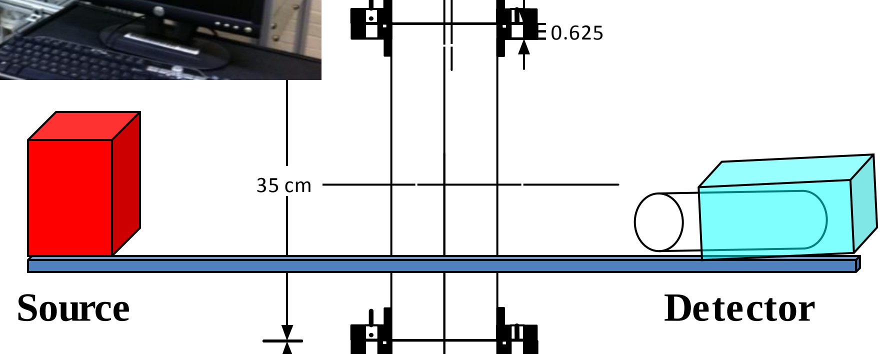
Manual

RPT Calibration

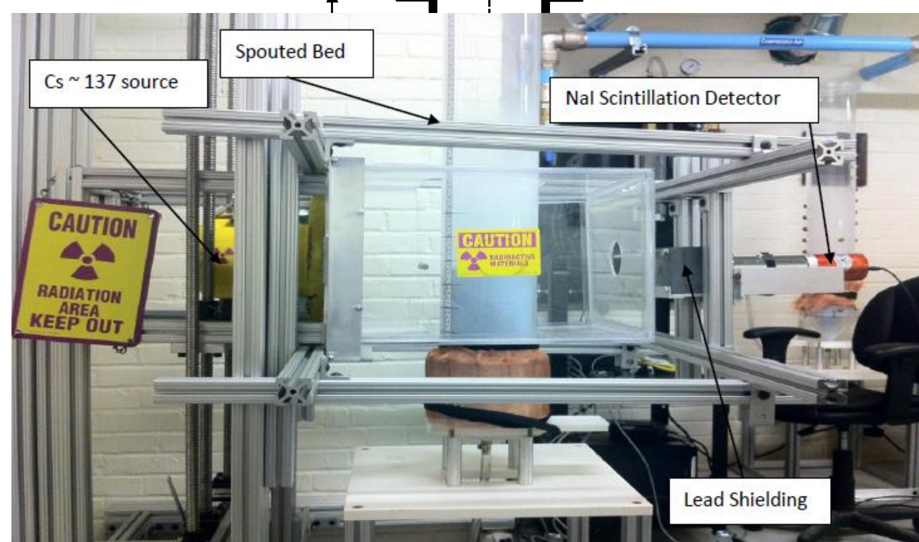
Tracer particle holding assembly



An On-line Technique Using NGD as Gamma Ray Densitometry (GRD)

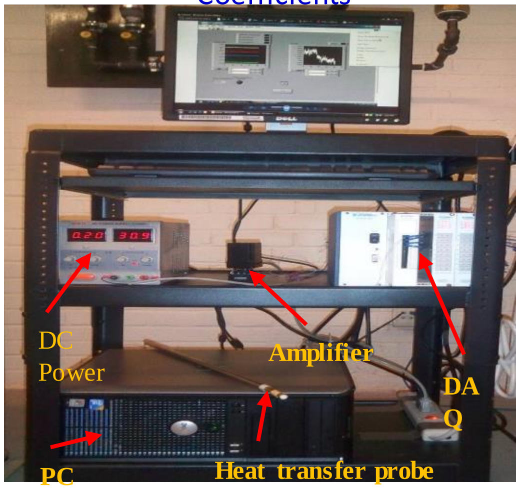


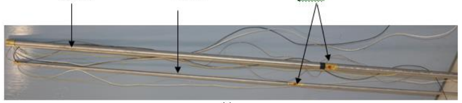
For Pinpointing Flow Pattern (Regime), Radial/Diameter Profile of Phases' Holdups Mal-distribution identification & Reduced Tomography



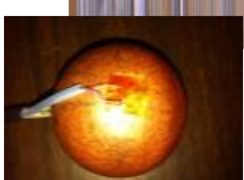
Other Selected Sophisticated Techniques at Glance

Heat Transfer Coefficients





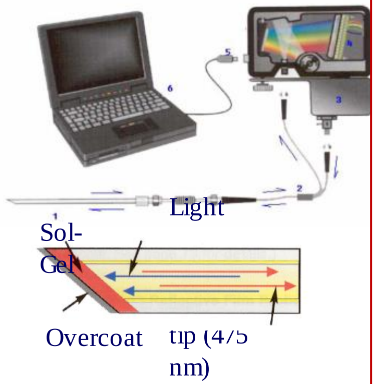
(a)



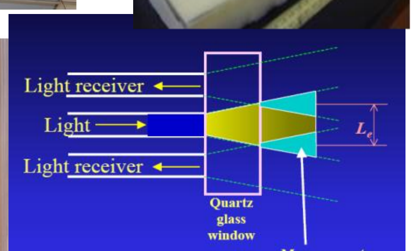
(b)

Pressure Transducers

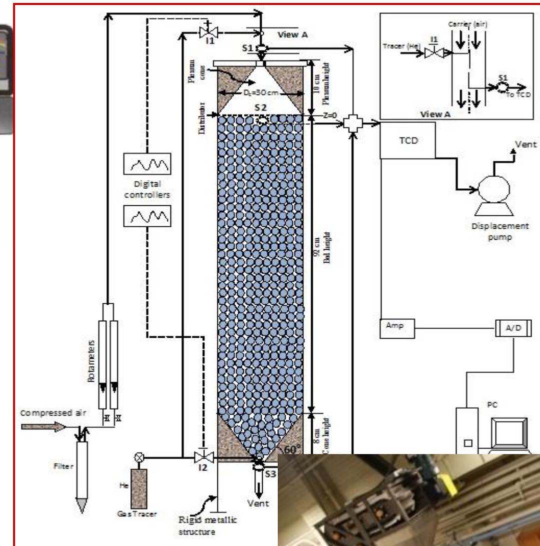
Mass Transfer Probes



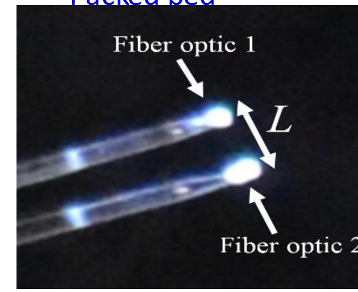
Gas-Solid optical probes

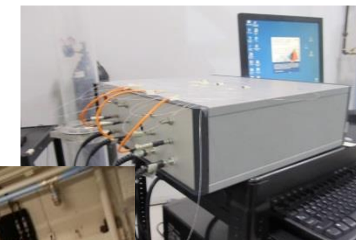


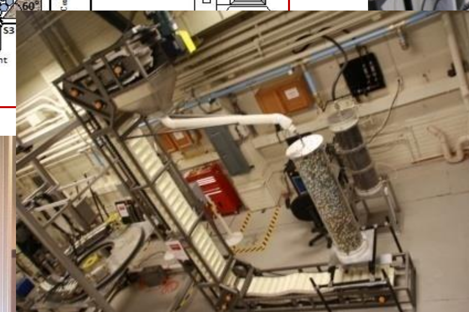
Gas/Liquid Dynamics – Tracer Techniques

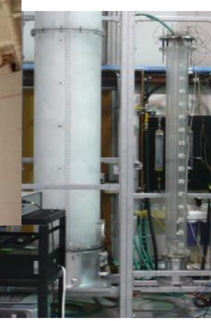


Optical Probes in Packed bed

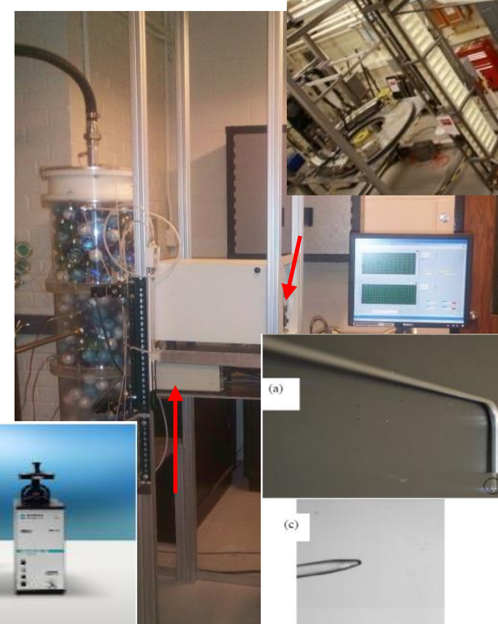








Rigs



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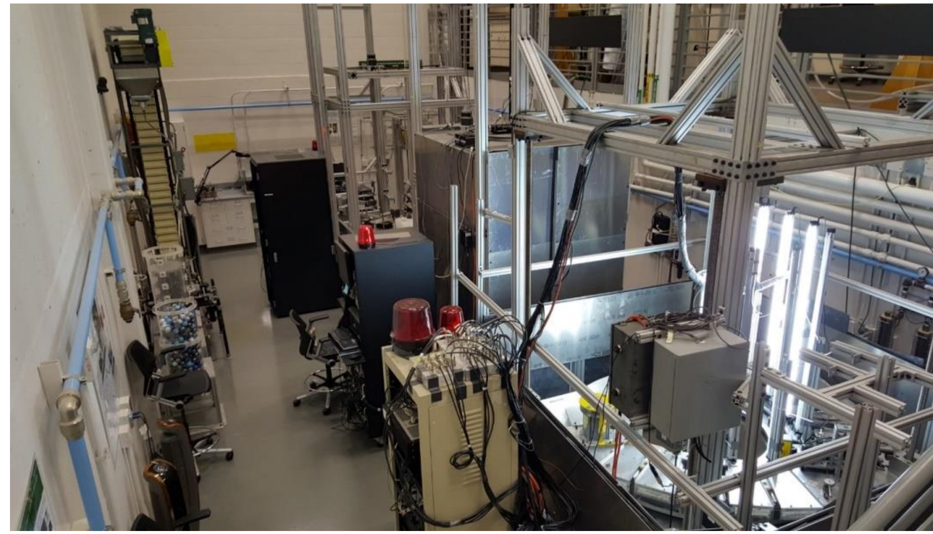
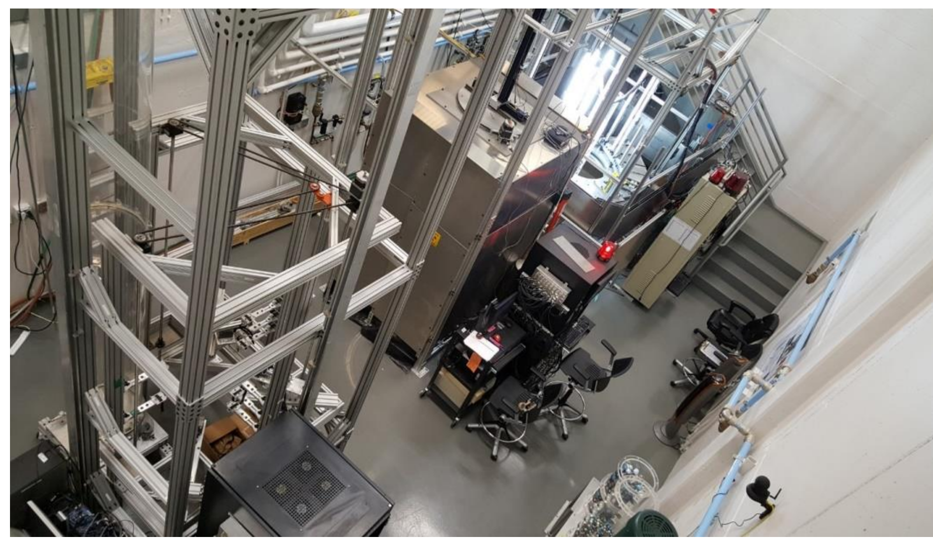
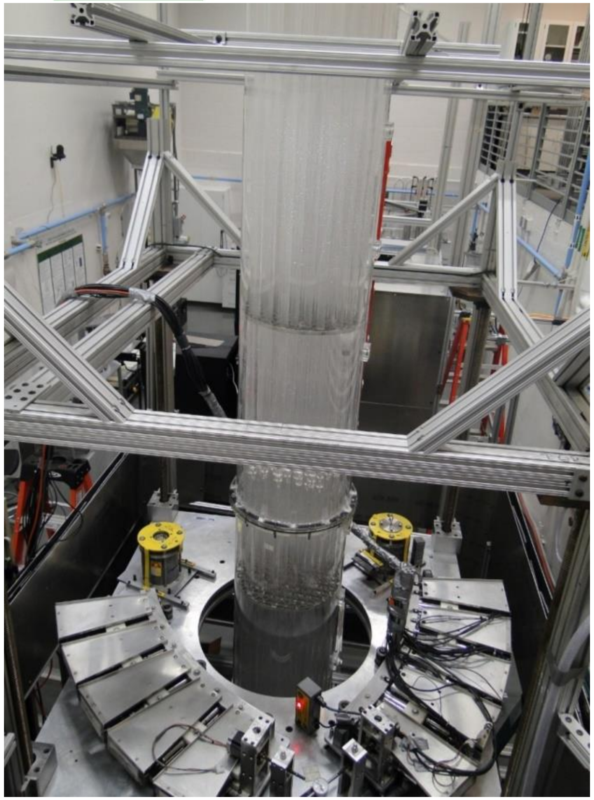
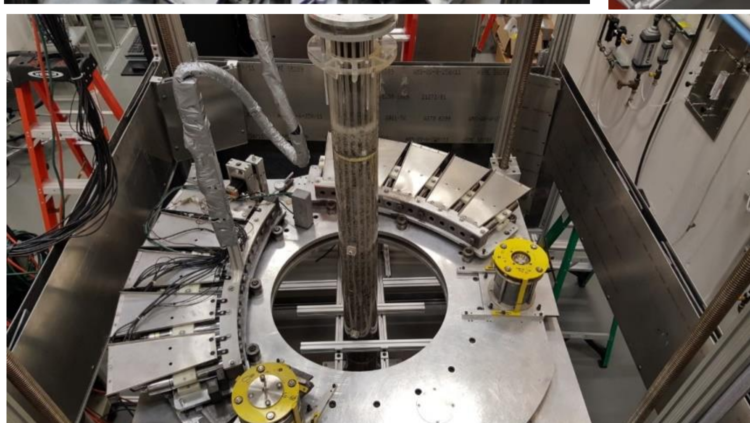
Radioisotope Laboratory for Advancing Industrial Multiphase Processes

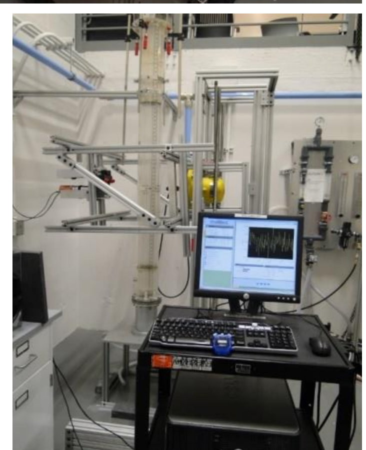




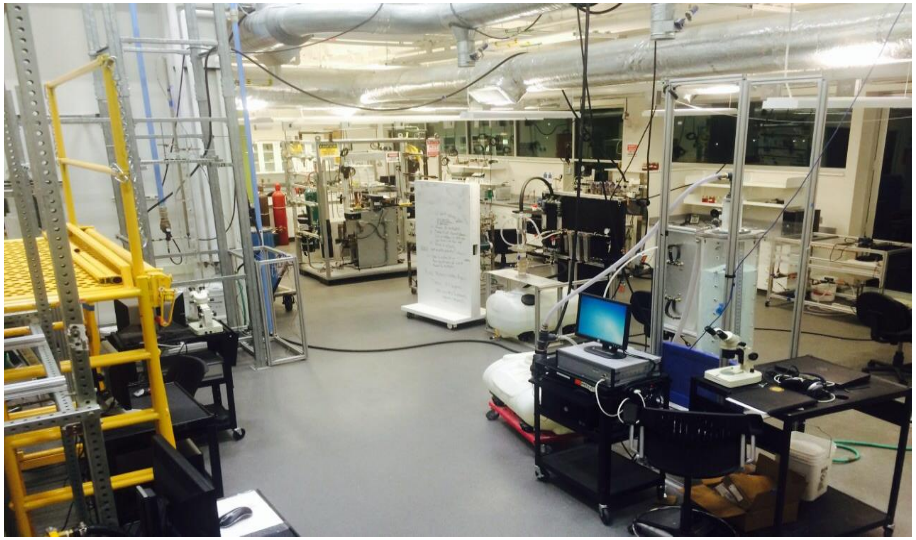


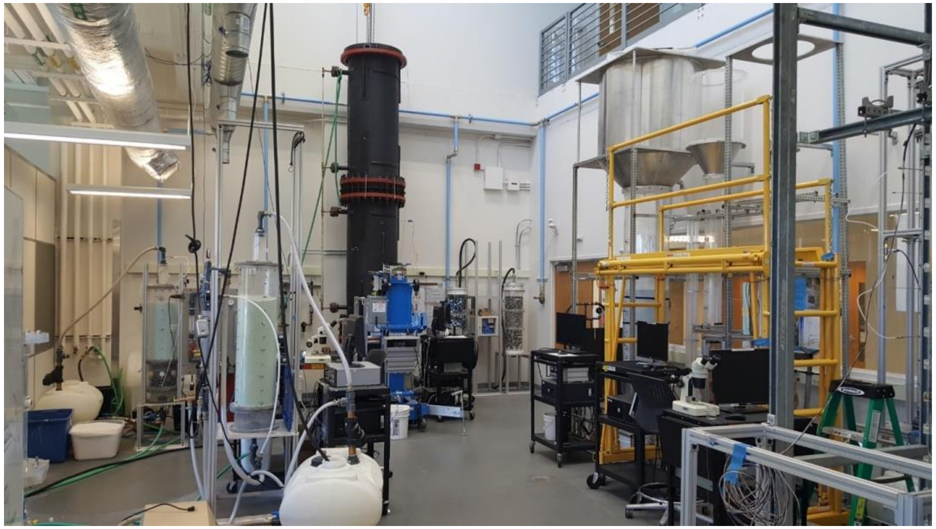


Dual Source Computed Tomography (DSCT) Technique

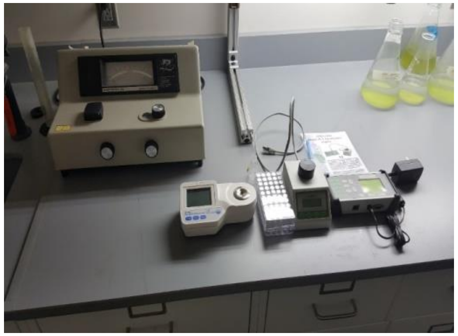


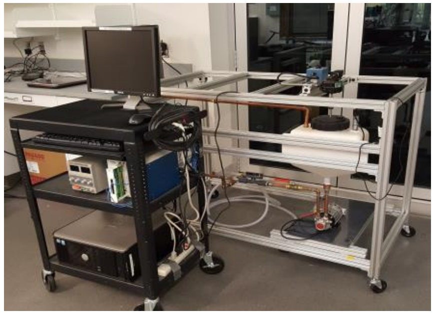
Non-Radioisotope Laboratory for Advancing Industrial Multiphase Processes





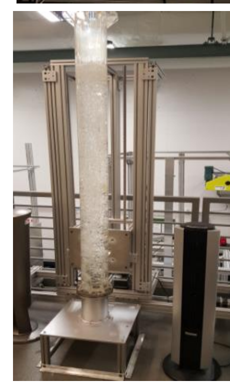
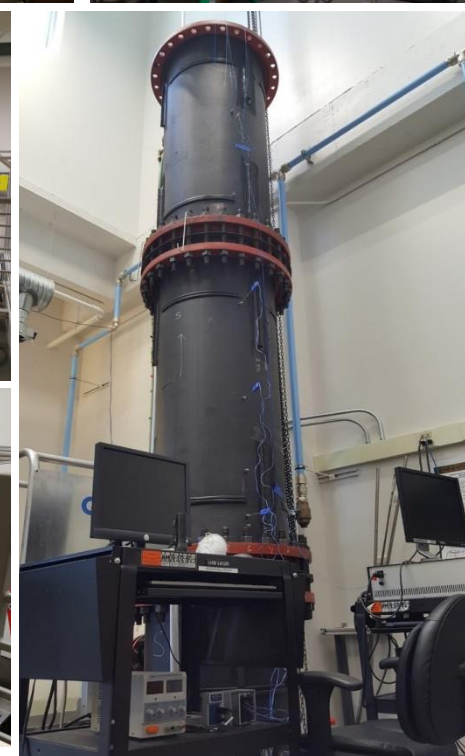
Microalgae Laboratory (Biological Lab)

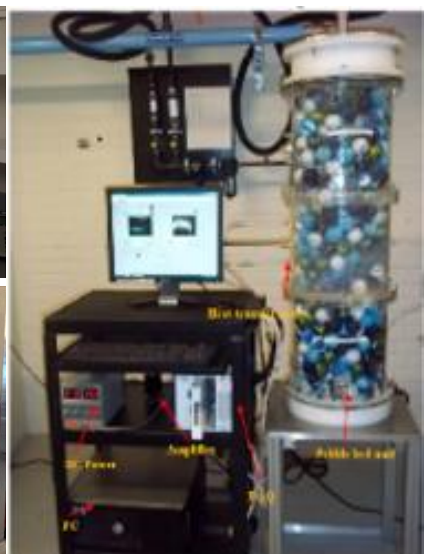










Acknowledgments

The authors acknowledge the financial support provided by Department of Energy (DOE) Nuclear Energy Research Initiative(NERI) project (NERI-08-043).

Thank You