Pebble Flow Experiments For Pebble Bed Reactors

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Abstract

A series of one-to-ten-scale experiments were conducted at the Massachusetts Institute of Technology (MIT) to explore several key aspects of pebble flow in pebble-bed reactors. These experiments were done to assess not only the flow lines but also the relative velocities of the pebbles of various radii from the center line of the core. Half-model and full 3-D experiments were performed to verify that there were no surface effects that would affect the flow lines. In addition, an experiment was conducted to determine whether, for dynamic annular cores, the mixing zone could be eliminated greatly improving the capability of the core to produce power. An analysis was performed to establish the size of a ring to be inserted in the top of the core that would preclude the central graphite pebbles from bouncing out of the center region and fuel pebbles in the outer periphery from bouncing in. These experiments showed conclusively that the mixing zone could be effectively eliminated while maintaining the annular column during the recirculation process. The flow tests were performed under fast and slow flow conditions replicating the actual performance in a reactor.

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1.0 Introduction

The issue of pebble flow in a pebble bed reactor is an important issue since it affects the neutronic behavior in the core as well as the safety analysis. Should the pebble flow not be well understood, significantly higher core peaking factors can result which may lead to higher local core temperatures and possibly fuel failures during normal operation and accident situations. Understanding pebble flow is also important since there are no internal means by which to measure core power distributions which are typically used to confirm analysis. For these and other reasons, confidence must be provided to the operator and the regulator that the behavior of pebbles in the reactor is well understood. In addition, to increase the core power of pebble bed reactors, proposals for the inclusion of a dynamic (graphite pebble) central column have been made. This added complication in the core design necessitated improved understanding of pebble flow dynamics.

There have been several flow models and experiments conducted which are not readily available in the literature to describe pebble flow. The Juelich Research Center has used flow models in their VSOP [1] code to compute the core power distributions for pebble bed reactors. This flow model is shown in Figure 1 and has been used as the standard for most pebble bed reactor analysis. In addition, molecular dynamic simulations have been performed by the PBMR, Pty company which generally confirm the German results. However, both are not fully accepted by the regulators.

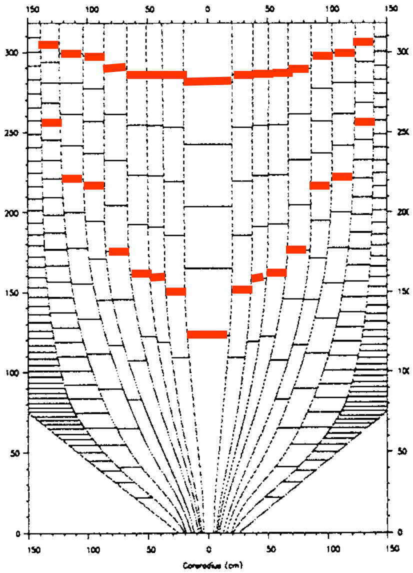

Figure 1: Assumed Pebble Flow Streamlines and Relative Velocities

In 2002, students at the MIT Nuclear Engineering Department conducted a design and experimental project to understand pebble flow dynamics [2]. The MIT Mathematics Department was conducting granular flow experiments at the time and joined us in this experiment. The prevailing mathematical theory was that the draining of the pebbles in such a reactor would conform to granular flow theory which suggested rapid mixing as opposed to linear flow lines previously predicted by German researchers. This paper will summarize the experimental results of this work.

1.1 Pebble Bed Reactor

The idealized pebble bed reactor is shown on Figure 2 which has a central core comprised entirely of reflector pebbles surrounded by a larger annulus of entirely fuel pebbles. Pebbles are dropped into the top of the core and are allowed to freely fall onto the pebble pile. The graphite pebbles are dropped only in the center while the fuel pebbles are dropped on the periphery.

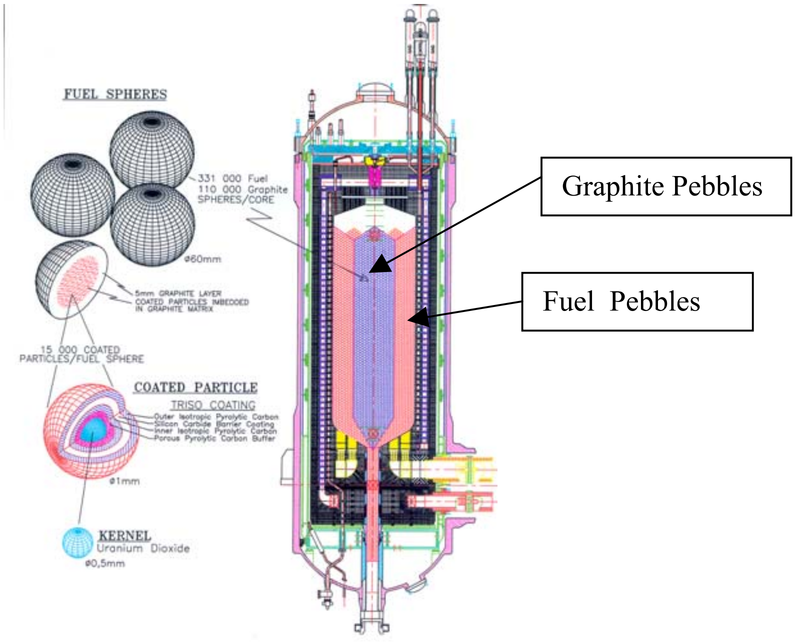

Figure 2: Pebble Bed Reactor with Graphite Dynamic Central Column

The pebbles are drained out through the bottom and reinserted at the top. The challenge is to maintain the idealized radial distribution as shown in Figure 2. The positions of the pebbles are determined entirely by granular flow, and by random dropping from the top of the core.

Both the pebble flow and the dropping of fuel pebbles are important to maintaining this idealized shape. The dropping of pebbles on to the core pile has a natural distribution as shown in Figure 3. As can be seen, due to the random dropping and pile dynamics, a mixing zone of graphite and fuel pebbles develops. This mixing zone creates high power peaking factors due to the graphite and fuel pebbles in close proximity which limits the maximum power capability of the reactor. One of the experiments discussed in this paper is to understand the characteristics of the mixing zone and what can be done to limit it in size if possible.

As the core drains, this annular distribution must be maintained. If the pebbles diffuse laterally as they travel downwards, the radial distribution will disappear towards the bottom of the core. On the other hand, if there is little or no lateral diffusion, the flow will be laminar, and the distribution can be maintained. Both possibilities are shown in Figure 4.

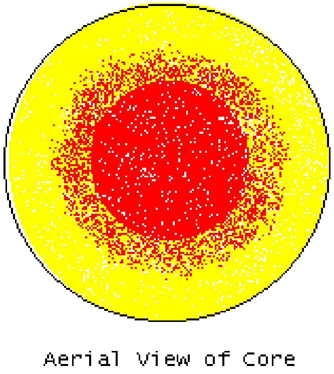

Figure 3: Mixing Zone Created by Central Graphite Column Dropping of Pebbles

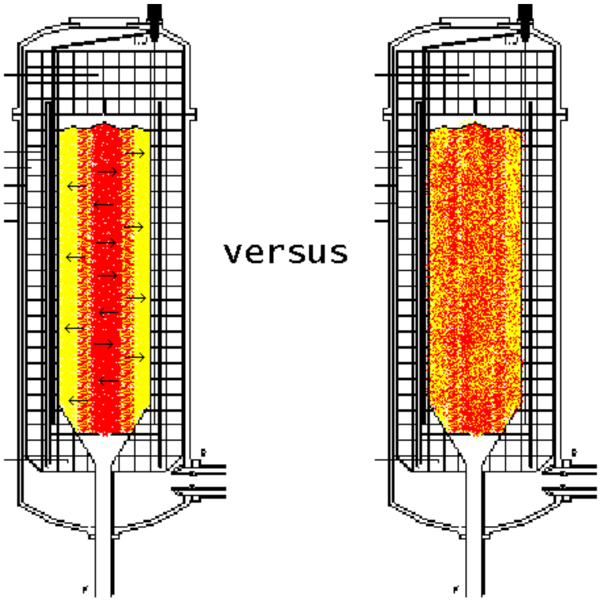

Figure 4: Comparison of Laminar or Diffusion Mixing Flow Models

Conventional mathematical theories of granular flow would have predicted the complete mixing model as shown on the right [3]. If this were the case, the peaking factors would be quite high making the operation of the reactor difficult. German experiments support the laminar flow model on the left. The purpose of the experiments is to provide the basis of a refined mathematical model to represent what actually occurs.

1.2 Pebble Flow in the Core

The behavior of pebble flow falls under granular material science is a complex but an evolving field. The Safety Analysis Report of the PBMR calculations assumes that the flow of pebbles through the core is relatively laminar, and that the pebble dropping can create these annular rings. Given below is a summary of the assumptions and reasoning which has led to the conclusions reached in the SAR about PBMR pebble flow[2], as excerpted from Chapter 5 of the SAR [4].

The in-core flow of pebbles is based on the following three assumptions:

- Parallel flow in the upper part of the pebble bed.
- Towards the bottom of the core, the cone together with the discharge tube has an effect on the flow velocity of the pebbles. Kleine-Tebbe experimentally determined the flow patterns of the pebbles during the final discharge from the THTR [Thorium High-Temperature Reactor, a PBMR precursor] which as performed without reloading of spheres. General agreement was found with flow rate experiments in the AVR [another PBMR predecessor]. Therefore, pebble flow patters derived by Kleine-Tebbe have been applied to model the characteristics of the PBMR in the lower core region.
- In the lower part of the core, a transition from parallel flow to the flow pattern based on the THTR experiments is achievable by interpolation.

The entire feasibility of the PBMR rests on the validity of these experiments and assumptions. Should the dropping and flow patterns within the PBMR during actual operation show significantly more lateral diffusion than expected, the core power and heat output will exceed the neutron physics calculations made in the SAR. This is not a trivial issue, and therefore, in order to evaluate the legitimacy of the flow patterns predicted, the design project group has been asked to examine granular flow and dropping dynamics in the PBMR reactor.

2.0 Core Flow Experimental Design and Measurements

2.1 Experimental Models

2.1.1 180º Half-Model

The basic objective of the core flow studies is to investigate whether fuel and graphite pebbles move in a streamlined manner or in a random haphazard fashion. For the purpose of experimentation, three models were designed. The first one is a 180º half-model with a clear window for visual inspection and data gathering. This model was scaled to a 1 to 10 ratio of the actual size of the pebbles. A schematic is shown on Figure 5 below:

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[2] It is recognized that the PBMR has recently changed its design of the annulus to a solid graphite structure. The SAR referenced is a preliminary version which assumed the dynamic central column.

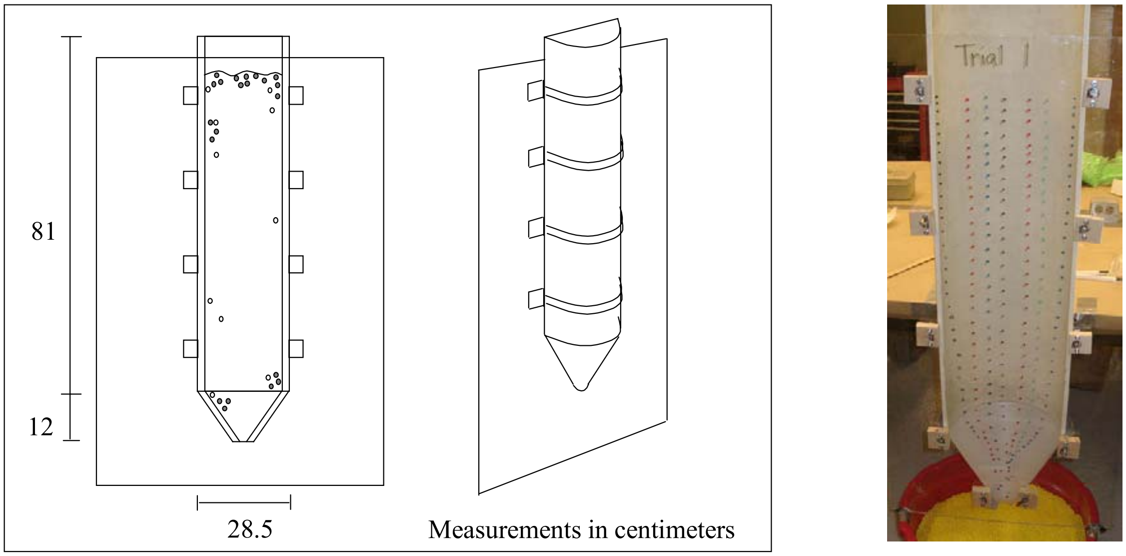

Figure 5: Half Model Configuration

Visual inspection is easy with the half-model. However, the pebbles at the half-plane are in contact with a surface and pebble-surface interaction can change the overall flow behavior. Therefore, to eliminate unreal boundary effects, a full three-dimensional model is also designed. This apparatus allows for the testing of different lower cones with varying openings and cone angles.

2.1.2 Three Dimensional Model

Three-dimensional model consists of a hollow opaque cylinder with a conical end with the same dimensions as the half model as shown on Figure 6. The challenge of this experiment is to obtain position measurements of the pebbles as they flow through the core. A novel imaging method was developed using Sodium 24 Tracer Pebble which was then located in the pebble bed during the experiment.

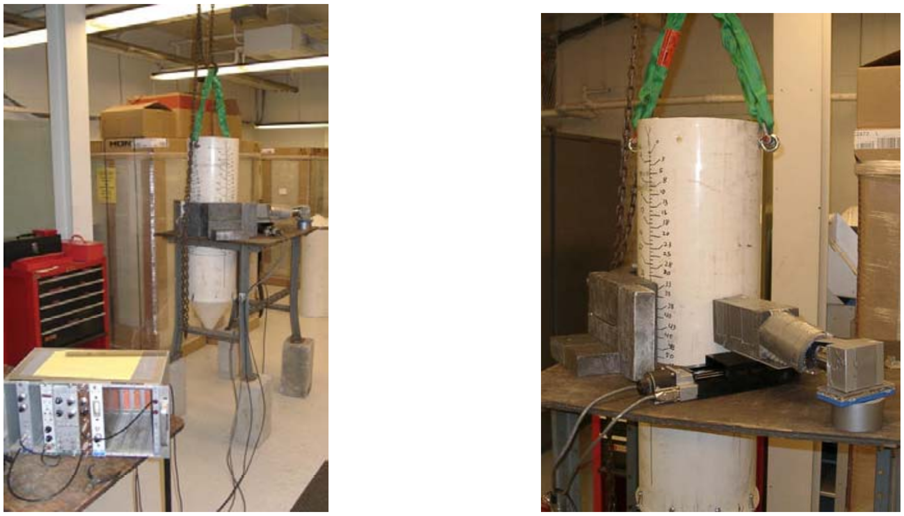

Figure 6: Three Dimensional Experiment showing Detection Equipment

The tracer pebble allows the streamline of an individual pebble to be tracked by virtue of its radioactive tracer. The tracer pebble is identical to all the pebbles in the core, except that it contains 1 mCi of Na-24, a gamma-ray emitting isotope of sodium. Collimated sodium iodide (NaI) scintillation detectors track the streamline of an individual radioactive tracer pebble. A horizontally collimated NaI detector mounted on a horizontal translator stage yields both the x-coordinate and the y-coordinate of the pebble to within 2mm. A stationary, vertically collimated NaI detector determines the z-coordinate to within 5mm. This imaging system is able to determine the position of the pebble to within less than one pebble diameter, and thus yields measurements sufficiently accurate to define the streamlines.

Data acquisition is a straightforward, repetitive process consisting of draining pebbles from the core for fixed amounts of time, and finding the position of the tracer pebble after the completion of each drain.

2.1.3 Pebbles

For the half-model and 3D model, 6 mm plastic balls are selected. They are composed of ABS plastic and have a very regular surface. Each pebble weighs about 1.2 grams and has a coefficient of friction of approximately 0.1. Note that graphite under high temperature has a static coefficient of friction of 0.6.

2.2 Half Model Data

The experimental procedure called for placing green pebbles at the top of the pebble pile and varying radii and then draining the pebbles for a specified time. After each time step, the location of the tracer pebbles was marked on the surface of the test assembly to provide a visual track of the position of the pebbles with time. A total of nine trials were run with the one-tenth scaled half model, testing three major variables on the streamlines and velocity of the pebbles: cone angle, exit diameter, and refilling during the trial. Table 1 outlines the specifics of the nine different trials. The half model was filled with approximately 240,000 yellow pebbles

Table 1: Details of Nine Half-Model Trials

Trial Number	Cone Angle	Exit Diameter	Refilling?	Time Step of Flow
1	60°	3.6 cm	No	Variable
2	60°	3.6 cm	No	Variable
3	60°	3.6 cm	No	5 s
4	60°	3.6 cm	Yes	5 s
5	30°	4 cm	No	10 s
6	30°	4 cm	Yes	10 s
7	30°	3 cm	Yes	Variable
8	30°	7 cm	Yes	10 s
9	30°	7 cm	No (Central Column Run)	Continuous Flow

Figures 7 and 8 compare the effect of exit diameters on the flow streamlines. Remarkably, for both cases, the pebbles move down vertically for till the conical section where they drift towards the exit hole. This shows that the exit hole width does not play an important role on the core flow paths. However, note that (from Table 1) that the co-ordinate locations are recorded in equal time steps (10s). So with a larger hole size, the pebbles move faster though they maintain the fairly vertical paths in the core.

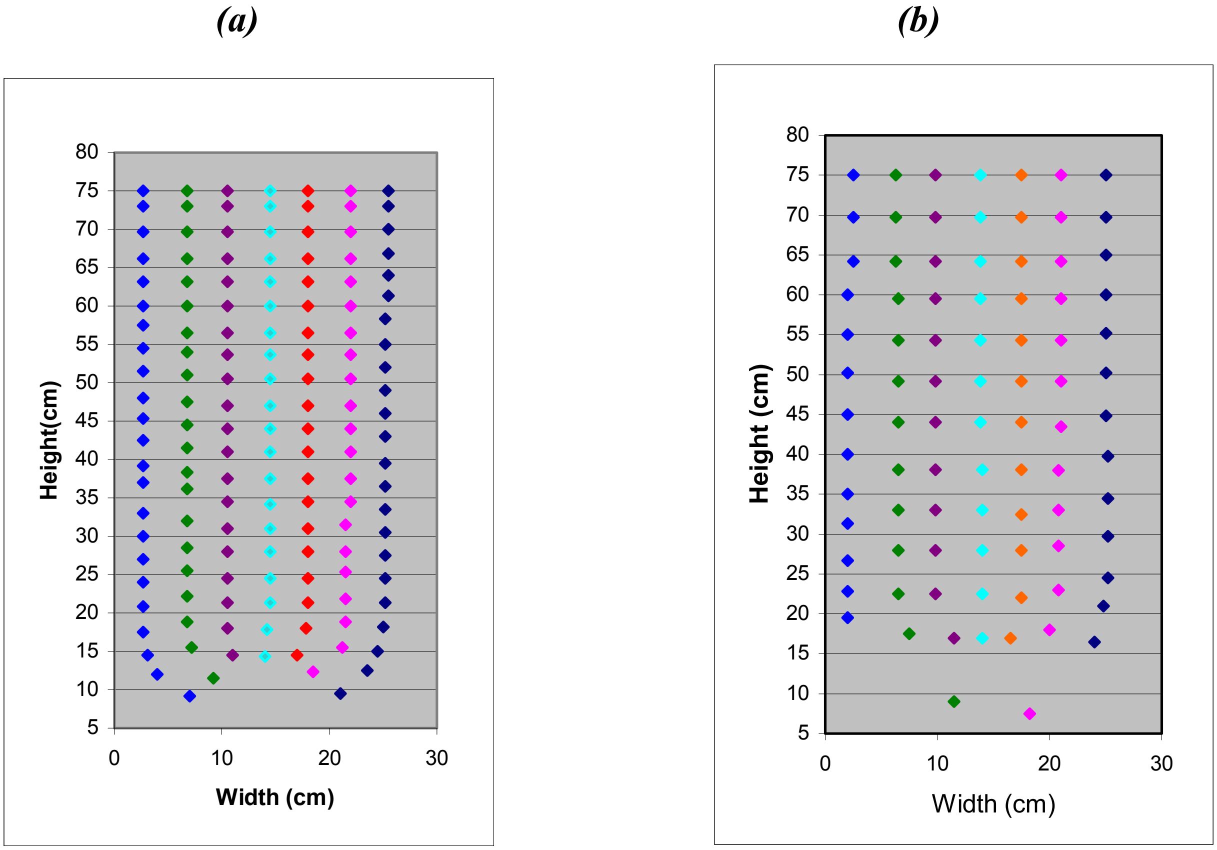

Figure 7: Effects of Exit Diameter on Streamline Coordinate Data For:

(a) Trial 6: 30° Cone Angle and 4 cm Exit Diameter
(b) Trial 8: 30° Cone Angle and 7 cm Exit Diameter

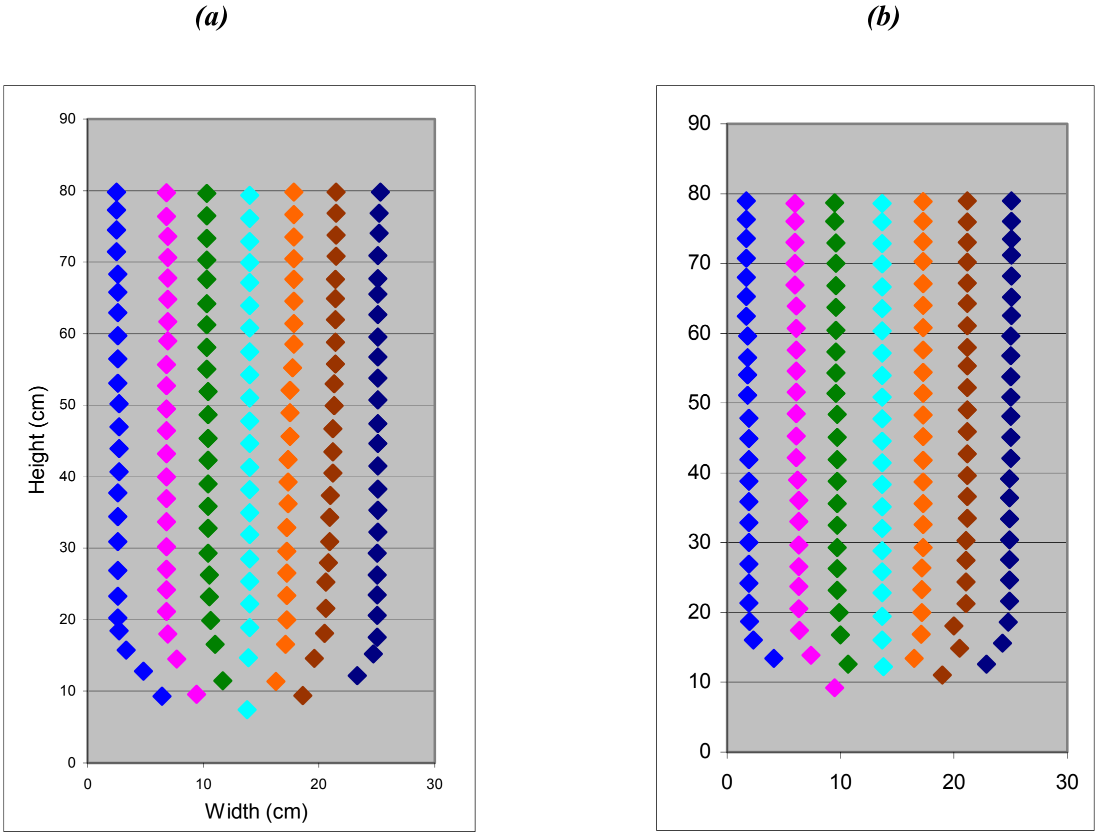

Figure 8: Effects of Refilling on Streamline Coordinate Data for:

(a) *Trial 3: 60° Cone Angle and 3.6 cm Exit Diameter and No Refilling, and*
(b) *Trial 4: 60° Cone Angle and 3.6 cm Exit Diameter with Refilling*

The above figures compare and contrast the effect of refueling on the pebble streamlines. As before, the streamlines do not change with refueling. Note that with refueling, a constant core height is maintained throughout the experiment while for the case with no refueling, the core height is not held constant and with drainage, the core height decreases.

In some sense, this is not a surprising behavior. The kinematic equations used to describe the flow are parabolic in vertical axis. Hence, the region of influence for the parabolic equation encompasses all 'future' z's. This means that the flow path of any pebble is governed by the paths taken by the pebbles below it and is unaffected by the pebble motion above it.

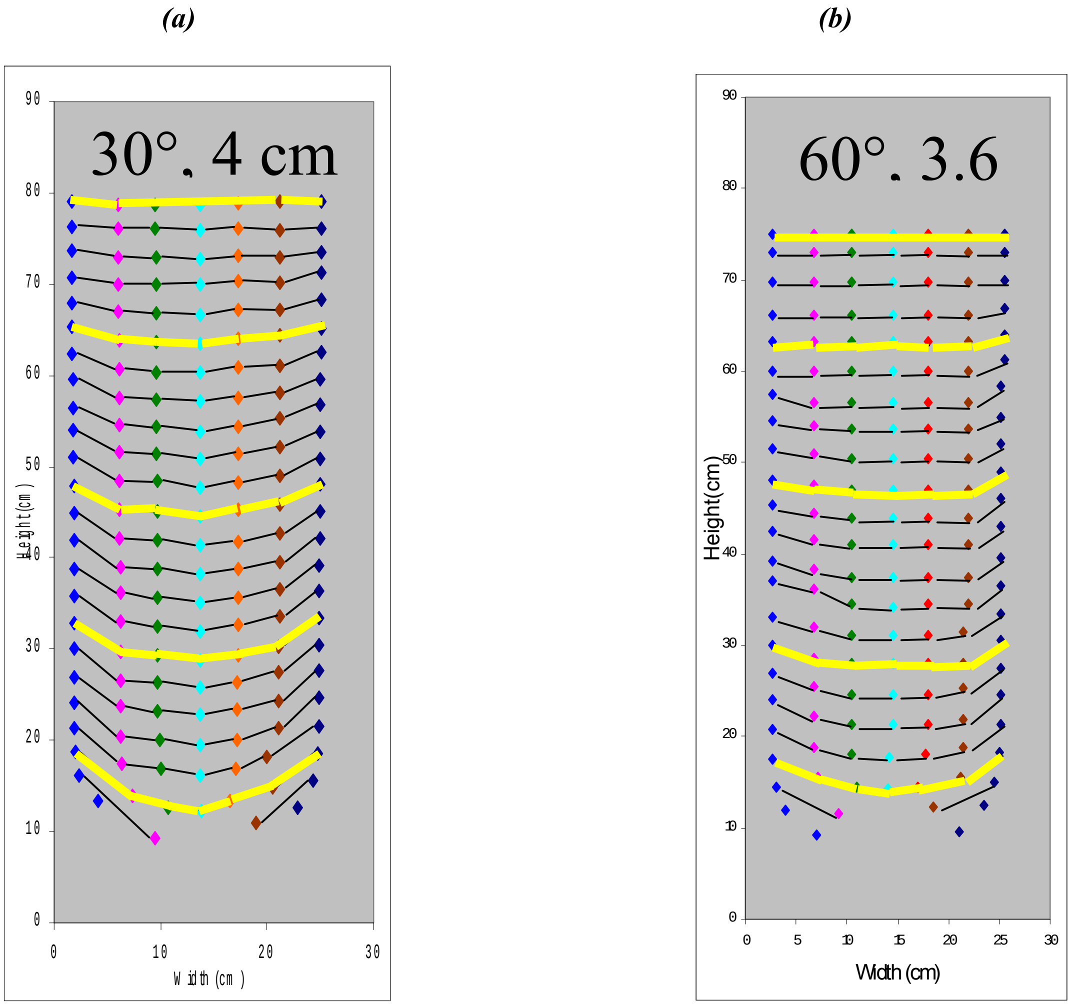

Figure 9: Shape of Velocity Profile as Determined by Cone Angle for:

(a) Trial 6: 30° Cone Angle and 4 cm Exit Diameter, and
(b) Trial 4: 60° Cone Angle and 3.6 cm Exit Diameter

The figures above delineate the effect of cone angle on the pebble flow paths. The pebble paths again are virtually unaffected by the changes in the cone angle. With a smaller cone angle, the velocity profiles appear to be more curved. However, it may be cautioned here that this caused perhaps, by the larger exit hole width for the 30° half-model. (see Table 1 for geometry comparison).

A key feature to observe here is the nearly flat velocity profiles (across the width) for most part of the core region. This means that both graphite pebbles and fuel pebbles 'fall' at the same rate (approximately). This observation is very critical for the pebble dispersion studies.

Figure 10 depicts the temporal variation of the velocities for different pebbles. The velocity values are not obtained from continuous flow. The pebbles are allowed to flow for equal amount of time and then stopped for displacement measurements. However, these data are indicative of the relative velocities between the balls. As can be seen from the above figure, the pebbles in the straight section *all* move together with about the same velocity. When the approach the conical section, the central ones accelerate (not shown in the figure) while the edge pebbles actually slow down. Note that the time axis is representative of the vertical height.

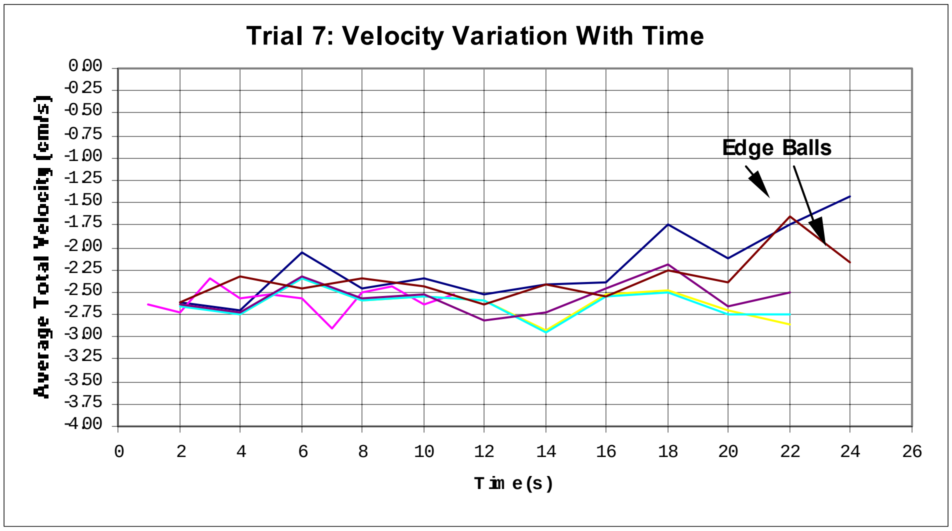

Figure 10: Typical Temporal Velocity Variation

Figure 11 compares the velocity profiles from the experiment and the velocity profile that is used in the design of PBMR [4]. It can be seen that the profiles are similar but the German experiments show a much more pronounced radial velocity difference. This difference needs further evaluation since it is significant relative to core neutronics. Both the experimental and design profiles show a pronounced concavity near the conical section while it is virtually flat in the straight section of the core.

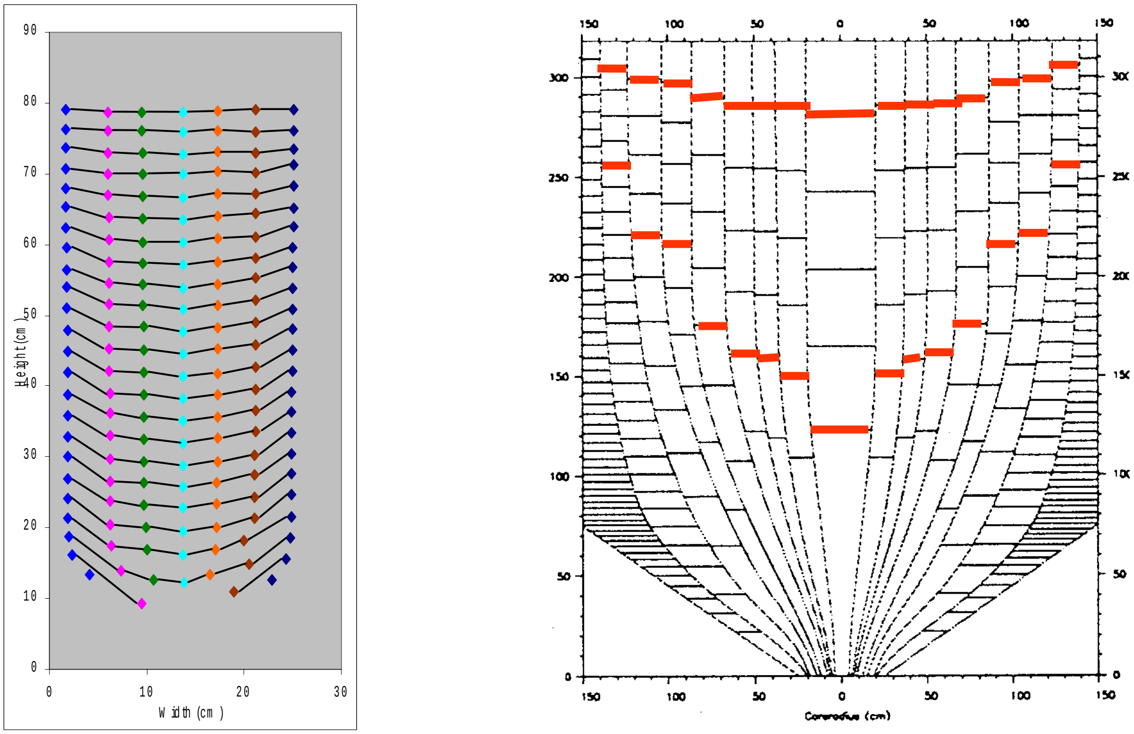

Figure 11: Comparison with Design Velocity Profiles

The pictures below show data collection during an experimental run.

2.3 Continuous Flow Experiment

The last test performed with the half model was the continuous flow test with an annular column of graphite pebbles (green). Shown on Figure xx is the pre and during the test flow pattern. A central column of green pebbles was created by inserting a half tube to shape the graphite column. This tube was carefully removed and then the entire core was allowed to drain. Figure 12 shows that with this fast flow, the central column is well maintained with the predicted shape.

Figure 12: Continuous Flow Experiment with Dynamic Central Column

2.4 Results Obtained With the 3D-Model

Figure 13 gives an overhead view of the pebble radial locations for the four trials runs performed. The large, circular dot in the figure (0,0) represents the relative size of one pebble. The four irregularly shaped dots represent the pebble behavior along their streamlines. This shows that the pebble streamlines are virtually straight vertical lines and there is no radial diffusion in the straight part of the core. This is better illustrated in Figure 14.

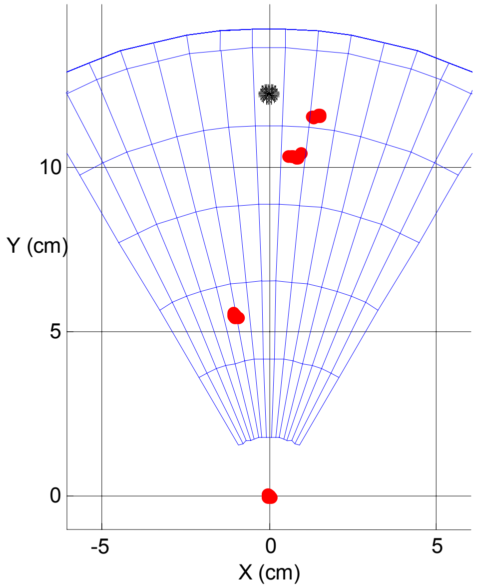

Figure 13: Top View of Pebble Vertical Track in the 3 Dimensional Experiment

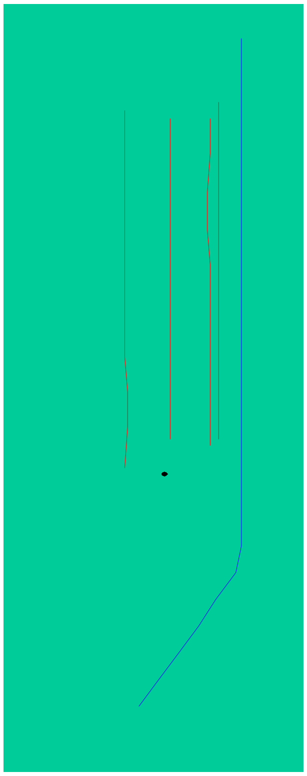

Figure 14: Pebble Pathlines, Longitudinal View – 3 Dimensional Experiment

The figure gives a clear graphical representation of the streamline trajectory. As shown in the figure, and in the preceding figures, the streamlines do not vary from a straight line by more than a fraction of a ball diameter. These data conclusively demonstrates that pebble flow is laminar in nature, with little or no mixing between radial zones of the core.

2.5 Experiments on Pebble Dispersion (Dropping)

2.5.1 Objective:

The purpose of the radial dispersion experiments is to investigate how the pebbles behave when dropped from various heights onto a bed of pebbles in the reactor core. The experimental setup includes a model of the upper portion of the reactor, with an assumed uniform formation of pebbles already in place in the lower portion of the reactor. From the core flow results, it is clear that pebbles move vertically down without any lateral diffusion and hence, the assumption of having a well-defined regions below the surface is valid. The only way to have dispersed graphite pebbles in the fuel region (and *vice versa*) is from dispersed pebbles at the top surface during refueling.

Verification of pebble pile formations, as well as their associated avalanching and mixing zones, is integral to the assumed starting formation of the flow dynamic experiment. Height, for example, is tested independently to determine its effect on the pile formation. If it cannot be proved that the reactor will start out in a condition such that the inner graphite column and outer fuel ring are clearly defined, then the flow dynamics of the pebbles is largely irrelevant. As discussed before, the collective purpose of these experiments is to show that both the pebble flow and refueling processes generate two distinct regions as per design specifications.

To prove the hypothesis of minimal mixing in a dynamic state (i.e. during the pebble flow), it is necessary to verify minimal mixing at the top surface of the fuel pile. Thus, if it can be proved that pebbles dropped from various heights and various points will indeed form the expected rings, then that basis can be assumed by the flow field experiment and results extrapolated.

An important factor is the angle of repose, the maximum angle a granular substance can make with a perfectly flat surface before the phenomenon of avalanching occurs. This is important to the experiments because avalanching is a major cause of mixing, second only to inelastic bouncing of the pebbles upon impact from dropping.

2.5.2 Experimental Design

The dimension of the experiment model is approximately 1/10th of the real reactor. A radius of 15cm plastic tube was used as a container of the pebbles. Plastic pebbles 6mm in diameter were used in the experiments instead of graphite pebbles. The weight of each ball bearing is 0.12g and its density is about 1.06g/cm^3, so it is smaller than the 1.75g/cm^3 density of graphite. The behavior of collision and bouncing of pebbles is dependent on the material properties of pebbles and dropping height as discussed in the scaling section.

The boundaries of the reactor vessel were simulated using circular sections of PVC tubing approximately 24 and 30 cm in diameter. In order to mimic the individual dropping mechanism in the real pebble bed reactor, a band of clear tape ran the diameter of the PVC tubing, with metric measurements written with permanent marker. A sheet of plexiglass covered the tubing, and pebbles were dropped individually from a hole drilled in the plexiglass. Beneath the tubing

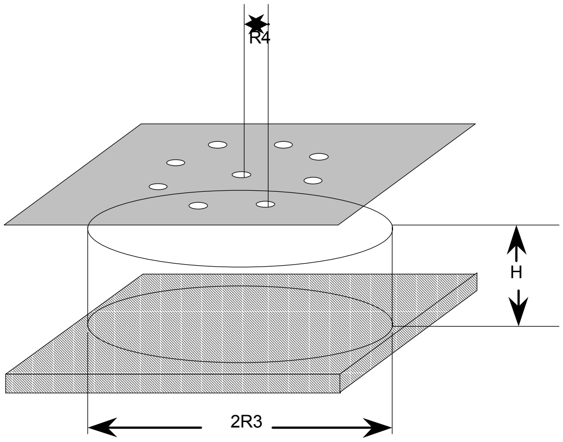

Figure 14: Experimental Apparatus for Pebble Dropping Experiments

was a piece of wood on which the model rests and the pebbles can easily be removed after experiments are completed (Figure13). Plastic pebbles were dropped at various locations (R4) from the center and at various heights (H) for these experiments.

2.4.3 Dropping Rates

The dropping rates of fuel and graphite pebbles are determined by their discharge rates from the reactor. When the reactor runs at the steady state condition the pebble discharge rate is one pebble per 30 seconds. The dropping rate ratio between fuel and graphite pebbles can be based on the area ratio of fuel and graphite zones if the pebbles in the top of the reactor move down at the same velocity. Since this has been observed in the pebble flow experiments, this assumption is justified. The top view of the reactor is shown in Figure 15.

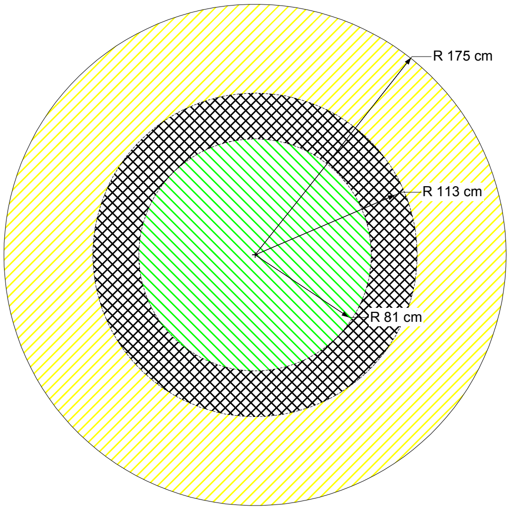

Figure 15: Top View of the Reactor Core

If the dropping rates are conserved and pebbles are evenly dropped into the core, the annular core will be formed as designed. But in the real reactor, pebbles will be dropped from discrete locations. There are eight dropping guide tubes for fuel pebbles on the top of the core which are evenly distributed in the periphery of the core and a centered dropping guide tube for graphite pebbles. Hence pebbles can only be dropped from these locations.

The initial location where the mixing zone forms is shown in Table 3 for the different dropping rates.

Table 3

Mix zone location for different ratio of pebbles dropped into 24 cm diameter vessel

Ratio of ball drops (outer location: inner location)	Location of mix zone, from center of vessel (cm)
1:1	5.0
2:1	4.5
3:1	4.0

It was determined that an annular core could be formed by adjusting the rate of fuel and graphite pebble insertion and the height from which the pebbles were dropped as well as the radial insertion of the pebbles. A pile will appear with a roughly round basis under the dropping hole without constraints around it. In order to control the mix under certain limit, the overlap between fuel and graphite piles should be minimized as much as possible. As a result, the location of the peripheral dropping holes is a key parameter to determine the mix.

2.5.4 Angle of Repose

A pile of pebbles can be tilted to measure the angle of repose, and experimentally it was found to be about 21° for plastic pebbles (Table 4) and 31° for graphite pebbles. It should be noted that the flow occurs only along the surface and that the pebbles deeper within the pile do not participate in the motion when the slope was increased slightly to create an avalanche. This angle provides some information about the profile of a pile of pebbles.

Table 4: Angle of repose data for plastic pebbles

Trial	Height opposite angle, in cm (h)	Length adjacent to angle, in cm(l)	Angle of repose = $\tan^{-1}(h/l)$
1	8	24	18.4°
2	9.5	24	21.6°
3	11	24	24.6°
4	9.5	24	21.6°
5	9	24	20.6°
6	8.5	24	19.5°
7	9.5	24	21.6°
Average angle of repose			21.1°

2.5.5 Pebble Probability Distribution

Pebble distribution after dropping was studied by dropping pebbles onto the flat surface made up of several layers of pebbles. The experiments were employed to investigate the probability distribution for both plastic and graphite pebbles. The diameter of graphite pebbles is 1 cm and that of plastic pebbles is 0.6 cm. We define $p(r)$ as the probability that the pebble will stop at a radial distance r from the original hitting point as shown in Figure16.

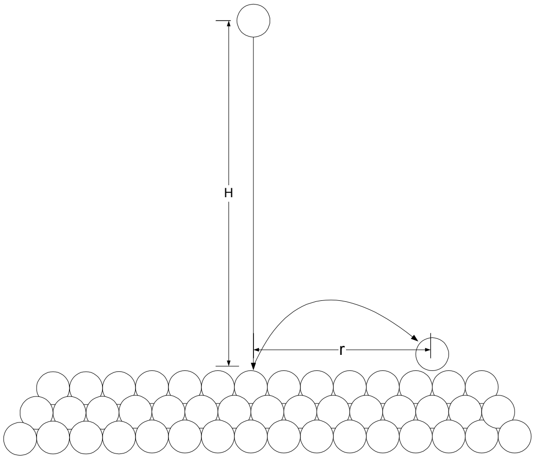

Figure 16: Pebble Dropping

In order to study the impacts of height on distribution, pebbles were dropped at three different heights: 18.5 cm, 40 cm and 66 cm. Figure 16 shows the probability distribution function (PDF) of plastic pebbles, and the cumulative distribution function (CDF) is shown in Figure 17.

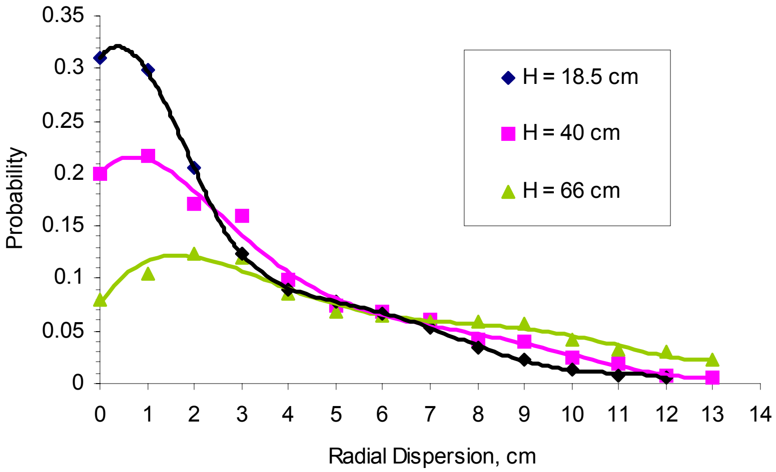

Figure 17: Probability distribution function of plastic pebbles

Figure 17 shows that the probability decreases with increasing radial dispersion, which means it is more likely for a ball to stop near the collision point. In addition, the probability for a ball to stop near the collision point decreases when the dropping height increases; hence, the probability for a pebble to bounce away increases.

2.5.7 Cylindrical Guide Ring

There is an alternative measure to avoid the mixing of graphite and fuel pebbles; a cylindrical guide ring can be applied to separate the graphite and fuel zones in the upper core as shown in Figure 18.

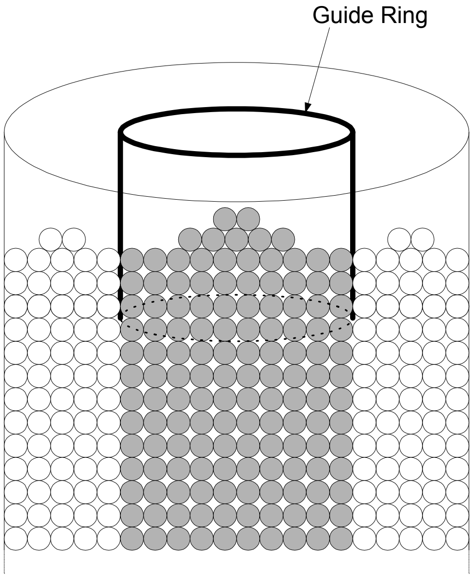

Figure 18: Cylindrical Guide Ring

Bases on analytical and experimental results, the maximum height of the ring needed to prevent fuel or graphite pebbles from entering the other zone is shown in Figure 19 as a function of dropping height. The variable introduced is f, the energy loss factor due to the impact on the pebble pile. For the PBMR, the fuel zone dominates the height limit which . experiments show that *f* of graphite is about 0.3-0.4, so the maximum height of the ring for the PBMR is about 20 cm.

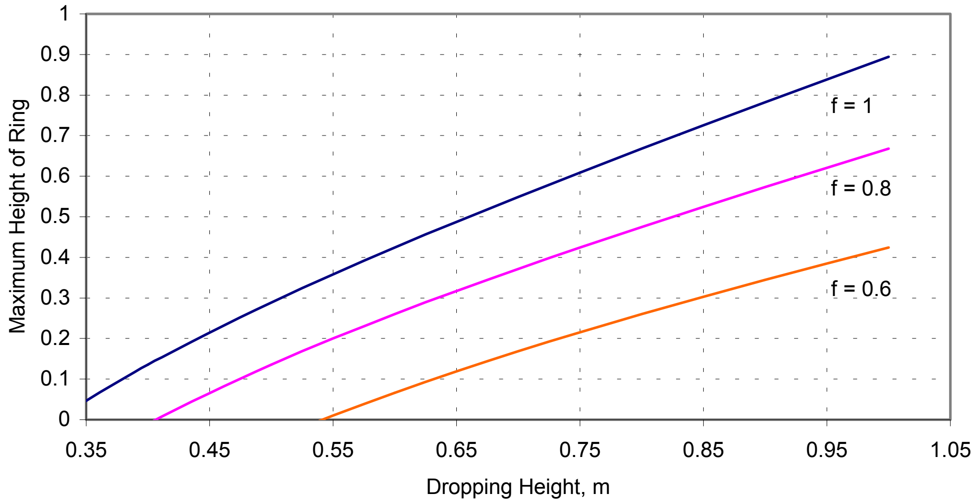

Figure 6.19: Maximum Height of Ring for Fuel Zone

2.5 Slow Flow Experiments

The previous experiments were carried out in what might be called fast flow situations. In the half model tests, the pebbles were allowed to empty without restraint. Thus whatever friction effects that may exist either on the surface of the plexiglass or amongst the pebbles would have diminished affect. In order to determine whether draining speed was a factor that might effect the previous results slow flow tests were conducted. The necessitated the introduction of a small motor operated removal device which used a large drill to extract the pebbles from the lower cone. Shown on Figure 20 is a picture of the removal device. The pebbles were removed at an average rate of 120 pebbles per minute of the 240,000 pebbles in the device. Several tests were conducted.

Shown on Figure 21 is the half model initial configuration. Seen near the top of the pebble bed are the green tracking pebbles that were similarly positioned as in the fast flow experiments described earlier. The lower part of the half model is filled with a mixture of green and yellow pebbles only to provide the bulk to fill the model and they are not part of the experiment which is limited to tracking the green pebbles near the top of the pile.

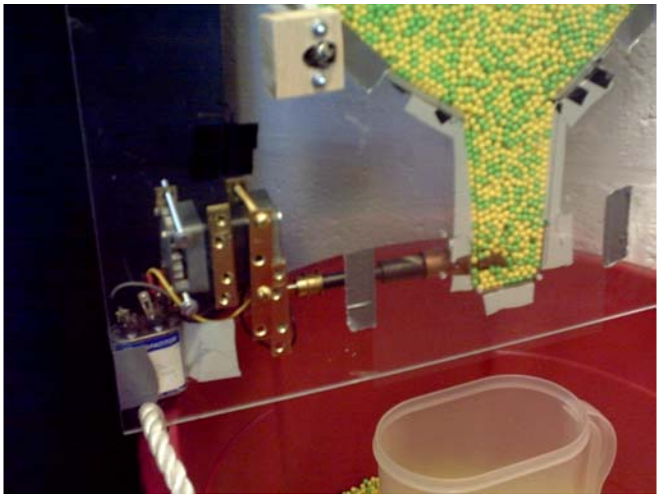

Figure 20: Motor and Drill Removal Device

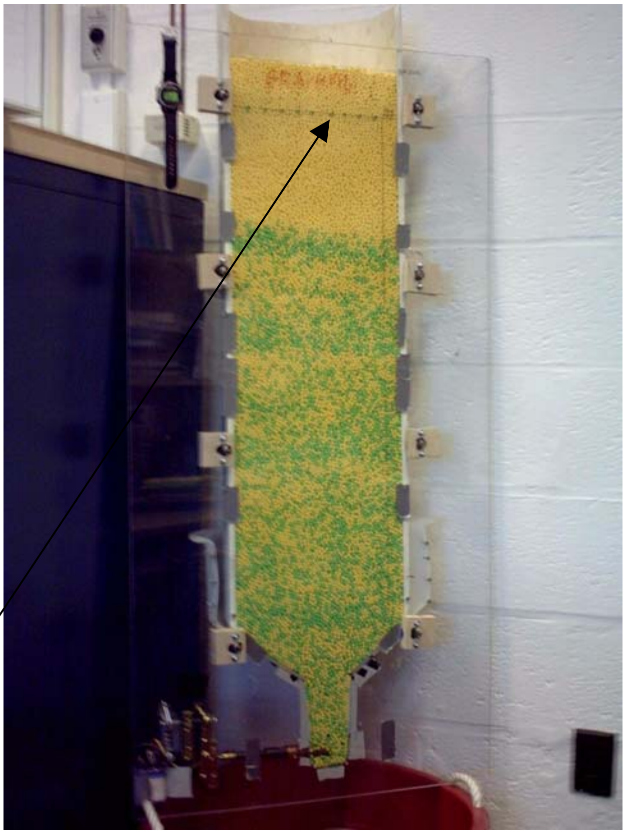

Figure 21: Initial SlowFlow Conditions locating the top layer of green tracking pebbles.

The results of the slow flow experiment are shown on Figure 22 which confirms the previous fast flow tests indicating laminar performance. One of the observations of this test was that there was some surface friction on the plexiglass which slowed the surface pebbles compared to those several layers behind. This was observed because as the core drained, it was backfilled by pebbles which were a mixture of green and yellow from the bottom bucket. It was observed that these pebbles behind the first row were catching up to the tracked pebbles by “bleeding” through.

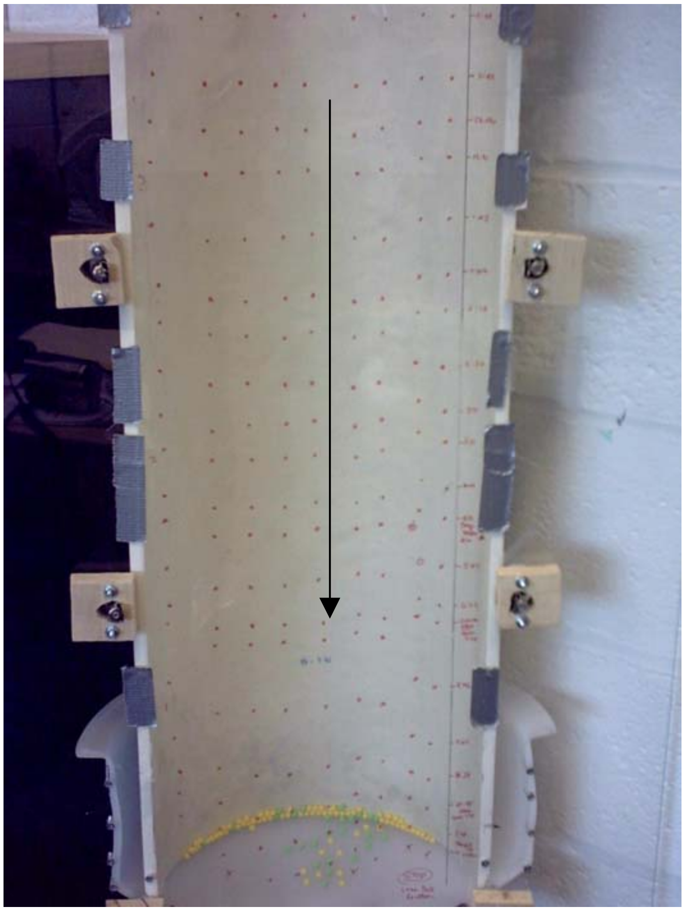

Figure 22: Results of Slow Flow Test Tracking Individual Pebbles
(note vertical paths)

2.6 Test of the Shaping Ring

Having conclusively shown that the flow is laminar with little, if any radial mixing, then next experiment conducted was to determine if the shaping ring proposed would be adequate in terms of maintaining a mixing zone free central dynamic column. This is important since the shaping ring can be easily installed and adjusted for different core configurations while maintaining the simplicity of a single discharge point reactor vessel. The PBMR has decided to use a hard central column of graphite replacing the dynamic pebble core at considerable complexity to the design of the reactor vessel which may require the replacement of the central column sometime during the life of the reactor. This study was conducted to see if, once formed a the top, the column would be maintained during a slow flow experiment.

It order to shape the column a smaller radius half cylinder was used to shape the upper 6 inches of the pebble bed. Green pebbles were back filled in the central column as were yellow pebbles in the fuel region. Later, back fill was stopped to observe the drain down behavior.

The initial configuration is shown in Figure 23 with a mid-experiment picture shown as Figure 24

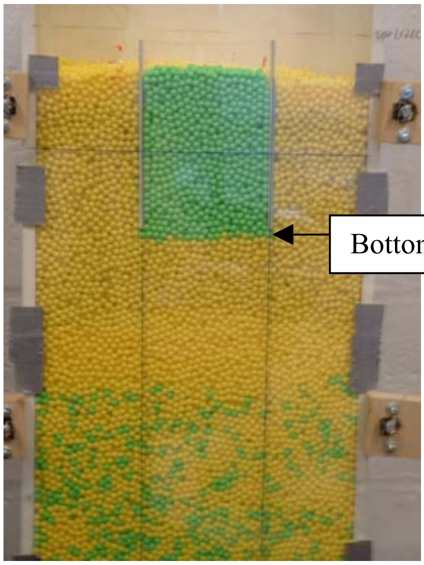

Figure 23: Initial Configuration

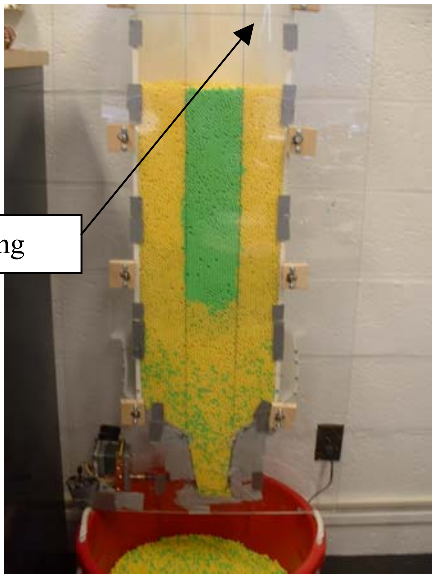

Figure 24: Annulus Maintained Below Shaping Ring

Figure 25: Annulus Behavior Near End of Drain Down

As can be seen by this shaping experiment, it can be used to create the annulus with high confidence and the shape of the column is maintained during draindown to within 1 or 2 pebble diameters well below the 25% of the core normally assumed for a dynamic column.

3.0 Conclusions and Recommendations:

3.1 Core Flow Experiments:

1. Vertical streamlines have been observed in the straight section with both two-dimensional (2D) half-model and three-dimensional (3D) model.
2. Lateral pebble motion or diffusion in the straight section of the core is limited to one pebble diameter.
3. Streamlines in the straight section are not significantly affected by changes in cone angle, refueling pattern, or drainage hole diameter.
4. Based on preliminary studies, material properties, including friction, do not appear to strongly influence the flow pattern. This indicates that the pebble flow in the core is more influenced by the geometry.
5. 3D model data from gamma measurements, confirms the validity of the 2D half-model experiments. Surface effects of half-model are seen to be negligible.
6. Once the central column is formed, mixing in the straight section is determined only by refueling and not through lateral diffusion of pebbles.

Overall, the data obtained, agree with the PBMR Safety Analysis Report data in terms of laminar flow but appear to disagree with the degree of pebble velocity near the cone region.

8. Slow Flow experiments confirm the laminar flow predictions of the fast flow tests.
9. The dynamic annular central column can be formed by a shaping ring near the top of the core. This column can be maintained during draindown to within 1 to 3 pebble diameters.

3.2 Pebble Dispersion Experiments:

1. The dispersion of pebbles in the pebble bed reactor is a function of drop height, dropping rate, location of the dropping point and the angle of repose of the pebbles.
2. A cylindrical guide ring can be applied to separate the graphite and fuel zones in the upper core to guarantee minimal mixing.

3.3 Recommendations for Future Work

One of the most promising outcomes of this study is the demonstration of the used of a shaping ring to form the central graphite column since it appears to be maintained during the draindown. This finding allows considerable flexibility in core design and optimization since the column can be adjusted by changing the diameter of the shaping ring. In addition, it removes one of the greatest concerns of the dynamic column in that it practically eliminates the mixing zone of high peaking factor pebbles. Thus, one of the largest concerns about using central columns is addressed. The other concern deals with by-pass flow of coolant in the central column area requiring higher fuel temperatures to obtain the desired outlet temperature. Bazant has proposed a study of smaller diameter graphite pebbles to increase the flow resistance in the central column forcing the coolant preferentially into the outer fuel ring. This series of experiments has been proposed as the next step in this study.

Another future area of inquiry is the effect of surface friction on the results reported. Studies using glass beads will be conducted to assess any effect.

4.0 References:

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