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LUCAS HEIGHTS

AN EXPERIMENTAL ASSESSMENT OF A PEBBLE REFLECTOR AND PEBBLE FLOW IN A SMALL SCALE RECIRCULATING PEBBLE BED

by

L.R. SCOTT ROGERS

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ABSTRACT

The erosion behaviour of a pebble reflector was examined using small scale, three-dimensional, pebble-bed models and the split-bed technique. An exponential-type change in the reflector-fuel interface angle was indicated. The levelled value was about 13° after recirculation of 30 - 40 bed inventories.

Data on downflow and upflow air tests with small-scale, recirculating pebble beds are also presented. These data indicated a variation in pebble discharge ratio of some 20 per cent. relative to the no-airflow case.

CONTENTS

1. INTRODUCTION

Studies of pebble flow in packed beds have been undertaken at Lucas Heights as part of the design study of the H.T.G.C. Pebble Bed Reactor. This work has led to an extensive fundamental study of various phenomena in random packed beds. The study, however, is essentially of a long-range nature.

To afford the reactor core designer a better appreciation of design problems, small-scale studies using the split-bed technique and the tracer pebble technique were undertaken. Using these techniques, design concepts could be quickly surveyed or semi-quantitative data given on a specific reactor core arrangement. This allowed a more detailed evaluation of a design in a shorter overall time period.

This report discusses two major aspects of the work:

(a) The consequence of pebble flow over a pebble reflector, using the split-bed technique for viewing the resultant boundary.

(b) The behaviour of pebble flow under no-flow and air-flow conditions using the tracer-pebble technique.

Although the experiments used models greatly reduced in scale, reactor terminology has been retained. Thus, terms such as fuel, reflector, and core are used analogously. Other particular terminology and specific parameters are defined below.

2. EXPLANATION OF TERMS

(a) The L/D Value is the ratio of the vertical distance, L, between the inlet and outlet tubes of the core model, to the mean internal diameter, D, of the core model and is, therefore, a measure of the bed-height for any particular model.

(b) The D/d Value is the ratio of the mean internal diameter of the core model to the mean diameter of a fuel pebble. The core models used in the tests reported here had D/d values between 24 and 49, though the model most often used, and the one used for air-flow tests, had a D/d value of 31.6.

(c) Bed Inventory refers to the volume of pebbles contained in the core model (apart from those forming the free repose angle of the pebble reflector) if the bed were discharged through the outlet tube. It is characteristic of a particular L/D value.

(d) The Pebble Discharge Ratio (PD) represents the mean value of a series of measurements of the number of bed inventories required to discharge a tracer pebble, placed at the wall at the top of the pebble bed, to the mean value of a series of measurements of the number of bed inventories required to discharge a tracer pebble over the length L, down the centre of the pebble bed.

(e) The Free Repose Angle is the equilibrium angle subtended at the lip of the pebble outlet tube to the horizontal by the free surface of the remaining pebbles of a reflector bed which has been discharged through the outlet tube. This angle is dependent on container shape and surface, outlet core shape and surface, and pebble characteristics. A similar definition applies to the free surface at the pebble inlet.

(f) The Interface Angle is the mean angle subtended at the lip of the pebble outlet tube to the horizontal, at any time instant, by the boundary between the reflector pebbles and fuel pebbles. In measuring this angle, negligible curvature along the boundary is assumed. Figure 8 shows the relative position of pebble reflector and core.

(g) The Equivalent P.B.R. Operation Time is based on the assumption that six reference P.B.R. bed inventories are recirculated every four years. This gives the volume discharge rate for the core models as 600 ml of fuel pebbles per 2.04 months' P.B.R. operation. The fuel pebbles were glass beads of average diameter 2.00 mm. A mean voidage in the random packed bed of 40 per cent. was assumed.

(h) The Volume Discharge Rate generally used was 800 (2 mm) glass beads per second. This was held fairly constant by throttling a simple cut-off valve.

Although this rate is far in excess of that specified for the reference design P.B.R., other experiments have indicated that the pebble circulation rate has only a secondary effect, if any, on velocity profile. Also, tests on the interruption of flow showed no detectable effect on velocity profile. The use of accelerated flow rate experiments was therefore considered justifiable.

3. EROSION OF A PEBBLE REFLECTOR BY A RECIRCULATING FUEL CHARGE

In the pebble reflector concept, a layer of beryllia reflector pebbles of a size equal to or less than the fuel pebbles in the core, forms a barrier layer between the fuel pebbles and the larger ceramic support pebbles beneath. The attractiveness of this concept is that one has a simple support structure which may be discharged partially or completely. This condition guards against the possibility of fuel pebble hold-up in the reflector boundary layer.

The erosive action of the moving fuel pebbles on the quasi-static reflector pebble surface was unknown, and the following tests were performed to obtain some information on this problem. Details of the split-bed technique are given in Appendix 1.

Test 1 - Single-Outlet Pebble Reflector Erosion: No Air Flow

(A) Copper-plated lead (Cu-Pb) pebbles (1.5mm mean diameter) were used as reflector pebbles in a single-outlet cylindrical Perspex core model having $L/D = 1.8$, $D/d = 31.6$, with glass pebbles (2.0 mm mean diameter) as the fuel material. The reflector was initially at a free repose angle of 29^{o}. No air flow was used. The results are given in Table 1 and the change of angle with time is shown in Figure 3.

The interface angle was measured by noting the mean height of the reflector interface above the top of the outlet tube at the wall of the Perspex cylinder. A straight line boundary was assumed. On the occasions that the bed was split and the reflector-fuel boundary examined, the interface was sufficiently straight to justify this assumption. A photograph of the split bed for the above test is shown as Figure 2 (a). It is seen that after recirculation of 50 core charges (an equivalent reactor time of about 4 years) the volume per cent. of eroded reflector pebbles had levelled out to approximately 0.04 per cent. and the interface angle at 13^{o}.

(B) The Cu-Pb reflector pebbles were levelled to one inch above the outlet tube and the interface angle and erosion rate again recorded with no air flow and with $L/D = 1.8$. In this instance, the curve starts above that of Test 1 (A), although after 30 core charges the erosion rate was similar to that of

Test 1 (A). The results are shown in Table 2.

The above two tests indicate that after about 30 core charges recirculated (an equivalent time of 2 years) the erosion rate is roughly constant and the interface angle is slowly changing with time. One would expect, therefore, that if the interface angle for a single outlet system were set at about 13° the erosion of the reflector would be slow and practically acceptable.

Test 2 - Single-Outlet Pebble Reflector Erosion: Downflow System

To determine whether there was any marked change in erosion behaviour under air-flow conditions, the apparatus was modified, as shown in Figure 6, and the system tested under air downflow conditions.

An inverted slotted 45° Perspex cone was used to support a bed of $\frac{1}{8}$ inch diameter steel pebbles, on top of which were the Cu-Pb reflector pebbles. The outlet tube was positioned above the level of the support pebbles and the reflector repose angle was again set at 29°. The core L/D value was set at 1.8 . An industrial floor cleaner was used for suction and the resulting pressure drop through the bed was 1.4 p.s.i. The results are shown in Table 3.

These results are similar to those of Test 1. This implies that the extra loading imposed by the gas flow (1.4 p.s.i. across the recirculating bed) was not sufficient to overcome the resistance to pebble motion imposed by the quasi-static reflector surface. In fact, as pressure drop increases, the void fraction decreases and the erosion rate may be expected to decrease also.

Test 3 - Single-Outlet Pebble Reflector Erosion: No Air Flow and Zero Angle Reflector

To test an extreme case of the pebble reflector concept, the Cu-Pb pebbles were initially levelled with the top of the outlet tube. A recirculating bed was used, with L/D = 1.8, and zero air flow. After recirculation of 90 bed inventories, 0.006 per cent. by volume of reflector pebbles were still being discharged. A photograph of the split-bed profile is shown in Figure 2(b) and the data obtained are shown in Table 4.

Figure 2 (a and b) also illustrates the change [illegible] tracer pebble (irradiated glass beads) profiles. In each case, the first layer is almost discharged and there is no evidence of tracer pebble displacement toward the

reflector surface. This is to be expected in the short time interval following introduction of the tracer pebbles. Very slow pebble movement was noticed at the interface-wall corner (commonly referred to as corner stagnation) and this is shown by the hold-up at the wall of pebbles in the second layer. The full effect on the pebble discharge ratio of this holdup is not clear, but, as illustrated in Figure 2, tracer pebbles moved away from the wall some distance above the interface corner. However, when the cone angle was increased (refer to Test 5 below) the hold-up became less pronounced and pebbles began their radial movement closer to the corner. An exploratory test of the slow movement of pebbles near the reflector surface was made by placing coloured tracer pebbles at the wall at various heights above a pre-formed Cu-Pb surface (equivalent to 11.3 years' P.B.R. operation - about 12°). The number of bed inventories required for the discharge of a particular tracer pebble was noted. The test was not conclusive as the tracer pebbles did not discharge relative to their positions above the reflector surface. Instead, their behaviour indicated that an individual pebble may be expected to discharge in any of a number of bed inventories rather than in any particular inventory. For instance, some pebbles moved away from the wall and then changed direction and moved downwards, where they were subject to a slower radial movement. Thus they tended to be discharged later than a pebble originally below them at the wall. The reflector interface angle remained essentially constant throughout this test.

Test 4 - Double-Outlet Pebble Reflector Erosion: No Air Flow

The effect of reflector pebble erosion between outlets was investigated in a double-outlet model.

The lateral cross-section, internal dimensions of the model were 3 in x 6 in and the outlets were 3 in apart, giving an effective D/d value of 38 per cell. The reflector profile was examined on the longitudinal cross-section through both outlets and it was judged that wall effects would have little influence on the profile between the two outlets. The L/D value per cell was set at 1.8 and the test continued until the Cu-Pb reflector (initially levelled at 1 in above the outlets) had eroded for 2 years' equivalent P.B.R. time. The split-bed technique was used to examine the reflector interface (see Figure 5) and the angles measured are shown in Table 5.

There was a 6° difference between the interface profiles, that is between the centre (no wall) and the outside (wall) angles. This was accounted for partly by drag at the wall surface and partly by the increased void coefficient at the wall.

In other words, the distribution of forces causing erosion is more effective between outlets than where a boundary is imposed.

Test 5 - Generation of Constant Angle Reflector Surface: No Air Flow

The pebble reflector interface angle can be held constant by continuously recharging with reflector pebbles. To test the effectiveness of this concept, two concentric cylinders were set up, the inner one serving as the core container and the annulus acting as the pebble-reflector reservoir. 2 mm glass beads were used as fuel in a core with L/D = 2.0 and D/d = 23.7. By raising or lowering the inner cylinder, reflector pebbles could be fed into the core at different heights, and the interface angle could thus be set to any desired value. The angle was varied over 10° and, as expected, the volume per cent. of eroded reflector pebbles changed accordingly. Also the pebble discharge ratio decreased by 20 per cent. for an increase of 10° on the interface angle.

Hence the effect of corner stagnation decreases with increasing cone angle at the outlet. The results are shown in Table 6.

4. MEASUREMENTS OF PEBBLE DISCHARGE RATIO FOR VARYING CORE CONFIGURATIONS UNDER AIR-FLOW AND NO-FLOW CONDITIONS

Measurement of the pebble discharge ratio is useful as it gives information on the extreme velocity regions. Tests were done to determine to what extent the ratio depends on:

(a) the angle and surface of the outlet cone;
(b) the shape of the outlet tube lip;
(c) the number of outlets;
(d) the bed height or L/D ratio;
(e) the effect of air flow.

Test 1 - Pebble Discharge Ratio for Single-Outlet Core Using Smooth, Rough, and Variable Angle Outlet Cones Under No Air Flow Conditions

The core model used had a D/d value of 31.6. The outlet-tube lip was internally bevelled and cone roughness was introduced by using a pebble reflector or a radially slotted 45° cone. However, the slots were sized to minimize pebble hold-up and the results indicate that the roughness of the slotted cone was essentially insignificant. Ratios (given in Table 7) were calculated from the average of results from 10 tracer pebbles placed around the core circumference and the average of results from 4 tracer pebbles that moved axially down the core. Note that D/d = 23.7 for the variable cone angle.

For the case of variable cone angle using the pebble reflector, the core container was not Perspex but steel. It is appreciated that wall friction has a bearing on the pebble discharge ratio, however, the extent of this factor has not been investigated.

Test 2 - The Effect of Outlet Tube Lip Shape on the Pebble Discharge Ratio

Only two cases were examined, (a) a square-edge lip of width 0.062 in (the same as the tube wall thickness), and (b) an internal bevel of about 60°. As pebbles that travel in regions apart from the central core region tend to pass over the outlet tube lip, any hold-up then affects the pebble discharge ratio and tends to increase the value, as indicated in Table 8.

The effect was not apparent when the pebble reflector was used as the pebble movement was probably controlled by the roughened reflector surface, and any effect due to the lip shape tended to be masked. Thus the pebble discharge ratio might be reduced by having an internally-bevelled and smooth, outlet tube lip shape.

Test 3 - The Effect of D/d Value on the Pebble Discharge Ratio

For this test, core containers of different material (Perspex, PVC, and steel) were used, with the pebble reflector. The effect of increasing the D/d value was not obvious. However, differences in conditions, such as container material, would probably have masked any effect that was present. No conclusion could therefore be obtained from this test.

Test 4 - The Variation of Pebble Discharge Ratio in a System with Two Outlets

Tracer pebbles were placed at various points along the free surface on the longitudinal cross-section through the two outlets. The pebble discharge ratio was determined between combinations of points such as: the left-side wall and right-side wall; each outlet; the walls and outlets; the virtual centre plane, the outlets, and the walls. For convenience the walls were referred to as left wall, LW, and right wall, RW; the free surface points above the left and right outlets were designated LC and RC; and the mid-point between the outlets was called the virtual centre, VC.

The averaged measured values are shown in Table 10.

Although the model was rectangular, it was sized so that wall effects would be minimal between the outlets. For the test a pebble reflector was used, which had been established at an L/D value of 1.8 per cell, and had eroded for about 2 years' equivalent reactor time. This L/D value is equivalent to an overall core L/D value of 0.6 for a reactor having seven ball outlets. The variation in the values for like combinations is due to a slight mis-match between discharge rates, indicated in the discontinuity shown in the tracer pebble profile of Figure 5. This profile also indicates the lack of any hold-up or stagnation region between the two pebble outlets. In fact, the actual wall drag and corner stagnation effect seem to increase the pebble discharge ratio for this particular model by a factor of about 1.5.

Test 5 - The Effect of Bed Height on the Pebble Discharge Ratio

Measurements of this effect are already given in Tables 7, 8, and 9. It is seen that for L/D values of 1.5 and greater, the pebble discharge ratio levels out to values of between about 1.5 and 3 depending on the system considered. For L/D values less than 1.5 the curve elbows sharply and there is a large change in pebble discharge ratio for a small change in L/D. This region of low L/D is also characterized by a wide variation in pebble discharge behaviour. For instance, 10 tracer balls may be discharged over a period equivalent to 8 weeks' P.B.R. operation, whereas for an L/D of 1.8 or more, the period is only about 1 week.

This scatter is thought to be connected with the relative position of the free surface and the region of "cave-in". The critical height (the distance of "cave-in" above the top of the outlet tube) is less in beds where the free surface is above the "cave-in" region than in beds where the free surface is close to the "cave-in" region. Thus, depending on the height of the free surface above the critical height, the flow for some distance below the critical height tends to be of uniform velocity (piston flow). Below the region of piston flow, pebble movement is disorganized. Hence for beds of low L/D value most of the bed region is subject to this disorganization, which contributes to the large scatter in pebble discharge times.

Test 6 - The Effect of Air Flow on the Pebble Discharge Ratio

The model used for these tests was the single-outlet, Perspex core with D/d = 31.6. The original apparatus was modified for air flow as indicated in Figure 6. An industrial floor cleaner was used for suction (giving a downflow system) though the pressure drop was only about 1.4 p.s.i. A blower was throttled to provide the upflow of air and this was changed with L/D value to maintain a constant bed pressure drop per unit core length, of ~68 per cent. of the levitation limit. Except for a short test using a pebble reflector, the 45° slotted cone was used in conjunction with the bevelled-lip outlet tube.

The results for upflow and downflow are compared with those for zero flow in Table 11.

In view of these data, it was of interest to determine the effect of air flow rate on the pebble discharge ratio for a constant L/D value. In the downflow case it was not immediately practical to measure the air flow rate. The pressure drop (ΔP) across the core was thus used as a measure of flow. At an L/D value of 1.2 the maximum value of ΔP obtained was 0.88 p.s.i. This was decreased and the pebble discharge ratio was measured at each flow level. The data (see Table 12) show about a 3 per cent. increase in the pebble discharge ratio for each successive halving of the bed ΔP down to a value of one eighth of the initial value.

In the upflow case, the pebble discharge ratios were measured for a bed L/D value of 2 and several values of air-flow. These data are tabulated in Table 13 against the percentage of bed density F, which is calculated from:

$$F = \frac{\Delta P/L}{\rho(1-e)\,62.4} \times 100\,\% \text{ of bed density,}$$

where
ΔP = measured bed pressure drop
ρ = specific gravity of glass (assumed 2.6)
e = bed void fraction (assumed 0.4)
L = bed height.

This equation reduces to:

$$F = 17.73\,\frac{\Delta P}{L}, \text{ where } \frac{\Delta P}{L} \text{ has the units of lb/in}^3.$$

The results show a relatively small change in pebble discharge ratio up to a flow which gives a $\frac{\Delta P}{L}$ value of 50 per cent. of the bed density. As flow (ΔP) is increased above this point, the pebble discharge ratio undergoes larger changes until it approaches a value of 2 at 80 per cent. of the bed density. This value is usually considered the maximum allowable value before pebble movement occurs.

The effect of air flow rate is depicted in Figure 7.

The data in Table 12 indicate that as pressure drop is increased the discharge ratio decreases. Hence the values for the downflow case in Table 11 would be expected to be lower for a larger ΔP value.

5. CONCLUSIONS

The pebble reflector concept has been examined from both a pebble flow profile and a pebble erosion viewpoint. The erosion tests showed an exponential change in the reflector-fuel interface angle, the levelled out value being about 13° after 30 to 40 bed inventories had been recirculated. Wall-pebble hold-up was more apparent with a pebble reflector than without and the pebble discharge (PD) ratio tended to be high (about 2.5) for L/D values of 1.6 and above. Depending on the relative importance of the PD ratio (and consequent problems of fuel management) on the one hand, and an acceptable erosion rate on the other, the pebble reflector concept appears feasible. The surface can be readily cleaned or recharged and the number of reflector pebbles eroded decreases with time. Thus, if recharging were not practical, the interface angle could be set at a low value, say 13^{o}, where it has been shown, at least in small scale, that the angle remains fairly constant for a long time.

The twin-outlet model indicated some 50 per cent. difference between discharge ratios for pebbles moving down the wall and those moving between the outlets. Pebbles moving between the outlets tended to travel faster.

Examination of pebble flow behaviour with upflow and downflow of air showed that the pebble discharge ratio in each case was significantly different from that obtained with no air flow. With upflow, at the flow design value of 68 per cent. bed density, the pebble discharge ratio was 20 to 30 per cent. above that for no air flow for L/D values of 1.4 and above. For downflow, the ratio was 15 to 20 per cent. below that for no air flow for L/D values of 1.4 and above. The air flow tests were done using a slotted 45^{o} cone.

The surface of the outlet cone affected the PD ratio. At an L/D value of 2.0 a PD ratio of 1.5 was obtained for both a smooth 45^{o} cone and a fine radially slotted 45^{o} cone, whereas the value for a pebble reflector (45^{o}) was 2.9 at the same L/D value.

The shape of the outlet tube lip affected the PD ratio. Use of a square-edged lip instead of a smooth bevelled lip increased the PD ratio by 20 per cent. for an L/D value of 1.8 under no flow conditions. This effect was greater for lower L/D values.

There was a significant variation in the PD ratio for a system with more than one outlet. With two outlets, a 50 per cent. difference existed between pebbles moving down the virtual boundary between the outlets to those moving down the container wall (for a cell with L/D = 1.8) and pebbles moved more rapidly between outlets.

Core bed height greatly affected the PD ratio. For a 14^{o} pebble reflector, the ratio levelled out to 2.4 at L/D values greater than 1.6. This ratio increased sharply for smaller L/D values. For the 45^{o} cones (smooth and slotted) the value

was about 1.5 for L/D values of 1.4 and above. For lower L/D values, the PD ratio again increased sharply.

Based on the above, the acceptance of a pebble reflector may be determined by fuel management problems. One could no doubt cope with an initial increased number of reflector pebbles discharged from the core. However, a PD ratio of 2.5 might be too high to be acceptable. This ratio can be decreased by increasing the angle of the outlet "cone" and this was done by continually recharging the reflector surface from a reflector pebble reservoir. Although there was an increased erosion with this arrangement, some erosion of the reflector surface may be desirable so that fuel pebbles do not become permanently lodged on the surface.

6. ACKNOWLEDGEMENT

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TABLE 1

SINGLE-OUTLET PEBBLE REFLECTOR EROSION : NO AIR FLOW: TEST 1(A)

Bed Inventories Recirculated (Cumulative)	Reflector Pebbles Eroded (Volume Per Cent.)*	Interface Angle (Degrees)	P.B.R. Operation Time (Years)
-	-	29.4	0
5	0.453	22.2	0.4
10	0.208	19.3	0.8
20	0.079	15.5	1.6
30	0.044	14.0	2.3
40	0.039	13.2	3.1
50	0.037	13.0	3.9

TABLE 2

SINGLE-OUTLET PEBBLE REFLECTOR EROSION : NO AIR FLOW: TEST 1(B)

Bed Inventories Recirculated (Cumulative)	Reflector Pebbles Eroded (Volume Per Cent.)*	Interface Angle (Degrees)	P.B.R. Operation Time (Years)
-	-	45	0
5	0.735	24.5	0.4
10	0.245	21.0	0.8
20	0.093	16.7	1.6
30	0.044	14.5	2.3

TABLE 3

SINGLE-OUTLET PEBBLE REFLECTOR EROSION : DOWNFLOW SYSTEM

Bed Inventories Recirculated (Cumulative)	Reflector Pebbles Eroded (Volume Per Cent.)*	Interface Angle (Degrees)	P.B.R. Operation Time (Years)
-	-	29.3	0
5	0.465	23.5	0.4
10	0.200	20.3	0.8
20	0.085	16.7	1.6
30	0.045	14.0	2.3

*Volume per cent. reflector pebbles of the pebbles discharged from the core.

TABLE 4

SINGLE-OUTLET PEBBLE REFLECTOR EROSION: NO AIRFLOW AND ZERO ANGLE REFLECTOR

Bed Inventories (Recirculated) (Cumulative)	Reflector Pebbles Eroded (Volume Per Cent.)*	P.B.R. Operation Time (Years)
5	0.030	0.4
10	0.026	0.8
20	0.020	1.6
30	0.016	2.3
40	0.013	3.1
50	0.011	3.9
60	0.009	4.7
70	0.008	5.4
80	0.007	6.3
90	0.006	7.0

TABLE 5

DOUBLE-OUTLET PEBBLE REFLECTOR EROSION: NO AIR FLOW

Interface Reference Region	Angle
LW - LC	28°
LC - VC	22°
VC - RC	19°
RC - RW	25°

Note: LW-LC and LC-VC refer to the angles subtended at the left hand outlet (LC) by the left hand wall (LW) and by the virtual wall (VC) between the two outlets; VC-RC and RC-RW have similar meanings in the right hand cell.

TABLE 6

GENERATION OF CONSTANT ANGLE REFLECTOR SURFACE: NO AIR FLOW

Interface Angle (Degrees)	Reflector Pebbles Eroded (Volume Per Cent.)*	Mean Pebble Discharge Ratio
38.6	0.07	3.2
45.0	0.53	2.9
50.2	1.90	2.7

* Volume per cent. reflector pebbles of the pebbles discharged from the core.

TABLE 7

PEBBLE DISCHARGE RATIO FOR SINGLE-OUTLET CORE USING SMOOTH, ROUGH, AND VARIABLE ANGLE OUTLET CONES UNDER NO AIR FLOW CONDITIONS

Case	L/D Value						
	0.8	1.2	1.4	1.6	1.8	2.0	2.8
Smooth Surfaced 45° Cone	7.8	1.8	-	1.5	-	1.4	-
Slotted Surfaced 45° Cone	5.9	1.9	-	1.6	-	1.5	-
Pebble Reflector 14° Cone Angle	-	12.2	4.4	2.5	2.5	2.4	2.4
Pebble Reflector 38.6° Cone Angle D/d = 23.7	-	-	-	-	-	3.2	-
Pebble Reflector 45.0° Cone Angle D/d = 23.7	-	-	-	-	-	2.9	-
Pebble Reflector 50.2° Cone Angle D/d = 23.7	-	-	-	-	-	2.7	-

TABLE 8

THE EFFECT OF OUTLET TUBE LIP SHAPE ON THE PEBBLE DISCHARGE RATIO

Case	L/D Value					
	0.8	1.2	1.4	1.6	1.8	2.0
Smooth Surfaced 45° Cone Bevelled Lip	7.8	1.8	-	1.5	-	1.4
Smooth Surfaced 45° Cone Straight Lip	-	3.6	2.4	-	1.8	-
Slotted Surface 45° Cone Straight Lip	-	3.8	-	-	-	-

TABLE 9

THE EFFECT OF D/d VALUE ON THE PEBBLE DISCHARGE RATIO

Case	L/D Value				
	1.2	1.4	1.6	1.8	2.0
Ball Reflector Angle 14° (steel) D/d = 23.7	-	18.0	4.1	3.1	2.9
Ball Reflector Angle 14° D/d = 31.6 (Perspex)	12.2	4.4	2.5	2.5	2.4
Ball Reflector Angle 14° D/d = 49.1 (PVC)	-	10.0	3.6	-	3.1

TABLE 10

THE VARIATION OF PEBBLE DISCHARGE RATIO IN A SYSTEM WITH TWO OUTLETS

LW	LC	VC	RC	RW	Pebble Discharge Ratio
X	X				2.9
			X	X	2.6
X			X		2.9
	X			X	2.6
	X		X		1.0
X				X	1.1
	X	X			1.8
		X	X		1.8
X		X			1.6
		X		X	1.4

TABLE 11

THE EFFECT OF AIR FLOW ON THE PEBBLE DISCHARGE RATIO

Case	L/D Value			
	0.8	1.2	1.6	2.0
UPFLOW Constant $\Delta P/L$ of 0.03 lb/in^3	8.0	2.6	1.8	1.8
NO-FLOW	5.9	1.9	1.6	1.5
DOWNFLOW Variable Bed Pressure Drop (ΔP p.s.i.)	5.0 (0.54)	1.6 (0.88)	1.3 (1.08)	1.3 (1.23)
DOWNFLOW Pebble Reflector (ΔP p.s.i.)	-	-	-	2.4 (1.4)

TABLE 12

THE EFFECT OF AIR FLOW RATE ON PEBBLE DISCHARGE RATIO: DOWNFLOW

ΔP (p.s.i.)	0.88	0.59	0.29	0.11	0
Pebble Discharge Ratio	1.69	1.74	1.79	1.86	1.90

TABLE 13

THE EFFECT OF AIR FLOW RATE ON PEBBLE DISCHARGE RATIO: UPFLOW

Percentage Bed Density	0	47	68	73	78
Pebble Discharge Ratio	1.46	1.55	1.77	1.85	2.0

APPENDIX I

DESCRIPTION OF THE SPLIT-BED TECHNIQUE

The method used to view reflector-fuel boundaries was the split bed technique. Basically, the steps followed were:-

(a) The core model (whether single or double outlet) was completely filled with fuel pebbles after a test run.

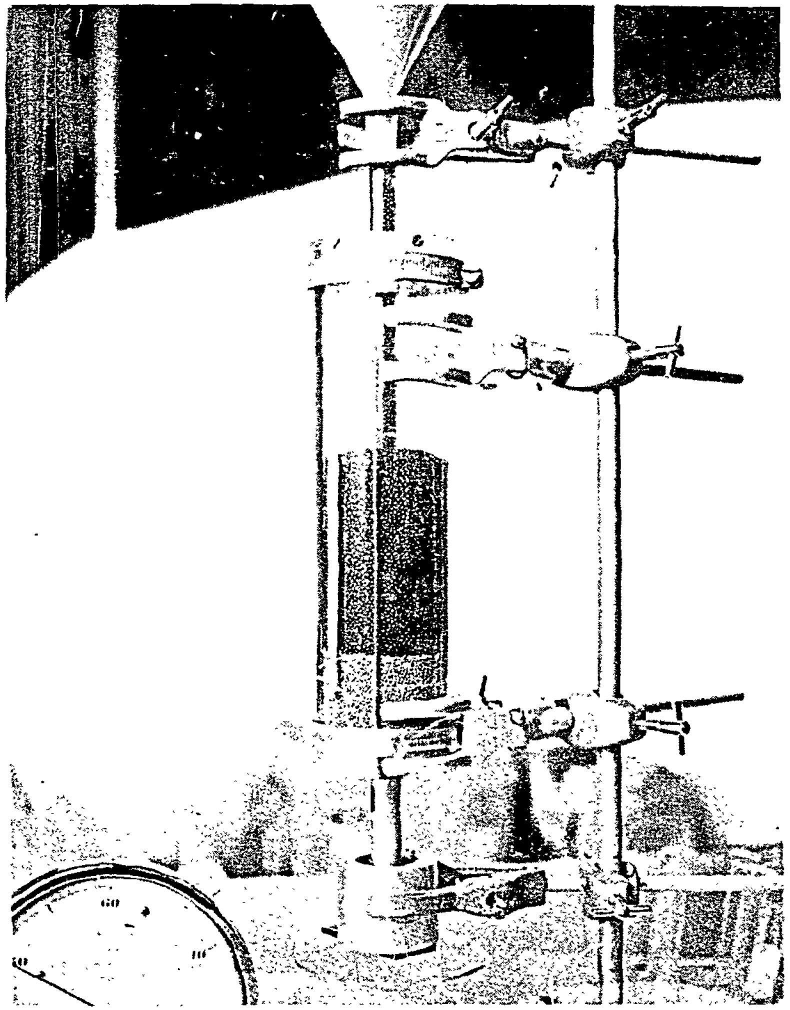
(b) The model was then removed from its supporting structure and inlet-outlet mechanisms, and placed on its side in a special saddle. This saddle was designed to hold the lower half of the core model firm whilst the upper half was lifted and removed.

(c) The convex-shaped pebble surface was then carefully vacuumed flat. This was done by fitting a fine vacuum nozzle to a traversing arm, on a rigid platform overhanging the saddle. By sweeping at a constant height, the surface was progressively levelled without disturbing pebbles in lower layers. Eventually the mid-core cross-section was revealed.

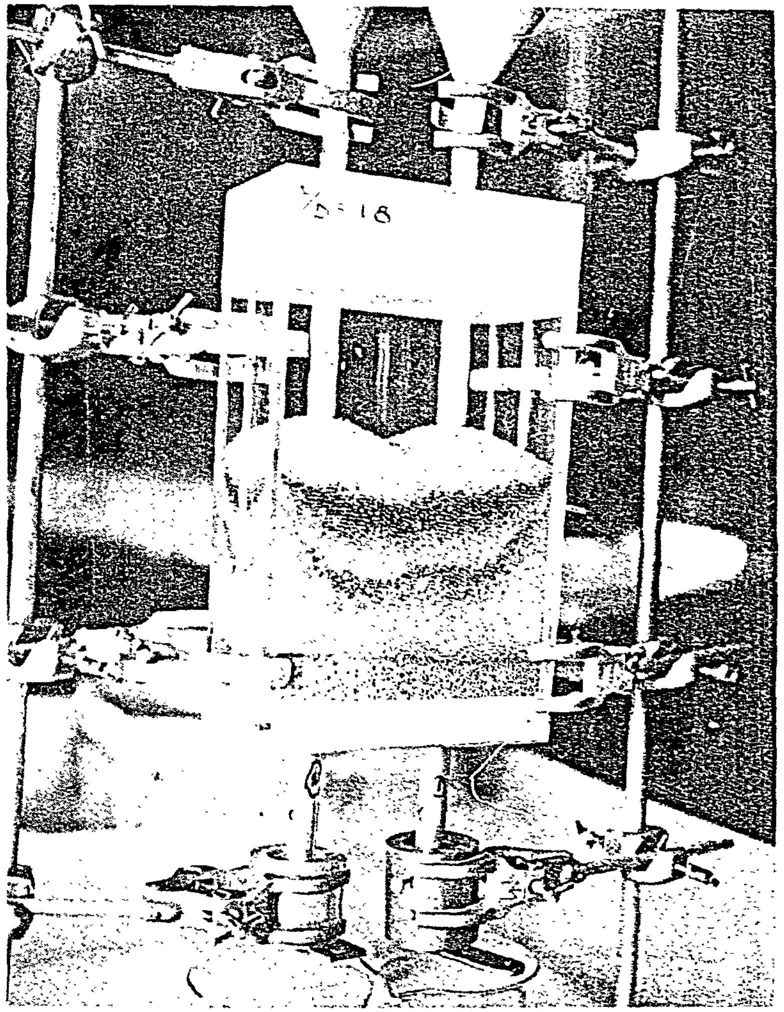
(d) Tracer pebble profiles were examined and boundary interface angles measured. A photographic record was also taken of the undisturbed cross-section.

(e) Tracer pebbles, fuel, and reflector pebbles were then separated, the apparatus was reassembled, and another test could then be performed.

The advantage of this technique over a method such as wax-freezing is that it dispenses with laboratory facilities for handling materials other than the pebbles themselves. Further, tests may be done rapidly and without destruction of any material, with the least complication in apparatus and facilities.

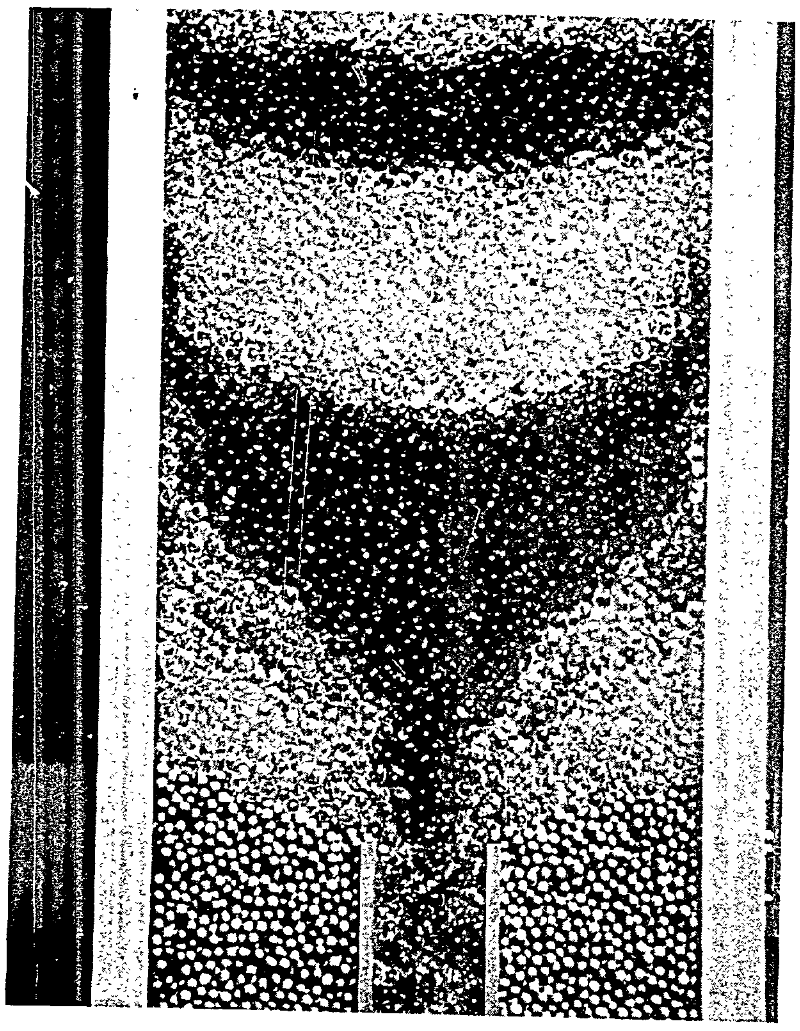


(a) SINGLE OUTLET

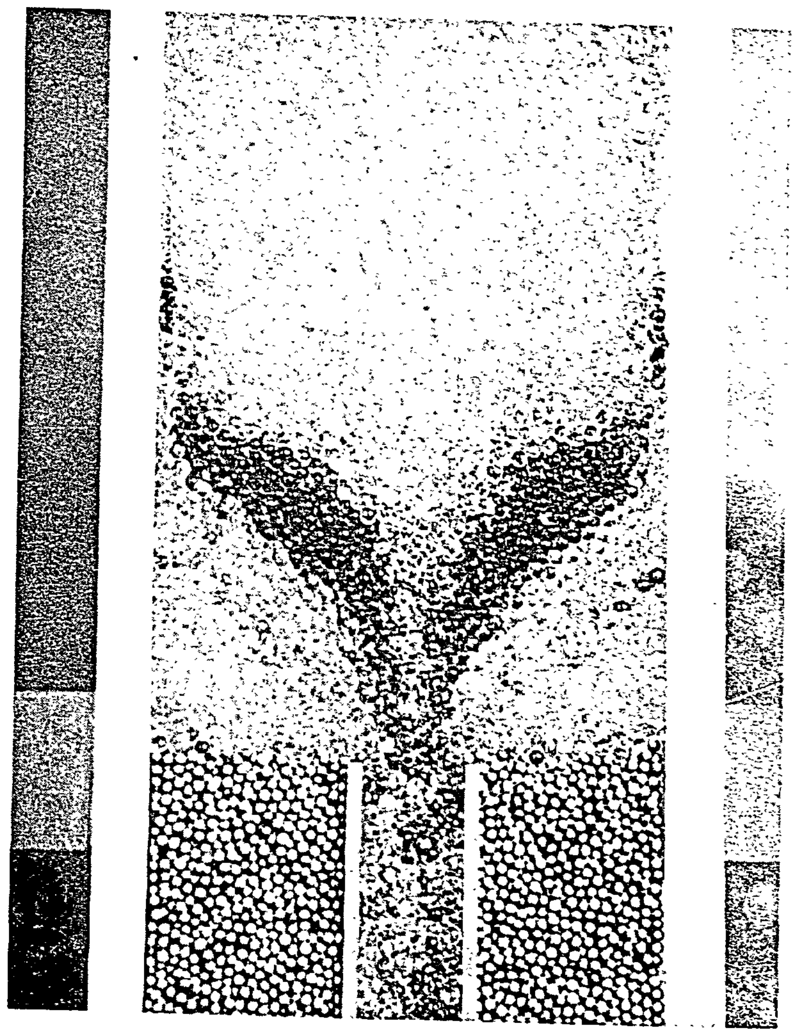


(b) DOUBLE OUTLET

FIGURE 1 CORE MODEL ASSEMBLIES



(a) 50 INVENTORIES RECIRCULATED
3.9 YEARS REACTOR OPERATION



(b) INITIALLY 0° REFLECTOR
7.0 YEARS REACTOR OPERATION

FIGURE 2 EROSION TEST – REFLECTOR AND BALL FLOW PROFILES

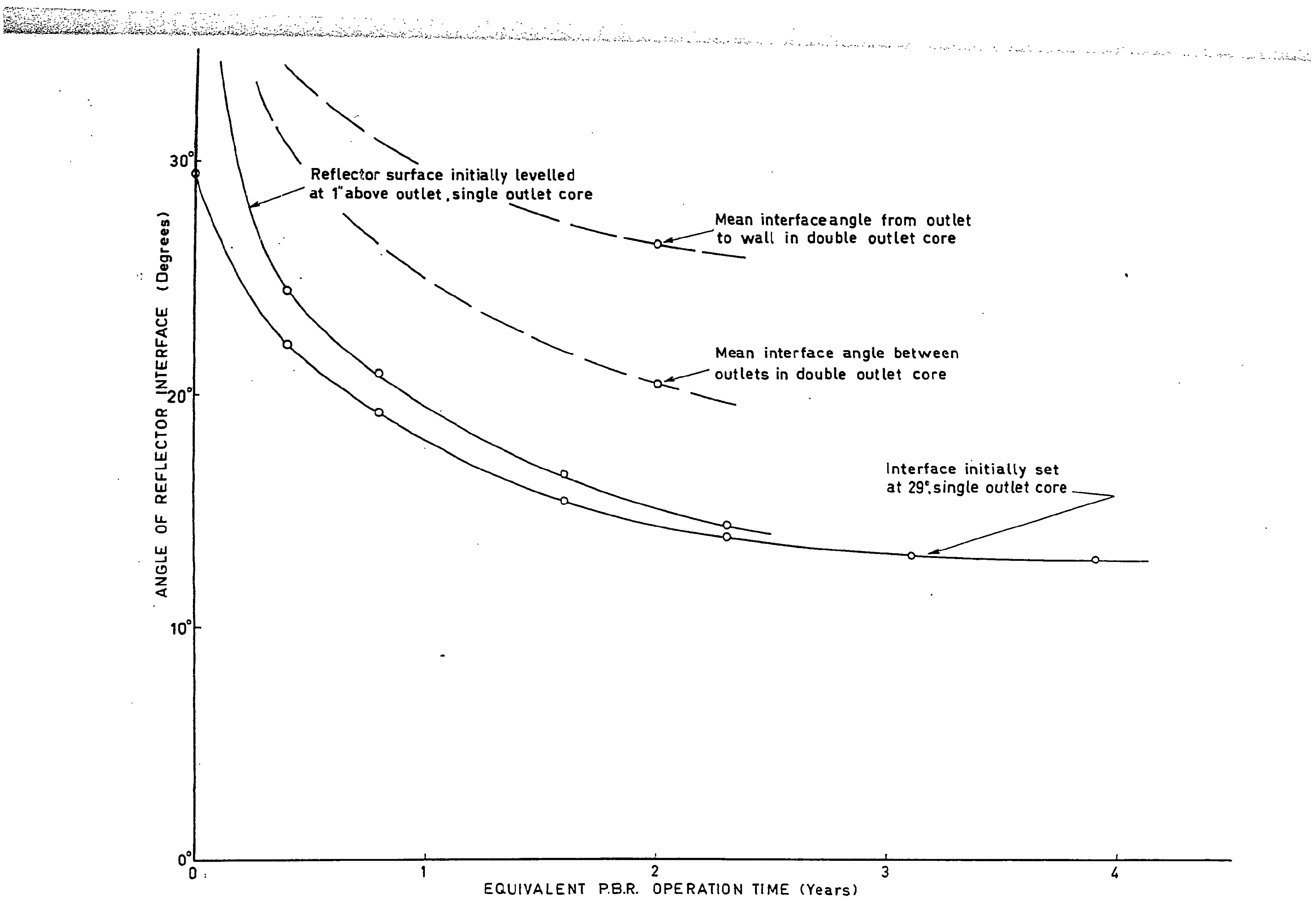


FIGURE 3. PEBBLE REFLECTOR EROSION: INTERFACE ANGLE VARIATION WITH TIME

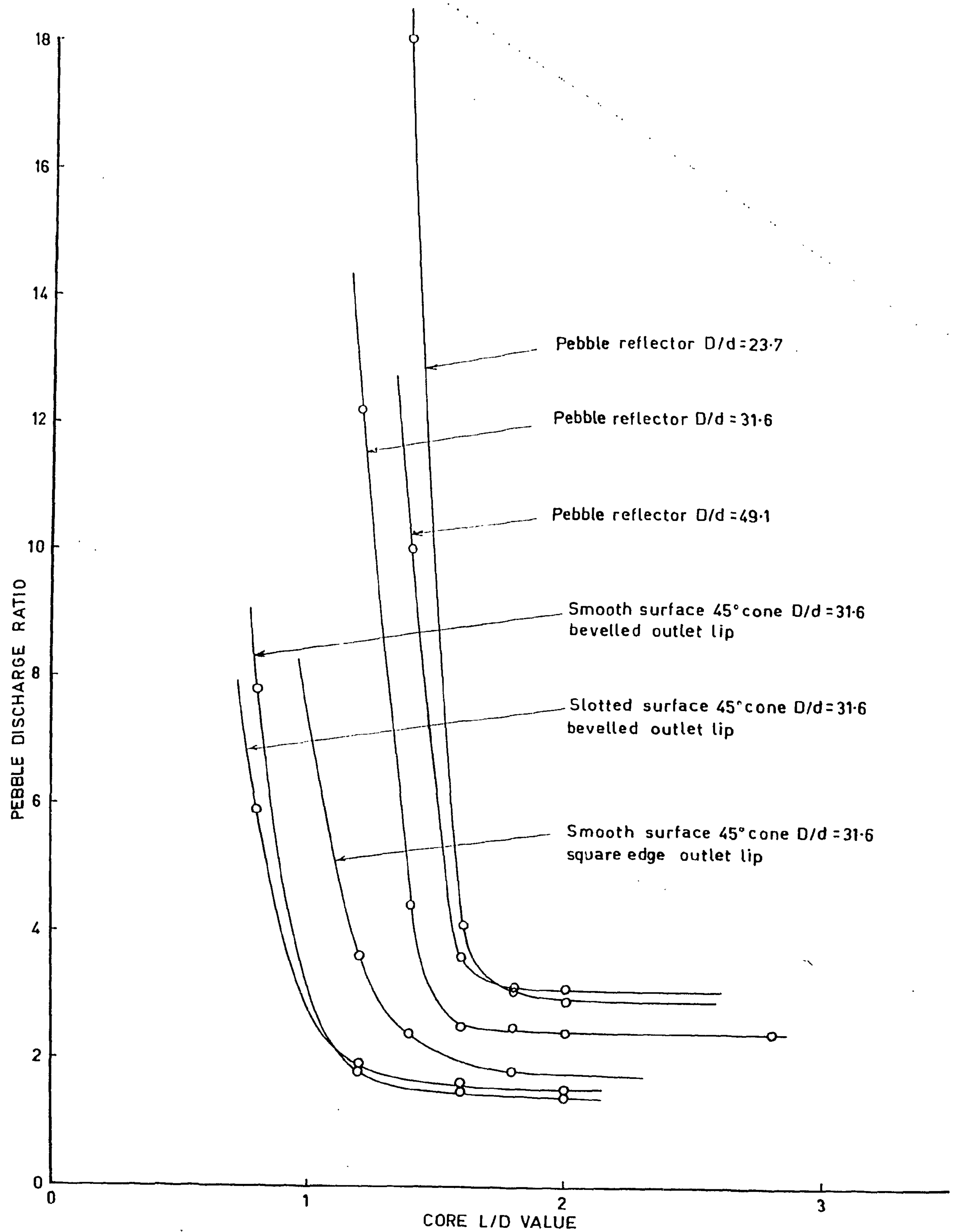
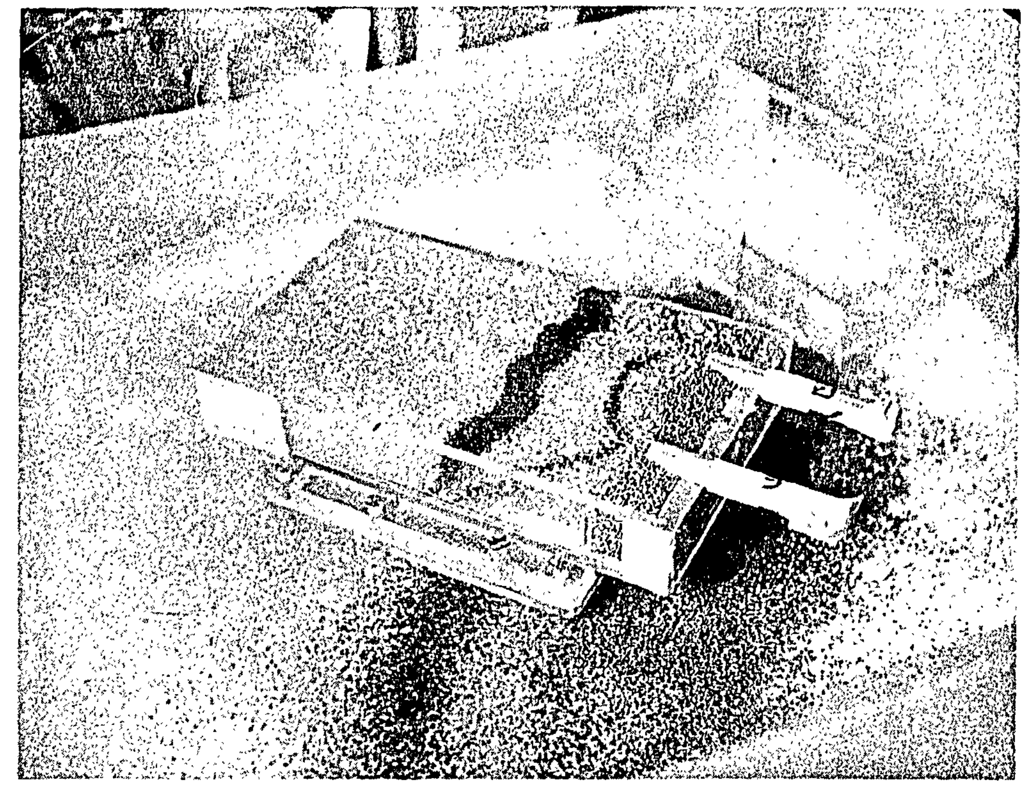
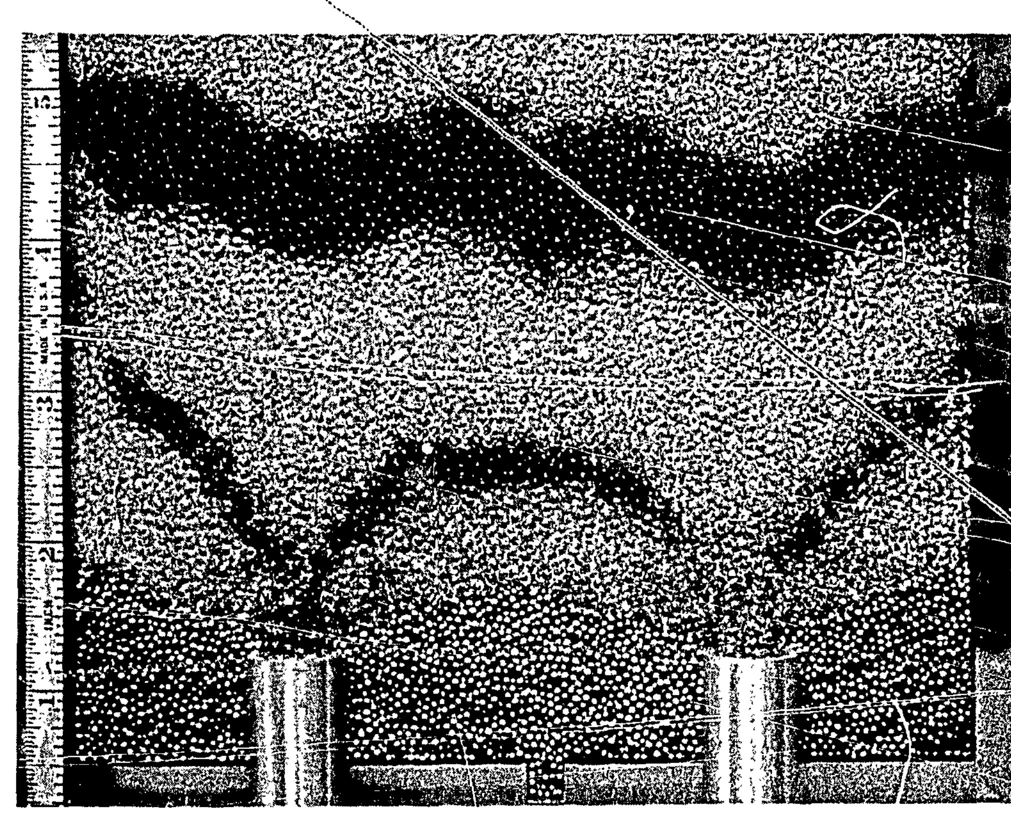


FIGURE 4. PEBBLE DISCHARGE RATIO VERSUS CORE L/D VALUE WITH NO AIRFLOW



(a) PRIOR TO VACUUMING



(b) AFTER VACUUMING

FIGURE 5 TWIN OUTLET MODEL REFLECTOR AND TRACER BALL PROFILES

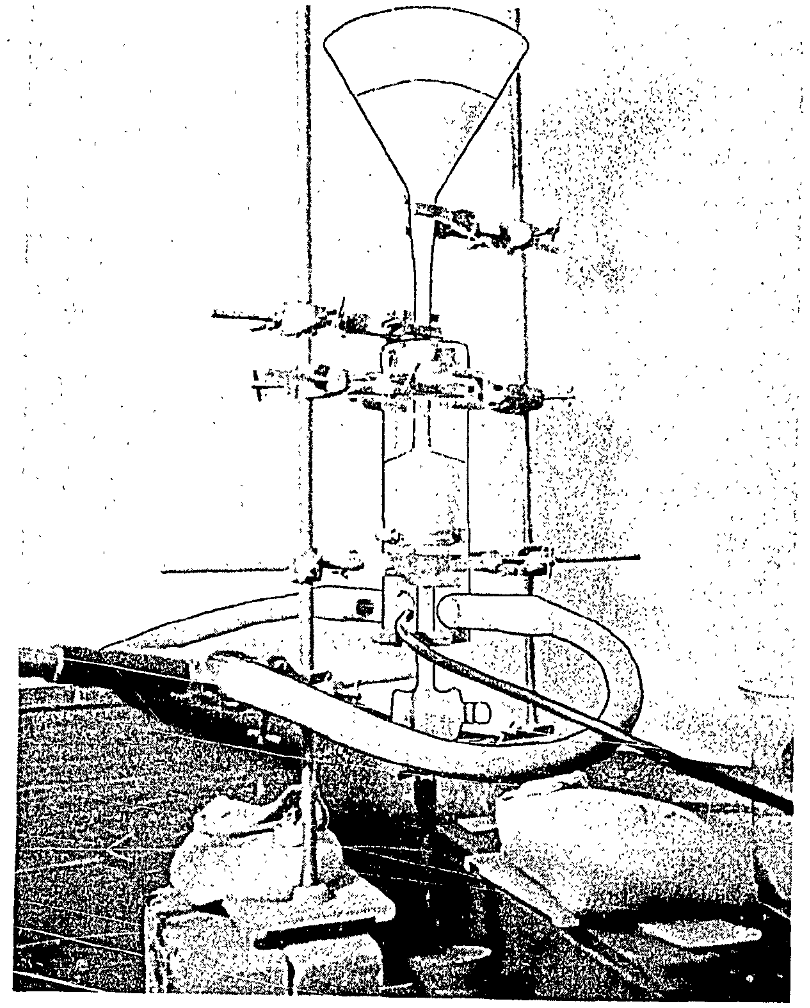


FIGURE 6 ASSEMBLY USED FOR UPFLOW AND DOWNFLOW TESTS

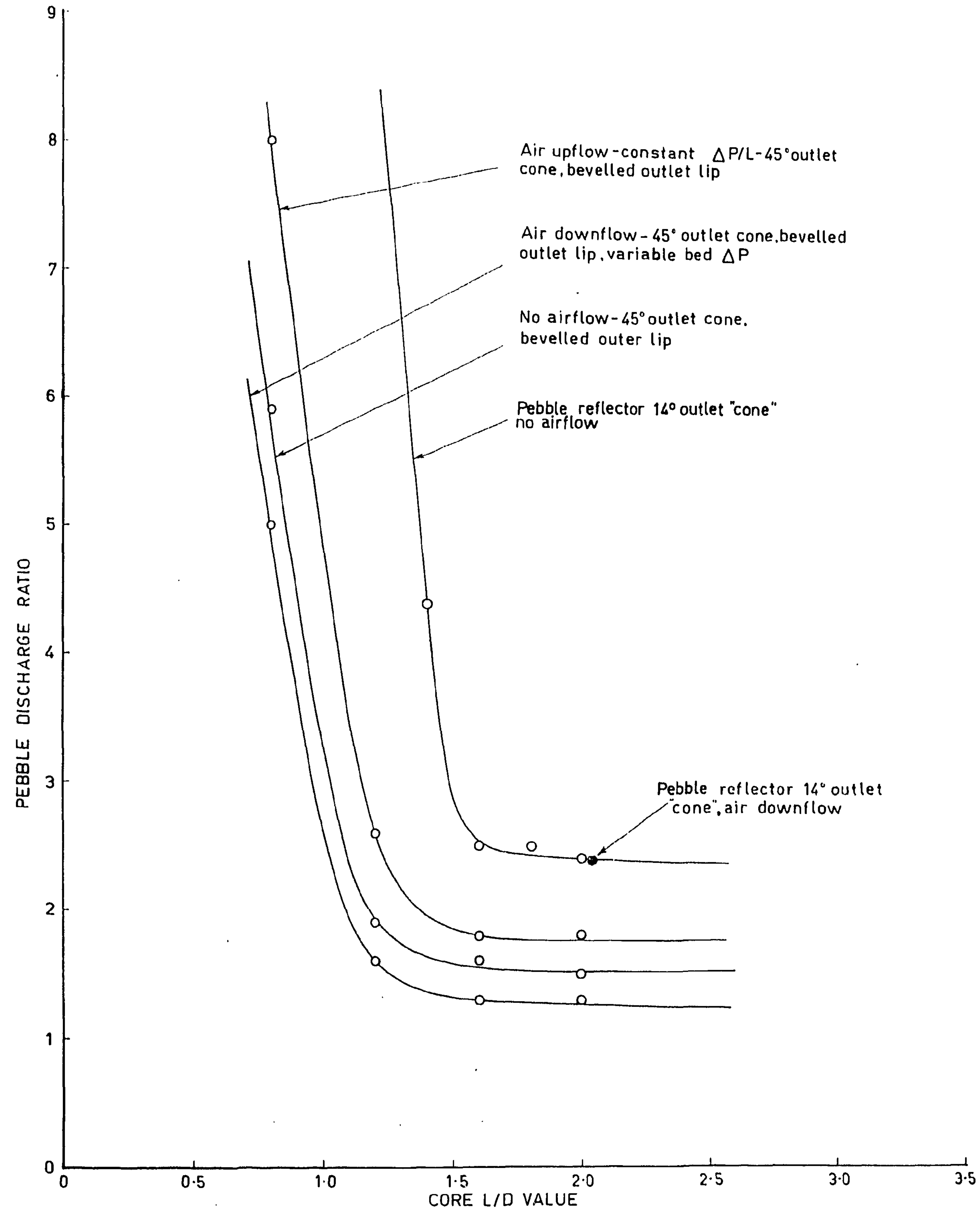
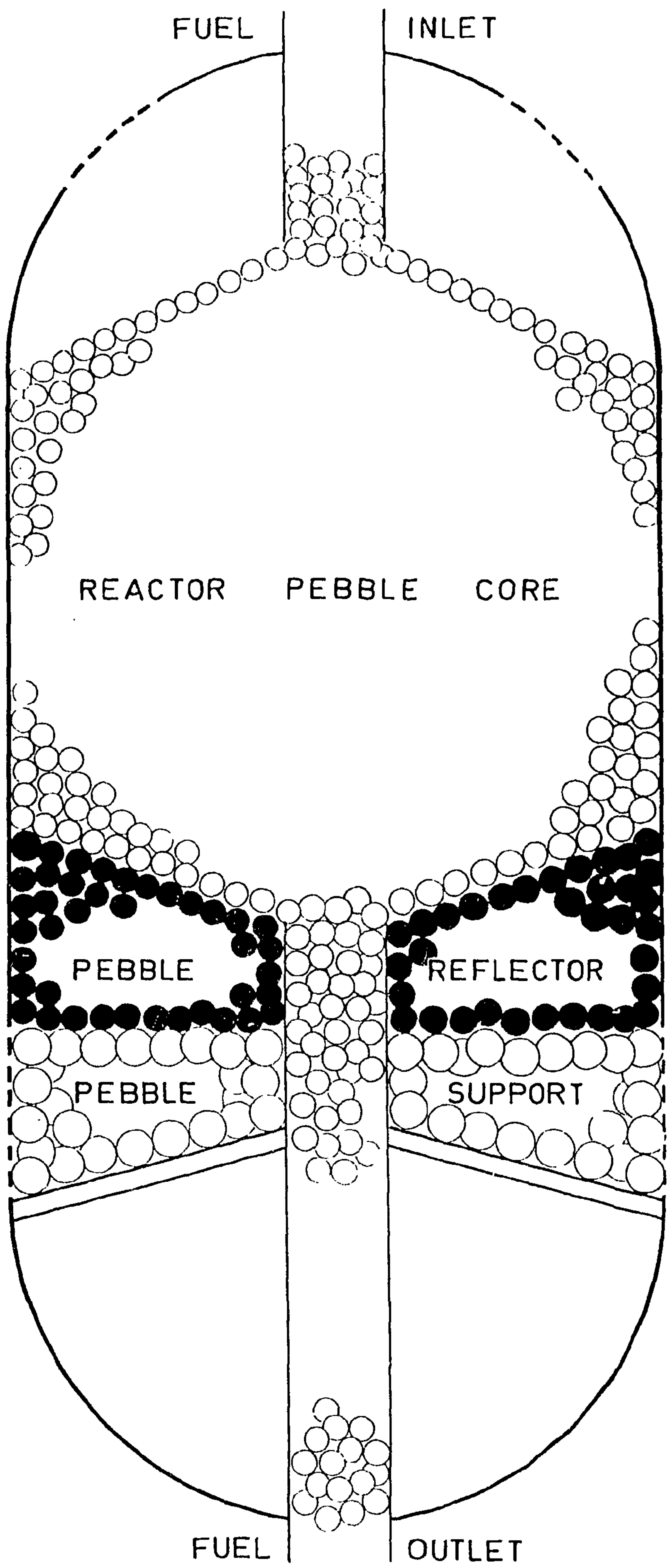


FIGURE 7. PEBBLE DISCHARGE RATIO VERSUS CORE L/D VALUE WITH AIRFLOW


FUEL
INLET
REACTOR PEBBLE CORE
PEBBLE
REFLECTOR
PEBBLE
SUPPORT
FUEL
OUTLET