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LUCAS HEIGHTS

FLOW OF SPHERES AND NEAR SPHERES IN CYLINDRICAL VESSELS
PART II - PEBBLE TRANSIT IN RECIRCULATED RANDOM PACKINGS

by

F.C. GATT

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ABSTRACT

An experimental and statistical investigation has been made of the transit of individual pebbles in recirculated random packings of equal spherical pebbles. Slightly aspherical pebbles were also studied. Pebbles of 1.00 inch or 0.75 inch nominal diameter were used to form 30 inch deep beds in a 30 inch diameter vessel with a concave base in the form of a cone with 25 degree slope. The pebbles flowed downwards under the influence of gravity. The independent variables whose effects were studied were the radial position of the pebble, the number of pebbles in the bed situated beneath the seeding position, the pebble size and sphericity, and the amount of recirculation. Both transient and equilibrium conditions were considered.

An estimate was made of the mean amount of recirculation required to reach equilibrium from an initially random packing. For spherical pebbles this was approximately 1.6 times the number of pebbles in the bed, and for aspherical pebbles it was 2.8 times the number.

Formulae are given for predicting the amount of recirculation required for a particular pebble to emerge from the bed.

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1. INTRODUCTION

In a pebble bed nuclear reactor, fuelled pebbles enter at the top of a container, in which they form a pebble bed, (Figure 1) and undergo a nuclear reaction producing heat. They pass through the bed and out through the base of the container.

An important parameter is the time it takes for the pebble to pass through the bed. Excessive time in parts of the bed could result in severe irradiation and thermal damage to the pebble with possible fission product escape. The extreme case would be permanent fixing of a given pebble or group of pebbles in a region of the vessel.

In this report an experimental and statistical study of pebble transit is given.

2. NATURE OF THE PROBLEM

The following quantities are of prime importance:

Bed inventory (N)	–	the total number of pebbles in the bed
Radial seeding position (R)	–	the radius of a seeded pebble from the bed centre line, (in inches)
Seeding inventory (F)	–	the number of pebbles below the horizontal plane containing a particular seeded pebble, expressed as a fraction of N
Inventory number (I)	–	the number of pebbles circulated from the start of recirculation before a particular event, expressed as a fraction of N
Seeding inventory number (I_S)	–	the inventory number of the bed when a particular pebble is seeded in the bed
Exit inventory number (I_E)	–	the inventory number of the bed when a particular pebble leaves the bed
Transit number (T)	–	the number of pebbles recirculated between the seeding of a pebble in the bed and its exit from the bed, expressed as a fraction of N.

Note that $T = \text{function}(R, F, I_S)$

and $T = I_E - I_S$. (1)

It was postulated that both the packing structure* (that is, the arrangement of the pebbles in the bed) and the initial velocity profile would change following the first loading of the vessel and subsequent recirculation. Here, velocity profile refers to the velocity of a pebble as it passes through each part of the bed. This change was believed likely to result in a corresponding change in the transit behaviour of any pebble commencing its motion from a given point. This assumed transit variation was believed to be transient, an equilibrium state eventually being attained where the packing structure gives a reproducible transit number versus frequency spectrum of a pebble repeatedly seeded in the same position.

Evidence of the packing or structure change was given by Murray (1966) who found that recirculation results in changes in the structure of the pebble packing near the vessel wall. It was found to be altered from a random to an ordered array. Such arrays tend to remain in a fixed position in the cylindrical vessel as recirculation proceeds.

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* The initial packing structure, though random, is regarded as being relatively loosely packed.

The purpose of the investigation was:

(a) To determine the amount of bed recirculation required to achieve a constant transit number for pebbles seeded in the same position.

(b) To find expressions relating T and I_E with R, F and I_S.

(c) To determine the variation of transit number with radial position of the pebble in the bed when pebbles are seeded at the top surface of a bed with inventory number zero.

3. DESCRIPTION OF PEBBLES

Four types of pebbles were press-formed from plastic bonded zircon sand, then cured to the desired hardness and coated with plastic for wear resistance. The finished pebbles had the following properties:

Surface finish (projections)	$\pm$ 0.001 in.
Sphericity	$\pm$ 2 percent
Diameters	1.00 $\pm$ 0.02 in. and 0.75 $\pm$ 0.02 in.
Density	3.40 $\pm$ 0.07 g cm^{-3} .

The value of the nominal pebble diameter (d) is used to specify the size of both spherical and aspherical pebbles.

In effect two sizes of aspherical pebble were produced by removing from each spherical pebble a slab of thickness 0.10 d centred on the pebble equator, and then joining the identical halves. The resulting pebble had an equatorial diameter of 0.999 d and a length through the poles of 0.90 d. Sphericity of the segments and dimensions were held to the above tolerances.

Pebbles intended for seeding were dipped into a staining solution of "Maruzen Ink" and identifying numbers were painted on when the ink was dry.

4. EQUIPMENT

The pebble vessel was an upright aluminium cylinder with diameter 30 in. and height 60 in. A cone (concave when viewed from above) formed the base. Data on 15°, 25°, 35° and 45° conical bases (cone angle measured from the horizontal) indicated that a 15° base formed a pronounced "dead zone" (Deutsch 1967) in the lower corners of the vessel where little or no movement of the bed took place. (See Figure 2). Also the transient behaviour of the pebble flow pattern disappeared with steeper angles, to be replaced by a flow pattern set up almost immediately upon start of recirculation.

The 25° base cone angle selected for the tests was assumed to give the maximum amount of structure and flow pattern change with minimum formation of dead zone. By contrast, the cone angle likely to be chosen for a practical reactor would be 35°.

An extraction mechanism situated at the vertex of the vessel base is shown in Figures 3 and 4. As pebbles were extracted one by one the bed flowed under its own weight down the vessel into the extractor. Pebbles leaving the extractor fell through a tube onto a sloping trough to be elevated to above the top of the bed by an endless bucket conveyor. Then they rolled by gravity along a second trough to drop approximately six inches onto the centre of the bed surface. When passing along the first trough, they were counted automatically with a photo-electric counter and the marked pebbles were picked out manually while the number registering on the counter was noted.

The extraction rate throughout the experiment was set at a nominal 350 pebbles per minute, the fastest attainable rate for the extractor used. The rate was checked at intervals and was found to vary ± 50 pebbles per minute.

5. EFFECTS OF RECIRCULATION RATE ON TRANSIT NUMBER AND INVENTORY NUMBER

It was assumed that these small variations in the recirculation rate had no effect on the transit number and the inventory number. Although in the work reported, these two dimensionless quantities were strictly valid only between the limits of the recirculation rate employed, it appears from Denton's (1953) work that with intermittent discharge, individual pebbles followed fairly consistent paths and this suggests that no radical change in transit number occurred even under these conditions.

Leesment and Stephenson (1964) compared two circulation rates of 75 and 510 pebbles per minute and found no detectable difference in the transit number.

Deutsch (1967) found that fundamental flow patterns were not affected significantly by changes in flow rate over a range of 100 to 600 pebbles per minute. He also found similar fundamental flow patterns at a flow rate of 80,000 pebbles per minute.

A similar finding was reported by Szomanski and Tingate (1967). A pebble recirculation rate varying from one per two minutes to 50,000 per minute had little or no effect on the pebble flow pattern.

These findings suggest that recirculation rate has very little effect on flow pattern, transit number or inventory number of pebbles in a randomly packed pebble bed.

6. EXPERIMENTAL PROCEDURE

To determine the required amount of bed recirculation to achieve a constant transit number for identically seeded pebbles, it was reasoned that equilibrium could be found by regular seeding of marked pebbles in the same position while extraction proceeded. A comparison of the transit number of each seeded pebble would show when equilibrium was reached. When the transit number remained constant (apart from random fluctuations) the part of the bed through which the seeded pebbles were travelling would be in equilibrium. The individual pebble need not always, (in fact would rarely) reach a transit number of unity. However the average transit number of all pebbles in the bed at equilibrium must be unity.

Marked pebbles could be seeded after recirculation commenced but they could also be incorporated into the bed as it was being built up. Of course, at this point transit numbers could not be compared but since the pebbles were seeded at regular intervals the difference between the transit numbers of successively seeded pebbles could be compared and when this difference levelled out (or was constant) the bed had reached equilibrium.

The four pebble types were used as follows to form four corresponding beds of equal pebbles. In each case sufficient pebbles were placed in the vessel to fill the conical base. A guide device was then used to place three horizontal rows of marked and numbered pebbles side by side along a bed radius (Figure 1). This is referred to as "a seeding", and the radial distance R of a seeded pebble from the vessel centre line is called its "radial seeding position". With both spherical and aspherical pebbles each seeding took 45 and 60 pebbles for the 1.00 in. and 0.75 in. sizes respectively. When the guide was removed the seeded pebbles adjusted their positions to conform to the adjacent packing, but this movement in any direction was not greater than the pebble diameter.

More unmarked pebbles were placed in the container, burying the coloured rows to a depth of about 7.5 in. and a second differently coloured layer of numbered pebbles was seeded similarly in a horizontal plane, directly above the first layer. Seeding and filling continued until the fifth seeding was in place 30 in. above the first. (The fifth initial seeding for 1 in. spherical pebbles was at 29 in. because of an early shortage of this type).

The bed was then topped to simulate the cone of pebbles which forms naturally during recirculation (Figure 1). Recirculation of the bed was then started. The number of pebbles in transit between extraction and re-insertion did not exceed 400 which is negligible when compared with a typical inventory of 30,000 pebbles. After a number of pebbles equal to the number contained in one-quarter of the cylindrical portion of the bed (approximately 20 percent of bed inventory) had been circulated, extraction was stopped, the top conical heap carefully removed, and another seeding placed at the top of the cylindrical portion of the bed (at the position previously occupied by the fifth seeding). The top cone was then re-shaped and extraction was started again.

This procedure was repeated until a total of 12 seedings including the initial five had been made. Recirculation and extraction continued until all coloured seeded pebbles had been extracted. The transit number of each coloured pebble and the corresponding exit inventory number was noted.

To determine the variability of the transit number for individual pebbles seeded at particular radii, the pebble bed was filled with unmarked pebbles to 30 in. cylindrical bed height (again 29 in. in the case of the 1.00 in. spherical pebble). On the horizontal plane located at the 30 in. cylindrical bed height (29 in. in the case of the 1.00 in. spherical pebble) and at radial distances of 3.0, 6.0, 9.0, 12.0 and 14.5 in. on this plane, coloured pebbles were seeded in rings, over which the pebble cone was formed manually as before. Recirculation was started and the exit inventory number of the bed and the transit number of the coloured pebble were noted at the moment of extraction of the coloured pebble.

7. RESULTS AND ANALYSIS

7.1 Exit Inventory Number Variations

On completion of the radially seeded runs, each set of three pebble bed exit inventory numbers and each set of three transit numbers was averaged. The transit numbers of the first five seedings of each bed are equivalent in magnitude to the exit inventory numbers of the bed (from Equation 1). The average exit inventory numbers of the particular pebble group were plotted against radial seeding position for the first seven seedings of each pebble type and are shown in Figures 5 and 6 for the two sets of spherical pebbles. Those for the aspherical type are similar. Figures 5 and 6 show that near the vessel wall, values of exit inventory number vary appreciably. There is substantial evidence from the experimental work that the different speed of each pebble results in mixing of pebble layers, causing in turn differences in the paths of pebbles seeded near the vessel wall, and marked pebbles emerging from the bed before other marked pebbles which had been seeded directly beneath them. A possible explanation of this behaviour is that some of the pebbles in the wall region enter the dead zone of the bed and remain there for periods varying with their depth of penetration, while those in the centre region are seeded in or pass through the fast flowing pipe zone (Figure 2).

7.2 Variation of Transit Number with Radius

A method of measuring the variations of exit inventory number is to take samples of the transit number values of pebbles seeded at various radii at the top of the bed and to calculate properties of the transit number distributions. With the pebbles seeded in circular arrays at various radii for a particular seeding level (30 in.) five transit number distributions were found (one at each radius) for each pebble type. The mean and standard deviation of each of these distributions are listed in Table 1. The results show that in the vessel wall region, defined by a radius greater than 80 percent of bed radius (12 in.) both the mean transit number and the spread of the transit number distribution increase. This of course implies that if these data are to be used for prediction one must expect a large uncertainty for that region. Further, for aspherical pebbles the spread of the transit number distribution is greater than for spherical pebbles in the vessel wall region.

The exit inventory numbers for the first seven seedings were taken from Figure 5 and converted to transit numbers using Equation 1. These were plotted against radial seeding position (Figure 7) showing that there is very little difference between the transit numbers beyond the fifth seeding.

7.3 Attainment of Equilibrium

It was postulated that, at the beginning of the bed recirculation, the structure of the packing would change, resulting in a change of the transit number of any pebble seeded in a given spatial position in the bed (i.e. constant height and radial co-ordinates). It would therefore be possible to detect the equilibrium condition by measuring the transit number of pebbles successively seeded in the same spatial position in the bed, and to determine the inventory number at which the successive transit numbers attain a constant value. In practice this is done by obtaining the difference between successive transit numbers and determining when successive differences are similar or zero.

Since the transit number of a pebble repeatedly seeded at the same spatial position and at the same seeding inventory number in the recirculation procedure is not a single value, but is characterised by a distribution, the differences between successive radial sets of transit numbers were tested using the Kolmogorov-Smirnov test (for the subroutine used see Gatt 1968). This gives a measure of the similarity between two populations, usually expressed as a percentage. The larger the difference between the two populations the smaller will be their similarity. The test finds the maximum difference between the cumulative relative distribution functions of the samples of the two populations and accepts the hypothesis that the populations are identical if the above maximum difference is less than a critical value dictated by the significance level of the test. The population samples in this instance are the differences between successive radial sets of transit numbers. Each radial set is the average of three transit numbers, obtained from a group of three pebbles, seeded side by side.

It was thought possible that the inner part of the bed could reach an equilibrium state after the wall region. To check on this possibility the Kolmogorov-Smirnov test was applied over both 80 and 100 percent of the bed radius. The results of these tests appear in Tables 2 and 3, for 80 and 100 percent of bed radius respectively. It must be realised that for small sample size, errors may arise from application of the test but the sample size taken (the number of pebbles seeded across the bed radius) was the maximum achievable under the experimental conditions. In Tables 2 and 3, n is the seeding number (each seeding consisting of three straight adjacent rows of marked pebbles extending from the pebble bed centre radially to the vessel wall). The transit number at each radial position is the average of the group of three transit numbers at that radial position. The sets of differences between the successive radial seedings (n) and (n + 1) are designated n'. The test results show that the percentage similarity figures change at approximately the fifth seeding. Before this the similarity is below ten percent and after the fifth seeding it is above the ten percent level and continues generally at a higher level. This indicates that a change in the transit number and exit inventory number pattern has taken place at approximately the exit of the fifth seeding from the bed. Now the number of pebbles used to obtain this information is only three at each radial seeding position. In order to find the range of transit number over which the change could occur, use is made of the results of the transit number distribution obtained in the circumferentially seeded bed since the marked pebbles used in this experiment were seeded in the same horizontal plane as the fifth seeding in the radial experiment.

In the circumferential experiment many more seeded pebble samples were taken. The mean and standard deviation values of the distribution at five radial positions are given in Table 1. At the extreme seeding position in the bed (R = 14.5 inches) for both the 1.0 and 0.75 inch pebbles, an amount of recirculation equal to about 1.6 N and 2.8 N for spherical and aspherical pebbles respectively would be sufficient to achieve a reproducible transit number for the outer zone, and because of the much lower transit numbers elsewhere in the bed it would also ensure a reproducible transit number throughout the bed; that is, the above amount of recirculation would achieve equilibrium of the pebble bed.

It may be concluded from a comparison of Tables 2 and 3 that equilibrium occurs at the same exit inventory number within the volume enclosed by an 80 percent radial distance, as within the complete bed, since in both tests the change occurs at the exit of the fifth seeding. In both sets of results (Tables 2 and 3) the low similarity before the fifth seeding could be due to the change in the differences of successive path lengths of individual pebbles seeded at the same radial seeding position, but at a different level in the vessel. Another possible explanation could be the settling effect of the pebble bed, from an initial random packing to the arrangement occurring during recirculation.

7.4 Void Fraction

An estimate of the void fraction of each pebble bed was made as follows:

The volume of the right cylindrical portion of the pebble bed is given by

$$V_r = \pi D^2 H/4 ,$$

where D = the vessel diameter, and

H = the height of the cylindrical portion of the pebble bed at the start of recirculation.

The volume of each conical end of the pebble bed is given by

$$V_c = \pi \tan \theta \, D^3/24,$$

where θ = the base cone angle measured from the horizontal,

$\equiv$ the angle of repose of the pebbles of the top cone (25°, in this case).

An approximation (Murray 1966) to the number of pebbles in the base cone (Table 4) is taken by allowing 5 percent less effective volume, to account for void fraction increase immediately adjacent to the base cone surface.

The volume of each pebble is given by

$$V_p = \frac{\pi d^3}{6} \text{, in the spherical case,}$$

or

$$V_p = \frac{\pi d^3}{6} - \frac{\pi d^3}{40} \text{, in the aspherical case.}$$

The pebble bed void fraction is

$$\frac{V_r + 2\,V_c - NV_p}{V_r + 2\,V_c} ,$$

where N = the total number of pebbles in the pebble bed (Table 4).

Using the above equations, the void fraction of each bed before recirculation was calculated and listed in Table 4. The results show that the random packings were initially in a loose state and were closer to Bernal and Mason's (1960) "type two" random loose packings of void fraction 0.40, than their "type one" random close packings of void fraction 0.36.

It appeared during the experimental work that the void fraction following attainment of equilibrium was but little different from the initial void fraction. For this reason no specific measurements were made of the equilibrium void fraction itself.

7.5 Relationship Between Transit and Exit Inventory Numbers

For each pebble type an attempt was made to fit a curve to the exit inventory number and the transit number using as independent variables R, F and I_S. The shape of Figures 5 and 6 suggested an exponential dependence on R (Gatt 1967) together with a constant times the sum of F and I_S. The form of the expression used was

$$I_E = a_1 + a_2 (F + I_S) + a_3 \exp(a_4 R), \quad (2)$$

where a_1, a_2, and a_3 are non-dimensional coefficients and a_4 is a coefficient having dimension inches^{-1}.

Substituting in Equation 1,

$$T = a_1 + I_S (a_2 - 1) + a_2 F + a_3 \exp(a_4 R). \qquad (3)$$

Initially all twelve seedings of each pebble type were curve fitted using a digital computer program by Sampson (undated) with an expression of the form of Equation 2. However the errors between the actual and calculated values were too large. Each set of twelve seedings was then divided into two sets, to each of which was fitted a curve of similar form, thereby increasing the curve fitting accuracy. The points at which the original twelve sets of each pebble type should be divided were found by trial and error testing for a good fit. The first three and last ten sets of one inch spherical values were fitted separately to Equation 2, while with the other three pebble types the first two and last eleven sets were fitted separately. The coefficients for each pebble type are given in Table 5.

An examination of the resulting values using the above coefficients shows that most errors between actual and calculated values occur in the vessel wall region. The maximum absolute error for each set of coefficients is given in Table 6 together with the corresponding percentage absolute error. Figure 8 shows a comparison between the measured transit numbers and those numbers calculated using Equation 3 for the first and fifth seeding with 1.00 in. spherical pebbles.

8. CONCLUSIONS

The amount of recirculation required to achieve constant pebble transit number in the pebble bed randomly packed with 1.00 in. or 0.75 in. diameter pebbles, is approximately 1.6 times the bed inventory for the spherical pebble, and 2.8 times the bed inventory for the aspherical pebble. The change in size (1.00 in. and 0.75 in.) of the pebbles appears to have very little effect on the amount of recirculation required to achieve constant pebble transit number.

After equilibrium occurs, the average number of pebbles required to be recirculated before a particular pebble seeded at the top of the bed emerges, is approximately equal to one bed inventory. However, individual pebbles seeded near the centre of the pebble bed emerge with a smaller transit number than those at the wall. It is possible that pebbles seeded near the centre of the bed travel relatively straight paths through the pipe zone to the extractor with a small scatter (or standard deviation) of transit numbers, while those seeded in the wall region follow many different paths. Some would be short, with movement almost directly across to the pipe zone (Figure 2); some would be long, extending down the vessel wall and across the base cone, with a large standard deviation of transit numbers.

The expressions relating exit inventory number of the bed and transit number of a particular pebble, with the radial position of the particular pebble in the bed can be used to predict the amount of recirculation required for a particular pebble seeded anywhere in the bed to pass completely or partially through the bed.

There is no noticeable difference between the amount of recirculation required to achieve equilibrium in the inner core of the bed (within 80 percent radius) and the amount required for the whole of the bed.

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11. NOTATION

a_1, a_2, a_3, a_4,	– Coefficients used in the transit number and inventory number expressions
d	– Nominal pebble diameter
D	– Vessel diameter
F	– Seeding inventory, the number of pebbles in the pebble bed beneath the horizontal seeding plane of the particular pebble, expressed as a fraction of the bed inventory
H	– Height of the cylindrical portion of the pebble bed at the start of recirculation
I	– Inventory number of a pebble bed, defined as the number of pebbles recirculated from the commencement of the initial recirculation of the pebble bed to the occurrence of a particular event expressed as a fraction of the bed inventory.
I_S	– The inventory number of the pebble bed at the seeding of the particular pebble
I_E	– The inventory number of the pebble bed at the exit of the particular pebble
N	– Bed inventory, defined as the total number of pebbles in the pebble bed
n	– Seeding number of each radial seeding
n'	– Sets of differences between seeding number n and seeding number n + 1
R	– Radius of seeded pebble from the bed centre line (inches)
T	– Transit number of a particular pebble, defined as the number of pebbles recirculated between the seeding of that pebble and its exit from the pebble bed, expressed as a fraction of the bed inventory

V_c	–	Volume of each conical end of the pebble bed
V_p	–	Volume of each pebble
V_r	–	Volume of the right cylindrical portion of the pebble bed
θ	–	Base cone angle measured from the horizontal

TABLE 1

MEAN TRANSIT NUMBERS FOR VARIOUS SEEDING RADII AT A PARTICULAR SEEDING LEVEL

Pebble Type \ Seeding Radius	3.0 in.	6.0 in.	9.0 in.	12.0 in.	14.5 in.
1.00 in. Spherical	0.62 (0.013)	0.65 (0.015)	0.73 (0.022)	0.92 (0.050)	1.35 (0.138)
0.75 in. Spherical	0.62 (0.010)	0.67 (0.014)	0.77 (0.027)	0.97 (0.075)	1.57 (0.245)
1.00 in. Aspherical	0.49 (0.008)	0.51 (0.010)	0.59 (0.017)	0.84 (0.080)	2.79 (0.995)
0.75 in. Aspherical	0.53 (0.008)	0.56 (0.012)	0.65 (0.023)	0.88 (0.055)	2.77 (1.33)

Standard deviation values are in brackets, e.g. for line 1, radius 12.0 inches, T = 0.92: approximately 33 percent of all pebbles will have transit numbers outside the limits 0.87 and 0.97 if the transit number distribution is a normal distribution.

NOTE: The above transit number values are for pebbles seeded on a horizontal plane at 30 inches cylindrical bed height (29 inches in the case of 1.00 in. spherical) in an unrecirculated randomly packed bed.

TABLE 2

RESULTS OF KOLMOGOROV–SMIRNOV TEST

OVER 80 PERCENT OF BED RADIUS

Seeding Number n	Differences Between Seedings n and n + 1 (n')	Percentage Significance Level of Similarity for Seeding Differences			
		Spherical		Aspherical	
		1.00 in.	0.75 in.	1.00 in.	0.75 in.
1					
	1'				
2		3	0	0	0
	2'				
3		0	0	0	0
	3'				
4		0	0	1	0
	4'				
5		85	0	10	21
	5'				
6		85	0	10	9
	6'				
7		85	21	25	42
	7'				
8		85	9	100	70
	8'				
9		3	0	25	4
	9'				
10		85	42	85	21
	10'				
11		0	70	100	0
	11'				
12					

TABLE 3

RESULTS OF KOLMOGOROV–SMIRNOV TEST

OVER 100 PERCENT OF BED RADIUS

Seeding Number n	Differences Between Seedings n and n + 1 (n')	Percentage Significance Level of Similarity for Seeding Differences			
		Spherical		Aspherical	
		1.00 in.	0.75 in.	1.00 in.	0.75 in.
1					
	1'				
2		8	1	1	0
	2'				
3		0	0	0	0
	3'				
4		0	0	8	8
	4'				
5		93	3	1	3
	5'				
6		18	8	66	17
	6'				
7		38	17	93	82
	7'				
8		93	33	66	33
	8'				
9		8	0	93	1
	9'				
10		18	56	66	33
	10'				
11		0	98	66	3
	11'				
12					

TABLE 4

PEBBLE, SEEDING AND VOID FRACTION DATA

Pebble Type	1.00 in. Spherical	0.75 in. Spherical	1.00 in. Aspherical	0.75 in. Aspherical
Total number of pebbles in each bed, N	28.0×10^3	68.0×10^3	34.0×10^3	79.0×10^3
Number of pebbles between each seeding	5.8×10^3	14.2×10^3	7.2×10^3	16.2×10^3
Number of pebbles in top cone (estimated)	2.0×10^3	4.6×10^3	2.3×10^3	5.4×10^3
Number of pebbles in base cone (estimated)	1.84×10^3	4.35×10^3	2.17×10^3	5.1×10^3
Individual pebble volume V_p (in^3)	0.52	0.22	0.45	0.19
Mean initial void fraction of bed	0.38	0.39	0.38	0.39

TABLE 5

COEFFICIENTS FOR EXIT INVENTORY NUMBER AND TRANSIT NUMBER EXPRESSIONS

Pebble Type	Seeding Numbers n	Coefficients			
		a_1	a_2	a_3	a_4
1.00 in.	1–3	–0.06678	0.46875	0.016231	0.26516
Spherical	3–12	–0.37766	1.0436	0.01018	0.31208
0.75 in.	1–2	–0.03114	0.22975	0.0075525	0.35612
Spherical	2–12	–0.27869	0.89619	0.00048947	0.53289
1.00 in.	1–2	–0.062799	0.75617	0.00022811	0.61129
Aspherical	2–12	–0.21904	0.91906	0.000065251	0.6946
0.75 in.	1–2	–0.035636	0.47035	0.007715	0.28456
Aspherical	2–12	–0.21431	1.0065	0.0030884	0.36783

The coefficients in this table are to be used in Equations 2 and 3.

TABLE 6

ERRORS FOR EXIT INVENTORY NUMBER EXPRESSION

Pebble Type	Seeding Numbers n	Maximum Absolute Error	Corresponding Percentage Absolute Error
1.00 in.	1–3	0.18	34
Spherical	3–12	0.22	8
0.75 in.	1–2	0.61	35
Spherical	2–12	0.34	29
1.00 in.	1–2	0.66	29
Aspherical	2–12	0.83	63
0.75 in.	1–2	0.13	22
Aspherical	2–12	0.20	9

The errors listed in this table are calculated from Equation 2.

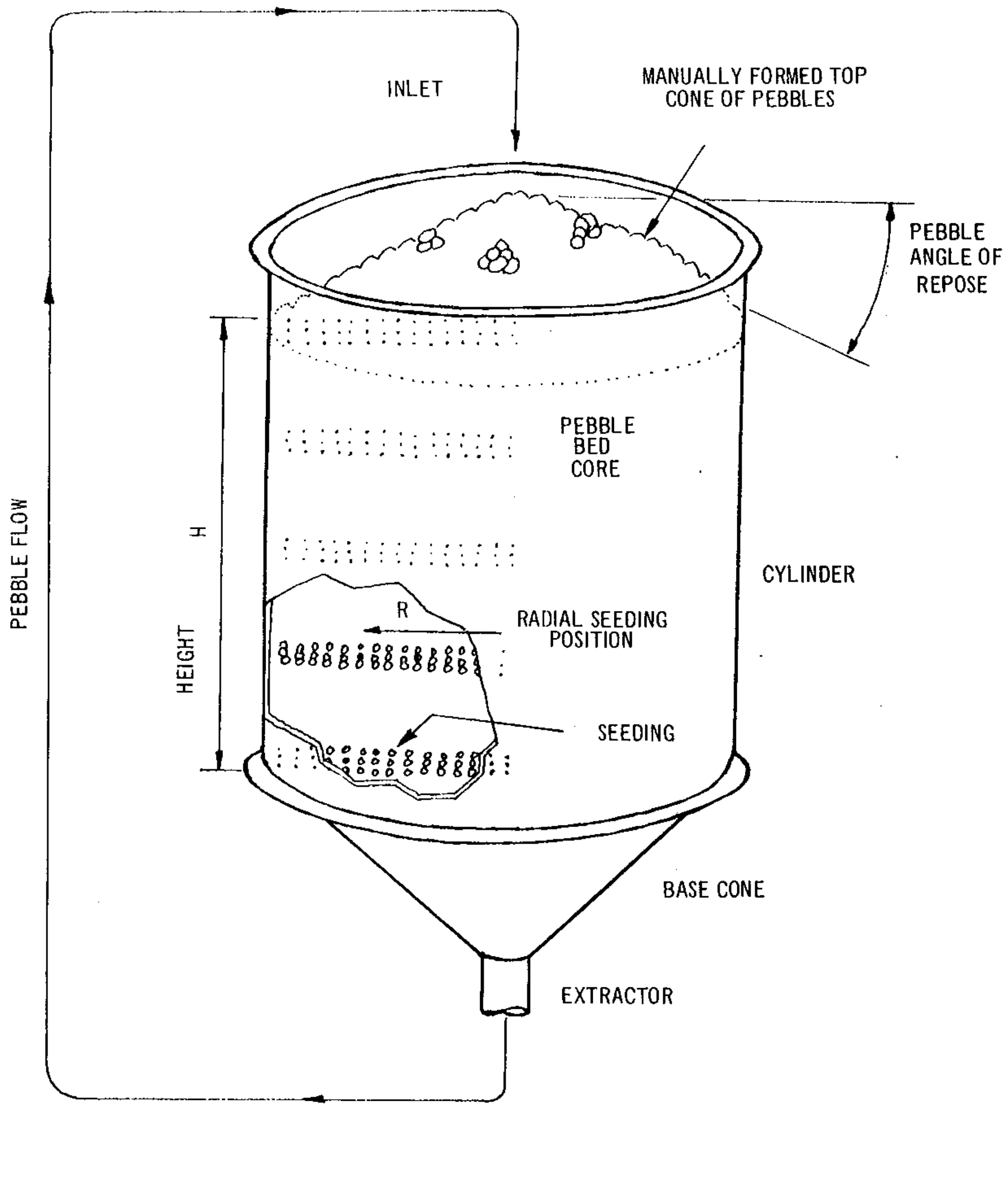

FIGURE 1. SKETCH OF PEBBLE BED NUCLEAR REACTOR SHOWING FULLY SEEDED PEBBLE BED BEFORE RECIRCULATION

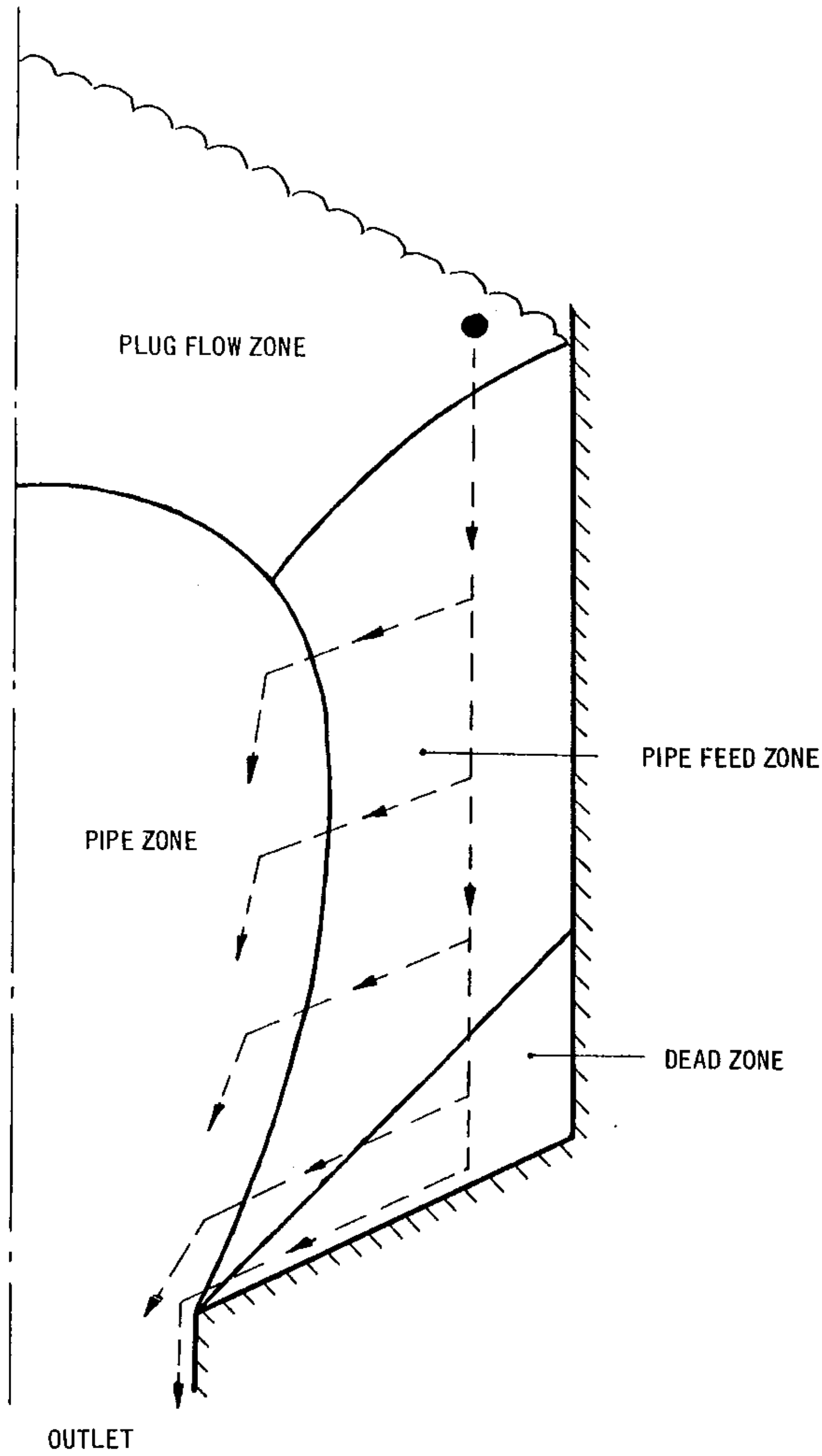

FIGURE 2. ASSUMED PEBBLE PATHS IN WALL REGION AND FLOW ZONES

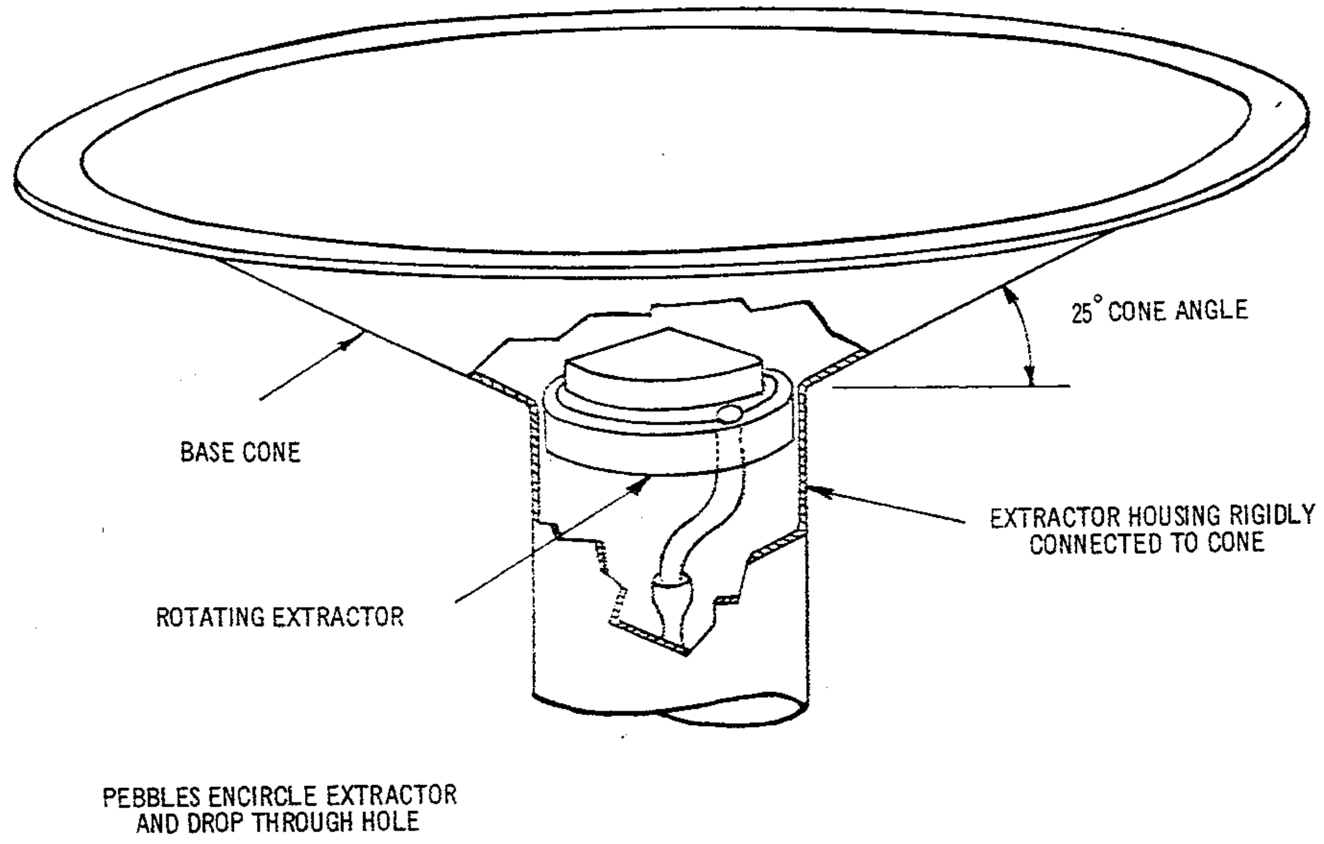

FIGURE 3. EXTRACTOR AND CONE

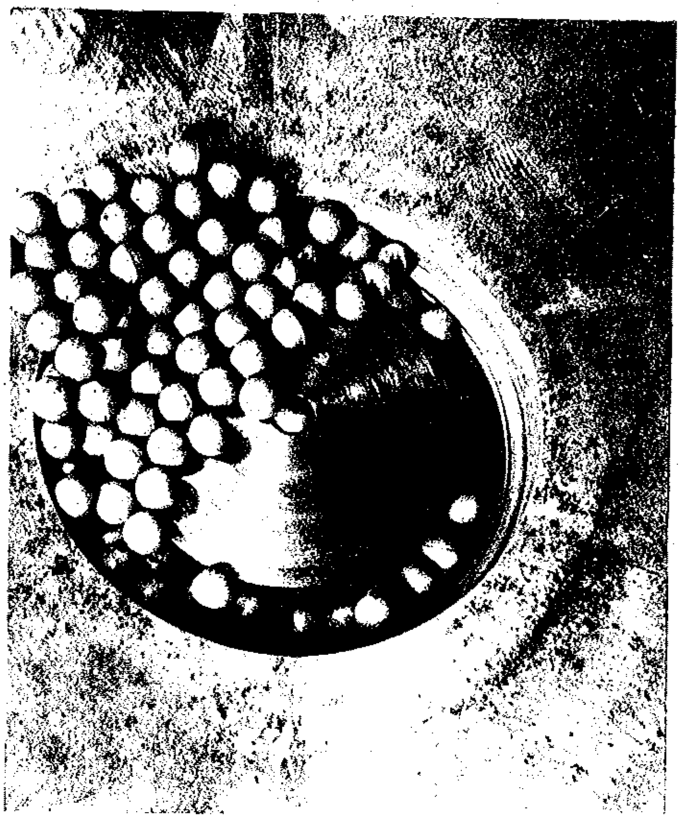

FIGURE 4. EXTRACTOR SHOWING OUTLET AND 0.75 INCH DIAMETER SPHERICAL PEBBLES

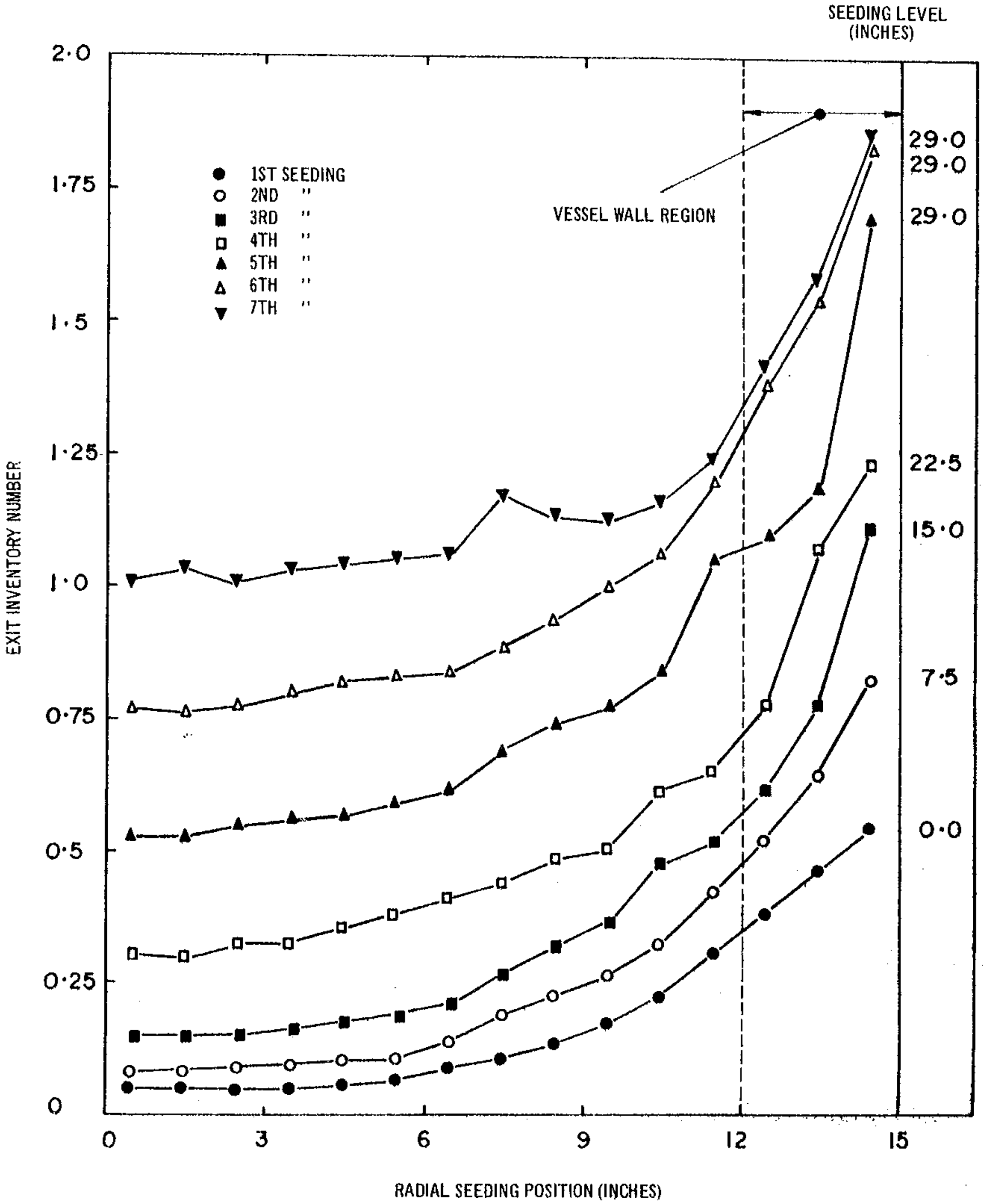

FIGURE 5. EXIT INVENTORY NUMBER VERSUS RADIAL SEEDING POSITION FOR FIRST SEVEN SEEDINGS WITH 1.00 INCH SPHERICAL PEBBLES

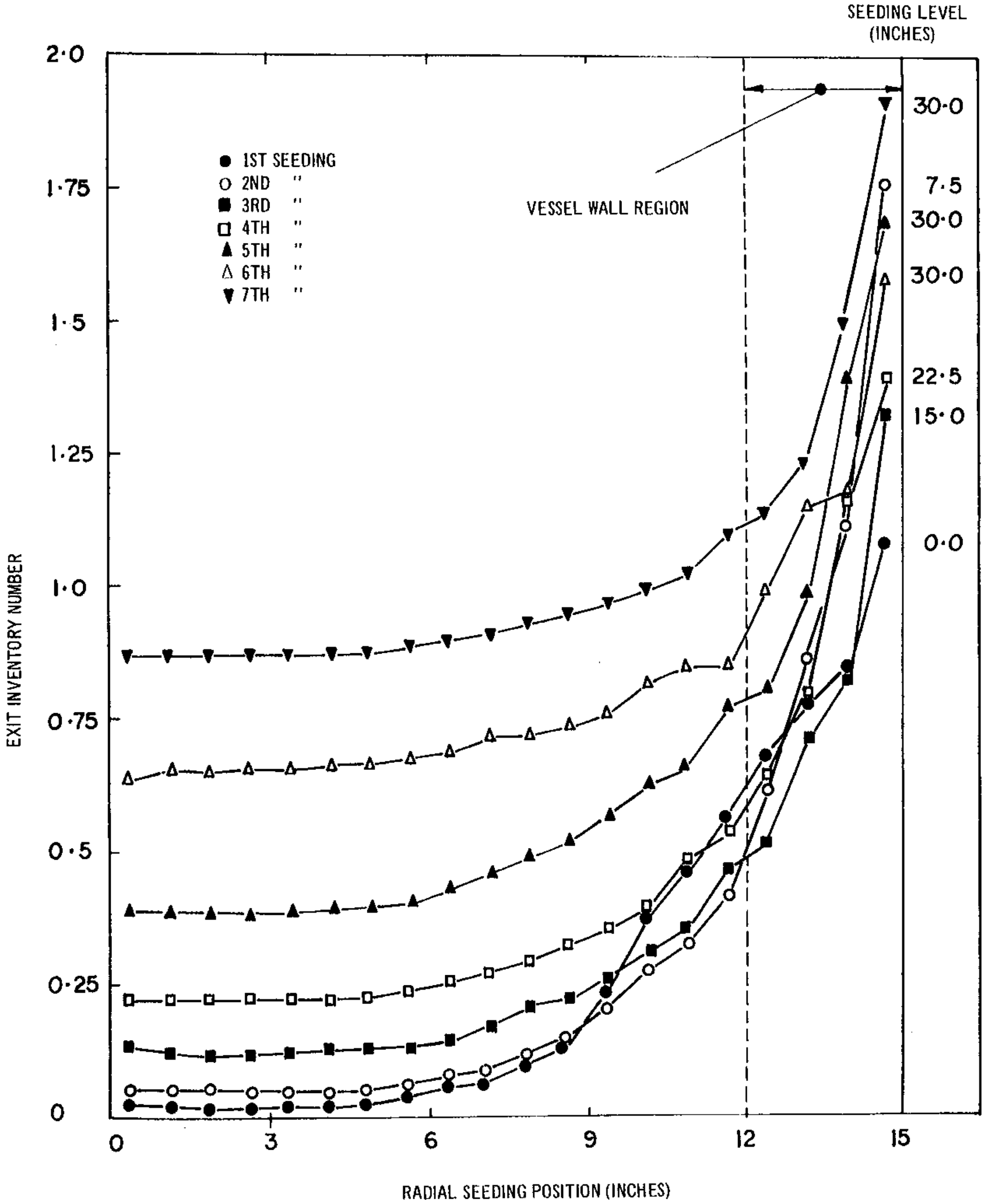

FIGURE 6. EXIT INVENTORY NUMBER VERSUS RADIAL SEEDING POSITION FOR FIRST SEVEN SEEDINGS WITH 0.75 INCH SPHERICAL PEBBLES

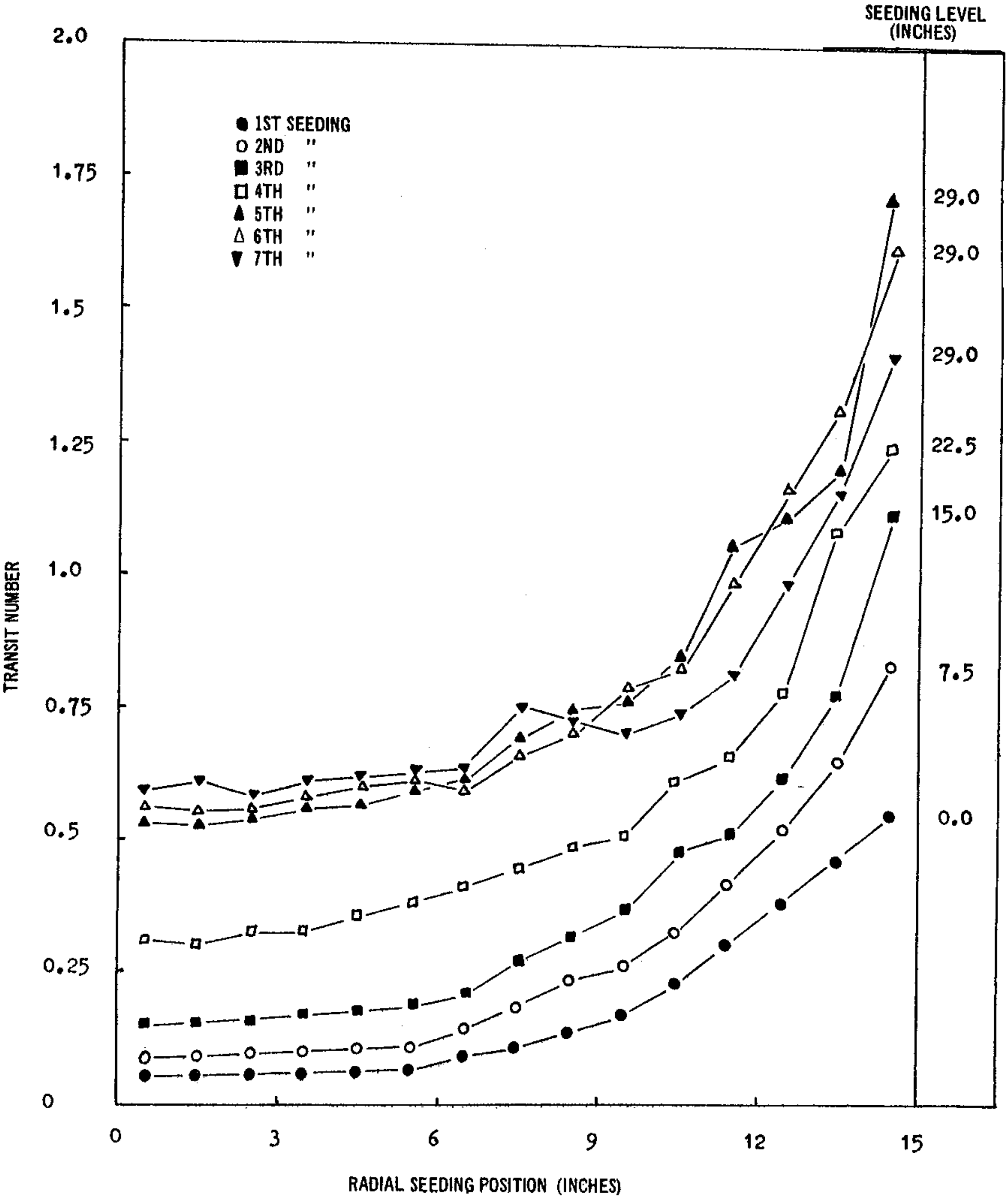

FIGURE 7. TRANSIT NUMBER VERSUS RADIAL SEEDING POSITION FOR FIRST SEVEN SEEDINGS WITH 1.00 INCH SPHERICAL PEBBLES

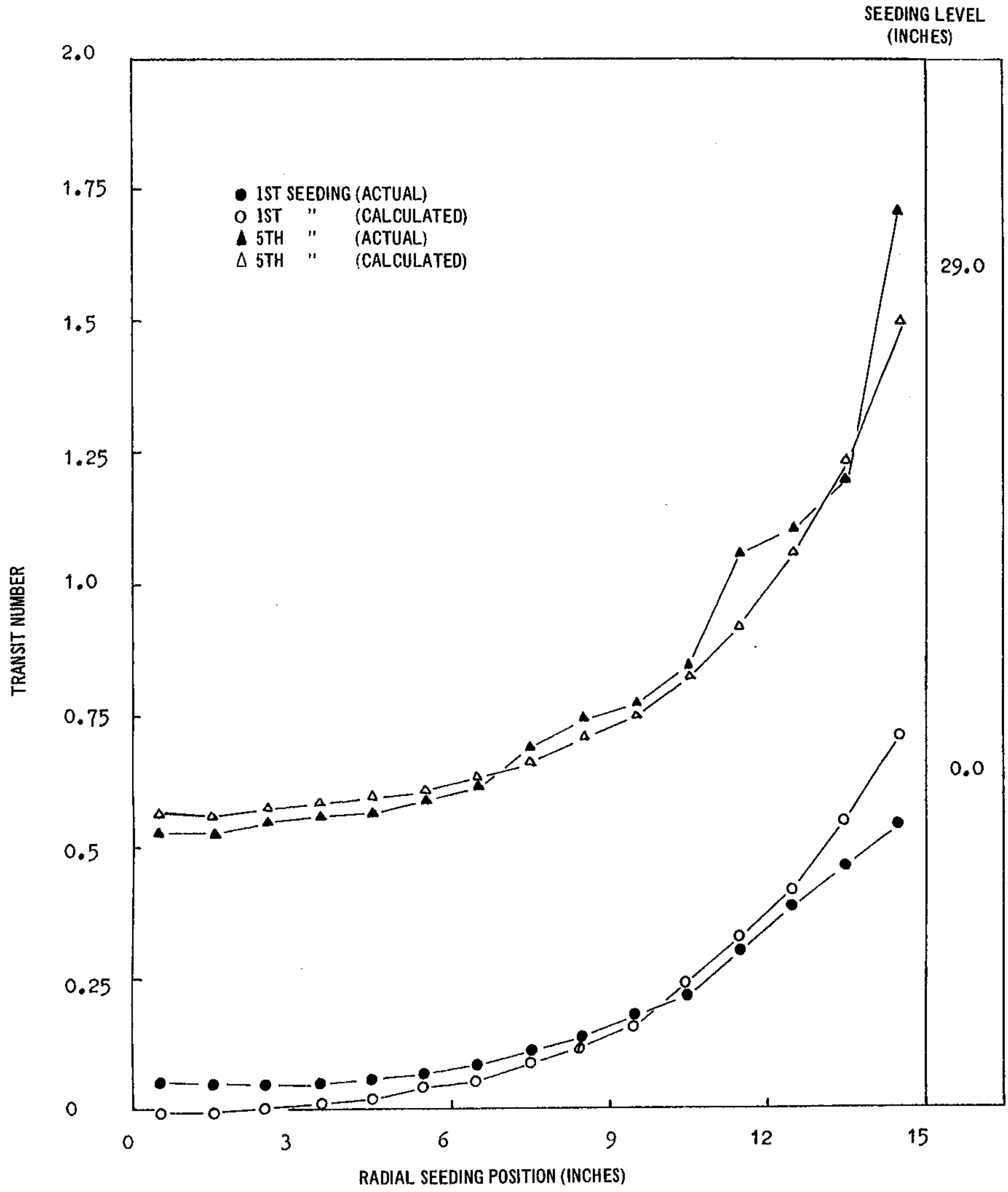

FIGURE 8. COMPARISON OF ACTUAL TRANSIT NUMBERS, AND TRANSIT NUMBERS CALCULATED USING EQUATION 3 FOR FIRST AND FIFTH SEEDINGS WITH 1.00 INCH SPHERICAL PEBBLES