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AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT

LUCAS HEIGHTS, N.S.W.

SYMPOSIUM

on

MOVEMENT OF GRANULAR MATERIAL

and

STRUCTURE, FLUID FLOW AND HEAT TRANSFER IN PACKED BEDS

February 16 – 17, 1967

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Programme and Abstracts of Papers

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GENERAL INFORMATION

PURPOSE: The Research Establishment has acquired a considerable amount of experimental information on the movement of granular material and on the structure, fluid flow and heat transfer in random and ordered packings of spheres and some information on non-spherical shapes. The Commission believes that this work will undoubtedly prove to be of wide interest in the many fields of Engineering and Applied Science. (Chemical reactors, pebble bed heaters and stores, water filters, soil mechanics, concrete structure, rock hoppers, silos, etc.).

The object of the Symposium is to ensure efficient dissemination of the Commission's work to scientists and engineers in Government Departments, Industrial Organizations and Universities and that the relevant work of other people is properly related to the Commission's efforts.

LOCATION: The Symposium will be held at the Commission's Research Establishment, Lucas Heights (approximately 20 miles south of Sydney near the town of Sutherland).

ACCOMMODATION AND TRANSPORT: Accommodation can be provided at Stevens Hall (the Commission's hostel at Lucas Heights. Bed and Breakfast, $4.50 per day). Arrangements will be made to transport Delegates from Sydney airport to Lucas Heights.

REGISTRATION: There will be a registration fee of $2.00 (payable at the Symposium).

PARTICIPATION: Attendance is open to all interested persons, but primarily the Symposium is to afford an opportunity to scientists and engineers actively engaged in the field to present and discuss their technical work.

PROCEEDINGS: Each contributor will be allowed 25 minutes (includes time for discussion) for oral presentation of the substance of his paper. Facilities for projection of slides are available (either 2" x 2" or 2¼" x 2¼"). There will be no formal publication of the Proceedings, but it is intended to publish a paper summarizing the main findings of the Symposium.

RECEPTION: The Acting Director of the Research Establishment extends an invitation to Delegates to attend a buffet dinner at Stevens Hall on Thursday, February 16 (5.45 p.m. for 6.30 p.m.).

ENQUIRIES: Enquiries should be addressed to the Symposium Secretary, Mr. J. L. Deegan, at the following address:-

A.A.E.C. Research Establishment,
Private Mail Bag,
Sutherland. N.S.W. (Telephone: 531.0111)

PROGRAMME

Thursday, February 16

9.30 - 10.00 a.m.	Registration and Morning Tea.
10.00 - 10.05	Welcoming address (Mr. G. Page, Acting Director of the Research Establishment).

SESSION NO. 1

(Chairman: Mr. G.W.K. Ford, A.A.E.C.)

10.05 - 10.30 (Paper 1.1)	Investigation on the Movement of Balls in a Pebble Bed Reactor. Dr. C.B. von der Decken (Brown Boveri/ Krupp Reaktorbau G.m.b.H., West Germany).
10.30 - 10.45	Disucssion.
10.45 - 11.10 (Paper 1.2)	Outline of the Commission's Pebble Bed Reactor Engineering Research Programme. Mr. E. Szomanski (A.A.E.C.)
11.10 - 1.10	Pebble Flow and Bed Structure (Papers 1.3 - 1.9).
11.10 - 11.25 (Paper 1.3)	Some Studies of Structure and Friction in Static Beds. Mr. F. A. Rocke (A.A.E.C.)
11.25 - 11.40 (Paper 1.4)	Parameters Influencing the Flow of Packings of Spheres and Near-Spheres in Cylindrical Vessels. Mr. G. A. Tingate (A.A.E.C.)
11.40 - 11.50 (Paper 1.5)	A Simple Mathematical Model of the Random Packing of Spheres in a Cylindrical Container. Mr. N. W. Ridgway (A.A.E.C.)
NOTE:	This paper will be presented by Mr. G. A. Tingate (A.A.E.C.)

(continued)

11.50 - 12.05 (Paper 1.6)	Some Geometrical Properties of Randomly Packed Beds of Spheres in Cylindrical Containers. Mr. G. A. Tingate (A.A.E.C.)
12.05 - 12.15 (Paper 1.7)	Some Interim Results of First Factorial Pebble Bed Experiments. Mr. F. C. Gatt (A.A.E.C.)
12.15 - 12.30 (Paper 1.8)	Development of a Gamma Radiation Attenuation Technique to Measure Voidage in Packed Beds. Mr. G. Saiva (A.A.E.C.)
12.30 - 12.45 (Paper 1.9)	Fluid Velocity Distributions for Randomly Packed Beds of Spheres. Mr. J. Price (A.A.E.C.)
12.45 - 1.10	Discussion. (Papers 1.2 - 1.9).
1.10 - 2.05	Lunch (A.S.C.O. Canteen).

SESSION NO. 2

2.15 - 4.15	Visit to the Engineering Research Laboratories. (Building No. 3). The following experiments and equipment will be on display:- (i) Bend Scale Experiments. (ii) Voidage Measurement. (iii) Water Tunnel. (iv) Velocity Distribution. (v) Local and Average Heat Transfer. (vi) Main Pebble Bed Reactor Experiment. (vii) Thermal Shock Model.
4.15 - 4.30	Afternoon Tea (Conference Room, Building 3).
4.30 - 5.30	Discussion of any aspects of the visit. (A Panel of Commission staff will be available to answer any questions).
5.45 (for 6.30 p.m.)	Buffet Dinner in Stevens Hall (Delegates will be the guests of the Acting Director of the Research Establishment).

(continued)

Friday, February 17

SESSION NO. 3

(Chairman: Mr. R. V. Dunkle, Division of Mechanical Engineering, C.S.I.R.O., Melbourne)

NOTE: The 25 minutes allowed for the presentation of each paper, includes time for discussion.

9.00 - 9.25 (Paper 3.1)

A Method of Studying Ball Flow by Digital Computer. Mr. N.W. Bennett (A.A.E.C.)

9.25 - 9.50 (Paper 3.2)

Segregation Studies in a Model Hopper of Granular Feed for Zinc-Lead Sintering. Mr. M. G. Taverner (Sulphide Corp. Pty. Ltd.

9.50 - 10.15 (Paper 3.3)

Flow of Granular Materials from Silos. Mr. G.P. Deutsch (Department of Civil Engineering, University of Melbourne).

10.15 - 10.40 (Paper 3.4)

Deposition of Small Particles from Turbulent Flow in Gas Streams. Messrs. T.Kneen and W. Strauss (Department of Chemical Engineering, University of Melbourne).

10.40 - 11.00

Morning Tea.

11.05 - 11.30 (Paper 3.5)

Development of the Fluid-Lift-Solids Recirculator. Mr. C. H. Hunt Department of Chemical Engineering, University of New South Wales).

11.30 - 11.55 (Paper 3.6)

Effect of Nozzle Design on Start Up of the Fluid-Lift-Solids Recirculator. Mr. R. J. Ring (Department of Chemical Engineering, University of New South Wales).

11.55 - 12.20 (Paper 3.7)

Load/Deformation Behaviour of Compacted Aggregates. Mr. C. G. Bennett (Department of Mining and Metallurgical Engineering, University of Queensland).

(continued)

12.20 - 12.45 (Paper 3.8)

Pressures on the Walls of Silos. Mr. G. P. Deutsch (Department of Civil Engineering, University of Melbourne).

12.45 - 1.35

Lunch (A.S.C.O. Canteen).

SESSION NO. 4

(Chairman: Mr. E. Szomanski, A.A.E.C.)

NOTE: The 25 minutes allowed for the presentation of each paper, includes time for discussion.

1.40 - 2.05 (Paper 4.1)

Transient Response of Packed Beds According to the Finite State Model. Mr. C. P. Jeffreson (Department of Chemical Engineering, University of Adelaide).

2.05 - 2.30 (Paper 4.2)

The Role of Axial Dispersion in Heat Transfer in Beds of Textile Fibres. Dr. P. Nordon (Division of Textile Physics, C.S.I.R.O., Ryde, N.S.W.).

2.30 - 2.55 (Paper 4.3)

Heat and Mass Transfer of Drying Granular Materials in Roto-Louvre Dryers. Dr. O. Myklestad (Division of Food Preservation, C.S.I.R.O., Ryde, N.S.W.).

2.55 - 3.15

Afternoon Tea.

3.20 - 3.45 (Paper 4.4)

Design Charts for Gravel Bed Heat Exchangers, Heat Storages and Evaporative Coolers. Mr. R. V. Dunkle (Division of Mechanical Engineering, C.S.I.R.O., Highett, Victoria).

3.45 - 4.10 (Paper 4.5)

Resistance to Air Flow of Packed Beds of Coke. Dr. P. L. Waters (Division of Coal Research, C.S.I.R.O., North Ryde, N.S.W.).

4.10 - 4.30

General Discussion.

4.30 - 4.45

Closing address. (Mr. G.W.K. Ford, A.A.E.C.).

ABSTRACTS

SESSION NO.1

1.1 Investigation on the Movement of Balls in a Pebble Bed Reactor
Dr. C.B. von der Decken (Brown Boveri/Krupp Reaktorbau G.m.b.H. West Germany)

(This abstract will be distributed to Delegates at the Symposium.)

1.2 Outline of the Commission's Pebble Bed Reactor Engineering Research Programme. Mr. E. Szomanski (A.A.E.C.)

(A preprint of this paper will be posted to Delegates.)

1.3 Some Studies of Structure and Friction in Static Beds.
Mr. F.A. Rocke (A.A.E.C.)

1. CYLINDRICALLY ORDERED ARRAYS OF EQUAL SPHERES

1.1 Preparation of Beds

Dense cylindrical shells of hexagonally ordered spheres tend to form peripherally in any packing in a vertical cylindrical vessel. With certain special shapes of vessel base, arrays consisting entirely of such shells were found to be self-forming under torsional agitation or linear vibration parallel to the cylinder axis, up to vessel-to-ball diameter ratio 40. The base may be a smooth or stepped 27° convex cone, a stepped 27° concave cone, or a flat ring-grooved plate.

1.2 Structure

A free (horizontal) surface consists of alternately raised and depressed concentric rings of spheres. The alignment of spheres in a ring is wave-like radially and axially, with period 1/5th or 1/6th of the ring circumference, this alignment being related to the ideal base cone angle of 27°. In general, there are gaps between some of the spheres in a ring.

The mean centre-to-centre vertical spacing of spheres in a shell is $\sim$ 1 per cent greater than that in a close-packed two-dimensional hexagonal array.

1.3 Voidage

Fully ordered beds formed with steel balls had $\sim$ 0.5 per cent vacancies. The mean voidage, for infinite axial length but including wall effect, and uncorrected for vacancies, is shown as a function of diameter ratio in Table 1. Ball surface friction had no significant effect on the voidage.

Table 1: Diameter Ratio and Voidage

Diameter Ratio	7.5	11.5	19.0	24.0	30.6	38.0
Voidage, %	36.6	33.7	32.3	31.8	31.3	30.6

1.4 Fluid Flow Characteristics

A bed with diameter ratio 24 and mean voidage 32 per cent had a flatter downstream velocity profile, and a friction factor about 10 per cent lower, than that of a comparable rhombohedrally packed bed with mean voidage 33 per cent.

1.5 Friction and Mobility

A longitudinally split vessel was used to simulate thermal cycling between room temperature and about 1200°C, with zero temperature gradient, of a bed of beryllium oxide spheres in an Inconel vessel. Friction effects were studied by using dry blued, dry bright and oil bright steel balls. No significant geometrical irreversibility was observed with these balls after repeated cycling. The ratio of the maximum restoring force (F) required to close the vessel halves to the theoretical value (F_o) for the frictionless (hydrostatic) case, with static and vibrating beds, is shown in Table 2.

Table 2: Values of F / F_o

	Static Bed	Vibrating Bed
Dry Blued	3.1	1.3
Dry Bright	2.2	1
Oily Bright	1.8	1

2. RANDOM ARRAYS OF EQUAL SPHERES

2.1 Geometrical Variables

Theoretical distribution functions ("spectra") were derived for randomly arrayed spheres with respect to the following variables:

(i) Length of chord on intersecting straight line,

(ii) diameter of exposed circle on intersecting plane, and

(iii) area of circle in (ii).

Experiment was in good agreement with theory, and suggests the use of "spectral" analysis to detect residual ordering in apparently random arrays. Ball counting was used in conjunction with the theoretical mean of the chord length to estimate voidage.

2.2 Friction and Voidage

Dry blued and oily bright steel balls were used with a standard vessel-loading procedure to determine the effect of friction on voidage. The means of the voidage (including wall effect) for ten trials in each case were 41.90 $\pm$ 0.03 per cent and 40.07 $\pm$ 0.04 per cent respectively for the above surfaces.

1.4 Parameters Influencing the Flow of Packings of Spheres and Near-Spheres in Cylindrical Vessels. Mr. G.A. Tingate (A.A.E.C.)

1. INTRODUCTION

The study of flow patterns in random packings is complicated, from the start, by the unknown and perhaps varying nature of its structure. Beds with dense concentric shells offer a way around this difficulty in that their structure is known at the commencement of flow and, in general, for the duration of the flow.

The slides accompanying this paper have been arranged in most cases to show the flow patterns for various packings in the same vessel. The dense concentric shell packing is used as the reference packing in each case.

The photographs on which the accompanying slides were based were taken on the pilot ball flow visualisation rig, which will be on display in the laboratory.

2. EXPERIMENTS

A wide range of extreme effects has been investigated, and the parameters investigated are listed in Appendix I. In general,

continuity has been found from dense concentric packings of precise spheres, through dense concentric packings of less precise ballotini, to random packings of precise spheres and ballotini. This trend will be brought out in the slides presented.

3. RESULTS

3.1 The following parameters have found to have a major effect on the pebble flow pattern.

(i) Packing height to diameter ratio

(ii) Hopper angle

(iii) Initial packing

(iv) Precision and uniformity of spherical shape of pebbles

(v) Gas upflow.

3.2 Little or no indication has been found of effect of any other parameters, including the following which might have been expected to play an important role -

(vi) Presence or absence of (lubricating) fluid

(vii) Pebble recirculation rate (no significant effect from 1 ball every 2 minutes to 50,000 per minute

(viii) Frequent interruptions of flow.

3.3 The following mechanisms have been isolated as having an important bearing on pebble flow:-

(i) Existence of running clearances wherever drag would otherwise occur (most evident in the case of dense concentric shells)

(ii) "Biting" of moving ball on stationary ball (e.g. at top of dead zone), and apparent lack of "bite" of moving ball on moving ball. The latter is possibly attributable to rotation of both moving balls.

(iii) Segregation of small balls from large at top of dead zone when two discrete ball sizes are used.

(iv) Transmission of upward thrust from hopper to an indefinite height with perfect, dense, concentric shells.

(v) Very limited transmission of upward thrust from hopper with random packings. This is limited to the dead zone, of height normally of the same order as the diameter of the vessel. The dead zone can be extended by the formation of dense stationary concentric shells in special cases.

4. RELEVANCE OF RESULTS TO THE DESIGN OF A PEBBLE BED NUCLEAR REACTOR

Several extreme effects were found which could jeopardise the behaviour of a pebble bed nuclear reactor. In most instances, considerable departures had to be made from the proposed reactor configuration to make the extreme effects show themselves. With a bed height to diameter ratio (H/D_v) of 1 (measured over cylindrical portion of bed) and a 35^o downward sloping cone, a satisfactory velocity profile was obtained throughout the bed, viz. a wall-to-centre residence time ratio of about 1.7 : 1. When the H/D_v ratio was reduced to 0.6, the residence time ratio deteriorated to 3 : 1, but was improved to an acceptable 2 : 1 by using a 45^o hopper.

With precise uniform spheres, close packed regular zones were observed to form in the outer cylindrical layer, but this was not accompanied by any increase in the wall-to-centre residence time ratio.

Appendix I - Pebble parameters and values selected

Parameter	Pebble bed reactor (PBR)	Main PBR experiment	Bench scale experiments
Pebble shape and material	Spherical or near spherical beryllium oxide matrix fuel element	Spherical and non-spherical (polar diameter =0.9xequatorial diameter) bonded pressed sand.	Spherical high precision steel Spherical ground glass Spherical commercial nylon Round glass ballotini
Nominal pebble diameter, Dp	1" ± 0.02"	0.75" ± 0.011" 1.00" ± 0.015"	Steel: 0.1250" ± 0.0002" 0.1875" ± 0.0002" 0.2500" ± 0.0002" Ground glass: 3.00mm ± 0.01 mm Nylon: 0.2435" ± 0.0015" Glass ballotini: 0.2mm ± 0.05mm 2.0mm ± 0.02mm 3.00mm ± 0.015mm
Specific gravity of pebble material	3.10 ± 0.03	3.00 ± 0.06 3.40 ± 0.07	Steel: 7.9 Glass: 2.5 Nylon: 1.3
Surface roughness	± 0.00003"	± 0.0005"	Not determined
Coefficient of friction (arbitrary units) at ambient temperature	1.3	1.0 2.0	Not determined

Appendix II - Bed parameters and values selected

Parameter	Pebble bed reactor (PBR)	Main PBR Experiment	Bench scale Experiments
Vessel diameter D_v	12.5'	30"	1" - 18"
Bed height, H (measured over cylindrical portion of packing)	9.5'	24" 30"	1" - 72"
H/D_v ratio	0.76 : 1	0.8 : 1 1 : 1	0.6 : 1 - 50 : 1
Vessel-to-pebble diameter ratio D_v/D_p	150:1	30 : 1 40 : 1	8 : 1 - 70 : 1
Number of outlet hoppers	7	1	1 7
Outlet hopper Shape	Hexagonal pyramid	Cone Hexagonal Pyramid	Cone
Outlet hopper angle *	To be determined	15^o, 25^o, 35^o, 45^o,	-27^o, -23.5^o, 0^o, 10^o, 15^o, 20^o, 23.5^o, 27^o, 30^o, 35^o, 45^o.
Vessel-to-outlet diameter ratio, D_v/D_p	To be determined	3.75 : 1 6 : 1	1.04 : 1 - 6 : 1
Outlet-to-pebble diameter ratio D_o/D_p	To be determined	5 : 1 6.67 : 1 8 : 1 10.67: 1	4.75 : 1 - 25 : 1
Control rods or equivalent internal surfaces	To be determined	Present Absent	Present Absent
Number of balls in bed	2,330,000 at 1"	75,000 at 3/4" 30,000 at 1"	10,000 - 500,000

* NOTE: Angle is measured with respect to the horizontal. A negative angle is one sloping upwards to the outlet.

Appendix II - Bed parameters and values selected - (Cont'd.)

Parameter	Pebble bed reactor (PBR)	Main PBR Experiment	Bench Scale Experiments
Bed Preparation method	To be determined	Bulk loading without free fall from vessel with gate at bottom	Wide range of mechanical methods in air and under liquid. Includes fast and slow placing and pouring vibration, tamping, torsional and axial stirring, and levitation and settling by air and liquid flow.
Initial packing structure before recirculation	To be determined	Loose random	Loose-random-dense random, also dense regular concentric shells.
Linear Scale	Not applicable	Not applicable	9.3 : 1 (Main flow visualisation rig and pilot flow visualisation rig. Both have glass balls in Plexidur vessel).

Appendix III - Dynamic parameters and values selected

Parameter	Pebble Bed Reactor (PBR)	Main PBR Experiment	Bench scale Experiments
Pebble flow rate per outlet	1 per minute (180 per minute for fast unload)	Up to 400 per minute	1 every two minutes - 50,000 per minute
Pebble extraction device	To be determined	One type in throat of hopper One type near bottom of outlet pipe.	Various types near bottom of outlet pipe. (also free unrestricted flow from hopper orifice).
Pebble drop height onto top of bed	Up to 24"	6" 12"	0
Ball temperature	400° - 1000°C	Ambient 120°C	Ambient
Fluid	Carbon dioxide	Air	Air. Mixture of geraniol and phenyl ethyl alcohol (to match refractive index of glass).
Fluid temperature	350 - 800°C	Ambient 120°C	Ambient
Fluid flow rate	Re = 56,000	Re = 0,2000, 37,000	Up to 84% levitation
Direction of fluid flow	To be determined	Down flow (Re = 2000) Up flow (Re = 37,000) (NOTE: Re = 37,000 is equivalent to 75% levitation	Down flow Up flow

1.5 A Simple Mathematical Model of the Random Packing of Spheres in a Cylindrical Container. Mr. N. W. Ridgway (A.A.E.C.)

1. MODEL

The cylindrical bed is considered to consist of an outer annular region one sphere diameter in width and the remaining interior cylindrical region.

It is assumed that, as the bed is vibrated to form denser packings, the ratio of the average number of points of contact (n_c) between neighbouring spheres in the interior region to the number of spheres (n_w) touching the container wall remains constant i.e., $\frac{n_{c_1} - n_{c_2}}{n_{w_1} \quad n_{w_2}} = k$, where the subscripts 1 and 2 refer to beds of different densities and k is a constant. Also it is assumed that both n_c and n_w are approximately linear with respect to the mean radial distance (ρ) between neighbouring spheres.

Two equations have been derived, one connecting the mean voidage (ε) of the interior region to the average number of points of contact between spheres in this region and the other connecting the mean voidage (ε) of the interior region to the number of spheres in contact with the container wall.

These equations are:

$$\varepsilon = 1 - \frac{1}{\left[\frac{1}{1-\varepsilon_1} - \frac{1}{1-\varepsilon_o}\right]\left[\frac{n_c - n_{c_o}}{n_{c_1} - n_{c_o}}\right] + \frac{1}{1-\varepsilon_o}} \qquad \ldots\ldots(1)$$

and

$$\varepsilon = 1 - \frac{1}{\left[\frac{1}{1-\varepsilon_1} - \frac{1}{1-\varepsilon_o}\right]\left[\frac{n_w - n_{w_o}}{n_{w_1} - n_{w_o}}\right] + \frac{1}{1-\varepsilon_o}} \qquad \ldots\ldots(2)$$

where the subscripts o and 1 refer respectively to the properties of the most dense and loose random packings possible.

2. COMPARISON WITH EXPERIMENTAL RESULTS

Equations (1) and (2) have been compared with experimental results taken from the literature and also results from the packing of 0.990 inch diameter aluminium spheres in a 5-3/4 inch diameter perspec cylinder carried out at the A.A.E.C. These results are shown on the accompanying graphs.

Figure (1) shows the mean voidage of the interior region plotted against the average number of points of contact between spheres in the interior region. The following information is displayed in the graph.

$n_{c_o} = 12$, $\varepsilon_o = 0.2595$; rhombohedral packing

$n_{c_1} = 5.5$, $\varepsilon_1 = 0.40$; taken from Bernal and Mason, and

$n_c = 6.0$, $\varepsilon = 0.391$; (compared with $\varepsilon = 0.39$ commonly quoted in the literature for random packings).

$n_c = 6.4$, $\varepsilon = 0.384$; (compared with $\varepsilon = 0.38$ determined by Bernal and Mason).

* D_v is the vessel diameter and D_p is the sphere diameter.

$n_c = 10$, $\varepsilon = 0.3093$; (F.A. Rocke's concentric shell packing, $\varepsilon \doteq 0.308$).

$n_c \doteq 7.7$, $\varepsilon = 0.36$ (Random packings of Scott lie between $\varepsilon = 0.4$ and $\varepsilon \doteq 0.36$ with $n_c = 5.5$ and $n_c \doteq 7.7$)

Figure (2) shows the mean voidage of the interior region plotted against the number of spheres touching the container wall. The curve is fitted to the concentric shell packing properties at the dense end and a mean value of six experimental packings at the loose end. Comparison with experimental points of a random packing which was vibrated through five stages of densification shows a maximum variation of less than 2% occurring towards the loose end.

Figure (3) illustrates the type of results which experiments with larger D_v/D_p ratio beds might give. The region of departure for the experimental results (hatched) would be expected to become smaller towards the dense end. The number of spheres touching the wall would remain constant in going from a bed having a concentric shell packing towards rhombohedral packing.

3. CONCLUSIONS

The model looks promising on comparison with existing experimental data and experiments with larger D_v/D_p ratio beds will be carried out to see if further refinements to the model are necessary.

4. REFERENCES

Bernal, J.D. and Mason J, - Co-ordination of randomly packed spheres - Nature, 188, 1960, 910-911.

Scott, G.D. - Packing of equal spheres - Nature, 188, 1960, 908-909.

Szomanski, E. - The A.A.E.C.'s Main Pebble Bed Reactor Engineering Experiment - Presented at the Applied Thermodynamics Conference, The Institution of Engineers, (Australia) November, 1966. (This Symposium Paper No. 1.2).

1.6 Some Geometrical Properties of Randomly Packed Beds of Spheres in Cylindrical Containers. Mr. G. A. Tingate (A.A.E.C.)

A method is given for determining some of the mean geometrical properties of packed beds of spheres in cylindrical vessels from a few straightforward observations. The bed is regarded as consisting of two regions - an outer annular cylindrical region enclosing the balls which touch the wall, and the central cylindrical region.

An analysis of the existing literature indicates that the mean void fraction of the central region is independent of the vessel-to-sphere diameter ratio D_v/D_p, for D_v/D_p greater than 5.6. Experimental results obtained with this ratio can therefore be extrapolated to much larger ratios with fair accuracy.

Essentially the experimental method involves the determination of three quantities of each packing in a transparent right cylindrical container of known dimensions - the total number of balls in the bed (N), the number of balls touching the cylindrical wall (n), and the volume of intruding ball material (V_1) - i.e. the volume of ball material in the outer region from balls not touching the wall.

The following results were obtained

(i) The structure is strongly dependent on packing method over a practical range.

(ii) The ratio of the number of balls not touching the wall to the number touching the wall increases rapidly as the bed density increases.

(iii) The balls touching the wall and the intruding balls compete for space in the outer annular region. The volume of the intruding ball material decreases linearly as the number of balls touching the walls increases. It is therefore only necessary to know N and n for a determination to be made of the mean properties of interest.

(iv) As a loose packing is densified by vibration or similar means, the number of balls touching the wall increases at about three times the rate of the number of balls in the central region.

NOTE: Preprints of this paper will be sent to Delegates.

1.7 Some Interim Results of First Factorial Pebble Bed Experiments. Mr. F. C. Gatt (A.A.E.C.)

1. INTRODUCTION

Originally it was intended to perform part of the main statistical experiment using "tagged" pebbles; however, due to the great length of time needed for these tagged pebble runs, coloured pebbles were used, enabling many to be seeded simultaneously.

2. METHOD

Seeding marked pebbles in concentric rings at the top of a bed of pebbles of similar properties and measuring the marked pebbles' transit times has led to an analysis of the distribution of pebble transit time.

The bed recirculation speed is kept constant at 400 pebbles per minute and the bed height is held at approximately one bed diameter. Vessel base cone angles of 15^{o}, 25^{o}, 35^{o} and 45^{o} were used.

3. RESULTS

3.1

On surveying the vessel base cone angles 1" and 3/4" diameter, spherical, coated, 3.4gms/cc density zirconite pebbles, wall/centre transit time ratios were found as below -

	Base Cone Angle			
	15^{o}	25^{o}	35^{o}	45^{o}
Pebble 3/4"	8.30	2.51	1.66	1.42
Diameter 1"	7.90	2.21	1.47	1.30

The minimum in both cases occurred with a 45^{o} base cover angle. Preliminary results have also been obtained with a 1/8 scale rig. These were of the same order for mean and standard deviation transit number. The model was not strictly to scale since pebble densities, surface friction, etc. differed; however, strict scale runs are being planned.

3.2

Again with the marked pebbles an empirical relation of the following exponential form was found to hold:

$$T = A\, e^{f(\Theta, R)}$$

Where T = Transit or Residence Time

A = Constant

Θ = Vessel Base Cone Angle

R = Seeding Radius.

3.3

Figures 1 and 2 illustrate the difference in mean transit time between seeding pebbles at 3" radius (near the centre) and 14-1/2" radius (at the wall). The plots are similar in shape and the minimum wall/centre ratio can be seen to be in the 45° cone angle region.

Generally, at all radii except 14-1/2" (at the wall), the standard deviation is less than 10% of the mean transit time.

3.4

From radioactive pebble tracking information, the transit time is found to be dependant not only on seeding radius and base cone angle, but also on the actual track of the pebble through the bed, as shown in figures 3 and 4. These are basically models proposed by G. P. Deutsch (University of Melbourne) of the streamline pattern in a random packed flowing bed, and fit the results so far available to a large extent.

3.5

It is well known that the pebble transit time of different tracks varies considerably. Figure 5 gives a visual indication of the transit time distribution, seeding at 6" and 14-1/2" radii. These distributions appear to have a direct relationship to the traffic density or the number of times each path through the bed is used. The further one seeds from the bed centre, the larger the number of possible pebble paths and the greater the spread of the distribution; resulting in a decrease in the prediction accuracy of individual transit times.

Further work will attempt to associate the frequency distribution plot with the possible pebble paths through the bed.

1.8 Development of a Gamma Radiation Attenuation Technique to Measure Voidage in Packed Beds. Mr. G. Saiva (A.A.E.C.)

A non-destructive method has been developed to determine the spatial voidage distribution in a packed bed. The method is based on the fact that a gamma radiation beam passing through the bed is attenuated and that the degree of attenuation depends on the mean voidage of the volume through which the beam is passed. It may be shown that if a large number of such attenuation measurements are made in two mutually perpendicular directions (e.g. axially and diametrically for a cylindrical packing) then the local voidage at any point in the packing may be expressed as the sum of the overall mean voidage, the local voidage spatial distribution function, and the stochastic component.

The packed beds used in these studies are formed by re-circulating 1 in. dia. zircon sand pebbles through a 30 in. dia. test vessel. To preserve the structure so formed, the pebbles are fixed in a wax matrix by admitting molten wax to the vessel and letting it solidify. To reduce the absorber dimensions in the vertical direction, the solidified packing is cut into two equal cylinders 15 or 12 in. high, depending whether the original bed height was 30 or 24 in. and readings in the horizontal direction are taken radially instead of diametrically; the latter being made possible by drilling a small co-axial hole in each bed through which the radiation source is passed.

A special voidage measuring rig has been constructed which automatically records axial readings every 4^{o} in azimuth and at 22 radii and radial readings every 4^{o} in azimuth and every 1/2 in. in height.

The gamma radiation is supplied by an encapsulated cobalt-60 radio-isotope, which emits two gamma photons, one 1.17 MeV, the other 1.33 MeV per disintegration. The radiation detection system consists of a collimated sodium iodide (Na I) scintillation detector, a photomultiplier, a non-overloading linear pulse amplifier, a pulse height selector and a scaler-printer combination. To stabilise the system against photo-multiplier drift a spectrum stabilizer is also used which works on the peak of a weak caesium-137 gamma source placed directly on the NaI crystal. The detector collimator consists of a 6 in. dia. lead cylinder, 4 in. long through which a 1/4 in. dia. hole has been drilled.

The relationship between count-rate, voidage and absorber length has been established experimentally using slabs of zircon and wax absorbers sandwiched together to form absorbers of different voidage and length. The relationship has been verified on regular packings of 1 in. dia. zircon pebbles in wax matrices. It has been found that the effective radiation beam size closely approximates that of the detector collimator hole, viz. 1/4 in. dia.

As an illustration of the method the results of the examination of an experimental bed are also presented. The Commission's IBM 360 computer has been programmed to process the attenuation data.

1.9 Fluid Velocity Distributions for Randomly Packed Beds of Spheres. Mr. J. Price (A.A.E.C.)

A review of the published literature on the fluid flow distribution through randomly packed beds has shown that marked discrepancies exist in the data for nominally similar beds and has raised doubts on the validity of some of the experimental techniques used[1].

A method for measuring the velocity profile has been developed which utilises a flow separator between the bed exit face and the plane of measurement in conjunction with a pitot static tube [2].

Velocity profiles have been measured for a number of right cylindrical, randomly packed beds of spheres; the objectives being to resolve the anomalies in the published literature and to provide a reliable basis for design calculations.

The results show that the variations of velocity across the bed are small except for a region within one half sphere diameter from the wall where the velocity increases markedly. This is attributed to the local increase in voidage fraction that occurs near a bounding surface.

The profile was found to be independent of Reynolds number ($1470 < N_R < 4350$) and bed length ($9 < L/d < 36$).

The velocity profiles measured for beds prepared by different packing methods (i.e. loosely packed by hand pouring from a beaker and tightly packed by vibration) were very similar; only small systematic effects were observed near the walls which can be explained by consideration of the packing structure of the spheres inside the bed.

The effects of different sphere materials (steel, glass and wood) and vessel to sphere diameter ratio ($12 < D/d < 48$) were also small and were only observed in the vicinity of the walls.

The velocity profile measured in these tests differs substantially from those of most previous investigators. The differences stem from the experimental techniques used; reasons for this are discussed in (2).

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(1) Price,J., - A review of fluid flow distribution through randomly packed beds. AAEC/TM332, July, 1966.

(2) Price,J., and Stevens, J.R. - A method for measuring the fluid flow distribution at exit from a right cylindrical, randomly packed bed. AAEC/TM354, October, 1966.

SESSION NO.3

3.1 A Method of Studying Ball Flow by Digital Computer. Mr. N.W. Bennett (A.A.E.C.)

Ball flow may be studied with the aid of a digital computer. The method consists of calculating elastic forces due to simple interactions and using these forces to track individual balls. Any shape of container may be simulated exactly, although protrusions into the container present difficulties. To date, only two-dimensional systems have been studied, but the method may be extended easily into three dimensions at a penalty of a tenfold increase in calculation time. This is caused by the extra dimension, the greater number of neighbours per ball and a more complete elastic analysis which must be applied in three dimensions.

Since elastic forces are being studied, the vibrations due to these forces must be followed. For hard balls this may involve real time intervals of milliseconds which may take seconds to calculate on the IBM 7040 computer on site.

A circulation model may be easily set up by arranging for balls which have fallen out of the bottom of a container to be replaced at the top of the array of balls.

The forces between balls and between a ball and the container wall are known at all times and may be given as output by the machine. The position and velocity of all balls is also known, and from the ball positions the voidage may be calculated.

A model involving friction has been investigated in simple situations. The friction model allows balls in contact to move against each other for a limited distance. A force may be associated with the distance of slip and the force between the balls. The point of maximum slip corresponds to the point of limiting friction.

An estimate is given of the cost to perform simple experiments.

3.2 Segregation studies in a Model Hopper of Granular Feed for Zinc-Lead Sintering. Mr. M.G. Taverner (Sulphide Corp.Pty.Ltd.

1. INTRODUCTION

In the Sinter Plant of the Sulphide Corporation's Cockle Creek Works, N.S.W., a granular feed of zinc-lead sulphides (flotation concentrates), limestone flux and sinter returns is prepared and the updraught sintered on a Dwight-Lloyd sinter machine, to produce a hard agglomerate comprising zinc oxide, lead oxide and slag. The latter is charged to the Imperial Smelting Furnace for the subsequent production of zinc and lead metals. Sulphur dioxide gas evolved from the sintering reactions is converted to sulphuric acid in a contact acid plant.

As sinter, physical quality is a major factor in furnace performance. Much work has been done in both the plant and laboratory to achieve the best operating conditions for producing sinter of good quality, and also ways to increase sinter production on the plant.

Associated with the latter investigations, segregation studies of granular machine feed have been carried out in the laboratory using a model hopper, one third the size of the plant main layer feed hopper. In practice, considerable segregation of the granular feed occurs in the plant hopper and, as a consequence of this, can seriously affect ignition transfer to the main bed if unsuitable sized material occurs at the interface of the ignition and main layers.

This paper deals with practical segregation studies carried out on the granular feed passing through the model hopper using three rill positions and several hopper configurations including that of the plant. The effect of hopper rill position on material segregation using different hopper configurations was closely studied and is observed in about 150' of 8 mm. cinefilm (this will be shown at the Symposium). The flow behaviour of the granular material is also observed as it passes through the hopper.

2. DESCRIPTION OF MODEL HOPPER

The model hopper is shown diagramatically in Figure I. It consists of a steel angle iron frame 26" long x 24" wide x 30" high mounted on a steel table 75" long x 30" high. The hopper is fitted with a front and back plate which can be adjusted to give the desired hopper configuration. One full side of the hopper is constructed of 1/4" plate glass through which the movement of granular feed can be observed.

Along the bottom of the hopper a steel tray 48" long x 24" wide x 4" high is constructed with a 1/4" plate glass side to observe movement of material at the throat of the hopper and segregation through the bed. To simulate the feeding of granular material from the plant hopper to the sinter machine, the feed is withdrawn below the model hopper by moving the tray horizontally with a hand operated winch.

Above the top of the hopper is a guide chute which is located to provide the desired hopper rill position for the granular feed.

3. EXPERIMENTAL WORK

3.1 Hopper Rill Position

The three rill positions used in the tests were as follows:-

No. I. The granular feed is directed to fall on the front plate of the hopper.

No. II. The granular feed is directed to fall into the hopper midway between the front and back plates.

No. III. The granular feed is directed to fall on the back plate of the hopper.

The three hopper rill positions were used with each hopper configuration where possible, but for obvious reasons only rill positions II and III could be used in a hopper configuration containing a vertical front plate.

A typical sizing analysis of the machine feed used was as follows:-

B.S.S.	%
+ $\frac{3}{16}$ in.	35.0
+ $\frac{1}{8}$ in.	20.5
+ 18 mesh	31.1
- 18 mesh	13.4

3.2 Hopper Configuration

Sketches of all the hopper configurations and rill positions used in the test work are shown in Figure II.

4. DISCUSSION OF RESULTS

1. In all the tests, the hopper rill position was the most significant factor in determining the nature of the segregation resulting in the bed. This is illustrated in the table below:-

	Granules Top of Bed	Granules Bottom of Bed
Rill 1	Very Fine	Coarse
Rill 2	Coarse	Fine
Rill 3	Very Coarse	Fine

2. Although the pattern of segregation was similar with each hopper configuration, the latter had a pronounced effect on the degree of segregation caused by a particular rill position. This is borne out by the two tests using hopper configuration 2 which produced the greatest amount of segregation through the bed with each rill position.

3. With each hopper configuration, rill position No. III produced the greatest amount of segregation through the bed. The greatest amount of segregation in all of the tests was produced with the second hopper configuration using No. III rill position. In this case, nearly 60% of the material contained in the top section of the bed was + $\frac{3}{16}$" material.

4. Rill position No. II gave the smallest amount of segregation with each hopper configuration. The smallest amount of segregation was produced with hopper configuration 5 using the No. II rill position. An increase of only about 4% + $\frac{3}{16}$" material occurred at the centre of the bed, while the proportion of + $\frac{3}{16}$" material contained in the top and bottom sections of the bed was almost the same.

5. More uniform flow of material was observed through the hopper with the three configurations possessing the curved front plate. With hopper configuration 5, the most uniform flow of material through the hopper occurred.

5. CONCLUSION

The work done to date has shown that both rill position and hopper configuration have a major influence on the pattern of segregation in granular feed material on the sinter machine. Segregation is known to be an important factor affecting sintering performance, including physical quality of the product.

It should be therefore possible to design a pattern of segregation which results in optimum sintering performance. At the time of writing, work in this final stage of the investigation was being undertaken using an experimental sintering bed.

3.3 Flow of Granular Materials from Silos. Mr. G.P. Deutsch (Department of Civil Engineering, University of Melbourne.)

INTRODUCTION

This paper includes some results of work carried out in a project aiming at developing a better understanding of the behaviour of a bed of granular material as discharge from a storage vessel occurs. The project, carried out in the Civil Engineering Department of the Melbourne University, is sponsored by the Australian Atomic Energy Commission in connection with the Pebble Bed Reactor Study.

Three distinct approaches to this problem have been made previously

(i) Investigation of boundary pressures[1]. Theories based on statical analyses using assumed stress ratios have been developed.

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1. Turitzin, A.M. - Dynamic Pressure of Granular Materials in Deep Bins, Proc. A.S.C.E., 89, ST2, April, 196

(ii) The parameters affecting discharge rates have been investigated by dimensional analysis[2].

(iii) A recent theoretical approach[3] considers the granular material as a continuum in which flow occurs by plastic failure.

FLOW PATTERNS

The flow patterns during discharge are very different from the steamline flow of fluids[4]. The behaviour at any point in the flowing mass (including the boundaries) is influenced by the conditions at all other points. Thus it is important to understand the flow patterns and their causes.

The flow patterns were investigated by discharging granular materials from a semi-cylindrical model silo. Sand, wheat, gravel and plastic balls have been used. Outlet conditions included flat bases, cones, multiple and raised outlets. Control tests with a full cylinder silo confirmed the results. Some tests were run with material entering the silo from above thus maintaining a constant head above the outlet. The plastic balls were tested with free flow and slow controlled flow rates. Confirmatory tests were conducted at Lucas Heights using glass beads in the pilot flow visualisation rig[5] and glass ballotini. Preliminary results from the main P.B.R. rig also confirm earlier results. The tests provided vessel to material diameter ratios from 24 : 1 to 4300 : 1.

These tests have shown that fundamental flow patterns occur during discharge. The flow patterns can be divided into four zones which have been called the pipe, pipe feed, dead and plug flow zones. These are shown schematically in Figure 1.

The material within the dead zone does not move. Small variations in the boundary to the pipe feed zone occur due to two secondary effects - The venturi effect and the preferred orientation effect. The plug flow zone is the region above the influence of the outlet. The velocity profile within this zone is uniform except for a boundary layer. When the influence of the outlet reaches the top surface cave-in occurs. Material entering the pipe feed zone receives a radial velocity component and thus feeds the pipe. The boundaries of these zones are clear and steady. All material leaves the silo via the pipe.

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3. Jenike, A.W. - Storage and flow of Solids, Bulletin No.123, Utah Engineering Experiment Station, November 1964.

4. Lenczner, D. - An Investigation into the Behaviour of Sand in a Model Silo, Structural Engineer, 41, No.12, 1963.

5. Gleed, D.B. and Leesment, H.H. - Pebble Bed Reactor Study, Flow Visualisation Experiment, Atomic Energy in Australia, October, 1965.

The scale of the flow patterns depends on material properties and boundary geometry. The stability of the flow patterns and the repeatability of results indicate that the discharge is (for an external reference system) a steady state phenomenon until cave-in occurs. The material within the pipe and pipe feed zones can be considered to be failing plastically. However, the plug and dead zones are in non-failure states as there is no evidence of shear failure within these zones. Experimental evidence shows that the stable failure state of a point in the failure zones may be the critical voids ratio state for a granular material.

3.4 Deposition of Small Particles from Turbulent Flow in Gas Streams. Messrs. T. Kneen and W. Strauss (Department of Chemical Engineering, University of Melbourne).

In some situations small particles in the approximate size range 0.5 - 50 microns are entrained in gas streams. These particles may deposit on the walls of a duct and it has been found experimentally that the deposition rate increases greatly in turbulent flow.

This review discusses this behaviour, in which the essential features of the problem are the behaviour of the flow close to the wall and the inertia of the particles. A distinguishing feature of the situation is the unimportance of a molecular transport mechanism and the need to consider the effect of turbulent fluctuations in the region usually regarded as stagnant.

Experimental results support the prediction that -

$$\frac{N_o}{U_\tau \, \bar{C}} \propto S^{*2}, \quad S^* < 5$$

where $$S^* = 0.05 \, \frac{\sigma}{\rho} \left(\frac{U_\tau \, d}{\nu} \right)^2$$

and N_o = deposition rate (particles per unit area per unit time).

$\bar{C}$ = mean concentration (particles per unit volume).

U_τ = shear velocity

σ = particle density

ρ = fluid density

d = particle diameter

ν = kinematic viscosity.

The application of this result to sampling lines is discussed.

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3.5 Development of the Fluid-Lift-Solids Recirculator.
Mr. C.H. Hunt (Department of Chemical Engineering, University of New South Wales).

The Fluid Lift Solids Recirculator was developed to overcome some of the disadvantages of both fluidized and spouted beds.

Fluidized beds, known since 1940, operate best with fine solids and where chemical changes are required in the fluid. Because of its thorough mixing, it has limited value where the change occurs in the solid and the offtake is a mixture of unburned and overburned material, such as gypsum plaster or iron pyrites.

The spouted bed was developed to dry larger particles, such as seed grains, and has been developed mainly in Canada to dry wheat, rye, peas, beans and other evenly sized particles. The main disadvantage is the high ratio of start-up pressure required to penetrate the static bed compared to the relatively low pressure (10%) required for normal operation. This required a high pressure pump and one spout per unit (i.e. it is not possible to have a multi-spouted bed from one manifold).

Buchanan and Manurung (1961) working with spouted beds, attempted to overcome the limited bed depth by stabilizing the spout with a draught tube. Buchanan and Wilson (1965) investigated the possibilities, but because the apparatus had a 2 ft. calming section below the entry to the bed and the draught tube was filled before the start-up, they reproduced most of the disadvantages of the spouted beds and had similar high pressure drops at start-up, with low running pressure.

Hunt and Cook investigated the use of streamlined poppet valves (1964) combined with tapered and hemi-spherical seats, to prevent the runback of solids, and found that a round ball in a stepped seat produced the least pressure loss, and for the first time achieved a start-up pressure less than the required running pressure.

This meant that self-starting spouts could be operated in the same bed from the same low-pressure manifold, and opened the way to multi-staged beds for the counter current treatment of solid as well as the fluid.

All investigations up to this date used a conical-bottom batch recirculator. Depending on the diameter of the draught tube there was always a minimum depth of solids over the valve even when the solid flow was cut off completely.

In 1965 Hunt, Edenborough and Kong designed a single pass unit so that the solids in the tube could be collected and weighed. The bottom was flat to eliminate the restriction to solids flow as the draught tube approached the inside of the cone.

Kong confirmed Brennan's work that, on a flat bottom, the solids formed their own cone, the angle being lower and the bottom edge further from the centre with each increase in air velocity.

Edenborough (1965) used 1/2, 3/4 and 1 in. nozzles, a 2 in. draught tube, and five materials, wheat, millet, rape seed, coal and sand. All showed a start-up pressure higher than that required for minimum solids flow, but below the maximum. With a screen over the nozzle to prevent solids choking it on shut-down, the pressure drop through the solids increased gradually to maximum lift rate without any peaks. His theoretical correlation agreed within 20% of the experimental results.

Because a screen could bind underneath when used in a series system, Ring (1966) used three different nozzles to find even lower start-up pressures - he will discuss these results in another paper at this Symposium.

Green (1966) using the last of Ring's nozzles and identical equipment, measured the heat transfer from air to sand. He found that for a 2 in. draught tube

$$\frac{(h\ Dt)}{k} = 0.175 \left(\frac{Dt\ G}{\mu}\right)^{0.96} \left(\frac{G}{G_s}\right)^{0.52} \left(\frac{L}{Dt}\right)^{0.12}$$

h = heat transfer co-efficient (BTU/ft^2 hr ^oF)

k = thermal conductivity of fluid (BTU/ft^2 hr. ^oF)

Dt = draught tube diameter (ft).

μ = fluid viscosity (lb/ft.sec)

G = mass rate of fluid (lb/min)

G_s = mass rate of solid (lb/min)

L = draught tube length (ft).

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3.6 Effect of Nozzle Design on Start Up of the Fluid-Lift-Solids Recirculator. Mr. R.J. Ring (Department of Chemical Engineering, University of New South Wales).

The fluid lift solids recirculator is basically a stabilised spouted bed. The mechanism of the F.L.S.R. has been described by Mr. C.H. Hunt (Symposium Paper No. 3.5).

The high start up pressure drop encountered by Buchanan and Wilson was due to the filling of the draft tube nozzle and inlet calming section with solids. The solids in the draft tube can easily be eliminated. The start up pressure drop has since been reduced by improvements in the design of the air entry device.

The most successful entry device to date was introduced by Edenborough and Kong. The fluid entered at the side of a flat-bottomed cylindrical section. In this section, the fluid was made to turn through 90^{o} before passing up a tubular nozzle into the bed. Edenborough found that the start up pressure drop could be completely eliminated by placing a screen over the inlet hole. This modification is unsatisfactory, if the units are to be used in series. In this arrangement the screens can easily become blinded from beneath.

This paper describes the study of three new inlet nozzles. It was hoped that these entry devices would clear of solids on start up, without causing a high pressure drop.

The major part of the recirculator is a flat bottom "Perspex" column. The column was 5-3/4" ID. The base section had a 1" diameter hole at the centre for the insertion of various nozzles. The draft tubes used were 3/4" and 1-3/4" ID. The draft tube lengths were 13-1/2" and 25-1/2". The materials used were wheat, rape and millet seeds.

The influence of draft tube separation, length and diameter on start up pressure drop and mass rates were thoroughly examined.

One nozzle was found to be far superior to the others. This nozzle consisted of a 2" diameter plate, centred 3/8" below the 3/4" air entry hole in the base plate of the main 6" column. A 1/8" x 1/8" ring was attached to the surface of the plate at the periphery to prevent solids spilling into the 6" diameter air distribution zone. This zone was 1-1/2" deep with a 5/8" ID. air entry pipe at the base.

This nozzle required start up pressure drops which were 50% lower than those recorded by previous investigators. The nozzle was found to operate most satisfactorily with a 1-3/4" ID. draft tube, at tube separations of 1-1/2" or 2".

The results obtained using this nozzle with the 1-3/4" ID. draft tube gave the following correlations.

Millet Seed

$$M = 0.47\ S^{0.85}\ Q^{1.03}$$

Rape Seed

$$M = 0.95\ S^{0.93}\ Q^{0.89}$$

Wheat Seed

$$M = 1.46\ S^{0.57}\ Q^{0.89}$$

where

M is the solids rate (lb/min)

S is the tube separation (inches) (1 to 3 inches)

Q is the actual air rate minus V (ft^3/min)

where

V is the solids initiation air rate (ft^3/min)

The correlations obtained for V were:-

Millet Seed

$$V = 18\ S^{0.15}$$

Rape Seed

$$V = 19.7\ S^{0.31}$$

Wheat Seed

$$V = 25\ S^{0.26}$$

3.7 Load/Deformation Behaviour by Compacted Aggregates.

Mr. C.G. Bennett (Department of Mining and Metallurgical Engineering, University of Queensland).

The paper covers part of an investigation into the load/deformation behaviour of foundry moulding materials and is confined to a discussion of the behaviour of particle size distributions of silica sand compacted to various bulk densities.

To study the influence of particle size distribution, degree of compaction and rate of deformation on the load/deformation behaviour, equipment was designed to determine the relationship between load and deformation by means of loading the granular mass to progressive failure, i.e. plastic flow of the material.

The equipment is basically a direct extrusion press in which the rate of deformation, controlled by the rate of travel of the ram, is the independent variable and the load, the dependent variable, is the resistance of the granular mass to the die before, and during, flow of the material through the die.

A sub-angular, high purity silica sand (99.63% SiO_2) was used for all test work. Particle size distributions within the size range 40-200 mesh (U.S. series) were compacted by means of vibration to bulk densities up to and including the maximum density for each distribution.

The load/deformation curves resulting from this extrusion process exhibit well-defined yield and flow characteristics. There is a condition of elastic equilibrium representing a linear relationship between load and deformation preceding a yield or condition of plastic equilibrium. Further deformation results in plastic flow representing continuous deformation at an approximate constant state of stress.

These characteristics are markedly influenced by the particle size distribution and the degree of compaction. The overall results also indicate that there is a critical rate of deformation such that the extent of particle rotation and movement varies considerably for deformation rates above and below this cricitcal rate.

By the application of the Soil Mechanics theory of Plastic Equilibrium of Soils, the values of the normal and shear stresses on surfaces of sliding within the granular mass may be computed for the deformation at the limit of stability of the mass.

3.8 Pressures on the Walls of Silos. Mr. G.P. Deutsch (Department of Civil Engineering, University of Melbourne).

INTRODUCTION

Many attempts to measure and predict the pressures occurring in silos have been made[1]. Theories were based on empirical parameters and assumed ratios of vertical to horizontal stresses at the walls. These theories gave some agreement with measured pressures under static conditions, but pressures up to four times the static pressures have been measured[2]. These overpressures have been termed "dynamic pressures". Theories as to the cause of these over-pressures vary from the effects of acoustical shock waves[3] to the breakdown of local arching patterns[4].

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It is essential for the safe structural desing of silos and vessels such as a container for a Pebble Bed Reactor, that the origin and extent of these overpressures be understood and predictable. This knowledge will also indicate likely material stresses within the silo.

PRESSURES

In a previous paper at this Symposium[5], fundamental flow patterns occurring during the discharge of granular materials from silos were described. These flow patterns are a steady state phenomenon (prior to cave-in) when viewed from an external reference system. It was shown that the failure state is only reached within the pipe and pipe feed zones and that the plug flow and dead zones are in non-failure states.

The stress states described above must occur immediately flow commences and remain at a steady state until flow ceases or a significant change in boundary conditions occurs. Failure stress states occur in the region where the pipe feed zone meets the wall of the silo. It is here that the greatest over-pressures are to be expected and have been measured. These overpressures are not "dynamic pressures" in the transient sense but are a result of the inherent steady flow behaviour. Thus they are to be expected in all silos containing granular materials and design methods must take them into account.

APPROXIMATE UPPER BOUND PRESSURE SOLUTION

An approximate plane strain theoretical solution is described which predicts an upper bound on the wall pressures during flow. The particular techniques of plasticity solutions[6] which predict a lower bound on the external forces required to cause collapse have been adapted to do this.

A stress field is chosen which resembles the observed flow patterns. The stress ratios within the failure zones are assumed to obey the Mohr-Coulomb failure criterion. Equilibrium is satisfied within the failure zones. By satisfying yield (failure) and equilibrium conditions, a lower bound on the load (head) required to cause collapse is obtained. Or conversely, an upper bound to the strength and thus the stresses, within the failure zones is obtained for a given head.

The stresses throughout the field are obtained by calculation from assumed centre line values. The values at the top of the pipe are assumed to be the Janssen[7] value since a statical analysis may be valid in a non-failure zone.

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Two stress fields have been used for various values of material properties and boundary geometry. In all cases pressures from 2 to 8 times the static pressures are predicted in the region of the pipe feed zone. Linear extrapolations are made outside this region. As is to be expected varying material properties and boundary geometry greatly affect the predicted pressures.

SESSION NO.4

4.1 Transient Response of Packed Beds According to the Finite Stage Model. Mr. C. P. Jeffreson (Department of Chemical Engineering, University of Adelaide).

1. INTRODUCTION

The object of the present work is to obtain valid models of transient packed bed behaviour. Such investigations have application to control studies of packed bed regenerators, chemical reactors and driers. The model under present investigation is the finite stage model of Deans and Lapidus[1]. This approach has recently received strong experimental support from the work of Mickley, Smith and Korchak[2].

This paper presents computational studies mainly in the form of frequency response plots which will be used to evaluate fluid particle and fluid wall heat transfer coefficients and other parameters in terms of the finite stage model. In particular the effects of

(a) Non-uniform velocity distributions,

and

(b) fluid-particle radial conduction are investigated computationally.

2. STEADY STATE EQUATIONS

The matrix formulations of Crider and Foss[3] [4] are used throughout since matrix manipulation is relatively standardised procedure and allows certain general conclusions to be made about the structure of the solution.

If the distribution of superficial mass velocity across a section of a packed bed is non-uniform, then it is necessary to modify the usual transition matrix for the bed. Thus if the superficial mass velocity through a cell (i,j) is denoted by $\sigma_{ij}\bar{G}$ where $\bar{G}$ is the overall average superficial mass velocity, the finite stage model predicts that successive velocity distributions may be computed by

$$\sigma_{i+1} = A_\theta \sigma_i$$

where $\sigma_i = \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_j \\ \vdots \\ \sigma_{M+1} \end{bmatrix}$ and $A_\theta = \begin{bmatrix} 0, & q_1' & & & & \\ P_2', & 0, & q_2' & & & \\ & \ddots & \ddots & \ddots & & \\ & & P_j', & 0, & q_j' & \\ & & & \ddots & \ddots & \\ & & & & P_{M+1}', & 0. \end{bmatrix}$

.....(2.1)

where the "transition probabilities" are

$$P_j' = P_j\theta_{j-1} = \frac{2j-3}{4j-4} \cdot \theta_{j-1}$$

$$q_j' = q_j\theta'_{j+1} = \frac{2j-1}{4j-4} \cdot \theta'_{j-1}$$

It is assumed that A_θ is independent of stage number. The values of θ_j may be chosen so that the velocity distribution across a given stage N+1 computed by

$$\sigma_{1+N} = A_\theta^N \sigma_1$$

matches a given experimental velocity distribution. They have a simple physical interpretation. The development of a velocity profile from any given inlet profile may also be observed computationally. In the simple case of uniform velocity profile the dominant eigenvalue of A_θ is 1 and the sum of each row is unity.

In the presence of radial particle-particle and fluid particle conduction the steady state matrix formulation has the form

$$B_{\sigma_i} T_{i+1} = A_{\theta_\omega} (\sigma T)_i$$

or

$$T_{i+1} = B_{\sigma_i}^{-1} A_{\theta_\omega} (\sigma T)_i \qquad \ldots\ldots(2.2)$$

Where matrix B_{σ_i} contains elements which are a function of the usual series fluid-solid conductivity and the wall coefficient both assumed relatively insensitive to velocity variation. Since experimentally and computationally velocity profiles are esentially fully developed within ten diameters of the inlet B_{σ_i} may be made independent of stage i and the temperature at stage N determined from

$$T_{N+1} = C_\theta^N T_1 \qquad \ldots\ldots(2.3)$$

The results of such computations are compared with the more usual ones which neglect velocity variation and radial series conductivity.

3. UNSTEADY STATE FORMULATIONS

It is shown that when the bed is insulated, the frequency response may be computed allowing for finite particle conductivity by the simple relation

$$G_N(j\omega) = \frac{T_{N+1}(j\omega)}{T_i(j\omega)} = \frac{1}{\left[j\omega + (1-G_P(j\omega))KV_H + 1\right]^N} \qquad \ldots\ldots(3.1)$$

Where T_i is the uniform temperature at a stage i and $G_p(s)$ is the transfer function relating the particle surface temperature to that of the surrounding fluid allowing for non-uniform particle temperature, K a parameter including the fluid particle film coefficient and V_H is the ratio of packing volumetric heat capacity to voids volumetric heat capacity. The problem is similar to that treated by Jones(5).

Plots of (3.1) are present in magnitude ratio and phase angle form both for the more usual case of infinite particle conductivity and for finite conductivity. The errors introduced into transient measurements of fluid - particle heat transfer coefficients by short bed lengths (N small) are discussed and the plots compared with the solution to

$$\frac{\partial T}{\partial z^*} + \frac{\partial T}{\partial t^*} - \frac{1}{P_{ea}} \frac{\partial^2 T}{\partial z^{*2}} = K (T_P - T) = \frac{dT_P}{dt^*} \qquad .....(3.2)$$

In the presence of significant radial conduction and non-uniform radial velocity distributions the frequency response formulation becomes more complex taking the form

$$B_\sigma (j\omega) \cdot T_i (j\omega) = A_\theta (\sigma T (j\omega))_{i-1} \qquad .....(3.3)$$

where $B(j\omega)$ and A_θ are matrices and the $T_i(j\omega)$ are the frequency response vectors at a given stage i.

In the formulation of (3.3) it has been found necessary to assume infinite particle conduction although this constraint is to be eliminated. It is hoped to present the solutions of (3.3) in frequency response form to show how non-uniform velocity distribution and series conduction affects the evaluation of heat transfer coefficients.

4. REFERENCES

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3. Crider, J.E. and A.S. Foss, A.I.Ch.E.J.,11,1012(1965).

4. Crider, J.E. and A.S. Foss, A.I.Ch.E.J.,12,514(1966).

5. Jones, J.C.M., "A Contribution to Heat Regenerator Theory", Second AINSE Heat Transfer and Fluid Flow Conference, (1965).

4.2 The Role of Axial Dispersion in Heat Transfer in Beds of Textile Fibres.

Dr. P. Nordon (Division of Textile Physics, C.S.I.R.O., Ryde, N.S.W.)

The problem of transfer of heat from a gas which is forced through a bed of textile fibres is examined. Apart from the intrinsic interest of this system, beds of this type are of particular interest as they cover a range of parameters not normally encountered in packed beds. Fibre diameters may be as small as 15μ and porosities 0.95 and greater.

The problem is analysed in terms of the two simultaneous differential equations

$$\alpha \frac{\partial^2 Tg}{\partial X^2} - \frac{\partial Tg}{\partial X} - \frac{\partial Ts}{\partial \theta} = 0 \qquad \ldots\ldots(1)$$

$$\frac{\partial Ts}{\partial \theta} = \beta \, (T_g - T_s) \qquad \ldots\ldots(2)$$

Which are solved by the method of finite differences T_g and T_s are the temperatures of the gas and solid, respectively, X is the dimensionless distance and θ dimensionless time. α is an inverse Péclet number and β a Stanton number. The second order term in equation (1) represents the contribution of axial dispersion and thermal conductivity to the transfer mechanism.

Solutions of equations (1) and (2) for various sets of values of α and β are examined in terms of the so-called "break-through" curves of temperature vs. time at the exit of the bed for a step-function input.

An increase in the value of α (or a large dispersion effect) or a decrease in the value of β (or a low heat transfer from the fluid to the solid phase) cause the break-through curves to become wider or more diffuse signifying less efficient transfer of heat.

There is an element of symmetry in the effect of α and β in that a similar (but not quite the same) break-through curve can be produced with either a high value of α and a high value of β or a low value of α and a low value of β. This can lead to wrong conclusions regarding local transfer of heat to the solid phase if the effect of axial dispersion is neglected in the analysis of the problem (i.e. a low value of α is assumed).

For typical beds of textile fibres, the value of β (calculated from published data on fine wires and from direct measurement) is high, and ranges from about 300 to 5000. The analysis shows that in this range the shape of the break-through curve is entirely dependent on the value of α. As a consequence, the problem can be expressed in terms of equation (1) only where Tg is set to equal Ts.

In this form, there are known analytical solutions of the equation for various boundary conditions.

Sinusoidal functions of temperature were used as boundary condition for an experimental determination of α for various textile beds and were found to range from about 5×10^{-3} to 1. The influence of gas velocity and porosity on the value of α were also determined.

The practical conclusion from this work is that forced convective transfer of heat in typical beds of textile fibres is determined solely by the structure of the bed (and its static thermal conductivity at low gas velocities) and not by any boundary layer resistance on the surface of the solid phase (fibres).

4.3 Heat and Mass Transfer of Drying Granular Materials in Roto - Louvre Dryers. Dr. O. Myklestad (Division of Food Preservation, C.S.I.R.O., Ryde, N.S.W.)

Theoretical and experimental studies on the drying of granular materials in roto-louvre dryers have been carried out, supported by experimental drying on fixed packed beds. For the time of drying required by a large number of materials, handled by the chemical and food industries, the rate equations for heat and mass transfer were solved in general terms.

The determination of constants in the derived equations was exemplified for the case of drying of granulated kelp in a fixed bed. The example involved measuring weight losses during drying under specified conditions, and numerical values for critical moisture contents and heat transfer coefficient were thereby obtained.

A study was also made of the movement of an agricultural product through a roto-louvre dryer as a function of operational conditions and dimensions of the dryer. In the whole root form of the product, its hold-up time could be correlated by operational parameters for rotary kilns derived by Sullivan, Maier, and Ralston (1927). However, when the material was handled in a sliced form a similar correlation was not obtained.

Temperatures and moisture contents of the same product, in both forms, were measured in a number of sampling locations during its passage through the dryer. After only a short distance, the temperature of the sliced material attained approximately the wet bulb temperature of the air, and this condition was maintained for about 74% of the passage in the dryer. After this point there was a sharp rise in temperature, while a considerable decrease in the rate of drying took place. A different pattern was apparent during drying of the whole root: with such material the temperature increased continuously, with a steady fall in moisture content.

4.4 Design Charts for Gravel Bed Heat Exchangers, Heat Storages and Evaporative Coolers. Mr. R. V. Dunkle (Division of Mechanical Engineering, C.S.I.R.O., Highett, Victoria).

Beds of screened gravel can be used as efficient regenerative heat exchangers, for storage of heat or coolth, or, if wet with water, as evaporative coolers. The design of these beds for specific applications was found to be tedious and difficult, so a design chart and procedure have been developed to simplify this task.

The first step consisted of the selection of heat transfer and pressure drop relationships from the voluminous literature on this subject. From these relationships four dimensionless groups involving bed depth, cycle length, volumetric heat transfer coefficient and gas velocity can be plotted as a function of a dimensionless flow parameter. This gravel bed design chart can be used in conjunction with appropriate regenerator design charts to quickly and easily design gravel beds for specified performance for any of the given applications.

For example, in designing a rock bed regenerative heat exchanger, four independent variables must be selected. It is thought that the logical (most important) criteria are:

1. Thermal effectivity, or mean dimensionless temperature approach.

2. Droop, or dimensionless temperature change from beginning to end of cycle.

3. Pressure drop in bed.

4. Rock size, equivalent spherical diameter.

The dependent variables are then the depth of the rock bed, the cycle length, the gas velocity and the volumetric heat transfer coefficient. The thermal effectivity and droop determine the dimensionless thermal length and time for a conventional regenerator design chart. The dimensionless thermal length combined with pressure drop and rock diameter form the dimensionless flow parameter which then allows the dependent variables to be found with the aid of the gravel bed design chart. Similar procedures also apply for the heat storage beds and the evaporative cooler gravel bed.

4.5 Resistance to Air Flow of Packed Beds of Coke. Dr. P. L. Waters (Division of Coal Research, C.S.I.R.O., North Ryde, N.S.W.)

The resistance, or permeability, of coke beds to gas flow is an important factor affecting the performance of cupolas and blast furnaces, because it determines the amount of air which can be supplied for combustion. Coke size is one of the main process variables under the operator's control, but inadvertent size degradation of coke during handling can greatly increase bed resistance to air flow and impair plant performance. Knowledge of pressure drop across packed beds of coke of various size grades is therefore of considerable practical importance in cupola and blast furnace operation. An outline is given of the work carried out by the Division of Coal Research on this topic.

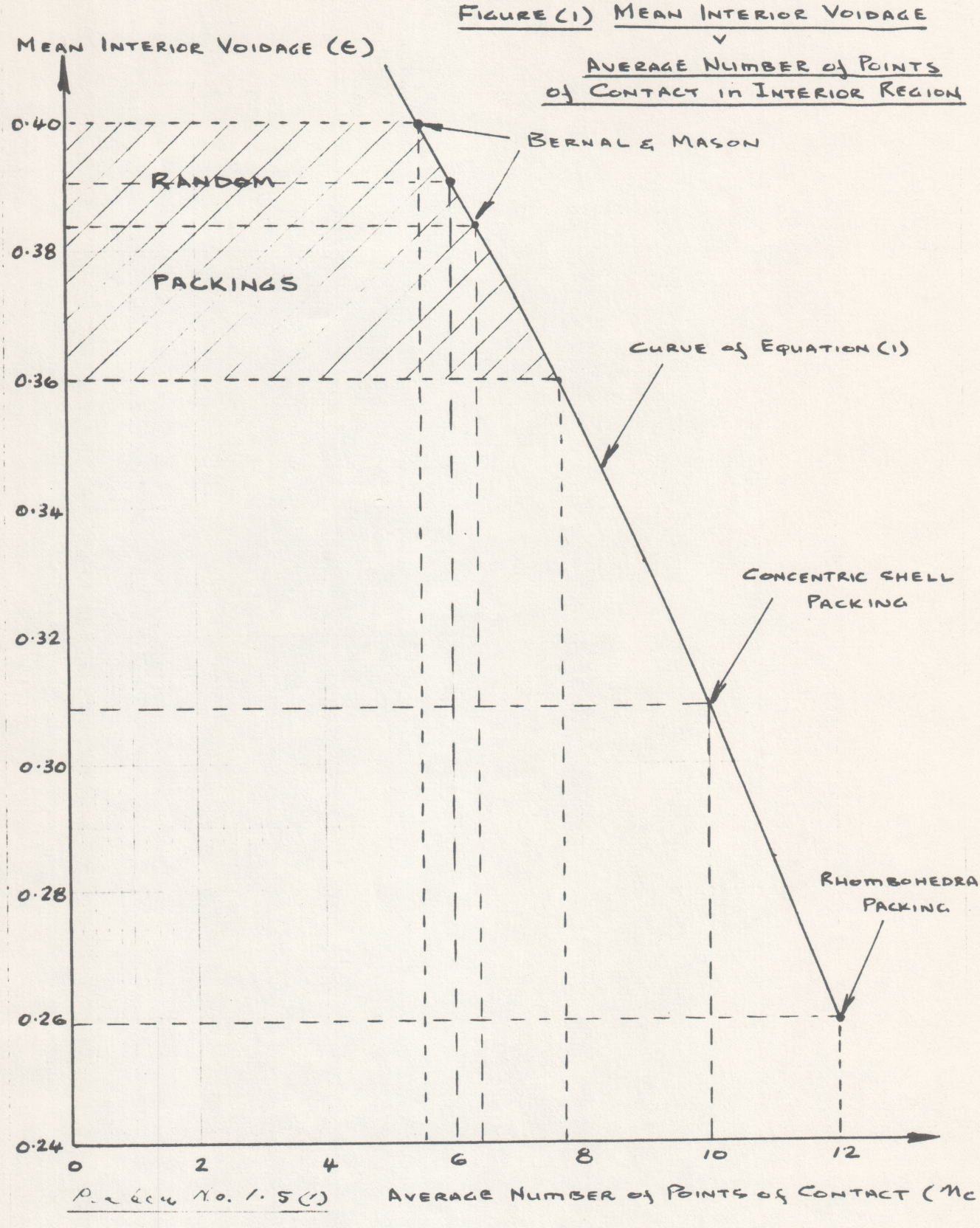
In a series of model experiments, the effects of coke particle size, bed voidage, and air-flow rate (up to 0.4 lb./ft.^{2}/s.) on the pressure drop across packed beds of graded metallurgical coke (up to 8 in. size, contained in a shaft 2 ft. diameter and 6 ft. high) were determined. Correlation of the data derived from these experiments led to a generalised empirical equation of flow, in which pressure drop is expressed as a function of flow rate, relative surface roughness, particle diameter, and voidage. The flow rate and the voidage function are discussed and compared with results published by other workers.

The pressure drop across packed beds of particulate material is very sensitive to the denseness of packing and, in the case of coke beds, varies inversely as the fourth power (approximately) of the voidage. The voidage function has therefore been given special attention, and the packing characteristics of the bed affecting voidage have been investigated in three different sets of experiments.

In the first, the variation in voidage with container size was examined; results suggest regions of different voidage - from the wall to the core of the bed - which in turn affect the distribution of air across the bed. Secondly, the variation in voidage with the mode of packing was studied. The factor having the greatest influence on the voidage of packed beds is size distribution; in the third set of experiments, therefore, the voidage of beds of mixed size grades of coke was investigated in some detail.

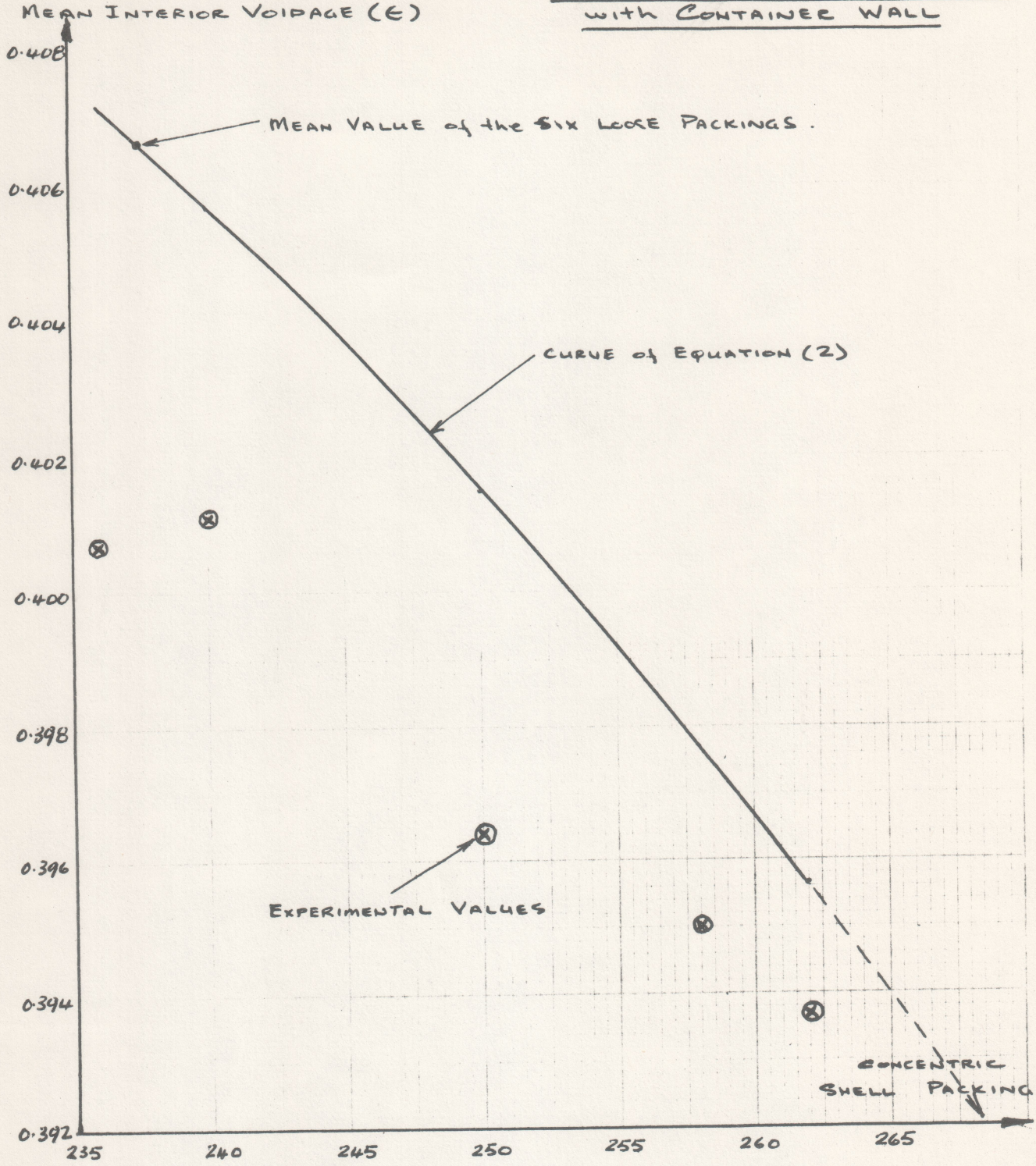
The mechanism of packing of such beds is discussed. As their aerodynamic resistance is of considerable practical importance in cupola operation, pressure drop measurements were undertaken. Empirical expressions relating pressure drop to voidage and the volumetric mean diameter of particles were derived from graphical correlations.

Results of this work have shown how great is the significance of coke size and bed voidage in cupola and blast furnace operation, and have indicated practical ways of controlling these process variables so as to achieve better plant performance.


FIGURE (1) MEAN INTERIOR VOIDAGE
v
AVERAGE NUMBER of POINTS
of CONTACT in INTERIOR REGION
MEAN INTERIOR VOIDAGE (ε)
0·40
0·38
0·36
0·34
0·32
0·30
0·28
0·26
0·24
RANDOM
PACKINGS
BERNAL & MASON
CURVE of EQUATION (1)
CONCENTRIC SHELL
PACKING
RHOMBOHEDRAL
PACKING
0
2
4
6
8
10
12
AVERAGE NUMBER of POINTS of CONTACT (Mc)

Page No. 1.5(1)

FIGURE (2) MEAN INTERIOR VOIDAGE
V
NUMBER of SPHERES in CONTACT
with CONTAINER WALL



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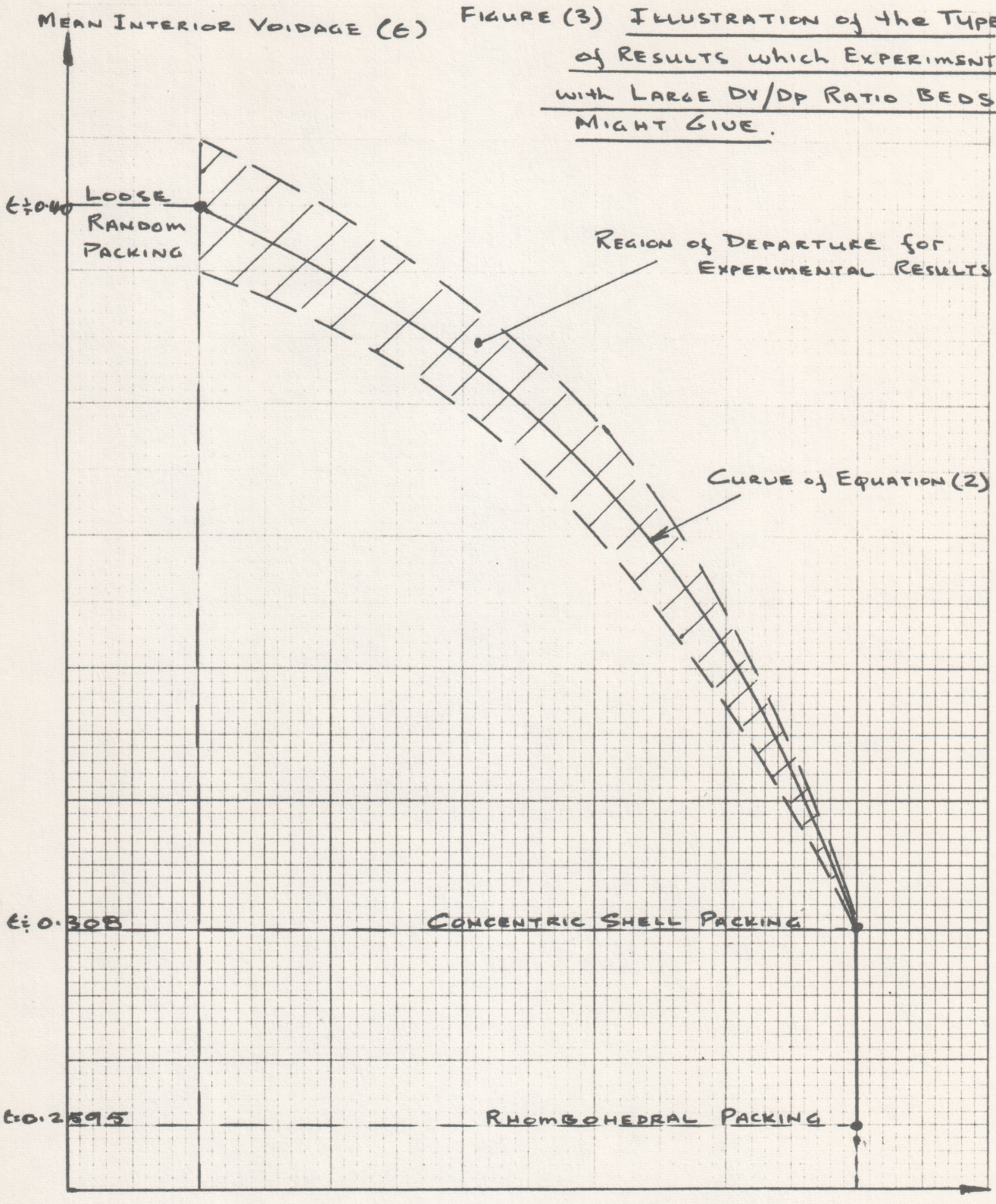


FIGURE (3) ILLUSTRATION of the TYPE of RESULTS which EXPERIMENTS with LARGE DV/Dp RATIO BEDS MIGHT GIVE.

Packing No. 1.5(3)

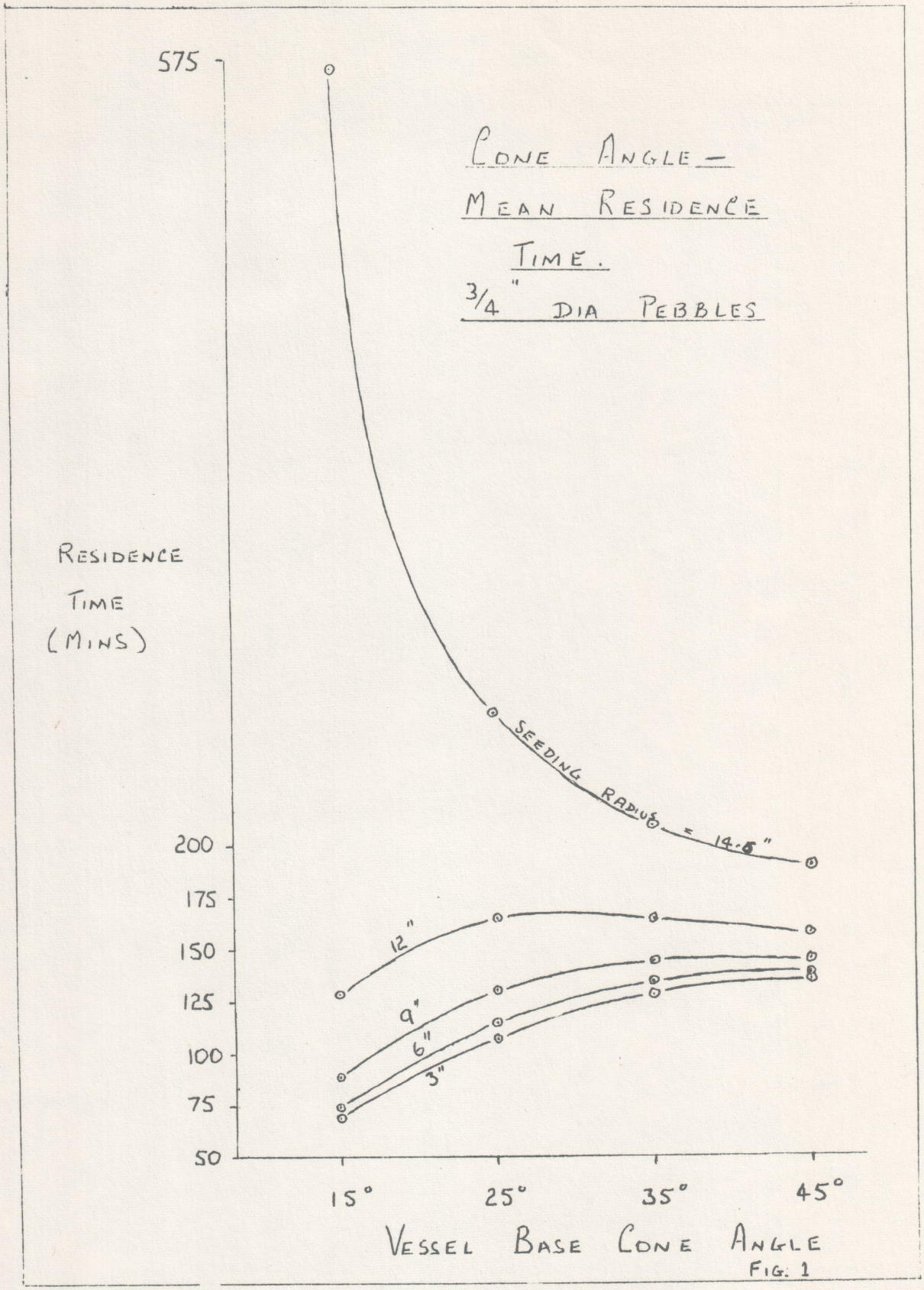


FIG. 1

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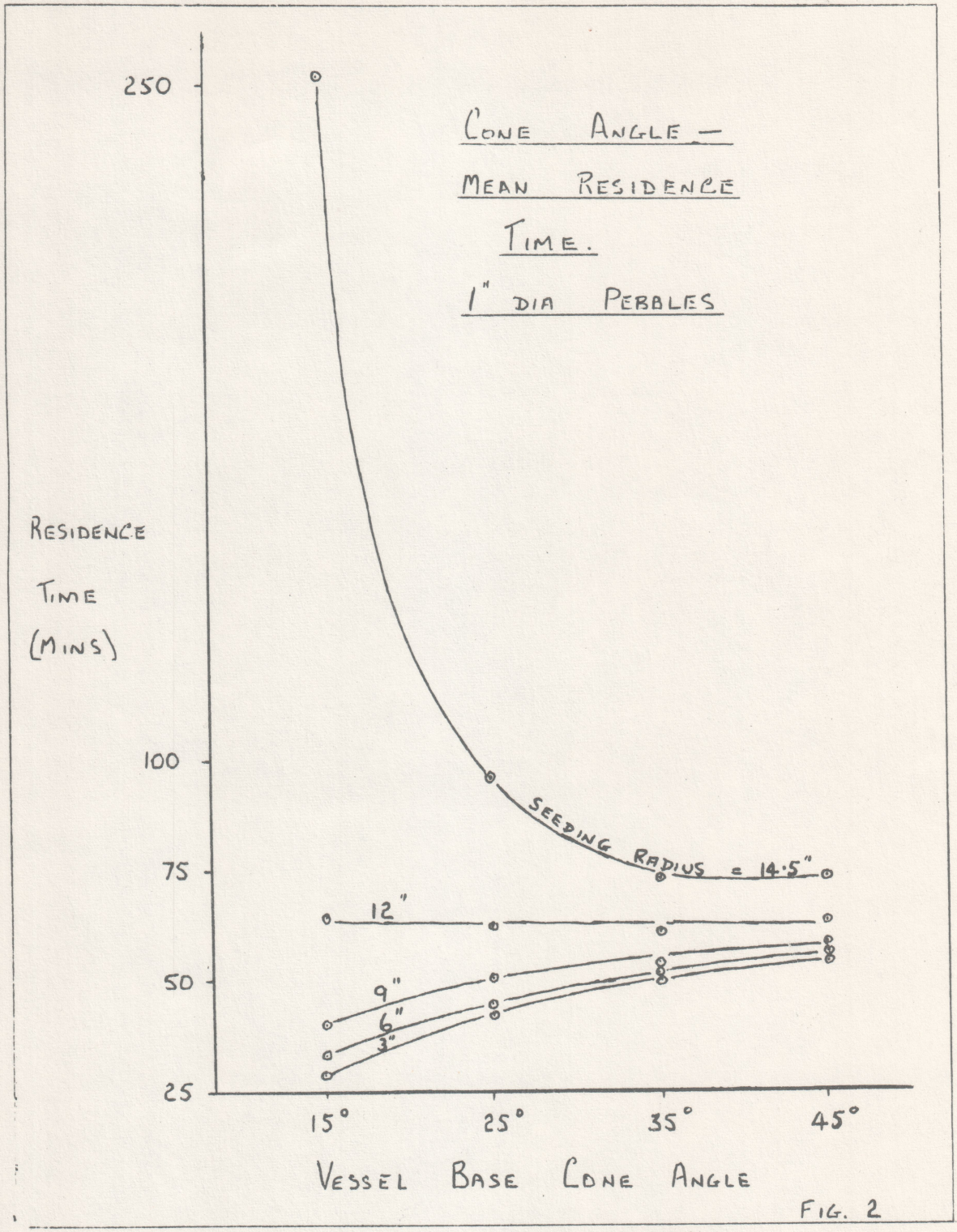
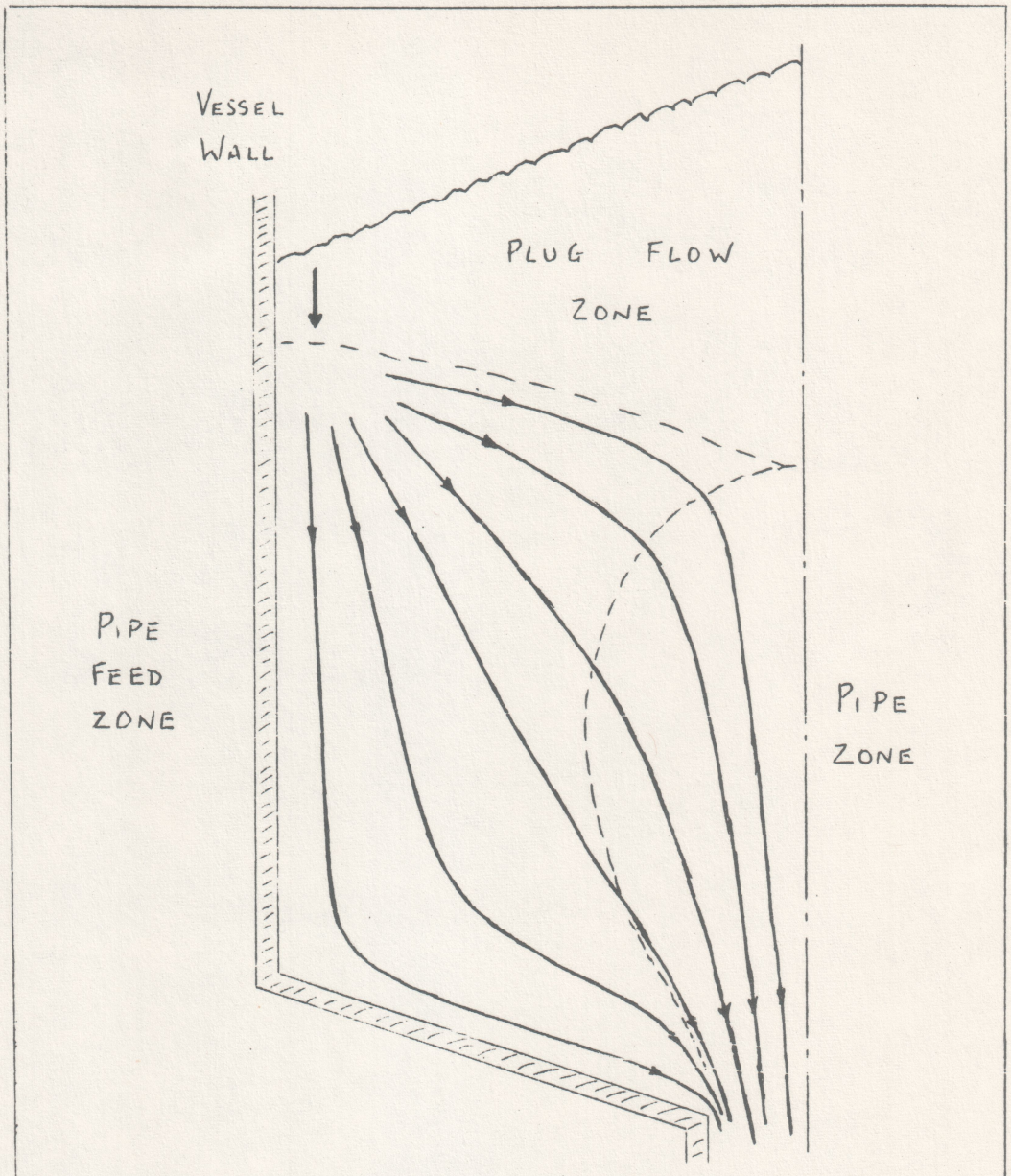


FIG. 2

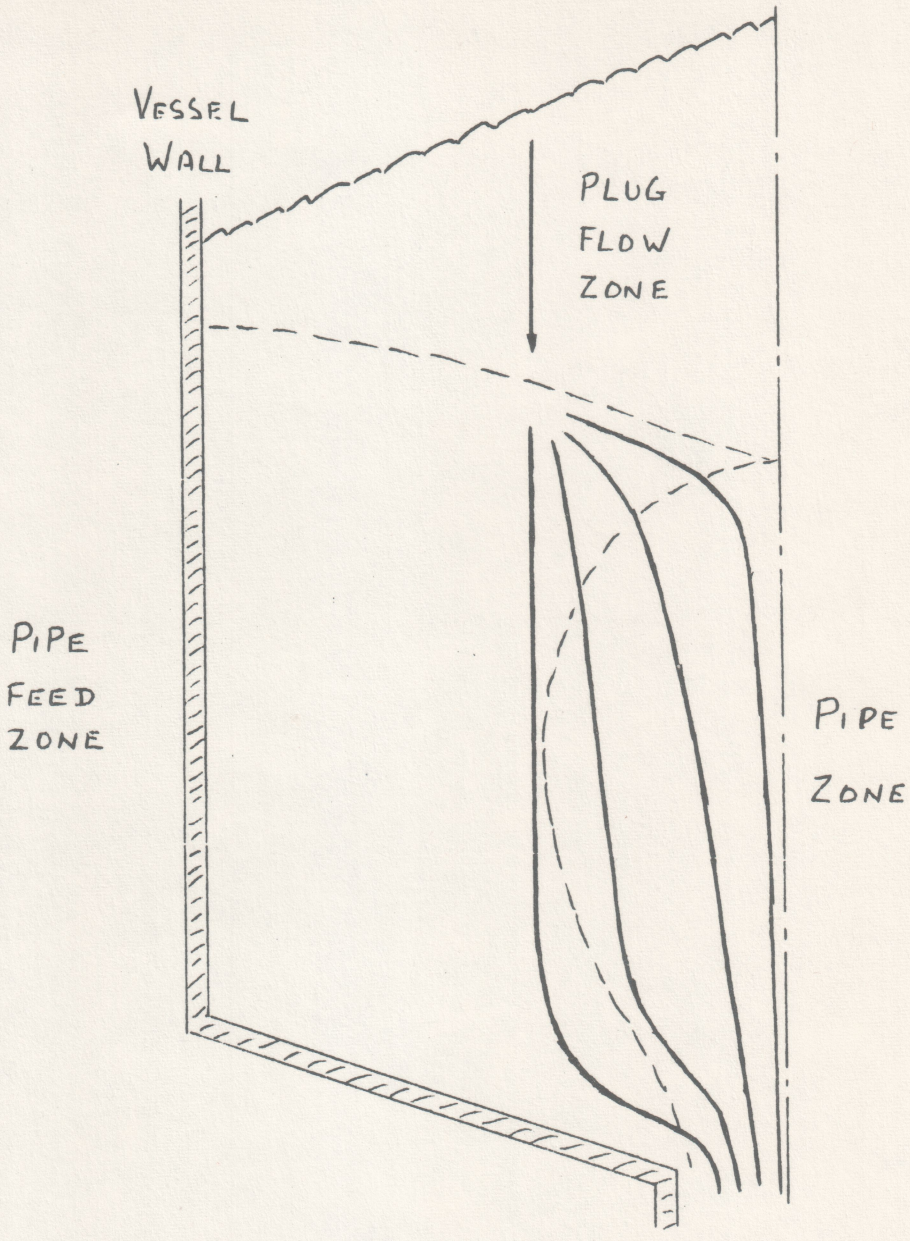
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POSSIBLE PATHS OF PEBBLE SEEDED AT VESSEL WALL.

FIG. 3

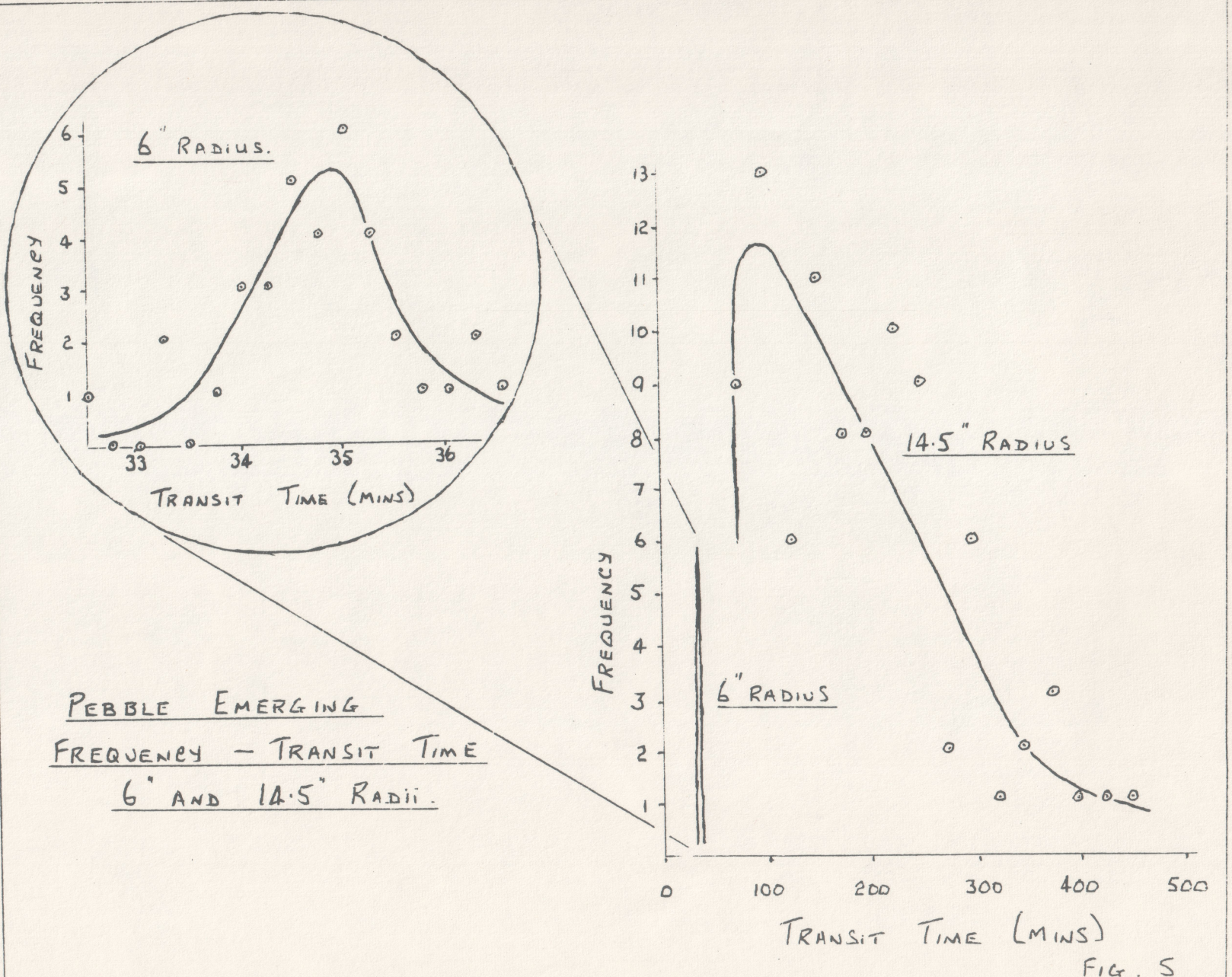
paper No. 1.7(3)



POSSIBLE PATHS OF PEBBLE
SEEDED AT ARBITRARY RADIUS

FIG. 4

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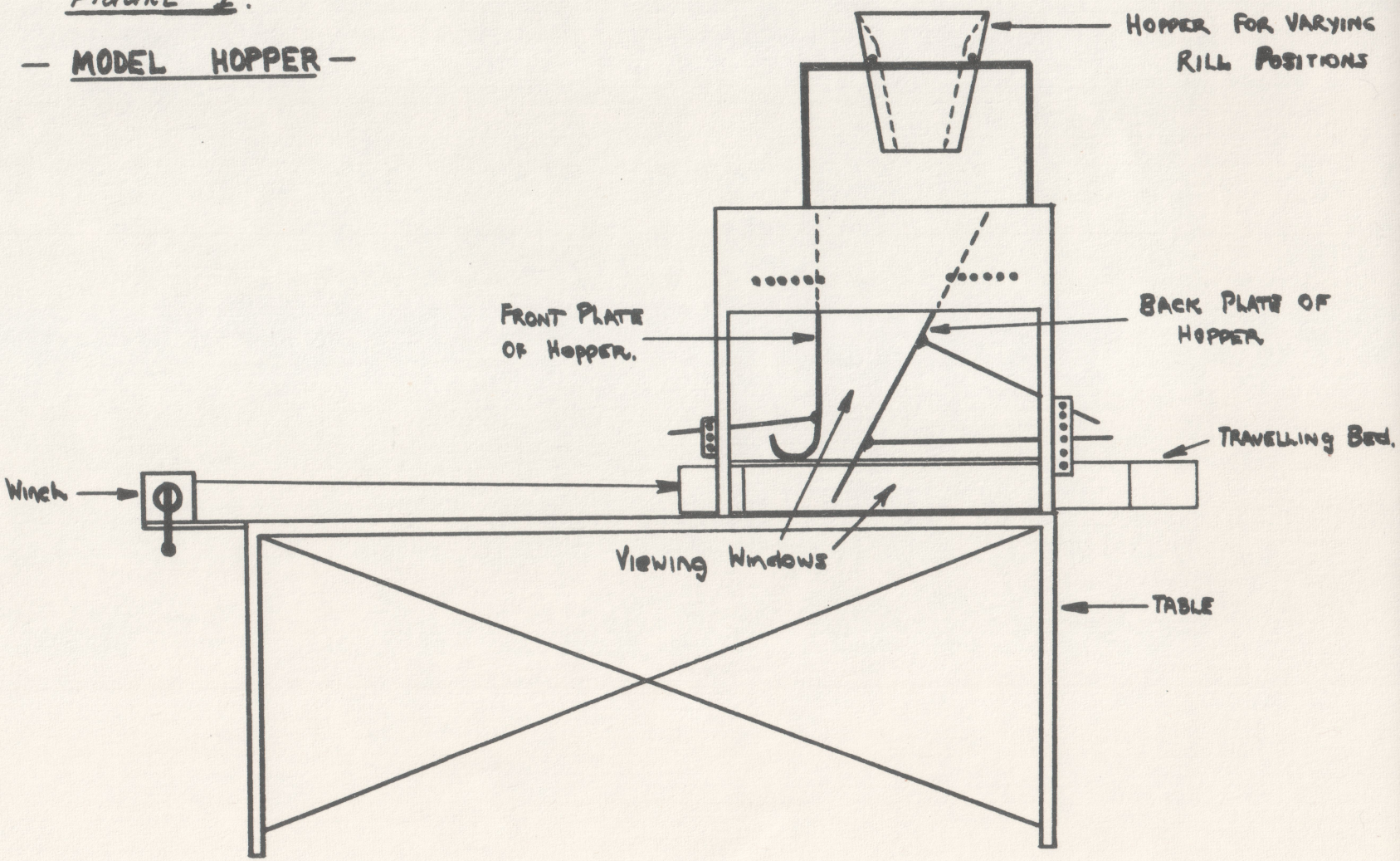


Pebble Emerging
Frequency – Transit Time
6" and 14·5" Radii.

Fig. 5

FIGURE I.

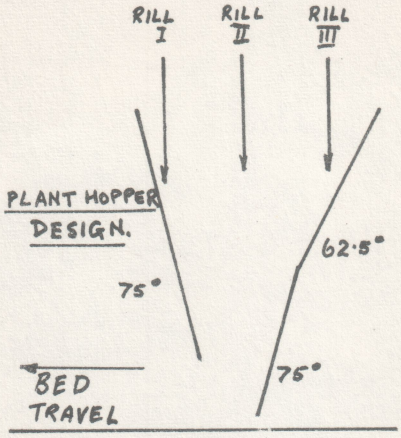
— MODEL HOPPER —



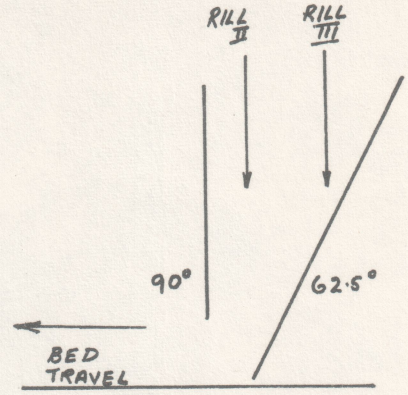
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FIGURE II

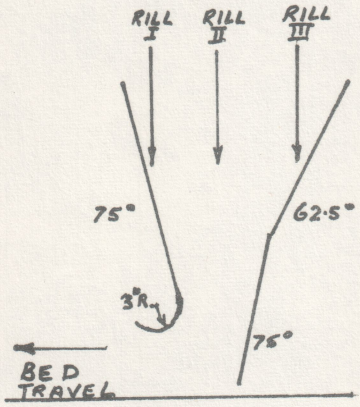
HOPPER CONFIGURATIONS STUDIED.



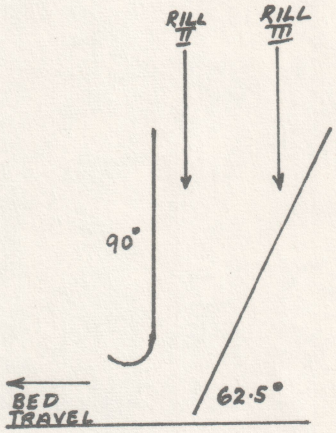
CONFIGURATION 1.



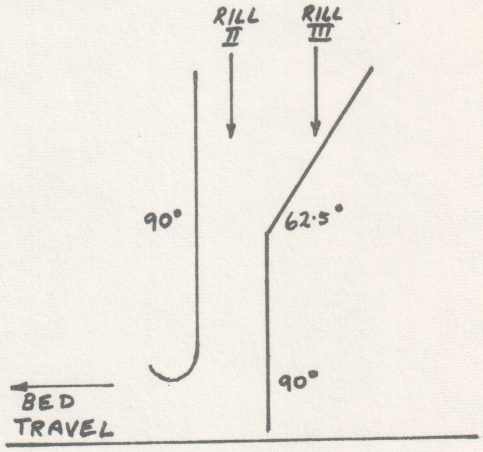
CONFIGURATION 2.



CONFIGURATION 3.



CONFIGURATION 4.



CONFIGURATION 5.

Paper No. 2 (2)

(Arrows indicate relative velocities)

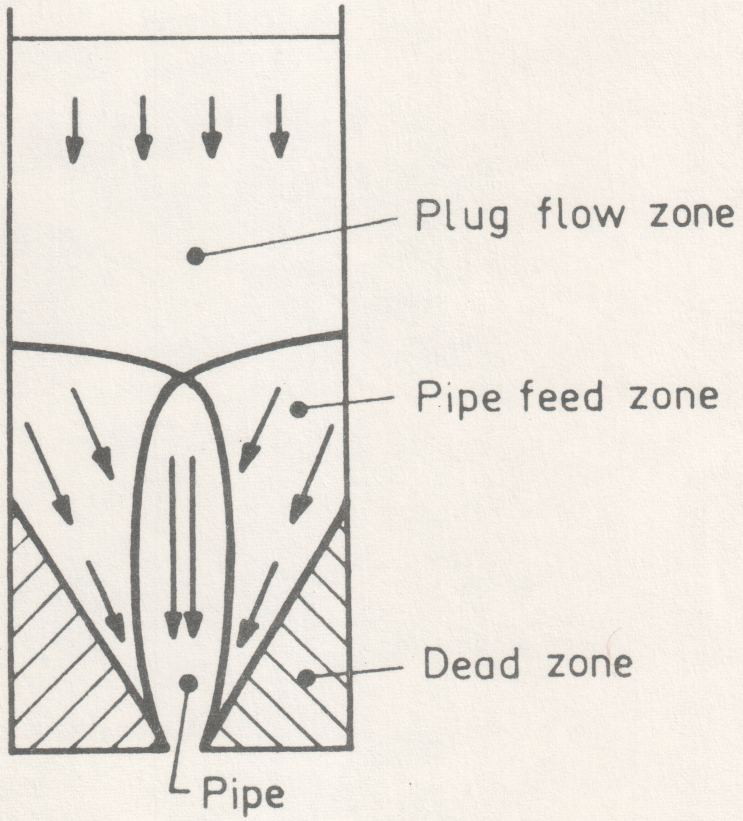


Fig. 1. Flow Patterns.

paper No. 3.3