AAEC/E.16

STUDIES OF SMALL PARTICLE SUSPENSIONS FOR L.M.F.R.

PART II FLUID FLOW WITH SUSPENSIONS

SIMULATING THE UBe_{13}–Na SYSTEM

by

R. C. Cairns

K. S. Turner

Abstract

Suspensions of barium sulphate in water at concentrations of up to 16.5% w/w were circulated in a 1–inch loop to simulate the behaviour of the UBe_{13}–Na system for L.M.F.R.

In a horizontal pipe the mean velocity for the formation of a moving bed was 1.6 feet per second and the mean velocity for the formation of a stationary bed was 1.4 feet per second. The corresponding mean Reynolds numbers were 15,000 and 13,000 respectively.

No agreement was found with Dallavalle's (2) equation previously suggested (1) for calculating the horizontal settling velocities.

For fully suspended flow, friction factors were the same as for clean water providing the density and viscosity terms in the Reynolds number related to the suspension.

The validity of the Orr and Dallavalle (5) viscosity equation for such systems was confirmed and non–Newtonian relationships were not required.

Striations similar to those previously reported for the tungsten–water system, were observed before and during settling.

TABLE OF CONTENTS

1. INTRODUCTION

Continuing on the tungsten water studies, (1), data have been collected for the barium sulphate–water system. This suspension was chosen to simulate the UBe_{13}–Na system for L.M.F.R. and to provide further data on suspensions with particles of sub–sieve size.

Precipitated barium sulphate was selected for the following reasons:–

(a) The effective densities (solid density minus liquid density) of UBe_{13} in sodium and precipitated barium sulphate in water are comparable, being 3.5 g/cc for both systems.

(b) The medium viscosities are comparable.

(c) Sub–sieve size barium sulphate is readily available.

For the UBe_{13}–Na system the volume ratio of UBe_{13} to Na corresponding to the 1 to 100 atomic ratio of U to Na is 1 to 34.8, assuming UBe_{13} to have a density of 4.4 g/cc at 500°C. On a volume concentration comparison and using 4.5 g/cc for the density of barium sulphate, this gives a mass ratio of 1 to 7.7 for the barium sulphate–water suspension or 11.5% by weight barium sulphate.

In the experimental work, mean initial concentrations of up to 16.5 per cent by weight were circulated.

2. EXPERIMENTAL APPARATUS

The loop shown in figures 1a and 1b, had the same general arrangement as that used for the tungsten–water studies. The modifications made included the use of stainless steel for the measuring tank, supply tank and pump, and stainless steel diaphragm valves throughout. The copper tube was replaced by a Dicon cellulose acetate butyrate tube so that the flow pattern over the full length of the tube could be observed. The diameter of the tube was measured at the pressure tapping holes and the ends. The diameter was calculated also from the volume of water held by the tube. The mean diameter from all these results was 1.004 inches.

The method of loop operation and collection of results were identical to that for the previous loop. It was found necessary to have density determinations with corrections for ambient temperature made on the monochlor–benzene and carbon tetrachloride manometer fluids for the pressure drop runs.

No difficulties were experienced in keeping the concentration of the $BaSO_4$ circulating constant, samples being taken from the discharge.

The precipitated barium sulphate used was Blanc Fixe, manufactured by Farbenfabriken Bayer, A.G., of Germany and supplied by H.H. York of Sydney.

Demineralised water was used for all suspensions. The mean particle size distribution of the precipitated barium sulphate before use was determined using the Andreasen method. The distribution using the Sharples Micromerograph was also obtained on powder before use. These are given in Table I. The wide differences in results obtained using the two methods illustrates the lack of correlation between different methods of particle size analysis for sub–sieve particles. Both these methods involve sedimentation but the Andreasen technique uses water as the sedimentation medium and the Micromerograph uses air.

It was not possible to obtain reproducible Andreasen analyses with samples of barium sulphate after use because of difficulties of sample preparation. Results varied from 14 per cent to 40 per cent by weight less than 15 microns. It was not convenient to attempt particle size analysis of material after use with the Micromerograph as the equipment was located in the U.S.A.

3. RESULTS AND DISCUSSION

The friction factor – Reynolds number correlation was determined for the Dicon tube with clean water. The results for this are given in Table II and are plotted in figure (2). The data were also plotted as head loss versus velocity, shown in figure (3). It was noticed that the friction factors for the Dicon tube were 5–10 per cent above the smooth tube curve for clean water over the Reynolds number range covered. This is in agreement with results supplied by Die Casters Ltd., 126 Cromwell Street, Collingwood, N.5., Victoria, Australia, who manufactured the tube.

Mean initial concentrations of approximately 5, 10 and 16.5 per cent by weight of barium sulphate were circulated. Horizontal settling velocity and pressure drop runs were made at each concentration. Concentrations were determined by drying and weighing a sample of the discharge.

(a) Horizontal Settling Velocities

The results for the horizontal settling velocities are given in Table III. These were determined by reducing the flow rate and observing the point at which settling first appeared in the Dicon tube.

The condition of a moving bed for this system was found to be much more reproducible than in the tungsten–water system. It was possible to determine the velocity at which a moving bed formed and the velocity at which an apparent stationary bed formed. This was done for mean initial concentrations of 5.5, 9.6 and 16.2 per cent barium sulphate and ten separate runs were done for each concentration. At the higher concentrations, it was more difficult to determine these velocities because of the denser medium. The horizontal settling velocity for the barium sulphate–water system was taken as the mean velocity at which a moving bed was first visually observed. The results in Table III have been summarised in Table IV. The mean horizontal settling velocity is 1.6 feet per second with the mean Reynolds number of 15,000. Little influence of concentration on settling velocity was noted over the concentration range covered. The velocity for the formation of an apparent stationary bed was 1.4 feet per second and the mean Reynolds number for this was 13,000.

It had been suggested previously (1) that the equation of Dallavalle (2) for predicting transport velocities of solids in air may be applicable for evaluating the settling velocities of small particles in liquids. It was shown that this equation did predict the right order of velocities required for several systems. However, using the 85 percent undersize diameter for the barium sulphate, this equation gave a value of 5.9 feet per second compared to the experimental value of 1.6 feet per second. This large difference is sufficient evidence to reject Dallavalle's equation for predicting horizontal settling velocities.

For the barium sulphate–water system, the classification by Durand and Condolios (3) and Newitt et al (4) is also not valid, since fully turbulent conditions with Reynolds numbers greater than 15,000 are required to prevent settling in the horizontal 1-inch pipe used.

(b) Pressure Drop

Pressure drop runs were made at mean initial concentrations of 5.3, 9.6 and 16.5 per cent barium sulphate. The experimental results and calculated data are given in Table V. They are plotted in figures (4) and (5) as friction factors versus Reynolds number, and head loss in feet of suspension per foot of pipe versus velocity, respectively.

The densities used in the calculations were mean densities calculated from the densities of barium sulphate and water and the concentration. The viscosities of all suspensions were calculated from the Orr and Dallavalle (5) equation used previously for the tungsten–water system. The results for the settled volume on the barium sulphate–water system are given in Table VI. The mean settled volume was 0.25.

In figure (4) the data for fully suspended flow are in excellent agreement with the clean water line. As no difficulties due to dissolution of solid were present, this tends to confirm the use of the Orr and Dallavalle (5) viscosity equation, when it is remembered that the viscosity calculated for the most concentrated suspension was approximately 40 per cent greater than the water viscosity. In figure (5) the data are seen to diverge from the clean water line at the velocities at which a bed forms. This divergence is not readily detected on linear plots of the same data. It was also noticed that after settling, runs in which the velocity is progressively increased give higher pressure losses, due to previous build up of deposited solid.

(c) Striations

The striations observed with the tungsten–water suspension were again observed with the barium sulphate–water system. These could be clearly seen as lines of more concentrated suspension moving along the lower curved surface of the test length. Negative striations were also observed. These appeared as lines of less concentrated suspension moving in the top half of the test length. With the test length illuminated with a 1000 watt Aldis projector, these striations were clearly seen with the naked eye.

Attempts were made to photograph the striations but considerable difficulty was encountered in obtaining suitable contrast. Figure (6) shows striations with an approximately 5 per cent barium sulphate suspension at a velocity of 1.4 feet per second, i.e., after settling has occurred. In this particular run a moving bed was present at these conditions but this bed cannot be seen in the photograph.

(d) Settling After Shut–down

It was observed that each time the loop was closed down, solid suspended in the six feet vertical leg in the loop, settled out and partially or completely blocked the elbow from the horizontal pipe. The degree of blockage depended on the concentration, but for the highest concentration used of 16.5 per cent by weight or only 4.2 per cent by volume, complete blockage resulted. Figures (7) and (8) are photographs of the observed build up.

No difficulties were encountered in resuspending the solid blocking the elbow the following day.

At the completion of all experimental work, the supernatant liquid was analysed and the total dissolved solids was found to be less than 0.03 per cent by weight.

4. FURTHER WORK

Further work should include an experimental investigation of horizontal settling velocities for other systems, and an attempt should be made to correlate all available data on horizontal settling velocities in order to predict these for other systems.

It is not considered necessary to do any more work on pressure drop characteristics for other aqueous systems as it has been shown that dilute suspensions of sub–sieve particles of powder and barium sulphate in water in fully suspended flow, behave as normal liquids provided the viscosity and density used are those of the suspension.

The work on concentration gradients should continue.

5. ACKNOWLEDGMENTS

Acknowledgments are due to Mr. E.J. Lee, who assisted with the experimental work, Mr. R.B. Beer, who drew the graphs, Mr. C.L.W. Berglin who gave much helpful advice, and the Analytical Chemistry Services Group who carried out all analytical work.

6. SYMBOLS

Re	=	Reynolds number, dimensionless.
f	=	Fanning friction factor, dimensionless.
D	=	pipe internal diameter, ft.
V	=	velocity, ft./sec.
ρ	=	density of water, lb/cu.ft.
ρ_s	=	density of suspension, lb/cu.ft.
μ	=	viscosity of water, lb/(ft)(sec.)
μ_s	=	viscosity of suspension, lb/(ft)(sec).

7. REFERENCES

(1) Cairns, R.C., and Turner, K.S., AAEC/E.5, August, (1957).

(2) Dallavalle, J.M., "Micromeritics," Second Edition, Pitman Publishing Corporation, page 385, (1948).

(3) Durand, R., and Condolios, E., Proceedings of a Colloquium on the Hydraulic Transport of Coal, (National Coal Board, London), Paper IV, page 39, (1952).

(4) Newitt, D.M., Richardson, J.F., Abbott, M., and Turtle, R.B., Trans. Instn. Chem. Engrs., 33, 93, (1955).

(5) Orr, C., and Dallavalle, J.M., Chem. Eng. Prog. Symposium Series, Vol. 50, No. 9, page 29, (1954).

8. APPENDIX.

NOTE: Four significant figures were used to avoid cumulative errors in the calculations.

TABLE I

PARTICLE SIZE ANALYSIS OF BARIUM SULPHATE USED

Stokes Diameter Microns	Percentage Undersize by Weight	
	Andreasen	Micromerograph
35	85	–
30	50	–
25	27	–
20	16	–
15	9	–
10	5	98
5	2	63

TABLE II

PRESSURE DROP DATA FOR CLEAN WATER IN DICON TUBE.

Run	Temperature. °C.	Deflection.	Time secs.	Discharge nett.	Velocity ft/sec.	Head Loss ft/ft.	Reynolds Number.	Friction Factor.
		cm. Hg.		cu.ft.				
21.1	24.5	9.0	26.0	2.313	16.18	0.933	139,000	0.0048
.2	25.0	8.1	28.0	2.340	15.20	0.840	132,000	0.0049
.3	25.0	5.7	33.4	2.303	12.54	0.591	109,000	0.0051
.4	25.5	4.1	41.8	2.372	10.32	0.425	90.300	0.0054
		cm. CCl_4.						
.5	26.0	61.2	50.8	2.398	8.586	0.295	75,800	0.0054
.6	26.0	44.0	61.0	2.393	7.136	0.212	63,200	0.0056
.7	26.5	32.0	70.4	2.319	5.992	0.154	53,500	0.0058
.8	27.0	23.4	83.8	2.319	5.033	0.113	45,500	0.0060
.9	27.0	15.8	104.4	2.324	4.049	0.0762	36,600	0.0063
.10	27.0	11.7	123.0	2.361	3.492	0.0564	31,600	0.0062
				lb.				
.11	27.5	7.7	29.0	26.65	2.688	0.0371	24,500	0.0069
.12	27.5	5.7	29.6	23.40	2.312	0.0275	21,100	0.0069
.13	28.0	3.5	37.0	21.86	1.728	0.0169	15,900	0.0076
		cm. C_6H_5Cl.						
.14	28.0	16.0	43.2	23.28	1.576	0.0136	14,500	0.0074
.15	28.5	11.0	53.4	23.13	1.267	0.00936	11,800	0.0079
.16	28.5	6.3	69.0	21.72	0.9208	0.00536	8,600	0.0085
.17	29.0	4.1	87.4	21.33	0.7140	0.00349	6,740	0.0092

TABLE II (contd.)

PRESSURE DROP DATA FOR CLEAN WATER IN DICON TUBE (contd.)

Run	Temperature. °C.	Deflection.	Time. Secs.	Discharge nett.	Velocity ft/sec.	Head Loss ft/ft.	Reynolds Number.	Friction Factor.
		cm. C_6H_5Cl.		lb.				
21.18	29.5	4.9	76.6	20.79	0.7938	0.00417	7,590	0.0089
.19	29.5	8.8	53.6	20.56	1.122	0.00749	10,700	0.0080
.20	29.5	14.2	46.2	23.34	1.478	0.0121	14,100	0.0075
		cm. CCl_4.						
.21	29.5	3.5	38.2	22.71	1.739	0.0169	16,600	0.0075
.22	29.5	5.6	31.4	24.59	2.291	0.0270	21,900	0.0069
.23	29.5	7.7	27.8	25.52	2.685	0.0371	25,700	0.0069
				cu.ft.				
.24	29.5	11.8	103.2	1.958	3.451	0.0569	33,000	0.0064
.25	29.5	16.2	85.2	1.926	4.113	0.0781	39,300	0.0062
.26	29.5	24.2	68.0	1.932	5.168	0.117	49,400	0.0059
.27	29.5	31.7	60.4	1.995	6.008	0.153	57,400	0.0057
.28	29.5	44.4	56.0	2.224	7.223	0.214	69,000	0.0055
.29	30.0	62.6	50.4	2.414	8.713	0.302	84,300	0.0054
		cm.Hg.						
.30	30.0	4.0	41.0	2.351	10.43	0.415	101,000	0.0051
.31	30.0	6.6	31.0	2.356	13.82	0.684	134,000	0.0048
.32	30.5	8.9	26.6	2.361	16.15	0.923	158,000	0.0048

TABLE II (contd.)

PRESSURE DROP DATA FOR CLEAN WATER IN A DICON TUBE (contd.)

Run	Temperature. °C.	Deflection.	Time secs.	Discharge nett.	Velocity, ft/sec.	Head Loss ft/ft.	Reynolds Number.	Friction Factor.
		cm.Hg.		cu.ft.				
23.1	29.0	8.7	25.6	2.276	16.17	0.901	153,000	0.0046
.2	29.5	3.7	42.0	2.337	10.12	0.383	96,700	0.0050
		cm.CCl_4.						
.3	30.0	14.8	90.4	1.956	3.936	0.0696	38,100	0.0061
				lb.				
.4	30.5	4.2	33.2	21.85	1.925	0.0198	18,800	0.0072
.5	31.0	7.5	25.6	23.73	2.711	0.0353	26,800	0.0065
				cu.ft.				
.6	31.0	32.1	59.2	1.981	6.086	0.151	60,100	0.0055
		cm.Hg.						
.7	31.5	6.0	31.8	2.333	13.34	0.621	133,000	0.0047

TABLE III

SETTLING VELOCITY DATA

	Run	Temp-erat-ure. °C.	Time secs.	Dis-charge nett. lb.	% $BaSO_4$ w/w.	Velocity ft/sec.	Reynolds Number.	Observations.
Data from Settling Velocity Experiments	15.1a	29.0	37.8	23.96	5.4	1.78	16,000	Before settling.
	b	29.0	44.4	23.67	5.4	1.50	13,400	Moving bed.
	c	30.0	48.4	23.34	5.3	1.35	12,500	Apparently stationary bed.
	15.2a	32.5	44.0	23.83	5.8	1.52	14,700	Before settling.
	b	34.0	44.8	24.11	5.3	1.51	15,100	Moving bed.
	c	34.5	49.0	23.39	5.3	1.34	13,500	Apparently stationary bed.
	15.3a	35.0	43.8	22.94	5.3	1.47	15,000	Moving bed.
	b	36.0	48.4	23.52	5.6	1.36	14,100	Apparently stationary bed.
	15.4a	37.0	47.8	24.11	5.6	1.42	15,000	Moving bed.
	b	37.0	48.8	24.12	5.8	1.39	14,700	Apparently stationary bed.
	15.5a	38.5	45.4	25.01	5.7	1.55	16,800	Before settling.
	b	39.0	44.6	23.49	5.4	1.48	16,300	Moving bed.
	15.6a	40.0	44.0	23.09	5.3	1.47	16,500	Before settling.
	b	40.5	49.0	23.18	5.2	1.33	15,000	Moving bed.
	c	41.0	53.4	23.91	5.4	1.26	14,400	Apparently stationary bed.
	15.7a	29.5	40.2	24.01	5.8	1.68	15,200	Before settling.
	b	30.0	44.4	23.30	5.3	1.47	13,600	Moving bed.
	15.8a	31.5	40.6	24.10		1.67	15,800	Before settling.
	b	32.5	44.6	23.74	5.4	1.49	14,500	Moving bed.
	15.9a	34.0	42.2	23.51	5.3	1.56	15,600	Before settling.
	b	34.0	50.4	24.56	5.	1.37	13,700	Moving bed.
	c	34.0	50.8	24.42	5.2	1.35	13,500	Apparently stationary bed.
	15.10a	35.0	41.6	23.81	5.4	1.61	16,400	Before settling.
	b	35.5	47.4	23.98	5.3	1.42	14,600	Moving bed.

TABLE III (contd.)

SETTLING VELOCITY DATA (contd.)

	Run	Temperature. °C.	Time secs.	Discharge nett. lb.	% $BaSO_4$ w/w.	Velocity ft/sec.	Reynolds Number.	Observations.
Data from Settling Velocity Experiments (contd.)	17.1a	26.5	27.2	25.26	9.6	2.51	20,400	Before settling.
	b	29.0	38.8	25.04		1.75	15,000	Moving bed.
	17.2a	31.0	39.2	26.27	9.6	1.81	16,300	Before settling.
	b	31.0	43.8	25.72		1.59	14,300	Moving bed.
	17.3a	34.5	32.0	21.56	10.0	1.82	17,600	Before settling.
	b	35.0	40.4	24.15		1.62	15,700	Moving bed.
	17.4a	36.0	36.0	23.19	9.7	1.74	17,300	Before settling.
	b	36.0	41.8	24.20		1.57	15,500	Moving bed.
	c	37.0	46.4	24.74		1.44	14,600	Apparently stationary bed.
	17.5a	37.0	35.2	21.51	9.7	1.65	16,700	Before settling.
	b	37.5	45.4	25.62		1.53	15,600	Moving bed.
	c	38.0	48.0	25.31		1.43	14,700	Stationary bed.
	17.6a	38.5	38.6	23.46	9.7	1.65	17,100	Before settling.
	b	38.5	45.2	24.35		1.46	15,200	Moving bed.
	c	39.0	46.4	23.96		1.40	14,700	Apparently stationary bed.
	17.7a	39.0	40.6	24.69	9.7	1.65	17,300	Before settling.
	b	39.0	46.6	24.34		1.41	14,900	Moving bed.
	c	39.0	47.6	24.26		1.38	14,500	Apparently stationary bed.
	17.8a	29.0	31.4	23.41	9.5	2.02	17,300	Before settling.
	b	30.0	37.0	24.82		1.82	16,000	Moving bed.
	c	31.5	44.6	23.79		1.44	13,100	Apparently stationary bed.
	17.9a	32.0	37.0	24.13	9.4	1.77	16,200	Before settling.
	b	32.5	43.4	25.11		1.57	14,500	Moving bed.
	c	34.0	47.6	25.23		1.44	13,700	Apparently stationary bed.
	17.10a	34.0	36.8	22.10	9.5	1.63	15,500	Before settling.
	b	34.5	47.8	24.04		1.36	13,100	Apparently stationary bed.

TABLE III (contd.)

SETTLING VELOCITY DATA (contd.)

	Run	Temperature. °C.	Time secs.	Discharge nett. lb.	% $BaSO_4$ w/w.	Velocity ft/sec.	Reynolds Number.	Observations.
Data from Settling Velocity Experiments (contd.)	19.1a	31.5	39.8	28.27	15.3	1.83	15,200	Before settling.
	b	32.0	46.8	27.04		1.49	12,600	Moving bed.
	c	33.0	49.2	27.02		1.41	12,200	Apparently stationary bed.
	19.2a	36.0	38.8	25.62	15.9	1.70	15,500	Before settling.
	b	36.0	41.8	25.43		1.57	14,300	Moving bed.
	19.3a	37.0	36.4	24.60	15.6	1.74	16,200	Before settling.
	b	37.5	40.2	26.69		1.71	16,100	Moving bed.
	19.4a	38.5	36.0	25.39	15.6	1.81	17,400	Before settling.
	b	38.5	43.6	25.62		1.51	14,500	Moving bed.
	19.5a	32.0	36.4	25.98	16.9	1.82	15,100	Before settling.
	b	32.5	43.8	27.75		1.61	13,500	Moving bed.
	c	33.0	46.6	26.10		1.43	12,100	Apparently stationary bed.
	19.6a	34.0	39.2	25.73	16.7	1.67	14,400	Moving bed.
	19.7a	36.5	34.0	26.98	16.6	2.02	18,300	Before settling.
	b	37.0	39.4	26.64		1.72	15,700	Moving bed.
	19.8a	38.0	43.0	28.15	16.7	1.67	15,500	Before settling.
	b	38.5	42.0	26.19		1.59	15,000	Moving bed.
	c	39.0	51.2	27.56		1.37	13,100	Stationary bed.
	19.9a	26.0	31.2	25.41	16.6	2.07	15,100	Before settling.
	b	26.5	39.0	26.55		1.73	12,700	Moving bed.
	c	29.0	43.8	25.52		1.48	11,500	Apparently stationary bed.
	19.10a	29.5	34.6	26.54	16.7	1.95	15,300	Before settling.
	b	30.0	39.6	26.34		1.69	13,500	Moving bed.
	d	33.0	47.6	26.42		1.41	12,000	Stationary bed.

TABLE III (contd.)

SETTLING VELOCITY DATA (contd.)

	Run	Temperature. °C.	Time secs.	Discharge nett.	% $BaSO_4$ w/w.	Velocity ft/sec.	Reynolds Number.	Observations.
Additional data from pressure drop experiments.				lb.				
	14.3	27.5	30.2	21.24	-	1.972	17,400	Before settling.
	.4	28.5	45.0	21.66	4.9	1.354	12,200	Moving bed.
	.5	29.5	60.6	20.32	4.0	0.9502	8,700	Apparently stationary bed.
	.9	31.5	45.4	22.65	-	1.410	13,500	Before suspending.
	.10	32.5	33.2	22.77	5.3	1.923	19,000	After suspending.
	18.12	35.0	36.8	24.45	9.6	1.802	17,500	Before settling.
	.13	35.5	40.6	24.06	9.6	1.608	15,800	Moving bed.
	.14	36.0	41.4	23.17	9.7	1.519	15,000	Moving bed.
	.15	36.0	43.6	22.33	9.6	1.390	13,700	Moving bed.
	.19	37.0	37.2	23.25	9.5	1.695	17,100	Before suspending.
	.20	37.5	31.4	25.75	9.5	2.225	22,700	After suspending.
	20.12	30.0	33.2	27.64	-	2.126	17,000	Before settling.
	.13	31.0	38.2	28.33	16.5	1.894	15,400	Moving bed.
	.14	31.0	35.0	24.01	16.5	1.752	14,300	Moving bed.
	.15	32.0	41.4	25.03	16.4	1.544	12,800	Moving bed.
	.16	32.5	44.8	25.12	16.5	1.432	12,000	Stationary bed.
	.18	33.5	46.6	25.06	16.4	1.375	11,800	Before suspending.
	.19	33.5	35.4	25.12	16.5	1.812	15,500	Almost suspended.
	.20	34.0	35.0	24.68	16.5	1.799	15,600	Moving bed.
	.21	34.5	34.8	26.20	16.5	1.921	16,700	After suspending.
	22.14	29.5	39.6	23.97	5.3	1.701	15,500	Before settling.
	.15	30.0	45.6	24.70	5.3	1.522	14,000	Moving bed.
	.16	30.5	51.2	24.98	5.2	1.372	12,700	Stationary bed.
	.22	34.0	48.4	24.05	5.4	1.395	14,000	Moving bed.
	.23	35.0	35.4	24.44	5.5	1.937	19,700	After suspending.

TABLE IV

SUMMARY OF DATA FROM SETTLING VELOCITY EXPERIMENTS

(excluding the additional data from pressure drop runs)

Mean Initial Concentration % w/w.	Mean Moving Bed Velocity ft/sec.	Mean Moving Bed Reynolds Number	Mean Stationary Bed Velocity ft/sec.	Mean Stationary Bed Reynolds Number	Temperature °C.
5.5	1.45	14,600	1.34	13,800	35
9.6	1.59	15,200	1.41	14,100	35
16.2	1.63	14,200	1.42	12,200	34
Means	1.6	14,700	1.4	13,400	35

TABLE V.

PRESSURE DROP DATA FOR BARIUM SULPHATE SUSPENSIONS.

Runs 14.4 to 14.9, 18.13 to 18.19, 20.13 to 20.30, 22.15 to 22.22, inclusive, are for settled conditions.

Run	Temperature °C.	Deflection.	Time. secs.	Discharge nett.	% $BaSO_4$ w/w.	Velocity ft/sec.	Head Loss ft. suspension/ft.	Reynolds Number.	Friction Factor.
		cm. CCl_4		cu.ft					
14.1	26.0	7.2	135.8	1.901	5.3	2.547	0.0338	21,800	0.0070
				lb.					
.2	27.0	4.9	30.2	22.75		2.112	0.0230	18,400	0.0070
.3	27.5	4.5	30.2	21.24		1.972	0.0212	17,400	0.0073
		cm. C_6H_5Cl							
.4	28.5	12.2	45.0	21.66	4.9	1.354	0.0103	12,200	0.0079
.5	29.5	8.2	60.6	20.32	4.0	0.9502	0.00696	8,700	0.0109
.6	30.5	14.1	71.2	19.79	4.0	0.7876	0.0120	7,300	0.0272
.7a	31.5	13.3	72.6	21.75	4.7	0.8442	0.0112	8,100	0.0222
.7b		13.0					0.0110		0.0217
.8a	31.5	12.8	61.6	20.80	4.4	0.9541	0.0108	9,100	0.0168
.8b		12.5					0.0106		0.0164
.9a	31.5	19.4	45.4	22.65		1.410	0.0164	13,500	0.0117
.9b		18.8					0.0159		0.0113
		cm. CCl_4							
.10a	32.5	4.3	33.2	22.77	5.3	1.923	0.0202	19,000	0.0074
.10b		4.3					0.0202		0.0074
.11a	33.0	7.9	27.2	26.59		2.741	0.0371	27,300	0.0067
.11b		7.9					0.0371		0.0067
				cu.ft					
.12a	33.0	13.1	95.2	1.907	5.3	3.643	0.0616	36,300	0.0061
.12b		12.8					0.0602		0.0063
.13	33.5	25.6	68.2	1.984	5.3	5.291	0.120	53,000	0.0058

PRESSURE DROP DATA FOR BARIUM SULPHATE SUSPENSIONS (contd.)

Run	Temperature. °C.	Deflection.	Time. secs.	Discharge nett.	% $BaSO_4$ w/w.	Velocity ft/sec.	Head Loss ft. suspension/ft.	Reynolds Number.	Friction Factor.
		cm.Hg.		cu.ft.					
18.1	28.0	8.7	27.0	2.256	9.6	15.20	0.837	127,000	0.0049
.2	29.0	5.5	35.8	2.329		11.83	0.529	101,000	0.0051
.3	29.5	3.9	43.4	2.340		9.808	0.375	85,000	0.0053
		$cm.CCl_4$							
.4	30.5	59.6	53.2	2.393		8.182	0.269	72,000	0.0054
.5	31.5	42.9	62.6	2.351		6.832	0.193	62,000	0.0056
.6	32.0	28.4	69.0	2.073	9.6	5.464	0.128	50,000	0.0058
.7	32.5	23.3	69.8	1.875		4.886	0.105	45,200	0.0059
.8	33.0	15.7	88.8	1.927		3.947	0.0708	36,900	0.0061
.9	34.0	10.3	109.8	1.880		3.114	0.0464	29,700	0.0065
.10	34.5	7.1	138.4	1.912		2.514	0.0320	24,200	0.0068
				lb.					
.11	34.5	5.8	30.2	25.37	9.5	2.279	0.0262	21,900	0.0068
.12	35.0	3.9	36.8	24.45	9.6	1.802	0.0178	17,500	0.0073
		$cm.C_6H_5Cl$							
.13a	35.5	16.8	40.6	24.06	9.6	1.608	0.0140	15,800	0.0073
.13b		16.4					0.0137		0.0071
.14a	36.0	14.8	41.4	23.17	9.7	1.519	0.0124	15,000	0.0072
.14b		14.8					0.0124		0.0072
.15a	36.0	13.5	43.6	22.33	9.6	1.390	0.0113	13,700	0.0079
.15b		13.5					0.0113		0.0079
.16a	36.5	11.5	51.4	23.79	9.3	1.258	0.00963	12,600	0.0082
.16b		11.7					0.00980		0.0083

TABLE V (contd.)

PRESSURE DROP DATA FOR BARIUM SULPHATE SUSPENSIONS (contd.)

Run	Temp-erat-ure. °C.	Deflection.	Time secs.	Dis-charge nett.	% $BaSO_4$ w/w.	Velocity ft/sec.	Head Loss ft. suspen-sion/ft.	Reynolds Number	Friction Factor
		cm. C_6H_5Cl		lb.					
.17a	37.0	10.1	62.4	22.77	8.5	0.9983	0.00851	10,200	0.0115
.17b		10.3					0.00868		0.0117
.18a	37.0	13.1	46.0	21.77	9.4	1.285	0.0110	13,000	0.0089
.18b		12.9					0.0108		0.0088
.19a	37.0	18.8	37.2	23.25	9.5	1.695	0.0157	17,100	0.0074
.19b		18.2					0.0152		0.0071
		cm. CCl_4							
.20	37.5	5.4	31.4	25.75	9.5	2.225	0.0244	22,700	0.0066
				cu.ft.					
.21	38.5	6.2	146.0	1.912		2.383	0.0280	24,800	0.0066
.22	38.5	14.4	90.2	1.885		3.802	0.0649	39,500	0.0060
.23	39.0	24.3	68.4	1.906		5.070	0.110	53,000	0.0057
.24	39.0	34.6	56.4	1.912		6.166	0.156	65,000	0.0055
.25	39.0	46.9	49.2	1.974	9.5	7.298	0.211	77,000	0.0053
.26	40.0	62.5	40.6	1.911		8.562	0.282	92,000	0.0052
		cm. Hg							
.27	40.0	4.2	34.2	1.953		10.39	0.404	111,000	0.0050
.28	41.0	5.2	32.8	2.146		11.90	0.500	130,000	0.0048
.29	41.0	7.8	29.4	2.372		14.68	0.750	160,000	0.0047
.30	41.5	9.1	27.6	2.397	9.7	15.80	0.875	174,000	0.0047

TABLE V (contd.)

PRESSURE DROP DATA FOR BARIUM SULPHATE SUSPENSIONS (contd.)

Run	Temperature. °C.	Deflection.	Time secs.	Discharge nett.	% $BaSO_4$ w/w.	Velocity ft/sec.	Head Loss ft.suspension/ft.	Reynolds Number.	Friction Factor.
		cm.Hg.		cu.ft.					
20.1	34.0	9.0	27.8	2.282	16.7	14.93	0.814	129,000	0.0049
.2	34.5	5.2	37.6	2.308		11.17	0.470	98,000	0.0051
.3	35.0	4.0	42.4	2.261		9.701	0.362	86,000	0.0052
		cm.CCl_4							
.4	35.5	58.1	52.2	2.240		7.805	0.246	70,000	0.0054
.5	36.0	39.8	54.8	1.916	16.4	6.359	0.169	57,000	0.0056
.6	36.5	29.2	64.0	1.880		5.344	0.124	48,600	0.0058
.7	37.0	22.5	75.0	1.912		4.637	0.0953	42,500	0.0060
.8	37.0	16.9	87.2	1.901		3.965	0.0716	36,400	0.0061
.9	37.5	10.4	112.0	1.890	16.4	3.070	0.0441	28,500	0.0063
.10	28.5	11.0	116.4	1.963	16.5	3.067	0.0466	23,600	0.0067
				lb.					
.11	29.5	7.6	31.2	30.94		2.532	0.0322	19,900	0.0068
.12	30.0	5.6	33.2	27.64		2.126	0.0237	17,000	0.0071
.13	31.0	4.4	38.2	28.33	16.5	1.894	0.0186	15,400	0.0070
		cm.C_6H_5Cl							
.14	31.0	19.6	35.0	24.01	16.5	1.752	0.0151	14,300	0.0066
.15a	32.0	16.1	41.4	25.03	16.4	1.544	0.0124	12,800	0.0070
.15b		16.0					0.0124		0.0070
.16a	32.5	14.2	44.8	25.12	16.5	1.432	0.0110	12,000	0.0072
.16b		14.2					0.0110		0.0072

TABLE V (contd.)

PRESSURE DROP DATA FOR BARIUM SULPHATE SUSPENSIONS (contd.)

Run	Temperature. °C.	Deflection.	Time secs.	Discharge nett.	% $BaSO_4$ w/w.	Velocity ft/sec.	Head Loss ft. suspension/ft.	Reynolds Number.	Friction Factor.
		cm. C_6H_5Cl		lb.					
.17a	33.0	10.3	60.6	25.84	15.9	1.094	0.00799	9,400	0.0090
.17b		10.7					0.00831		0.0094
.18a	33.5	14.5	46.6	25.06	16.4	1.375	0.0112	11,800	0.0080
.18b		14.3					0.0111		0.0079
.19a	33.5	20.7	35.4	25.12	16.5	1.812	0.0160	15,500	0.0066
.19b		20.9					0.0161		0.0066
.20	34.0	20.8	35.0	34.68	16.5	1.799	0.0160	15,600	0.0067
		cm. CCl_4.							
.21	34.5	4.5	34.8	26.20	16.5	1.921	0.0190	16,700	0.0070
.22	34.5	6.1	30.8	27.30		2.261	0.0258	19,700	0.0068
				cu.ft.					
.23	36.5	8.4	127.6	1.916		2.732	0.0356	24,800	0.0064
.24	37.0	12.3	103.6	1.896		3.329	0.0521	30,400	0.0063
.25	37.0	17.8	85.4	1.937		4.125	0.0754	37,700	0.0060
.26	37.5	25.9	68.8	1.901		5.026	0.110	46,500	0.0058
.27	37.5	25.3	68.8	1.896		5.013	0.107	46,400	0.0057
.28	38.0	32.5	60.2	1.896	16.6	5.730	0.138	53,000	0.0056
.29	38.0	46.9	49.0	1.885		6.998	0.199	65,000	0.0055
.30	38.0	46.9	49.6	1.916		7.027	0.199	66,000	0.0054
.31	38.5	65.5	41.0	1.901		8.435	0.277	80,000	0.0053
		cm. Hg							
.32	38.5	4.2	34.0	1.875		10.03	0.380	95,000	0.0051
.34	39.0	5.9	31.8	2.098		12.00	0.533	114,000	0.0050

TABLE V (contd.)

PRESSURE DROP DATA FOR BARIUM SULPHATE SUSPENSIONS (contd.).

Run	Temperature. °C.	Deflection.	Time secs.	Discharge nett.	% $BaSO_4$ w/w.	Velocity ft/sec.	Head Loss ft. suspension/ft.	Reynolds Number.	Friction Factor.
		cm.Hg		cu.ft.					
.35	39.5	5.9	31.2	2.068		12.06	0.533	116,000	0.0049
.36	40.0	8.1	29.0	2.287	16.8	14.34	0.732	139,000	0.0048
22.1	35.5	8.1	29.2	2.408		15.00	0.806	154,000	0.0048
.2	35.5	5.6	35.0	2.372	5.4	12.33	0.557	127,000	0.0049
.3	36.0	4.3	40.8	2.382		10.62	0.428	110,000	0.0051
		$cm.CCl_4$							
.4	36.5	59.8	50.4	2.319		8.369	0.275	86,000	0.0053
.5	36.5	42.9	61.6	2.372		7.005	0.197	74,000	0.0054
.6	37.0	32.3	71.6	2.350		5.970	0.148	63,000	0.0056
.7	37.0	22.2	86.9	2.319	5.3	4.855	0.102	51,000	0.0058
.8	37.0	15.2	89.5	1.932		3.927	0.0695	41,600	0.0061
.9	37.5	11.6	102.4	1.917		3.405	0.0529	36,500	0.0062
.10	38.0	8.0	126.0	1.927		2.781	0.0363	30,100	0.0063
.11	38.0	5.3	159.6	1.912		2.179	0.0239	23,500	0.0068
.12	38.5	3.8	198.0	1.942	5.3	1.784	0.0170	19,500	0.0072
				lb.					
.13	28.5	5.7	31.6	25.47		2.265	0.0262	20,200	0.0069
		$cm.C_6H_5Cl$							
.14	29.5	20.2	39.6	23.97	5.3	1.701	0.0161	15,500	0.0075
.15	30.0	16.7	45.6	24.70	5.3	1.522	0.0133	14,000	0.0077

TABLE V (contd.)

PRESSURE DROP DATA FOR BARIUM SULPHATE SUSPENSIONS (contd.)

Run	Temperature. °C.	Deflection.	Time secs.	Discharge nett.	% $BaSO_4$ w/w.	Velocity ft/sec.	Head Loss ft. suspension/ft.	Reynolds Number.	Friction Factor.
		cm. C_6H_5Cl		lb.					
.16a	30.5	13.9	51.2	24.98	5.2	1.372	0.0110	12,700	0.0079
.16b		13.9					0.0110		0.0079
.17a	31.0	8.4	70.4	22.91	4.3	0.9222	0.00662	8,700	0.0105
.17b		8.8					0.00695		0.0110
.18a	32.0	6.8	98.4	23.10	3.1	0.6714	0.00536	6,600	0.0160
.18b		7.7					0.00610		0.0180
.19b	33.5	4.1	137.6	18.90	1.1	0.3991	0.00318	4,110	0.0270
.19b		4.8					0.00377		0.0320
.20a	34.0	15.1	133.8	21.57	2.7	0.4628	0.0122	4,750	0.0770
.20b		16.4					0.0133		0.0840
.21a	34.0	17.2	102.8	20.37	3.2	0.5666	0.0139	5,800	0.0580
.21b		17.8					0.0144		0.0610
		cm. CCl_4							
.22a	34.0	9.0	48.4	24.05	5.4	1.395	0.0413	14,000	0.0290
.22b		9.2					0.0423		0.0290
.23	35.0	4.5	35.4	24.44	5.5	1.937	0.0207	19,700	0.0074
				cu.ft.					
.24	37.5	7.5	130.8	1.896	5.3	2.638	0.0345	28,200	0.0067
.25	37.5	8.3	124.2	1.922		2.816	0.0381	30,100	0.0065
.26	38.0	12.6	100.2	1.942		3.525	0.0579	38,100	0.0063
.27	38.0	16.4	85.8	1.932		4.096	0.0754	44,200	0.0060

TABLE V (CONTD.)

PRESSURE DROP DATA FOR BARIUM SULPHATE SUSPENSIONS (contd.)

Run	Temp-erature °C.	Deflection	Time secs.	Dis-charge nett.	% $BaSO_4$ w/w.	Velocity ft/sec.	Head Loss ft. suspension/ft.	Reynolds Number.	Friction Factor.
		cm. CCl_4		cu. ft.					
28	38.5	23.5	70.8	1.942		4.990	0.108	54,000	0.0058
29	39.0	34.2	60.2	2.037		6.155	0.157	68,000	0.0056
30	39.0	46.3	56.0	2.240	5.4	7.276	0.213	80,000	0.0054
31	39.5	63.5	46.8	2.214		8.606	0.292	96,000	0.0053
		cm. Hg.							
32	40.0	4.1	39.6	2.282		10.48	0.408	118,000	0.0050
33	40.0	5.5	35.4	2.414		12.40	0.547	139,000	0.0048
34	40.5	8.8	28.2	2.475	5.5	15.97	0.875	181,000	0.0046

TABLE VI

SETTLED VOLUME DATA

Settled Volume = x_{vb} = Volume fraction occupied by the solid component in a bed formed by gravity sedimentation from the liquid.

Run	Weight of $BaSO_4$	Volume of Water	Container	Volume of Bed	Settled Volume
	g.	cc.			
1	10	50	50 ml.measuring cylinder.	8.5	0.261
2	10	50	,,	8.4	0.265
3	8	50	,,	6.9	0.258
D	8	50	,,	6.9	0.258
E	8	50	,,	7.0	0.254
4	5	50	,,	4.7	0.236
5	5	50	,,	4.7	0.236
					Mean =
					0.25

These results are for a settling time of 3 days.

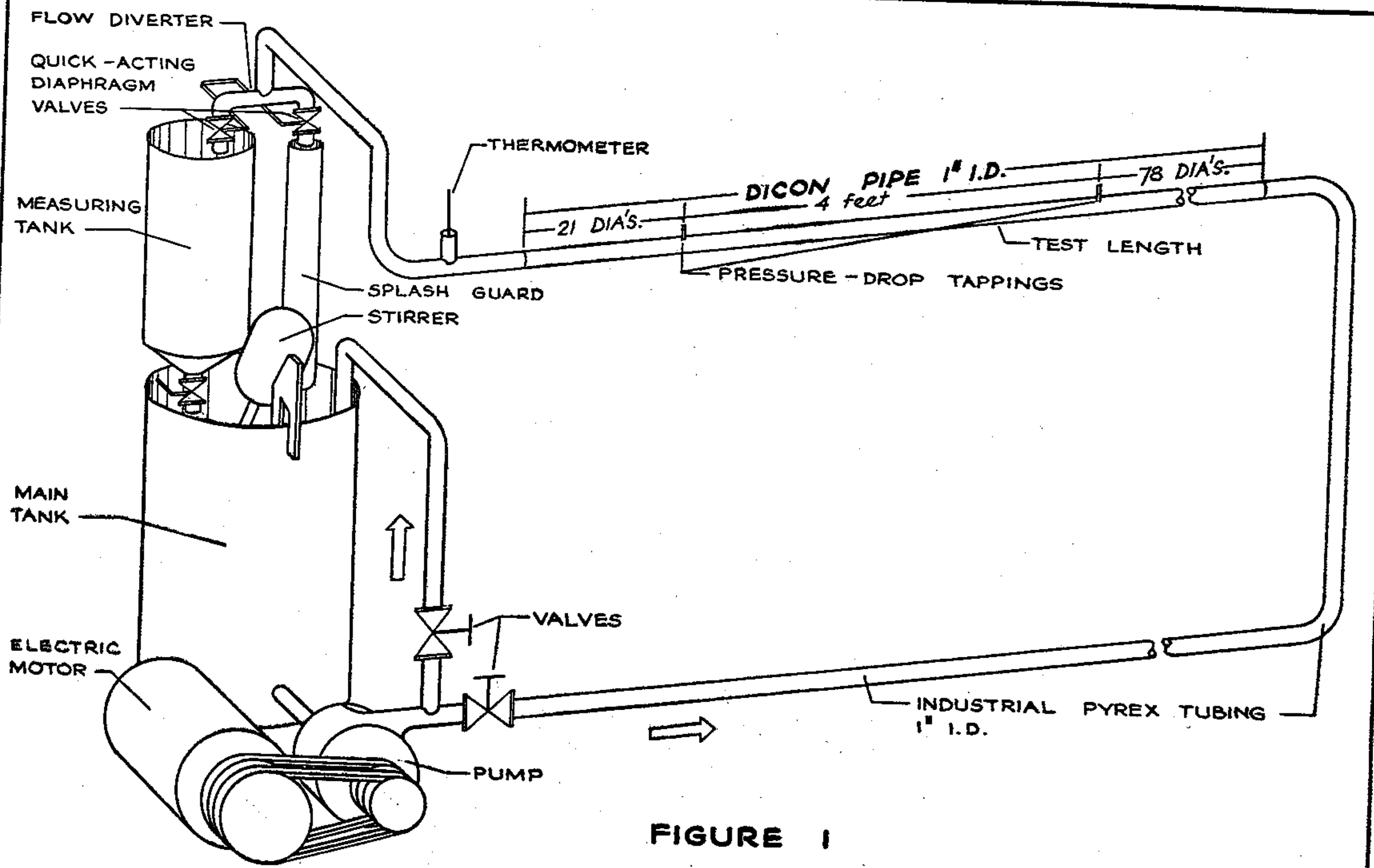
FLOW DIVERTER
QUICK-ACTING DIAPHRAGM VALVES
MEASURING TANK
THERMOMETER
DICON PIPE 1" I.D.
4 feet
21 DIA'S.
78 DIA'S.
TEST LENGTH
PRESSURE-DROP TAPPINGS
SPLASH GUARD
STIRRER
MAIN TANK
VALVES
ELECTRIC MOTOR
PUMP
INDUSTRIAL PYREX TUBING
1" I.D.

FIGURE 1

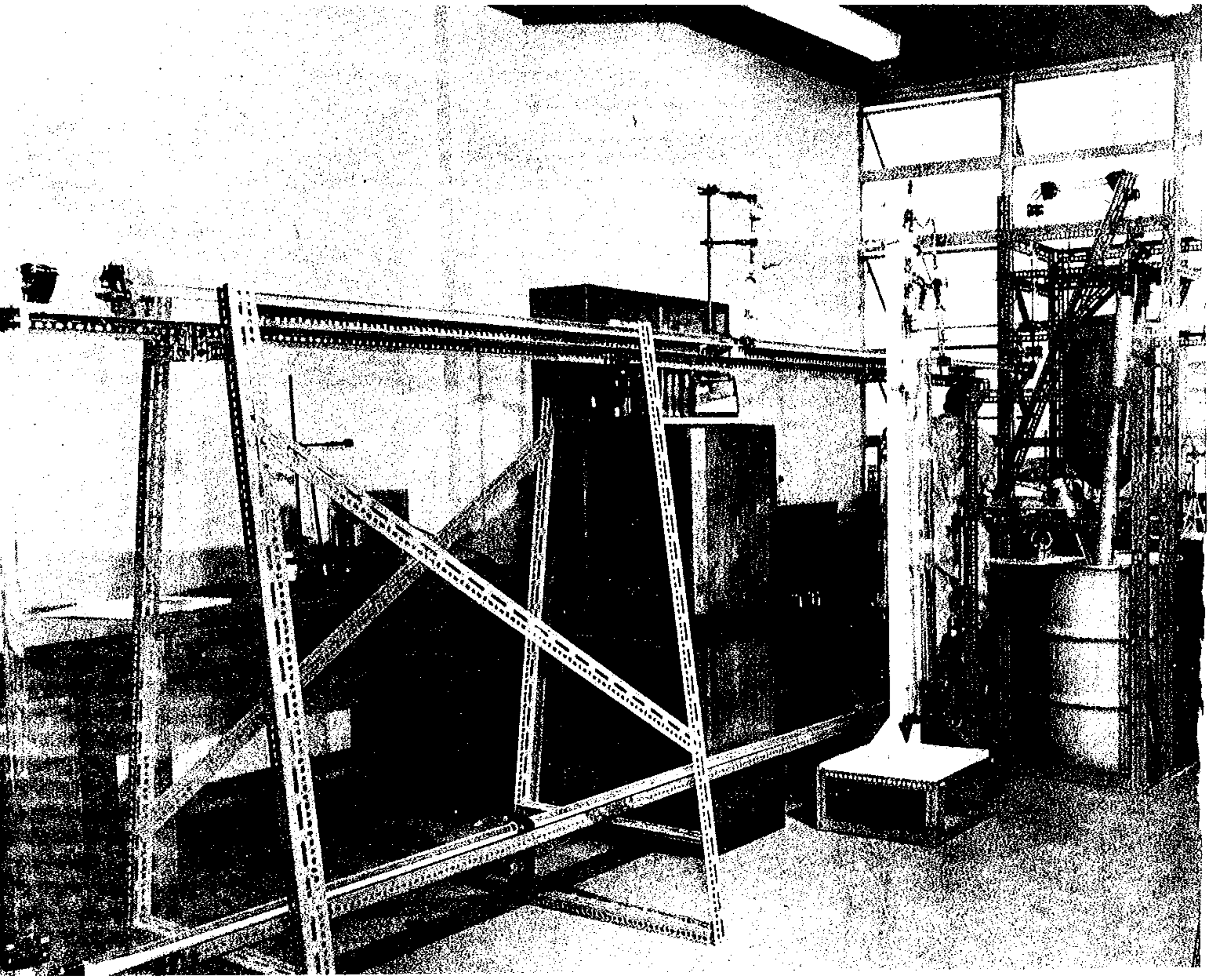

FIGURE 1b. View of Loop Used for $BaSO_4$ Experiments at no flow.

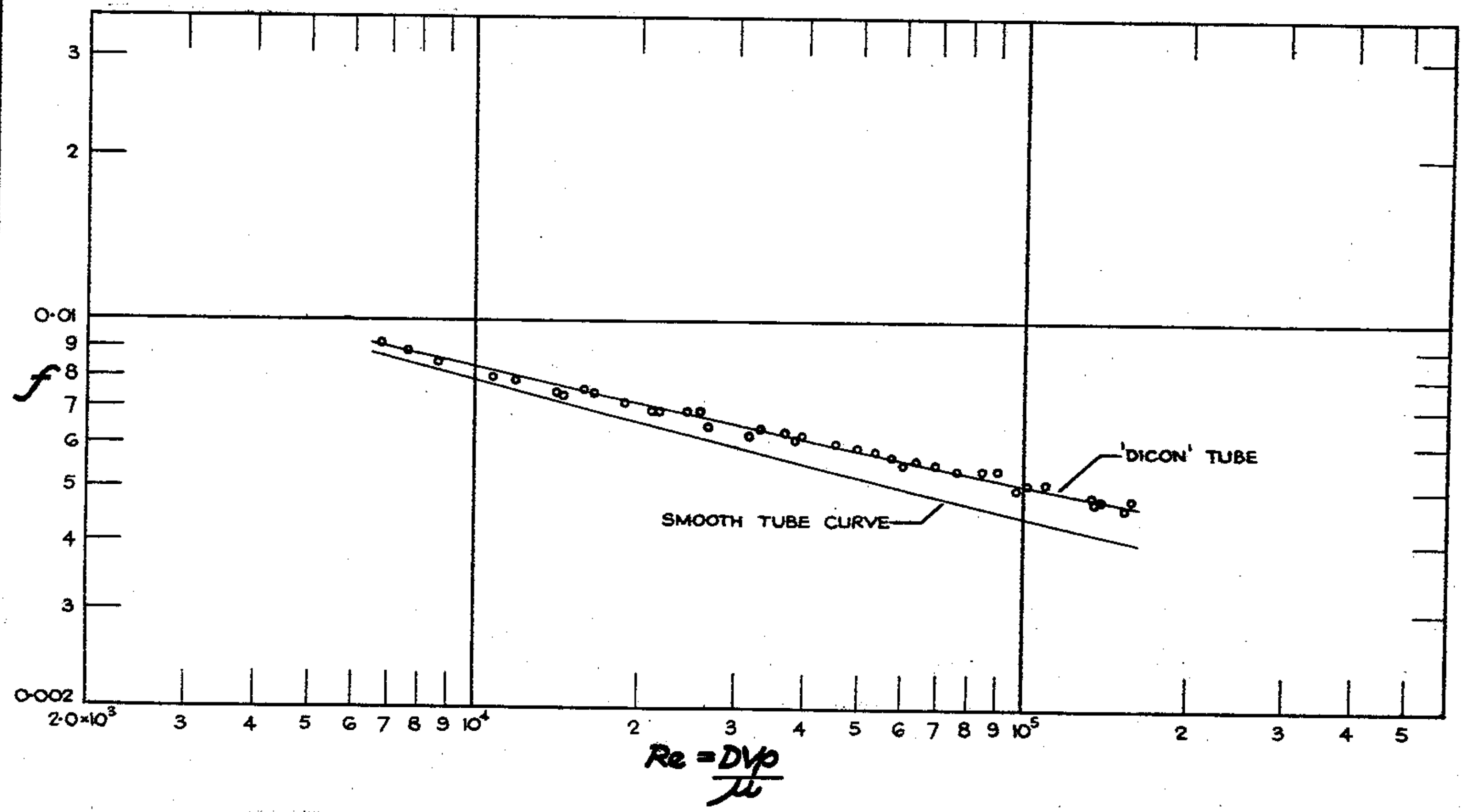

FIGURE 2 : Plot of f vs Re for clean water in the Dicon tube.

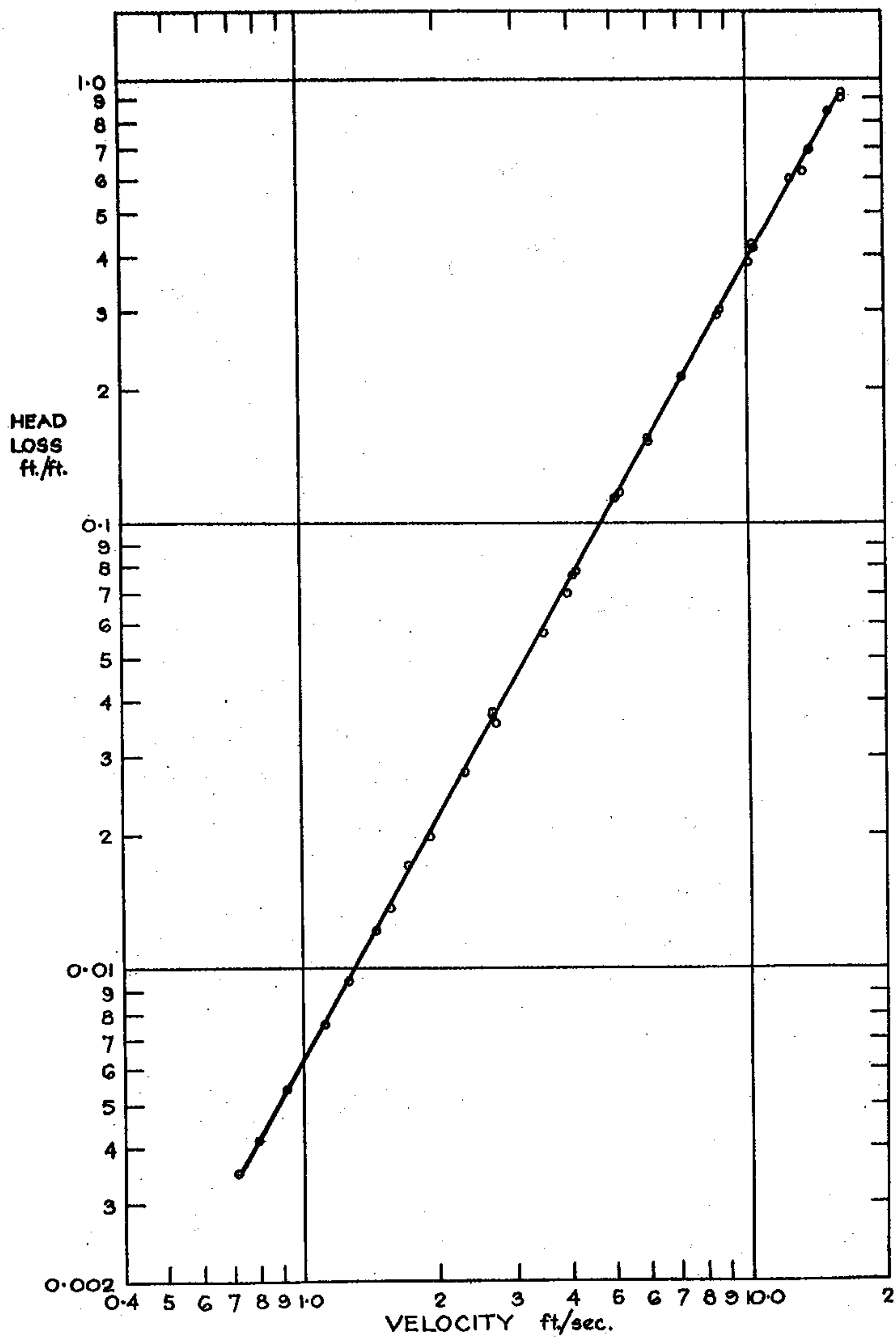

FIGURE 3 :
Plot of Head Loss vs Velocity for clean water in the Dicon tube.

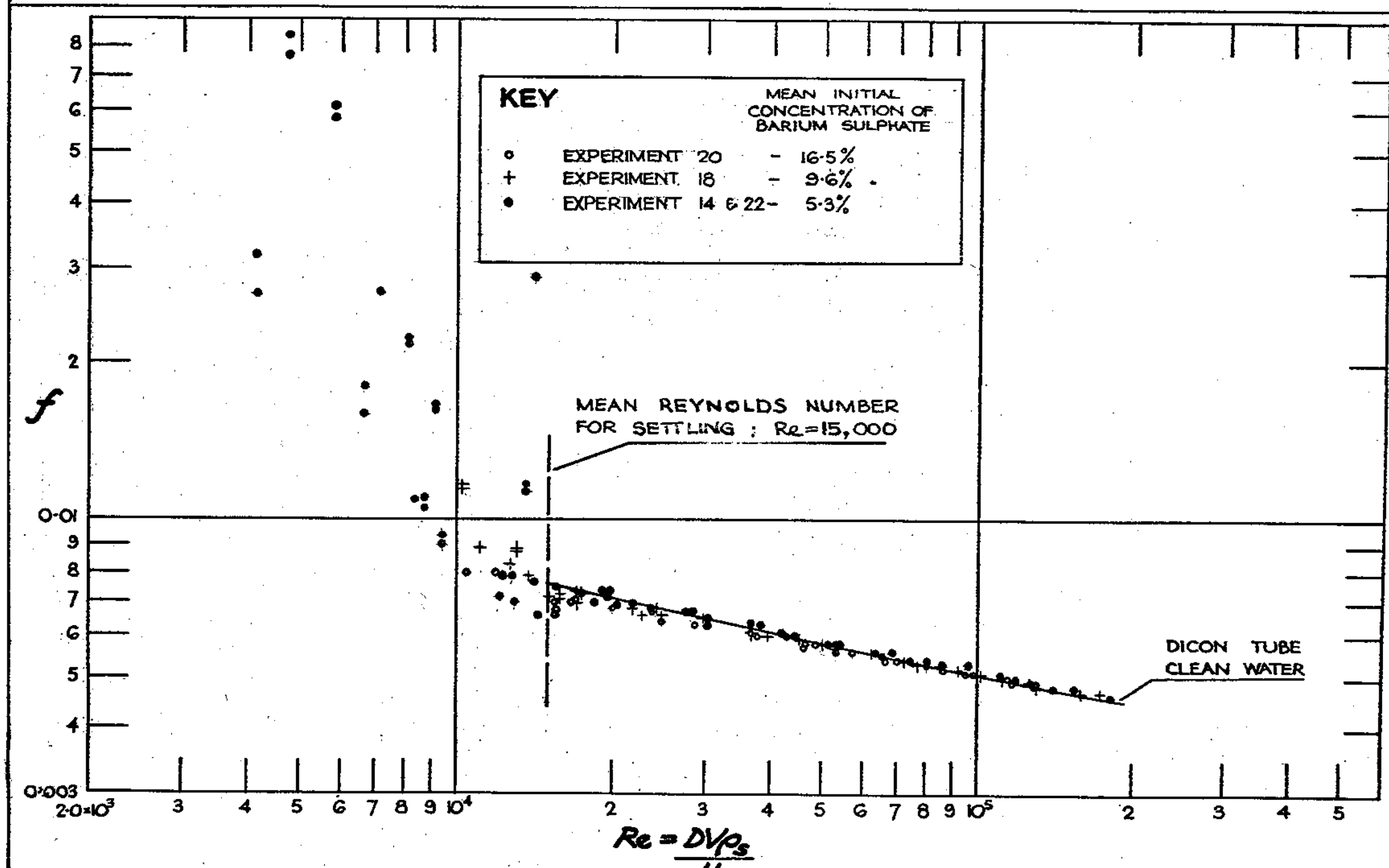

FIGURE 4: Plot of f vs Re for Barium Sulphate suspensions.

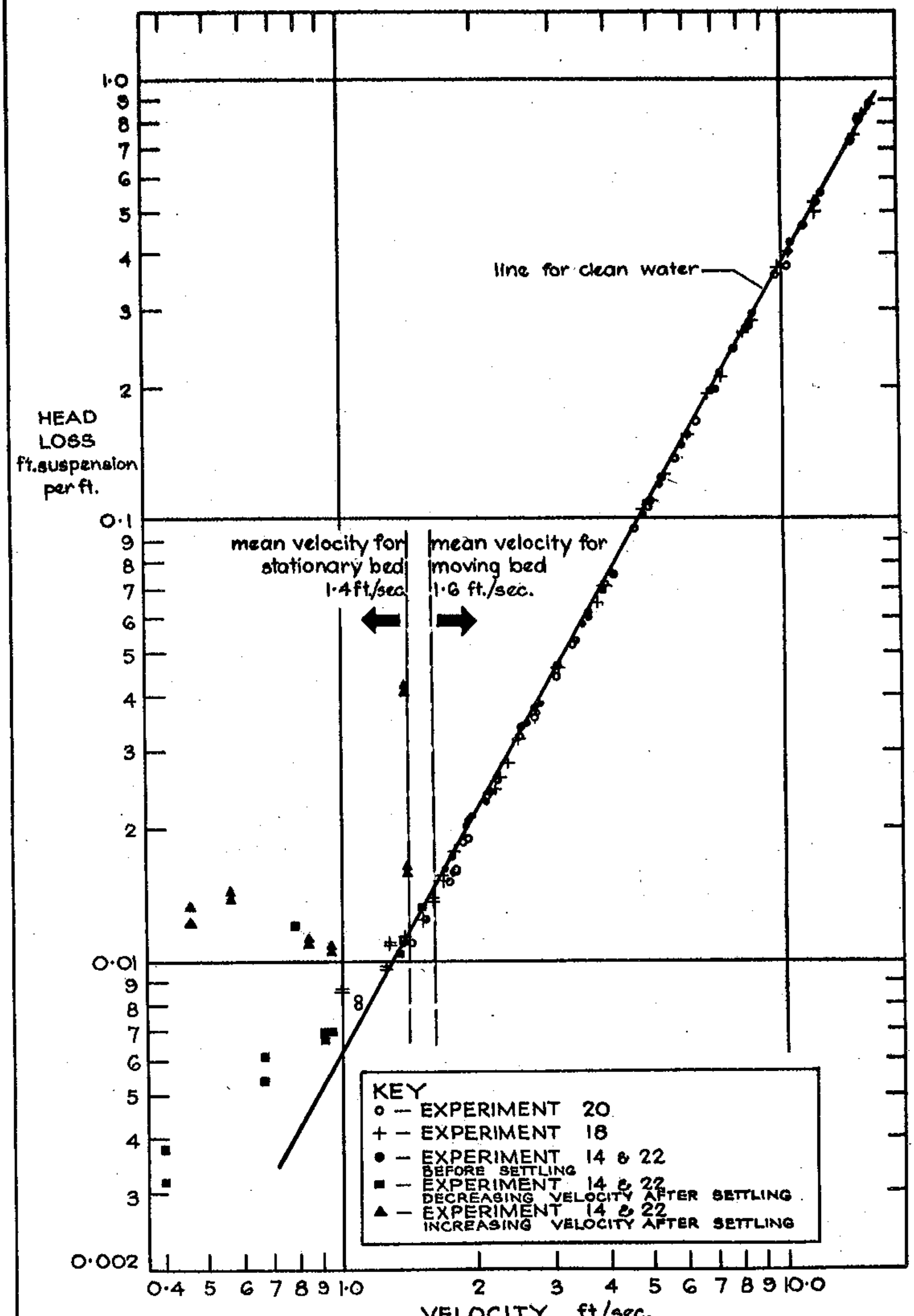

FIGURE 5 :
Plot of Head Loss vs Velocity for Barium Sulphate suspensions.

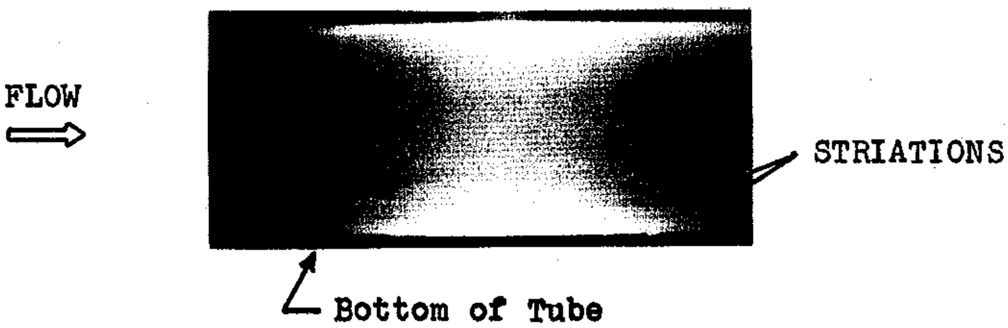

FIGURE 6 ACTUAL SIZE

Striations present with approximately 5% $BaSO_4$ suspension at 1.4 ft/sec. in the Dicon tube.

↑ Vertical leg, 6 feet long.

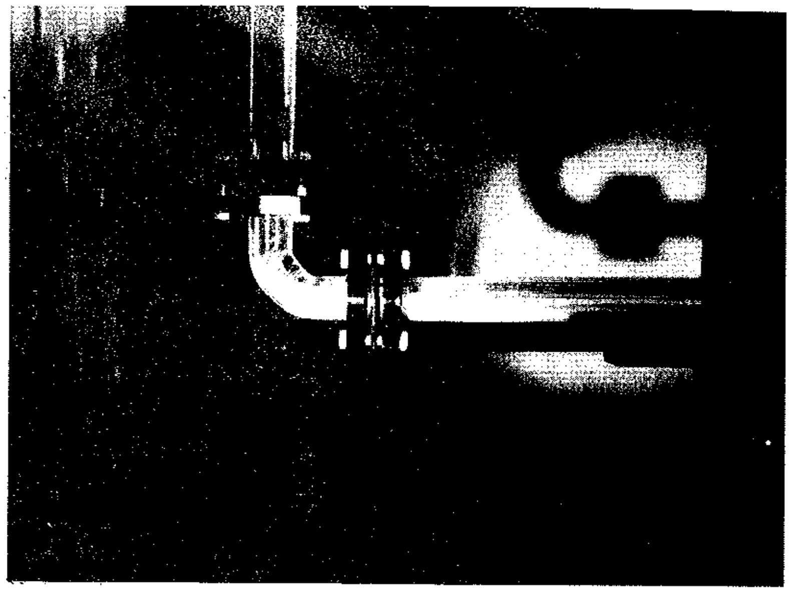

FIGURE 7. Build up observed after shut down for 10% w/w $BaSO_4$ suspension.

↑ Vertical leg, 6 feet long.

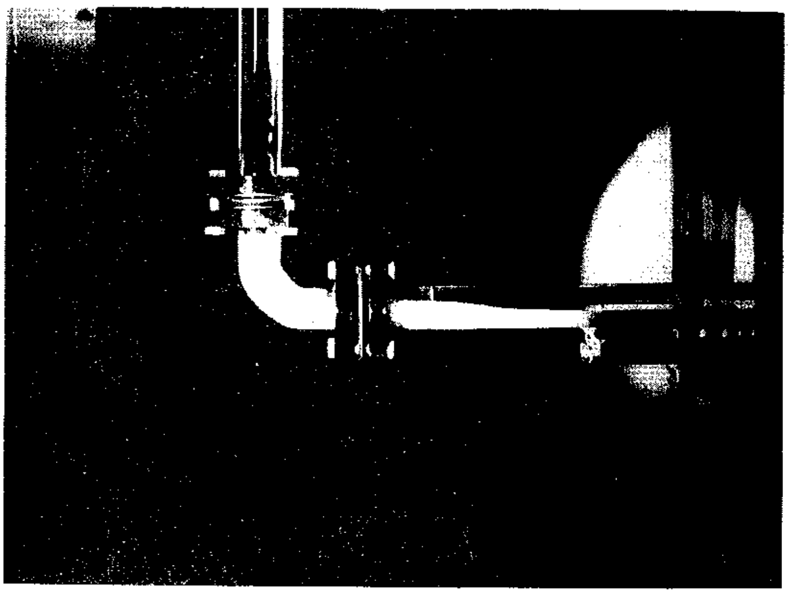

FIGURE 8. Build up observed after shut down for 16.5% w/w $BaSO_4$ suspension.