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SEPARATING SMALL PARTICLES FROM LIQUIDS WITH THE HYDROCYCLONE

PART II – EFFECTS OF MAJOR DESIGN VARIABLES

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ABSTRACT

Hydrocyclone feed, overflow and underflow diameters are established for optimum concentration of solid and maximum clarification of liquid using an 11.5 ± 0.5 per cent. by weight suspension of sub–sieve barium sulphate in water.

For a hydrocyclone with a nominal diameter (D_c) of 10 millimetres the dimensions for optimum concentration are:

Feed diameter (D_i) = 0.082 inch ($D_c/5$)
Overflow diameter (D_o) = 0.098 inch ($D_c/4$)
Underflow diameter (D_u) = 0.037 inch ($D_c/11$)
Vortex finder outside diameter (VFOD) = 0.197 inch

and the dimensions for maximum clarification are:

D_i = 0.055 inch ($D_c/7$)
D_o = 0.079 inch ($D_c/5$)
D_u = 0.058 inch ($D_c/7$)
VFOD = 0.197 inch

Brief observations are given on the air core and the effects of feed solid concentration and feed solid particle size.

CONTENTS

1. INTRODUCTION

Because of their simplicity of design and operation, hydraulic cyclones or hydrocyclones, are envisaged as a convenient means of separating solids from liquids under radioactive conditions. Specific applications relative to the research programme have been the separation of the fuel particles from the liquid metal carrier in a liquid metal fuelled reactor (L.M.F.R.) (Alder, 1958) and the clarification of feed solutions to solvent extraction plants processing irradiated fuels.

A literature search (Cairns et al., 1959) has shown that for the separation of particles in the sub-sieve range, which is the anticipated size of the particles to be removed, small diameter cyclones are required. It was also shown that in order to achieve maximum concentration simultaneously with maximum clarification a two stage hydrocyclone unit is required in which one hydrocyclone operates as a concentrator and the other as a clarifier. A programme of experimental work has been commenced to establish optimum design details and operating conditions for such a unit (using a hydrocyclone having a nominal diameter of 10 millimetres) because it is considered that the published literature is inadquate for this purpose.

The work completed at September, 1959, is described in this report and a choice is given of feed, overflow and underflow diameters and vortex finder outside diameter for both optimum concentration of solid and maximum clarification of liquid for one particular system. The feed used was an approximately 11.5 per cent. by weight suspension of barium sulphate in water. This suspension simulates in many respects a proposed system using a uranium-beryllium alloy fuel as a suspension in molten sodium (UBe_{13}-Na system) for the L.M.F.R. Pressure drop and horizontal settling velocity data for flow in pipes had been collected previously for this barium sulphate suspension (Cairns and Turner, 1958a, 1958b) and this was a convenient system on which to commence work on hydrocyclones.

2. APPARATUS AND METHOD

The experimental loop is shown diagrammatically in Figure 1. The supply tank was fabricated from stainless steel and had a working capacity of approximately 8 gallons. The outlet pipe was positioned to prevent blocking of lines after shut-down and was covered with a piece of 60-mesh stainless steel gauze to prevent blocking of the hydrocyclone by stray coarse particles. The suspension was fed to the hydrocyclone by a 2H3 two-stage Mono pump with 1¼ inch inlet and outlet. The pump was fitted with a hard chromium plated stainless steel rotor and soft rubber stator and was driven by a 1 h.p. motor at 712 r.p.m. Feed pressure was controlled by a valve in a by-pass line to the supply tank. Uniform suspension of the solid in the supply tank was maintained by a ¼ h.p. motor driven propeller type agitator.

The hydrocyclone unit shown diagrammatically in Figure 2, was similar to that used by Bradley (1956). Overflow/vortex finder inserts with two different vortex finder outside diameters (VFOD) were used. For each series, a range of six overflow diameters (D_o) was used. In each insert the orifice was maintained approximately 10 times the overflow diameter and then enlarged. This was done to avoid possible effects due to change in cross section. The length of the vortex finder was made equal to the cyclone diameter in all cases. Four different underflow diameters (D_u) were used.

A splash eliminator was necessary to prevent losses when operating with a vigorous vortex discharge. In some cases there was only a weak vortex discharge and the splash eliminator tended to run full with the possible elimination of the air core. Under these circumstances air could be admitted via the air bleed shown in Figure 2.

Six different feed diameters (D_i) were used. The hydrocyclone end of each feed nozzle was shaped to match the hydrocyclone wall. The orifices were positioned so that the outside edge of the feed stream was tangential to the inner surface of the cylindrical section of the hydrocyclone body. In each feed insert the orifice was maintained at the feed diameter for a distance of approximately 20 times the feed diameter from the nozzle and then enlarged. This was done to avoid possible entrance effects.

To minimise erosion, stainless steel was used for the cylindrical portion and all the feed inserts except the smallest which was difficult to bore in stainless steel. The first underflow inserts used (0.058 inch) were made of Perspex but the other underflow inserts were made of Teflon when it was found that this material eroded less than Perspex. The remainder of the hydrocyclone and the smallest feed insert were made of Perspex.

Calibrated Bourdon type pressure gauges from the National Instrument Company of Sydney were used and periodically checked with a dead weight tester. The gauges were connected to the pressure tappings with ¼ inch OD 18 gauge stainless steel tubing. The tapping holes were 1/8 inch diameter and deburred.

Runs were made for a range of feed pressures for numerous combinations of D_i, D_o, D_u and VFOD. A timed discharge was taken for each run for both overflow and underflow. Total suspended solids were determined by drying and weighing samples taken from the feed sampling line and the underflow stream. Four feed samples were taken for each combination used and at least two underflow samples were taken for each run.

The barium sulphate used was blanc fixe manufactured by Farbenfabriken Bayer, A.G., of Germany and supplied by H.H. York and Co. of Sydney. The particle size distribution of the barium sulphate was determined by the Andreasen pipette and Micromerograph methods, before and after use and several times during the experimental work.

Demineralised water was used for the suspension. The temperature of the suspension circulating during the experimental work varied between 30°C and 39°C but did not vary by more than 2°C during testing of any one combination.

3. RESULTS AND DISCUSSION

Using a single hydrocyclone, for a given feed concentration there is a combination of feed overflow and underflow diameters, which gives optimum efficiency of separation, defined as the highest solid concentration in the underflow consistent with as low as possible solid concentration in the overflow. A higher concentration than this may be obtained by decreasing the underflow but this causes more solids to appear at the overflow. Similarly, an increase in the underflow results in a lower overflow concentration, but due to the extra water which appears at the underflow gives a lower underflow concentration. Therefore as Trawinski (1953) states, to get both maximum concentration of solid and maximum clarification of liquid, it is necessary to use a two-stage unit, with the first-stage hydrocyclone selected to give maximum concentration of solid in the underflow and the second-stage hydrocyclone maximum clarification of liquid in the overflow.

For design purposes it is necessary to consider each operation separately and, to measure the degree of concentration and clarification, two efficiencies have been proposed.

The normal solids elimination efficiency is:

$$E_1 = [(x_u W_u) / (x_f W_f)] \times 100$$

The concentration efficiency E_2 has been defined (Cairns et al., 1959) such that

$$E_2 = [(x_u - x_f) / (1 - x_f)] \times 100$$

and the clarification efficiency E_3 has been defined (Cairns et al., 1959) such that

$$E_3 = [(x_f - x_o) / x_f] \times 100$$

which can also be expressed as $\dfrac{E_1/100 - R_f}{1 - R_f} \times 100$.

E_3 is similar to the efficiency suggested by Kelsall (1953) and which Bradley (1957) defined as the centrifugal efficiency.

The data reported here have been interpreted in terms of the concentration and clarification efficiencies which are given as gross efficiencies and do not refer to a particular size. It is the maximum removal of all solids at the highest possible concentration that is important. Because of the present difficulty in determining the correct particle size distribution for particles the sizes of which are well into the sub-sieve region, separation curves with efficiencies plotted against particle size lose their meaning unless the particle sizes shown correspond to those diameters effective within the hydrocyclone. At present no method is known which will provide these effective diameters, as experience has shown that the distributions obtained vary with the method of measurement, particularly for the very small and irregularly shaped particles normally encountered.

To allow for the possible effect of size distribution on the concentration and clarification efficiencies, it is intended to vary the feed particle size distribution as determined by a specified method which gives reproducible results (Cairns et al., 1959).

Experimental runs were made at minimum feed pressure (by-pass valve fully open, approximately 10 p.s.i.g.) and at 20, 40 and 80 p.s.i.g. for each combination of D_i, D_o, D_u and VFOD used. Concentration and clarification efficiencies were then calculated.

A series of plots of E_2 and E_3 against D_i with constant D_o and with feed pressure as parameter were made for each underflow diameter. Because of the large amount of experimental data collected only the most important results have been reproduced here and these are shown in Figures 3 to 8.

All the results reported are for operation with the air bleed open. It was found that with the 0.037 inch D_u and the range of overflow and feed diameters shown in Figure 3, the entry of air could be prevented by blocking the air bleed and injecting water up into the splash eliminator causing the splash eliminator to run full. In general, this gave no significant changes in E_2 or E_3 despite the absence of a vortex discharge and apparent lack of an air core, but for isolated runs variations of up to approximately 20 per cent. were obtained.

A number of the runs were repeated with water instead of suspension as feed. In the case of the 0.037 inch D_u the entry of air was prevented as before and the observations using suspension were confirmed. The hydrocyclone could be operated without a vortex discharge and air core. In the case of the 0.098 inch D_u with the air bleed closed, it was not possible to make the splash eliminator run full unless it was partially blocked but the condition observed using a suspension feed was confirmed. This was that with the unrestricted 0.098 inch D_u the hydrocyclone operated with alternating full bore and non full bore flow in the overflow line, in association with an apparently discontinuous air core.

It appears from these observations that for the system under consideration the presence of an air core is associated with the hydrodynamic conditions existing in the hydrocyclone but its absence has little effect on the separation obtained.

Erosion was observed in the overflow inserts, feed nozzles and underflow inserts. Some replacements were necessary but the dimensional changes measured were not significant.

In this work the feed concentration was maintained at 11.5 ± 0.5 per cent. by weight suspended solids and in any one experiment the feed concentration did not vary by more than 0.3 per cent. by weight. Four experiments (0.058 inch D_u, 0.197 inch VFOD, 0.116 inch D_i, with 0.079, 0.098, 0.116, and 0.136 inch D_o) were repeated with a feed concentration of 10.5 ± 0.1 per cent. In the first three cases E_2 showed a slight decrease and in the fourth a slight increase with decrease in concentration. In all cases E_3 increased slightly with decrease in concentration. Additional work is planned to determine the effect of feed concentration as it is expected that larger changes in concentration will have significant effects on both E_2 and E_3.

(a) Dimensions for Optimum Concentration

When using two hydrocyclones in series so that the first concentrates and the second clarifies the overflow of the first, there are two requirements which should be met by the first hydrocyclone. These are that E_2 must be high and the concentration of the overflow should be as low as possible.

Figure 3 shows that for a 0.037 inch D_u and a 0.197 inch VFOD, E_2 increases rapidly and then commences to level out at a D_o of 0.098 inch and D_i of 0.082 inch. Figure 4 shows that as the overflow diameter is increased E_3 decreases because the overflow concentration is increasing. The optimum diameters to give a high E_2 consistent with a low overflow concentration were taken as 0.098 inch for D_o and 0.082 inch for D_i. No improvement was obtained by increasing the underflow diameter, since in all cases E_2 was either lower than the optimum or else the overflow concentration was higher than that given by the optimum dimensions. Again no improvement was obtained when the combination of the 0.058 inch D_u with a 0.277 inch VFOD was used.

Typical results for larger underflows are shown in Figures 5 and 6 for the 0.098 inch underflow with a VFOD of 0.197 inch. In Figure 6 the overflow concentration has decreased resulting in higher values for E_3 than given by Figure 4 for values of D_o of 0.098 inch and above. However, this has occurred at the expense of much lower values of E_2 as seen in Figure 5. High values of E_2 are considered to be more important and the final optimum dimensions chosen from the available data to provide optimum concentration are

D_i = 0.082 inch = $D_c/5$

D_o = 0.098 inch = $D_c/4$

D_u = 0.037 inch = $D_c/11$

VFOD = 0.197 inch

The flow rates corresponding to 10, 20, 40 and 80 p.s.i.g. feed pressures for this cyclone are 21, 30, 43 and 59 g/sec respectively.

(b) Dimensions for Maximum Clarification

Plots of additional clarification efficiencies for some of the data obtained are shown in Figures 7 and 8. The highest values of E_3 were obtained for the conditions shown in Table 1.

Examination of Figures 4, 7 and 8 shows that of the various combinations, those given in Figure 7 for a 0.079 inch D_o are more suitable. The 0.055 inch D_i gives higher clarification efficiencies at low feed pressures than the 0.042 inch D_i and as the use of high feed pressures are to be avoided wherever possible under radioactive conditions, the 0.055 inch D_i is preferred. For maximum clarification the recommended dimensions are:

D_i = 0.055 inch = $D_c/7$

D_o = 0.079 inch = $D_c/5$

D_u = 0.058 inch = $D_c/7$

VFOD = 0.197 inch

The flow rates corresponding to 10, 20, 40 and 80 p.s.i.g. feed pressures for this cyclone are 12, 16, 22 and 32 g/sec respectively.

(c) Feed Solid Particle Size

In work on the dynamic properties of suspensions (Cairns and Turner (1958b) it was suggested that correlations requiring the evaluation of a particle size could not be obtained for sub-sieve particles, unless the method of particle size determination used for the solid gave the effective or working diameter of the particle for the conditions under consideration. For hydrocyclone work correlations have been derived on the assumption that the particles obey Stokes' Law, so a sedimentation method such as the Andreasen pipette appears to be a logical method to use. However in a hydrocyclone high shear stresses are present (Trawinski 1953) and deagglomeration of particles could be expected. In view of this, the Micromerograph method which determines the size distribution of a deagglomerated sample in terms of Stokes' diameter may be of more value.

In this work eleven samples were taken for feed solid particle size analysis and the results are given in Table 2. It was observed that as the work progressed the Andreasen particle size distribution shifted, although the Micromerograph particle size distribution showed no significant change.

When large changes in distribution as determined by the Andreasen pipette method were noticed, some of the experimental work was repeated and results compared for particles showing large diameters in their distribution with particles showing small diameters in their distribution. No consistent differences were noticed in the values of E_2 and E_3 obtained, and for these experiments it appears that the particle size distribution as measured by the Andreasen method had little effect on concentration or clarification. This can also be said to suggest that the material used behaved as a powder with uniform particle size, but further work is necessary to decide this point.

Table 2 also shows the wide differences obtained when different methods of particle size analysis are used.

4. CONCLUSIONS

Different orifice dimensions are required for optimum concentration of solid and maximum clarification of liquid. For a nominal 10-millimetre hydrocyclone the optimum concentration dimensions are:

D_i = 0.082 inch ($D_c/5$)

D_o = 0.098 inch ($D_c/4$)

D_u = 0.037 inch ($D_c/11$)

and the maximum clarification dimensions are:

D_i = 0.055 inch ($D_c/7$)

D_o = 0.079 inch ($D_c/5$)

D_u = 0.058 inch ($D_c/7$)

In practice, severe erosion of underflow and feed inserts and also of the upper internal portion of the cyclone could be expected and suitable materials of construction would be necessary.

The Andreasen method for particle size determination for hydrocyclone operation is unsatisfactory. The Micromerograph shows promise but further work on other systems is required.

Additional work is also required on the effects of the density, particle size distribution and concentration of the feed solid.

5. ACKNOWLEDGMENTS

The authors acknowledge advice received from Mr. C.L.W. Berglin.

6. SYMBOLS

D_c = hydrocyclone diameter (in.)

D_i = feed diameter (in.)

D_o = overflow diameter (in.)

D_u = underflow diameter (in.)

E_1 = solids elimination efficiency (per cent.)

E_2 = concentration efficiency (per cent.)

E_3 = clarification efficiency (per cent.)

R_f = flow ratio = underflow flow rate/feed flow rate.

VFOD = vortex finder outside diameter (in.)

W_f = feed flow rate (g/sec)

W_u = underflow flow rate (g/sec)

x_f = weight fraction of solids in feed stream

x_u = weight fraction of solids in underflow stream

x_o = weight fraction of solids in overflow stream

7. REFERENCES

Alder, K.F., 1958. Liquid metal fuel reactors. Australian Atomic Energy Symposium: p.346 Melb. Univ. Press.

Bradley, D., 1956. A contribution to the theory of the hydraulic cyclone and data on the performance of small diameter cyclones. A.E.R.E. CE/R2016.

Bradley, D., 1957. Theoretical correlation of the efficiency of hydraulic cyclones A.E.R.E. CE/M211.

Cairns, R.C. and Turner, K.S., 1958a. Studies of small particle suspensions for L.M.F.R., Part II. Fluid flow with suspensions simulating the UBe_{13}–Na system. AAEC/E16.

Cairns, R.C. and Turner, K.S., 1958b. Studies of small particle suspensions for L.M.F.R., Part V. The effects of concentration, pipe diameter and solid density on the horizontal settling velocity. AAEC/E 34.

Cairns, R.C., Thurstan, E.G. and Turner, K.S., 1959. Separating small particles from liquids with the hydrocyclone, Part I. Conclusions and recommendations arising from literature search. AAEC/E 45.

Kelsall, D.F., 1953. A further study of the hydraulic cyclone. Chem. Eng. Sci., 2: 254.

Trawinski, H., 1953. The hydrocyclone as an auxiliary apparatus for the refinement of raw materials. A.E.R.E. Lib/Trans. 605 from Chemie-Ingenieur Technik, 25: 331.

TABLE 1

Conditions for High Values of E_3

Fig. No.	D_u in.	VFOD in.	Feed Pressure Approx. 80 p.s.i.g.			Feed Pressure Approx. 10 p.s.i.g.		
			E_3 %	D_o in.	D_i in.	E_3 %	D_o in.	D_i in.
4	0.037	0.197	84	0.060	0.042			
			85	0.060	0.055			
			83	0.079	0.042			
7	0.058	0.197	85	0.060	0.042	68	0.060	0.055
			85	0.079	0.042	66	0.079	0.042
			83	0.079	0.055	72	0.079	0.055
8	0.058	0.277	83	0.098	0.042			
			86	0.098	0.055			
			83	0.098	0.082			

TABLE 2

Particle Size Analyses

Method	Andreasen											Micromerograph					
Feed sample number	1	2	3	4	5	6	7	8	9	10	11	1	4	6	9	10	11
Approximate number of hours circulation of suspension prior to sampling	0	17	52	62	100	106	107	111	122	20	43	0	62	106	122	20	43
Per cent. undersize by weight	Stokes' diameter, microns																
100	–	–	–	–	–	–	–	–	–	NOT DONE	–	20	28	–	17	13	17
95	–	–	18	–	–	–	–	34	–		–	8.4	8.4	8.4	8.4	8.2	8.4
85	31	32	8.1	–	–	–	34	18	20		34	6.1	6.3	6.4	6.2	6.4	6.1
70	28	28	6.1	–	–	–	29	13	15		33	4.8	5.0	5.1	4.9	5.0	4.8
50	24	24	5.0	31	33	32	23	8.4	9.6		31	3.7	4.0	4.2	3.9	4.1	3.9
30	20	20	4.2	29	27	26	15	5.8	6.2		28	2.9	3.1	3.3	3.0	3.2	3.0
15	18	16	3.3	24	17	12	7.3	–	4.5		20	2.3	2.4	2.6	2.4	2.5	2.3
5	10	8.6	–	14	7.0	4.6	4.2	–	–		11	1.8	1.8	2.0	1.9	1.9	1.8
0	–	–	–	–	–	–	–	–	–		–	1.4	1.2	1.4	1.4	1.4	1.4

Note (i) Sample 1 taken from powder before use.
(ii) Sample 4 taken after a make up addition of $BaSO_4$.
(iii) Duplicates on Andreasen samples 2, 6 and 9 varied from the mean by up to 20 per cent., but the mean results have been tabulated.

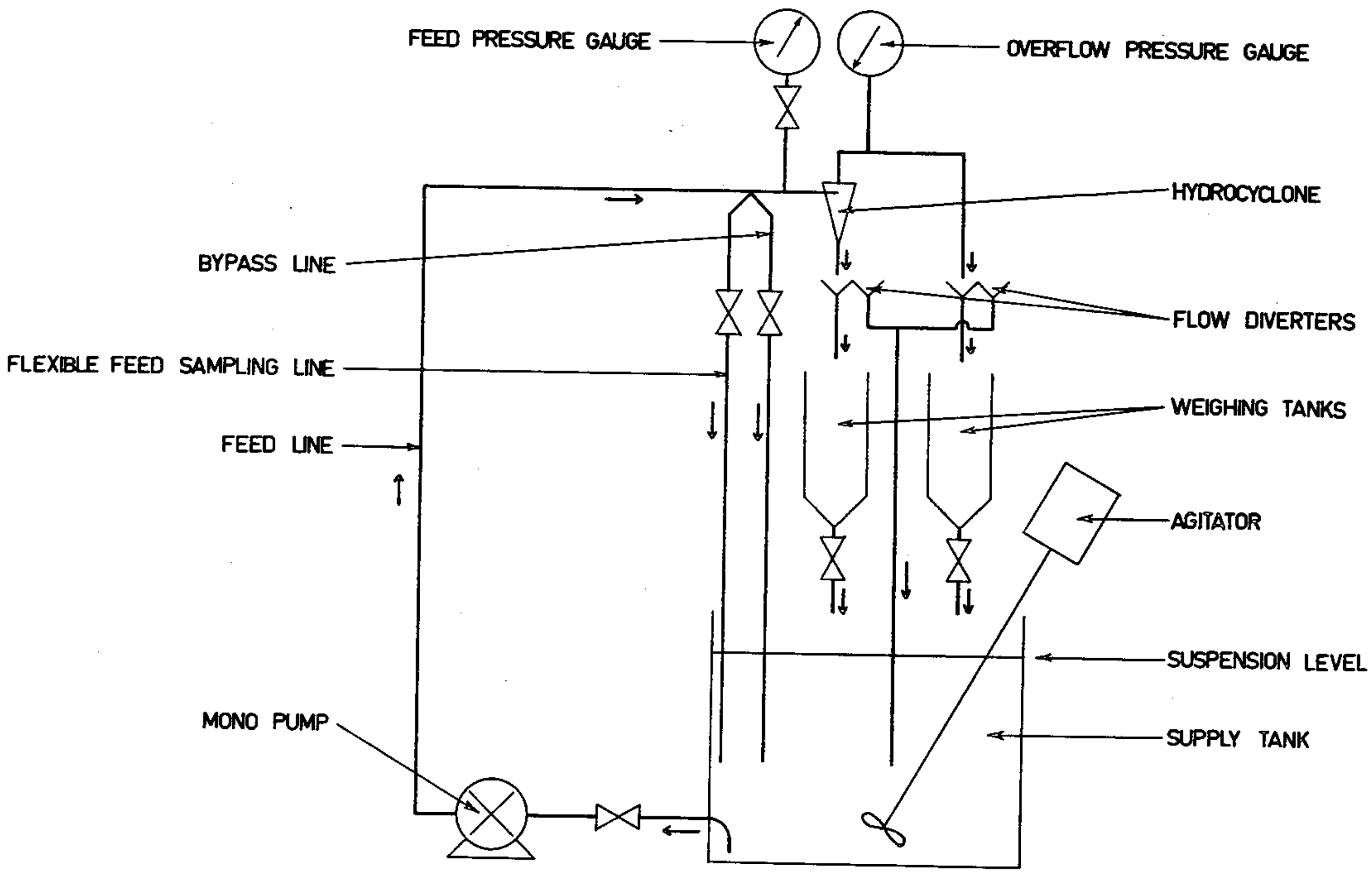
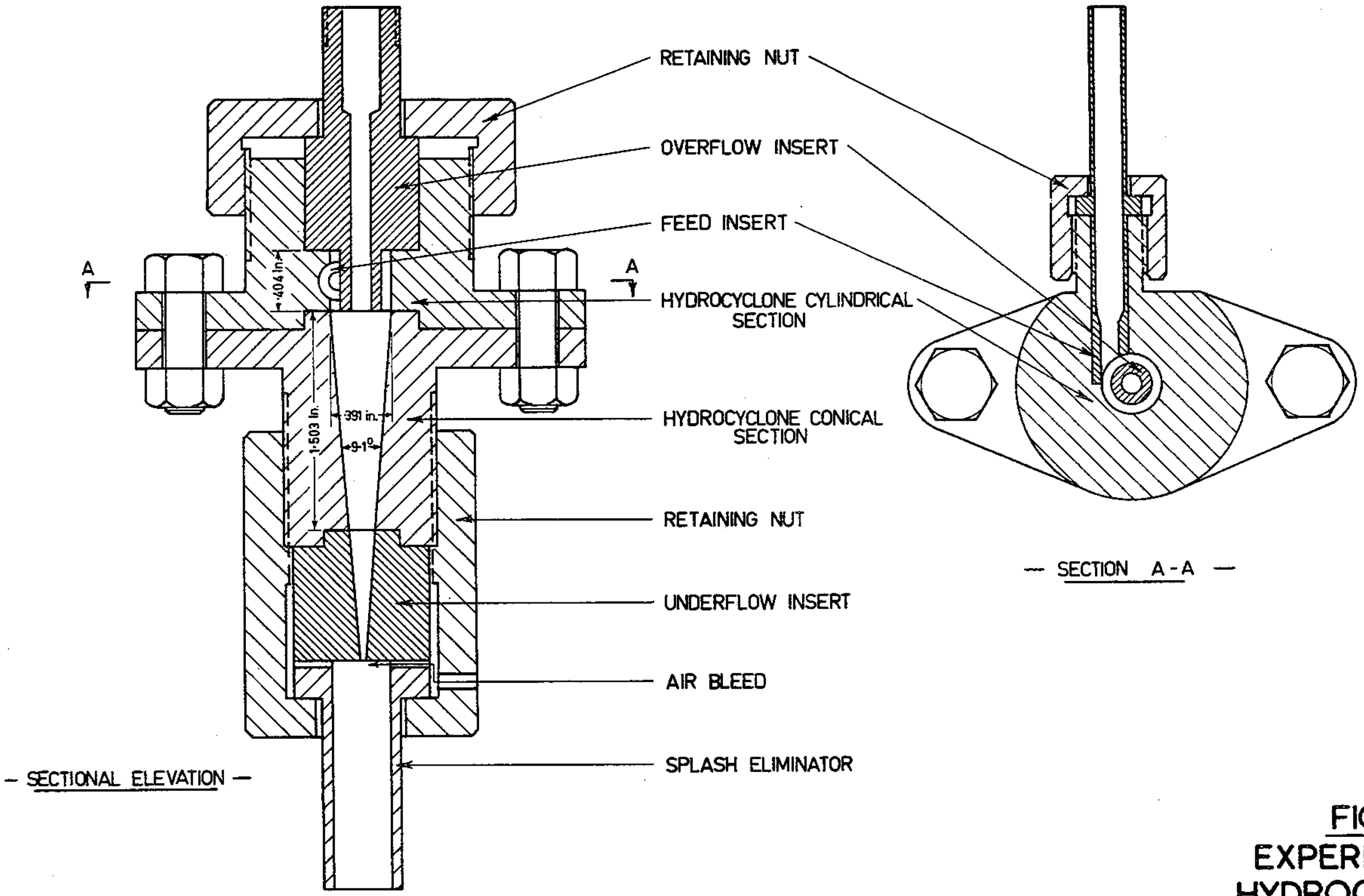


FIG. 1

FLOW DIAGRAM OF
HYDROCYCLONE LOOP



— SECTIONAL ELEVATION —

— SECTION A - A —

FIG. 2
EXPERIMENTAL HYDROCYCLONE
(IN SECTION)

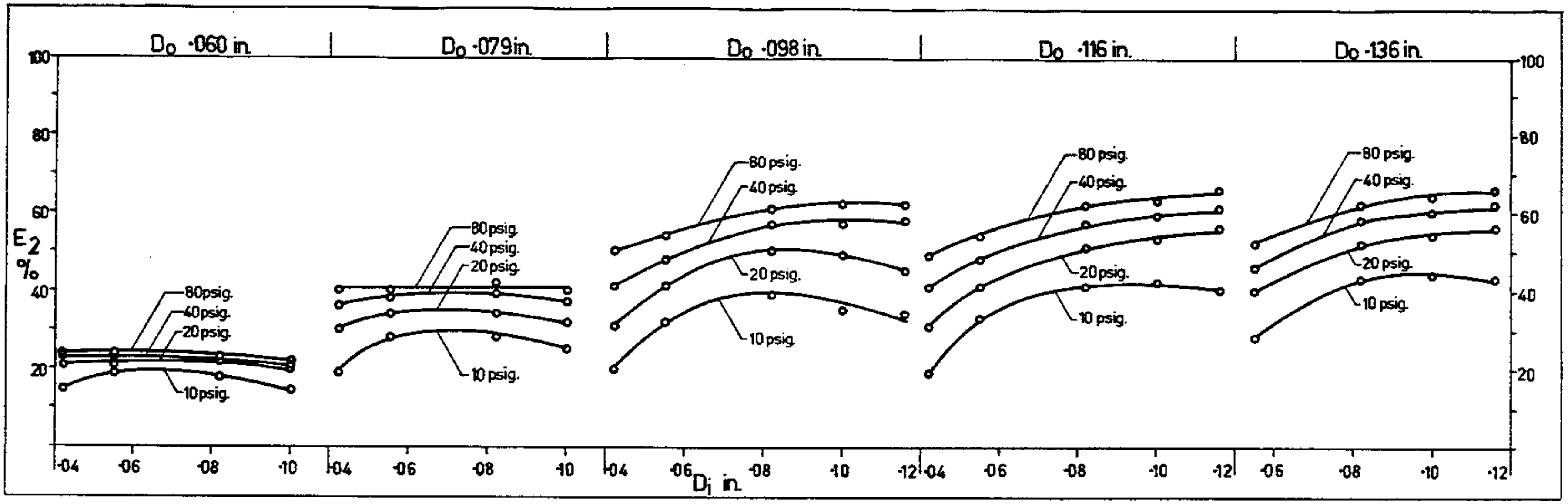


FIG. 3 RESULTS FOR E_2 USING THE 0·037 inch D_u WITH A 0·197 inch VFOD.

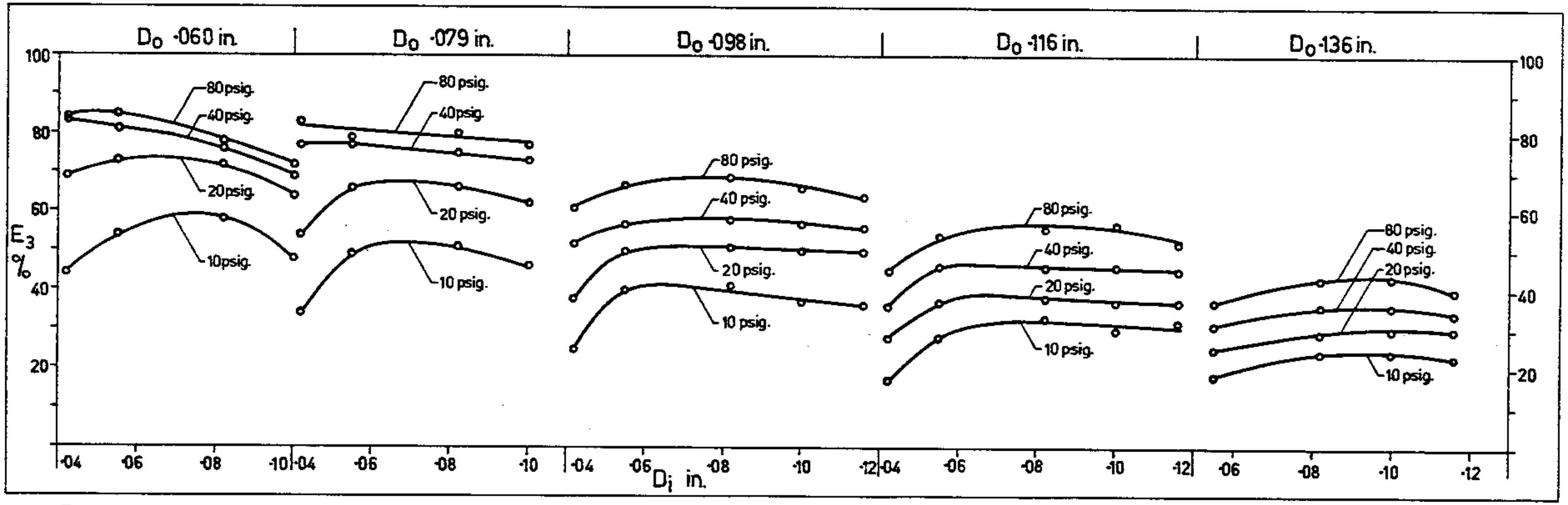


FIG. 4 RESULTS FOR E_3 USING THE 0·037 inch D_u WITH A 0·197 inch VFOD.

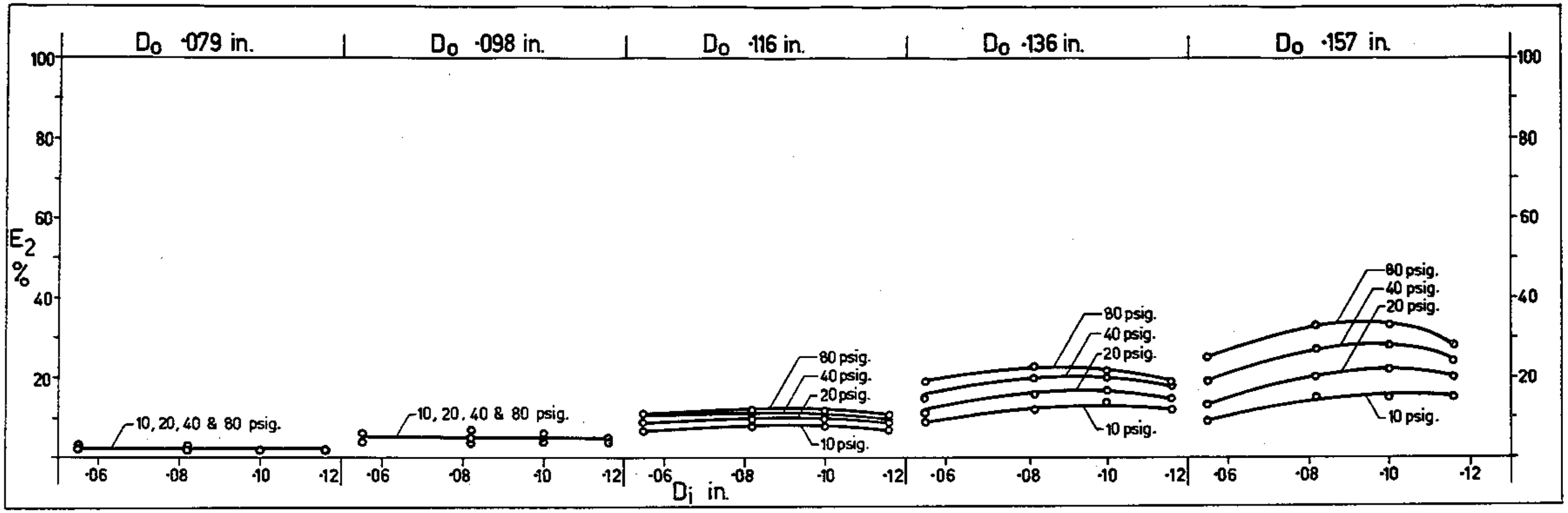


FIG. 5 RESULTS FOR E_2 USING THE 0·098 inch D_u WITH A 0·197 inch VFOD.

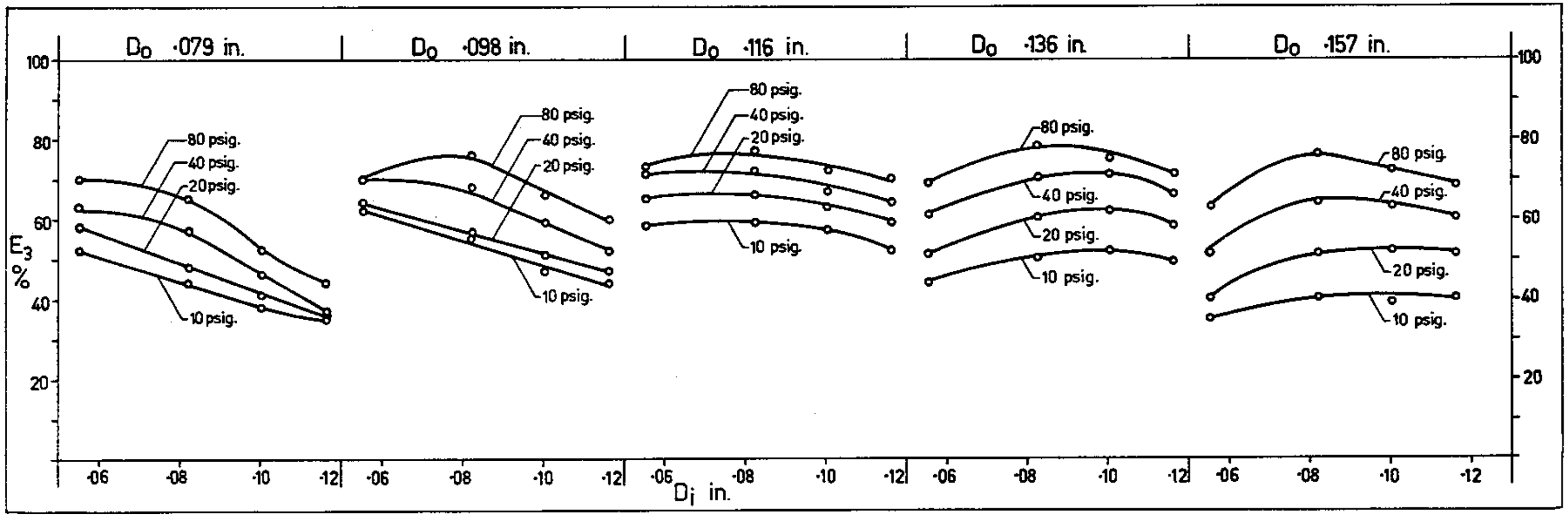


FIG. 6 RESULTS FOR E_3 USING THE 0·098 inch D_u WITH A 0·197 inch VFOD.

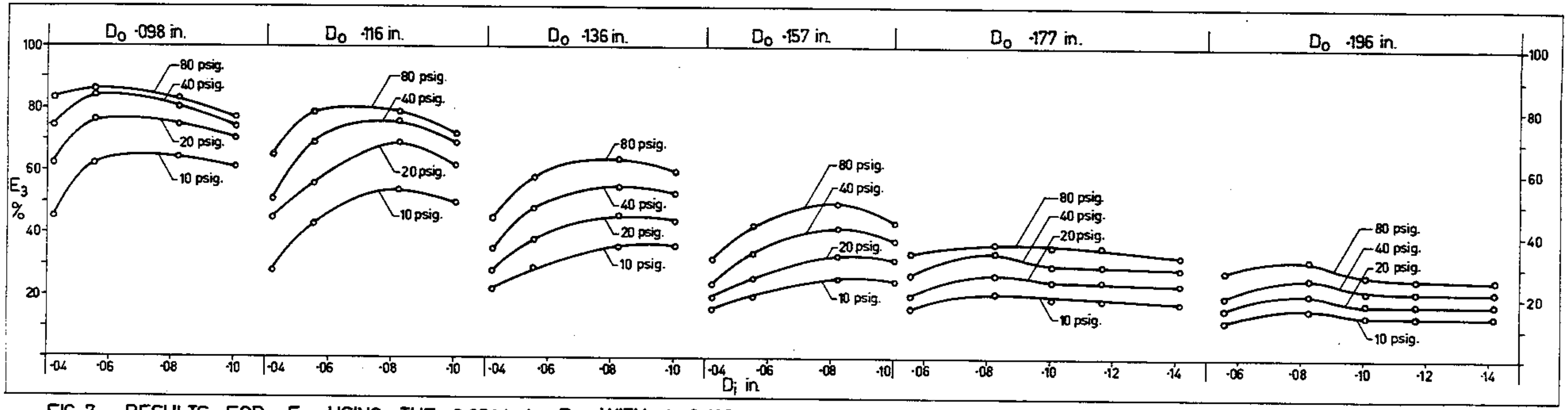


FIG. 7 RESULTS FOR E_3 USING THE 0·058 inch D_u WITH A 0·197 inch VFOD.

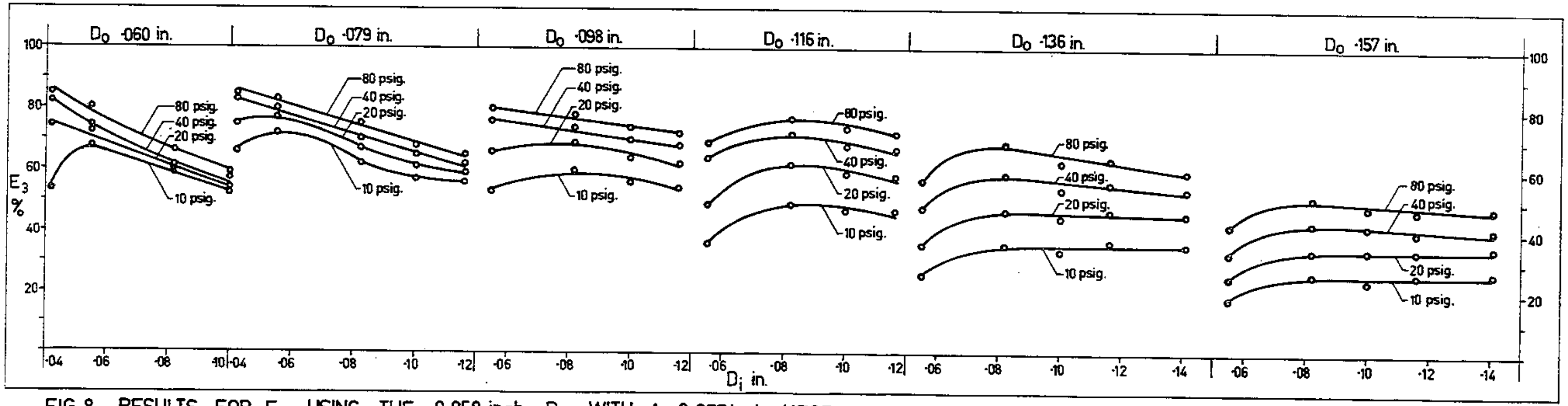


FIG. 8 RESULTS FOR E_3 USING THE 0·058 inch D_u WITH A 0·277 inch VFOD.