EXPERIMENTAL INVESTIGATION OF PRESSURE DROP IN HELICAL COILS

Thesis by

Lt. Comdr. A. H. Clancy Jr., U.S.N.

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ABSTRACT

The purpose of this study was to begin an investigation of the pressure drop in flow through helical coils. In general, the procedure followed was to define the governing parameters and then to isolate the effect of each on the pressure drop. The pressure drop was assumed to depend upon the length of the tube, the inside diameter of the tube, the diameter of the helix, the roughness of the inside of the tube, and Reynolds number. Variation of pressure drop with change in diameter of the tube was not investigated. Five different lengths of plastic tubing were tested separately on five helices of different diameters at Reynolds numbers from 3,000 to 100,000 to study the effects of length and helix diameter. Twelve steel coils of different inside roughnesses were tested over the same Reynolds number range to obtain the effect of roughness on pressure drop.

The results of the investigation indicated that pressure drop in a helical coil is linearly dependent on length, is only slightly affected by roughness, and is a function of both Reynolds number and diameter of helix as indicated in the attached curves. These conclusions, of course, hold only for the limited field covered by the investigation.

SYMBOLS

d_t - Inside diameter of test tubing, ft.

D_H - Mean diameter of helix, ft.

f - Friction factor for straight circular pipe.

f_c - Friction factor for coiled circular pipe. $(= fh_c)$

h_c - Ratio of friction factor for helical coil and friction factor for equivalent straight pipe.

g - Acceleration of gravity, ft./sec.^{2}

L - Length of test tubing, ft.

$\mathring{m}$ - Mass flow rate, slugs/sec.

n - Number of turns in helix.

Δp - Pressure drop, lbs./ft.^{2}

r - Roughness of tube, microinches.

Re - Reynolds number.

v - Flow velocity, ft./sec.

μ - Fluid absolute viscosity, slugs/ft.-sec.

ρ - Fluid mass density, slugs/ft.^{3}

INTRODUCTION

The use of regenerative cooling in rocket motors has emphasized the lack of experimental data concerning the pressure drop in helical coils. All standard texts in Fluid Mechanics deal at length with pressure drop through straight conduits and pressure drop for flow around bends. The existing data on flow around bends, however, normally covers only bends up to 90 degrees and pipe sizes many times the diameter of the tubing for which information is desired in connection with rocket cooling.

The present investigation was undertaken as the beginning of the detailed collection of information concerning the pressure drop in helical coils in the hope of providing a concrete basis upon which the design engineer could make intelligent estimates of the pressure losses.

An attempt was made to isolate all the variables involved in order to discover quantitatively the factors contributing to the increase in pressure drop in a helical coil over that in a straight tube.

EQUIPMENT

In this investigation it was assumed that the pressure drop in a helical coil was some function depending on the length of the tube, L, the inside diameter of the tube, d_t, the diameter of the helix, D_H, the inside roughness, r, and the Reynolds number, Re.

The first series of tests was designed to investigate the effects of roughness on pressure drop in a helical coil. To this end, twelve ten foot lengths of stainless steel tubing, one half inch nominal outside diameter, were sandblasted to various inside roughnesses. These tubes were tested straight and then bent into helices of the same diameter and tested at various Reynolds numbers. (See Table I for test configurations). In this manner all of the variables with the exception of r and Re were held as constant as the fabrication technique would allow. As indicated in Table I there was some variation in d_t because of the fact that the tubes were out of stock and not machined, and some variation in D_H because of the springback in the helices after they were bent.

The tubes were sandblasted by "The Sandblaster's Studio" of Los Angeles. A special nozzle was designed by this company for a hose small enough to fit inside the steel tubing. The hose was inserted through the steel tube and then withdrawn at a steady rate during the blasting operation. The direction of withdrawal was then reversed in order to make the roughness as uniform as possible throughout the length of the tubing. Different size grit was used for different roughnesses. It was desired to vary the roughness between the tubes as uniformly as possible from 10 to 100 microinches.

The values obtained, as measured on a profilometer, are listed in Table I. The distribution was not very uniform; however, it was decided to test the specimens anyway, inasmuch as there was an appreciable roughness spread between the smoothest and roughest tube.

The technique for bending the steel tubing into helices was as follows. The inner surface of the tubing was coated with light machine oil and the entire tube was heated in boiling water. The tube was then filled with a molten, low-boiling point metal, "Cerrosafe", while still in the heating bath. After the tube cooled, it was formed by hand into a helix, using a cylinder of the desired diameter for the coiling process. The helix was then emptied of the Cerrosafe by heating with a blowtorch. Remnants of the Cerrosafe were then further removed by a steam jet. The tubes were weighed before and after the coiling operation to insure that no particles of Cerrosafe remained in the helices. There were no evidences of residual Cerrosafe.

The second set of tests was designed to hold roughness constant and to vary the remaining parameters. For these tests a plastic tubing called "Jescolite" was chosen. This tubing had a nominal one-half inch outside diameter and about a 0.05 inch wall thickness. By using the same piece of tubing for the remaining tests the roughness and inside diameter of the tubing were held constant while length, diameter of helix, and Reynolds number were varied. For the purpose of varying helix diameter, five wooden mandrels were constructed of different diameters, each having a one-half inch wide by one-half inch deep helix cut into them. (Fig. 1). Twenty-five runs were made using the five helix diameters and five different lengths. (See Table II for test configurations).

Before the Jescolite was accepted for use it was statically tested to determine to what extent it would expand under pressure. This was quite an important consideration when it is remembered that pressure loss in a straight conduit is inversely proportional to the product of the hydraulic diameter and the square of the cross sectional area. The tubing was wound in an unsupported helix of four inches diameter and then statically tested up to a pressure of 200 p.s.i. With the pressure at 125 p.s.i. or less the expansion was negligible. The maximum static pressure during the runs was 120 p.s.i. at the upstream end of the tubing. To investigate the distortion in the shape of the tubing due to winding, the ratio of the major and minor axes (assuming the tube to be in the shape of an ellipse) was recorded with no pressure on the four inch helix. This ratio was found to be 1.10. Using this ratio, the error between hydraulic radius of the ellipse and radius of a circle of equal perimeter was computed to be only four tenths of one per cent. With pressure in the Jescolite and with the tubing wound in the helical grooves this error should be even less. Thus the plastic tubing was considered to be circular in cross section and rigid in dimensions throughout the tests.

The inside diameter of the plastic tubing was measured by measuring the outside diameter of a piece of aluminum rod machined to fit snugly in the Jescolite. This dimension was checked at both ends of the tubing after each cut was made and did not vary throughout the tests.

PROCEDURE

The test setup is shown schematically in Fig. 2, while photographs of the equipment are shown in Figs. 3, 4, and 5. Standard equipment was used with the exception of the test specimens and the wooden helices previously described. The test fluid was water.

In general, the test procedure was as follows: (1) Establish a flow rate, (2) Measure and record a differential pressure, (3) Simultaneously obtain flow rate by weighing a mass of water during a specific time interval, (4) Measure and record temperature of water. From these recorded data and specimen dimensions, the quantities Re and f_c were calculated.

Three methods of pressure measurement were used to obtain maximum accuracy over all ranges of pressure drop. The first pressure measurements at low flow rates were made on a ten foot water manometer. Measurements were then shifted to a ten foot mercury manometer. At high rates of flow, above the range of the two manometers, two pressure gauges were used. In all runs, overlapping readings of the pressure measuring devices were made to insure continuity in the data when a shift of instrument was made. In all cases the agreement at the shift point was excellent.

The test procedure was designed to furnish a curve of friction factor, f, versus Re for a straight section of test tubing which could be compared with a curve of f_c versus Re for the corresponding coiled tube.

In both the steel and the plastic tests it was desired to isolate the pressure drop through the coiled portion of the test specimens in order to obtain greater accuracy in the comparison of results. This required the subtraction of the pressure drop in the straight sections of tubing leading in and out of the coil from the total pressure drop measured. For each steel specimen and for the single plastic specimen a one foot straight length was tested and curves obtained of pressure drop versus mass flow rate. In every helical configuration, both steel and plastic, six inch leads were allowed at each end of the coil for connection to the pressure taps. In the calculations, the pressure drop of the one foot length was subtracted from the total measured pressure drop of the corresponding helical specimen for the same mass flow rate. In subsequent calculations, a new length was used, one foot shorter than the original tap to tap length. In this manner, the end effects of leads and taps were removed. This method is not entirely accurate because the flow pattern in the tested one foot lengths was probably not the same as the flow pattern in the leads during the helical tests. However, the magnitude of the correction was small compared to the overall pressure drop and thus the resultant error would be negligible.

Each steel sample was run straight before it was coiled, to get the corresponding straight pipe curve. Inasmuch as the same piece of plastic was used in all the plastic runs, only two comparison runs were made with the plastic straight. One was made at the beginning and the other after the first reduction in length. They checked within one per cent.

PRESENTATION OF RESULTS

The direct results of the investigation are values of friction factor versus Reynolds number. For the steel tubing, tabulated results are found in Tables III to VIII inclusive. Plotted results for the steel are found in Figs. 6-9. For the plastic test specimens, tabulated data appears in Tables IX to XV inclusive. Figs. 10-19 show the plotted results for the plastic tubing.

The following dimensionless parameters are used in the discussion of the results:

h_c - Ratio of friction factor for coiled specimen to that of same specimen run straight

D_H/d_t - Ratio of helix diameter to tube diameter

L/d_t - Ratio of length of tube to tube diameter

r/d_t - Ratio of roughness (microinches) to tube diameter

Re - Reynolds number

The Darcy equation, shown below, was used to calculate f.

$$\Delta p = f \frac{L}{dt} \frac{1}{2} \rho v^2$$

Δp - pressure drop, lbs/ft^2

f - friction factor, dimensionless

L/d_t - ratio of length to diameter of tube

ρ - mass density of fluid, slugs/cu.ft.

v - velocity, ft/sec.

There was some question as to whether the number of turns in the helical coil should have been used as one of the parameters of the discussion, but it was felt that the use of L/d_t and D_H/d_t was more logical and convenient inasmuch as the former parameter appears directly in the Darcy equation. Note, however, that when L/d_t and D_H/d_t are given, the number of turns is defined.

References are made throughout the report to curves of f versus Re, for different relative roughnesses, published by Moody (Ref. 1). In this work Moody defines relative roughness as ε/d_t where ε is a length proportional to the internal roughness of the pipe. He then correlates this ratio with different types of commerical grade pipes. In this investigation the question of the relation between r/d_t and ε/d_t arises. When the steel samples and the plastic tubing were tested straight, it was found that their curves of f versus Re coincided very closely with Moody's curves for a straight pipe where r/d_t was set equal to ε/d_t. This fact was used as justification for relating Moody's results to results obtained in this study.

On each curve of f versus Re, for both the steel and the plastic tubing, there appears a plot of h_c versus Re. A compilation of these curves is shown for the steel in Fig. 20, and for the plastic in Fig. 22.

For the plastic tubing, crossplots of h_c versus L/d_t appear in Figs. 23, 24, and 25 for Reynolds numbers of 8,000, 20,000, and 60,000 respectively. Crossplots of h_c versus D_H/d_t appear for the plastic in Figs. 26 and 27 for the Reynolds numbers indicated. A compilation of the curves from Figs. 26 and 27 appear in Fig. 28.

DISCUSSION

In evaluating the results of this investigation no attempt was made to express any of the variations in analytic form. The relationship of h_c with either Re or D_H seemed to follow no simple law.

Fig. 20 is a plot of h_c versus Re for representative values of r/d_t for the steel coils. Fig. 21 shows a crossplot of h_c versus r/d_t for fixed values of Re. Note that in these crossplots and in subsequent ones, the plotted points are used to identify the source of data and not to indicate experimental points.

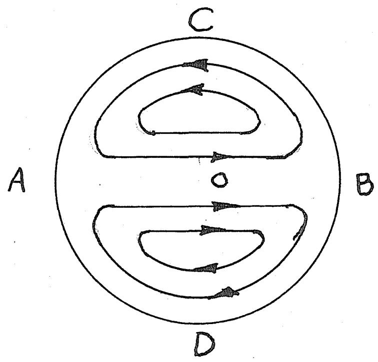
A study of Fig. 21 indicates that h_c shows very little dependence on r/d_t over the range of relative roughnesses covered in this report. No definite statement can be made concerning the trend of the variation because of the scatter of the points. The smoothness of the curves through the original experimental points justifies the belief that the random nature of the points was not caused by errors in pressure measuring technique. It is felt that the aimless distribution was caused by ignorance of the overall physical characteristics of the steel test specimens. Although extreme care was taken in measuring the diameters of the tubing, the measurements could naturally only be taken at the ends of the tubes and no account could be made of the variation of d_t along the length. Similarly, the profilometer roughness readings were taken on samples cut off the ends of the specimens and had to be taken as representative of the entire tube. The fact that the variation of h_c with r/d_t was small can be somewhat justified by noting that for similar ranges of Re and relative roughnesses, Moody obtained only slight differences of friction factor from that of a smooth straight pipe. It must be borne in mind that the small variation obtained applies only to the narrow limits of this investigation. Again looking at Moody's curves, and assuming that the overall behaviour of the coiled tubes will be generally similar, it can be expected that, for higher values of relative roughness or higher values of Re, the effect of relative roughness on the pressure drop will be more pronounced.

The use of the plastic tubing in the investigation was very effective in cutting down the number of parameters upon which the pressure loss depended. By using the same piece of tubing for the runs involving different helix diameters and different lengths, the factors of relative roughness and tube diameter were held constant. The effects of the remaining three parameters, L/d_t, D_H/d_t, and Re, could then be easily separated.

Fig. 22 shows the variation of h_c with Re for the plastic coils. A very distinct minimum was recorded in every case in the Re range between 7,000 and 11,000. There appears to be no obvious explanation for this phenomenon.

Figs. 23, 24, and 25 indicate the variation of h_c with L/d_t. The results confirm what might have been suspected; that is, there is no variation of h_c for different lengths of the same tubing. This linearity of pressure drop with length is the same as is found in straight pipe theory and experiment. This conclusion might be expected to hold for higher values of L/d_t than used in this study, but there is doubt as to its validity for lower values of L/d_t which involve a fraction of a turn. It is reasonable to assume that, after a secondary flow has been established in a uniformly coiled tube, it will continue unchanged and that the pressure loss will be linear with length. However, the mechanism of establishing the flow in the first turn or turns is unknown and the probability of a variation of h_c with L/d_t in the lower range must be considered. There was a definite limitation to the lower value of L/d_t in this experiment. This was brought about by the technique of removing the end effects as previously described. As the length of the tubing was decreased, the correction factor became a greater and greater percentage of the total pressure drop, thus decreasing the accuracy of the results. A more refined technique for tapping the test specimen itself for static pressure measurement might allow an investigation of the distance required for secondary flow development.

The secondary flow referred to above may be described as follows. Consider the cross section of a coiled tube.



In the sketch, point "A" is the inside of the turn and point "B" is the outside of the turn. The velocity of the fluid at points "C" and "D" is lower than the velocity at point "O" because of the friction of the walls of the tube. Because the velocities in the center section "OB" are higher than those in the regions "BC" and "BD", the centrifugal force and thus the pressure in region "OB" is higher and the fluid tends to take up a spiral motion from "B" towards "C" and "D". By continuity it then continues to "A" and back up the center. This spiral flow is superimposed on the axial flow.

Figs. 26 and 27 show the results of h_c vs. D_H/d_t for various Reynolds numbers. Here again, crossplot points indicate the source of the data and not experimental points. The curves indicating the variation were drawn through the mean of the L/d_t points. These curves were collected in Fig. 28 to show their relative positions more clearly. For further clarity in emphasizing both the minimum with respect to Re and the observed inflection with respect to D_H/d_t, a three dimensional plot of h_c vs. D_H/d_t and Re is shown in Fig. 29. The widest variation of the points in Figs. 26 and 27 appeared at Re 3,000. This might be expected because of the low flow rates used to obtain this Re. The values of Δp corresponding to the low flow rates were themselves so small that an error in reading the manometer would be a much higher percentage of the total than would be the case at a higher flow rate.

Fig. 28 shows not only the minimum found before with respect to Re, but also indicates an inflection of h_c with respect to D_H/d_t. This inflection is not evident in the curves corresponding to Reynolds numbers of 3,000 and 8,000, but is quite clear in the curves drawn for Re 15,000 and higher. The inflection occurs at a value of D_H/d_t of about 22.5. Hughes and Safford, (Ref. 2, p. 233), quote some results from experiments by Brightmore, (Ref. 3), in which inflections with respect to D_H/d_t were found, but at different values of D_H/d_t. Brightmore's experiments were made with elbows instead of full coils. It is interesting to note that in Fig. 28, for Reynolds numbers of 15,000 and above, there is practically no variation of h_c with D_H/d_t values from 20.0 to 28.0.

In Fig. 30 a comparison is made between a plastic coil and two steel coils whose configurations were most nearly the same as the plastic coil. The anomalous result followed that there was a greater pressure drop in the plastic coil than in the steel coil, the latter assumed to be the rougher. A possible explanation, discussed previously with regard to the variation of h_c with r/d_t, might lie in the fact that the dimensions of the steel tubing were not known exactly and that the plastic tubing was more uniform in its physical properties than the steel. The agreement between the plastic and the steel was within ten per cent. The inconsistency seen in Fig. 30 coupled with the scatter of points in Fig. 21 seems to indicate that reproducibility of results with the stainless steel tubing technique is poor. On the other hand, all of the results in this experiment using the plastic tubing are quite consistent. This fact further justifies the use of the plastic tubing in these tests.

It must be remembered that this study covered only a limited field, and thus it is difficult to extend any of the conclusions which were reached. This, of course, suggests further investigation over a wider range of the independent parameters. Other vital concerns of the rocket motor designer are the questions of pressure drop in coils of varying D_H/d_t which would be found around the throat of a rocket, and pressure drop in helical coils whose cross section is not circular.

CONCLUSIONS

Recalling that $h_c = \phi(L/d_t, D_H/d_t, r/d_t, Re)$, the conclusions reached in this investigation are enumerated below. In each case where h_c is considered as a function of one of the variables, it is implied that the other variables are held constant.

1. h_c varies only slightly with r/d_t over the range of r/d_t from 0.00005 to 0.00030, and follows no consistent trend.

2. h_c is independent of L/d_t over the range of L/d_t from 77.8 to 628.0.

3. h_c is dependent on Re over the Re range of 3,000 to 100,000 and has a minimum between the Reynolds numbers of 7,000 and 11,000. The position of the minimum moves from the lower to the higher value of Re as D_H/d_t decreases from 31.3 to 10.9.

4. h_c is dependent on D_H/d_t as the latter parameter varies from 10.9 to 31.3, decreasing generally as D_H/d_t increases. For values of Re of 15,000 and above, however, an inflection occurs at D_H/d_t equal to approximately 22.5. After a very slight increase, h_c begins its downward trend again at D_H/d_t equal to about 28.0. Over the range of D_H/d_t from 20.0 to 28.0, h_c can be considered constant ($15,000 \leq Re \leq 100,000$).

5. The independence of h_c with L/d_t can be extended to values of L/d_t greater than those tested but not to L/d_t values less than those tested.

6. The plastic tubing, "Jescolite", was found to be quite

satisfactory for use in experiments of this type if caution is used to keep the expansion within allowable limits.

7. The range of roughnesses tested in this study was not great enough to establish the dependence of h_c with r/d_t.

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TABLE I

DIMENSIONS OF STAINLESS STEEL SPECIMENS

SPECIMEN NUMBER →	1	2	3	4	5	6
L FT.	7.66	7.69	7.70	7.70	7.70	7.695
d_T IN.	.440	.440	.432	.433	.438	.434
d_T FT.	.0367	.0367	.0359	.0358	.0365	.0361
ռ MICROINCHES	23.	36.	40.	29.	23.	20
D_H FT.	.590	.590	.590	.590	.590	.590
D_H/d_T	16.06	16.06	14.22	14.27	13.85	14.10
L/d_T	208.5	209.0	214.0	215.	211.	213.
n (APPROX)	4	4	4	4	4	4

SPECIMEN NUMBER →	7	8	9	10	11	12
L FT.	7.68	7.515	7.695	7.69	7.496	7.695
d_T IN.	.436	.397	.432	.436	.437	.433
d_T FT.	.0363	.0331	.0360	.0363	.0364	.0361
ռ MICROINCHES	31.	93	30.	24.	21.	62
D_H FT.	.585	.585	.590	.590	.585	.580
D_H/d_T	16.11	15.75	16.39	16.25	16.09	16.08
L/d_T	211.5	227.0	213.5	212.	206.	213.
n (APPROX.)	4	4	4	4	4	4

TABLE IIa

PLASTIC TUBE TEST CONFIGURATIONS

TEST No.	1	2	3	4	5	6
L FT.	24.26	20.2	20.2	20.2	20.2	20.2
d_t IN.	0.386	0.386	0.386	0.386	0.386	0.386
d_t FT.	0.0322	0.0322	0.0322	0.0322	0.0322	0.0322
D_H FT.	STRAIGHT	1.005	0.84	0.64	0.51	0.35
D_H/d_t	STRAIGHT	31.3	26.1	21.1	15.86	10.9
L/d_t	754.0	628.0	628.0	628.0	628.0	628.0
n (approx)	0	6.5	7.7	9.6	13.0	19.5

TEST No.		7	8	9	10	11
L FT.		12.085	12.085	12.085	12.085	12.085
d_t IN.		0.386	0.386	0.386	0.386	0.386
d_t FT.		0.0322	0.0322	0.0322	0.0322	0.0322
D_H FT.		1.005	0.84	0.64	0.51	0.35
D_H/d_t		31.3	26.1	21.1	15.86	10.9
L/d_t		375.0	375.0	375.0	375.0	375.0
n (approx.)		3.7	4.7	5.7	7.7	11.7

TEST No.		12	13	14	15	16
L FT.		8.065	8.065	8.065	8.065	8.065
d_t IN.		0.386	0.386	0.386	0.386	0.386
d_t FT.		0.0322	0.0322	0.0322	0.0322	0.0322
D_H FT.		1.005	0.84	0.64	0.51	0.35
D_H/d_t		31.3	26.1	21.1	15.86	10.9
L/d_t		251.0	251.0	251.0	251.0	251.0
n (approx.)		2.6	3.0	4.0	5.1	7.7

TABLE IIb

PLASTIC TUBE TEST CONFIGURATIONS

TEST No.	17	18	19.	20	21	
L FT.	5.555	5.555	5.555	5.555	5.555	
d_t IN.	0.386	0.386	0.386	0.386	0.386	
d_t FT.	0.0322	0.0322	0.0322	0.0322	0.0322	
D_H FT.	1.005	0.84	0.64	0.51	0.35	
D_H/d_t	31.3	26.1	21.1	15.86	10.9	
L/d_t	172.5	172.5	172.5	172.5	172.5	
n(approx.)	1.7	2.1	2.6	3.5	5.2	

TEST No.	22	23	24	25	26	
L FT.	2.505	2.505	2.505	2.505	2.505	
d_t IN.	0.386	0.386	0.386	0.386	0.386	
d_t FT.	0.0322	0.0322	0.0322	0.0322	0.0322	
D_H FT.	1.005	0.84	0.64	0.57	0.35	
D_H/d_t	31.3	26.1	21.1	15.86	10.9	
L/d_t	77.8	77.8	77.8	77.8	77.8	
n(approx.)	0.8	1.0	1.1	1.5	2.2	

TABLE III

STEEL TUBING TEST RESULTS

SPECIMEN NO. 1 – STRAIGHT $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.21 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				SPECIMEN NO. 1 – COILED $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.42 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	Re	f	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	Re	f_{hc}
9.7	0.00219	3,450	0.0416	11.7	0.00176	2,525	0.0778
15.9	0.00292	4,590	0.0387	29.6	0.00341	4,890	0.0524
31.2	0.00424	6,660	0.0361	42.3	0.00436	6,250	0.0458
43.2	0.00511	8,040	0.0341	55.5	0.00523	7,500	0.0418
102.0	0.00845	13,250	0.0297	93.4	0.00712	10,220	0.0378
226.0	0.0133	20,900	0.0263	224.5	0.0114	16,370	0.0355
374.0	0.0176	27,700	0.0249	406.0	0.0158	22,750	0.0333
627.0	0.0238	37,400	0.0229	677.0	0.0212	30,400	0.0310
1148.0	0.0337	52,900	0.0209	1297.0	0.0302	43,200	0.0294
2990.0	0.0578	90,900	0.0185	2385.0	0.0423	60,700	0.0275
5290.0	0.0791	124,100	0.0175	5370.0	0.0665	95,300	0.0250
6640.0	0.0894	140,400	0.0172	7420.0	0.0784	112,300	0.0248

SPECIMEN NO. 2 – STRAIGHT $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.21 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				SPECIMEN NO. 2 – COILED $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.325 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	Re	f	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	Re	f_{hc}
18.0	0.00301	4,730	0.0408	20.4	0.00272	4,060	0.0568
27.1	0.00389	6,110	0.0368	131.8	0.00867	12,920	0.0362
42.7	0.00504	7,890	0.0348	420.0	0.0165	24,660	0.0317
53.1	0.00576	9,040	0.0328	838.0	0.0243	36,200	0.0293
92.3	0.00798	12,530	0.0298	2490.0	0.0448	66,800	0.0256
201.0	0.01248	19,620	0.0265	5010.0	0.0659	98,200	0.0238
354.0	0.0172	27,100	0.0244				
616.0	0.0236	37,100	0.0277				
1144.0	0.0333	52,400	0.0212				
2075.0	0.0473	74,500	0.0190				
4340.0	0.0713	112,000	0.0176				
5150.0	0.0790	124,100	0.0170				

TABLE IV

STEEL TUBING TEST RESULTS

SPECIMEN NO. 3 - STRAIGHT				SPECIMEN NO. 3 - COILED			
$\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.21 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.325 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp LBS/FT^2	$\overset{\circ}{m}$ SLUGS/SEC	Re	f	Δp LBS/FT^2	$\overset{\circ}{m}$ SLUGS/SEC	Re	f_{hc}
20.1	0.00316	5,060	0.0377	13.7	0.00204	3,110	0.0616
32.7	0.00413	6,580	0.0362	30.6	0.00339	5,150	0.0498
44.1	0.00484	7,750	0.0353	55.0	0.00505	7,720	0.0402
87.4	0.00728	11,660	0.0309	93.9	0.00687	10,480	0.0373
214.0	0.01232	19,750	0.0263	428.0	0.0159	24,200	0.0317
376.0	0.0169	27,100	0.0245	1267.0	0.0291	44,400	0.0280
646.0	0.0229	36,700	0.0231	2355.0	0.0412	62,800	0.0260
1183.0	0.0325	52,100	0.0210	7660.0	0.0783	119,400	0.0234
2140.0	0.0457	73,100	0.0192				
4510.0	0.0693	110,800	0.0176				
5650.0	0.0793	126,800	0.0168				

SPECIMEN NO. 4 - STRAIGHT				SPECIMEN NO. 4 - COILED			
$\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.21 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.325 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp LBS/FT^2	$\overset{\circ}{m}$ SLUGS/SEC	Re	f	Δp LBS/FT^2	$\overset{\circ}{m}$ SLUGS/SEC	Re	f_{hc}
12.2	0.00237	3,780	0.0416	12.8	0.00179	2,710	0.0759
26.2	0.00387	6,170	0.0332	28.7	0.00332	5,040	0.0495
38.7	0.00469	7,360	0.0346	63.4	0.00559	8,470	0.0386
52.4	0.00553	8,810	0.0326	99.6	0.00724	10,950	0.0362
81.8	0.00715	11,460	0.0305	330.0	0.0140	21,200	0.0322
208.0	0.0119	18,970	0.0280	1260.0	0.0296	44,900	0.0273
344.0	0.0165	26,300	0.0241	4540.0	0.0605	91,800	0.0236
630.0	0.0230	36,600	0.0228	7360.0	0.0782	118,600	0.0229
1180.0	0.0341	54,400	0.0194				
2150.0	0.0466	74,300	0.0189				
4480.0	0.0700	111,700	0.0174				
5570.0	0.0786	125,400	0.0172				

TABLE V

STEEL TUBING TEST RESULTS

SPECIMEN No. 5 - STRAIGHT				SPECIMEN No. 5 - COILED			
$\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.325 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.325 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	Re	f	Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	Re	f_{hc}
15.6	0.00284	4,250	0.0390	14.4	0.00191	2,860	0.0794
36.6	0.00447	6,700	0.0368	32.6	0.00358	5,350	0.0513
79.5	0.00733	10,990	0.0299	50.8	0.00497	7,440	0.0414
389.0	0.0178	26,600	0.0198	94.6	0.00720	10,780	0.0369
1163.0	0.0335	50,100	0.0209	411.0	0.0161	24,050	0.0321
4910.0	0.0736	110,300	0.0182	1267.0	0.0303	45,400	0.0278
				2335.0	0.0422	63,200	0.0264
				7225.0	0.0787	117,800	0.0235

SPECIMEN No. 6 - STRAIGHT				SPECIMEN No. 6 - COILED			
$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.42 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.325 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	Re	f	Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	Re	f_{hc}
16.0	0.00277	4,040	0.0399	13.9	0.00193	2,920	0.0715
33.4	0.00426	6,200	0.0354	31.9	0.00388	5,860	0.0408
88.3	0.00734	10,680	0.0315	51.0	0.00501	7,570	0.0391
333.0	0.0158	23,100	0.0254	92.9	0.00697	10,510	0.0367
1138.0	0.0337	49,100	0.0193	426.0	0.0161	24,400	0.0314
5140.0	0.0736	107,200	0.0182	1274.0	0.0297	44,800	0.0278
				2370.0	0.0417	63,000	0.0261
				7600.0	0.0780	117,800	0.0240

TABLE VI

STEEL TUBING TEST RESULTS

SPECIMEN No. 7 - STRAIGHT				SPECIMEN No. 7 - COILED			
$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.42 \times 10^{-5} \frac{SLUGS}{FT-SEC}$				$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.325 \times 10^{-5} \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f	Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f_{hc}
12.4	0.00234	3,390	0.0449	10.9	0.00157	2,360	0.0875
46.2	0.00501	7,240	0.0365	32.2	0.00361	5,430	0.0489
97.9	0.00775	11,190	0.0322	49.4	0.00485	7,290	0.0415
346.0	0.01597	23,100	0.0269	434.0	0.0165	24,750	0.0316
1315.0	0.0353	51,100	0.0209	1272.0	0.0300	45,200	0.0279
4970.0	0.0737	106,500	0.0182	2335.0	0.0418	62,800	0.0265
				5380.0	0.0664	99,800	0.0241
				7350.0	0.0781	117,200	0.0239

SPECIMEN No. 8 - STRAIGHT				SPECIMEN No. 8 - COILED			
$\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.325 \times 10^{-5} \frac{SLUGS}{FT-SEC}$				$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.35 \times 10^{-5} \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f	Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f_{hc}
22.3	0.00263	4,360	0.0405	13.5	0.00144	2,360	0.0810
30.5	0.00317	5,250	0.0380	25.2	0.00230	3,780	0.0593
42.7	0.00384	6,370	0.0364	35.7	0.00295	4,830	0.0513
56.9	0.00462	7,660	0.0334	56.2	0.00406	6,660	0.0426
93.6	0.00613	10,160	0.0312	97.3	0.00571	9,300	0.0377
228.0	0.0102	16,990	0.0272	221.0	0.00894	14,610	0.0347
383.0	0.0138	22,950	0.0250	457.0	0.0134	21,900	0.0319
637.0	0.0184	30,550	0.0235	681.0	0.0168	30,200	0.0303
1254.0	0.0272	45,100	0.0212	1358.0	0.0244	39,800	0.0277
2390.0	0.0391	64,800	0.0196	2490.0	0.0340	55,600	0.0270
4740.0	0.0575	95,300	0.0179	4710.0	0.0484	79,100	0.0246
8070.0	0.0771	127,600	0.0170	7360.0	0.0621	101,600	0.0239
				9430.0	0.0717	117,300	0.0229

TABLE VIII

STEEL TUBING TEST RESULTS

SPECIMEN No. 9- STRAIGHT				SPECIMEN No. 9 - COILED			
$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.45 \times 10^{-5} \frac{SLUGS}{FT-SEC}$				$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.29 \times 10^{-5} \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f	Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f_{hc}
14.8	0.00259	3,730	0.0417	16.9	0.00227	3,500	0.0616
47.2	0.00505	7,270	0.0349	31.4	0.00351	5,420	0.0478
96.8	0.00760	10,930	0.0316	55.2	0.00516	7,970	0.0389
308.0	0.01486	21,400	0.0263	128.4	0.00828	12,810	0.0351
1220.0	0.0329	47,400	0.0212	402.0	0.0156	24,000	0.0312
4670.0	0.0695	100,000	0.0182	1284.0	0.0296	45,700	0.0275
				2310.0	0.0410	63,200	0.0258
				5590.0	0.0667	103,100	0.0235

SPECIMEN No. 10 - STRAIGHT				SPECIMEN No. 10 - COILED			
$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.45 \times 10^{-5} \frac{SLUGS}{FT-SEC}$				$\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.25 \times 10^{-5} \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f	Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f_{hc}
20.2	0.00320	4,560	0.0391	15.4	0.00221	3,440	0.0624
59.5	0.00580	8,260	0.0344	31.1	0.00366	5,700	0.0457
109.5	0.00834	11,880	0.0312	55.6	0.00535	8,330	0.0383
364.0	0.0167	23,850	0.0258	123.1	0.00831	12,940	0.0352
1220.0	0.0330	47,100	0.0221	384.5	0.0155	24,100	0.0316
4680.0	0.0715	102,000	0.0182	1243.0	0.0295	46,000	0.0281
				2285.0	0.0416	64,800	0.0260
				5530.0	0.0674	105,000	0.0239

TABLE VIII

STEEL TUBING TEST RESULTS

SPECIMEN No. 11 – STRAIGHT $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.47 \times 10^{-5} \frac{SLUGS}{FT-SEC}$				SPECIMEN No. 11 – COILED $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.325 \times 10^{-5} \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f	Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f_{hc}
20.4	0.00328	4,640	0.0387	15.5	0.00225	3,380	0.0625
63.0	0.00615	8,690	0.0340	28.9	0.00347	5,220	0.0490
111.3	0.00867	12,250	0.0302	54.9	0.00537	8,690	0.0387
358.0	0.0172	24,300	0.0248	126.9	0.00860	12,910	0.0350
1235.0	0.0350	49,500	0.0205	399.0	0.0162	24,300	0.0311
4620.0	0.0730	103,100	0.0178	1279.0	0.0309	46,500	0.0272
				2305.0	0.0428	64,400	0.0256
				5370.0	0.0681	102,400	0.0236
				7210.0	0.0791	119,000	0.0234

SPECIMEN No. 12 – STRAIGHT $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.325 \times 10^{-5} \frac{SLUGS}{FT-SEC}$				SPECIMEN No. 12 – COILED $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.37 \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f	Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f_{hc}
29.4	0.00389	5,890	0.0371	17.6	0.00216	3,210	0.0715
46.2	0.00510	7,720	0.0339	32.3	0.00362	5,410	0.0466
86.1	0.00722	10,920	0.0314	48.4	0.00474	7,080	0.0406
218.5	0.0126	19,130	0.0261	86.0	0.00676	10,100	0.0356
366.0	0.0169	25,600	0.0244	207.0	0.0108	16,120	0.0335
612.0	0.0226	34,400	0.0227	425.0	0.0160	23,850	0.0314
1178.0	0.0328	49,700	0.0208	658.0	0.0204	30,400	0.0299
2150.0	0.0465	70,500	0.0188	1261.0	0.0293	43,800	0.0277
4490.0	0.0695	105,200	0.0176	2340.0	0.0414	61,800	0.0258
6340.0	0.0838	126,800	0.0171	4300.0	0.0578	86,400	0.0242
				5670.0	0.0675	100,900	0.0234

TABLE IX

PLASTIC TEST RESULTS

TEST No. 1				TEST No. 2			
$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.42 \times 10^{-5} \frac{SLUG}{FT-SEC}$				$\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.235 \times 10^{-5} \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	Re	f	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	Re	f_{hc}
49.8	0.00196	3,220	0.0436	50.7	0.00182	3,230	0.0621
64.6	0.00222	3,640	0.0433	74.4	0.00247	4,380	0.0494
82.8	0.00258	4,230	0.0418	110.6	0.00328	5,820	0.0416
111.2	0.00307	5,010	0.0397	210.5	0.00483	8,550	0.0367
245.0	0.00483	7,920	0.0353	474.0	0.00742	13,150	0.0348
499.0	0.00734	12,030	0.0311	718.0	0.00927	16,450	0.0339
622.0	0.00823	13,450	0.0310	1505.0	0.0139	24,700	0.0312
916.0	0.01040	17,040	0.0285	3035.0	0.0206	36,600	0.0289
1820.0	0.01552	25,500	0.0253	5480.0	0.0290	51,400	0.0264
3610.0	0.0233	38,200	0.0223	6880.0	0.0333	59,100	0.0251
5820.0	0.0312	51,100	0.0201				

TEST No. 3				TEST No. 4			
$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.335 \times 10^{-5} \frac{SLUGS}{FT-SEC}$				$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.335 \times 10^{-5} \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	Re	f_{hc}	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	Re	f_{hc}
78.2	0.00232	3,940	0.0590	48.6	0.00164	2,790	0.0729
117.8	0.00312	5,310	0.0488	74.4	0.00218	3,695	0.0638
224.5	0.00475	8,050	0.0404	106.9	0.00288	4,890	0.0525
455.0	0.00689	11,680	0.0390	211.5	0.00459	7,800	0.0399
744.0	0.00900	15,280	0.0373	494.0	0.00742	12,600	0.0365
1463.0	0.01309	22,200	0.0347	761.0	0.00935	15,850	0.0355
2940.0	0.0194	32,900	0.0318	1450.0	0.0132	22,500	0.0335
5120.0	0.0266	45,200	0.0293	2930.0	0.0196	33,300	0.0309
6540.0	0.0310	52,700	0.0276	5260.0	0.0270	45,900	0.0292
				6670.0	0.0309	52,500	0.0283

TABLE X

PLASTIC TEST RESULTS

TEST No. 5				TEST No. 6			
$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.335 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.335 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp $\frac{LBS}{FT^2}$	$\mathring{m}$ $\frac{SLUGS}{SEC}$	Re	f_{hc}	Δp LBS/FT^2	$\mathring{m}$ $SLUGS/SEC$	Re	f_{hc}
76.5	0.00210	3,565	0.0705	138.9	0.00264	4480	0.0809
113.4	0.00282	4,790	0.0580	221.0	0.00424	7,200	0.0500
203.0	0.00420	7,130	0.0468	537.0	0.00701	11,910	0.0443
448.0	0.00675	11,460	0.0400	800.0	0.00884	15,020	0.0416
752.0	0.00896	15,210	0.0380	1475.0	0.0126	21,460	0.0375
1480.0	0.0130	22,100	0.0356	2957.0	0.0183	31,100	0.0358
2950.0	0.0192	32,500	0.0327	5300.0	0.0254	43,000	0.0336
5250.0	0.0264	44,800	0.0306	6725.0	0.0290	49,200	0.0325
6690.0	0.0302	51,300	0.0298				

TEST No. 7				TEST No. 8			
$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.29 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.29 \times 10^{-5} \frac{SLUG}{FT\text{-}SEC}$			
Δp LBS/FT^2	$\mathring{m}$ $SLUGS/SEC$	Re	f_{hc}	Δp LBS/FT^2	$\mathring{m}$ $SLUGS/SEC$	Re	f_{hc}
14.4	0.00103	1,791	0.0907	17.0	0.00111	1,923	0.0934
32.9	0.00190	3,280	0.0621	38.9	0.00208	3,610	0.0607
44.5	0.00240	4,140	0.0526	49.4	0.00244	4,220	0.0564
60.6	0.00302	5,240	0.0450	62.4	0.00291	5,040	0.0499
115.1	0.00451	7,800	0.0385	116.9	0.00448	7,750	0.0395
255.0	0.00689	11,910	0.0365	265.0	0.00689	11,910	0.0380
464.0	0.00946	16,380	0.0352	461.0	0.00926	16,010	0.0366
721.0	0.0121	20,900	0.0336	734.0	0.0119	20,650	0.0351
1390.0	0.0176	30,400	0.0305	1400.0	0.0171	29,500	0.0327
2630.0	0.0248	42,900	0.0291	2600.0	0.0240	41,700	0.0305
4870.0	0.0351	60,800	0.0268	4710.0	0.0336	58,000	0.0284
6450.0	0.0412	71,400	0.0258	6410.0	0.0401	69,400	0.0271

TABLE XI

PLASTIC TEST RESULTS

TEST No. 9				TEST No. 10			
$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.29 \times 10^{-5} \frac{SLUGS}{FT.-SEC}$				$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.29 \times 10^{-5} \frac{SLUGS}{FT.-SEC}$			
Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f_{hc}	Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f_{hc}
20.3	0.00124	2,140	0.0900	21.1	0.00124	2,140	0.0937
42.4	0.00209	3,620	0.0659	45.9	0.00215	3,730	0.0672
52.5	0.00250	4,320	0.0571	57.9	0.00253	4,380	0.0613
72.1	0.00312	5,400	0.0504	79.5	0.00316	5,470	0.0542
132.1	0.00455	7,870	0.0434	141.7	0.00467	8,090	0.0440
270.0	0.00693	12,000	0.0381	277.0	0.00673	11,610	0.0417
452.0	0.00914	15,800	0.0368	454.0	0.00889	15,400	0.0396
740.0	0.0119	20,650	0.0352	766.0	0.0119	20,600	0.0366
1400.0	0.0171	29,500	0.0326	1460.0	0.0171	29,500	0.0341
2687.0	0.0246	42,500	0.0302	2690.0	0.0241	41,700	0.0315
4675.0	0.0336	58,200	0.0280	4710.0	0.0331	57,200	0.0292
6340.0	0.0401	69,400	0.0268	6460.0	0.0396	68,500	0.0280

TEST No. 11				TEST No. 12			
$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.285 \times 10^{-5} \frac{SLUGS}{FT.-SEC}$				$\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.29 \times 10^{-5} \frac{SLUGS}{FT.-SEC}$			
Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f_{hc}	Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	Re	f_{hc}
17.8	0.000998	1,730	0.122	14.2	0.00138	2,395	0.0757
46.4	0.00194	3360	0.0836	31.7	0.00252	4,360	0.0506
56.9	0.00227	3,940	0.0746	39.9	0.00298	5,150	0.0457
72.0	0.00265	4,590	0.0696	50.0	0.00349	6,040	0.0417
124.8	0.00388	6,730	0.0562	100.0	0.00522	9,025	0.0373
269.0	0.00624	10,790	0.0472	225.5	0.00807	13,980	0.0351
479.0	0.00870	15,070	0.0431	443.0	0.0116	20,150	0.0333
723.0	0.0109	18,900	0.0413	690.0	0.0148	25,700	0.0318
1430.0	0.0160	27,800	0.0379	1330.0	0.0214	37,000	0.0296
2650.0	0.0226	39,300	0.0350	2490.0	0.0305	52,800	0.0272
4770.0	0.0315	54,600	0.0326	4450.0	0.0424	73,300	0.0253
6520.0	0.0376	65,300	0.0313	6080.0	0.0508	87,800	0.0240

TABLE XII

PLASTIC TEST RESULTS

TEST No. 13				TEST No. 14			
$\rho = 1.937 \frac{\text{SLUGS}}{\text{FT}^3}$; $\mu = 2.29 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$\rho = 1.937 \frac{\text{SLUGS}}{\text{FT}^3}$; $\mu = 2.25 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	Re	f_{hc}	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	Re	f_{hc}
17.5	0.00156	2,700	0.0728	8.9	0.00106	1,862	0.0814
27.6	0.00215	3,720	0.0608	18.3	0.00164	2,880	0.0695
38.8	0.00278	4,800	0.0512	25.8	0.00204	3,585	0.0633
77.2	0.00444	7,690	0.0398	37.6	0.00266	4,680	0.0541
187.7	0.00714	12,340	0.0375	77.5	0.00444	7,800	0.0400
330.5	0.00969	16,750	0.0358	188.0	0.00720	12,660	0.0369
581.0	0.0132	22,900	0.0284	566.0	0.0131	23,000	0.0336
1083.0	0.0187	32,400	0.0315	1128.0	0.0193	33,900	0.0308
1995.0	0.0264	45,600	0.0292	2004.0	0.0266	46,700	0.0289
4390.0	0.0402	69,600	0.0276	4190.0	0.0405	71,300	0.0259
6040.0	0.0495	85,600	0.0250	6040.0	0.0497	87,400	0.0249

TEST No 15				TEST No. 16			
$\rho = 1.937 \frac{\text{SLUGS}}{\text{FT}^3}$; $\mu = 2.285 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$\rho = 1.936 \frac{\text{SLUGS}}{\text{FT}^3}$; $\mu = 2.22 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	Re	f_{hc}	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	Re	f_{hc}
8.6	0.00089	1,540	0.112	16.7	0.00108	1,936	0.145
18.1	0.00152	2,640	0.0793	20.2	0.00147	2,630	0.0949
30.4	0.00216	3,740	0.0664	28.0	0.00184	3,300	0.0838
39.4	0.00259	4,500	0.0597	38.4	0.00230	4,120	0.0736
75.2	0.00406	7,050	0.0464	78.8	0.00381	6,820	0.0552
190.0	0.00700	12,110	0.0396	191.0	0.00663	11,860	0.0441
335.5	0.00952	16,500	0.0378	333.0	0.00893	15,960	0.0426
566.0	0.0128	22,100	0.0354	580.0	0.0124	22,300	0.0381
1150.0	0.0189	32,800	0.0328	1125.0	0.0178	31,900	0.0360
2010.0	0.0259	45,000	0.0304	2030.0	0.0249	44,600	0.0335
4260.0	0.0396	68,600	0.0276	4290.0	0.0378	67,700	0.0304
6050.0	0.0485	84,000	0.0262	6120.0	0.0467	83,500	0.0286

TABLE XIII

PLASTIC TEST RESULTS

TEST No. 17				TEST No. 18			
$\rho = 1.936 \frac{\text{SLUGS}}{\text{FT}^3}$; $\mu = 2.25 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$\rho = 1.936 \frac{\text{SLUGS}}{\text{FT}^3}$; $\mu = 2.24 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
Δp LBS/FT^2	$\dot{m}$ SLUGS/SEC	Re	f_{hc}	Δp LBS/FT^2	$\dot{m}$ SLUGS/SEC	Re	f_{hc}
9.3	0.00135	2,390	0.0754	9.6	0.00135	2,387	0.0784
16.9	0.00206	3,630	0.0591	16.2	0.00191	3,380	0.0658
25.1	0.00280	4,940	0.0473	26.9	0.00269	4,750	0.0550
34.0	0.00347	6,120	0.0417	35.8	0.00354	6,250	0.0423
69.4	0.00527	9,310	0.0368	71.0	0.00519	9,175	0.0390
180.1	0.00871	15,390	0.0351	185.2	0.00860	15,210	0.0370
303.0	0.0116	20,300	0.0337	315.5	0.01153	20,430	0.0349
550.0	0.0163	28,600	0.0308	545.5	0.01578	27,900	0.0324
1036.0	0.0228	40,100	0.0296	1059.0	0.0226	39,980	0.0306
1880.0	0.0320	56,400	0.0272	1898.0	0.0314	55,500	0.0284
4120.0	0.0501	88,400	0.0242	4135.0	0.0505	89,200	0.0240
5630.0	0.0598	105,500	0.0232	5710.0	0.0590	104,200	0.0243

TEST No. 19				TEST NO. 20.			
$\rho = 1.936 \frac{\text{SLUGS}}{\text{FT}^3}$; $\mu = 2.25 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$\rho = 1.936 \frac{\text{SLUGS}}{\text{FT}^3}$; $\mu = 2.22 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
Δp LBS/FT^2	$\dot{m}$ SLUGS/SEC	Re	f_{hc}	Δp LBS/FT^2	$\dot{m}$ SLUGS/SEC	Re	f_{hc}
9.5	0.00125	2,200	0.0900	11.7	0.00115	2050	0.131
16.2	0.00186	3,270	0.0693	18.2	0.00182	2,960	0.0971
27.6	0.00277	4,870	0.0532	26.9	0.00255	4,540	0.0611
35.8	0.00355	5,890	0.0473	36.8	0.00317	5,650	0.0542
69.9	0.00511	9,000	0.0396	73.0	0.00502	8,950	0.0427
191.5	0.00875	15,400	0.0370	189.3	0.00854	15,200	0.0384
315.5	0.0116	20,400	0.0346	312.5	0.0113	20,050	0.0364
536.0	0.0156	27,350	0.0328	527.0	0.0150	26,800	0.0344
1044.0	0.0225	39,600	0.0306	1060.0	0.0222	39,550	0.0318
1909.0	0.0316	55,600	0.0282	1923.0	0.0311	55,400	0.0294
4160.0	0.0496	87,400	0.0249	4205.0	0.0483	86,000	0.0267
5720.0	0.0595	104,700	0.0240	5720.0	0.0579	103,000	0.0252

TABLE XIV

PLASTIC TEST RESULTS

TEST No. 21.				TEST No. 22			
$\rho=1.936 \frac{SLUGS}{FT^3}$; $\mu=2.25\times10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				$\rho=1.936 \frac{SLUGS}{FT^3}$; $\mu=2.22\times10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp LBS/FT^2	$\dot{m}$ SLUGS/SEC	Re	f_{hc}	Δp LBS/FT^2	$\dot{m}$ SLUGS/SEC	Re	f_{hc}
13.0	0.00142	2,490	0.0960	5.8	0.00166	2,970	0.0694
18.9	0.00182	3,210	0.0839	9.7	0.00251	4,490	0.0502
30.0	0.00255	4,490	0.0682	12.6	0.00305	5450	0.0442
38.4	0.00304	5,350	0.0616	25.2	0.00464	8,290	0.0384
73.8	0.00467	8,210	0.0500	67.3	0.00776	13,880	0.0366
190.0	0.00811	14,280	0.0426	111.1	0.0103	18,370	0.0345
311.0	0.0107	18,880	0.0400	218.5	0.0148	26,400	0.0328
549.0	0.0147	25,920	0.0374	386.0	0.0203	36,300	0.0306
1089.0	0.0215	37,800	0.0348	700.0	0.0283	50,600	0.0286
1925.0	0.0297	52,300	0.0322	1465.0	0.0433	77,300	0.0257
4260.0	0.0466	82,000	0.0290	3690.0	0.0735	131,200	0.0224
5810.0	0.0560	98,400	0.0274				

TEST No. 23				TEST No. 24			
$\rho=1.936 \frac{SLUGS}{FT^3}$; $\mu=2.22\times10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				$\rho=1.936 \frac{SLUGS}{FT^3}$; $\mu=2.22\times10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp LBS/FT^2	$\dot{m}$ SLUGS/SEC	Re	f_{hc}	Δp LBS/FT^2	$\dot{m}$ SLUGS/SEC	Re	f_{hc}
4.4	0.00133	2,380	0.0811	5.3	0.00128	2,280	0.106
6.4	0.00171	3,055	0.0711	6.7	0.00168	3,000	0.0785
9.8	0.00244	4,360	0.0537	10.2	0.00234	4,190	0.0609
13.3	0.00299	5,340	0.0488	14.4	0.00308	5,510	0.0498
26.7	0.00459	8,210	0.0415	25.4	0.00454	8,130	0.0404
63.0	0.00763	13,620	0.0355	65.4	0.00759	13,560	0.0373
112.6	0.0101	18,020	0.0363	111.8	0.0102	18,180	0.0355
224.0	0.0147	26,300	0.0339	217.5	0.0146	26,200	0.0333
391.0	0.0200	35,900	0.0319	315.5	0.0180	32,200	0.0319
704.0	0.0280	50,000	0.0295	708.0	0.0283	50,600	0.0290
1462.0	0.0424	75,800	0.0267	1462.0	0.0427	76,400	0.0262
3740.0	0.0728	130,100	0.0232	3700.0	0.0733	131,000	0.0226

TABLE XV

PLASTIC TEST RESULTS

TEST No. 25				TEST No. 26			
$\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.25 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				$\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.27 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp LBS/FT^2	$\dot{m}$ SLUGS/SEC	Re	f_{hc}	Δp LBS/FT^2	$\dot{m}$ SLUGS/SEC	Re	f_{hc}
3.80	0.00108	1,900	0.107	7.6	0.00172	3,000	0.0844
7.1	0.00170	3,010	0.0801	11.1	0.00220	3,840	0.0755
9.8	0.00224	3,940	0.0637	14.6	0.00269	4,690	0.0663
14.1	0.00290	5,110	0.0547	27.8	0.00422	7,360	0.0512
26.4	0.00447	7,880	0.0434	70.8	0.00736	12,820	0.0429
63.5	0.00753	13,250	0.0367	115.3	0.00972	16,960	0.0401
111.9	0.00994	17,500	0.0371	225.0	0.0142	24,800	0.0366
220.5	0.0145	25,550	0.0344	388.5	0.0192	33,400	0.0348
382.0	0.01966	34,650	0.0323	723.0	0.0269	46,900	0.0328
701.0	0.0275	48,400	0.0304	1530.0	0.0413	72,000	0.0295
1481.0	0.0422	79,800	0.0274	3860.0	0.0705	123,000	0.0255
3830.0	0.0722	127,000	0.0241				

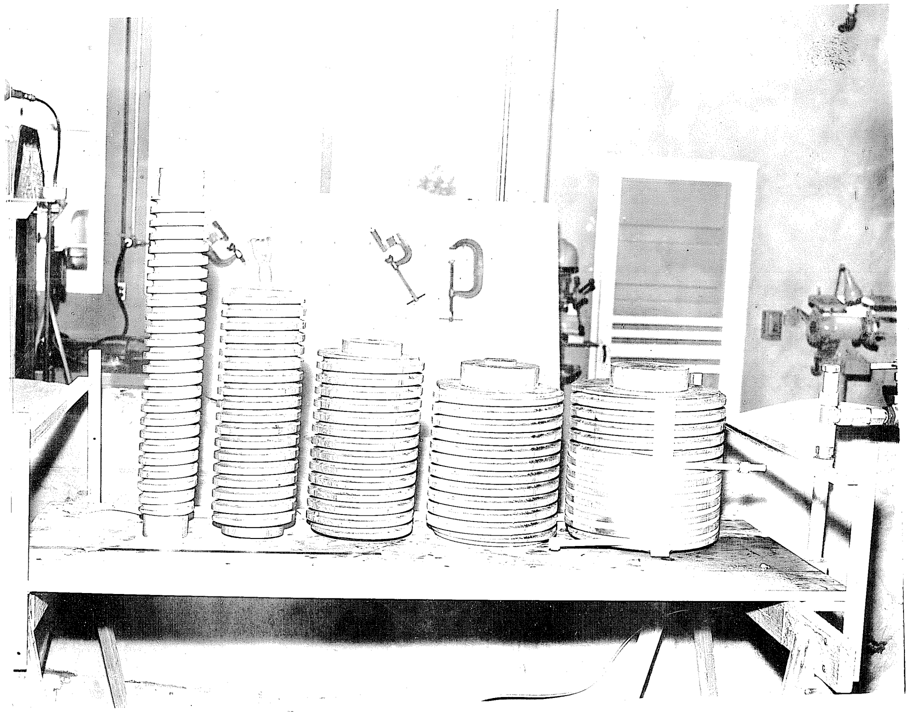
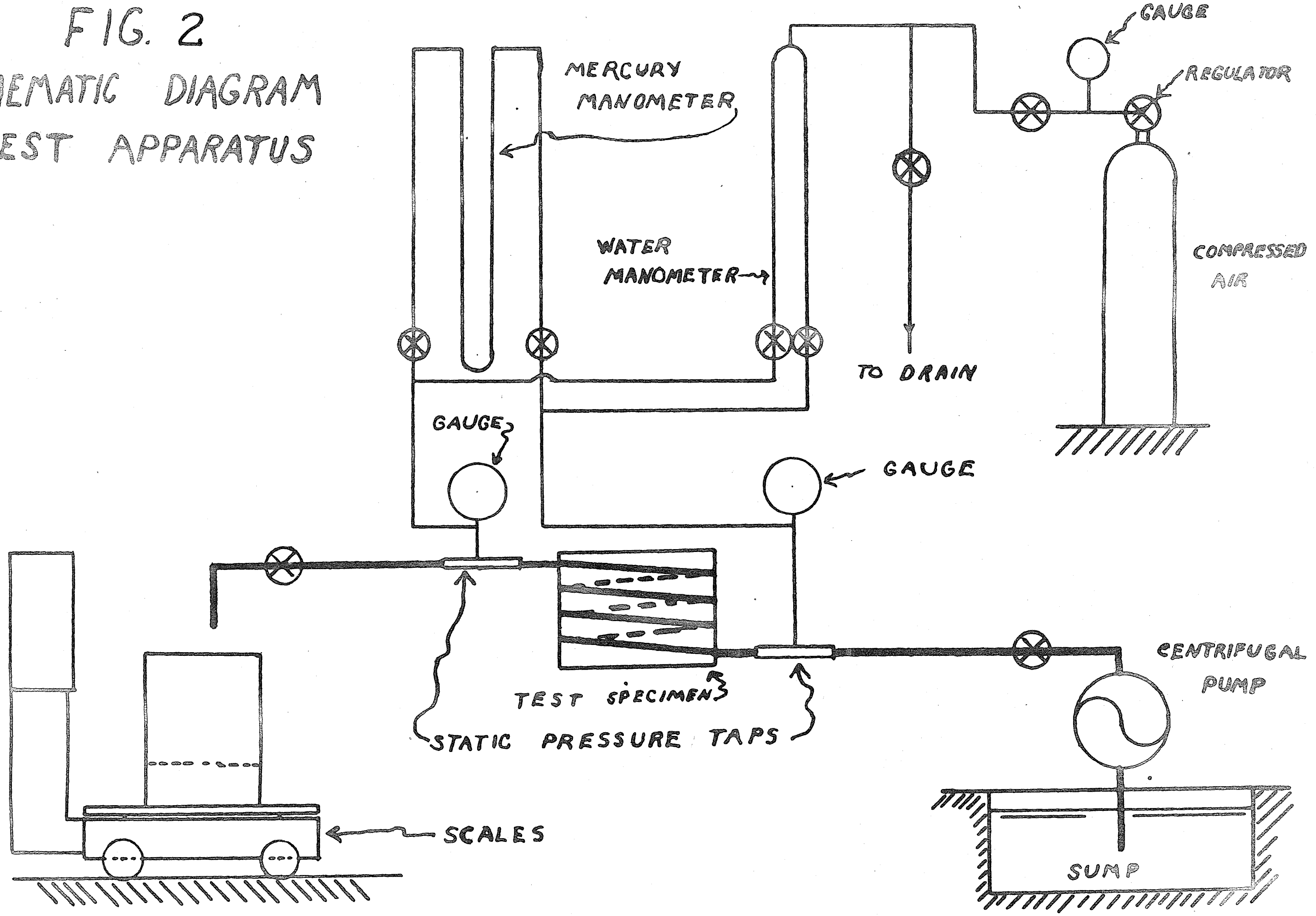


FIG. 1

Wooden mandrels for forming plastic tubing into helices.

FIG. 2
SCHEMATIC DIAGRAM
TEST APPARATUS



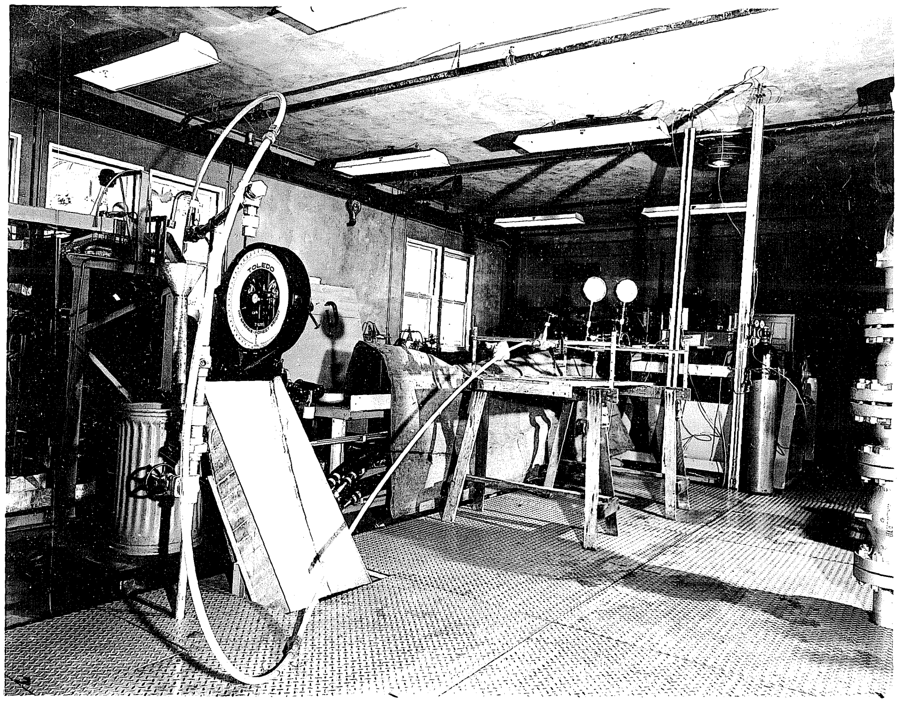


FIG. 3

Test setup.

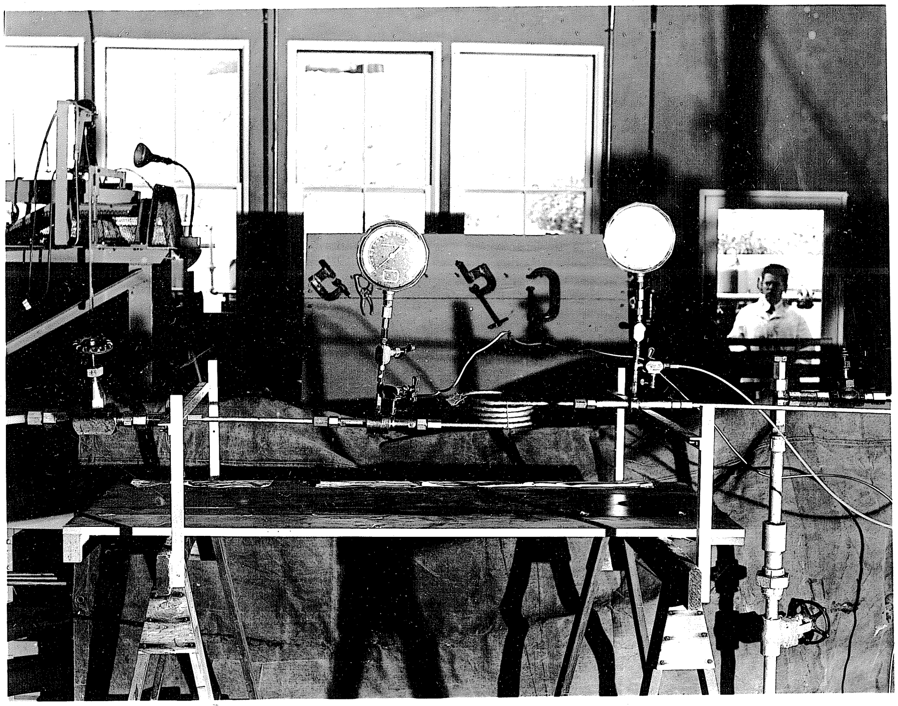


FIG. 4

Steel coil in test position.

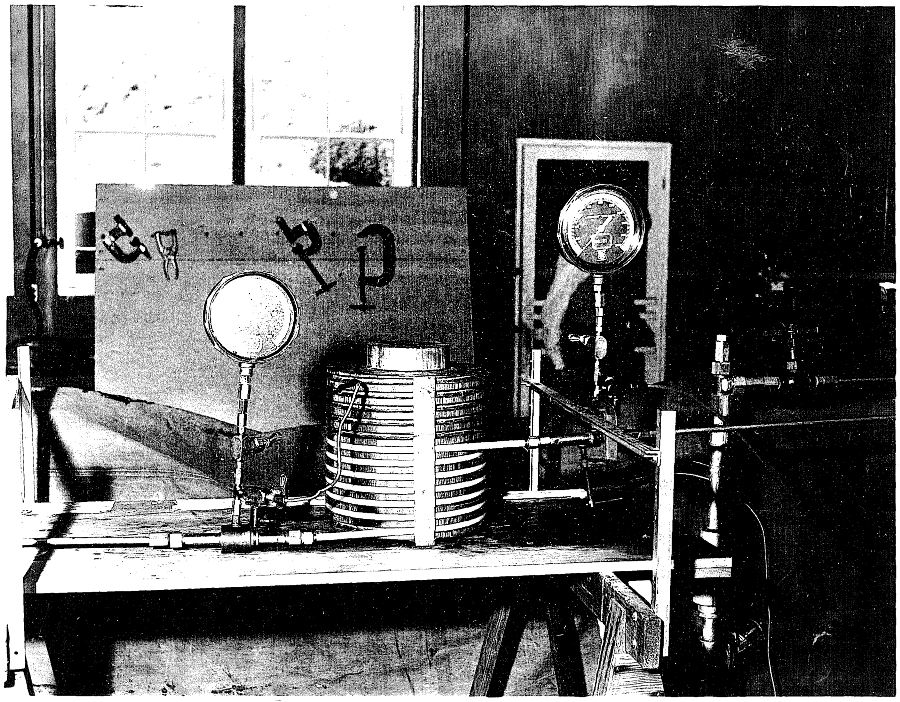


FIG. 5

Plastic coil in test position.

FIG. 6

STEEL TUBING TEST RESULTS

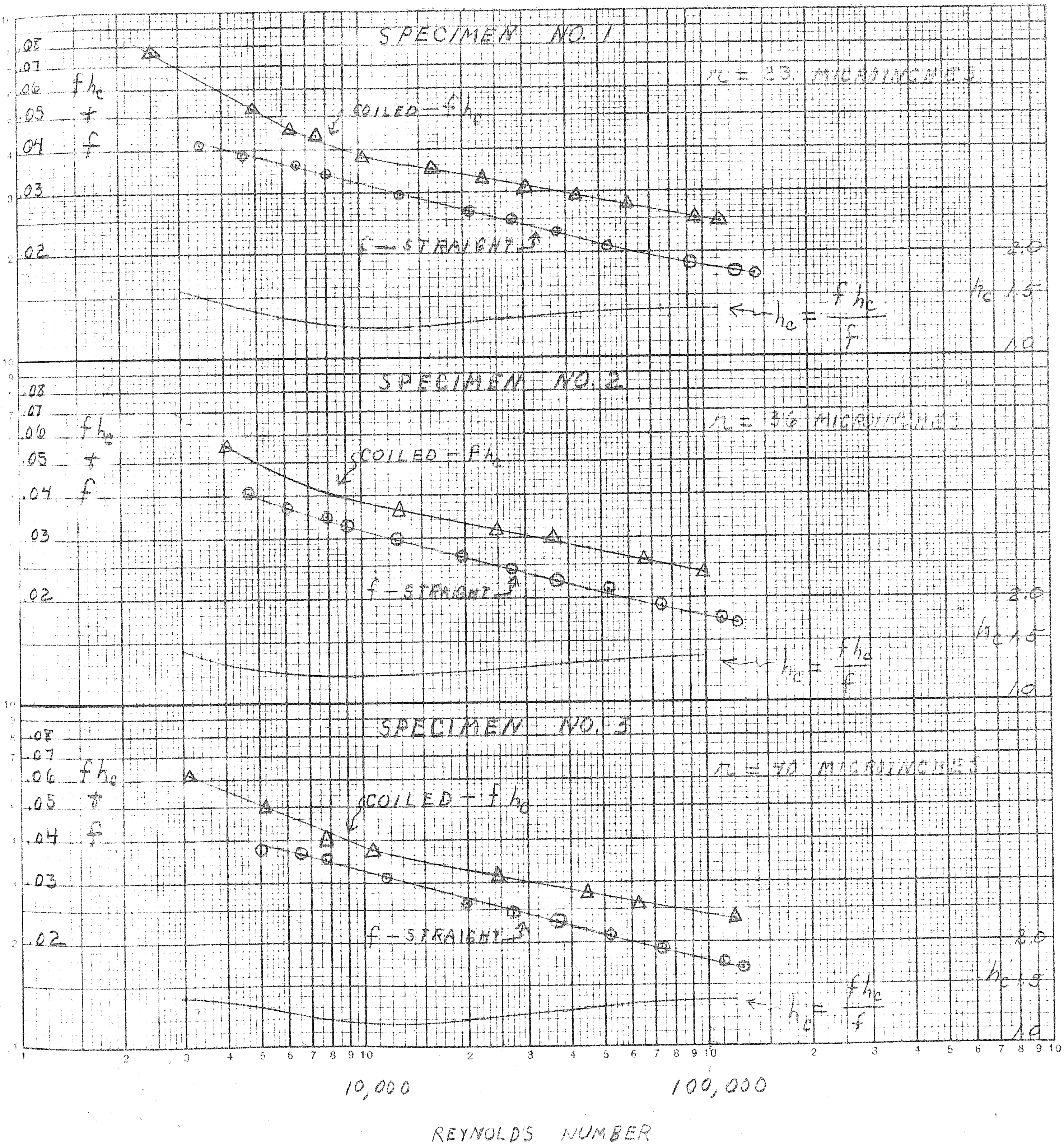


FIG. 7

STEEL TUBING TEST RESULTS

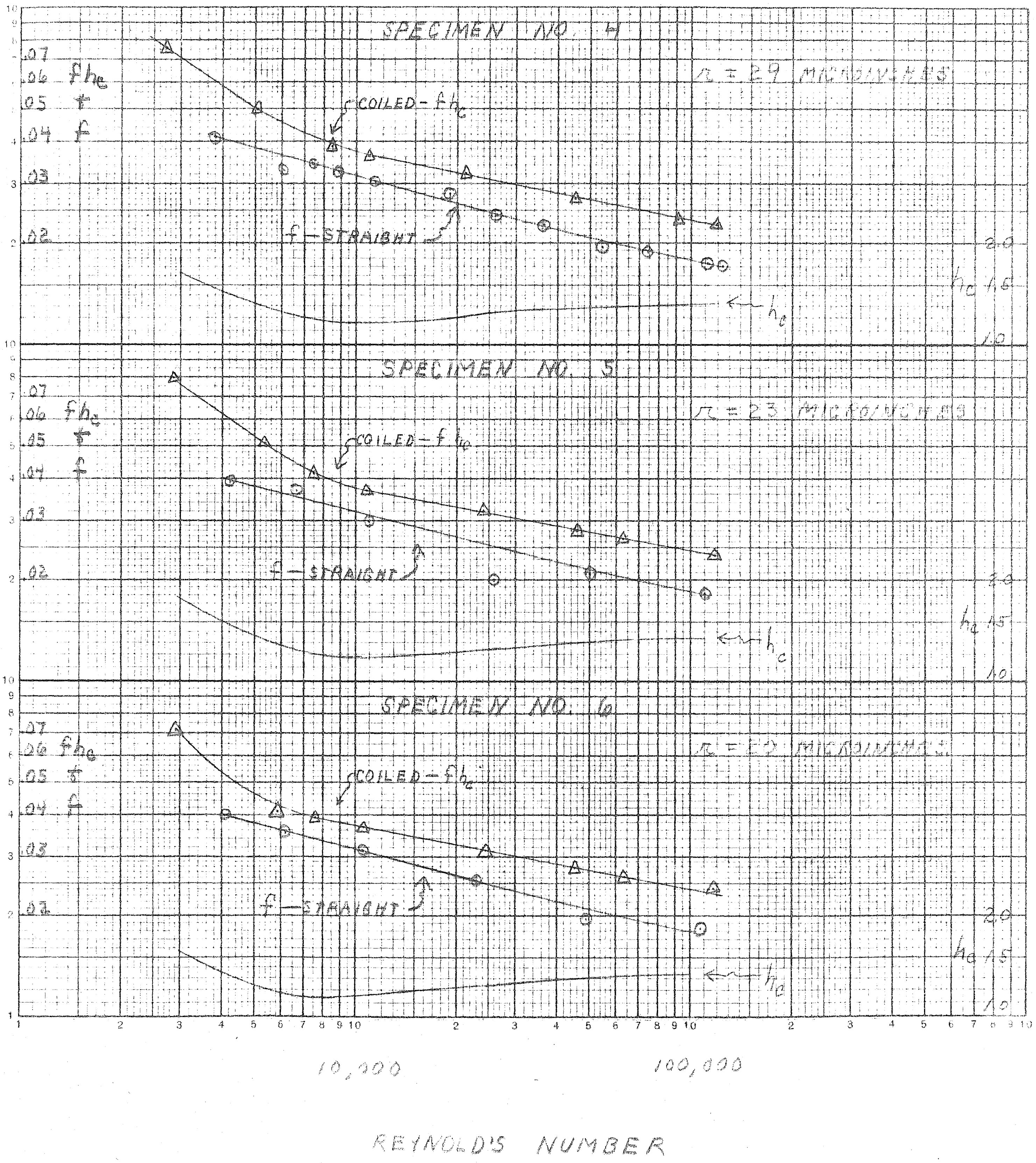


FIG. 8

STEEL TUBING TEST RESULTS

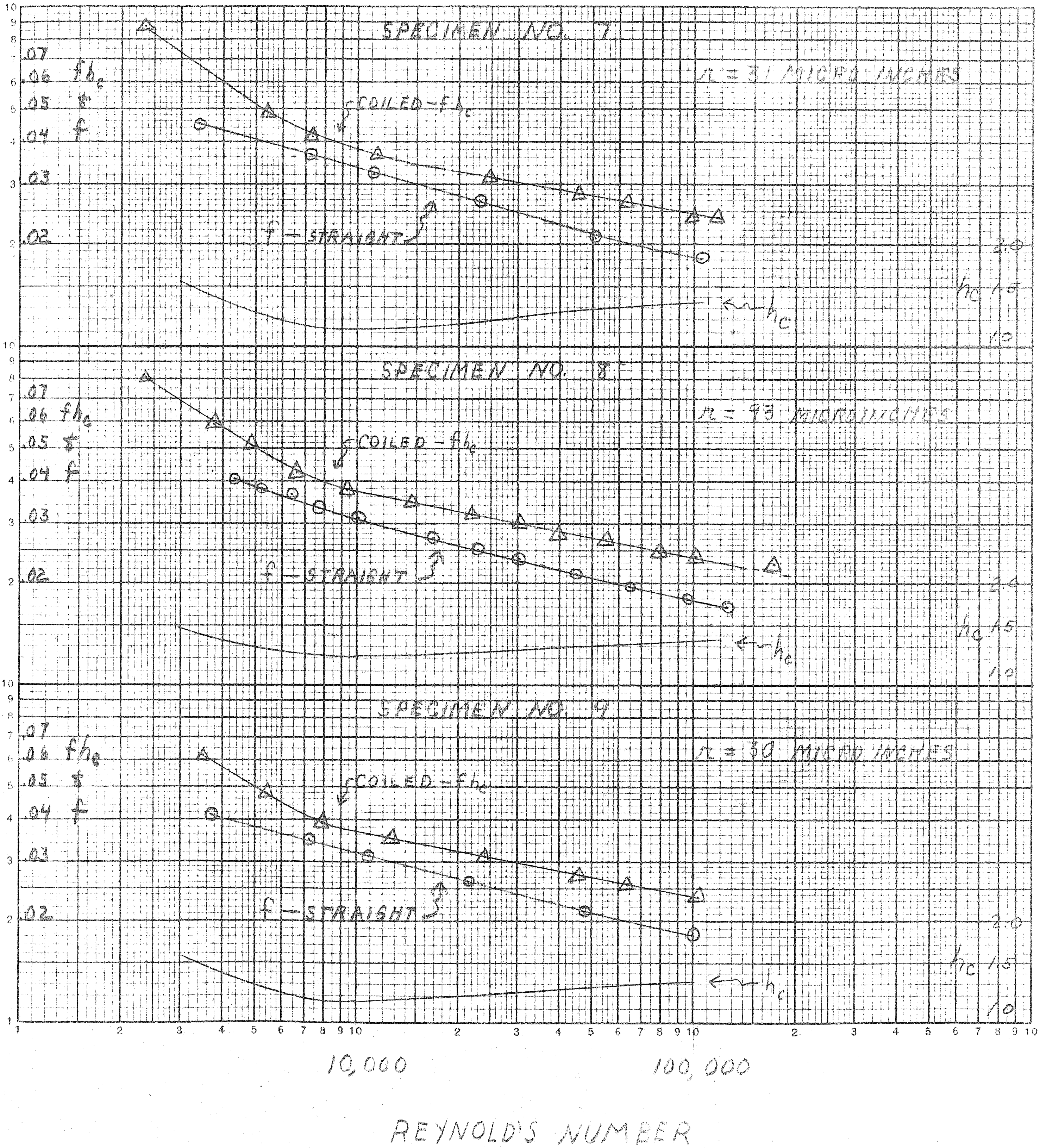


FIG. 9

STEEL TUBING TEST RESULTS

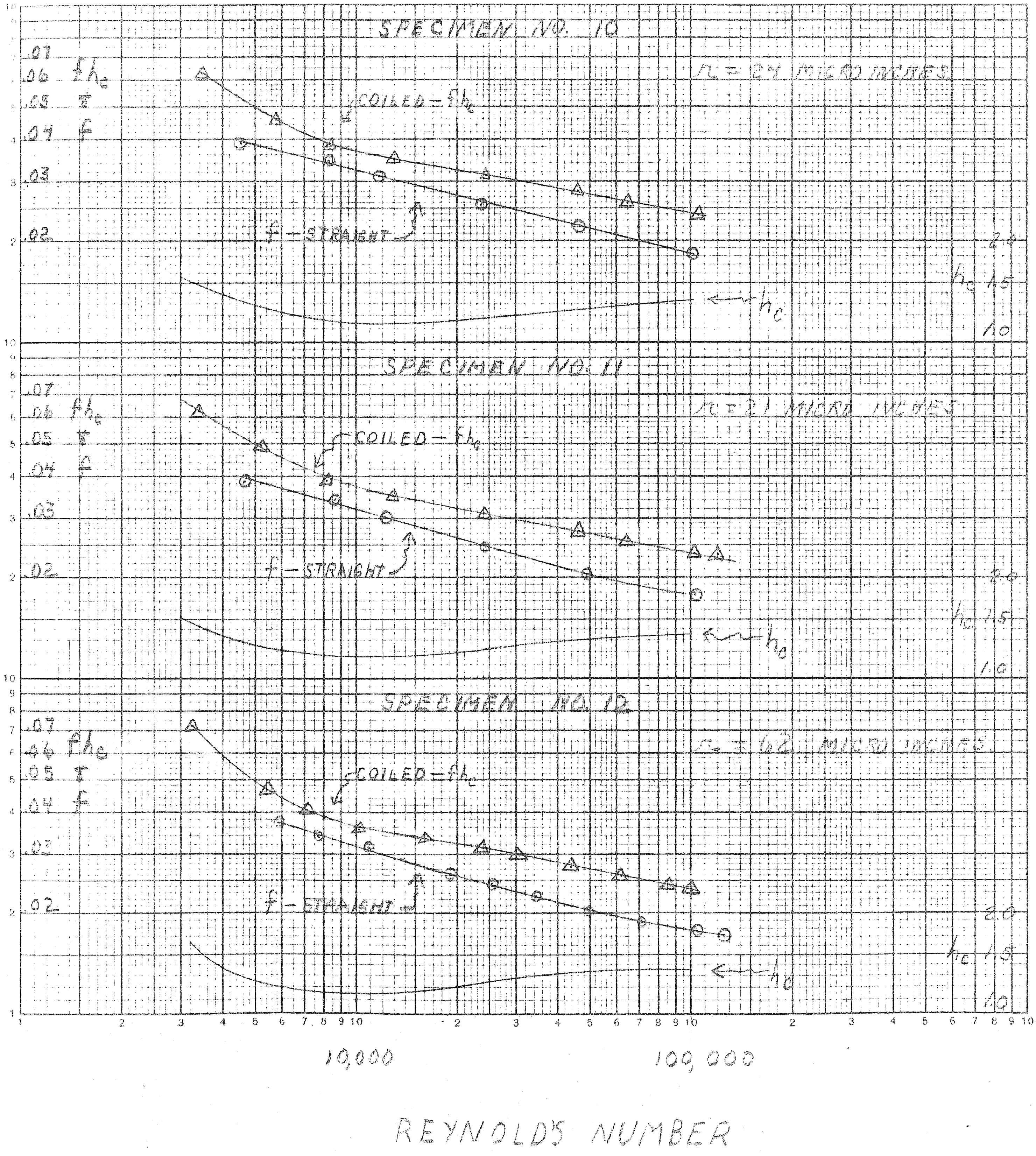


FIG. 10

PLASTIC TEST RESULTS

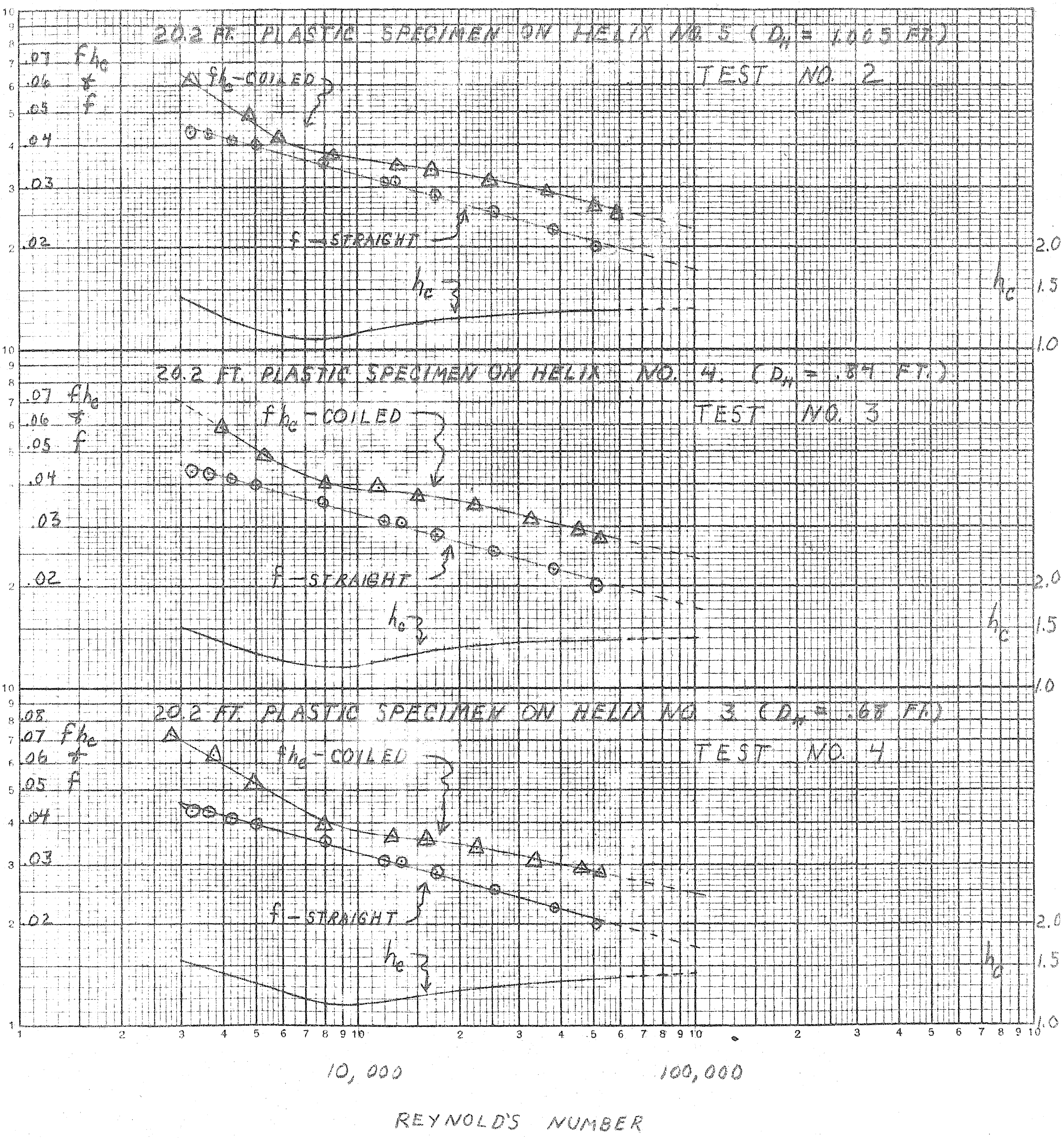


FIG. 11

PLASTIC TEST RESULTS

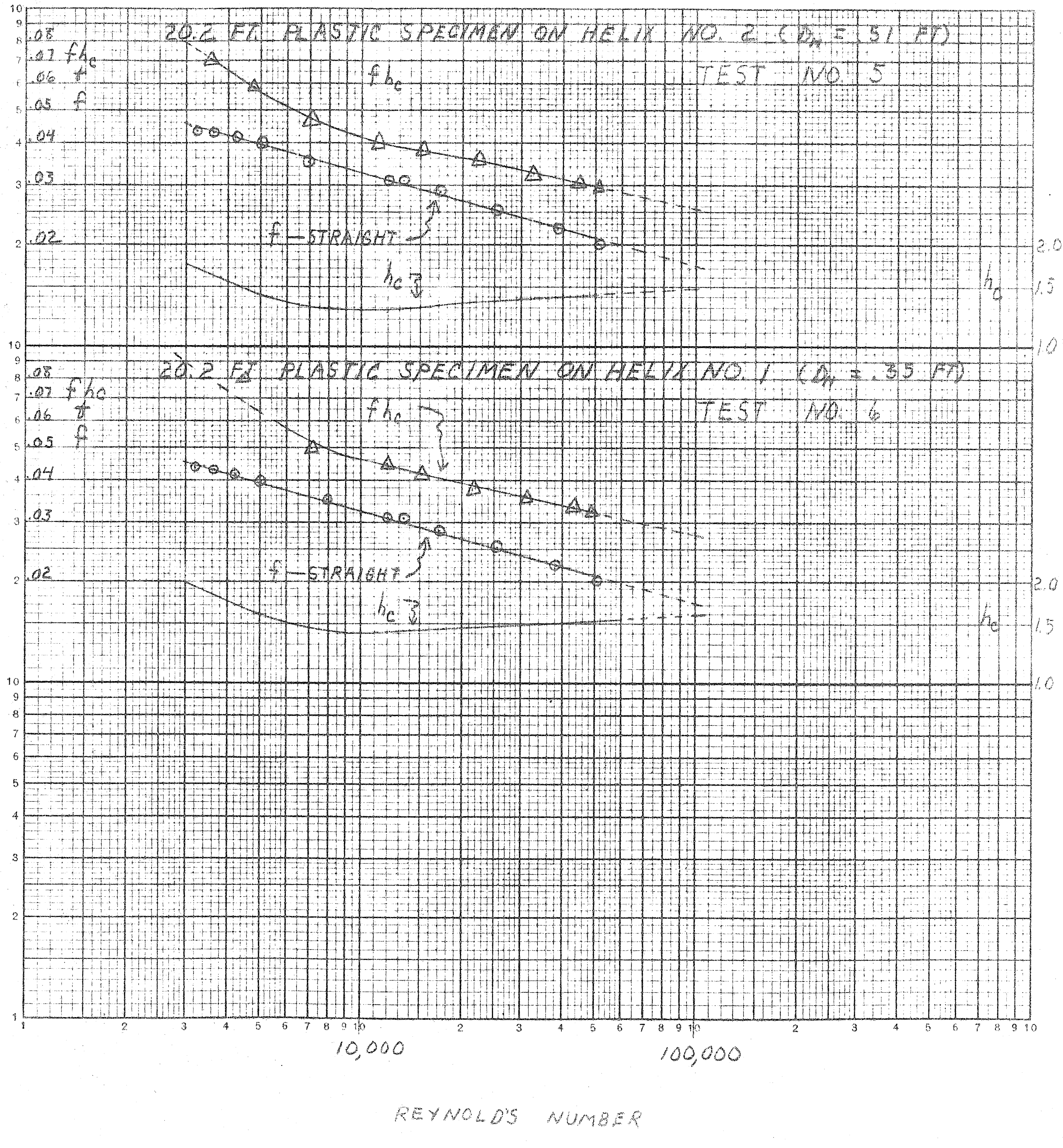


FIG. 12

PLASTIC TEST RESULTS

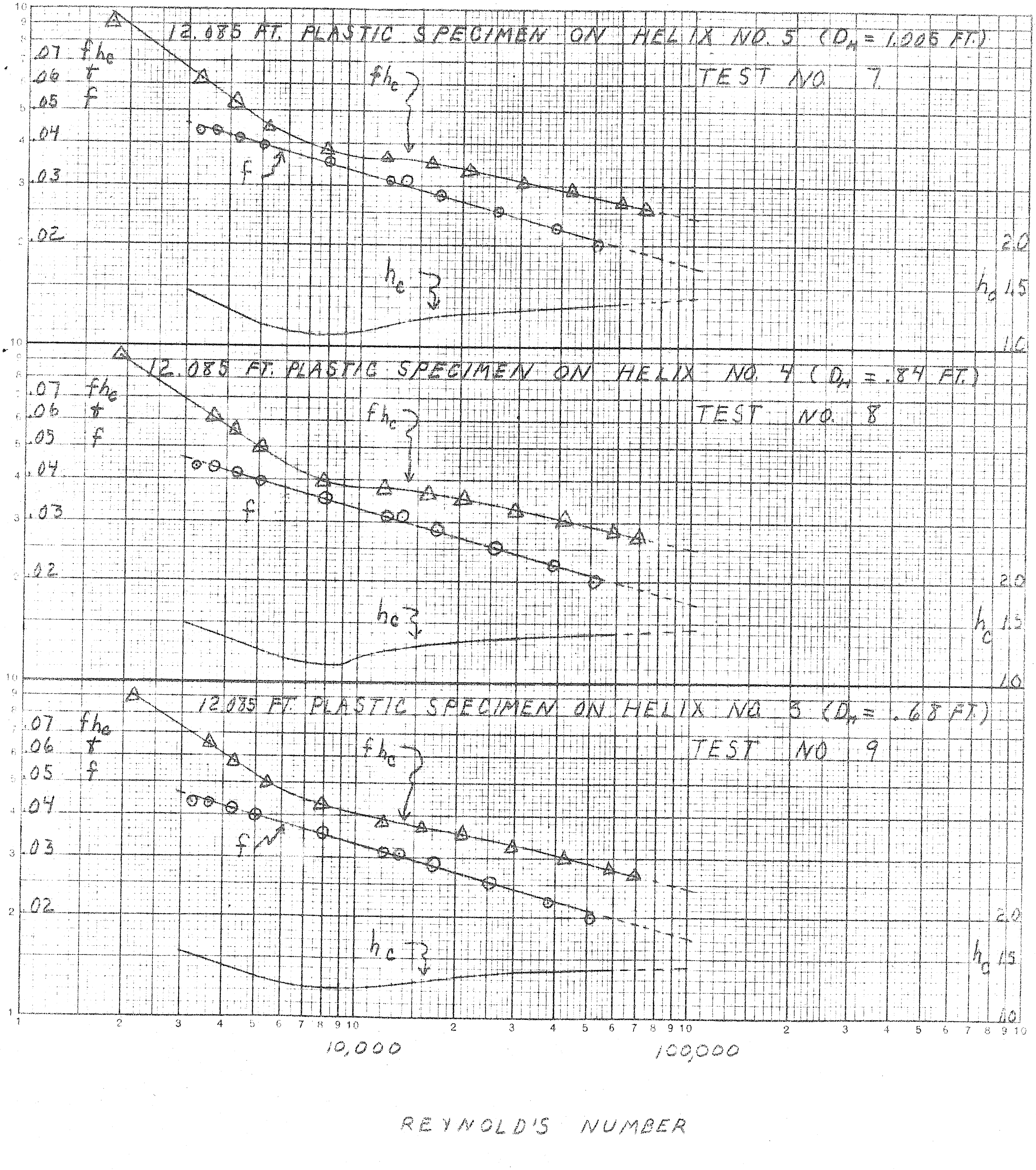


FIG. 13

PLASTIC TEST RESULTS

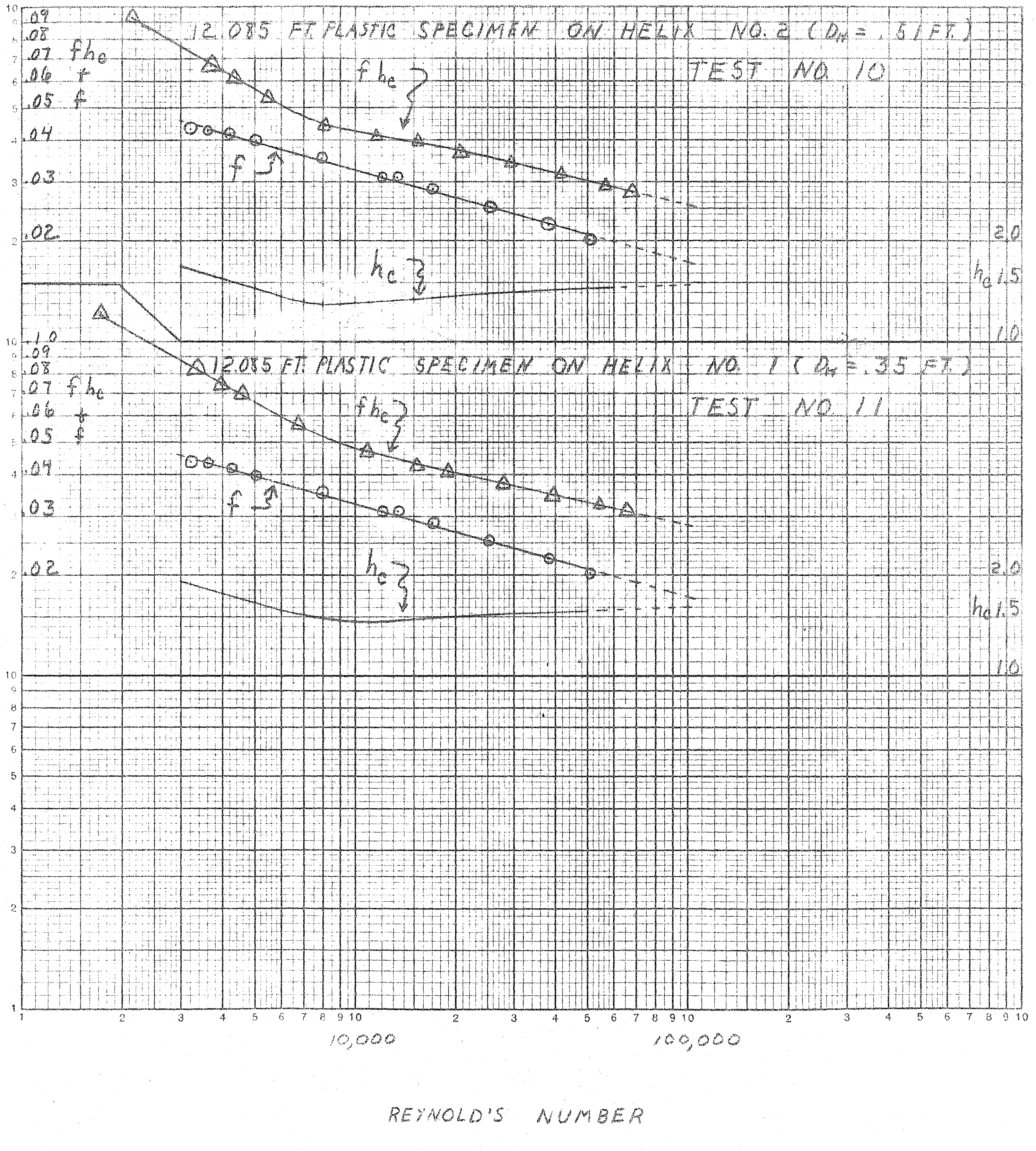


FIG 14

PLASTIC TEST RESULTS

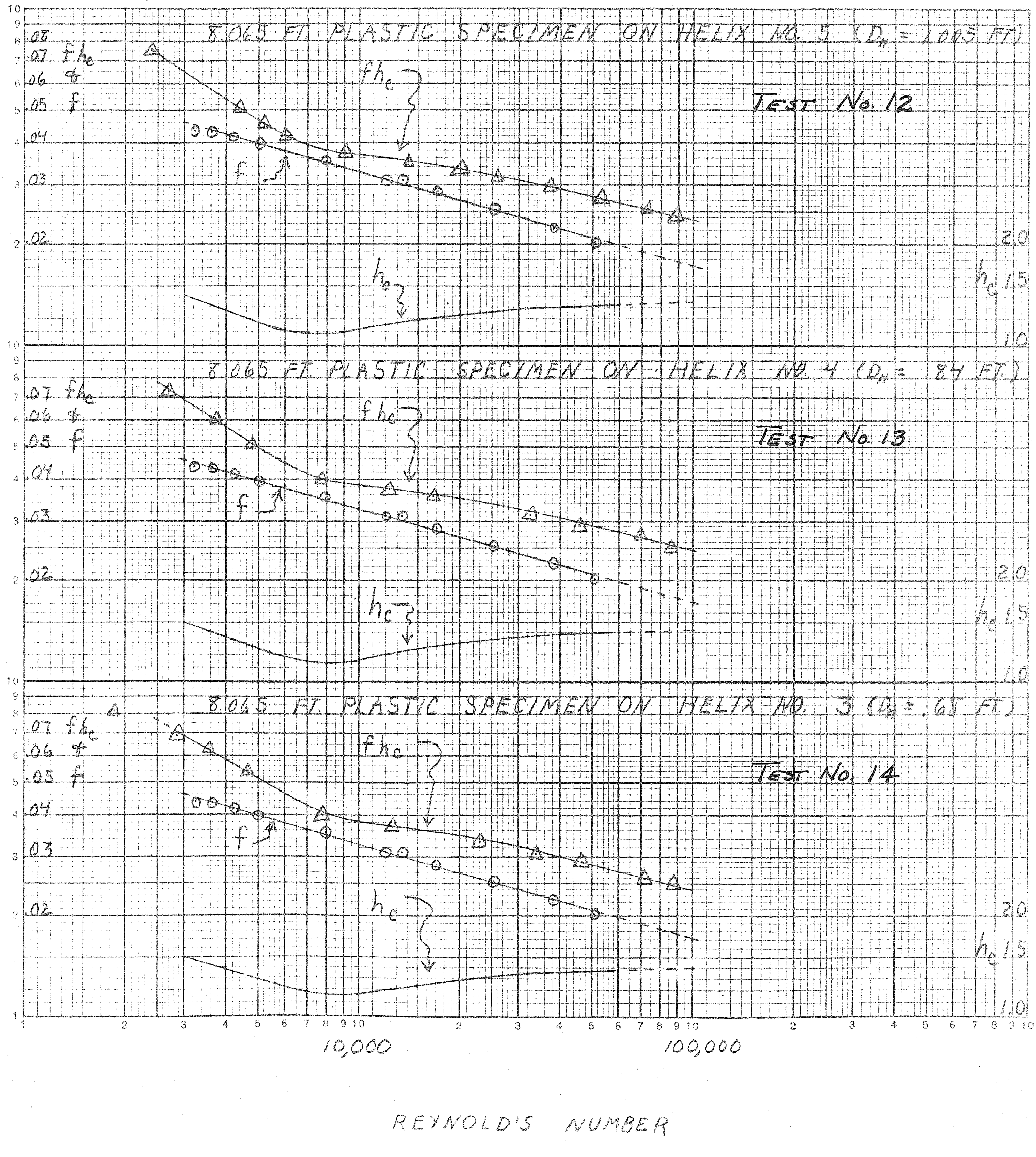


FIG. 15

PLASTIC TEST RESULTS

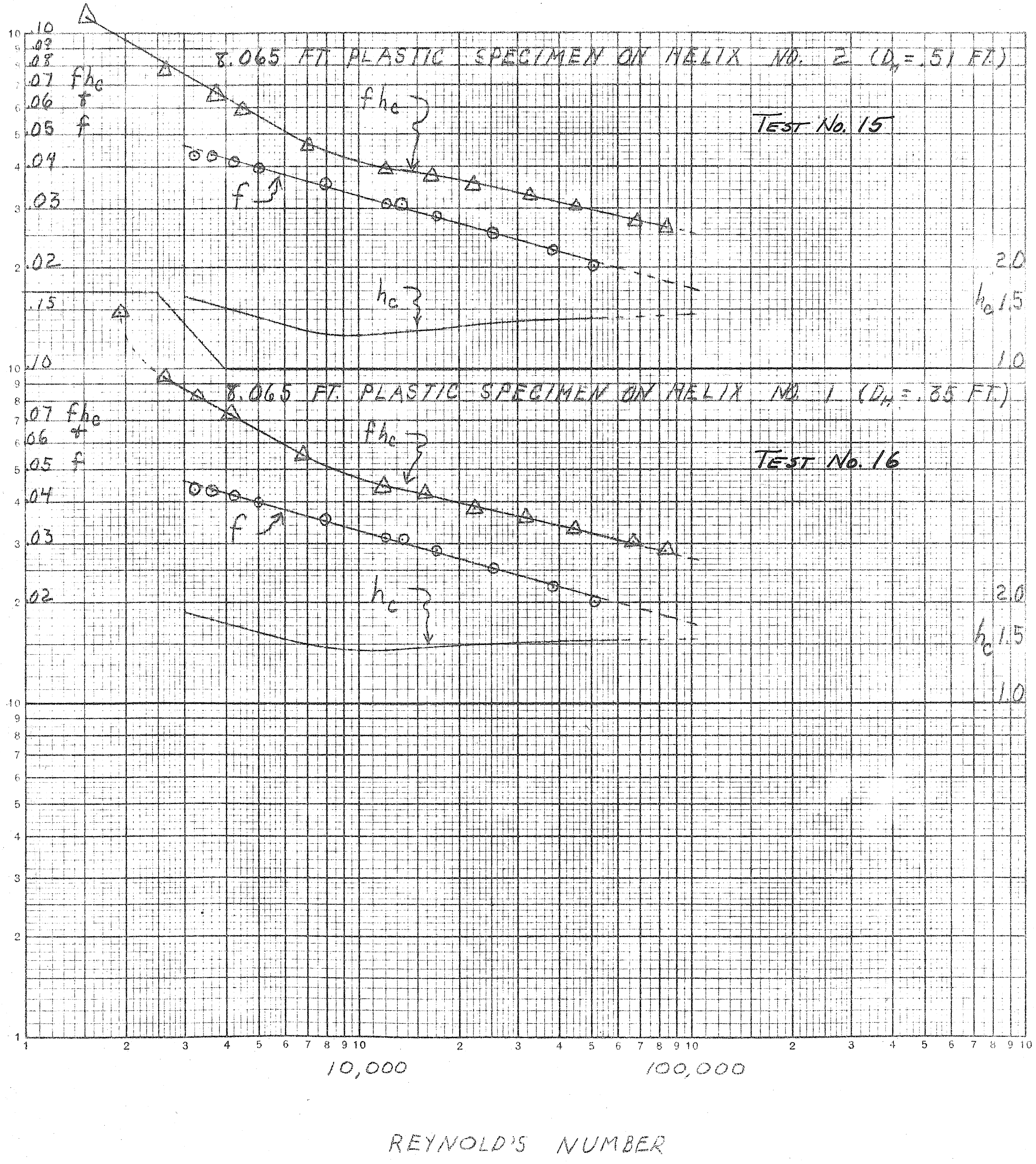


FIG. 16

PLASTIC TEST RESULTS

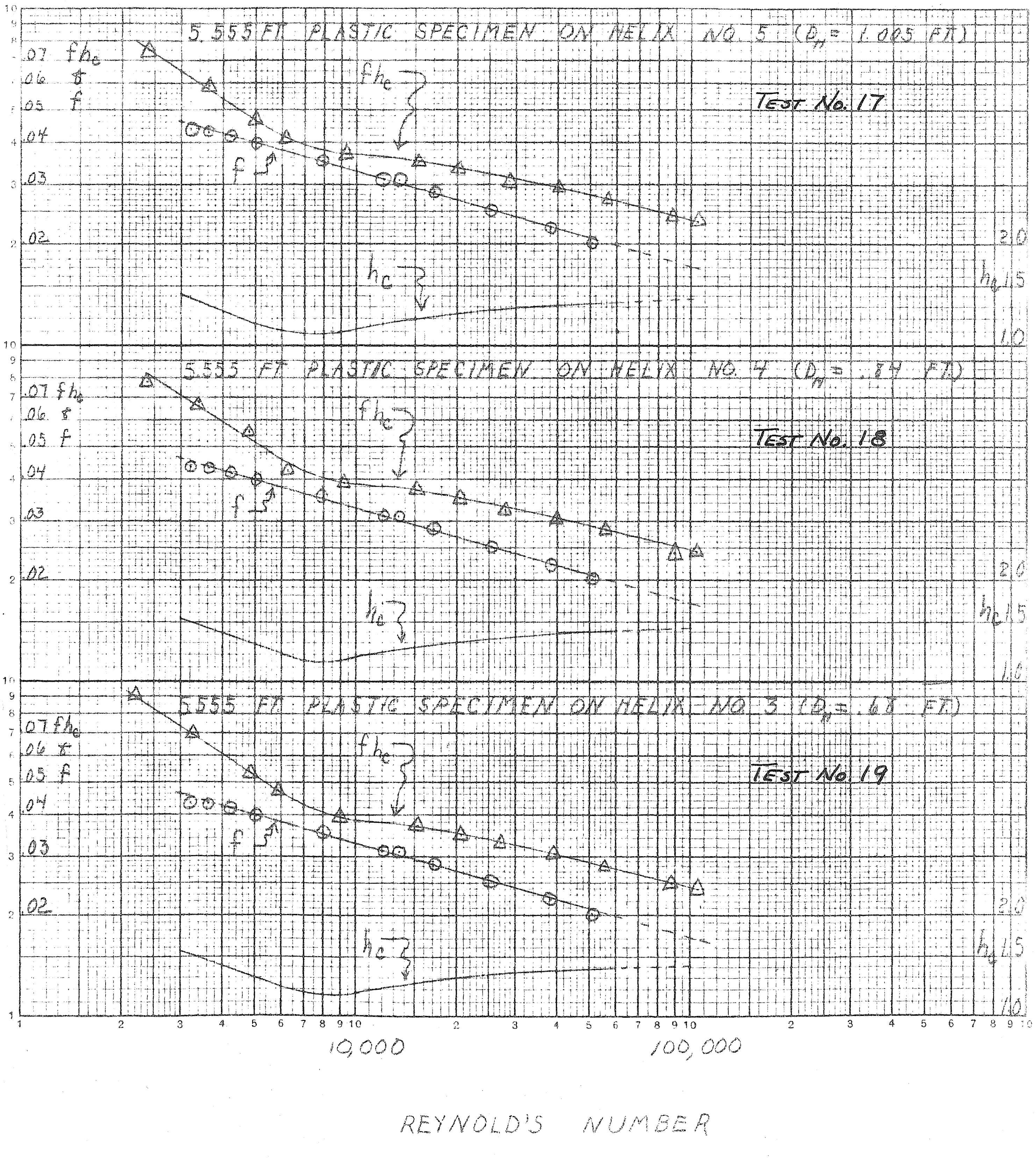


FIG. 17

PLASTIC TEST RESULTS

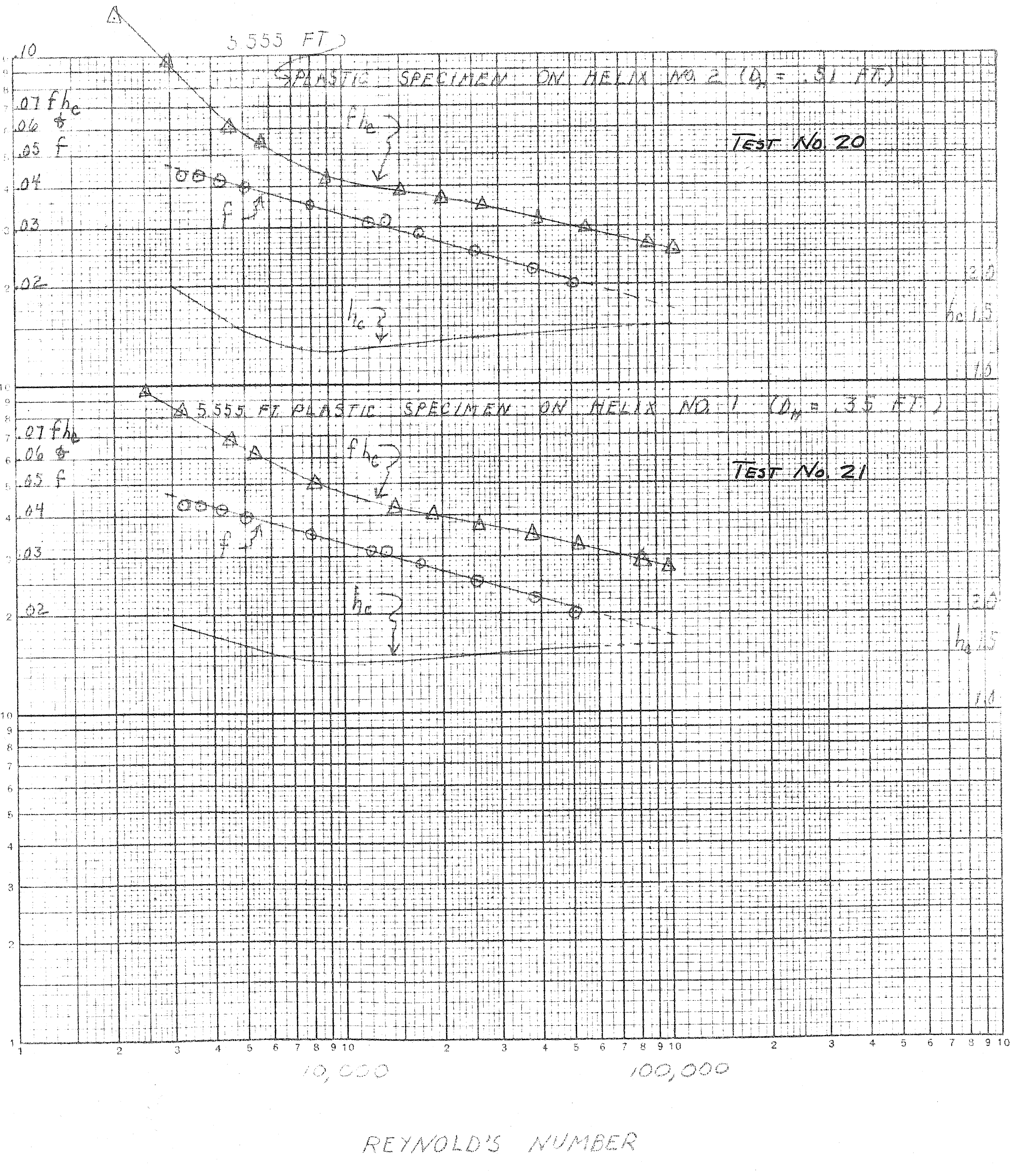


FIG. 18

PLASTIC TEST RESULTS

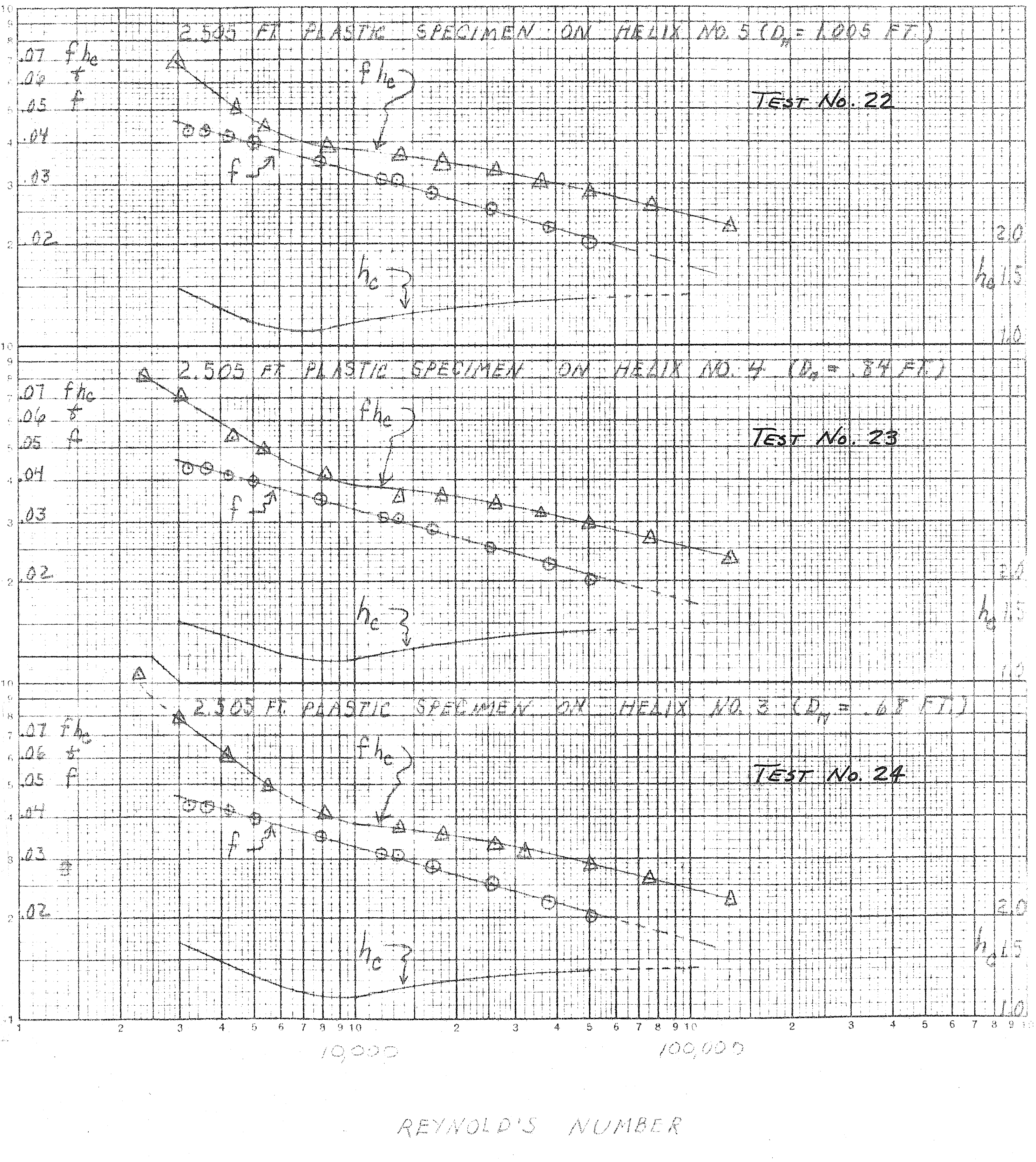
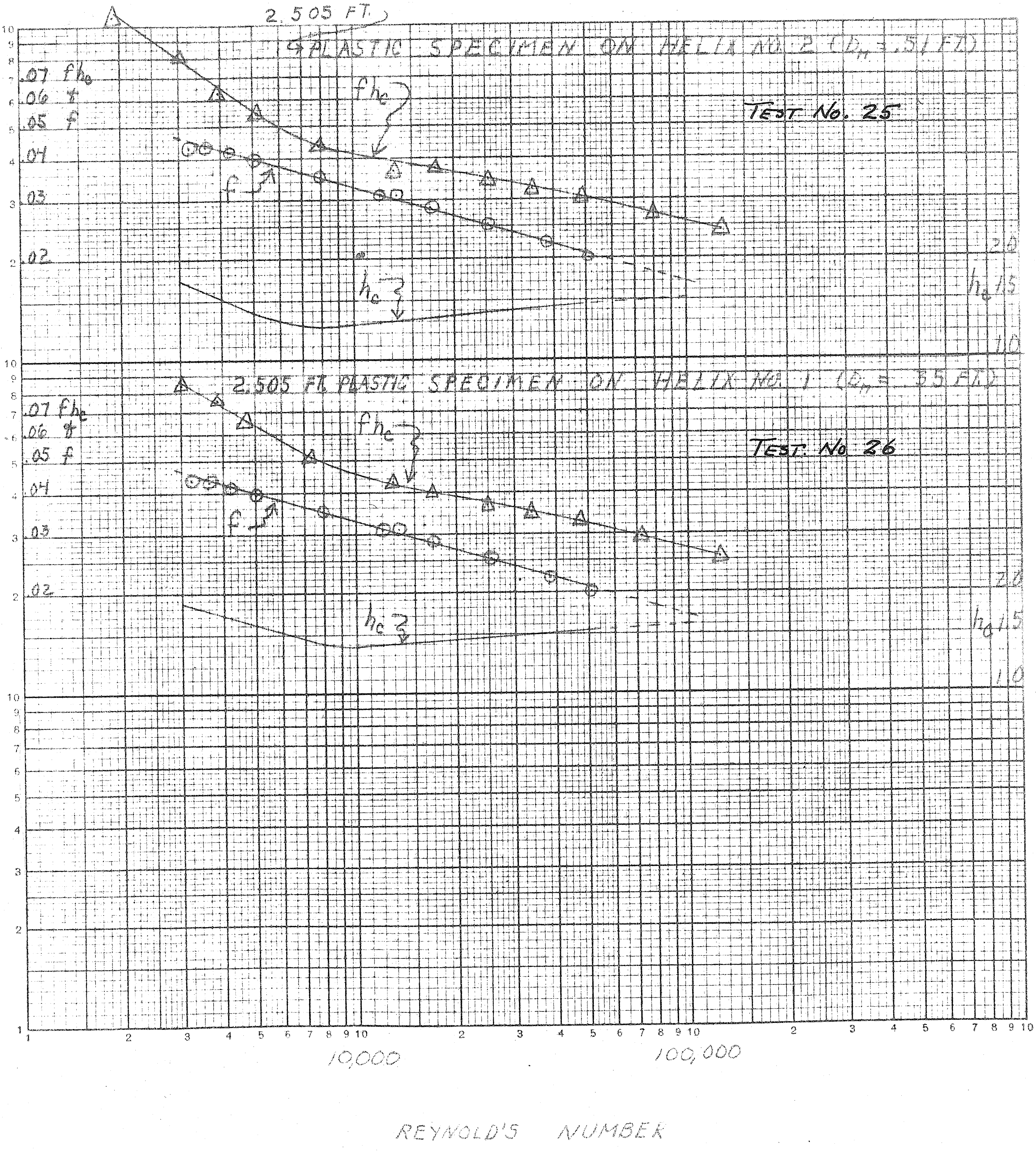


FIG. 19

PLASTIC TEST RESULTS



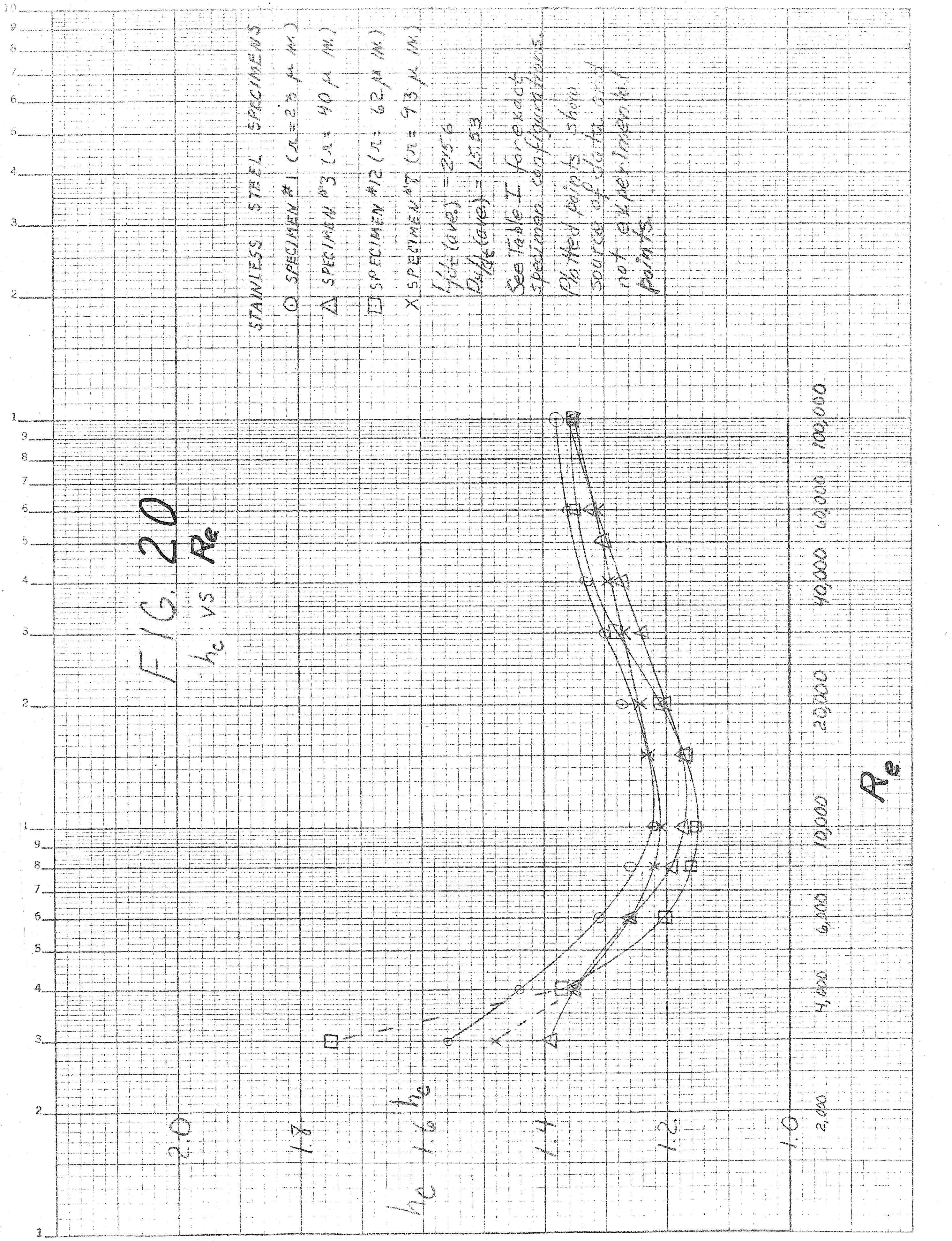
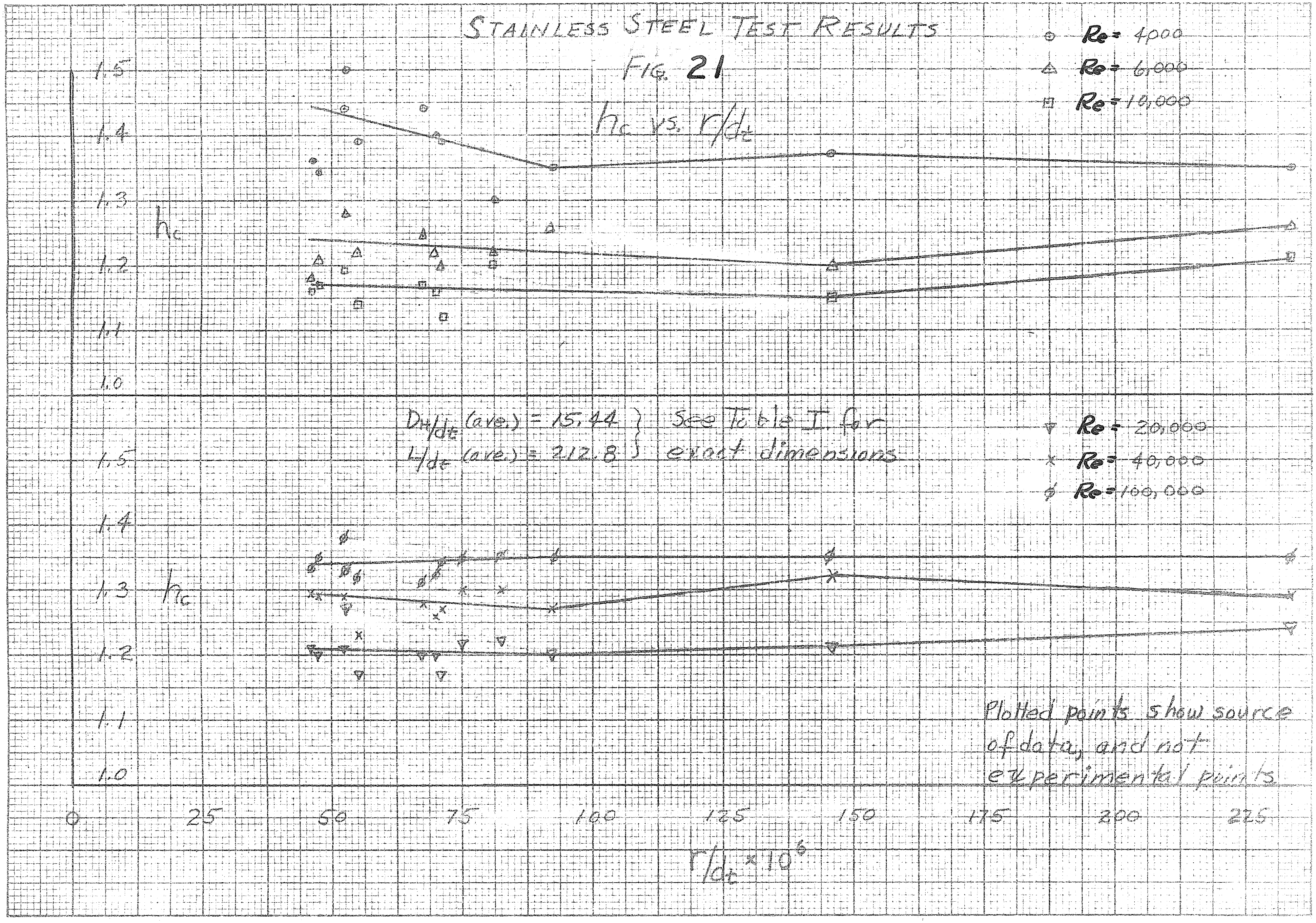


FIG. 20

h_c vs Re

See Table I for exact specimen configurations.

Plotted points show source of data and not experimental points.



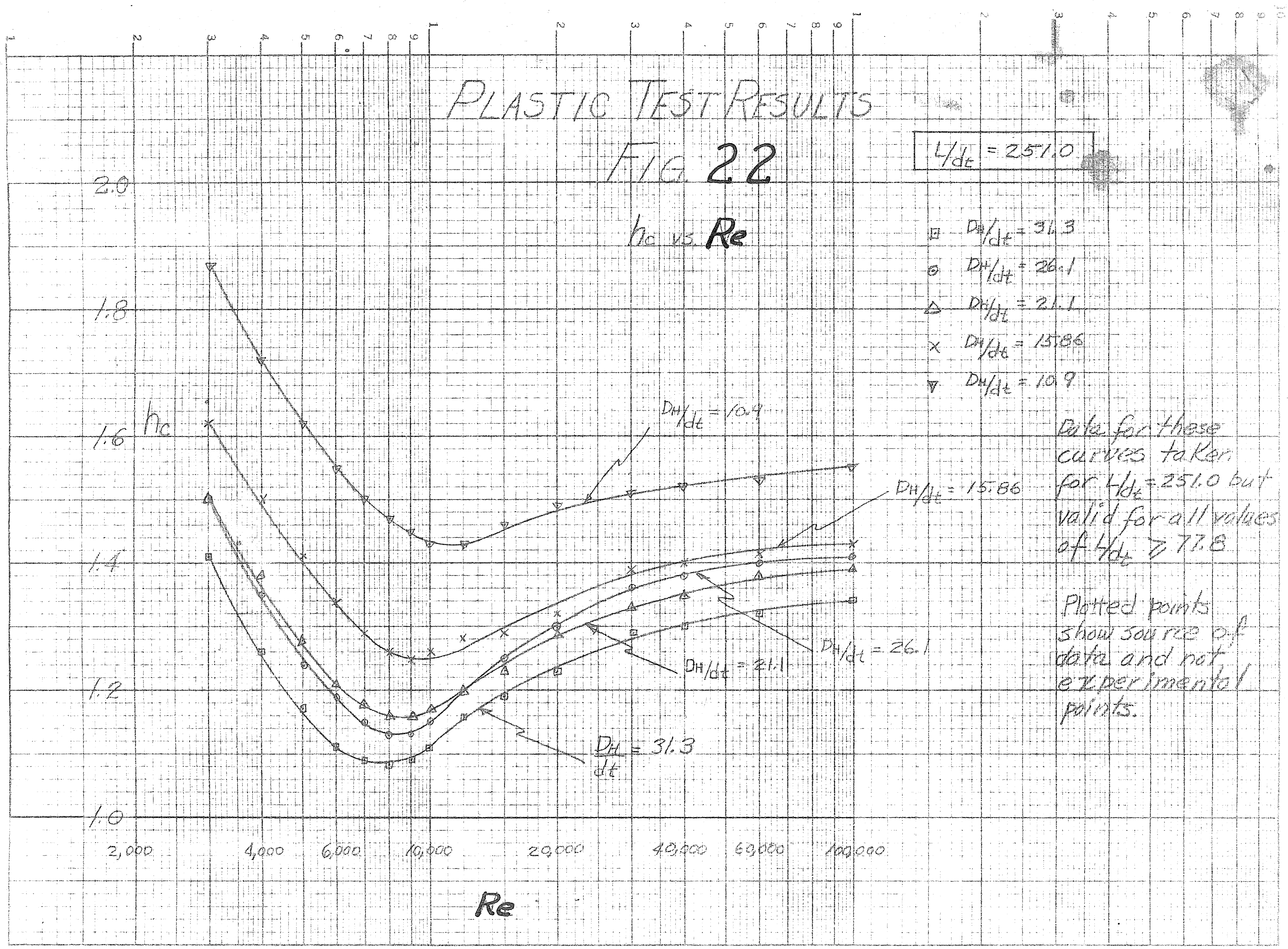
STAINLESS STEEL TEST RESULTS

FIG. 21

h_c vs. r/d_t

D_H/d_t (ave.) = 15.44 } See Table I for
L/d_t (ave.) = 212.8 } exact dimensions

Plotted points show source of data, and not experimental points



PLASTIC TEST RESULTS

FIG 22

h_c vs. Re

$L/d_t = 251.0$

Data for these curves taken for $L/d_t = 251.0$ but valid for all values of $L/d_t \geq 77.8$

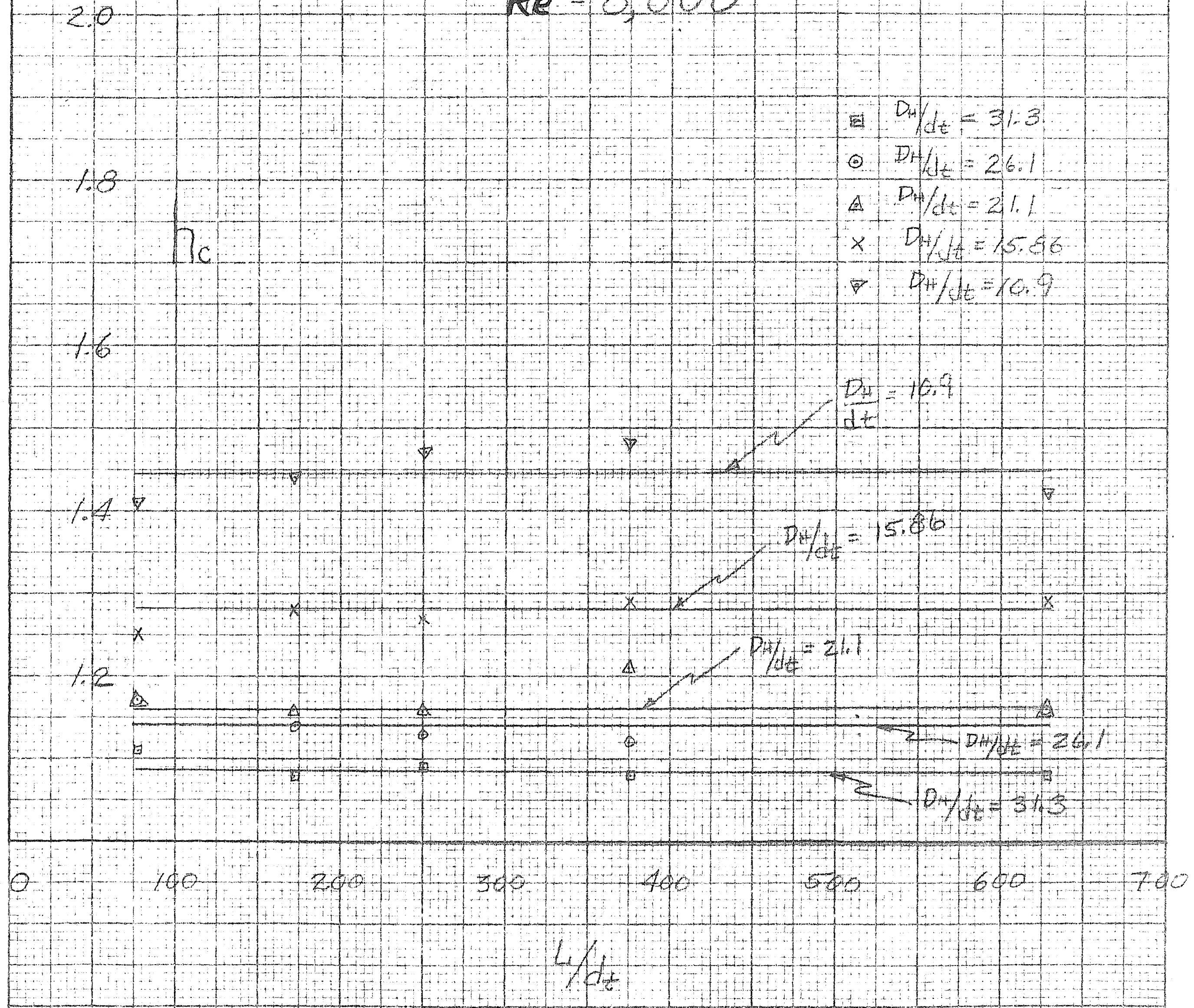
Plotted points show source of data and not experimental points.

PLASTIC TEST RESULTS

FIG. 23

η_c vs L/d_t

Re = 8,000

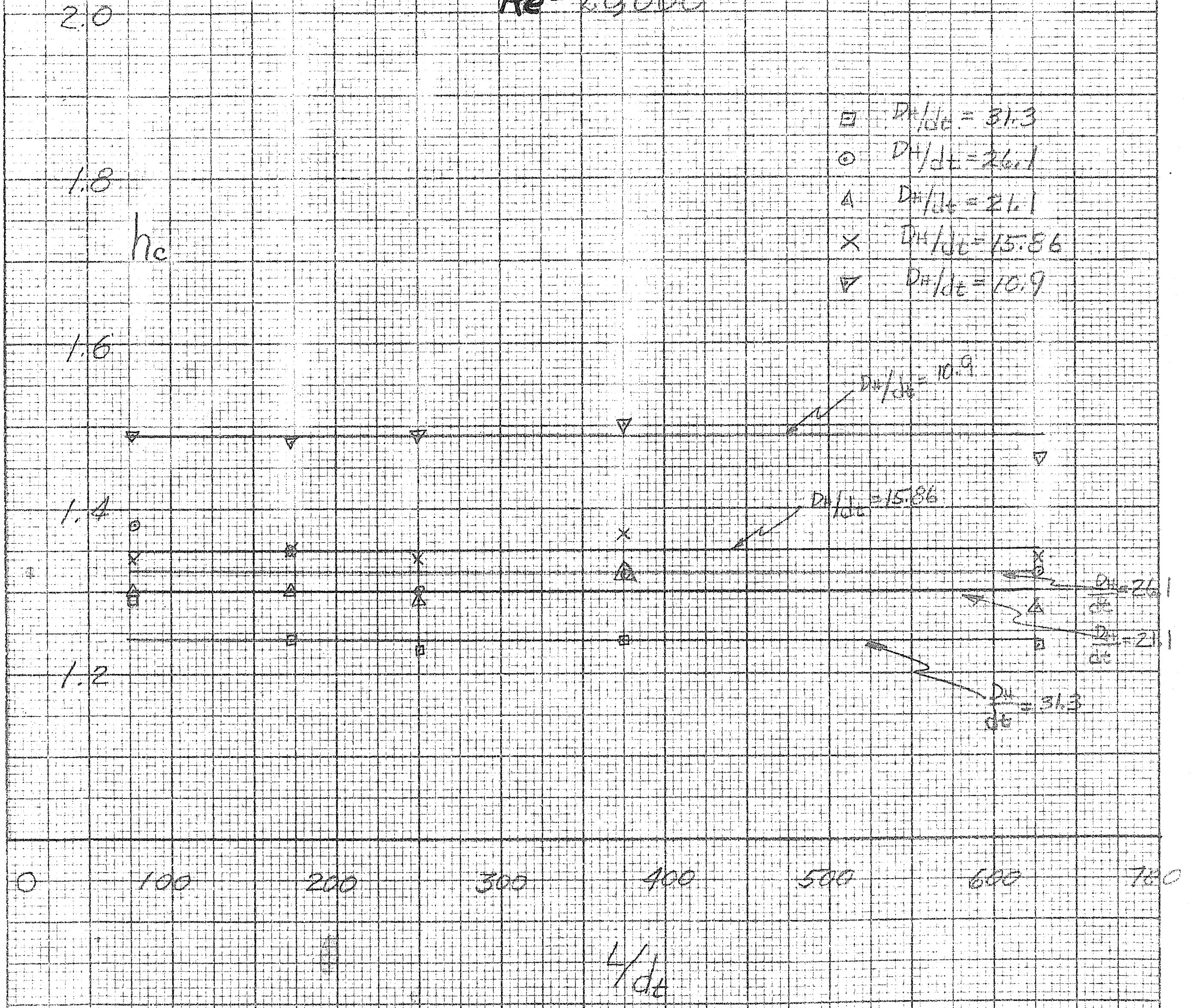


PLASTIC TEST RESULTS

FIG. 24

h_c vs. L/d_t

Re = 20,000

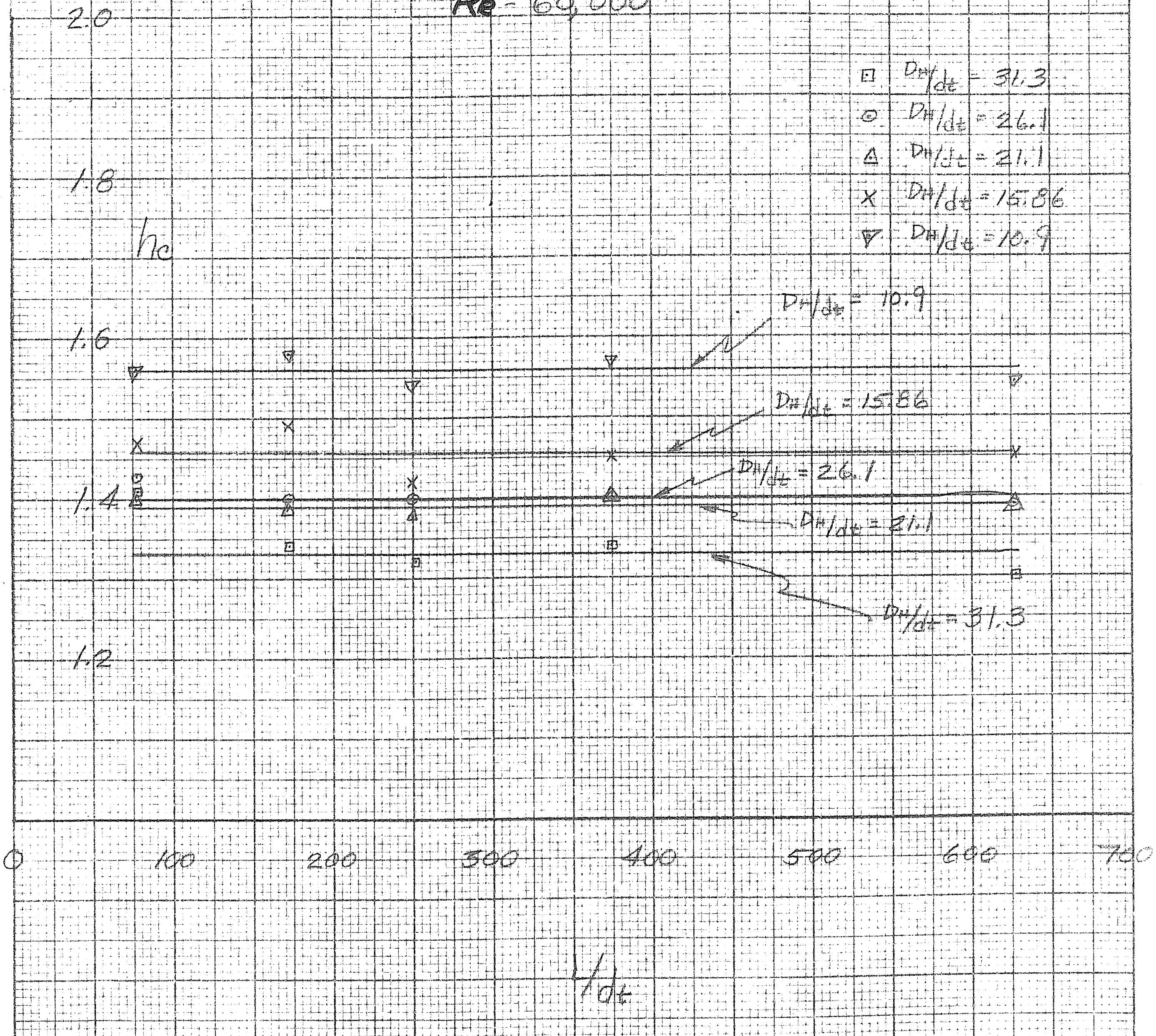


PLASTIC TEST RESULTS

FIG. 25

h_c vs. L/d_t

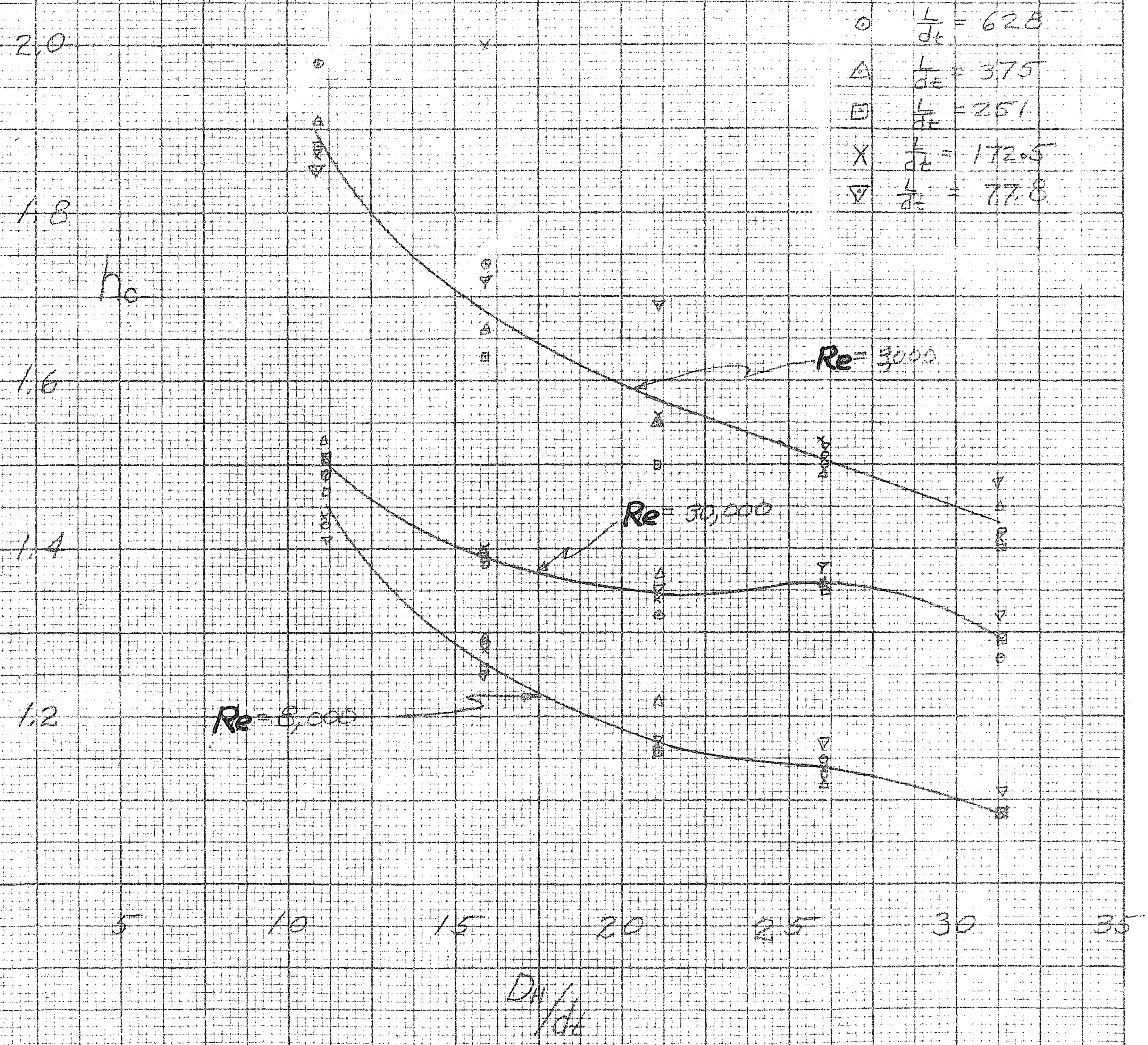
Re = 60,000



PLASTIC TEST RESULTS

FIG. 26

h_c vs. D_H/d_t

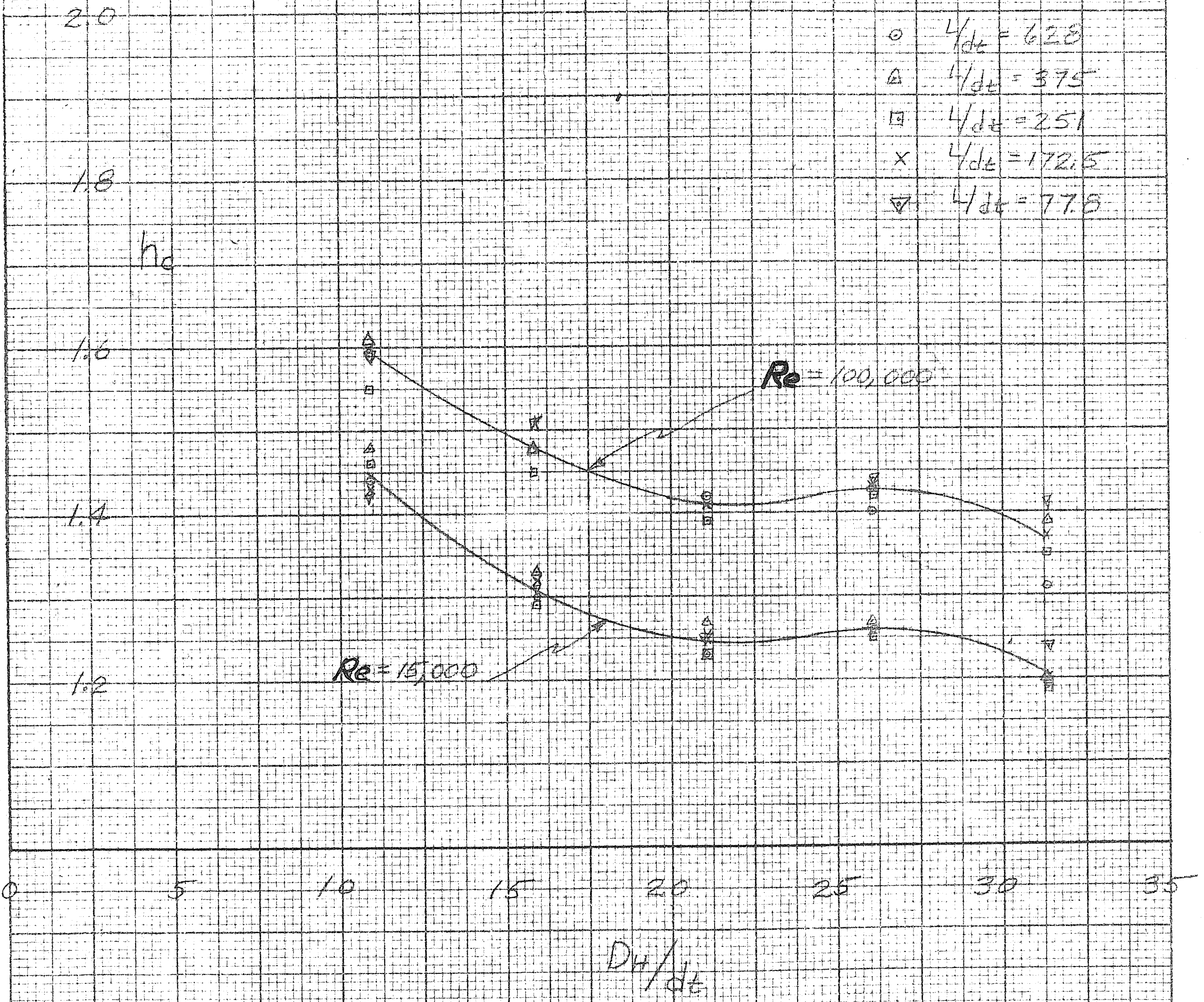


Plotted points show source of data and not experimental points

PLASTIC TEST RESULTS

FIG. 27

h_c vs. D_H/d_t

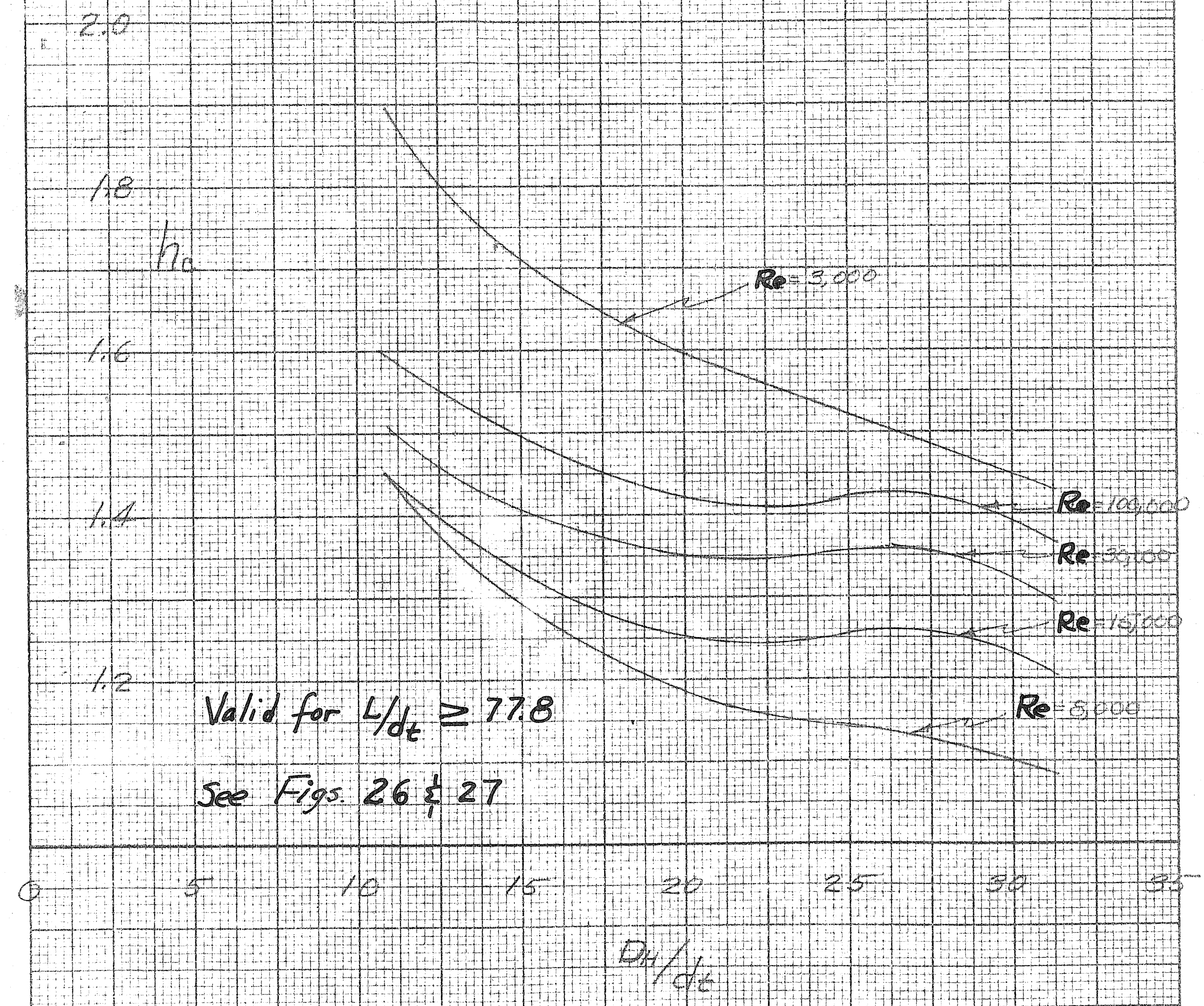


Plotted points show source of data and not experimental points.

PLASTIC TEST RESULTS

FIG. 28

h_c vs. D_H/d_t

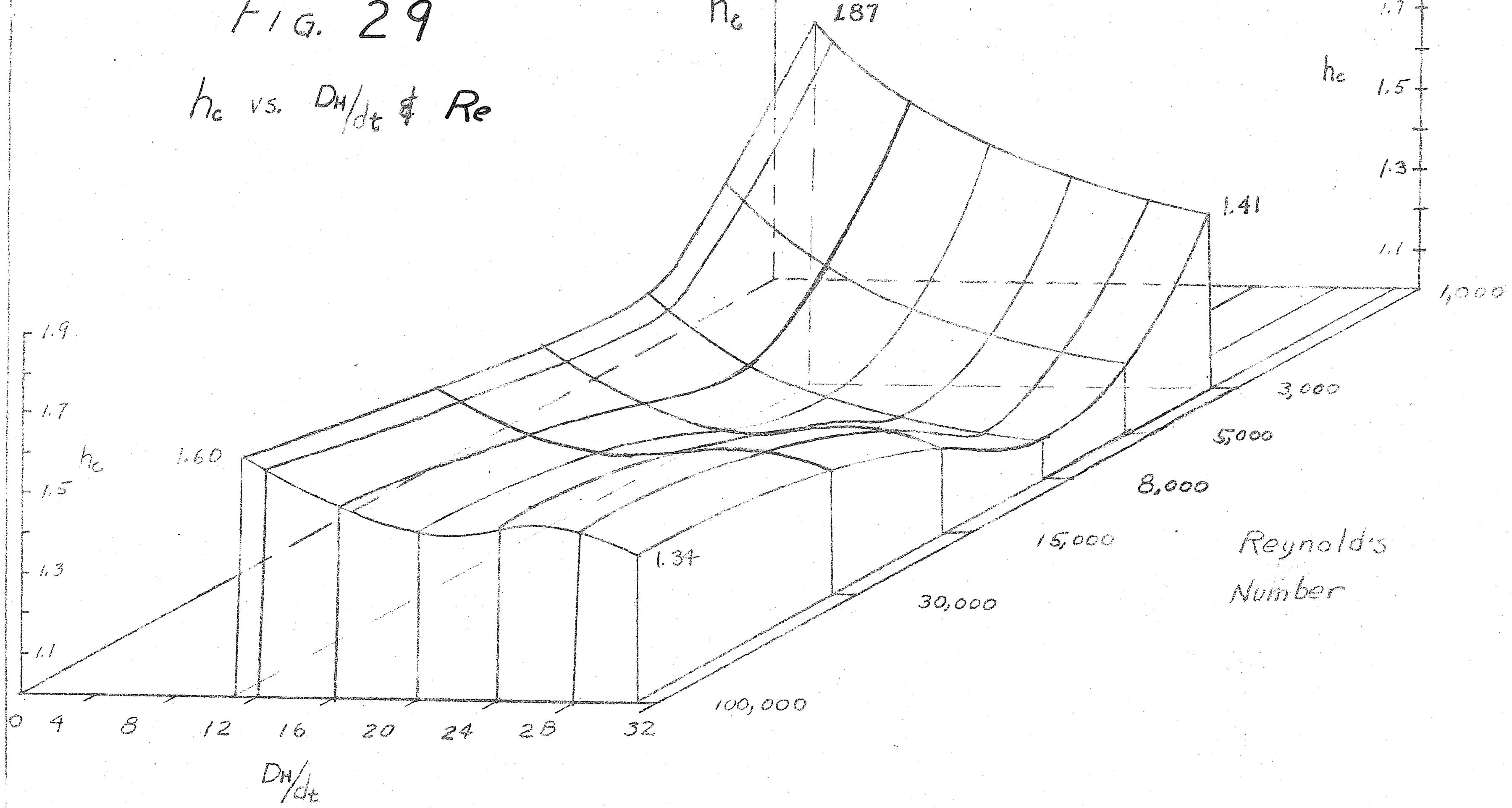


Valid for $L/d_t \geq 77.8$

See Figs. 26 & 27

PLASTIC TEST RESULTS
FIG. 29

h_c vs. D_H/d_t & Re



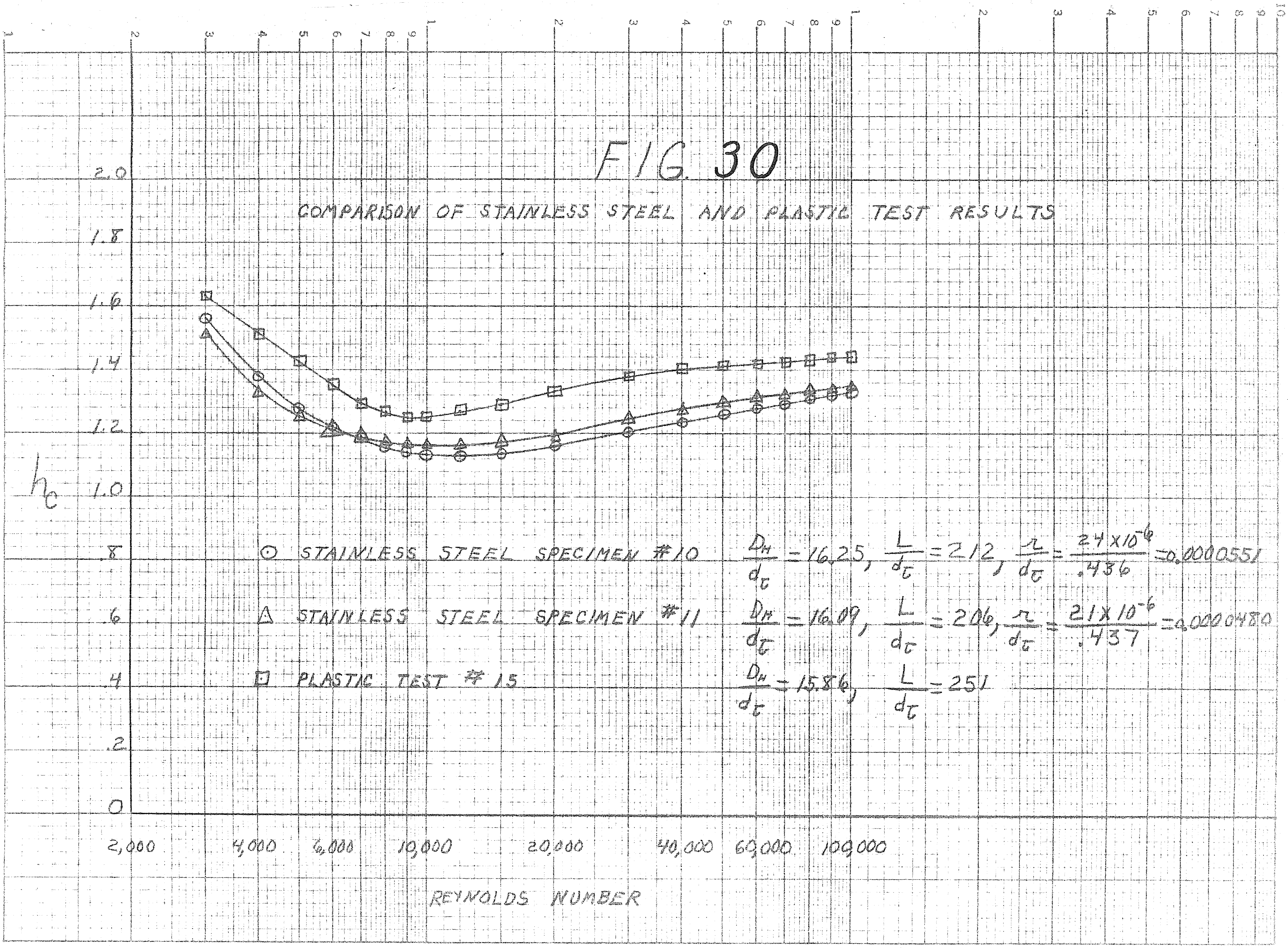


FIG. 30

COMPARISON OF STAINLESS STEEL AND PLASTIC TEST RESULTS