AN EXPERIMENTAL INVESTIGATION OF THE PRESSURE LOSS IN FLOW THROUGH HELICAL COILS

Thesis by

Lieutenant Commander Robert A. Weatherup, USN

In Partial Fulfillment of the
Requirements for the
Degree of Aeronautical Engineer

California Institute of Technology
Pasadena, California

1949

ACKNOWLEDGEMENT

The author is indebted to the staff of the Jet Propulsion Laboratory, California Institute of Technology.

In particular he wishes to express his appreciation to Dr. Howard S. Seifert who suggested the problem, to Mr. Robert Rose under whose supervision the investigation was conducted and to Lieutenant Commander Albert H. Clancy, Jr., USN, with whom the experiments were conducted.

SYMBOLS

f --Friction factor for straight pipe.

h_c --Multiplicative factor by which the straight pipe friction factor is increased in order to obtain the effective friction factor for a helical coil.

$f\,h_c$ --Effective friction factor for helical coil.

p --Pressure.

Δp --Pressure loss.

v --Mean velocity of fluid flow.

$\mathring{m}$ --Mass flow rate.

ρ --Mass density.

d_i --Inside diameter of tubing.

L --Length of tubing.

r --Internal surface roughness of the tubing. (Root mean square of surface irregularities as measured by profilometer.)

D_H --Mean diameter of the helix.

P_H --Pitch of the helix.

N_R --Reynolds number.

μ --Absolute viscosity.

TABLE OF CONTENTS

	Page Number
Summary	1
Introduction	2
Equipment	4
Procedure	6
Results and Discussion	8
Conclusions	15
Recommendations	16
References	17
Formulas	17a
Tables	18
Figures	34

SUMMARY

This thesis is a report of an experimental investigation of pressure losses in flow through helical coils of circular cross section. The investigation aimed at the determination of a multiplying factor h_c which could be applied to the friction factor for an equivalent straight pipe in order to determine the effective friction factor for flow through a helical coil.

The following conclusions were reached:

1. The multiplicative factor h_c is a function of Reynolds number and has a minimum value at a Reynolds number of approximately 8,000.
2. The factor h_c is also dependent on the ratio $\frac{D_H}{d_T}$. The general effect of this ratio is to increase h_c as the ratio $\frac{D_H}{d_T}$ is decreased. At Reynolds numbers above 8,000, however, h_c was found to be rather insensitive to variation in $\frac{D_H}{d_T}$ over the range from $\frac{D_H}{d_T} = 20$ to 30 with a minimum at $\frac{D_H}{d_T} \cong 23$.
3. The factor h_c was found to be independent of the ratios $\frac{L}{d_T}$ and $\frac{r}{d_T}$ over the ranges investigated.

INTRODUCTION

Considerable literature exists relative to the computation of pressure loss in flow through straight pipes. Experiments have shown that curvature results in higher pressure loss than is predicted by the straight pipe relations. There is comparatively little literature relative to the quantitative effect of curvature on pressure loss. This is especially true in the case of turbulent flow. References 1 and 2 contain information relative to laminar flow in curved pipes. It should be noted that the ratios of friction factors given in Reference 1 are based upon the laminar flow friction factor.

This investigation was concerned with the problem of determining the pressure loss through helical coils and was limited to flow in helices formed from tubing having a circular cross section.

This investigation aimed at the determination of a multiplicative factor, h_c, which could be applied to the pressure drop computed for an equivalent straight pipe in order to obtain the pressure drop in a helical coil. A dimensional analysis which is given under the heading RESULTS AND DISCUSSION indicated that the following dimensionless ratios were of importance in this problem:

RATIO	LIMITS OF INVESTIGATION
1. $\frac{\rho v d_t}{\mu}$ (Reynolds no.)	3,000 to 100,000
2. $\frac{D_H}{d_t}$	10.9 to 31.3
3. $\frac{L}{d_t}$	77.8 to 628
4. $\frac{P_H}{d_t}$	Not investigated.
5. $\frac{r}{d_t}$	4.61×10^{-5} to 23.4×10^{-5}

This investigation was conducted at the Hydraulics Laboratory of the Jet Propulsion Laboratory, California Institute of Technology during the school year 1948--49.

EQUIPMENT

A schematic diagram of the test apparatus is shown in Fig. 1. Photographs of the test apparatus are included as Figs. 2, 3, 4 & 5. Fig. 2 is a photograph of the complete apparatus. Fig. 3 shows one of the steel helices tested. Fig. 4 shows one of the five wooden helical forms used with a plastic test specimen in place. Fig. 5 shows all five of the wooden helical forms which were used to form helices with plastic tubing. All tests were made with water as the working fluid.

Twelve helices of stainless steel were tested to determine the effect of surface roughness on h_c . These helices were practically identical except for surface roughness. The dimensions of these specimens are given in Table I. Stainless steel was selected so that the roughness would not change during the tests as a result of corrosion. Commercial stainless steel tubing was used. The interior surfaces were roughened by sand blasting. (A local firm developed a sand blasting head which was drawn through the tubing.) The specimens were tested in the straight condition and then bent and tested in the helical form. Distortion of the cross section was avoided by filling the tubing, before bending, with a low melting point alloy known as "CERROSAFE". After the alloy had solidified the tubing was bent on a cylindrical form. Then the "CERROSAFE" was removed by careful steam cleaning at a temperature well above the melting point of the "CERROSAFE".

The effect of the ratios $\frac{D_H}{d_t}$ and $\frac{L}{d_t}$ was investigated by using a plastic specimen wound on various wooden forms. The configurations of the plastic specimen as tested are given in Table II. The plastic selected had a very smooth interior. A sample of this plastic tubing was subjected to static pressure tests and showed negligible expansion under the pressures employed in this investigation.

Pressure measurements were made using a water manometer, a mercury manometer, and calibrated laboratory bourdon gages as applicable. Simultaneous pressure measurements were made on the above instruments whenever their pressure ranges overlapped. Both the water and mercury manometers were approximately twelve feet high. Gage readings were required for only a relatively few experimental points.

PROCEDURE

The test procedure involved the determination of the pressure loss at various flow rates. The pressure loss was measured on the water manometer, mercury manometer, or bourdon gages as applicable. The flow rate was determined by collecting the water over a suitable time interval and weighing. The temperature of the water collected was recorded from which values of viscosity and density were determined from tables in Ref. 3.

The pressure taps were located six inches from the helix in all tests in order that the flow might be relatively uniform at the point where the pressure orifices of the taps were located. The location of the pressure taps is shown in Figs. 3 & 4. The pressure loss measured between the orifices of the pressure taps was corrected for the pressure loss in the pressure taps themselves and in the six inch leads to and from the helices in order to obtain the pressure loss in the helices alone. This correction was obtained by testing the pressure taps with a one foot length of tubing between them at various flow rates and plotting a curve of Δp vs. $\mathring{m}$. Corrections from this curve were subtracted from the measured pressure loss between the pressure taps for corresponding flow rates in order to obtain the pressure loss in the helices themselves. A small error was possibly involved in this procedure since flow conditions in the one foot length tested between the pressure taps were not the same as in the six inch leads to and from the helix. However, any error should be negligible since the correction was small in comparison to the total pressure loss from the upstream pressure tap to the down stream tap.

RESULTS AND DISCUSSION

The following physical quantities were considered necessary to define the problem:

PHYSICAL QUANTITY	DIMENSIONS (M = Mass, L′ = Length, T = Time)
1. Viscosity-- μ	$\frac{M}{L'T}$
2. Velocity-- v	$\frac{L'}{T}$
3. Density-- ρ	$\frac{M}{(L')^3}$
4. Diameter of tube-- d_t	L'
5. Pressure loss-- Δp	$\frac{M}{L'T^2}$
6. Diameter of Helix-- D_H	L'
7. Pitch of Helix-- P_H	L'
8. Length of the tube-- L	L'
9. Root mean square of surface irregularities as measured by profilometer (Roughness)-- r	L'

Application of Dimensional Analysis indicates that the following ratios may be of importance in this problem:

1. $\dfrac{\Delta p}{v^2 \rho}$ (Newton's number)

2. $\dfrac{\rho v d_T}{\mu}$ (Reynolds number)

3. $\dfrac{L}{d_T}$

4. $\dfrac{D_H}{d_T}$

5. $\dfrac{r}{d_T}$

6. $\dfrac{P_H}{d_T}$

The usual formula for computing pressure loss in a straight pipe is

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

The friction factor f is known to be a function of two factors, Reynolds number and relative surface roughness. The following formula was considered for computing pressure loss in a helical coil:

$$\Delta P = h_c f \frac{L}{d_T} \frac{1}{2} \rho v^2$$

The multiplicative factor h_c was considered to be a possible function of the ratios indicated below:

$$h_c = \text{function}\left(\frac{\rho v d_T}{\mu}, \frac{L}{d_T}, \frac{D_H}{d_T}, \frac{r}{d_T}, \frac{P_H}{d_T}\right)$$

The effect of Reynolds number was investigated by varying the mean velocity v while holding all other ratios constant. The effect of $\frac{L}{d_T}$ was investigated by testing shorter and shorter lengths of the original plastic specimen. Variation of $\frac{D_H}{d_T}$ was accomplished by winding the same specimen of plastic tubing on helical forms of various diameters. Variation of $\frac{r}{d_T}$ was investigated over a narrow range by testing a series of twelve stainless steel helices which were practically identical except for roughness. The ratio $\frac{P_H}{d_T}$ was not investigated. All the steel helices were tightly wound having a pitch of approximately one half inch. All of the plastic helices were wound on wooden forms which had a pitch of one inch.

The dimensions of the stainless steel specimens are given in Table I. The approximate number of turns in the helices is included in Table I as an aid in visualizing the helices although the helices are completely defined by the dimensions L, P_H and D_H. The test results for the stainless steel specimens are tabulated in Table III and plotted in Fig. 6. Fig. 6 shows curves of the friction factor f for all of the specimens when tested in straight condition. These curves of friction factor are all very close to the friction factor curve for smooth straight pipes as given by

Moody in Ref. 4. Curves of the friction factor $f h_c$ obtained after coiling the tubing are also given in Fig. 6. The values of h_c plotted in Fig. 6 were obtained by dividing the ordinates of the $f h_c$ curve by the ordinates of the f curve for the same Reynolds number. Fig. 6A is a combination of certain of the h_c vs. N_R curves from Fig. 6. Fig. 6B is a cross plot of h_c vs. $\frac{r}{d_T}$ from Fig. 6. Fig. 6B shows no correlation between h_c and surface roughness. Therefore the conclusion was reached that h_c was not a well defined function of surface roughness over the limited range investigated. The sand blasting technique did not produce the anticipated variation in surface roughness. (The points shown in the cross plots of this report are not experimental points, but legends indicating source of data.)

The dimensions of the plastic tubing test configurations are given in Table II. The test results are tabulated in Table IV and plotted in Figs. 7, 8, 9, 10 and 11. All of these figures show the friction factor f for the straight plastic tubing and the friction factors $f h_c$ for same plastic specimen when it was coiled into a helix on the various wooden forms. Figs. 7, 8, 9, 10 and 11 all show that h_c is strongly influenced by Reynolds number. The similarity of Figs. 7, 8, 9, 10 and 11 suggests that h_c is not a function of $\frac{L}{d_T}$. Figs. 12, 13 and 14 are cross plots of h_c vs $\frac{L}{d_\tau}$ from the data of Figures 7, 8, 9, 10 and 11. From these cross plots, h_c does not appear to be a function of $\frac{L}{d_\tau}$ over the range investigated. This indicates that the nature of the flow in a helical coil is established rather rapidly. Investigation of the establishment of the flow pattern at lower values of $\frac{L}{d_\tau}$ would be of interest, but a more elaborate experimental technique involving multiple pressure taps in the direction of flow would probably be required. Reference 5 contains some charts which show the nature of the flow patterns established in bends. It is interesting to note that the disturbances created by the bend are propagated for a considerable distance downstream.

Figs. 15 and 16 are cross plots of h_c vs $\frac{D_H}{d_\tau}$ from the data of Figs. 7, 8, 9, 10 and 11. Fig. 17 is a reproduction of the curves from Figs. 15 and 16. Fig. 17 shows the effect of $\frac{D_H}{d_\tau}$ upon h_c and the rather unexpected result that h_c has a minimum value at $\frac{D_H}{d_\tau} \cong 23$ for the higher values of Reynolds number. A somewhat similar phenomenon has been reported in Ref. 6 for 90° pipe bends.

Fig. 18 is a cross plot of h_c vs N_R from Fig. 9. Fig. 18 shows the very strong effect of Reynolds number upon h_c . Fig. 18 was drawn from the experimental data for the ratio of $\frac{L}{d_T} = 251$. However, Fig. 18 is valid for all ratios of $\frac{L}{d_T}$ greater than $\frac{L}{d_T} = 77.8$ since Figs. 12, 13, and 14 show that h_c is independent of $\frac{L}{d_T}$ at least for values of $\frac{L}{d_T}$ greater than $\frac{L}{d_T} = 77.8$.

Either Fig. 17 or Fig. 18 may be used to estimate the value of h_c depending upon which is most convenient.

This investigation shows that h_c is a function of N_R and $\frac{D_H}{d_T}$. The factor h_c was independent of $\frac{L}{d_T}$ and $\frac{r}{d_T}$ over the ranges investigated. The effect of the ratio $\frac{P_H}{d_T}$ was not investigated.

It is interesting to note that the values of determined from the steel coils are about 10% higher than those from the plastic coils for corresponding values of $\frac{D_H}{d_T}$ and N_R . The curves are of the same general shape and are shown in Fig. 19. Fig. 19 is a combination of roughly comparable test results from steel and plastic tubing. The variation of 10% is not considered unreasonable in view of the somewhat uncertain effect of variation in surface roughness and the slightly different values of the ratios $\frac{L}{d_T}$ and $\frac{D_H}{d_T}$. It might also be noted that the steel helices had a pitch of approximately ½ inch while the plastic helices had a pitch of 1 inch.

Fig. 20 shows h_c as a function of both Reynolds number and $\frac{D_H}{d_\tau}$. This figure aids in visualizing the combined effect of the two most important variables.

CONCLUSIONS

The following conclusions were reached as a result of this investigation:

1. The multiplicative factor h_c is a function of Reynolds number and has a minimum value at a Reynolds number of approximately 8,000. The functionality is shown in Fig. 18.

2. The factor h_c is also a function of the ratio $\frac{D_H}{d_\tau}$. The general effect of this ratio is to increase h_c as the ratio $\frac{D_H}{d_\tau}$ is decreased. At Reynolds numbers above 8,000, however, h_c was found to be rather insensitive to variation in $\frac{D_H}{d_\tau}$ over the range from $\frac{D_H}{d_\tau}$ = 20 to 30 with a minimum at $\frac{D_H}{d_\tau} \cong 23$. The functionality is shown in Fig. 17.

3. The factor h_c was found to be independent of the ratios $\frac{L}{d_\tau}$ and $\frac{r}{d_\tau}$ over the ranges investigated.

RECOMMENDATIONS

The following recommendations are submitted with regard to any further research on this problem:

1. Larger tubing should be used in order to obtain higher values of Reynolds number.

2. The effect of surface roughness should be investigated over a greater range. The technique of sand blasting is unsatisfactory on stainless steel tubing. An attempt should be made to develop a more satisfactory method of producing surface roughness.

REFERENCES

1. Goldstein, S.: Modern Developments in Fluid Dynamics, Vol. I, Page 312, Oxford University Press, 1938.

2. White, C. M.: Streamline Flow Through Curved Pipes, Proceedings of the Royal Society of London, Vol. 123, Page 645, 1929.

3. Hodgman, C. D.: Handbook of Chemistry and Physics, 13th Edition, Chemical Rubber Publishing Co., Cleveland, Ohio.

4. Moody, L. F.: Friction Factors of Pipe Flow, Trans. ASME, Vol. 66, Page 671, Nov. 1944.

5. Weske, John R.: NACA Technical Note No. 1471.

6. Hughes and Safford: Hydraulics, Revised Edition, Paragraphs 309, 312 and 313, MacMillian, 1926.

FORMULAS

1. Straight pipe.

$$\Delta p = f \frac{L}{d_t} \frac{1}{2} \rho v^2 \quad \text{OR} \quad f = \frac{2 \Delta p \, d_t}{L \rho v^2}$$

2. Helical coil.

$$\Delta p = f_{hc} \frac{L}{d_t} \frac{1}{2} \rho v^2 \quad \text{OR} \quad f_{hc} = \frac{2 \Delta p \, d_t}{L \rho \, v^2}$$

3. Mean velocity.

$$v = \frac{4 \mathring{m}}{\pi \rho d_t^2} \quad \text{OR} \quad \mathring{m} = \frac{\pi d_t^2}{4} v \rho$$

4. Reynolds number.

$$N_R = \frac{\rho v d_t}{\mu}$$

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
r 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
r 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 II

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 II

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	0.51	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 $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.21\times10^{-5} \frac{SLUGS}{FT-SEC}$				SPECIMEN No. 1 - COILED $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.42\times10^{-5} \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	f	Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	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 $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.21\times10^{-5} \frac{SLUGS}{FT-SEC}$				SPECIMEN No. 2 - COILED $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.325\times10^{-5} \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	f	Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	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 III CONT'D

STEEL TUBING TEST RESULTS

SPECIMEN No. 3 - STRAIGHT $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.21 \times 10^{-5} \frac{SLUGS}{FT-SEC}$				SPECIMEN No. 3 - COILED $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.325 \times 10^{-5} \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT^2	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	f	Δp LBS/FT^2	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	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 $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.21 \times 10^{-5} \frac{SLUGS}{FT-SEC}$				SPECIMEN No. 4 - COILED $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.325 \times 10^{-5} \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT^2	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	f	Δp LBS/FT^2	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	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	0.00557	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 III CONT'D

STEEL TUBING TEST RESULTS

SPECIMEN No. 5 - STRAIGHT $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.325 \times 10^{-5} \frac{SLUGS}{FT-SEC}$				SPECIMEN No. 5 - COILED $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.325 \times 10^{-5} \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	f	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	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 $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.42 \times 10^{-5} \frac{SLUGS}{FT-SEC}$				SPECIMEN No. 6 - COILED $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.325 \times 10^{-5} \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	f	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	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 III CONT'D

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/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	f	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	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/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	f	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	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 III CONT'D

STEEL TUBING TEST RESULTS

SPECIMEN No. 9 - STRAIGHT $\rho = 1.937\ \frac{SLUGS}{FT^3}$; $\mu = 2.45\times10^{-5}\ \frac{SLUGS}{FT-SEC}$				SPECIMEN No. 9 - COILED $\rho = 1.937\ \frac{SLUGS}{FT^3}$; $\mu = 2.29\times10^{-5}\ \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	f	Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	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 $\rho = 1.937\ \frac{SLUGS}{FT^3}$; $\mu = 2.45\times10^{-5}\ \frac{SLUGS}{FT-SEC}$				SPECIMEN No. 10 - COILED $\rho = 1.936\ \frac{SLUGS}{FT^3}$; $\mu = 2.25\times10^{-5}\ \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	f	Δp LBS/FT^2	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	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 III CONT'D
STEEL TUBING TEST RESULTS

SPECIMEN NO. 11 – STRAIGHT; $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.47\times10^{-5} \frac{SLUGS}{FT-SEC}$				SPECIMEN NO. 11 – COILED; $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.325\times10^{-5} \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	f	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	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	8,090	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; $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.325\times10^{-5} \frac{SLUGS}{FT-SEC}$				SPECIMEN NO. 12 – COILED; $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.37 \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	f	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	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

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	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	f	Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	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	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	f_{hc}	Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	f_{hc}
78.2	0.00232	3,940	0.0590	48.6	0.00164	2790	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	4890	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 IV CONT'D

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 LBS/FT²	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	f_{hc}	Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	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/FT²	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	f_{hc}	Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	~~Re~~ N_R	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 IV CONT'D

PLASTIC TEST RESULTS

TEST No. 9 — $\rho = 1.937\ \frac{SLUGS}{FT^3}$; $\mu = 2.29 \times 10^{-5}\ \frac{SLUGS}{FT.-SEC}$				TEST No. 10 — $\rho = 1.937\ \frac{SLUGS}{FT^3}$; $\mu = 2.29 \times 10^{-5}\ \frac{SLUGS}{FT.-SEC}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	f_{hc}	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	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 — $\rho = 1.937\ \frac{SLUGS}{FT^3}$; $\mu = 2.285 \times 10^{-5}\ \frac{SLUGS}{FT.-SEC}$				TEST No. 12 — $\rho = 1.937\ \frac{SLUGS}{FT^3}$; $\mu = 2.29 \times 10^{-5}\ \frac{SLUGS}{FT.-SEC}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	f_{hc}	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	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 IV CONT'D

PLASTIC TEST RESULTS

TEST No. 13 $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.29 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				TEST No. 14 $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.25 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	N_R	f_{hc}	Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	N_R	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 $\rho = 1.937 \frac{SLUGS}{FT^3}$; $\mu = 2.285 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				TEST No. 16 $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.22 \times 10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	N_R	f_{hc}	Δp LBS/FT²	$\mathring{m}$ SLUGS/SEC	N_R	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 IV CONT'D

PLASTIC TEST RESULTS

TEST No. 17				TEST No. 18			
$\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.25\times10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				$\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.24\times10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	f_{hc}	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	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.			
$\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.25\times10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				$\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.22\times10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	f_{hc}	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	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 IV CONT'D

PLASTIC TEST RESULTS

TEST No. 21. $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.25\times10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				TEST No. 22 $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.22\times10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	f_{hc}	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	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	5,450	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 $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.22\times10^{-5} \frac{SLUGS}{FT\text{-}SEC}$				TEST No. 24 $\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.22\times10^{-5} \frac{SLUGS}{FT\text{-}SEC}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	f_{hc}	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	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 IV CONT'D.

PLASTIC TEST RESULTS

TEST No. 25				TEST No. 26			
$\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.25 \times 10^{-5} \frac{SLUGS}{FT-SEC}$				$\rho = 1.936 \frac{SLUGS}{FT^3}$; $\mu = 2.27 \times 10^{-5} \frac{SLUGS}{FT-SEC}$			
Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	f_{hc}	Δp LBS/FT²	$\dot{m}$ SLUGS/SEC	~~Re~~ N_R	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

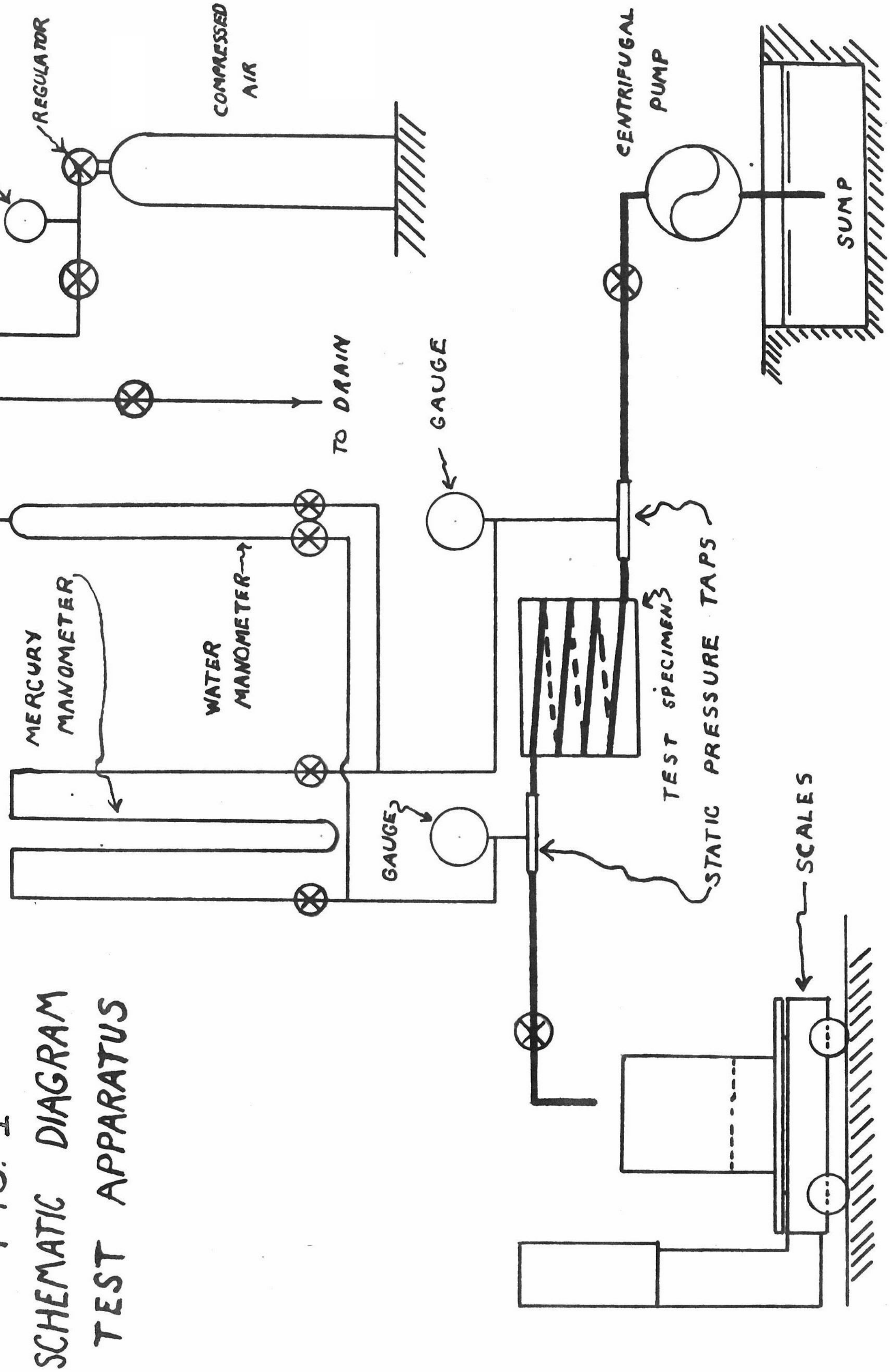
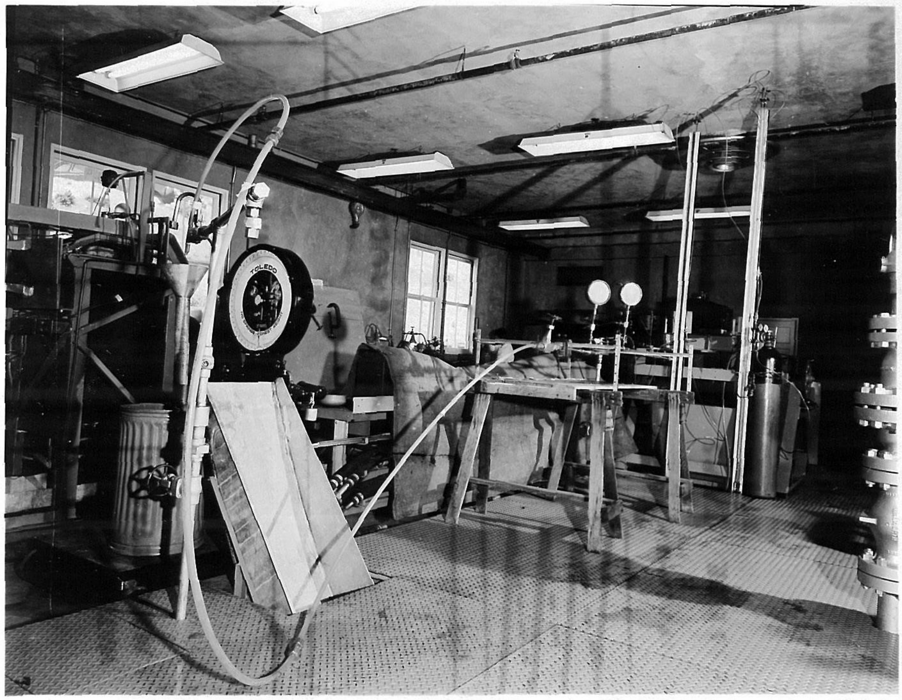
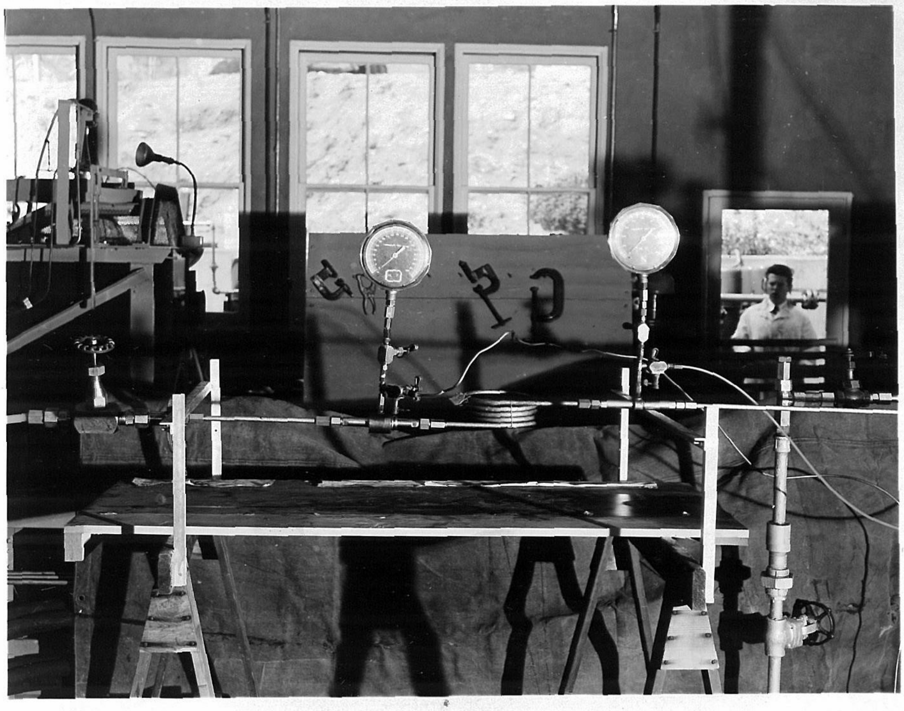


FIG. 1
SCHEMATIC DIAGRAM
TEST APPARATUS



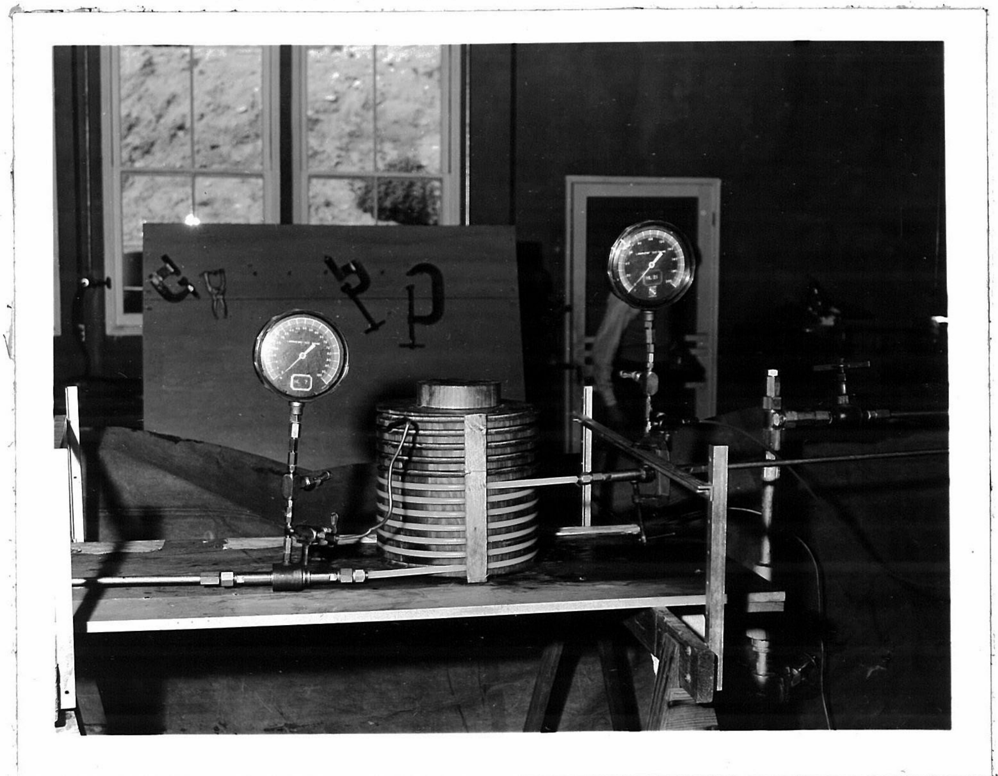
General View of Complete Apparatus

Fig. 2



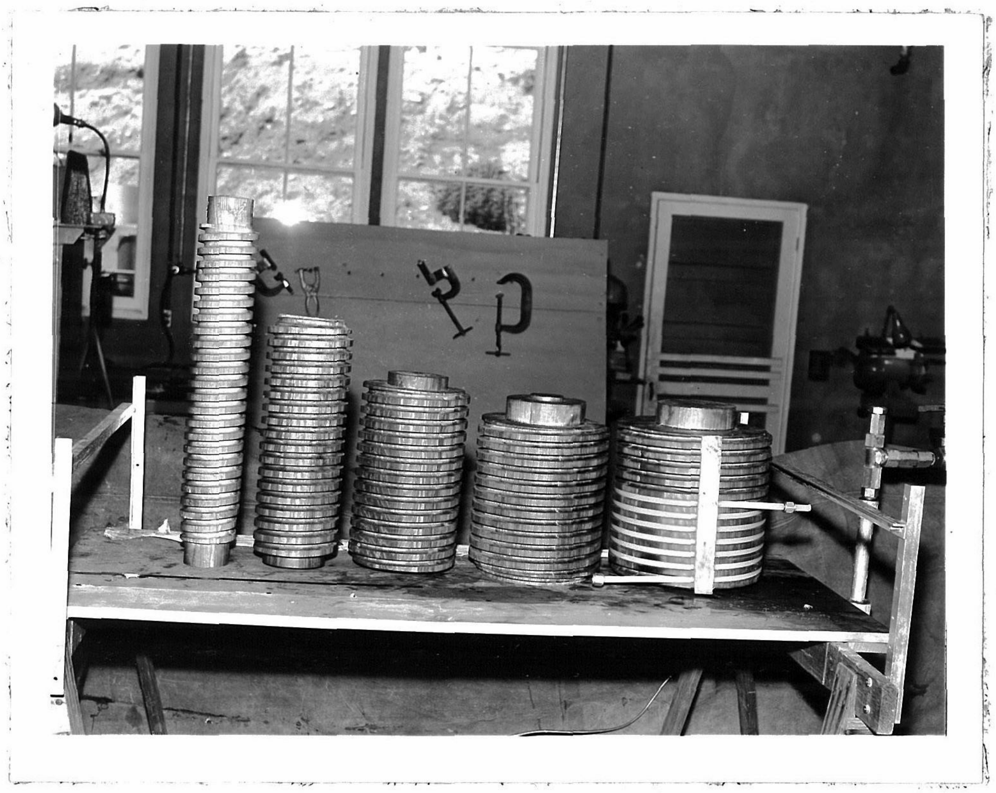
Stainless Steel Helix on Test Stand

Fig. 3



Plastic Helix on Test Stand

Fig. 4



Forms for the Plastic Helices

Fig. 5

FIG. 6

STEEL TUBING TEST RESULTS

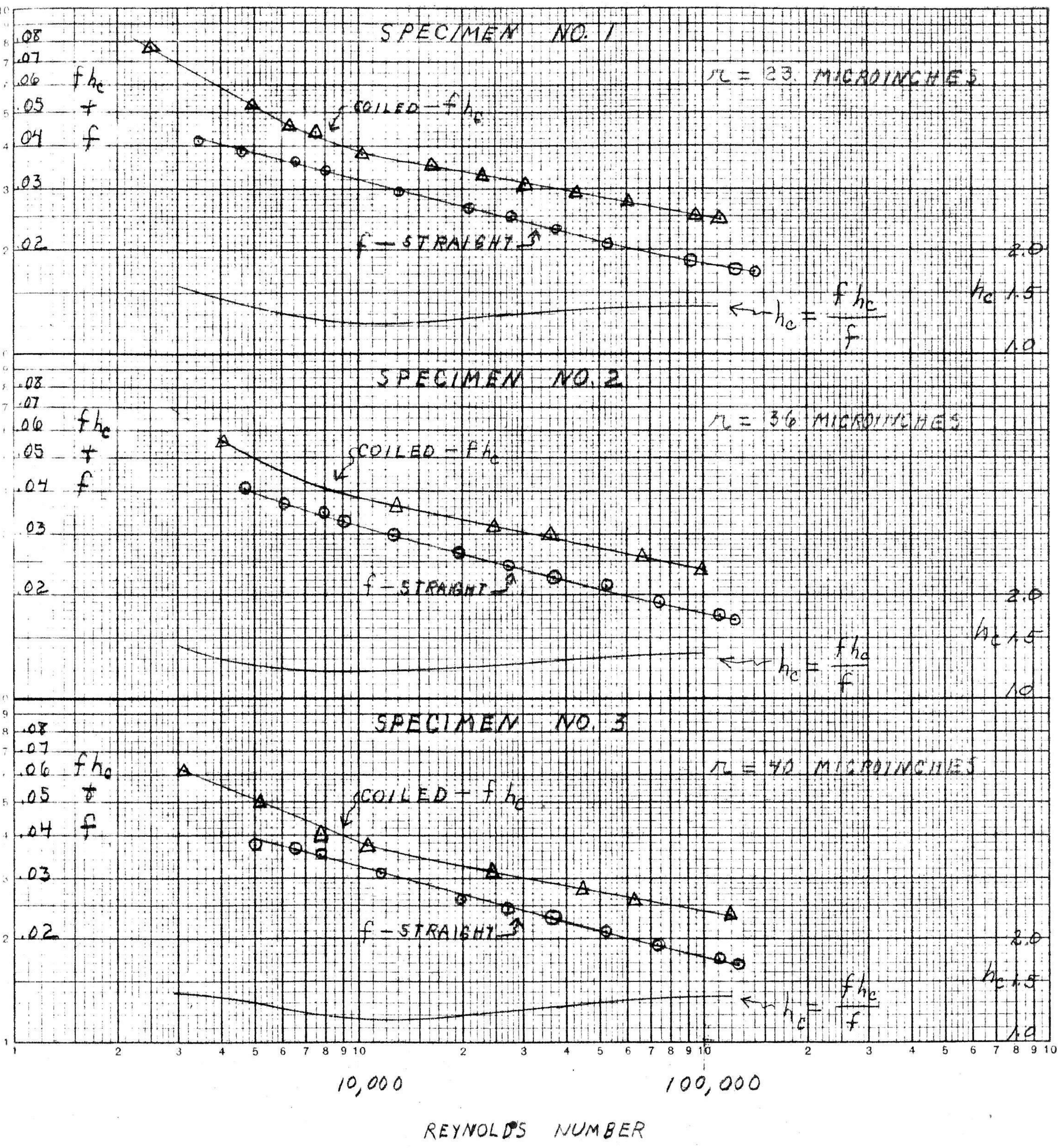
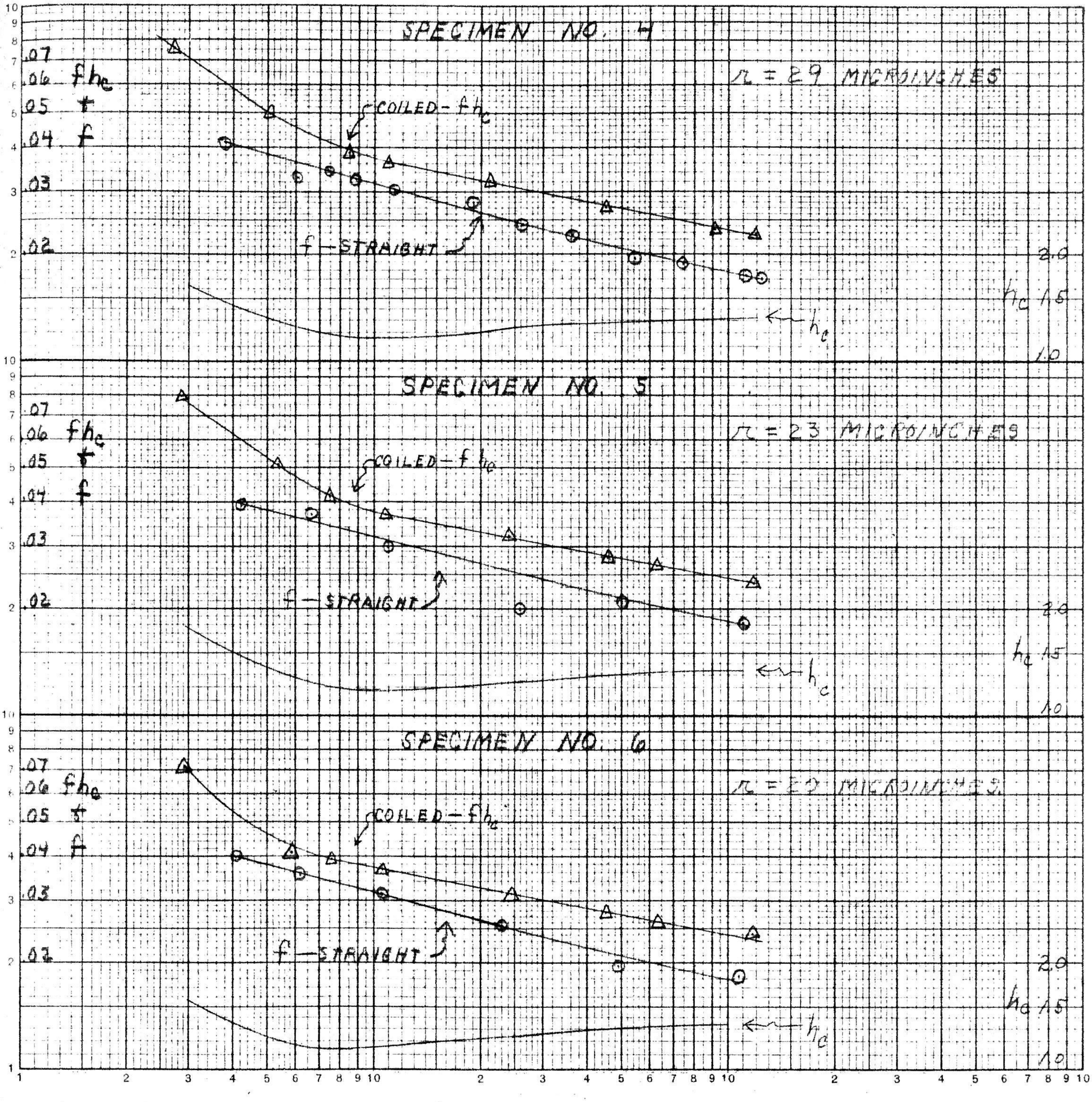


FIG. 6 CONT'D

STEEL TUBING TEST RESULTS



REYNOLD'S NUMBER

FIG. 6 CONT'D

STEEL TUBING TEST RESULTS

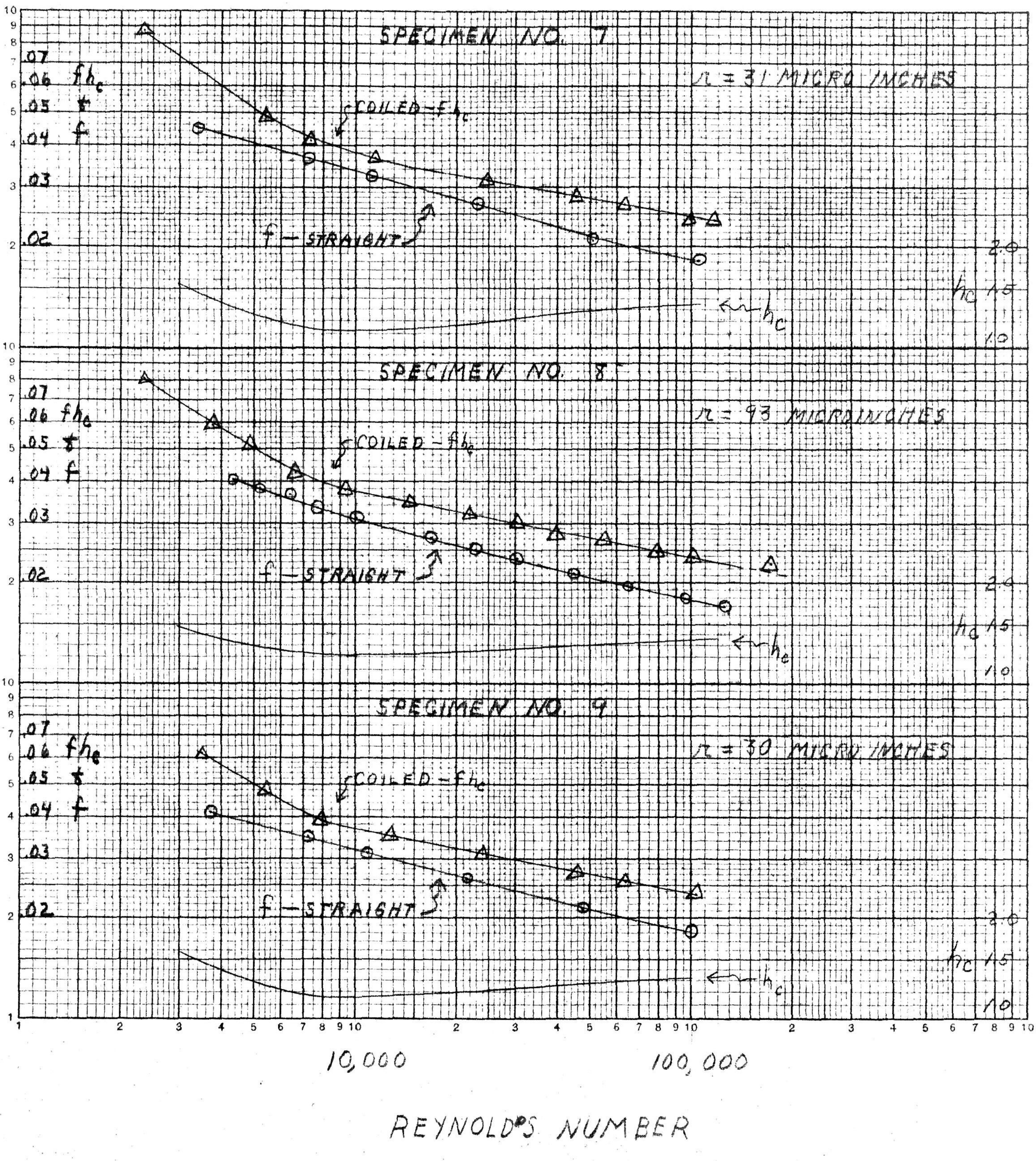
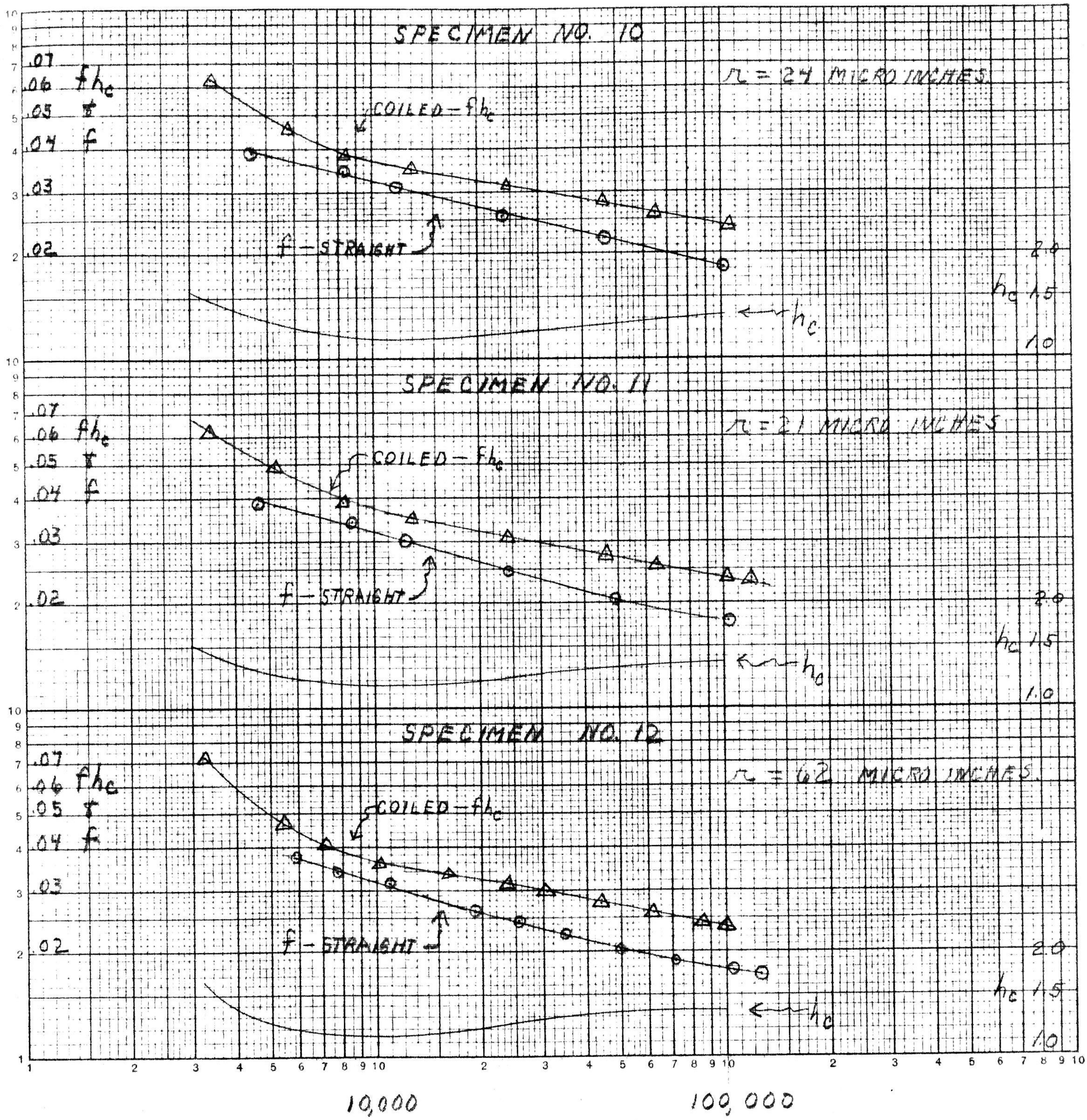


FIG. 6 CONT'D

STEEL TUBING TEST RESULTS



REYNOLD'S NUMBER

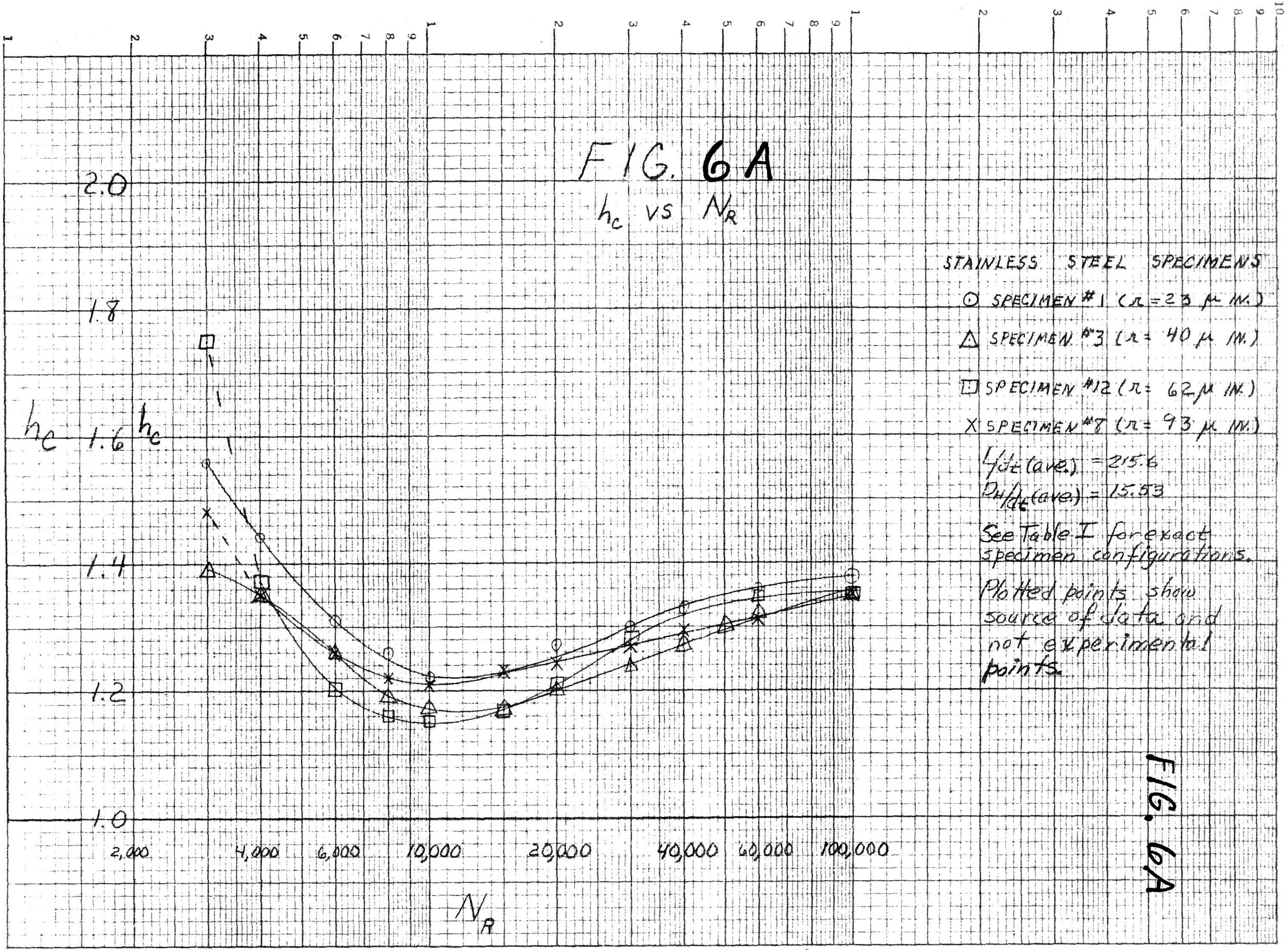
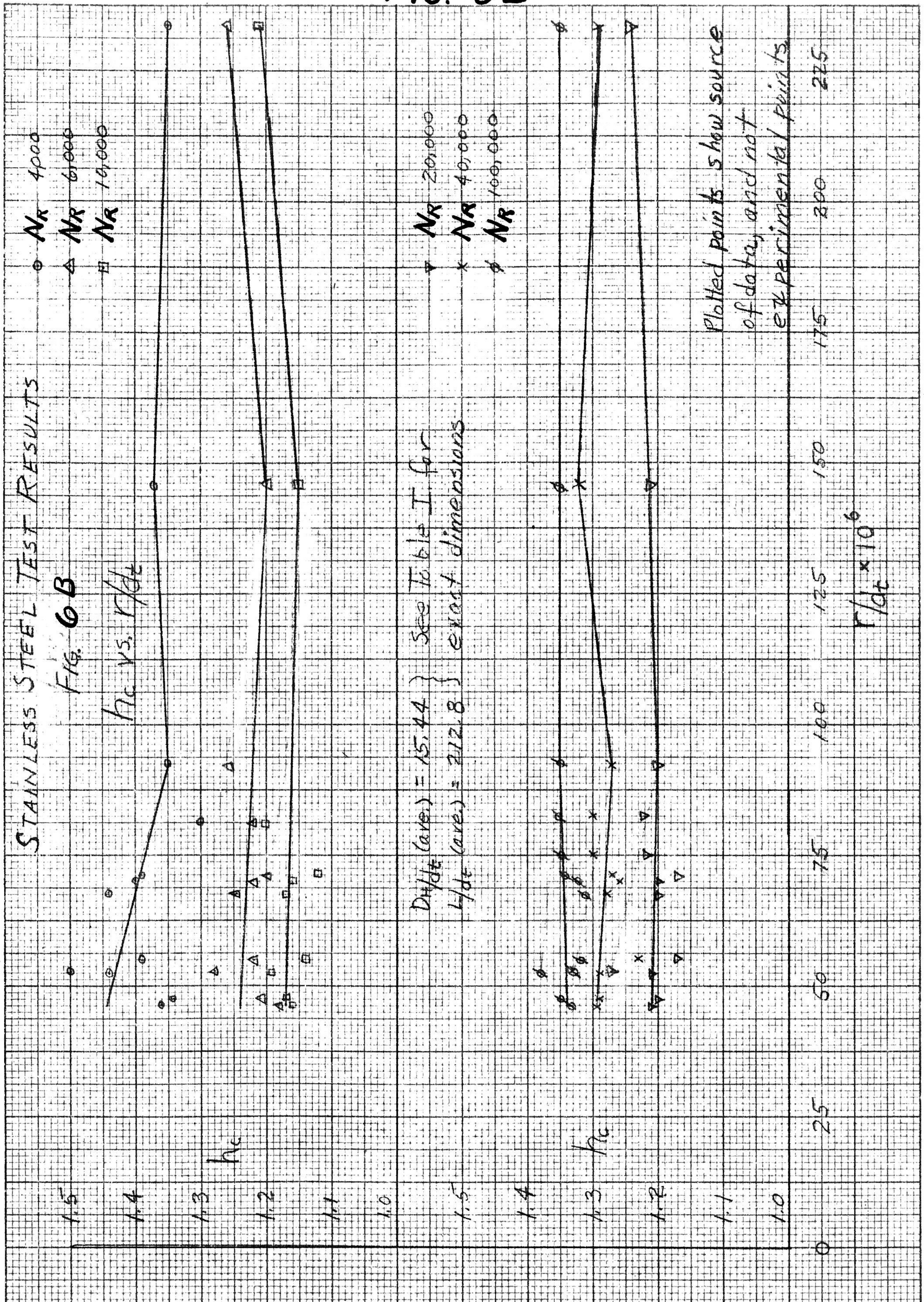


FIG. 6A
h_c vs N_R
STAINLESS STEEL SPECIMENS
⊙ SPECIMEN #1 (r = 23 μ IN.)
△ SPECIMEN #3 (r = 40 μ IN.)
□ SPECIMEN #12 (r = 62 μ IN.)
X SPECIMEN #8 (r = 93 μ IN.)
L/d_t (ave.) = 215.6
D_H/d_t (ave.) = 15.53
See Table I for exact specimen configurations.
Plotted points show source of data and not experimental points.
h_c
2.0
1.8
1.6
1.4
1.2
1.0
2,000
4,000
6,000
10,000
20,000
40,000
60,000
100,000
N_R
FIG. 6A

FIG. 6B



STAINLESS STEEL TEST RESULTS
FIG. 6B
h_c vs. r/d_t
N_R 4,000
N_R 6,000
N_R 10,000
N_R 20,000
N_R 40,000
N_R 100,000
D_H/d_t (ave.) = 15.44
L/d_t (ave.) = 212.8
See Table I for exact dimensions
Plotted points show source of data, and not experimental points.
h_c
$r/d_t \times 10^6$

FIG. 7

PLASTIC TEST RESULTS

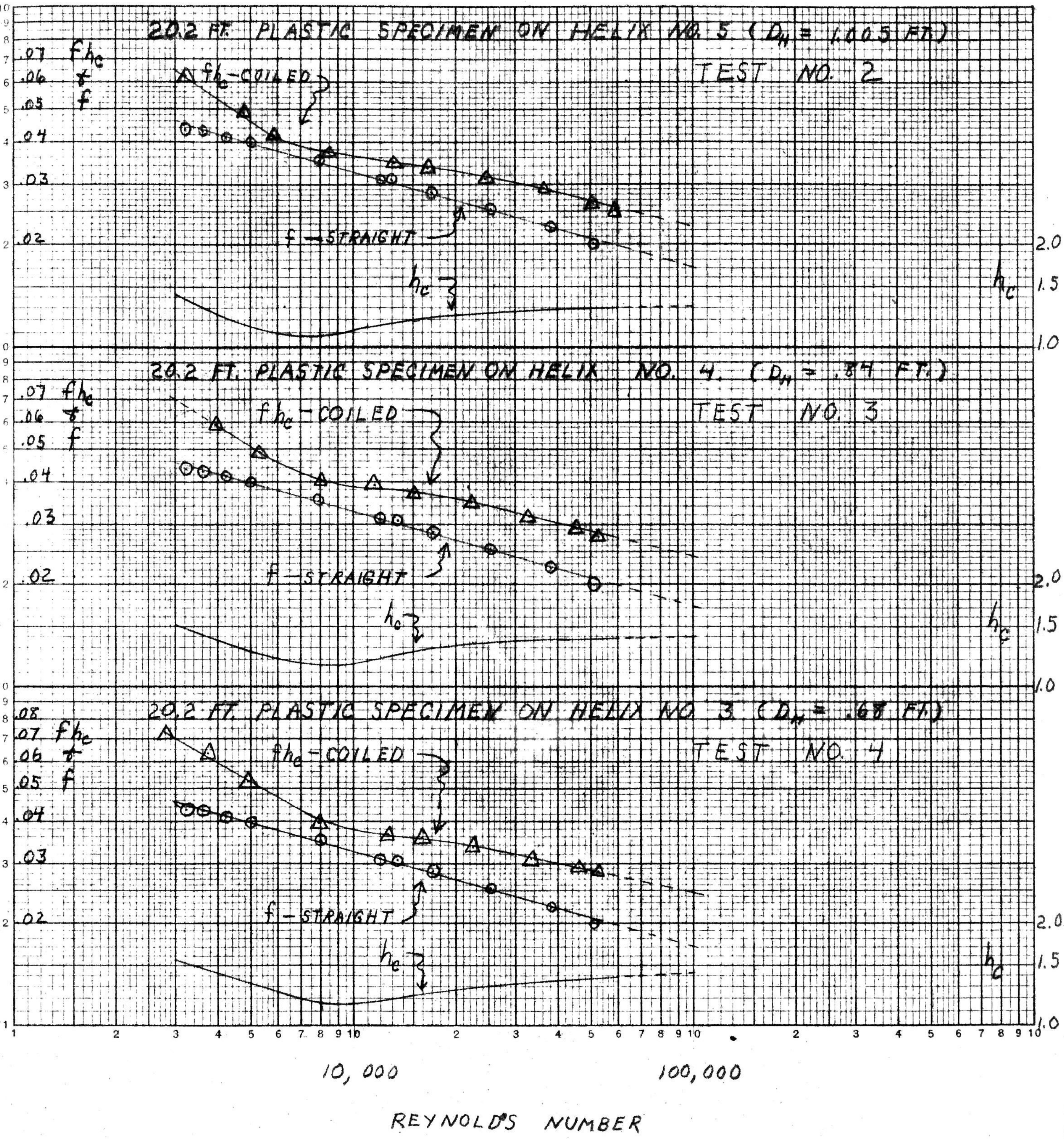
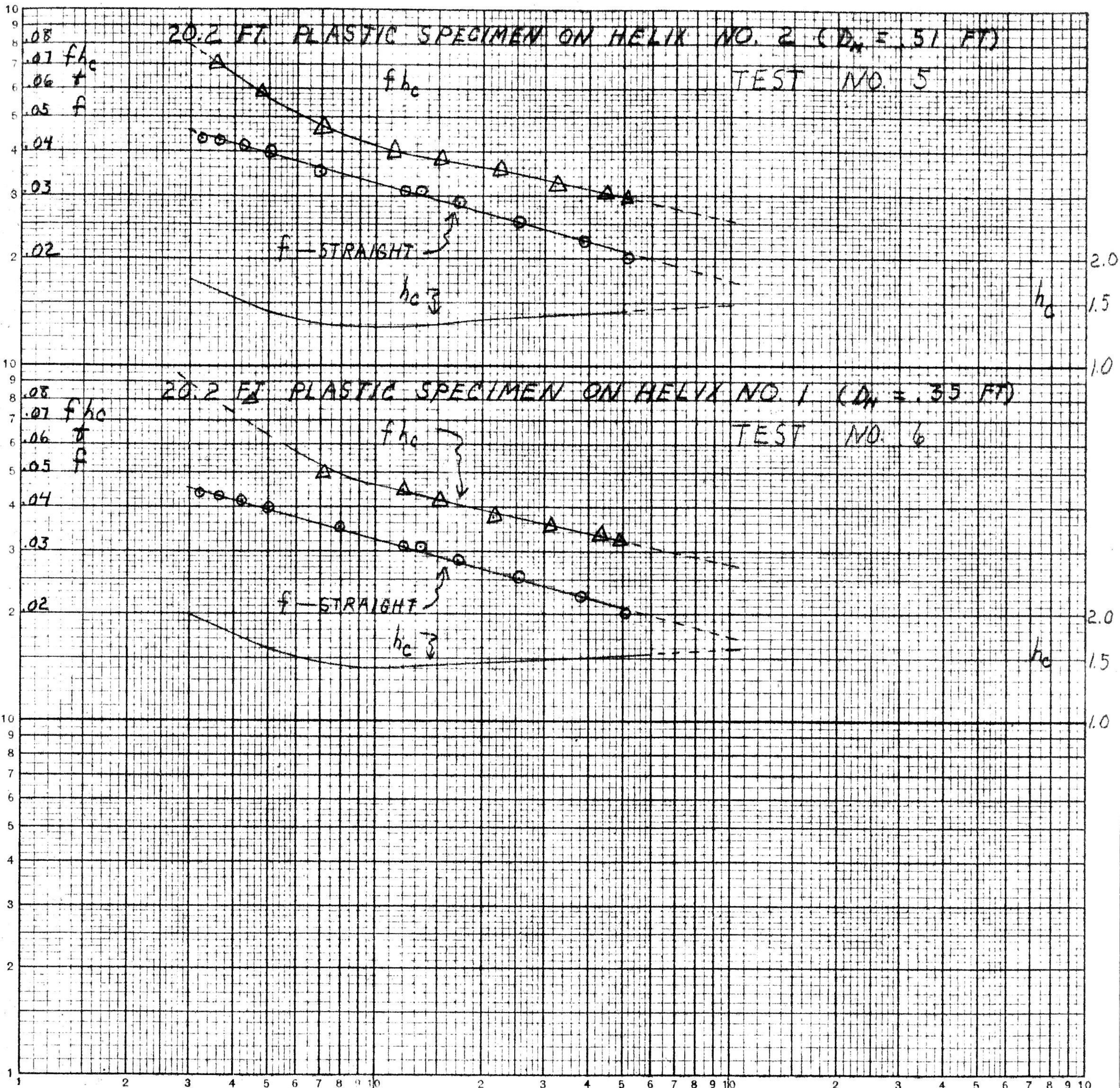


FIG. 7 CONT'D.

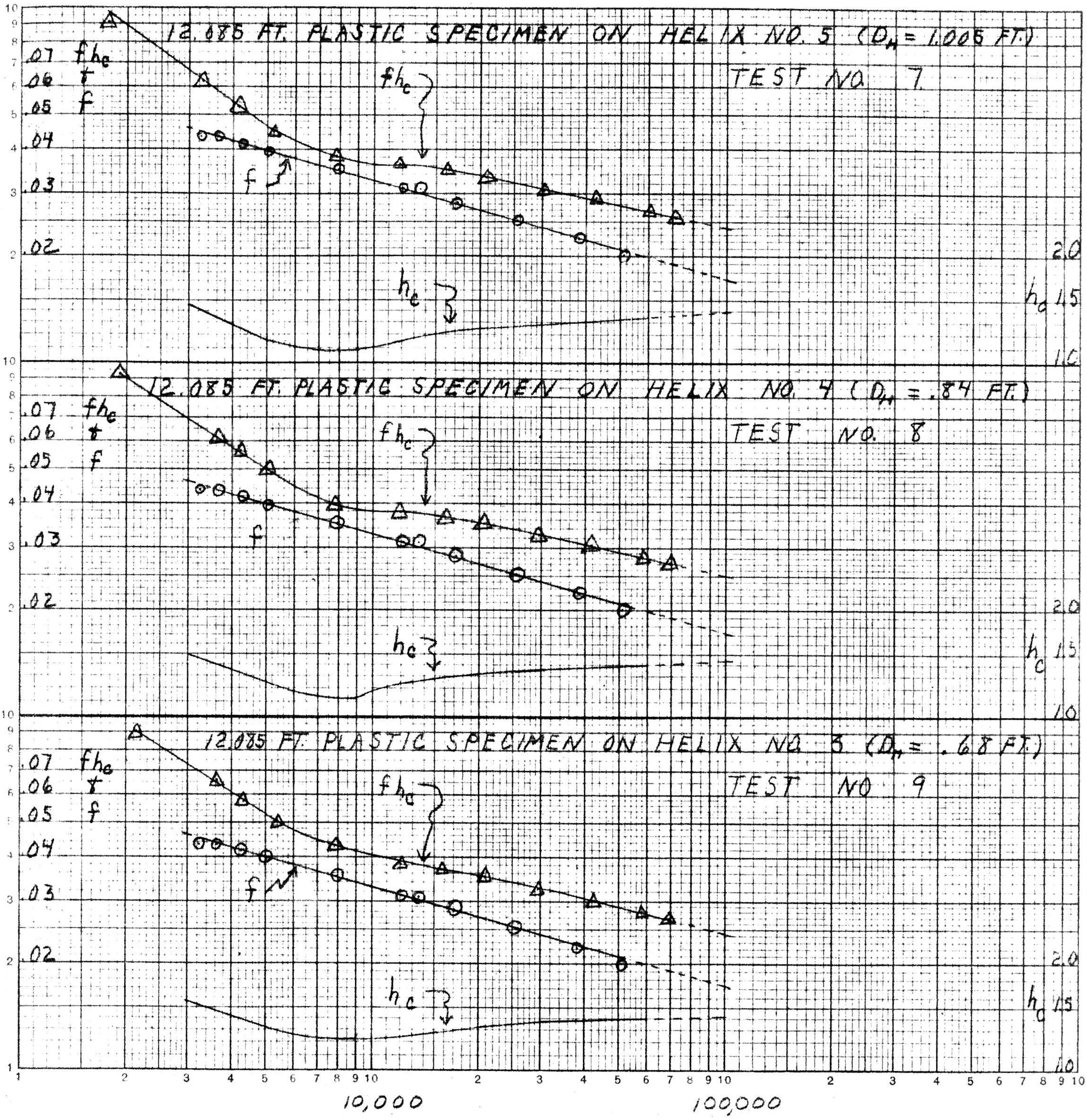
PLASTIC TEST RESULTS



REYNOLD'S NUMBER

FIG. 8

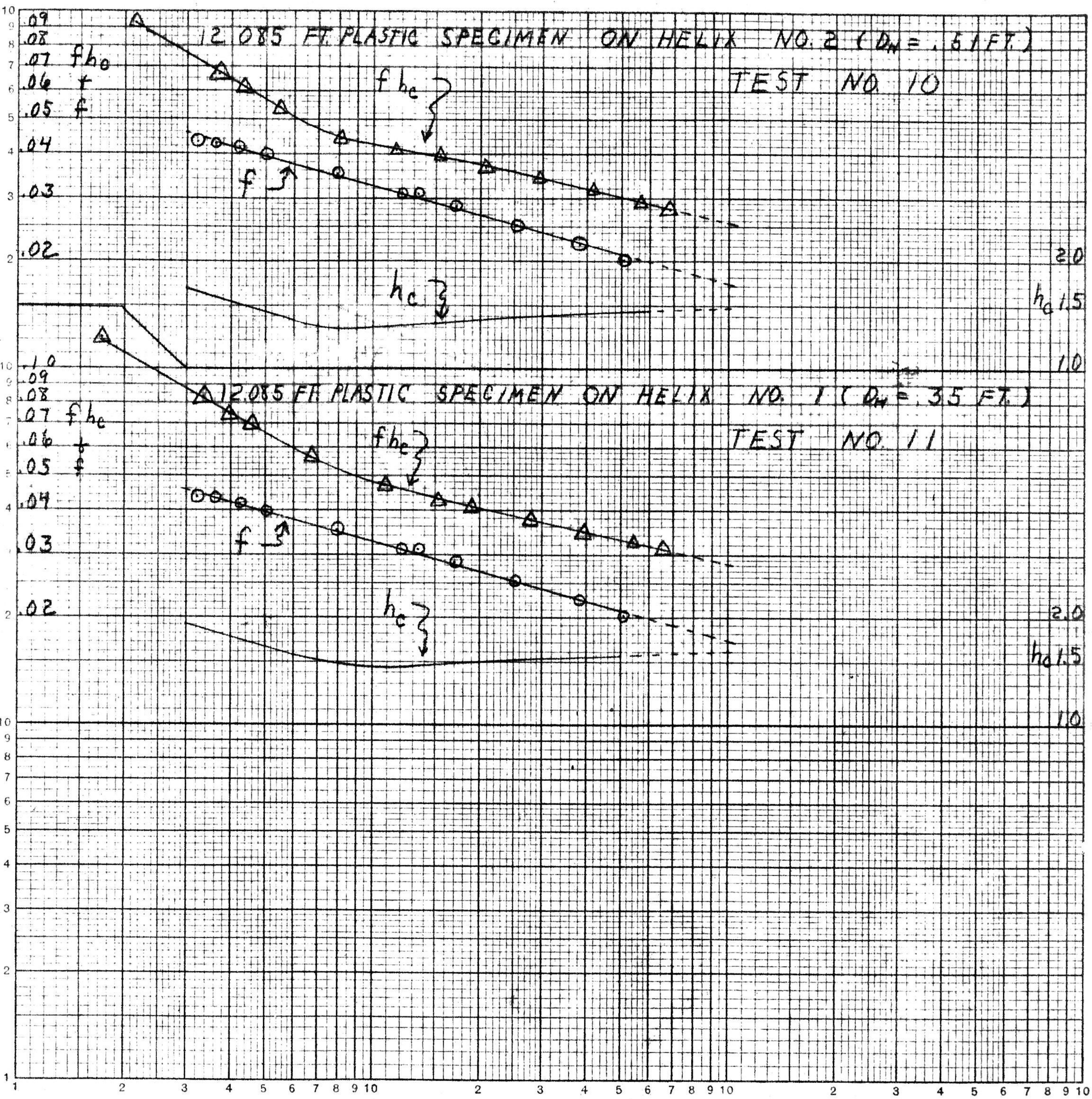
PLASTIC TEST RESULTS



REYNOLD'S NUMBER

FIG. 8 CONT'D

PLASTIC TEST RESULTS



REYNOLD'S NUMBER

FIG 9

PLASTIC TEST RESULTS

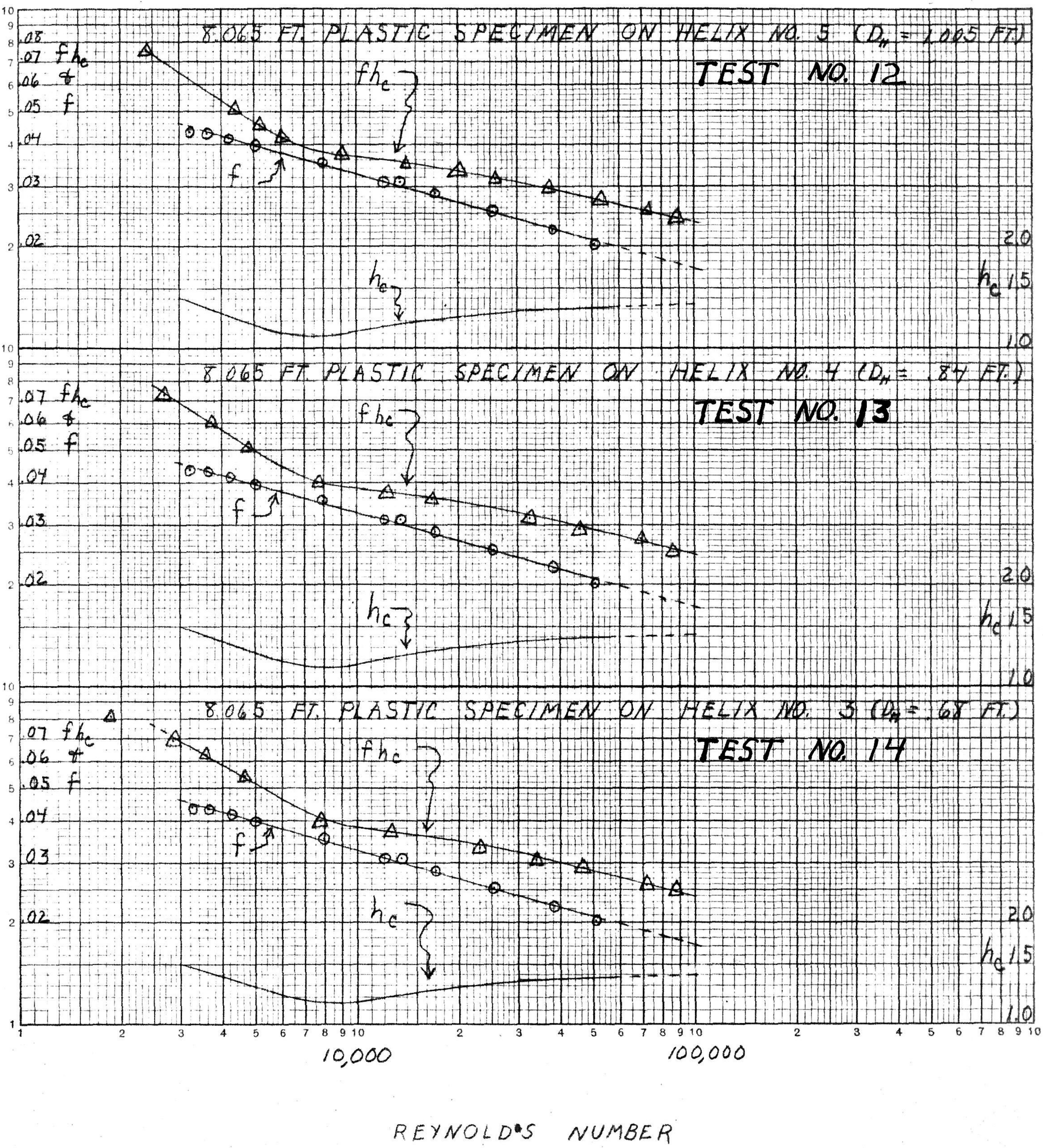


FIG. 9 CONT'D

PLASTIC TEST RESULTS

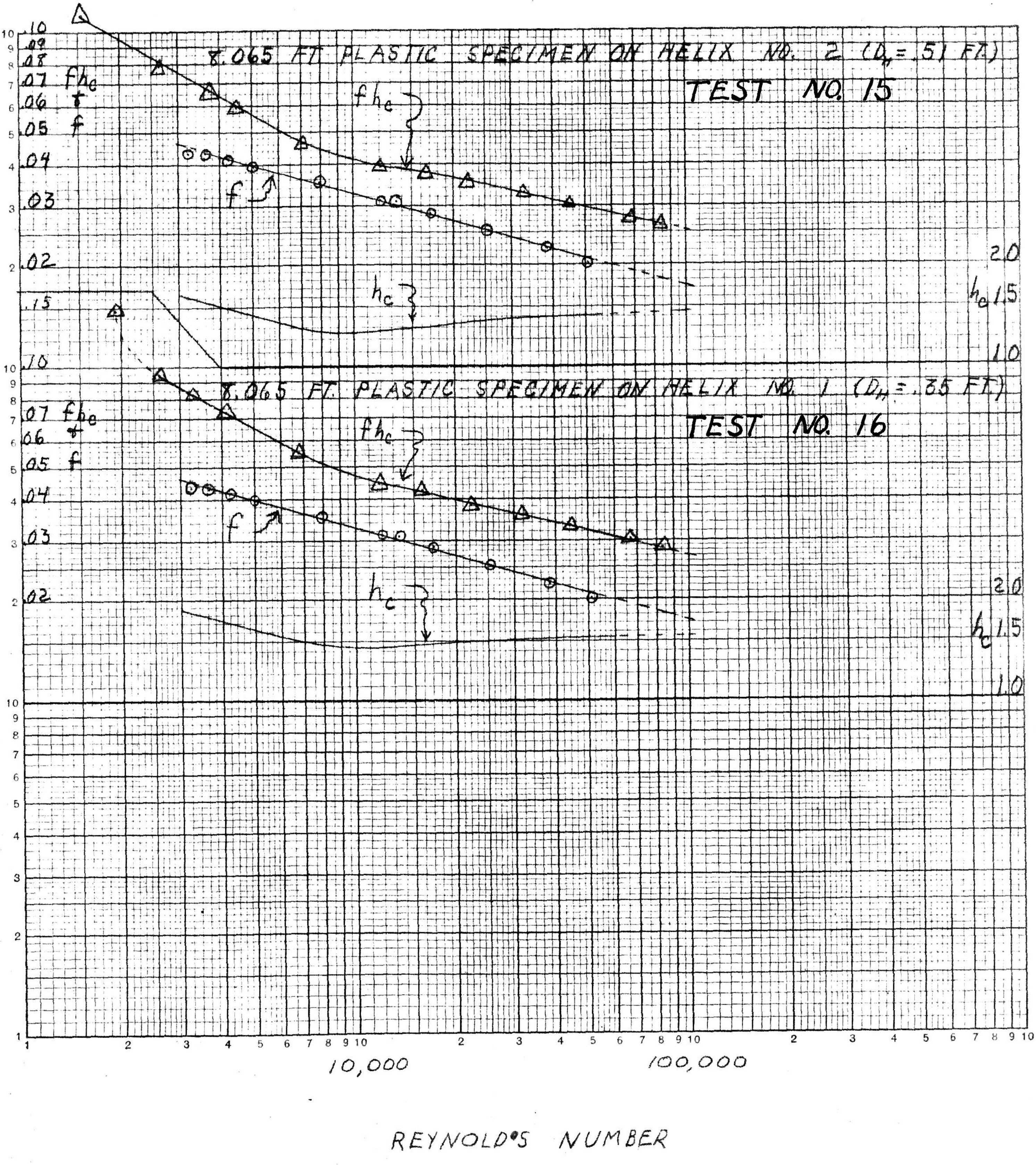
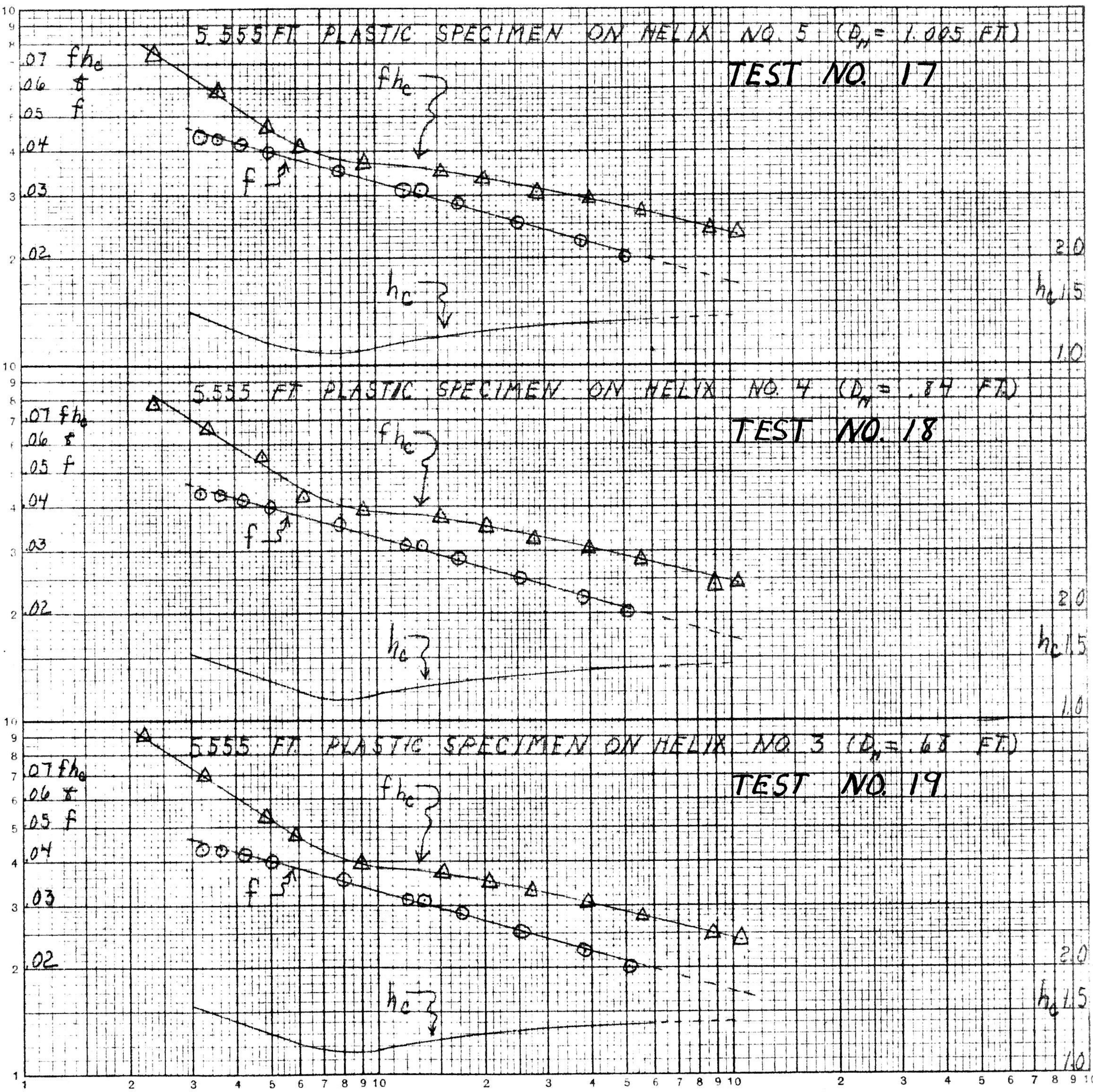


FIG. 10

PLASTIC TEST RESULTS



REYNOLD'S NUMBER

FIG 10 CONT'D.

PLASTIC TEST RESULTS

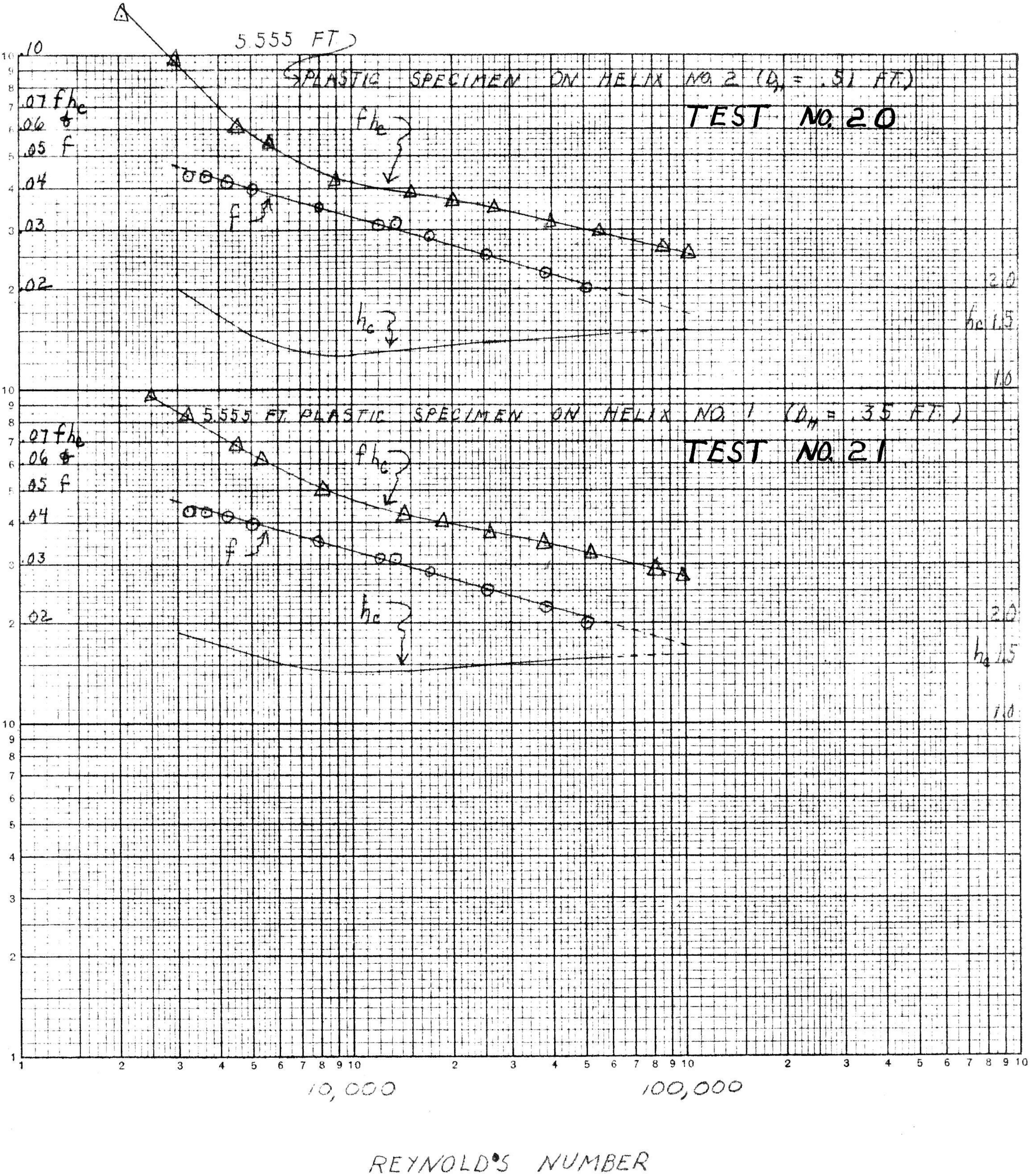
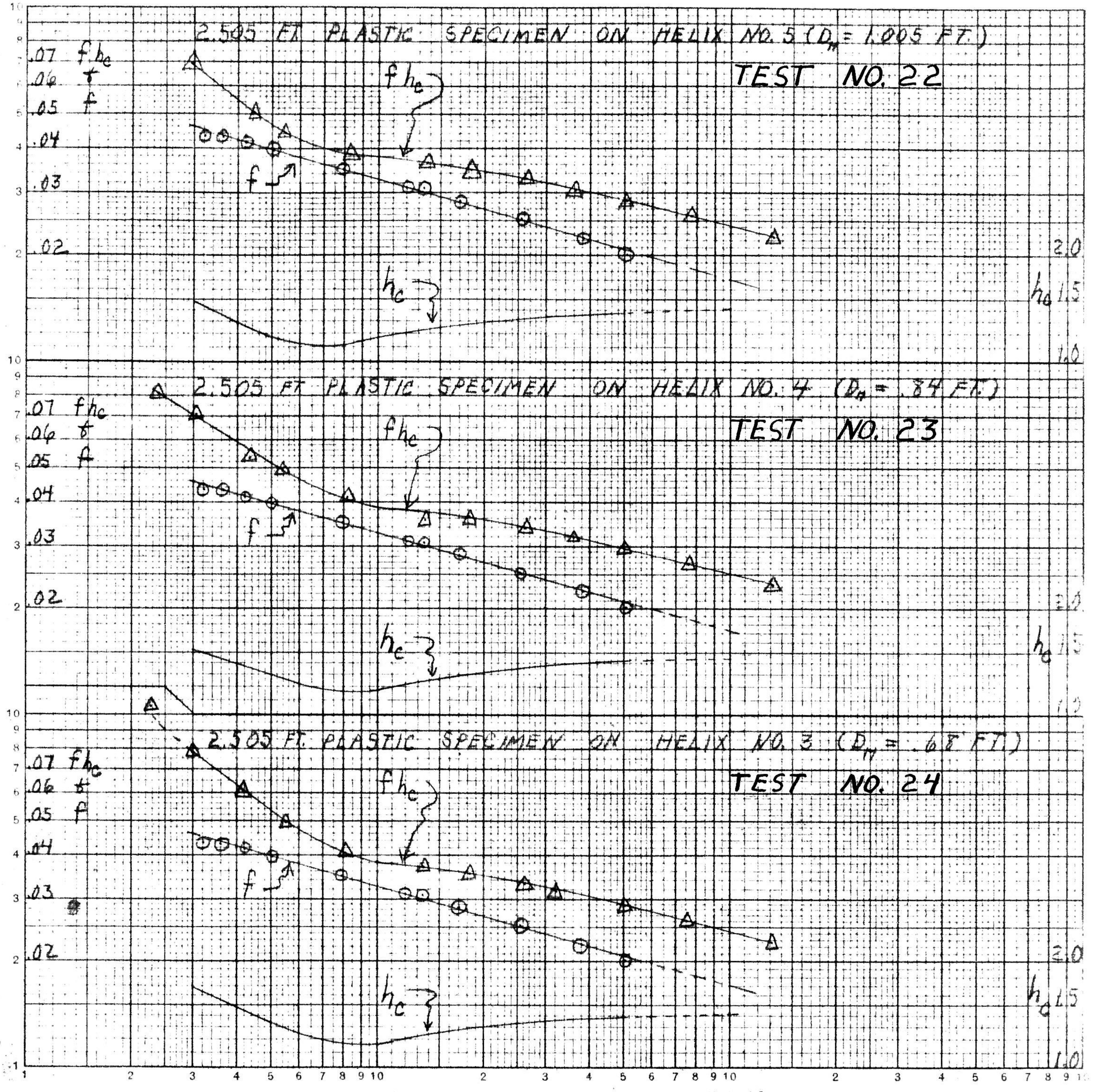


FIG. 11

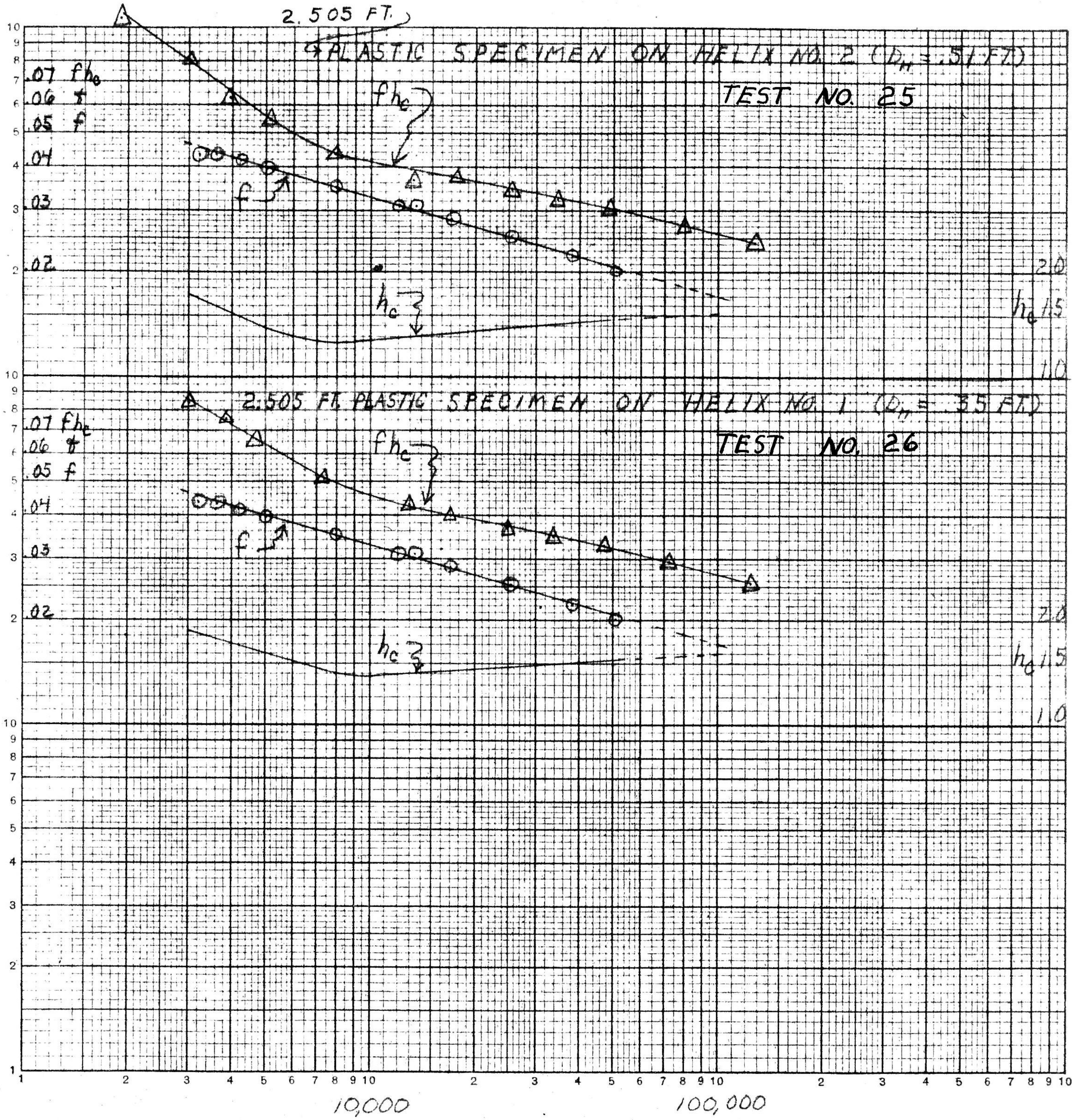
PLASTIC TEST RESULTS



REYNOLD'S NUMBER

FIG. 11 CONT'D

PLASTIC TEST RESULTS

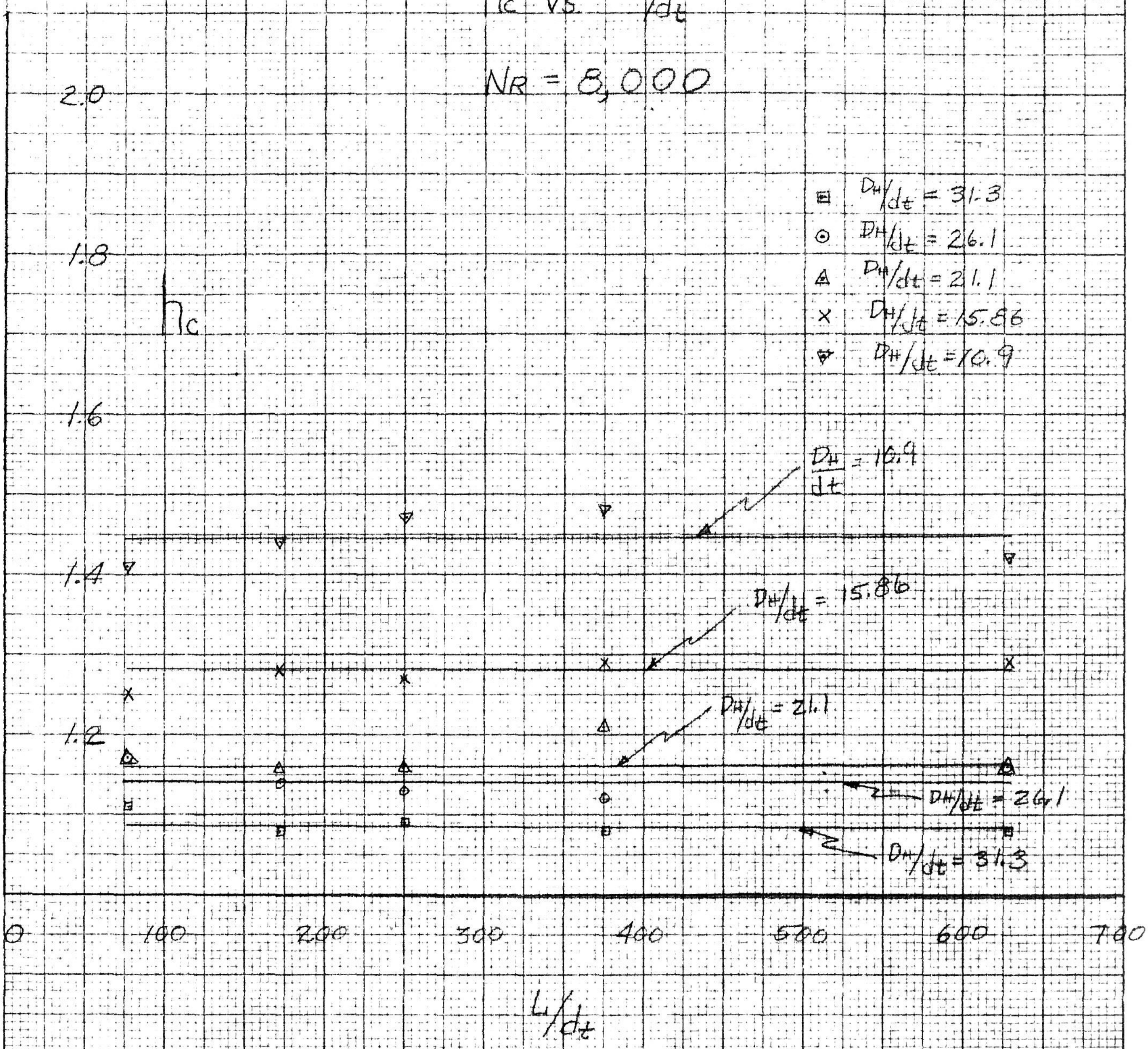


REYNOLD'S NUMBER

FIG. 12

h_c vs L/d_t

N_R = 8,000



DATA FROM PLASTIC TEST RESULTS

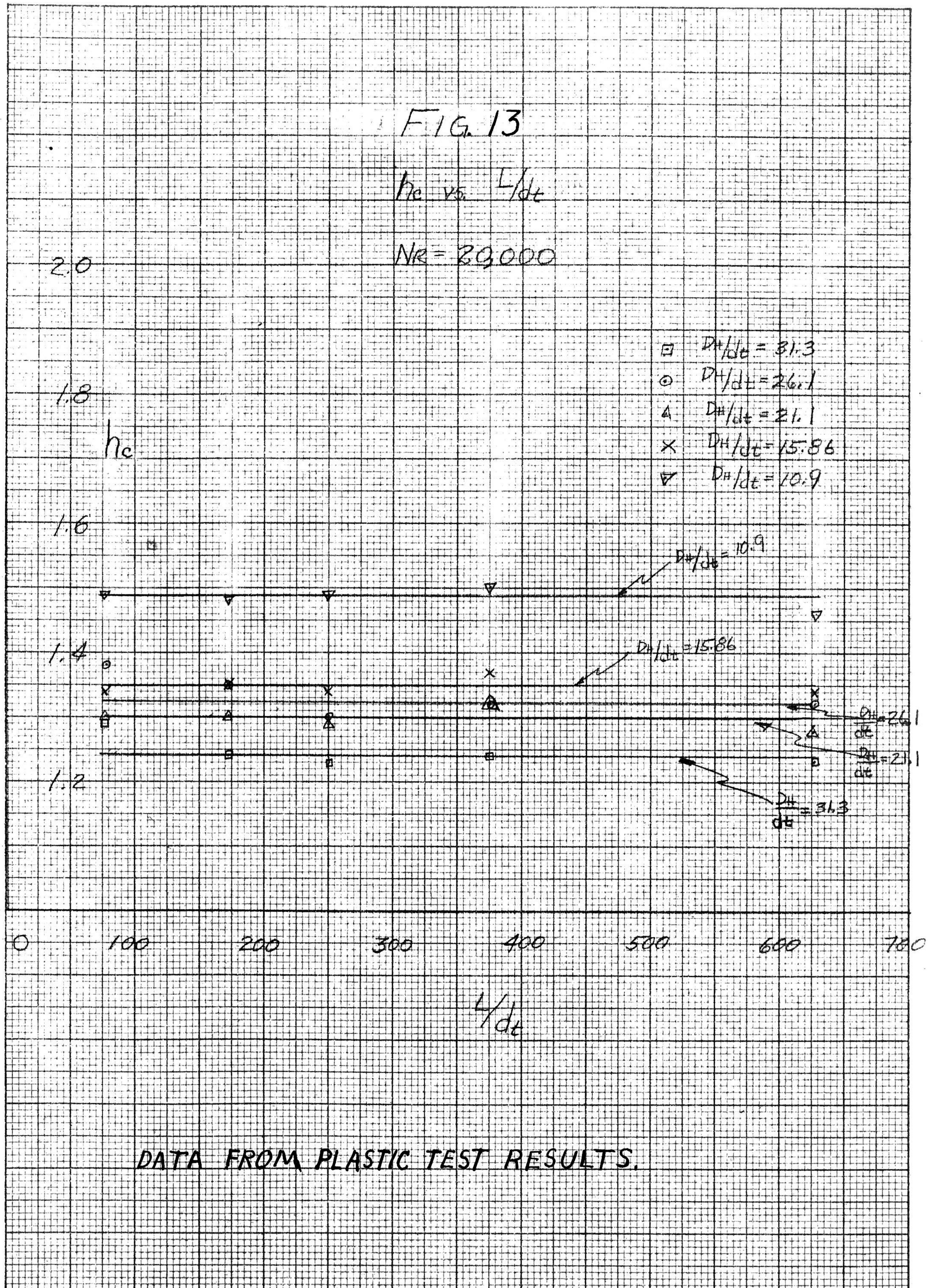


FIG. 13
hc vs. L/dt
NR = 20,000
2.0
1.8
1.6
1.4
1.2
hc
DH/dt = 31.3
DH/dt = 26.1
DH/dt = 21.1
DH/dt = 15.86
DH/dt = 10.9
DH/dt = 10.9
DH/dt = 15.86
DH/dt = 26.1
DH/dt = 21.1
DH/dt = 31.3
0
100
200
300
400
500
600
700
L/dt
DATA FROM PLASTIC TEST RESULTS.

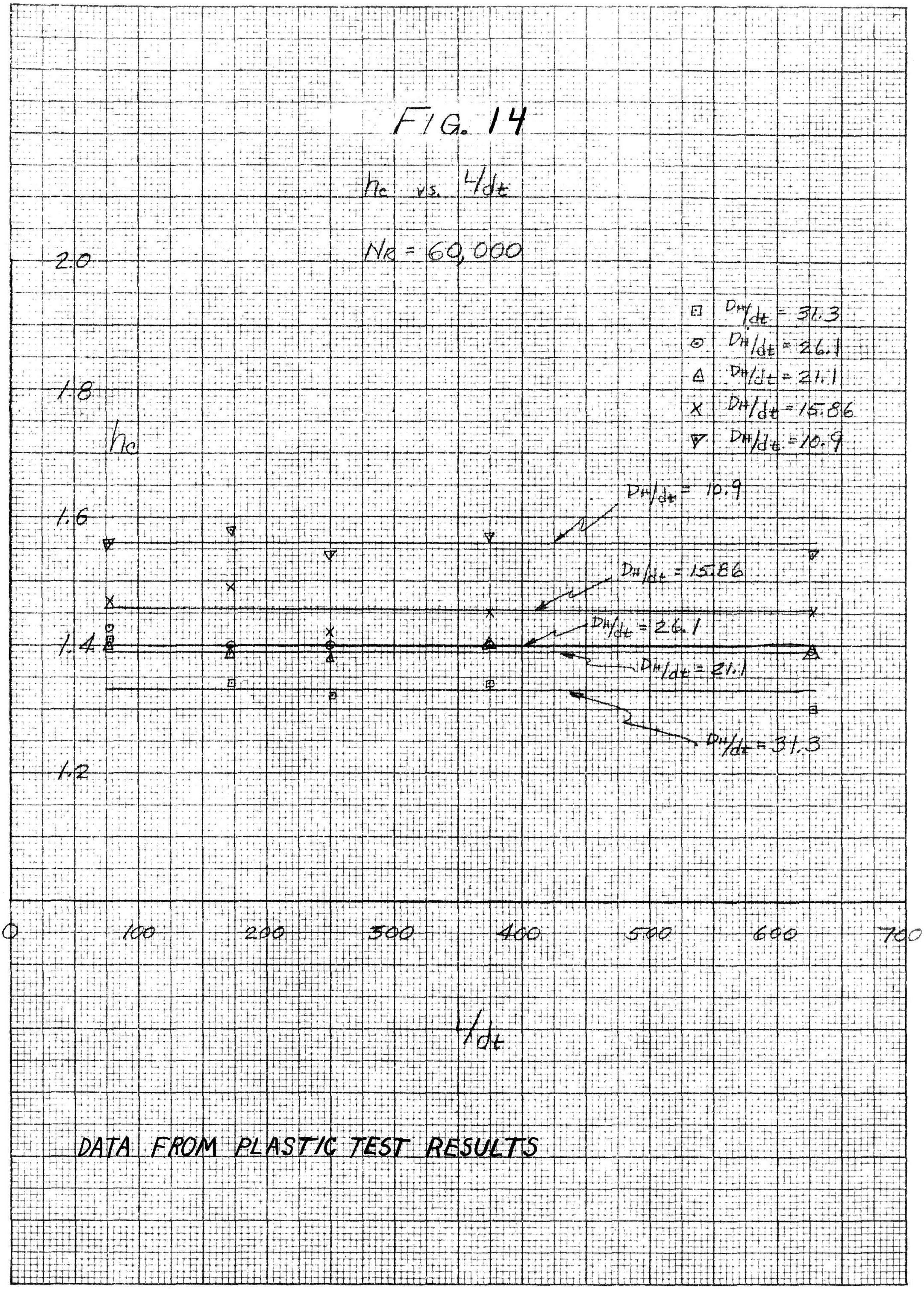
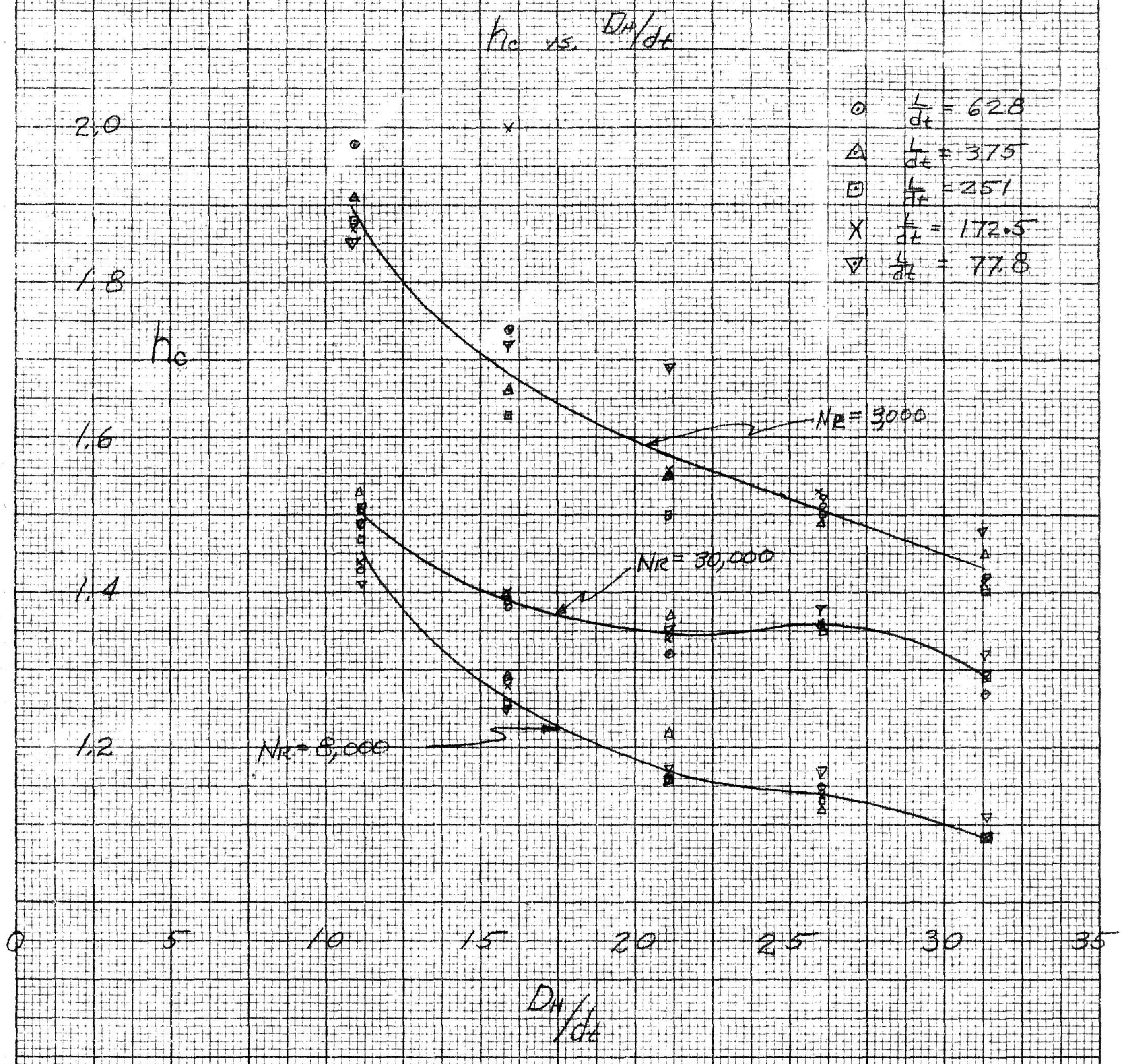


FIG. 14
hc vs. L/dt
NR = 60,000
2.0
1.8
1.6
1.4
1.2
hc
DH/dt = 31.3
DH/dt = 26.1
DH/dt = 21.1
DH/dt = 15.86
DH/dt = 10.9
DH/dt = 10.9
DH/dt = 15.86
DH/dt = 26.1
DH/dt = 21.1
DH/dt = 31.3
0
100
200
300
400
500
600
700
L/dt
DATA FROM PLASTIC TEST RESULTS

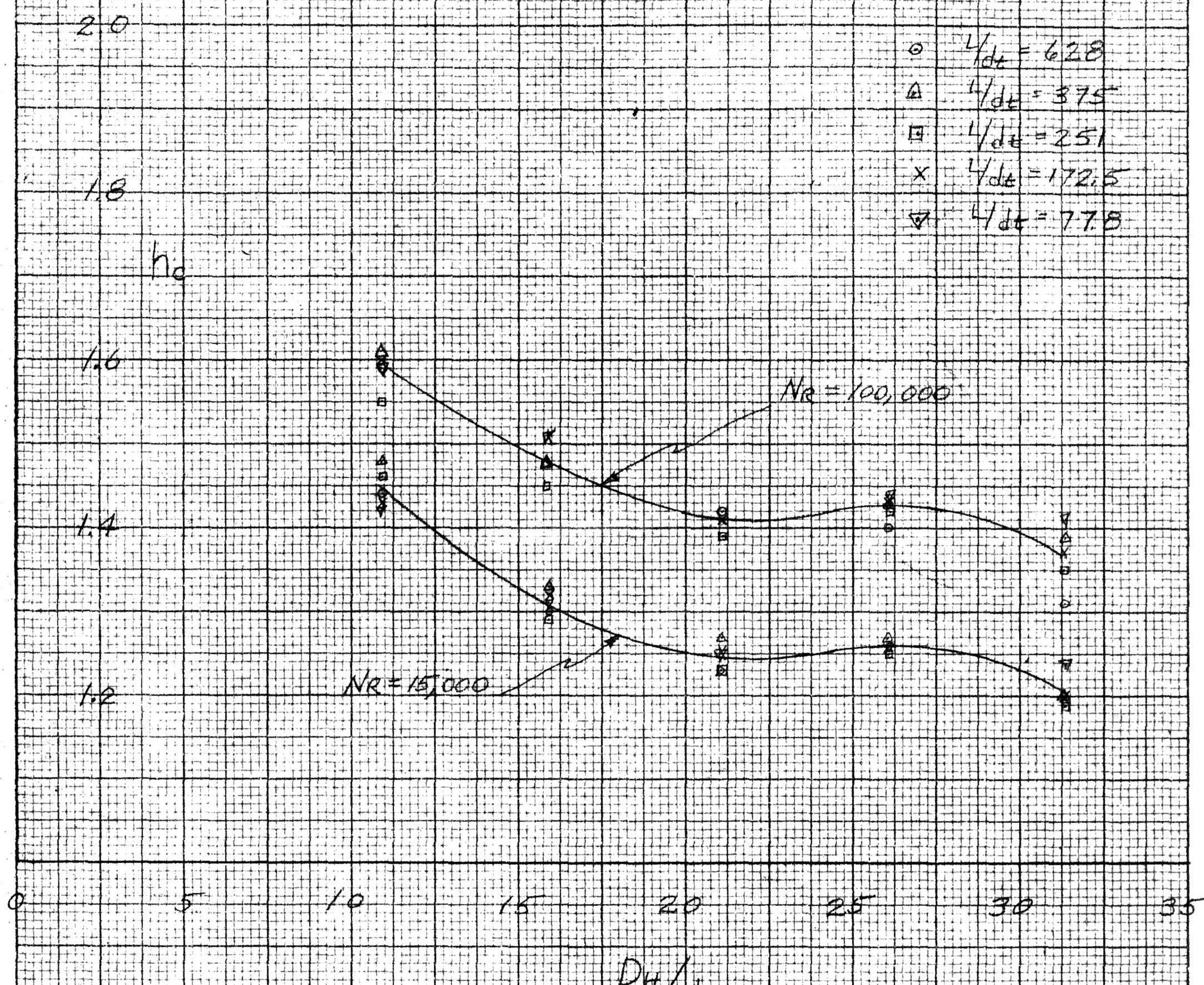
FIG. 15



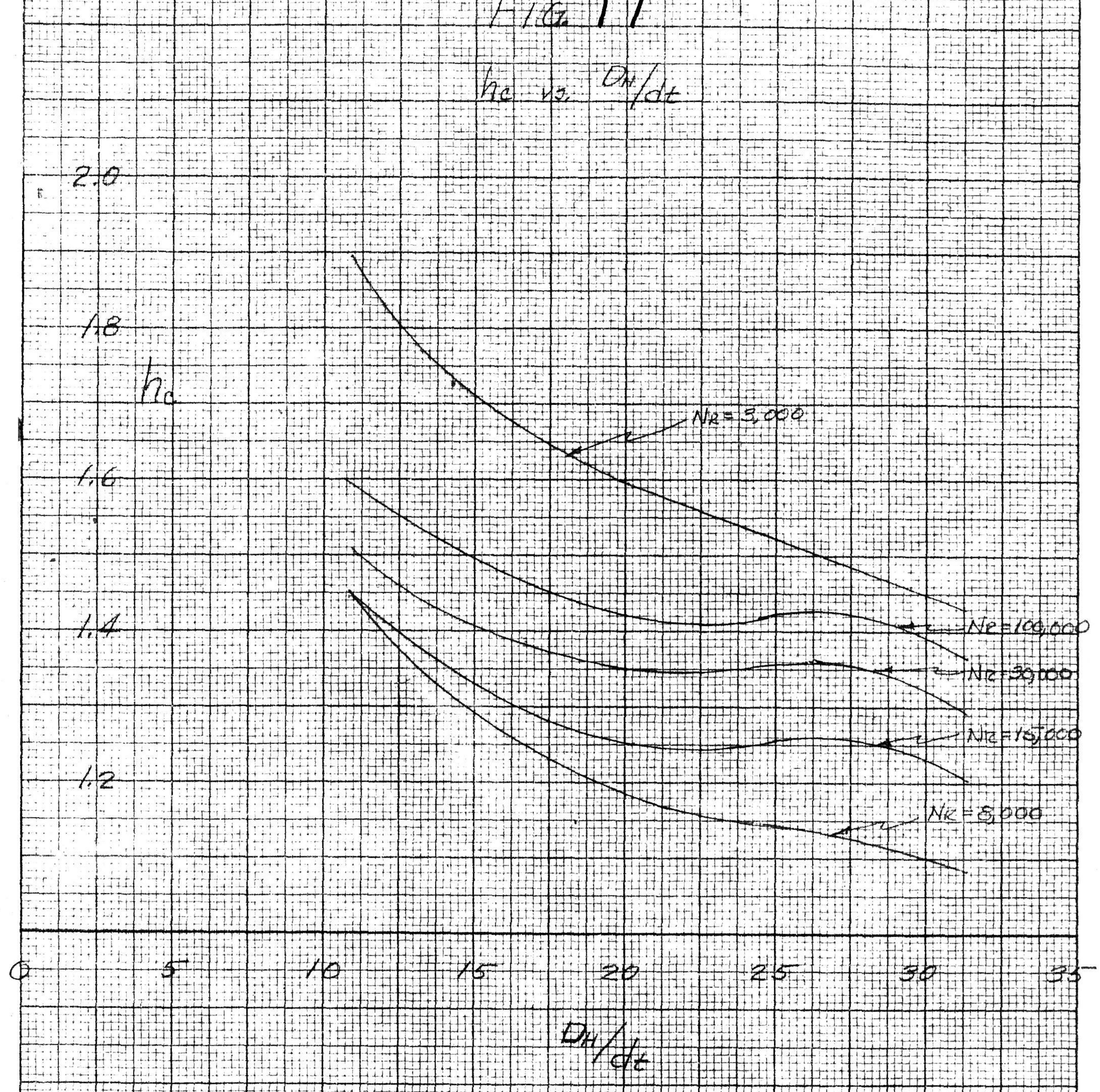
DATA FROM PLASTIC TEST RESULTS

FIG. 16

h_c vs. D_H/d_t



DATA FROM PLASTIC TEST RESULTS



DATA FROM PLASTIC TEST RESULTS

THESE CURVES ARE FROM FIGS 15 & 16

FIG. 18

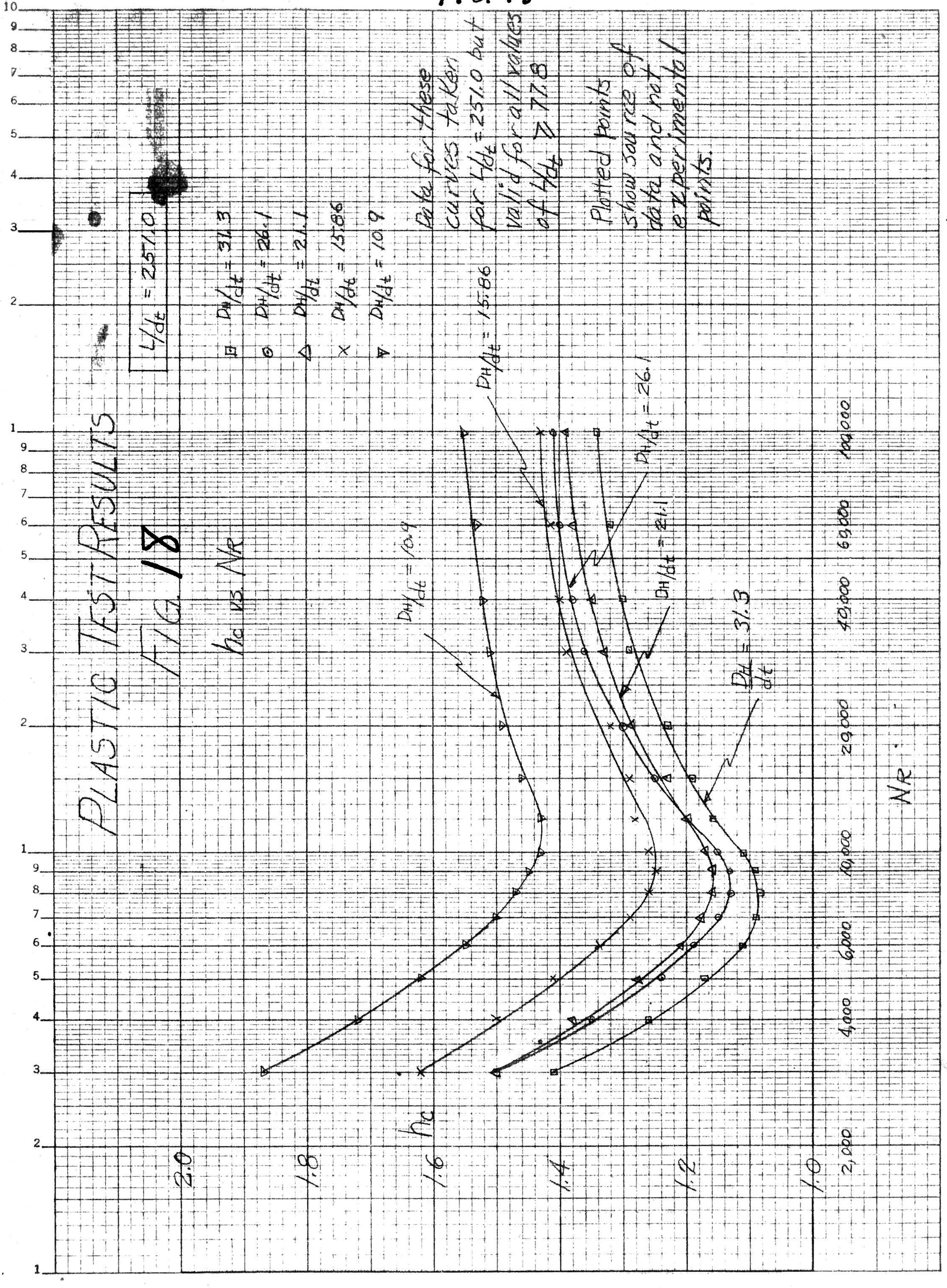

PLASTIC TEST RESULTS
FIG. 18
hc vs. NR
L/dt = 251.0
□ DH/dt = 31.3
⊙ DH/dt = 26.1
△ DH/dt = 21.1
× DH/dt = 15.86
▽ DH/dt = 10.9
Data for these curves taken for L/dt = 251.0 but valid for all values of L/dt ≥ 77.8
Plotted points show source of data and not experimental points.
DH/dt = 10.9
DH/dt = 15.86
DH/dt = 26.1
DH/dt = 21.1
DH/dt = 31.3
hc
2.0
1.8
1.6
1.4
1.2
1.0
NR
2,000
4,000
6,000
10,000
20,000
40,000
60,000
100,000

FIG. 19

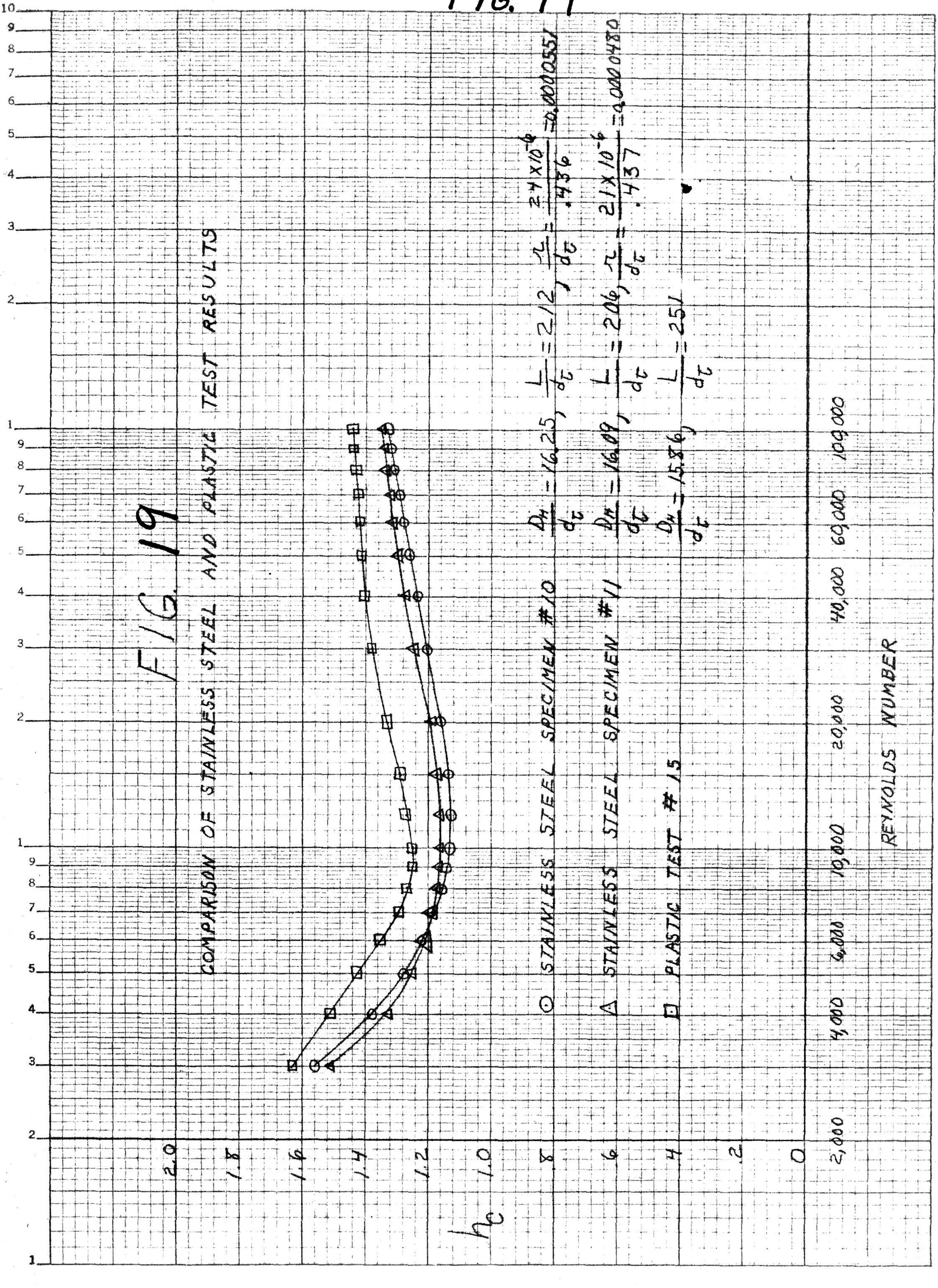


FIG. 19
COMPARISON OF STAINLESS STEEL AND PLASTIC TEST RESULTS
⊙ STAINLESS STEEL SPECIMEN #10, D_H/d_τ = 16.25, L/d_τ = 212, r/d_τ = 24 X 10^-6/.436 = 0.0000551
△ STAINLESS STEEL SPECIMEN #11, D_H/d_τ = 16.09, L/d_τ = 206, r/d_τ = 21 X 10^-6/.437 = 0.0000480
□ PLASTIC TEST #15, D_H/d_τ = 15.86, L/d_τ = 251
h_c
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
2,000
4,000
6,000
10,000
20,000
40,000
60,000
100,000
REYNOLDS NUMBER

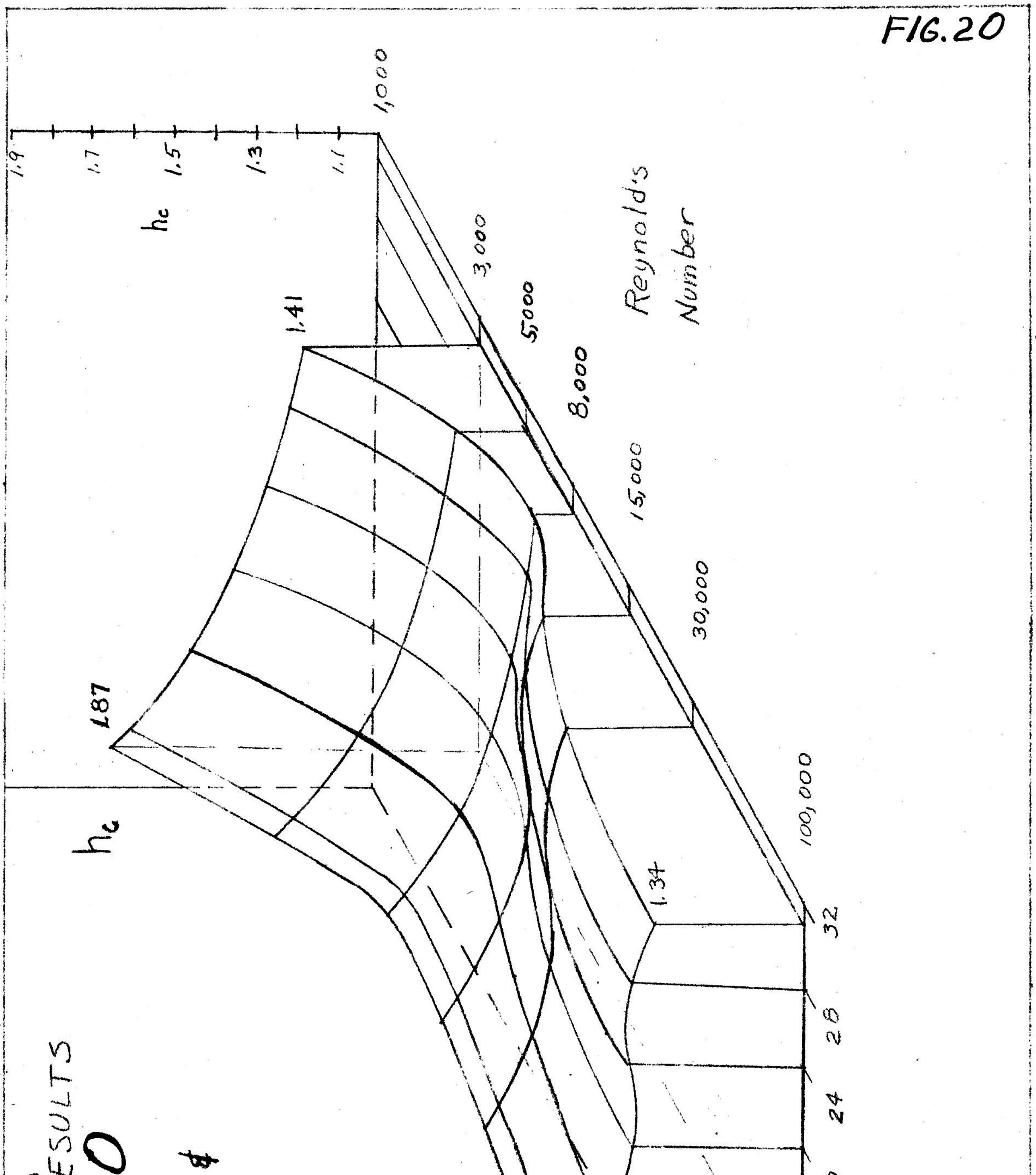


FIG. 20
PLASTIC TEST RESULTS
FIG. 20
hc vs. DH/dt ¢
hc
1.9
1.7
1.5
1.3
1.1
1.87
1.41
1.34
1.60
Reynold's Number
1,000
3,000
5,000
8,000
15,000
30,000
100,000
DH/dt
0
4
8
12
16
20
24
28
32