INVESTIGATION
OF
PRESSURE DROP THROUGH HELICAL COILS

Thesis by

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In partial Fulfillment of the Requirements
For the Degree of
Aeronautical Engineer

California Institute of Technology
Pasadena, California
September, 1948

ACKNOWLEDGEMENT

The author is indebted to Mr. R. F. Rose, Dr. H. S. Seifert, the Staff and the Personnel of the Hydraulics Laboratory, Jet Propulsion Laboratory, California Institute of Technology, for their valuable aid and guidance in the formulation of this thesis.

The author is further indebted to Lieutenant Commander O. S. Dwire. All calculations, tables and curves herein are the combined efforts of Lt. Cmdr. Dwire and the author.

ABSTRACT

This investigation was conducted to determine the character of the pressure drop through helically wound pipes by comparing the pressure drops of straight pipes and helically wound pipes of comparable relative roughness.

The scope of the study was limited to Reynolds Numbers below 10^5 and to flow through 3/8 and 1/2 inch stainless steel tubing of circular cross section. It was further limited by the use of water as the only working fluid and by the fact that no control was established over the exact character of the surface roughness.

The results show that the correction factor Hc' is rather insensitive to Reynold's number and that it has greater dependence upon roughness and less dependence upon curvature than was previously thought probable. In addition, it is shown that an empirical formula of the type $Hc = 1 + K(\epsilon/D)^a(D/D_h)^b$, where $a \gg b$, is probably more realistic than the $A_c = 1 + 3.5\ D/D_h$ expressed in current literature. It is further shown that within the scope of this study, the relative roughness, r/D, as determined by the profilometer and the relative roughness ϵ/D as used by L. F. Moody correspond, and r/D may be used to determine a friction factor from the Moody curves.

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INTRODUCTION

Only a limited amount of research has been done on the flow of a fluid through a helical coil and the literature reveals little of the actual phenomena that are involved. In the past, research has been concentrated on flow through a straight pipe using various sizes and lengths and controlling the roughness of the conduits used. L. F. Moody in Ref. 1 and H. Rouse in Ref. 4 cover this problem rather conclusively. Some work has been done by Mr. B. T. Morris of the Aerojet Engineering Corporation and by Dr. H. S. Seifert of the CIT Jet Propulsion Laboratory on the flow of coolant through the helical cooling conduits of small rocket motors. Their main contribution to this study is the use of an empirical formula for a helical pressure drop factor, $Ac = 1 + 3.5\ D/Dh$. This factor, when applied to the straight tube theory gives a helical pressure drop, $\Delta p = f(L/D)d(v^2/2g)Ac$.

Because of this use of helical cooling conduits for cooling passages in rocket motors, it is essential that a more complete knowledge of the character of this helical pressure drop be determined. This report will cover the investigation of water flow through stainless steel tubular helices of varying diameter and number of turns with emphasis on the resultant increase in pressure drop by comparing the pressure drop through straight pipe with that through a helically wound pipe. An attempt will be made to separate this helical pressure drop from the normal pressure drop and to formulate a new approach to the helical pressure drop factor.

This study is subject to certain limitations and assumptions as follows:

(1) *Limitation of the flow velocity to fifty feet per second, thus restricting the range of Reynolds Numbers to a maximum of* 10^5.

(2) *Limitation of the research to 3/8 inch and 1/2 inch stainless steel tubing of circular cross section*.

(3) *No control over the character of the roughness was attempted and a profilometer was used to determine the degree of the roughness*.

(4) *It was assumed that there was no change in the character of the roughness of a straight tube after it had been formed into a helix*.

This investigation was conducted at the California Institute of Technology Jet Propulsion Laboratory during the period April through August of 1948 by Lt. Cmdrs. R. H. McElligott and O. S. Dwire.

EXPLANATION OF SYMBOLS

f	Friction factor, dimensionless. Defined by the Darcy equation for pressure drop in a straight circular conduit: $\Delta P = f(L/D)d(v^2/2g)$
f'	Predicted friction factor for straight conduit from known relative roughness ratio and Reynolds Number (Cf. Ref. 1)
f_o	Observed friction factor
ΔP	Pressure drop, lb/ft^2
v	Mean flow velocity, ft/sec.
W	Flow rate, lb/sec.
g	Acceleration due to gravity, 32.2 ft/sec.
d	Specific weight of fluid, lb/ft^3
D	Diameter of conduit, inches
L	Length of conduit, inches
D_h	Mean diameter of helix, inches
ν	Kinematic viscosity, $ft^2/sec.$
Re	Reynolds Number, $(v/\ )(D/12)$, dimensionless
r	Roughness as measured by profilometer, micro-inches
r/D	Relative roughness ratio from profilometer value
ε/D	Relative roughness ratio from absolute roughness (Cf. Ref. 1)
Hc	Correction factor for increase of pressure drop of helical coil over that of equivalent straight pipe as may be calculated from a formula arrived at by an extension of this study.

Ac	Correction factor for helical pressure drop as used by Morris and Seifert
Hc'	Correction factor for increase of pressure drop of helical coil over that of equivalent straight pipe as determined experimentally in this study.

EQUIPMENT AND PROCEDURE

EQUIPMENT. *The equipment used consisted essentially of*:

(a) *a pump to supply a variable flow of water, the working fluid*,

(b) *two piezometer ring pressure taps*,

(c) *a water manometer, a mercury manometer, and pressure gauges for measuring pressure drop*,

(d) *a weighing tank, scale, and stop watch for determining flow rates, and*

(e) *the test sections of straight tubing and helical coils*.

A schematic sketch of the equipment is shown in Fig. 1.

The helical test sections were formed from seamless drawn stainless steel tubing of 0.375 inches outside diameter and 0.035 inches wall thickness. *The forming technique was as follows:*

1. *The inner surface was coated with light machine oil and the entire tube heated in boiling water*.

2. *The tube was filled with a molten low-boiling-point metal known as "Cerrasafe" while immersed in the heating bath.*

3. *When cool, the tube was formed by hand around a circular pipe of suitable diameter*.

4. *The helix was then boiled in water to remove the metal filler and washed out with a steam jet for the final cleaning*.

The maximum distortion of cross-section created by this technique was a 1.3 per cent decrease in diameter in the direction of the helical radius. The conduit was therefore considered circular in cross-section throughout the investigation. The helices are described in detail in Table I.

The straight test sections were of standard commercial seamless drawn stainless steel tubing of 0.50 inches outside diameter and 0.035 inches wall thickness They were four feet in length and of various values of roughness. In order to vary the roughness, the interior surface of these sections was treated by two different processes: sand blasting and electrolytic polishing. It was because these two processes could not be applied to the 0.375 inch tubing that the 0.50 inch tubing was chosen for the straight test sections. The 0.375 inch tubing had previously been chosen for the helices due to its ease of fabrication. The details of the straight test sections are listed in Table II.

PROCEDURE. The following is a step-by-step description of the procedure employed:

(1) Install test section in apparatus and wash out for fifteen minutes at a flow rate well above the maximum test value.

(2) Reduce flow rate to produce about four inches of water pressure drop, allow flow to stabilize and read pressure drop.

(3) Simultaneously with (2) collect the full water flow in the weighing tank for a timed period. Record the weight of water and time of flow.

(4) Increase flow rate to reach maximum in 20 to 30 steps; record readings at each step.

(5) Correct observed pressure drops for effect of pressure pick-ups, straight leads and gauge calibration (if necessary).

(6) Measure water temperature and determine density and viscosity (Cf. Ref. 2 and 3). No change in water temperature occurred during the test of any one section in this study due to the large size of the sump used.

(7) Compute Reynolds Number for each step.

(8) Compute friction factor, f_o, for each step.

(9) Plot f_o against Re for the section.

(10) Cut up test section and measure roughness.

In order to eliminate the effects of the pressure pick-ups (step 5 above), the following procedure was used. The two pick-ups employed in the test were connected to each end of a one-foot straight length of the test section tubing. A complete test of this short section was made and a curve of pressure drop versus flow rate was constructed This curve was used to correct the observed pressure drop of the parent straight test section at each flow rate. In calculating f_o, the effective length of the parent section was consequently reduced one foot from the measured value.

The helical test sections, because the straight leads varied in length from coil to coil, required a small additional correction. The effect of the pressure taps plus six inches of straight lead was corrected for in the same manner as that described above for the taps plus one foot on the straight sections. The pressure drop through the length of straight leads in excess of six inches was corrected for by a curve of pressure drop per unit length versus flow rate. The data for this curve were obtained as follows:

(a) three representative 0.375 inch straight tubing samples, eight feet in length, were tested over the range of flow rates of the parent tests,

(b) the tests of these three samples were corrected for the effects of the pressure pick-ups plus one foot of length as outlined above,

(c) for each flow rate the average pressure drop of the three tubes was divided by the length less one foot (seven feet),

(d) this value of pressure drop per unit length was plotted against flow rate to yield the desired curve.

The two corrections to the observed pressure drop of the helices can be summarized as follows: a deduction, taken from the first curve, for the effect of the pressure pick-ups plus six inches of straight lead, and a deduction for the remaining straight leads obtained by multiplying the total length of leads less six inches by the figure obtained from the second curve.

Steps 7 and 8 entail the following calculations:

(a) Conversion of flow rate to mean flow velocity:

$v = W/dA$ where

v = velocity in feet per second

W = flow rate in pounds per second

d = specific weight of water at working temperature in pounds per cubic foot (Cf. Ref. 3)

A = cross sectional area of conduit in square feet

(b) Calculation of Reynolds Number:

$Re = (v/\nu)(D/12)$ where

v = velocity, ft/sec.

ν = kinematic viscosity, ft^2/sec.

D = inside diameter of conduit, inches.

(c) Calculation of friction factor:

$f_o = (\Delta P/d)(D/L)(2g/v^2)$ where

ΔP = observed pressure drop, lb/ft^2

d = specific weight, lb/ft^3

D = inside diameter of conduit, inches

L = length of conduit, inches

g = acceleration due to gravity, 32.2 ft/sec^2

v = velocity, ft/sec.

LIMITATIONS AND ASSUMPTIONS

In arriving at the conclusions presented by this report and in carrying out the basic research, certain assumptions and limitations were made. These are listed below with the reasons that made their inclusion and acceptance necessary.

ASSUMPTIONS

(1) That there was no change in the character of the roughness of a straight tube after it had been formed into a helix. This was roughly substantiated by comparing visually the inside of a helix and of a straight tube. A negligible difference in character was noted.

(2) That the electrolytic polishing and sand blasting of tubes to obtain varying degrees of roughness did not materially affect the character of the surface roughness.

(3) That the pressure drop across the pressure taps and a short straight section would be the same as that across the pressure taps and equivalent straight lengths on the roughened samples and on the helices.

(4) That the average roughness determined by taking samples at one foot intervals along the specimen would be representative of the effective overall relative roughness. This procedure was necessary because it was impracticable to obtain profilometer readings over more than a two inch sample of either straight or curved tubing.

(5) It was originally expected that by sand blasting and electrolytic polishing a range of profilometer readings from 10 to 100 could be obtained which would give relative roughness values comparable to those obtained from the helices. As it turned out, only 1/2 inch tubes could be treated and only 3/8 inch tubing could be easily formed into helices. The range of profilometer readings actually obtained was from 20 to 45. This gave r/D ratios for the straight tubes much smaller than the r/D ratios obtained from the 3/8 inch helices.

<u>In assuming that the nature of the roughness did not change when the tubing was formed into helices, the meaning is that the type of variation in the surface of the tubing as originally drawn did not noticeably change</u>. The degree of roughness, that is, the actual variation in the surface normal to the axis of the tube as read in micro inches by the profilometer, might change. Actually, the degree of roughness of the tubes did change slightly after being formed into helices. The surface along the inner curvature of the helix became slightly rougher and the surface along the outer curvature of the helix became slightly smoother.

<u>The only basis of comparison then between the straight tubes and the helices was predicted friction factor versus observed friction factor</u>. Since the theory had already been established as shown in Ref. 1, it was only necessary

to check thoroughly the experimental results against the straight pipe theory, i.e., compare f' and f_o for the straight test sections. Consequently, r/D was substituted for ϵ/D and an f taken from the curves in Ref. 1. This value was compared with the experimental friction factor for the straight sections. *The maximum error was only 4%.*

It was therefore assumed that the r/D values for the helices could be used as ϵ/D and obtain friction factors for the helices based on straight pipe theory. This was done and the difference between this friction factor and the observed friction factor for the helices $\frac{(f_o - f')}{f'}$ was used in the analysis of the helices as Hc' - 1. This difference was considered attributable to the effect of the helical shape of the conduit.

The above assumptions are perhaps of questionable validity; however, checking the character and degree of the surface roughness by profilometer and by magnified inspection showed little difference in the character of the surface roughness from straight to helical or from treated to untreated pipe. The profilometer did record a slight difference in the degree of roughness between the inner and outer curvature of the helices. Average profilomet readings for the helices appear in Table I, Col. 7, and those for the straight sections appear in Table II, Col. 2.

LIMITATIONS

(1) The maximum water velocity was arbitrarily limited to 50 feet per second thus setting the upper limit of Reynolds Numbers at about 10^5.

(2) The scope of the experiment was restricted to a series of 3/8 inch tubular helices, one 1/2 inch helix of about 5.69 inch Dh, and one 3/8 inch tubular helix of thirty-six inch Dh. All were of circular cross section. This limitation was necessary because of the relatively short time allowed for completion of this report.

(3) There was no control established over the character of the surface roughness of the test sections as explained in the assumptions above, nor were any absolute roughness measurements made. Profilometer readings of the degree of roughness in root mean square micro inches were the only mechanical description of surface roughness available.

(4) The investigation covered only water as the working fluid because of the limited time for completion of the work.

(5) No attempt was made to differentiate between the nature of the flow in a straight section and in a helical section.

RESULTS AND DISCUSSION

The increase in friction factor from a straight tube to a helically wound tube as indicated in Figures 2 through 11 can be accounted for by one or all of the following variables:

(a) Re - Reynolds Number.
(b) N - Number of coils in the helix.
(c) Dh - Helix diameter.
(d) r - Roughness of the helix.
(e) D - Inside diameter of the tubing.

Friction factor for a straight conduit of circular cross section is defined as follows by Moody in Ref. 1, and by Rouse in Ref. 4:

(1) $\Delta p = f\ (L/D)\ d\ (v^2/2g)$

where Δp is the pressure drop across the section under test. Now since the pressure drop is greater for a helical conduit that for a straight conduit, and if the conventional straight pipe friction factor is to be used, some other factor, say Hc, depending upon the helical shape only, must be present to account for the increased pressure drop. Thus, (1) becomes,

(2) $\Delta p = f\ (L/D)\ d\ (v^2/2g)\ Hc$

This Hc corresponds to the Ac used by both Seifert and Morris in the expressions

$\Delta p = f(L/D)\ d\ (v^2/2g)\ Ac$ and $Ac = 1 + 3.5\ D/Dh$.

This Hc, therefore, if it relates to the increase in p and, consequently, in the increase in f_o for the helix, is directly caused by the helical shape and is a function of (a), (b), (c), (d), and (e) above. That is,

(3) $\underline{Hc = \phi (Re, N, r, D, Dh)}$

Further, if it is to be used as shown in (2), then when the helix is of infinite diameter and approaches a straight tube, Hc must be equal to unity and the factor Hc must take the following form,

(4) $\underline{Hc = 1 + \phi (Re, N, r, D, Dh)}$

For purposes of this report, including Reynolds Number in Hc cannot be justified because while some change in Hc' - 1 is shown in Col. 6 of Tables III and IV as Re changes from 2×10^4 to 10^5, the range of Reynolds Numbers covered is too limited to be conclusive. Furthermore, the accuracy of observations at the higher Reynolds Numbers is poorer than that at the lower Reynolds Numbers. This was caused by small timing errors at high flow rates and by the larger instrument errors at high pressures. These errors could be eliminated by more careful and judicious use of equipment. Figures 2 and 12 are marked examples of the variations of f_o with Re at high Reynolds Numbers, caused possibly by changing gages at Re = 6×10^4 and Re = 12×10^4. Column 6 of Tables III and IV indicates the relative insensitivity of Hc' to a change of Reynolds Number from 2×10^4 to 10^5. A plot of Hc' - 1 vs Reynolds

Number for several specimens appears in Figure 15, substantiating Tables III and IV and the belief that Hc' is relatively insensitive to changes in Reynolds Number. It is evident that for helices number 3, 5, and 6 as plotted, there is no appreciable or functional change in Re from 10^4 to 10^5.

Likewise, N can be eliminated as a variable since the results show no definite trend in Hc' - 1 for a uniform change in N. Helices 7 and 8, at Re = 2×10^4, of 3 and 6 turns respectively, with the same r/D and D/Dh ratios, show a slight decrease in Hc' - 1. On the other hand, helices 5 and 6, with 6 and 9 turns respectively, and comparable r/D and D/Dh ratios, show a slight increase in Hc' - 1. This same contradiction is apparent throughout Table IV and in the plot of Hc' vs N appearing in Figure 14. No regular or functional relationship between Hc' - 1 and N can be deduced from this plot. The data in this report are not adequate to permit a complete evaluation of this apparently minor variable, but there appears to be no regular dependence of Hc' upon N.

This elimination leaves,

(5) $\underline{Hc = 1 + \phi\ (r, D, Dh)}$.

In order to make Hc dimensionless and to cause the function ϕ (r, D, Dh) to go to zero at Dh = ∞, the following is proposed,

(6) $Hc = 1 + \phi\,(r/D, D/Dh)$.

<u>Tabulations of the variables r/D and D/Dh are shown in Tables III and IV</u>. Examination of these variables shows that a marked decrease from the average in D/Dh, as in helix 9, does not indicate a substantial change in Hc' - 1, while a small decrease in $r/D \times 10^4$, as in helix 10, does show a marked change in Hc' - 1. This would seem to indicate that $r/D \times 10^4$ should be a more heavily weighted factor than D/Dh. Further investigation by plotting $r/D \times 10^4$ versus Hc' - 1 and a similar plot using Hc' - 1 versus D/Dh appear in Figures 16 and 17. Figure 16, a plot of Hc' - 1 versus D/Dh for both $Re = 2 \times 10^4$ and 10^5 for all accurate helices, shows an irregular scatter of points. Figure 16 also shows, if a slope line through the points is used, that the slope would be much less than that shown for $Ac = 1 + 3.5(D/Dh)$. Conversely, Figure 17, a plot of Hc' - 1 versus $(r/D) \times 10^4$, shows a distinct grouping of points along a steep slope line. This again lends belief to the fact that r/D is the more heavily weighted factor. Thus, (6) could conceivably become,

(7) $Hc = 1 + K(r/D)^a\,(D/Dh)^b$, where $a \gg b$.

Using (7) and values of Hc' - 1 as indicated in Tables III and IV, an emperical formula for Hc could be deduced, if sufficient data were obtained, that would be more accurate than the present one, $Ac = 1 + 3.5\ D/Dh$.

It is felt that such a formula derived from (7) would show that the correction factor Hc depends jointly upon r/D and D/Dh. This would be an entirely different relation from that proposed by present literature in that the ratio D/Dh is believed to be practically a constant, if raised by a small coeffecient, somewhere in the vicinity of .9 for most values of D or Dh. As has previously been pointed out though, the ratio D/Dh must be zero for a Dh equalling infinity. Thus, a constant cannot be used and some small coeffecient must be used. It is also contrary to the present trend of thought that the factor Hc should be markedly dependent upon the r/D ratio. The data presented by this study shows this ratio to be the most heavily weighted variable although the data have a great deal of scatter and are far from adequate to allow much faith being placed in the apparent results. A tentative evaluation of the proposed formula and the meager data indicates that the pressure drop through a helix varies almost directly with about the third power of the value $(r/D) \times 10^4$, and that the actual helical diameter has a negligible effect. The increase in pressure drop does exist, though, and it may well be that while the actual degree of curvature is of small consequence, the fact that it <u>is bent</u> may change the character of the flow pattern in the helix to such an extent that the effect of roughness is greatly magnified. Such a study of the changes in the flow or velocity pattern was not undertaken.

It should be noted that this is an approximation and that no claim is made that this is a stable solution in any way, shape or manner. Other variables or a different approach to the problem could give other values to K, a, and b. Further, helices 1 and 2 were not used in the estimation because of their excessively high $Hc' - 1$. Inspection after cutting revealed that particles of CERRASAFE still remained on the surface of these helices.

Table V is a comparison of $Hc' - 1$ and $Ac - 1$. Except for helices 1 and 2, which gave erratic values and should not be used, the $Hc' - 1$ shows the trend of the necessary correction even for the 36 inch helix diameter (helix 9) and for the 1/2 inch tubular helix (helix 10) as greatly at variance with the Ac as used by Seifert and Morris, which appears uniformly low.

Another apparent result of this study is the close agreement between f' and f_o using ϵ/D from Ref. 1 equal to r/D as computed from experimental observations.

Since it was necessary to use this in the analysis of the helices, it was established by computation for all the straight sections that the maximum error in friction factor was four per cent. Figure 12 is a typical comparison of f' and f_o for a straight section and shows f' versus Re for tube C using r/D as ϵ/D. Plotted with it are the computed values of f_o from experimental observations. Thus it would seem that for stainless steel or other smooth tubing, the profilometer readings can be used as the absolute roughness to compute relative roughness, ε/D, for use with the Moody data of Ref. 1 in obtaining a friction factor.

It should be especially noted, however, that this study was conducted at ε/D and Re values very near the smooth tube portion of Moody's curves as shown in Figure 13. It is entirely possible that with increased Reynolds Numbers and relative roughness, the correspondence between r/D and ε/D may cease to exist, since it is apparent from Figure 13 that as ε/D and Re increase, the greater is the distance between lines of constant ε/D.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

(1) The factor that should be included in the expression for the pressure drop in a helically wound pipe as a result of the helical shape is of the general form $Hc = 1 + K\,(r/D)^a(D/Dh)^b$, where $a \gg b$.

(2) The profilometer reading r can be used in place of the absolute roughness, and the resulting ratio r/D may be used to predict a friction factor from Moody's curves in Ref. 1 as long as nearly smooth conduits are being considered.

(3) Although the data are far from adequate, it appears from this study that Hc does exist and is more dependent upon the relative roughness than upon the ratio of D/Dh, as formerly thought. In any case, the experimental values do not agree with the formula $Ac = 1 + 3.5\ D/Dh$.

(4) The data collected in this study are neither of sufficient quantity nor scope to make a definite statement as to the dependence of Hc' upon Re; however, the data presented do show that Hc' is relatively insensitive to Re between $Re = 2 \times 10^4$ and $Re = 10^5$. For a 500% increase in Reynolds Number, there was only a 21% decrease in Hc' - 1, taking a numerical average of all data at each of the two Reynolds Number.

RECOMMENDATIONS

(1) Extend the scope of this study to include greater variations in r/D, D/Dh and Re to obtain more families of points at constant values of the same variables, in order that the exponents in the formula for Hc may be obtained accurately. It is possible that Re may have a functional relationship to Hc'.

(2) Extend the scope of this study to include different conduit cross sectional shapes.

(3) Do not cut up coils or straight sections until it has been determined that the data are consistent.

(4) Various techniques of roughening and smoothing tubes should be investigated in order to produce specimens of known and uniform character and degree of roughness.

(5) Since commercial tubing varies greatly in roughness, not only from sample to sample, but also along the length of any given sample, all specimens should probably be treated before forming into helices.

(6) If it is possible, the straight sections and the helices should be of a machined type so that uniformity of the character and degree of roughness could be obtained.

(7) Great care should be exercised in selecting adequate instruments for determining pressure drops and flow rates.

(8) Investigate the indicated correspondence between r/D and ϵ/D in obtaining friction factors at higher values of roughness and Reynolds Numbers.

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TABLE I

DETAILS OF HELICAL TEST SECTIONS

(1) HELIX NO.	(2) Dh INCHES	(3) D INCHES	(4) STR.LEADS INCHES	(5) L INCHES	(6) NO. OF TURNS	(7) r MICRO-IN	(8) r/D $x10^4$
1	3.41	0.305	9.63	32.15	3	37.5	1.23
2	3.46	0.305	9.75	54.60	6	43.5	1.43
3	3.46	0.305	8.88	131.00	12	48.0	1.57
4	5.09	0.305	12.62	48.25	3	46.0	1.51
5	5.08	0.305	11.63	95.70	6	43.3	1.42
6	5.15	0.305	11.75	145.60	9	42.0	1.38
7	7.51	0.305	13.13	70.90	3	43.0	1.41
8	7.59	0.305	13.50	143.00	6	43.0	1.41
9	36.00	0.305	12.00	113.20	1	36.0	1.18
10	5.69	0.430	12.00	107.20	6	42.0	0.98

NOTE. All helices were tightly wound, i.e., pitch equal to outside diameter of tubing.

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TABLE II

DETAILS OF STRAIGHT TUBE TEST SECTIONS

(1) IDENTIFYING NUMBER	(2) r MICRO-IN	(3) r/D $x10^4$	(4) PROCESS
1	37	0.861	SANDBLAST
2	37	0.861	"
3	34	0.792	"
B	42	0.978	"
C	45	1.050	"
X	25	0.582	ELECTROPOLISH
XI	26	0.605	"

NOTE: All straight test sections were prepared as five foot lengths of one-half inch stainless steel tubing of wall thickness 0.035 inches. Prior to testing, a one-foot length was cut from one end of each section to determine the pressure tap corrections as described under PROCEDURE.

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TABLE III

ANALYSIS AT Re = 2×10^4 SHOWING APPARENT INCREASE OF FRICTION FACTOR (OBSERVED) OF HELIX OVER STRAIGHT PIPE

(1) HELIX NO.	(2) r/D $\times 10^4$	(3) D/D_h	(4) f'	(5) f_o	(6) OBSERVED INCREASE (Ho'-1)
*1	1.23	.089	.0262	.0370	.412
*2	1.43	.088	.0263	.0440	.674
3	1.57	.088	.0263	.0350	.331
4	1.51	.060	.0263	.0330	.255
5	1.42	.060	.0263	.0324	.232
6	1.38	.059	.0263	.0345	.312
7	1.41	.041	.0263	.0340	.293
8	1.41	.040	.0263	.0330	.255
9	1.18	.0085	.0262	.0324	.237
# 10	0.98	.076	.0258	.0277	.74

*Erratic results caused by local fouling in conduit. Not considered in analysis.

Helix No. 10 was formed from 1/2" tubing with a helical diameter of 5.69 inches and should not be included for comparitive purposes.

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TABLE IV

ANALYSIS AT Re = 10^5 SHOWING APPARENT INCREASE OF FRICTION FACTOR (OBSERVED) OF HELIX OVER STRAIGHT PIPE

(1) HELIX NO.	(2) r/D $\times 10^4$	(3) D/D_h	(4) f'	(5) f_o	(6) OBSERVED INCREASE (Hc'-1)
*1	1.23	.089	.0186	.0272	.505
*2	1.43	.088	.0187	.0321	.717
3	1.57	.088	.0188	.0257	.367
4	1.51	.060	.0188	.0269	.431
5	1.42	.060	.0187	.0247	.321
6	1.38	.059	.0186	.0258	.386
7	1.41	.041	.0187	.0258	.379
8	1.41	.040	.0187	.0240	.289
9	1.18	.0085	.0186	.0228	.226
#10	0.98	.076	.0184	.0197	.707

* Erratic results caused by local fouling on conduit. Not considered in analysis.

\# Helix No. 10 was formed from 1/2" tubing with a helical diameter of 5.69 inches and should not be included for comparative purposes.

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TABLE V

COMPARISON of A_c-1 and H_c-1 FOR ALL HELICES TESTED

(1) HELIX NO.	(2) H_c-1 at Re2x10^4	(3) H_c-1 at Re 10^5	(4) A_c-1	(5) (2)minus(4)	(6) (3)minus(4)
* 1	.412	.505	.311	.101 LOW	.194 LOW
* 2	.674	.717	.308	.366 "	.409 "
3	.331	.367	.308	.023 "	.059 "
4	.255	.431	.210	.045 "	.221 "
5	.232	.321	.210	.022 "	.111 "
6	.312	.386	.206	.106 "	.180 "
7	.293	.379	.143	.150 "	.236 "
8	.255	.289	.140	.115 "	.149 "
9	.237	.226	.0298	.0272 "	.197 "
#10	.740	.707	.266	.474 "	.441 "

* Erratic results caused by local fouling in conduit. Not considered in analysis.

\# Helix No. 10 was formed from 1/2" tubing with a helical diameter of 5.69" and should not be included for comparative purposes.

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2. ROUSE, H., "Fluid Mechanics for Hydraulic Engineers", Engineering Societies Monographs, McGraw Hill Book Company, New York, N. Y., 1938.
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FIGURE 1

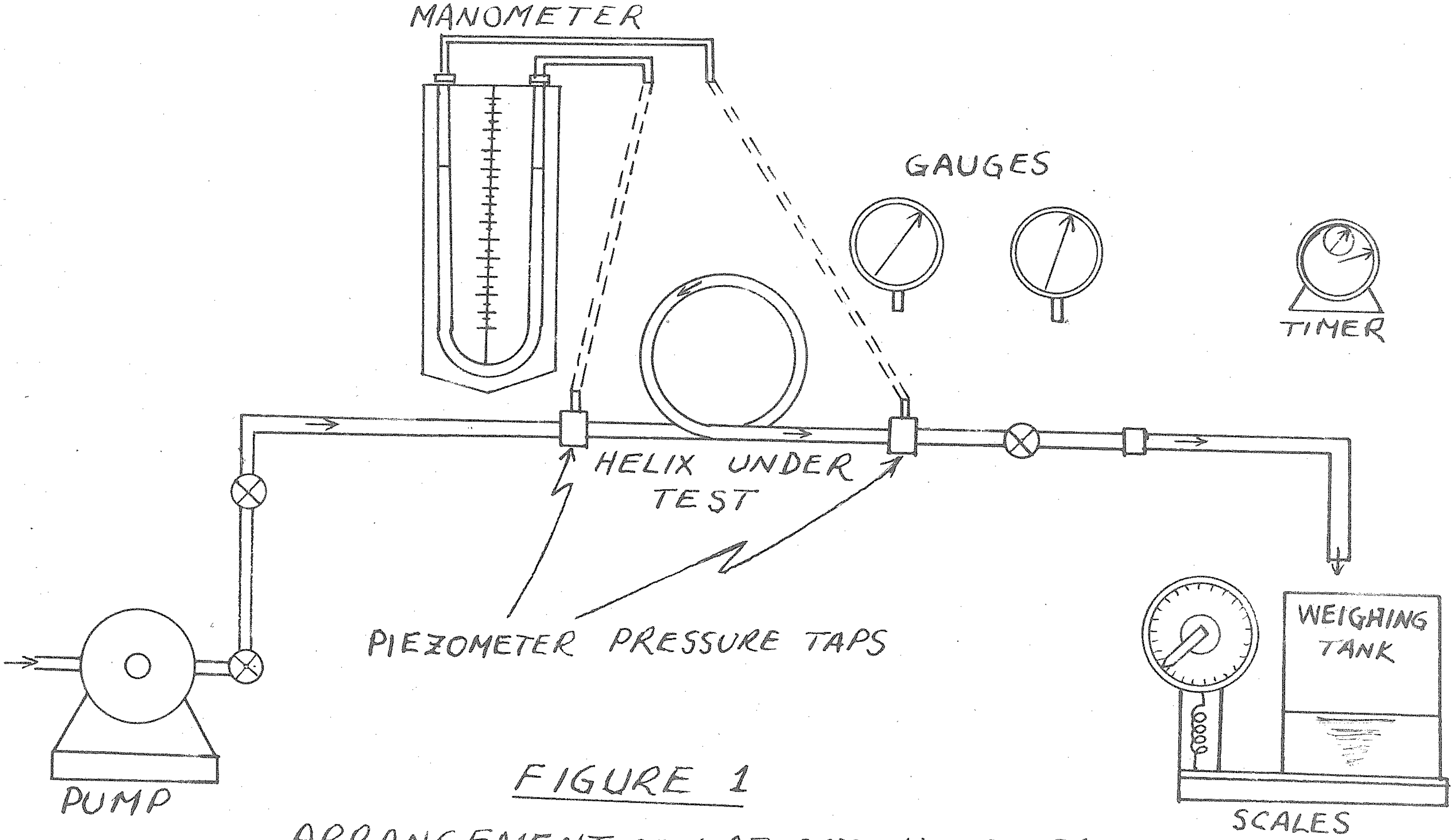


FIGURE 1

ARRANGEMENT OF LABORATORY EQUIPMENT

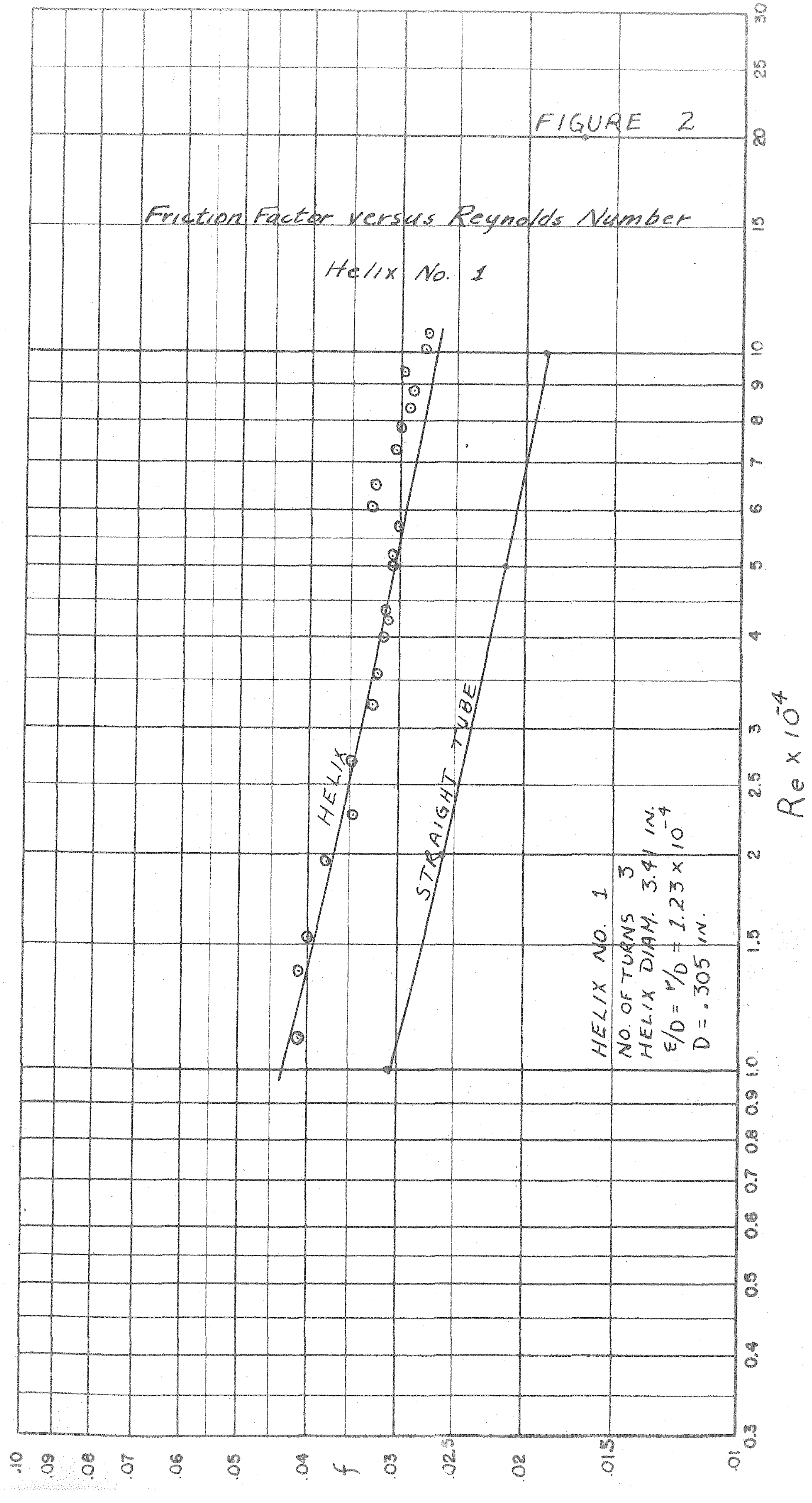


FIGURE 2

Friction Factor versus Reynolds Number

Helix No. 1

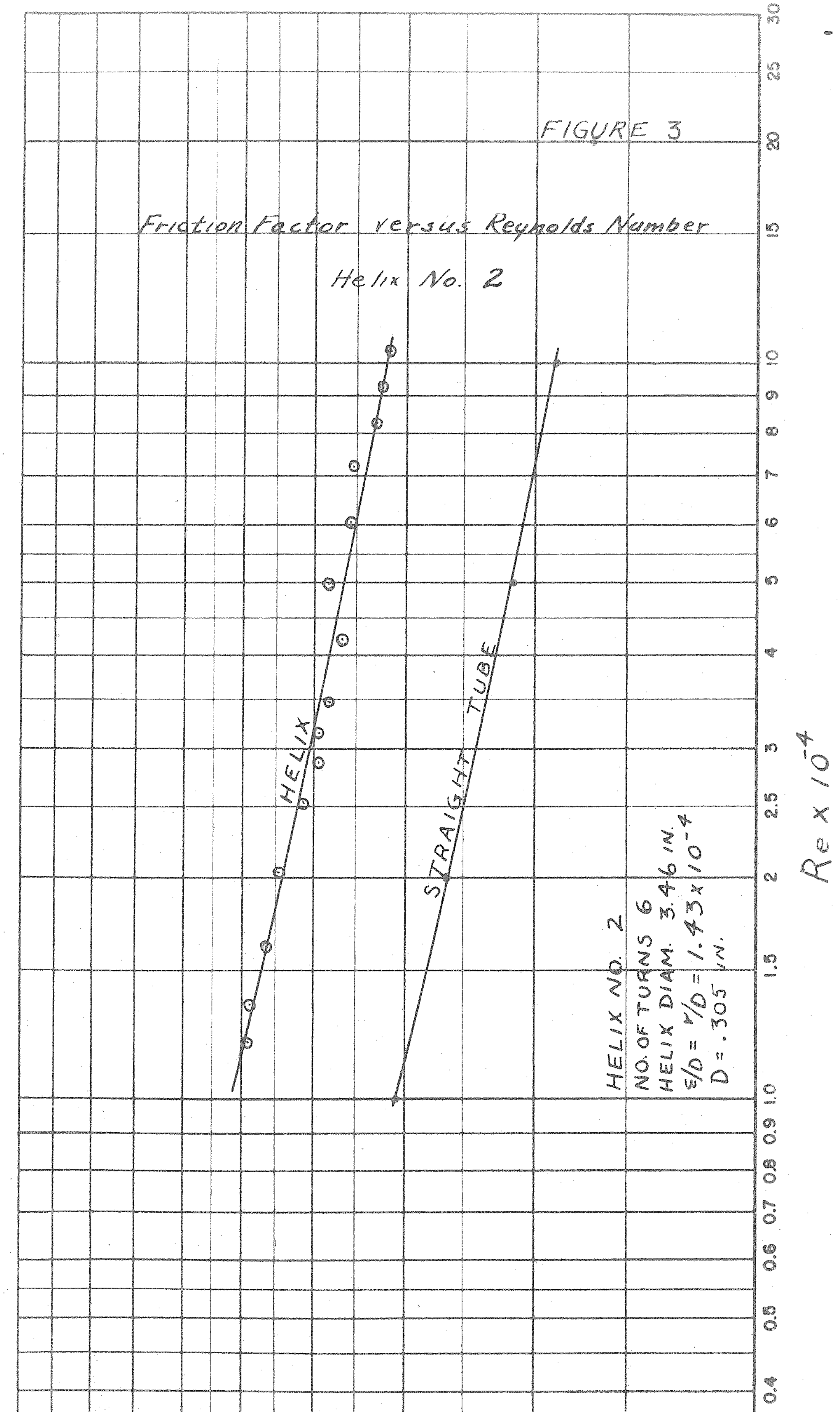


FIGURE 3

Friction Factor versus Reynolds Number

Helix No. 2

HELIX NO. 2
NO. OF TURNS 6
HELIX DIAM. 3.46 IN.
$\varepsilon/D = r/D = 1.43 \times 10^{-4}$
D = .305 IN.

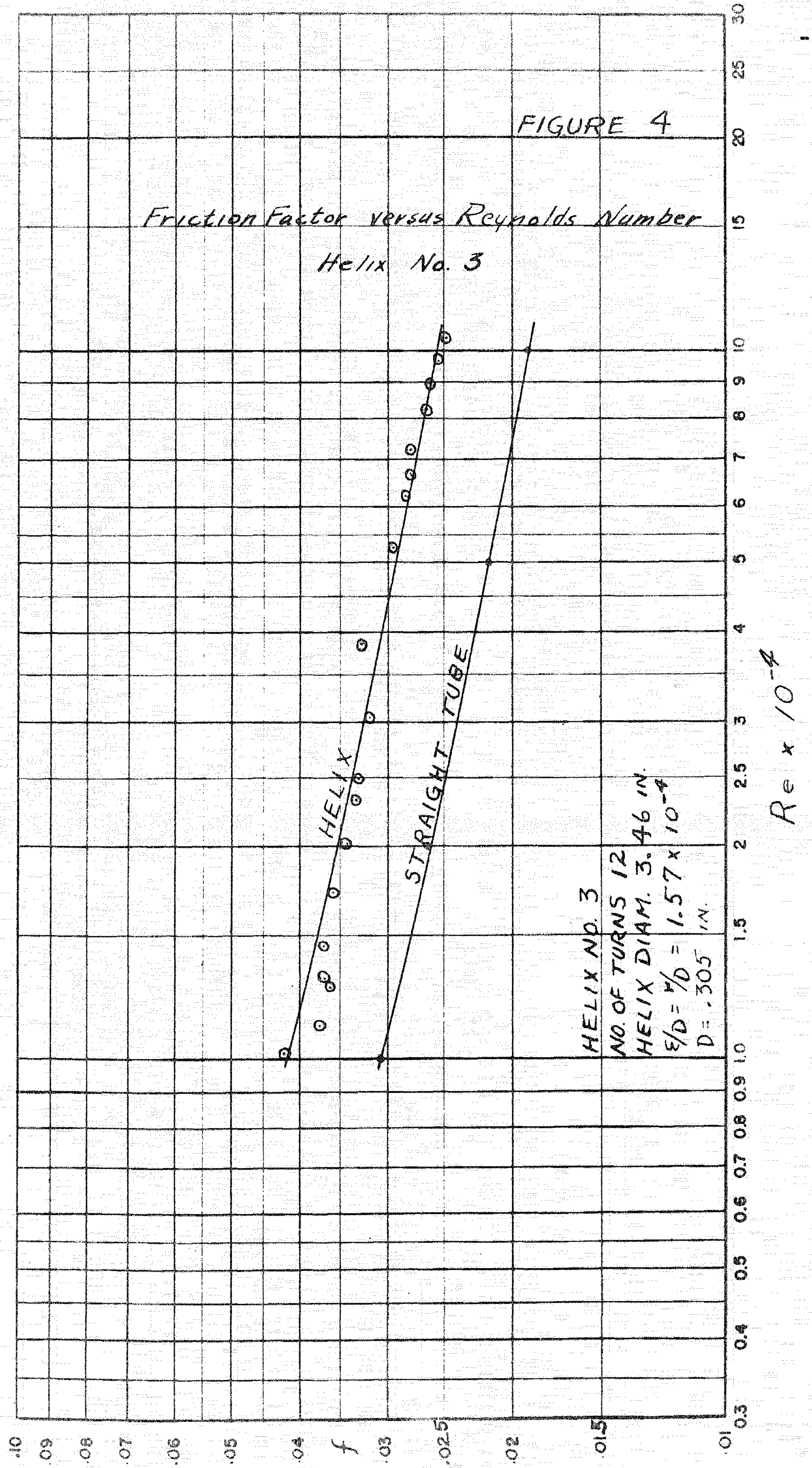


FIGURE 4

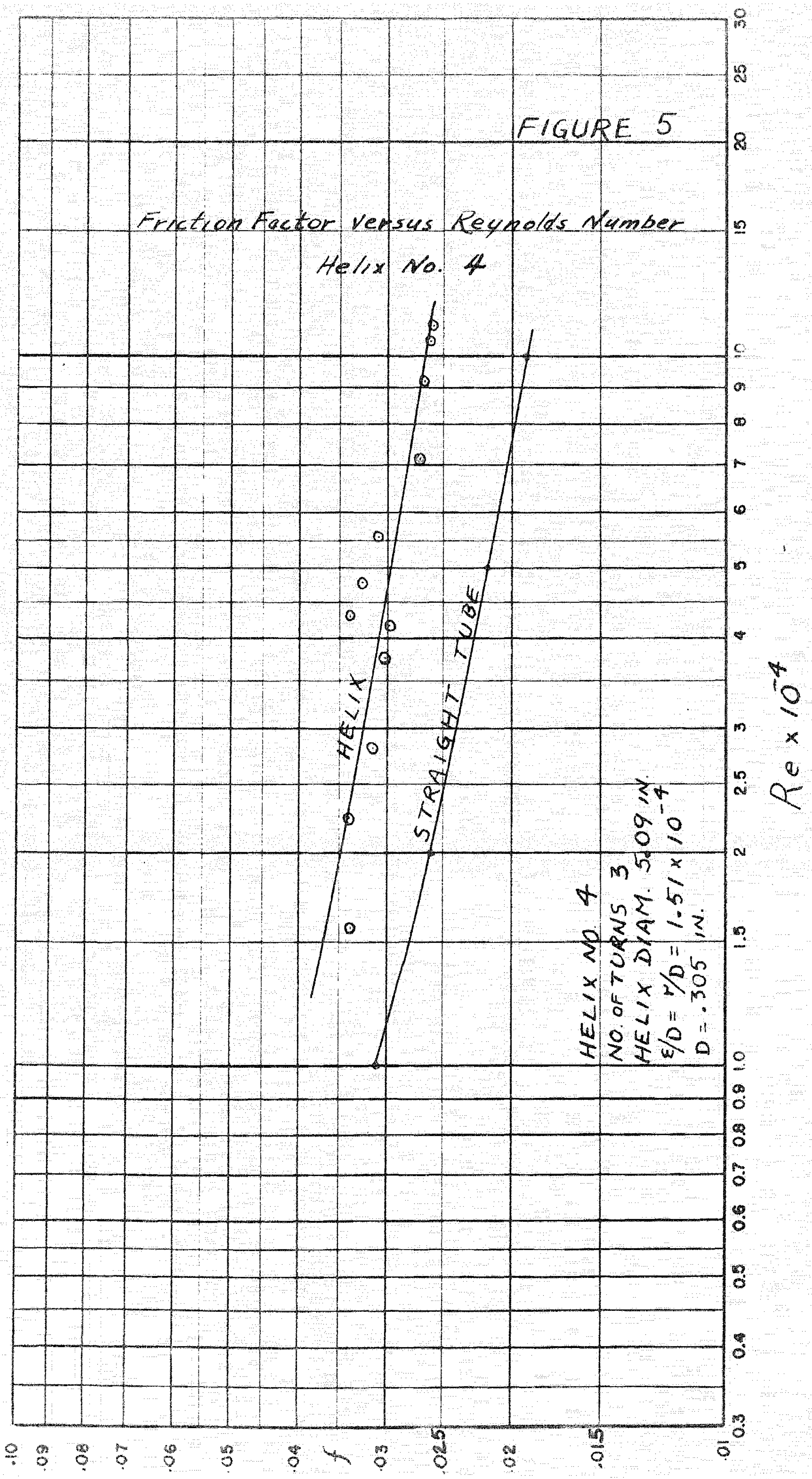
Friction Factor versus Reynolds Number

Helix No. 3

FIGURE 5

Friction Factor versus Reynolds Number

Helix No. 4



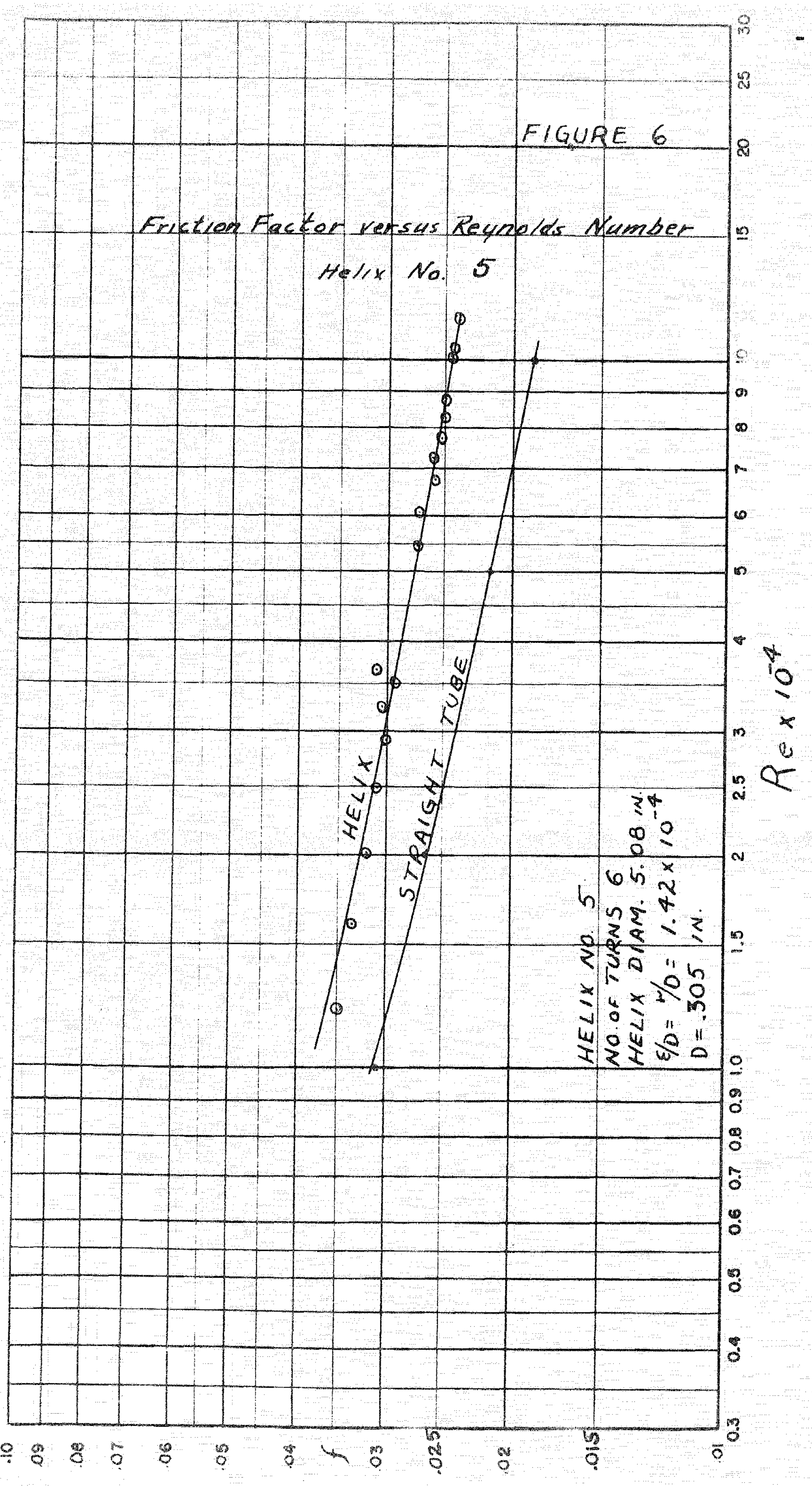


FIGURE 6

Friction Factor versus Reynolds Number

Helix No. 5

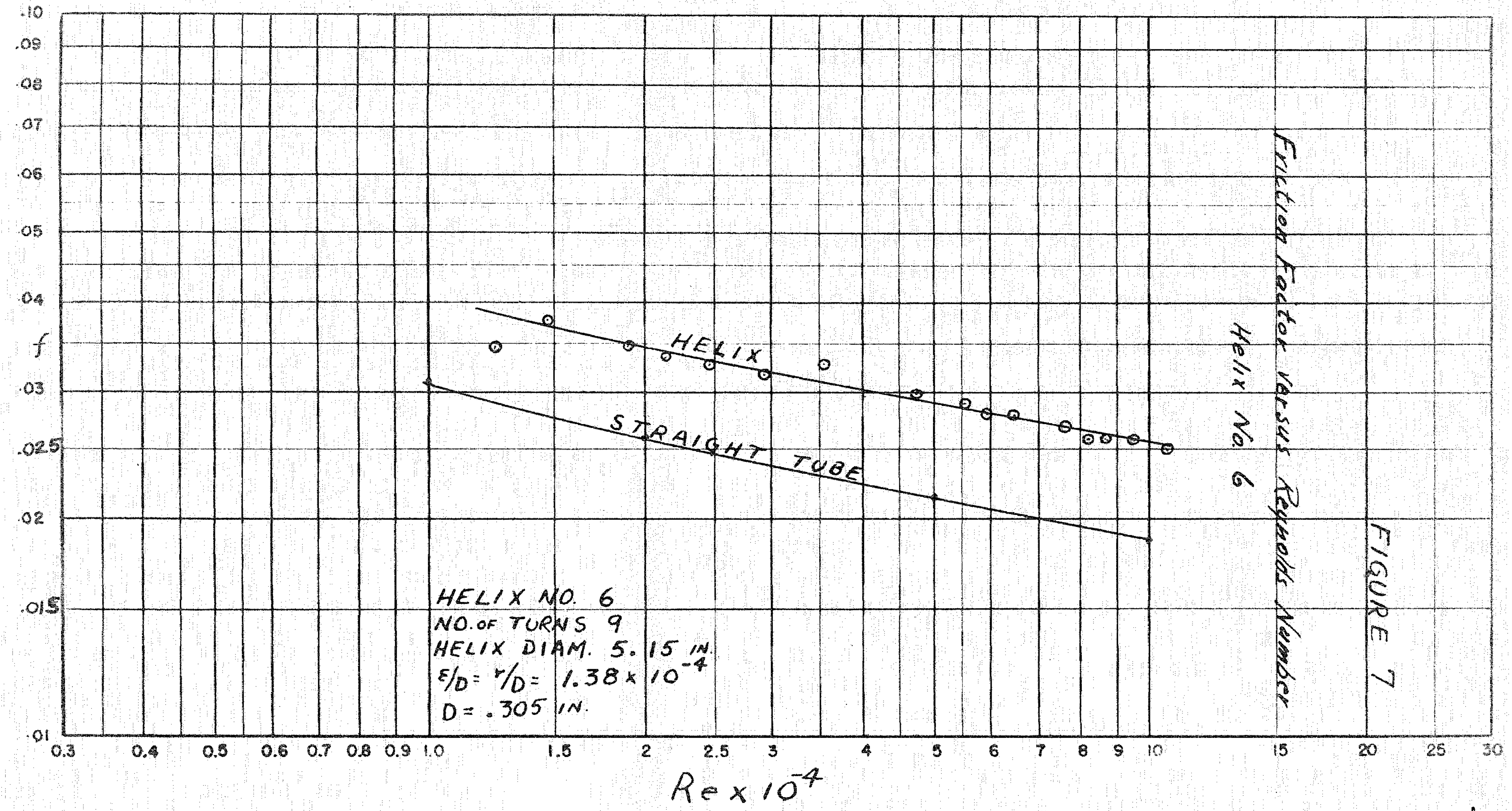


FIGURE 7

Friction Factor versus Reynolds Number

Helix No. 6

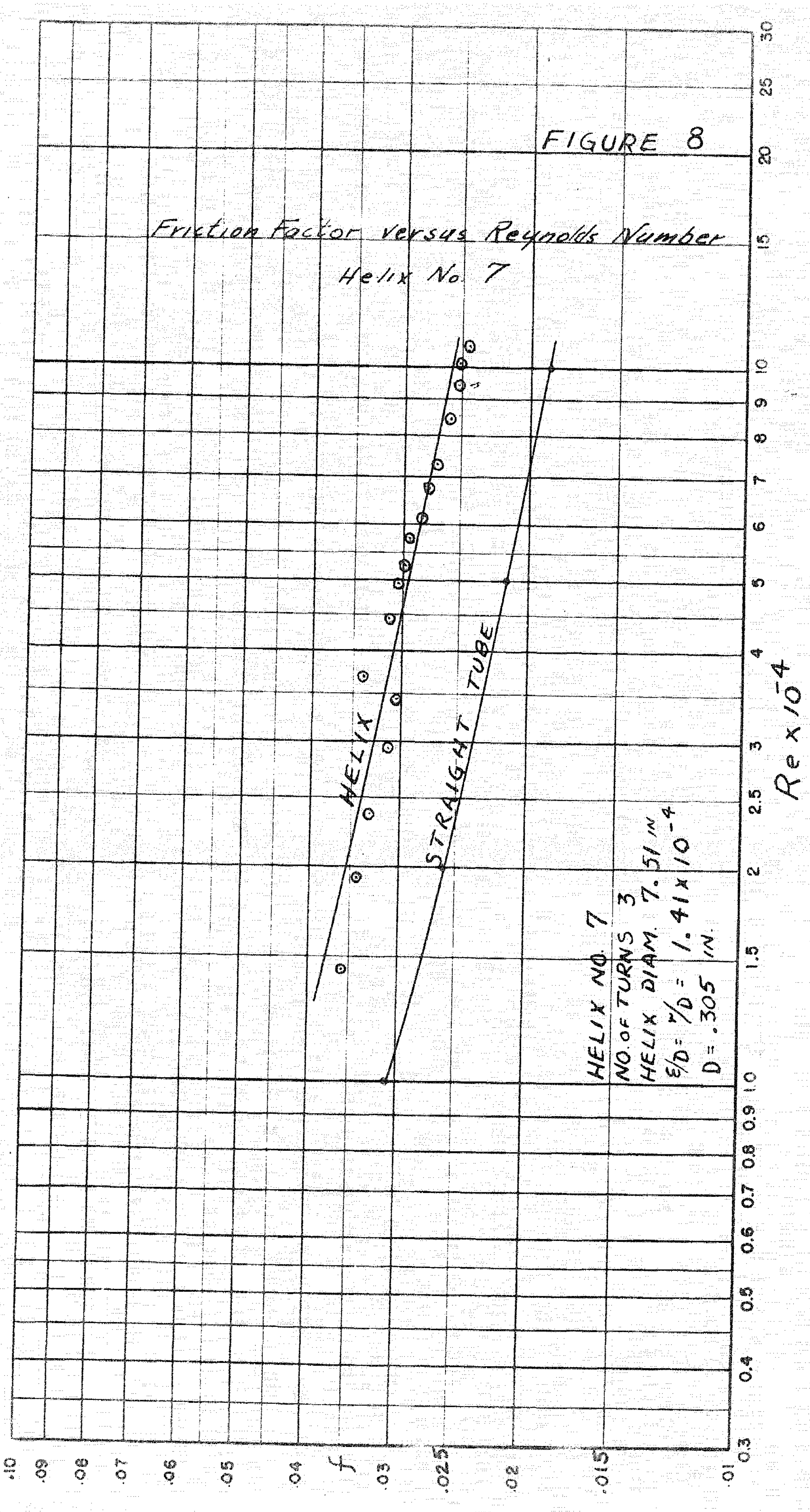


FIGURE 8

Friction Factor versus Reynolds Number

Helix No. 7

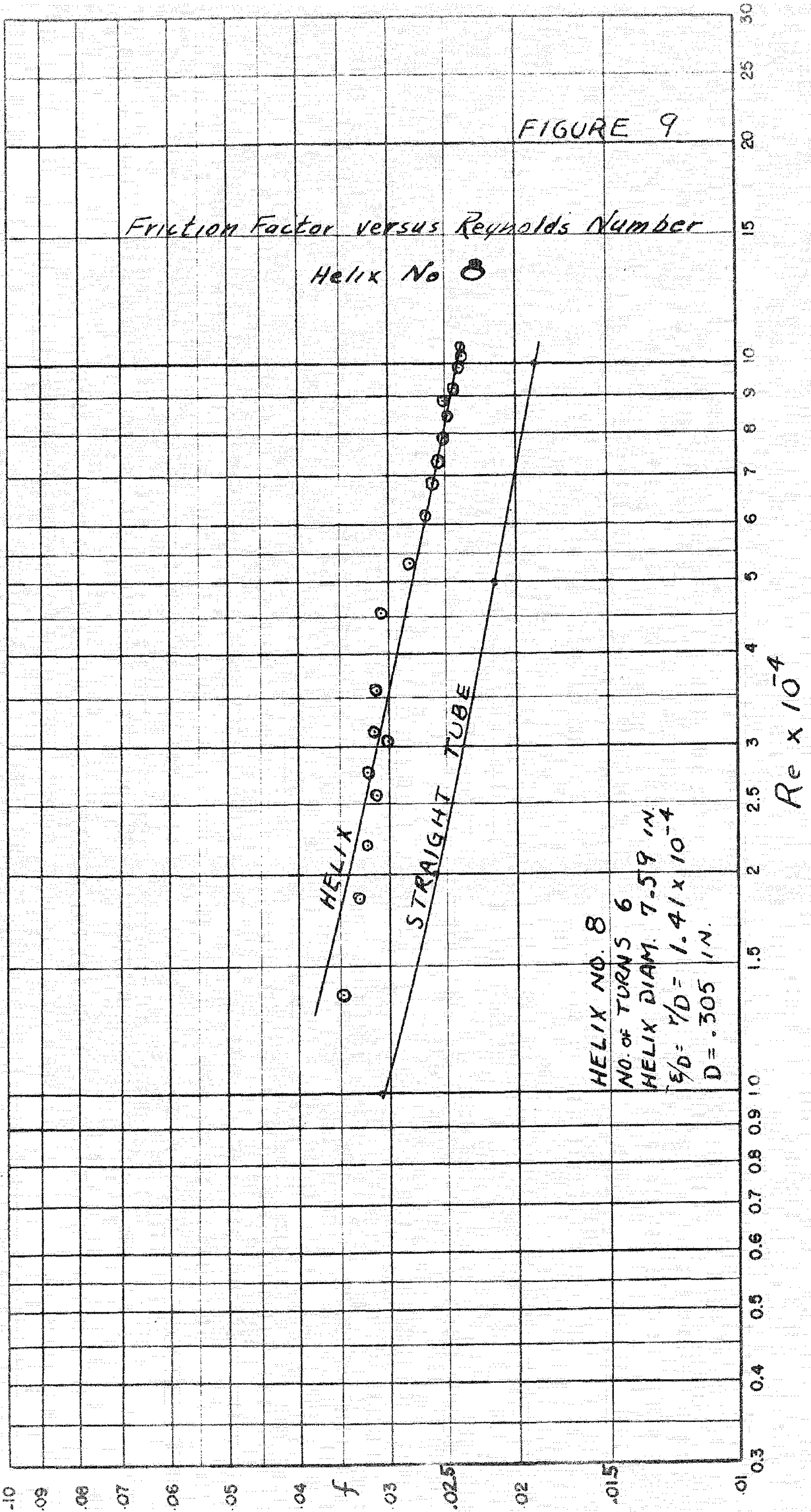


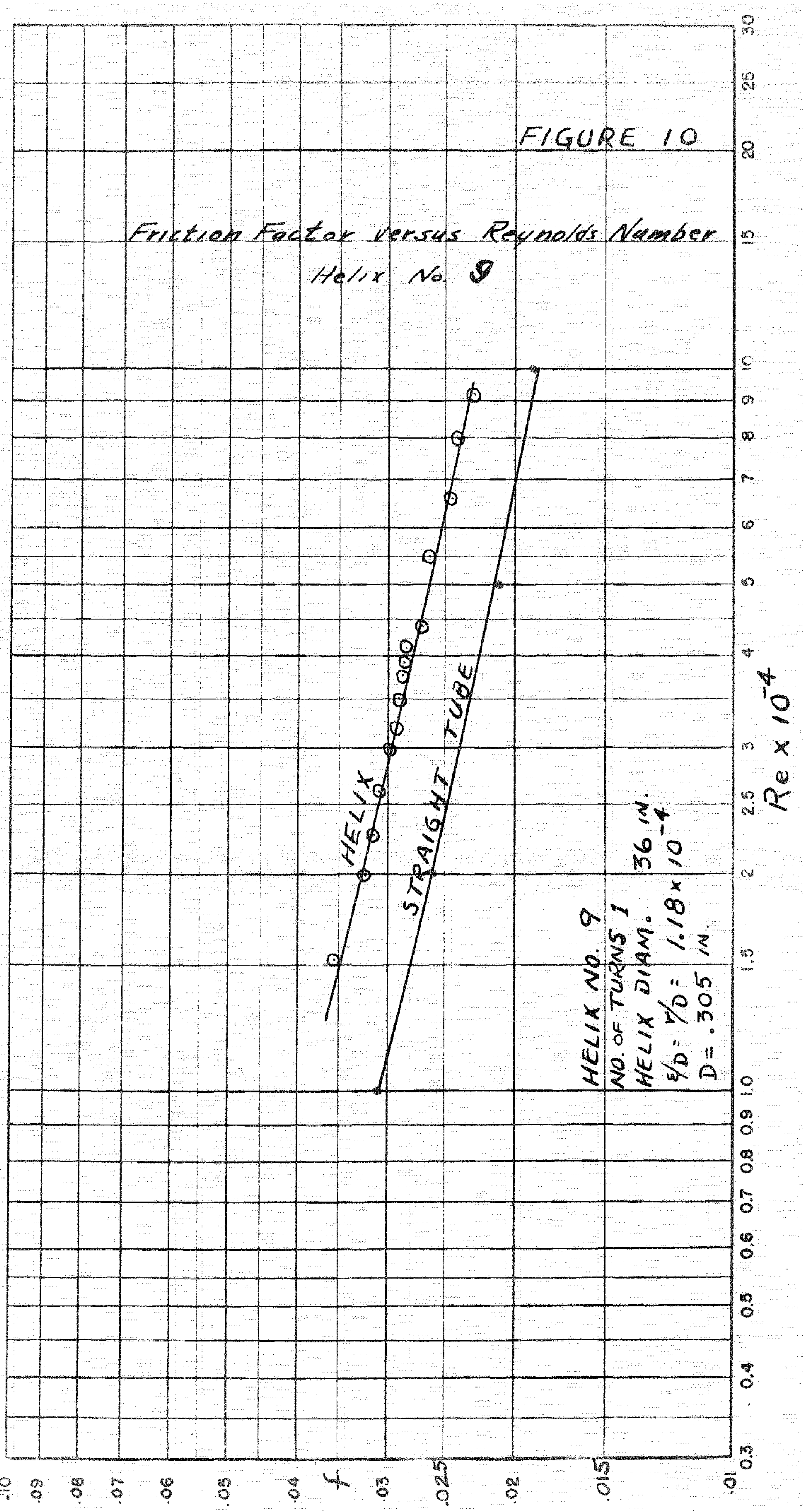
FIGURE 9

Friction Factor versus Reynolds Number

Helix No 8

FIGURE 10

Friction Factor versus Reynolds Number
Helix No. 9



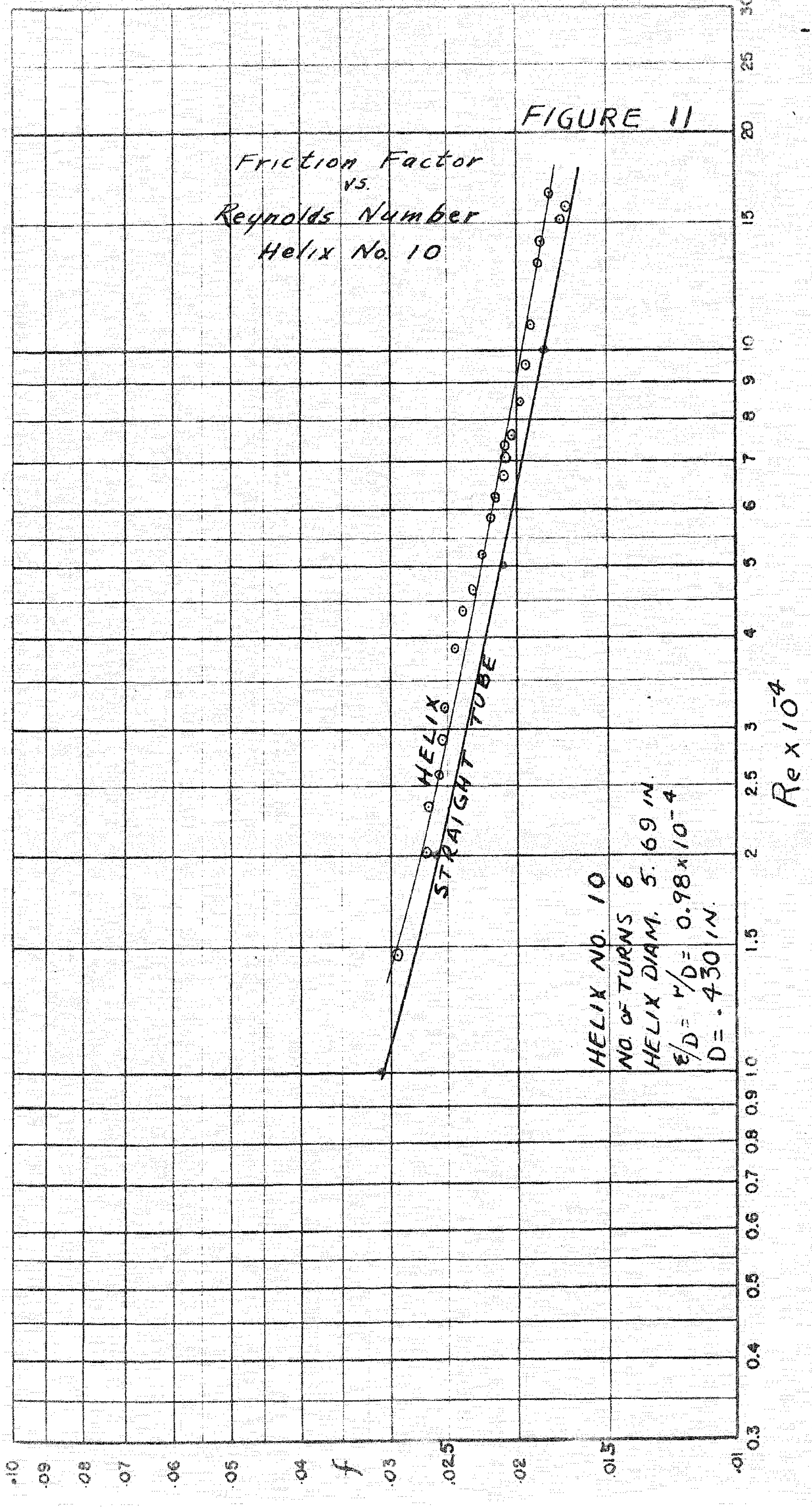


FIGURE 11

Friction Factor vs. Reynolds Number Helix No. 10

HELIX NO. 10
NO. OF TURNS 6
HELIX DIAM. 5.69 IN.
$\epsilon/D = r/D = 0.98 \times 10^{-4}$
D = .430 IN.

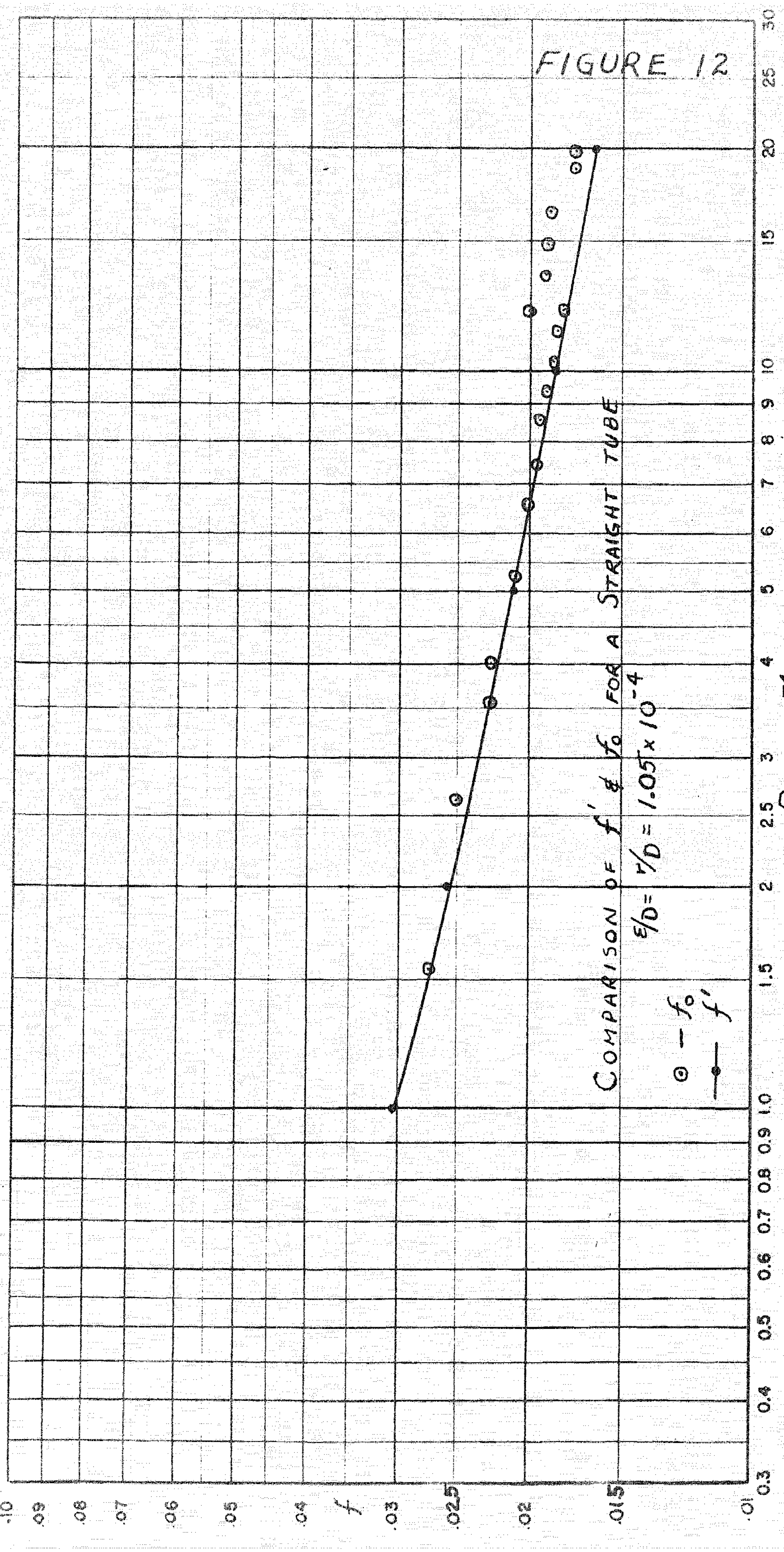


FIGURE 12

COMPARISON OF f' & f_o FOR A STRAIGHT TUBE

$\epsilon/D = r/D = 1.05 \times 10^{-4}$

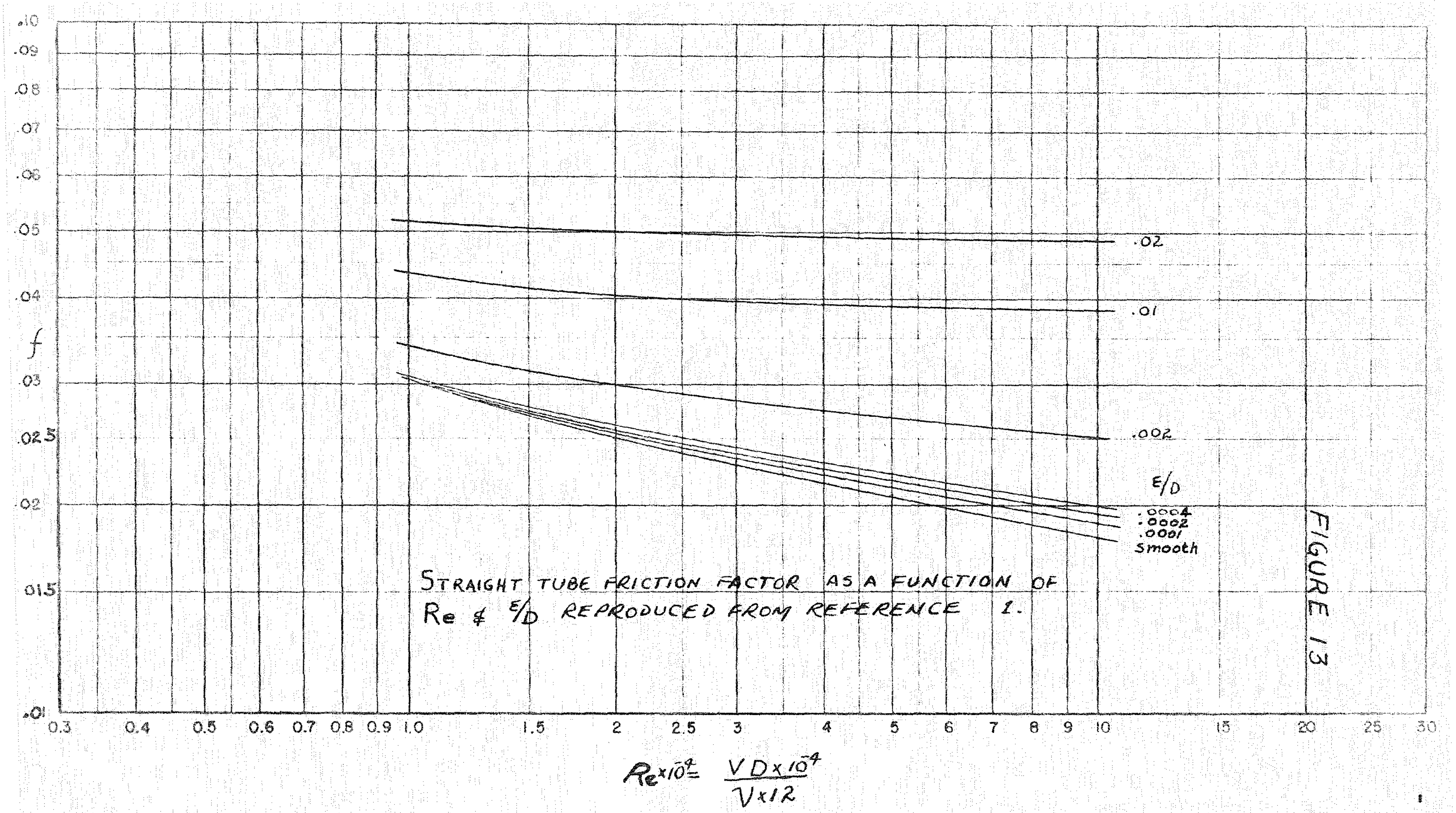


FIGURE 13

STRAIGHT TUBE FRICTION FACTOR AS A FUNCTION OF Re & E/D REPRODUCED FROM REFERENCE 1.

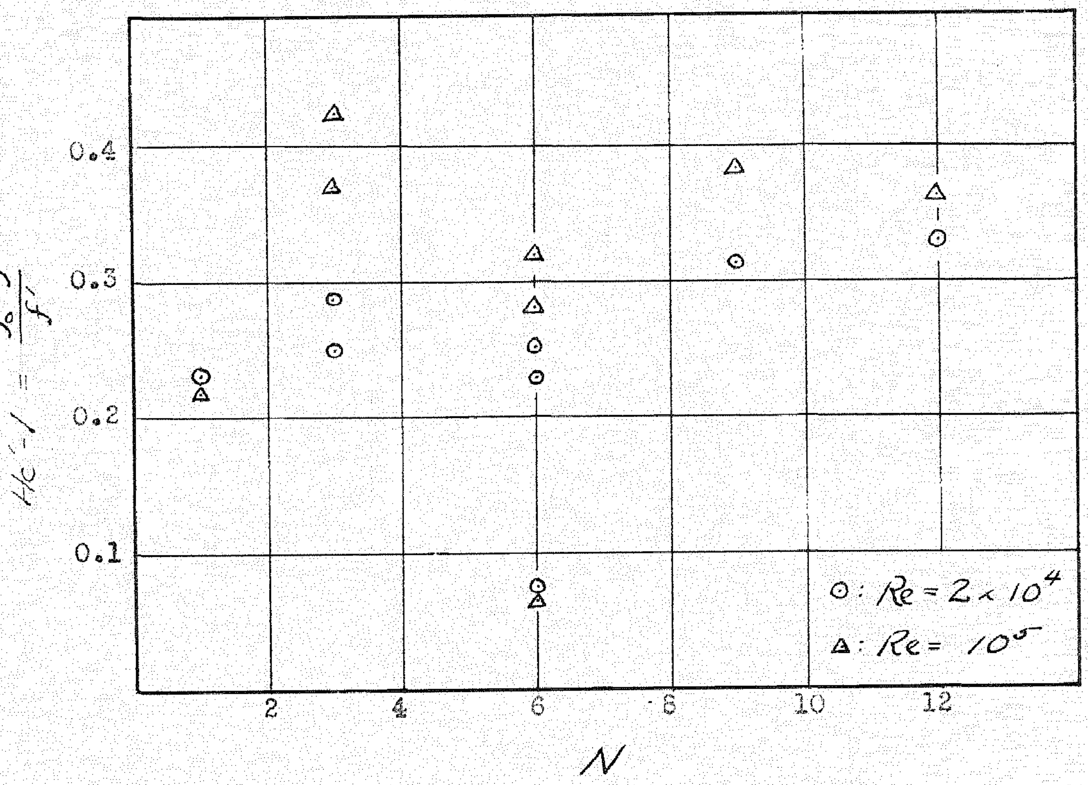


FIGURE 14
Hc'-1 vs. Number of Turns

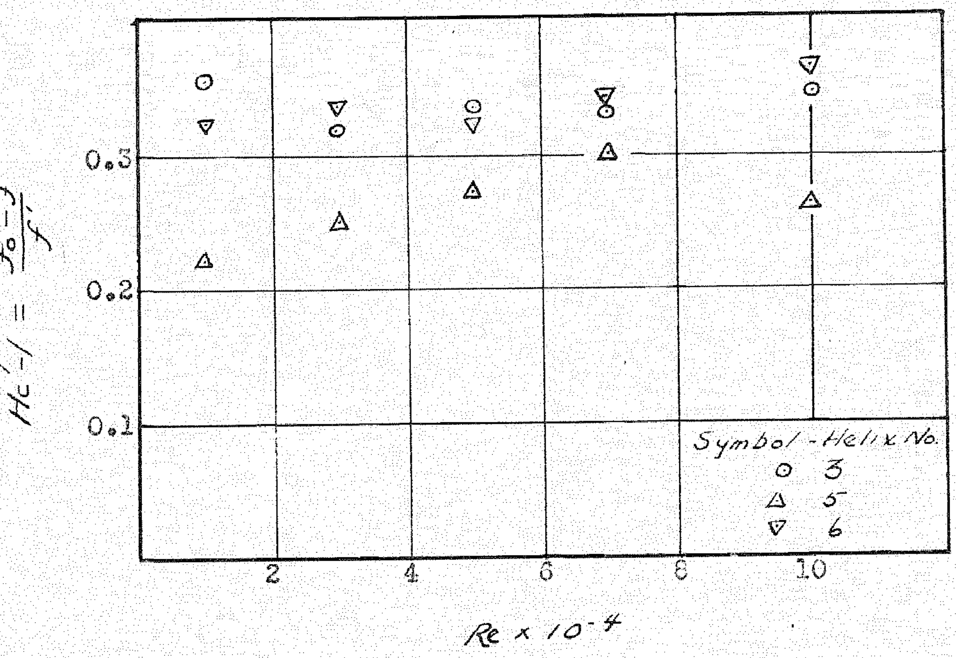


FIGURE 15
Hc'-1 vs. Reynolds Number

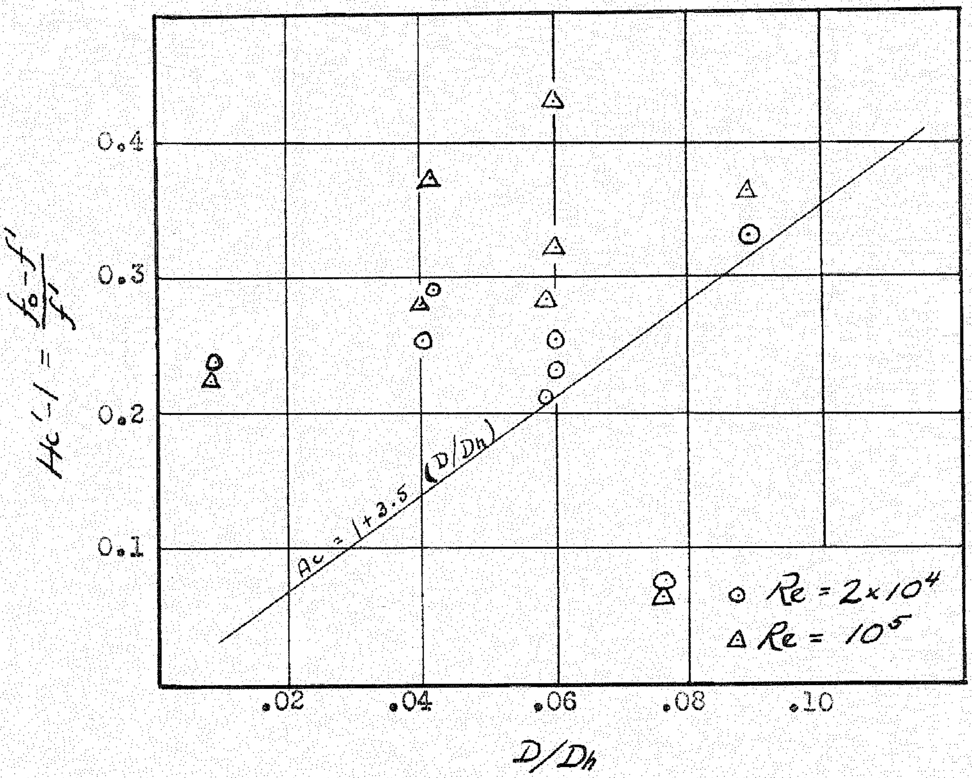


FIGURE 16
Hc'-1 vs. Diameter Ratio

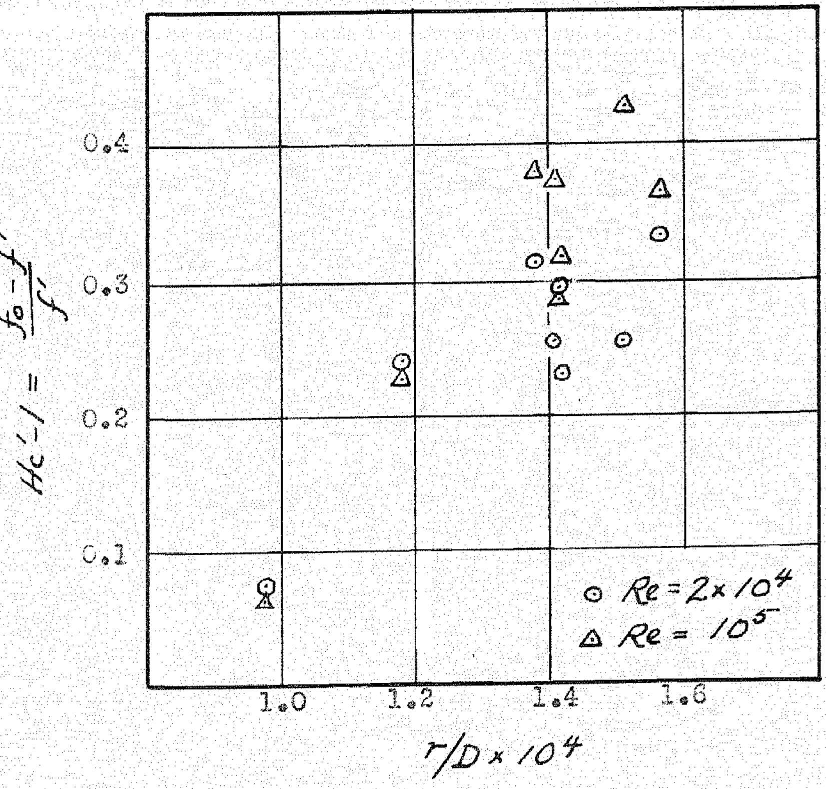


FIGURE 17
Hc'-1 vs. Relative Roughness