WIND TUNNEL CALIBRATION

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Submitted to the Department of Mechanical Engineering
Oklahoma Agricultural and Mechanical College
In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE
1948

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TABLE OF CONTENTS

ACKNOWLEDGEMENT

The writers wish to express their sincere appreciation for the advice, supervision, and constructive criticism given by Professor Vincent W. Young during the progress of this investigation. Professor Young designed the Wind Tunnel tested in this investigation and supervised its construction by his Aeronautical students in 1939 and 1940.

Thanks are also due Professor E. C. Baker, Head of the Department of Mechanical Engineering, for his advice and aid in obtaining necessary equipment.

The writers also wish to express their appreciation to the entire staff of the Engineering Experiment Station of the Oklahoma Agricultural and Mechanical College, especially to Doctor C. A. Dunn, Vice Director of the Experiment Station, and Professor J. R. Norton. It would have been extremely difficult to obtain the models and equipment used in this investigation without the full cooperation of the Experiment Station.

PREFACE

Knowledge in the field of Aeronautical Engineering depends to a large extent upon information determined experimentally. New ideas and new theories can be completely proved only in practice. In the field of Aeronautics, however, failure in practice is entirely too often accompanied by loss of life and a destruction of expensive equipment. For this reason great dependence is placed upon the experimental testing of new ideas.

The greatest single source of experimental information in this field is, of course, the wind tunnel. Wind tunnels vary greatly in size, in air velocity, in power requirement, and in the balance system used. No wind tunnel can reproduce perfectly the effect of a body moving through still air; however, certain calibration tests on a given wind tunnel will allow test results to be interpreted in the light of what may be expected of similar full-scale results.

No tunnel can be effectively operated or the results obtained correctly interpreted and applied without a thorough knowledge of the operating characteristics of the tunnel itself. Among the more important of these characteristics are the Turbulence Coefficient, the Energy Ratio, and the Pressure-Drop Coefficient. The distribution of air velocity across the throat and any tendency toward rotation of the air passing through the test section are also of paramount importance.

This investigation has consisted of a series of calibration tests made for the purpose of determining the more important operating characteristics of the tunnel which is used at the Oklahoma Agricultural and Mechanical College. This is a small tunnel of the return flow type used entirely for instructional purposes.

LIST OF SYMBOLS AND ABBREVIATIONS

"A"	Glaishers factor
bhp	brake horsepower
C_d	coefficient of drag
C_l	coefficient of lift
D.B	Dry bulb temperature
D.C	direct current
d	density
dP	pressure rise across fan
E	voltage
E_L	line voltage
Eff.	efficiency
E.R.	energy ratio
F_t	turbulence factor
f.p.s., ft/sec	feet per second
I_a	armature amperes
I_f	field amperes
I_L	line amperes
k	pressure loss coefficient
K	scale constant
mph	miles per hour
P_1	pressure correction
P_r	corrected pressure
q	velocity head
Q	quantity of air flowing
R_a	armature resistance

Re..................Reynolds number

rpm.................revolutions per minute

S ....surface area

V ....velocity

Greek letters

μ ....coefficient of viscosity

ρ ....mass density

INTRODUCTION

"The object of tests on airfoils is to obtain data that will permit calculating the forces acting on airplanes in flight."[1] In order to accomplish this object it is necessary to take into consideration the similarity between test conditions and flight conditions. Certain basic concepts along this line have been developed from the equations of Navier-Stokes.[2] Consider the statement:

> "If a body of given shape and given orientation is exposed to a uniform flow of an incompressible fluid (or moves with constant velocity through an incompressible fluid at rest), each component of the force which the fluid exerts on the body can be expressed as the product of the dynamic pressure, a certain area of reference, and a coefficient the value of which depends exclusively on the Reynolds number (Re.)" [3]

This is equivalent to the statement that where such force components are set up as Lift $= C_1 \frac{\rho}{2} SV^2$, Drag $= C_d \frac{\rho}{2} SV^2$ etc, the force coefficient i.e., C_1 and C_d, in any case depends upon the Reynolds number and on the shape and orientation of the body. The Reynolds number is a dimensionless quantity and can be shown to be equal to $\frac{\rho Vl}{\mu}$.[4]

By introducing the concept of boundary conditions, i.e., boundaries which the flow cannot traverse, and the velocity distribution at entrance and exit surfaces a particular solution of the Navier-Stokes equations can

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[1] Wood, Karl D., Technical Aerodynamics, p. 117.

[2] Prandtl and Tietzjens, Fundamentals of Hydro and Aero Mechanics, p. 258.

[3] Von Mises, Richard, Theory of Flight, p. 79.

[4] Ibid., p. 78.

be obtained. The velocity value at some suitably chosen point at entrance and some particular linear dimension of the wall are used for determining the particular Reynolds number. If from the boundary conditions of the flow under consideration, boundary conditions of a second flow may be derived by multiplying all coordinates by a certain factor and all velocities by another factor, the conditions are said to be similar. This leads to the statement that:

> "If in two cases of steady motion of a viscous fluid the boundary conditions are similar and if, moreover, the Reynolds number has the same value in the two cases, the two flows will be similar; each force component will be proportional to qA."[5]

The real fluid, in this case air, is a viscous fluid and as such will not fulfill exactly the specifications of a perfect fluid. In addition, the flow in a wind tunnel is not strictly steady but is rather of the quasi steady type. The velocity considered is a mean value disregarding small fluctuations and not an instantaneous value as in a perfect fluid.

There are in fact quite serious discrepancies between the facts and the theory of both perfect and viscous fluids. However, an hypothesis that has proved to be sufficiently applicable in most cases is that:

> "the fluid motion at large, i.e., everywhere except in the immediate neighborhood of rigid bodies, may be considered approximately as a perfect fluid motion, at least as far as the velocity distribution is concerned.--For example, the flow around an airfoil in a wind tunnel is doubtless a turbulent flow of a viscous fluid. But if the small oscillations are disregarded, the remaining steady velocity values agree very well with those computed from the theory of perfect fluids."[6]

If we consider then the case of a round body such as a sphere, the force coefficient may be determined as $C_d = \frac{\text{Drag}(2)}{\rho A V^2}$, where the actual value of the drag is determined by experimental test. Early experiments at relatively low Reynolds numbers indicated that for such a body the value of C_d was practically

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[5] Ibid., p. 81.

[6] Ibid., p. 84.

independent of Reynolds number. Later experiments, however, extending into higher Reynolds numbers showed that there exists a comparatively narrow range of Reynolds numbers, within which the value of C_d drops rapidly from a value of approximately .5 for moderate Reynolds numbers to a much lower value, .1 to .2, for high Reynolds numbers. This variation is shown schematically in Figure 1.

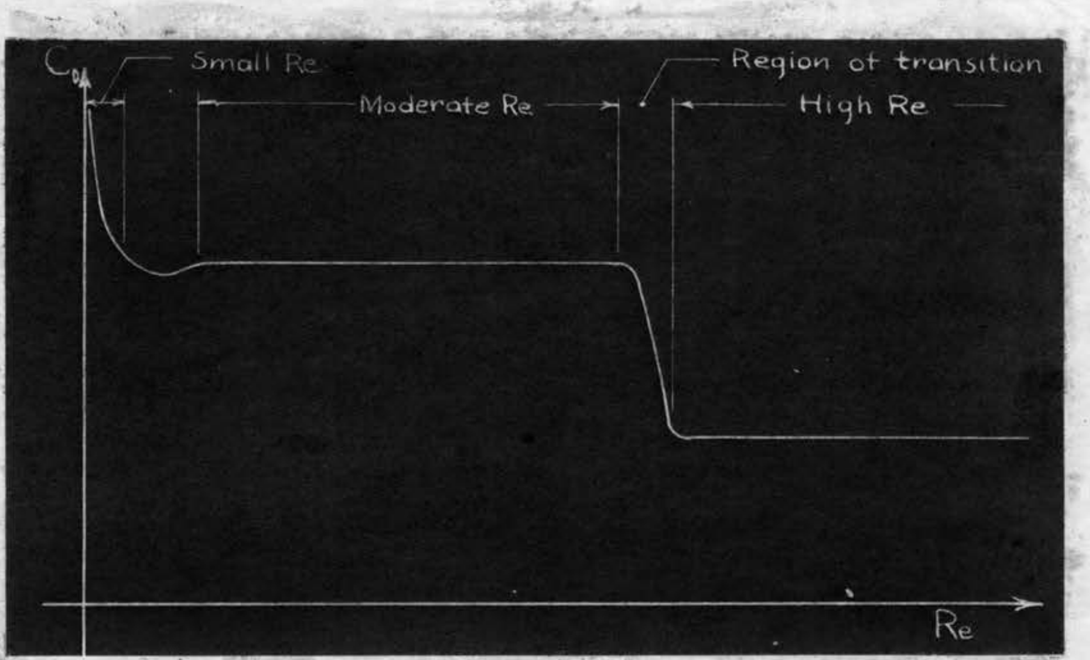

Fig. 1. Drag of Round Bodies.

The behavior of C_d suggests that two distinct stream patterns exist, one at moderate Reynolds numbers and another at high Reynolds numbers, with probably intermediate patterns in the region of transition. Recent investigations indicate that the flow in the boundary layer is laminar for moderate values of Reynolds numbers and turbulent for high values. A broad wake accompanies the laminar flow and a narrower wake accompanies the turbulent flow.[7] This is illustrated in Figure 2.

As this transition region is determined by the value of Reynolds number, the viscosity of the fluid must have a decisive effect upon the phenomenon. Also, being a transition from laminar to turbulent flow it might be expected

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[7] *Ibid.*, pp. 99-101.

that initial turbulence in the free stream would tend to cause the transition to take place at lower Reynolds numbers. Experiments bear this out, showing that the greater the free stream turbulence the lower the Reynolds number at which the transition occurs.

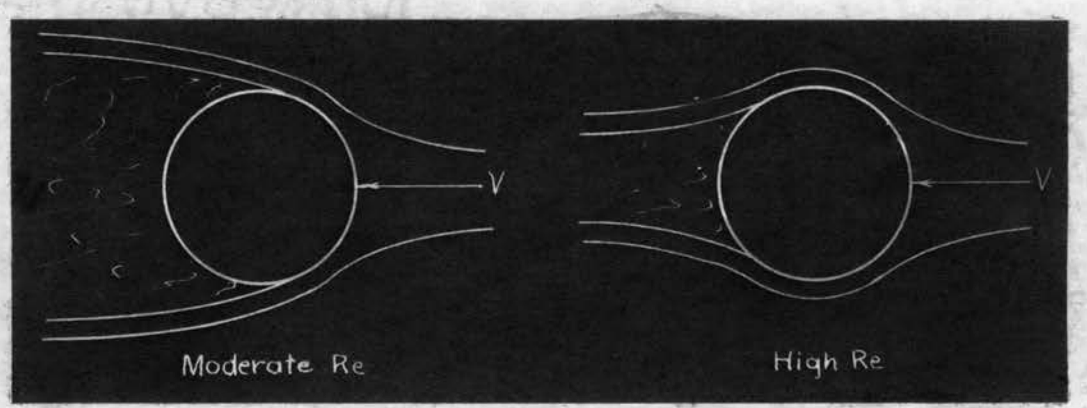

Fig. 2. Wake Behind Circular Bodies for Moderate and Large Reynolds Numbers.

It is impossible in a wind tunnel to remove all turbulence from the air stream. Therefore stream patterns about a model in a wind tunnel would not necessarily be similar to stream patterns about the model moving through still air as the transition from laminar to turbulent flow would take place at different Reynolds numbers. Jacobs[8] first noted the essential similarity between the curves for various degrees of turbulence and found that the curves could be reduced to a single curve by multiplying the Reynolds number for each curve by a Turbulence factor F_t, so chosen as to make the intersections at $C_d \doteq .3$ coincide. The product F_tRe is referred to as the effective Reynolds number or the Jacobs number. The effective Reynolds number then, would represent the Reynolds number at which the flow pattern in the atmosphere would be similar to that existing in the tunnel. In determining a Turbulence factor or coefficient for a tunnel the obvious basis is the curve corresponding to the atmosphere in which the airplane will fly. In other words, it would be

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[8] Jacobs, E. N. and A. S., Airfoil Section Characteristics as Affected by Variations in the Reynolds Number. N. A. C. A. Tech. Report 586.

desirable to determine a factor which would make the transition curve for a given tunnel coincide with the curve for the atmosphere.

The National Advisory Committee for Aeronautics has run numerous drag tests of spheres in the atmosphere. These tests have established an accepted value of the critical Reynolds number, i.e., the Reynolds number at which a sphere shows a drag coefficient of .3, as 385000 for the atmosphere.[9] The Turbulence factor F_t for a given tunnel would, therefore, be 385000 divided by the critical Reynolds number for the tunnel.

In any wind tunnel of the return flow type (Figure 3) it is necessary to install curved vanes at each point where the flow makes a major change of direction to assist the air in making the turn and to keep turbulence a minimum. Most tunnels are also equipped with a honeycomb installed ahead of

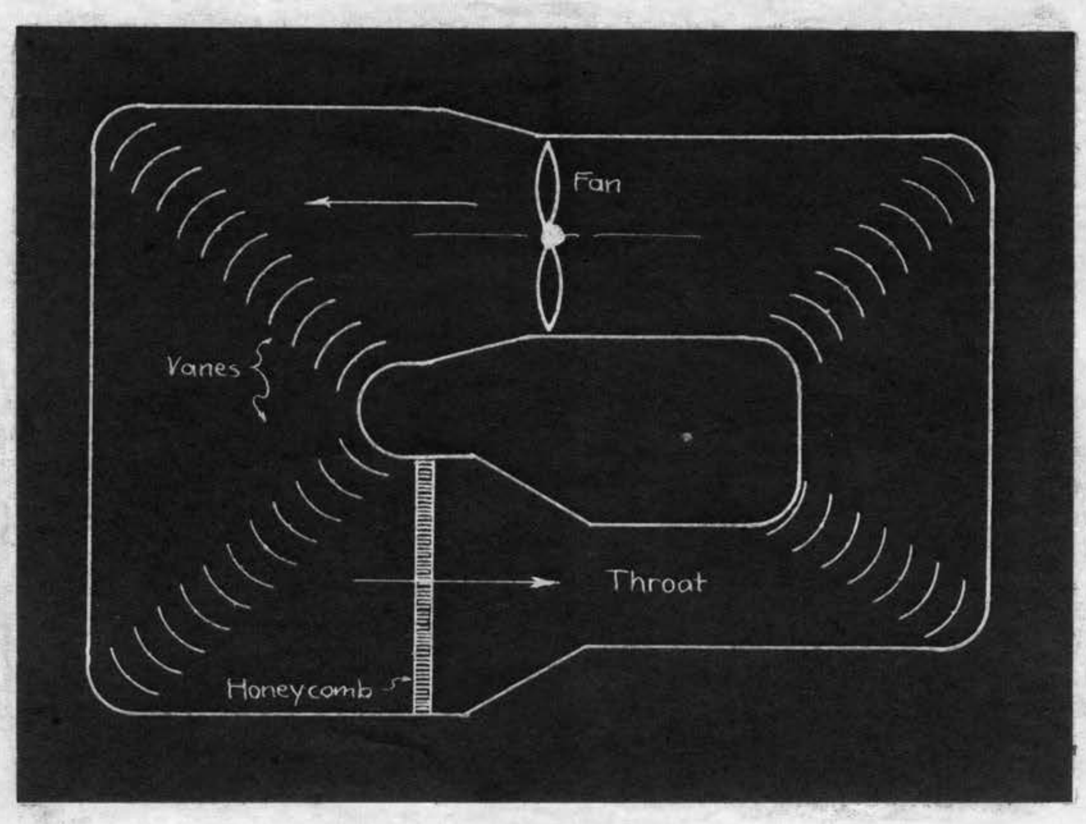

Fig. 3. Typical Return Flow Tunnel.

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[9] Platt, Robert C., Turbulence Factors of N.A.C.A. Wind Tunnels as Determined by Sphere Tests. (N.A.C.A. Report No. 558, p. 13.

the test section. This is for the purpose of aligning the air flow and removing the rotation imparted by the propeller so that the air will pass through the test section as straight as possible.

PERFORMANCE CRITERION OF THE WIND TUNNEL

> "The major aerodynamic feature of a closed-circuit wind tunnel is the friction loss in total head around the closed circuit, which is made up by a rise in pressure dP across the fan disk. The head loss in each part of the tunnel is proportional to V^2 in that part; with fixed area ratios, it is also true that $dP = kq_t$."[10]

The value of the constant k then is $\frac{dP}{q_t}$, or the ratio of the rise in pressure at the fan disk to the impact head at the throat or test section. This constant is referred to as the pressure loss coefficient.

Overall performance of a tunnel is commonly described by the Energy Ratio expressed as

$$\text{E.R.} = \frac{A_t V_t^3 \rho}{1100 \text{ Bhp}} \tag{1}$$

If the efficiency is defined by

$$\text{Eff.} = \frac{Q\ dP}{550 \text{ Bhp}} \tag{2}$$

Where Q = quantity of air flowing around the circuit, cubic feet per second.

Combining equation (2) with $k = \frac{dP}{q_t} = \frac{2\ dP}{V_t^2 \rho}$ gives

$$\text{Eff.} = \text{E.R.}(k) \tag{3}$$

The specific purposes of this investigation may be itemized as follows:

1. A series of sphere drag tests to determine the Turbulence factor F_t for the tunnel based on a critical Reynolds number for air of 385000.

2. Determination, by pressure and velocity measurements, of the pressure-loss coefficient.

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[10] Wood, op. cit., p. 118.

3. Determination of the Energy Ratio.

4. Determination, from obtained values of k and E.R., of the overall efficiency of the tunnel.

APPARATUS

The principal apparatus used in this investigation was the wind tunnel with its balances, controls etc., and several wooden spheres used for test models.

THE WIND TUNNEL.--This wind tunnel is a small return flow tunnel of plywood construction. It was built in 1939 by the Aeronautical Engineering students at Oklahoma Agricultural and Mechanical College. Figure 5 on page 9 shows a plan view of the tunnel with the major dimensions.

The test section is elliptical in shape, 36 inches wide and 18 inches high. Figure 4 is a view looking through the test section in the direction

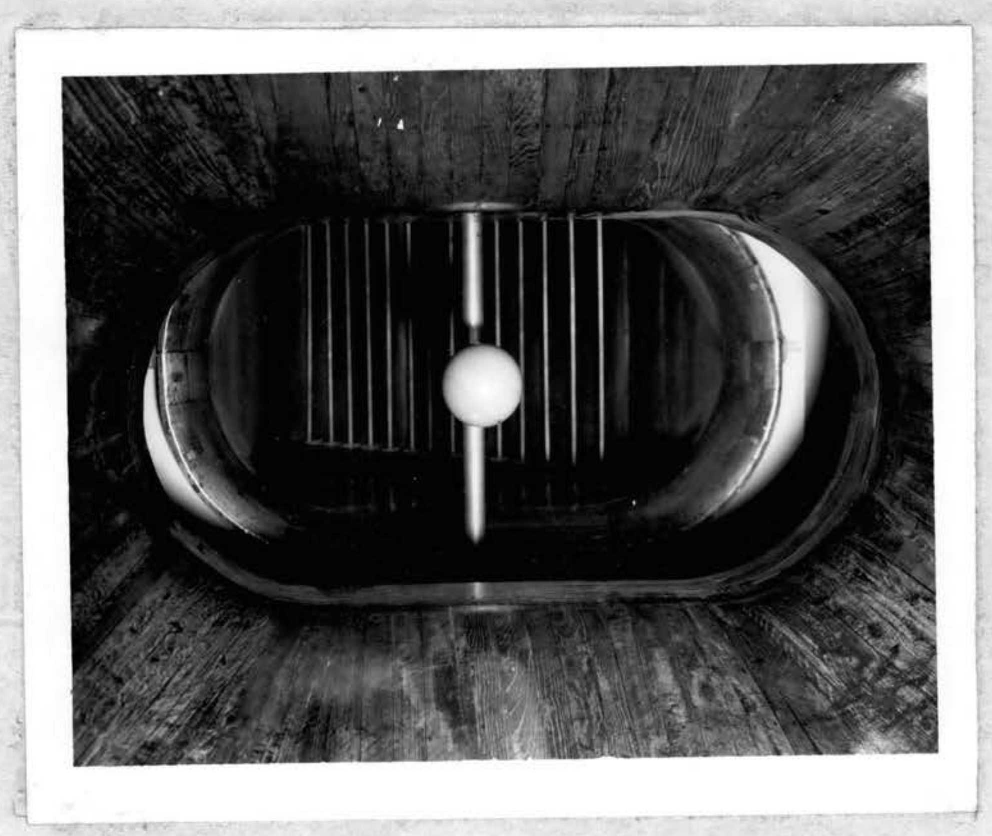
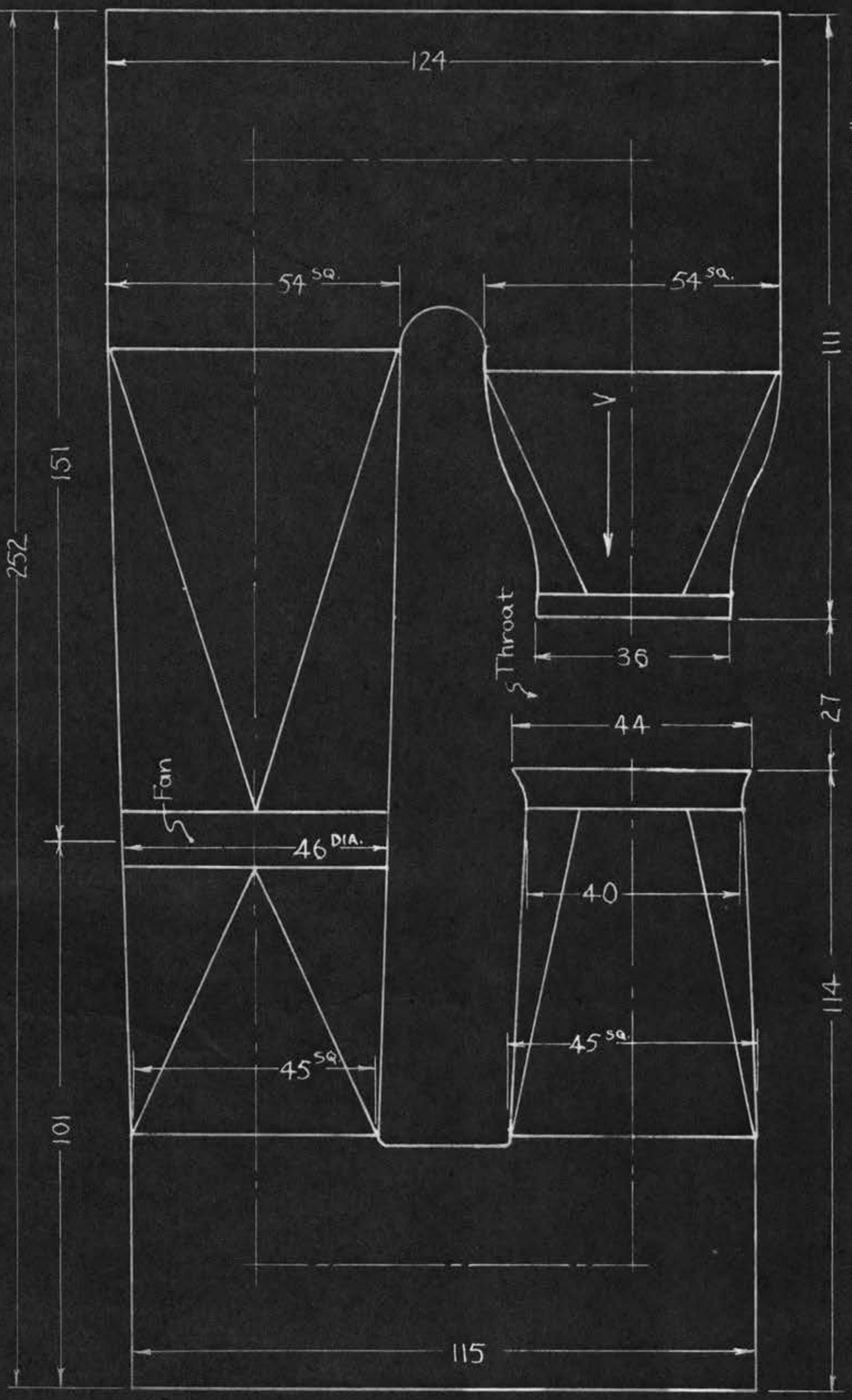


Fig. 4. Test Section of Tunnel.



Scale $\frac{1}{30}'' = 1''$

Figure 5 - Plan View Wind Tunnel.

of air flow. A 5 inch sphere is shown mounted in test position.

Air flow is induced by a 44 inch, 6 blade metal propeller driven by 5 V-belts. The Ratio of $\frac{\text{Fan RPM}}{\text{Motor RPM}} = .667$. Figure 6 shows the propeller section of the tunnel looking against the air flow.

Fig. 6. Propeller Section of Tunnel.

POWER SUPPLY.--Power is supplied to the propeller by a 220 volt D.C. motor. This motor was originally shunt wound, rated as 10 horsepower at 1100 rpm. It has been rewound, however, and develops approximately 15 hp at 1900 rpm.

MOTOR CONTROL.--Speed control is accomplished normally by a field rheostat by which the motor speed may be varied from 1100 to 1900 rpm. A motor speed of 1100 rpm corresponds to an air velocity in the throat of approximately 55 miles per hour. For this investigation, a variable resistance was placed in series with the armature windings to further reduce the speed. By the use of this armature resistance the air velocity was reduced to approximately 35 miles per hour, corresponding to a motor rpm of 1.800 and a fan rpm of 532.

VELOCITY MEASUREMENT.--Throat velocity was measured by a pitot tube mounted in the test section. The water manometer was installed at an angle such that a difference in water level of 1 inch resulted in a difference along the manometer of 4 inches. A sliding scale was built so that the vertical difference in water level could be read directly in hundredths of an inch.

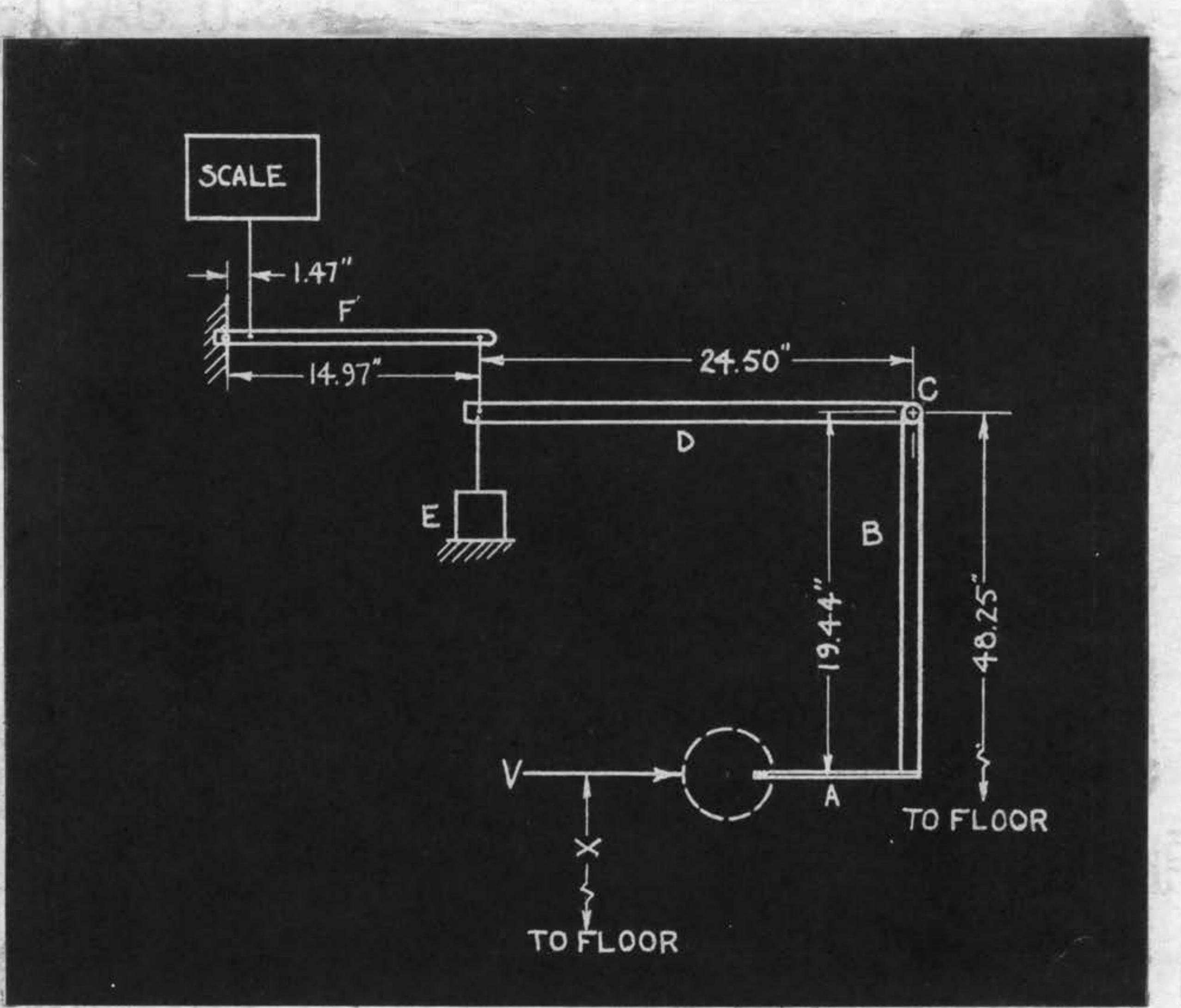


Fig. 7. Wind Tunnel Balance.

BALANCE.--The original wire support balance system was not considered suitable for this investigation. Figure 7 illustrates the type finally decided on and installed. The stinger A was made of 3/8 inch round rod and threaded for attachment of the model. Steel stock 3/8 by $1\frac{1}{4}$ inch was used for arms B and D. Shaft C was mounted on ball bearings to reduce friction to a minimum. An oil dash pot was installed at E to damp the minor fluctuations of drag so that a mean drag could be measured on the scale. The pull exerted by D is multiplied by 10 through the lever F. A beam type scale of 70 pounds capacity was used for measurement. With a sphere perfectly centered on the stinger, this arrangement registered 8.2 pounds on the scale for each pound of drag on the sphere. Tests showed that the balance of the scale was sensitive to less than .02 pound on the scale. This corresponds to a change in drag on the model of less than .003 pound. A hollow streamlined guard was installed over the arm B

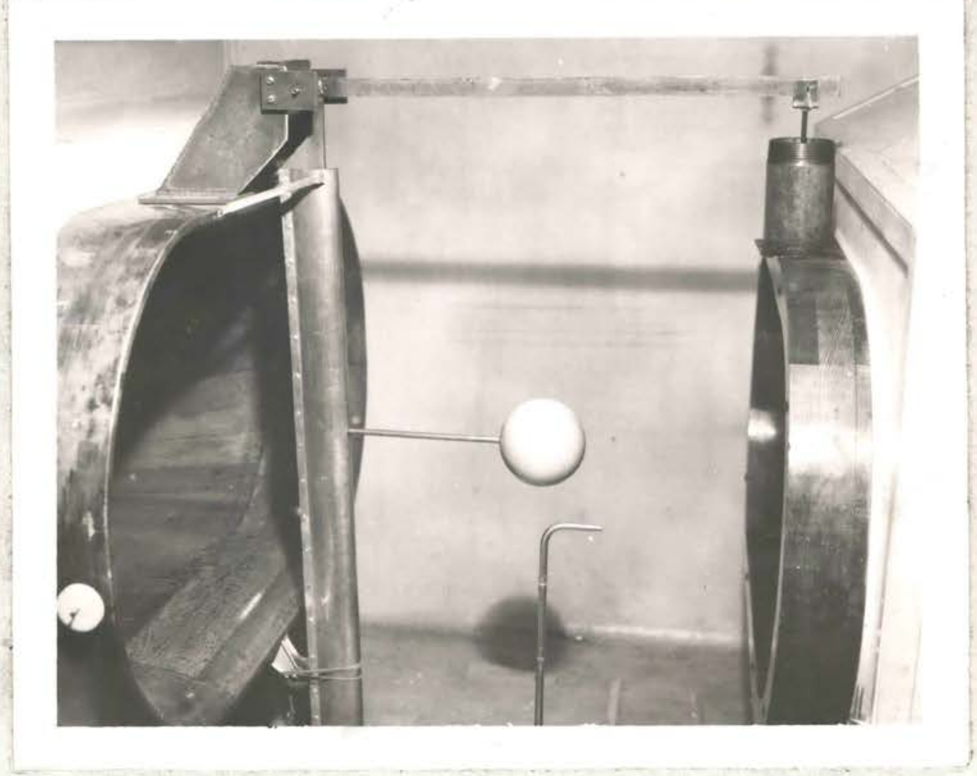


Fig. 8. Test Section of Tunnel.--5" Model Mounted.

with a small hole for the stinger A. This prevented the air stream from striking the arm B, so that only the drag of the sphere was recorded. Figure 8 shows the balance installed in the throat of the tunnel.

MODELS.--Based on estimated values of the Turbulence factor, sphere diameters of 3, $3\frac{1}{2}$, 4, $4\frac{1}{2}$, 5, $5\frac{1}{2}$, 6, $6\frac{1}{2}$, and 7 inches were selected. It was desired to determine the turbulence at several air speeds over the range of the tunnel's capacity. These spheres were turned out of white pine in the Oklahoma Agricultural and Mechanical College woodwork shop. During the course of the investigation, it developed that these spheres were not accurate enough to give consistent results. Additional spheres were obtained from the Lignum Vitae Corporation, turned out of Lignum Vitae. These proved to be accurate to less than .01 inch diameter and gave consistent results.

PRELIMINARY INVESTIGATION OF AIR FLOW IN THROAT

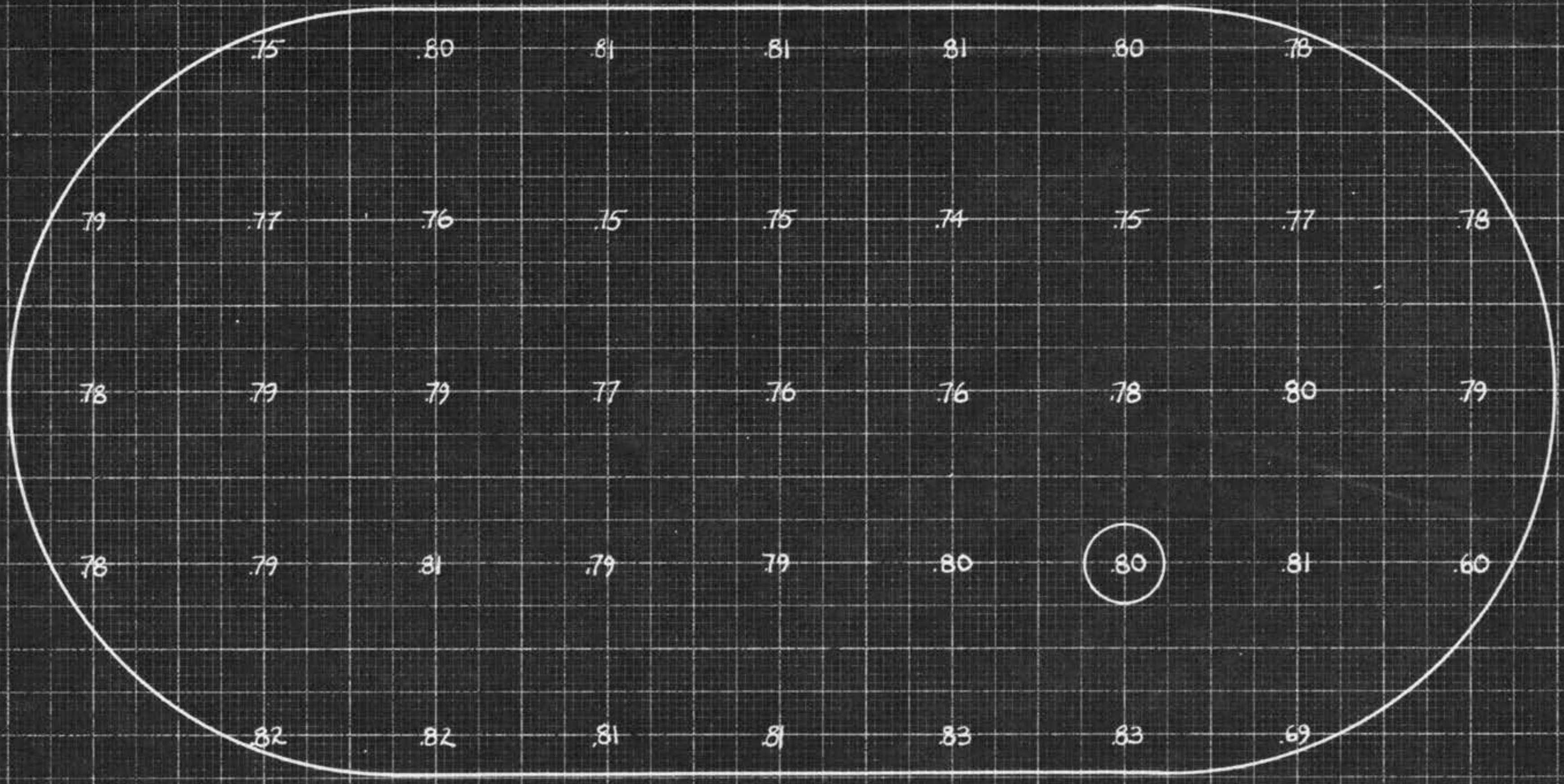
DIRECTION OF AIR FLOW.--In order to obtain some idea of the general air flow through the test section of the tunnel, light silk threads were placed in the air stream. Threads placed at various sections throughout the throat showed that over the major section of the throat the flow was very close to horizontal. However, the threads indicated that the rotation imparted to the air by the propeller was not entirely removed by passing through the two sets of vanes between the propeller and throat sections. Observation of the threads from above showed that through the upper half of the stream the air slanted to the left as it passed through the throat. Through the lower half, the air slanted to the right. No definite measurement of the rotation was attempted; however, points on the vertical centerline of the throat, 6" above and below the center, showed a deviation of approximately 4 degrees to left and right respectively. This tunnel would obviously be unsuitable for original research without the installation of a honeycomb in the airstream ahead of the test section. Such an installation would be of doubtful value in this tunnel however, due to the extremely short approach section between the vanes and the test section. This section could not be lengthened due to space limitations.

VELOCITY VARIATION.--The pitot tube was selected for velocity measurement in this investigation due to the extremely small error introduced into such measurements by imperfect alignment of the pitot tube and the air stream.

In order to select a location for the pitot tube installation, a series of velocity profiles were obtained at various air speeds. Figures 9, 10, 11, 12, 13 and 14 show the pitot reading in inches of water for speeds of approximately 40, 50, 60, 70, 80 and 90 miles per hour respectively.

The point shown circled in Figures 9-14 was selected as the best location for the pitot tube. Pitot readings for this point were consistently .04 to .06 inches of water higher than for the center of the throat. By the subtraction of a constant of .05 inches from the pitot readings, the pitot values for the center of the throat may be obtained with an accuracy of .01 inches of water.

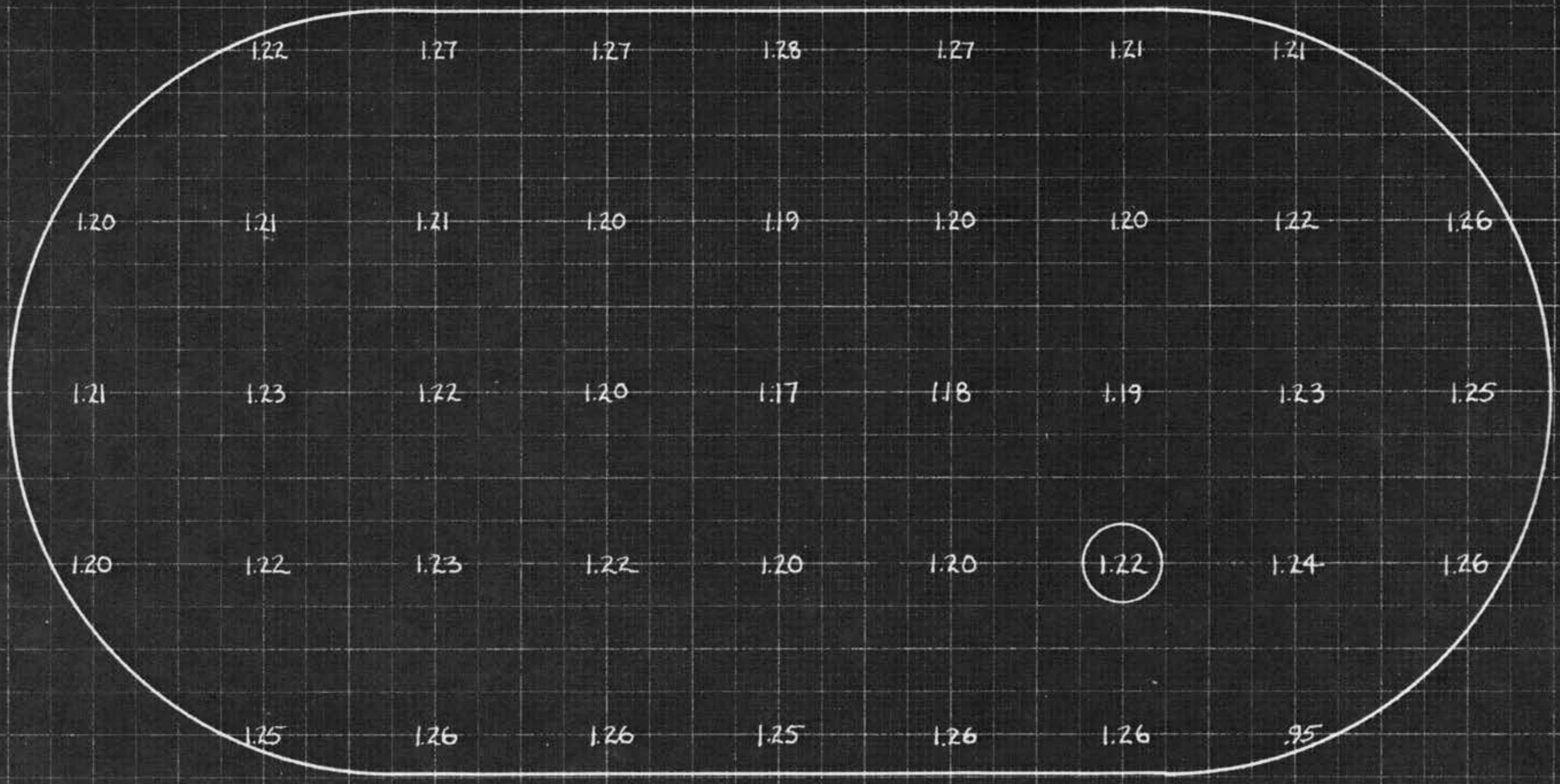
VELOCITY PROFILE NO. I
APPROX. 40 M.P.H.



SCALE 1" = 4"

FIG. 9

VELOCITY PROFILE NO. 2.
APPROX. 50 M.P.H.

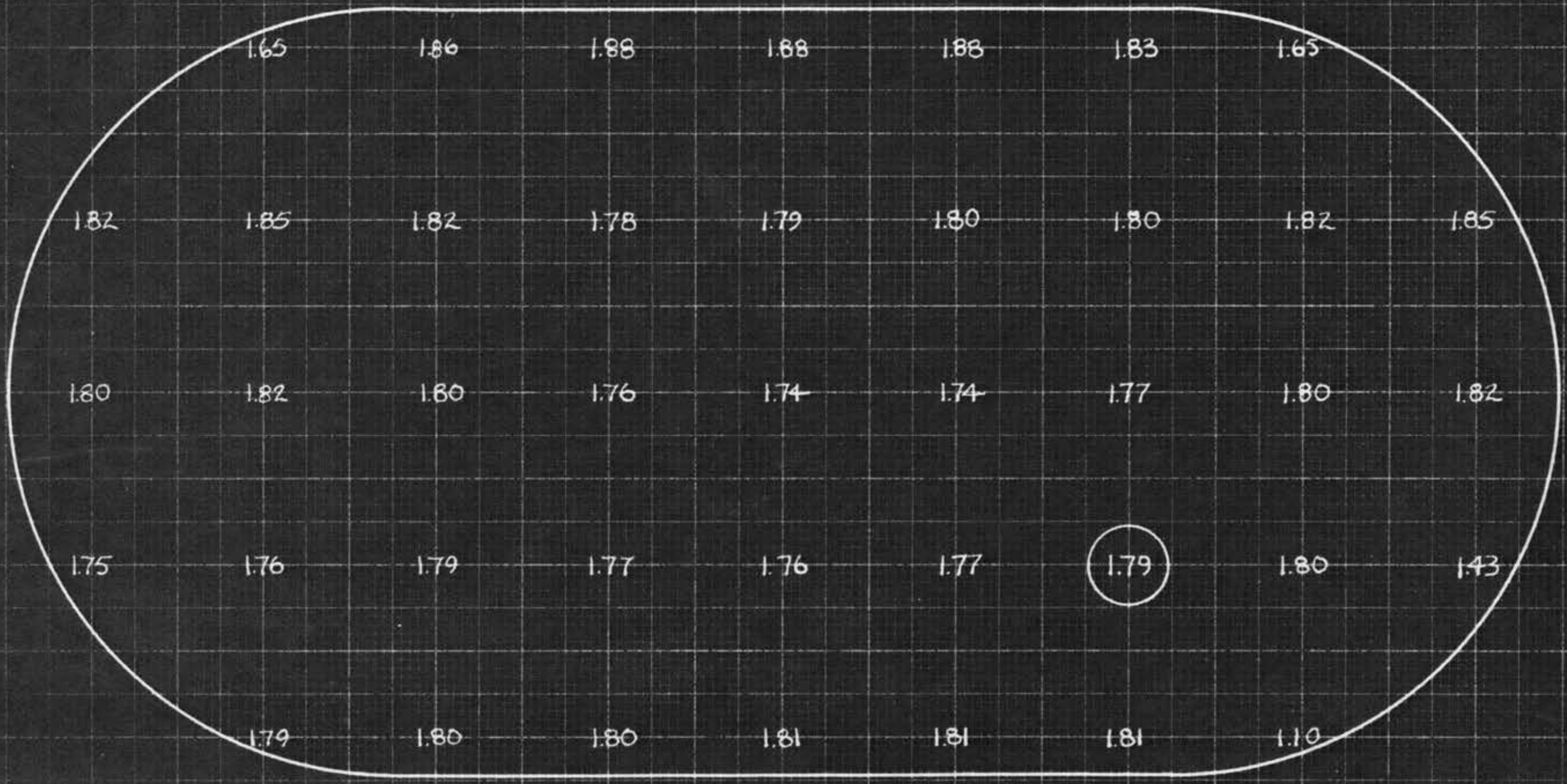


SCALE 1" = 4"

FIG. 10

VELOCITY PROFILE NO. 3

APPROX. 60 M.P.H.



SCALE 1" = 4"

FIG. 11

VELOCITY PROFILE NO. 4
APPROX. 70 M.P.H.

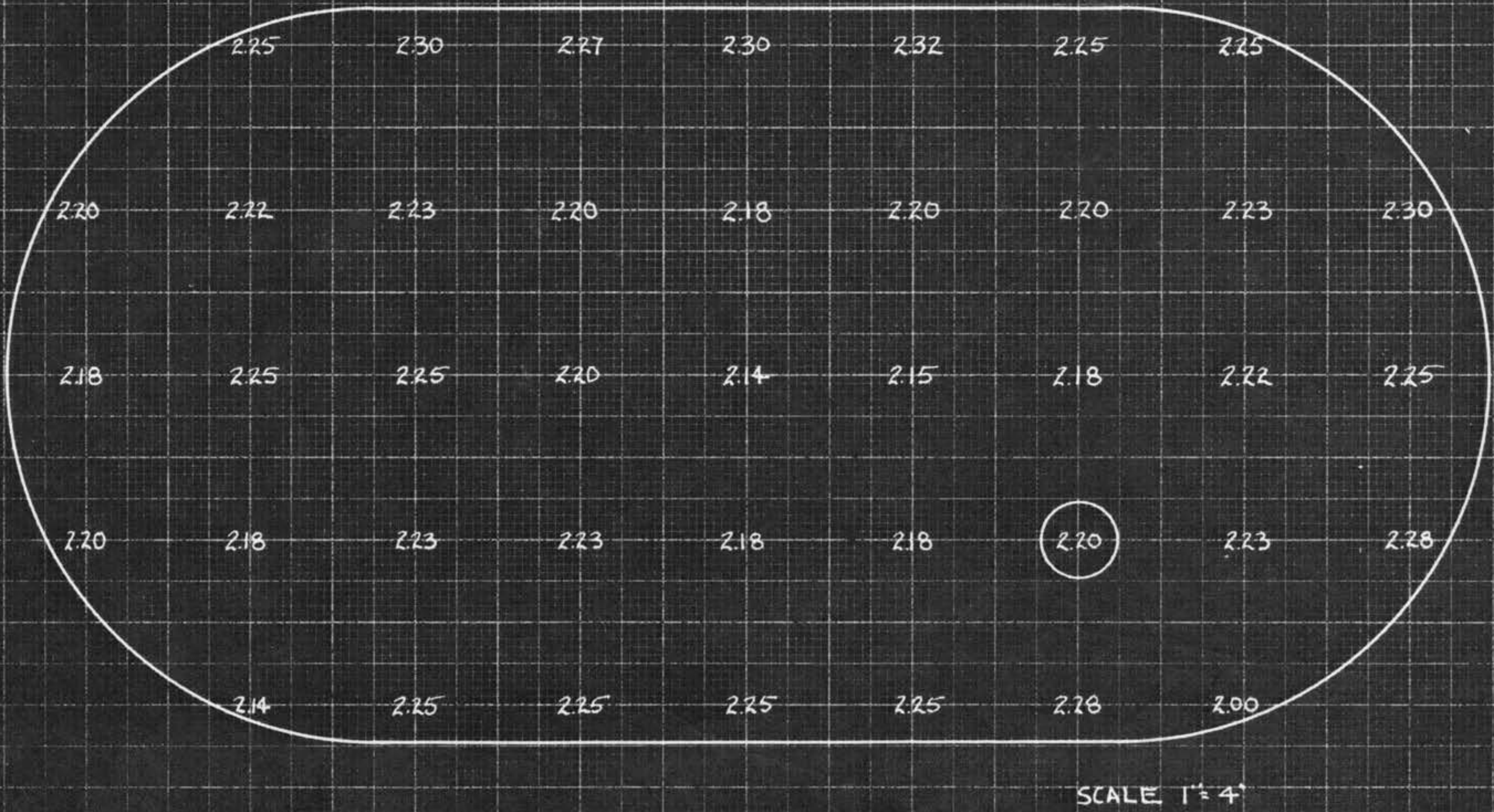
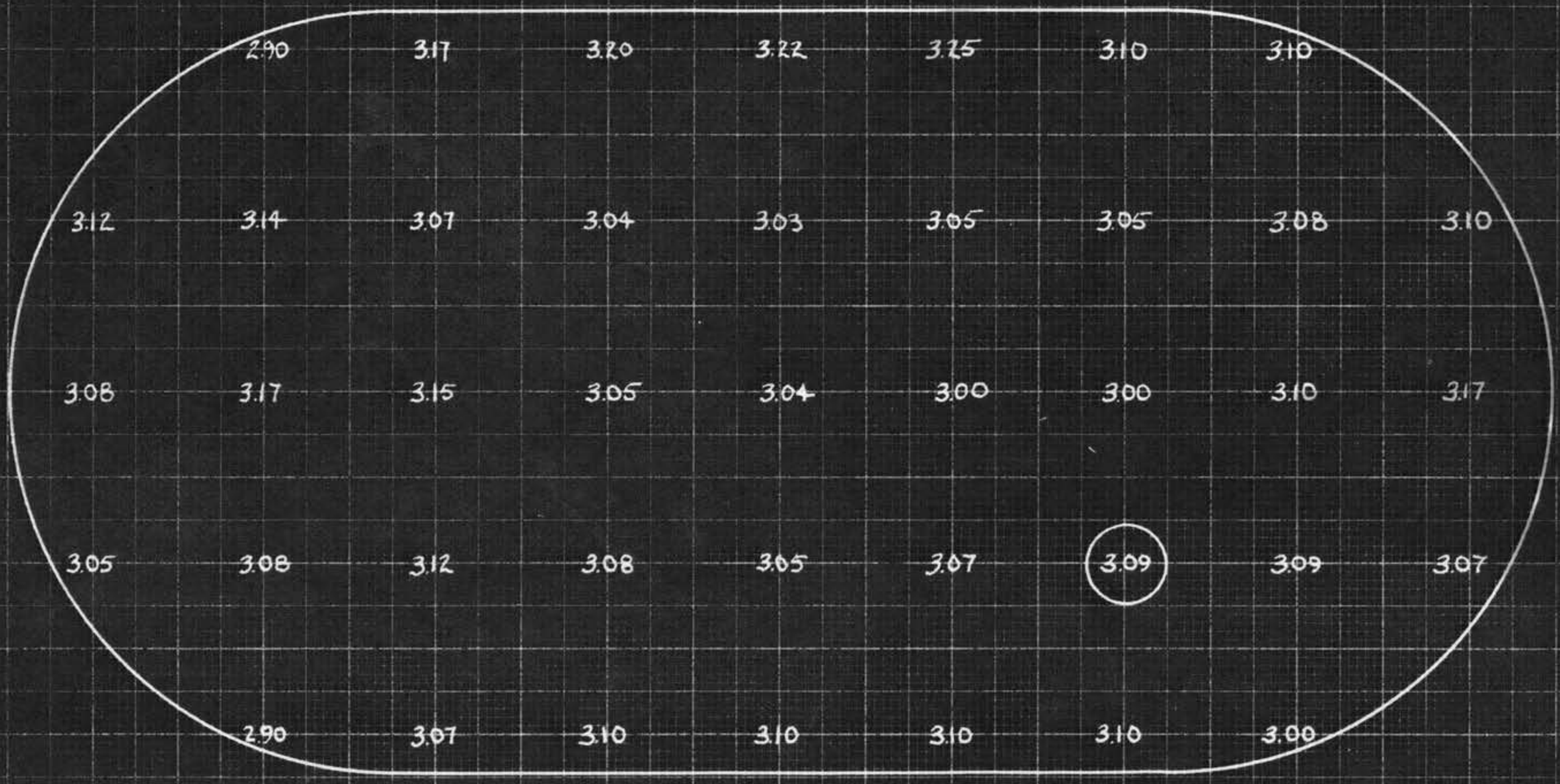


FIG. 12

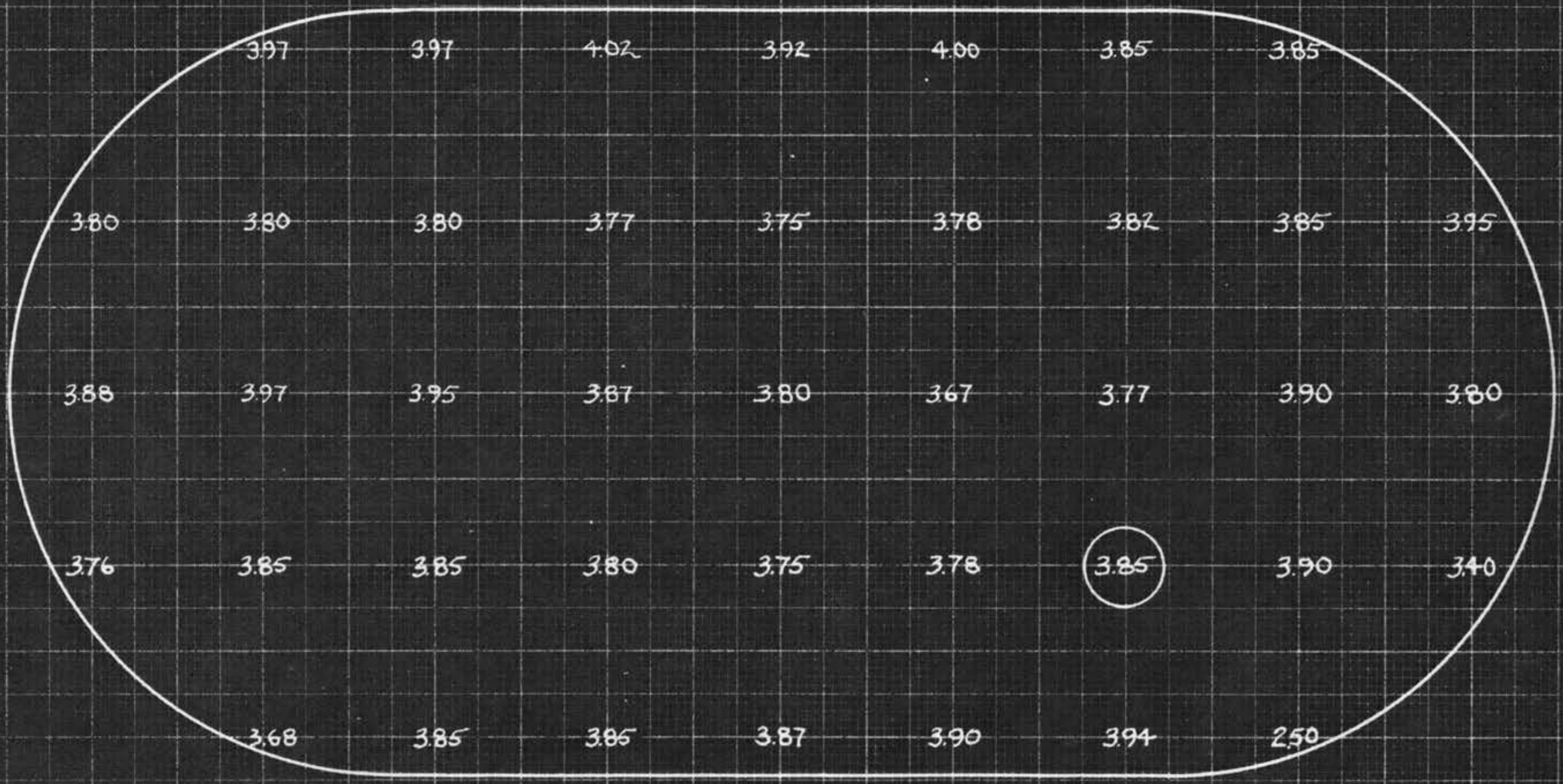
VELOCITY PROFILE NO. 5
APPROX. 80 M.P.H.



SCALE 1" = 4'

FIG. 13

VELOCITY PROFILE NO.6.
APPROX. 90 M.P.H.



SCALE 1" = 4'

FIG. 14

DETERMINATION OF THE TURBULENCE FACTOR

TEST PROCEDURE.--The sphere was mounted on the stinger, care being taken to insure that none of the threaded portion of the stinger was exposed to the air flow. The sphere was then given two coats of wax and polished to a high finish. The drag scale was balanced carefully to obtain the tare of the balance system and sphere. The motor was then started and brought up to the maximum safe operating speed. This speed was maintained until the airspeed reached a constant value. The pitot tube manometer and the drag balance readings were recorded and the motor speed reduced for the next reading. Manometer and drag data were recorded at velocity intervals of approximately .3 to .4 inches of water on the pitot tube manometer down to the minimum speed of the tunnel. Barometric pressure and wet and dry bulb temperatures were also recorded for the run. This procedure was repeated for each sphere tested.

Table I shows complete data for a run on a 5 inch pine sphere. The Net Drag Scale Readings (column 4) were obtained by subtracting the Drag Scale Zero from each Drag Scale Reading (column 3). The Actual Net Drag on Model (column 5) was obtained by dividing the Net Drag Reading (column 4) by the scale constant K. Referring to Figure 7, page 11, and setting Drag Scale Reading = K(Drag of Model),

$$K = \frac{19.44\,(14.97)}{24.5\,(1.47)} = 8.09$$

That is, 1 pound of drag on the model causes a Net Drag Scale Reading of 8.09 pounds.

TABLE I

5" Sphere--Run No. I

Sphere Diameter 4.98"	Dry Bulb Temp. 92°F.
Barometer 29.30" Hg.	Wet Bulb Temp. 78°F.

Drag Scale Zero Reading 27.17#

Reading No. (1)	q inches H_2O (2)	Drag Scale Reading # (3)	Net Drag Scale Reading--# (4)	Actual Net Drag on Model # (5)
1	3.93	29.30	2.13	.2636
2	3.57	29.70	2.53	.3132
3	3.25	30.35	3.18	.3940
4	2.96	30.78	3.61	.4470
5	2.64	30.89	3.72	.4620
6	2.36	30.96	3.79	.4700
7	2.17	30.79	3.62	.4480
8	1.93	30.60	3.43	.4245
9	1.76	30.51	3.34	.4130
10	1.62	30.38	3.21	.3975
11	1.34	30.12	2.95	.3650
12	1.09	29.76	2.59	.3210
13	.76	29.02	1.85	.2290

CALCULATIONS.--Air density was calculated for each run based on the barometric pressure, temperature and humidity. Humidity effects were corrected for as recommended in Von Mises.[1] Figure 15 is reproduced from Von Mises, page 20, and was used for obtaining values of the constants "A" and P_1.

Air density calculations for t_d the data of Table I follow:

From Fig. 15, "A" = 1.625

Wet Bulb depression = 92 - 78 = 14

t_d = D.B. - "A"(Depression)

= 92 - 1.625(14) = 69.2

From Fig. 15, P_1 = .27

P_r = 29.30 - .27 = 29.03"Hg

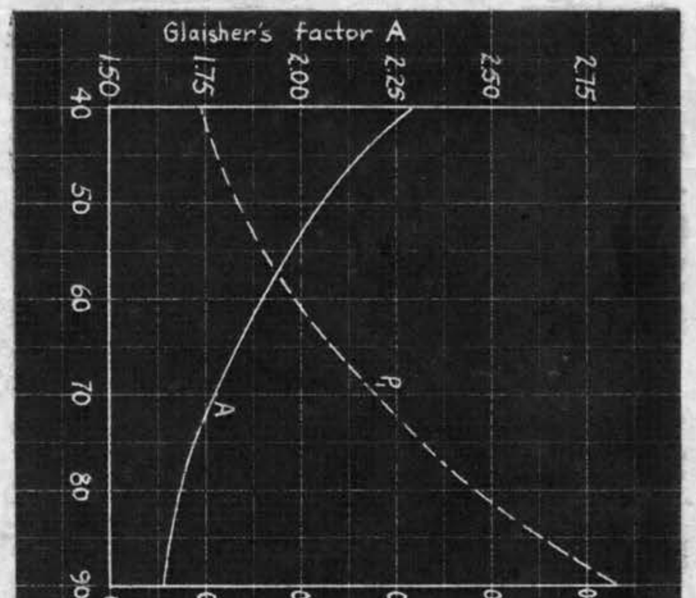


Fig. 15. "A" plotted against Dry Bulb Temp. and P_1 plotted against t_d.

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[1] Von Mises, *op. cit.*, p. 20.

Density $d = \frac{P_r}{RT} = \frac{29.03(.491)(144)}{53.33(551.7)} = .0696$ #/ cu. ft.

Mass density $\rho = \frac{d}{g} = \frac{.0696}{32.17} = .002175$ slug / cu. ft.

Air velocity was determined from observed values of q which represented the velocity head in inches of water. The relationship may be expressed as, $q = \frac{\rho V^2}{2}$, where q is in #/sq. ft. and V is in ft./ sec.

Expressing q in inches of water, and solving for V

$$\frac{q(62.4)}{12} = \frac{\rho V^2}{2}$$

$$V^2 = \frac{2(62.4)q}{12\rho} = \frac{10.396\ q}{\rho}$$

$$\text{or}\quad V = \sqrt{\frac{10.396\ q}{\rho}}$$

For the data of Table I,

$$V = \sqrt{\frac{10.396\ q}{\rho}} = 69\sqrt{q}$$

Reynolds Number calculations were based on the diameter of the spheres in feet, $Re = \frac{\rho VD}{\mu}$. Figure 16 shows values of μ, the coefficient of viscosity, plotted against temperature in degrees Fahrenheit. For the data in Table I, $\mu = 3.91 \times 10^{-7}$ from Figure, 16.

$$Re = \frac{.002175(4.98)V}{12(3.91 \times 10^{-7})}$$

$$Re = 2308V$$

C_d values were based on the formula, Drag $= C_d\ \frac{\rho}{2} S\ V^2$. Expressing the cross sectional area in sq. inches and solving for C_d;

$$C_d = \frac{2(144)\text{Drag}}{\rho S V^2} = \frac{288\ \text{Drag}}{\rho S V^2}$$

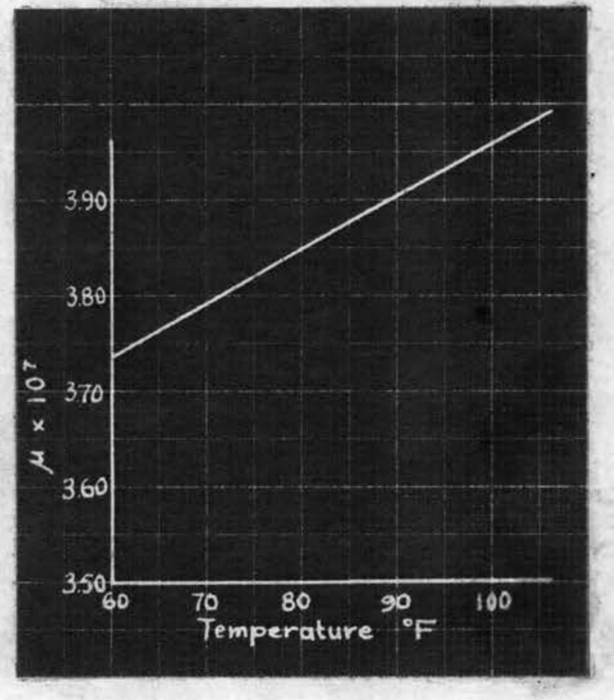


Fig. 16.

For the data in Table I,

$$C_d = \frac{288 \text{ Drag}}{.002175(.7854)(4.98)^2 V^2} = 6780\frac{\text{Drag}}{V^2}$$

C_d and Re calculations were carried out in tabular form as illustrated in Table II for the data of Table I. There follow detailed calculations for Reading No. 1 based on the above formulas:

Values of q and Drag, columns (2) and (3) Table II, were tabulated directly from columns (2) and (5), Table I.

$$V = 69\sqrt{q} = 69\sqrt{3.93} = 136.8 \text{ ft/sec.}$$

$$V^2 = (136.8)^2 = 18{,}700$$

$$C_d = 6780\frac{\text{Drag}}{V^2} = \frac{6780(.2636)}{18{,}700} = .0955$$

$$Re = 2308\,V = 2308(136.8) = 316{,}000$$

TABLE II

Reading No. (1)	q inches H_2O (2)	Drag # (3)	V ft./sec. (4)	V^2 (5)	C_d (6)	Re (7)
1	3.93	.2636	136.8	18,700	.0955	316,000
2	3.57	.3132	130.4	17,000	.1248	301,000
3	3.25	.3940	123.8	15,330	.1740	286,000
4	2.96	.4470	118.8	14,100	.2145	274,000
5	2.64	.4620	112.2	12,580	.2485	258,600
6	2.36	.4700	106.0	11,230	.2830	245,000
7	2.17	.4480	101.6	10,320	.2945	234,600
8	1.93	.4245	95.8	9,180	.3130	221,500
9	1.76	.4130	91.5	8,370	.3350	211,400
10	1.62	.3975	87.8	7,700	.3490	202,600
11	1.34	.3650	79.8	6,370	.3880	184,200
12	1.09	.3210	72.0	5,180	.4190	166,200
13	.76	.2290	60.1	3,610	.4290	138,800

Test data and calculated results for 10 pine spheres ranging in diameter from 2½ to 7 inches are presented in condensed tabular form. These tables are followed by curves showing the variation of C_d with Re for the 10 pine spheres tested.

TABLE III

Sphere diameter 2.46"
Run No. 1
Barometric Pressure 29.3"Hg.

Dry Bulb Temp. 88°F
Wet Bulb Temp. 72°F
$\rho = .002190$ slug/cu. ft.

$V = 68.8\sqrt{q}$

$Re = 1152\ V$

$C_d = 27{,}700\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	4.05	.273	138.3	.394	159,500
2	3.80	.252	134.0	.388	154,500
3	3.62	.248	130.8	.401	150,800
4	3.37	.237	126.2	.412	145,300
5	3.24	.222	123.8	.401	142,700
6	3.08	.209	120.8	.396	139,100
7	2.75	.190	114.0	.405	131,300
8	2.46	.168	107.8	.400	124,100
9	2.21	.156	102.1	.413	117,800
10	1.98	.138	97.8	.400	112,700
11	1.73	.125	90.5	.422	104,100
12	1.45	.101	82.8	.408	95,500
13	1.18	.086	74.8	.427	86,200
14	.95	.064	67.0	.396	77,200
15	.82	.059	62.3	.423	71,800

TABLE IV

Sphere diameter 2.99"
Run No. 1
Barometric Pressure 29.3"Hg.

Dry Bulb Temp. 83°F
Wet Bulb Temp. 73°F
$\rho = .002205$ slug/cu. ft.

$V = 68.7\sqrt{q}$

$Re = 1419\ V$

$C_d = 18{,}550\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	3.95	.341	136.5	.339	192,200
2	3.65	.330	131.2	.358	186,000
3	3.30	.320	124.5	.377	176,500
4	2.85	.299	116.0	.413	164,700
5	2.53	.275	109.0	.433	154,800
6	2.17	.240	101.0	.437	143,300
7	1.89	.205	94.3	.427	134,000
8	1.72	.193	90.0	.442	127,700
9	1.49	.167	83.8	.440	119,000
10	1.20	.138	75.3	.453	107,000
11	1.02	.117	69.4	.452	98,500
12	.78	.090	60.7	.454	86,300

TABLE V

Sphere diameter 3.48"
Run No. 1
Barometric Pressure 29.09"Hg.

Dry Bulb Temp. 100°F
Wet Bulb Temp. 81°F
$\rho = .002132$ slug/cu. ft.

$V = 69.75\sqrt{q}$

$Re = 1562\,V$

$C_d = 14{,}170\,\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	4.29	.234	144.5	.186	225,500
2	4.06	.287	140.5	.206	219,000
3	3.82	.319	136.1	.244	212,700
4	3.36	.346	127.6	.301	199,000
5	3.04	.342	121.5	.329	189,700
6	2.70	.338	114.5	.365	178,800
7	2.43	.329	108.6	.395	169,400
8	2.13	.303	101.8	.416	159,000
9	1.81	.268	93.8	.432	146,500
10	1.57	.235	87.3	.437	136,200
11	1.17	.168	75.4	.419	117,700
12	.81	.124	62.7	.433	98,000

TABLE VI

Sphere diameter 4.00"
Run No. 1
Barometric Pressure 29.3"Hg.

Dry Bulb Temp. 87°F
Wet Bulb Temp. 75.5°F
$\rho = .00218$ slug/cu. ft.

$V = 69\sqrt{q}$

$Re = 1867\,V$

$C_d = 10{,}530\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	4.12	.203	140.0	.109	261,800
2	3.76	.203	134.0	.119	250,000
3	3.47	.199	128.5	.127	240,000
4	3.17	.210	122.7	.147	229,000
5	2.77	.229	114.7	.183	214,000
6	2.48	.249	108.5	.223	203,000
7	2.25	.264	103.4	.260	193,300
8	1.93	.292	95.8	.335	179,000
9	1.72	.299	90.4	.383	169,000
10	1.53	.292	85.3	.425	159,500
11	1.12	.239	73.0	.474	136,400
12	.77	.175	60.6	.502	113,200

TABLE VII

Sphere diameter 4.48"
Run No. 1
Barometric Pressure 29.3"Hg.

Dry Bulb Temp. 91°F
Wet Bulb Temp. 79°F
ρ = .00218 slug/cu. ft.

$V = 69\sqrt{q}$ Re = 2082 V $C_d = 8,365\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	3.85	.270	135.2	.123	282,000
2	3.47	.240	128.3	.122	267,500
3	3.15	.214	122.5	.120	255,300
4	2.87	.193	117.7	.119	243,000
5	2.60	.191	111.0	.129	231,400
6	2.21	.197	102.2	.157	213,400
7	1.86	.196	94.2	.184	196,000
8	1.63	.199	88.1	.215	183,500
9	1.36	.188	80.4	.243	167,700
10	1.12	.205	72.9	.321	152,000
11	.77	.202	58.6	.492	122,000

TABLE VIII

Sphere diameter 4.98"
Run No. 1
Barometric Pressure 29.3"Hg.

Dry Bulb Temp. 92°F
Wet Bulb Temp. 79°F
ρ = .002175 slug/cu. ft.

$V = 69\sqrt{q}$ Re = 2308 V $C_d = 6,780\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	3.93	.264	136.8	.095	316,000
2	3.57	.313	130.4	.125	301,000
3	3.25	.394	123.8	.174	286,000
4	2.96	.447	118.8	.214	274,000
5	2.64	.462	112.2	.248	258,600
6	2.36	.470	106.0	.283	245,000
7	2.17	.448	101.6	.294	234,600
8	1.93	.424	95.8	.313	221,500
9	1.76	.413	91.5	.335	211,400
10	1.62	.397	87.8	.349	202,600
11	1.34	.365	79.8	.388	184,200
12	1.09	.321	72.0	.419	166,200
13	.76	.229	60.1	.429	138,800

TABLE IX

Sphere diameter 5.48"
Run No. 1
Barometric Pressure 29.21"Hg.

Dry Bulb Temp. 82°F
Wet Bulb Temp. 74°F
$\rho = .002205$ slug/cu. ft.

$V = 68.6\sqrt{q}$ Re = 2610 V $C_d = 5{,}510\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	3.59	.195	130.0	.064	338,800
2	3.23	.198	123.2	.072	322,000
3	2.95	.217	117.8	.086	307,500
4	2.54	.267	109.3	.123	285,500
5	2.32	.348	104.5	.176	272,600
6	2.10	.399	99.4	.222	259,500
7	1.86	.435	93.6	.274	244,100
8	1.61	.455	87.0	.331	227,000
9	1.44	.458	82.3	.373	214,800
10	1.19	.437	74.8	.430	195,300
11	.97	.401	67.6	.483	176,500
12	.76	.331	59.8	.509	156,200
13	.65	.264	55.3	.477	144,200

TABLE X

Sphere diameter 5.99"
Run No. 1
Barometric Pressure 29.21" Hg.

Dry Bulb Temp. 85°F
Wet Bulb Temp. 75°F
$\rho = .002155$ slug/cu. ft.

$V = 69.3\sqrt{q}$ Re = 2776 V $C_d = 4{,}740\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	3.50	.210	129.6	.059	360,000
2	3.04	.196	120.8	.064	335,400
3	2.63	.188	112.3	.071	311,500
4	2.35	.195	106.2	.083	295,000
5	1.98	.237	97.6	.118	270,500
6	1.69	.300	90.1	.175	250,000
7	1.50	.317	84.8	.209	235,500
8	1.23	.357	76.8	.287	213,300
9	1.00	.377	69.3	.371	192,300
10	.77	.340	60.8	.435	168,800
11	.66	.320	56.2	.479	156,200

TABLE XI

Sphere diameter 6.50"
Run No. 1
Barometric Pressure 29.19"Hg.

Dry Bulb Temp. 90°F
Wet Bulb Temp. 80°F
ρ = .002155 slug/cu. ft.

$V = 69.4\sqrt{q}$

$Re = 2990\ V$

$C_d = 4{,}030\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	3.65	.380	132.5	.087	396,200
2	3.31	.361	126.3	.091	378,100
3	2.99	.341	120.0	.096	359,000
4	2.62	.272	112.5	.087	336,500
5	2.25	.232	104.1	.086	311,500
6	1.92	.190	96.2	.083	288,000
7	1.65	.178	89.2	.090	266,800
8	1.50	.186	85.0	.104	254,200
9	1.26	.207	78.0	.138	233,300
10	1.00	.147	69.4	.123	207,800
11	.82	.158	62.8	.162	188,000
12	.62	.227	54.5	.308	163,000

TABLE XII

Sphere diameter 7.01"
Run No. 1
Barometric Pressure 29.19"Hg.

Dry Bulb Temp. 96°F
Wet Bulb Temp. 80°F
ρ = .00214 slug/cu. ft.

$V = 69.6\sqrt{q}$

$Re = 3180\ V$

$C_d = 3485\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	3.50	.521	130.2	.107	414,000
2	3.15	.463	123.5	.106	393,000
3	2.84	.415	117.2	.106	372,500
4	2.40	.362	108.0	.108	343,000
5	2.09	.316	100.5	.109	319,000
6	1.83	.251	94.3	.099	300,000
7	1.53	.200	86.0	.094	273,500
8	1.26	.226	78.0	.129	251,500
9	1.02	.274	70.3	.194	223,900
10	.83	.321	63.0	.281	200,100
11	.62	.314	54.8	.365	174,400
12	.53	.303	50.7	.412	161,200

TABLE XIII

Sphere diameter 2.99"
Run No. 2
Barometric Pressure 29.09"Hg.

Dry Bulb Temp. 96°F
Wet Bulb Temp. 79°F
$\rho = .00214$ slug/cu. ft.

$V = 69.7\sqrt{q}$ Re = 1355 V $C_d = 19{,}150\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	4.33	.304	145.0	.276	196,800
2	4.05	.314	140.5	.305	190,000
3	3.77	.326	135.4	.340	183,600
4	3.47	.316	130.0	.359	176,000
5	3.15	.316	123.8	.395	167,800
6	2.86	.302	117.8	.416	159,700
7	2.59	.281	112.2	.428	152,000
8	2.42	.260	108.3	.424	147,000
9	2.17	.232	102.6	.423	139,000
10	1.89	.208	95.8	.432	129,900
11	1.72	.190	91.4	.436	123,900
12	1.42	.159	83.0	.443	112,500
13	1.08	.129	72.4	.470	98,300
14	.82	.099	63.1	.475	85,600

TABLE XIV

Sphere diameter 4.00"
Run No. 2
Barometric Pressure 29.09"Hg.

Dry Bulb Temp. 98°F
Wet Bulb Temp. 80°F
$\rho = .002135$ slug/cu. ft.

$V = 69.7\sqrt{q}$ Re = 1800 V $C_d = 10{,}170\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	4.23	.577	143.3	.300	268,000
2	3.98	.577	139.2	.319	250,500
3	3.68	.557	133.8	.334	240,700
4	3.38	.536	128.2	.349	231,000
5	3.08	.506	122.3	.362	220,000
6	2.73	.445	115.1	.360	207,200
7	2.45	.366	109.0	.330	196,300
8	2.09	.307	100.0	.324	181,700
9	1.71	.262	91.2	.339	164,000
10	1.40	.232	82.6	.365	148,700
11	1.06	.180	71.8	.376	129,200
12	.80	.152	62.3	.420	112,200

FIG. 17.

PINE 2.46" D. FROM TABLE III

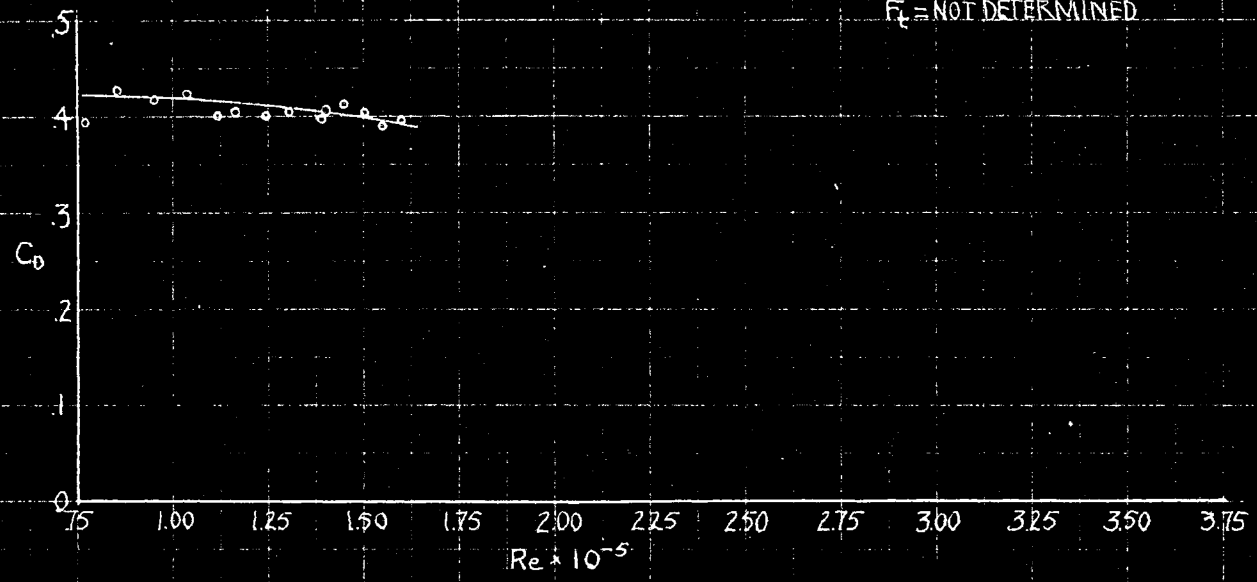


FIG. 18.

PINE 2.99" D. FROM TABLE IV

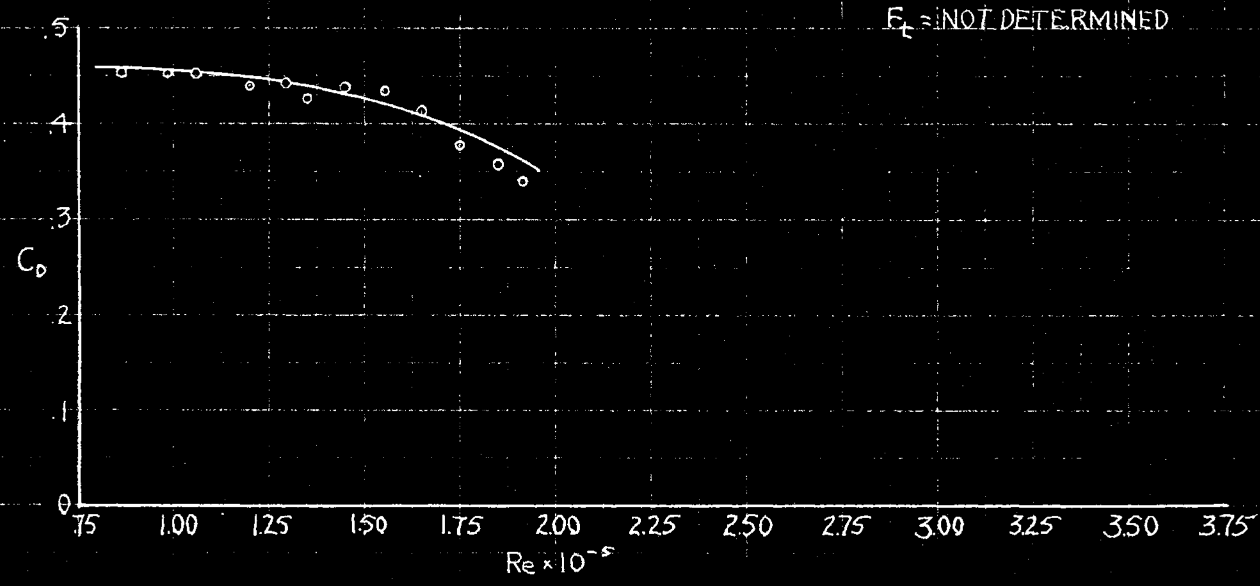


FIG. 19

PINE 3.48"D. FROM TABLE V

$F_t = 1.92$

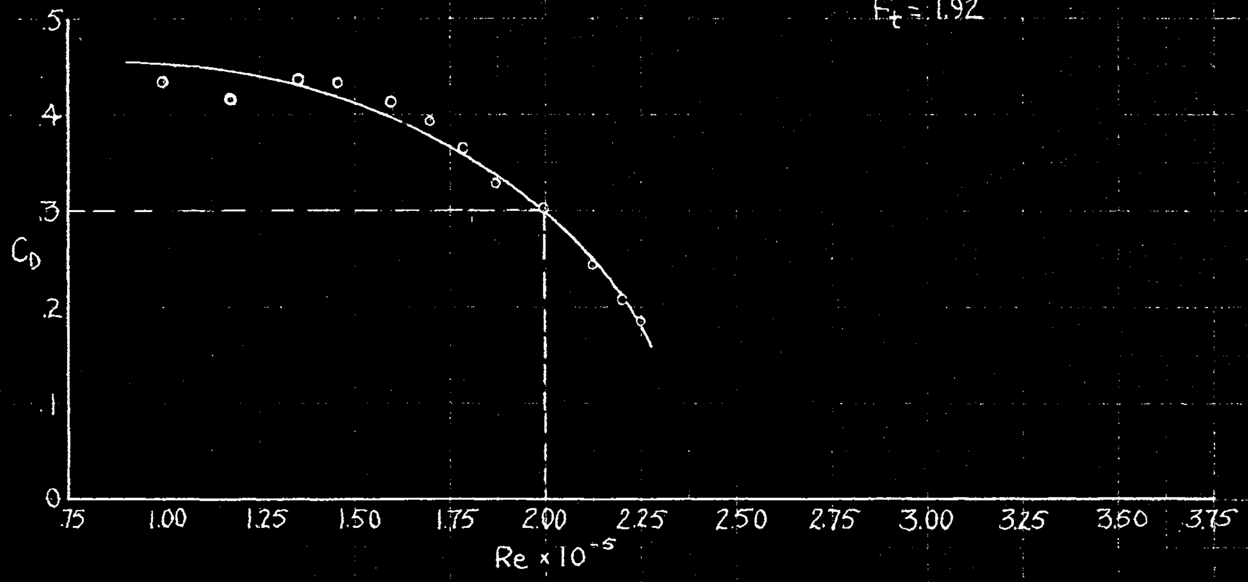


FIG. 20

PINE 4.00"D. FROM TABLE VI

$F_t = 2.06$

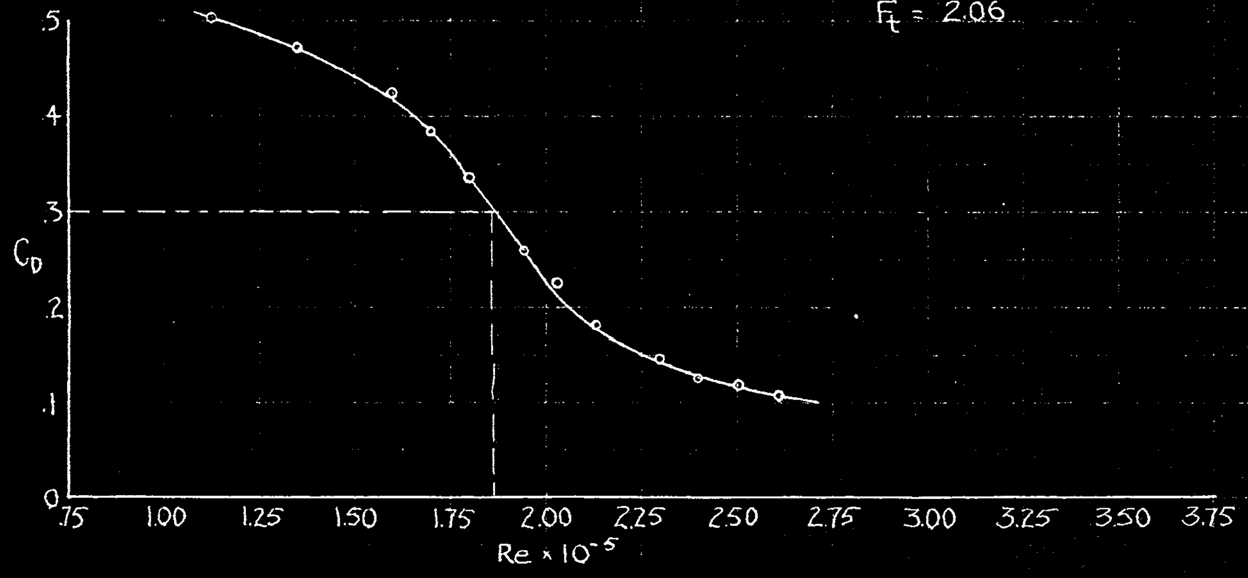


FIG. 21

PINE 4.48"D. FROM TABLE VII

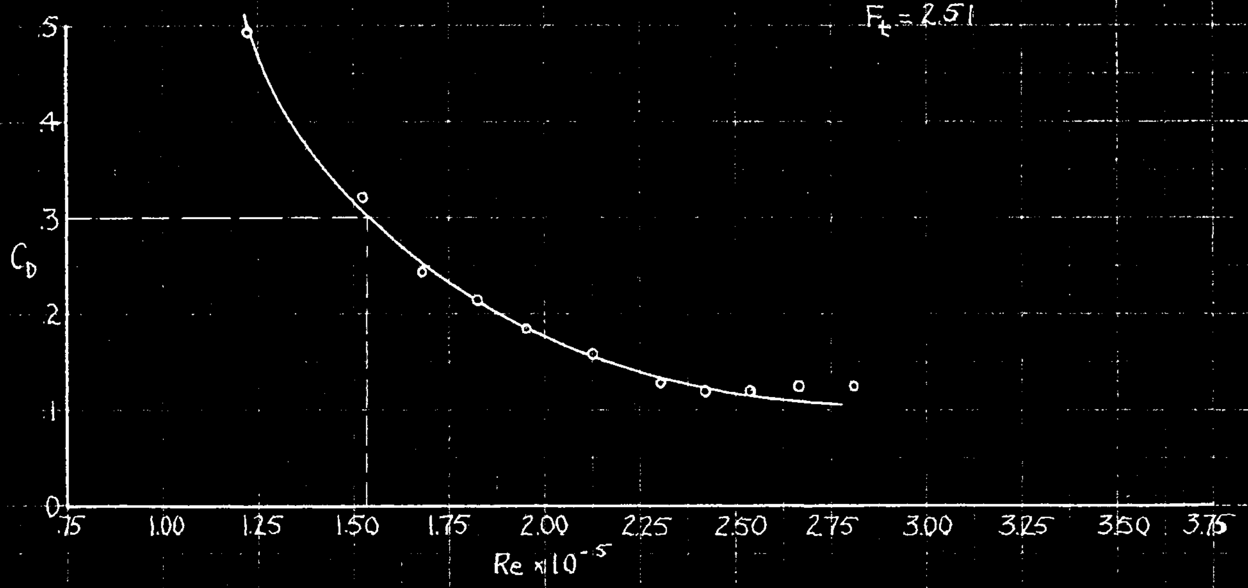


FIG. 22

PINE 4.98"D. FROM TABLE VIII

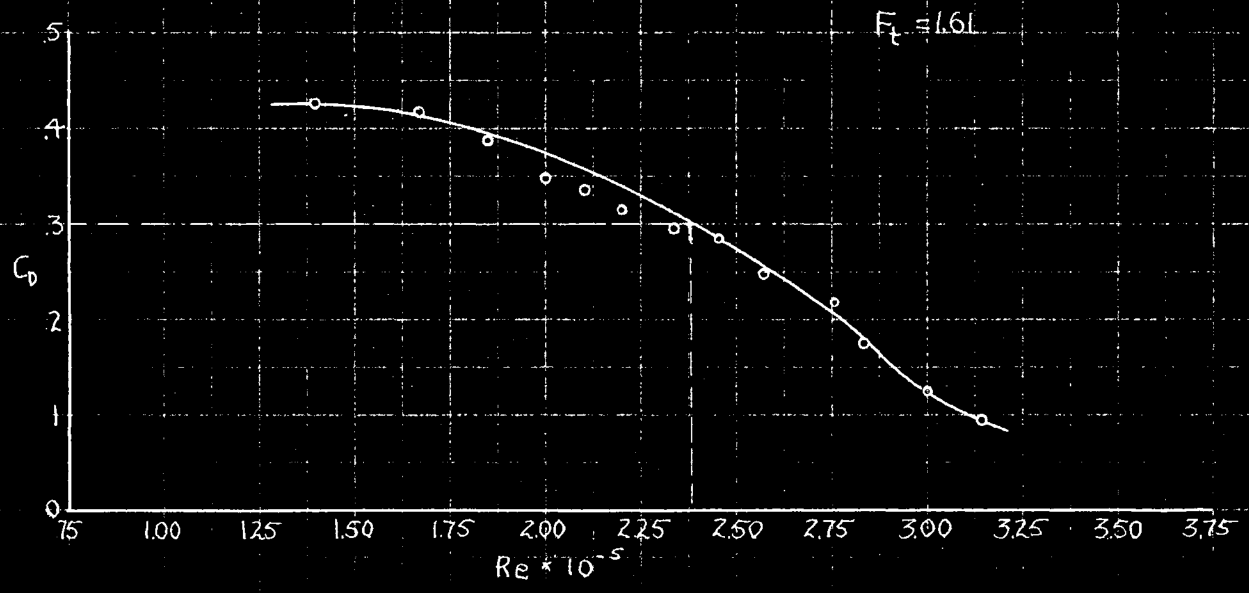


FIG. 23

PINE 548" D. FROM TABLE IX

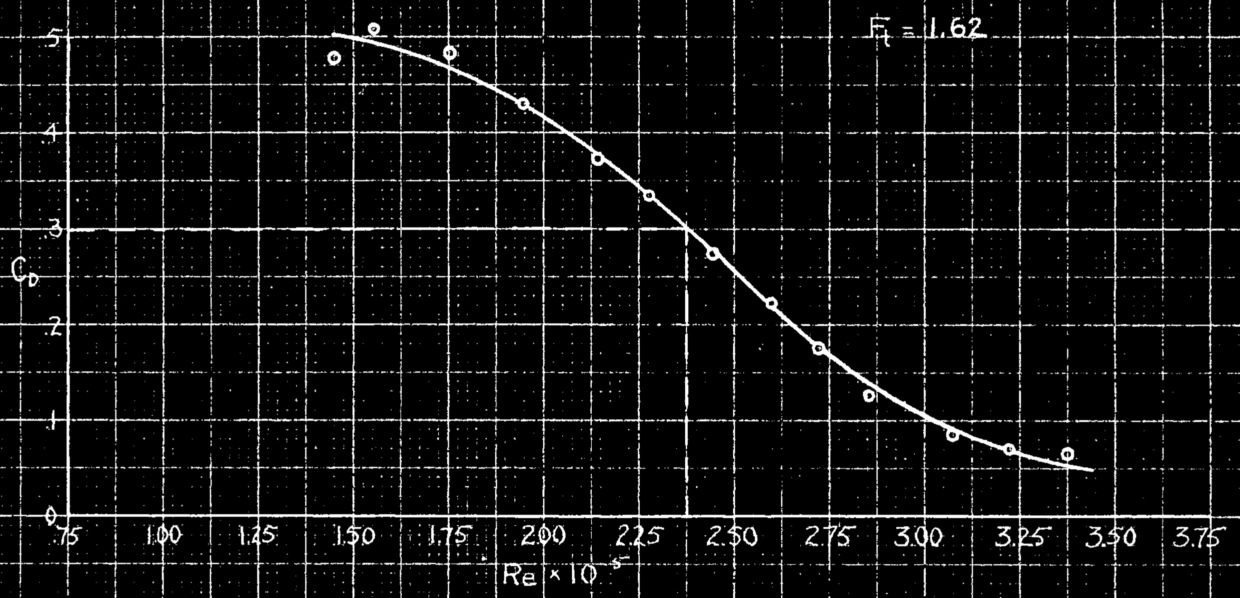


FIG. 24

PINE 599' D. FROM TABLE X

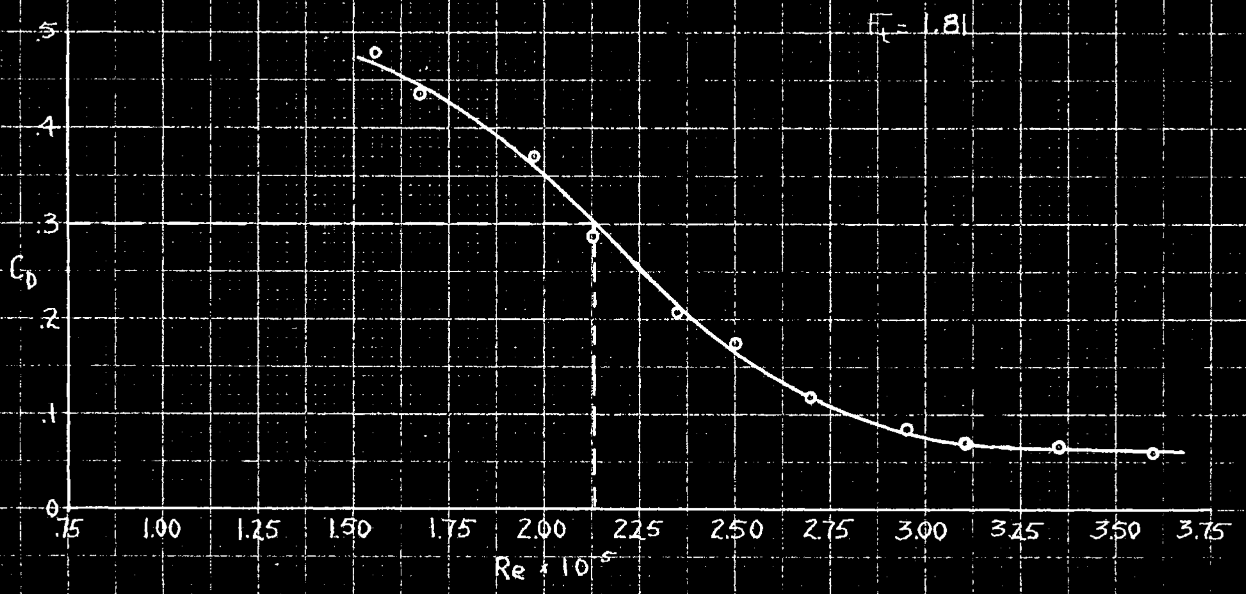


FIG. 25

PINE 6.50"D FROM TABLE XI

$F_t = 2.47$

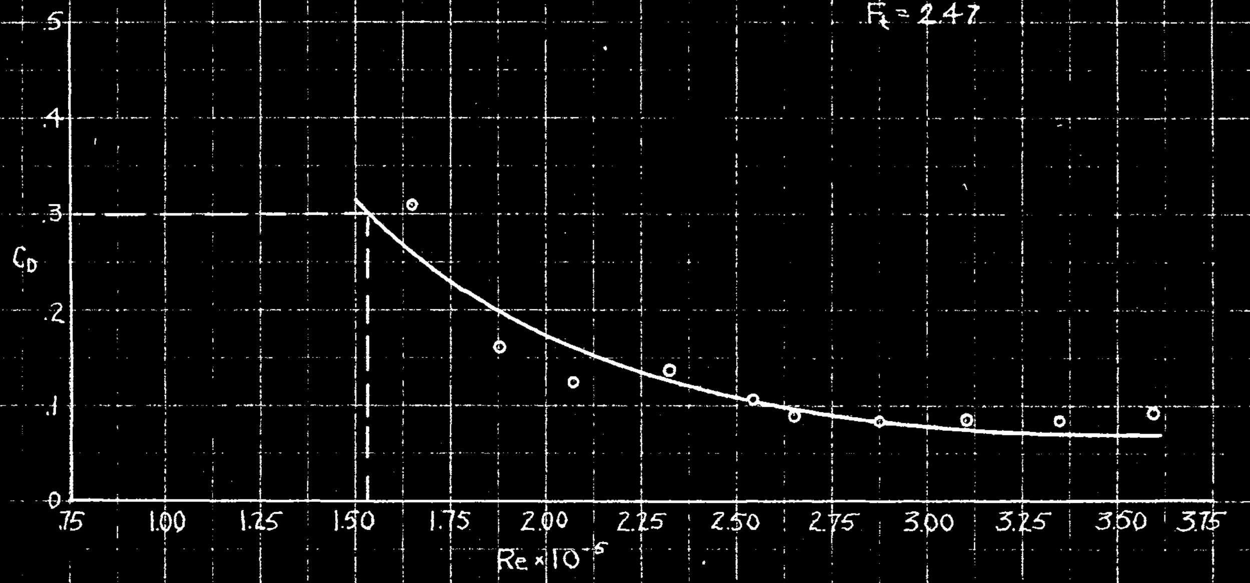


FIG. 26

PINE 7.01"D FROM TABLE XII

$F_t = 2.02$

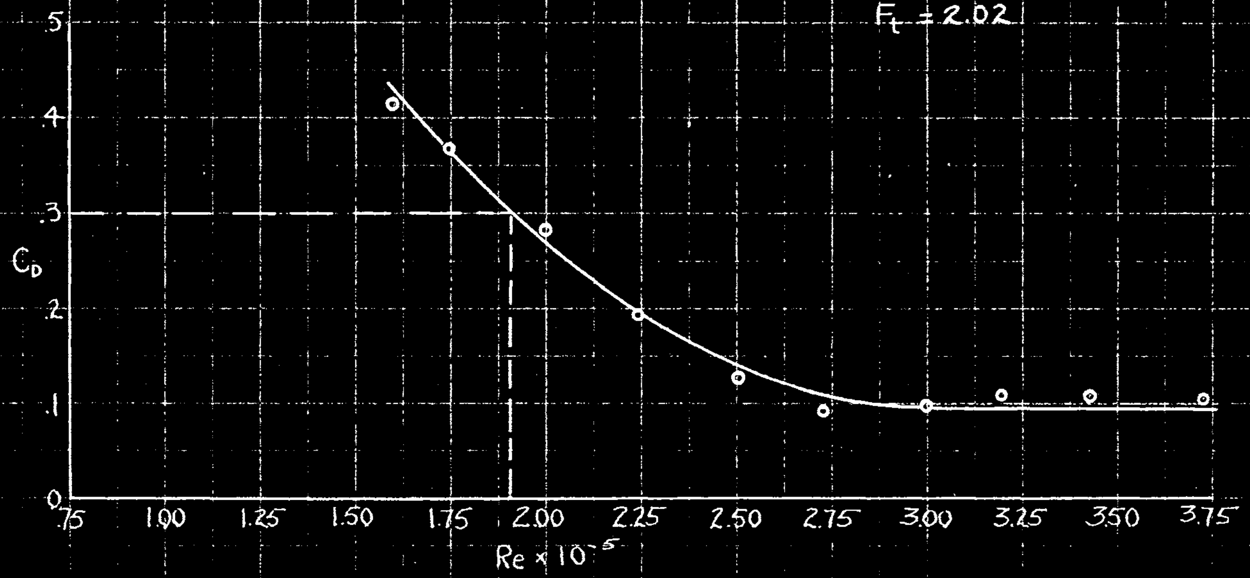


FIG 27

PINE 2.99" D. FROM TABLE XIII

$F_t = 2.02$

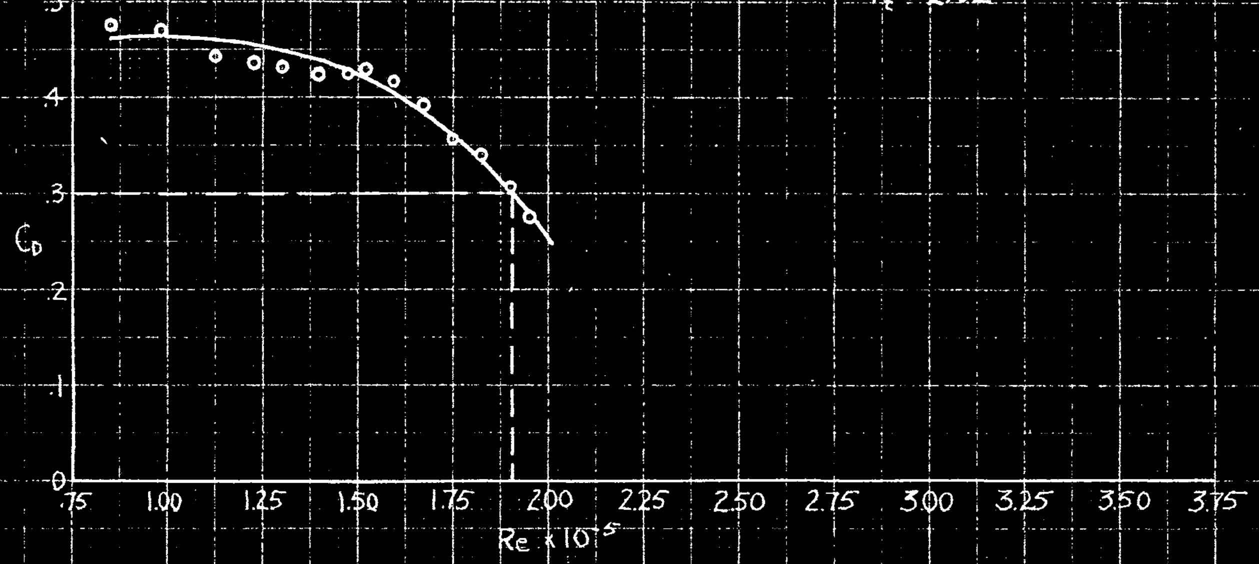
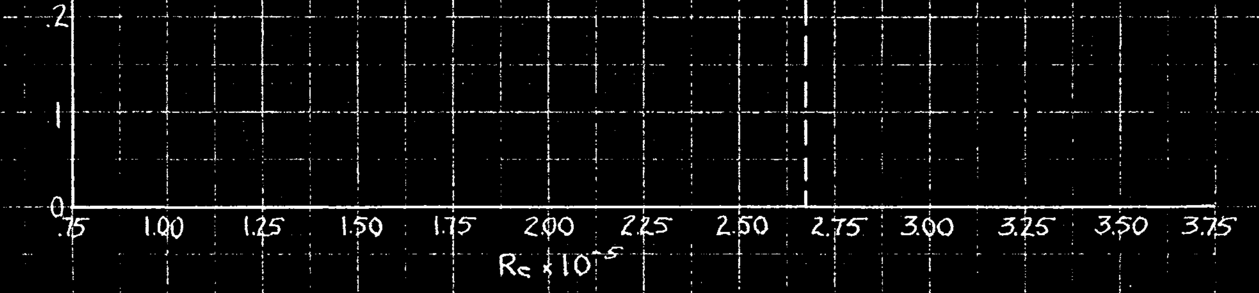


FIG. 28

PINE 4.00" D. FROM TABLE XIV

$F_t = 1.45$



DISCUSSION OF TEST RESULTS ON PINE SPHERES.--A study of the preceding test results shows that the pine spheres tested gave widely different values for the Turbulence factor. The 3" and 4" spheres, which were run twice, show very inconsistent results. It was decided that the inconsistency was probably caused by one or more of the following factors:

1. Threaded hole for mounting not truly radial.
2. Noticeable vibration of model during test.
3. Model not a perfect shpere, i.e., flat spots causing lift.

The following tests were run in an effort to determine which of the above factors were responsible for the inconsistency.

The 5" pine sphere was selected for detailed observation since it was near the middle of the size range and the mounting hole was very close to radial. This sphere was mounted in the tunnel and short tests were run with it in four

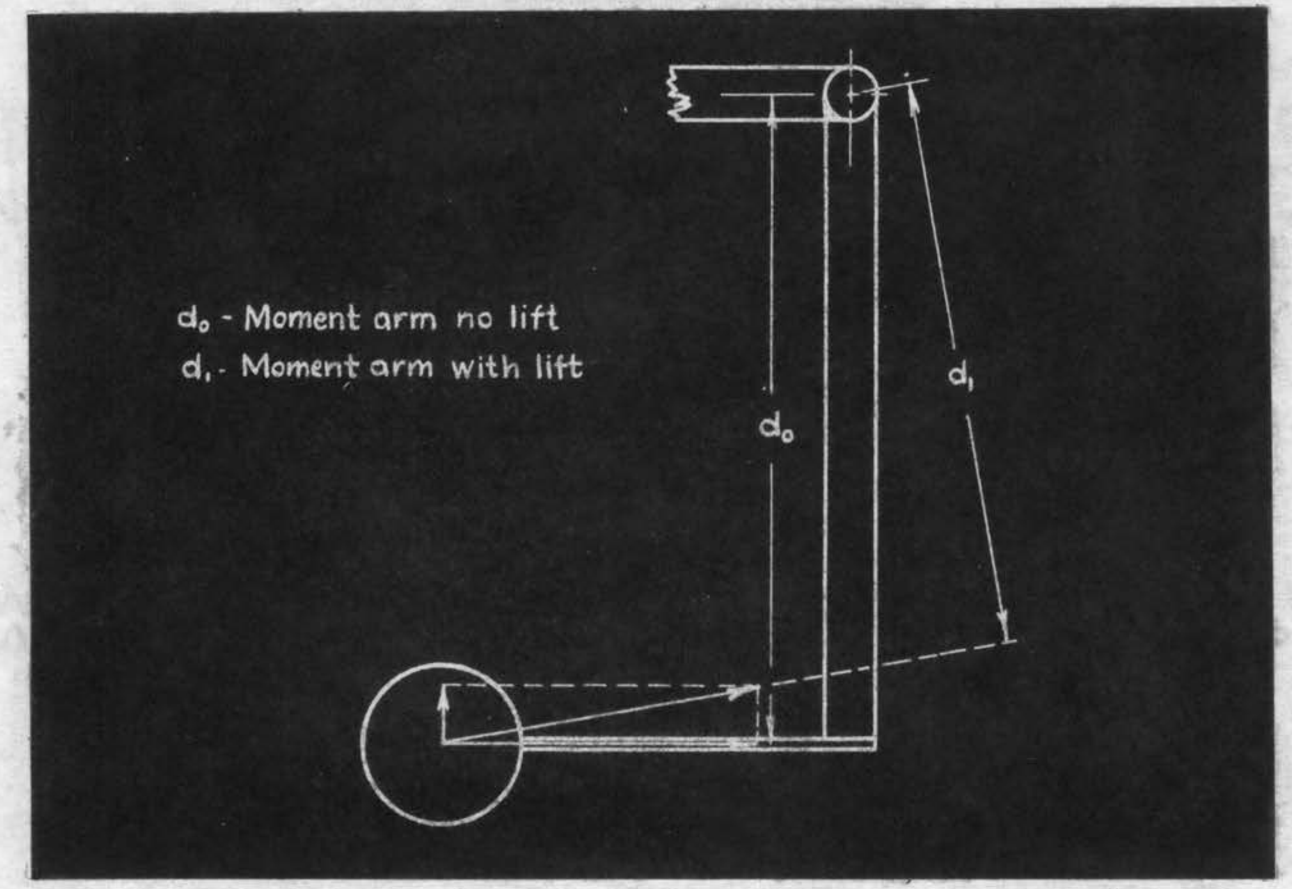


Fig. 29. Effect of Lift on Moment Arm.

TABLE XV

Sphere diameter 4.98"
Special Run (Pine Sphere)
Barometric Pressure 29.4"Hg

Dry Bulb Temp. 84°F
Wet Bulb Temp. 70°F
$\rho = .0222$ slug/cu. ft.

$V = 68.3\sqrt{q}$ $Re = 2445\ V$ $C_d = 6630\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
Pos. 0°					
1	3.97	.289	136.0	.103	332,600
2	3.63	.208	130.0	.081	318,000
3	3.37	.166	125.3	.070	306,400
4	3.11	.102	120.4	.047	294,600
5	2.84	.121	114.9	.061	281,000
6	2.51	.106	108.2	.060	264,800
7	2.20	.097	102.2	.063	247,800
8	1.91	.102	94.4	.076	231,000
9	1.58	.102	85.9	.091	210,400
10	1.20	.102	74.7	.121	183,000
11	.85	.121	62.9	.203	154,000
Pos. 90°					
1	4.09	.220	138.0	.077	337,500
2	3.60	.127	129.3	.054	316,500
3	3.42	.163	126.2	.069	309,000
4	3.02	.212	118.5	.100	290,000
5	2.73	.254	112.7	.132	275,500
Pos. 180°					
1	4.02	.237	136.8	.084	334,600
2	3.68	.350	131.0	.135	320,000
3	3.38	.467	125.3	.197	306,500
4	3.07	.531	119.4	.246	292,000
5	2.72	.544	112.7	.284	275,500
Pos. 270°					
1	3.96	.215	136.0	.077	332,000
2	3.65	.339	130.3	.132	318,500
3	3.35	.388	125.0	.165	305,500
4	2.97	.450	117.8	.201	287,500
5	2.58	.447	109.8	.246	268,000

positions. It was rotated 90° on the stinger between each test. With the reference point on the top of the sphere for the first run, the positions are referred to as 0°, 90°, 180°, and 270°. The angles indicate the amount the sphere was rotated clockwise from its position for the first test. A similar

TABLE XVI

Sphere diameter 2.875"
Special Run (Ball Bearing)
Barometric Pressure 29.26"Hg.

Dry Bulb Temp. 75°F
Wet Bulb Temp. 67°F
$\rho = .002245$ slug/cu. ft.

$V = 68\sqrt{q}$ $\quad$ $Re = 1410\ V$ $\quad$ $C_d = 19{,}700\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
Pos. 0°					
1	4.67	.428	147.0	.390	207,000
2	4.15	.393	138.5	.406	195,200
3	3.89	.371	134.0	.407	189,000
4	3.59	.357	129.0	.424	182,000
5	3.28	.325	123.2	.422	174,000
6	3.03	.302	118.4	.425	167,000
7	2.69	.272	111.5	.430	157,200
8	2.32	.234	103.5	.432	146,000
9	1.90	.208	93.8	.465	132,500
10	1.61	.163	86.3	.432	122,000
11	1.20	.126	74.5	.448	105,000
12	.85	.093	62.7	.465	88,400
Pos. 90°					
1	4.50	.410	144.2	.388	204,000
2	4.15	.393	138.5	.406	195,200
3	4.00	.378	136.0	.402	192,000
4	3.53	.341	127.8	.412	180,500
5	3.11	.307	120.0	.420	169,300
6	2.43	.252	106.0	.441	149,000
7	1.75	.184	90.0	.444	127,000
8	1.22	.129	75.0	.451	105,800
9	.85	.094	62.7	.472	88,400

series of tests were then run on a sphere known to be truly spherical. For this test, a 2 7/8 inch steel ball bearing was used. The mounting hole was very carefully drilled so that it was radial in direction.

Tables XV, XVI, and XVII show the data and results for these tests. Figures 30 and 31 show the results of the tests on the pine sphere and steel ball respectively. These curves show clearly that while the pine sphere gave widely different results for different positions, the steel ball gave consistent results for all positions. In view of the fact that both mounting holes were very close to radial and both spheres showed similar vibration tendencies, it

TABLE XVII

Sphere diameter 2.875	Dry Bulb Temp. 78°F
Special Run (Ball Bearing)	Wet Bulb Temp. 70°F
Barometric Pressure 29.26"Hg.	ρ = .00222 slug/cu. ft.

$V = 68.4\sqrt{q}$ $Re = 1390\ V$ $C_d = 19950\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
Pos. 180°					
1	4.52	.418	145.2	.396	202,000
2	4.09	.386	138.2	.403	192,200
3	3.90	.372	135.0	.407	187,500
4	3.44	.335	126.8	.415	176,200
5	3.04	.299	119.2	.420	165,700
6	2.5[illegible]	.266	109.1	.446	151,700
7	2.03	.215	97.5	.452	135,600
8	1.57	.166	85.7	.450	119,000
9	1.18	.124	74.2	.448	103,100
10	.90	.094	64.8	.445	90,000
Pos. 270°					
1	4.53	.414	145.8	.390	202,500
2	4.33	.398	142.2	.393	197,700
3	3.90	.373	134.9	.408	187,400
4	3.45	.348	126.8	.433	176,200
5	3.01	.299	118.5	.425	164,700
6	2.48	.253	107.8	.435	149,800
7	1.97	.214	95.8	.465	133,200
8	1.40	.149	80.8	.456	112,200
9	.91	.098	65.2	.458	90,600

was concluded that the pine sphere was actually producing lift due to small variations in shape. Figure 29 illustrates how relatively small lift components would radically affect the effective moment arm of the drag force.

The pine spheres were abandoned and a new set obtained from the Lignum Vitae Corporation. The Lignum Vitae spheres were machine turned and accurate to less than .01 inch.

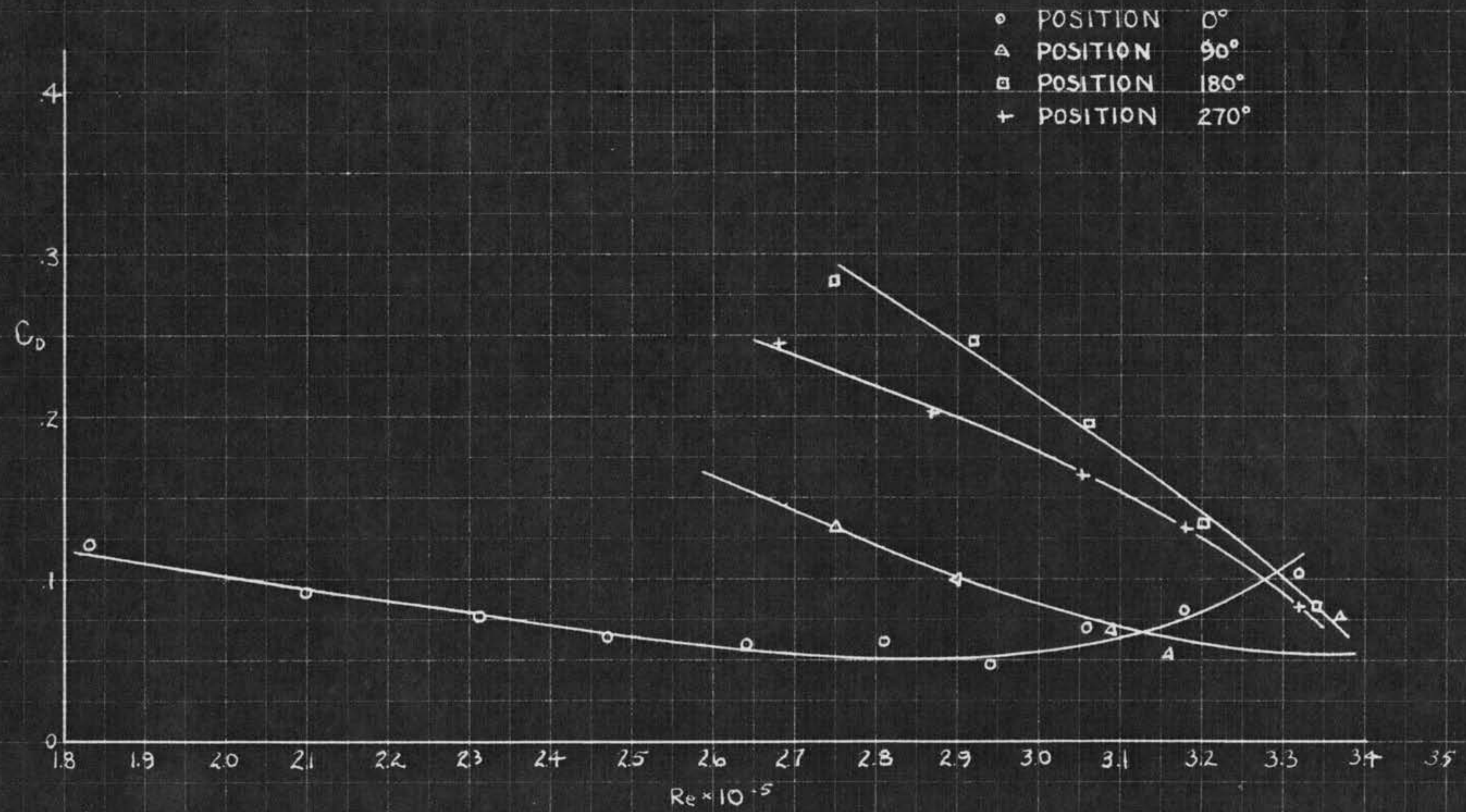


FIG. 30 PINE SPHERE 4.98 D.
FOUR ROTATED POSITIONS

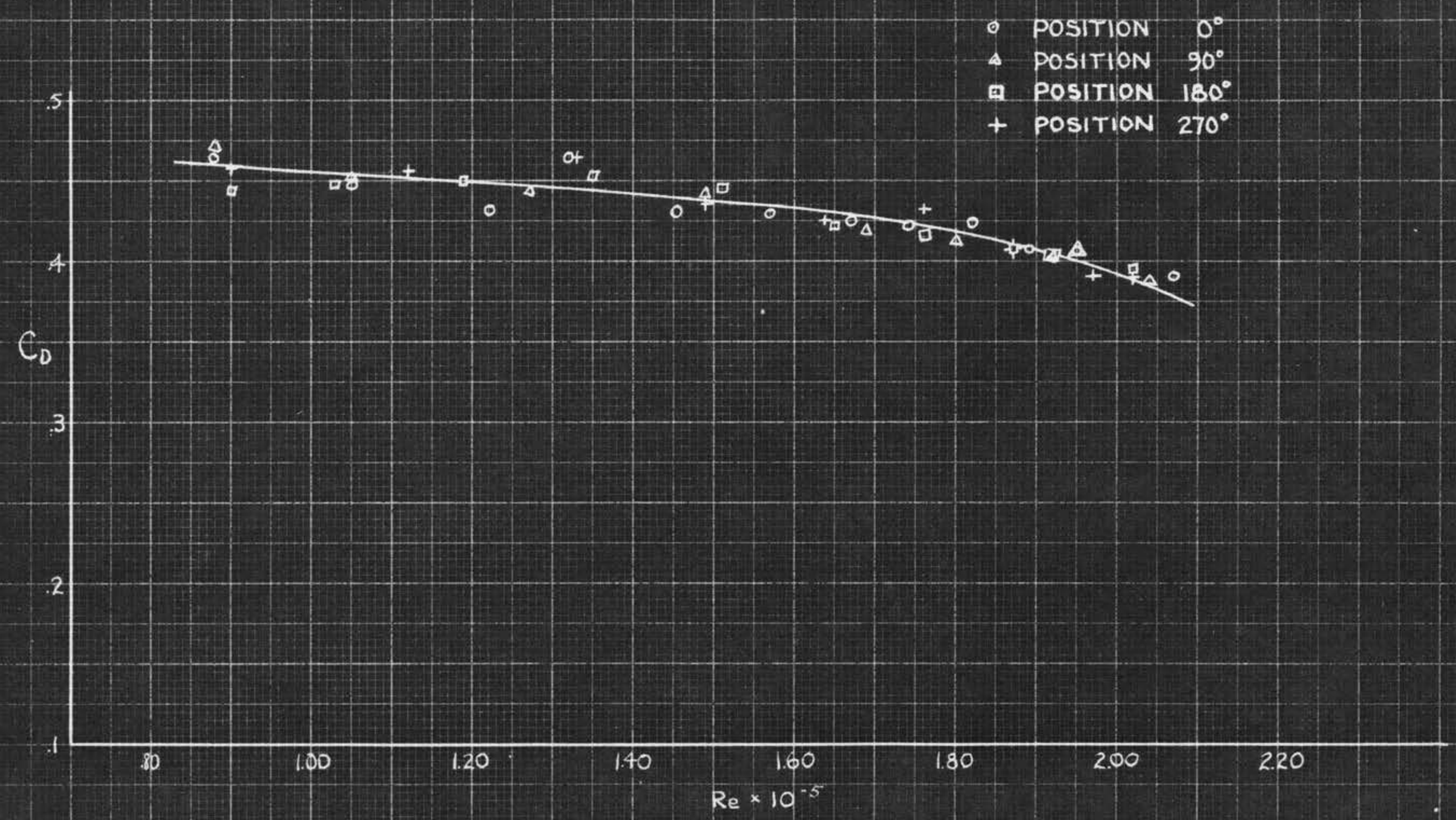


FIG. 31 STEEL BALL BEARING 2.875 D.
FOUR ROTATED POSITIONS

TESTS ON LIGNUM VITAE SPHERES.--These spheres were filled, lacquered and rubbed to a smooth finish. Test procedure was the same as before and the same data was recorded with one exception. The distance "X", Figure 7, page 11 was measured and used to calculate the scale constant for each run. This was for the purpose of eliminating any inconsistency due to the sphere not being exactly centered on the stinger.

NEW CALCULATIONS.--The calculations were identical for these spheres and the pine spheres except for the scale constant K. Referring to Figure 7, page 11, and using the dimension "X", the scale constant was calculated as;

$$K = \frac{14.97}{24.5(1.47)}\left[48.25 - (X - \frac{D}{2})\right]$$

Tables XVIII to XXXVIII and Figures 32 to 52 show data and results for the tests run on the Lignum Vitae spheres. Three runs were made on each size sphere so that any inconsistencies could be readily observed.

TABLE XVIII

Sphere diameter 3.468"
Run No. 1
Barometric Pressure 29.28"Hg.

Dry Bulb Temp. 78°F
Wet Bulb Temp. 63°F
$\rho = .00223$ slug/cu. ft.

$V = 68.2\sqrt{q}$ $\quad$ $Re = 1677\,V$ $\quad$ $C_d = 13{,}680\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	4.67	.298	147.2	.188	247,000
2	4.17	.298	139.2	.211	234,000
3	3.88	.318	134.2	.241	225,000
4	3.57	.328	128.7	.270	215,000
5	3.22	.338	122.4	.309	205,000
6	2.95	.338	117.0	.337	196,000
7	2.67	.324	111.4	.357	187,000
8	2.32	.305	103.8	.388	174,000
9	1.84	.261	92.4	.417	155,000
10	1.52	.224	84.0	.433	141,000
11	1.28	.190	77.2	.437	129,000
12	1.01	.151	68.5	.438	115,000
13	.77	.119	59.8	.455	100,000

TABLE XIX

Sphere diameter 3.468"
Run No. 2
Barometric Pressure 29.28"Hg.

Dry Bulb Temp. 76°F
Wet Bulb Temp. 61°F
$\rho = .00224$ slug/cu. ft.

$V = 68.2\sqrt{q}$

$Re = 1688\ V$

$C_d = 13,620\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	4.18	.327	139.4	.229	235,000
2	3.72	.327	131.4	.258	222,000
3	3.43	.342	126.2	.293	213,000
4	3.10	.339	120.0	.321	202,000
5	2.87	.342	115.4	.350	195,000
6	2.40	.305	105.5	.374	178,000
7	1.90	.261	93.9	.403	158,000
8	1.58	.232	85.7	.429	145,000
9	1.32	.201	78.3	.447	132,000
10	1.10	.164	71.5	.437	121,000
11	.78	.129	60.6	.479	102,000

TABLE XX

Sphere diameter 3.468"
Run No. 3
Barometric Pressure 29.28"Hg.

Dry Bulb Temp. 79°F
Wet Bulb Temp. 64°F
$\rho = .00223$ slug/cu. ft.

$V = 68.2\sqrt{q}$

$Re = 1677\ V$

$C_d = 13,680\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	4.15	.309	138.7	.211	232,000
2	3.97	.317	136.0	.234	228,500
3	3.45	.342	126.5	.292	212,500
4	2.88	.334	116.0	.341	195,000
5	2.60	.324	110.0	.366	184,000
6	2.37	.317	105.0	.394	176,000
7	1.91	.281	95.8	.419	161,000
8	1.62	.242	86.8	.439	145,000
9	1.37	.200	79.8	.428	134,000
10	1.09	.164	71.2	.442	119,000
11	.72	.107	57.8	.438	97,000

TABLE XXI

Sphere diameter 3.981
Run No. 1
Barometric Pressure 29.17"Hg.

Dry Bulb Temp. 71°F
Wet Bulb Temp. 60°F
ρ = .00225 slug/cu. ft.

$V = 68\sqrt{q}$ Re = 1972 V $C_d = 10{,}279\frac{D}{V^2}$

Reading No.	q Inches H_2O	Drag #	V ft./sec.	C_d	Re
1	3.95	.283	135.2	.159	267,000
2	3.76	.280	131.9	.166	260,000
3	3.47	.276	126.7	.177	250,000
4	2.95	.307	116.8	.231	230,000
5	2.67	.330	111.1	.275	219,000
6	2.22	.344	101.4	.344	200,000
7	1.80	.309	91.3	.381	180,000
8	1.48	.275	82.7	.412	163,000
9	1.27	.281	76.6	.491	151,000
10	[illegible]	.231	67.5	.521	133,000
11	.78	.149	60.0	.425	118,000

TABLE XXII

Sphere diameter 3.985
Run No. 2
Barometric Pressure 29.17"Hg.

Dry Bulb Temp. 73°F
Wet Bulb Temp. 62°F
ρ = .00225 slug/cu. ft.

$V = 68\sqrt{q}$ Re = 1972 V $C_d = 10{,}257\frac{D}{V^2}$

Reading No.	q Inches H_2O	Drag #	V ft./sec.	C_d	Re
1	3.85	.314	133.5	.181	263,000
2	3.47	.315	126.7	.201	250,000
3	3.28	.324	123.2	.210	243,000
4	2.88	.354	115.3	.272	227,000
5	2.50	.330	107.5	.293	212,000
6	2.07	.308	97.8	.330	193,000
7	1.78	.302	90.7	.376	179,000
8	1.52	.273	83.8	.399	165,000
9	1.30	.257	77.5	.439	153,000
10	1.08	.237	70.7	[illegible]	139,000
11	.90	.194	64.5	[illegible]	127,000

TABLE XXIII

Sphere diameter 3.935"
Run No. 3
Barometric Pressure 29.17"Hg.

Dry Bulb Temp. 78°F
Wet Bulb Temp. 61°F
ρ = .00222 slug/cu. ft.

$V = 68.4\sqrt{q}$ Re = 1929 V $C_d = 10,390\frac{D}{V^2}$

Reading No.	q Inches H_2O	Drag #	V ft./sec.	C_d	Re
1	3.96	.317	136.0	.177	262,000
2	3.62	.329	130.0	.202	251,000
3	3.16	.332	121.7	.233	234,000
4	2.95	.339	117.5	.254	226,000
5	2.62	.354	110.8	.299	214,000
6	2.30	.346	103.8	.334	200,000
7	1.90	.329	94.4	.374	182,000
8	1.65	.300	87.8	.404	169,000
9	1.44	.269	82.1	.406	158,000
10	1.15	.222	73.4	.428	141,000
11	.93	.190	66.0	.452	127,000
12	.78	.146	60.4	.416	116,000

TABLE XXIV

Sphere diameter 4.465"
Run No. 1
Barometric Pressure 29.17"Hg.

Dry Bulb Temp. 78°F
Wet Bulb Temp. 65°F
ρ = .00222 slug/cu. ft.

$V = 68.4\sqrt{q}$ Re = 2173 V $C_d = 8,220\frac{D}{V^2}$

Reading No.	q Inches H_2O	Drag #	V ft./sec.	C_d	Re
1	3.53	.388	127.0	.191	276,000
2	3.10	.369	120.0	.207	261,000
3	2.90	.360	116.0	.220	252,000
4	2.67	.391	111.5	.257	242,000
5	2.35	.373	104.5	.281	227,000
6	2.15	.368	100.5	.300	217,500
7	1.83	.340	92.2	.327	201,000
8	1.50	.319	83.7	.373	182,000
9	1.13	.257	72.5	.400	158,000
10	.76	.186	59.6	.430	129,500

TABLE XXV

Sphere diameter 4.485"
Run No. 2
Barometric Pressure 29.17"Hg.

Dry Bulb Temp. 79°F
Wet Bulb Temp. 65°F
ρ = .00222 slug/cu. ft.

$V = 68.4\sqrt{q}$ $Re = 2158\,V$ $C_d = 8{,}220\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	3.70	.265	131.6	.126	284,000
2	3.43	.296	126.7	.152	273,000
3	3.09	.335	120.1	.191	259,000
4	2.76	.357	113.8	.227	245,000
5	2.44	.371	106.8	.268	230,000
6	2.15	.378	100.2	.308	216,000
7	1.90	.371	94.3	.342	203,000
8	1.56	.330	85.3	.372	184,000
9	1.32	.292	78.5	.388	169,000
10	1.02	.235	69.0	.404	149,000
11	.79	.187	60.7	.416	131,000

TABLE XXVI

Sphere diameter 4.485"
Run No. 3
Barometric Pressure 29.17"Hg.

Dry Bulb Temp. 80°F
Wet Bulb Temp. 66°F
ρ = .00222 slug/cu. ft.

$V = 68.4\sqrt{q}$ $Re = 2152\,V$ $C_d = 8{,}220\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	3.75	.267	132.5	.125	285,000
2	3.49	.289	127.8	.145	275,000
3	3.18	.347	122.0	.192	262,500
4	2.87	.359	116.0	.220	250,000
5	2.55	.379	109.2	.261	235,000
6	2.15	.369	100.2	.301	216,000
7	1.76	.362	90.6	.362	195,000
8	1.59	.340	86.2	.376	186,000
9	1.33	.298	79.0	.394	170,000
10	1.10	.260	71.7	.415	154,500
11	.79	.189	60.7	.420	131,000

TABLE XXVII

Sphere diameter 4.97"
Run No. 1
Barometric Pressure 29.33"Hg.

Dry Bulb Temp. 79°F
Wet Bulb Temp. 68°F
ρ = .00222 slug/cu. ft.

$V = 68.4 \sqrt{q}$ Re = 2400 V $C_d = 6,685 \frac{D}{V^2}$

Reading No.	q Inches H_2O	Drag #	V ft./sec.	C_d	Re
1	3.57	.273	129.0	.109	310,000
2	3.30	.296	124.2	.128	298,000
3	2.93	.305	117.2	.146	281,000
4	2.71	.320	112.7	.168	270,000
5	2.37	.355	105.3	.214	253,000
6	2.02	.355	97.3	.251	233,500
7	1.67	.358	88.4	.303	212,000
8	1.41	.345	81.2	.349	195,000
9	1.06	.293	70.5	.394	169,000
10	.76	.235	59.6	.442	143,000

TABLE XXVIII

Sphere diameter 4.97"
Run No. 2
Barometric Pressure 29.32"Hg.

Dry Bulb Temp. 81°F
Wet Bulb Temp. 63°F
ρ = .00222 slug/cu. ft.

$V = 68.4 \sqrt{q}$ Re = 2280 V $C_d = 6,640 \frac{D}{V^2}$

Reading No.	q Inches H_2O	Drag #	V ft./sec.	C_d	Re
1	3.43	.294	126.8	.122	290,000
2	3.13	.311	121.0	.141	276,000
3	2.77	.330	113.8	.170	260,000
4	2.55	.344	109.3	.192	250,000
5	2.26	.363	102.8	.228	235,000
6	2.02	.352	97.2	.247	222,000
7	1.73	.347	90.0	.286	206,000
8	1.43	.342	81.8	.340	187,000
9	1.07	.301	70.7	.401	162,000
10	.76	.225	59.5	.422	136,000

TABLE XXIX

Sphere diameter 4.97"
Run No. 3
Barometric Pressure 29.33"Hg.

Dry Bulb Temp. 82°F
Wet Bulb Temp. 63°F
$\rho \doteq .002215$ slug/cu. ft.

$V \doteq 68.5\sqrt{q}$ Re $\doteq$ 2375 V $C_d \doteq 6,700\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./ sec.	C_d	Re
1	3.47	.302	127.5	.124	302,000
2	3.22	.314	122.5	.139	291,000
3	2.91	.318	117.0	.155	278,000
4	2.54	.350	109.0	.197	259,000
5	2.16	.362	101.0	.238	239,000
6	1.93	.366	95.2	.271	226,000
7	1.74	.341	90.3	.280	214,000
8	1.45	.344	82.5	.338	196,000
9	1.07	.297	70.9	.394	168,500
10	.76	.223	59.8	.422	142,000

TABLE XXX

Sphere diameter 5.48"
Run No. 1
Barometric Pressure 29.32"Hg.

Dry Bulb Temp. 75°F
Wet Bulb Temp. 60°F
$\rho \doteq .00224$ slug/cu. ft.

$V \doteq 68\sqrt{q}$ Re $\doteq$ 2685 V $C_d \doteq 5,420\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	2.89	.263	115.8	.106	311,000
2	2.52	.263	108.2	.176	291,000
3	2.19	.270	100.8	.198	271,000
4	1.82	.301	91.8	.194	246,500
5	1.56	.340	85.0	.255	228,000
6	1.30	.357	77.6	.321	208,000
7	1.08	.323	70.7	.350	190,000
8	.81	.275	61.3	.398	165,000

TABLE XXXI

Sphere diameter 5.48"
Run No. 2
Barometric Pressure 29.32"Hg.

Dry Bulb Temp. 76°F
Wet Bulb Temp. 60°F
ρ = .00224 Slug/cu. ft.

$V = 68\sqrt{q}$ $\quad$ $Re = 2685\,V$ $\quad$ $C_d = 5{,}420\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	2.98	.252	117.5	.099	315,000
2	2.68	.259	111.5	.113	300,000
3	2.20	.278	101.0	.148	271.000
4	1.63	.324	86.8	.234	233,000
5	1.28	.344	77.0	.315	207,000
6	1.06	.329	70.0	.364	188,000
7	.81	.273	61.2	.395	165,000

TABLE XXXII

Sphere diameter 5.48"
Run No. 3
Barometric Pressure 29.32"Hg.

Dry Bulb Temp. 77°F
Wet Bulb Temp. 60°F
ρ = .00224 slug/cu. ft.

$V = 68\sqrt{q}$ $\quad$ $Re = 2680\,V$ $\quad$ $C_d = 5{,}420\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	2.88	.276	115.8	.112	310,000
2	2.51	.254	107.8	.119	288,000
3	2.17	.288	100.2	.156	269,000
4	1.87	.300	93.0	.190	249,000
5	1.54	.336	84.4	.256	226,000
6	1.29	.360	77.3	.327	207,000
7	1.07	.324	70.4	.356	189,000
8	.82	.276	61.5	.396	165,000

TABLE XXXIII

Sphere diameter 5.94"
Run No. 1
Barometric Pressure 29.32"Hg.

Dry Bulb Temp. 76°F
Wet Bulb Temp. 60°F
ρ = .00224 slug/cu.ft.

$V = 68\sqrt{q}$

$Re = 2910\ V$

$C_d = 4{,}625\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./ sec.	C_d	Re
1	2.76	.233	113.0	.084	329,000
2	2.45	.210	106.6	.086	310,000
3	2.00	.188	96.1	.094	280,000
4	1.70	.232	88.8	.136	258,000
5	1.40	.327	80.5	.234	234,000
6	1.17	.363	73.5	.311	214,000
7	1.00	.332	68.0	.332	198,000
8	.81	.293	61.2	.362	178,000

TABLE XXXIV

Sphere diameter 5.94"
Run No. 2
Barometric Pressure 29.32"Hg.

Dry Bulb Temp. 77°F
Wet Bulb Temp. 60°F
ρ = .00224 slug/cu. ft.

$V = 68.1\sqrt{q}$

$Re = 2900\ V$

$C_d = 4630\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	2.68	.254	111.5	.095	324,000
2	2.29	.180	103.0	.079	299,000
3	1.93	.209	94.6	.108	275,000
4	1.59	.234	85.8	.147	249,000
5	1.43	.297	81.4	.207	236,000
6	1.16	.353	73.3	.305	213,000
7	1.00	.324	68.1	.324	200,000
8	.83	.300	62.0	.362	180,000

TABLE XXXV

Sphere diameter 5.94"
Run No. 3
Barometric Pressure 29.32"Hg.

Dry Bulb Temp. 77°F
Wet Bulb Temp. 60°F
$\rho = .00224$ slug/cu. ft.

$V = 68.1\sqrt{q}$ Re = 2900 V $C_d = 4{,}630\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	2.55	.200	109.0	.078	316,000
2	2.15	.195	100.0	.090	290,000
3	1.80	.214	91.4	.119	265,000
4	1.47	.314	82.6	.213	240,000
5	1.21	.354	75.0	.292	217,500
6	1.10	.354	71.4	.321	207,000
7	.97	.335	67.1	.334	195,000
8	.83	.300	62.1	.360	180,000

TABLE XXXVI

Sphere diameter 6.45"
Run No. 1
Barometric Pressure 29.15"Hg.

Dry Bulb Temp. 78°F
Wet Bulb Temp. 63°F
$\rho = .00222$ slug/cu. ft.

$V = 68.4\sqrt{q}$ Re = 3115 V $C_d = 3{,}970\frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./ sec.	C_d	Re
1	2.77	.209	114.0	.064	355,000
2	2.50	.211	108.2	.072	337,000
3	2.08	.179	98.7	.073	307,000
4	1.70	.195	89.1	.098	277,500
5	1.55	.205	85.1	.113	265,000
6	1.25	.272	76.5	.185	238,000
7	1.05	.333	70.0	.270	218,000
8	.80	.314	61.2	.332	190,500

TABLE XXXVII

Sphere diameter 6.45"
Run No. 2
Barometric Pressure 29.15"Hg.

Dry Bulb Temp. 76°F
Wet Bulb Temp. 63°F
ρ = .0022 slug/cu. ft.

$V = 68.4 \sqrt{q}$ $\quad$ $Re = 3120\ V$ $\quad$ $C_d = 3{,}970 \frac{D}{V^2}$

Reading No.	q inches H_2O	Drag #	V ft./sec.	C_d	Re
1	2.73	.205	115.0	.061	359,000
2	2.35	.193	105.0	.070	327,000
3	2.05	.181	97.8	.075	306,000
4	1.68	.193	88.7	.098	277,000
5	1.53	.207	84.6	.115	264,000
6	1.23	.278	75.8	.192	237,000
7	1.03	.338	69.4	.280	217,000
8	.79	.314	60.8	.337	190,000

TABLE XXXVIII

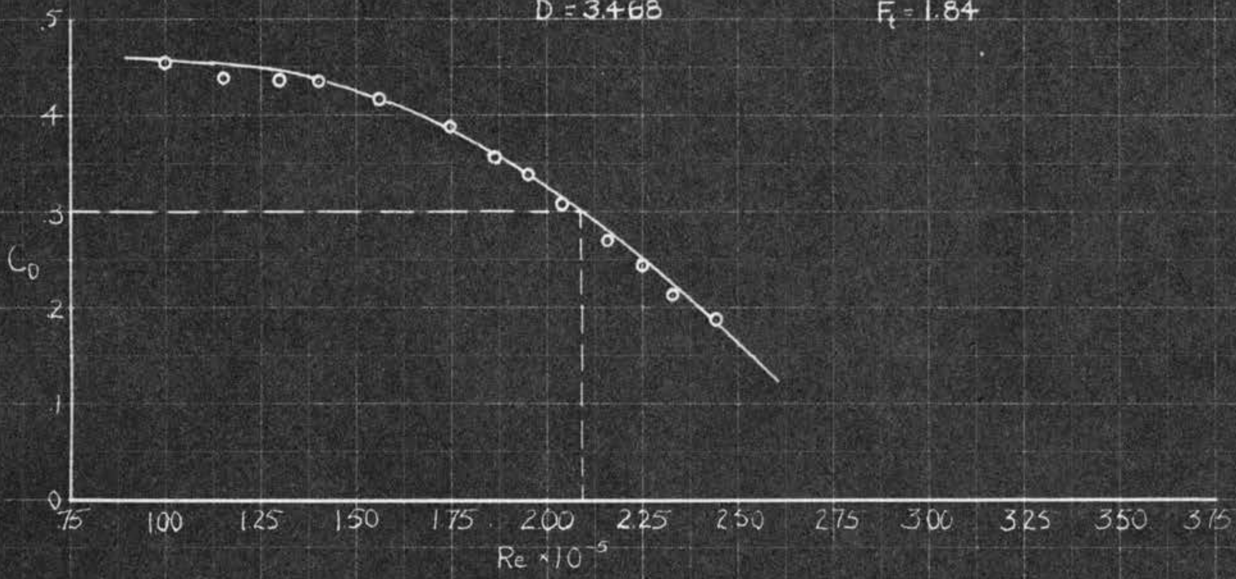
Sphere diameter 6.45"
Run No. 3
Barometric Pressure 29.15"Hg.

Dry Bulb Temp. 77°F
Wet Bulb Temp. 62°F
ρ = .00222 slug/cu. ft.

$V = 68.4 \sqrt{q}$ $\quad$ $Re = 3120\ V$ $\quad$ $C_d = 3{,}970 \frac{D}{V^2}$

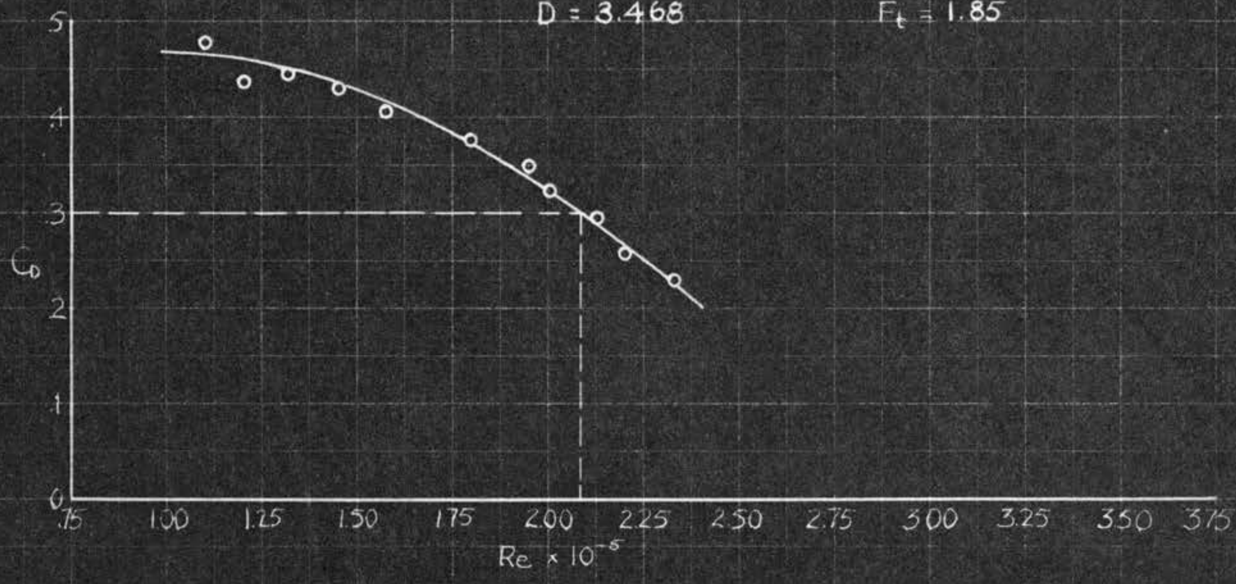
Reading No.	q inches H_2O	Drag #	V ft./ sec.	C_d	Re
1	2.83	.205	115.0	.062	359,000
2	2.45	.205	107.0	.071	334,000
3	2.11	.187	99.3	.075	310,000
4	1.81	.193	92.0	.091	287,000
5	1.53	.211	84.5	.117	264,000
6	1.21	.284	75.2	.200	235,000
7	1.03	.344	69.4	.283	216,500
8	.80	.320	61.2	.339	191,000

FIG. 32


LIGNUM VITAE FROM TABLE XVIII

D = 3.468 F_t = 1.84

FIG. 33


LIGNUM VITAE FROM TABLE XIX

D = 3.468 F_t = 1.85

FIG 34

LIGNUM VITAE FROM TABLE XX

$D = 3.468$ $F_t = 1.85$

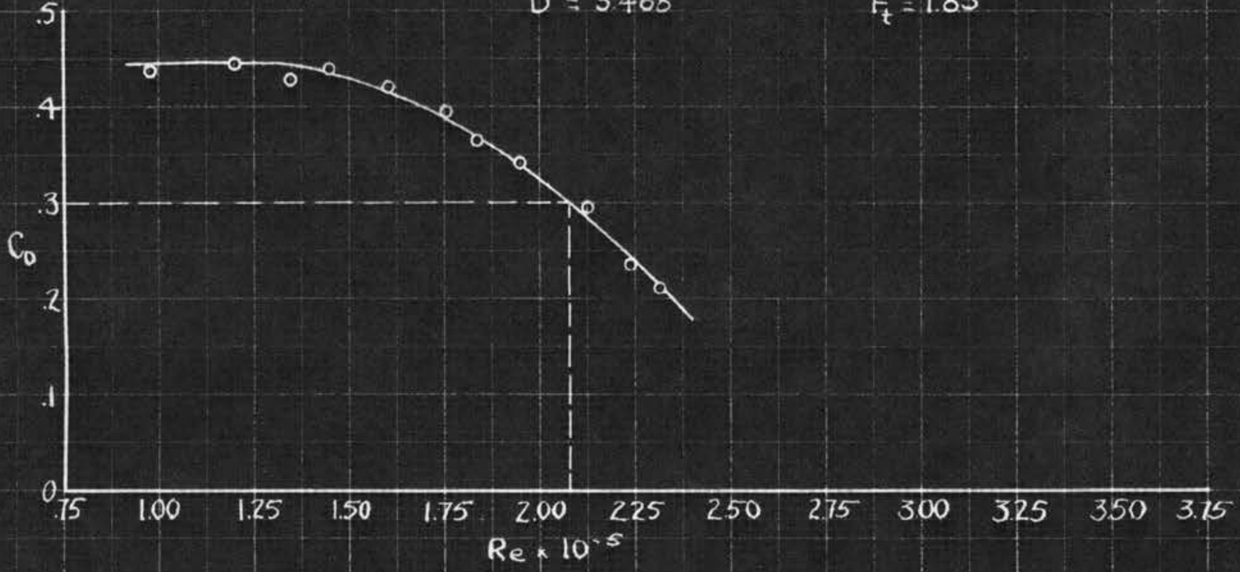


FIG. 35

LIGNUM VITAE FROM TABLE XXI

$D = 3.985$ $F_t = 1.81$

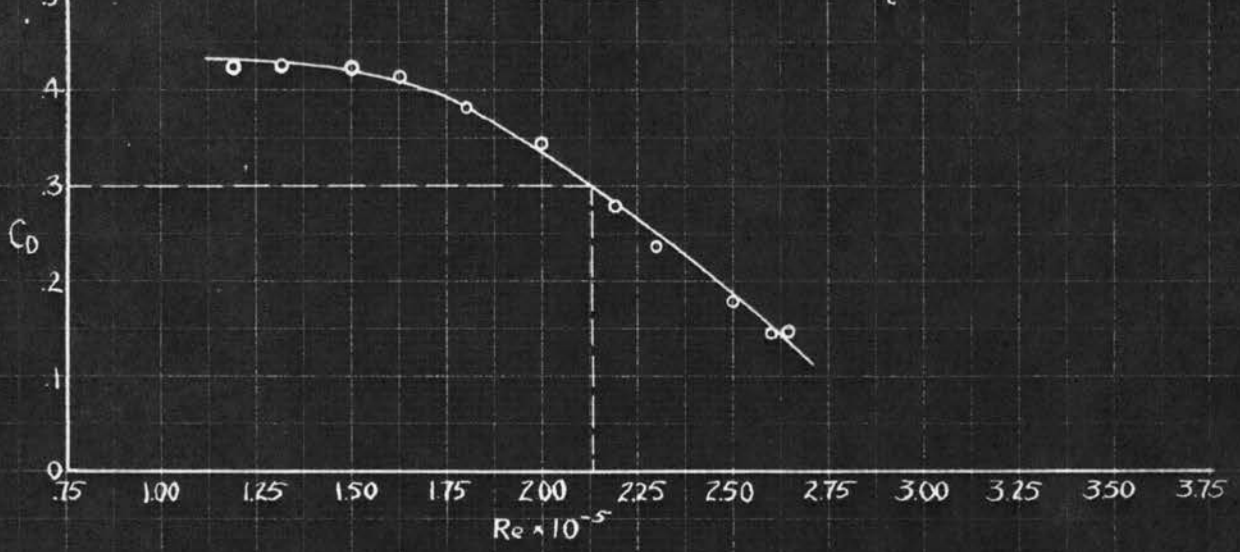


FIG. 36

LIGNUM VITAE FROM TABLE XXII

D = 3.985 F_t = 1.82

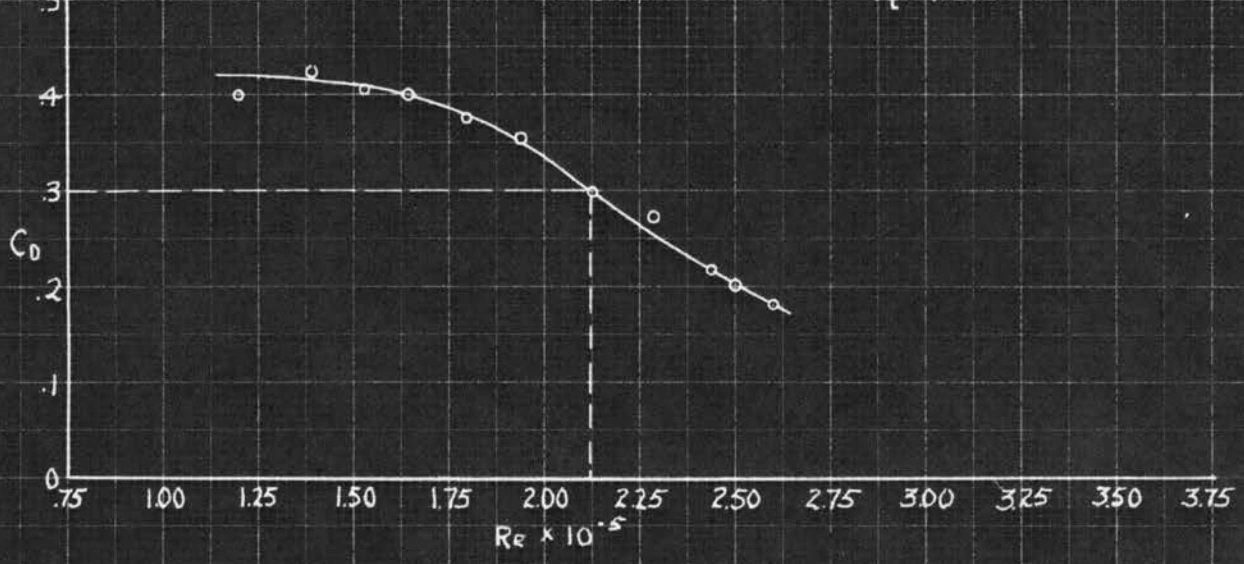


FIG. 37

LIGNUM VITAE FROM TABLE XXIII

D = 3.985 F_t = 1.83

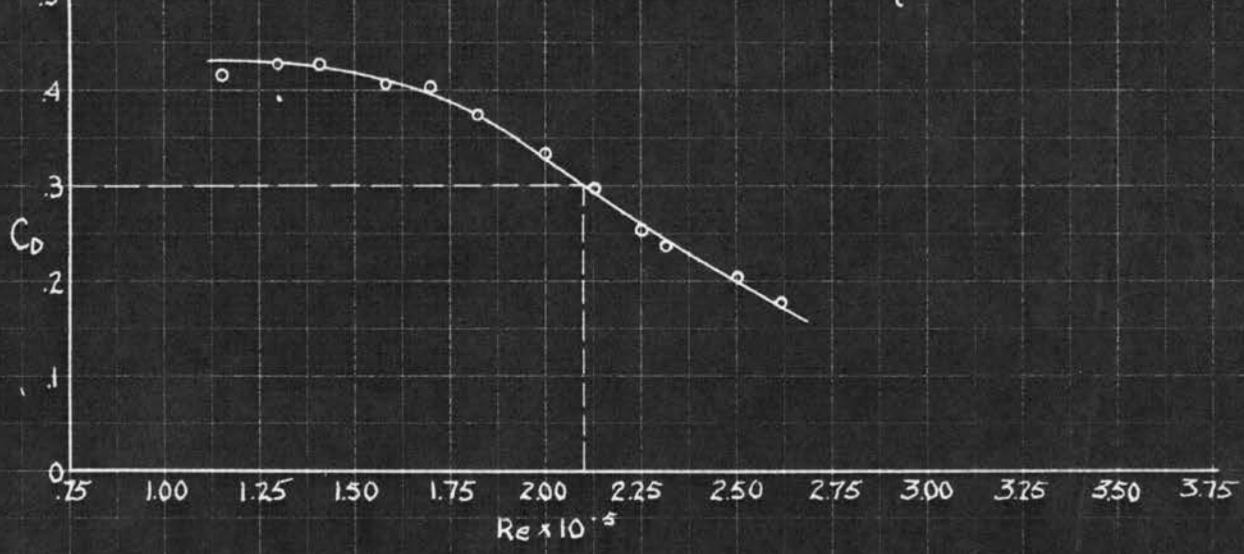


FIG. 38

LIGNUM VITAE FROM TABLE XXIV

D = 4.485 F_t = 1.80

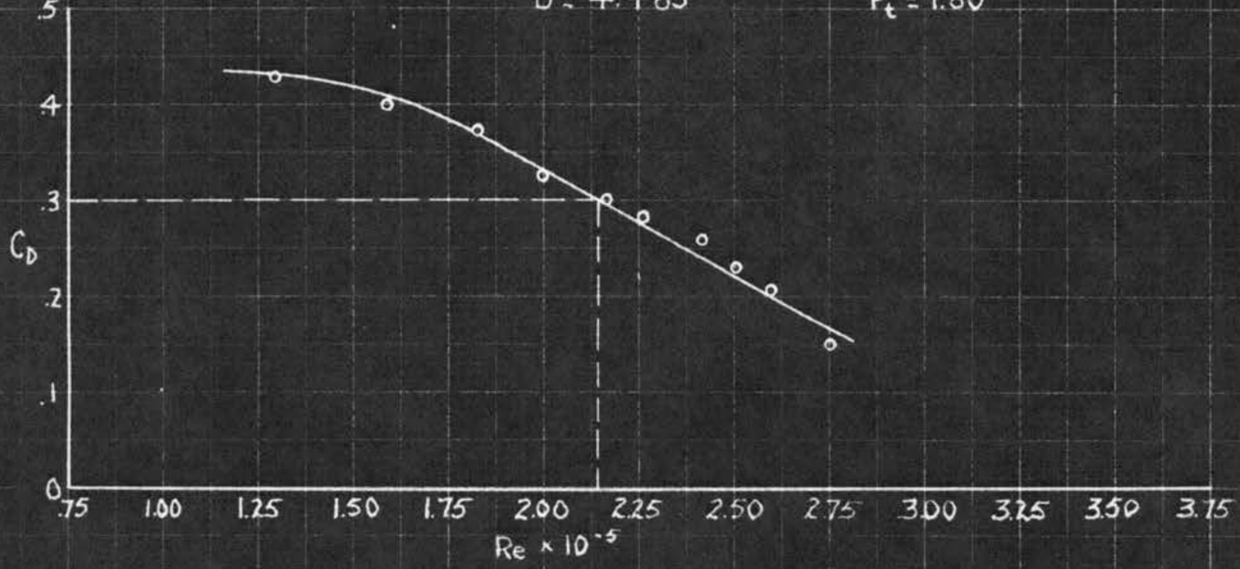


FIG. 39

LIGNUM VITAE FROM TABLE XXV

D = 4.485 F_t = 1.78

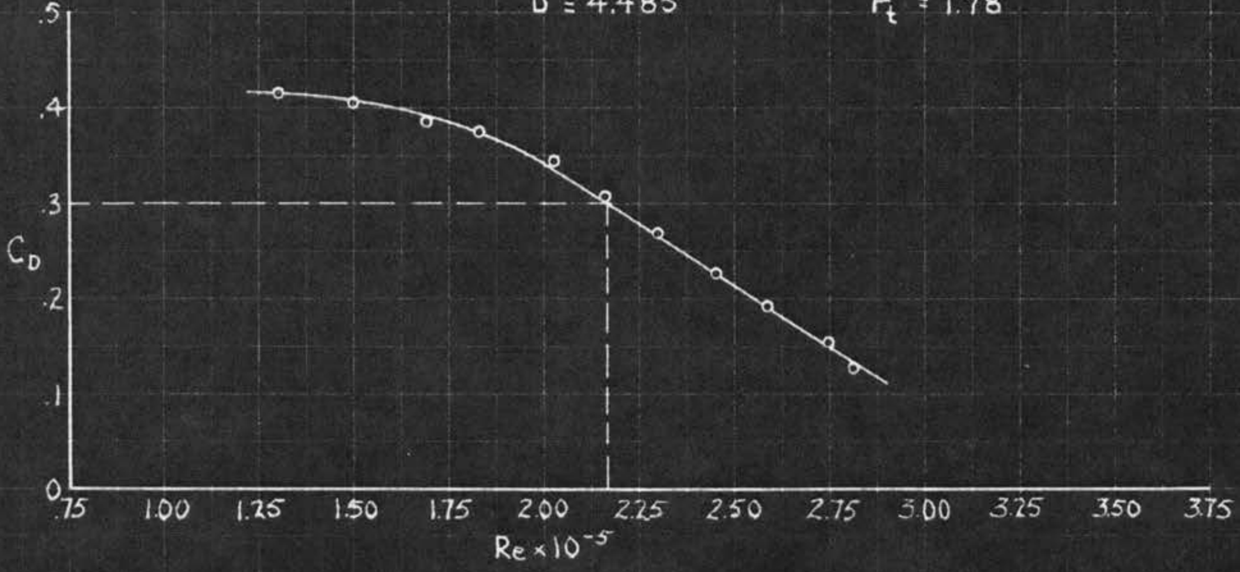


FIG. 40

LIGNUM VITAE FROM TABLE XXVI

D = 4.485 F_t = 1.77

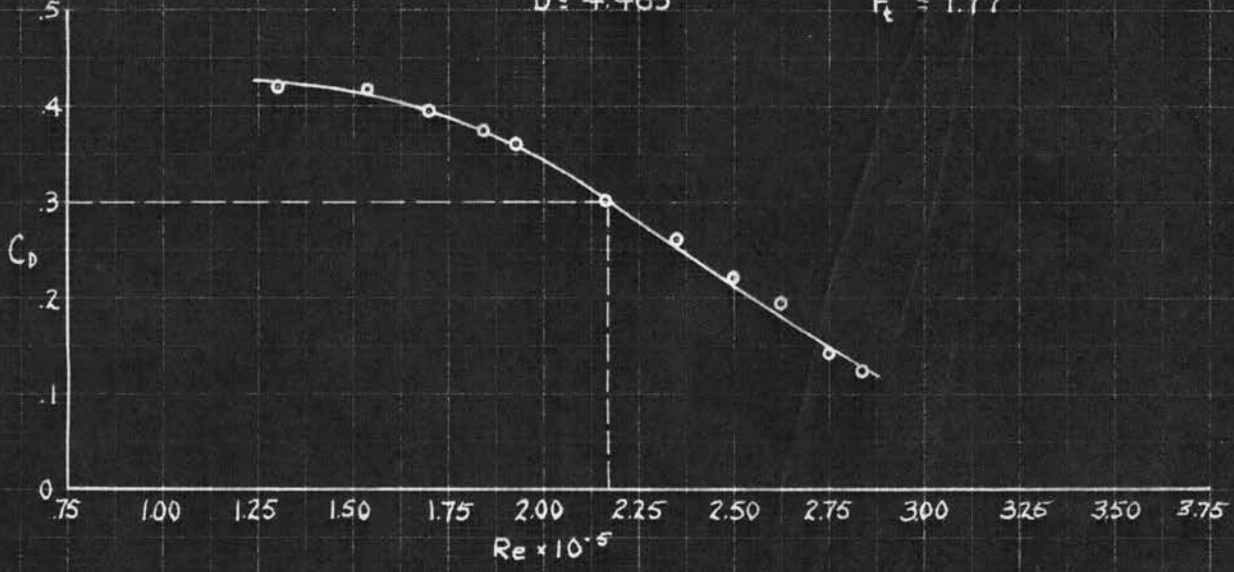


FIG. 41

LIGNUM VITAE FROM TABLE XXVII

D = 4.97 F_t = 1.81

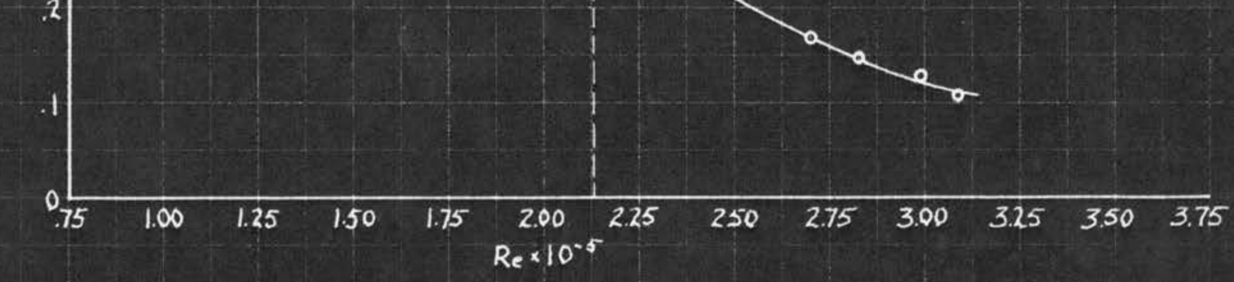


FIG. 42

LIGNUM VITAE FROM TABLE XXVIII

D = 4.97 F_t = 1.83

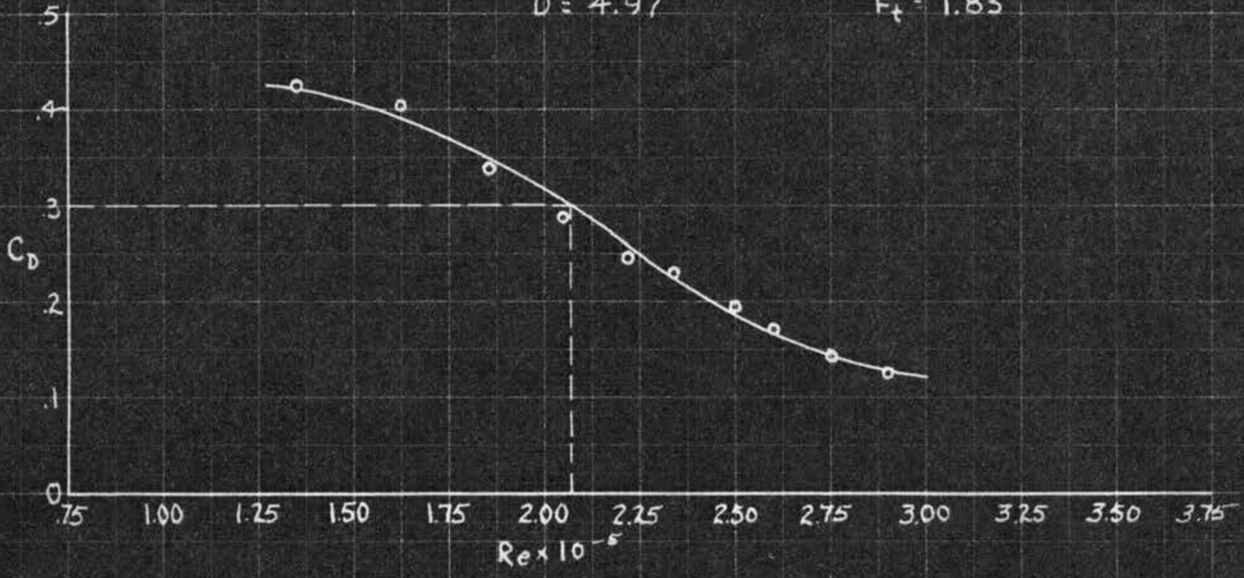


FIG. 43

LIGNUM VITAE FROM TABLE XXIX

D = 4.97 F_t = 1.81

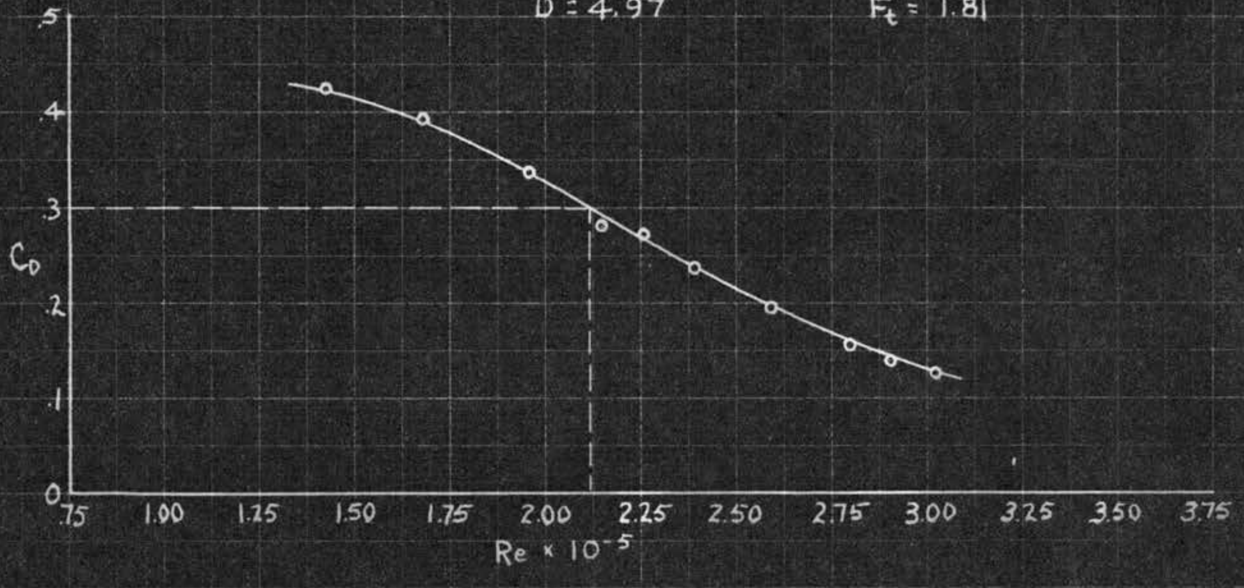


FIG. 44

LIGNUM VITAE FROM TABLE XXX

D = 5.48 $F_t = 1.81$

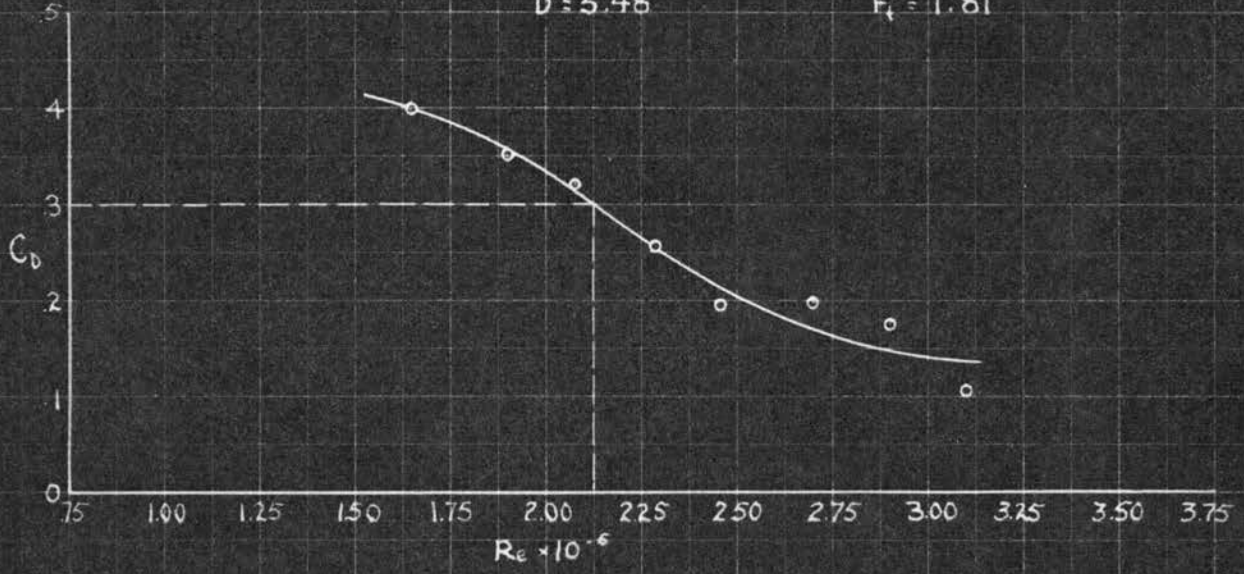


FIG. 45

LIGNUM VITAE FROM TABLE XXXI

D = 5.48 $F_t = 1.83$

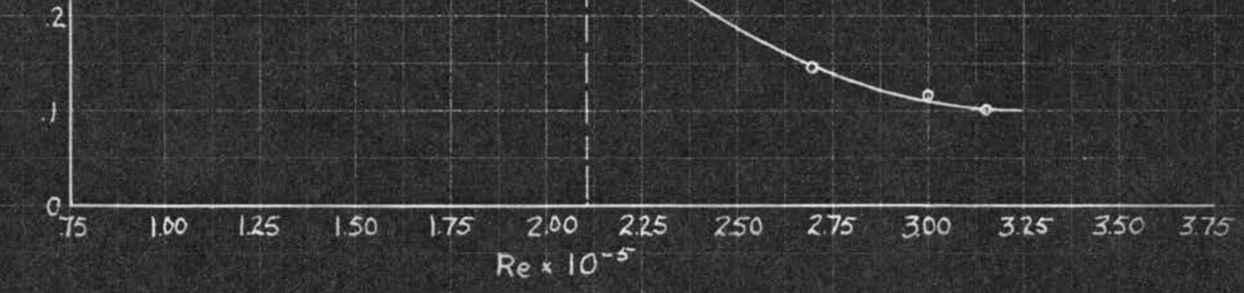


FIG. 46

LIGNUM VITAE FROM TABLE XXXII

D = 5.48 F_t = 1.81

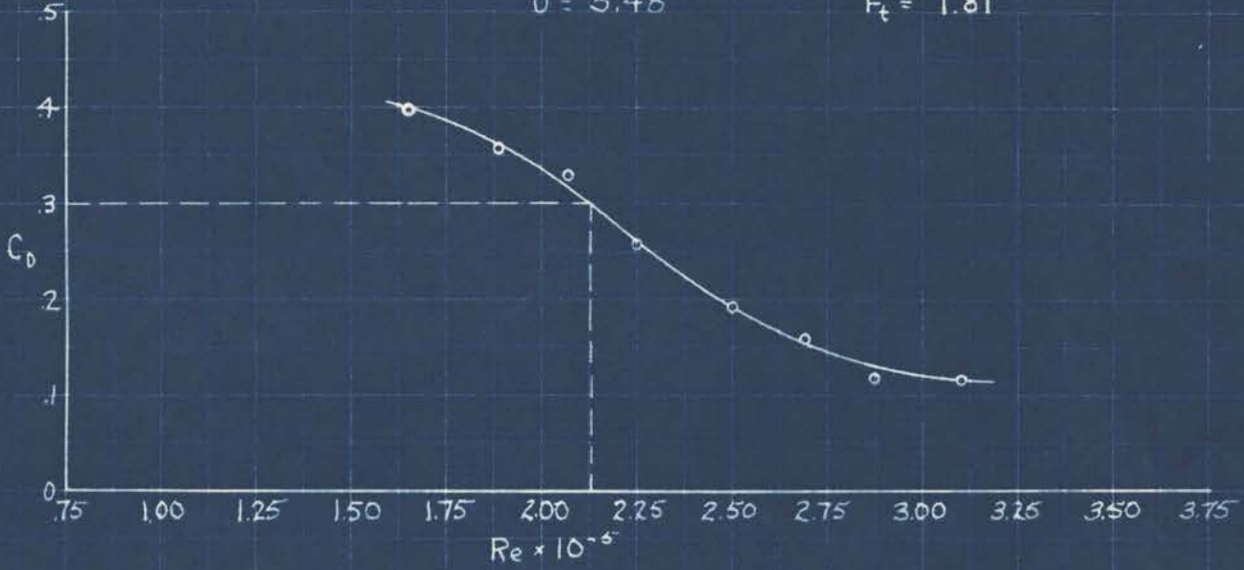


FIG. 47

LIGNUM VITAE FROM TABLE XXXIII

D = 5.94 F_t = 1.82

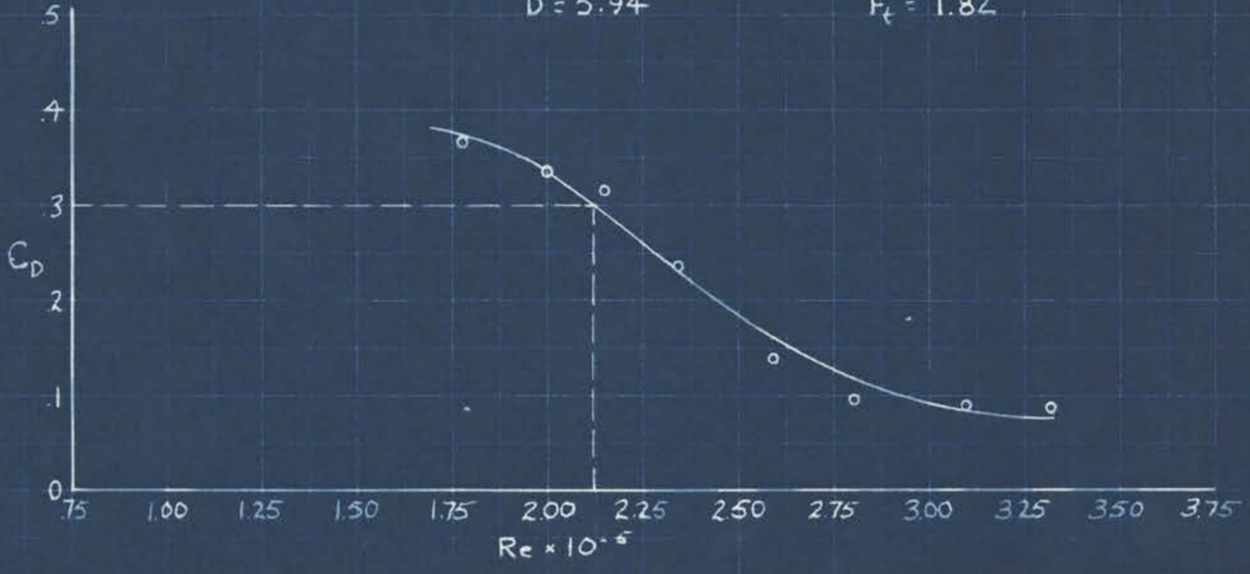


FIG 48

LIGNUM VITAE FROM TABLE XXXIV

D = 5.94 F_t = 1.82

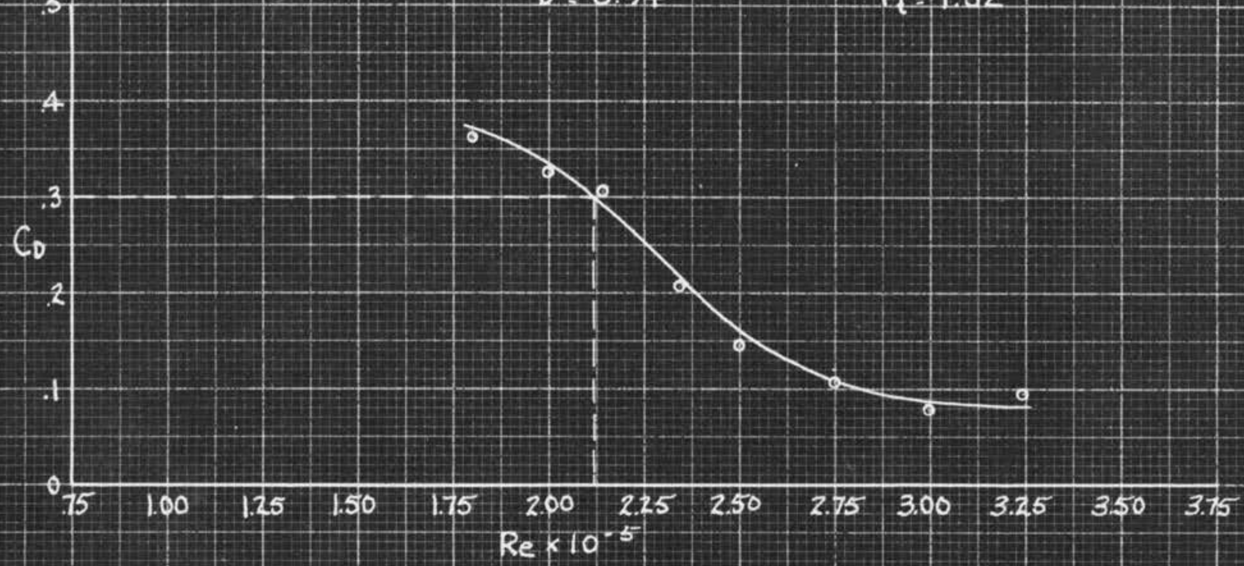


FIG. 49

LIGNUM VITAE FROM TABLE XXXV

D = 5.94 F_t = 1.84

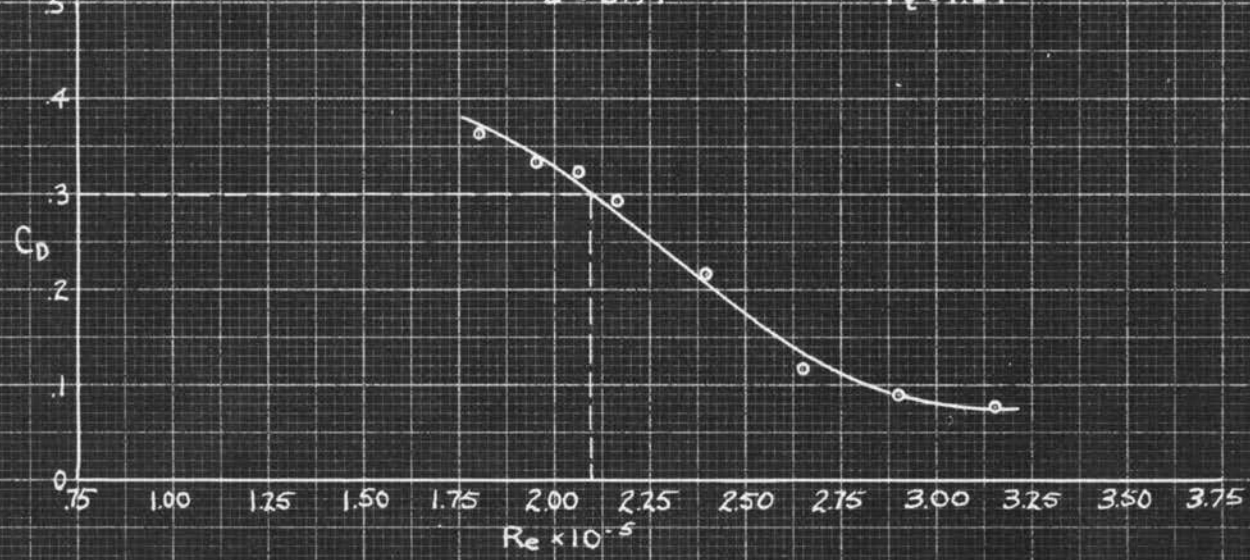


FIG. 50

LIGNUM VITAE FROM TABLE XXXVI

D = 6.45 F_t = 1.87

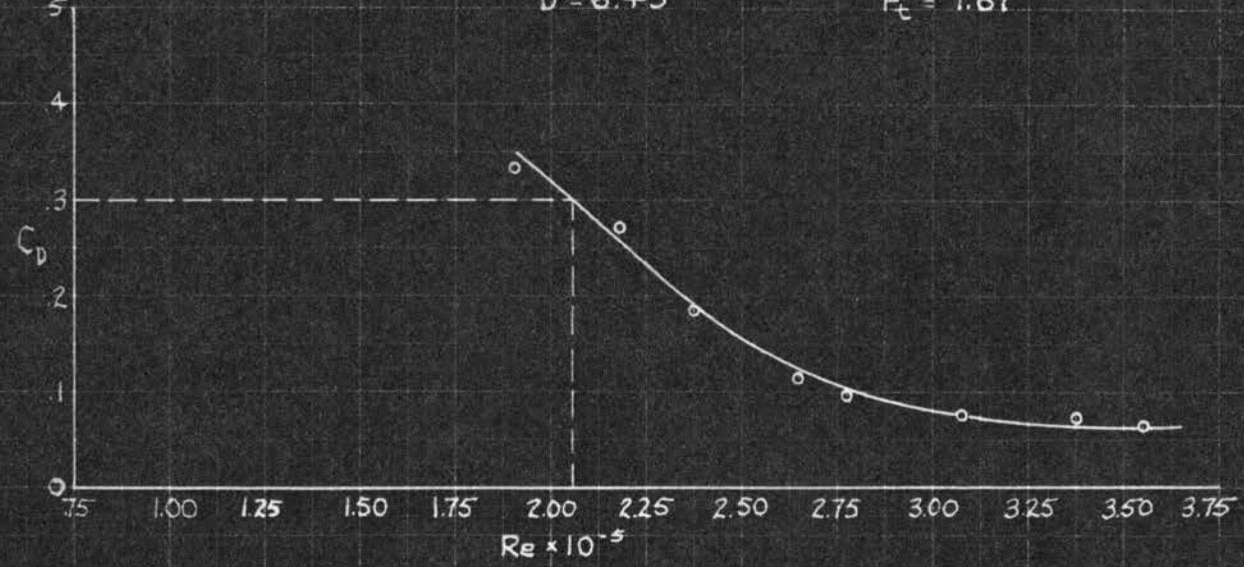


FIG. 51

LIGNUM VITAE FROM TABLE XXXVII

D = 6.45 F_t = 1.85

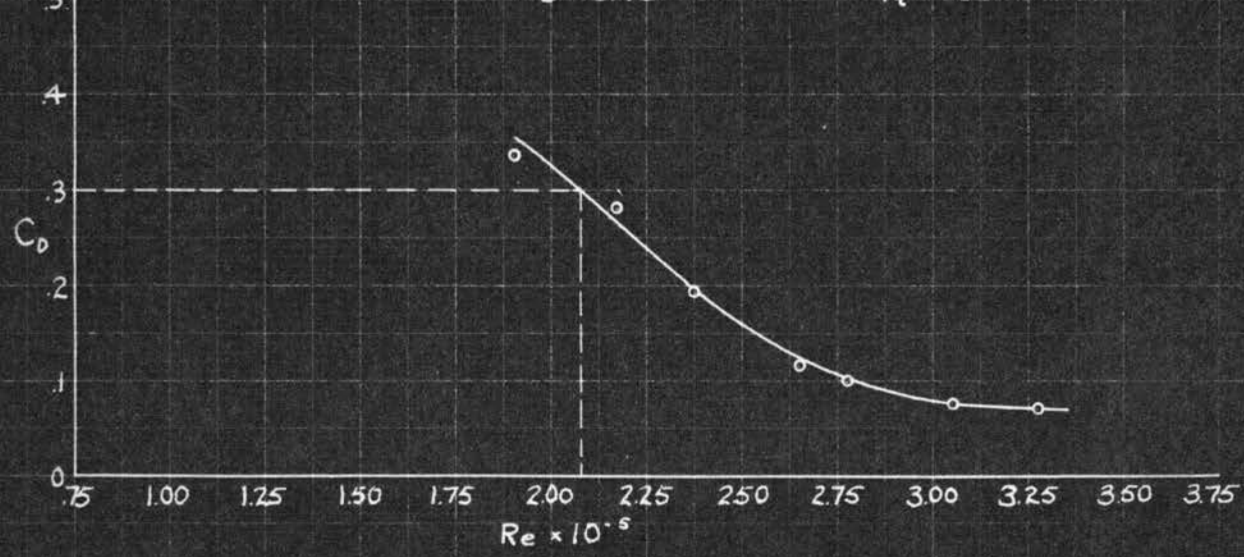
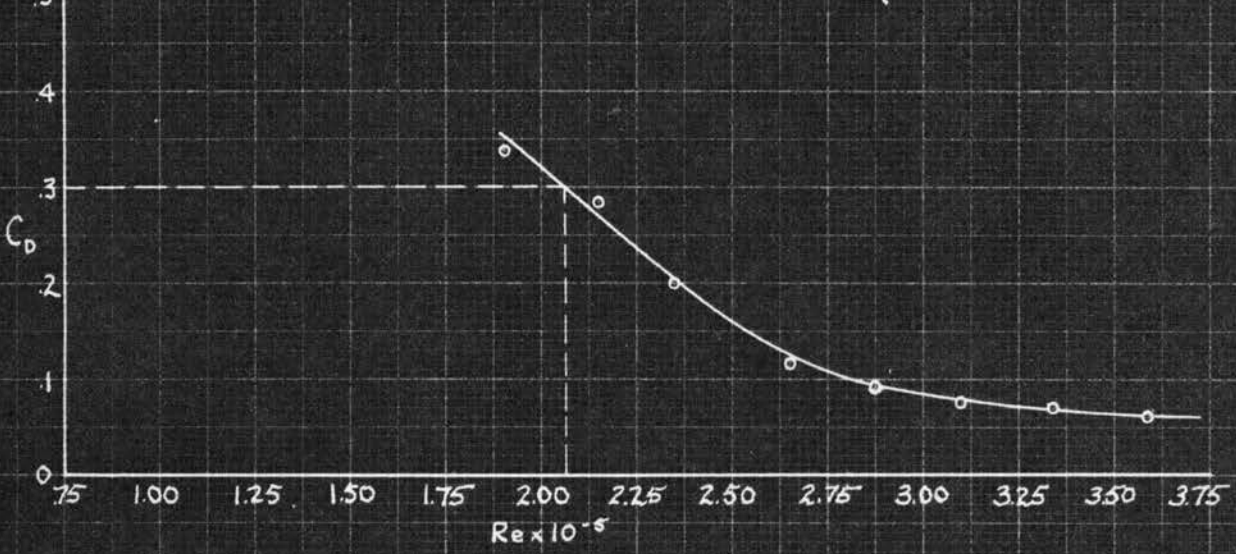


FIG. 52

LIGNUM VITAE FROM TABLE XXXVIII

D = 6.45 F_t = 1.87



SUMMARY AND CONCLUSIONS.--The results of the series of tests on the Lignum Vitae spheres as presented in Fig. 32 to 52 may best be summarized in table form. This is presented in Table XXXIX.

TABLE XXXIX

Summary of Test Results

Sphere Diam. inches	F_t Run No. 1	F_t Run No. 2	F_t Run No. 3	F_t Average	Vel. at which * F_t determined ft./sec.
3½	1.84	1.85	1.85	1.85	120
4	1.81	1.82	1.83	1.82	105
4½	1.80	1.78	1.77	1.78	97
5	1.81	1.83	1.81	1.82	85
5½	1.81	1.83	1.81	1.82	77
6	1.82	1.82	1.84	1.83	71
6½	1.87	1.85	1.87	1.86	64

*(corrected to standard sea level conditions.)

The values of Average F_t are plotted against the air velocity at which they were determined in Figure 53. These results are as consistent as could be expected of experimental testing and show a mean value of the Turbulence factor for the tunnel to be about 1.83 over the operating range of air velocity.

According to Pope[2], a turbulence factor of 1.83 corresponds to approximately 1.05 percent turbulence. This is somewhat high for good testing, about .8 percent being the accepted limit. It is, however, much lower than many of the tunnels in use in this country. Considering size, space limitations etc., this tunnel has very satisfactory turbulence characteristics.

Wing sections of 3" chord are commonly used in this tunnel. At a maximum safe operating speed for sustained testing of 120 ft./sec. this would allow Reynolds numbers of 192,000 to be obtained under standard conditions. With a Turbulence factor of 1.83, this would mean a maximum effective Re with this size model of about 1.83 x 192,000 = 352,000.

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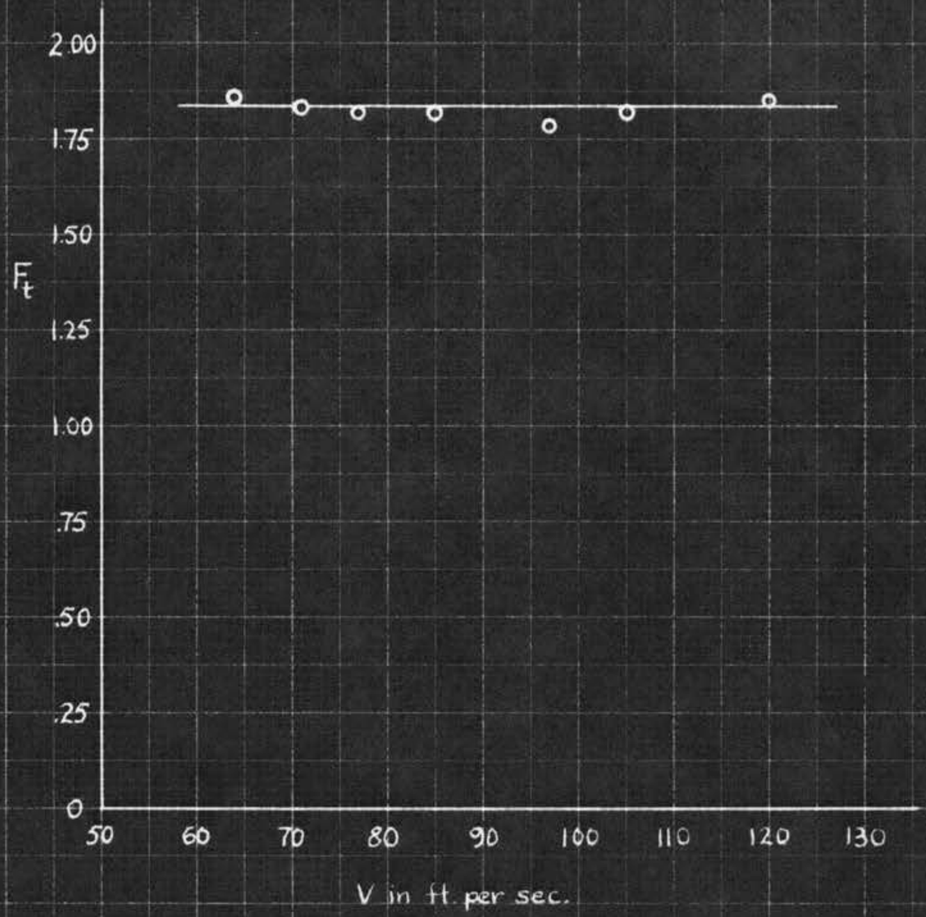
[2] Pope, Alan, Wind Tunnel Testing, p. 89

FIG. 53

F_t PLOTTED AGAINST $V_{STD.}$



DETERMINATION OF
PRESSURE LOSS COEFFICIENT, ENERGY RATIO AND TUNNEL EFFICIENCY

DESCRIPTION OF TESTS.--In order to obtain values of the Brake Horsepower being developed by the motor, it was necessary to measure the resistance of the armature windings. This resistance was changed only at low speeds when additional resistance was placed in series with the armature for speed reduction. The motor was operated at 1500 rpm for a period of one hour before resistance measurements were taken to insure that the windings were up to their operating temperature. Measurements were taken for each setting of the control handle. In the following tables these resistances are listed as R_a.

The V-belts were removed and a no load run made on the motor to determine its constant losses. Data recorded included RPM, Line Voltage, Line Amperes, and Field Amperes. It would have been desirable to remove the fan and leave the motor driving the V-belts and fan bearing, but such a procedure was not feasible in this case.

After the constant losses of the motor were determined, a water manometer was installed across the propeller section so that it recorded the increase in static pressure as the air passed through the propeller. The tunnel was then put into operation and readings of RPM, Line Voltage, Line Amperes, Field Amperes, Velocity Head in the Throat, and Pressure Rise across the Fan were taken. These readings were recorded at intervals of 100 rpm from 1100 to 1900 rpm. Wet and Dry bulb temperatures and barometric pressure were recorded for calculating air density.

CALCULATIONS.--Air density and air velocity in the throat were calculated as before. Power input to motor was calculated as the product of Line Voltage times Line Amperes thus:

$$\text{Power} = E_L I_L$$

On the No Load run the full power put into the motor was absorbed by various losses. These were taken as follows:

Armature $I_a^2R_a$, a variable loss.

Brush loss $2I_a$, a variable loss.

Field EI_f, a variable loss.

Constant loss due to windage, friction etc. This is expressed as

Constant loss $= E_LI_L - (I_a^2R_a + 2I_a + EI_f)$ ---(No Load Run).

This constant loss does not vary with the load the motor is carrying at a given rpm.

The Armature amperes were obtained by subtracting Field amperes from Line amperes, $I_a = I_L - I_f$.

The power output of the motor under load was calculated as the input minus the variable and constant losses as

$$\text{Power Output} = E_LI_L - (I_a^2R_a + 2I_a + EI_f + \text{Constant loss})$$

$$\text{B.H.P.} = \text{Watts}(.00134)$$

The pressure loss coefficient k is defined as the ratio of the pressure rise across the fan to the velocity head in the throat or

$$k = \frac{dP}{q}$$

The Energy Ratio, defined in the introduction, was calculated as

$$\text{E.R.} = \frac{\rho A_tV_t^3}{1100(\text{BHP})}$$

The Efficiency of the tunnel was calculated as

$$\text{Eff.} = \text{E.R.}(k)$$

The values of k, E.R. and Efficiency are, of course, dependent upon one another and will all be dependent to a certain extent upon the blade setting of the propeller. The blades were originally set at 24°, measured at a radius of 15.5 inches. Characteristics were determined at this setting and also at a blade angle of 19°. According to Figure 4:40 in Wood[1] a blade angle of 19° should give maximum efficiency for the propeller in this tunnel.

Table XL shows condensed data and results for the No Load test. Figure 54 shows the constant losses of the motor plotted against R.P.M. Tables XLI and XLII show data and results of tests determining the Energy Ratio, Pressure Loss coefficient, and Efficiency of the tunnel with the propeller blades set at 24° and 19° respectively. Figures 55 and 56 show Efficiency curves for the two blade settings investigated.

TABLE XL

No Load Run On Motor--Fan Removed.

R.P.M.	Line Voltage E_L (Volts)	Line Amperes I_L (Amps)	Field Amperes I_f (Amps)	Armature Amperes I_a (Amps)	Armature Resistance R_a (Ohms)	Constant Losses (Watts)
1900	238	4.55	1.30	3.25	.5925	759.25
1800	238	4.55	1.40	3.15	.5925	736.8
1700	238	4.65	1.52	3.13	.5925	733.9
1600	238	4.66	1.63	3.03	.5925	710.5
1500	237.5	4.76	1.88	2.88	.5925	671.3
1400	237	4.98	2.25	2.73	.5925	635.1
1300	237	5.39	2.81	2.58	.5925	600.9
1200	237	5.59	3.09	2.50	1.970	462.5
1100	237	5.47	3.05	2.42	24.944	421.2

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[1] Wood, Karl D., Technical Aerodynamics, p.259

TABLE XLI

ENERGY RATIO, PRESSURE LOSS COEFFICIENT AND EFFICIENCY (BLADE ANGLE 24°)

Barometric pressure 28.51"Hg.

Dry Bulb Temp. 74°F
Wet Bulb Temp. 64°F

ρ = .002185
$V = 68.9\sqrt{q}$

R.P.M.	Line Voltage E_L (Volts)	Line Amperes I_L (Amps)	Field Amperes I_f (Amps)	Armature Amperes I_a (Amps)	Armature Resistance R_a (Ohms)	B.H.P.	dP inches H_2O	q inches H_2O	k	V_t ft./Sec.	E.R.	Eff. %
1900	223	62.5	1.13	61.37	.5925	14.18	1.25	4.25	.294	142.0	1.61	47.3
1800	227	51.5	1.28	50.22	.5925	12.18	1.12	3.75	.299	133.2	1.55	46.4
1700	228	42.8	1.41	41.39	.5925	10.22	1.03	3.30	.307	125.0	1.52	46.7
1600	228	36.0	1.58	34.42	.5925	8.54	.87	2.95	.297	118.2	1.55	46.2
1500	228	30.0	1.76	28.24	.5925	7.02	.75	2.55	.294	110.0	1.53	45.0
1400	228	26.1	1.92	24.18	.5925	6.01	.69	2.30	.299	104.5	1.52	45.7
1300	228	21.3	2.38	18.92	.5925	4.65	.63	1.90	.329	95.0	1.48	48.6
1200	228	18.9	2.87	16.03	.5925	4.04	.56	1.65	.340	88.4	1.37	46.5
1100	228	17.5	3.02	14.48	1.24	3.48	.44	1.48	.296	83.7	1.35	40.0

TABLE XLII

ENERGY RATIO, PRESSURE LOSS COEFFICIENT AND EFFICIENCY (BLADE ANGLE 19°)

Barometric pressure 28.80"Hg.

Dry Bulb Temp. 79°F
Wet Bulb Temp. 65°F

ρ = .002205
$V = 68.6 \sqrt{q}$

R.P.M.	Line Voltage E_L (Volts)	Line Amperes I_L (Amps)	Field Amperes I_f (Amps)	Armature Amperes I_a (Amps)	Armature Resistance R_a (Ohms)	B.H.P.	dP inches H_2O	q inches H_2O	k	V_t ft./sec.	E.R.	Eff. %
1900	212	48.4	1.09	47.31	.5925	10.5	1.09	3.48	.315	128.1	1.62	51.0
1800	213	40.4	1.20	39.20	.5925	8.9	.94	3.13	.299	121.6	1.63	48.7
1700	213	34.2	1.29	32.91	.5925	7.47	.844	2.78	.304	114.2	1.60	48.8
1600	213	29.0	1.42	27.58	.5925	6.25	.719	2.45	.293	107.3	1.60	46.9
1500	212	24.5	1.54	22.96	.5925	5.21	.609	2.16	.282	101.0	1.59	44.8
1400	209	21.2	1.72	19.48	.5925	4.25	.485	1.88	.258	94.0	1.56	40.3
1300	209	17.9	2.00	15.90	.5925	3.41	.391	1.62	.241	87.3	1.57	37.8
1200	208	15.8	2.30	13.50	.5925	2.97	.313	1.39	.225	80.8	1.43	32.2
1100	208	14.2	2.56	11.64	1.24	2.29	.203	1.17	.174	74.2	1.44	24.9

FIG. 54
CONSTANT LOSSES vs. R.P.M.

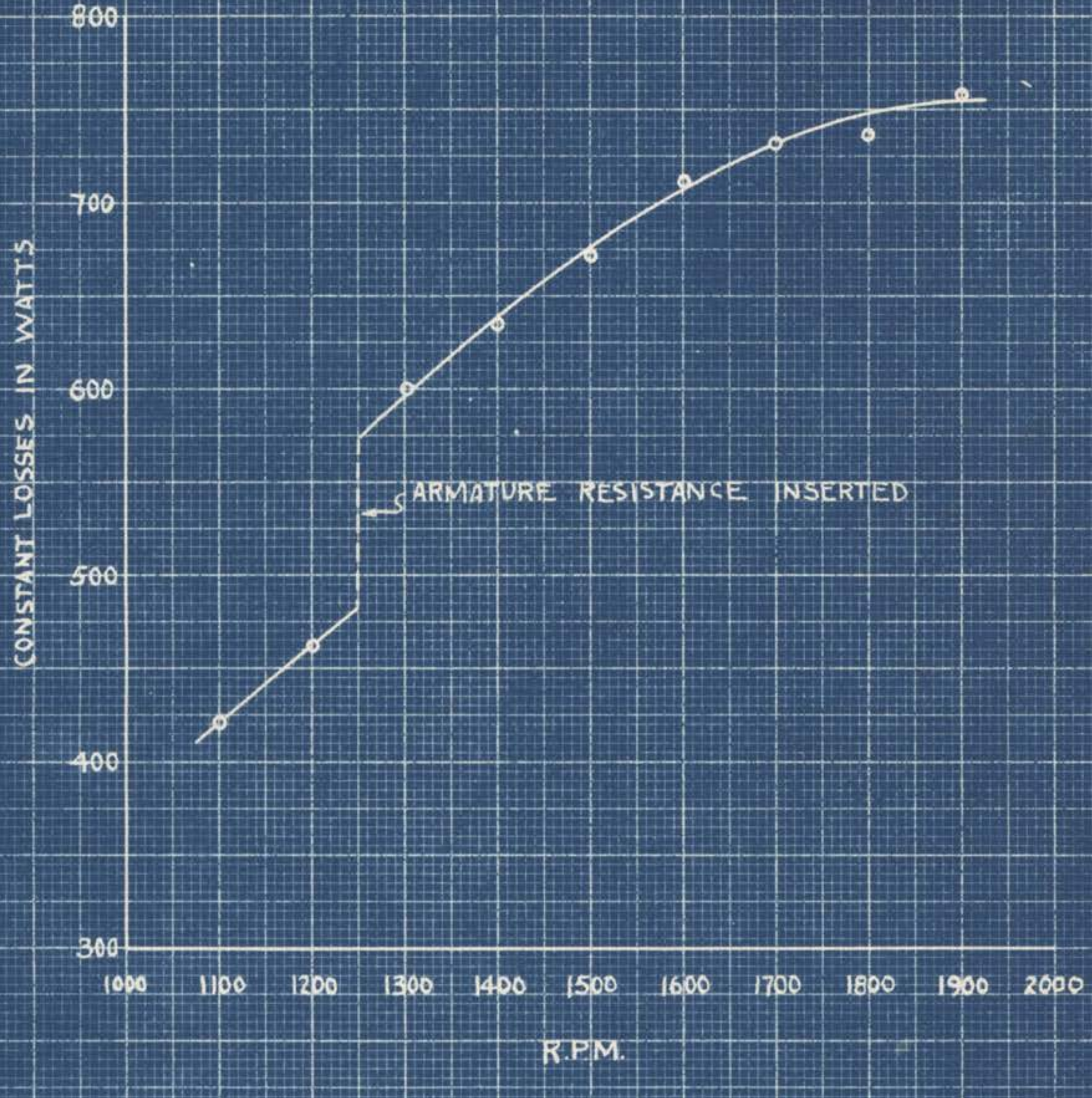


FIG 55
CURVES FROM TABLE XLI
24° BLADE ANGLE

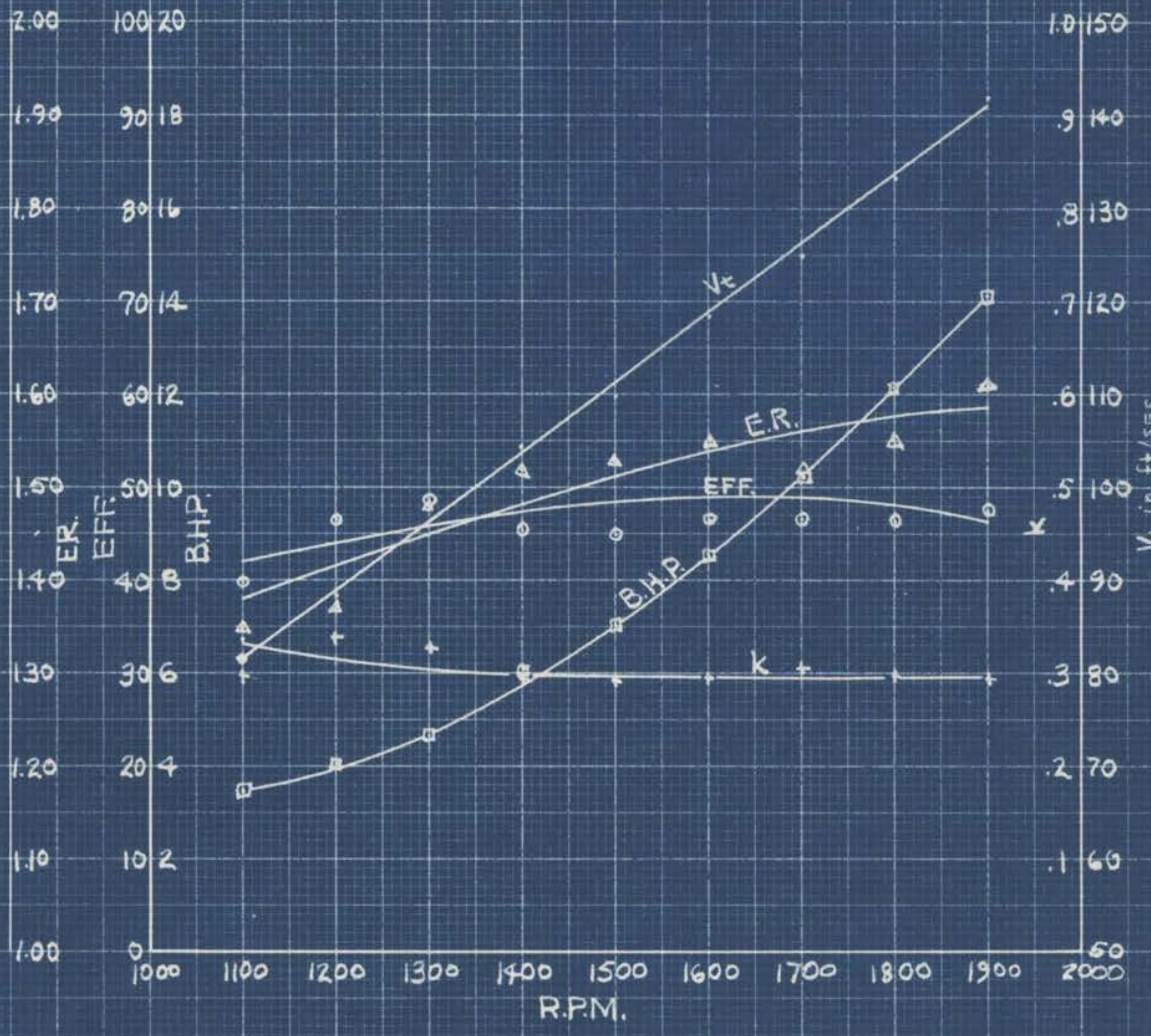
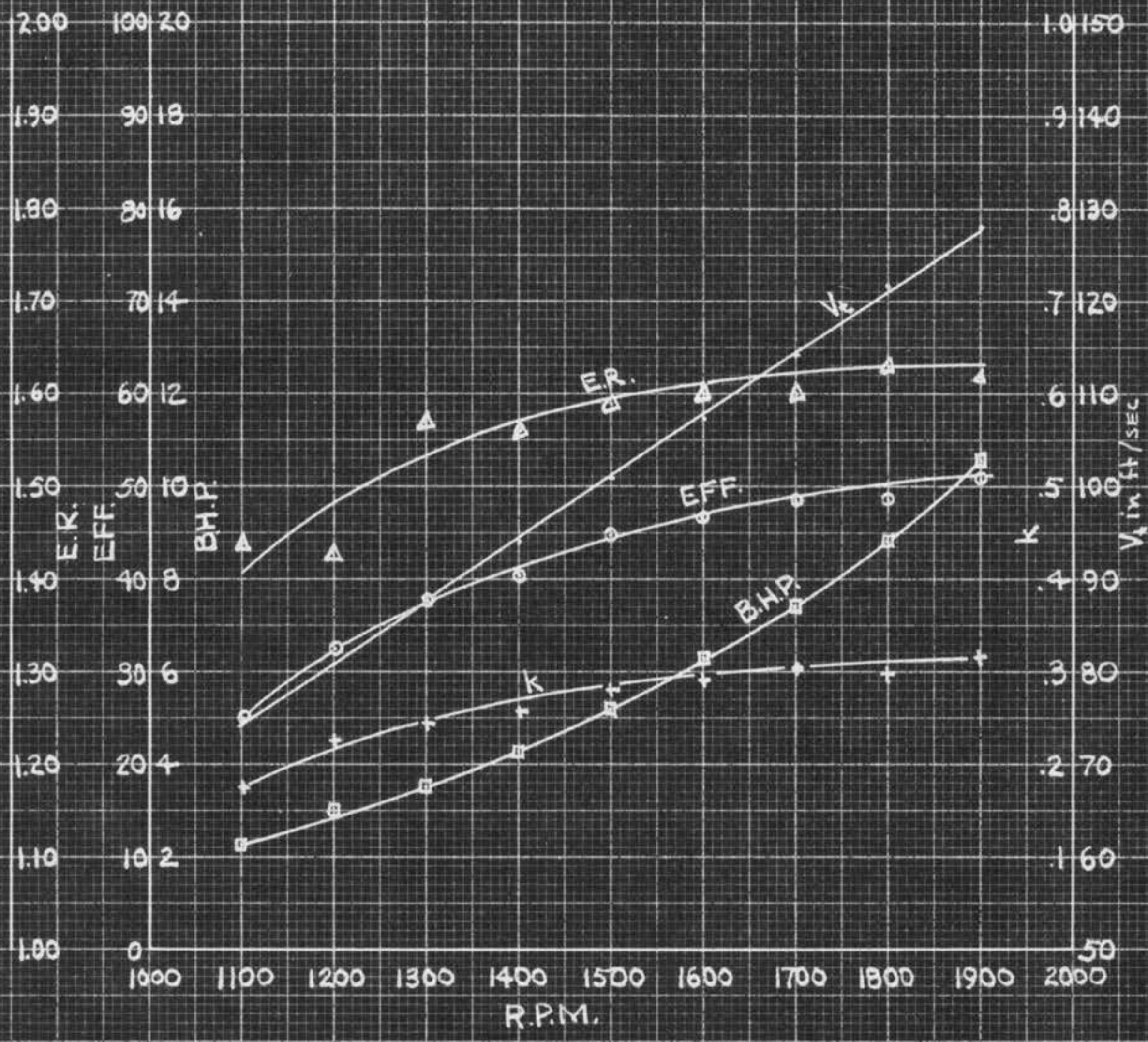


FIG. 56
CURVES FROM TABLE XLII
19° BLADE ANGLE



SUMMARY AND CONCLUSIONS.--Figures 55 and 56 show curves of V_t, k, B.H.P., E.R. and Efficiency for blade settings of 24° and 19° respectively. The maximum V_t attained was approximately 14 ft/sec higher with the 24° setting, however, the corresponding B.H.P. was some 3.7 H.P. higher. The value of k, the pressure loss coefficient was almost constant for the 24° setting but decreased considerably with rpm for the 19° setting. The Energy Ratio, while showing the same general tendency at both settings, was distinctly higher for the 19° blade setting both for corresponding values of rpm and V_t. The Efficiency, which represents the combined efficiency of the fan, fan bearing and V-belts reached a higher maximum at the 19° setting but dropped rapidly with rpm to a very low value at low airspeeds.

The Energy Ratio is the most important of these characteristics as it indicates the overall performance of the tunnel. These results indicate that if a more complete investigation were to be made, some blade angle between 24° and 19° or possibly even as low as 15° might result in still higher values of the Energy Ratio. Such a blade setting, however, would probably result in still lower values of the maximum velocity.

In view of the fact that this tunnel is used primarily for instructional purposes and is normally operated over a rather wide range of airspeeds, the 24° blade angle is considered the more suitable as it results in a higher attainable Reynolds number and more nearly constant values of k, E.R. and Efficiency.

Although it might appear that still higher Reynolds numbers could be obtained at a blade angle of 30°, the opposite would probably be true since the present motor installation would not be able to turn up 1900 rpm with the blade at a higher angle than 24°. This could be expected to result in lower maximum air velocities.

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