VIRGINIA ENGINEERING EXPERIMENT STATION

The Engineering Experiment Station was established in 1921 by action of the Board of Visitors of the Virginia Polytechnic Institute, to stimulate and advance engineering education and to investigate problems of special importance to the professional engineers and to the manufacturing, mining, transportation and other industrial interests of the State and the Nation. The creation of a distinct research organization within the School of Engineering has resulted in many benefits both to the institution and to the industrial life of the state. The chief benefit, as well as the primary aim, is the solution of technical problems of industry and the extension of knowledge; but of almost equal importance to the college as an educational institution is the stimulation which it gives faculty and students through the contact and study of actual, live problems from industry. The young engineering graduates are made of more immediate value to industry through having been brought by their teachers into some understanding of the current problems of industry. Of equal value is the number of research fellows who are each year given post graduate training and research experience, thus fitting them for positions in industrial research organizations. The Station will be glad to receive suggestions from industries regarding research and investigation and, where possible, will cooperate with individuals and organizations in conducting such work. When research is undertaken for the private benefit of an industry, the industry will be expected to finance the work. Studies made at public expense will be published in the form of bulletins where the results are of general interest. In other cases reports are made to those concerned. Results of commercial value may be patented and the proceeds applied to the promotion of the research work of the Engineering Experiment Station, with suitable recognition as to the rights of any industries which may have assisted in financing the work.

Several research fellowships for graduate students in engineering are offered by the Station. This research is confined to problems of general interest and benefit. Under suitable conditions funds may be accepted from industries for the establishment of research fellowships where the results of the investigations would be of value only to the industries concerned. It is especially suggested that smaller industries which are individually unable to finance needed research work may find it possible by group organization to finance such work at a nominal expense to each member of the group. The Station will welcome such an arrangement by which its facilities may be made of service to the smaller industries.

Suggestions of research projects are always welcome.

EARLE B. NORRIS, *Director*
Engineering Experiment Station
Blacksburg, Virginia.

BULLETIN

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VIRGINIA POLYTECHNIC INSTITUTE

The Construction and Calibration of the V. P. I. Wind Tunnel

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FOREWORD

So many requests have been received for information on the construction and capacity of the V. P. I. wind tunnel that it has been found desirable to present that information in bulletin form. This bulletin is presented in the hope that it may serve a number of purposes. It will give information on the tunnel for the benefit of other institutions which may be planning on the construction of one of similar characteristics. Moreover, the bulletin will advise engineers and industries of the wind tunnel facilities which are available at V. P. I. for research on their aerodynamic problems. For this reason, particularly, the bulletin contains the results of tests made upon standard geometric forms and the turbulence is shown in Table II in comparison with the tunnels of other well-known aerodynamic laboratories.

The attention of engineers and industrial executives is called to the fact that the wind tunnel may be used not only for studies relative to airplanes and airplane parts, but also for the testing of the wind resistance of models of automobiles and locomotives, and for studies of wind forces on buildings and structural elements, with suitable correction factors for the scale of the model tested.

E. B. Norris, *Director*
Engineering Experiment Station

FIGURES AND CAPTIONS

The Construction and Calibration of the V. P. I. Wind Tunnel

INTRODUCTION

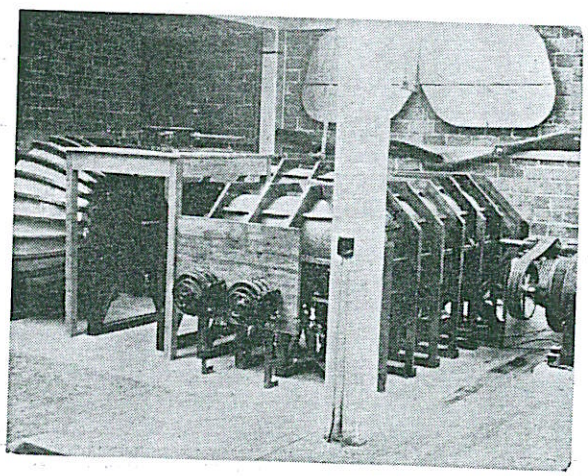
The science of aerodynamics has been rapidly developed since the first successful flight by a heavier-than-air machine. Experiments to determine air forces on various types and shapes of bodies are recorded dating back several centuries; but the advent of the airplane made a more extensive and exact study necessary. Modern air travel by means of both the lighter-than air and the heavier-than-air craft is the result of a great deal of painstaking investigation and experiments rewarded with an occasional success after a long series of failures.

Aerodynamic research is conducted in most all of the countries of the world at the present time. The laboratories in which these investigations are conducted are usually government-owned, although some of the important ones are operated by universities. The largest and best equipped of these laboratories is that of the National Advisory Committee for Aeronautics at Langley Field, Hampton, Virginia. Well known laboratories abroad are that at Göttingen in Germany, that of the National Physical Laboratory in England, and the Eiffel Laboratory in France.

Tests and investigations in the field of aerodynamics in all of these laboratories are carried out in wind tunnels; a wind tunnel being an apparatus for producing a stream of air which moves relative to the stationary object on which the resulting forces can be measured. If it is desired to determine the characteristics of a wing section or airfoil, the test in most tunnels must be conducted on a model airfoil very much smaller than the full-size wing. This is necessary because few wind tunnels are large enough to accommodate a full size wing. The results of such tests on models, while they may be accurate for the model, are not true for the full-scale wing unless several corrections are made. These corrections are not altogether satisfactory and experiments are under way to determine more exactly how they should be made. The N.A.C.A. variable-density tunnel was built especially to verify the Reynolds number theory by which the speed and scale effect are accounted for. The only full-scale wind tunnel in the world is that of the N.A.C.A. at Langley Field. This tunnel will accommodate a full-size airplane, the air jet being 30 feet high and 60 feet wide.

Besides being used for model testing, wind tunnels are also extensively used for purposes of instruction. In order to offer adequate instruction in aerodynamics a school is confronted with the problem of building a wind tunnel. The solution of this problem will depend upon the amount of money available. To be of any real service or value rather high standards of accuracy of design and construction must be maintained. Construction costs increase very rapidly as the size of the tunnel is increased. The size, therefore, will vary from a small table model a few inches in diameter up to a tunnel several feet in diameter.

There is no standard method or material for the construction of a wind tunnel. Wood, concrete, and steel have all been used, depending upon conditions, and each with excellent results. Also the tunnel may be either horizontal or vertical; with an open or closed return circuit; and the throat may be either open or closed. If the tunnel is large the closed circuit is usually preferred because the power required for this type is less than for the open one-way type.



No. 1. — The Wind Tunnel.

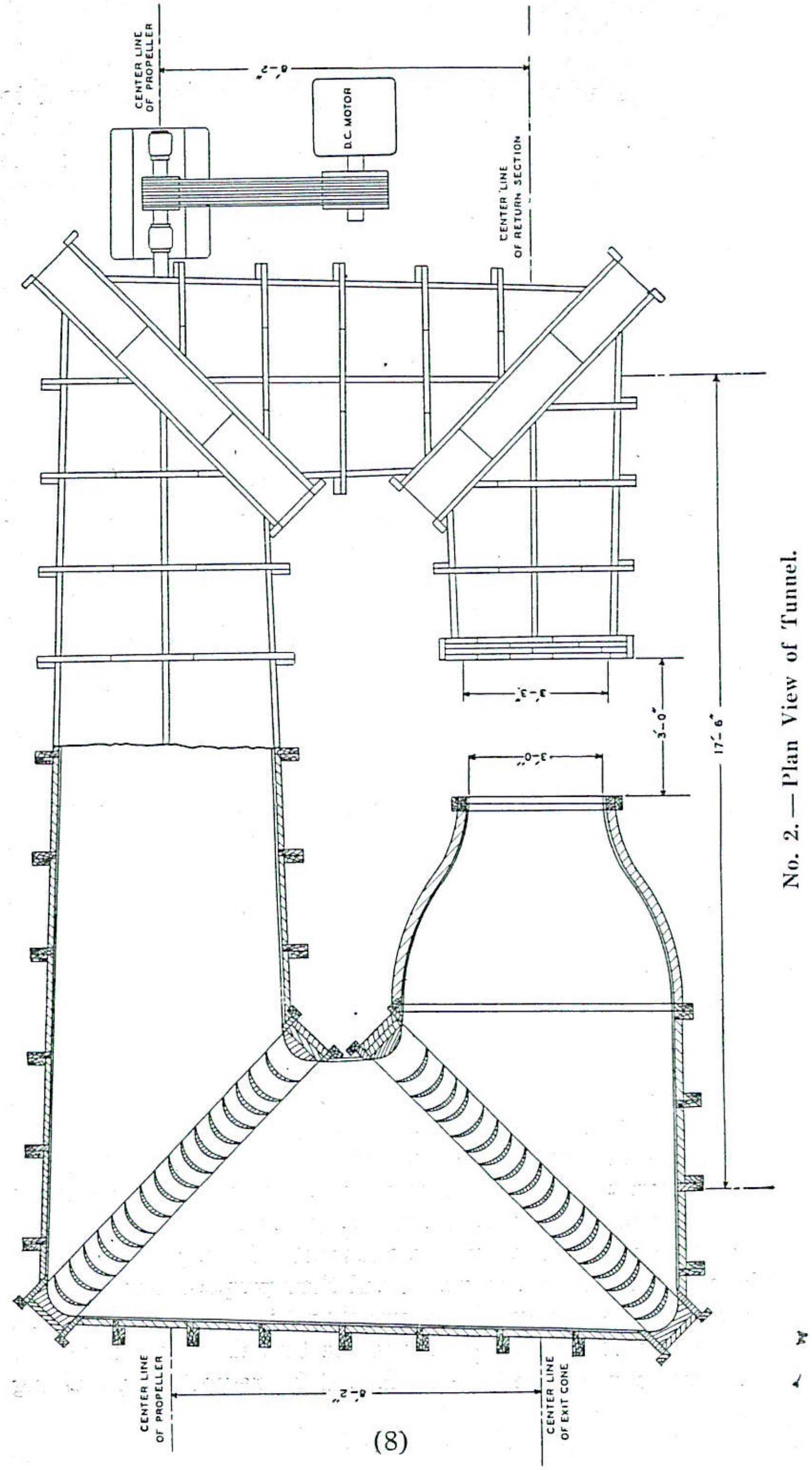
The wind tunnel described in this bulletin was designed to serve for model testing as well as instruction in aerodynamics. The cost was one of the major considerations and use was made of some equipment already available. Many of the construction details are unique and were used in an effort to keep down the final cost without sacrificing quality. A brief description of this tunnel and some of the unusual methods employed in its construction are therefore given.

DESCRIPTION OF TUNNEL

The V. P. I. wind tunnel is an open-throat return type. A photograph of it is shown in Figure 1, and a plan view showing some of the construction details is given in Figure 2. The tunnel will be seen to consist of a tube of circular section with diameter varying from 39 inches to 72 inches. The main body of the tunnel is constructed of two thicknesses of ¼-inch waterproof plywood nailed on the inside of circular forms placed at intervals of 16 inches. The plywood construction was finally chosen after a study had been made of several alternatives such as steel, concrete, and wood. The cost of the concrete was prohibitive and the use of steel was eliminated because of difficulty of construction and the probability of its being noisy because of a sound-board effect. The inside walls were given one coat of shellac which was rubbed down to a smooth finish followed by four coats of spar varnish, each of which was rubbed down. The outside was finished in a similar manner except that each coat was not rubbed.

The exit cone is of unusual design. A wooden form was first built which was larger than the final section but approximating it in shape. Wire netting was nailed over this form and cement plaster applied to it. By means of a sweep which was the shape of the desired section, the plastered interior was worked down to the correct contour. After the plaster had set it was more accurately finished by hand and finally varnished.

In the corners of the tunnel are four sets of straightening vanes. These vanes are equally spaced and their purpose is to turn the air around the corners of the tunnel and to maintain a uniform air velocity across the sections of the tunnel. The numbers in successive corners are 16, 17, 18, and 20, respectively, starting

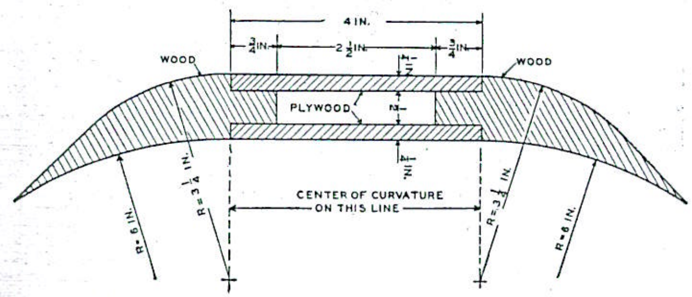


No. 2. — Plan View of Tunnel.

from the throat and following the direction of air flow. The construction of these vanes departs from the usual method employed and for that reason is worthy of mention.

Figure 3 shows the cross-section of one of these vanes. The length of a vane will, of course, depend upon its location in the frame. The leading edge and the trailing edge were formed on a shaper which was fitted with a special cutter. These two pieces were fastened together with plywood. Each vane was carefully finished by hand to insure the smoothest possible surface. Since the purpose of the vane is to deflect the air stream, each vane is structurally a beam carrying a uniform load over its entire length. Bending takes place about the axis of least moment of inertia and, for that reason, it was necessary to provide a means of bracing the vanes. This was done by the use of horizontal spacers which were placed at intervals to carry the loads which come on the vanes back to the frame or cage in which the vanes are built. The vanes are mounted in frames separate from the tunnel itself which frames can be removed for any adjustments that may be required. One of the vane sets is shown in Figure 4.

Power is furnished by a 40 h.p. D.C. motor which is supplied by a motor-generator set. Both the D.C. motor and motor-generator were already on hand, but they had to be partially rebuilt and repaired. The motor was originally designed for 220 volts but was changed to 110 volts because the motor-generator supplied only 110 volts. In order to get the desired speed control, separate excitation was furnished by a smaller motor-generator set. The wiring diagram shown in Figure 5, which is self-explanatory, shows the arrangement used. The propeller is

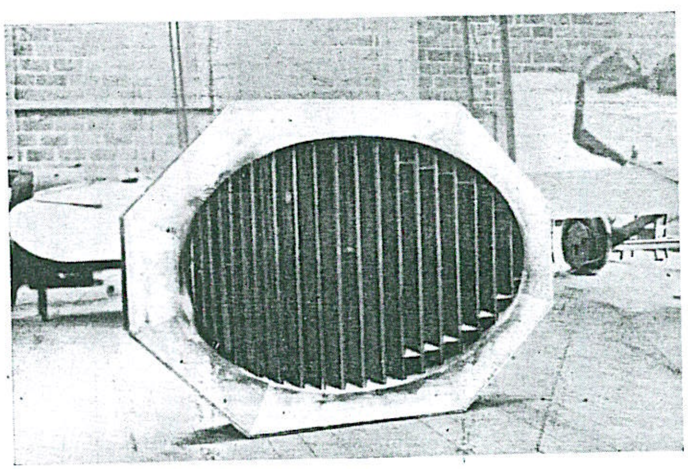


No. 3. — Cross-Section of Straightening Vane.

a four-bladed Hartzell propeller which was specially made according to specifications furnished the company. The propeller drive shaft is a solid steel shaft mounted on three S.K.F. ball bearing assemblies. One bearing is inside the tunnel and is supported by two struts which go through the tunnel to the foundation and a third strut to the top of the tunnel. This method prevents any movement which might cause the propeller to strike the wall. The clearance between the wall and the propeller is 3/16 inch. The driven pulley on the shaft is carried between the two outside bearings. The end bearing is used to carry the propeller thrust as well as part of the radial load from the belt and pulley, the other bearings being free to move axially.

The speed range of the tunnel is from 0 to 150 miles per hour, but for most routine work a speed of 100 miles per hour is the maximum used. A vibration point occurs at 36 miles per hour.

Air speed is measured by two methods. A Pitot-static tube was used first to explore the test section to determine the quality of the air flow. Leads from the static and dynamic tubes are conncteed to an inclined differential monometer graduated to read to .01 inch of water. The calibration of the tube and monometer includes a correction for compressibility of air. Readings of the monometer are taken directly and referred to a curve which gives the corrected air velocity in feet per second.

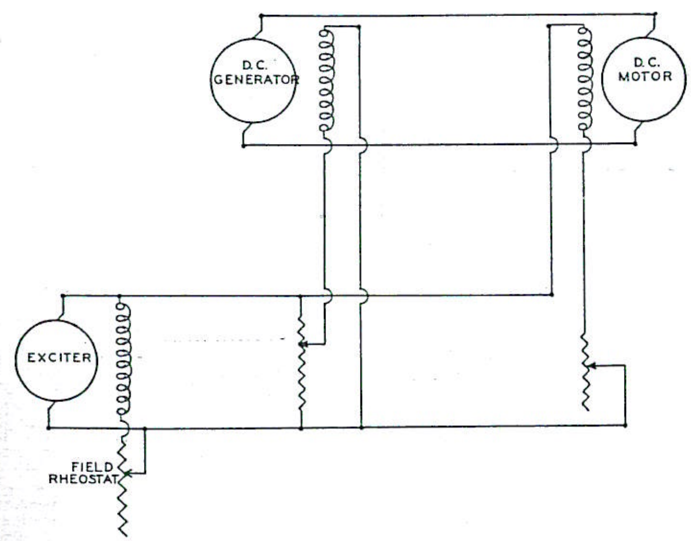


No. 4.— Set of Vanes in Frame.

Air velocity is also determined by means of an orifice which is located in the tunnel wall just back of the exit cone. An inclined differential monometer is calibrated to give the air velocity at the test section in feet per second. Calibration of this orifice was made by use of the Pitot tube.

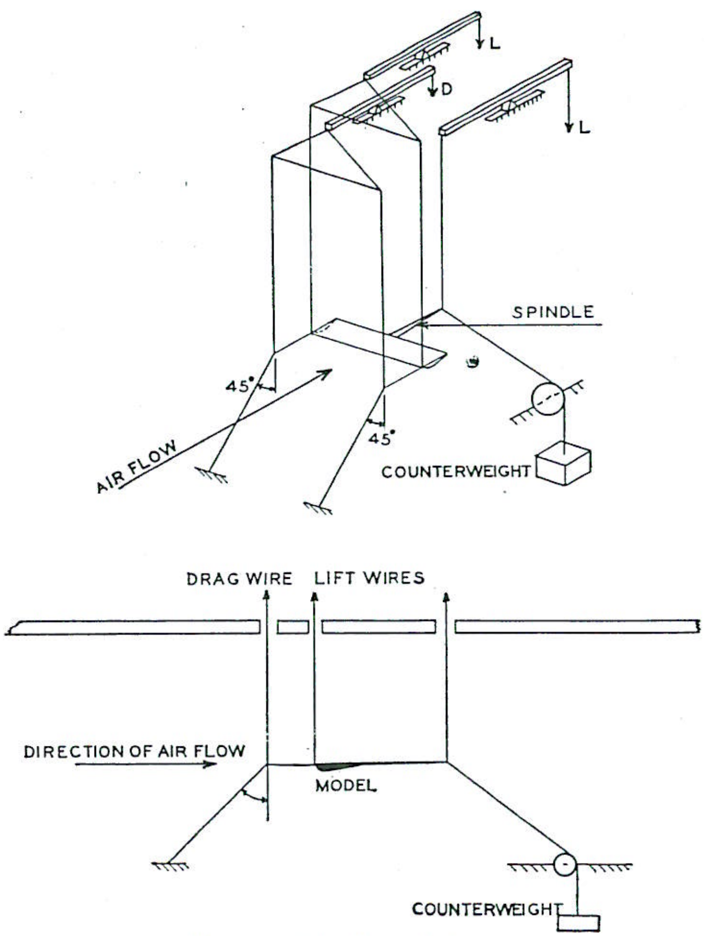
The method employed for measuring forces in a wind tunnel will depend upon the model to be tested and the investigator will use whatever arrangement is best suited to his particular experiment. No system of balance is considered to be standard, although most systems used are modifications of either a wire-type balance, the N.P.L., or the N.A.C.A. six component balance. For tests later described, measurement of forces was done by a wire balance and also by a special type of balance which is a modification of the N.P.L. design. In the tests of the airfoil and the flat plate at different angles of attack the wire balance was employed. A schematic representation of the airfoil set-up is shown in Figure 6. For testing the sphere and disk the other special balance was used, the set-up for testing the disk being shown in Figure 7.

By use of the wire balance, lift, drag, and center-of-pressure measurements can be made. The other type serves only for



No. 5.— Wiring Diagram for Motor Control.

determination of drag. Forces in each method are measured by platform scales which read to 0.1 grams. Three scales are necessary when using the wire balance and only one when using the modified N.P.L. balance.

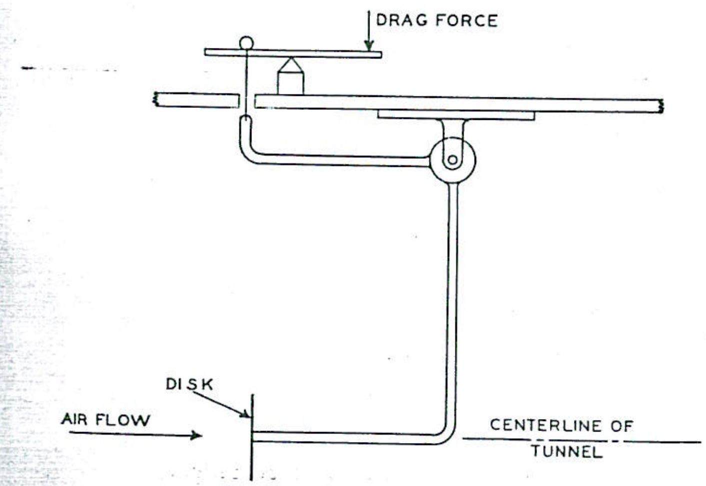


No. 6. — Wire-Type Balance.

CALIBRATION TESTS

The accuracy of results obtained from a wind tunnel depends upon the accuracy of the instruments used, the character of the air flow produced, and the size of the model tested. The first two items can usually be made satisfactory for any size tunnel. Correction of data from a small scale model is uncertain at the present time; the smaller the model the larger the corrections, and the more unreliable the results. If A is the cross-section area of the air jet in square feet and V the air velocity in miles per hour, the scale of the test will be proportional to $V\sqrt{A}$. Another factor affecting wind-tunnel tests is turbulence. By this term is meant the steadiness of the velocity of the airstream; and if dV is the mean velocity fluctuation, turbulence is defined as $\frac{dV}{V}$. Turbulence can be measured by comparing readings of a Pitot-tube with those of a hot-wire anemometer. The turbulence in free air in which airplanes fly is almost zero. In wind tunnels it varies from 1 to 6 percent and it is estimated to cause from 3 to 18 percent difference between free-flight tests and wind tunnel tests.

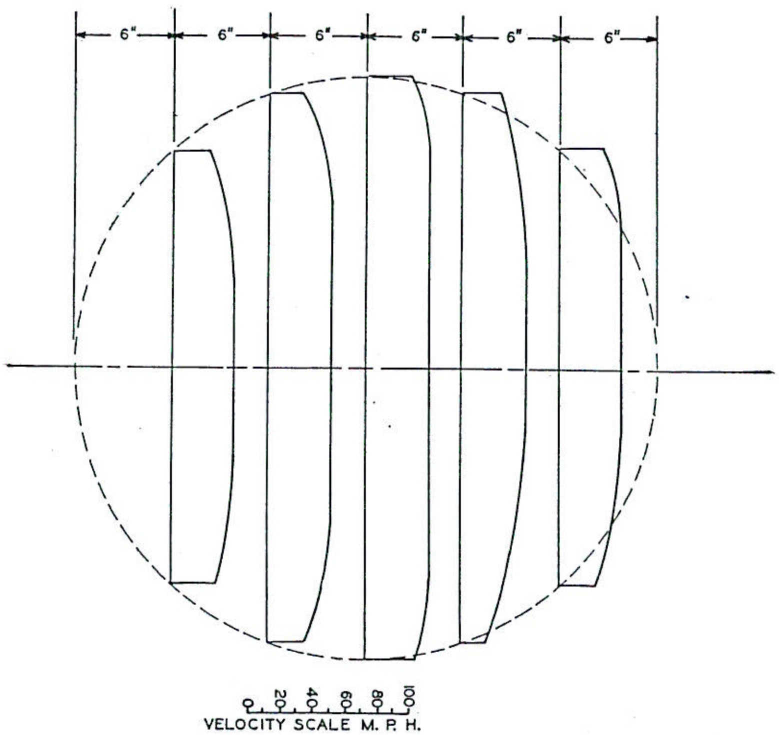
In an attempt to determine how results from this wind tunnel compared with those from other tunnels a series of tests was



No. 7. — Lever-Type Balance.

made. A sphere was used to measure the turbulence, since the hot-wire anemometer was impractical at the time. Tests were also run on a disc, flat plate, and an airfoil.

The test section was explored by the Pitot-tube to determine the variation of airflow across the section. The 36-inch circular section was divided by six horizontal and six vertical lines and readings taken at the intersection of these lines, making 25 points in the test section. Planes every six inches from the exit cone to the return section were thus investigated for air speeds every 10 miles per hour up to 100 miles per hour. Figure 8 is a diagrammatic sketch showing the results of the test at the mid-section for a speed of 40 miles per hour. The ideal test section would have a constant velocity at every point in any transverse plane. Since the maximum variation within a 30-inch diameter



No. 8. — Air Flow Across Test Section.

circle was less than 2 percent, the flow was regarded as being satisfactory. The maximum variation at any place in the test section was 8 percent. From the exit cone to the entrance cone, or measuring longitudinally, the maximum variation was 5 percent, with the lower values occurring near the entrance cone. The variation within the area occupied by any model was only about 0.5 percent.

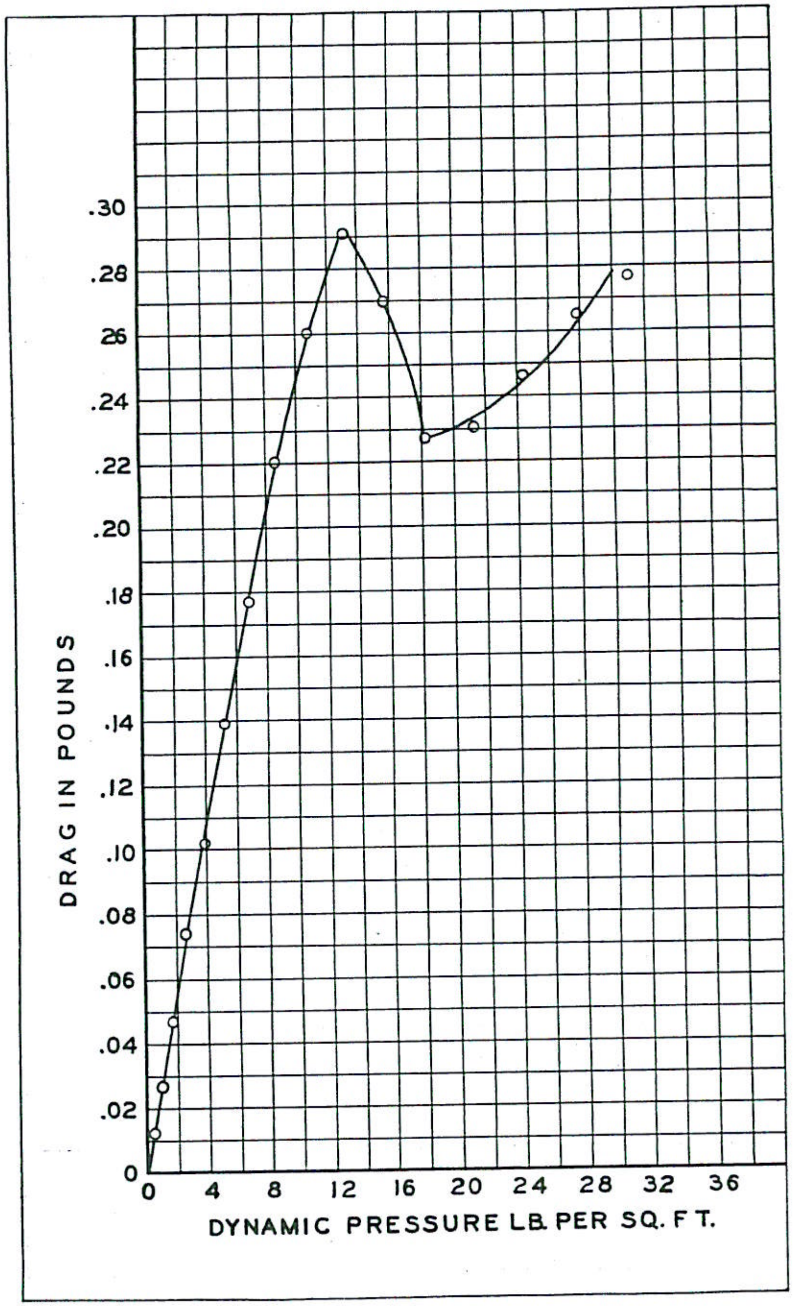
The results mentioned above would seem to indicate that the air flow was also satisfactory from the standpoint of its being in lines parallel to the axis of the tunnel. Although there is some spilling of air over the edge of the entrance cone, the air velocity is steady without surging. The spilling is minimized by having the intake cone larger than the exit, and it could be corrected further by cutting slots around the section just back of the entrance cone. The usual honeycombing was left out when the tunnel was built, the plan being to add it later if necessary. Tests indicate that the flow is satisfactory without the addition of honeycombing.

Test of Sphere

A sphere 3 inches in diameter was mounted using a back spindle, the back of the sphere being 8 inches from the vertical part of the balance. The sphere had a very smooth surface and a diameter which was constant within very close limits. Determinations of drag were made at speeds varying by 10 miles per hour from 10 to 100. The test was repeated three times and the results given in Table I are the average.

Considerable difficulty was experienced with stability conditions when the airflow passed through the transitional range, but repeated tests showed a close agreement of results. Figure 9 is the sphere drag plotted against impact pressure. The transition points occur at values of impact pressure of 13 and 17.

Impact pressure was calculated from the defining equation $\frac{\rho V^2}{2}$, where ρ is the mass density of air in slugs per cubic foot and V the air velocity in feet per second. The air density in pounds per cubic foot is calculated from the relation $PV = WRT$ where W is the air density; P the pressure in pounds per square inch;



No. 9. — Drag of Sphere.

V is one cubic foot; $R=53.36$; and T the absolute temperature in degrees Fahrenheit. For this test

$$W=\frac{13.9\ \times 144}{53.36\times 538}=.0696 \text{ lb. per cu. ft.}$$

and

$$\rho=\frac{.0696}{32.2}=.002165 \text{ slugs per cu. ft.}$$

Turbulence

The turbulence of the tunnel can be estimated from the sphere test by the N.A.C.A. method given in Technical Report No. 342. The coefficient of drag is plotted against the logarithm of Reynolds number in Figure 10 to furnish the data for an estimate of turbulence and also to show the magnitude of the unstable region of flow. For a drag coefficient of .3 and a Reynolds number of 162,000, the turbulence is found to be 1.6. For comparison, the estimated turbulence of several well known wind tunnels is given in Table II. Reynolds number is given by $\frac{\rho VD}{\mu}$ where ρ is the mass density in slugs per cubic foot; V the velocity in feet per second; D the diameter of the sphere in feet; μ the coefficient of viscosity in slug-feet seconds. The value of μ used in the calculations was 3.77×10^{-7} which is for a temperature of 78 degrees Fahrenheit. This value of μ was calculated as follows, using the approximation that μ varies as the $\frac{3}{4}$ power of absolute temperature: Expressed mathematically

$$\mu \ \alpha \ T^{3/4}$$

and $\mu=kT^{3/4}$ where k is a constant.

Substituting the value of $\mu=3.72$ at 58 degrees Fahrenheit, which is the value given by the N.A.C.A.

$$3.72=k\ 518^{3/4}$$

$$3.72=k\times 108$$

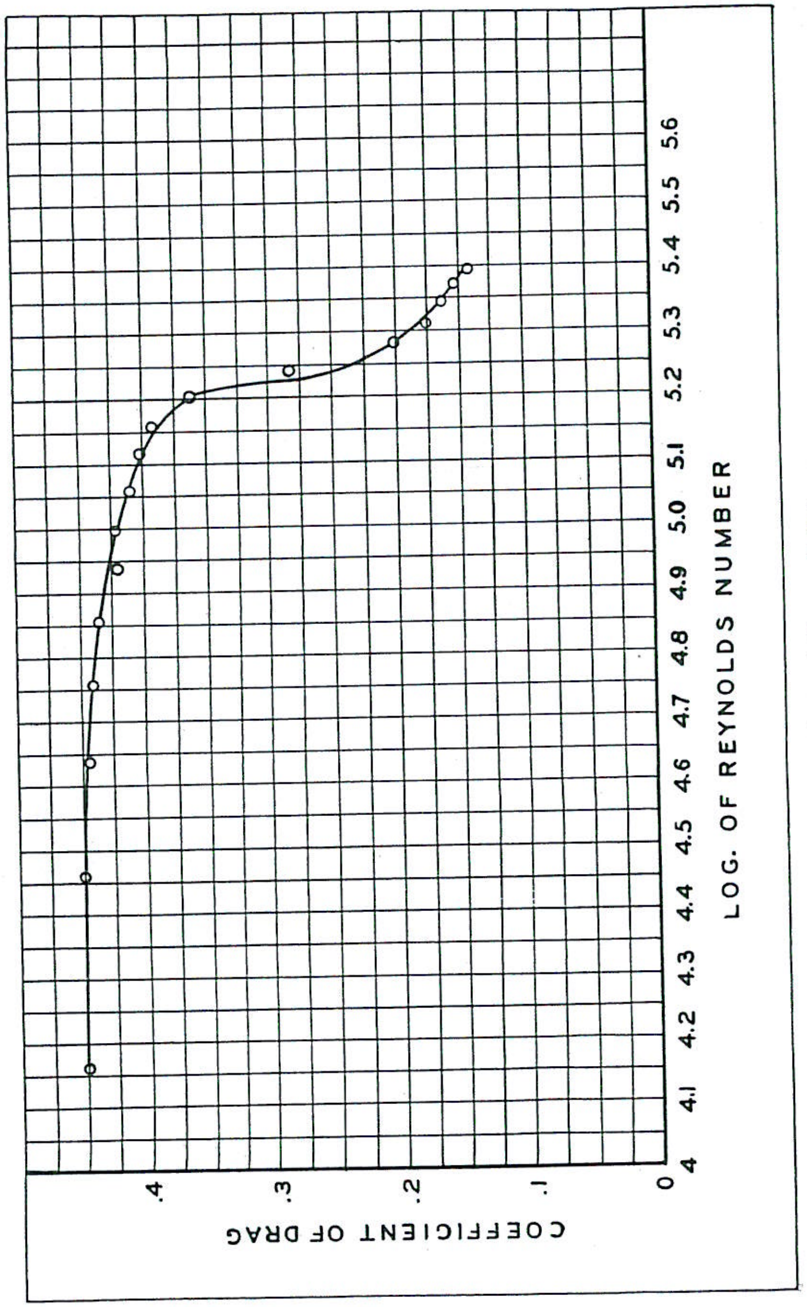
and

$$k=.0345$$

For a temperature of 78 degrees Fahrenheit, 538 degrees absolute

$$\mu=.0345\times 638^{3/4}=3.79\times 10^{-7} \text{ slug-feet second.}$$

It is to be noted that $\frac{\mu}{\rho}$ is known as the "kinematic viscosity."



No. 10.—Coefficient of Drag of Sphere.

The coefficient of drag was calculated from the expression

$$\text{Drag} = C_D \frac{\rho}{2} d^2 V^2,$$

in which C_D is the coefficient of drag for the sphere; ρ is the mass density of air in slugs per cubic foot; d is the sphere diameter in feet; V is the air velocity in feet per second.

Results of the sphere test seem to be in general agreement with data obtained from other tunnels. The points at which the transitions occur are not significant since they occur at different points in different tunnels. Values of C_D appear to be rather low, but this fact can be explained in several ways such as the character of the surface of the sphere and the high value of Reynolds number at which the critical flow régime occurs.

Test of Disk

Drag determinations were made on a steel disk 6 inches in diameter and .08 inch thick. The back was chamfered at 45 degrees to give a knife edge around the circumference. The disk was supported in the same manner as the sphere, exactly the same device being used. The speed range covered was from 0 to 160 feet per second. Table III contains both test data and calculated values of C_D, Reynolds number, and dynamic pressure. Values of drag in pounds against dynamic pressure are plotted in Figure 11. C_D for the disk at different values of velocity is calculated from the drag equation

$$D = C_D \frac{\rho}{2} A V^2,$$

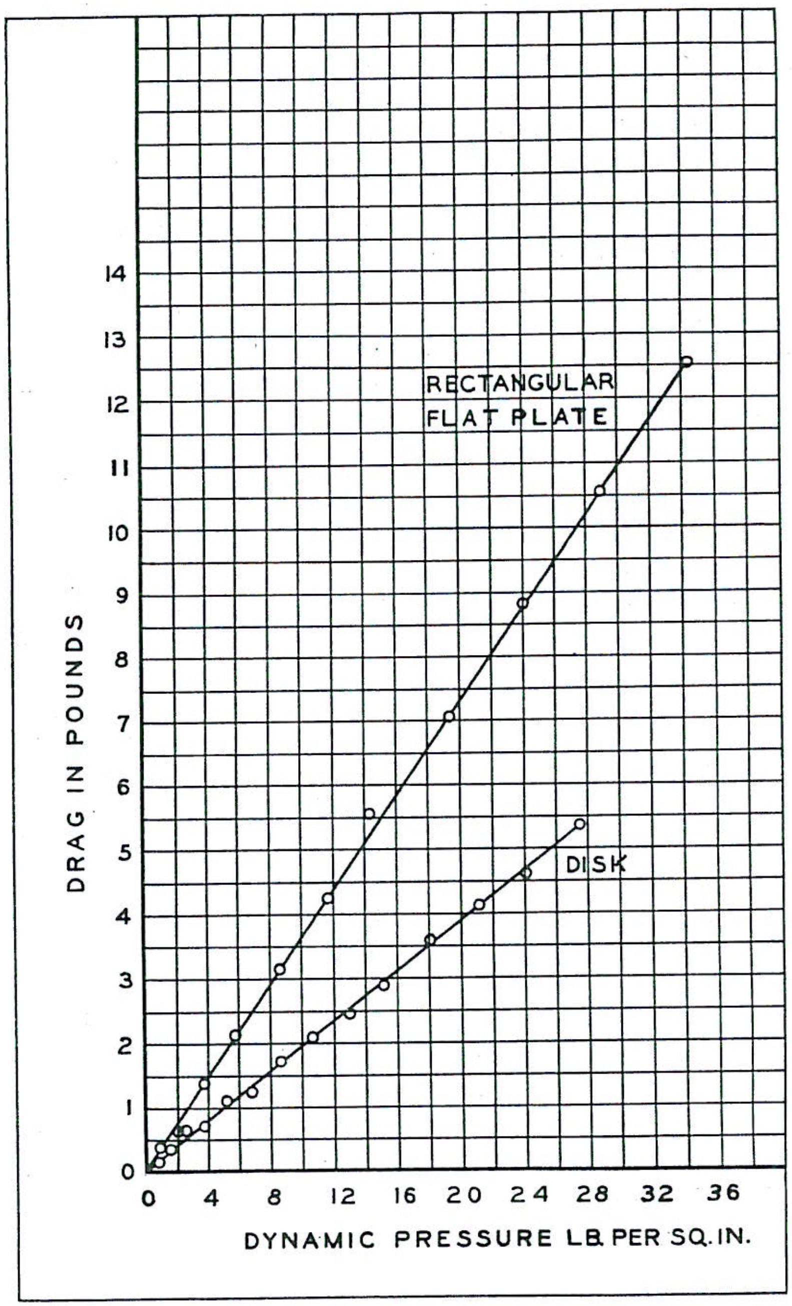
in which D is the drag in pounds

ρ is the mass density of air in slugs per cubic foot

A is the disk area in square feet

V is the air velocity in feet per second.

No unusual results were found in this test; as will be noticed, the values of drag coefficient agree very well with those obtained by other investigators.



No. 11.—Drag of Disk and Rectangular Flat Plate.

TABLE I.—SPHERE 3-In. DIAMETER.

$T = 78°F.$ $W = .0696$ lb./cu.ft.

$P_B = 13.9$ lb./sq.in. $\rho = .002165$ slugs/cu.ft.

$\mu = 3.77 \times 10^{-7}$ lb.-sec./sq.ft.

VELOCITY		Drag Lb.	C_D	R.N.	Log. R.N.
M.P.H.	Ft./Sec.				
6.82	10	.00304	.45	14350	4.1555
13.65	20	.01216	.45	28700	4.4575
20.44	30	.02710	.445	43100	4.6340
27.30	40	.04760	.440	57400	4.7590
34.10	50	.07450	.435	71800	4.8560
40.8	60	.1023	.42	86200	4.9350
47.7	70	.1392	.42	100500	5.0026
54.5	80	.1775	.41	115000	5.0602
61.4	90	.2210	.403	129100	5.1100
68.2	100	.2640	.391	143500	5.1570
75.0	110	.2940	.360	158000	5.1990
81.9	120	.2725	.280	172200	5.2360
88.6	130	.2270	.200	186600	5.2710
95.5	140	.2320	.175	201000	5.3030
102.2	150	.2465	.162	215000	5.3320
109.1	160	.2650	.153	229500	5.3600
116	170	.2770	.142	244000	5.3880

M.P.H. = Miles per hour.
C_D = Drag coefficient.
R.N. = Reynolds number.

TABLE II.—TURBULENCE IN WIND TUNNELS.

Tunnel	R.N. for $C_D = 0.3$	Estimated turbulence
		Percent
Free air, NACA dropping tests	400000	0
Free air, NACA towing tests	375000	0
Calif. Inst. of Technology	320000	0.2
Göttingen	270000	0.5
Bureau of Standards, 10 ft.	230000	0.9
NACA, atmospheric 5 ft.	200000	1.3
NYU, 9 ft.	190000	1.5
VDT, redesigned, open throat	160000	2.0
NPL, Teddington, England	150000	2.2
VDT, redesigned, closed throat	120000	2.5
VDT, redesigned, closed, with screen	65000	5.2
VDT, original	60000	5.5
Va. Poly. Inst.	162000	1.6

TABLE III.—DISK DIAMETER = 6 In.

$T = 80°F.$ $W = .0689$ lb./cu.ft.
$P_b = 13.8$ lb./sq.in. $\rho = .00214$ slugs/cu.ft.
$\mu = 3.79 \times 10^{-7}$ lb.-sec./sq.ft.

VELOCITY M.P.H.	VELOCITY Ft./Sec.	Drag Lb.	C_D	R.N.	$\frac{\rho V^2}{2}$
6.82	10	.0193	.92	28400	.107
13.65	20	.0950	1.13	56800	.427
20.44	30	.174	.92	85200	.962
27.30	40	.403	1.20	113600	1.712
34.10	50	.689	1.31	142000	2.675
40.8	60	.711	.941	170400	3.850
47.7	70	1.12	1.089	198800	5.240
54.5	80	1.26	.938	227200	6.850
61.4	90	1.75	1.028	255600	8.660
68.2	100	2.10	1.00	284000	10.70
75.0	110	2.59	1.02	312000	12.96
81.9	120	2.89	.954	341000	15.40
88.6	130	3.61	1.015	369000	18.1
95.5	140	4.15	1.001	398000	20.98
102.2	150	4.62	.977	426000	24.10
109.1	160	5.36	1.00	454000	27.40

$\frac{\rho V^2}{2}$ = Dynamic pressure.

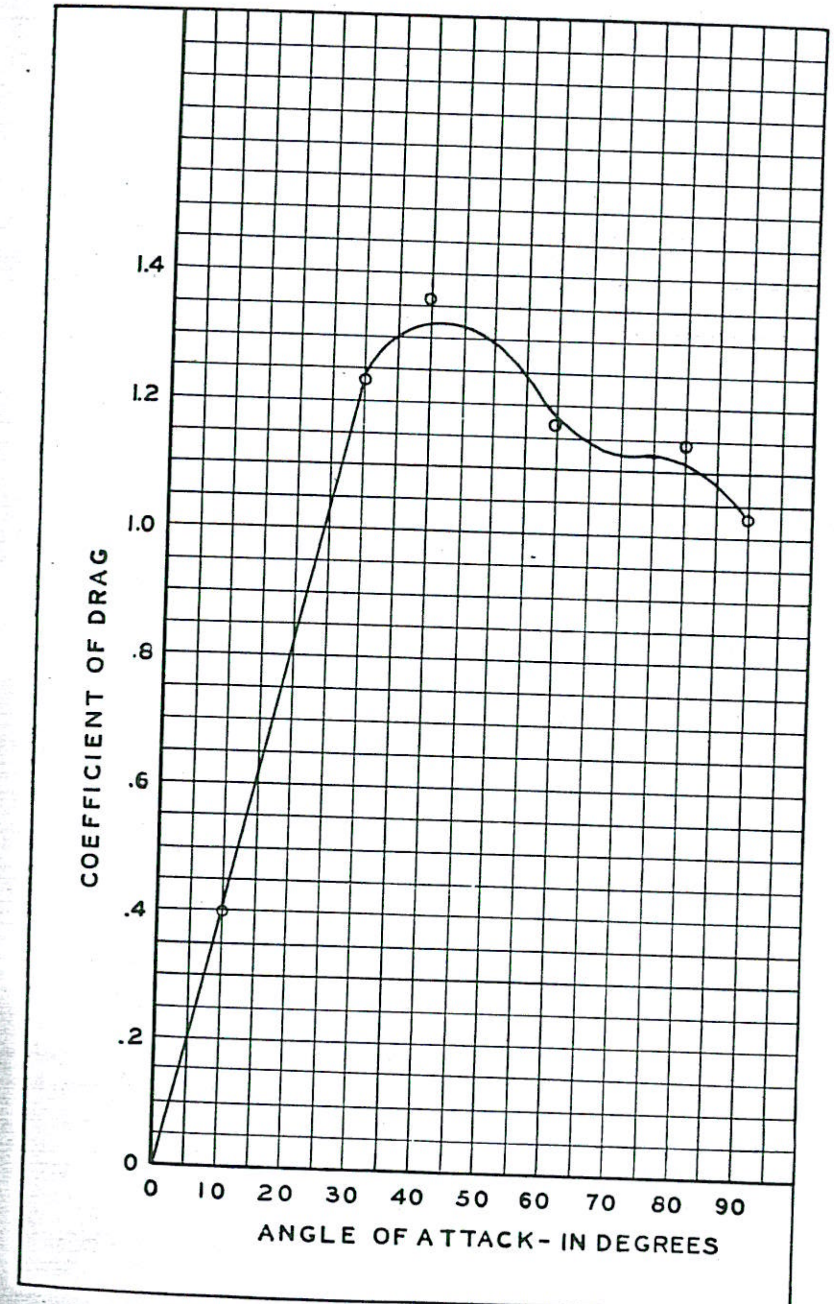
TEST OF FLAT PLATE

A 6-inch by 8-inch flat steel plate was tested using the same balance device as was used for the sphere and disk; the back spindle being screwed into the center of the plate. The edges of the plate were finished at right angles to the faces. Drag determinations were made with the face of the plate perpendicular to the air flow through the speed range.

Values of C_D were calculated from the equation

$$D = C_D \frac{\rho}{2} A V^2,$$

in which D is the total drag in pounds; ρ the mass density of air; A is the area of the plate in square feet; and V the air velocity in feet per second. Table IV gives the values of drag, coefficient of drag, Reynolds number, and dynamic pressure $\frac{\rho V^2}{2}$. The



No. 12.—Coefficient of Drag of Rectangular Flat Plate.

TABLE IV.—FLAT PLATE 6 In. × 8 In.

Angle of Attack (α) = 90°

$T = 70°F.$ $\quad$ $W = .0718$ lb./cu.ft.
$P_b = 14.1$ lb./sq.in. $\quad$ $\rho = .00223$ slugs/cu.ft.
$\mu = 3.76 \times 10^{-7}$ lb.-sec./sq.ft.

VELOCITY M.P.H.	VELOCITY Ft./Sec.	Drag Lb.	C_D	R.N.	Log R.N.	$\frac{\rho V^2}{2}$
0	0	0		0		
10	14.67	.0871	1.03	58000	4.763	.238
20	29.35	.400	1.175	116100	5.064	.955
30	44	.68	.89	174100	5.240	2.15
40	58.70	1.394	1.023	232000	5.365	3.82
50	73.40	2.150	1.013	290000	5.462	5.97
60	88	3.139	1.025	348000	5.541	8.59
70	102.8	4.280	1.042	406000	5.608	11.7
80	117.4	5.560	1.046	464000	5.666	15.3
90	132	7.06	1.025	521000	5.717	19.35
100	146.7	8.82	1.035	575000	5.759	24.05
110	161.4	10.55	1.025	637000	5.802	28.9
120	176	12.52	1.022	695000	5.842	34.4

relations between total drag in pounds and dynamic pressure are shown in Figure 11.

Results obtained from this test are about as expected. The values of C_D agree closely with those found in other experiments.

The plate was next suspended by a wire balance, the method used being similar to that used for the airfoil and shown in Figure 6. Lift and drag determinations were made for angles of attack of 10, 30, 40, 60, and 80 degrees, and at speeds varying by 10 miles per hour from 10 to 110 miles per hour. Drag readings were measured by one scale and lift by two scales. Resultant drag was calculated from these determinations of lift and drag components. Tables V to IX, inclusive, give the data as determined by these tests as well as the calculated coefficients of drag and Reynolds number. The values of C were calculated by the same formula as was used for the plate perpendicular to the wind, but are based upon the resultant force and not on drag alone. Figure 12 gives the relation between angle of attack and C as determined from all of the flat plate tests.

TABLE V.—FLAT PLATE 6 In. × 8 In.

Angle of Attack 10°

$T = 74°F.$ $\quad$ $W = .0705$ lb./cu.ft.
$P_b = 13.92$ lb./sq.in. $\quad$ $\rho = .00219$ slugs/cu.ft.

VELOCITY M.P.H.	VELOCITY Ft./Sec.	Lift Lb.	Drag Lb.	Resultant Lb.	C	R.N.
0	0	0	0	0	0	0
10	14.67	.03117	.0055	.0316	.408	57600
20	29.35	.1261	.0222	.128	.413	115000
30	44	.270	.0475	.2741	.393	172800
40	58.7	.508	.0895	.516	.417	230000
50	73.40	.7822	.138	.794	.409	288000
60	88	1.142	.202	1.160	.415	345000
70	102.8	1.533	.270	1.558	.409	403500
80	117.4	2.006	.348	2.03	.407	462000
90	132	2.562	.452	2.60	.414	517500
100	146.7	3.116	.548	3.16	.407	576000
110	161.4	3.782	.667	3.84	.407	634000
120	176	4.52	.795	4.57	.410	691500

TABLE VI.—FLAT PLATE 6 In. × 8 In.

Angle of Attack 30°

$T = 74°F.$ $\quad$ $W = .0705$ lb./cu.ft.
$P_b = 13.92$ lb./sq.in. $\quad$ $\rho = .00219$ slugs/cu.ft.

VELOCITY M.P.H.	VELOCITY Ft./Sec.	Lift Lb.	Drag Lb.	Resultant Lb.	C	R.N.
0	0	0		0		0
10	14.67	.083	.0479	.0958	1.24	57600
20	29.35	.381	.220	.440	1.42	115000
30	44	.647	.3738	.747	1.07	172800
40	58.7	1.325	.765	1.53	1.23	230000
50	73.4	2.045	1.18	2.36	1.2	288000
60	88	2.99	1.725	3.45	1.235	345000
70	102.8	4.08	2.36	4.72	1.24	403500
80	117.4	5.30	3.06	6.12	1.23	462000
90	132	6.72	3.87	7.75	1.24	517500
100	146.7	8.40	4.85	9.70	1.251	576000
110	161.4	10.05	5.80	11.6	1.23	634000
120	176	11.92	6.79	13.78	1.23	691500

TABLE VII.—FLAT PLATE 6 In. × 8 In.

Angle of Attack 40°

$T = 72°F.$ $W = .0703$ lb./cu.ft.
$P_b = 13.85$ lb./sq.in. $\rho = .002182$ slugs/cu.ft.

VELOCITY M.P.H.	VELOCITY Ft./Sec.	Lift Lb.	Drag Lb.	Resultant Lb.	C	R.N.
0	0	0	0	0		0
10	14.67	.0820	.0687	.107	1.37	57350
20	29.35	.3764	.3159	.492	1.57	114980
30	44	.6395	.537	.835	1.185	172100
40	58.7	1.312	1.10	1.71	1.36	230000
50	73.4	2.024	1.698	2.64	1.34	287500
60	88	2.94	2.475	3.85	1.37	344500
70	102.8	4.038	3.388	5.27	1.36	402000
80	117.4	5.242	4.397	6.84	1.36	460000
90	132	6.673	5.61	8.72	1.37	516000
100	146.7	8.31	6.975	10.85	1.38	574000
110	161.4	9.938	8.339	12.98	1.36	632000
120	176	11.5	9.642	15.0	1.34	688000

TABLE VIII.—FLAT PLATE 6 In. × 8 In.

Angle of Attack 60°

$T = 72°F.$ $W = .0703$ lb./cu.ft.
$P_b = 13.85$ lb./sq.in. $\rho = .002182$ slugs/cu.ft.

VELOCITY M.P.H.	VELOCITY Ft./Sec.	Lift Lb.	Drag Lb.	Resultant Lb.	C	R.N.
0	0	0		0	0	0
10	14.67	.0453	.0785	.0906	1.16	57350
20	29.35	.2085	.361	.417	1.33	114980
30	44	.3535	.6125	.707	1.00	172100
40	58.7	.725	1.256	1.45	1.15	230000
50	73.4	1.117	1.927	2.235	1.14	287500
60	88	1.635	2.83	3.270	1.17	344500
70	102.8	2.23	3.865	4.46	1.16	402000
80	117.4	2.89	5.021	5.78	1.15	460000
90	132	3.67	6.362	7.35	1.16	516000
100	146.7	4.58	7.94	9.16	1.17	574000
110	161.4	5.33	9.24	10.67	1.12	632000
120	176	6.51	11.29	13.02	1.13	688000

The results of flat plate tests are in good agreement with those found by other tests, although the values of C as determined from the disk show more variation than do those calculated from the rectangular flat plate tests. In view of this fact the tests were repeated on different days but the results were the same. An explanation may be in the slight flutter of the disk since it was not as rigidly held as the rectangular plate. However, when the plate was mounted on the spindle as in the first test, no such flutter was noticed.

TABLE IX.—FLAT PLATE 6 In. × 8 In.

Angle of Attack 80°

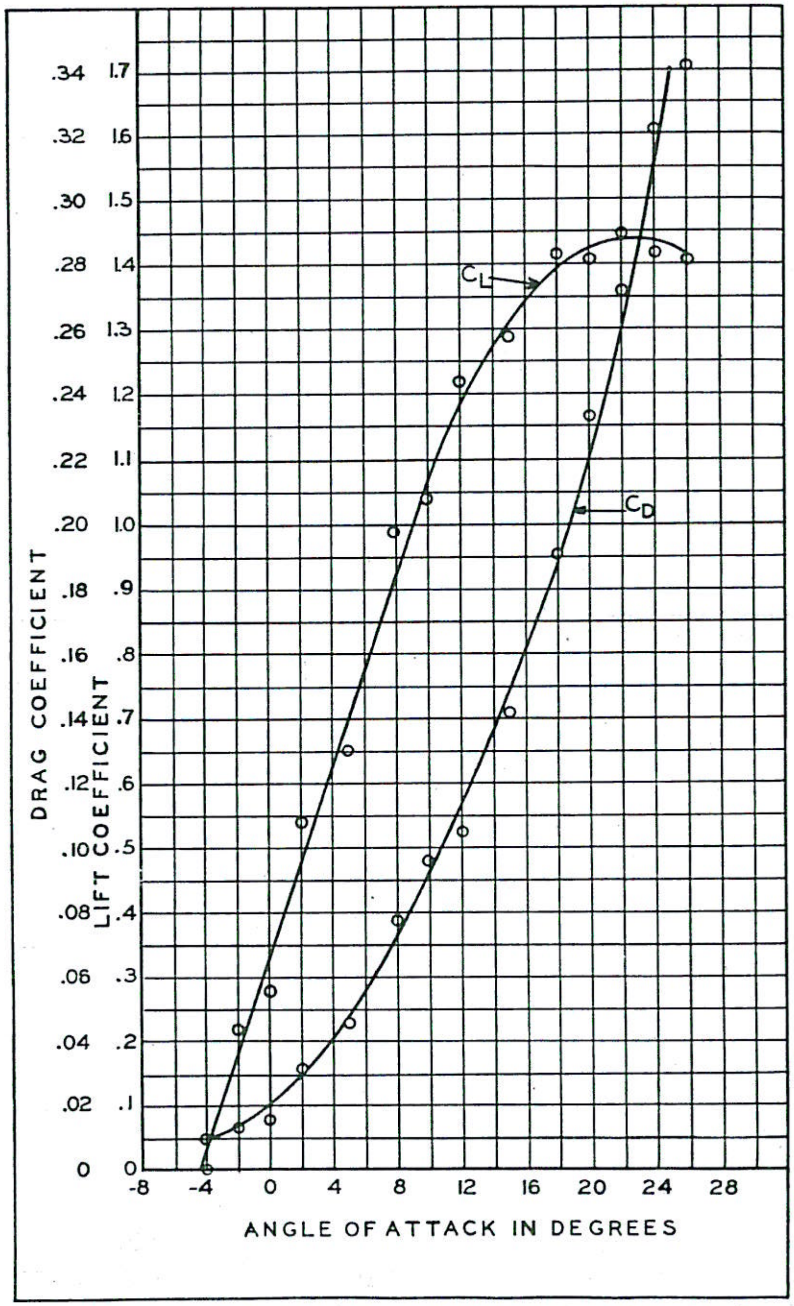
$T = 74°F.$ $W = .0705$ lb./cu.ft.
$P_b = 13.9$ lb./sq.in. $\rho = .00219$ slugs/cu.ft.

VELOCITY M.P.H.	VELOCITY Ft./Sec.	Lift Lb.	Drag Lb.	Resultant Lb.	C	R.N.
0	0	0		0	0	0
10	14.67	.0154	.08725	.0887	1.13	57600
20	29.35	.0709	.402	.408	1.3	115000
30	44	.1205	.682	.693	.978	172800
40	58.7	.2465	1.398	1.421	1.14	230500
50	73.4	.380	2.157	2.19	1.11	288000
60	88	.556	3.148	3.20	1.13	345000
70	102.8	.7625	4.321	4.39	1.14	403500
80	117.4	.9348	5.582	5.67	1.12	462000
90	132	1.271	7.197	7.32	1.15	517500
100	146.7	1.563	8.855	9.00	1.15	576000
110	161.4	1.881	10.65	10.82	1.14	634000
120	176	2.218	12.58	12.78	1.13	691000

TEST OF AIRFOIL

An airfoil which was a modified Göttingen No. 398 was suspended in a wire balance and determinations of lift and drag made for various angles of attack. An air velocity of 40 miles per hour was used throughout the test.

The airfoil chord was 2 inches and it had a span of 12 inches. It was constructed of wood by forming to a steel template which was made from a reduced photograph of the airfoil outline drawn on a 4-foot chord. The template was in two pieces and the top



No. 13.—Göttingen No. 398 Airfoil.

and bottom of the airfoil were rubbed down by hand until they would fit the template. A back spindle or sting 8 inches long was built into the trailing edge at the center-span.

Figure 6 shows the airfoil mounted (upside down). The lift is carried to the scales by four wires—two wires going to each scale. Drag is carried by two wires to one scale. By this method not only could the lift and drag be determined, but also the location of the center of pressure.

Table X gives values of lift and drag as determined by the test as well as calculated values of C_L, C_D, and C_p from the leading edge. The location of the center of pressure back from the leading edge (C_p) for any particular angle of attack was calculated as follows:

If x denotes the distance of the center of pressure measured

TABLE X.—TEST OF AIRFOIL.

(Göttingen No. 398)

Air Velocity 40 M.P.H.

Model = 2 In. × 12 In.

$T = 80°F.$
$P_b = 13.9$ lb./sq.in.
R.N. = 56800

$W = .0696$ lb./cu.ft.
$\rho = .00216$ slugs/cu.ft.
$\mu = 3.78 \times 10^{-7}$ lb.-sec./sq.ft.

Angle of Attack (α)	Drag	LIFT			C_P	C_L	C_D
		Front	Rear	Total	Percent		
−2	.00806	.1215	.0149	.1364	55	.22	.013
−4	.0062	0	0	0	100	0	.010
0	.00992	.159	.0142	.1735	42	.28	.016
2	.01985	.3081	.0269	.335	40	.54	.032
5	.02850	.375	.0280	.403	35	.65	.046
8	.0484	.581	.0330	.614	32	.99	.078
10	.0595	.620	.0350	.655	32	1.04	.096
12	.0651	.710	.0460	.756	31	1.22	.105
15	.0875	.752	.0480	.800	30	1.29	.141
18	.1185	.826	.0540	.880	30	1.42	.191
20	.451	.818	.0560	.874	32	1.41	.234
22	.1689	.836	.0640	.900	34	1.45	.272
24	.1997	.817	.0630	.880	36	1.42	.322
26	.214	.810	.0640	.874	37	1.41	.342

$C_P = x$ expressed as percent of chord back from leading edge of airfoil.

from the leading edge, then x is expressed by the equation

$$x = \frac{10\ L_R \cos \alpha}{(L_R \cos \alpha - D \sin \alpha)}$$

where L_R is lift carried by the rear lift wire, L the total lift, and D the total drag. This relation is only good for a particular arrangement where the chord of the airfoil is 2 inches, the length of the sting 8 inches, and the distance between the drag wires and front lift wires is 5 inches. However, a similar expression may be written for any other arrangement. For an airfoil of chord C and sting length S, the expression for x becomes

$$x = \frac{(C+S)\ L_R \cos \alpha}{(L_R \cos \alpha - D \sin \alpha)}$$

The calculated values of lift and drag are plotted against angle of attack in Figure 13. The data used in these curves have not been corrected and they are not given as correct values for the Göttingen No. 398 airfoil. The model used is also of questionable accuracy. It was made to be a close approximation of the No. 398, but it had only a 2-inch chord which is too small for obtaining accurate data pertaining to the particular airfoil.

CONCLUSION

The purpose of the investigations described in this bulletin was to determine the operating characteristics of the wind tunnel. Such standardization tests are necessary because results obtained from wind tunnel tests are dependent upon several factors. The bodies used in the tests were selected so that the resulting data could be easily compared with those from other laboratories.

The accuracy and reliability of wind tunnel results depend upon three things. First, the wind tunnel itself; second, the person performing the tests; and third, the interpretation of the data.

In order for test results to be satisfactory, the wind tunnel should be capable of maintaining constant conditions of air flow. Not only should the flow be steady, but it should also be constant across the test section. It will be seen that the quality of the flow in the V. P. I. wind tunnel is excellent in that respect.

The weighing apparatus and balances must be accurate enough to check results consistently. The balances must also be sufficiently sensitive to record the forces involved in a test. Repeated checks of data show that the balances were entirely satisfactory as to both sensitivity and accuracy.

The results obtained from any wind tunnel will be governed in a large measure by the methods employed by the person conducting the tests. Only by the exercising of a large amount of patience and a certain amount of skill can the operator expect to secure satisfactory results. A skilled, experienced person can get better results from poor equipment than can a careless one from the best equipment available.

The proper interpretation of results requires a study of three factors which have a modifying influence on the data secured from the test. These three factors are: the scale effect or Reynolds number, the wall effect or wall interference, and the turbulence in the air stream.

Since the tests herein described were primarily for the purpose of determining just what could be expected from the wind tunnel, the results should be interpreted as referring to the wind tunnel rather than the models. The results show the wind tunnel to be entirely suitable for carrying on aerodynamic investigation. It is well to point out that the turbulence is about the average of the values found for other tunnels. It should also be noted that any program for aerodynamic investigation should be completed in one particular wind tunnel and that results from one should not be compared with results from another, unless it is known what factors affect such a comparison. For example, if it is desired to compare the air resistance of two automobiles, models of both should be tested in the same wind-tunnel; instead of testing one model in one tunnel and the other in a different one.

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