A.3.c. Wind tunnels, 36.
(T. 2267.)

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(Ae. 226.)

ON THE ADVANTAGES OF AN OPEN JET TYPE OF WIND TUNNEL FOR AIRSCREW TESTS.—By

H. Glauert, M.A., and C. N. H. Lock, M.A.

MAY, 1926.

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ON THE ADVANTAGES OF AN OPEN JET TYPE OF WIND TUNNEL FOR AIRSCREW TESTS.

By H. Glauert, M.A., C. N. H. Lock, M.A.

Reports and Memoranda, No. 1033. *May*, 1926.
(Ae. 226.)

Summary.—It is suggested that an open jet and wind tunnel of the Eiffel or Göttingen type is more suitable for testing airscrews than the closed (National Physical Laboratory) type on account of the smaller correction for tunnel interference. The evidence for the latter statement is:—

(*a*) *Theoretical.*—A formula due to Mr. R. McKinnon Wood is available which gives a small but definite correction to be applied to a 3 ft. diameter airscrew working in a 7 ft. square closed tunnel. By the same argument the correction for an open jet tunnel is zero. An independent argument based on considerations of vorticity leads to the same conclusion.

(*b*) *Experimental.*—In the course of experiments on the American family of airscrews Dr. Durand tested a set of four similar airscrews of diameters 2 ft. to 4 ft. in an open jet tunnel of diameter 5½ ft. and obtained agreement between the performance of the extreme screws. The evidence for the closed type of tunnel is less definite but points to the accuracy of the theoretical formula.

(*c*) *Extreme working conditions.*—Under extreme working conditions it is probable that the correction becomes large for a screw in a closed tunnel and there is some evidence that the open jet tunnel retains its advantage in this case.

1. *Introduction.*—The majority of tests on model airscrews during recent years have been made in wind tunnels, the forward motion of the screw being simulated by the flow of air past a model screw rotating at a fixed point in the tunnel. As in all wind tunnel work it is desirable that the model should be as large as possible in order to approach as nearly as possible to full scale conditions; the size is however always limited by the size of wind tunnel.

In this country the only wind tunnels available are of the closed National Physical Laboratory type; the majority of model airscrew tests of recent years have been made in a tunnel of this type of 7 ft. square section, and the model screws have generally been of 3 ft. diameter. It will appear later that the interference effect on a screw due to the finite size of the wind

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tunnel may in extreme cases equal or exceed the corresponding effect on an impervious disc of area equal to the disc area of the airscrew; although the effect is usually much less than this it is evident that it may be of importance for a 3 ft. screw working in a 7 ft. tunnel.

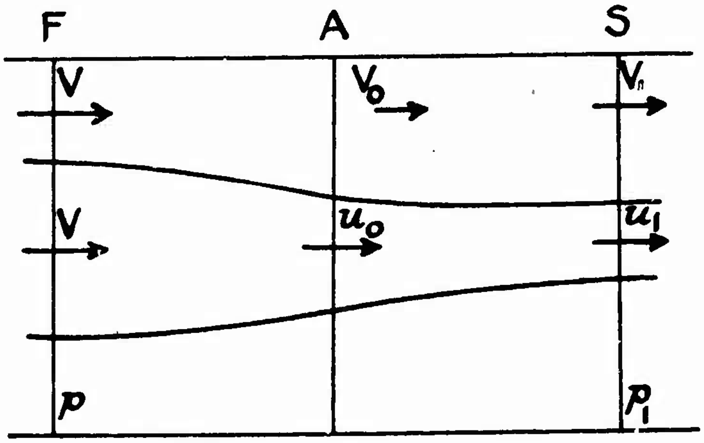
In America a large number of tests on model airscrews have been made in an open jet tunnel of the Eiffel type with a jet of diameter 5 ft. 6 ins.* There is both theoretical and experimental evidence (*see* below) that the interference effect on a screw is appreciably less for an open jet than for a closed type of wind tunnel; actually the American experimenters do not apply any correction for tunnel interference to a screw of diameter 3 ft. working in a 5½ ft. jet, whereas an appreciable correction has been applied to the results for a 3 ft. screw working in a closed tunnel of 7 ft. square. An attempt is made in the present report to discuss all the available sources of evidence on the subject, in view of the possibility that a wind tunnel of the open jet type might be constructed in this country for these and other purposes. It appears that in an open jet tunnel an airscrew of given size could be tested with greater accuracy than in a closed tunnel or alternatively a screw of larger size might be tested.

In making a correction for the effect of a wind tunnel on an airscrew it is usual to assume that the entire effect may be represented by a change in the forward velocity of the screw. This will be true if the flow in the wind tunnel in the immediate neighbourhood of the airscrew disc for a given rotational speed of the screw and for a certain measured tunnel velocity V is identical with the flow relative to an identical screw moving forward through free air with the same rotational speed but with a forward speed V' which differs slightly from V. The velocity V' is then known as the "equivalent free air speed" corresponding to the tunnel velocity V. All the forces on the two screws should also be identical. In all wind tunnel tests on airscrews the screw should be small enough relative to the tunnel for the above conditions to be fulfilled: then provided that a reliable method is available for determining V', the actual magnitude of the correction $V' - V$ is of no importance. In practice however we may take the relative magnitude $(V' - V)/V$ of the correction as a criterion; the smaller this correction is, the more accurately the above conditions are likely to be fulfilled, and the less important will be any uncertainty in the determination of the correction. We proceed to discuss various theoretical and experimental methods of determining the correction.

2. ***Wood's theory of an airscrew working in a wind tunnel.***—**A theoretical method of estimating the correction to be applied to the measured tunnel velocity for an airscrew working under normal conditions in a closed wind tunnel is given by R. McKinnon**

* Experimental Research on Air Propellers. N.A.C.A. Report No. 14.

Wood and R. G. Harris in R. & M. 662.* The results are obtained by means of the Froude theory applied successively to a screw in a wind tunnel and in free air. The flow in a closed tunnel is illustrated in the attached figure.



Section A is the plane of the airscrew disc. At section F in front of the airscrew, and at section S behind it, the flow is parallel to the axis and the pressure is constant over the section. The Froude relations connect the velocities and pressures at the sections F and S with the thrust of the airscrew and the flow through the disc, which must be assumed to be the same in the wind tunnel as it is in free air. Since u_1 differs from V, it follows by the condition of continuity that in a closed tunnel V_1 also differs from V, and hence that p_1 differs from p. Hence the Froude relations between u_1, V and the conditions at the screw differ from those in free air, where $V_1 = V$ and $p_1 = p$. If the screw gives the same thrust in the closed tunnel as in free air for the same velocity u_0 through the disc, then the velocity V in front of the screw in the tunnel will differ from the corresponding velocity V' in front of the screw in free air. V' is called the equivalent free air speed.

In an open jet type of tunnel the condition of continuity is replaced by the condition that the pressure has the same value at sections F. and S. It follows that there is no correction to be applied in an open jet tunnel according to the present theory of tunnel interference.

The correction in a closed tunnel is quite important and its magnitude may be obtained with sufficient accuracy from the approximate form given by equation (19) of the appendix of R. & M. 662. This formula is :—

$$1 - \frac{V'}{V} = \frac{\alpha}{2} \cdot \frac{y}{\sqrt{1 + 2y}}$$

* "Some notes on the theory of an airscrew working in a wind channel." R. McKinnon Wood and R. G. Harris, R. & M. 662. (Revised.)

where

V = velocity in the forward datum plane (F) of the tunnel.
V' = equivalent free air speed.
z = ratio of disc area of airscrew to tunnel area.

$$y = \frac{T}{\pi R^2 \rho V^2}.$$

T = measured thrust of airscrew.
R = radius of airscrew.

3. *An alternative theory of wind tunnel interference.*—The interference experienced by an airscrew in a wind tunnel can also be examined by considering the nature of the flow pattern. The velocity at any point is the resultant of the uniform axial velocity V and of the induced velocity due to the vortex system which constitutes the slipstream of the airscrew. As a first approximation the rotation and contraction of the slipstream may be neglected, and the vortex system may be conceived as a uniform cylinder formed by a close succession of vortex rings. If Γ is the vortex strength per unit length of this cylinder, the axial velocity in the plane of the airscrew is $(V + \frac{1}{2}\Gamma)$ for points of the disc and V for points outside the disc. There is also a radial velocity component v, whose value in the plane of the airscrew at radial distance r, assumed greater than the airscrew radius R, is given by the equation :—

$$V = -\frac{\Gamma}{\pi}\left\{\frac{K-E}{1+k'} - \frac{1-k'}{2}K\right\}$$

where E and K are the complete elliptic integrals for the modulus k, and where

$$\frac{r}{R} = \frac{1+k'}{1-k'}.$$

Numerically, this equation gives

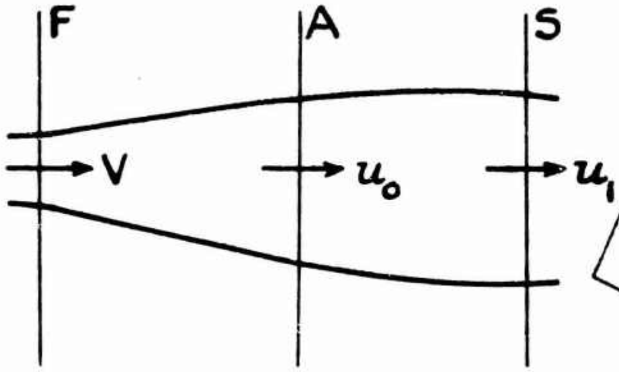
$$\frac{r}{R} = 1\cdot70, \quad 2\cdot04, \quad 2\cdot47, \quad 3\cdot00.$$

$$\frac{V}{\frac{1}{2}\Gamma} = -0\cdot20, \ -0\cdot13, \ -0\cdot09, \ -0\cdot06.$$

and so the induced radial velocity v at a distance from the airscrew at which the boundaries of the tunnel stream are likely to occur is of the order of one-fifth to one-tenth of the axial induced velocity $\frac{1}{2}\Gamma$ at the airscrew disc.

The boundaries of a closed tunnel impose the condition of zero radial velocity at the boundary, while the boundaries of an open jet tunnel impose the condition of constant pressure. The constraint on the flow is therefore of the order v or $0\cdot1\ \Gamma$ for a closed tunnel, in order to neutralise the radial velocity component v, whereas the boundary condition for an open jet tunnel can be satisfied by a correction of order v^2 or $0\cdot01\ \Gamma^2$ to the axial velocity component. It follows that airscrew data obtained from an open jet tunnel should agree closely with those for free air conditions in the ordinary working range of an airscrew, but corrections may be necessary near the static condition when V is of the same order as v or $0 \cdot 1\ V$, *i.e.*, when the axial interference factor a is of the order ·5.

4. *General discussion of the extreme working ranges of an airscrew.*—The Froude equations on which the result of R. & M.662 is based break down for a screw, acting as a windmill, when the retardation of the air through the screw exceeds a certain value.



According to the Froude formula, when the mean velocity u_0 through the airscrew disc falls to $\frac{1}{2}V$, the value of u_1 falls to zero so that the area of the wake in Section S becomes infinite, thus indicating a breakdown of the theory. Again, the fundamental assumptions cannot well apply to an airscrew which is driving air against the tunnel stream (specified R. & M. 1014* as the Vortex ring state). An empirical method of calculating the performance of a screw in these extreme conditions which has been described in R. & M. 1014, is based on the use of an empirical relation between u_0, V and the thrust of the screw. In these circumstances there is no theoretical method, analogous to the theory of R. & M. 662, available for correcting for tunnel interference. It is suggested however that the difference between V_0 and V, the mean velocities outside the airscrew stream may give a measure of the order of magnitude of the velocity correction required.

In the normal working range, it may be shown by the method of R. & M. 662 that V_0 is given in terms of V to the same approximation as formula (1) by the formula :—

$$1 - \frac{V_0}{V} = \tfrac{1}{2} z \left\{ \sqrt{1 + 2y} - 1 \right\}$$

so that $V_0 = V$ to the first order in y.

In general by continuity

$$1 - \frac{V_0}{V} = \frac{z}{1 - z}\left(\frac{u_0}{V} - 1\right).$$

* "An extension of the Vortex Theory of Airscrews." Lock, Bateman and Townend, R. & M. 1014.

Thus if u_0 is zero

$$\frac{V_0}{V} - 1 = \frac{z}{1-z}$$

which has the value of 0·168 for a 3-ft. screw working in a 7-ft. closed tunnel, while if u_0 is negative, V_0/V may attain any value.

It might be suggested that a direct measurement of V_G would be superior to a measurement of V but the latter is found to give a steadier reading in addition to being more convenient.

Turning to the case of an open jet tunnel it is obvious that in extreme cases the distortion of the outer surface of the jet may become so large that its effect on the velocity reading is no longer negligible but it seems likely that the superiority of the open jet type will be maintained for all working conditions of the screw.

5. *Experimental evidence. American family of airscrews.*—The most definite experimental evidence available for the case of an open jet type of tunnel is contained in the original report of the Experimental Research on Air Propellers carried out at the Leland Stanford Junior University U.S.A. under the direction of Dr. Durand.* The tunnel used was of the Eiffel type having an open jet 5·5 ft. in diameter by about 14 ft. long. The wind speed was determined in the usual way from the drop of pressure within the experiment chamber which was calibrated against the readings of a standard velocity head in the air stream. The experiments made to determine the influence of the airscrew on the measured velocity may conveniently be quoted verbatim from the original report :—

Relations between Diameters of Wind Stream and Diameter of Model Propeller.

It was assumed from precedent and from general experience in wind-tunnel work that a propeller model 3 ft. in diameter could be properly run in a wind stream 5½ ft. diameter without sensible disturbance at the boundaries of the stream and hence with sensibly the same result as though in an indefinite stream.

The experimental examination of this question was approached from three different directions, as follows :—

(*a*) Successive reduction of wind-stream diameter with comparative study of thrust and torque coefficients.

(*b*) Pitot tube survey of wind stream with model propeller in operation, with special reference to distribution of velocity in the cylindrical shell outside the tip circle of the propeller.

(*c*) Comparison of thrust and torque coefficients for four sizes of propellers of successively increasing diameters.

* Experimental Research on Air Propellers. N.A.C.A. Report No. 14.

The result of these three examinations may be briefly indicated.

The diameter of the wind stream was reduced by 6-inch steps by blanking over the delivery end of the collector with suitable flat annular rings. This had the effect of closing off an outer zone of cells of the honeycomb baffle, leaving the remainder operative. This gave wind streams of diameters, successively, 66, 60, 54 and 48 inches, and within which a propeller of 3 ft. diameter was run. The results were then reduced to the form of thrust and torque coefficients by assuming, at equal values of V/ND, a force variation with the square of the speed.

The torque and thrust coefficient curves thus derived give the following indications:—The torque and thrust of the 3-ft. model in wind streams of 5 ft. and 5·5 ft. in diameter are sensibly identical. For a wind stream 4·5 ft. in diameter the torque and thrust were about 2·5 per cent. greater than for the wind streams of 5 ft. on 5·5 ft. diameter.

For a wind stream 4 ft. diameter the torque and thrust were 6 to 7 per cent. greater than for the wind streams of 5 ft. or 5·5 ft. diameter.

With the model propeller in operation and throwing aft a slipstream of pronounced velocity, the wind stream across the entire section forward of and about the propeller was subject to survey by Pitot tube. The results indicated a relatively abrupt break in the influence of the propeller close about the tips of the blades, and that the size of the slipstream proper at and just in advance of the propeller was practically determined by the diameter swept by the tips of the blades. The velocities in the cylindrical ring lying outside the blade tips were also compared with the depression within the chamber and found to agree as previously stated. These tests indicate that the special influence of the propeller in disturbing the distribution of velocities through the windstream extends to but a slight distance beyond the circle swept by the tips of the blades. The indications of this test, therefore, support fully the anticipated relation between diameter of propeller and of wind stream.

As a final test in regard to this important question, four propellers of diameters, successively, 30, 36, 42, and 48 inches, and similar geometrically, were tested out in regular course and the results reduced to thrust and torque coefficients by assuming, at equal values of V/ND, a force variation with the square of the speed and with the square of the diameter. The results of these tests are shown in Fig. 1. of this report for thrust only and indicate substantially the same values of the coefficients for the same value of V/ND for all four propellers. This indicates apparently that the diameter of the propellers might have been increased to 42 inches, or possibly even to 48 inches, and run in a wind stream of diameter 66 inches without sensible departure from the conditions in an indefinite stream.

As a matter of fact, as may be noted in the figures the values of the coefficients for the diameters 30, 42 and 48 inches lie most satisfactorily on a continuous smooth curve. Those for the diameter 36 inches lie slightly above. This slight variation is apparently due to some slight departure in geometrical similarity between the propeller for 36-inch diameter and the other three.

In any event these results together with the others noted above seem to justify fully the use of the propeller models of 36 inches diameter in the wind stream of 66 inches diameter.

(End of quotation from the American Report.)

The figure (Fig. 1) referred to in the above description contains the thrust coefficients plotted against V/nD reproduced from the figure in the original report but with the original coefficients reduced to the form commonly used in this country, viz., $k_T = T/\rho n^2 n^4$. For this reason the discrepancies between the various screws appear much more pronounced than in the original figure. In Fig. 2 is shown a continuous curve, through the observation points for the screw of 3 ft. diameter only. In order to compare the results with what would be expected in a closed tunnel, the dotted curves (Fig. 2) have been calculated by Wood's formula and represent the *uncorrected* thrust curves, which would be obtained with screws of diameter 2·5, 3·0, 3·5, 4·0 ft. in a 5·6 ft. circular closed tunnel on the assumption that Wood's theory is accurate, the corresponding values of z being 0·207, 0·297, 0·405 and 0·529 respectively. Finally a curve is given showing the uncorrected results for a similar 3 ft. screw tested in a 7 ft. square closed tunnel for which the value of z is 0·144.

6. *Experiments relating to the velocity correction for an airscrew working under normal conditions in a closed tunnel.*—The curve in the above diagram shows that the correction for velocity to be applied to a 3 ft. screw of mean type working in a 7 ft. square closed tunnel nowhere becomes large in the normal working range, the correction being equivalent to a change of k_T whose value for $V/nD = 0·3$, is only about 0·002 or less than 2 per cent. of k_T. This was the real justification for accepting the value of the correction as determined by Wood's formula as being sufficiently accurate for the reduction of the tests in the family of airscrews.

A type of experiment which would provide a direct check on the correction to be applied in a closed tunnel, is a direct comparison between the performance of the same airscrew in a wind tunnel and on a whirling arm. The only experiment of this type that has been traced occurs in a report "Experiments to determine the Lateral Force on a Propeller in a Side Wind," by Bramwall, Relf and Bryant, R. & M., No. 123, March, 1914, Technical Reports, 1913-14, p. 291. A four-bladed wooden airscrew of 2 ft. diameter (illustrated on p. 291 of the same report) was tested successively on the propeller balance of the N.P.L. Whirling Arm and in a 4-ft. square wind tunnel (closed type). The values of thrust coefficient extracted from this Report are shown in Fig. 3. The continuous curve is drawn through the observations taken on the Whirling Arm, and points are plotted for the wind tunnel observations both uncorrected and corrected by Wood's formula. It is evident that the experimental accuracy is not sufficient to give definite evidence as to the accuracy of the correction.

Other experiments bearing on the subject are described in R. & M. 829 and 830* and relate to explorations of velocity round the airscrew. So far as they go they fully confirm the accuracy of the corrections. A direct comparison with a similar screw of smaller diameter would have required in addition a motor of smaller diameter to obtain similarity of interference; in view of the smallness of the correction it was not thought worth while to undertake such an experiment.

The only experiment of this kind (R. & M. 919)† was made to check the velocity correction in the airscrew body experiments described in R. & M. 830. The results again served to verify the accuracy of the original corrections but here again the advantages of the open jet type of tunnel are obvious.

7. *Experimental results under extreme working conditions.*—The only experiments on an airscrew working in the extreme conditions specified in § (4) $\left(\frac{u_0}{V}\right.$ less than 0·5 and $\frac{u_0}{V}$ negative$\left.\right)$ are those made at the N.P.L. and described in R. & M. 885 and R. & M. 1014 for a closed type of wind tunnel; for an open jet type the American experiments "Model Tests on the economy and effectiveness of Helicopter Propellers" by Munk, Technical Notes N.A.C.A. No. 221. The latter experiments refer to the range $0 < \frac{u_0}{V} < 0{\cdot}5$ only. The evidence available from the N.P.L. experiments consists of a few measurements of the velocity field round the screw and only serves to confirm the conclusion of § 4 that the correction may become large. In the American report there is no mention of such a correction which is evidently assumed to be zero.

Conclusions.—For the normal working state of an airscrew the results of the above investigation may be summarised as follows :—The theoretical value of the correction to equivalent free air speed for a 3-ft. diameter airscrew working in a 7-ft square closed wind tunnel ($z = 0{\cdot}144$) is small but by no means negligible. Experimental evidence is scanty but appears to favour the theoretical value. For an open jet tunnel, the theoretical correction is zero; experiments on a series of similar screws of different diameter indicates that for a 4-ft. diameter screw working in a

* Experiments with a family of airscrews.

† The effect of wind tunnel interference on a combination of airscrew and tractor body.

$5\frac{1}{2}$ ft. diameter open circular tunnel, the correction is negligible within the limits of experimental error.

In extreme working conditions there are theoretical reasons to believe that the correction for a closed tunnel may become large; for an open jet tunnel the evidence is scanty but indicates that the correction is likely to be much smaller. It seems, therefore, that if an open jet type wind tunnel were available in this country it would be of considerable use both for absolute and comparative experiments on airscrews.

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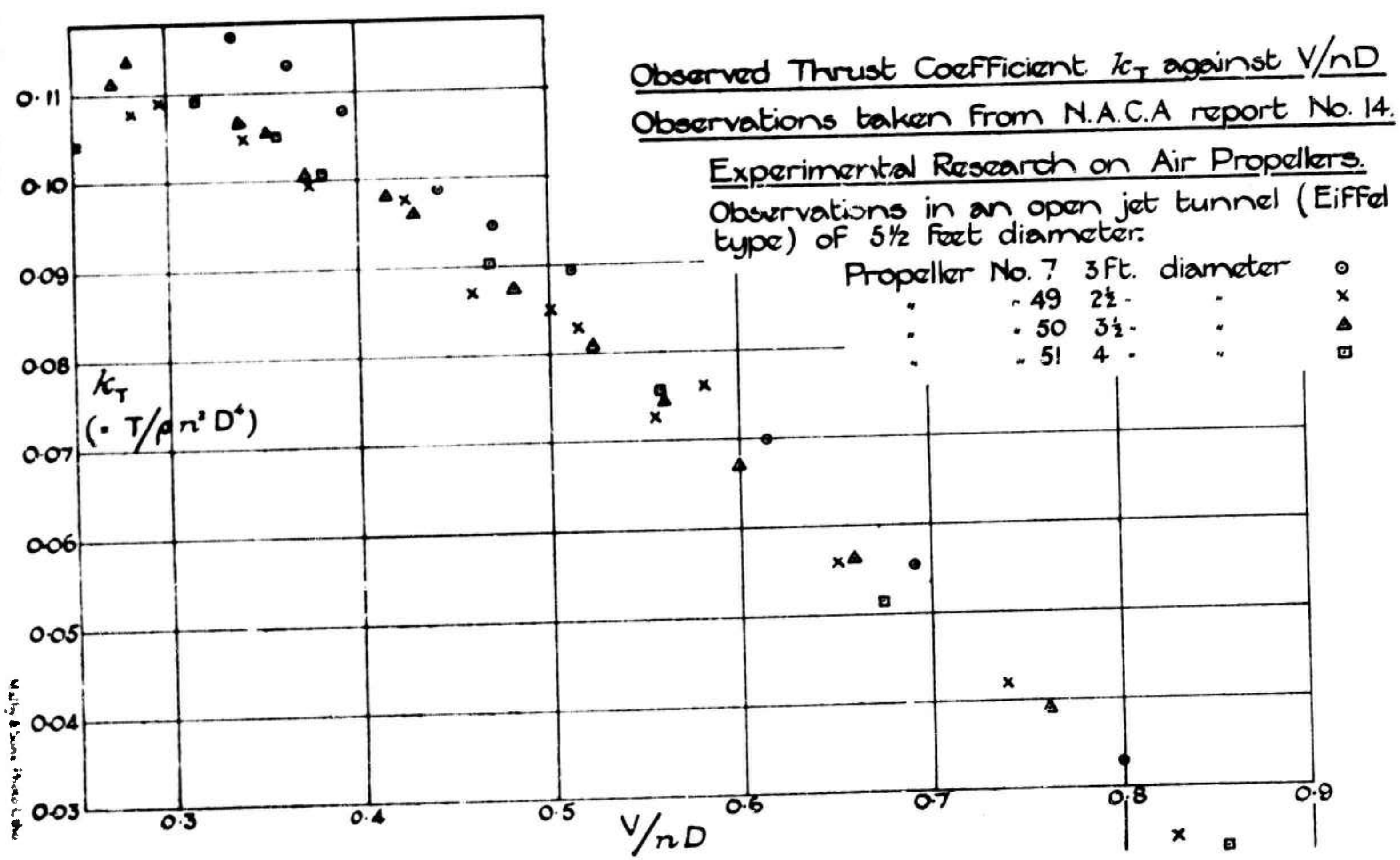
FIG. 1.


Observed Thrust Coefficient k_T against V/nD
Observations taken from N.A.C.A report No. 14.
Experimental Research on Air Propellers.
Observations in an open jet tunnel (Eiffel type) of 5½ feet diameter.
Propeller No. 7 3 Ft. diameter ⊙
" " 49 2½ " " ×
" " 50 3½ " " △
" " 51 4 " " ⊡
k_T
$(= T/\rho n^2 D^4)$
0·11
0·10
0·09
0·08
0·07
0·06
0·05
0·04
0·03
0·3
0·4
0·5
0·6
0·7
0·8
0·9
V/nD

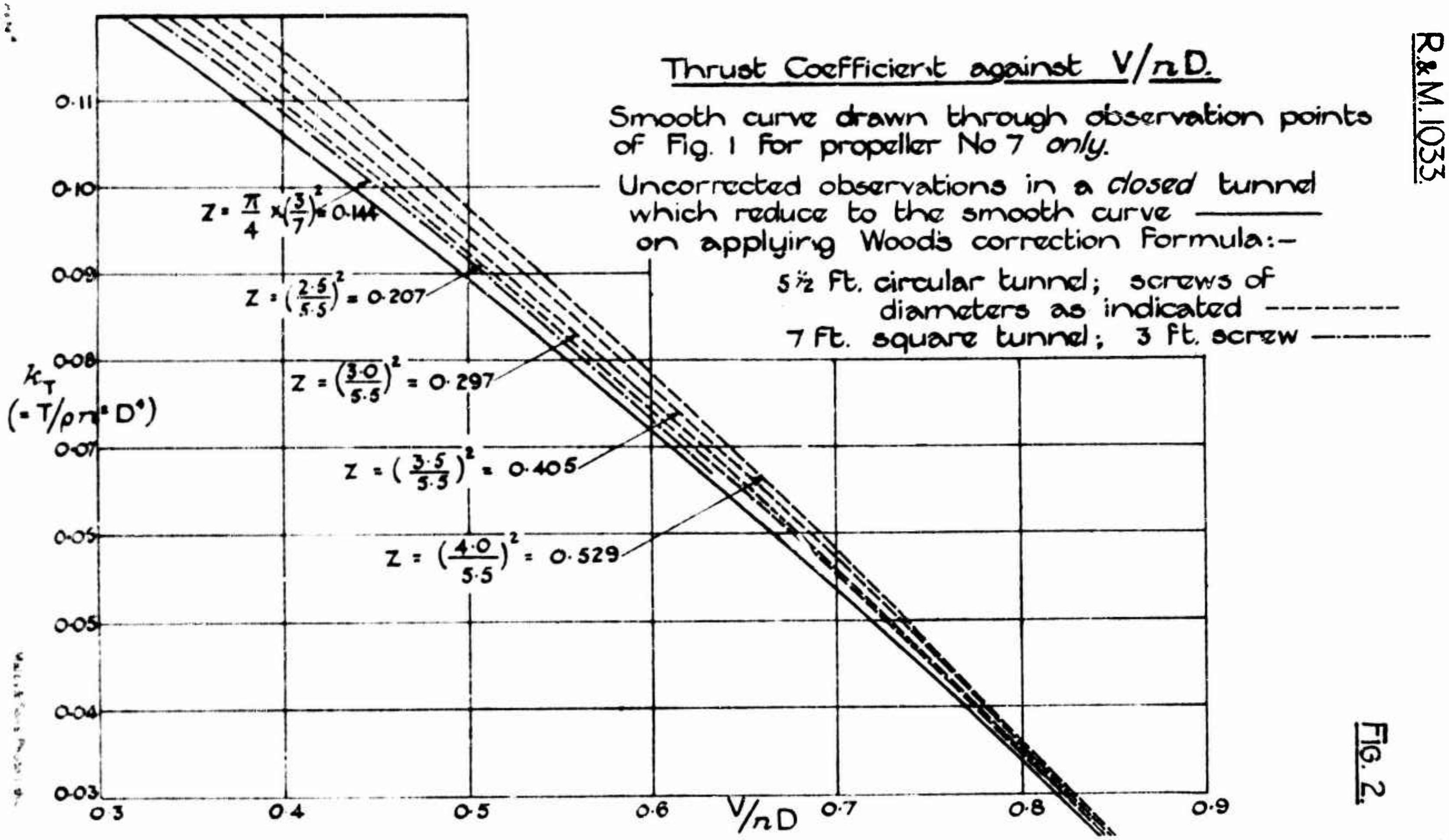
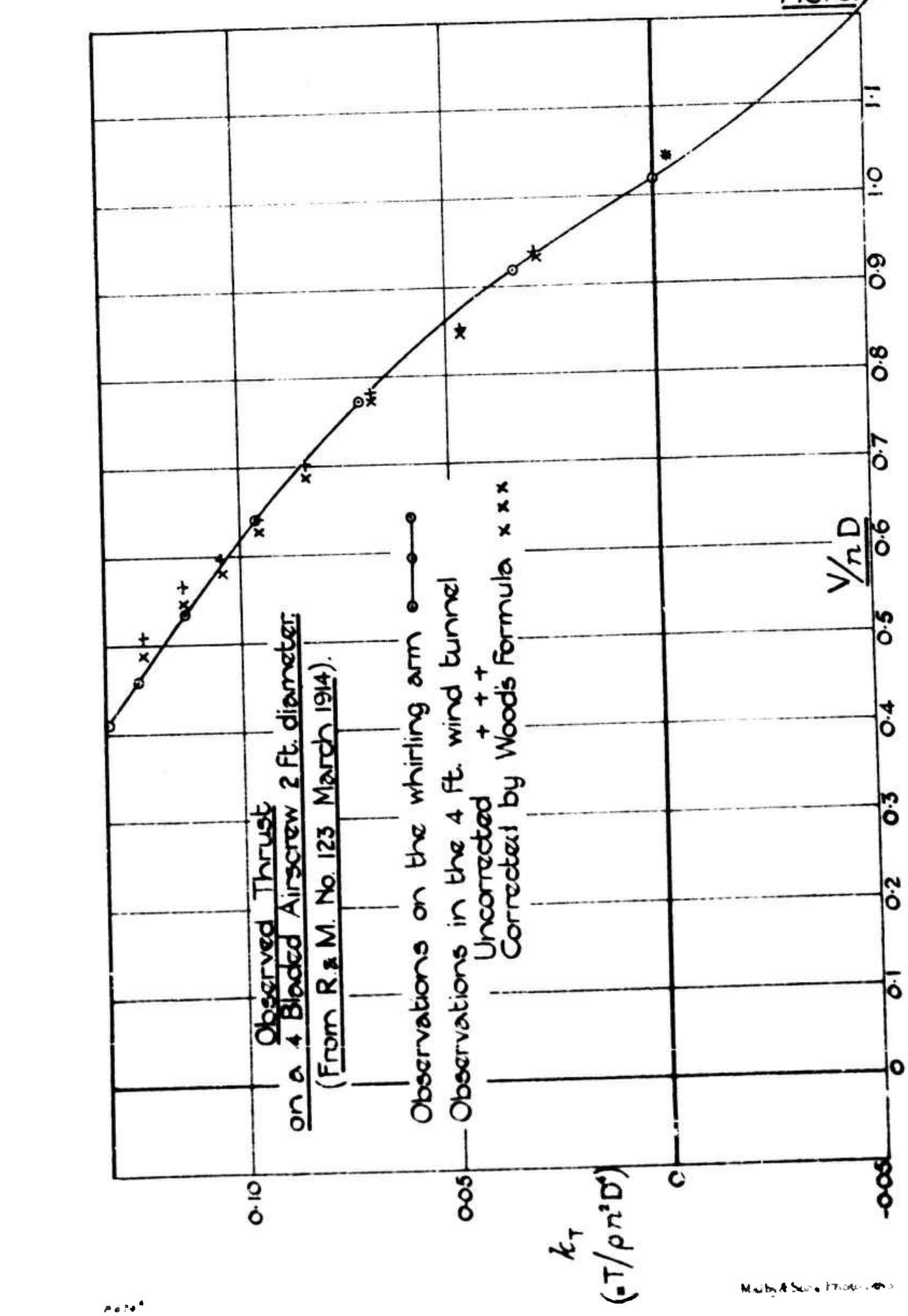

Thrust Coefficient against V/nD.
Smooth curve drawn through observation points of Fig. 1 for propeller No 7 only.
Uncorrected observations in a closed tunnel which reduce to the smooth curve
on applying Wood's correction Formula:-
5½ ft. circular tunnel; screws of diameters as indicated
7 ft. square tunnel; 3 ft. screw
Z = π/4 × (3/7)² = 0.144
Z = (2.5/5.5)² = 0.207
Z = (3.0/5.5)² = 0.297
Z = (3.5/5.5)² = 0.405
Z = (4.0/5.5)² = 0.529
k_T (= T/ρn²D⁴)
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.3
0.4
0.5
0.6
0.7
0.8
0.9
V/nD

Fig. 2.

R. & M. 1033.

FIG. 3.



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