DESIGN OF A WIND TUNNEL

by

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Submitted in Partial Fulfillment
of the Requirements for the

Bachelor of Science Degree
in Aeronautical Engineering

from the

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Acceptance:

Adviser in charge of Thesis, Signature redacted

May 16, 1940

Graduate House, M.I.T.
Cambridge, Massachusetts
May 16, 1940

Professor George W. Swett
Secretary of Faculty
Massachusetts Institute of Technology
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Dear Sir:

I have the honor of submitting this Thesis, DESIGN OF A WIND TUNNEL, in partial fulfillment of the requirements for the Bachelor of Science Degree in Aeronautical Engineering.

Very respectfully,

Signature redacted

Ernesto T. Mendoza

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INTRODUCTION

The importance of the wind tunnel in the rapid development and progress of aviation to its present stage cannot be overemphasized. The first successful machine-driven airplane invented by the famous Wright brothers was really a product of a crude wind tunnel in which they made painstaking "preliminary measurements on a great number of different shaped surfaces, so varied in design as to bring out the underlying causes of differences noted in their pressures. Measurements were tabulated on nearly fifty of these at all angles from zero to 45 degrees, at intervals of 2-1/2 degrees. Measurements were also secured showing the effects on each other when surfaces are superposed, or when they follow one another." (Reference 1).

Today, as in the past, the wind tunnel is the chief and indespensable equipment in any aeronautical laboratory. It is used extensively in studying the aerodynamic properties of various airfoils; in the design of propellers and in solving problems on propeller vibrations; in the design of the various parts of the airplane from engine nacelles, ailerons, wing flaps, landing gear, etc., etc. to trimming tabs; in the study of wing and tail flutter; and most important of all, in predicting the performance and flight characteristics of a new airplane from model tests.

In universities and technical schools, the wind tunnel is used chiefly in making experiments to supplement and corraborate aerodynamic theories profounded in classrooms and in conducting investigations or researches on new airplane designs.

I. REASON FOR THE SELECTION OF THE SUBJECT.

The University of the Philippines is a state institution, being supported by the Philippine Government. One of the main objectives of its founding and organization by the Philippine Assembly in 1908 was to train and educate young men and women in the Arts and Sciences needed by the country in promoting the educational, social, political and economic growth and development of the Filipino people into a progressive nation. In compliance with this function and in view of the interest of the Philippine Commonwealth Government in aviation, the University of the Philippines is planning to open a course in aeronautics in the near future. If this plan prospers, then the design and construction of even a small and modest wind tunnel will be inevitable. It is, therefore, for the interest of my work in the said University that I have chosen "The Design of a Wind Tunnel" as the subject for my Thesis.

II. PURPOSE OF THE INVESTIGATION.

In designing any wind tunnel, it is essential to know:

1. The objective of the proposed design.
2. The different types of wind tunnels, and the advantages and disadvantages of each type.
3. The important factors to be considered in the design to produce a smooth relative wind, resulting in an efficient tunnel.
4. The different forms and types of wind tunnel balances.
5. The instruments employed in measuring air pressure and wind speed as well as the kind of electric motors to be used in driving the propeller.

The purpose of this study is to collect useful information and pertinent data on the above items and use them as guides in the design of a small wind tunnel. On account of the vast amount of literature already written on the subject of wind tunnels and due to the limited time allowed for this work, it is impossible to make this study very exhaustive and detailed. As far as possible only the latest treatments on the subject were consulted.

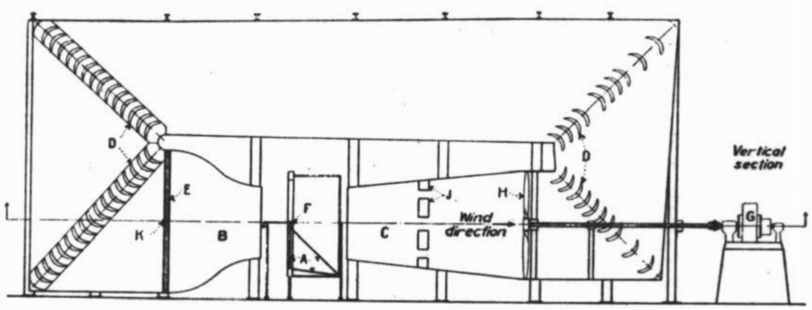


Fig. 1. DIAGRAM OF A WIND TUNNEL.

A—Balance and Model Support
B—Entrance Cone
C—Exit Cone
D—Guide Vanes
E—Honeycomb
F—Model
G—Motor
H—Propeller
I—Return Passage
J—Slots
K—Static Plate

III. WIND TUNNELS AND THEIR CLASSIFICATIONS.

A wind tunnel is "an apparatus producing an artificial wind or air stream, in which objects are placed for investigating the air flow about them and the aerodynamic forces exerted on them". [1]

A diagram of a wind tunnel is shown in Fig. 1. The model is placed at the throat or working section. Air is sucked in by a propeller (or propellers) past the model from the entrance cone into the exit cone which is sometimes called the diffuser. If the propeller end of the diffuser is open, the tunnel is called an open return tunnel in which case the room serves as a return passage for the air from the diffuser. If the air stream from the exit cone is guided by a closed tube or circuit in returning to the entrance cone, the tunnel is a closed return type. Hence, wind tunnels are broadly classified into closed or open return types.

The working or test section of the tunnel may be totally enclosed or open. This leads into another classification of wind tunnels, closed throat and open throat. Depending upon the closed circuit guiding the air from the exit to the intake cone, wind tunnels may also fall under any of the following categories: (1) single return, (2) double return, and (3) annular return. As to position of the test section, a wind tunnel may be either horizontal

1 Nomenclature for Aeronautics, T.R. 474.

or vertical. Most wind tunnels are horizontal.

At present, a tunnel is usually described with reference to its throat and return passage. For example, the NACA 7 x 10-ft. tunnel is an open throat single closed return; the 10-ft. tunnels at C.I.T. and M.I.T. are closed throat single return types; the NACA 20-ft. tunnel is an open throat double return; and the French full scale tunnel is an open return open throat.

Sometimes one hears also of atmospheric and variable density tunnels. The first one operates under atmospheric pressure, while the variable density under varying pressures ranges from one up to twenty atmospheres or even more. The purpose of the variable or high density tunnel is to obtain large values of Reynold's number.

IV. OPEN AND CLOSED THROAT TUNNELS. THEIR ADVANTAGES AND DISADVANTAGES.

In an open throat tunnel the jet of air is exposed to a constant atmospheric pressure existing in the room and this makes the velocity of the jet over the length of the open section pretty nearly constant. The setting of the model, adjustment of the connections of the wire balance, and installation of any instrument at the working section become relatively easy in an open throat. The air stream flows more freely around a rather large size model if the throat is open than when it is closed due to the absence of restraining walls around the jet. The main trouble of an open jet is that it is subject to the disturbing influences of the air in the room especially if the tunnel is an open return. For this reason, open return tunnels usually have closed throats. If the throat has to be open, the room must be air-tight. For the same jet size and speed an open throat tunnel requires more power than a closed throat. When the test section is open, some air is sucked in from the room and provisions, in the form of slots or holes in the diffuser, should be made to allow the extra air to escape again from the tube and stabilize the air flow in the tunnel.

The closed throat type has a slight edge over the open throat in the useful length of the test section. The walls at the working section shield the model from any undesirable air disturbance from the outside. In connection with construction, it may be said that a closed throat tunnel is cheaper to build than an open throat, especially if the tunnel is small. One drawback of a closed throat section is that the speed of the air stream over the whole length of the test section increases due to the fact that the thickness of the boundary layer in the test section increases along the direction of the air flow.

V. COMPARISON BETWEEN OPEN AND CLOSED RETURN TUNNELS.

In a closed return tunnel the air is confined and guided to flow around a closed path. It is therefore easy with this type of tunnel to conserve the energy of the air stream and also to reduce the air resistance losses. This fact is important to remember, especially in the design of large size and high speed tunnels requiring big power. Steadiness of air flow and high speed can be easily secured in a closed return type. This is hard to accomplish with open return tunnels for a large portion of the energy of the air discharged into the room is lost in turbulence. For small wind tunnels operated at low speeds, an open return is easier and cheaper to construct and will need less space than a closed return.

As a rule, the closed return is much more efficient and economical to operate than an open return. Nowadays, most of the newly built tunnels are closed return.

VI. THE EFFICIENCY OF RETURN FLOW WIND TUNNELS.

The following study of the different factors which affect the efficiency of a return flow tunnel was made by Wattendorf (Reference 5), in connection with the design of the Tsing Hua wind tunnel, China. An abstract of his analysis was also read and presented before the Fifth International Congress of Applied Mechanics held here at M.I.T. and Harvard in 1938. His treatment of the subject of losses in wind tunnels is simple, straightforward and practical. It involves the analysis of the following:

1. The isolation of the individual factors which contribute to the losses in return flow tunnels.
2. A study of the influence of tunnel dimensions on these factors.
3. A study of the influence of tunnel speed.
4. A study of the effect of roughness.
5. Calculation of the optimum angle of divergence of the expanding sections.
6. Calculation of the conditions for the theoretical maximum efficiency of return flow tunnels.

(A). Energy Ratio: The efficiency of a wind tunnel is usually called the Energy Ratio (E.R.). It is defined as the ratio of the air energy per unit time at the throat to the power delivered by the motor driving the propeller.

In symbols,

$$(E.R.)_1 = \frac{(K.E.)_o}{P_m} \qquad (1)$$

where

$(E.R.)_1$ = the energy ratio of the tunnel.

$(K.E.)_o$ = the kinetic energy of the air at the throat.

P_m = power of the electric or motive power driving the propeller.

Sometimes the energy imparted by the propeller to the air is used in defining the energy ratio. If η_p is the propeller efficiency, $P_m \times \eta_p$ is the power delivered to the air by the propeller. In this case the equation for the energy ratio, call it now $(E.R.)_2$, is

$$(E.R.)_2 = \frac{(K.E.)_o}{\eta_p \times P_m} = \frac{1}{\eta_p} \times (E.R.)_1 = \frac{(K.E.)_o}{\text{Total Losses in Tunnel}} \qquad (2)$$

$(E.R.)_2$ is more convenient to use in the calculation of the energy losses in the different portions of a tunnel.

(B). Different Portions of a Tunnel: The component parts of a return flow tunnel as that shown in Fig. 1 may be put under four general groups as follows:

1. Cylindrical sections.
2. Divergent sections.
3. Corners with vanes.
4. Reducing cone.

(C). Process of Evaluating the Energy Loss in Each Group:

The kinetic energy of the flow through the test section is

$$(K.E.)_o = \frac{1}{2} \rho A_o V_o^3 \qquad (3)$$

where the subscript o refers to the throat; ρ , the air density; V_o, air mean speed; and A_o, the cross-sectional area of the test section. Hence,

$$(E.R.)_2 = \frac{\frac{1}{2} \rho A_o V_o^3}{\sum \text{losses}} \qquad (4)$$

At any section where the speed is V the energy loss may be expressed as

$$(\text{loss}) = k \cdot \tfrac{1}{2} \rho V^3 A \qquad (5)$$

where k is called the loss coefficient at the section having an area A. Assuming no air leaves or enters the tunnel, the amount of air Q in the tunnel remains constant, that is,

$$Q = AV\rho = A_o V_o \rho_o$$

In a closed return tunnel the density of the air remains practically constant and the same at the different sections. Therefore,

$$Q = A.V = A_o V_o$$

or

$$V = \frac{A_o}{A} \cdot V_o = \left(\frac{D_o}{D}\right)^2 \cdot V_o \qquad (6)$$

where D is the section diameter. Equation (5) can now be rewritten in this form,

$$\text{loss} = k \cdot \rho/2 \cdot \frac{V_o^2 D_o^4}{D^4} \cdot \frac{V_o A_o}{A} \cdot A$$

$$= k \cdot \left(\frac{D_o}{D}\right)^4 \cdot \left(\tfrac{1}{2} \rho A_o V_o^3\right) \qquad (7)$$

$$= k_o \left(\tfrac{1}{2} \rho A_o V_o^3\right) \qquad (8)$$

and

$$k_o \equiv k \cdot \left(\frac{D_o}{D}\right)^4 \qquad (9)$$

k_o is the basic loss coefficient. The total energy loss in the tunnel is the summation of all the losses in the various sections, or

$$\text{Total loss} = \sum k_o \cdot \left(\tfrac{1}{2} \rho A_o V_o^3\right) \qquad (10)$$

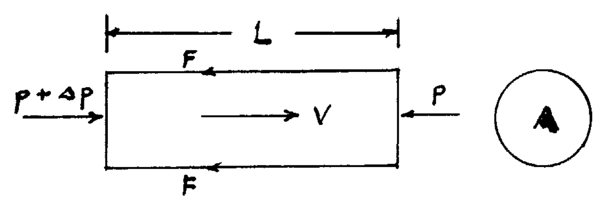
and

$$(E.R.)_2 = \frac{\frac{1}{2} \rho A_o V_o^3}{\sum k_o \cdot \frac{1}{2} \rho A_o V_o^3}$$

$$\frac{1}{\sum k_o} \qquad (11)$$

Equation (11) affords a method of evaluating the energy ratio or efficiency of a tunnel by simply summing up all the losses in the different sections. How these losses are determined for cylinders, divergent sections, corners with vanes, and cones will be discussed now.

<u>(D). Energy Loss in a Cylinder</u>: Take a cylinder of length L and cross-sectional area A. If a stream of air is flowing in it with a velocity V, the loss in energy will be mostly due to wall friction F whose magnitude is readily seen to be



$$F = (p + \Delta p) A - pA = \Delta p \cdot A \qquad (12)$$

The pressure drop Δp is a function of the length and diameter of the tube, kind of fluid, and the velocity of flow. The equation for it is

$$\Delta p = \lambda \cdot \frac{L}{D} \cdot \rho/2 \cdot V^2 \qquad (13)$$

where λ is a constant called the resistance coefficient.

The product of F and V gives the power lost in overcoming the wall resistance of the cylinder. Algebraically,

$$(\text{loss})_{\text{cyl.}} = F \times V = \Delta p . AV$$

$$= \lambda \cdot \frac{L}{D} \left(\tfrac{1}{2} \rho \, AV^3\right) \qquad (14)$$

From equations (5), (9) and (14),

$$(K_o)_{\text{cyl.}} = \lambda \cdot \left(\frac{L}{D}\right)_{\text{cyl.}} \cdot \frac{D_o}{D_{\text{cyl.}}} \qquad (15)$$

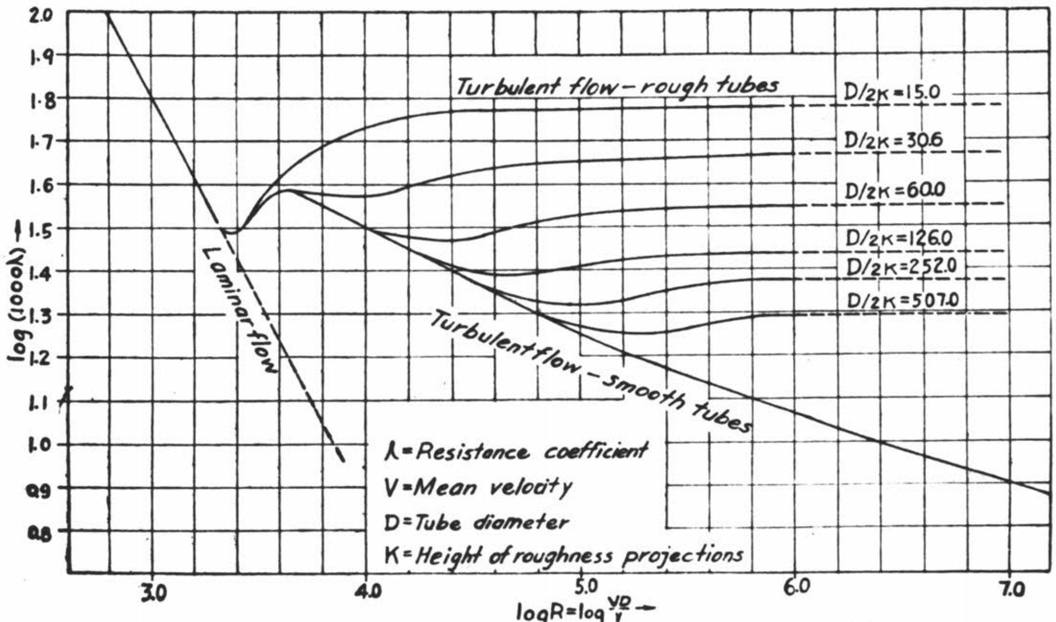
For smooth pipes the value of λ is a function of Reynold's number, R. The logarithmic equation for λ and R, attributed to T. von Kärman, is

$$\frac{1}{\sqrt{\lambda}} = 2 \log (R . \sqrt{\lambda}) - 0.8 \qquad (16)$$

For rough pipes, the value of λ was experimentally determined by Nikuradse, a Russian, in terms of the diameter D of the pipe and the height "h" of the projections on the cylinder walls. The formula of Nikuradse is

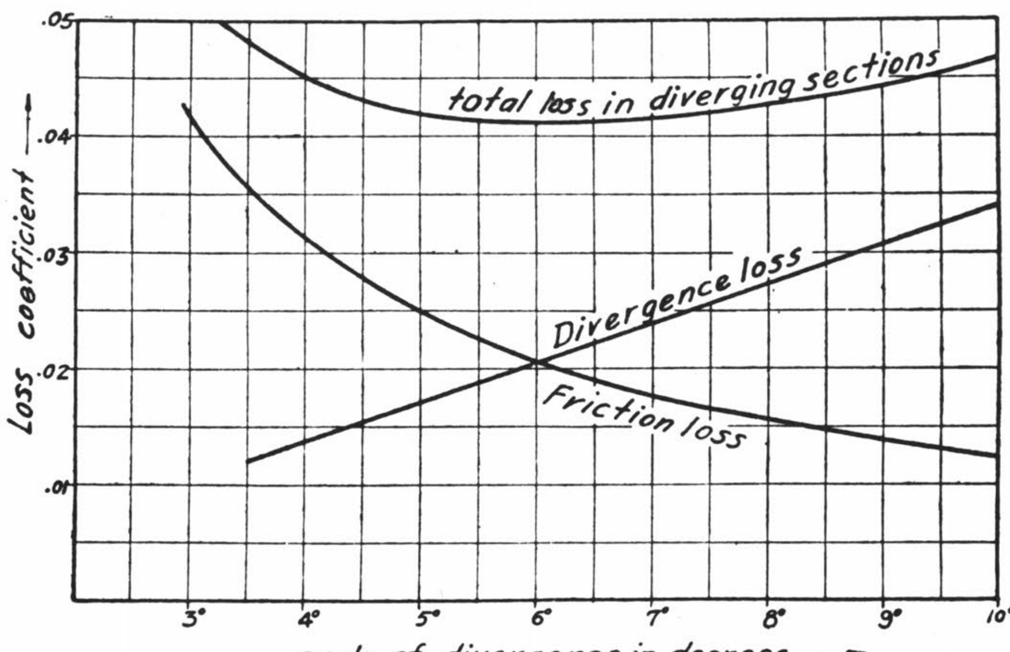
$$\sqrt{\lambda} = \frac{2.83}{4.75 + 5.75 \log \frac{D}{2h}} \qquad (17)$$

$\frac{D}{2h}$ is a measure of the roughness (or smoothness) of the tube. The larger the value of $\frac{D}{2h}$ becomes, the smoother is the tube. From this equation it is obvious that for the same height "h" of the projections, the value of λ will decrease as the cylinder diameter increases. In other words, of two cylinders having equal projections, the larger cylinder will appear smoother than the smaller one. Equations (16) and (17) are graphically represented in



Resistance Law for Flow in smooth and rough tubes

Fig. 2.

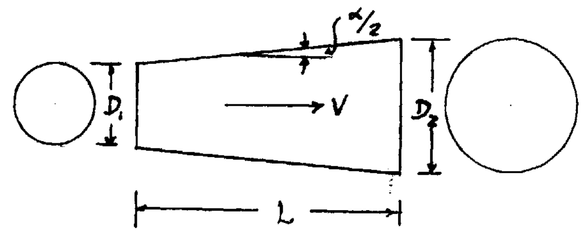


Loss in diverging sections as function of divergence angle

Fig. 3

Fig. 2, where h appears as k.

(E). Energy Loss in Expanding Sections: The loss of energy in a divergent section is caused by (1) wall friction, and (2) expansion of the air. If the divergent angle α is reasonably small, as assumed by Wattendorf, the resistance coefficient λ does not change appreciably. With this assumption, he showed that the basic coefficient k_o due to friction alone is equal to



$$k_o \text{ (friction)} = \frac{\lambda}{8 \tan \frac{\alpha}{2}} \left[1 - \left(\frac{D_1}{D_2}\right)^4 \right] \cdot \left[\frac{D_o}{D_1} \right]^4 \qquad (18)$$

and due to expansion,

$$k_o \text{ (expansion)} = \sin \alpha \left[1 - \left(\frac{D_1}{D_2}\right)^2 \right]^2 \cdot \left[\frac{D_o}{D_1} \right]^4 \qquad (19)$$

The total basic coefficient for the expanding section is then

$$k_o \text{ (total)} = \left\{ \frac{\lambda}{8 \tan \frac{\alpha}{2}} \left[1 - \left(\frac{D_1}{D_2}\right)^4 \right] + \sin \alpha \left[1 - \left(\frac{D_1}{D_2}\right)^2 \right]^2 \right\} \cdot \left\{ \frac{D_o}{D_1} \right\}^4 \qquad (20)$$

(F). Energy Loss at Corners: The basic loss coefficient at the corner was considered to be composed of the profile friction, k_f, and the flow rotation coefficient k_r, where

$$k_f = \frac{4.55}{(\log R)^{2.58}}$$

and

$$k_r \doteq 0.10$$

From these values of k_f and k_r, the basic coefficient for the corner is found to be

$$k_o \text{ (corner)} = \left[0.10 + \frac{4.55}{(\log R)^{2.58}} \right] \cdot \left[\frac{D_o}{D} \right]^4 \quad (21)$$

Experimental tests on the Tsing Hua tunnel confirmed the above equation. An important guiding principle in the design of a tunnel can be established from this equation also. To reduce the loss at the corner, increase the corner diameter as much as practically possible.

<u>(G). Loss at Converging Cone</u>: For smooth converging cones, the energy loss is very small and is mostly due to friction. The pressure drop Δp arising from this loss was experimentally found to be

$$\Delta p = C \cdot \frac{\rho}{2} (V_o^2 - V^2) \quad (22)$$

where C is a constant and V is the velocity at the larger section of the cone. In terms of the diameters at the ends of the cone, equation (22) becomes

$$\Delta p = C \left[1 - \left(\frac{D_o}{D}\right)^4 \right] \cdot \left[\frac{\rho}{2} V_o^2 \right] \quad (23)$$

From this last equation, the basic coefficient k_o for the cone is obtained. The experimental value of C is about 0.005.

$$k_o \text{ (cone)} = .005 \left[1 - \left(\frac{D_o}{D}\right)^4 \right] \quad (24)$$

(H). <u>Reynold's Number at Any Section</u>: Let R and R_o be the values of Reynold's numbers at any section and at the throat respectively. From the previous assumption that the density of the air throughout the tunnel is the same, since the actual change is very small, then it follows that the kinematic viscosity ν is also practically constant, or

$$\nu = \frac{VD}{R} = \frac{V_o D_o}{R_o}$$

or $$R = R_o \cdot \frac{VD}{V_o D_o}$$

but $$\frac{V}{V_o} = \frac{A_o}{A} = \left(\frac{D_o}{D}\right)^2$$ (from the law of continuity)

$$R = R_o \cdot \frac{D_o}{D} \qquad (25)$$

Knowing R at the section, the corresponding value of the resistance coefficient λ is read from Fig. 2.

(I). <u>Alterations in Design</u>: In designing any structure it is always necessary to make a preliminary sketch of the structure. From this rough sketch, the final design is evolved by making alterations or modifications here and there on the first sketch. So it is in the design of a wind tunnel. In that case it may be interesting to know the effects on the energy ratio of each of the following changes or combination of changes:

1. Blowing up all the diameters in the same ratio, keeping the speed constant.
2. Changing the air speed alone.

3. Increasing or decreasing the angle of divergence.

Examination of equations (15), (20), (21) and (24) for the basic loss coefficients for the cylinder, expanding section, corner, and cone respectively will reveal the following information:

1. By increasing (or decreasing) the diameters in the same proportion, there will not be any change in the losses at the corners and cone. The only changes will be at the cylinders and diverging sections due to the variation of the resistance coefficient λ which is dependent upon the value of Reynold's number. For large values of R, and increase in diameter means a decrease in λ and a consequent increase in efficiency.
2. If the speed is raised, R will go up alsq and λ will decrease. This change in λ will cut down the losses at the cylinders, corners, and expanding sections. The losses at the cone remain unaffected. The net result of increasing the speed is to improve the efficiency of the tunnel.
3. The variation of the friction and expansion losses in a diverging section can be calculated from equations (18) and (19) and then plotted at various values of α as shown in Fig. 3. The total loss, which is the sum of the two above losses, for the expanding section is seen to be

a flat curve, concave upward and having a minimum in the neighborhood of 6°. Therefore, for maximum efficiency, the diverging angle should be from 6 to 8 degrees.

(J). Where Losses are Greatest: Examination of the losses at the different sections of a tunnel by the application of Wattendorf procedure will indicate the portions where the losses are greatest. When this was done with the Tsing Hua tunnel, it was found that about 30 per cent of the total losses occurred at the corner at the end of the diffuser and nearly 20 per cent for the succeeding corner. For these two corners alone the combined loss amounted to about one-half of all the tunnel losses. The magnitude and importance of these corner losses were recognized a long time ago. Warner, Norton and Hebbert (Reference 15) prepared a chart by means of which the proper exit cone proportions can be selected to give a maximum efficiency for a given diameter of the test section and length of the exit cone.

(K). Guide Vanes and Straighteners: The high losses at the corners with guide vanes prompted several researchers, Prandtl being the most noted, to experiment on different designs of guide vanes that would give the minimum loss. Prandtl developed the well known and widely used Göttingen guide vane. The latest data on guide vanes are those given by Green, Klein, and Tupper (Reference 12) and by Kröber (Reference (14).

The most desirable characteristics of guide vanes to be efficient in deflecting an air stream are:

1. Minimum turbulence.
2. Uniform velocity distribution on the exit side.
3. Minimum pressure drop across the vanes.

Green, Klein, and Tupper experimented on several types of guide vanes and the high spots of their findings are listed below:

1. Vane shape not a very critical factor. Even crudest vanes give remarkable effect in smoothing flow.
2. Corner resistance for all vane shapes have minimum when gap/chord ratio ranges from 0.3 to 0.5 and rise more steeply on the side of increasing spacing.
3. Obviously, spacing is a critical factor. With large spacings, the turbulence in the stream passing through the vanes creates larger corner resistance. Smaller spacing increases skin friction.
4. The effect on the velocity distribution of the angle of incidence - the angle of incidence is measured from the normal position of the vane chord to the plane of the corner - was tried on one of the vanes (vane #5) for angles of incidence from -4° to $+10^{\circ}$. It appeared from the results that no particular advantage is gained by using any incidence other than 0°.

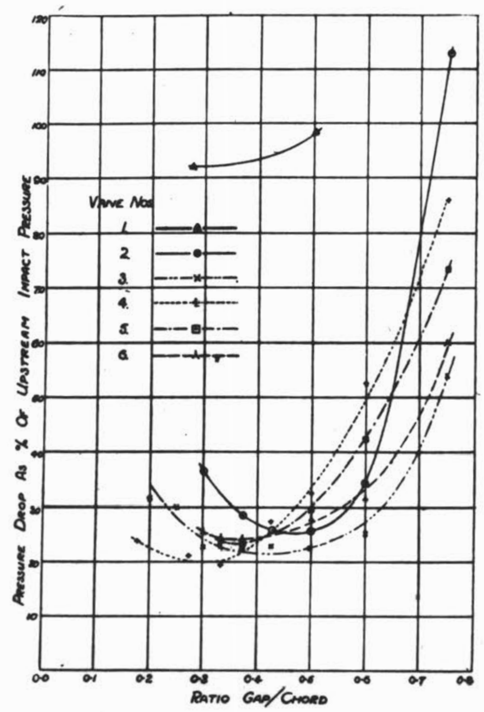


Fig 4. Corner resistance curves for all vane shapes.
Note that vane No. 4 gives the minimum resistance at a gap/chord ratio of 0.3

Fig. 4 shows the resistance of all the various vanes tested. Vane No. 4 is a simple quarter circular arc. It is made out of a flat plate and is recommended for small tunnels. Vanes Nos. 5 and 6 are thick and streamlined and should be used for large wind tunnels where loading is heavy. The shapes and geometric properties of these two vanes are given below. They were found to be the best of the vanes tested.

Distance from L.E. along chord as % of chord	VANE NO. 5 Top surface, distance from chord as % of chord	VANE NO. 5 Bottom surface, distance from chord as % of chord	VANE NO. 6 Top surface, distance from chord as % of chord	VANE NO. 6 Bottom surface, distance from chord as % of chord
0	2.03	2.03	2.36	2.36
2.5	6.66	0.07	8.44	0.11
5	9.68	1.14	12.50	1.24
10	14.45	3.70	17.60	4.28
20	21.65	8.14	24.70	10.25
30	26.70	11.43	28.70	14.90
40	29.30	13.45	30.60	17.60
50	29.93	14.12	30.60	18.70
60	28.79	13.78	29.10	18.40
70	25.90	12.37	25.90	16.40
80	20.44	9.41	20.30	12.40
90	12.71	5.14	11.80	6.42
95	7.40	2.62	5.14	2.93
100	0.27	0.27	0.79	0.79

Vane 5.

Vane 6.

<u>(L). Fans for Wind Tunnels</u>: A wooden propeller usually driven by an electric motor is used to make the air in the tunnel circulate. In designing a tunnel, the questions of propeller diameter, number of blades, blade width and propeller tip speed are involved. Since a propeller is generally installed at the exit end of the diffuser or somewhere near the entrance of the return tube, if the tunnel is a closed return, its diameter is more or less fixed by the size of the tunnel at the said locations. The number of blades and blade widths always go together as it is the total blade width which is critical for the propeller performance. However, it might be said that for a given thickness and strength, the blades should be sufficiently wide to make them operate without flutter or excessive vibration. The number of blades should not be less than two, and preferably four for moderately sized tunnels. The tip speed must be kept below a certain limit, say 700 to 800 ft./sec., to prevent the tunnel noise from being annoying and disturbing.

From the theory of momentum and from the definitions of energy ratio and fan efficiency (which was assumed to be 70 per cent), the following formula was developed in our 16:62 class:

$$2.5 = \sqrt{\frac{(\pi n D_f)^2}{V_o^2} \cdot \frac{Bb}{D_f} \cdot (E.R.)}$$

where $n =$ R.P.S.; $(\pi n D_f)$, the tip speed; V_o, the air velocity at the throat; D_f, B, and b are respectively the fan diameter, number of blades, and blade width; and E.R. is the over-all energy ratio.

(M). Power Required: If the energy ratio and fan efficiency are known (or assumed), the power required to operate a wind tunnel may be computed from the following equation:

$$\text{Motor H.P.} = \frac{\frac{1}{2} \rho A_o V_o^3}{\eta_p \times (E.R.) \times 550}$$

in which ρ is the air density in slugs/ft.^{3}; A_o, the area in sq.ft. of the throat; V_o, the velocity in ft./sec. at the throat; η_p, the fan efficiency; and E.R., the over-all energy ratio.

From a survey of the actual E.R. of several existing tunnels, N.A.C.A. supplies the following information (1) on the values of E.R. For open throat types of normal design, the energy ratio varies from 1.5 to 2.5 for small tunnels; and for preliminary design of this kind of tunnel an E.R. of 1.75 may be used. If the test section is closed, a design E.R. of 3 may be used.

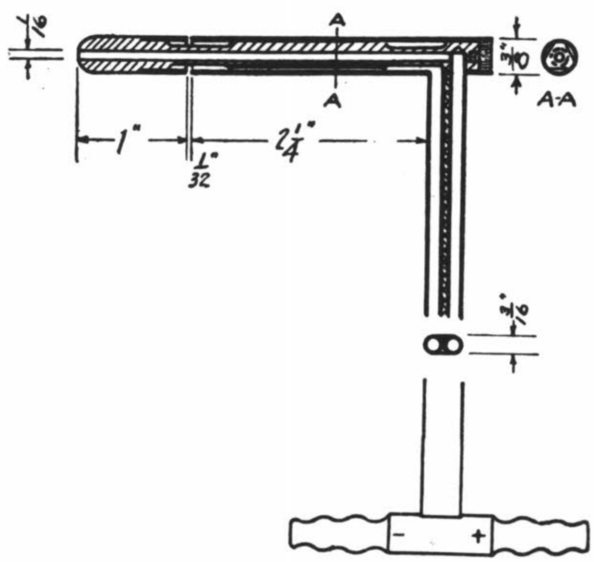
(1) N.A.C.A. "General Information on W.T. Design".

(N). Types of Electric Motors Used: The electric motor which supplies power to the propeller is always a D.C. motor whose speed can be regulated. It may be a series, a shunt or a compound wound motor. The methods with which the speeds of these motors can be controlled, are shown in Fig. 5. The most satisfactory method of controlling the speed of a D.C. motor is the Ward-Leonard system which is also schematically shown in Fig. 5. M is the motor driving the propeller. G is a generator which supplies the D.C. current to M. By adjusting the field currents of G and M, which field currents come from the same D.C. supply line, the speed of M can be varied from zero to maximum.

(O). Auxiliary Instruments: In wind tunnel work it is necessary to know under existing conditions the following characteristics of air:

1. Velocity
2. Density
3. Pressure
4. Temperature

There are several methods of measuring accurately the velocity of an air stream in a tunnel. It can be done with a simple Pitot tube which is usually made out of an ordinary glass tubing. For very accurate and refined velocity measurements in boundary layer, the Pitot tube is in the form of a hypodermic needle. The most convenient and satisfactory instrument now used in velocity measure-



PRANDTL TYPE PITOT-STATIC TUBE.

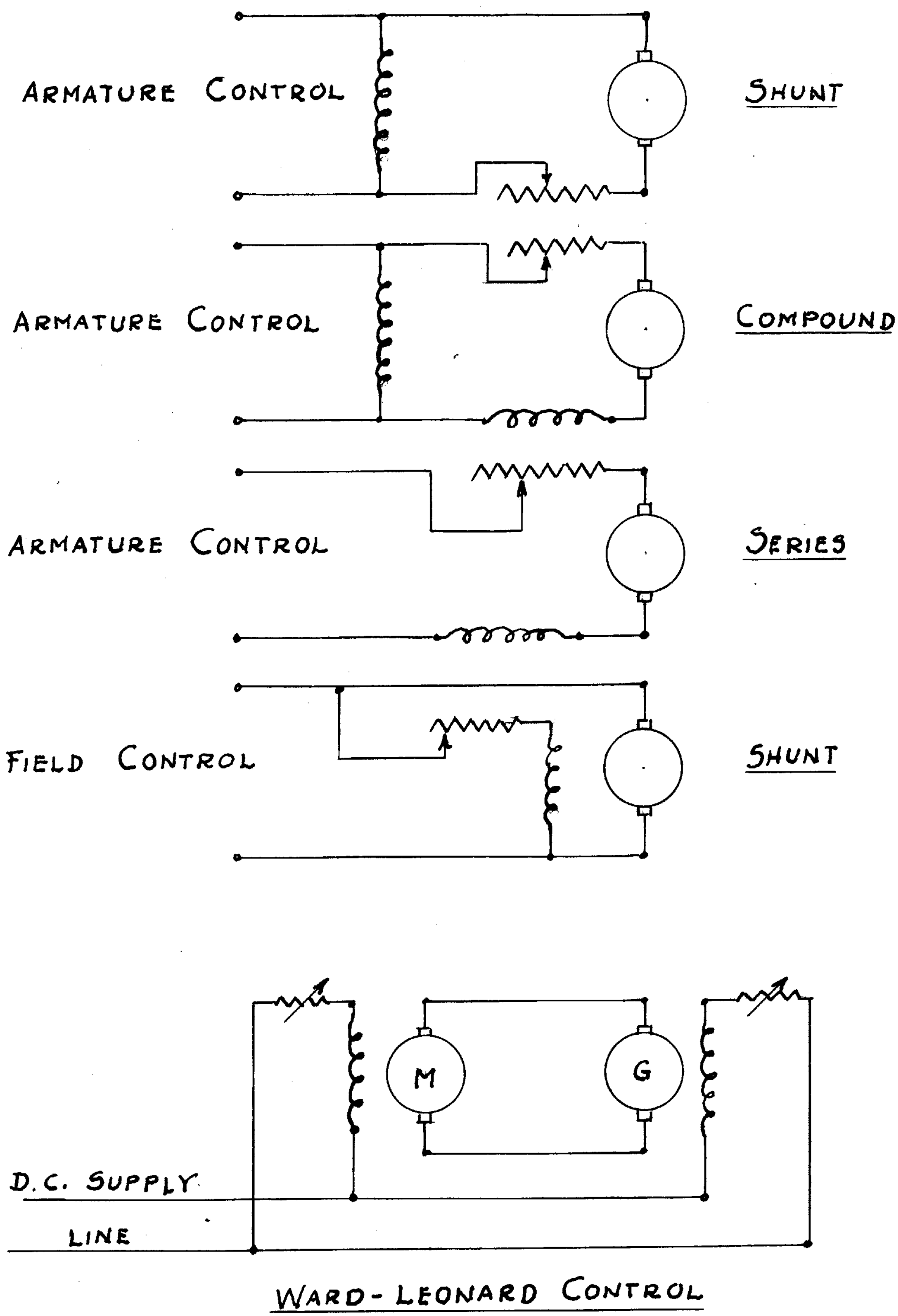
Fig. 6.

ments is the Pitot-static tube designed and developed by Prandtl. This is shown in Fig. 6 . In this instrument the wall of the Pitot tube portion is constructed in the form of an annular passage, in the outer surface of which the static-pressure holes are drilled. The total pressure of the air stream is thus carried through the central passage while the static pressure is transmitted through the outer passage. These two passages may be connected to opposite ends of a differential manometer, which then indicates the head equivalent to the dynamic pressure. The main limitations (Reference 11) of the Pitot-static tube are as follows:

1. At low velocities, it requires an extremely sensitive manometer, and hence of a complex design.
2. The mean reading of the manometer does not correspond to the average velocity if the velocity fluctuates rapidly.
3. The Pitot-static tube is sensitive to the angularity of the axis of the tube with respect to the line of flow.

Another instrument employed in measuring the magnitude of the velocity, especially if this is low and varies rapidly, is the hot wire anemometer. The principle of this instrument is based upon the fact that the electrical resistance of a wire is a function of its temperature and the rate of cooling of a hot wire placed in an air stream is a function of the air speed.

Fig. 6. Speed Controls of D.C. Motors.



For the measurement of the static pressure at the walls of the tunnel or at the surface of any solid body placed in the air stream, an inclined liquid manometer is very suitable. The liquid commonly used is water or alcohol, preferably colored.

VII. WIND TUNNEL BALANCES.

When a model is placed in the air stream at the test section of a tunnel, it will be subjected to lift, drag and side forces, and to rolling, yawing and pitching moments. A balance designed to measure all of these quantities is called a six-component balance. In most wind tunnel work, only the lift and drag forces and the pitching moment are required. The balance used for this purpose is known as a three-component balance. The following discussion will be confined to the three-component balance which is fitted for a small wind tunnel.

In passing, it may be stated that wind tunnel balances are generally classified into three types: (a) wire types, (b) rigid strut types, and (c) a combination of the wire and rigid types. As wire type balances are the simplest and cheapest to make, a great majority of tunnel balances are of this type.

In connection with design, it is essential to be acquainted with the general constructional and operational requirements asked to produce a good satisfactory balance. These are:

A - Constructional Requirements.

1. Inexpensive.
2. Simple and easy to make.
3. Rugged but light.

B - Operational Requirements.

1. High degree of accuracy.

2. Sensitive.
3. Ease of attaching model to balance.
4. Readings easily obtained and directly measured.
5. Attachments to the model offer the least drag and disturbance to the air flow.
6. Deflections or elastic deformations under load to be negligible.
7. Range for angle of attack from -20° to $+30^\circ$ and for yaw, $\pm 20^\circ$.
8. Provisions for damping.

The two tunnel balances which will serve as good examples of well designed tunnel balances are those developed at the Worcester Polytechnic Institute (Reference 3) and for the M.I.T. 5-ft. tunnel. The first one belongs to the wire-strut combination type and the second is a wire type. Both of these balances are schematically shown at the back.

VIII. CALCULATIONS

Preliminary Remarks: The wind tunnel shown in blue print was designed with the following assumptions at the beginning:

1. Room size, 30 x 25 x 20 ft.
2. Throat diameter, between 2 and 3 feet.
3. Maximum air speed, 100 M.P.H.
4. Horizontal jet near ground floor.

The small laboratory rooms in the College of Engineering of the University of the Philippines have dimensions given above. The throat diameter between 2 and 3 feet is considered fairly satisfactory for the size of the room if the tunnel is a closed return. It may not be necessary to run the tunnel at 100 M.P.H. but 100 M.P.H. is arbitrarily chosen as the maximum air speed to determine the maximum horse-power to be needed. As the tunnel is to be made of wood which is likely to be attacked by white ants, it must be elevated high enough above the ground floor to facilitate frequent inspection. Lack of ceiling height prohibits the installation of the balances on a raised platform above the working jet. As this tunnel is intended for class demonstrations, and in performing aerodynamic experiments by student groups, an open throat was deemed advisable. Provisions can be easily made to convert this tunnel into a closed throat if this would be desired at any time.

With the above assumptions, preliminary size calculations based on the foregoing principles were made, changed or modified until a tunnel, considered adequate and large enough for the available space, was obtained.

(A). Calculations of Losses at Different Sections.

(Note: All losses are calculated in terms of the basic loss coefficient k_o.)

Assumptions: $V_o = 100$ M.P.H. $= 147$ ft./sec.

$D_o = 2.5$ ft.

$A_o = \frac{\pi D^2}{4} = 4.9$ ft.^{2}

$(K.E.)_o = \frac{1}{2} \rho A_o V_o^3$

$= 18,450$ ft.lbs./sec.

$R_o = \frac{\rho VD}{\mu} = \frac{.002378 \times 147 \times 2.5}{373 \times 10^{-9}}$

$= 2,350,000$

$\alpha = 6^o$ for all diverging sections

$\sin \alpha = 0.1045$

$\tan \frac{\alpha}{2} = 0.052$

(Starting from the diffuser and going around the tube in the clockwise direction.)

1. Diffuser: $R = R_o \times \frac{D_o}{D} = 2.35 \times 10^6 \times \frac{2.5}{3.2}$

$= 1.835 \times 10^6$

$= .0107$ (from Fig. 2 and by computations.)

$8 \tan \frac{\alpha}{2} = 8 \times .052 = .416$

$$(D_1/D_2)^4 = (2.8/3.5)^4 = .410 \quad \& \quad \left(\frac{D_1}{D_2}\right)^2 = .64$$

$$(D_o/D_1)^4 = (2.5/2.8)^4 = .634$$

$$k_o = \left[\frac{.0107}{.416}(1-.410) + .1045(1-.64)^2\right] \cdot \left[.634\right]$$

$$= .0183$$

2. First Corner: $R = R_o \times \frac{D_o}{D} = 2.35 \times 10^6 \times \frac{2.5}{3.5}$

$$= 1.675 \times 10^6$$

$$(\log R)^{2.58} = (6.227)^{2.58} = 112$$

$$k_o = \left(0.10 + \frac{4.55}{112}\right)\left(\frac{2.5}{3.5}\right)^4$$

$$= .0367$$

3. Diverging Section: $R = R_o \times \frac{D_o}{D} = 2.35 \times 10^6 \times \frac{2.5}{3.6}$

$$= 1.635 \times 10^6$$

$\lambda = .0107$ (obtained as before)

$$(D_1/D_2)^4 = \left(\frac{3.5}{3.7}\right)^4 = .797$$

$$(D_1/D_2)^2 = .893$$

$$(D_o/D_1)^4 = \left(\frac{2.5}{3.5}\right)^4 = .26$$

$$k_o = \left[\frac{.0107}{.416}(1-.797) + .1045(1-.893)\right] \cdot \left[.26\right]$$

$$= .0046$$

4. Second Corner: $R = 2.35 \times 10^6 \times \frac{2.5}{3.7} = 1.59 \times 10^6$

$$(\log R)^{2.58} = 111$$

$$k_o = \left(.10 + \frac{4.55}{111}\right)\left(\frac{2.5}{3.7}\right)^4$$

$$= .0292$$

5. Cylinder: $R = 2.35 \times 10^6 \times \frac{2.5}{3.7} = 1.59 \times 10^6$

$$\lambda = .0107$$

$$k_o = \lambda \cdot \frac{L}{D} \cdot \left(\frac{D_o}{D}\right)^4 = .0107 \times \frac{1.9}{3.7} \times \left(\frac{2.5}{3.7}\right)^4$$

$$= .0012$$

6. Return Tube: $R = 2.35 \times 10^6 \times \frac{2.5}{4.35} = 1.35 \times 10^6$

$$\lambda = .011$$

$$(D_1/D_2)^2 = (3.7/5)^2 = .547$$

$$(D_1/D_2)^4 = .300$$

$$(D_o/D_1)^4 = (2.5/3.7)^4 = .207$$

$$k_o = \left[\frac{.011}{.416}(1-.3) + .1045\,(1-.55)^2\right] \cdot \left[.207\right]$$

$$= .0082$$

7. Third Corner: $R = 1.18 \times 10^6$

$$(\log R)^{2.58} = 105$$

$$k_o = \left(0.10 + \frac{4.55}{105}\right)\left(\frac{2.5}{5}\right)^4$$

$$= .00894$$

8. Fourth Corner: $k_o = .00894$ (equal to third corner)

9. Cylinder (no honeycomb): $R = 1.18 \times 10^6$

$$\lambda = .0117$$

$$k_o = \lambda \times \frac{L}{D} \times \left(\frac{D_o}{D}\right)^4$$

$$= .0117 \times \frac{.5}{5} \times \left(\frac{2.5}{5}\right)^4$$

$$= .000073 \quad \text{(very small)}$$

10. Cone: $k_o = .005 \left[1-\left(\frac{D_o}{D}\right)^4 \right]$

$= .005 \left[1-\left(\frac{2.5}{5}\right)^4 \right]$

$= .00468$

11. Throat: $k_o = .17$ (taken from 16.62 lecture notes)

12. For Whole Tunnel:

$\sum k_o = .0183 + .0367 + .0046 + .0292 + .0012 +$
$.0082 + .00894 + .00894 + 0 + .00468 +$
$.17 = .291$

$(E.R.)_2 = \frac{1}{\sum k_o} = 3.44$

and $(E.R.)_1 = \eta \times (E.R.)_2$

$= .70 \times 3.44$

$= 2.41$ (overall E.R.)

(B). Determination of Motor H.P. at 100 M.P.H.

Assume $\eta_p = 70\%$

$E.R. = 1.5$

Motor H.P. $= \frac{\frac{1}{2}\rho A_o V_o^3}{\eta_p \times E.R. \times 550}$

$= \frac{18,450}{.70 \times 1.5 \times 550}$

$= 32.0$ at 100 M.P.H.

Motor H.P. at Different Speeds.

V (m.p.h.)	H.P.
100	32.0
90	23.3
80	16.4

V (m.p.h.)	H.P. (cont.)
70	11.0
60	6.9
50	4.0
40	2.1
30	0.9
20	0.3
10	---

(C). Number of Blades and Blade Width of Propeller.

$D = 3.6$ ft. (Fixed by tunnel size)

If $N = 2,400$ R.P.M.

$\pi nD = 3.14 \times 40 \times 3.6$

$= 452$ ft./sec. (propeller tip speed)

E.R. $= 1.5$ (as assumed in B)

$V_o = 147$ ft./sec.

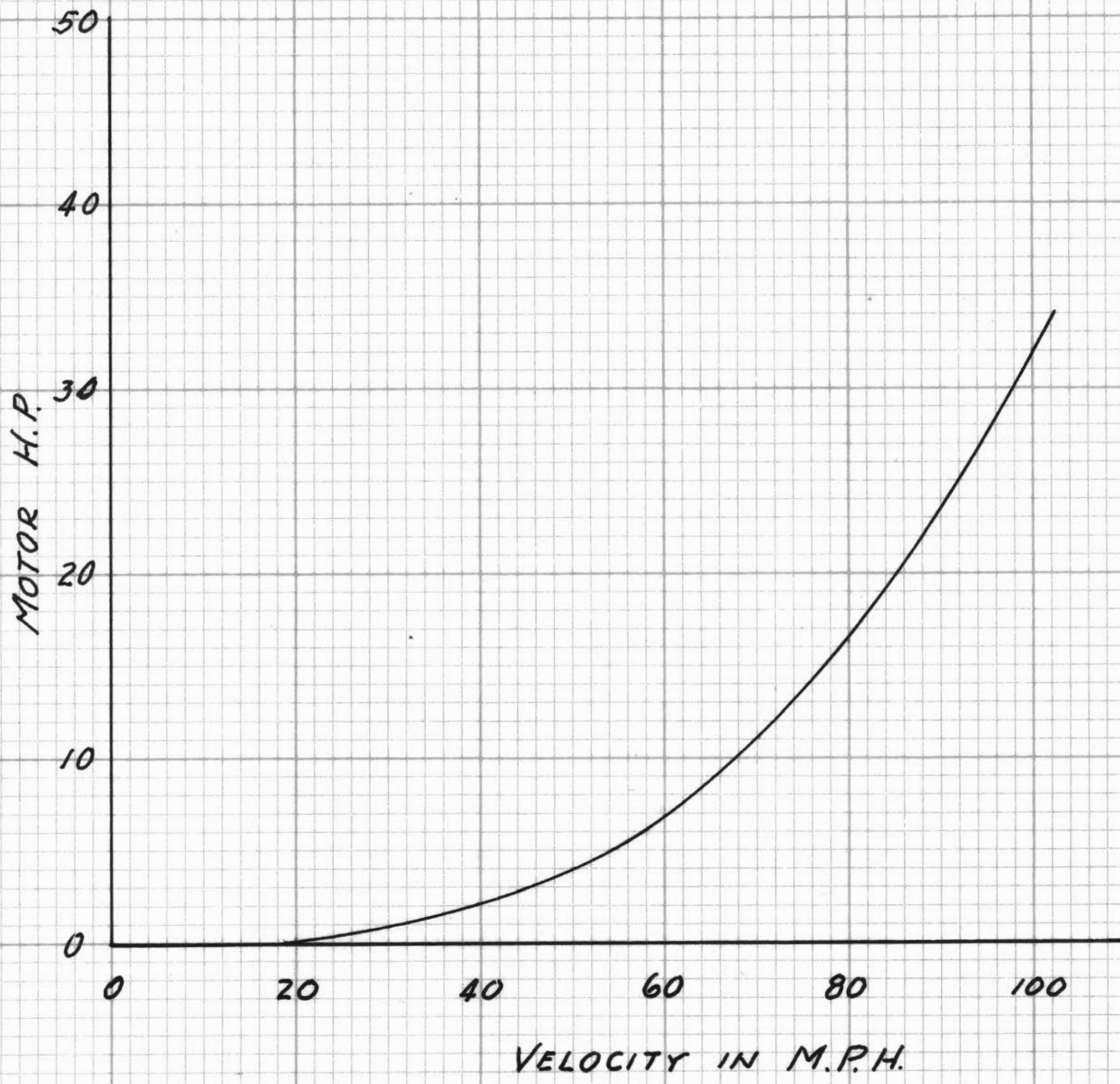
$$(2.5)^2 = \frac{(\pi nD)^2}{V_o^2} \times \frac{Bb}{D} \times (E.R.)$$

$$= \left(\frac{452}{147}\right)^2 \times \frac{Bb}{3.6} \times (1.5)$$

or $Bb = 1.59$ ft.

If B 2, $b = 0.8$ ft. (too wide)

B 4, $b = 0.4$ ft. (about right)



POWER REQUIRED AT DIFFERENT SPEEDS

REFERENCES

1. Goldstrom, J.: A Narrative History of Aviation; Macmillan Co., 1930.

2. Merrill, A. A.: The Pasadena Junior College Wind Tunnel; J.A.S. August 1936.

3. Merriam, K. G.: Equipment for Laboratory Instruction in Aerodynamics; J.A.S. August 1936.

4. Harrington, R. P.: Closed Return Type 42-inch Wind Tunnel at the Polytechnic Institute of Brooklyn; Aero Digest, December 1939.

5. Wattendorf, F. L.: The Efficiency of Return Flow Wind Tunnels; The Science Reports of National Tsing Hua University, Series A, Vol. III, Nos. 4 and 5.

6. Harris, T. A.: The 7 x 10-feet Wind Tunnel of the National Advisory Committee for Aeronautics; N.A.C.A., T.R. 412.

7. Zahm, A. F.: The Six-Component Wind Balance; N.A.C.A., T.R. 146.

8. Jacobs, E. N. and Abbot, I. H.: The NACA Variable-Density Wind Tunnel; N.A.C.A., T.R. 416.

9. Prandtl-Tietjens: Applied Hydro- and Aero- Mechanics; McGraw Hill Book Co., 1934.

10. Durand, W. F.: Aerodynamic Theory, Vol. III.

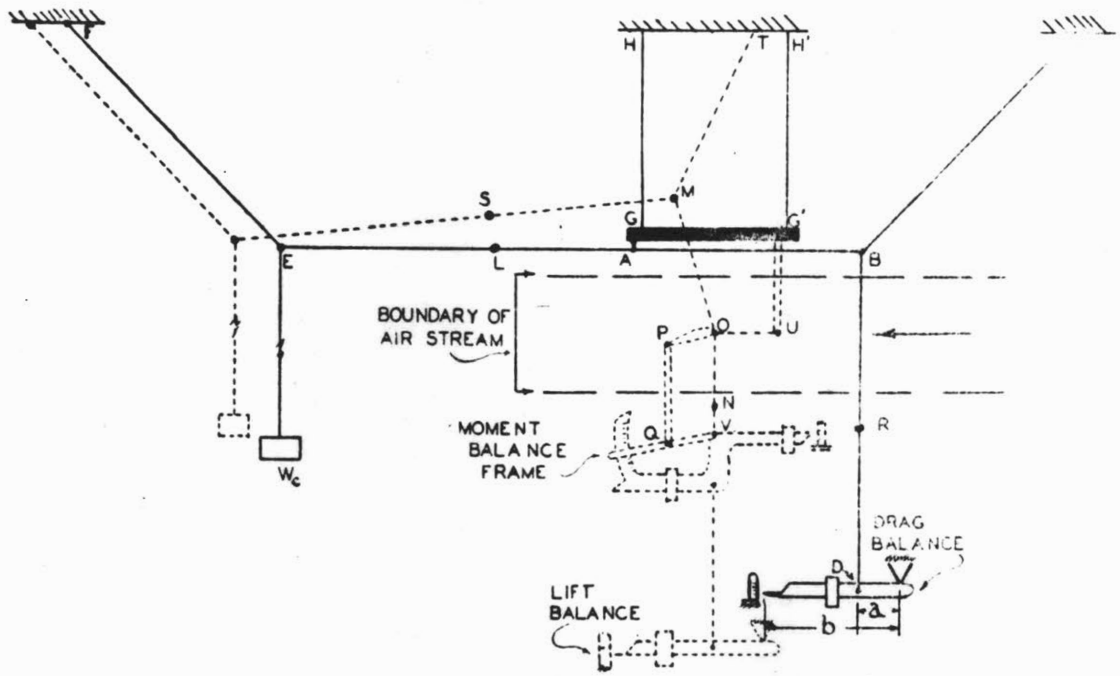
11. Pavian, H. C.: Experimental Aerodynamics; Pitman Publishing Corporation, New York, 1940.

12. Green, J. J., Klein, C. J., Tupper, K. F.: Design of Corners in Fluid Channels; Canadian Journal of Research, 1930.

13. Wieselsberger, C.: The Aachen Wind Tunnel Balance; N.A.C.A., T.M. 757.

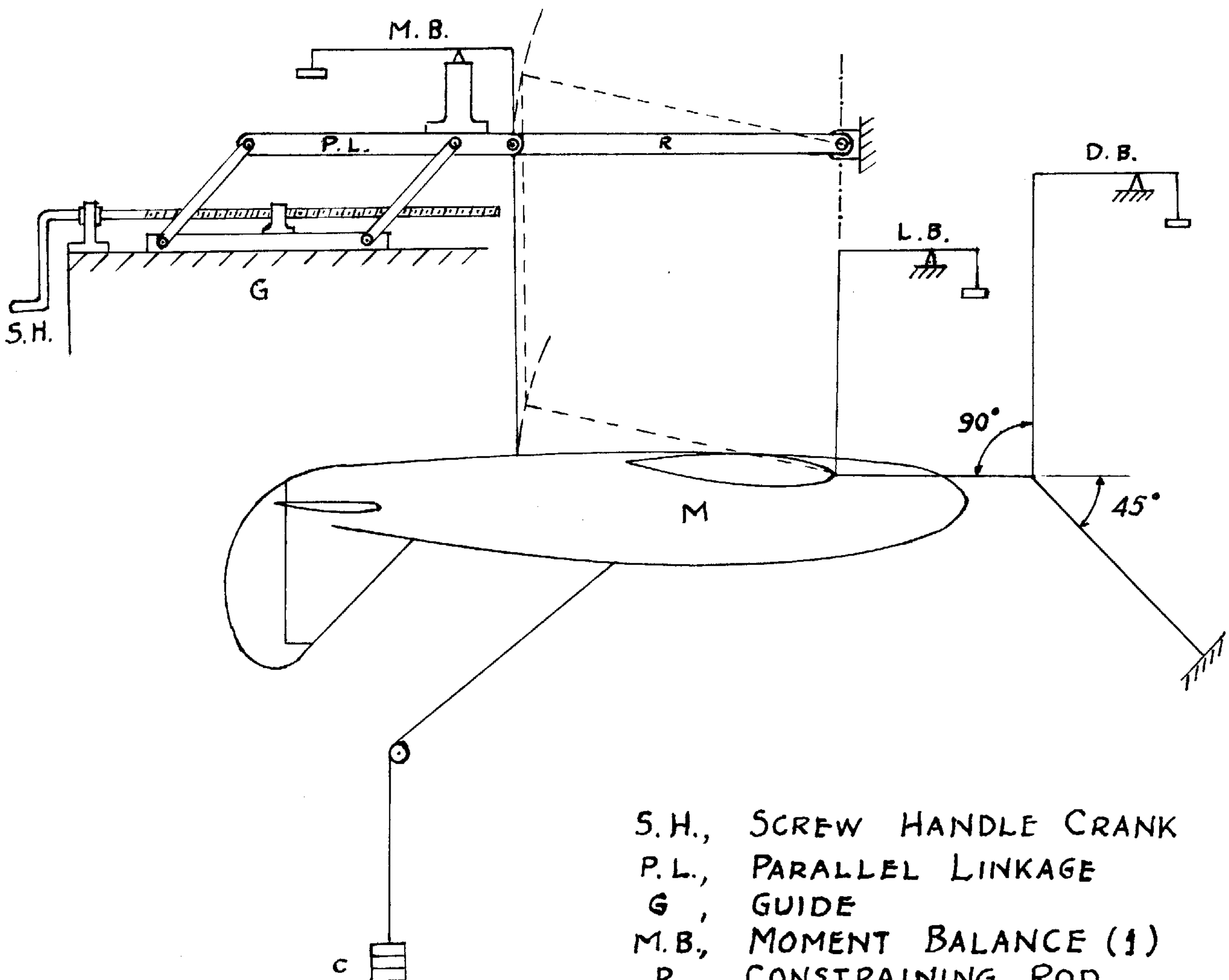
14. Kröber, G.: Guide Vanes for Deflecting Fluid Currents with Small Loss of Energy; N.A.C.A., T.M. 722.

15. Warner, E. P., Norton, F. H., Hebbert, C. M.: The Design of Wind Tunnels and Wind Tunnel Propellers; N.A.C.A., T.R. 73.

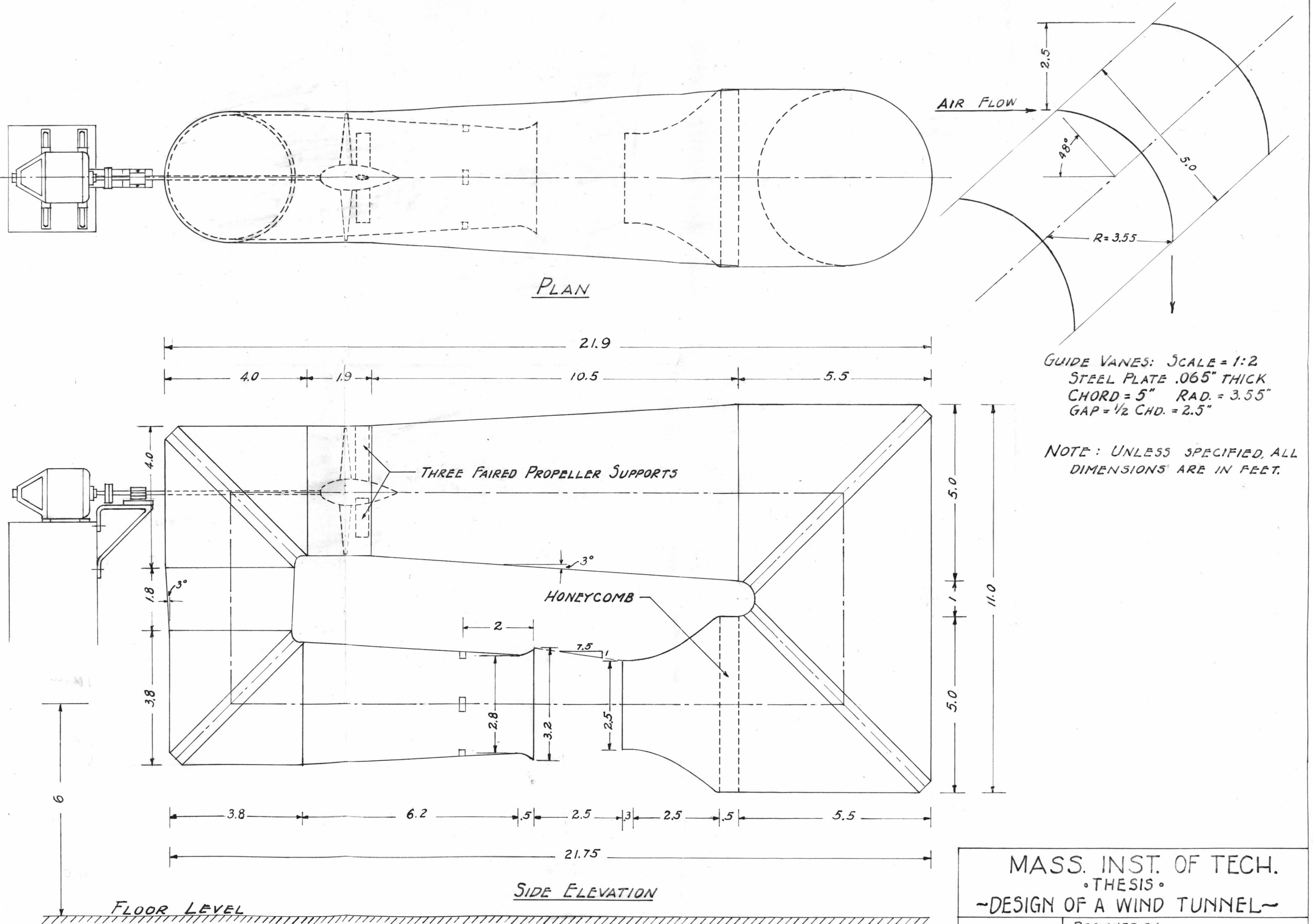


WORCESTER POLYTECHNIC INSTITUTE THREE COMPONENT BALANCE.

SCHEMATIC DIAGRAM OF 5-FT. TUNNEL WIRE BALANCE AT M.I.T.

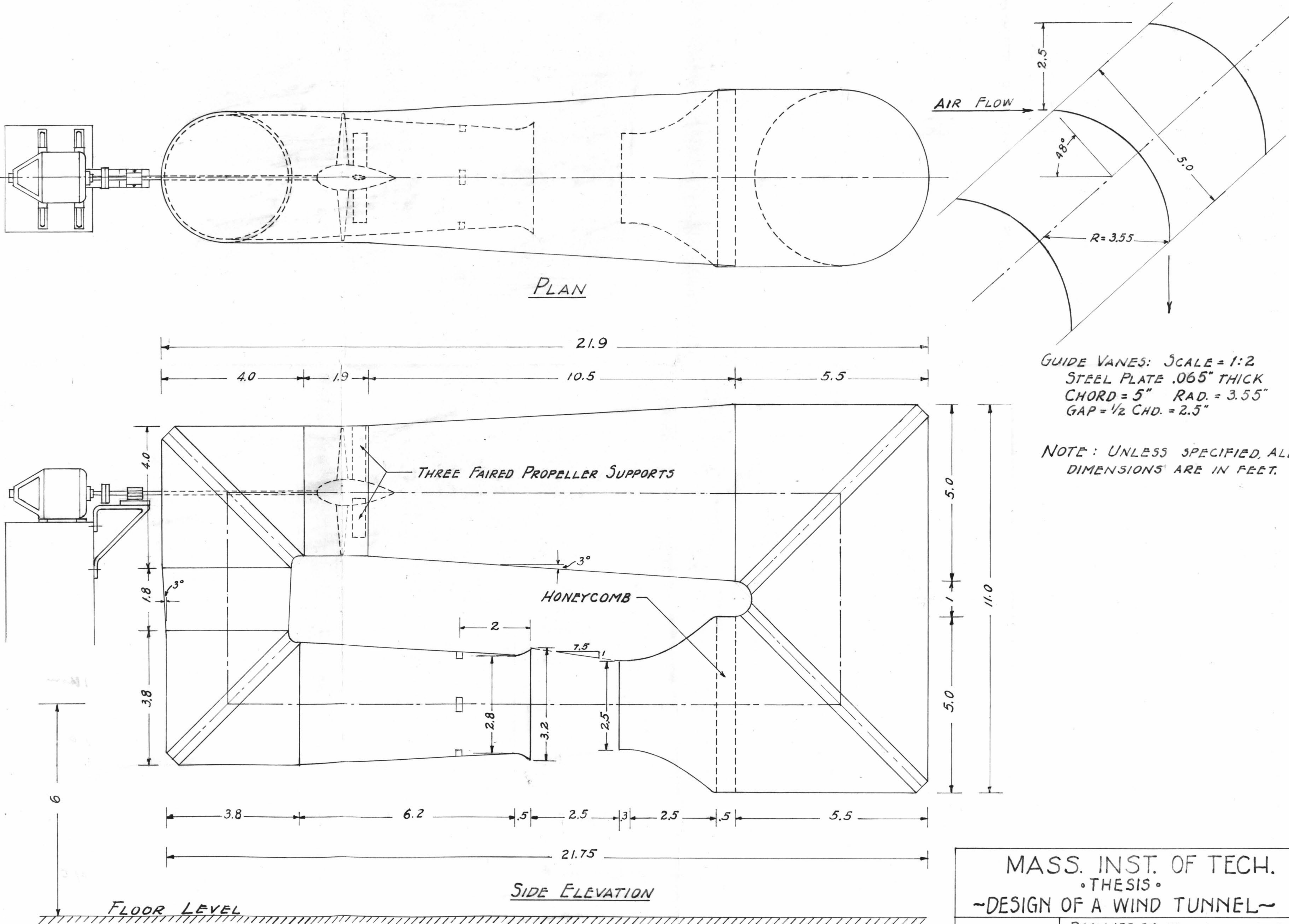


S. H., SCREW HANDLE CRANK
P. L., PARALLEL LINKAGE
G, GUIDE
M. B., MOMENT BALANCE (1)
R, CONSTRAINING ROD
L. B., LIFT BALANCES (2)
D. B., DRAG BALANCES (2)
M., MODEL
C., COUNTER WEIGHT



MASS. INST. OF TECH.
• THESIS •
~DESIGN OF A WIND TUNNEL~

SCALE 1:20	DESIGNED BY: E. T. Mendoza
MAY 15, '40.	APPROVED BY: (ADVISER) PROF. ________



MASS. INST. OF TECH.
• THESIS •
~DESIGN OF A WIND TUNNEL~

SCALE 1:20	DESIGNED BY: Signature redacted
MAY 15, '40.	APPROVED BY: (ADVISER) PROF.