REPORT No. 227

THE VARIABLE DENSITY WIND TUNNEL OF THE NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

By MAX M. MUNK and ELTON W. MILLER
Langley Memorial Aeronautical Laboratory

REPORT No. 227

THE VARIABLE DENSITY WIND TUNNEL OF THE NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

By Max M. Munk and Elton W. Miller

SUMMARY

This report contains a discussion of the novel features of this tunnel and a general description thereof.

PART I

FUNDAMENTAL PRINCIPLES

By Max M. Munk

All the novel features of the new variable density wind tunnel of the National Advisory Committee for Aeronautics were adopted in order to eliminate the scale effect. The leading feature adopted was the use, as the working fluid, of highly compressed air rather than air under normal conditions.

It is not at once obvious that the substitution of compressed air eliminates the scale effect with aerodynamic model tests, although the necessary theoretical discussion has been available for some years. The idea of using compressed air must have occurred, in all probability, to many. It was not, however, till early in 1920 that the thought came to the writer; and in what follows is given his own line of reasoning, expressed in as simple language as possible.

In a paper entitled "Similarity of Motion in Relation to the Surface Friction of Fluids," by T. E. Stanton and J. R. Pannell, Philosophical Transactions A, volume 214, pages 199–224, 1914, will be found an excellent treatment of the subject, with references to the earlier discussions by Newton, Helmholtz, and Rayleigh.

Proceeding at once to the motion of a rigid body immersed in a fluid, the aim of the investigation is to obtain information concerning the fluid forces on such a body. Everything in connection with the problem has to be studied to that end, and has to be included in the investigation, whether this latter be analytical or, as we suppose now, experimental. There are the properties of the immersed body, its shape, its direction of motion, eventually the character of its surface. Even more important is the action of the fluid brought into play by these properties. Every detail of the motion of the fluid, together with the physical properties of the fluid, is immediately connected with the kind and magnitude of the forces created. We can only attain to a full knowledge of the forces created by regarding their cause, the fluid motion. All velocity components at all points of the flow are important and characteristic details of the cause of the forces on the body immersed in the fluid.

Then, why do investigators think that they can learn about what will occur on a large scale by observing what occurs on a small scale? Not from any intuitive feeling, inexpressible in words because devoid of thought; not from any vague metaphysical argument difficult to explain. There is a definite, extremely sound, and simple reason why we expect to obtain reliable information from model tests. It is because we expect the two cases when compared with each other will perfectly, at all points, conform to each other, point by point. We do not mentally confine the geometrical similarity to the bodies immersed and to the dimensions of the entire arrangement, leaving as an unsolved and uninteresting question what the fluid does in the two cases. We do not expect that, for some mysterious reason, the fluid forces will correspond to each

other in accordance with some simple rule. On the contrary, we include the flow patterns in our conception of "model." Any two corresponding portions of the flow, however small, are supposed to be similar with respect to shape and direction of the streamlines and with respect to the magnitude of velocities. The ratio of the lengths of a pair of corresponding portions of a streamline is supposed to be constant throughout the flow, and so is the ratio of two velocities corresponding to each other. We are under the impression that with respect to every detail the entire small-scale experiment is an exact replica of what occurs on a large scale, and we believe that the smallest quantity, whatever it is, occurs in a numerically corresponding way with the same conversion factor throughout the entire flow. In such a case, and only then, are we entitled to expect a simple relation between the fluid forces of the model test and those on the large-scale experiment. Such forces are the integrals of the elementary forces, and hence they stand in a constant ratio if the elementary forces do. This constant ratio can furthermore be expected to be a simple algebraic expression of the ratios between the characteristic quantities of the two arrangements.

Not only the model but the entire flow is the replica. There is a good illustration. It sometimes occurs in aerodynamics that the same body moved in the same way in the same fluid gives rise to different configurations of flow. The air forces are then also different.

The question, "Can we learn from aerodynamic model tests?" is thus reduced to the equivalent question, "Can flow patterns be geometrically similar?" If so the boundaries of the flow in general, and the immersed bodies in particular, have to be similar, but this alone is no sufficient reason why the similarity should extend to every streamline. The question whether a test is really a model test in the strict meaning, the question whether the small-scale flow is similar to the large-scale flow, requires a special examination. This examination will decide whether we can obtain reliable information from the test. If the flows are not exactly similar, but only approximately, the information also will only be approximately correct and not wholly reliable. There will exist a "scale effect."

Two configurations of aerodynamic flow are created in different fluids under conditions geometrically similar. We wish to know whether the flow patterns are geometrically similar. We imagine a small-scale flow to exist exactly similar to the large-scale flow really existing, and we ask whether this imagined small-scale flow is compatible with the general laws of mechanics and hence identical with the actual small-scale flow. More particularly, we examine whether each particle of the imagined small-scale flow is in equilibrium, remembering that the corresponding particle of the large-scale flow is.

We assume first that no physical properties of the fluids, nor differences of such properties, have any influence on the shape of the flow pattern or on the fluid forces, except the density of the fluids. We dismiss also any external influence, like that of gravity. Then the only type of force brought into action by the motion of the fluid is the mass force of all the particles, and they are equalized by means of a variable pressure. The pressure distribution is only the natural reaction against changes of mutual positions of all the fluid particles, which changes must be compatible with the continuity conditions of the fluid. Each particle has the natural tendency to move straight ahead with constant velocity. This tendency is in conflict with the other tendency of each fluid particle to claim its own space, not to share its space with any other particle. These two conflicting tendencies lead to a distribution of varying pressure and to mass forces on the particles due to their motion along curved paths and with varying velocities. The pressure distribution gives rise to an elementary force on each particle, and the flow arranges itself in such a configuration that this pressure force is in equilibrium with the mass force.

Let us consider now the case when the linear dimensions are diminished in the ratio $\frac{l_2}{l_1}$, all velocities diminished in the ratio $\frac{V_2}{V_1}$, and the density ρ_2 bears the ratio $\frac{\rho_2}{\rho_1}$ to the original density.

The mass forces are expressed mathematically by a type of term occurring in Euler's[1] or Bernouilli's[2] equation. Per unit volume, they are of the type

$$\frac{\text{Density} \times \text{Velocity}^2}{\text{Length}}$$

and hence resultant mass forces of corresponding portions of the flow are of the type

$$(1) \quad \text{Density} \times \text{Length}^2 \times \text{Velocity}^2$$

Such forces are in equilibrium with the pressure forces, and this determines the latter. Hence a change of density, scale, and velocity gives rise to a change of all elementary forces and hence of all resultant forces in the ratio

$$\frac{\rho_2\, l_2^2\, V_2^2}{\rho_1\, l_1^2\, V_1^2}$$

The equilibrium of the particles remains unimpaired by the change of scale, and we conclude that corresponding flow patterns are necessarily similar. Hence, if the density of the fluid were the only property influencing the fluid paths and hence the fluid forces, all aerodynamic model tests would be interpreted correctly by the application of the so-called "square law." Corresponding fluid forces would be proportional to the fluid density, to the square of the velocity, and to the square of the linear scale. Accordingly, the absolute coefficients generally in use for expressing the magnitude of fluid forces would not only be absolute, but also constant for similar shapes and arrangements.

Experience has shown that the "square law" does not strictly hold, but that the air-force coefficients vary, sometimes slightly and sometimes in a very pronounced way. This is due to the influence of other properties of fluid, neglected before. There arises the question which other property of air is the principal cause of variations of flow patterns under conditions otherwise geometrically similar. All men who have devoted much thought to this problem agree that viscosity has such an effect, greatly in excess of that of other properties. The point is that the forces taken care of by the introduction of such properties of the fluid are very small when compared with the mass forces, which latter alone are governed by the "square law." This holds true at all points of the flow and with respect to all fluid properties, except with viscosity, where it only holds at most points. Viscous forces are proportional to the rate of sliding of adjacent layers of fluid, and are expressed by terms of the type,[3]

$$(2) \quad \mu \frac{\partial u}{\partial y}\, dxdz$$

Here the constant quantity μ is called the modulus of viscosity. u, a velocity, is at right angles to y, a Cartesian coordinate, together with x and z. Hence $\frac{\partial u}{\partial y}$ has the physical dimension of an angular velocity, $\frac{1}{\text{Time}}$. Now, this rate of sliding is small throughout an aerodynamic flow except near the boundary. There it may assume a very large magnitude. So, in spite of the small value of the modulus of friction of air, μ, the friction $\mu \frac{\partial u}{\partial y}$ can assume a very large value

---

[1] Euler's equation:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=X-\frac{1}{\rho}\frac{\partial p}{\partial x}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=Y-\frac{1}{\rho}\frac{\partial p}{\partial y}$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=Z-\frac{1}{\rho}\frac{\partial p}{\partial z}$$

Lamb, 4th edition, article 6.

[2] Bernouilli's equation:

$$\frac{p}{\rho}=\frac{P}{\rho}+gz-\frac{1}{2}V^2$$

Lamb, 4th edition, article 24.

[3] Friction per unit area

$$pxy=\mu\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)$$

Lamb, 4th edition, article 326, equation 6.

and can become dominating at certain points of the flow. It can then produce essential changes of the entire flow pattern. Very little in detail is known about these things, and it seems useless to carry the discussion on at this point. Experience has shown that proper attention to the viscosity brings system and regularity into results of tests otherwise obscure and contradictory. It is for this reason that the elimination of the effect of viscosity for many years was thought desirable in the first place as a fundamental improvement of aerodynamic model tests, resulting in the elimination of the scale effect.

There has been some controversy as to whether these arguments are sufficient for the final decision that viscosity is the all-important fluid property. No arguments whatsoever will definitely decide that, but only final success. The separation of the physical effects to be taken into consideration for any practical purpose from those which may be neglected is a mental step which can not be accomplished by mere logics.

Granted, now, that viscosity is of practical importance, the question arises, Are similar flows possible in viscous fluids; and if so, under what conditions will the flows be similar? It is understood now that the arrangements are geometrically similar, that only the density ρ and viscosity μ of the fluid have to be considered in addition to the linear scales of the arrangement and the ratio of the velocities.

The answer to the last question depends again upon the result of the examination whether each particle of an imagined small-scale flow, similar to an actual large-scale flow, is in equilibrium or not. Now, in viscous fluids the mass forces are not in equilibrium with the pressure forces, but in equilibrium with the combination of both the pressure forces and the viscosity forces. We have now three types of forces in equilibrium with each other, and that gives rise to a variety of possibilities. Two forces in equilibrium are, of necessity, numerically equal, hence if one of them be changed in a given ratio the other will too. With three forces, all three may be changed in a different ratio and still the equilibrium maintained.

The criterion for the similarity of flows is, therefore, that two of the three forces be changed in the same ratio. Then the third, in equilibrium with the two, will be changed in this same ratio and needs no special examination.

We compare the ratio of change of the mass forces and of the viscosity forces with each other. We have seen already (1) that the mass forces are changed in the ratio $\frac{\rho_2 V_2^2 l_2^2}{\rho_1 V_1^2 l_1^2}$. The viscous forces being of the type $\mu \frac{\partial u}{\partial y} dxdz$, are seen to be changed in the ratio $\frac{\mu_2 V_2 l_2}{\mu_1 V_1 l_1}$. Now, the two flow patterns will be similar and the test will be a strict model test only if the mass forces and the viscosity forces are changed in the same ratio. Hence we obtain, as the condition of an exact model test,

$$\frac{\rho_2 V_2^2 l_2^2}{\rho_1 V_1^2 l_1^2} = \frac{\mu_2 V_2 l_2}{\mu_1 V_1 l_1}$$

or, written in a different way,

$$(3) \quad \frac{V_1 l_1 \rho_1}{\mu_1} = \frac{V_2 l_2 \rho_2}{\mu_2}$$

The expressions on either side of equation (3) are generally called "Reynolds Numbers," from Osborne Reynolds, who was the first to emphasize their importance. Since V and l are certain velocities and lengths in the two flows, corresponding to each other, but otherwise arbitrarily chosen as "characteristic" velocity or length, the value of one special Reynolds Number in one single case has as little meaning as the scale of one single object. The equality of the Reynolds Numbers of two arrangements, different but geometrically similar, expresses the dynamic equivalence of the two flows compared.

If the ratio of the two Reynolds Numbers is different from unity the value of this ratio can be considered as a kind of relative scale between these two tests, not of the geometric scale but one which may be called dynamic scale. The ratio of the Reynolds Numbers indicates differences in the relative importance of the mass forces and of the viscosity forces. A single Reynolds

Number, together with the definition of the characteristic velocity and length, is only an identification number, not much more than the street number of a house. Comparison of Reynolds Numbers of flows where the conditions are not geometrically similar have hardly any meaning.

The preceding discussion has led us to the condition under which a wind tunnel will have no scale effect due to viscosity, and probably not any scale effect of practical importance. This condition is not equal velocity in model test and in flight. Full velocity is only of value for investigating certain original airplane parts and original flight instruments. The test with a model of diminished scale but at the velocity of flight is by no way distinguished from tests at other wind-tunnel velocities. On the other hand, if there is no scale effect expected, the Reynolds Number being equal in both model test and free flight, the dynamic scale being 1, and if there are still arguments raised doubting the validity of such tests, such arguments hold with equal right or wrong against all other model tests, more particularly against such tests in ordinary atmospheric wind tunnels. For the principal difference between the variable density tunnel and atmospheric tunnels is the elimination of one source of error, of the one moreover, which is believed by most experts to be the most serious.

The fact is, then, that in general model tests in atmospheric wind tunnels are made at a Reynolds Number smaller than in free flight. The linear dimensions of the model are largely diminished, and nothing is done to make up for this; the velocity is at best the same as in flight and the ratio μ/ρ is the same, the same fluid being used in test and in flight.

It is neither practical nor sound to make up for the diminution of the model by correspondingly increasing the velocity so as to obtain the original value of the product $V\,l$ as required in equation (3). It is not practical because such a wind tunnel would consume an excessively high horsepower, and because the air forces on the model would become excessive to such an extent as to make the test practically impossible. Such a method would also be unsound. For the differences in air pressure, which amount only to little more than 1 per cent in flight and in ordinary wind tunnels, would increase rapidly with velocities approaching the velocity of sound. Thereby the influence of the compressibility would be rapidly increased, and thus another error, now negligible, would make the results unsuitable for the desired purpose.

There remains then only the diminution of the ratio $\frac{\mu}{\rho}$ often denoted by ν, in order to make up for the diminution of l in equation (3). This means the choice of another fluid. The use of water instead of air has been seriously proposed. With water $\nu=\frac{\mu}{\rho}$ is indeed seven times as small as with air. The problem of the large power consumption could eventually be solved, either by using a natural stream or by towing the model. However, water is about 800 times as dense as air, and hence the forces produced at the same velocity are 800 times as large, giving rise to stresses 800 times enlarged. It is practically impossible to make ordinary model tests with forces on the model 800 times as large as they are now.

What we need is a fluid which may be denser than atmospheric air at sea level, but only so to a moderate degree. Its dynamic viscosity modulus $\nu=\mu/\rho$ should be distinctly smaller than that of air, in order to make up for the scale of the model and eventually for the diminished velocity necessary for bringing down the pressure on the model and the absorbed horsepower. No such fluid is known under ordinary atmospheric conditions. Further consideration showed that a high pressure transforms air (or another gas) into a fluid suitable for wind-tunnel work giving results without scale effect. This fact depends on the physical property of air of keeping the same viscosity modulus μ under all variations of pressure. This has been confirmed by experiments and is mentioned in treatises on physics. It is in keeping with the molecular theory, with denser air the average free paths are proportionally shorter. The viscosity modulus μ remains the same, but the density increases when the pressure increases. Hence the ratio $\nu=\frac{\mu}{\rho}$ varies inversely with the pressure (the temperature remaining unchanged).

Hence we have

Kinematic viscosity	~ Pressure^{-1}	
Model pressure	~ Pressure	× Velocity.^{2}
Absorbed horsepower	~ Pressure	× Velocity.^{3}

Assuming a model scale of say 10, we want a kinematic viscosity at least 10 times as small as with air. With pressure of 20 atmospheres we could get

Test velocity = ½ flight velocity.

Resultant model pressure = 20 $(\frac{1}{2})^2$, 5 times actual pressure.

Horsepower consumption of the tunnel = 20 $(\frac{1}{2})^3$, 2.5 that of an atmospheric tunnel of the same size and operating at full scale velocity.

Reynolds Number = Reynolds Number in free flight. These figures seemed practical. On them the design of the variable density wind tunnel of the National Advisory Committee for Aeronautics has been based.

More generally it can be seen that the principle of compressing the air allows any Reynolds Number, even with a small model, if only the pressure can be produced and maintained. For keeping the Reynolds Number constant and increasing the pressure in the ratio A, decreases the resultant pressure on the model as A^{-1} and the required horsepower as A^{-2}.

The throat diameter of 5 feet was chosen in order to be able to use the same models as in the atmospheric wind tunnel of the National Advisory Committee for Aeronautics. A small diameter would require smaller models, and it becomes increasingly difficult to construct such models accurate enough.

Furthermore, 5 feet is the smallest diameter for a closed tunnel where a man can walk and work without exceeding discomfort. The choice of the smallest diameter suitable was necessary in view of the large costs and difficulties for procuring a large enough housing strong enough to withstand an internal pressure of 25 atmospheres.

The same restriction of space decided the choice of a closed (not free jet) type of tunnel.

All other novel features can be traced back to the particular features of this tunnel, the large inside pressure and the larger resultant force on the model. They are described in the second part of this paper.

REPORT No. 227

THE VARIABLE DENSITY WIND TUNNEL OF THE NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

PART II

DESCRIPTION OF TUNNEL

By Elton W. Miller

In the pages which follow a description is given in some detail of the tunnel and the methods of operation. The purpose in preparing this report is to make clear the testing methods employed, in order that the technical reports now in preparation may be better understood. The building of this tunnel was first suggested by Dr. Max M. Munk in 1921 (Reference 1). The writer has assisted Doctor Munk and Mr. David L. Bacon in the design and development of the mechanical features of the tunnel.

The tunnel is shown in sectional elevation in Figure 1, and consists briefly in an experiment

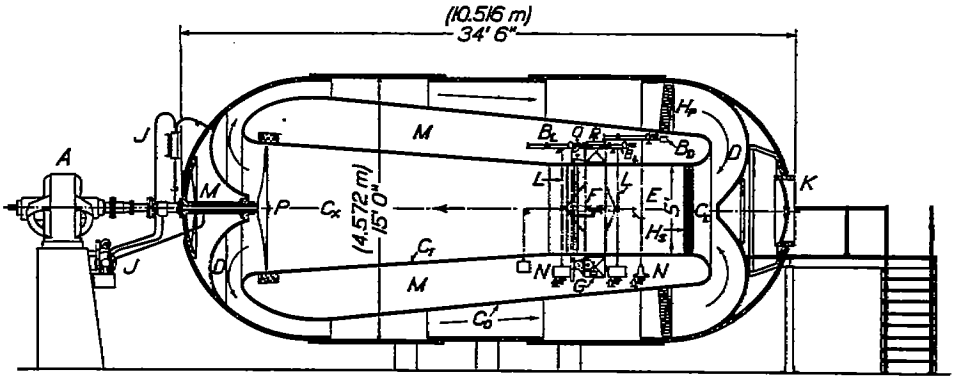

Fig. 1.—Sectional elevation of variable density wind tunnel

section, E, 5 feet (1.52 meters) in diameter, with entrance and exit cones housed within a steel tank 15 feet (4.57 meters) in diameter and 34 feet 6 inches (10.52 meters) long. The air is circulated by a two-blade propeller, returning from the propeller to the entrance cone through the annular space between the walls of the tank and an outer cone, C_O. The balance, which is of novel construction, is mounted in the dead, or noncirculating, air space between the walls of the experiment section and the outer cone. The balance is operated electrically, and readings are taken through peepholes in the shell of the tank. Figures 2 and 3 are general views of the tunnel. Figure 4 is a plan of the building showing the tunnel and compressors.

The tank, which was built by the Newport News Shipbuilding & Dry Dock Co., of Newport News, Va., is capable of withstanding a working pressure of 21 atmospheres. It is built of steel plates lapped and riveted according to the usual practice in steam boiler construction, although,

because of the size of the tank and the high working pressure, the construction is unusually heavy. There is a cylindrical body portion of 2⅛-inch (53.98 millimeters) steel plate with hemispherical ends 1¼ inches (31.75 millimeters) in thickness. Entrance to the tank is gained

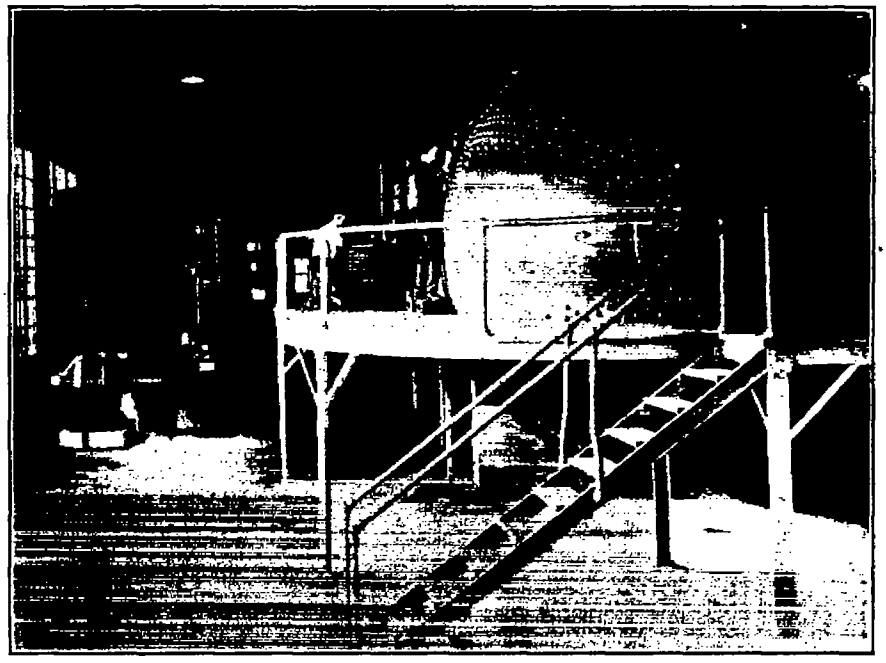

FIG. 2.—General view of tunnel looking west

by an elliptical door K 36 inches (914 millimeters) wide by 42 inches (1,066 millimeters) high. The tank, which with its contents weighs about 100 tons (90.7 metric tons), is supported by a foundation of reinforced concrete.

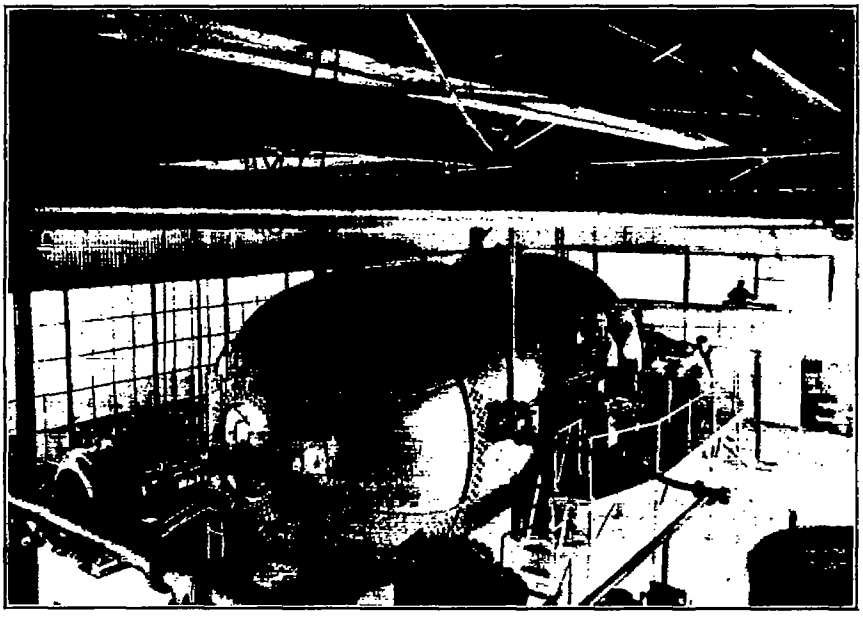

FIG. 3.—General view of tunnel looking east

The walls of the experiment section and cones are of wood; those of the experiment section consist of a series of doors which may be unbolted and removed to gain access to the balance. The cross-sectional area at the large end of the exit cone is substantially twice that

of the experiment section, and the cross-sectional area of the return passage at its largest part is about five times that of the experiment section. Two honeycombs, H_P and H_S, are provided for straightening the air flow. Honeycomb H_P is of 2-inch (50.8 millimeters) round cells, while honeycomb H_S is of 1¼-inch (31.75 millimeters) square cells. The latter honey-

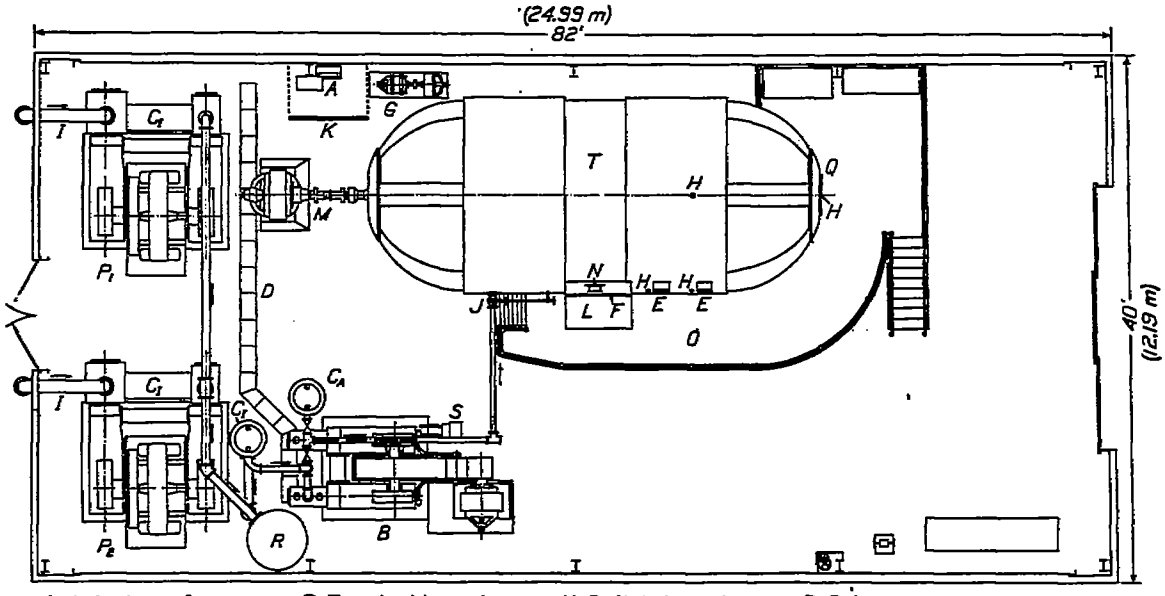

FIG. 4.—Floor plan of variable density wind tunnel and equipment

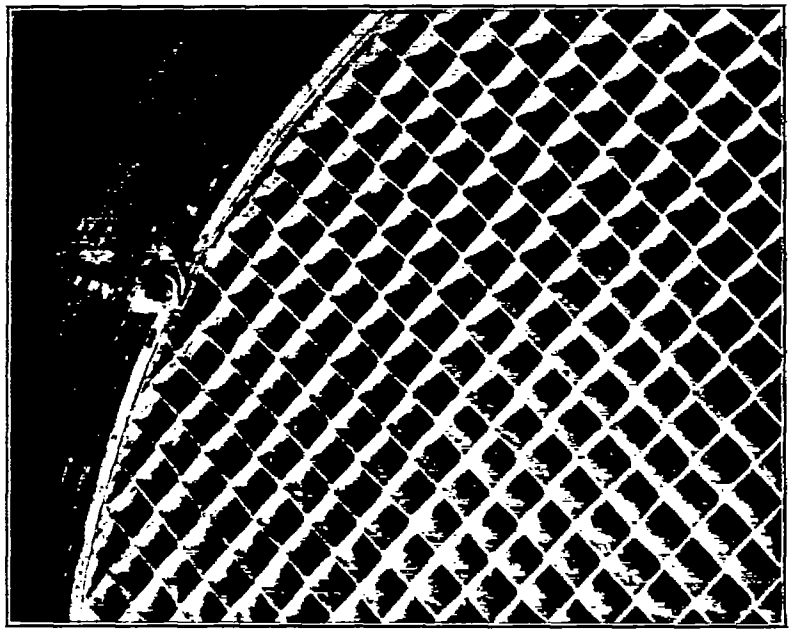

FIG. 5.—Honeycomb (H_S) showing locking device

comb is made removable to permit access to the experiment section; it is suspended from a removable trolley track by which it may be rolled to one side of the entrance cone. In order that the honeycomb may be returned to exactly the same place each time, it is made to seat on three conical points where it may be securely locked. Arrangements have also been made for adjusting the position of the honeycomb, as shown in Figure 5.

The propeller is driven directly by a synchronous motor of 250 horsepower (253.5 metric horsepower), which runs at a speed of 900 revolutions per minute. The synchronous motor has an advantage over the usual direct-current motor in that no complicated devices are necessary for maintaining a constant speed of revolution. Such variations in dynamic pressure as are made in the ordinary atmospheric tunnel by changing the air velocity are here made by changing the density of the air. It is therefore not necessary to vary the air velocity. Fluctuations of a fraction of a per cent occur, due to variations in the frequency of the electric current supplied to the motor; otherwise the velocity is constant for a given tank pressure. There is a slight increase in air velocity with an increase in tank pressure, as shown in Figure 16, but this is not objectionable.

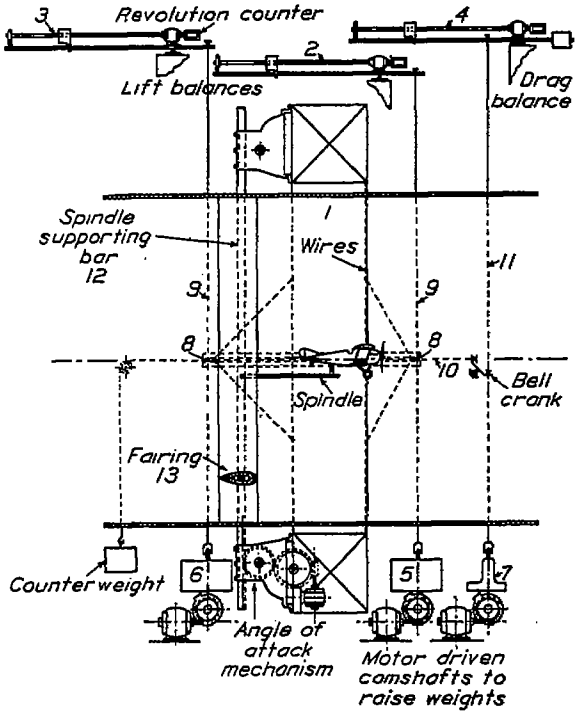

FIG. 6.—Diagrammatic drawing of variable density wind tunnel balance

The propeller, which is 7 feet (2.14 meters) in diameter, is mounted on a ball-bearing shaft which passes through one end of the tank. The stuffing box through which this shaft passes is only loosely packed, and air leakage is reduced to a minimum by means of oil which is fed by gravity from a reservoir above. The oil which is carried through the stuffing box is returned to the reservoir by a motor-driven pump.

Air compressors for filling the tank with air are shown in Figure 4. The air is compressed in two or three stages, according to the terminal pressure in the tank. A two-stage primary compressor is used up to a terminal pressure of about seven atmospheres. For pressures above this a booster compressor is used in conjunction with the primary compressor. The booster compressor may be used also as an exhauster when it is desired to operate the tunnel at pressures below that of the atmosphere. The primary compressors are driven by 250-horsepower synchronous motors and the booster compressor by a 150-horsepower squirrel-cage induction motor.

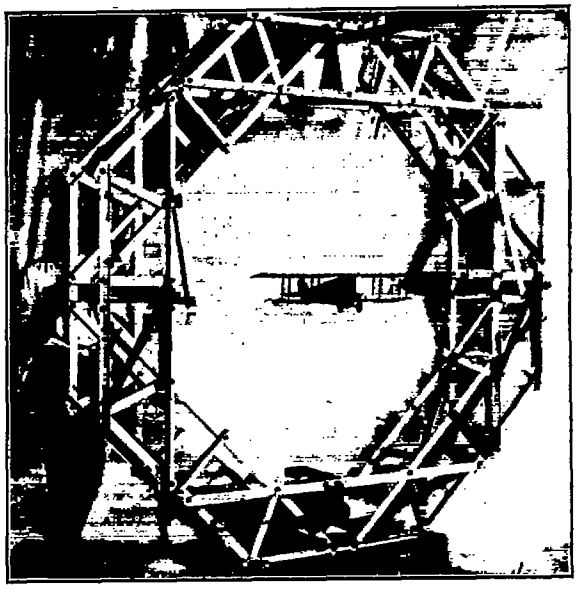

FIG. 7.—Balance ring before assembly in tunnel

A diagrammatic drawing of the balance is shown in Figure 6. It consists essentially in a structural aluminum ring (1) which encircles the experiment section, two lever balances (2) and (3) for measuring lift, and a third lever balance (4) for measuring drag. The ring as it looked before assembly in the tunnel is shown in Figure 7. An assembly view in the tunnel is seen in Figure 8. The doors which surround the experiment section have here been removed, exposing the balance to view. The model is attached to the ring by wires or other means, and all forces are transmitted to the ring and thence to the lever balances. The ring is suspended from lever balances (2) and (3), Figure 6, by the vertical members (9), of which there are four, two on

each side. Cross shafts and levers are employed in order to carry the full weight of the ring to the two lever balances. The drag forces are transmitted by horizontal members (10) to bell cranks and thence by vertical members (11) to lever balance (4). Hanging from the ring are bridges which carry coarse weights (5) and (6). Any desired number of coarse weights may be added or removed by means of motor-driven cam shafts. A similar bridge carrying coarse weights (7) is hung from lever balance (4).

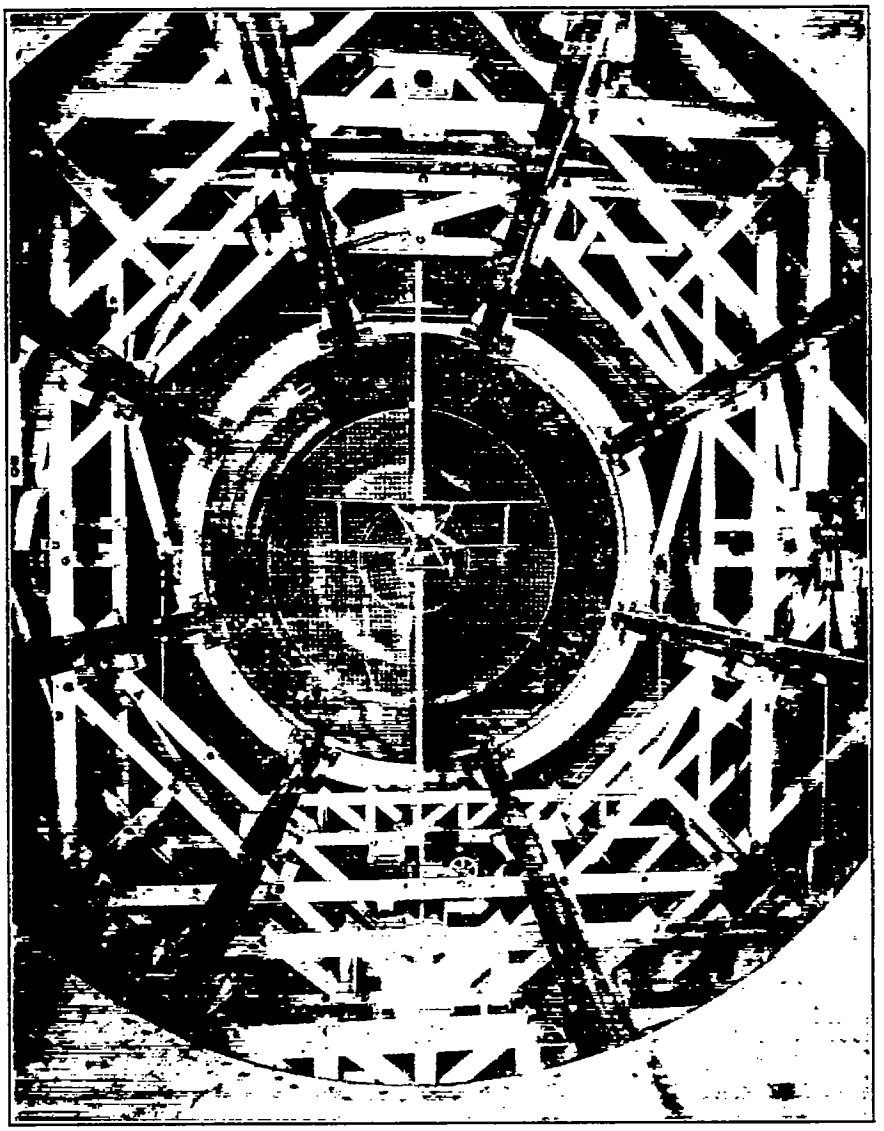

FIG. 8.—Balance with doors of experiment section removed

The sliding weights are moved by motor-driven screws to which are geared revolution counters; these may be read through peepholes in the shell of the tank. At the end of each beam is a pair of electrical contact points by which the beam may be made to balance automatically. The sliding weights may also be controlled by a manually operated switch. The lift balances are sensitive to plus or minus 10 grams and the drag balance to plus or minus 1 gram.

It is possible with this balance to measure any three components; for instance, lift, drag, and pitching moments. The lift is first approximately counterbalanced by increasing or decreasing the number of coarse weights hanging from the two weight bridges. The remainder is then counterbalanced by moving the sliding weights on the two lever balances. The drag is

measured similarly. The total lift is the sum of the readings of the two lift balances; the pitching moment is the algebraic sum of the three balance readings multiplied by their respective lever arms.

The model may be supported in the tunnel by wires only, or by a combination of wires or struts and a spindle. In the latter case the spindle is attached to a vertical bar (12) which may be raised or lowered by appropriate gearing, thus changing the angle of attack of the model. The angle of attack is indicated by an electrically controlled dial on the outside of the tank. The vertical bar (12) is protected from the air flow by a fairing (13).

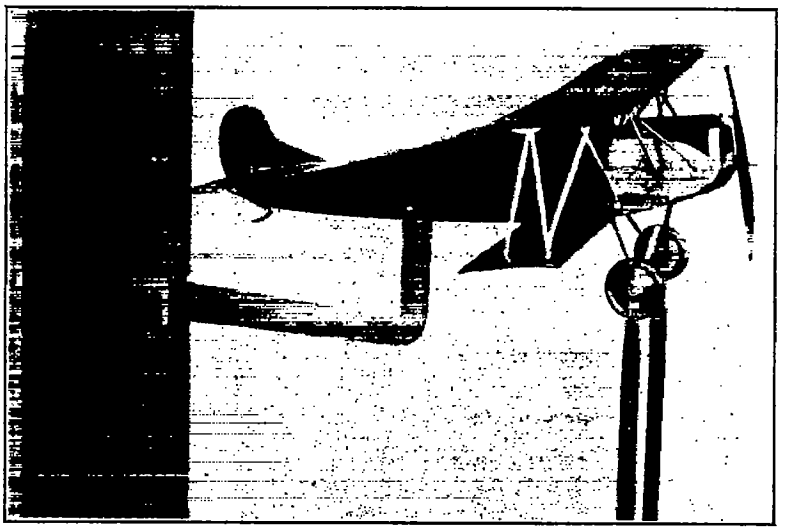

FIG. 9.—Method of supporting Fokker D-VII Model

Round wires of about 0.040 inch (1 millimeter) diameter have been used for supporting models, this much larger diameter being necessary because of the large forces, but streamlined wires of much larger section have been found preferable. These wires are attached to the balance ring below and to the model above, thus serving as struts or free columns to support the weight of the model when the air stream is not on. The struts may be attached to the wheels of the model as shown in Figure 9 or to threaded plugs screwed into the wings as in Figures 10 and 11. The advantage of the streamline wires over the round wires is illustrated in Figure 12. The wire and spindle drag for two airfoils and one airplane model have been reduced to a percentage of the gross minimum drag of the model with wires and plotted against Reynolds Number.

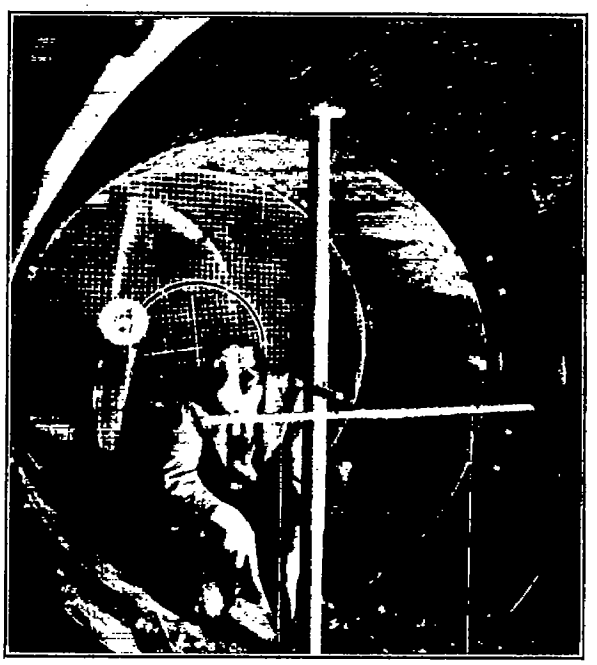

FIG. 10.—Airfoil set-up.

All the various operations required within the tunnel while running, such as the shifting of balance weights and the setting of the manometers, are performed by small electric motors. It has been necessary, therefore, to carry a large number of electric wires through the shell of the tank. These wires pass through a suitable packing gland and are attached to terminal boards inside and out. The outside terminal board may be seen in Figure 3.

The air speed is measured by static plates, one of which is located in the wall of the experiment section and the other in the wall of the other cone. The static plates are calibrated against Pilot tubes placed in the experiment section. A micromanometer designed especially for use in this tunnel is shown in Figure 13. Alcohol is the liquid used, and a head up to 1 meter may be measured. This manometer is similar in principle to that described in National Advisory Committee for Aeronautics Technical Note No. 81, but is different in that the index

tube is stationary and the reservoir is raised or lowered by a motor-driven screw. A revolution counter geared to the motor indicates the head to 0.1 millimeter. It is possible to determine the dynamic pressure to an accuracy of plus or minus 0.2 per cent.

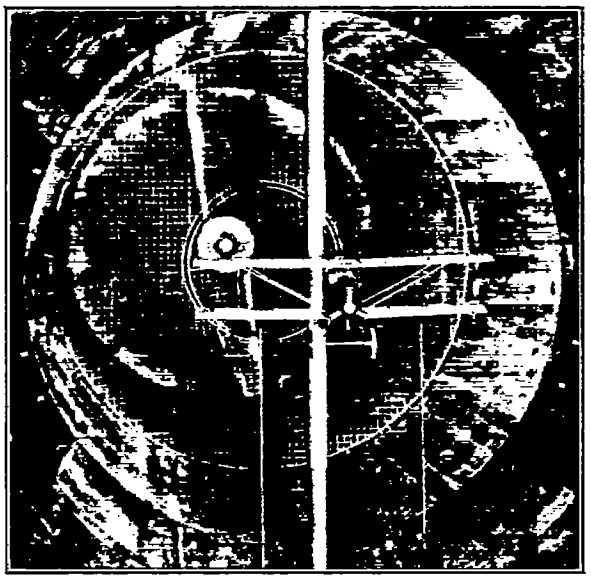

FIG. 11.—Method of supporting Sperry messenger model

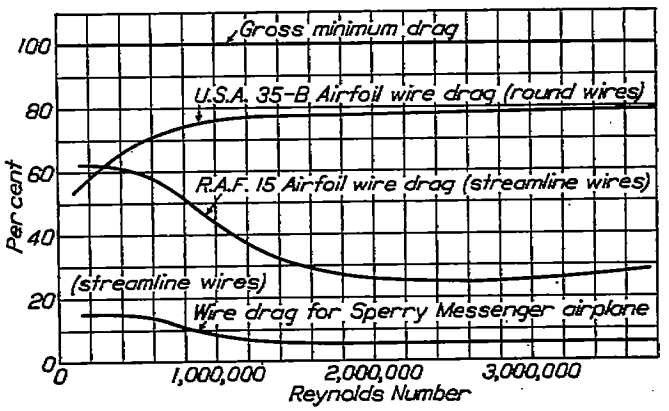

FIG. 12.—Drag of streamline wires as compared with round wires for holding model

The dynamic pressure distribution in the experiment section is represented by contour lines in Figure 14. This survey was made by using a number of Pitot tubes mounted on a bar which could be revolved in the tunnel. Observations were thus made at a large number of points. The dynamic pressure will be seen to vary in the region occupied by the model within a range of plus or minus 2 per cent. This survey was made at one and two atmospheres only. We know from check runs that the same flow condition holds for other pressures. The horizontal static pressure gradient in the tunnel at various pressures is shown in Figure 15. Pressures are given with reference to a static plate located in the wall of the experiment section. It will be noted that the curves which are plotted on semilog paper are parallel, indicating that the pressure gradient is proportional to the density. Operating data of general interest, as the time required for raising pressure in the tank, the time required to exhaust the tank, the power consumption of the compressors and drive motor, are shown in Figure 16. The velocity change with change of tank pressure is also shown. The energy ratio of the tunnel for various tank pressures is shown in Figure 17.

The building of this tunnel and the development of its various mechanical devices to a point where routine testing may be done has required the solution of a number of mechanical problems. This development period has passed, and the results now being obtained in the tunnel are believed to be as consistent and reliable as those obtained in any other wind tunnel. Two airplane models and thirty-seven airfoils have so far been tested. Tests of a Sperry Messenger airplane model provided with eight different sets of wings are now in progress.

The variation of the aerodynamic characteristics of an airplane model with change of scale is shown in Figure 18. This figure gives the polar curves of the Fokker D-7 airplane model tested at various tank pressures. The minimum drag and the lift/drag ratio for this model, and also for a Sperry Messenger model, are plotted against Reynolds Number in Figure 19.

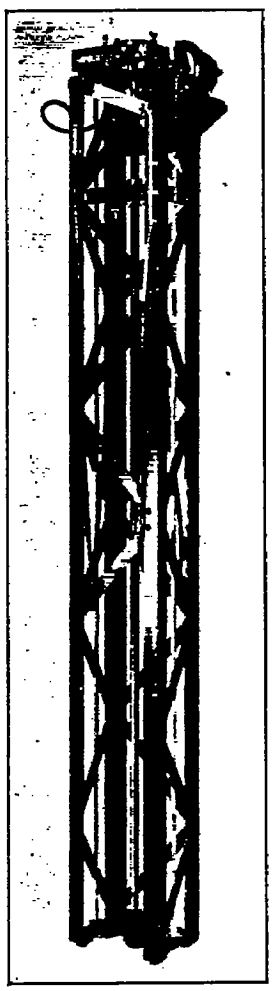

FIG. 13.—Micromanometer

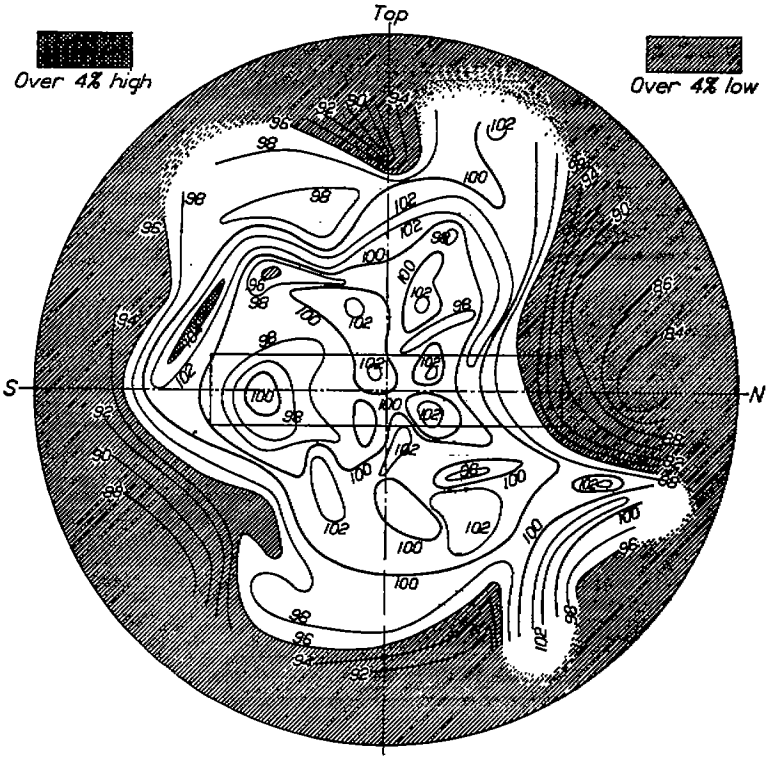

FIG. 14.—Variable density wind tunnel dynamic pressure survey. Observations taken at 161 different points. Pressures are in per cent of arbitrary reference point. Plane of survey —49.5" in rear of honeycomb. Rectangle at center indicates approximate position of airfoil

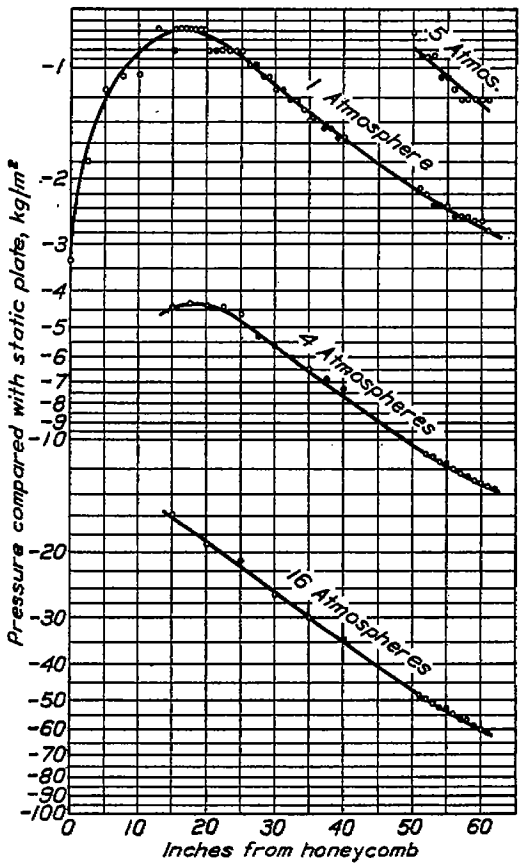

FIG. 15.—Horizontal static pressure gradient for various tank pressures

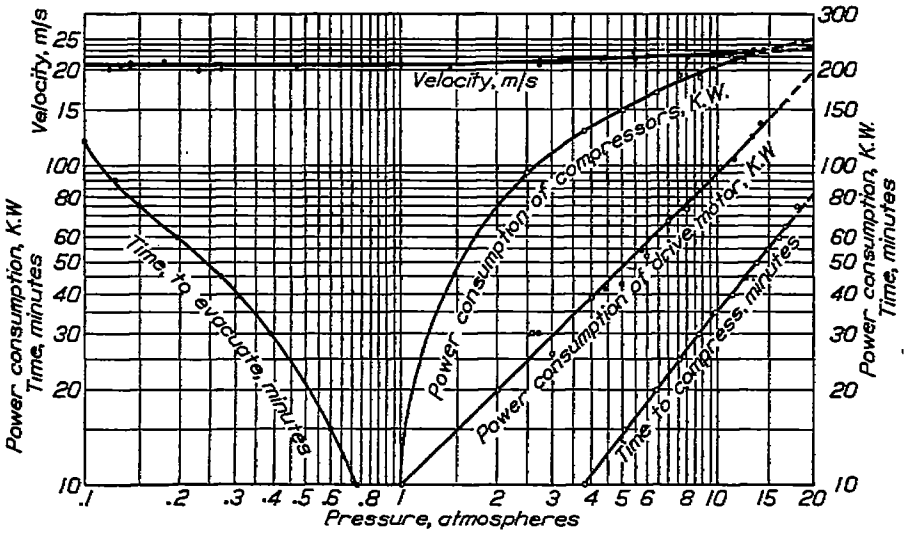

FIG. 16.—Variable density wind tunnel power plant data

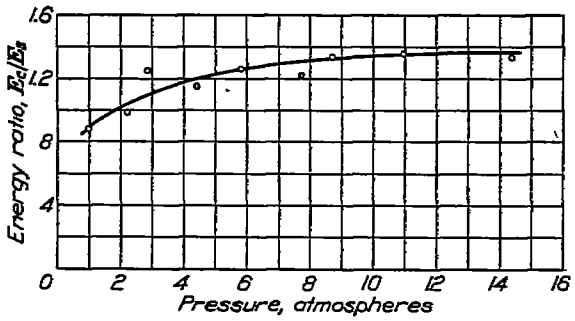

FIG. 17.—Variable density wind tunnel, energy ratio E_k/E_t. E_k=Kinetic energy in throat, kg/m/s., E_t=Energy input to motor, including exciting energy

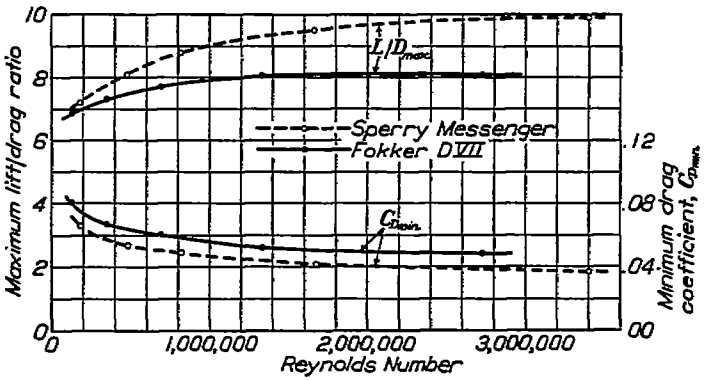

FIG. 19.—Scale effect on airplane models

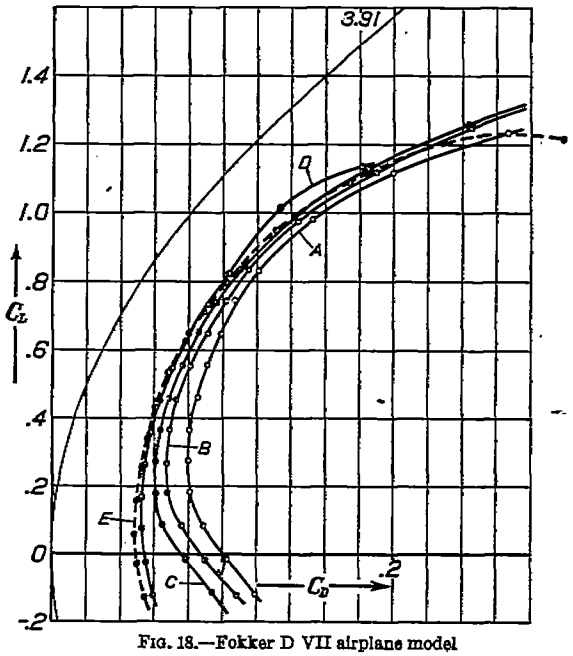

FIG. 18.—Fokker D VII airplane model

	Tank pressure atmosphere	Dynamic pressure q=kg/m²	Reynolds Number
Curve A	1.00	27.5	135,000
Curve B	2.64	75.6	358,000
Curve C	5.17	149.0	695,000
Curve D	10.14	293.0	1,330,000
Curve E	20.10	625.0	2,720,000

CONCLUSIONS

The underlying theory of the variable density tunnel has been discussed, the mechanical construction of the tunnel has been described, and some typical results obtained on an airplane model have been given. The tunnel is in continuous operation, and there is every reason to believe that the results obtained at the higher densities are truly representative of full-scale conditions.

REFERENCES

Reference 1.—"On a New Type of Wind Tunnel," by Dr. Max M. Munk. N. A. C. A. Technical Note No. 60

"Abriss der Lehre von der Flüssigkeits und Gasbewegung," by Dr. L. Prandtl. Handwörterbuch der Naturwissenschaften, vol. 4.

"Experimental Investigations," by O. Reynolds, Phil. Trans. 174 (1883), and "On the Dynamic Theory of Viscous Fluids," Phil. Trans. A. 186 (1894).

"Similarity of Motion in Relation to the Surface Friction of Fluids," by T. E. Stanton and J. R. Pannell, Phil. Trans. A, vol. 214, pp. 199–224, 1914.