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JET PROPULSION WITH SPECIAL REFERENCE TO THRUST AUGMENTORS

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SUMMARY

This investigation was carried out at the Bureau of Standards at the request and with the financial assistance of the National Advisory Committee for Aeronautics.

The purpose of the work was to investigate the possibility of using thrust-augmented jets as prime movers. The augmentation was to be effected by allowing the jet to mix with the surrounding air in the presence of bodies which deflect the air set in motion by the jet.

Previous work is reviewed briefly. It is pointed out that propulsion by jets is fundamentally simple and therefore attractive, but because of its low thrust per horsepower, it cannot compete with the engine-driven air-screw propeller without augmentation.

Six augmentation schemes were tested experimentally with compressed air at room temperature at jet speeds up to 1,240 feet per second. The results show that a small amount of augmentation is possible, but that the gain in efficiency is far too small to make the jet a competitor of the screw propeller.

INTRODUCTION

In its broadest sense, jet propulsion is the name for that type of propulsion which is characteristic of prime movers designed to work in a fluid medium such as air or water, or in empty space. In a fluid the jet may be composed of the medium itself set in motion by some mechanical device such as a screw. In empty space the fluid must come from within the vehicle itself. At one extreme we find the air screw and water screw, and at the other the rocket. Usage has eliminated air and water screws from the class of jet propellers, and has restricted that term to propellers in which the jet issues from nozzles. In particular, the term "jet propulsion" refers to propulsion by means of high-speed jets of relatively small diameter forced from nozzles by high pressure. Jet propellers in this restricted sense have a low propulsive efficiency as compared to the screw, because of the smaller amount of fluid from which propulsion is derived. To offset this is the simplicity that results from creating the jet by means of fluid under pressure, rather than by means of a moving mechanical mechanism external to the vehicle.

It is hard to imagine any combination of heat engine and propeller more simple and positive in its action than a hollow cylinder with one end closed, thrust being exerted on that end by gases ejected from fuel burning within the cylinder. This is the simplest type of jet propeller, namely, the rocket. Not all forms of propulsion by jets of gas are as simple as this. There is another type in which only the combustible material is contained within the vehicle itself, the oxygen to support combustion being taken from the outside. Air is taken from the outside by a compressor and mixed with the fuel carried within the vehicle; and after the burning of the fuel in a combustion chamber, the products of combustion are ejected rearward through a nozzle. In the former type (rocket propulsion) the propulsion is derived from the acceleration of gases from rest with respect to the vehicle to some final, usually high, speed. In the latter, since the intake usually faces the wind moving past the vehicle, propulsion results partly from the acceleration of air from the initial speed at which it was taken in to a higher speed, and partly from an acceleration of combustible material from rest with respect to the vehicle to the same final speed. While this latter type may be far from simple, it is not the jet principle that makes it complicated, but rather the arrangements required to supply the oxygen for combustion.

Probably because of its simplicity the jet propeller has always been regarded as an attractive type of prime mover. Experimenters, many of them in Germany, have tried with varying degrees of success to use jets of gas for the propulsion of land vehicles, light airplanes, and gliders. (References 1, 2, 3, 4, 5, 6, 7.) Nearly all experimentation is directed toward one goal, that of propelling vehicles flying through air or space. This type of work is of value in contributing toward the development of rocket fuels and toward the proper design of vehicles for jet propulsion, but very little if any knowledge is gained thereby concerning the jet principle and, in particular, the efficiency of jet propulsion. At best it merely confirms knowledge already obtained from the laws of thermodynamics and aerodynamics.

The laws of heat engines and jet flow have been applied by a number of workers in this field to determine the complete performance of the jet. (References 8, 9, 10, 11, 12, 13.) Deductions from established laws agree in general with observed facts to within a few per cent; whence it is well known to most experimenters that ordinarily the fuel consumption of the jet propeller is very high for the propulsive force obtained, as compared with the performance of an ordinary screw propeller driven by an internal-combustion engine. However, those experimenting with rockets justify their work by aiming to apply the jet to the propulsion of airplanes moving at very high speeds and to the attainment of these speeds at high altitudes, where, because of both the speed of the airplane and the rarity of the air, the efficiency of a screw propeller is much reduced. On the other hand, the propulsive efficiency of a jet increases with the speed of advance of the vehicle; and if the jet is formed on the rocket principle, requiring no taking in of air from without, it is independent of the altitude. It is therefore possible to find, for any given altitude, a speed of flight at which rocket propulsion has the same efficiency as screw propulsion, and above which the rocket method is the more efficient. In the limiting case of flight through free space, where there is no surrounding medium for a screw to act on, rocket propulsion is the only kind available.

It is generally believed that high speeds at high altitude will become important in future transportation. If this is true, then jet motors or rockets will find an important application, and experimentation of the kind we have mentioned is not to be regarded as useless.

The other application of jet propulsion, namely, the propulsion of airplanes as they exist to-day, has been shown by Buckingham (reference 8) and Roy (reference 9) to be entirely unsatisfactory because of the vast superiority of the screw propeller with regard to fuel consumption and thrust. As computed by Roy, the speed at which an airplane must fly in order to be propelled as efficiently by a jet on the rocket principle as it would be at ordinary speeds by a screw propeller is about 800 miles per hour, a much higher speed than is attainable at present. As previously mentioned, rocket propulsion has simplicity and lightness in its favor. This may not be true of jet propulsion in general, where a heavy and complicated compressor may be required. However, if the thrust of a jet could be increased sufficiently without increasing the power required, the jet might easily become a competitor of the screw propeller as a prime mover. It is safe to say that propulsion on the rocket principle would assume importance if the thrust/power ratio of the jet were made the same as that of an engine-driven screw propeller.

PREVIOUS ATTEMPTS TO INCREASE JET THRUST

A few attempts have been made to increase the thrust of a jet by combining it with auxiliary devices. One such scheme, treated mathematically by Roy (reference 9), is to combine the jet and the screw propeller and thereby take advantage of the higher efficiency of the latter. Nozzles are placed at the propeller tips and the jet reaction is directed tangential to the helical path pursued by the tips when the propeller is whirling and moving forward. In this way advantage is taken of the greatest attainable speed of the nozzles, which, as we have stated, is the condition for maximum efficiency. Roy, by a quite exhaustive treatment, finds the arrangement inferior to that of the ordinary engine-driven propeller. So far as the writer knows, no experimental tests of such a combination have been made. The essence of the scheme is a simplified gas turbine of the reaction type. As such it has those mechanical limitations which so far have hindered the development of gas turbines. (Reference 10.) Strictly speaking, such applications of the jet belong rather to the field of gas turbines than to true jet propulsion. However, any modification of the jet, no matter how far it departs from simple reaction propulsion, will be welcomed if it yields the desired results.

Another scheme, which is perhaps more often suggested than any other, is that of surrounding the jet, after it leaves the nozzle, with guide rings such as are shown in Figure 1. Included in this class of augmentors is the Venturi tube, which amounts simply to a ring with an exit cone. The only work done on this type of augmentor seems to be that by Mélot (reference 14) some years ago, and later tests of Mélot's augmentor by Jacobs and Shoemaker at the Langley Memorial Aeronautical Laboratory. (Reference 23.) Mélot's original augmentor is shown in Figure 1. The sketch here shown was copied from the report of the work of Jacobs and Shoemaker and is like the one shown in Melot's sketches. Mélot reported satisfactory results from this augmentor when used on an intermittent jet produced by the exhaust from a combustion chamber in which the explosive mixture had been compressed by a freely moving piston. For more details the reader is referred to reference 14. More definite results are reported by Jacobs and Shoemaker from tests made with a steady jet of air at room temperature. Their tests showed a maximum thrust of nearly 1.4 times the theoretical free-jet reaction, at 90 pounds per square inch gage pressure. They also tested separate parts of the augmentor and found that the Venturi tube made the greatest contribution to the increased thrust. The conclusion which they drew after testing modifications in size and arrangement was that the increase in thrust was in every case too small to make the jet feasible as a prime mover in competition with the engine-driven screw propeller.

The writer knows of no other type of augmentor either suggested or tried. The simplicity of the jet suggests that only a limited number of augmenting processes can exist; and further limitations are imposed if the simplicity of jet propulsion is to be preserved. However, it seems unlikely that the schemes already investigated have completely exhausted the possibilities.

THE PROBLEM

The problem of increasing the thrust/power ratio of a jet centers upon the jet itself, for the thermal efficiency of a nozzle in giving kinetic energy to the jet is from 10 to 15 per cent higher than that of the internal-combustion engine in producing mechanical energy under the same thermodynamic conditions. As indicated earlier, the kinetic energy of the jet can be converted to propulsive work by allowing the jet reaction to move the nozzle, the amount converted being proportional to the speed of the motion. At ordinary airplane speeds, say 100 miles per hour, about 8 per cent of the kinetic energy of a jet with a speed of 2,500 miles per hour (roughly the speed of a jet corresponding to the temperature and pressure found in the ordinary internal-combustion engine after combustion) can be made useful in this manner. The remaining 92 per cent stays in the jet after it leaves the nozzle and is available for further gain in useful work if means are provided for its conversion. In the application to airplanes, with which this paper is mainly concerned, the forward speed will be regarded as the same as the speed of the airplane since we shall not consider the case where nozzles are mounted on propeller tips. With this speed fixed, the only other variable at our disposal to increase the useful work is the propulsive force. This depends entirely upon the momentum of the jet and of the fluid set in motion by it. A greater force can result only if this momentum is increased; and consequently, if the jet is to produce greater propulsive force by its action on surrounding objects, this momentum must be increased thereby. The kinetic energy in the jet, representing 92 per cent of the total energy in the above example, is normally dissipated without change of momentum, the average speed decreasing, and the mass of air in motion increasing, in such a way that the product remains constant. The problem of thrust augmentation is to transfer the energy to a still larger mass of air in an efficient manner, so that the momentum is increased. This can be done, if at all, only by material surrounding objects exerting a force on the air, the reaction to which constitutes the thrust augmentation.

It is a very convenient fact that changes made in the jet after it leaves the nozzle do not affect the reactive force arising on the interior of the nozzle unless the change is in the nature of an obstruction which blocks the air passage very near the nozzle. Therefore additional force may be obtained from the action on neighboring objects of the fluid set in motion by the jet without impairing the original reaction.

ORIGIN OF THE PRESENT WORK

In view of the advantages of the jet as a prime mover and of the fact that the number of types of augmentors already investigated is small, an experimental study of thrust augmentors for jets was started at the Bureau of Standards in October, 1930, with the financial assistance and cooperation of the National Advisory Committee for Aeronautics. The purpose of the study was to investigate a large variety of schemes. The program was an ambitious one, including all the schemes suggested by members of the staff in the light of present-day knowledge of jets. No attempt was made to refine the devices, since this would have required more time than was available for the problem.

GENERAL DESCRIPTION OF EXPERIMENTAL WORK

AT THE BUREAU OF STANDARDS

Nozzles and augmenting devices upon which tests were conducted were mounted in the 3-foot wind tunnel of the Bureau of Standards. The jet was supplied by air from a compressor outside the tunnel. Everything outside the wind tunnel may be regarded as the interior of a vehicle, and the nozzle in the tunnel as attached to the vehicle. If we wish to regard the vehicle as moving, we may think of its motion relative to the air in the tunnel. Since the intake of the compressor was not in the tunnel, the material constituting the jet was supplied from within the vehicle itself. We have then a case analogous to the rocket type of propeller in which the propulsive force is the result of an acceleration of mass from rest within the vehicle.

In the present work we are interested primarily in the thrust produced by the jet per unit of power. Efficiency of propulsion, usually defined as the ratio of power absorbed in the motion of the vehicle being propelled to the power supplied to the propelling system, has a meaning only when referred to the rate of motion of the vehicle. When in our experiment we have measured the thrust per unit of power, we have merely to multiply this quantity by the speed of the wind relative to the room (referring to the foregoing analogy) to obtain the efficiency of the jet.

It was necessary to simplify the experimental work by using compressed air at room temperature to supply the jets. This procedure is doubtless allowable in comparative tests and should yield absolute values of sufficient exactness to indicate the usefulness of practically applied heated jets. (Reference 19.) The nozzles were small (about one-fourth inch in diameter) because of the limited supply of compressed air, and the augmentors were correspondingly small. With our very meager knowledge of scale effect (reference 20) we cannot say whether jets enough to propel airplanes would yield similar results.

The tests involved, in general, three determinations: (1) the reaction of the free jet was either measured or computed from the applied pressure; (2) the total thrust with the augmentor was measured; and at the same time (3) the mass flow of the jet and the pressure causing it were also measured. These give enough data for comparing the propulsive force of the augmented jet with that of the free jet at the same power.

THE APPARATUS

All forces were measured on the inverted type N.P.L. balance of the 3-foot wind tunnel of the Bureau of Standards. The ordinary balance spindle was replaced by a tube which served the double role of compressed air lead and model support. Details of the arrangement are shown in Figure 3. Compressed air was conducted to the balance by a 1-inch, thin-walled, flexible rubber tube wrapped with enough ordinary friction tape to withstand the pressure (maximum 25 pounds per square inch, gage). The position of the tube is shown in the photograph. (Fig. 2.) It was so chosen by experiment that a pressure applied to the tube caused no deflection of the drag arm of the balance. In measuring forces along the axis of the tunnel, it was possible by using a null method, to eliminate entirely the effect of the flexible lead. In measuring forces at right angles to the tunnel axis, the effect of pressure in this flexible lead could not be eliminated with the tube in this position; but the effect was small as compared to the lift forces obtained on the models in which the lift was of interest, and was neglected. A small flexible tube, the position of which did not affect the balance reading, connected a small copper tube extending to the model in the tunnel to another running to a mercury manometer for measuring nozzle pressures. A fluid meter of the orifice type inserted in the compressed-air line at a convenient place was used to measure the quantity of air flowing from the nozzles. All forces were measured by means of a pendulum-type balance.

THE FREE JET

Computation of jet performance.- The reader may find various phases of the thermodynamics of jets treated in references 8 to 13, inclusive. Here it is sufficient merely to state and interpret those relations useful in the present work, since their derivation may be found in most text books on engineering thermodynamics.

Notation.- The notation to be used is collected below for reference.

p_1, absolute pressure of the gas before expansion, in pounds per square foot.

p_2, absolute pressure of the gas after expansion, in pounds per square foot.

T_1, absolute temperature of the gas before expansion, in degrees C.

R, gas constant (96.03 ft-lb. per lb. per degree C.).

g, acceleration of gravity (32.17 ft. per $sec.^2$).

K, specific heat ratio (1.4 for air).

A, cross-sectional area of the mouth of the nozzle, in square feet.

d, diameter of fluid meter orifice, in inches.

ρ, density of the gas upstream from the orifice of the fluid meter in pounds per cubic foot.

Δ, pressure drop across the orifice of the fluid meter in pounds per square inch.

C, hydraulic discharge coefficient.

S, theoretical jet speed produced by adiabatic expansion from the pressure P_1 to P_2, in feet per second.

M_i, theoretical mass flow of the jet produced by adiabatic expansion from the pressure P_1 to P_2, in slugs per second.

M, mass flow of the actual jet as measured by the fluid meter, in slugs per second.

F, theoretical reaction of jet of mass flow M and speed S.

P, power required to produce the jet, in foot-pound per second.

P_h, power required to produce the jet, in horsepower.

R_{tp}, thrust-power ratio, in pounds per horsepower.

Formulas.- The thermodynamic formulas to be presented here are true for the following conditions:

1. The nozzle is designed to allow complete expansion.

2. The kinetic energy of the gas approaching the nozzle is zero.

3. The expansion takes place adiabatically and without friction.

The theoretical speed of the jet is given by (1).

$$S = \sqrt{2g \frac{K}{K-1} R T_1 \left[1 - \left(\frac{p_2}{p_1} \right)^{\frac{K-1}{K}} \right]} \qquad (1)$$

The speed S, as computed by formula (1) is the uniform speed of an ideal jet. Owing to friction, the actual speed is not uniform; it is reduced near the boundary of the jet. But the average of the actual speed, taken over the entire cross section of the jet, is usually only a few per cent less than S. The actual speed was not measured; hence all later references to jet speed will mean theoretical speed as computed by formula (1).

When $\frac{p_2}{p_1} = 0.528$, S is equal to the speed of sound at the temperature of the jet. If $\frac{p_2}{p_1} < 0.528$ the nozzle must have a diverging exit cone if the expansion of the gas is to be complete and the speed of the jet is to be greater than the speed of sound. In order to allow for flexibility in the choice of pressures, the nozzles used in the present work were of the converging type with a cylindrical exit which did not allow complete expansion of the gas for $\frac{p_2}{p_1} < 0.528$. Hence when such pressure ratios were used, the nozzles became inefficient and formula (1) was not exactly applicable. The actual jet speed for this type of nozzle cannot exceed the speed of sound.

The theoretical mass flow through the nozzle is given by (2).

$$M_i = A \sqrt{\frac{2\ K}{g(K - 1)} \frac{{p_1}^2}{R\ T_1} \left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{K}} - \left(\frac{p_2}{p_1}\right)^{\frac{K+1}{K}} \right]} \qquad (2)$$

Formula (2) like formula (1) is inexact whenever $\frac{p_2}{p_1} < 0.528$. Because of friction, M_i has a greater value than is actually observed for a jet of gas.

The actual rate of mass flow M was measured by a fluid meter. For the fluid meter used in the present work, M is given by (3).

$$M = 0.01632\ C\ d^2 \sqrt{\rho\ \Delta}$$

The value of the discharge coefficient C, depends upon the location of the pressure taps, upon the value of d, and to some degree upon the value of Δ. For more details on fluid meters and their coefficients the reader is referred to reference 21. The values of C used in the computations were taken from that paper.

The theoretical reaction, in pounds, of a jet of uniform speed S ft./sec., whose rate of mass flow is M slugs/sec., is

$$F = M\ S \qquad (4)$$

and the power in ft-lb./sec. required to produce this jet is

$$P = \tfrac{1}{2} M\ S^2 \qquad (5)$$

or, in horsepower,

$$P_h = \frac{M\ S^2}{1100} \qquad (6)$$

The theoretical thrust-power ratio in pounds per horsepower is given by the expression

$$R_{t_p} = \frac{F}{P_h} = \frac{MS}{\frac{MS^2}{1100}} = \frac{1100}{S} \qquad (7)$$

As previously mentioned, a jet with a mass flow M_i never exists. Since we are always dealing with a real jet, we are interested in obtaining the greatest possible reaction corresponding to the actual mass flow and a given initial pressure for the energy required to produce the jet is determined by these two quantities. Hence formulas (4), (5), (6), (7), all embodying M, represent the maximum performance that can be obtained for a given energy. The reaction F, is the ideal reaction of the existent jet, and is the reaction of a jet which requires for its maintenance the power P. Measured reactions must always be less than F because the average true speed is always less than S; the amount by which the measured reaction is less than F is equal to the axial component of frictional force integrated over the nozzle. While the power P is required to produce the jet, the power in the jet as it leaves the nozzle is not P, but something less, because of the frictional losses in the nozzle.

Formula (2) is useful in estimating the magnitude of these frictional losses in the nozzle, especially in those cases where augmenting devices are used. By combining formula (2) with formula (4) to give the ratio M/M_i for a given initial pressure P_1, an indication is obtained of the nozzle losses, since M/M_i increases as the friction loss diminishes and approaches unity as the loss approaches zero. This ratio will be termed the efficiency of the nozzle.

Experimental results.- Throughout the paper the free jet will be made the basis of comparison for all augmented jets. Figure 3 is a diagram, drawn to scale, of the 1-inch L-tube running from the N.P.L. balance above the wind tunnel to the center of the tunnel. A nozzle, shown in the same figure, was soldered in the end of the L-tube. This nozzle will be called the ordinary nozzle. A pressure tap was placed 3 inches back of the orifice and was connected to a mercury manometer as described earlier. All types of jets and augmentors were attached to tubes similar to the L-tube shown In Figure 3.

The reaction of the jet at various pressures was measured on the balance while simultaneously the pressure applied 3 inches behind the orifice and the rate of flow of air through the orifice were measured by the mercury manometer and fluid meter. From the observed pressure and temperature of the air before reaching the nozzle the theoretical speed, mass flow, reaction, and horsepower of the jet were calculated by means of formulas (1), (3), (4), and (6), respectively.

A number of tests of the ordinary nozzle were made, all of which showed good agreement. Maximum forces were about 1 pound at a differential nozzle pressure of about 23 pounds per square inch. An average of the results of two runs is shown in Figures 4, 5, and 6. Figure 4 shows the variation with jet speed of observed reactive force in pounds. In Figure 5, curve (a) shows the variation with jet speed of the observed reaction, and curve (b) that of the ideal reaction, each in pounds per horsepower. Curves (a) and (b) are in good agreement. The ratio of observed force to the ideal force as given by formula (4) is a measure of the reaction lost through nozzle friction. Figure 6 shows the variation of this ratio with jet speed. The ideal reaction is represented by the straight line parallel to the speed axis and of ordinate unity. While the observed curve for a free jet can never have ordinates greater than unity, the curve for an augmented jet may lie either above or below the straight horizontal line, depending upon whether the augmentor is beneficial or the reverse. The position of the augmented curve with relation to the straight horizontal line is the best indication of the value of the augmentor.

A wind in the tunnel would not be expected to have an effect upon the reaction of the jet since, as was pointed out earlier, the reaction of a free jet is very nearly independent of the surrounding medium and its state of motion. Figure 7 in which reaction curves for various wind speeds are given shows this independence by the fact that the curves are all parallel. The displacement of the different curves from that for zero wind is the drag of the L-tube by the wind.

In a diagram such as Figure 6, it is possible to draw a curve below which that for an augmented jet may not fall if it is to equal the performance of the screw propeller. The ordinates of that curve will be the ratio of the reaction (4.5 pounds per horsepower) for an ordinary screw propeller, working statically, to that (formula 7) for the ideal free jet; hence, the equation of the curve is

$$Y = 0.0041\ S \tag{8}$$

This line is shown in Figure 8, the scale of Figure 6 being unsuitable for its satisfactory representation. The line at unit ordinate of Figure 6 is redrawn in Figure 8. It is apparent that below a jet speed of 245 feet per second the jet requires no augmentation. However, at such low speeds the thermodynamic efficiency of the jet working as a heat engine is below the practical limit. At higher speeds the augmentation required to secure equality is the numerical value of the ordinate of this line. For example, if the jet is produced by gases at 7 atmospheres and 1,200° C., as may be the case if the gases are produced by combustion, then the ideal jet speed (formula 1) will be about 3,700 feet per second, which corresponds to $Y = 15.2$, approximately. That is, when such a jet is working at its best, the augmentor must multiply the thrust by a factor exceeding 15. This is a severe requirement.

The discussion in the last paragraph assumes that the thrust at a given jet speed is to be made equal to that of the ordinary screw propeller. It is possible that jet propulsion might be considered advantageous with a smaller augmentation.

PRINCIPLES OF AUGMENTATION

To determine what may be done by way of augmentation and how augmentation may be accomplished, it will be helpful to examine the free jet in detail. For this purpose the jet will be regarded as a stream of fluid passing from a condition of high pressure through an appropriate nozzle of circular section into an outer medium of lower pressure.

The classical treatment of an inviscid and incompressible jet is of importance in our problem because of the light which it throws on actual conditions. Classical hydrodynamics describes two distinct and totally different forms of the jet. The first of these is the type in which the flow is continuous, with the stream lines spreading from the end of the nozzle in all directions like the flow induced in a quiescent medium when a long cylindrical body moves endwise through it, the flow being seen by a stationary observer. The end of the body corresponds to the orifice of the nozzle and the body proper to the cylinder of fluid moving through the orifice. In this case the speed and pressure both fall with increasing distance from the orifice. The second type of flow treated by classical hydrodynamics requires discontinuity between the jet and the surrounding medium, the jet having the form of a cylindrical column of fluid moving through the surrounding medium without disturbance. The boundary of the jet is a surface of slip where the velocity gradient is infinite. The speed of the jet is constant and equal to its speed at the orifice and the pressure in it is constant and equal to the pressure of the surroundings.

Conditions are, however, quite different in a real compressible fluid with viscosity, such as air. Nevertheless, points of similarity between the ideal jet and the jet of real fluid do appear. Dorsey (reference 17) has remarked that a jet of liquid at a low velocity corresponds to the first type of ideal jet; at higher velocities a stem in which the flow corresponds to the second or nonspreading type develops under a mushroom-like head. Motion pictures of air flowing through nozzles (reference 18) show that the spreading type of flow exists for a very short period of time and that the cap-like formation of spreading flow never extends outward a distance greater than the diameter of the orifice. As soon as the cap appears it begins to curl inward at the periphery and to form into a ring vortex which is carried along near the head of the jet. At the speeds with which we shall be concerned, a continuous jet whether liquid or gas consists of a stem topped by a ring vortex; the stem is similar to the second type of ideal jet, that is, to a nearly cylindrical column of moving gas with a steep velocity gradient at the boundary. Motion is induced in the surrounding medium by the friction between the jet and the medium. The transverse velocity gradient is found to decrease as the axial distance from the orifice increases, the region of influence spreading and the jet being retarded more and more by the continued action of friction. (Reference 19.)

At high speeds, such as are encountered in jet propulsion, a probable picture of the jet boundary is that of a turbulent sheath separating the jet from the surrounding medium. The sheath, according to the view of Lord Kelvin (reference 20), consists of a series of ring vortices following one another in rapid succession and acting like rollers between the jet and the medium next to it. We know that turbulence exists, but it is probably not as orderly as this picture might lead one to believe. Owing to the turbulence, there is a certain amount of mixing between the jet and its surroundings, which mixing assists in the acceleration of the medium adjacent to the jet. Because of this mixing there is no definite surface of separation between the jet and the surroundings, the sheath being made up of fluid from the nozzle and from the outside. As the jet recedes from the nozzle the turbulent sheath thickens. The fluid which issues from the nozzle is sometimes referred to as the "core stream," and the induced flow in the surrounding medium as the "jacket stream." This terminology will be adopted here, together with the term "turbulent sheath," to denote the turbulent intermediate region comprising portions of both core and jacket. The reaction on the nozzle arising from the acceleration of the core will be termed "core reaction." A free jet will be defined as one whose only reaction is core reaction, and an augmented jet as one used in conjunction with devices to change its momentum.

All of the energy imparted to the air must come from the energy of the jet. True augmentation can be secured only by making use of energy imparted to the air that would otherwise be lost. The use of devices near the nozzle which impede the flow and increase the pressure within the combustion chamber does not give true augmentation since additional power is required to produce the jet. It is helpful to examine the motions of the core and jacket streams of a steady air jet, the energy of which may be utilized for augmentation.

The most apparent motion is an axial one which is initially imparted to the core by the pressure in the nozzle and which is later given to the jacket by friction and turbulent mixing. A closer examination of the picture previously given will show that other motions can and do exist. One of these is the rotaty motion of the eddies which make up the turbulent sheath, and which embodies additional energy. Another motion present is that normal to the jet axis consisting of the inflow of air to replace that carried downstream by the jet. Finally there is the molecular motion resulting from the decay of all other motions. The energy of this molecular motion cannot be recovered in the form of mechanical energy.

The energy of these motions can be utilized to secure augmentation only by the use of devices which direct the induced motions in a direction that is parallel to the axis of the jet and a large augmentation can be secured only by at the same time distributing the energy through as large a mass of fluid as possible. The redirection of these motions can be done by suitable systems of guide vanes, and the augmentation of the thrust will appear as pressure changes on the vanes. The friction of the vanes with the air will, of course, limit their effectiveness and introduce a factor of uncertainty difficult to estimate.

While no physical device can be made fine enough in structure to direct the random distribution of momentum among the molecules, it might be thought that a system of guide vanes could be devised which would break up vortices and convert their angular momentum into linear momentum. But when we realize that the distribution of eddies is entirely random and that the turbulence may be so fine as to require guide vanes as small as those appropriate to the directing of molecular motions, it becomes evident that both the directing of molecular and of turbulent motions must be regarded as impossible. As these motions represent energy that is lost in so far as it is not available for propulsion, any arrangement which will reduce eddy formation and friction loss in mixing will increase the strength of other motions.

Another apparent possibility of augmentation lies in the directing axially of the normal or influx motions of the fluid in the jacket. Here we are dealing with bulk flow rather than with microscopic portions of fluid and the required size of the vanes is not prohibitively small. It is required merely that the vanes be so placed in the normal flow and have such shape, size, and orientation as will effectively change the direction of the flow from normal to axial, and distribute the energy through a suitable mass of fluid. Mélot's augmentor (fig. 1) is of this type. It rests upon a sound basis in the light of our analysis and seems to hold inviting possibilities.

The Venturi tube, too, falls into this class of augmentors, in so far as their entrance cones are annular vanes. The question arises as to what function, if any, the exit cone of the Venturi performs. Previous work not only in propulsion but in the general use of Venturi tubes to increase the flow about jets (reference 22) would indicate that the addition of an exit cone to the annular vane makes it possible for the jet to induce a greater flow. Nothing in our analysis so far has predicted this. We must, in fact, look beyond the jet, to the characteristics of Venturi flow to find a reason for the observed effects.

Figure 9 shows a Venturi tube in which, for simplicity, the end sectional area of the entrance cone is made equal to that of the exit cone. These areas are denoted by A_1 and A_2, respectively. The throat area is denoted by A, $A < A_1$ or A_2. When a jet passes along the axis of the Venturi, as shown in Figure 9, air surrounding the jet but within the tube will be given a motion parallel to the axis by frictional forces. The axial speed of the air in the tube will tend to have its maximum value in the throat, decreasing to some lower value at the ends, because of the characteristics of Venturi flow. The jet, however, by its accelerating action in the exit cone tends to change the characteristics of the flow in such a manner that the speed at A_2 is higher than it would have been had the jet action been absent. As a result, the speed and the rate of flow of air through A_1 tends to be increased. Consequently, more air must flow into the Venturi from the surroundings at the entrance end. This inflow must in turn be deflected axially by the entrance cone, and the propulsive force arising from a favorable pressure distribution here will be increased thereby in proportion to the flow increase resulting from the action of the jet in the exit cone. The Venturi tube in this case acts to increase the inflow, transferring the energy of the jet to a larger mass of air.

Guide Rings and Venturi Tubes

Returning to the ordinary type of nozzle, let us inquire into its use with guide rings and Venturi tubes. The variations in size and shape of rings and Venturis used may be seen in Figures 10 to 17. Most of these yielded no improvement whatever over the free jet; and some, by the disturbance which they created, actually lowered the resultant force. Since from the examination of the jet a wind does not appear to be essential to augmentation, we should not expect a wind to make the results more favorable. In fact, if a device of this sort were found to yield a satisfactorily high augmentation, there would still remain the question of its utility in the propulsion of a vehicle because of the relative wind set up by the motion of the vehicle. The drag of the augmenting device by the relative wind might partially or totally neutralize its propulsive force. An increase in static thrust is necessary, but not sufficient to insure the success of the augmentor. It is useless then to test a particular ring or Venturi in a wind unless it merits the test by its high static thrust. None were found to merit the test. However, to settle experimentally the question of the dependence of augmentation upon the wind and to determine in a general way the drag of the Venturi type of augmentor, wind test of the Venturi shown in Figure 16 was made.

The augmentor was usually held by a support with a spring clip which slipped over the horizontal part of the L-tube of Figure 3. Removals and adjustments were easily made by sliding the clip over the tube. The experimental procedure was to measure the reaction of the free jet at a given nozzle pressure, then at the same pressure to make measurements with the augmentor in place at various distances from the nozzle. The thrust was a function of this distance, the maximum being found from curves like the one shown in Figure 18 for the Venturi of Figure 15d. The ratio of the maximum total force to the free reaction is thus obtained directly from those observations. The ratio of the maximum total thrust to the ideal reaction was then calculated by multiplying the preceding ratio by the appropriate small numerical factor obtained from Figure 6.

The second and third columns of Table I give the free jet reaction and the maximum total thrust, respectively, for the augmentor indicated in column 1. The fourth column gives the ratio of maximum total thrust to free jet reaction, and this ratio multiplied by the ordinate of Figure 6 corresponding to the jet speed indicated furnishes the corresponding number in column 5, which is the ratio of the maximum total thrust to the ideal reaction. The values in column 5 fit into such diagrams as Figures 6 and 8.

The slotted diverging cone, or series of Venturis, shown in Figure 12, yielded a total thrust far below the reaction of the free jet. The jet was found to fill the cones only partially and to cling to their sides. It is probable that the alignment of the separate Venturis with the nozzle must be very exact, if they are to act efficiently. Since proper adjustment was never obtained, the results are not given in Table I.

TABLE I. THRUST AUGMENTATION OF ORDINARY NOZZLE
WITH GUIDE RINGS AND VENTURI TUBES

Figures	Free jet reaction lb.	Maximum total thrust with augmentor lb.	Total thrust / Free jet reaction	Total thrust / Ideal reaction	Ideal jet speed ft./sec.
10	0.0906	0.0906	1.00	0.987	435
	.286	.285	.996	.996	736
	.465	.465	1.00	.990	908
	.662	.653	.987	.971	1,030
	.795	.794	1.00	.981	1,120
	.952	.947	.984	.965	1,190
	1.072	1.078	1.005	.995	1,240
11	.0906	.906	1.00	.987	435
	.286	.284	.993	.993	736
	.465	.463	.997	.987	908
	.662	.629	.950	.934	1,030
	.795	.785	.988	.969	1,120
	.952	.936	.995	.980	1,190
	1.072	1.056	.986	.977	1,240
Largest ring of Figure 10	1.06	1.07	1.01	1.00	1,240
Largest ring of Figure 11	1.06	1.09	1.03	1.02	1,240
Intermediate ring of Figure 11	1.06	1.07	1.01	1.00	1,240
Smallest ring of Figure 11	1.06	1.07	1.01	1.00	1,240

TABLE I. THRUST AUGMENTATION OF ORDINARY NOZZLE
WITH GUIDE RINGS AND VENTURI TUBES (Contd.)

Figures	Free jet reaction lb.	Maximum total thrust with augmentor lb.	Total thrust / Free jet reaction	Total thrust / Ideal reaction	Ideal jet speed ft./sec.
12	-	-	-	-	-
13	.625	.631	1.01	1.00	990
14	.631	.666	1.055	1.045	990
15a	1.06	1.12	1.094	1.084	1,240
15b	1.06	1.18	1.11	1.10	1,240
15c	1.06	1.135	1.07	1.06	1,240
15d	1.06	1.135	1.07	1.06	1,240
15e	1.06	1.14	1.075	1.065	1,240
16	.091	.091	1.00	.987	435
	.288	.298	1.035	1.035	736
	.465	.485	1.043	1.033	908
	.630	.666	1.057	1.040	1,030
	.782	.848	1.084	1.063	1,120
	.940	1.008	1.074	1.057	1,190
	1.055	1.130	1.071	1.061	1,240

Figure 19 shows that in the case of the Venturi of Figure 16 the effect of a wind upon augmentation is null, the successive curves being merely displaced from that of zero wind by the drag of the Venturi, its mounting, and the L-tube by the wind.

The drag curve of Figure 20 showing the contribution to the drag made by the Venturi of Figure 16 in the presence of the L-tube was obtained by subtracting the ordinates of a drag curve for the L-tube alone from those of a similar curve for the L-tube with the Venturi attached. From this curve and Table I we see that the small beneficial effect of this particular Venturi at a jet speed of 1,240 feet per second would be completely destroyed in a wind of only 40 feet per second. If we take this as an indication of the drag of rings and Venturis in general, we may conclude that while this type of augmentor is far from satisfactory statically it is even less so when we consider its ability to propel with speed.

The Mélot type of augmentor tested by Jacobs and Shoemaker gave much better augmentation than any of the types tested here, but at higher jet speeds. Jacobs and Shoemaker find an augmentation as compared with the theoretical thrust of a free jet of nearly 40 per cent at a speed of about 1,700 feet per second. Even at the greater speed, the augmentation is insignificant as compared with the sevenfold value (fig. 8) demanded for equality with screws. In the present work speeds were limited by the equipment to about 1,240 feet per second, at which speed an augmentation of 10 per cent was obtained with the arrangement shown in Figure 15b. This value is considered to agree satisfactorily with correspondingly low values obtained by Jacobs and Shoemaker at the lower speeds.

Annular Nozzles

The annular nozzle with a flat-ended core shown in Figure 21a gave very poor results when used free and was not considered worth combining with augmentors. Adding a tail to the core (fig. 21b) considerably increased the force, but the nozzle was still inefficient as compared with the ordinary type of nozzle. With the tail piece the jet has the form of a cone covering the tail, and has greater area than the same jet from an ordinary nozzle. Tests were made with augmentors to determine how this greater area would effect the acceleration of air in the presence of the augmentor. A set of results similar to those of Table I is given for this nozzle in Table II.

TABLE II. THRUST AUGMENTATION OF ANNULAR

NOZZLE WITH GUIDE RINGS AND VENTURI TUBES

Figures	Free jet reaction lb.	Maximum total thrust with augmentor lb.	Total thrust / Free jet reaction	Total thrust / Ideal reaction	Ideal jet speed ft./sec.
21b and 15c	0.510	0.485	0.951	0.945	1,250
21b and large ring of Figure 10	.499	.485	.972	.966	1,250
21b and large ring of Figure 11	.508	.510	1.004	.999	1,250
21b and 17	.500	.500	1.00	.994	1,250

The annular nozzles represented in Figures 22 to 25 and consisting of hollow cone-shaped devices of which the sections are shaped like airfoil profiles represent a modification of the guide ring and Venturi type of augmentor. They will be referred to as annular nozzles Nos. 1, 2, 3 and 4, respectively. The nozzle itself is an annular slot in the trailing edge, with parallel walls formed by the inner and outer walls of the annular chamber. It will be observed in the figures that these slots diverge with a total angle ranging from a few degrees up to 40°. A diverging annular jet is thus obtained which surrounds a central core of exterior air drawn in through the entrance cone of the chamber by jet friction and the Venturi effect gained by the divergence of the jet. The nozzle and the jet may be imagined to be a Venturi tube with the jet as the exit cone. This scheme of augmentation is based entirely upon a pressure decrease in the entrance cone arising from the accelerating power of the jet.

Nozzles Nos. 1, 2 and 3 differ mainly in their angular divergence, the total angles being 7°, 18° and 40°, respectively. No. 4 is half the size of the first three, with a nozzle divergence of 18°. The nozzles have the angles indicated, but the jets assume smaller angles, proportional, however, to the nozzle angles.

A series of force measurements was made on the four nozzles without wind. The maximum observed force was about one pound. In Figure 26 the ratio of observed thrust to ideal reaction is plotted against jet speed for each of the four nozzles, the curves being numbered correspondingly. The dotted curve is that for the free jet, repeated here for comparison. It is apparent that nozzle No. 3 is the only one that shows an improvement over the free jet, and this improvement is so small as to be scarcely worth noting.

We should not expect the augmenting power of an annular nozzle to be increased by a wind. Nevertheless two drag runs to test this point were made upon nozzle No. 3., one without a jet and the other with a jet of 720 feet per second. The two curves are shown in Figure 27. These curves give no fair indication of the drag of the nozzle, since the drag of the 1/2-inch tube by which the nozzle was connected to the balance is included. The difference in the ordinates of the two curves at a given wind speed is, however, an indication of the effect of the wind upon augmentation at that speed, an increase of ordinate difference with increase in wind indicating an improvement in the augmentation. The practically constant difference marked at three different points along the curves shows definitely no improvement in augmentation.

The failure to observe any augmentation when we change from the ordinary nozzle to the annular ones may arise from an attendant increase in the energy losses in the nozzle itself. That this is actually the case is indicated by the following observations. From an integration of pressures measured over the entrance cone of No. 2 a thrust force of

0.067 pound was found, the observed total thrust being 0.635 pound, or a contribution of 10.5 per cent. Hence in the absence of nozzle losses we should expect to observe a total thrust about 10 per cent higher than the ideal jet reaction. Actually we find the computed ideal reaction to be 0.648 pound, 2 per cent greater than the above total observed thrust. The latter is, therefore, some 12 per cent less than would be anticipated on the assumption that the losses in the nozzle are the same. That the presence of the conical entrance does actually result in some 10 per cent increase in the thrust is shown by observations obtained when nozzles Nos. 1 and 2 were modified by having placed in each of them a sharp-edged hollow cylinder fitting tightly at the throat of the cone and extending forward to the leading edge. Its leading edge being sharp, the cylinder introduced no counterthrust, but by eliminating air flow over the inner surface of the cone, it eliminated the cone's contribution to the thrust. In both cases reductions between 10 and 12 per cent were observed. Thus it appears that the losses in these annular nozzles amount to about 12 per cent as compared to about 5 per cent in the ordinary nozzle used in the present work. Previously it was shown how the nozzle losses could be estimated from the ratio $\frac{M}{M_i}$. Here, however, it was impossible to measure the orifice area accurately enough to compute M_i, and the above procedure becomes the only one possible.

It is clear also that jet reaction has been sacrificed by diverging the jet, the reaction being proportional to the cosine of the angle between the jet and the nozzle axis. The cosines for Nos. 1, 2, 3 and 4 are 0.998, 0.983, 0.940 and 0.988, respectively. For Nos. 1 and 2 only 0.2 and 1.2 per cent of the observed 12 per cent loss can be accounted for in this way. Furthermore, since No. 3 should have suffered most from jet divergence but gave the best results, the more favorable condition for augmentation brought about by the more rapid expansion of the cone-shaped jet must have more than compensated for the loss.

Thus far, only the accelerating power of the inner surface of the jet has been employed for augmentation. The outer surface of the annular jet should be no different from the ordinary jet in its ability to give rise to an inflow of air; hence guide rings and Venturis placed around it should act as augmentors. A test of nozzle No. 2 and the Venturi tube of Figure 17 failed to show any contribution from the Venturi. Without doubt some helpful effect could have been derived had the Venturi been appropriately designed, but indications are that the augmentation would have been too small to be of any consequence.

We conclude that although the cones of such annular nozzles do afford a certain amount of augmentation, this is largely offset by a loss of jet reaction through nozzle friction, the aggregate result being that the augmented jet under the best conditions is only slightly better than the free jet from an ordinary nozzle. Practically, these effects were too small to concern us; the problem of propulsion is as much unsolved as ever.

JETS IN AIRSHIP MODELS

Jet in tail of airship model.- We now have to ascertain by how much the thrust exerted by a free jet, or by a system of them, is influenced by the form of the surface from which it issues, and especially by such forms as will probably be encountered in the application of jets in aeronautics. The simplest case is that in which the jet issues from the tail of an airship.

In order to study the case, the L-tube and nozzle of Figure 3 were placed in an airship model, as shown in Figure 28. A fairing was placed about the vertical portion of the L-tube extending from the model to the balance, so as to reduce the disturbance in the air flow over the model.

The reason for investigating such a combination of jet and airship model is this: When a streamlined body of revolution, such as an airship model, is pointed into a wind, a definite flow pattern exists around it. If a jet is emitted from the tail of the model, it is probable that the streamlines near the body will be altered. The question may be asked, does the jet alter the flow in such a manner as to decrease the drag of the model, or even go so far as to make its drag negative? In other words, is the airship capable of retrieving any of the energy put into the wind stream by the jet? If so, there will be observed not only the reaction of the jet, but also an additional force arising from the altered pressures on the surface of the model.

The thrust which the jet produced in this position was first determined in still air. The way in which the ratio of total thrust to ideal reaction varied with jet speed is shown by curve (a) of Figure 29, curve (b) being the standard curve for the free jet, taken from Figure 6. From the proximity of curve (b) to (a) we may conclude that the model in still air has no effect upon the jet reaction, or vice versa, that the jet induces no air flow over the model which yields either thrust or drag forces different from those on the L-tube alone.

A series of tests on the effect of the jet in the presence of a wind was next made. The results are given by the series of curves in Figure 30 which is a representation similar to that of Figure 7. Negative forces indicate that the resultant force on the model is a drag while positive forces indicate a resultant thrust. The displacement of each curve from that corresponding to zero wind is the drag exerted by the wind on the model and faired tube. The fact that the curves for different wind speeds are all parallel shows that the effect of the jet is the same in a wind as in still air. As it is not likely that a change in the flow (and consequently in the pressure distribution) could occur without causing some change in the force, we conclude that the jet causes too slight an alteration in the flow about the airship to be observed in such measurements.

Airship model with radial jet in nose.- In view of certain proposed schemes for the propulsion of airships, in which a centrifugal fan or similar device is used to pump air from in front of the ship, thus creating a region of lowered pressure at the nose, it was thought interesting to try the effect of a certain type of nozzle at the nose, a type which we shall call the radial nozzle.

Radial nozzles are illustrated in Figures 31b and 33b. The air is discharged approximately radially and in a thin sheet from an annular orifice. The efficiency of a radial nozzle may be compared to that of an ordinary nozzle by comparing the ratios $\frac{M}{M_i}$ for the two. The calculation of M_i by formula (2) requires a measurement of orifice area; and since this area could not be determined accurately in the case of Figure 31b, we have a comparison of only Figure 33b with the ordinary one. The calculated coefficient $\frac{M}{M_i}$ for Figure 33b is 0.95. This compares favorably with values of the same coefficient, ranging from 0.92 to 0.98, for the ordinary type of nozzle. Hence we may conclude that nozzle efficiency need not be sacrificed in obtaining the jet in the radial form.

Figure 31a shows the airship model of Figure 28 so modified as to accommodate the L-tube when turned in the reverse direction. The radial nozzle shown in Figure 31b was soldered in the end of the L-tube and the whole adjusted relative to the model so that the back wall of the nozzle and the surface of the model were continuous.

In Table III are reproduced the results of a test with no wind. The second column of the table shows the variation of observed total force with jet speed. The third column gives the ideal reactive force that would have resulted had the entire jet been directed backward. Column 4 gives the ratio of observed force (column 2) to the ideal force (column 3). It will be seen by comparison with Figure 29 that this ratio lies far below that for jets previously tested. This is not surprising, for we would expect no resultant force on the model if the jet passed radially outward. Actually the jet clings to the surface of the model and is directed backward. The low ratio shows that either the directing action is incomplete or friction losses of the high-speed jet on the nose of the model are great.

TABLE III. PERFORMANCE OF RADIAL

NOZZLE AT NOSE OF AIRSHIP MODEL

Jet speed (ft./sec.)	Observed force (lb.)	Ideal reaction (lb.)	Ratio of obs. force ideal reaction
658	0.252	0.404	0.624
845	.410	.648	.633
981	.546	.873	.626

The results of tests with winds of different speeds are shown in Figure 32, by curves similar to those of Figures 7, 19, and 30. As before, the fact that the curves are parallel indicates that a wind does not change the forces due to the jet. As the wind increases a break begins to appear in the series of curves at 52 feet per second. This may be interpreted as some instability of the flow at low nozzle pressures, which is accentuated by the wind.

We may conclude definitely from these results that the radial jet in the nose of an airship model is entirely valueless as a scheme of propulsion.

Airship model with radial jet in tail.- For the sake of completeness, measurements were also made on the effect of a radial nozzle at the tail of an airship model. In this case a streamlined body of revolution of the form and size shown in Figure 33a was used. A smaller L-tube (1/2-inch instead of 1-inch) was used, so as to reduce the drag. A fairing was attached to it so as to reduce the disturbances it would have otherwise produced in the airflow about the model. An improved radial nozzle (fig. 33b) in which the cap was given an internal support was used, thus eliminating the two obstructions at the orifice present in the nozzle of Figure 31b.

Curve (a) of Figure 34 shows there is a small force from the jet at no wind. This may be attributed to a backward inclination of the jet, which had previously been shown to exist for a jet of water issuing from the nozzle. This small force at no wind is of little interest, since in a perfectly radial nozzle the entire core reaction is absent.

Curve (b) of Figure 34 shows the change produced by the jet in the drag of the model at a wind speed of 79 feet per second. Shifting curve (b) parallel to itself until the point corresponding to zero speed of jet coincides with the corresponding point of (a), we obtain curve (b'). As (b') rises faster than (a) it is plain that the presence of the wind has increased the thrust exerted by the jet. Pressure measurements made over the model from the section of greatest diameter to the tail showed this increase in force to be due to an increase of pressure over the rear portion of the body.

To find a helpful effect from the wind is somewhat encouraging, but for it to be of any practical use the increase would have to be very much greater. The increment of force at P_1 = 1.56 atmospheres, where the jet speed is 860 feet per second, is found from curves (a) and (b') to be 0.06 lb. Had the same jet been directed straight backward by an ordinary nozzle the ideal core reaction would have been 0.44 lb. The ratio of increment to ideal core reaction is 0.14 approximately, far below the value 3.5 required by Figure 8.

The results for the airship models may be summarized as follows: An ordinary cylindrical jet in the tail is no improvement over the free jet. A radial jet in the nose is inferior to the free jet and gives no indication of helpful effects from flow modification. A radial jet in the tail sacrifices the core reaction, but does give rise to a slight propulsive force on the model.

THE INTERMITTENT JET

No tests of augmentors employing the intermittent jet were made because of the experimental difficulty involved. Nevertheless, the possibilities of the intermittent jet should be considered, since the flow of the jet in starting is of an entirely different type. The intermittent jet is discussed briefly because it suggests a different method of application of a continuous jet.

The principle of the intermittent jet flowing from an ordinary nozzle is as follows: As the jet begins, a spreading type of flow is given to the air as it is pushed away from the orifice by the issuing core. The core itself rolls up into a ring vortex on the head of the jet, and as time goes on the whole flow pattern, including the spreading flow in the exterior medium, probably becomes a growing ring vortex with the core pushing through its center from the back and winding up in the vortex which is carried along at the head of the jet. In the earlier stage the spreading motion of the exterior medium is available for redirection by suitable guide vanes to unidirectional motion, and in the later stage there exists the ring vortex which is equally capable of direction by guide vanes.

The flow in the early stages is of the potential type having a minimum dissipation of energy in friction. Turbulence does not arise until the development of the ring vortex. At speeds near and above the speed of sound, other losses arise due to the development of compression waves, the energy of which can not be utilized by guide vanes. But the fact that at speeds below that of sound, the initial motion communicated to the air by the jet is of an orderly type with minimum turbulence and friction loss suggests that those conditions offer a better opportunity for efficient augmentation.

We may imagine an augmentor designed with guide vanes capable of redirecting and utilizing the energy of this orderly flow. Emission of the jet would be terminated when the ring vortex and core begin to develop. A difficulty now arises when we attempt to get the next formation by allowing the jet to start; for now unless the nozzle and auxiliary augmenting apparatus have been moved to another position where the air is undisturbed, the jet as it begins to emerge will find the exterior medium already moving axially due to the previous emission. Hence, either the nozzle must be moved laterally or the time between emissions must be long. Both are undesirable. Furthermore, a valve mechanism to interrupt the jet might involve serious mechanical complications. If we desire an augmentative process involving the characteristics of an intermittent jet we must look to some other scheme.

THE TRANSVERSE JET

The concept of the transverse jet arises from that of an intermittent jet which is continually displaced to find undisturbed air. We may imagine a nozzle moved from place to place while the jet is stopped, then resting long enough in an undisturbed position to allow an emission of duration limited to the time of the existence of spreading flow. It is never possible to move the nozzle to completely undisturbed air, and hence some disturbance will exist wherever the next emission takes place. The allowable time of emission will be shorter the nearer the nozzle is to the position of the previous emission and the stronger the jet. We may imagine a series of small displacements and correspondingly short emissions for which spreading flow will result. In the limit the motion of the nozzle is a uniform translation and the jet is continuous, having a strength determined by the rate of translation. Then by moving transversely a nozzle from which a jet is issuing the exterior induced flow should be of the same general type as that in the starting jet and as such the kinetic energy should be distributed through orderly motions rather than through the turbulent and molecular kind. An augmenting apparatus must be carried with the nozzle to convert the spreading motion to a unidirectional one. The jet will be called a transverse jet, the name signifying jet translation with respect to the wind in some direction other than that along its axis.

An attempt was made to build a device to utilize the spreading flow characteristics of the transverse jet. From previous experience with vanes and guide surfaces it appears that any process, even though characterized by an abundance of orderly air motions capable of being directed, might yield little or no force augmentation due to the inefficiency of the directing mechanism. To reduce this mechanism to a simple and seemingly efficient one, the following nozzle-in-airfoil combination was evolved.:

The apparatus consists essentially of a hollow sheet-metal airfoil of symmetrical section shown in Figure 35. The nozzle is placed at the extreme trailing edge with an orifice in the form of a long narrow slit extending the entire length of the airfoil, the orifice being made of this form to distribute the effect along the airfoil. The nozzle walls converge to the orifice, and their orientation is such that the jet makes an angle of about 70° with the chord line. The jet is fed from the interior with compressed air led into the airfoil at one end by a 1-inch brass tube, which also acts as the model support. The nozzle pressure is measured at the midspan, the pressure tap being the open end of a copper tube extending to that point.

In an actual vehicle, the whole apparatus would move with respect to still air. The counterpart in the wind tunnel experiment is a motion of air with respect to the vehicle held at rest. In this case instead of displacing the jet with respect to the air in a direction approximately at right angles to the axis of the jet, the air is displaced past the stationary jet. The motion of the airfoil through still air in any given direction with respect to the chord of the airfoil is simulated in the wind tunnel by setting the chord of the airfoil at the corresponding angle to the wind.

The principle of the transverse jet may be restated as follows: It has been shown how the exterior flow of a transverse jet approximates that of the constantly displaced intermittent jet in the limit where the displacements become infinitesimal and the emission vanishingly short in duration. For purposes of illustration in discussing the intermittent jet the ordinary type of jet with cylindrical core was used; now the picture is changed to that of a jet whose core is a ribbon of width equal to the length of the airfoil and thickness equal to the width of the orifice. The fundamental mechanism is unchanged, the ribbon jet being used merely to distribute the effect along the airfoil. To illustrate the function of transverse action, let us imagine the airfoil set at zero angle of attack (for symmetrical section, angle of no lift) with the air moving past it at such a rate that the parallel component of the velocity of the jet (jet 70° to the wind for zero angle of attack) is equal to and in the same direction as the wind. This wind-tunnel condition corresponds to the horizontal motion of the airfoil through still air along its chord with the jet traveling vertically downward with respect to the air. The jet as it impinges upon the air gives rise to a superposed exterior flow of the spreading type. In short, when we consider this flow, the jet is producing the same type of motion in the surrounding air as an airfoil would produce if from its shape or angle of attack it were deriving a lift. The jet should then, aside from its reaction, give rise to a lift upon the airfoil. Since the airfoil is finite in length any lift must result from a change of momentum in the surrounding air. In other words, if the airfoil derives a lift when set at zero angle of attack, it can do so only by imparting downward momenta to the passing air. The selection of a wind speed equal to the parallel component of the jet was made merely for simplifying the illustration. The same general argument holds for any wind speed.

Imagine the airfoil free to move under the action of the lift force. It is clear that the lift then becomes a propulsive force, doing work upon the airfoil. In the wind tunnel we have merely to make the angle of attack negative to simulate this upward motion. If a propulsive force results, we should observe a decrease in drag or even a negative drag. These are the effects to be expected from the foregoing argument.

To avoid confusion in the terms "lift", "drag", and "propulsive force," we shall here define lift as a force normal to the wind in the tunnel, and drag as a force parallel to the wind and directed downstream. Negative drag, or thrust, will always be used to designate forces parallel to the wind and directed upstream, We shall introduce two new terms, one called the "total lift" defined as the lift including the normal component of jet reaction; and "total drag", the drag including the parallel component of jet reaction.

The results are given by the eight curves of Figure 36. The ordinates are lift and drag forces in pounds, negative numbers indicating negative drag, or thrust. The abscissas are differential nozzle pressures. The unprimed letters accompanying the curves represent results at zero angle of attack, while the primed letters represent results at a negative angle of 5°. Curve A shows the variation with nozzle pressure of the lift component of the jet without a wind. It is assumed that this force arises in the nozzle and that no forces exist on other portions of the airfoil. Curve B represents the total lift in a wind of 94 feet per second. With no jet the lift in this wind was zero. Curve C represents the thrust (parallel component of the jet) without a wind, and D the total drag in a wind of 94 feet per second, including the drag of the model arm. We see that, while the total lift was very greatly increased by the wind, the drag curve, C, was merely shifted vertically by the drag of the airfoil and support in a wind of 94 feet per second. Interpreting this in terms of momentum, we may say that the jet has produced motions the energy of which has been used by the airfoil to impart a large momentum at right angles to the wind, but none parallel to the wind. So far, the results are true to expectation. Curves A', B', C' and D' are corresponding results for a negative angle of attack of 5°. The orientation of the jet has now been changed and curves A' and C' of normal and parallel components of jet reaction respectively are shifted correspondingly. Curve B' compared to B shows that the total lift force has been reduced, but a comparison of C' and D' shows no compensating increase in thrust, the difference between C' and D' being a drag displacement of about the same magnitude as that between C and D. Another test made at a negative angle of 8°, not given here, again gave no indication of thrust force other than that derived from the jet itself. This result is totally at variance with predictions.

Other experiments of a rather diversified nature were tried. Tip shields were placed on the ends of the airfoil with very little change in the previous results except for a larger lift force. Rectangular guide vanes of various widths and of a length equal to that of the airfoil were placed at various positions back of the airfoil in an attempt to change the direction of the downwash. Again, while it was possible materially to reduce the lift, very little or no thrust resulted.

The transverse jet appears from the present work to hold very meager possibilities, but the author does not believe that enough work has been done to exhaust all of them. For example, the long slit orifice might be closed off at intervals breaking the wide ribbon-like jet into a number of narrower ones with free edges. The resulting disturbance instead of being fore and aft would then be lateral, the pattern for each ribbon being two vortex filaments. If guide vanes may be relied upon to perform their function, these filaments may be broken up into linear flow. Numerous suggestions of this sort might be made, but we can think of none which do not require guide vanes, and in view of the small success so far met with in their use, we do not feel that any process depending upon them is likely to succeed.

CONCLUSION

We are faced with the experimental fact that the augmentation obtained was insignificantly small. As to why it was so, we have indications that the trouble may lie with the parts essential to any augmentor, with the directing mechanism or the guide vanes themselves. This is shown in the following brief summary:

The augmentors tried may be divided into two classes; in the first the jet mixes naturally with the surrounding air, and in the second the mixing is controlled by a process called transverse jet action. Referring to natural mixing, we find that we have no knowledge of the distribution of kinetic energy among the two resulting motions, orderly and chaotic. An attempt was made to direct the orderly motions by guide vanes. The small success obtained has not answered the question whether guide vanes are inefficient or whether only an insignificant portion of the kinetic energy results in orderly motion. A greater degree of augmentation was expected in the case of the transverse jet where it is believed that a greater part of the energy was shifted from the chaotic turbulent and molecular motions to the more orderly spreading type. The experimental fact that the increase was not found indicates that the fault may lie in the directing mechanism.

On the whole the outlook is not especially favorable. The present work may be taken not as proof, but only as an indication that the jet can never find use at low speeds unless such lighter, more concentrated, and cheaper fuels than those now in use become available, as will enable the free jet, in spite of its low thrust per horsepower, to compete with the engine-driven screw propeller.

Bureau of Standards,
Washington, D. C., August 6, 1932.

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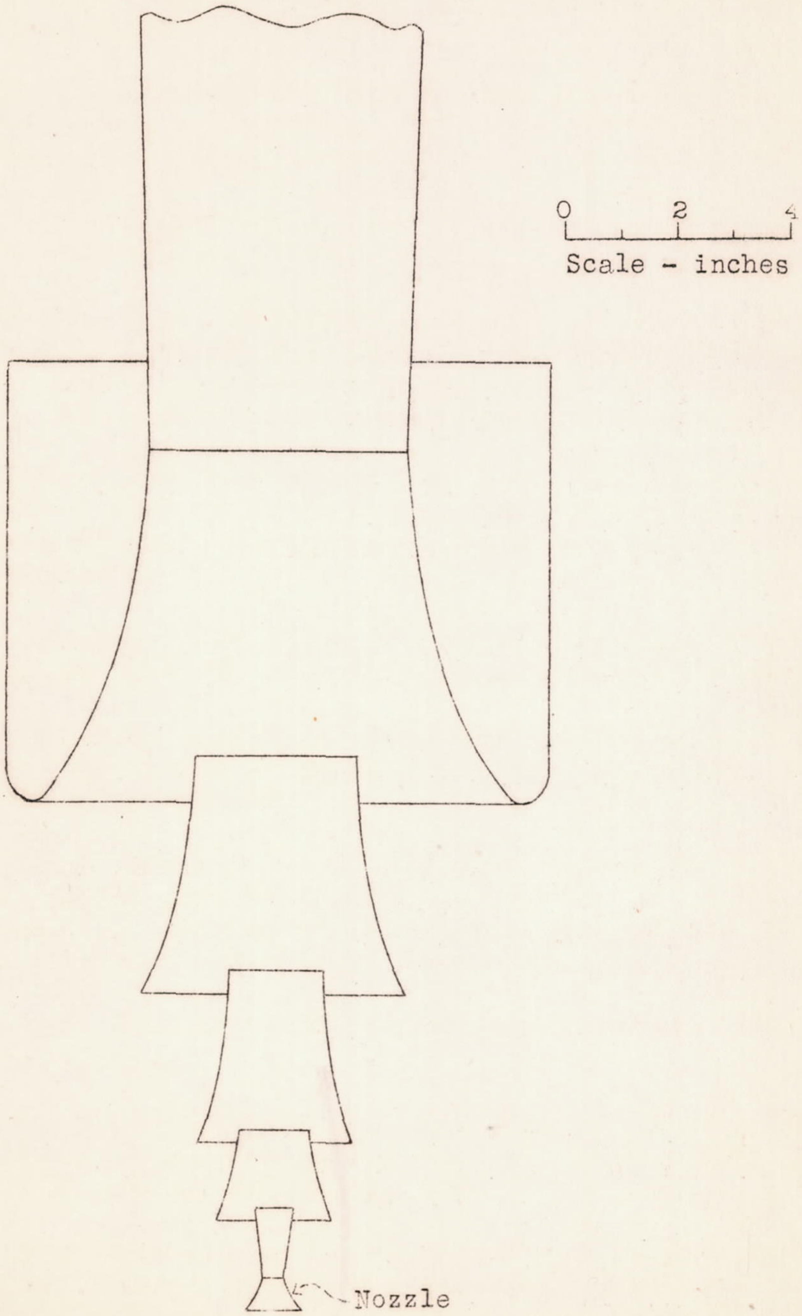

Figure 1. - Mélot type augmentor.

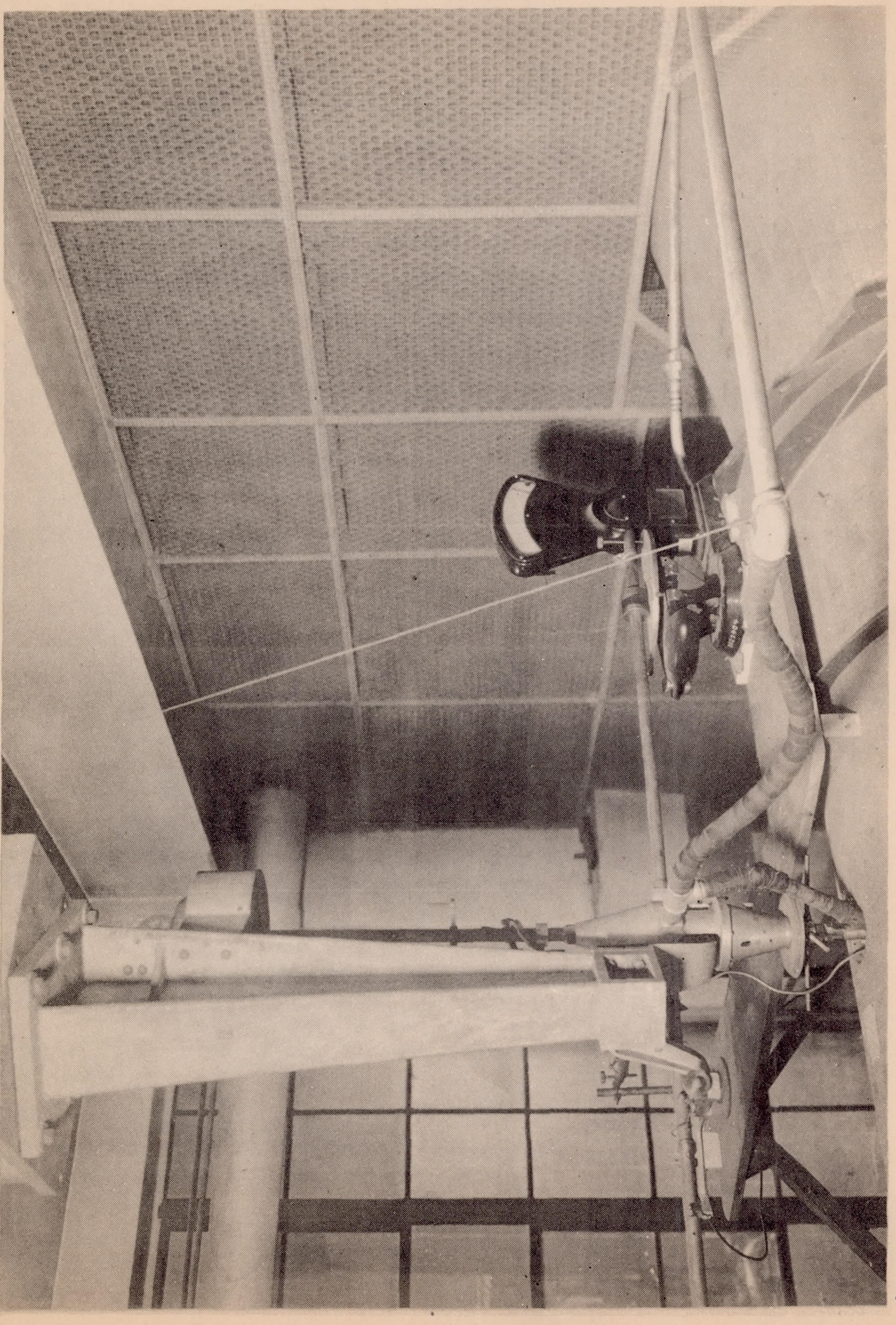

Fig. 2 General view of balance

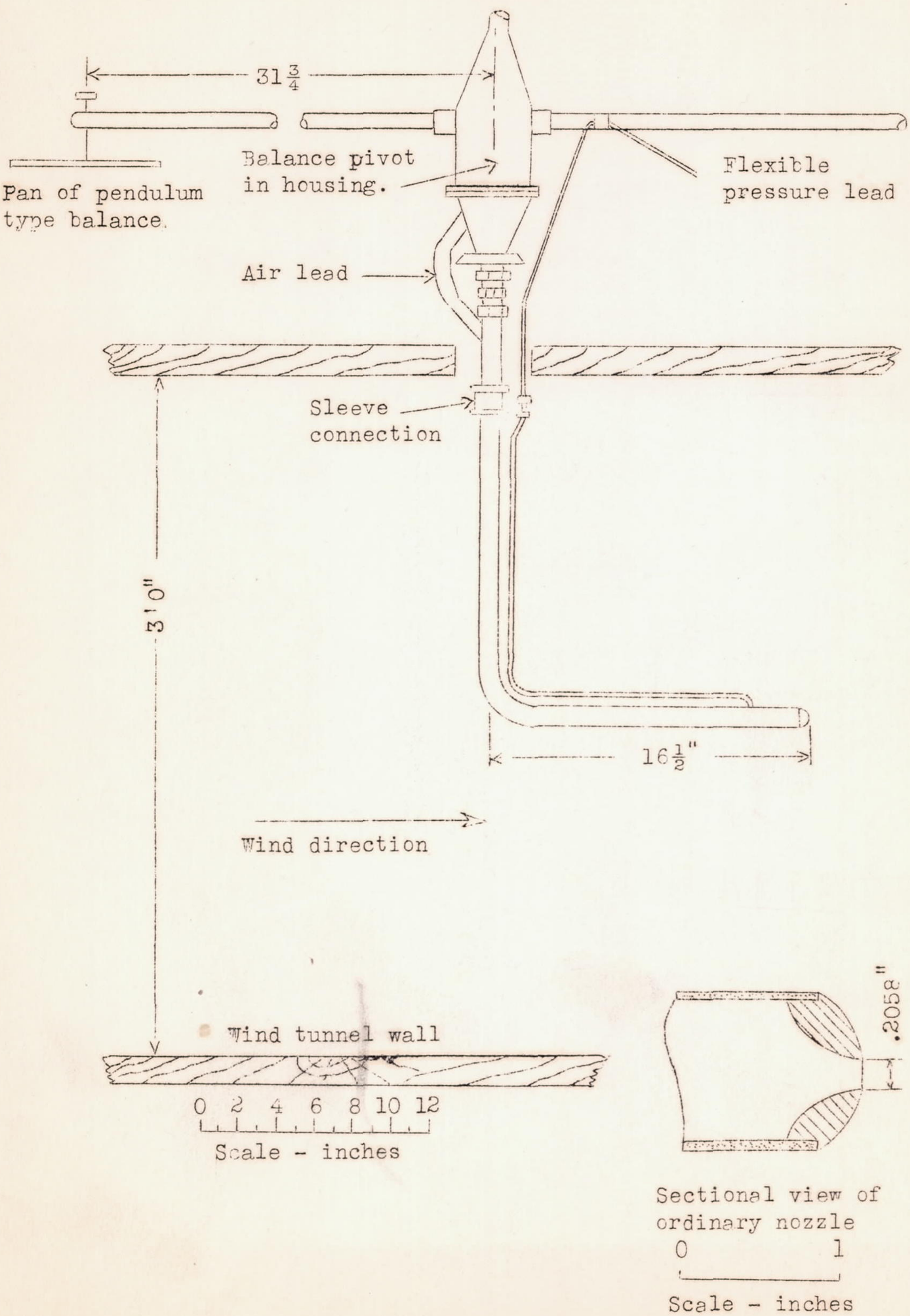

Figure 3. - Inverted N.P.L. balance, L-tube, and nozzle.

40

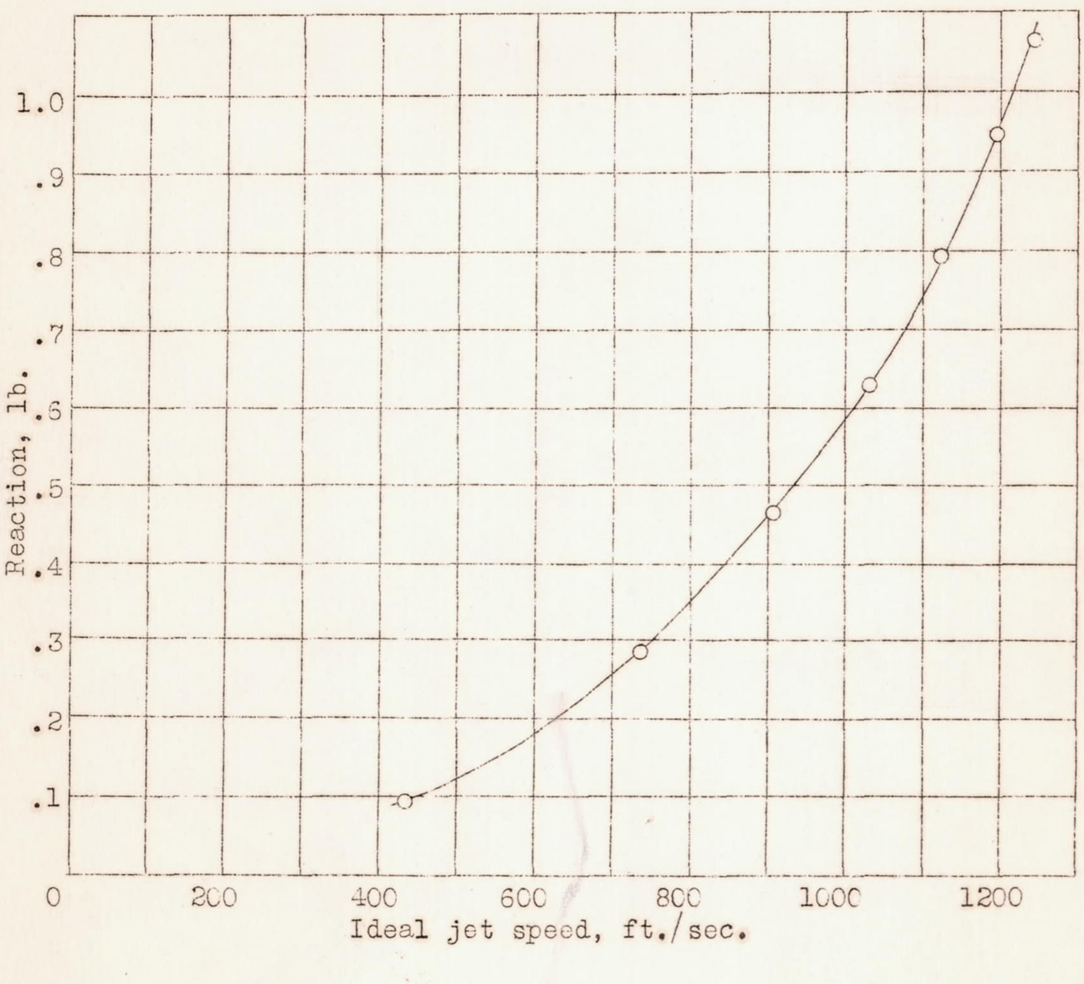

Figure 4.- Variation of observed free jet reaction with ideal jet speed, ordinary nozzle.

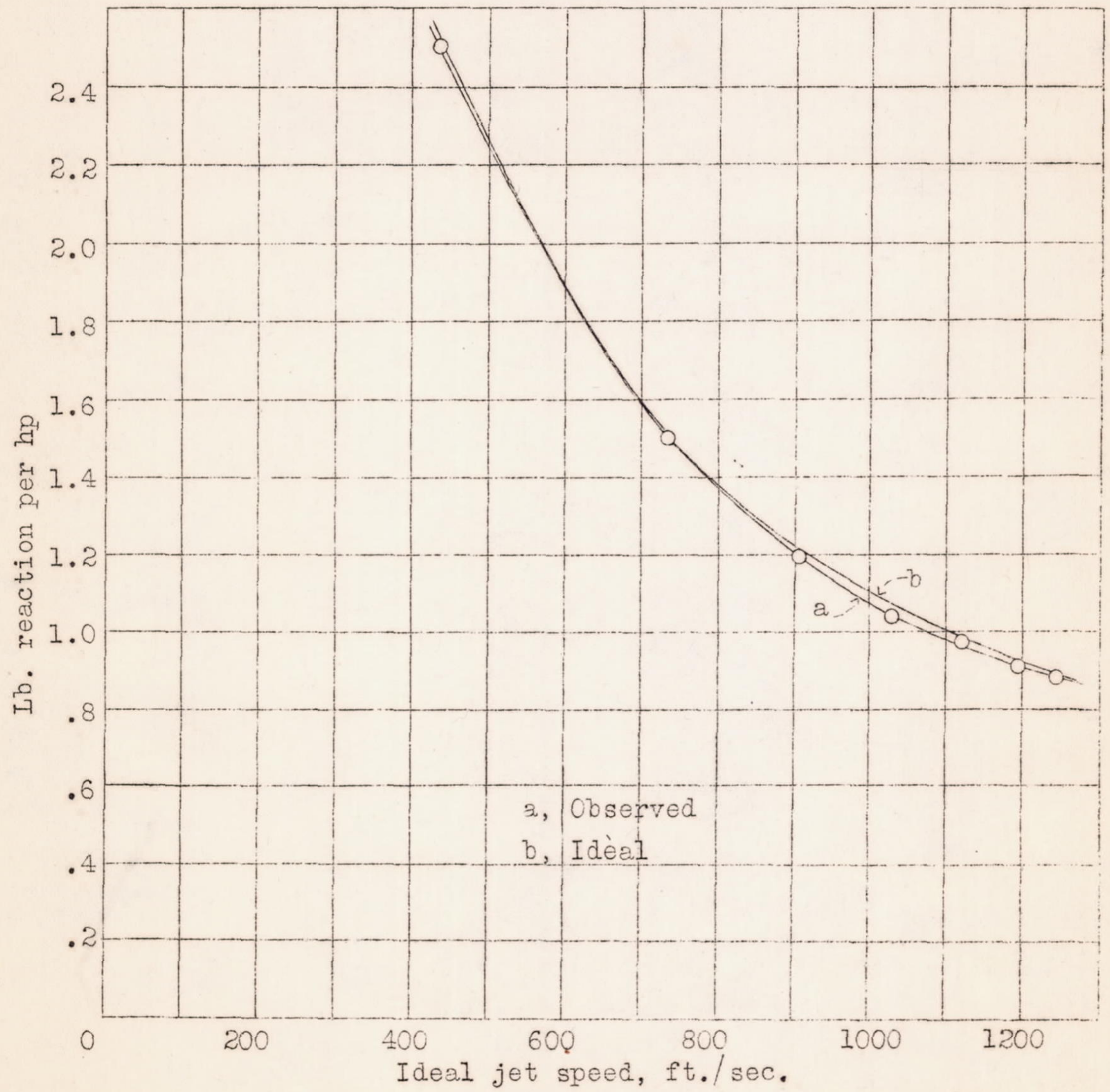

Figure 5.- Variation of lb. reaction per hp with ideal jet speed, free jet, ordinary nozzle.

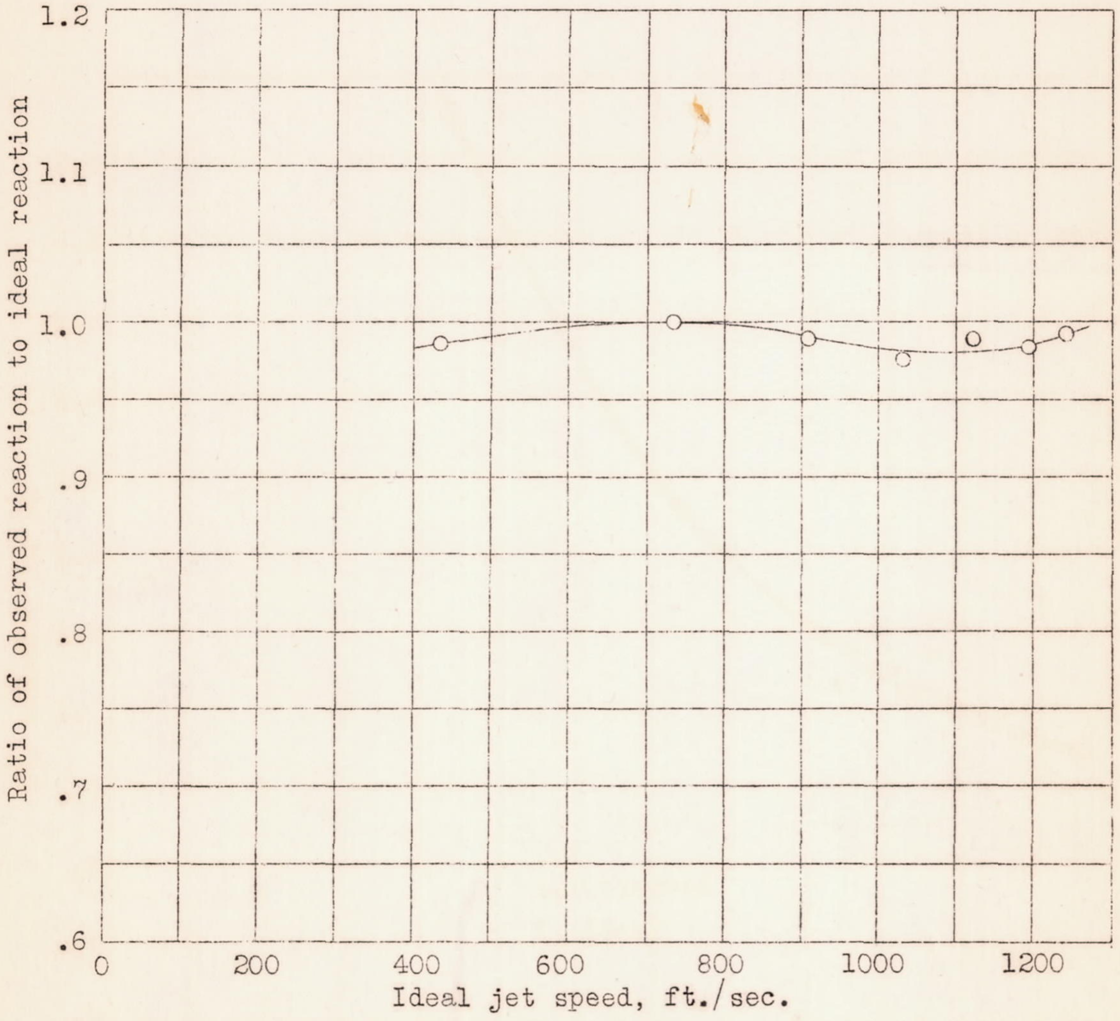

Figure 6.- Variation of ratio of observed free jet reaction to ideal free jet reaction with ideal jet speed.

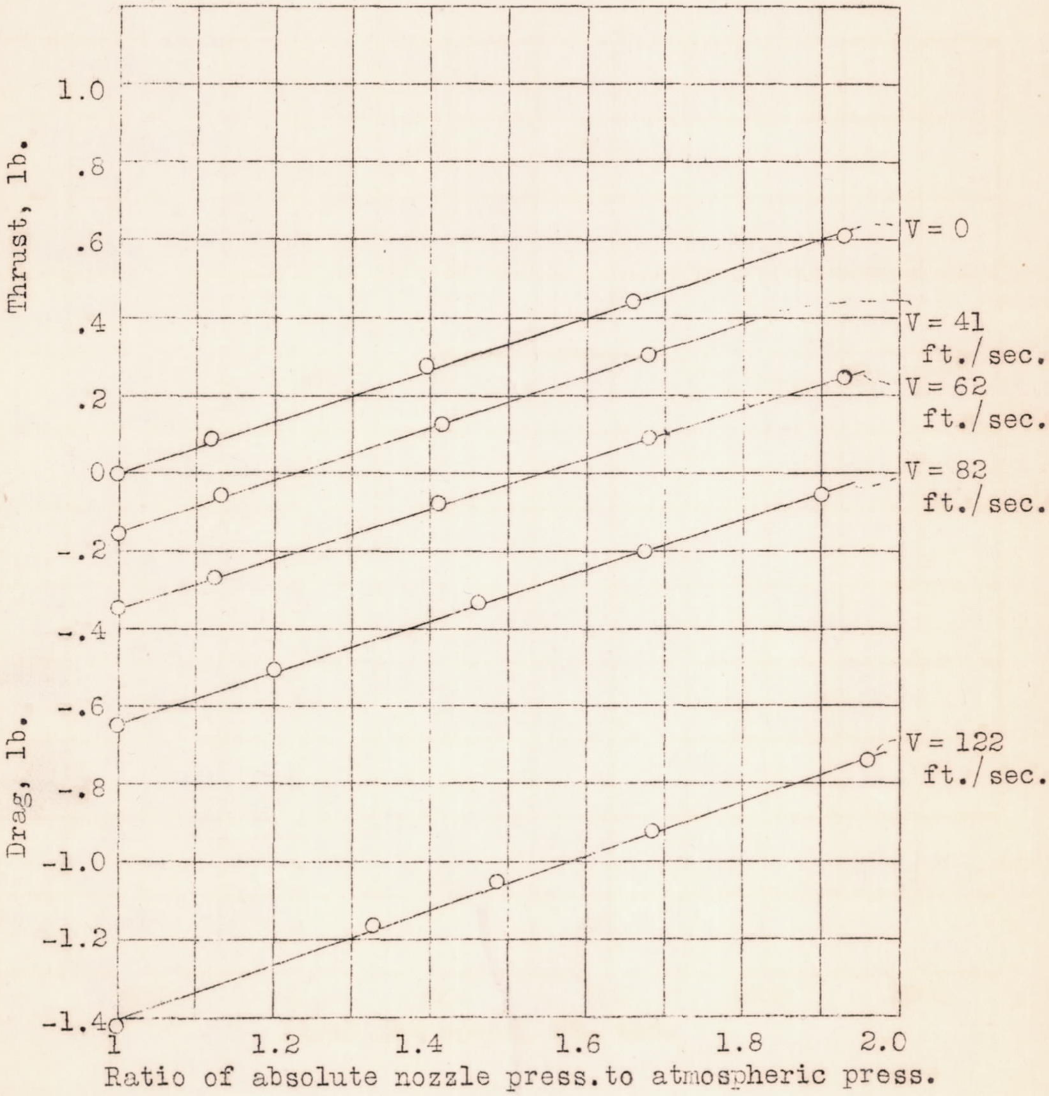

Figure 7.- Free jet reaction at various wind speeds.

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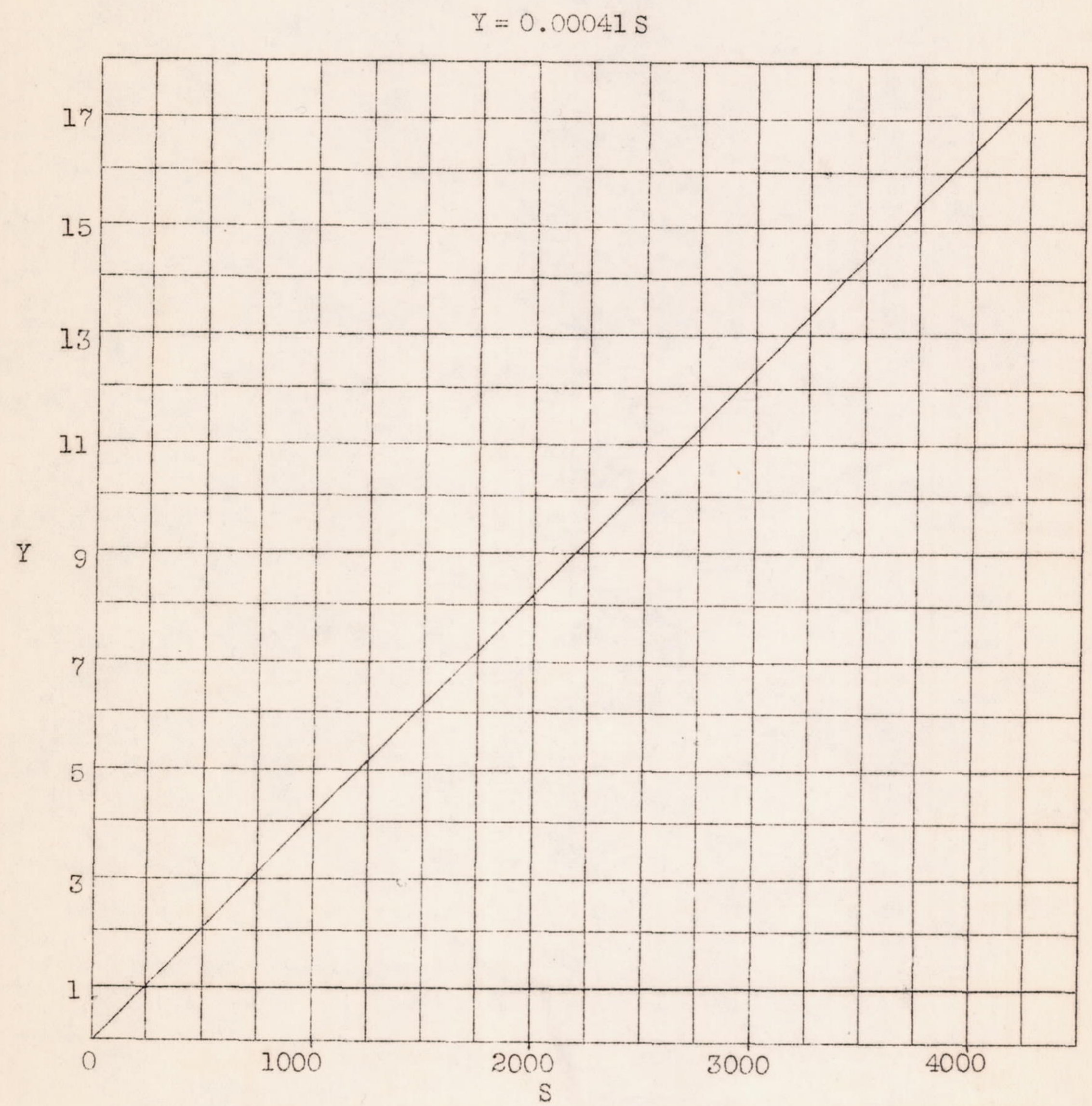

Figure 8. - Performance of augmented jet equal to that of screw propeller.

45

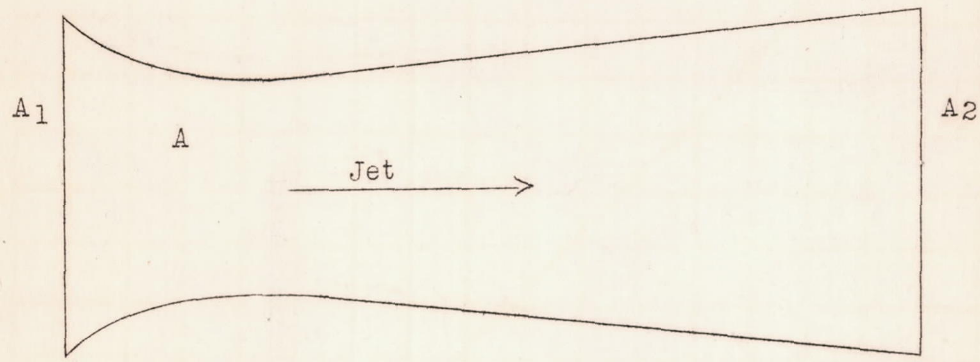

Figure 9. - Venturi tube

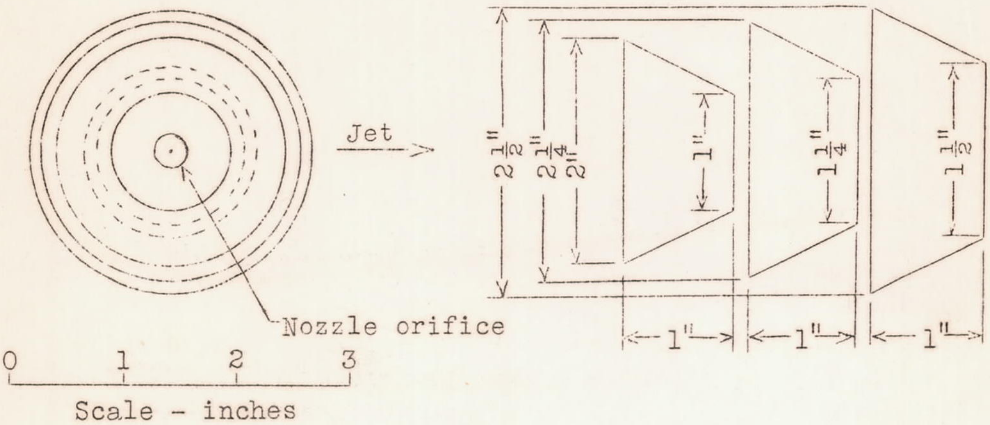

Figure 10.- Straight guide rings.

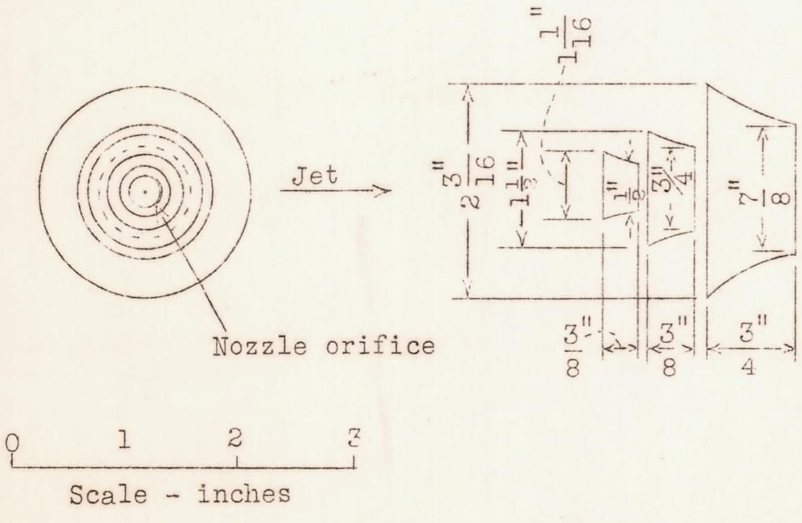

Figure 11.- Curved guide rings

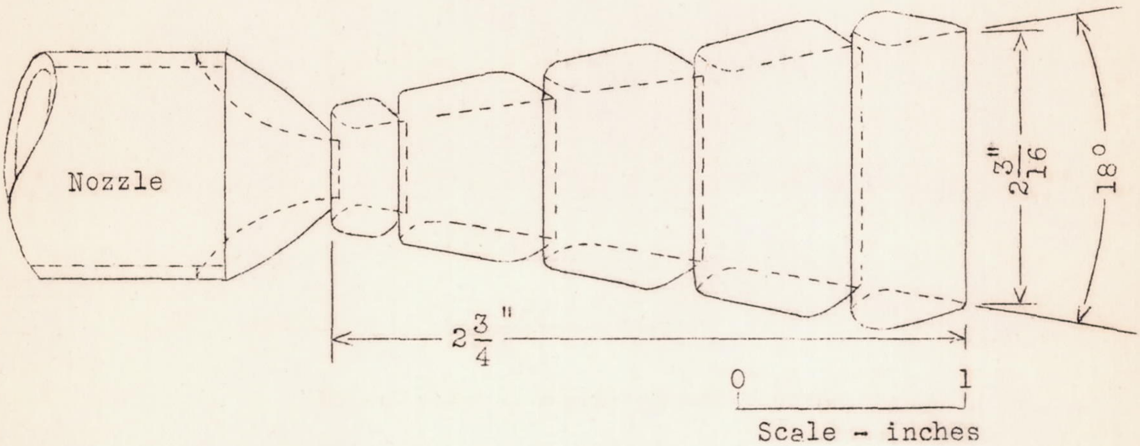

Figure 12.- Large slotted expanding cone or Venturi series.

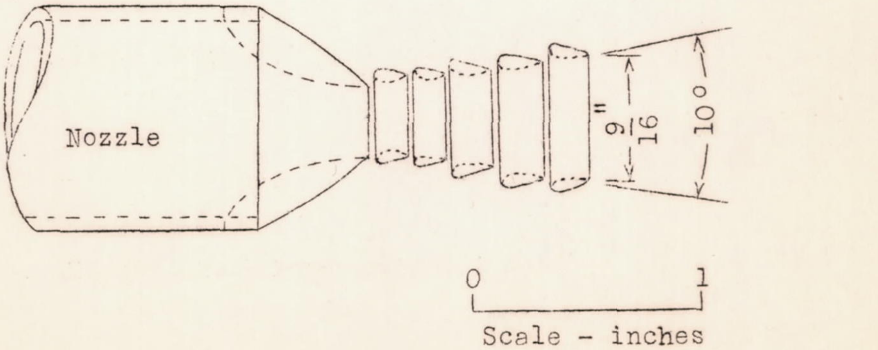

Figure 13.- Small slotted expanding cone or Venturi series.

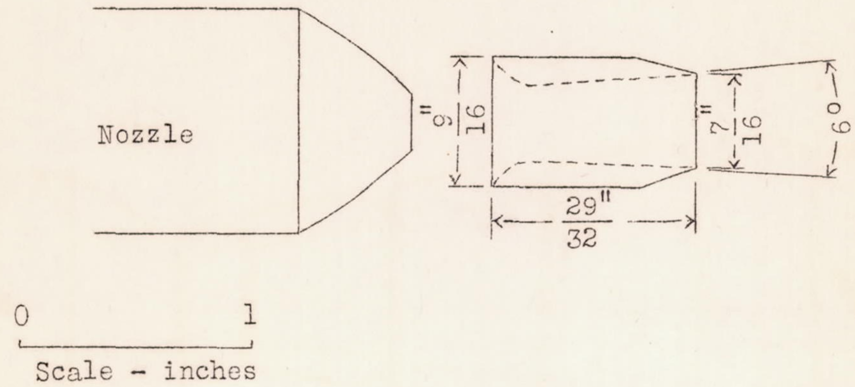

Figure 14. - Small curved throat Venturi.

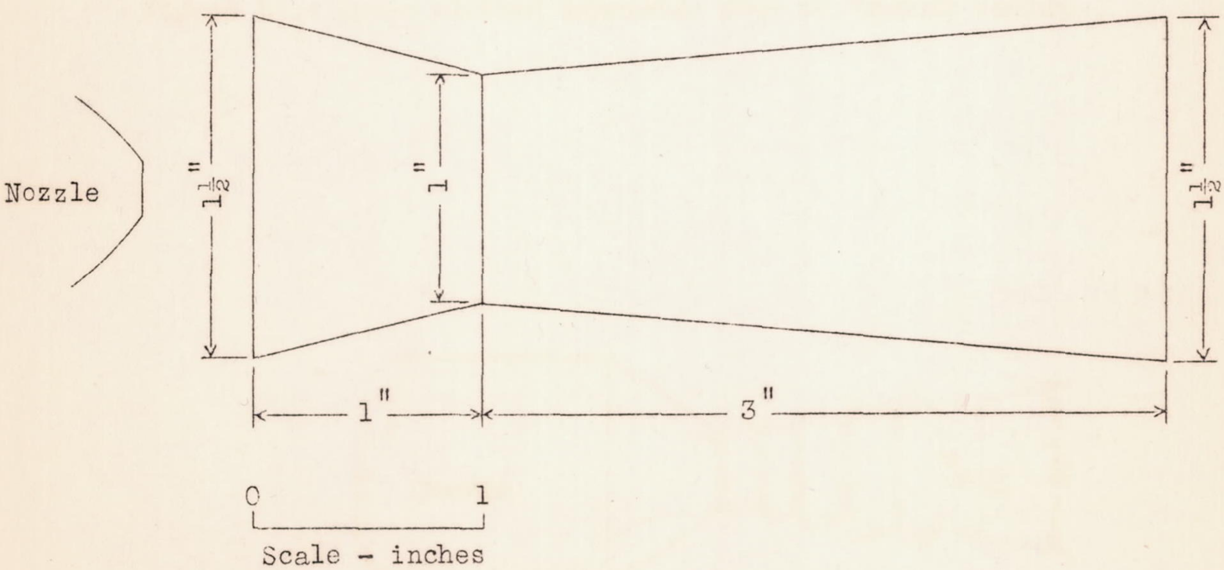

Figure 15a.- Angular throat Venturi with modifications.

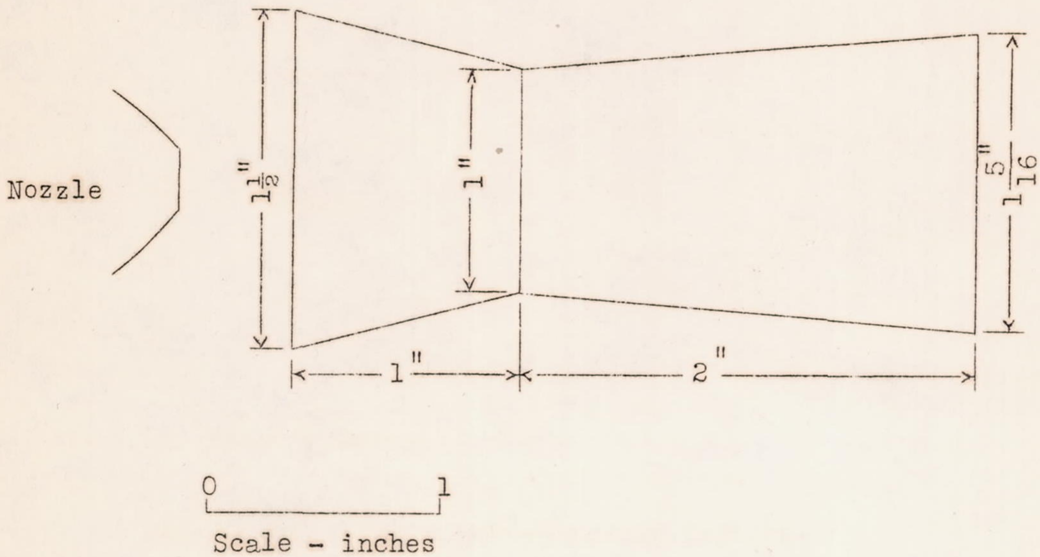

Figure 15 b

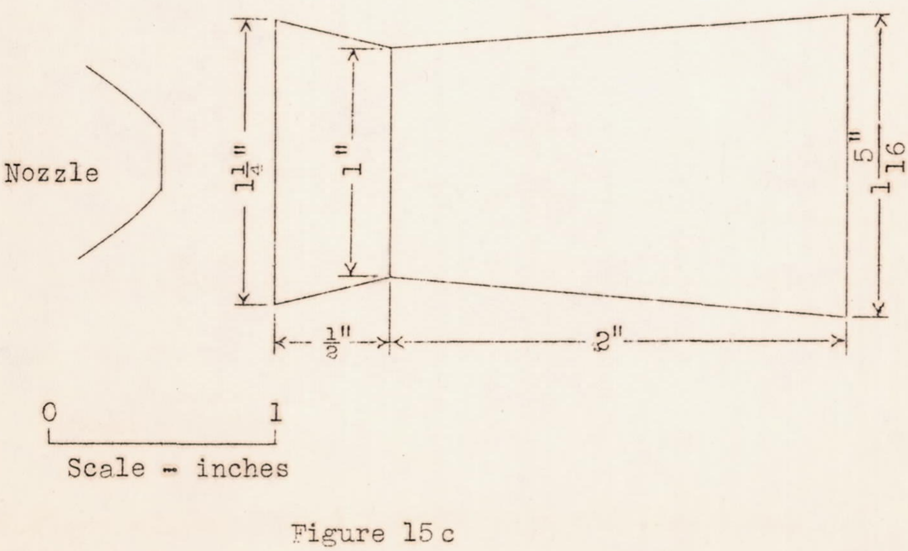

Figure 15 c

Figures 15b,15c. - Angular throat Venturi with modifications.

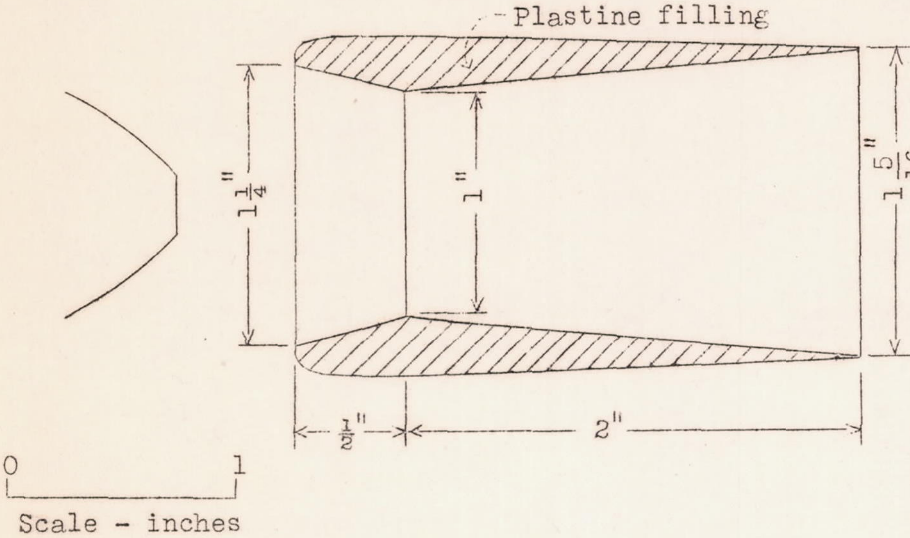

Figure 15d.

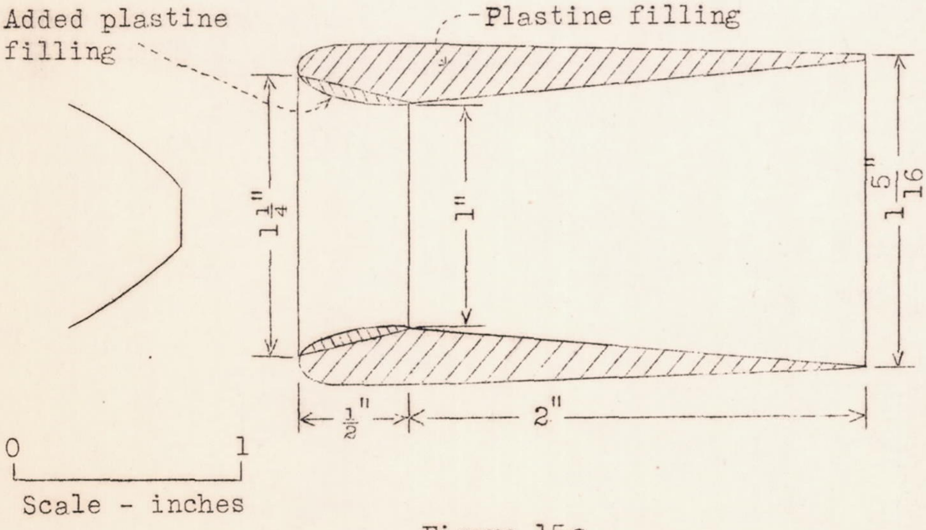

Figure 15e

Figures 15d, 15e. Angular throat Venturi with modifications.

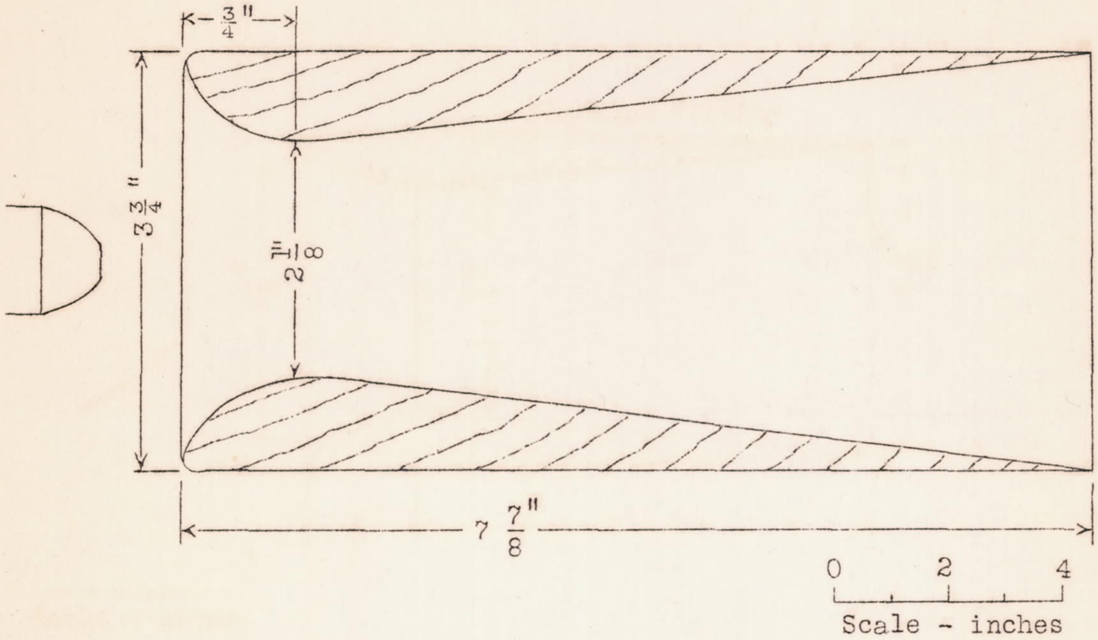

Figure 16.- Wooden Venturi with curved throat.

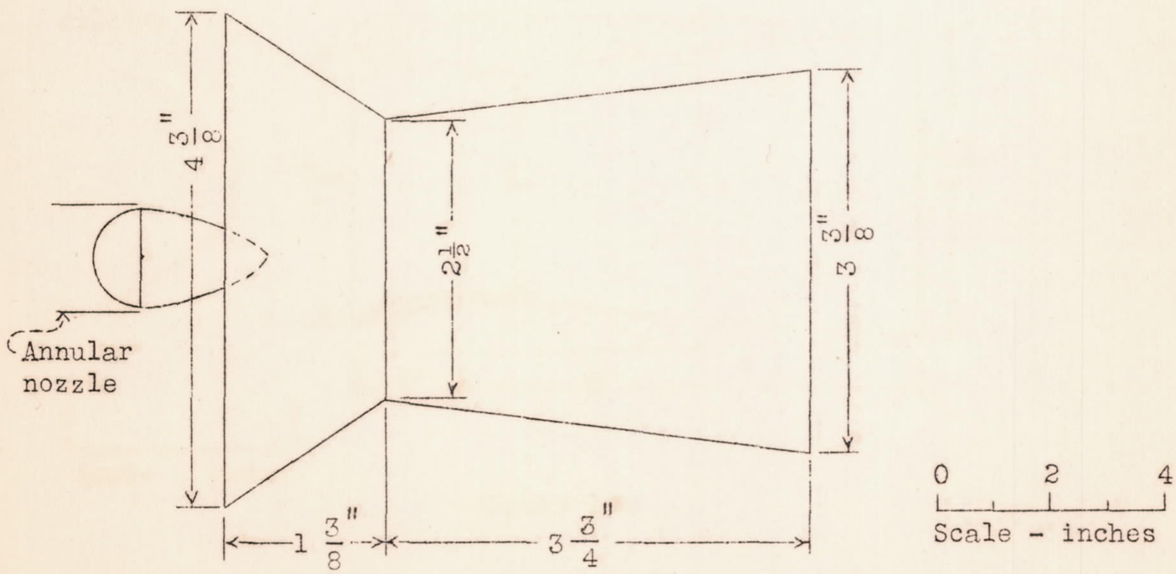

Figure 17. - Large Venturi with angular throat.

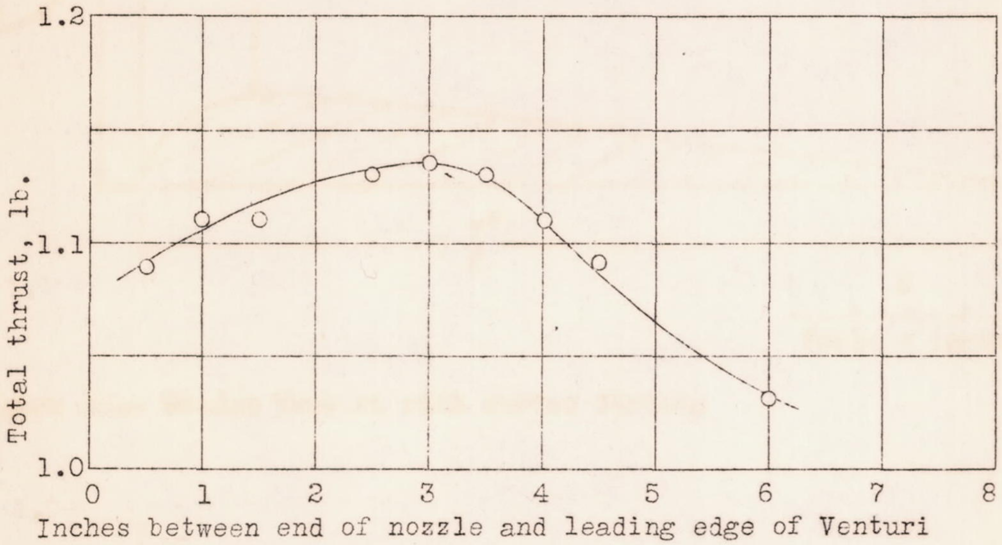

Figure 18. - Variation of force with position of Venturi (Fig.15d)

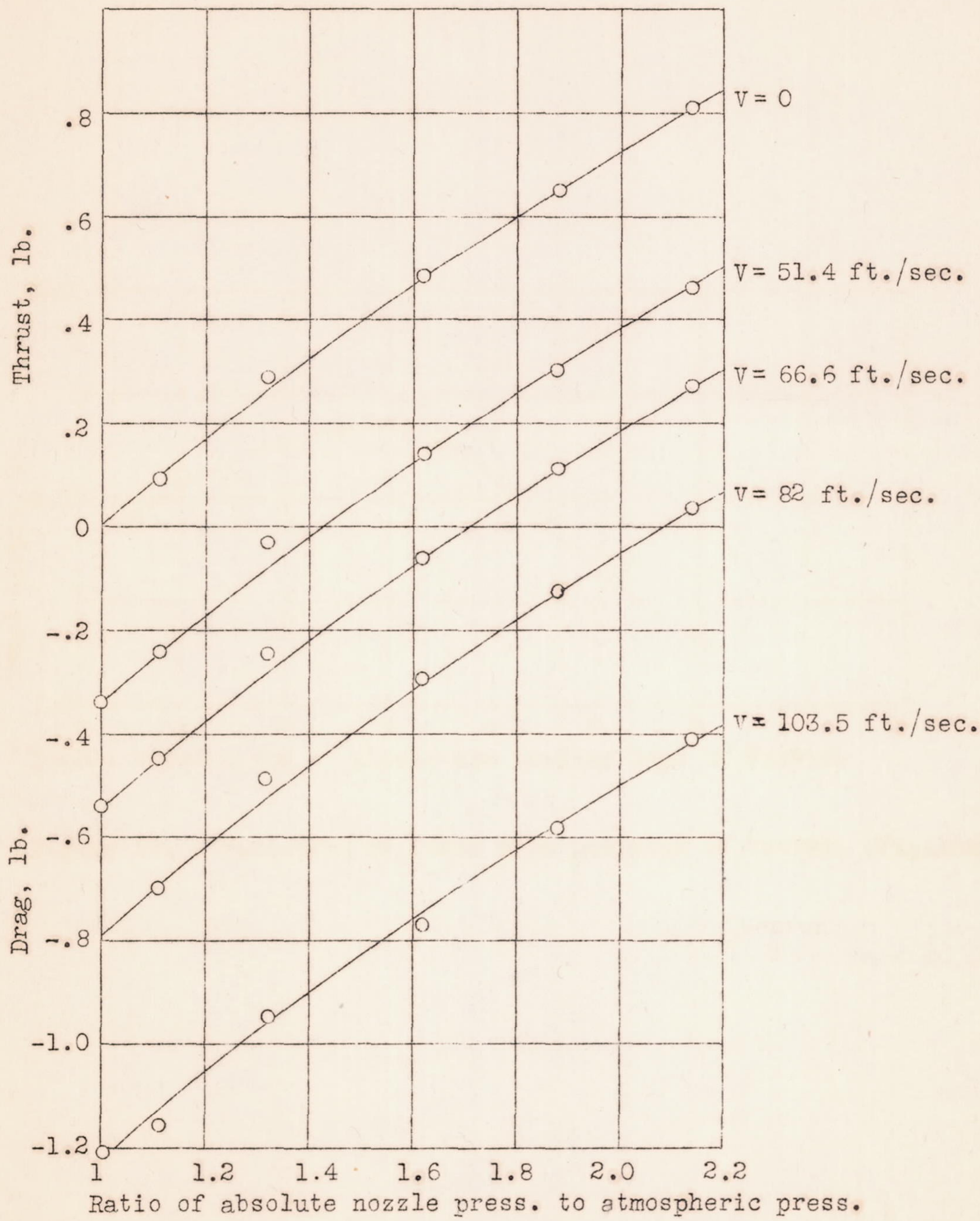

Figure 19. - Total force on Venturi (Fig. 16) and L- tube, wind and jet.

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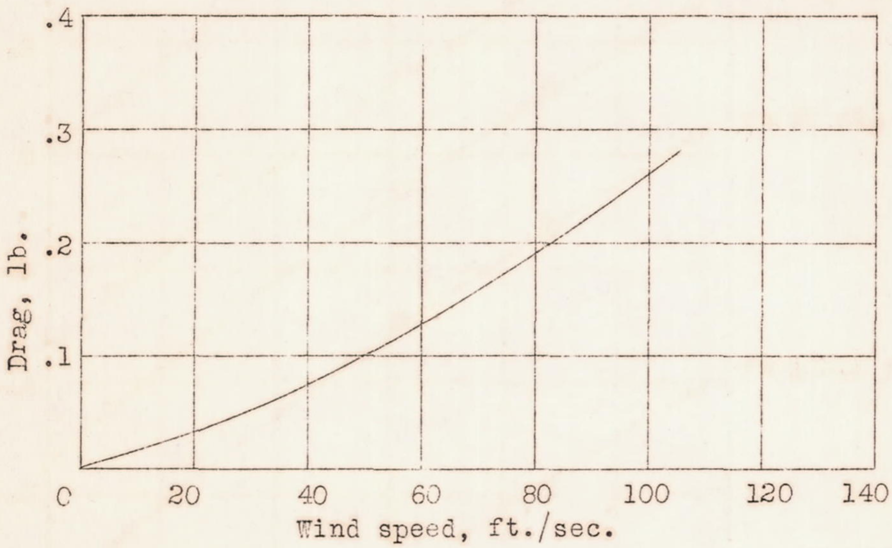

Figure 20. - Drag contributed to L- tube by Venturi tube (Fig. 16)

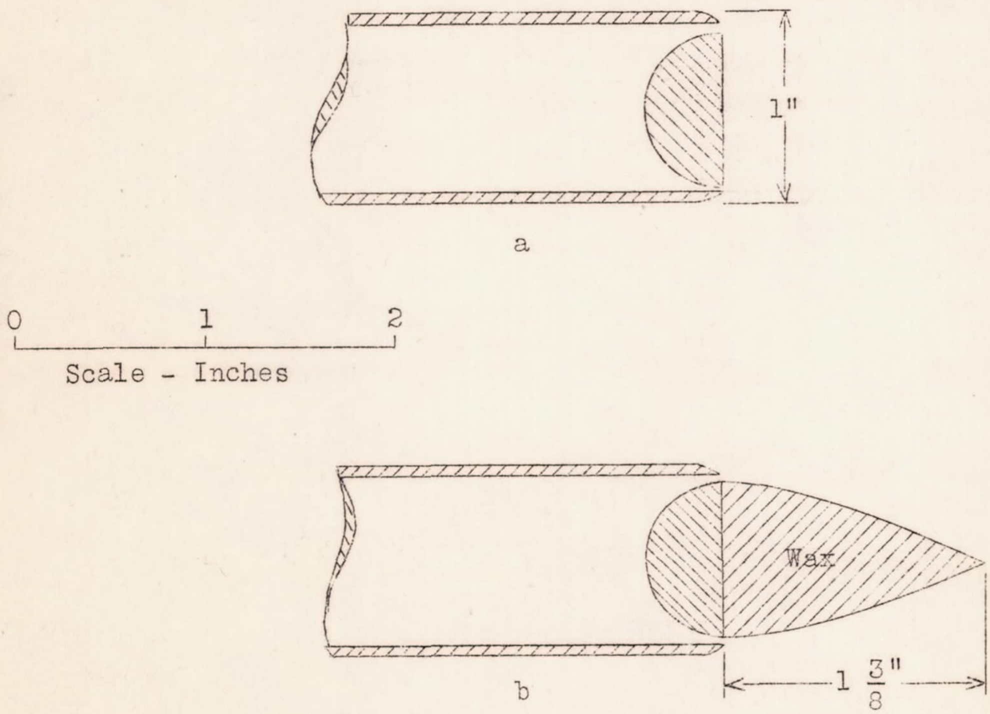

Figure 21.-Annular nozzle.

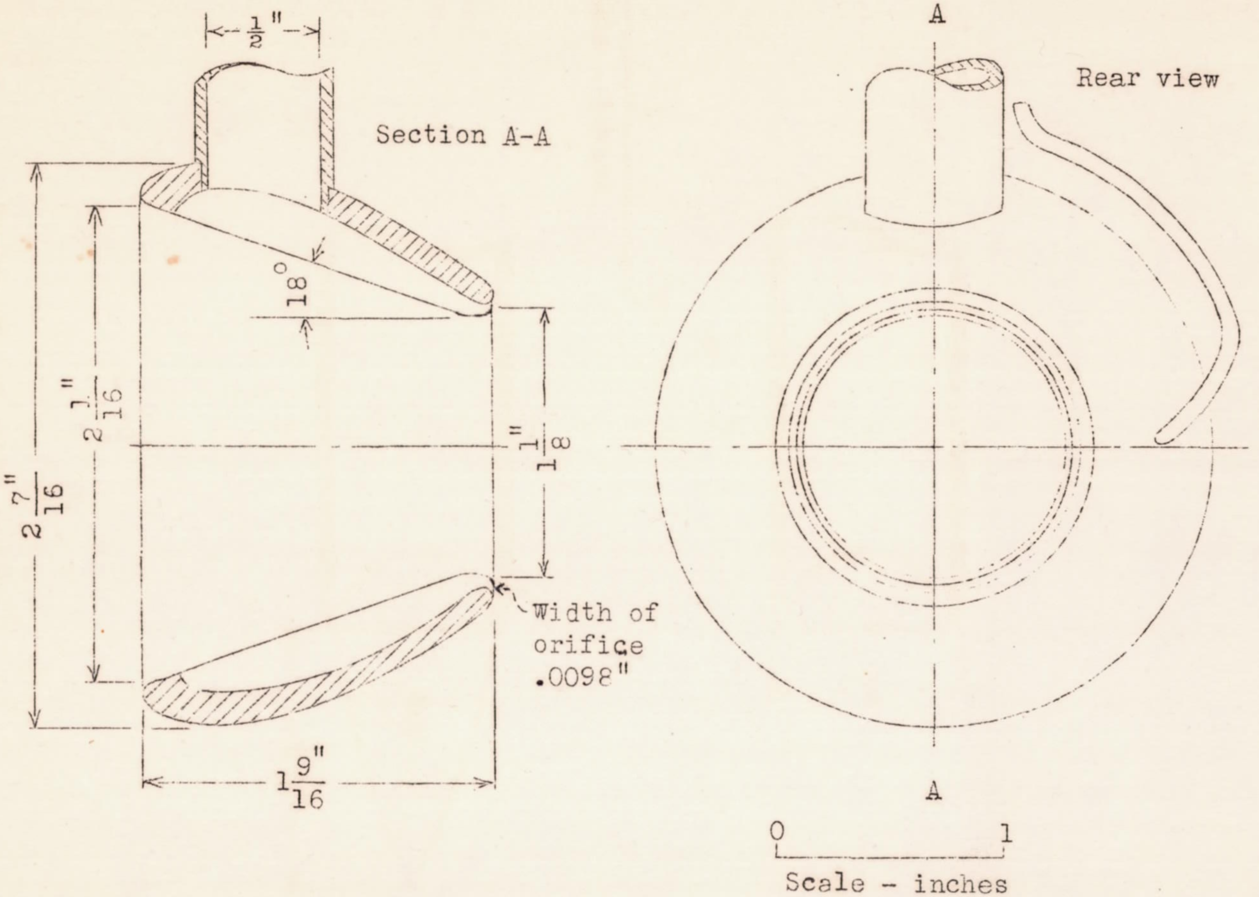

Figure 22. - Annular nozzle No. 1

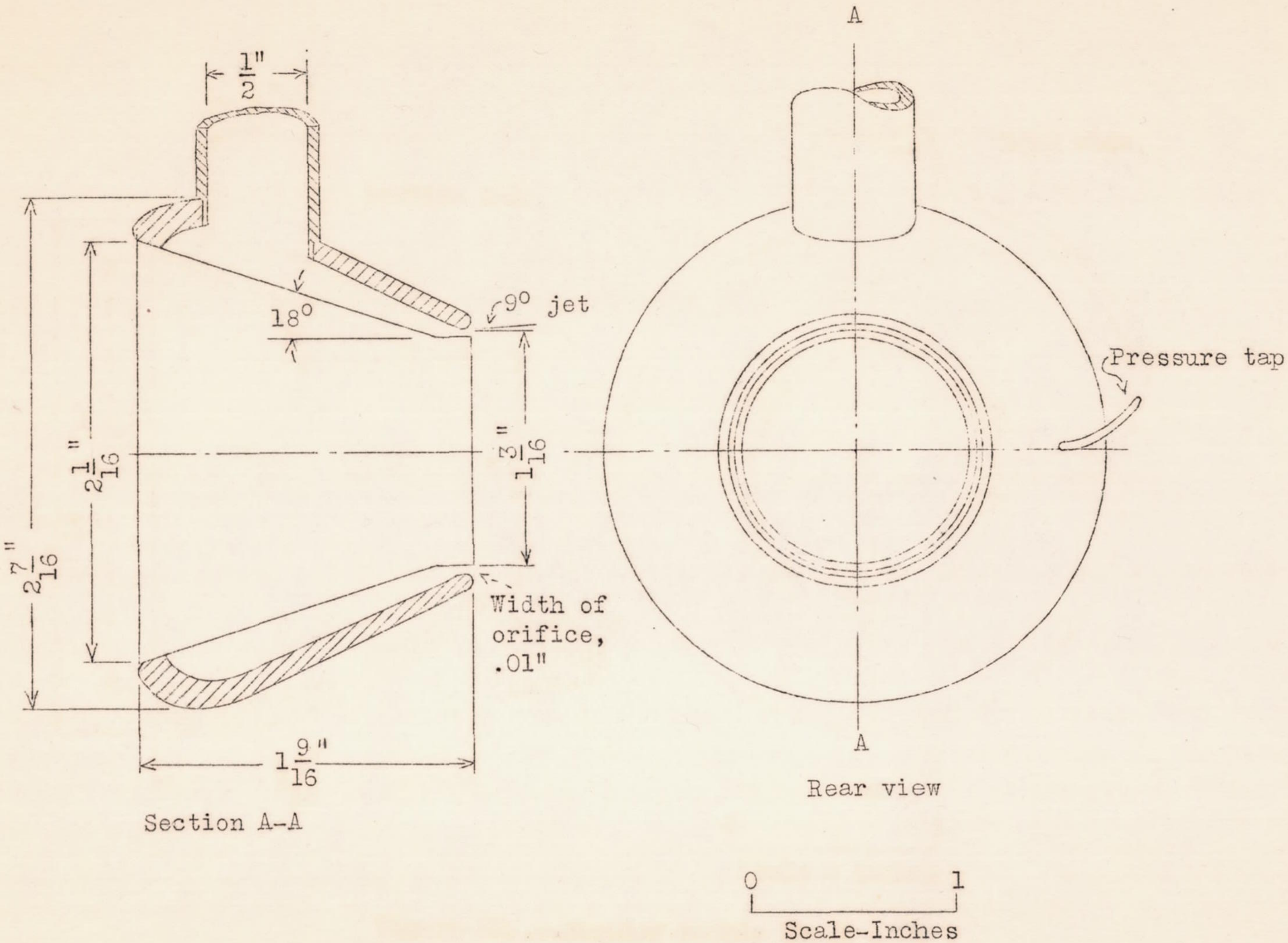

Figure 23.-Annular nozzle No.2

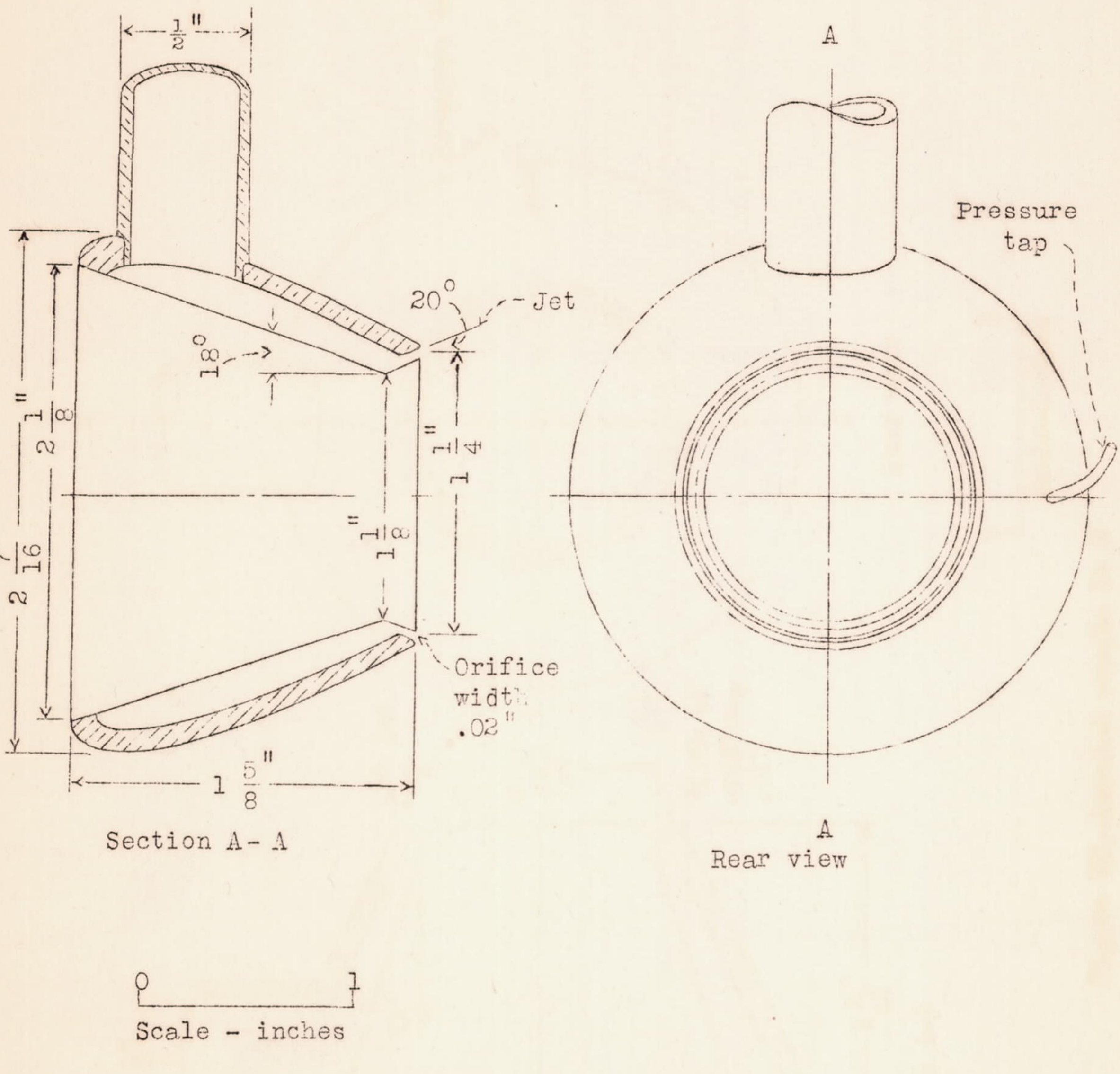

Figure 24. - Annular nozzle No. 3.

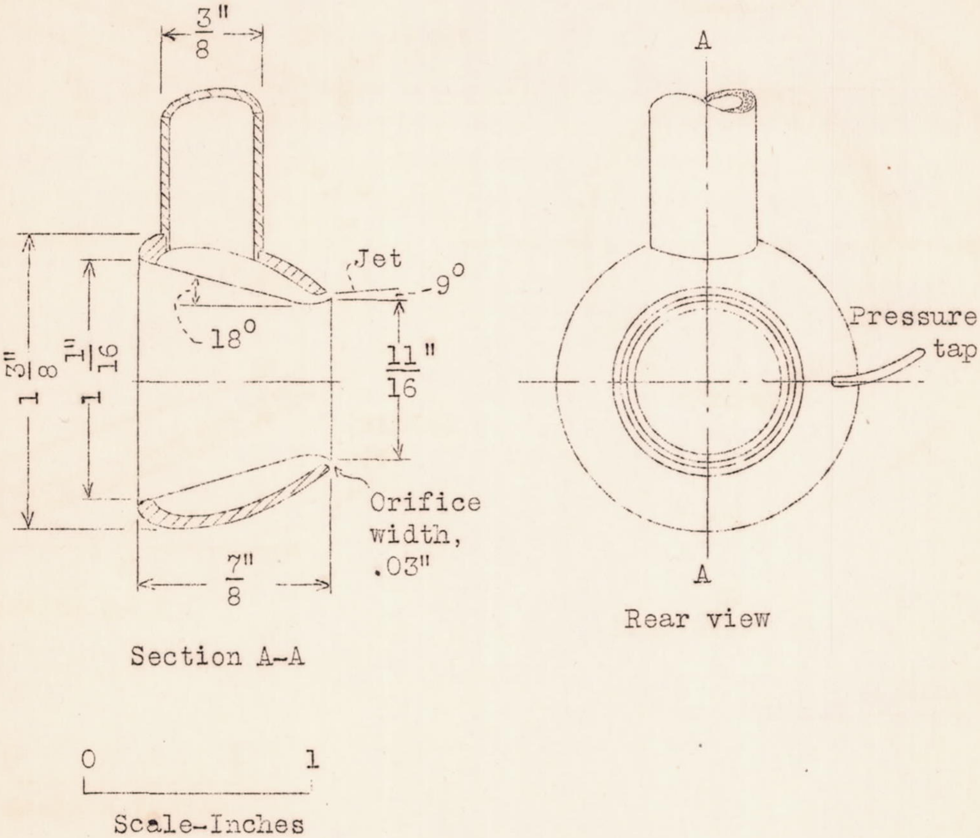

Figure 25.-Annular nozzle No.4

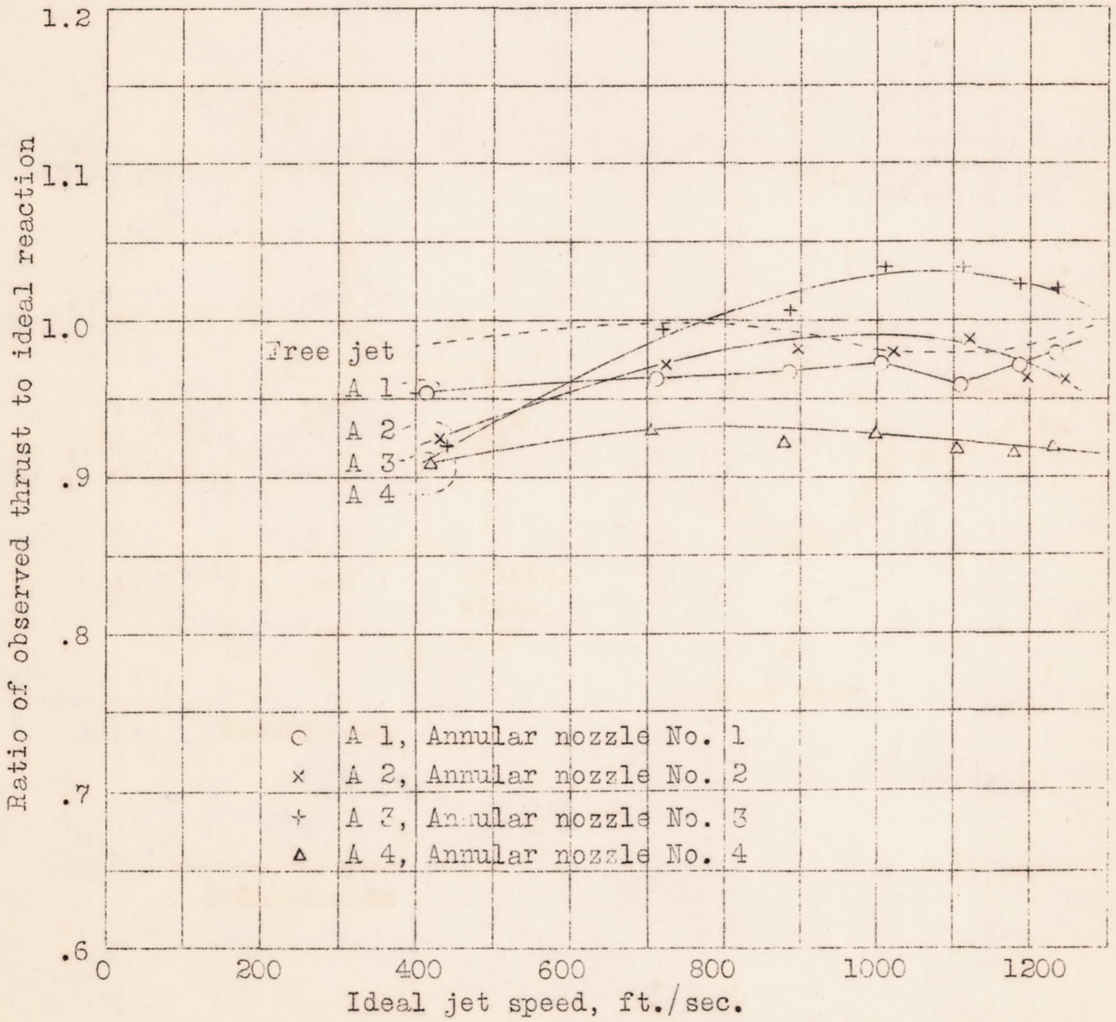

Figure 26.- Variation of ratio of observed total thrust to ideal jet reaction with ideal jet speed.

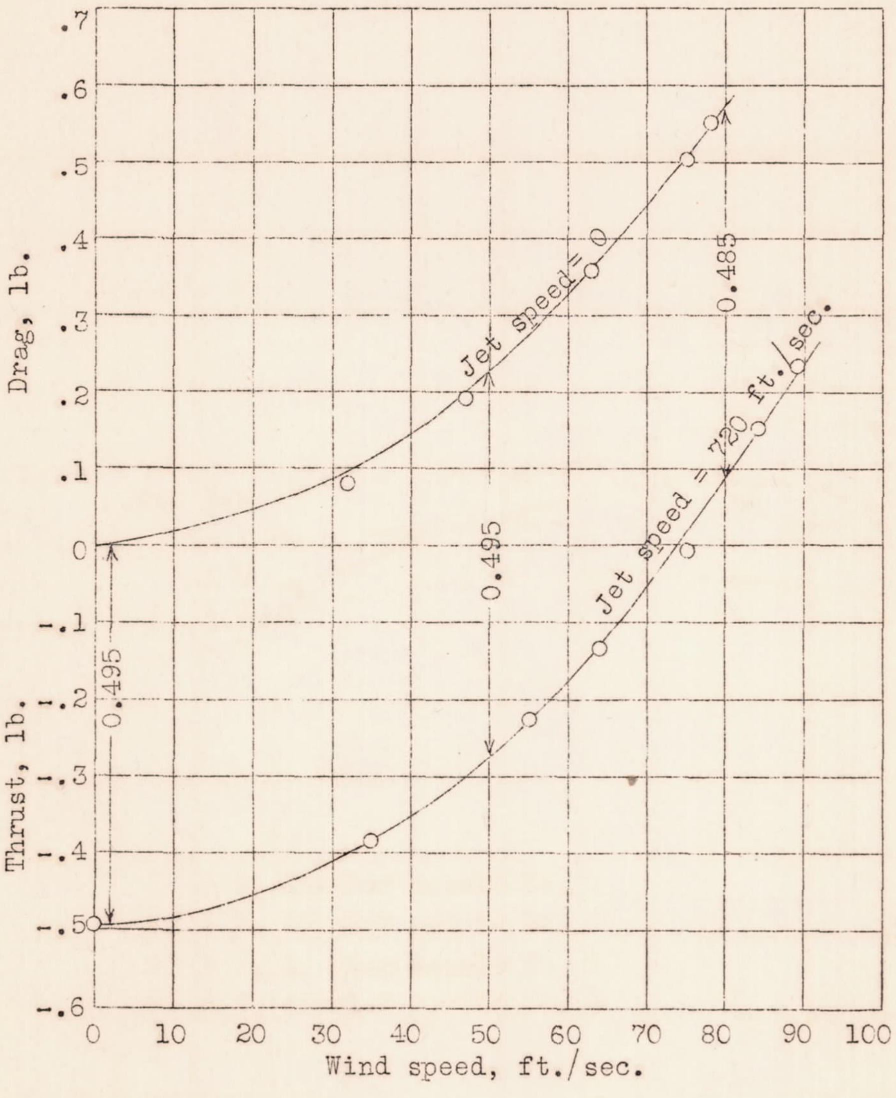

Figure 27.- Drag of annular nozzle No.3 showing effect of jet

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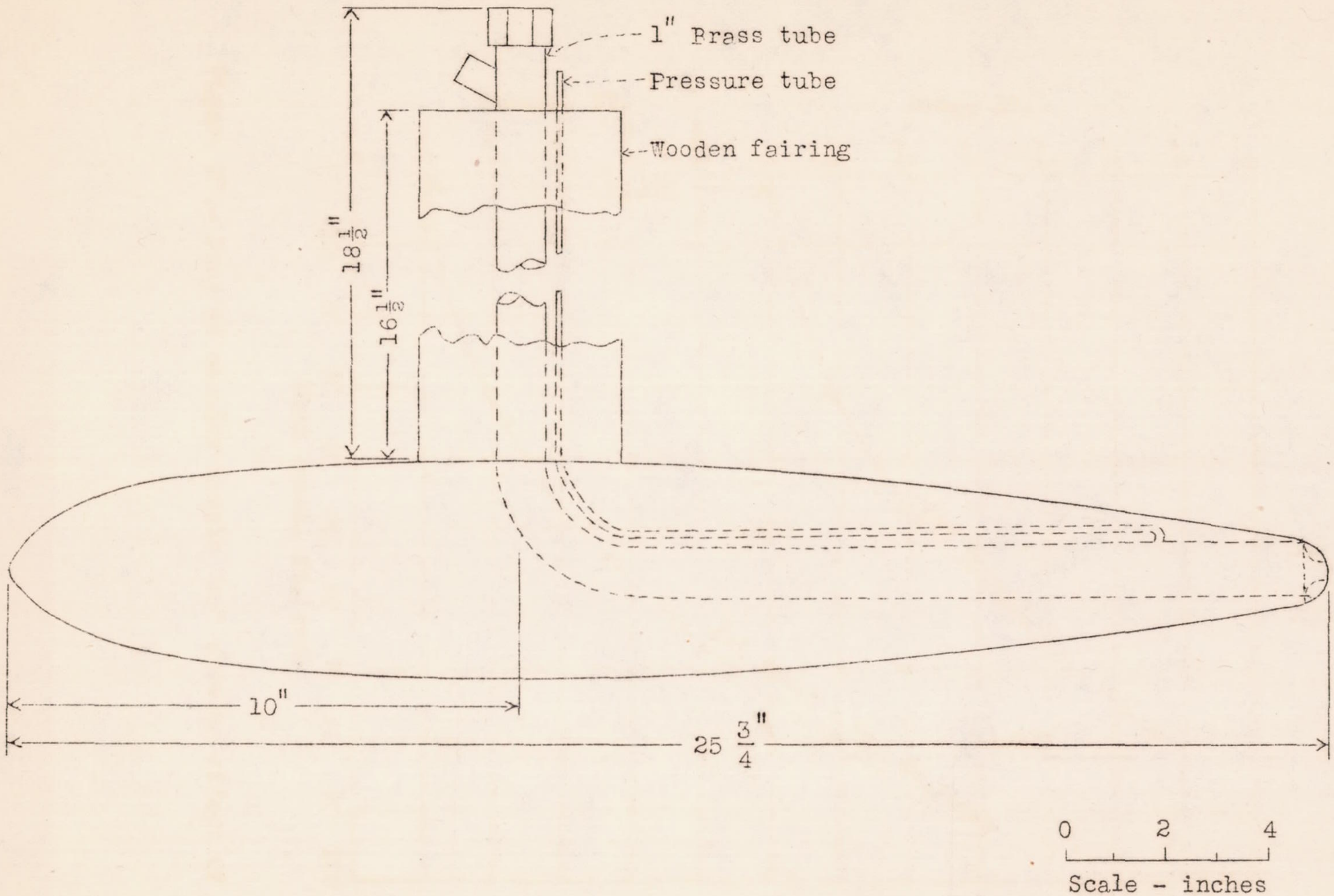

Figure 28. - Airship model, ordinary nozzle in tail.

63

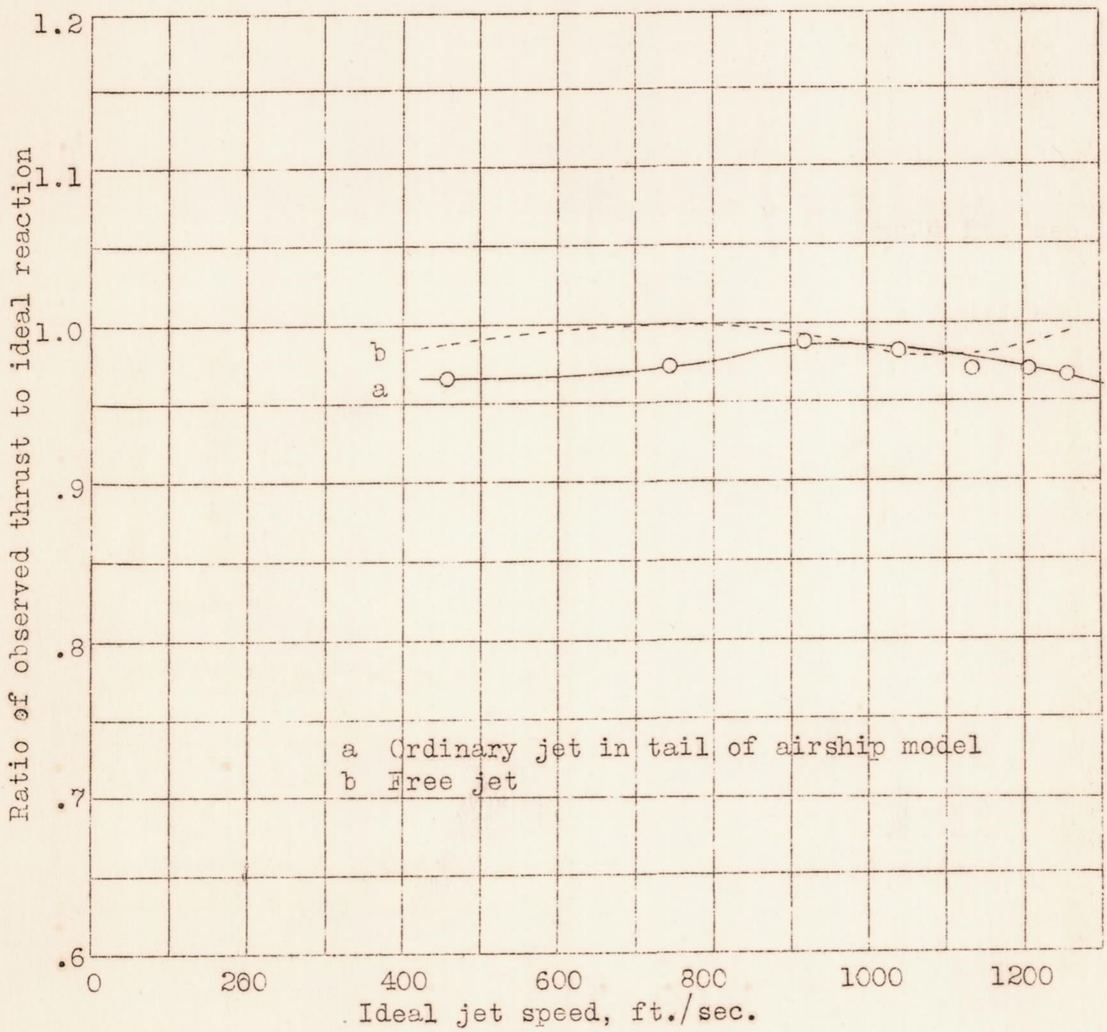

Figure 29.- Variation of ratio of observed total thrust to ideal jet reaction with ideal jet speed.

64

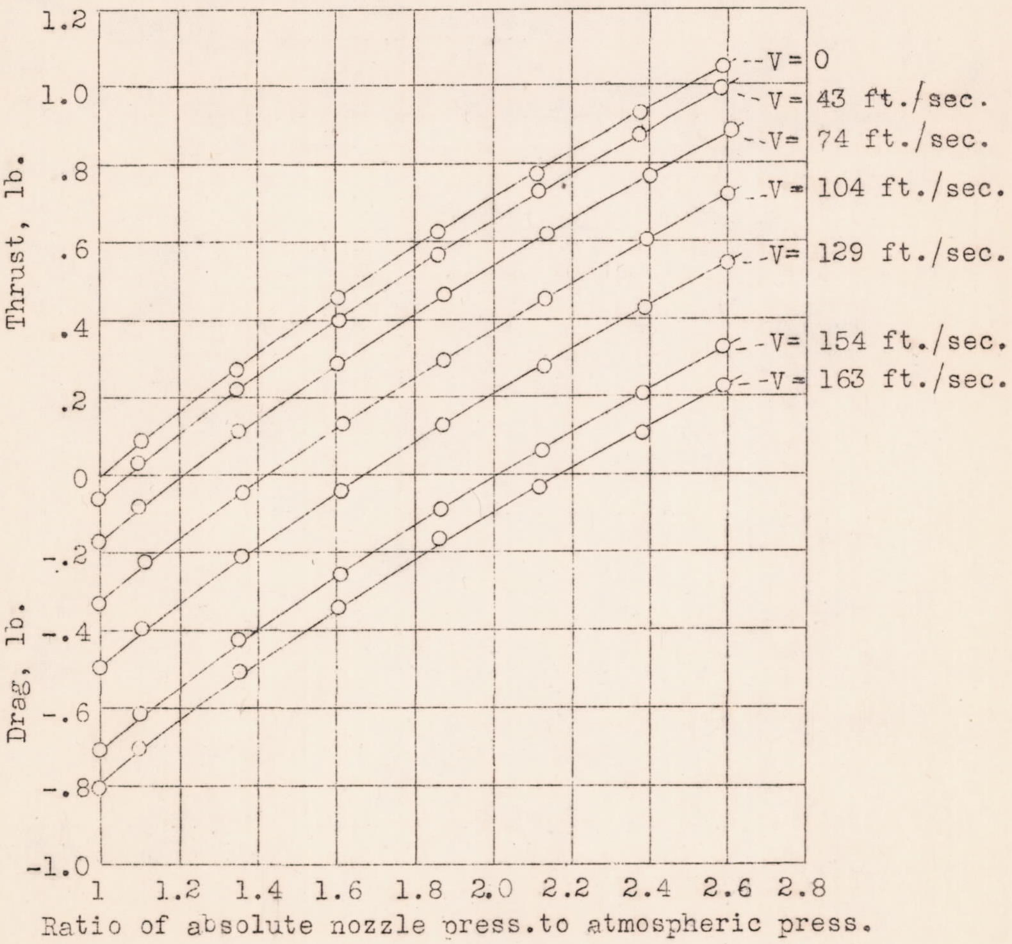

Figure 30.- Total force on airship model and support (Fig. 28), wind and jet, ordinary nozzle in tail.

65

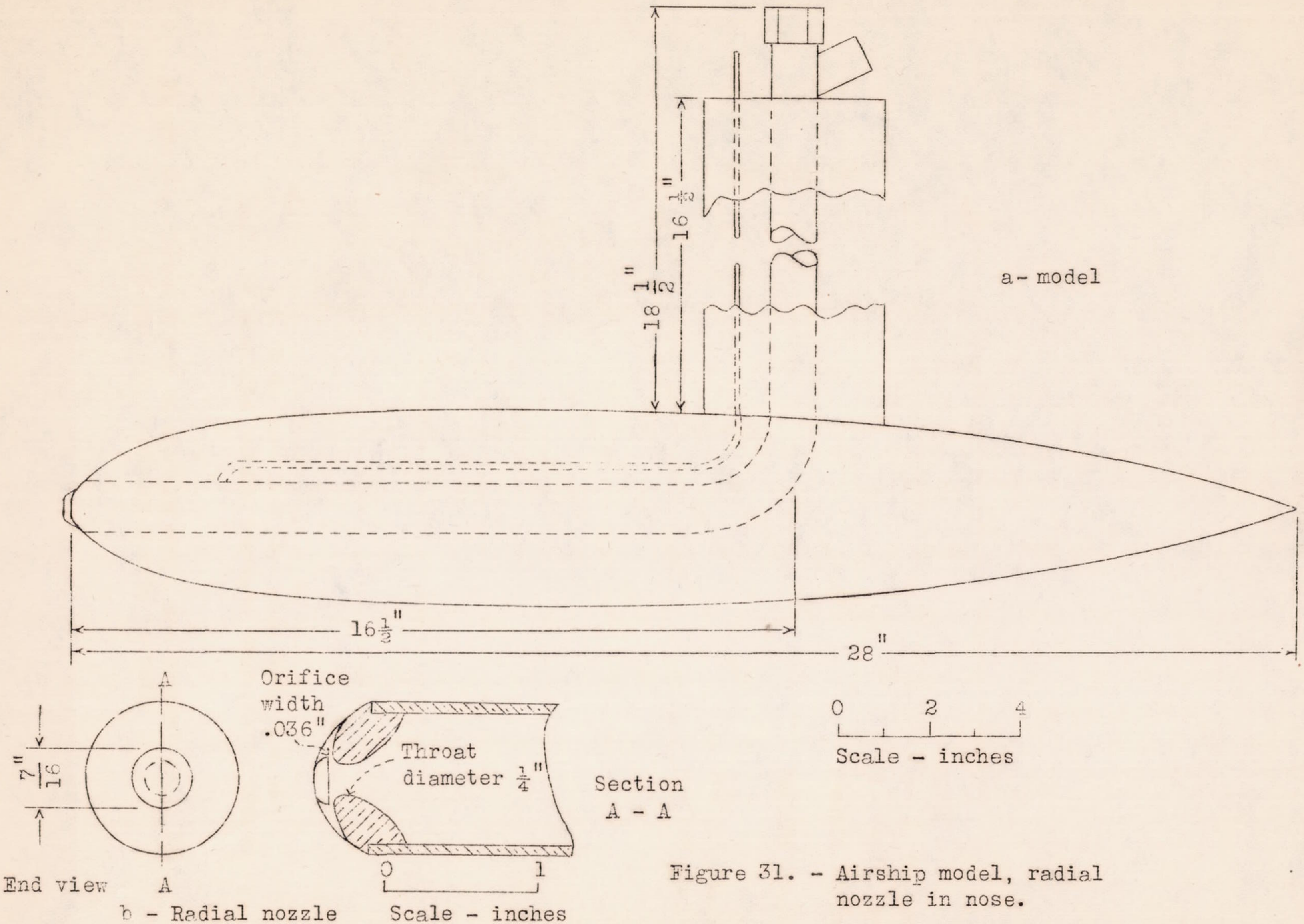

Figure 31. - Airship model, radial nozzle in nose.

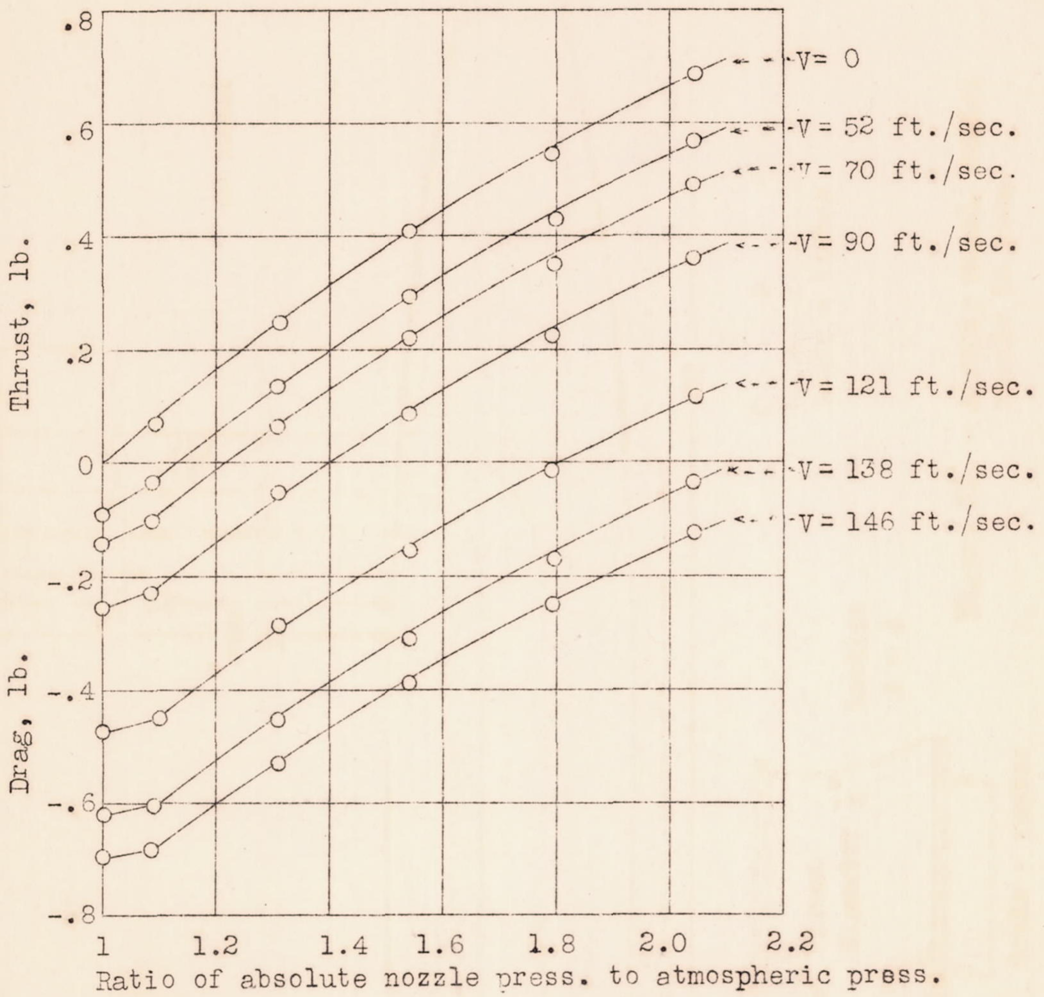

Figure 32. - Total force on airship model and support (Fig. 31), wind and jet, radial nozzle in nose.

67

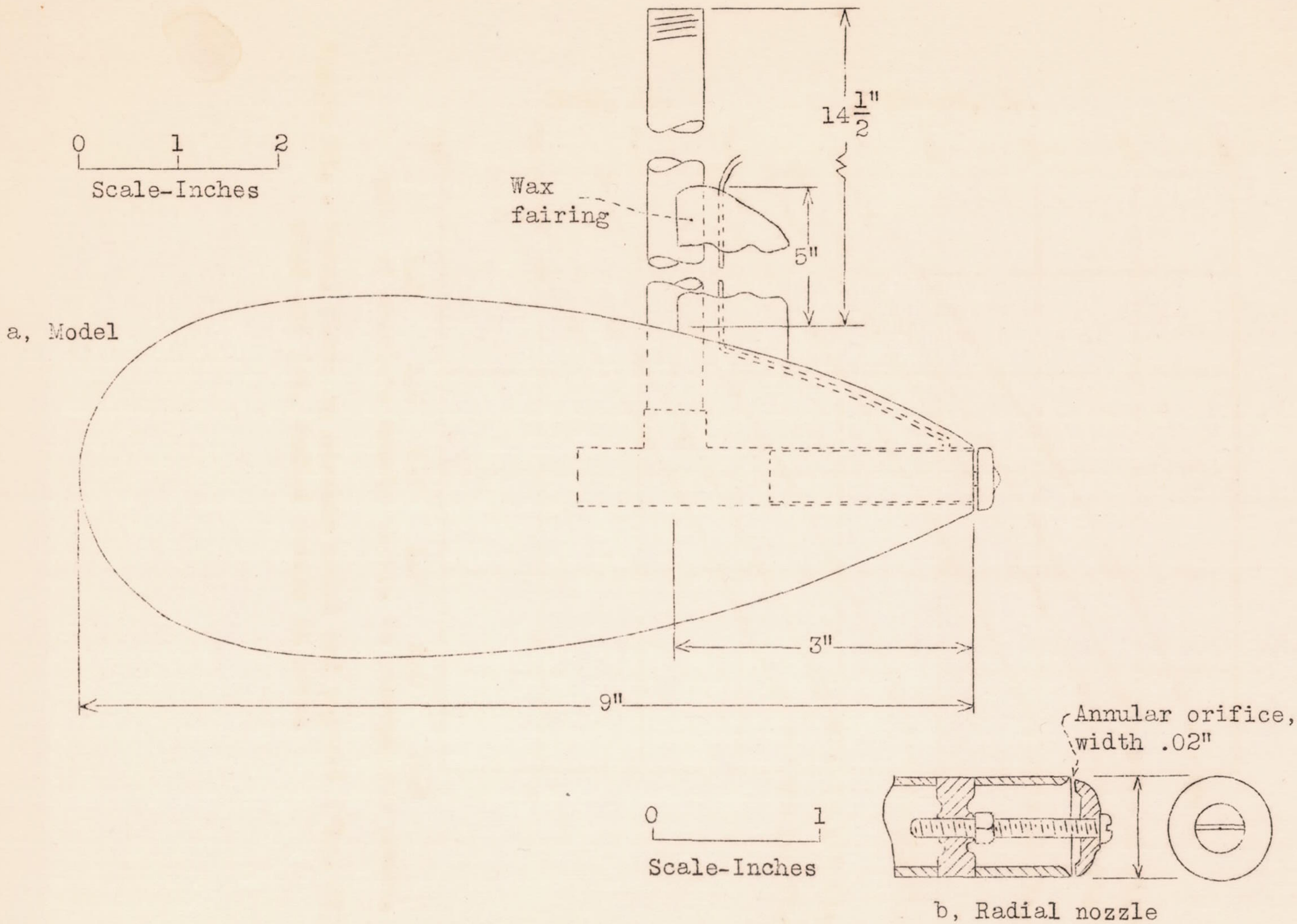

Figure 33.-Airship model,radial nozzle in tail.

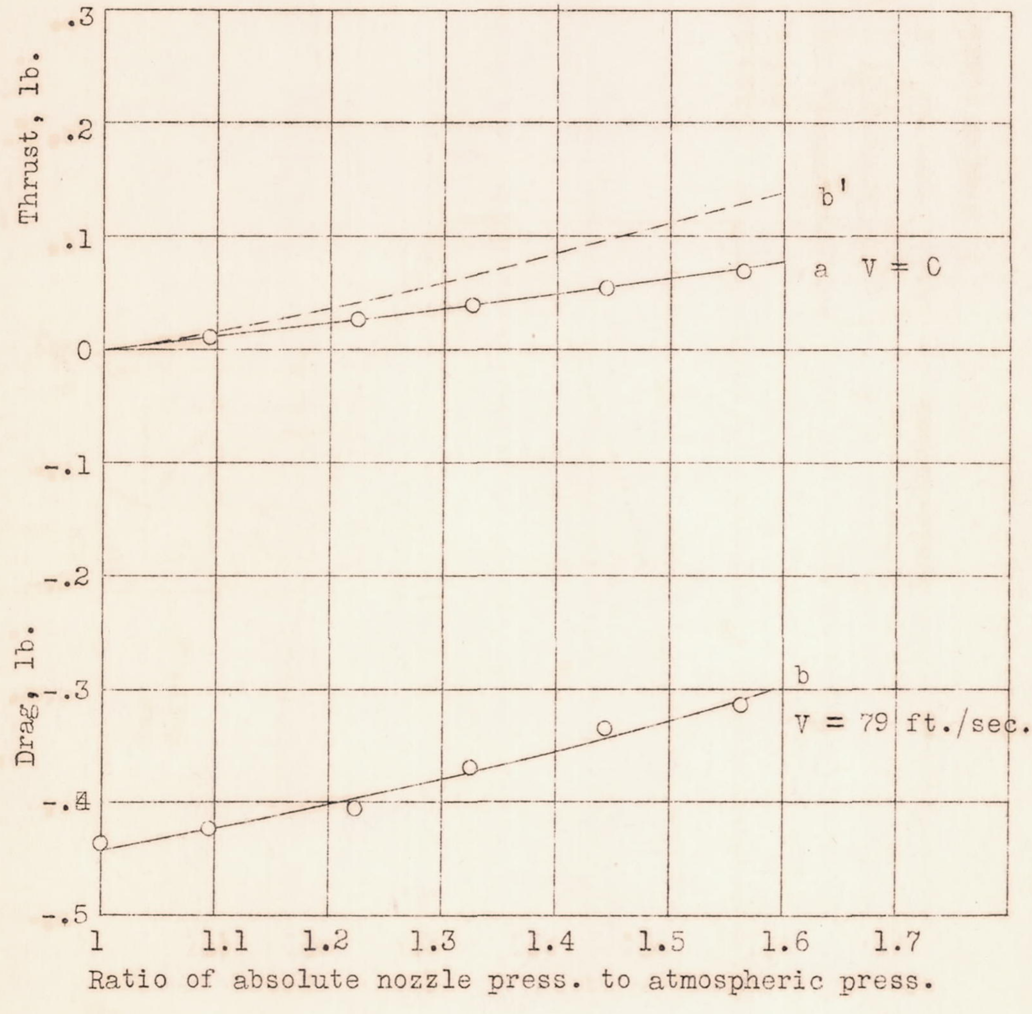

Figure 34. - Total force on airship model and support (Fig. 33), wind and jet, radial nozzle in tail.

69

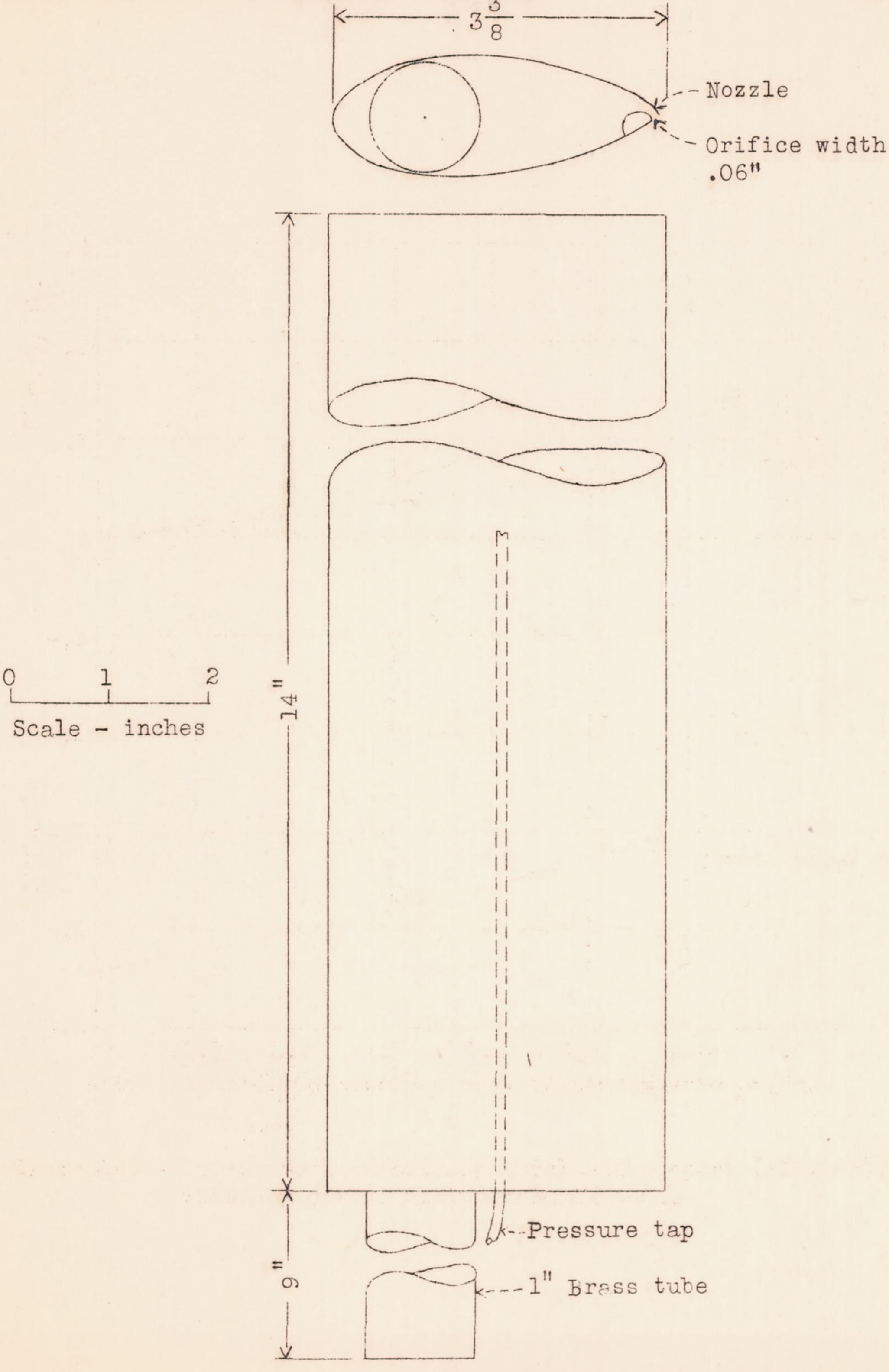

Figure 35. - Airfoil with nozzle.

70

A, $\alpha = 0^{\circ}$, V = 0 A', $\alpha = -5^{\circ}$, V = 0

B, $\alpha = 0^{\circ}$, V = 94 ft./sec. B', $\alpha = -5^{\circ}$, V = 94 ft./sec.

C, $\alpha = 0^{\circ}$, V = 0 C', $\alpha = -5^{\circ}$, V = 0

D, $\alpha = 0^{\circ}$, V = 94 ft./sec. D', $\alpha = -5^{\circ}$, V = 94 ft./sec.

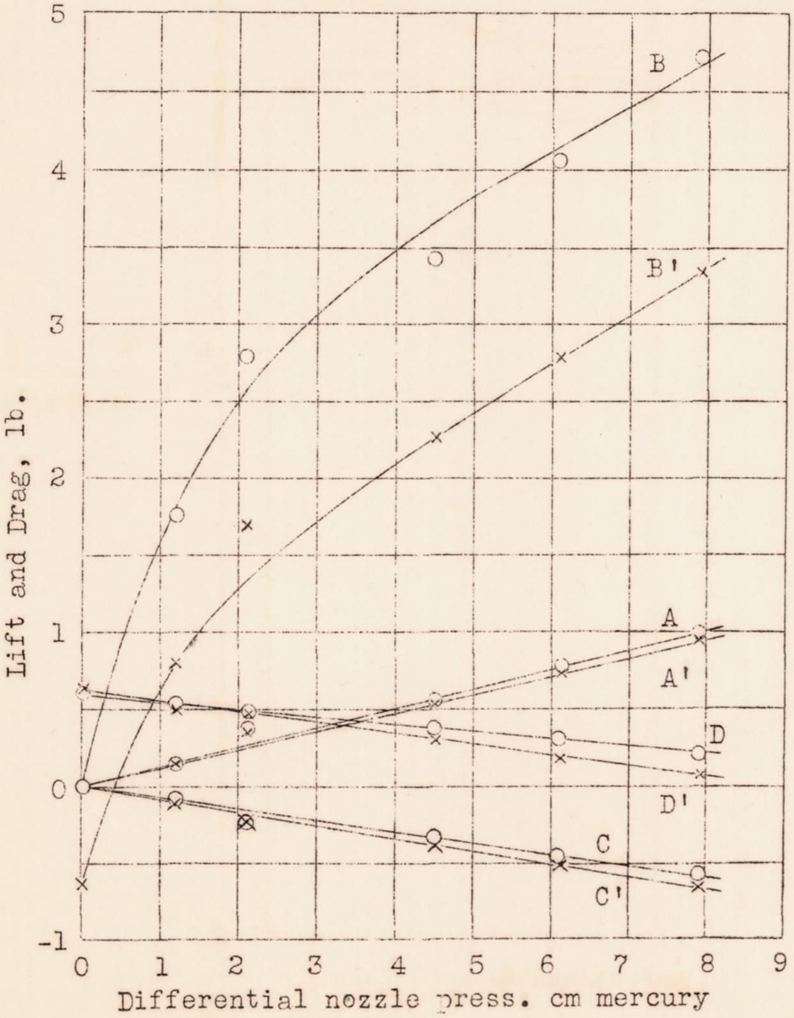

Figure 36.- Transverse jet, lift and drag.