A STUDY OF THE THRUST AUGMENTOR

A THESIS

Submitted in partial fulfillment
of the requirements for the Degree
of Master of Science in Mechanical Engineering

By

Leland B. Salters, Jr.

Georgia School of Technology
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Approved by:

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Contents

Introduction

Because of the limited use of the thrust augmentor and its lack of success up to the present, it is not widely known and the principles underlying its operation are not clearly understood; therefore, it was thought best by the author to include at the beginning of the thesis a brief explanation and description of the thrust augmentor.

The term, <u>thrust augmentor</u>, applies roughly to any device which increases the thrust derived from a free jet. That is, a free jet of gas discharging into the atmosphere creates a reaction upon the nozzle in a direction opposite to the direction of flow of the gases. The augmentor is a device which creates additional force so that the total reaction will be greater than that of the jet alone.

The type of augmentor used up to the present time takes the form of an air ejector which, by definition, is a " device in which the kinetic energy of one fluid is used to pump another fluid from a region of lower to a region of higher pressure".[1] Although the pressure differential is zero in the thrust augmentor, it is basically an air ejector since the kinetic energy of one fluid is used to impart momentum to another. The operation of the ejector may be briefly explained as follows. The jet is directed so that it comes in contact and mixes with the fluid to be expelled and, due to its high velocity, forceably ejects and carries the fluid to the place and conditions for which it was designed.

[1] <u>Principles of Engineering Thermodynamics</u>, Kiefer and Stewart, p.271

The principal application of the ejector, used as an augmentor, would be in the field of rocketry and aircraft propulsion. The jet alone, used as a propeller, is very inefficient except at extremely high speeds, higher speeds than are obtained at present. By increasing the thrust, the augmentor or ejector should make the jet as efficient as a propeller at lower speeds. Should the thrust of the jet be increased a sufficient amount by the addition of the augmentor and should the proper efficiency be obtained, it would then compare with the internal combustion engine and the air screw.

The following definitions apply to the terms as used in this thesis:

Motor gases - The gases issuing from the nozzle which furnish the energy to operate the augmentor.

Induced air - The air drawn into the ejector and entrained by the motor gases.

Mixture of gases - The gases at exit, consisting of a mixture of motor gases and induced air.

Thrust ratio - Ratio of the thrust of the augmentor to that of the jet alone.

Mass ratio - Ratio of the mass of the mixture to that of the motor gases.

Ratio of momenta - Ratio of the momentum of the mixture to that of the motor air.

Scope

This thesis is a study of the present type thrust augmentor in conjunction with the design, construction, and test of a series of thrust augmentors.

It became evident soon after the preliminary work commenced that the success or failure of the augmentor would depend upon the efficiency with which the motor air and the induced air could be mixed. It was also observed that the mixing process occurring when a gaseous jet discharged freely into the atmosphere is extremely inefficient, approaching the condition of total inelastic impact between the motor and induced air. It was also evident that little improvement has been made along this line even in the best augmentors produced at present.

An attempt to study and remedy this situation would have entailed more time than was available, therefore, the scope of this thesis was limited to a study of the basic principles of augmentation. That is, a study was made of the present type augmentor in an attempt to analyze its present situation as to state of development, problems hindering its development, and its possible future. Several types of augmentors were tested to aid in the analysis of some of the basic principles of augmentation.

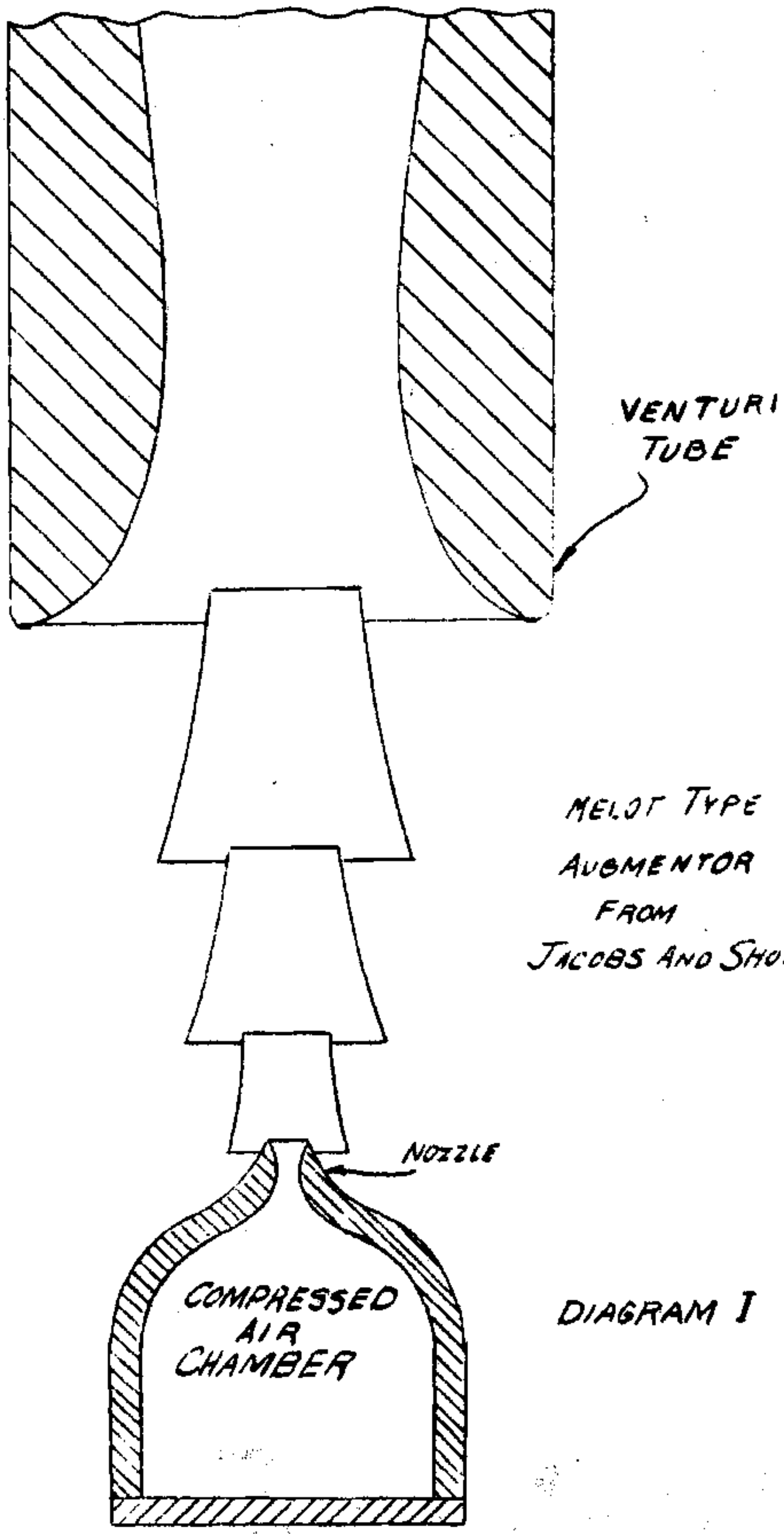
Previous Work

For a number of years the principle of the thrust augmentor has been considered as a possible means of propelling aircraft. Experimenters have been working on a proper design of such a device in various countries, France, England, Germany, and the United States to the knowledge of the writer. However, very little success has been attained in this field, and most of the experimenters have either become disheartened or given up the project as being impracticable. The most outstanding worker in this field is most probably Monsieur Melot who gained recognition from the French Government in the early twenties for his development of the so-called " Melot thrust augmentor". The name augmentor was given to the device because it increased the thrust above that of the jet alone. The jet was furnished originally by kerosene burners, but these were found to be very inefficient due mainly to the fact that only low pressures or compression could be obtained. Melot finally designed an internal combustion engine with no crankshaft, only a piston which shuttled back and forth in a cylinder having combustion chambers in both ends. During the expansion stroke the piston uncovered exhaust ports which conducted the high pressure gases to a nozzle creating an intermittant jet. The augmentor consisted, as shown by Diagram 1, of a series of converging conical sections through which the jet passed followed by a venturi tube. The French Government conducted tests on the device but evidently considered it impracticable, hence no more information could be found by the writer concerning this augmentor. However, the results of tests performed by other experimenters on similar devices are available.

Since the Melot type is generally considered one of the most effective kinds, a diagram showing its principal features is included. The diagram is followed by a set of curves illustrating the result of tests performed on this type. Another apparatus which compares in effectiveness with the Melot augmentor is that designed by Von Paul Schmidt of Germany.[1] Its main features are also shown by Diagram 2. The results obtained from the latter are somewhat better than those of the former as tested by Jacobs and Shoemaker.[2] These types will be considered further in the discussion.

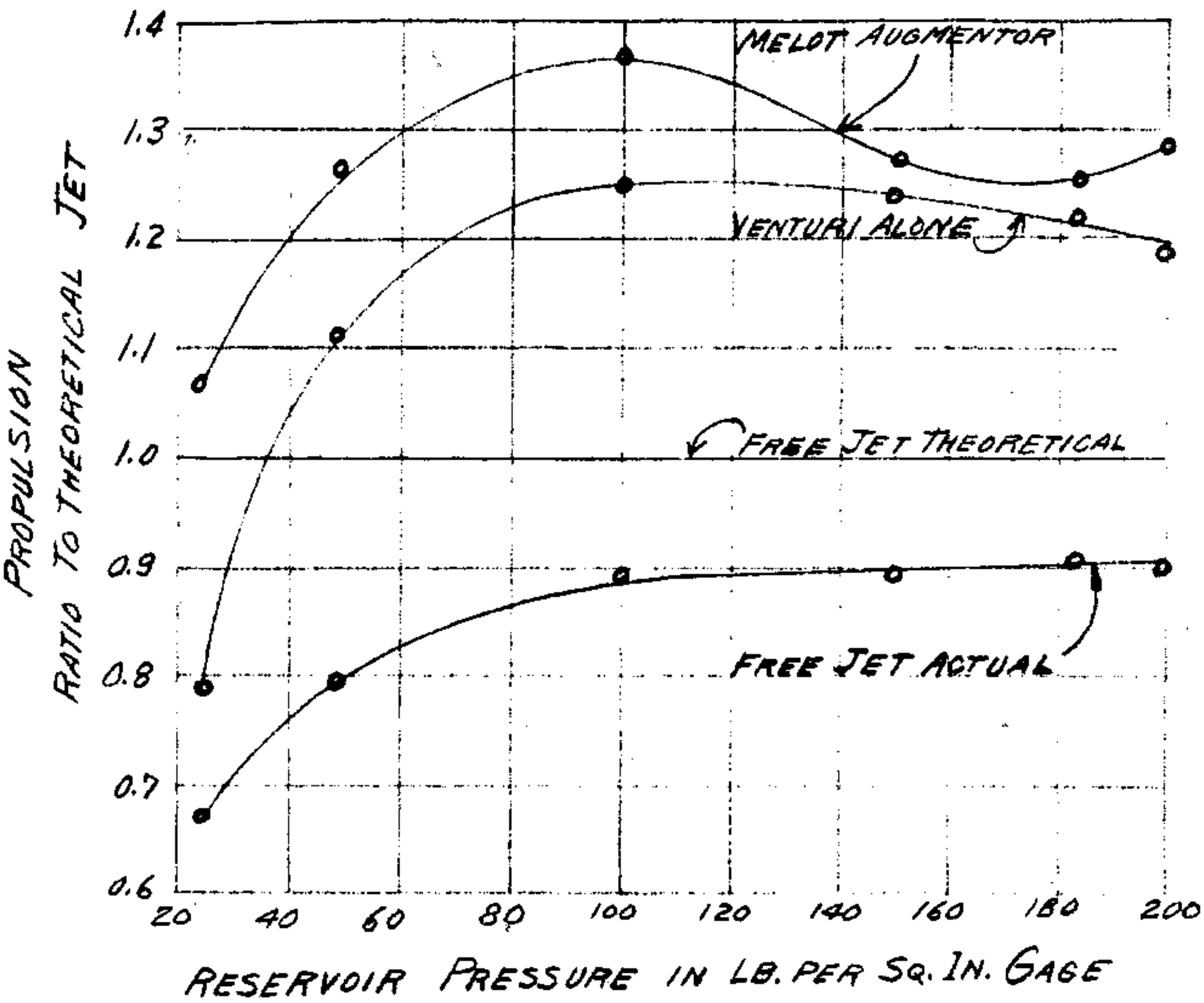
[1] Rockets with Jet Apparatus, by Von Paul Schmidt, Z.F.M., August, 1933, Nr. - 15.

[2] Tests on Thrust Augmentors for Jet Propulsion, By Jacobs and Shoemaker, N.A.C.A., Technical Notes No.431, Sept.1932.



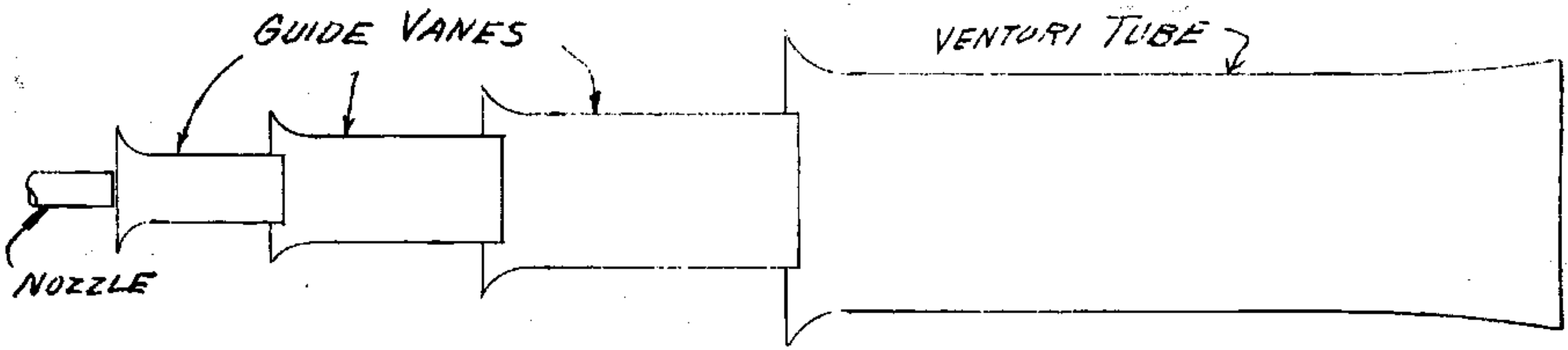
MELOT TYPE
AUGMENTOR
FROM
JACOBS AND SHOEMAKER

DIAGRAM I



FROM
JACOBS AND SHOEMAKER

DIAGRAM I-A



TYPE OF AUGMENTOR
BY VON L. KORT

SCHEMATIC ARRANGEMENT

DIAGRAM 2

Design

Before beginning the design, some of the basic laws and principles which affect the design and operation of the augmentor should, in the opinion of the writer, be set forth and explained.

It may be proper first to consider the energy exchange taking place between the motor and the induced air. Should the kinetic energy of the motor gases be conserved during the period of impact, so that the kinetic energy of the mixture is equal to that of the motor gases, then elastic impact is said to have occurred between the motor gases and the induced air. However, should the mixing process be so inefficient that only the momentum of the motor gases be conserved, then the condition of total inelastic impact is said to exist. The latter type is analogous to the impact between plastic bodies such as putty and clay while the former may be compared to the impact between billiard balls and other bodies made of elastic materials.

It is then the goal of the designer to bring about the former condition during the mixing process. Very little progress has been made in this direction and, consequently, the development of the augmentor has been extremely slow. Even in the most efficient augmentors of to-day the condition of little better than total inelastic impact has been obtained.

This section of the thesis under the heading of Design is divided into two parts, the first being devoted to the consideration of the problems as they would exist should elastic impact be obtained, and the second part devoted to a study of the situation as it remains to-day.

In the first part an attempt is made to analyze the situation and suggest a design effective under such conditions; likewise, in the second part a design is attempted to aid in the study of the present situation.

Part 1

An important phenomenon which occurs under the conditions of elastic impact is that of the momentum increase of the mixture. To illustrate this principle let us consider what takes place in the augmentor during impact. The gases issue from the nozzle at a high rate of speed and, consequently, its kinetic energy is large. When the gases mix with the induced air, the gas velocity is lowered and that of the air increased, the loss in kinetic energy by the gases being absorbed by the air. Due to the increase in mass, the resulting momentum of the mixture will be larger than that of the original motor gases. This phenomenon is best explained by an example. Let us assume that the gases issue from the nozzle at the rate of one pound per second with a velocity of 3000 feet per second, and that in passing through the augmentor it mixes with one pound of air per second. The kinetic energy of the initial pound of gases is:

$$\frac{1}{2}\,MV^2 = \frac{(3000)^2}{2 \times 32.2} = 139{,}700 \text{ foot pounds,}$$

$$\text{Momentum,} \qquad MV = \frac{1 \times 3000}{32.2} = 93.3 \text{ pound seconds.}$$

Since, the kinetic energy of the mixture is equal to that of the original jet, the velocity of the mixture will be:

$$\text{Velocity} = \sqrt{\frac{64.4 \times 139{,}700}{2}} = 2120 \text{ feet per second.}$$

$$\text{Momentum, } MV = \frac{2 \times 2120}{32.2} = 131.5 \text{ pound seconds.}$$

This shows an increase of 38.2 pound seconds or 41 per cent. A more practical situation would be one in which the mass of the mixture is 150 times that of the original gases, the velocity of the mixture being in this case:

$$\text{Velocity} = \sqrt{\frac{64.4 \times 139{,}700}{150}} = 244.7 \text{ feet per second.}$$

$$\text{Momentum} = \frac{150 \times 244.7}{32.2} = 1140 \text{ pound seconds.}$$

The latter momentum is more than 1200 per cent of the original motor gases.

The relation of the momentum of the motor gases and that of the final mixture can be found in terms of the mass ratio. Continuing the assumption of perfect efficiency, the following equation holds true:

$$\frac{1}{2} M_1 V_1^2 = \frac{1}{2} M_2 V_2^2$$

from which

$$V_2 = V_1 \sqrt{\frac{M_1}{M_2}} \quad .$$

Substituting the value of V_2 in the ratio of momenta:

$$\text{Ratio of momenta} = \frac{M_2 V_2}{M_1 V_1} = \frac{M_2 V_1 \sqrt{\frac{M_1}{M_2}}}{M_1 V_1} = \sqrt{\frac{M_2}{M_1}} \quad .$$

M_1 = Mass of motor gases.

M_2 = Mass of mixture gases.

V_1 = Velocity of motor gases.

V_2 = Velocity of mixture.

This shows the ratio of momenta to be equal to the square root of the mass ratio.

Another principle that should be explained before beginning the design is that of the forces created on surfaces near an accelerating fluid, as is illustrated by Diagram 3. An incompressible fluid is used, for convenience, to flow from the nozzle as shown. The impulse of the jet thus formed is equal to the momentum of the jet, M V. It was found that the force due to the pressure acting upon the unequal areas of the two opposite sides of the tank will account for but one-half of the impulse. Since the total impulse of the jet must be transmitted to the tank to satisfy the fundamental laws of action and reaction, it was assumed that the remaining force was transmitted to the tank by means of the lowered pressure of the high velocity fluid acting upon surfaces near the nozzle and upon the surfaces of the nozzle.

The proof of the above assumptions as given by A. Stodola is as follows:[1]

Impulse due to Jet = F = MV (1)

Force due to unbalanced area = F = PA

but M (Equation 1) = Density x Volume

and Volume = AV

then $M = \frac{DVA}{g}$

[1]Steam and Gas Turbines, by Aurel Stodola, p. 265

Therefore, substituting this value of M in Equation 1:

$$\left(\frac{DVA}{g}\right)V = \frac{DAV^2}{g} \qquad (2)$$

$$F = MV$$

Equating velocity head to the head producing flow:

$$\frac{V^2}{2g} = H$$

but $$H = \frac{P}{D}$$

or $$\frac{V^2}{2g} = \frac{P}{D}$$

then $$\frac{V^2}{g} = \frac{2P}{D} \quad .$$

Substituting $\frac{2P}{D}$ for $\frac{V^2}{g}$ in Equation (2),

$$F = DA \times \frac{2P}{D} = 2\,PA \quad .$$

M = Mass rate of flow of jet.

V = Velocity of jet.

A = Unbalanced area or area of nozzle.

D = Density of fluid.

g = Acceleration of gravity.

H = Head producing flow.

Therefore, the impulse is twice the force due to the pressure acting upon the unequal areas and hence, one-half of the impulse due to the lowering of the pressure upon the areas near the nozzle. This is merely another application of Bernouilli's theorem.

This principle may be applied to the augmentor by providing a large streamlined entrance. Should the area of the streamlined entrance be infinitely large, a force equal to one-half the momentum of the induced air could be obtained upon the surface. However, a large proportion of the force should be obtained upon surfaces of finite size since the velocity of the approaching air is negligible until it nears the immediate vicinity of the intake.

Another phenomenon which should be understood before beginning the design is that occurring when air is sucked into a tube. Under these conditions free atmospheric air may be accelerated without the customary force being exerted on the tube; for example, the high velocity air may be turned at right angles with no force upon the tube. This peculiar effect is caused by the fact that the total head of air remains the same during the process, the total head being that of the surrounding atmosphere. Thus, in making a right angle turn the air loses its velocity head in one direction and regains it in another. In losing this velocity head in the original direction of flow, the pressure builds up to atmospheric again, exactly balancing the atmospheric pressure acting on the outside of the tube. Thus, the forces are balanced, the resulting force on the tube being zero.

It must also be borne in mind while designing a thrust augmentor that the air may be accelerated and ejected at a high velocity without a force being produced upon the apparatus. One of the principal problems is to bring about conditions which will cause the force, due to the acceleration of the air, to register upon the augmentor. In the

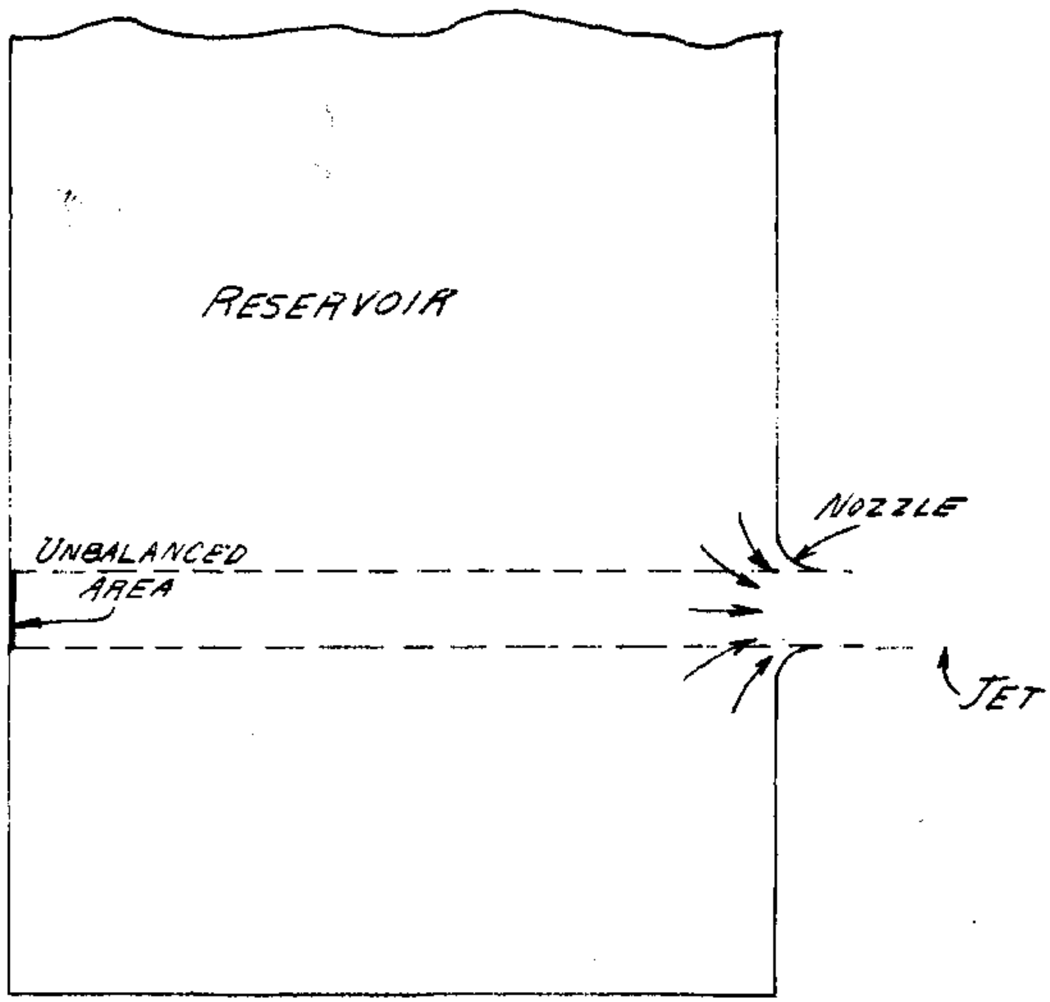
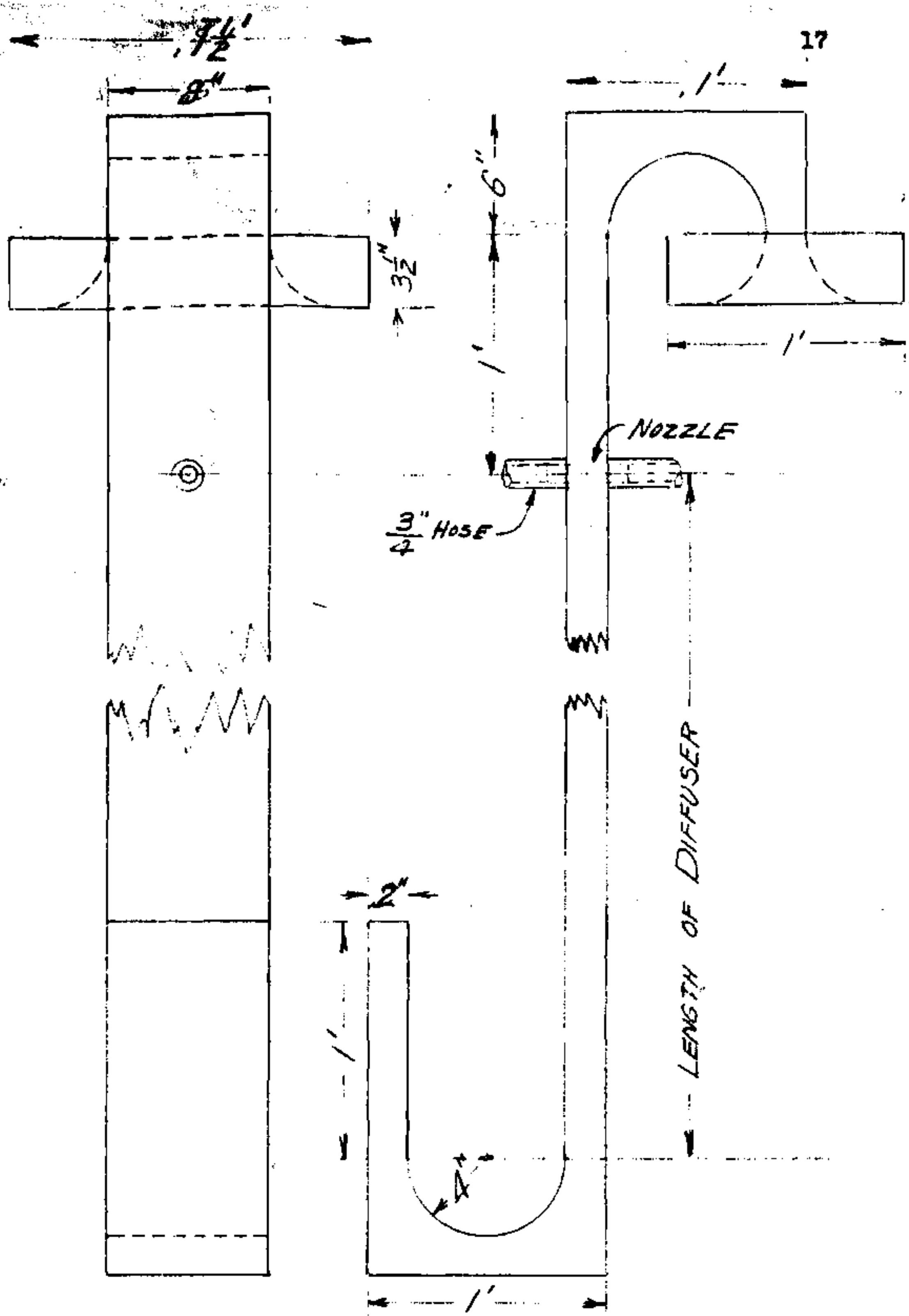


DIAGRAM 3

opinion of the writer, failure to recognize the above fact has been a contributing factor in the unsuccessful operation of many designs. For example, if a jet is discharged freely into the atmosphere, it will entrain a relatively large quantity of air in its path and give it a high velocity; however, the only force which is obtained is that due to the original jet. As will be seen later in the results of the tests of an arrangement consisting of a jet surrounded by a parallel walled tube, although air was entrained and given a velocity of between 150 and 200 feet per second, no force was obtained from the acceleration of this air, the only force being that of the jet alone.

In the designing of a thrust augmentor under ideal conditions it should be remembered that as the mass ratio increases, the ratio of momenta increases, the momentum of the motor gases becoming less in proportion to that of the final mixture. The arrangement should, then, be made so that the momentum of the final mixture could be utilized rather than that of the motor gases. In the opinion of the writer, the arrangement which would be best suited to this purpose is something along the lines of Design 1.

Upon examining the arrangement, it is apparent that a thrust equal to twice the momentum of the mixture will be obtained at the exhaust end of the air tube due to the 180 degree bend. A thrust of half the momentum of the induced air may also be obtained at the entrance of the tube. As explained before, the effect of the induced air in turning the 180 degree bend, immediately following entrance to the tube, is negligible. Then the total thrust obtainable from such



DESIGN I

SCHEMATIC ARRANGEMENT

SCALE = 1 1/2" = 1'

DIAGRAM 4

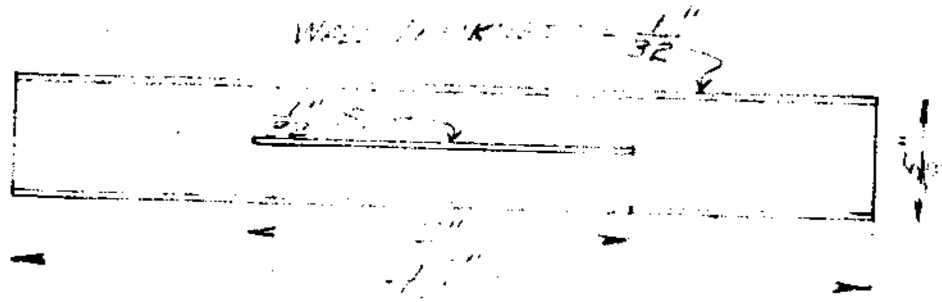
an arrangement should be, theoretically, twice the momentum of the mixture plus half the momentum of the induced air minus the momentum of the motor air. For convenience, let us assume the momentum of the induced air to be equal to that of the mixture which is not unreasonable, if the mass ratio is large. Assuming a mass ratio of 100, the ratio of momenta would be $\sqrt{100} = 10$ and the thrust ratio:

$$2\tfrac{1}{2} \times 10 - 1 = 24.$$

To simplify the construction of the various types of augmentors, the parts of the augmentors were made interchangeable so that all types could be assembled from one group of sections or parts. This necessitated compromises in the individual designs. It was decided to use compressed air from the system of the Georgia School of Technology to furnish the power necessary for operation of the augmentors. The nozzle decided upon was in the form of a longitudinal slot in a section of aircraft tubing, the air being supplied from both ends of the tubing. The form of jet produced by this shaped nozzle presented a relatively large surface area, insuring a speedy mixing process. Its principal features are shown by Diagram 5.

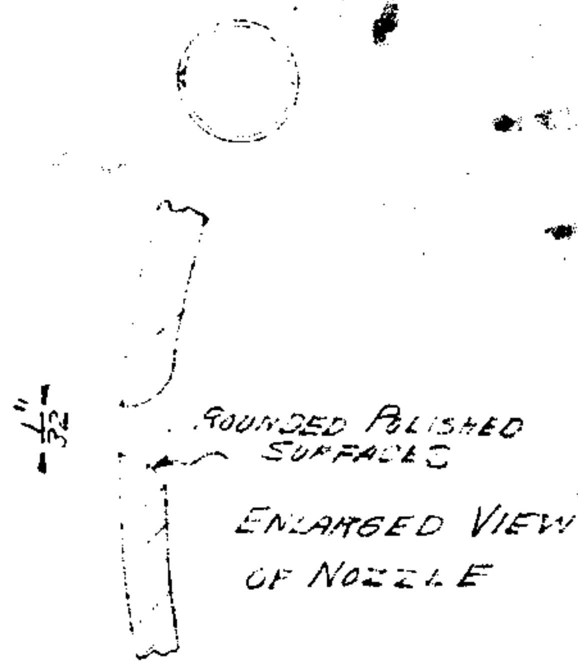
The main problem in the design of Number 1 proved to be decreasing friction losses in the elbow turns. From the results of a series of tests run on friction losses in elbow bends in air duct systems by Loring Wirt[1], it was found that the following rules may be stated:

[1] New Data for the Design of Elbows in Duct Systems, by Loring Wirt, General Electric Review, June, 1927, p.286.



NOZZLE DESIGN

SCALE = FULL SIZE



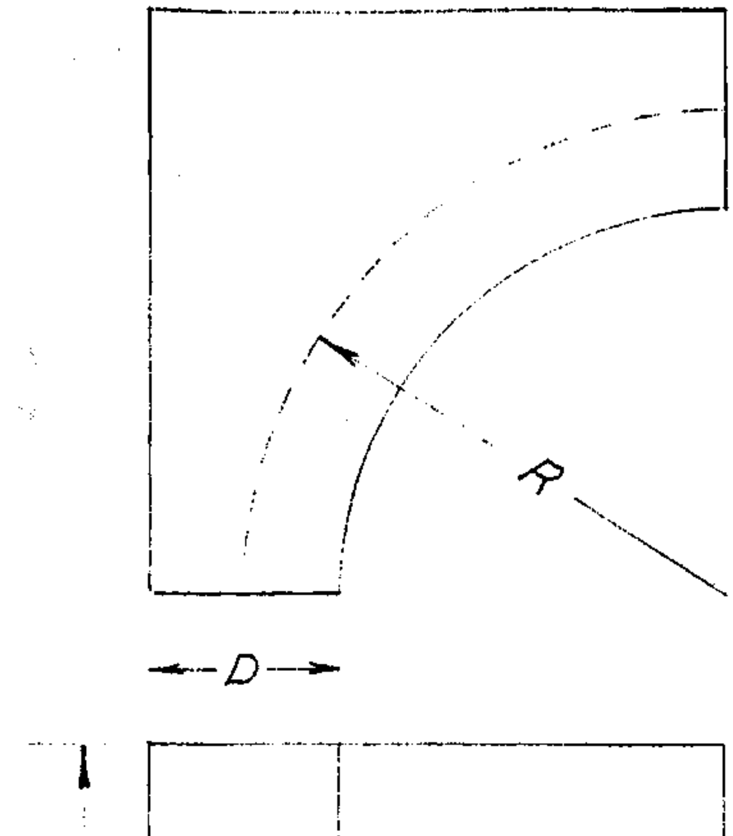
ENLARGED VIEW OF NOZZLE

DIAGRAM 5

1. The radius ratio should be large.
2. The aspect ratio should be large.
3. A square corner is 10 per cent more efficient than a rounded corner.
4. A section of a straight duct following an elbow regains some of the energy lost in the elbow.

The meaning of the above terms, radius ratio and aspect ratio, are illustrated by Diagram Number 6. According to these rules, a radius ratio of 2.5 and an aspect ratio of 4 were chosen. Square corners were used in the elbows and, for simplicity of construction, a rectangular cross section was used for the air tube. From the above article, the losses in each right angle turn of the above design was found to be 8 per cent of the kinetic energy of the air stream. This value compares favorably with the value of approximately 100 per cent which applies to an ordinary right angle turn.

A series of tests were made to determine whether the diffuser should have parallel sides or a taper. Parallel sides proved to be the more desirable. The dimensions of the nozzle and the air tube were determined by the capacity of the compressed air system and the range of mass ratio desired. The diffuser was divided into sections of such length that its length could be varied in one foot increments from 2 to 12 feet.



RIGHT ANGLE BEND IN AIR TUBE

RADIUS RATIO = $\frac{R}{D}$ FROM LORING WEST[12]

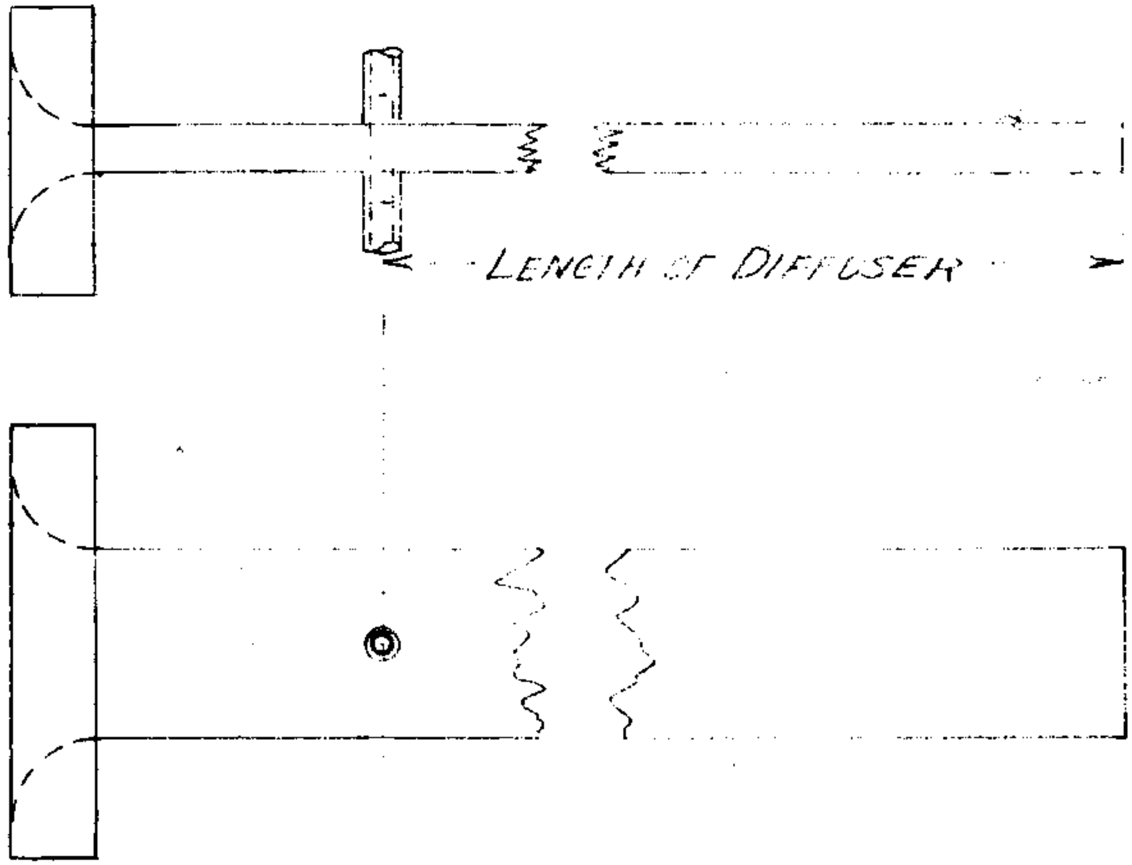
ASPECT RATIO = $\frac{W}{D}$

DIAGRAM 6

Part 2

Design 2 was an attempt to gain maximum thrust increase under actual conditions of inefficient mixing of motor and induced air. Although it would not be the best arrangement should any degree efficiency be obtained in the mixing process, it is, in the opinion of the writer, of good basic design under conditions of inelastic impact. Under these conditions, where the momentum of the motor air is approximately equal to that of the final mixture, the nozzle must be turned in an opposite direction to that of the thrust so that its now relatively large force may be added to that produced by the remainder of the apparatus. An added thrust may be obtained in this arrangement by providing a large streamlined entrance form, the added thrust, as previously explained, being one-half the momentum of the induced air. As the mass ratio increases, the momentum of the induced air approaches that of the mixture and since, in the case of totally inelastic impact (which is assumed in Part 2), the momentum of the motor air is equal to that of the mixture. Then we may assume, for simplicity, that the momenta of the motor and induced air are equal. Should the above situation be the case, the total thrust would be the momentum of the motor air plus half this value, or the thrust ratio would be 1.5 .

It would appear that the thrust ratio of 1.5 is the maximum that is theoretically obtainable so long as inelastic impact exists; however, another effect comes into play which enhances the efficiency. This effect is produced by the initial velocity of the induced air.



DESIGN 2

SCHEMATIC ARRANGEMENT

SCALE = $1\frac{1}{2}'' = 1'$

DIAGRAM 7

As the velocity of the induced air increases, the difference in velocity between the motor and induced air decreases, assuming that the velocity of the motor air remains constant. The loss of energy upon impact will then be reduced as shown by the equation for losses during inelastic impact. The loss in energy is:

$$\text{Loss} = \frac{1}{2} \frac{M_1 M_2}{M_1 + M_2} (V_1 - V_2)^2 .$$

M_1 = Mass rate of flow of motor air.

M_2 = Mass rate of flow of mixture air.

V_1 = Velocity of motor air.

V_2 = Velocity of mixture.

It is then apparent that the loss is proportional to the square of the velocity difference, and, due to this effect, thrust ratios higher than 1.5 may be obtained although inelastic impact occurs during the mixing process. No attempt was made to utilize this effect; however, a certain benefit was gained due to the initial velocity of the induced air.

Construction

All parts of the air tube were constructed of white pine materials, the sides being made of $\frac{1}{4}$ inch plywood and the top and bottom strips of $\frac{3}{4}$ inch thickness. All surfaces exposed to the air stream were finished with number 120 sandpaper. The joints were of the sleeve-collar type and were fastened together by wire.

The nozzle was made from aircraft tubing, the opening consisting of a longitudinal slot $\frac{1}{32}$ inches wide and two inches long. The inside surfaces of the slot were rounded and polished to form a smooth converging nozzle. The ends of the nozzle tube were connected to the air supply pipe by two lengths of $\frac{3}{4}$ inch air hose. The principal features of the construction are shown by Diagram 4.

Apparatus

The augmentor was suspended from a stationary support by means of vertical wires arranged so that no undue strain was placed upon the joints of the air tube. By arranging the hoses so that they approached the air tube at right angles, all side forces, such as those caused by the stiffening of the hose under pressure and the inertia of the high velocity air flowing through the hoses, were eliminated. As shown by Diagram 8, a pulley was attached to the bottom of the air tube and the cord so arranged that the thrust could be measured upon the scales. Tension in the cord lessened the weight on the scales and decreased the scale reading accordingly . By fastening the other end of the cord to a movable weight, the operator could counteract the stretch in the cord by shifting the weight. The stops were so arranged that their surfaces were barely in contact while the apparatus remained at rest.

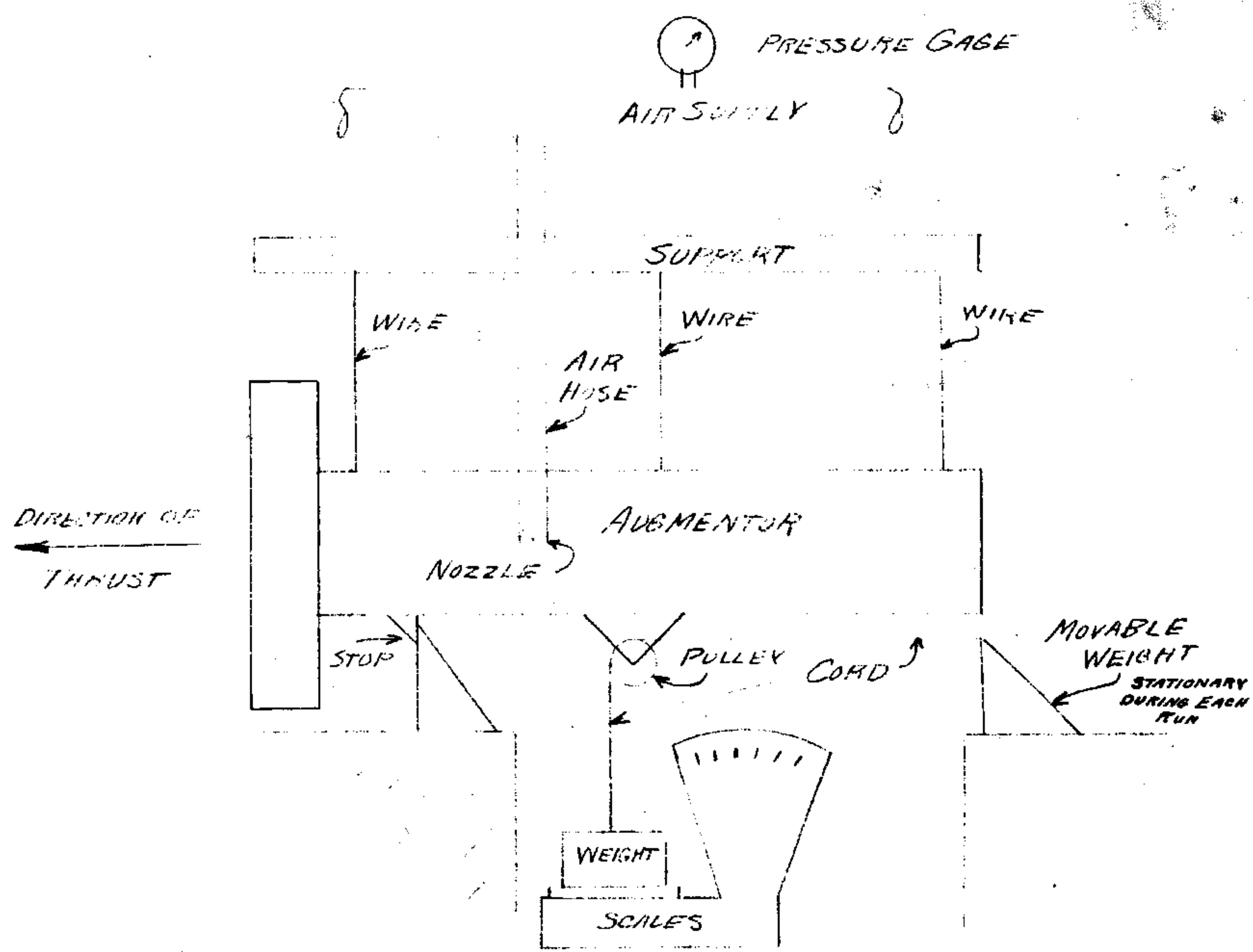


DIAGRAM OF APPARATUS

DIAGRAM 8

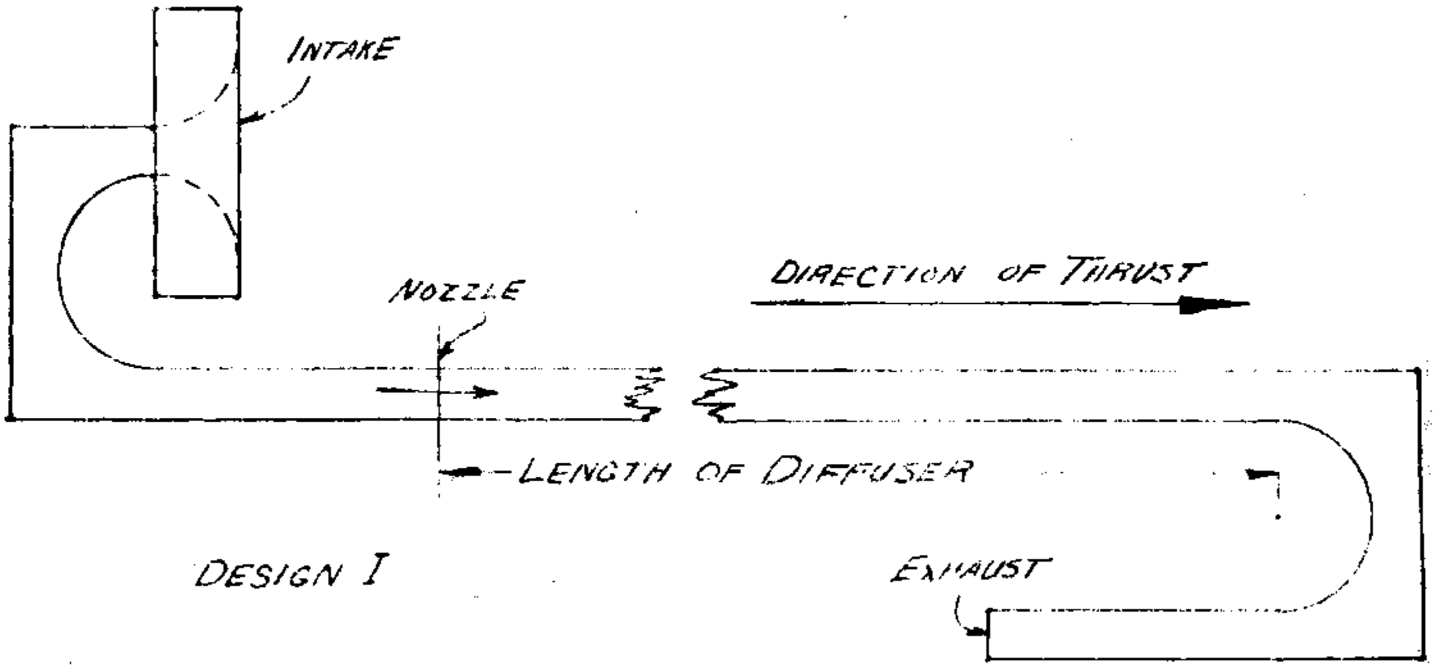
Method

The apparatus was set up as shown by Diagram 8, the hoses having been tested and found to have negligible effect upon the scale readings so long as they remained vertical. With the apparatus at rest, the stops were placed barely in contact, the cord aligned both vertically and horizontally, and the scales set on the maximum reading.

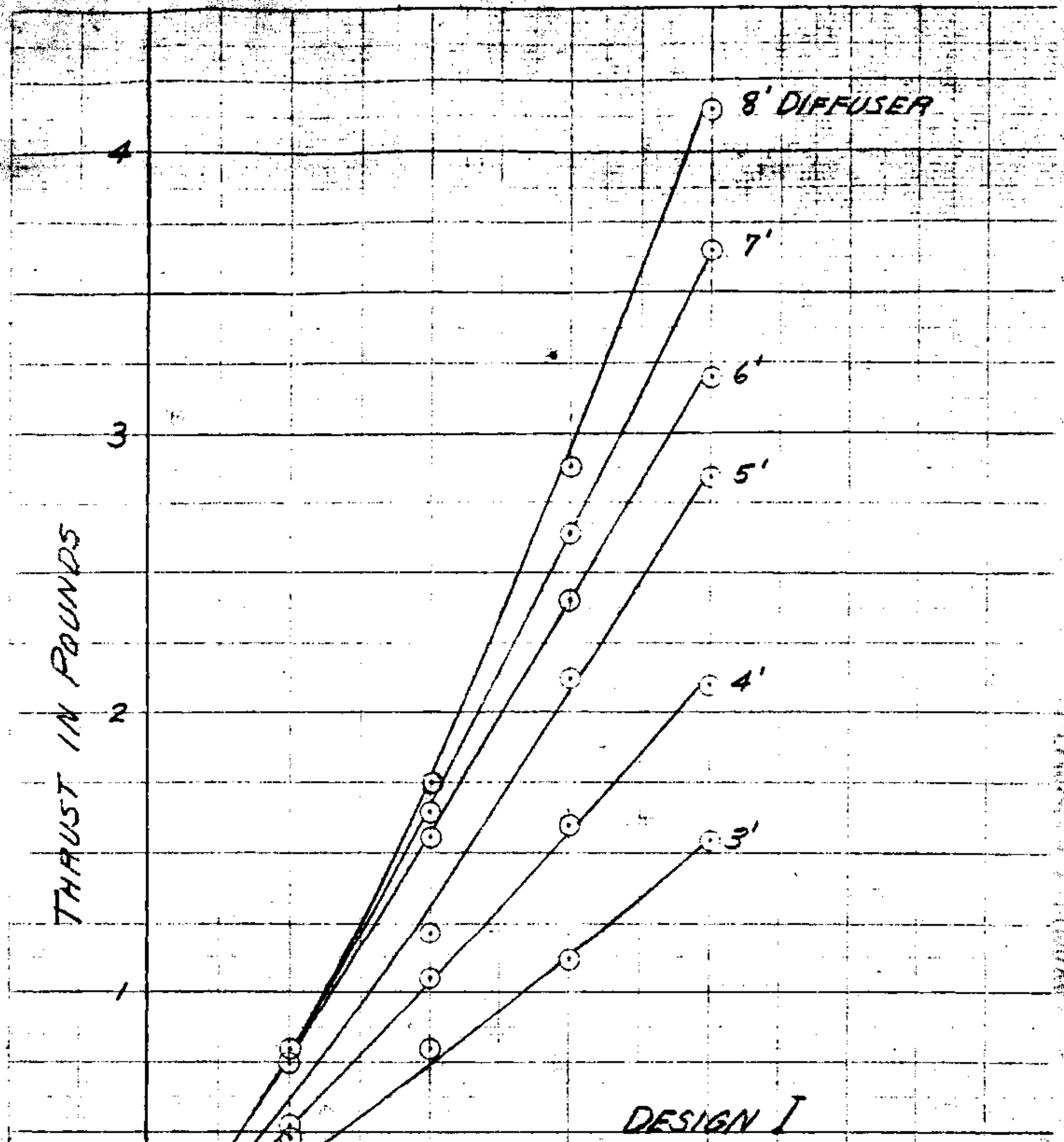
As the air valves were opened, the augmentor would move forward stretching the string and pulling the contact surfaces apart. The position of the movable weight was then changed to bring the augmentor back to its original position of rest with the stops almost in contact. The reading was then recorded as the difference between the scale readings before and after the air valve was opened. In testing the nozzle alone, the nozzle was removed from its position in the center of the air channel and fastened to the top of the air tube. All wires and connections, whose frictional resistance in the air stream would have affected the scale readings, were removed.

RESULTS

Gage Pressure in Lb. per Sq. Inch	Thrust in Pounds						
	Length of Diffuser - Ft.						
	3	4	5	6	7	8	12
20	.40	.50	.55	.75	.75	.80	.50
40	.80	1.05	1.25	1.55	1.65	1.75	1.35
60	1.15	1.60	2.15	2.40	2.65	2.90	2.35
80	1.55	2.10	2.85	3.20	3.65	4.15	3.25

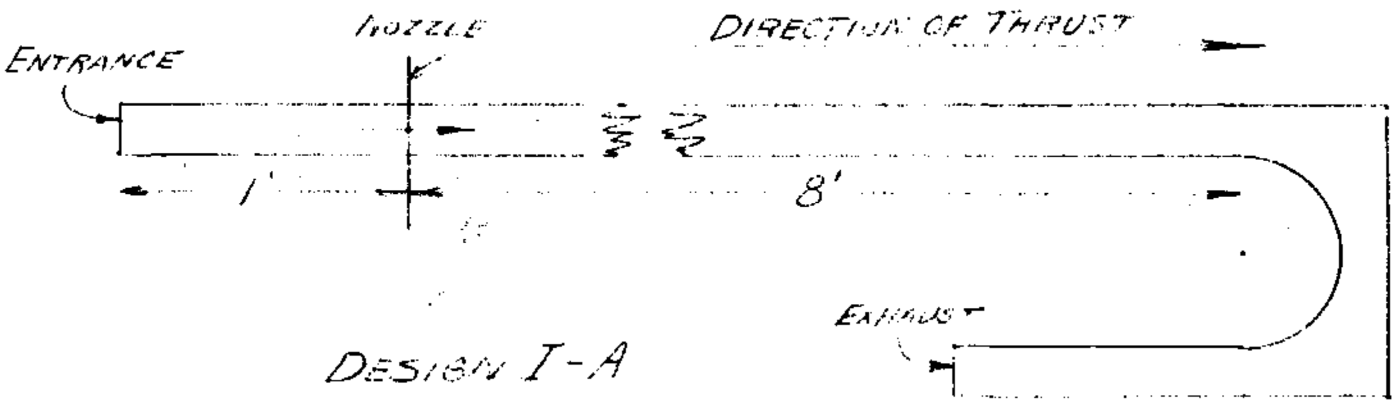


DESIGN I



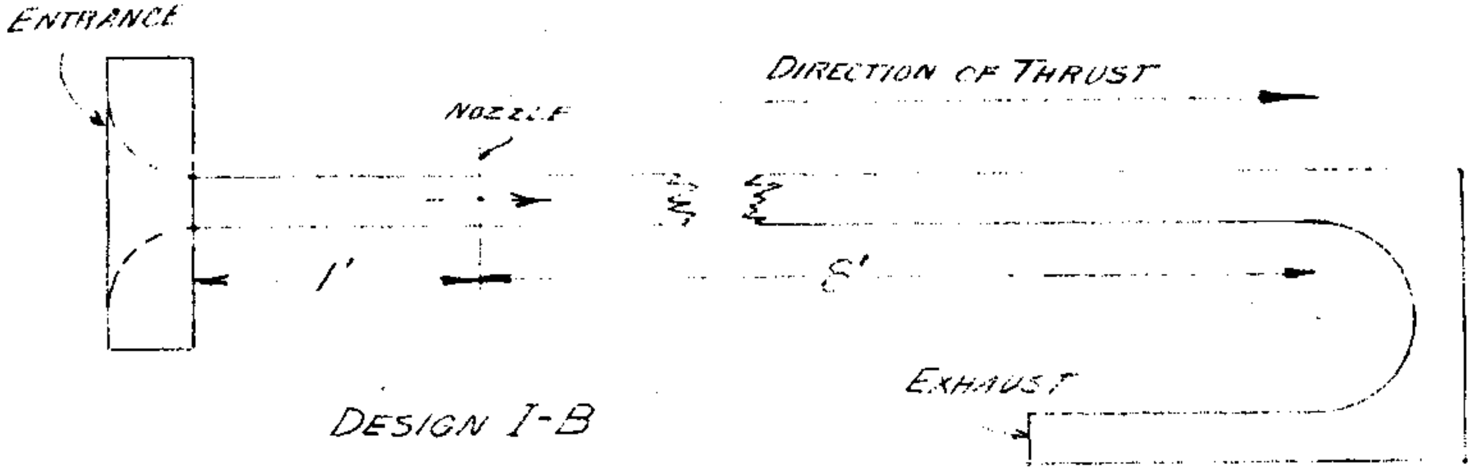
8' DIFFUSER
7'
6'
5'
4'
3'
DESIGN I
THRUST IN POUNDS
4
3
2
1
0
0
20
40
60
80
AIR PRESSURE IN LB. PER SQ.IN.-GAGE

GAGE PRESSURE IN LB. PER SQ. IN.	THRUST IN POUNDS
20	0.60
40	1.40
60	2.35
80	3.40



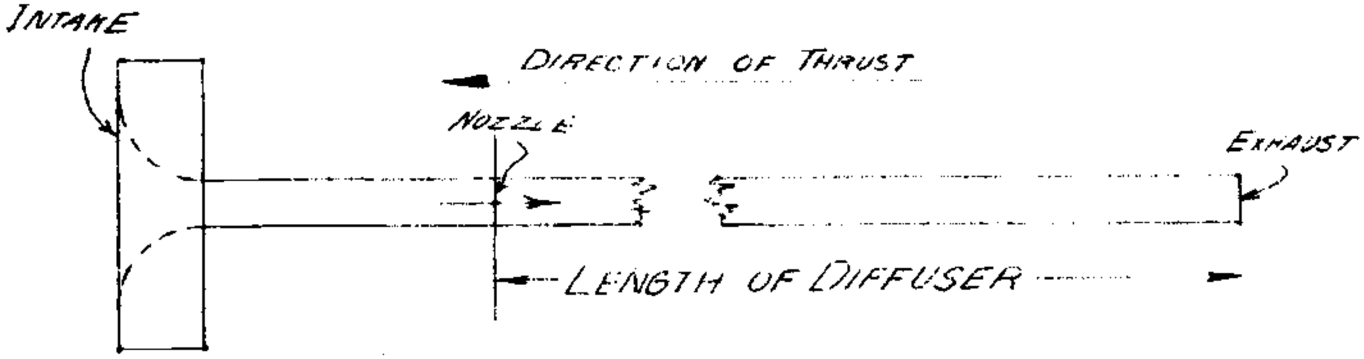
DESIGN I-A

GAGE PRESSURE IN LB. PER SQ. IN.	THRUST IN POUNDS
20	0.60
40	1.40
60	2.35
80	3.40

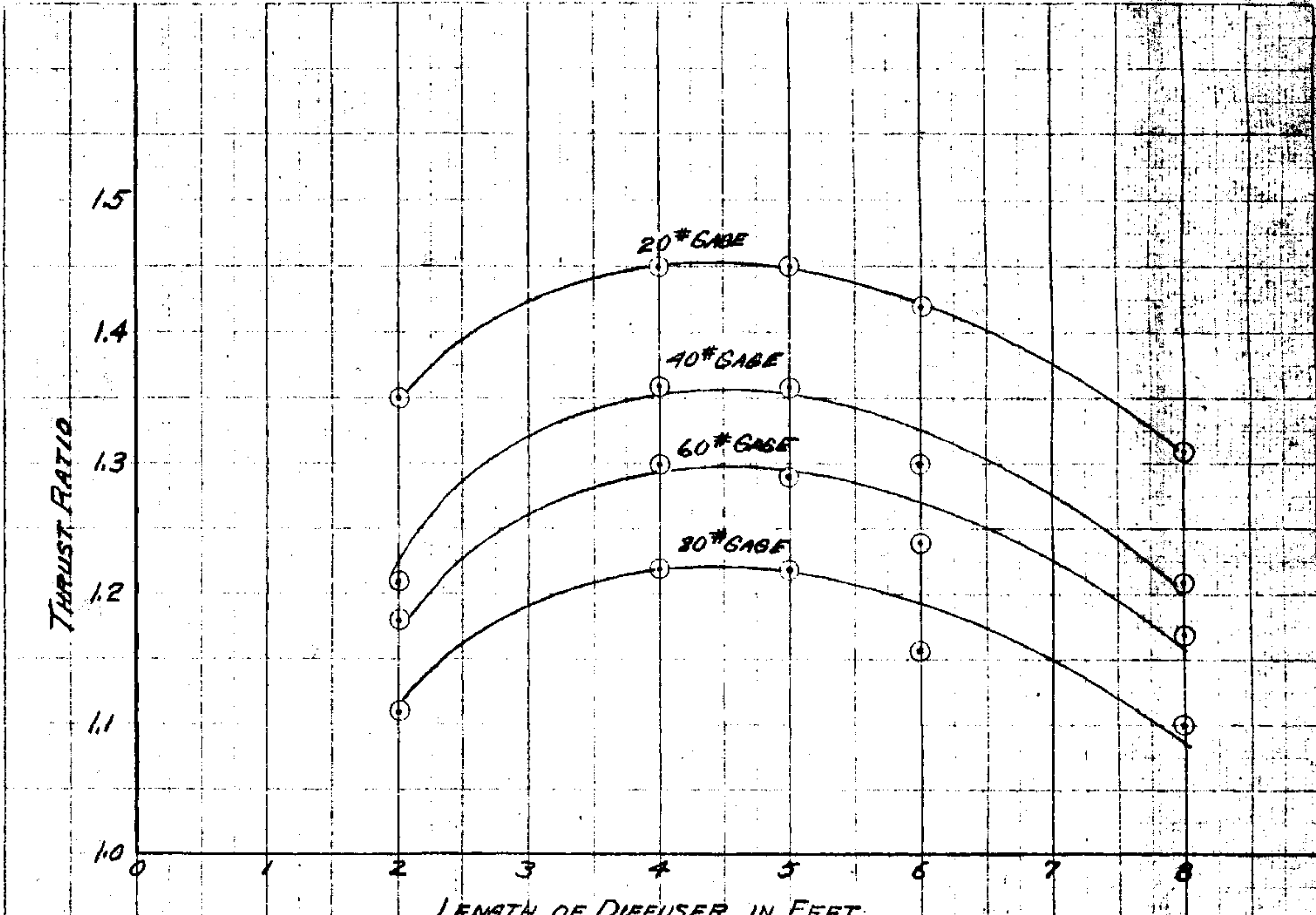


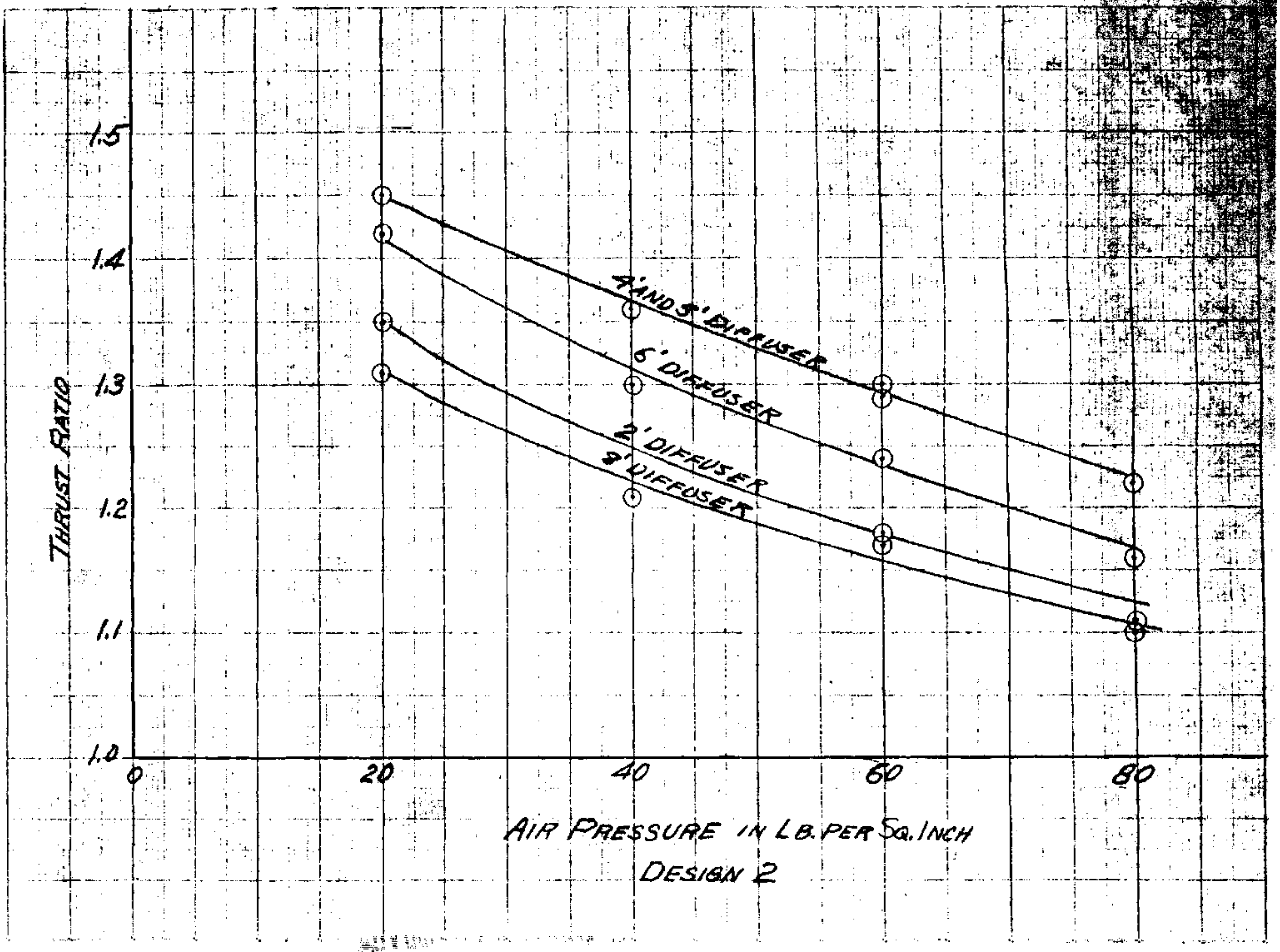
DESIGN I-B

GAGE PRESSURE IN LB. PER SQ. INCH	THRUST IN POUNDS				
	LENGTH OF DIFFUSER - FT.				
	2	4	5	6	8
20	2.10	2.30	2.30	2.25	2.05
40	3.75	4.25	4.25	4.05	3.80
60	5.65	6.25	6.20	5.95	5.65
80	7.45	8.15	8.15	7.75	7.35



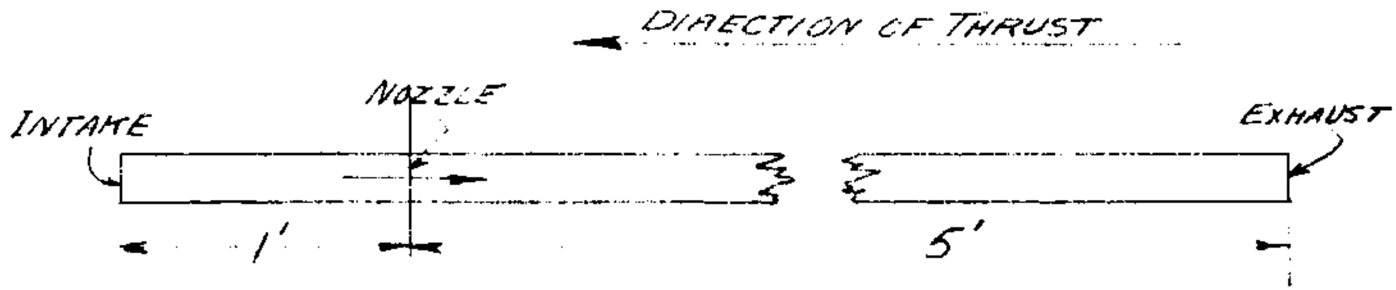
DESIGN 2


THRUST RATIO
1.5
1.4
1.3
1.2
1.1
1.0
0
1
2
3
4
5
6
7
8
20# GAGE
40# GAGE
60# GAGE
80# GAGE
LENGTH OF DIFFUSER IN FEET
DESIGN 2

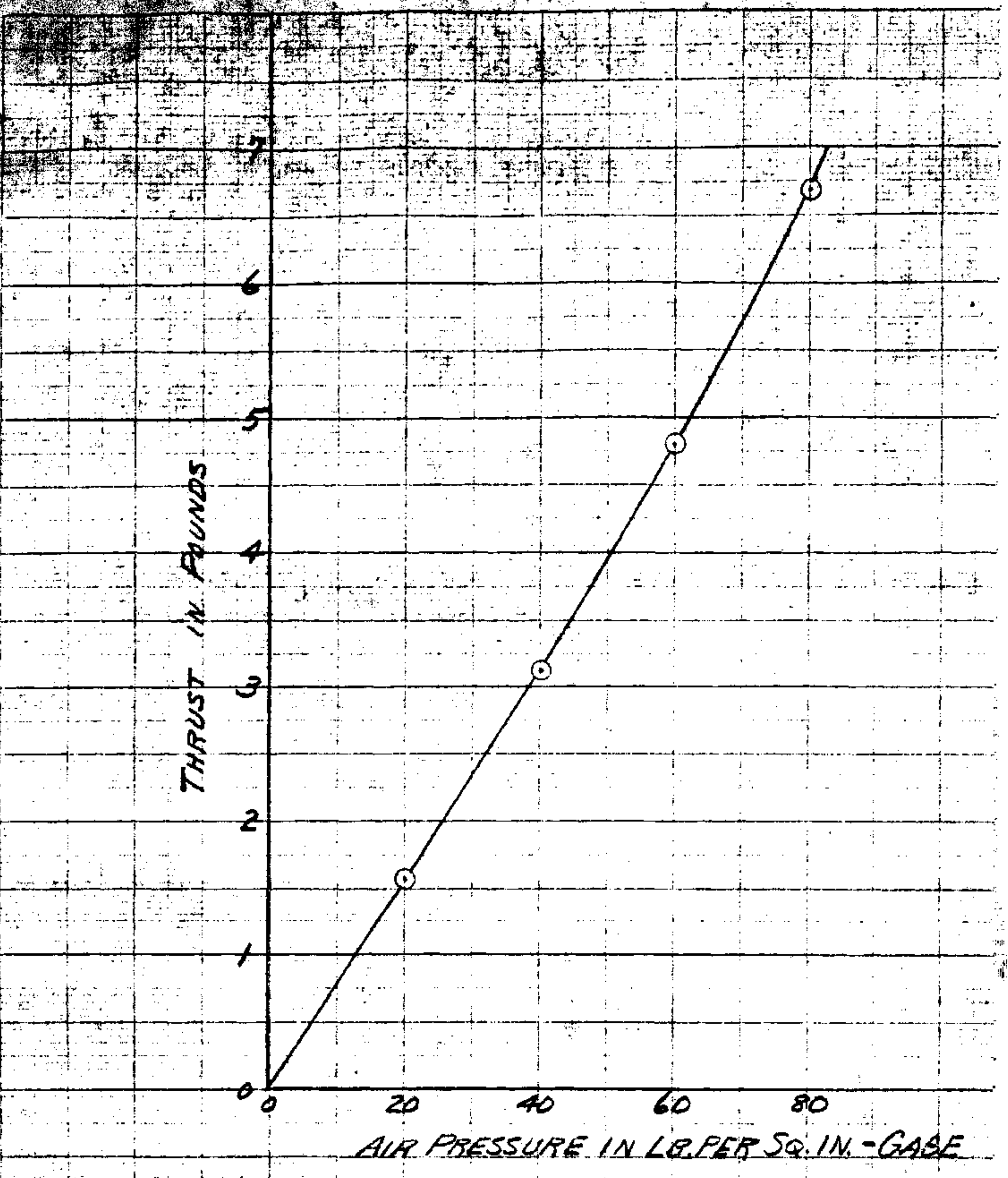


1.5
1.4
1.3
1.2
1.1
1.0
THRUST RATIO
0
20
40
60
80
4' AND 5' DIFFUSER
6' DIFFUSER
2' DIFFUSER
8' DIFFUSER
AIR PRESSURE IN LB. PER SQ. INCH
DESIGN 2

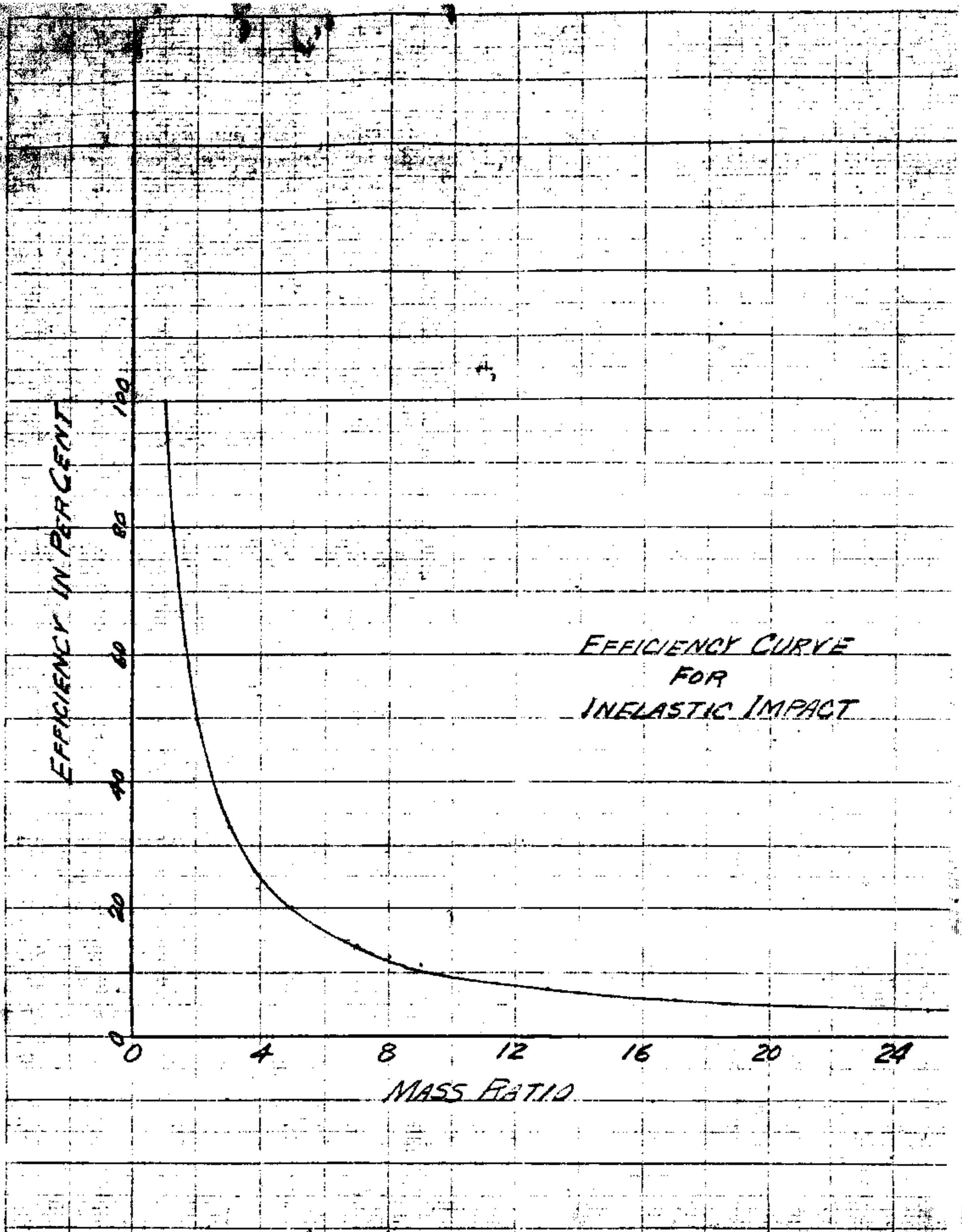
GAGE PRESSURE IN POUNDS PER SQ. INCH	THRUST IN POUNDS			
	ENTRANCE OPEN	ENTRANCE HALF OPEN	ENTRANCE ENTIRELY CLOSED	NOZZLE ALONE
20	1.65	0.70	0.04	1.57
40	3.30	1.35	0.06	3.12
60	5.00	1.95	0.18	4.80
80	6.65	2.70	OMITTED	6.68



DESIGN 2-A



NOZZLE ALONE



EFFICIENCY IN PER CENT
0
20
40
60
80
100
0
4
8
12
16
20
24
MASS RATIO
EFFICIENCY CURVE
FOR
INELASTIC IMPACT

Discussion

The thrust ratios of designs 1, 1-A, and 1-B proved to be very small. In the opinion of the writer, this was due to two principle causes; first, this type was designed for conditions of elastic impact during the mixing process and, hence, requires a large ratio of momenta for successful operation. Second, the friction losses in the elbows were excessive, amounting to approximately 30 per cent of the kinetic energy of flow.

The results of the tests on 1-B proved that the losses in the first 180° bend more than offset any benefit that might have been gained due to the entrance form being turned in such a direction as to add its component to the net thrust of the apparatus. When the entrance form was omitted, as in 1-A, the entrance losses increased considerably, so much that the losses more than balanced the detrimental effect of the entrance cone being turned in the wrong direction.

The results of the tests on Design 2 coincided to a large extent with those predicted by the theory of inelastic impact. The thrust ratios approached the value of 1.5 at low nozzle pressures. The fact that the thrust ratio increased with decrease in nozzle pressure may be explained as follows. The mass ratio increases as the nozzle pressure becomes smaller, causing the momentum of the induced air to approach that of the motor air. This causes the value of the thrust ratio, namely $\frac{1}{2}$ MV of the induced air plus MV of the motor air, to increase and approach the value of 1.5 the MV of the motor air.

Conversely, when the mass ratio is small, the relative value of the induced air momentum is small as compared with that of the motor air, hence the net thrust ratio is further from the possible value of 1.5.

The results of the tests on Design 2-A proved that the total increase in the thrust of Design 2, above that of the nozzle alone, was due to the decreased pressure acting upon the surfaces of the entrance form. This shows that in the design of an augmentor, great care must be taken to cause the force due to the acceleration of the induced air to register upon the apparatus; since, in the case of Design 2-A, no increase was affected above the thrust of the nozzle alone. The fact that the thrust of Design 2-A was slightly above that of the nozzle alone needs some explanation. This was most probably caused by an increase in the volume of air discharged by the nozzle when encased in the air tube. The lowered pressure of the high velocity induced air, surrounding the nozzle, would tend to decrease the back pressure acting upon the nozzle and cause its discharge to increase.

In the opinion of the writer, better results would have been obtained should the area of the entrance form have been larger, because, according to theory, an impulse equal to the full value of $\frac{1}{2}$ MV of the induced air could only be obtained should the area of the entrance form be infinitely large. However, a large proportion of the impulse was obtained because the velocity of the induced air, as it approached the entrance, is negligible until in the immediate vicinity of the entrance.

It is interesting to note the effect of a constriction at the mouth of the air tube upon the operation of the augmentor. When the area of the mouth was reduced by half, the thrust was reduced to less than half its original value. With the mouth entirely closed, very little thrust was obtained although the nozzle was discharging its normal rate. The thrust of the nozzle was counteracted by the reduced pressure acting upon the constriction in the mouth of the air tube. The pressure at this point was reduced to such an extent that full air pressure could not be used because of excessive bowing in of the plywood. Regular vibrations were set up in the augmentor during the latter test.

The results of these tests are valuable only as they offer a basis for a logical approach to the problems met in the design of the augmentor. The practical value of these designs is very small due to the low thrust ratios obtained.

The thrust ratios obtained by the Melot augmentor as tested by Jacobs and Shoemaker[1] were somewhat larger than those of Design 2. In the opinion of the writer, the design produced by Schmidt is an improvement over the Melot augmentor. Thrust ratios of approximately 1.65 were obtained by Schmidt as compared with 1.5 by the former. The reason for this increased performance, in the opinion of the writer, is that the Schmidt augmentor raises the velocity of the induced air to a large value before the mixing process, in this way reducing the velocity difference between the induced and motor air. This increases the efficiency of the mixing process by reducing the losses of impact. Should the areas of its entrance forms have been large, apparently better results would have been obtained.

[1] Tests on Thrust Augmentors for Jet Propulsion, Jacobs and Shoemaker, N.A.C.A. Technical Notes No. 431, 1932.

Conclusions

It may be concluded that the thrust augmentor has promise of success provided the energy of the motor gases can be efficiently transferred to the induced air. This not being possible to-day, the present form of augmentor is unsuitable for application as a propeller. There seems to be sufficient grounds upon which to base expectation that this may be accomplished in the future. The reason for the failure, at present, is due to the condition of inelastic impact between motor gases and induced air. Although the impact of the air masses are inelastic, the individual molecules comprising the mixture are perfectly elastic so far as science can determine. Also, a confined body of air is perfectly elastic in an adiabatic process; therefore, the fact that the impact between the motor gases and induced air is inelastic must be the fault of the method of mixture.

Although science knows little about what actually takes place during such a mixing process, it may be profitable to attempt an explanation of the phenomenon in an effort to produce a working theory. Apparently the mixing of the induced and motor air is caused by the interchange of molecules in their state of violent agitation. The molecules of surrounding atmosphere would then enter the stream and, in being accelerated with the stream, their inertia would cause a force against the moving particles, setting up momentarily a pressure between these particles. The pressure would then cause an expansion in every direction until the condition of normal pressure is again reached. In this process much energy would be lost. This idea may be better explained by considering the type of impact occurring between the individual molecules.

Consider two molecules of air, A and B, each of mass M, enlarged to the size of billiard balls. Let A remain stationary while B approaches it with velocity V. Let these molecules act as would the average molecules of a large body of air. The chances of a direct hit would be small, the average molecule striking with a glancing blow, the angle of contact of the two molecules being somewhere between 0 and 90 degrees. It seems plausible that the average molecule would strike in the middle of the two extremes, in which case the angle of contact would be the angle whose sine is $\frac{1}{2}$ or 30 degrees, as shown by Diagram 9.

Assuming the impact to be perfectly elastic and the surfaces frictionless, half the kinetic energy of molecule B would be absorbed by molecule A, the direction of motion of A after impact being 30 degrees from the initial direction of motion of B. The direction of B after impact will be 30 degrees to the other side of the initial direction. The energy of B before impact was $\frac{1}{2} MV^2$ and after impact would be $\frac{1}{4} MV^2$, its component of velocity in the initial direction being $\frac{V}{\sqrt{2}}$. Its energy component in this direction is then:

$$\frac{1}{4} \frac{MV^2}{2} = \frac{1}{8} MV^2 .$$

The same conditions are present in the case of molecule A; so that the combined energy of the two molecules is now $\frac{1}{2} MV^2$, their energy components in the initial direction being $\frac{1}{4} MV^2$. This is the condition of total inelastic impact since the energy components 90 degrees to

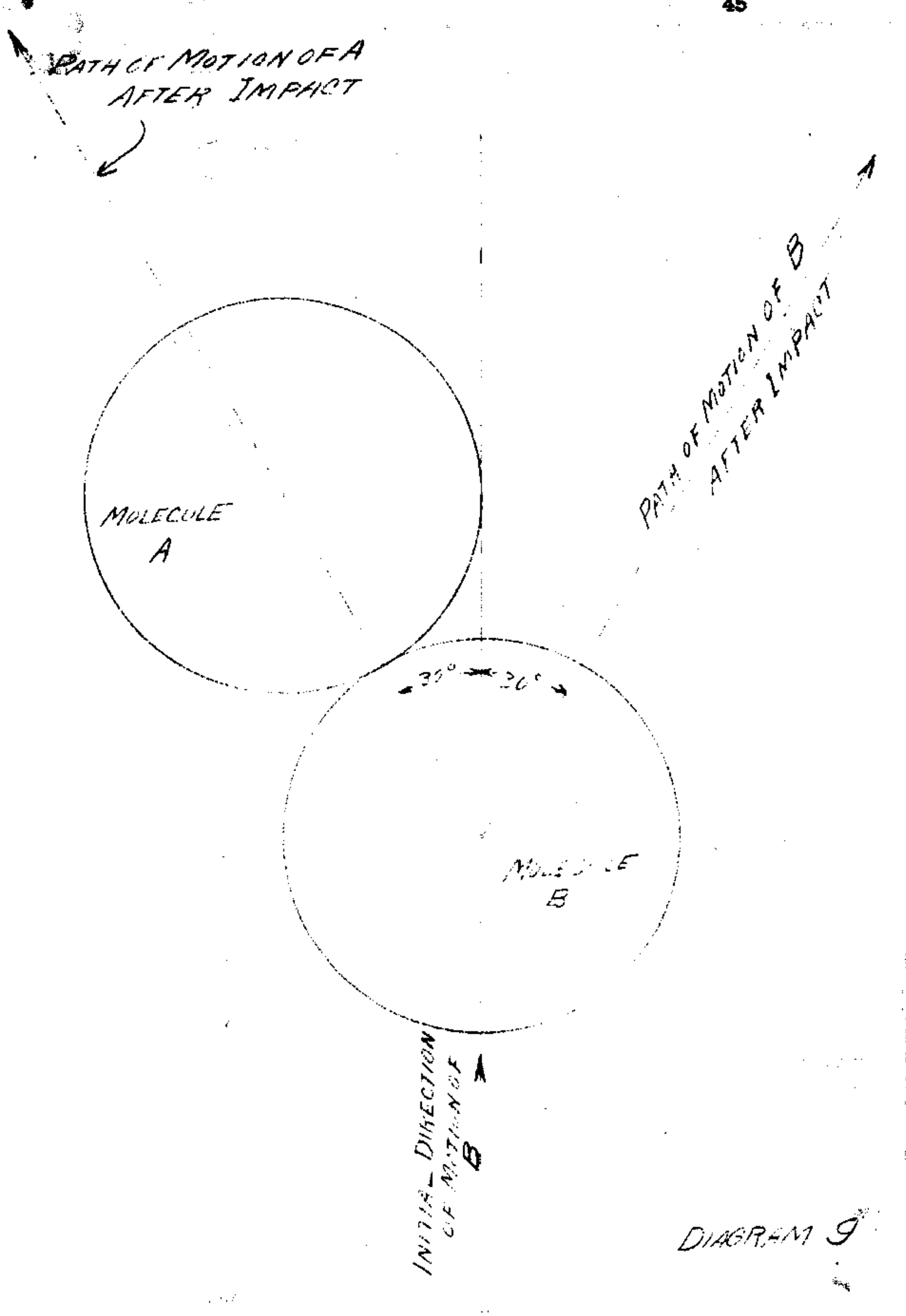

PATH OF MOTION OF A
AFTER IMPACT
PATH OF MOTION OF B
AFTER IMPACT
MOLECULE
A
30°
30°
B
INITIAL DIRECTION
OF MOTION OF
B

DIAGRAM 9

the initial direction are unavailable. The effect of the components of motion of the molecules at right angles to the initial direction is similar to that of molecules of plastic materials such as clay and putty during impact.

This plastic action, according to the above reasoning, is due to the inefficiency of the mixing process, and the problem would then confine itself to redirecting the molecules of air so that the energy of lateral motion could be regained. This problem, in the opinion of the writer, is not without solution and may well be the object of another set of experiments or thesis.

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