VORTEX FLOW IN AN ACTUAL GAS

by

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TABLE OF CONTENTS

SUMMARY

Applications of the vortex have been used in engineering for many years. Since the recent publication of Rudolph Hilsch's work in Germany[1], it is widely known that there is a transfer of energy from the center to the outside of a vortex in an actual gas. However, there is no theory which satisfactorily explains this transfer of energy in a vortex.

In this investigation, an effort was made to determine the characteristics of a vortex in an actual gas, the vortex being formed inside a pipe by the introduction of air tangent to the inside wall of the pipe.

It was found that the equilibrium condition for a vortex in an actual gas is a state in which there is no heat transfer and in which there are no viscous forces acting. These conditions call for the static temperature and $\frac{\text{velocity}}{\text{radius}}$ being constant and for the total temperature, static pressure, and total pressure increasing with increasing radius.

The investigation was conducted by the author in the Mechanical Engineering Department, Rensselaer Polytechnic Institute, Troy, New York

SYMBOLS

Subscript (R) refers to quantities at the outer radius of the vortex.

Subscript (c) refers to quantities at the center of the vortex.

F = force.

g = acceleration of gravity in ft. per sec. per sec.

k = thermal conductivity in Btu per hr. per square ft. per degree per ft.

M = Mach number.

M' = Mach number as computed using the uncorrected static pressure reading.

P_o = total pressure.

P' = static pressure as obtained from probe before correcting for instrument error.

P = static pressure.

P_1 = pressure before metering nozzle.

P_2 = pressure after metering nozzle = supply pressure to vortex.

P_3 = static pressure in center of vortex at closed end of pipe.

P_4 = static pressure at a radius of $\frac{1}{2}$ inch at closed end of pipe.

P_5 = static pressure at a radius of 5/8 inch at closed end of pipe.

SYMBOLS (cont'd)

P_6 = static pressure on pipe wall at a distance of 7/16 inch from closed end of pipe.

q = heat transferred in Btu per hr.

r = radius in inches.

R = maximum radius in inches.

R' = specific gas constant for air.

T_o' = total temperature as obtained from thermocouple before correcting for instrument error.

T_o = total temperature.

T = static temperature.

v = velocity in ft. per sec.

W = weight flow in lbs. air per sec.

X = distance from closed end of pipe in inches.

$\alpha_p = \frac{v_R^2}{2gRT}$ as computed using the pressure ratio in the vortex.

$\alpha_T = \frac{v_R^2}{2gRT}$ as computed using the total temperature ratio in the vortex.

γ = adiabatic gas constant. In this report, (γ = 1.395) was used.

ρ = density, slugs per cu. ft.

μ = coefficient of viscosity in slugs per sec. per sq. ft. per ft.

ω = angular velocity in radians per sec.

VORTEX FLOW IN AN ACTUAL GAS

INTRODUCTION

The classical free vortex derived from potential flow theory is based upon reversibility and constant total energy, neglecting the heat transfer, viscosity, and diffusion which are present in an actual gas. Writing an equation for the summation of radial forces in a vortex, and solving this equation in accordance with the above assumptions leads to the result that vr = constant. This requires that the velocity become infinite and the absolute pressure become zero at the center of the vortex where the radius is zero. These results are, of course, physically impossible. Also, it is known that the assumption of constant total energy is not true, since large total temperature gradients have been observed from the center to the periphery of a vortex.

The purpose of this investigation was to determine the characteristics of vortex flow in an actual gas.

Rudolph Hilsch, a German low-temperature physicist, used a vortex to obtain low temperatures, drawing off cold air from the center of the vortex.[1] High total temperatures were observed at the outer radius. Hilsch gave credit to an unidentified Frenchman for the discovery of this phenomenon. Also in Germany, the vortex has been successfully used as a dust separator.[2] There are other applications of the vortex in engineering, for example, centrifugal oil purifiers, and centrifugal compressor design. So far as is known, however, there has been no theory evolved, supported by experimental data, which will explain the phenomena occuring in a vortex.

The U.S. Navy and the U.S. Air Forces have conducted flights through tropical cyclones for the purpose of collecting data. The author has been unable to obtain copies of this data or any information concerning any theory which may have been developed from the data so obtained.

C.J. Ricketts and J.L. Genta[3] investigated the vortex about a year ago. Unfortunately, due to instrumentation difficulties, Ricketts and Genta were unable to obtain sufficient data to build up a theory.

Textbooks on fluid mechanics and aerodynamics present the vortex as being a free vortex with a thin, solid, cylindrical core rotating with constant angular velocity. In this way, the physically impossible situation of the velocity becoming infinite in the center is avoided. However, no account is taken of the decrease in total energy which actually occurs from the periphery to the center of such a vortex.

Professor Neil P. Bailey, head of the Department of Mechanical Engineering, Rensselaer Polytechnic Institute, Troy, New York, and members of his staff, have proposed a theory that a vortex in an actual gas comes to a state of equilibrium in which there is no heat transfer and in which there are no viscous forces acting. Such a theory accounts for the total temperature gradient in a vortex, however this theory has not yet been checked with actual data.

This report is concerned with the case of a vortex in an actual gas in a cylindrical container, the vortex being induced by the injection of air tangent to the wall of the container. The investigation was conducted in the Mechanical Engineering Department, Rensselaer Polytechnic Institute, Troy, New York, during the period February-May 1948.

The author wishes to acknowledge the invaluable guidance and advice of Professor Neil P. Bailey. Thanks also are due to members of Professor Bailey's staff for helpful advice and the services of the machine shop.

EQUIPMENT AND PROCEDURE

To obtain a vortex, a vortex valve designed by Professor Neil P. Bailey was used. (See Fig. 2). On one end of this valve is a series of vanes spaced around the periphery, these vanes being adjustable so that the angle at which the flow enters the pipe may be varied. For this investigation, the vanes were set at an angle of ten degrees with the tangent to the inside pipe wall. The end of the valve which has the vanes is inserted into the plenum chamber, thus the flow enters through the vanes and is discharged out the two inch diameter copper pipe.

To obtain the static pressures in the center of the vortex along the pipe axis, a probe was traversed along the pipe axis; the probe being entered from the open end of the pipe. This probe was a stainless steel tube, 0.101 inch outside diameter, with a hole in the side 7/16 inch from the end.

The center traverse for total temperature was made with an iron-constantan thermocouple. The thermocouple wires were led through insulators, which, in turn, were led through a length of $\frac{1}{4}$ inch outside diameter copper tubing; thus making a stiff probe which could be traversed along the pipe axis.

To obtain measurements at any radius away from the center of the vortex, it was not practicable to use probes traversed along the pipe as was done for the center traverses. The forces which existed in the vortex away from the center were sufficient to break these long slender probes. If the probes were made strong enough to resist breakage, they would still be bent or deflected so that it was impossible to position the probe at any desired point. The vibration was so violent as to make accurate readings impossible. Also, as soon as the probe was moved away from the center of the vortex, the flow was altered as indicated by a distinct change in sound.

These conditions made it necessary to obtain data by traversing probes along the radius. In this manner, a much shorter and much smaller probe could be used. Such a probe would be rigid, could be accurately positioned, and being very small would not disturb the flow as much as the probes which were inserted axially.

Before designing the probes, it was necessary to know a little about the character of the flow. It was known that there was a velocity component parallel to the pipe axis, but it was not known whether or not there was a radial component of velocity. To try to determine this, an open end impact tube with a right angle bend at the end was used. The probe was carefully positioned so that the open end was at the pipe axis, then the probe was traversed horizontally along the radius. At various points along the radius, the probe was rotated and its position noted when the reading was a maximum. As nearly as could be determined by eye, the bent end of the probe was vertical at the point of maximum reading, thus indicating that the flow was in concentric circles, there being no radial component. This was done for various supply pressures up to twenty inches of mercury gage. Above this supply pressure, no check could be made because the probe was bent by the forces in the vortex.

Although the above check was admittedly approximate, the probes to be used were designed assuming that there was no radial component of flow. The axial component of flow would not affect the accuracy of the readings from the type of probes which were in mind. Investigation was limited to a supply pressure of about twenty inches of mercury gage, inasmuch as the possibility of radial flow was not investigated at higher supply pressures.

Total pressure, static pressure, and total temperature were desired along the radius; and probes were made to obtain these quantities. All three probes were made of stainless steel tubing. The outside diameter was 0.048 inches, and the inside diameter was 0.029 inches. The probes were all approximately three inches long.

For the total pressure tube, one end of the steel tube was closed and a 0.0135 inch diameter hole was drilled in the tube wall 0.10 inch from the closed end. A 3/8 inch diameter brass hose fitting was soldered on the other end. This probe was tested against an open end impact tube and gave the same reading. The total pressure was obtained by rotating the probe for the maximum reading.

For static pressure, a Ser's disk[4] was used. A small brass circular disk was soldered on the end of the stainless steel probe, the plane of the disk being perpendicular to the axis of the probe. This disk was 0.2 inch in diameter and 0.02 inch thick. The hole in the disk was the same as the outside diameter of the steel tube, so the end of the tube was brought out flush with the bottom of the disk. The bottom of the disk was flat, and the top side was beveled to produce a sharp edge. A 3/8 inch diameter brass hose fitting was soldered on the other end. This probe was tested in straight flow, using an ordinary static pressure traverse tube with a hole in the side as the standard. The Ser's disk was found to give low readings, therefore it was compared with the static pressure traverse tube at various Mach numbers and a correction curve was made up. (See Curve No. 1). Mach number was determined from total and static pressure.

Although the Ser's disk was tested in straight flow, it was used in circular flow. This gives the possibility of some component of velocity pressure being measured due to the fact that the flow is curved and is not exactly parallel to the Ser's disk. This might cause the static pressure reading to be slightly high and tend to cancel out the low reading which it gave in straight flow. Therefore, the value of Curve No. 1 is questionable. However, all data presented in this report were reduced using the corrections from Curve No. 1. Some of the data were reduced using the corrections of Curve No. 1 and again without this correction, and the conclusions to be drawn from the data were not affected. Obtaining static pressures presented the greatest problem, and no doubt the static pressures obtained can be improved upon. It is believed, though, that the effect of the flow curvature is not sufficient to affect the validity of the conclusions regarding the character of the flow.

It may be noted that the smaller the disk, the smaller would be the effect of the velocity component in a curved flow. However, smaller disks were tried, and they gave such large errors in straight flow that they were discarded.

The thermocouple was made of 30 gage iron and constantan wire. The wires were led through the 0.048 inch diameter steel tube and brought out through a hole in the side of the tube approximately 0.1 inch from the end, this end of the tube being closed. The thermocouple junction was placed about even with the outside of the steel tube, thereby forming a good impact area. When tested, this thermocouple gave readings slightly lower than total temperature, so a curve of error versus Mach number was made up. (See Curve No. 2). The thermocouple was tested by placing it in a nozzle attached to the plenum chamber. It was assumed that there was constant total energy from the plenum chamber through the nozzle, and the reading of a testing thermometer in the plenum chamber was taken as standard. Mach number was determined from total and static pressure.

All three of the probes discussed above, which were used for measurements along the radius, were led through brass plugs. These plugs had a packing gland and packing nut on one end and were threaded on the other end. At points along the pipe where it was desired to obtain measurements, a small square brass pad was soldered to the pipe to increase the thickness. The pad and pipe were then drilled and tapped to receive the plug with the probe. Dividers and a scale were used to position the probes along the radius.

For temperature measurement, a Leeds and Northrup potentiometer indicator No. 8657-C was used, with the cold junction at room temperature.

All pressures were measured with mercury manometers.

Air was supplied by a Schramm air compressor, Model 210, rated at 206 cu. ft. of free air per min. at 1175 r.p.m.

The air compressor was driven by a Westinghouse three phase, 60 cycle, 220-440 volt, 50 horsepower induction motor with a rated full load speed of 1175 r.p.m.

A schematic drawing of the set-up is shown in Figure 1. The plenum chamber was supported on a lathe bed.

The vortex valve was originally six inches from the closed end to the open end. This six inch length was used to obtain the center traverses for static pressure and total temperature shown on Curves No. 3 and 4. A back flow of air from the room down the center of the pipe existed due to the low pressure in the center of the vortex. On the basis of Curves No. 3 and 4, it was thought that a radial traverse could be made at X = 2.5 inches and be free from this back flow. Accordingly, the pipe was instrumented and traverses were made at X = 2.5 inches. However, a back flow down the center was still present, as indicated by the direction in which the total pressure tube pointed for maximum reading. This direction was indicated by a scribe mark on the hose fitting in the same plane as the impact hole. To try to get away from this back flow, the vortex valve was increased in length from six inches to two feet, and holes for traversing were provided at: X = 1.4 inches; X = 2.5 inches; X = 3.8 inches; X = 8.1 inches; X = 14.1 inches; and X = 20.1 inches. Plugs were provided to seal off the holes not in use. When traverses were again made, a small back flow was still indicated from X = 8.1 inches to X = 24 inches. Next, a 1 3/4 inch diameter disk was used to plug out the back flow. This disk was moved axially until it appeared that all back flow had ceased. This position for the disk was about 1/8 inch outside the pipe. If placed farther outside, room air leaked around the edge of the disk and entered the pipe. If placed inside the pipe, the annular passage between the disk and pipe wall was not large enough to let all the flow pass, resulting in some of the flow going to the center of the pipe at the disk and flowing back up the pipe. The data thus obtained with the back flow cut out was of the same character as the data obtained with a small back flow present.

All tables and curves presented in this report are from data taken in the two foot long pipe without cutting out back flow, except that Curves No. 3 and 4 and Table No. X are from data taken in the six inch long pipe, also without cutting out the back flow.

Preliminary investigation showed considerable agreement with the theory proposed by Professor Neil P. Bailey. (This theory was discussed briefly in the introduction to this report). Therefore, the general procedure in this investigation was as follows:

(a) To obtain reliable data in a vortex.

(b) To compare this data with Professor Bailey's theory in an effort to prove or disprove this theory.

(c) If the theory in (b) is disproved, develop a theory based on the data obtained.

THEORY

Since the procedure in this investigation was to prove or disprove the theory proposed by Professor Neil P. Bailey, and if the theory was disproved, to develop a theory based on the data: the theory will be presented at this point so that it may be freely referred to in the discussion of the results.

As mentioned in the introduction to this report, the theory is based upon the assumption that at equilibrium:

(a) there is no heat transfer.

(b) there are no viscous forces acting.

From assumption (a), we may write:

$$q = - k\, 2\pi r \frac{dT}{dr} = 0 \qquad \text{.......................(1)}$$

This requires that:

$$\frac{dT}{dr} = 0 \qquad \text{.......................(2)}$$

And integrating eq. (2) gives:

$$T = \text{const.} \qquad \text{.......................(3)}$$

Since the flow is curvilinear, it is the angular velocity gradient, $(\frac{d\omega}{dr})$, of which adjacent layers are conscious and not the linear velocity gradient, $(\frac{dv}{dr})$. From assumption (b) we may write:

$$F_{viscous} = -\mu 2\pi r \frac{d\omega}{dr} = 0 \qquad \text{.......................(4)}$$

This requires that:

$$\frac{d\omega}{dr} = 0 \qquad \text{.......................(5)}$$

And integrating eq. (5) gives:

$$\omega = \text{const.} \qquad \text{.......................................(6)}$$

Hence, since $\omega = \frac{v}{r}$:

$$\frac{v}{r} = \text{const.} \qquad \text{..............................(7)}$$

or $v = \text{const.} \times r$ ....(7a)

At equilibrium, the pressure gradient must balance the centrifugal forces, or :

$$dP = \frac{v^2}{r} \rho \, dr \qquad \text{..............................(8)}$$

Substituting $\rho = \frac{P}{gR'T}$ from the gas equation:

$$dP = \frac{v^2}{r} \frac{P}{gR'T} dr \qquad \text{........................(9)}$$

Rearranging:

$$\frac{dP}{P} = \frac{v^2}{r} \frac{1}{gR'T} dr \qquad \text{........................(10)}$$

Multiplying and dividing by (r), eq. (10) may be written:

$$\frac{dP}{P} = \frac{v^2}{r^2} \frac{1}{gR'T} r \, dr \qquad \text{......................(11)}$$

From eq. (7), $\frac{v}{r}$ = const.; and from eq. (3), T = const.; therefore eq. (11) may be written:

$$\int \frac{dP}{P} = \left(\frac{v}{r}\right)^2 \frac{1}{gR'T} \int r \, dr \qquad \text{....................(12)}$$

Since $\frac{v}{r}$ = const. = $\frac{v_R}{R}$:

$$\int \frac{dP}{P} = \left(\frac{v_R}{R}\right)^2 \frac{1}{gR'T} \int r \, dr \qquad \text{.................(13)}$$

Integrating eq. (13) from the center of the vortex to any radius:

$$\int_{Pc}^{P} \frac{dP}{P} = \left(\frac{v_R}{R}\right)^2 \frac{1}{gR'T} \int_{0}^{r} r \, dr \qquad \text{..........(14)}$$

Or: $$\ln\left(\frac{P}{P_c}\right) = \left(\frac{v_R}{R}\right)^2 \frac{1}{gR'T} \quad \frac{r^2}{2} \qquad \text{......................(15)}$$

Rearranging:

$$\ln\left(\frac{P}{P_c}\right) = \frac{v_R^2}{2gR'T}\left(\frac{r}{R}\right)^2 \qquad \text{.........................(16)}$$

Letting:

$$\frac{v_R^2}{2gR'T} = \alpha \qquad \text{................................(17)}$$

And substituting this into eq. (16) and taking the anti-log:

$$\frac{P}{P_c} = e^{\alpha\left(\frac{r}{R}\right)^2} \qquad \text{................................(18)}$$

Equation (18) describes the manner in which the static pressure increases from the center of the vortex to the maximum radius of the vortex. Integrating eq. (13) from the center of the vortex to the maximum radius of the vortex:

$$\int_{P_c}^{P_R} \frac{dP}{P} = \left(\frac{v_R}{R}\right)^2 \frac{1}{gR'T} \int_0^R r \, dr \qquad \text{........(19)}$$

Integrating and rearranging gives:

$$\ln\left(\frac{P_R}{P_c}\right) = \frac{v_R^2}{2gR'T} \qquad \text{...........................(20)}$$

Using eq. (17) in eq. (20) gives:

$$\alpha = \ln\left(\frac{P_R}{P_c}\right) \qquad \text{..............................(21)}$$

Equation (21) provides a means for evaluating the constant (α) if the pressures at the center and outer radius of the vortex are known. Equation (21) may also be written:

$$\frac{P_R}{P_c} = e^{\alpha} \qquad \text{...............................(22)}$$

Integrating eq. (12) from the center of the vortex to the outer radius, we obtain:

$$\ln\left(\frac{P_R}{P_c}\right) = \left(\frac{v}{r}\right)^2 \frac{R^2}{2gR'T} \quad \text{.........................(23)}$$

Solving for $\left(\frac{v}{r}\right)^2$:

$$\left(\frac{v}{r}\right)^2 = \frac{2gR'T}{R^2} \ln\left(\frac{P_R}{P_c}\right) \quad \text{.....................(24)}$$

Combining equations (21) and (24):

$$\left(\frac{v}{r}\right)^2 = \alpha \frac{2gR'T}{R^2} \quad \text{.........................(25)}$$

From "The Thermodynamics of Air at High Velocities" by Neil P. Bailey[5] (hereafter referred to simply as H.V.T.), the following relationship between static temperature, total temperature, and Mach number is obtained:

$$\frac{T_o}{T} = 1 + \frac{\gamma - 1}{2} M^2 \quad \text{..............................(26)}$$

Also from H.V.T.:

$$M^2 = \frac{v^2}{\gamma gR'T} \quad \text{..............................(27)}$$

Combining equations (26) and (27):

$$\frac{T_o}{T} = 1 + \frac{\gamma - 1}{2} \frac{v^2}{\gamma gR'T} \quad \text{....................(28)}$$

Multiplying and dividing by (r^2) in the last term:

$$\frac{T_o}{T} = 1 + \frac{\gamma - 1}{2} \frac{r^2 \left(\frac{v}{r}\right)^2}{\gamma gR'T} \quad \text{.....................(29)}$$

Substituting eq. (25) for $\left(\frac{v}{r}\right)^2$ and simplifying:

$$\frac{T_o}{T} = 1 + \frac{\gamma - 1}{\gamma} \left(\frac{r}{R}\right)^2 \alpha \quad \text{......................(30)}$$

From eq. (7a), the velocity is zero at the center of the vortex, therefore static temperature and total temperature are the same at the center of the vortex. From eq. (3), the static temperature is a constant, therefore the total temperature at the center of the vortex may be substituted for the static temperature at any radius, and eq. (30) may be written:

$$\frac{T_o}{T_{o_c}} = 1 + \frac{\gamma - 1}{\gamma} \left(\frac{r}{R}\right)^2 \alpha \quad \text{.........................(31)}$$

Equation (31) describes the manner in which the total temperature increases from the center of the vortex to the outer radius.

Taking conditions at the maximum radius in eq. (28):

$$\frac{T_{o_R}}{T} = 1 + \frac{\gamma - 1}{\gamma} \frac{V_R^2}{2gR'T} \quad \text{.........................(32)}$$

Combining equations (17) and (32); and substituting $T = T_{o_c}$:

$$\frac{T_{o_R}}{T_{o_c}} = 1 + \frac{\gamma - 1}{\gamma} \alpha \quad \text{.........................(33)}$$

Solving for (α):

$$\alpha = \frac{\gamma}{\gamma - 1} \left[\frac{T_{o_R}}{T_{o_c}} - 1\right] \quad \text{.........................(34)}$$

Equation (34) provides a means of evaluating the constant (α) if the total temperature is known at the center and the maximum radius of the vortex.

From H.V.T., the relationship between static pressure, total pressure, and Mach number is:

$$\frac{P_o}{P} = \left[1 + \frac{\gamma - 1}{2} M^2\right]^{\frac{\gamma}{\gamma - 1}} \quad \text{.........................(35)}$$

Combining equations (26) and (35):

$$\frac{P_o}{P} = \left(\frac{T_o}{T}\right)^{\frac{\gamma}{\gamma-1}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(36)$$

Combining equations (30) and (36):

$$\frac{P_o}{P} = \left[1+\frac{\gamma-1}{\gamma}\left(\frac{r}{R}\right)^2 \alpha\right]^{\frac{\gamma}{\gamma-1}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(37)$$

From equation (18):

$$P = P_c e^{\alpha\left(\frac{r}{R}\right)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(38)$$

Combining equations (37) and (38):

$$\frac{P_o}{P_c} = e^{\alpha\left(\frac{r}{R}\right)^2}\left[1+\frac{\gamma-1}{\gamma}\left(\frac{r}{R}\right)^2 \alpha\right]^{\frac{\gamma}{\gamma-1}} \quad \ldots\ldots\ldots\ldots(39)$$

It has already been shown that the velocity at the center of the vortex is zero. Therefore, the static pressure and total pressure are the same at the center of the vortex, and (P_{o_c}) may be substituted for P_c in equation (39):

$$\frac{P_o}{P_{o_c}} = e^{\alpha\left(\frac{r}{R}\right)^2}\left[1+\frac{\gamma-1}{\gamma}\left(\frac{r}{R}\right)^2 \alpha\right]^{\frac{\gamma}{\gamma-1}} \quad \ldots\ldots\ldots(40)$$

Equation (40) describes the manner in which the total pressure increases from the center of the vortex to the outer radius. From the equations developed above, it can be seen what the characteristics of the vortex are according to this new theory. From equation (3), the static temperature is constant. From equations (7) and (7a), $\left(\frac{V}{r}\right)$ is a constant, or the velocity is zero at the center and increases with increasing radius. From equation (18), the static pressure is a minimum in the center and increases with increasing radius. From equation (31), the total energy is not constant, the total temperature being a minimum in the center and increasing with increasing radius. And finally, from equation (40), the total pressure is a minimum in the center and increases with increasing radius.

RESULTS AND DISCUSSION

The data taken in this investigation consists of static pressure, total pressure, and total temperature taken along the radius at various points along the pipe as the vortex develops and starts to dissipate. From these data, Mach number, velocity, static temperature, and $(\frac{V}{r})$ were computed. $(\frac{P}{P_c})$ and $(\frac{T_o}{T_{o_c}})$ were also computed from the data for various radii for comparison with the theoretical values as computed from equations (18) and (31) in the section on theory.

Data taken at X = 2.5 inches in the two foot long pipe using approximately ten inches of mercury (gage) supply pressure, and quantities derived from these data, are presented in Tables I and II and in Curves 5 and 5-A. A comparison of static pressure ratio and total temperature ratio with theory is presented in Table III and Curves 5-B and 5-C.

Data taken at X = 8.1 inches in the two foot long pipe using approximately ten inches of mercury (gage) supply pressure, and quantities derived from these data are presented in Tables IV and V and Curves 6 and 6-A. A comparison of static pressure ratio and total temperature ratio with theory is presented in Table VI and Curves 6-B and 6-C.

Data taken at X = 14.1 inches in the two foot long pipe using approximately ten inches of mercury (gage) supply pressure, and quantities derived from these data are presented in Tables VII and VIII and Curves 7 and 7-A. A comparison of static pressure ratio and total temperature ratio with theory is presented in Table IX and Curves 7-B and 7-C.

Data taken at X = 2.5 inches in the six inch long pipe using approximately ten inches of mercury (gage) supply pressure are presented in Table X.

Data taken at X = 1.4 inches in the two foot long pipe using 21 inches of mercury (gage) supply pressure are presented in Table XI.

In this investigation, r = 0.9 inch was taken as the maximum radius of the vortex due to the difficulty of obtaining reliable readings on the pipe wall.

In comparing the curve of $(\frac{V}{r})$ versus (r) on Curves 5-A, 6-A, and 7-A, it will be noted that $(\frac{V}{r})$ is greater at the outer radii than at the inner radii at X = 2.5

inches; while at X = 14.1 inches, $(\frac{V}{r})$is greater at the inner radii than at the outer radii. The theory calls for $(\frac{V}{r})$ being constant at equilibrium. Before the vortex is fully developed and equilibrium attained, one might expect that $(\frac{V}{r})$ would be greater at the outer radii than at the inner radii As a limiting case, one could take the moment at which the air supply is turned on. The air in the pipe is at rest and $(\frac{V}{r})$ equals zero. As the air enters at high velocity at the outer periphery of the pipe, the $(\frac{V}{r})$ will be high at these outer radii; while at the inner radii, $(\frac{V}{r})$ will still be zero. By viscous action, the inner mass of air will be pulled around until equilibrium is reached, at which time there will be no viscous forces acting, and $(\frac{V}{r})$ will be constant, as was shown in the theoretical development. As the effect of friction at the pipe wall begins to be felt, the flow at the outer radii will commence to decrease in velocity, thus causing $(\frac{V}{r})$ to be less at the outer radii than at the inner radii. Viscous forces will again start to act due to relative motion between adjacent layers, the velocity being reduced toward the center until the angular velocity is zero, and the vortex will dissipate.

At X = 8.1 inches (Curve 6-A) it is seen that $(\frac{V}{r})$ is constant from the center out to r = 0.6 inches, and that from this point on out, $(\frac{V}{r})$ falls off gradually, apparently due to friction effects. By the time the flow reaches X = 14.1 inches (Curve 7-A), the effect of friction is very noticeable and $(\frac{V}{r})$ decrease sharply from the center to the outside the vortex quite definitely dissipating. At X = 2.5 inches (Curve 5-A), $(\frac{V}{r})$ increases sharply from the center to the outside, the vortex being not fully developed at this point. The slight drop in $(\frac{V}{r})$ at the maximum radius is probably due to friction. It would not be expected that the vortex would be found in equilibrium exactly in accordance with the theory, due to friction at the wall, which the development of the theory did not take into account. The curves of $(\frac{V}{r})$ versus (r) are, then, quite in accord with the theory.

It will be noted that, in drawing curves through the experimental points, the point r = 0.1 has been neglected. The worst case is at X = 8.1 inches (Curve 6-A). To bring this point on to the curves requires a ratio of total pressure to static pressure of 1.004 instead of the ratio 1.001 which was obtained. This error is well within the experimental error in reading which might be expected. Also, a small error in velocity becomes greatly magnified when divided by 0.1 to obtain $(\frac{V}{r})$. It was, therefore, considered necessary to neglect this point, since with the instrumentation used, it was not possible to obtain the required degree of accuracy at such low Mach numbers.

The comparison of the static pressure ratio in the vortex with the static pressure ratio as determined by theory is shown on Curves 5-B, 6-B, and 7-B. If one again takes the moment at which the air is turned on, the ratio $(\frac{P}{P_c})$ will be unity across the vortex, or less than is called for by the theory. As the vortex develops, this ratio will build up until the vortex is fully developed, and the pressure ratio as determined by test will agree with the pressure ratio as determined by theory. As friction affects are felt and the static pressure at the outside increases as the Mach number decreases, this pressure ratio will become greater than that called for by theory. At X=2.5 inches (Curve 5-B), it is seen that the the ratio $(\frac{P}{P_c})$ as determined by test is less than the theoretical value; at X = 8.1 inches (Curve 6-B), the agreement between test and theory is quite good; and at X = 14.1 inches (Curve 7-B), the ratio by test is greater than theoretical. As with the curve of $(\frac{V}{r})$, the pressure ratio $(\frac{P}{P_c})$ as determined by test is in very good agreement with the theory.

An examination of Curves 5-C, 6-C, and 7-C comparing the total temperature ratio $(\frac{T_o}{T_{o_c}})$ in the vortex with the theoretical curves shows that the test is in close agreement with the theory at X = 2.5 inches. Beyond this point, heat is being transferred back to the center of the vortex. A comparison of these results with the results for the pressure ratio would indicate that equilibrium in heat transfer is attained before equilibrium in balance of forces is reached.

It will be remembered that the theory calls for the static temperature being constant. If once more, the limiting case is taken just at the moment at which the air supply is turned on; the total temperature is constant, and the ratio $(\frac{T_o}{T_{o_c}})$ is unity, or less than theoretically called for. As air at high velocity enters at the outer radii, the static temperature at these outer radii will be less than at the center, and a transfer of heat from the center to the outside will occur. This process will continue until equilibrium is reached, at which time the total temperature gradient will be a maximum and the static temperature gradient will be zero. As friction effects are felt and the Mach number decreases at the outer radii, the static temperature at these outer radii will rise above the static temperature at the inner radii and heat will be transferred back toward the center, causing the ratio $(\frac{T_o}{T_{o_c}})$ to become greater than the theoretical value.

The curves of static temperature versus radius for the three values of (X) investigated are shown on Curves 5, 6, and 7. It can be seen that the static temperature is approximately constant, as called for by theory. The peculiar shape of the curve at X = 2.5 inches (Curve 5) is not readily explained. As has been mentioned previously, there was a slight recirculation of room air down the center of the pipe. Since this room air is about 30 degrees Fahrenheit cooler than the air supplied to the vortex from the plenum chamber, it was thought possible that the center had been cooled and that the static temperature curve should have a negative slope at this point, indicating that the transfer of heat to the outer radii was not yet complete. To check this point, data was taken at X = 2.5 inches with the back flow cut out, as described in the section on "Equipment and Procedure". All other conditions were the same as for Curve No. 5. The resulting data was almost an exact duplication of the data taken originally, therefore it was concluded that the back flow was not sufficient to have any noticeable effect on the vortex. An examination of the total temperature curves and total temperature ratio curves reveals the fact that actually the transfer of heat is completed, or nearly completed, by the time the flow reaches X = 2.5 inches. The maximum total temperature gradient observed was at X = 2.5 inches (Curve 5), indicating that the transfer of heat had been completed before the next point of investigation was reached at X = 8.[illegible] inches. The comparison of $(\frac{T_o}{T_{o_c}})$ by test and by theory at X = 2.5 inches (Curve 5-C), indicates that the transfer of heat back to the center has already started at the outer radii, since the test points fall above the theoretical points at the outer radii. It will be remembered that the effect of friction was noted at the outer radii at X = 2.5 inches on the velocity and $(\frac{V}{r})$ curves also. All of this would lead one to expect the static temperature curve at X = 2.5 inches to rise toward the outer radii. The curve, in fact, does this, but at the extreme outer radii it again falls off. This may well be due to heat transfer through the copper pipe. A temperature differential exists across the pipe, and since the flow is circular, it has been in contact with the pipe a much greater distance than the axial distance of 2.5 inches. For the small weight flow involved, (0.066 lbs. per sec.), a small heat transfer would have a noticeable effect on the temperature.

The results of this investigation, then, lend very strong support to the theory that a vortex in an actual gas comes to a state of equilibrium in which there is no heat transfer and in which there are no viscous forces acting.

In Table X are presented data taken at X = 2.5 inches in the six inch long pipe with approximately ten inches of mercury (gage) supply pressure. Upon reducing this data, it was indicated that making the pipe shorter had the effect of speeding up the development of the vortex and of producing slightly larger temperature and pressure gradients. At X = 2.5 inches, in the short pipe, the vortex was definitely dissipating.

In Table XI are presented data taken at X = 1.4 inches in the two foot long pipe with 21 inches of mercury (gage) supply pressure. Reducing these data indicated that increasing the supply pressure increased the temperature and pressure gradients and resulted in higher flow Mach numbers.

It is of interest to note, on Curve 4, that a temperature of minus 16.6 degrees Fahrenheit was observed in the center of a vortex in the six inch long pipe, with a supply pressure of 60.4 inches of mercury (gage) and an air supply total temperature of 107 degrees Fahrenheit.

CONCLUSIONS AND RECOMMENDATIONS

From the results of this investigation, it may be concluded that a vortex in an actual gas reaches a state of equilibrium in which there is no heat transfer and in which there are no viscous forces acting. As was shown in the section on "Theory", this means that the static temperature and $\left(\frac{V}{r}\right)$ are constant, and that the total temperature, static pressure, and total pressure increase with increasing radius. The above statements apply to a vortex which is induced by the injection of air at the outer radius.

It is recommended that an investigation be made into the case where the air is introduced at the inner radius, as in a vaneless diffuser. The same vortex valve used for this investigation could be modified to serve for the recommended investigation. Air could be introduced through the copper pipe and discharged out through the vanes, just the reverse of the process in this investigation. If a container were placed around the vanes, the equivalent of a vaneless diffuser would be obtained.

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CALCULATIONS

In order to illustrate the manner in which the data was reduced, the data for r = 0.5 inches at X = 8.1 inches will be worked out here.

$$\frac{P_o}{P'} = \frac{29.90}{28.77} = 1.04$$

From H.V.T.[5]:

$$\left(\frac{P_o}{P}\right)^{\frac{\gamma-1}{\gamma}} = \left[1 + \frac{\gamma-1}{2} M^2\right]$$

Curve No. 2 in H.V.T. is a graphical solution of the above equation. Using this curve and $\frac{P_o}{P'} = 1.04$, we obtain:

$$M' = 0.238$$

Using Curve No. 1 of this report, the error of the static pressure reading for M' = 0.238 is 0.26 per cent. Then the true static pressure is:

$$P = \frac{P'}{.9974} = \frac{28.77}{.9974} = 28.82 \text{ in Hg, abs.}$$

$$\frac{P_o}{P} = \frac{29.90}{28.82} = 1.037$$

From Curve No. 2 of H.V.T., the true Mach number is:

$$M = 0.229$$

From Curve No. 2 of this report, for M = 0.229, the error of the thermocouple reading is 0.263 per cent. Then the true total temperature is:

$$T_o = \frac{T'_o}{.9973} = \frac{552.7}{.9973} = 554^\circ \text{ R.}$$

From H.V.T:

$$\frac{T_o}{T} = 1 + \frac{\gamma - 1}{2} M^2$$

From a tabular solution of this equation, for M = 0.229:

$$\frac{T_o}{T} = 1.011$$

Then the static temperature is:

$$T = \frac{T_o}{1.011} = \frac{554}{1.011} = 548^{\circ} \text{ R.}$$

Curve No. 1 in H.V.T. is a curve of Mach number versus the function $\frac{v}{\sqrt{gR'T_o}}$. This curve was used to determine the velocity:

$$v = 263.3 \text{ ft./sec.}$$

$$\frac{v}{r} = \frac{263.3}{.5} = 526 \text{ ft./in.sec.}$$

$$\frac{r}{R} = \frac{0.5}{0.9} = 0.5555$$

From the test data:

$$\frac{P_R}{P_c} = \frac{30.42}{28.04} = 1.0849$$

From equation (21) of this report:

$$\alpha_p = \ln\left(\frac{P_R}{P_c}\right) = \ln 1.0849 = 0.0815$$

From equation (18) of this report:

$$\frac{P}{P_c}\text{ (theory)} = e^{\alpha\left(\frac{r}{R}\right)^2} = 1.0255$$

From the test data:

$$\frac{P}{P_c}\text{ (test)} = \frac{28.82}{28.04} = 1.0278$$

From the test data:

$$\frac{T_{o_R}}{T_{o_c}} = \frac{563.5}{542.5} = 1.0387$$

From equation (34) of this report:

$$\alpha_T = \frac{\gamma}{\gamma - 1}\left[\frac{T_{o_R}}{T_{o_c}} - 1\right] = .1366$$

From equation (31) of this report:

$$\frac{T_o}{T_{o_c}}\text{ (theory)} = 1 + \frac{\gamma - 1}{\gamma}\left(\frac{r}{R}\right)^2 \alpha = 1.012$$

From the test data:

$$\frac{T_o}{T_{o_c}}\text{ (test)} = \frac{554.0}{542.5} = 1.021$$

TABLE I

DATA OBTAINED AT X = 2.5 INCHES

r Inches	P_o "Hg. Gage	P_o "Hg. Abs.	P' "Hg. Gage	P' "Hg. Abs.	T_o' Milli volts	T_o' Deg. R.
0.9	5.48	35.23	0.23	29.98	3.03	565
0.8	3.79	33.54	-0.38	29.37	2.95	562.3
0.7	1.86	31.61	-0.80	28.95	2.82	557.9
0.6	0.41	30.16	-1.01	28.74	2.70	553.7
0.5	-0.47	29.28	-1.16	28.59	2.54	548.2
0.4	-0.88	28.87	-1.25	28.50	2.45	545
0.3	-1.17	28.58	-1.36	28.39	2.37	542.3
0.2	-1.32	28.43	-1.42	28.33	2.325	540.8
0.1	-1.44	28.31	-1.46	28.29	2.31	540.3
0	-1.49	28.26	-1.49	28.26	2.31	540.3

$P_1 - P_2$ = 1.16 in. Hg. Barometer = 29.754 in. Hg.

P_2 = 10.42 in. Hg. Gage T_{o_2} = 108° F.

P_3 = -1.57 in. Hg. Gage Room Temp. = 76° F.

P_4 = -1.07 in. Hg. Gage W = 0.0665 lb./sec

P_5 = -0.45 in. Hg. Gage Iron-Constantan Thermocouple

P_6 = 2.79 in. Hg. Gage Reference 0° F.

TABLE II

X = 2.5 INCHES

r Inches	M'	P "Hg.Abs.	M	T_o Deg.R.	T Deg.R.	v ft./sec.	v/r ft./in.sec
0.9	.489	30.38	.468	568.5	544	535	594
0.8	.441	29.70	.422	565.3	546	486	608.5
0.7	.358	29.17	.342	560	546	393.5	561.5
0.6	.262	28.80	.254	555	546.5	292	486
0.5	.185	28.60	.177	549	545.5	203.2	406
0.4	.128	28.50	.128	546	544	146.4	366
0.3	.076	28.39	.076	543	541.5	86.9	289.5
0.2	.04	28.33	.04	541	541	45.6	228.2
0.1	.01	28.29	.01	540.3	540.3	11.4	114
0	0	28.26	0	540.3	540.3	0	ind.

TABLE III

$X = 2.5$ INCHES

r Inches	P_R/P_c	P/P_c Theory	P/P_c Test	T_{o_R}/T_{o_c}	T_o/T_{o_c} Theory	T_o/T_{o_c} Test
0.9	1.075	1.075	1.075	1.052	1.052	1.052
0.8	"	1.0576	1.050	"	1.0422	1.046
0.7	"	1.0438	1.031	"	1.0323	1.036
0.6	"	1.0321	1.019	"	1.0238	1.027
0.5	"	1.0222	1.011	"	1.0165	1.016
0.4	"	1.0141	1.009	"	1.0103	1.011
0.3	"	1.008	1.0025	"	1.00595	1.005
0.2	"	1.0025	1.001	"	1.00264	1.001
0.1	"		1.0005	"	1.00066	1.000
0	"	1.0000	1.0000	"	1.0000	1.000

TABLE IV

DATA OBTAINED AT X = 8.1 INCHES

r Inches	P_o"Hg. Gage	P_o"Hg. Abs.	P'"Hg. Gage	P'"Hg. Abs.	T_o' Milli volts	T_o' Deg. R.
0.9	2.93	32.66	0.50	30.23	2.925	561.5
0.8	2.49	32.22	0.12	29.85	2.86	559.3
0.7	1.74	31.47	-0.30	29.43	2.79	556.8
0.6	0.89	30.62	-0.68	29.05	2.73	554.7
0.5	0.17	29.90	-0.96	28.77	2.67	552.7
0.4	-0.45	29.28	-1.21	28.52	2.59	550
0.3	-0.97	28.76	-1.45	28.28	2.52	547.5
0.2	-1.35	28.38	-1.58	28.15	2.44	544.7
0.1	-1.61	28.12	-1.65	28.08	2.40	543.3
0	-1.69	28.04	-1.69	28.04	2.375	542.5

$P_1 - P_2$ = 1.15 in. Hg.

P_2 = 10.33 in. Hg. Gage

P_3 = -1.56 in. Hg. Gage

P_4 = -1.05 in. Hg. Gage

P_5 = -0.45 in. Hg. Gage

P_6 = 2.72 in. Hg. Gage

Barometer = 29.73 in.Hg.

T_{o_2} = 107° F.

Room Temp. = 76° F.

W = 0.0666 lb./sec.

Iron - Constantan Thermocouple

Reference 0° F.

TABLE V

X = 8.1 INCHES

r Inches	M'	P "Hg.Abs.	M	T_o Deg.R.	T Deg.R.	v ft./sec.	v/r ft./in.sec
0.9	.335	30.42	.320	563.5	551	368.6	410
0.8	.333	30.07	.316	561	550	362.2	453
0.7	.313	29.60	.298	559	549	341.7	488
0.6	.275	29.17	.270	556	548	310.6	517.5
0.5	.238	28.82	.229	554	548	263.3	526
0.4	.199	28.58	.185	551.5	548	213	532.5
0.3	.135	28.32	.135	549	546	155	517
0.2	.089	28.15	.089	545	544.5	101.8	509
0.1	.01	28.08	.01	543.3	543.3	11.42	114.2
0	0	28.04	0	542.5	542.5	0	ind.

TABLE VI

X = 8.1 INCHES

r Inches	P_R/P_c	P/P_c Theory	P/P_c Test	T_{cR}/T_{o_c}	T_o/T_{oc} Theory	T_o/T_{oc} Test
0.9	1.0849	1.0849	1.0849	1.0387	1.0387	1.0387
0.8	"	1.0665	1.0724	"	1.03055	1.0341
0.7	"	1.0505	1.0556	"	1.0234	1.0304
0.6	"	1.03695	1.0403	"	1.0172	1.0249
0.5	"	1.0255	1.0278	"	1.01196	1.0212
0.4	"	1.0162	1.0193	"	1.00764	1.0166
0.3	"	1.009	1.010	"	1.0043	1.012
0.2	"	1.004	1.004	"	1.00191	1.0046
0.1	"	1.001	1.001	"	1.00048	1.0015
0	"	1.000	1.000	"	1.000	1.000

TABLE VII

DATA OBTAINED AT X = 14.1 INCHES

r Inches	P_o"Hg. Gage	P_o"Hg. Abs.	P'"Hg. Gage	P'"Hg. Abs.	T_o' Milli volts	T_o' Deg. R.
0.9	1.97	31.63	0.44	30.10	2.91	561
0.8	1.76	31.42	0.16	29.82	2.89	560.3
0.7	1.38	31.04	-0.22	29.44	2.84	558.6
0.6	0.95	30.61	-0.55	29.11	2.82	557.9
0.5	0.40	30.06	-0.86	28.80	2.76	555.7
0.4	-0.20	29.46	-1.20	28.46	2.71	554
0.3	-0.81	28.85	-1.45	28.21	2.64	551.8
0.2	-1.33	28.33	-1.65	28.01	2.62	551
0.1	-1.68	27.98	-1.80	27.86	2.60	550.4
0	-1.83	27.83	-1.83	27.83	2.59	550

$P_1 - P_2$ = 1.15 in. Hg. Barometer = 29.66 in. Hg.

P_2 = 10.33 in. Hg. Gage T_{o_2} = 106° F.

P_3 = -1.56 in. Hg. Gage Room Temp. = 76° F.

P_4 = -1.05 in. Hg. Gage W = 0.0665 lb./sec.

P_5 = -0.45 in. Hg. Gage Iron-Constantan Thermocouple,

P_6 = 2.72 in. Hg. Gage Reference 0° F.

TABLE VIII

X = 14.1 INCHES

r Inches	M'	P "Hg.Abs.	M	T_o Deg.R.	T Deg.R.	v ft./sec.	v/r ft./in.sec.
0.9	.270	30.20	.262	563	554.5	303.8	337.4
0.8	.274	29.94	.266	562	554	306.5	383.5
0.7	.274	29.58	.266	560	551.5	306.2	438
0.6	.270	29.20	.262	559.5	551	302.2	504
0.5	.249	28.86	.242	558	551	279	558
0.4	.223	28.56	.212	555	550	245	612
0.3	.176	28.27	.162	535.5	550	187	624
0.2	.112	28.01	.112	551.5	550	129	645
0.1	.045	27.86	.045	550.7	550.7	51.8	518
0	0	27.83	0	550	550	0	ind.

TABLE IX

X = 14.1 INCHES

r Inches	P_R/P_c	P/P_c Theory	P/P_c Test	T_{o_r}/T_{o_c}	T_o/T_{o_c} Theory	T_o/T_{o_c} Test
0.9	1.0852	1.0852	1.0852	1.024	1.024	1.024
0.8	"	1.0669	1.076	"	1.01893	1.0218
0.7	"	1.0509	1.063	"	1.0145	1.0182
0.6	"	1.0372	1.049	"	1.01068	1.0173
0.5	"	1.0256	1.037	"	1.0074	1.0145
0.4	"	1.0163	1.026	"	1.00474	1.0091
0.3	"	1.009	1.016	"	1.00267	1.00636
0.2	"	1.003	1.006	"	1.00118	1.0027
0.1	"	1.001	1.001	"	1.0004	1.0013
0	"	1.000	1.000	"	1.000	1.000

TABLE X

DATA OBTAINED AT X = 2.5 INCHES

SIX INCH LONG PIPE

r Inches	P_o "Hg. Gage	P' "Hg. Gage	T_o' Milli volts	T_o' Deg. R.
0.9	4.97	0.66	3.02	564.7
0.8	3.77	0.11	2.92	561.3
0.7	2.47	-0.55	2.78	556.4
0.6	1.39	-1.13	2.64	551.7
0.5	0.29	-1.69	2.55	548.6
0.4	-0.90	-2.20	2.42	544
0.3	-1.84	-2.63	2.31	540.3
0.2	-2.45	-2.83	2.19	536.1
0.1	-2.85	-3.01	2.12	533.6
0	-3.06	-3.07	2.08	532.1

$P_1 - P_2$ = 1.21 in. Hg.

P_2 = 10.68 in. Hg. Gage

P_3 = -1.82 in. Hg. Gage

P_4 = -1.19 in. Hg. Gage

P_5 = -0.53 in. Hg. Gage

P_6 = 2.78 in. Hg. Gage

Barometer = 30.27 in. Hg.

T_{o_2} = 110° F.

Iron - Constantan Thermocouple: Reference 0° F.

TABLE XI

DATA OBTAINED AT X = 1.4 INCHES

r Inches	P_o "Hg. Gage	P' "Hg. Gage	T_o' Millivolts	T_o' Deg. R.
0.9	12.07	0.83	2.99	563.7
0.8	8.49	-0.62	2.95	562.3
0.7	4.10	-1.39	2.73	554.7
0.6	0.96	-1.89	2.50	546.8
0.5	-0.81	-2.21	2.29	539.6
0.4	-1.65	-2.47	2.07	531.8
0.3	-2.20	-2.62	1.98	528.7
0.2	-2.57	-2.80	1.95	527.7
0.1	-2.83	-2.94	1.98	528.7
0	-2.97	-2.97	2.00	529.3

$P_1 - P_2$ = 2.10 in. Hg.

P_2 = 21.0 in. Hg. Gage

P_3 = -3.17 in. Hg. Gage

P_4 = -2.13 in. Hg. Gage

P_5 = -0.81 in. Hg. Gage

P_6 = 5.31 in. Hg. Gage

Barometer = 29.74 in. Hg.

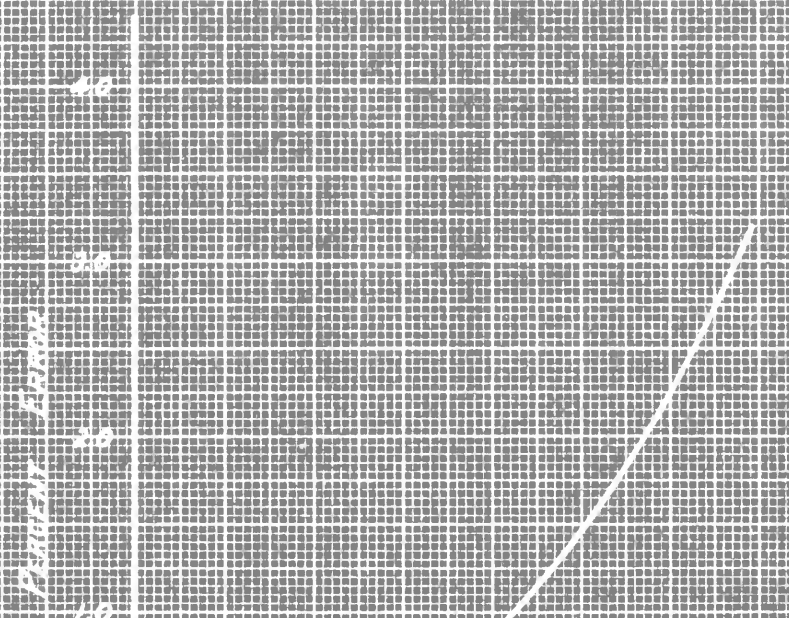
T_{o2} = 111.5° F.

Iron - Constantan Thermocouple: Reference 0° F.

CURVE NO. 1
CORRECTION CURVE FOR STATIC PRESSURE PROBE

M' IS MACH NUMBER COMPUTED FROM UNCORRECTED STATIC PRESSURE READING

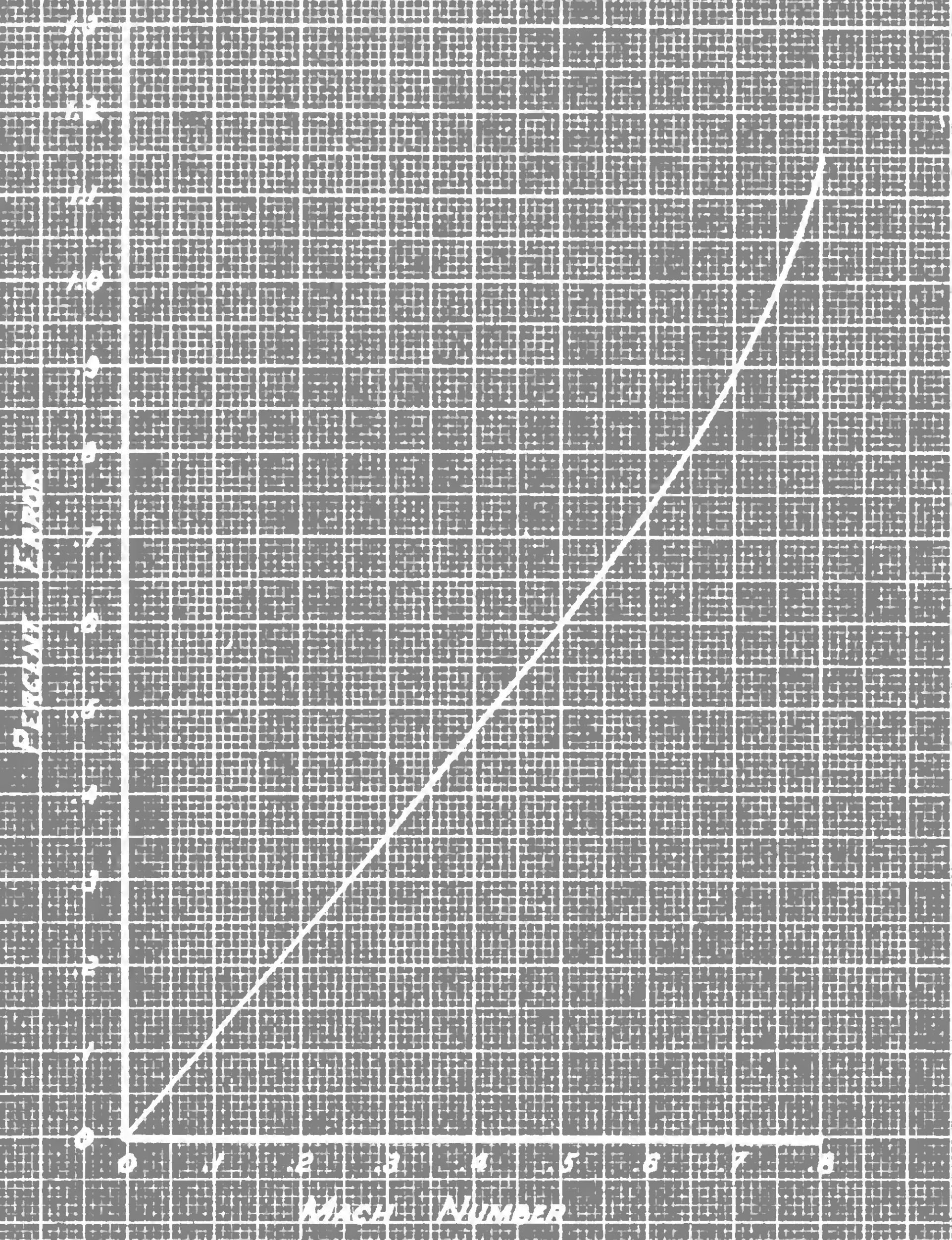
PERCENT ERROR IS THE AMOUNT BY WHICH THE STATIC PRESSURE PROBE READS LOW IN PERCENT OF [illegible] ABSOLUTE STATIC PRESSURE

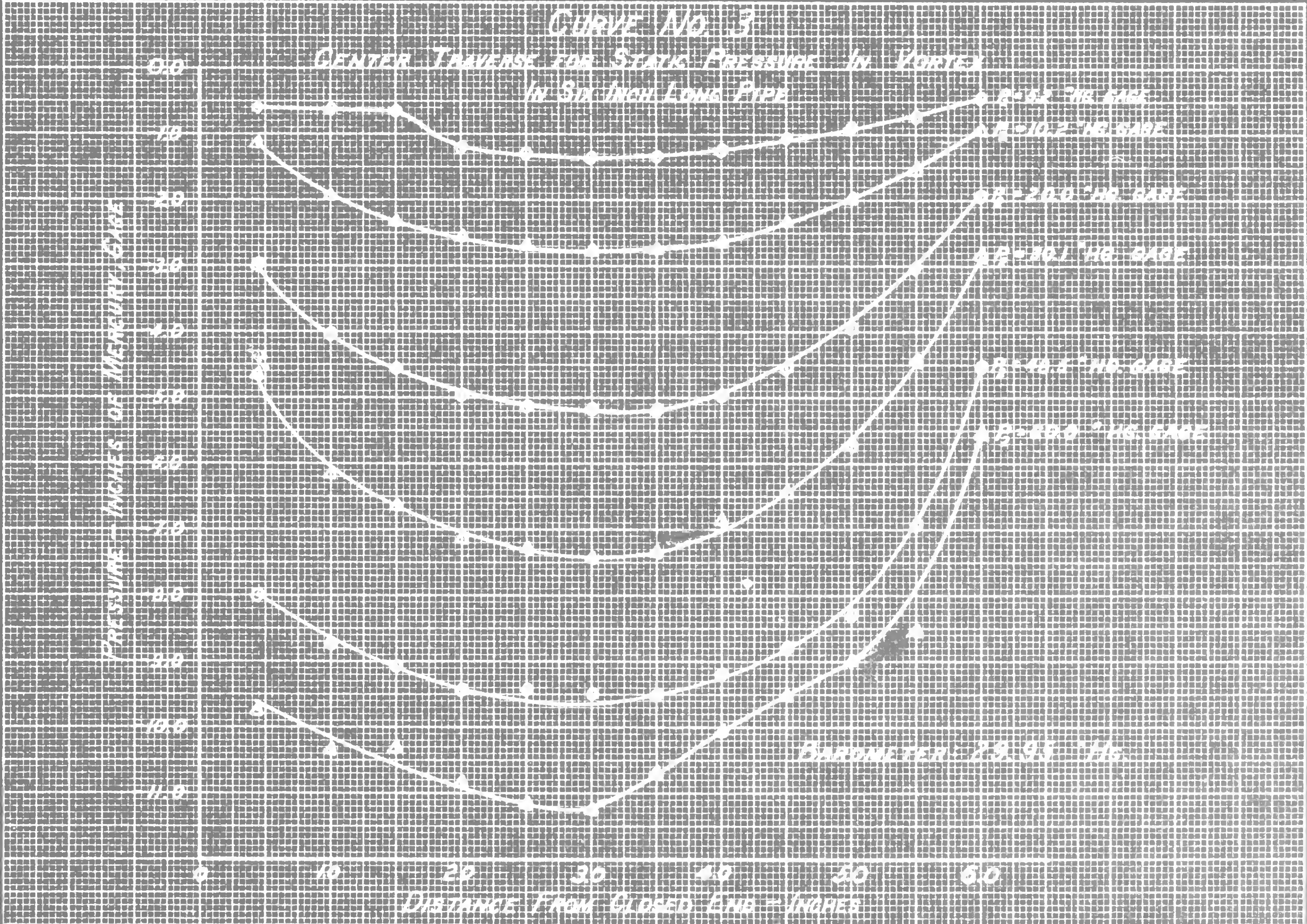


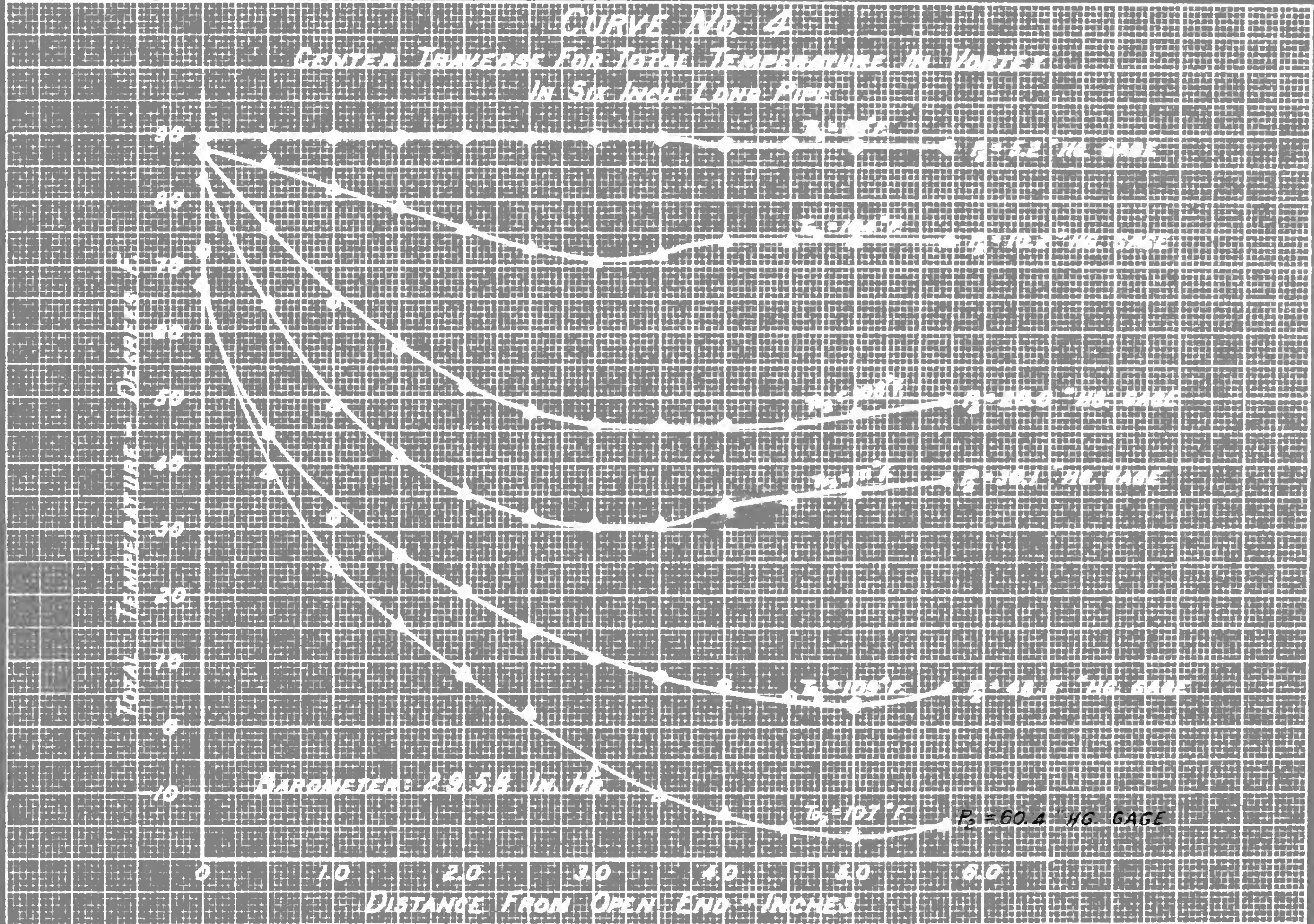
Curve No. [illegible]

Correction Curve for Thermocouple

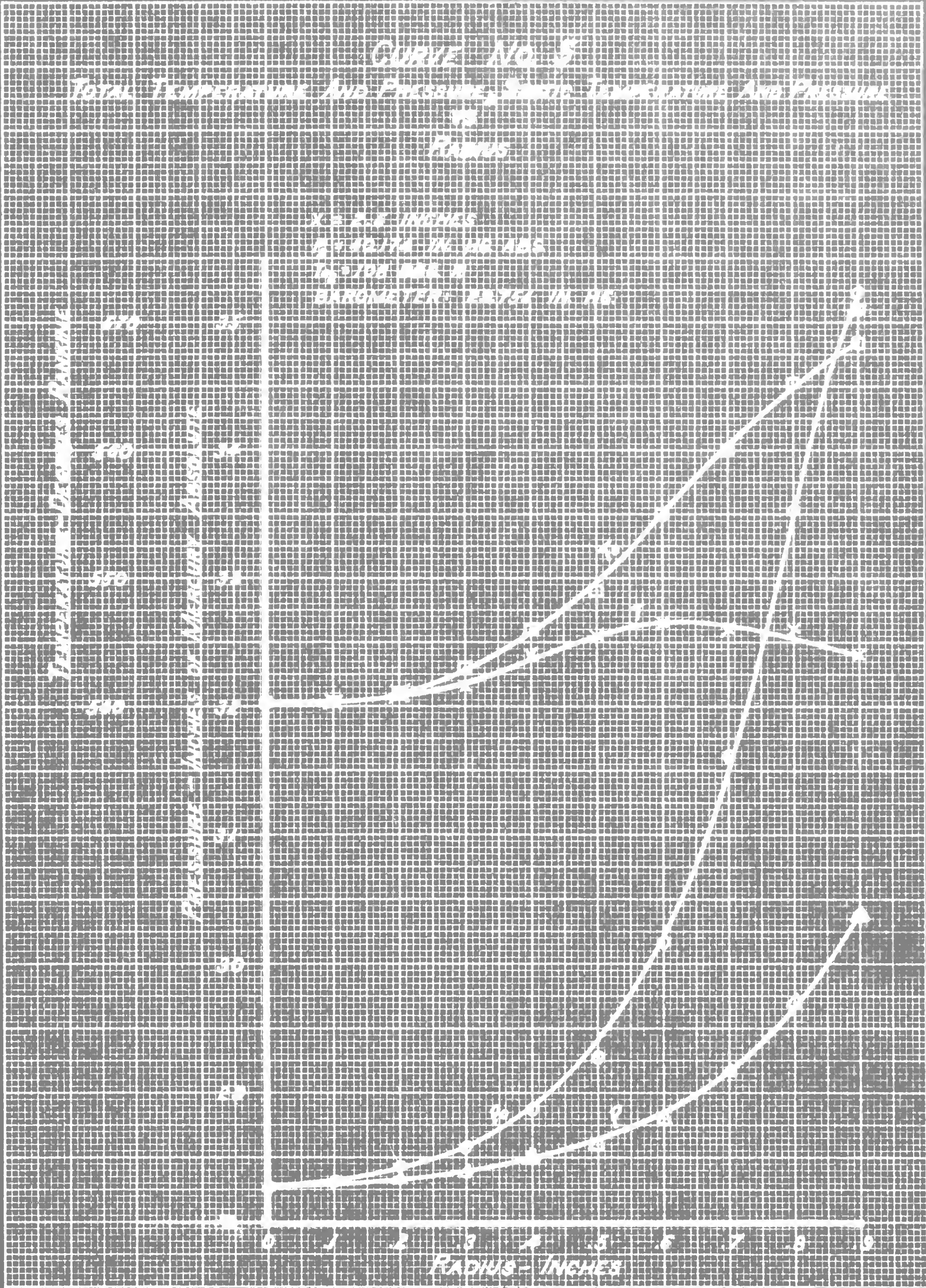
Percent error is amount at which thermocouple reads low in percent of absolute total temperature




CURVE NO. 3
CENTER TRAVERSE FOR STATIC PRESSURE IN VORTEX
IN SIX INCH LONG PIPE
R=10.2 "HG. GAGE
R=20.0 "HG. GAGE
R=30.1 "HG. GAGE
BAROMETER: 29.95 "HG.
PRESSURE - INCHES OF MERCURY, GAGE
DISTANCE FROM CLOSED END - INCHES
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
-9.0
-10.0
-11.0
0
1.0
2.0
3.0
4.0
5.0
6.0



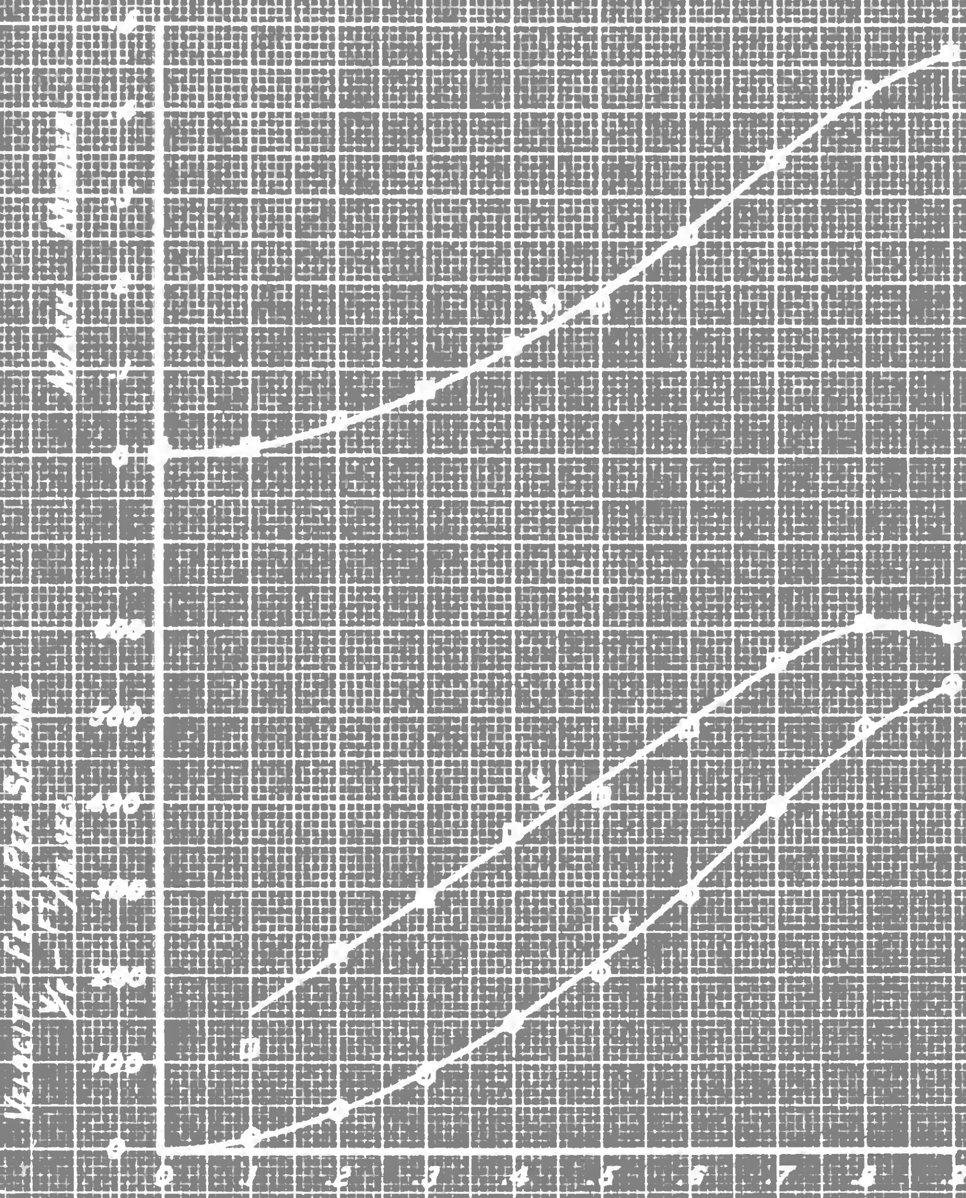
CURVE NO. 4
CENTER TRAVERSE FOR TOTAL TEMPERATURE IN VORTEX
IN SIX INCH LONG PIPE
TOTAL TEMPERATURE - DEGREES F.
90
80
70
60
50
40
30
20
10
0
-10
0
1.0
2.0
3.0
4.0
5.0
6.0
DISTANCE FROM OPEN END - INCHES
BAROMETER: 29.58 IN. HG.
T_{O_2} = 107 °F.
P_2 = 60.4 " HG. GAGE


CURVE NO. 5
TOTAL TEMPERATURE AND PRESSURE, STATIC TEMPERATURE AND PRESSURE
VS
RADIUS
TEMPERATURE - DEGREES RANKINE
PRESSURE - INCHES OF MERCURY ABSOLUTE
RADIUS - INCHES

CURVE NO. 5-A

MACH NUMBER - VELOCITY - V_r
VS
RADIUS

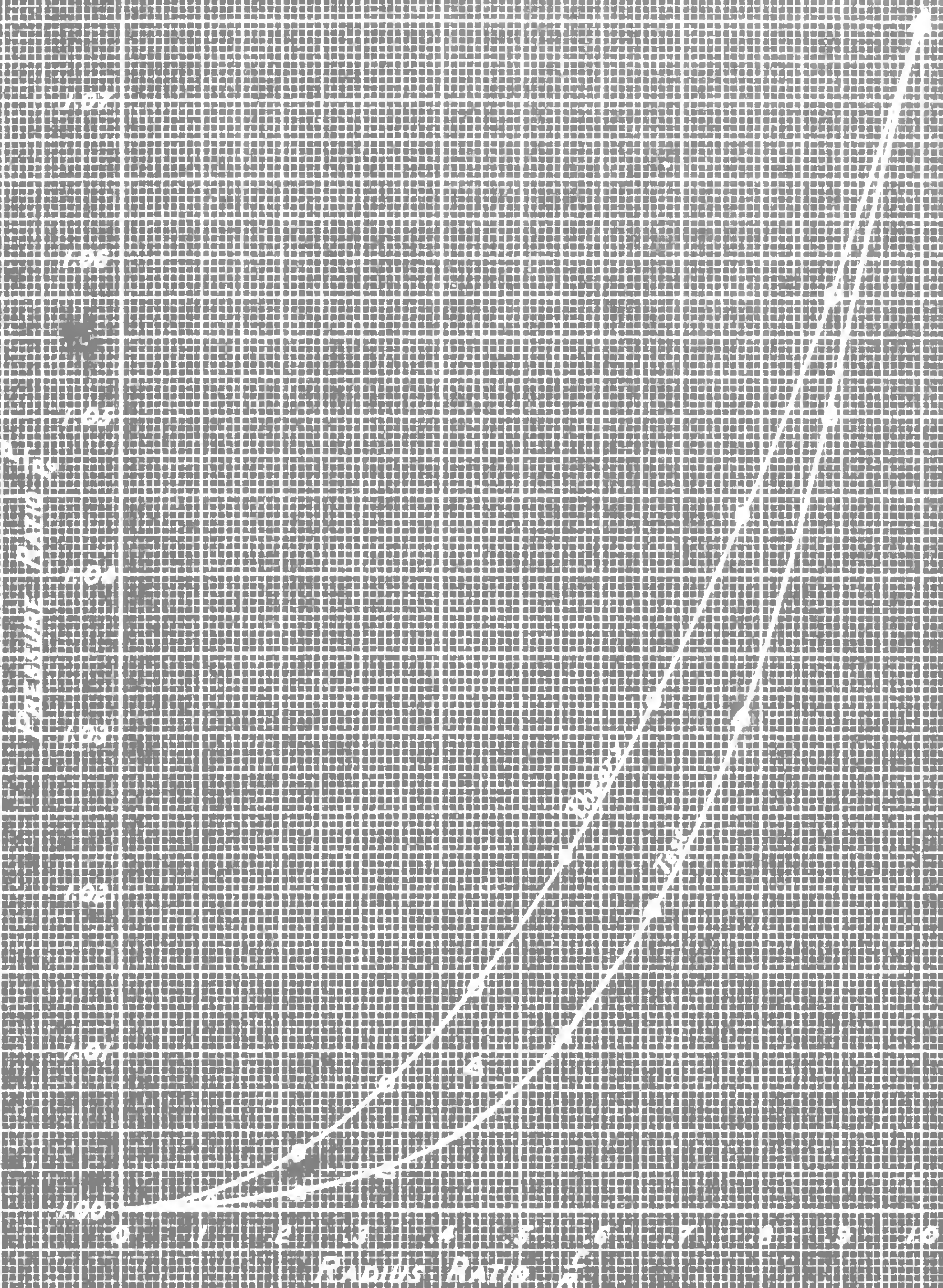
X = 2.5 IN.



CURVE NO. 5-B

PRESSURE RATIO vs RADIUS RATIO

COMPARISON OF TEST WITH THEORY

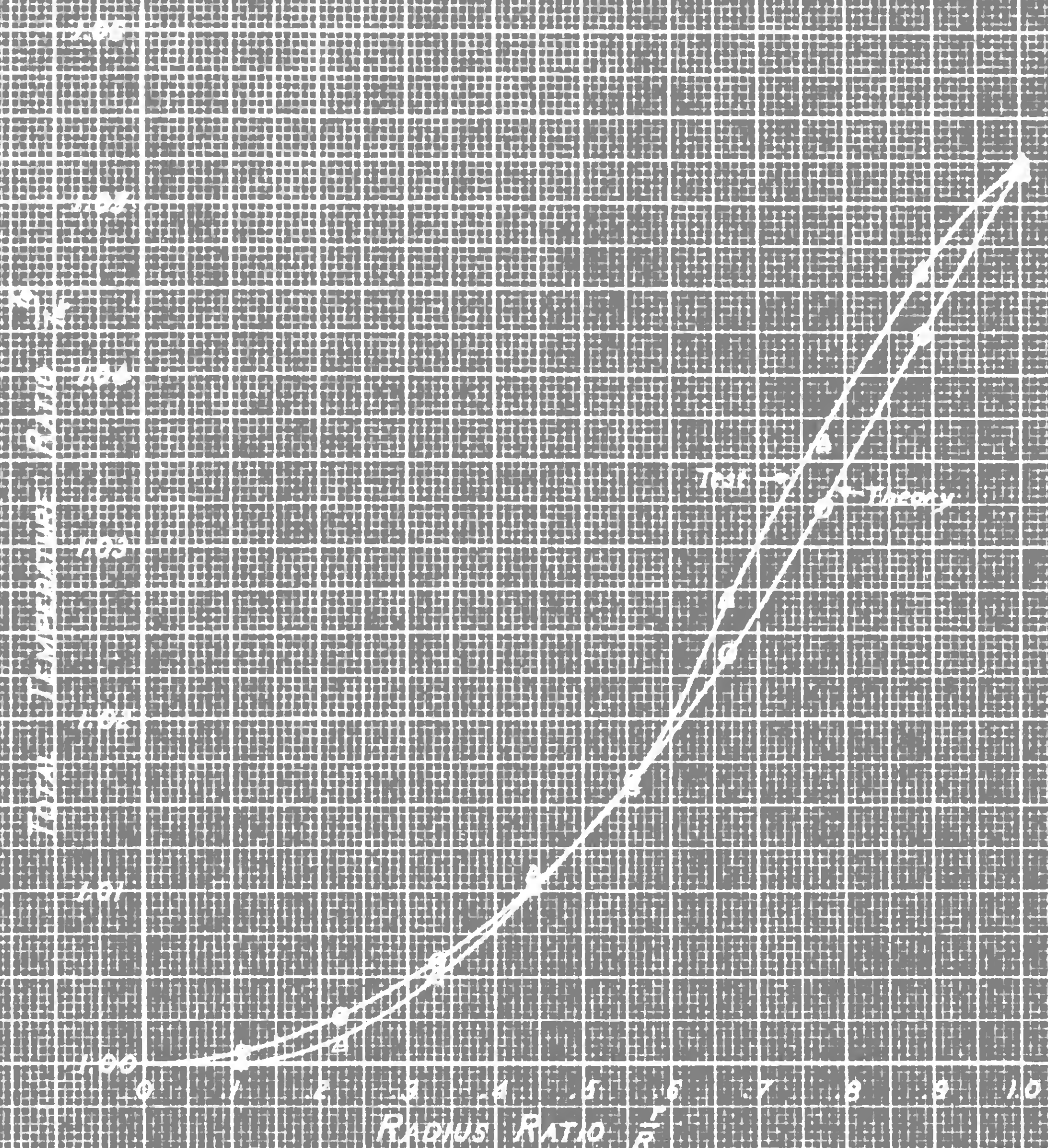


CURVE NO. 5-C

TOTAL TEMPERATURE RATIO VS RADIUS RATIO

COMPARISON OF TEST WITH THEORY

X = 2.6 IN.

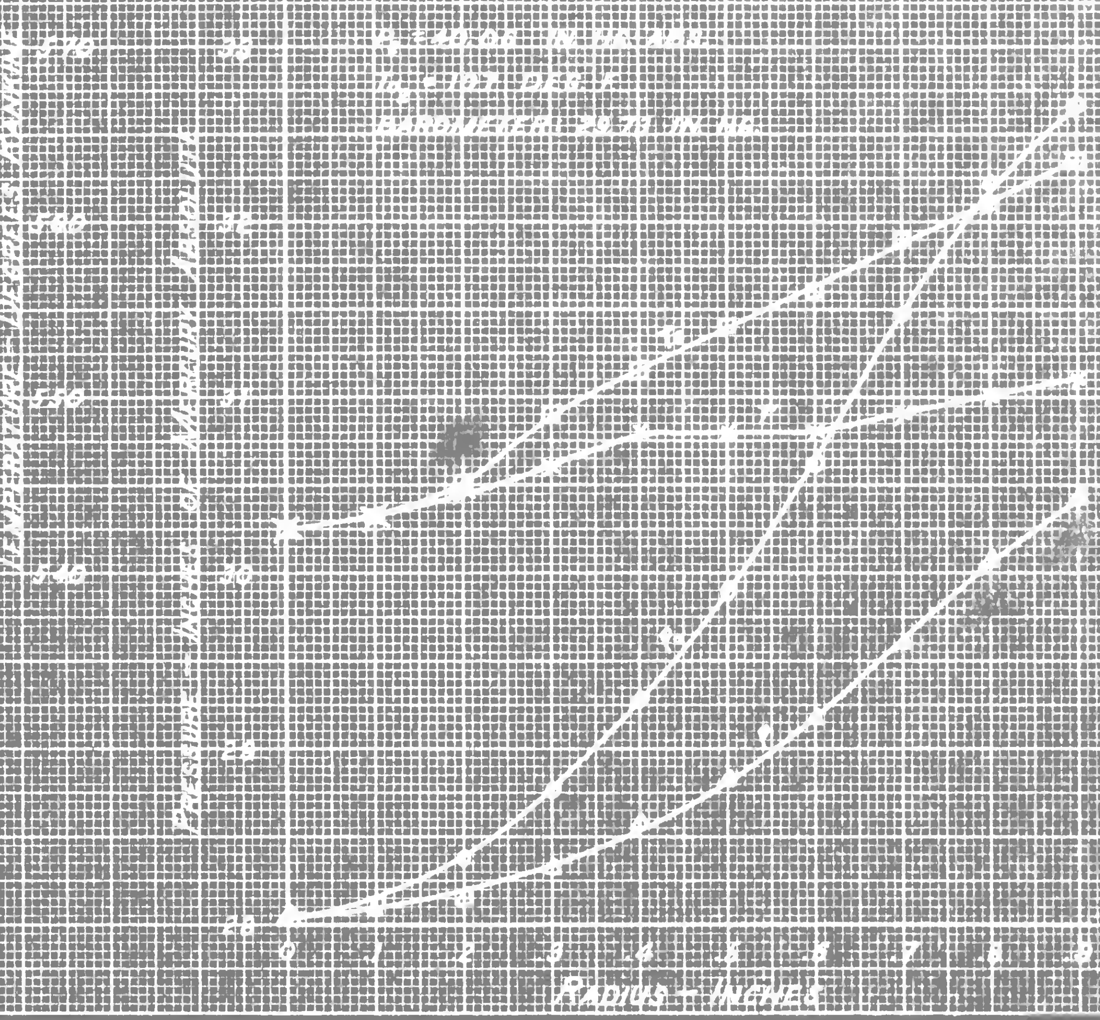


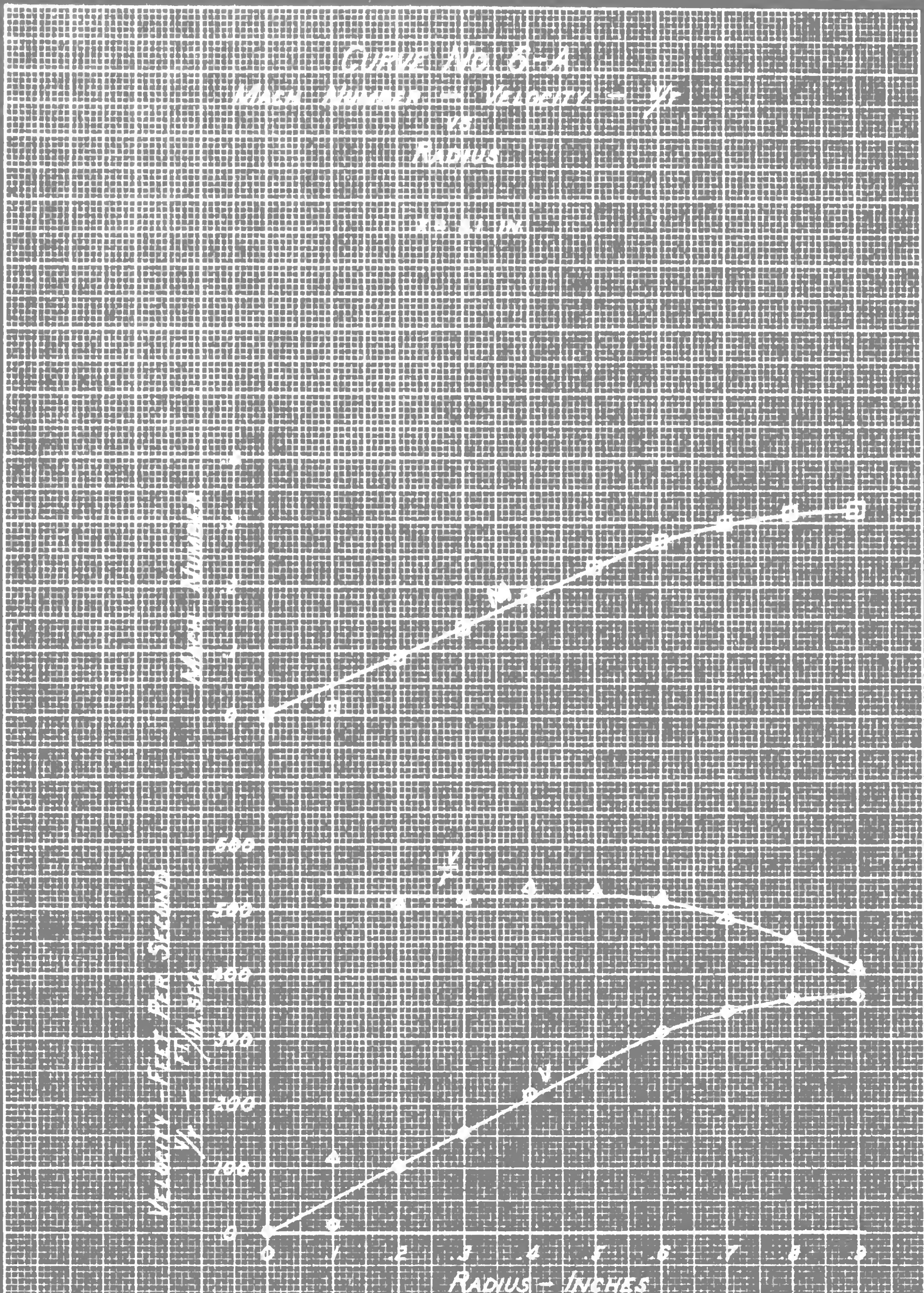
CURVE NO. 6

TOTAL TEMPERATURE AND PRESSURE, STATIC TEMPERATURE AND PRESSURE

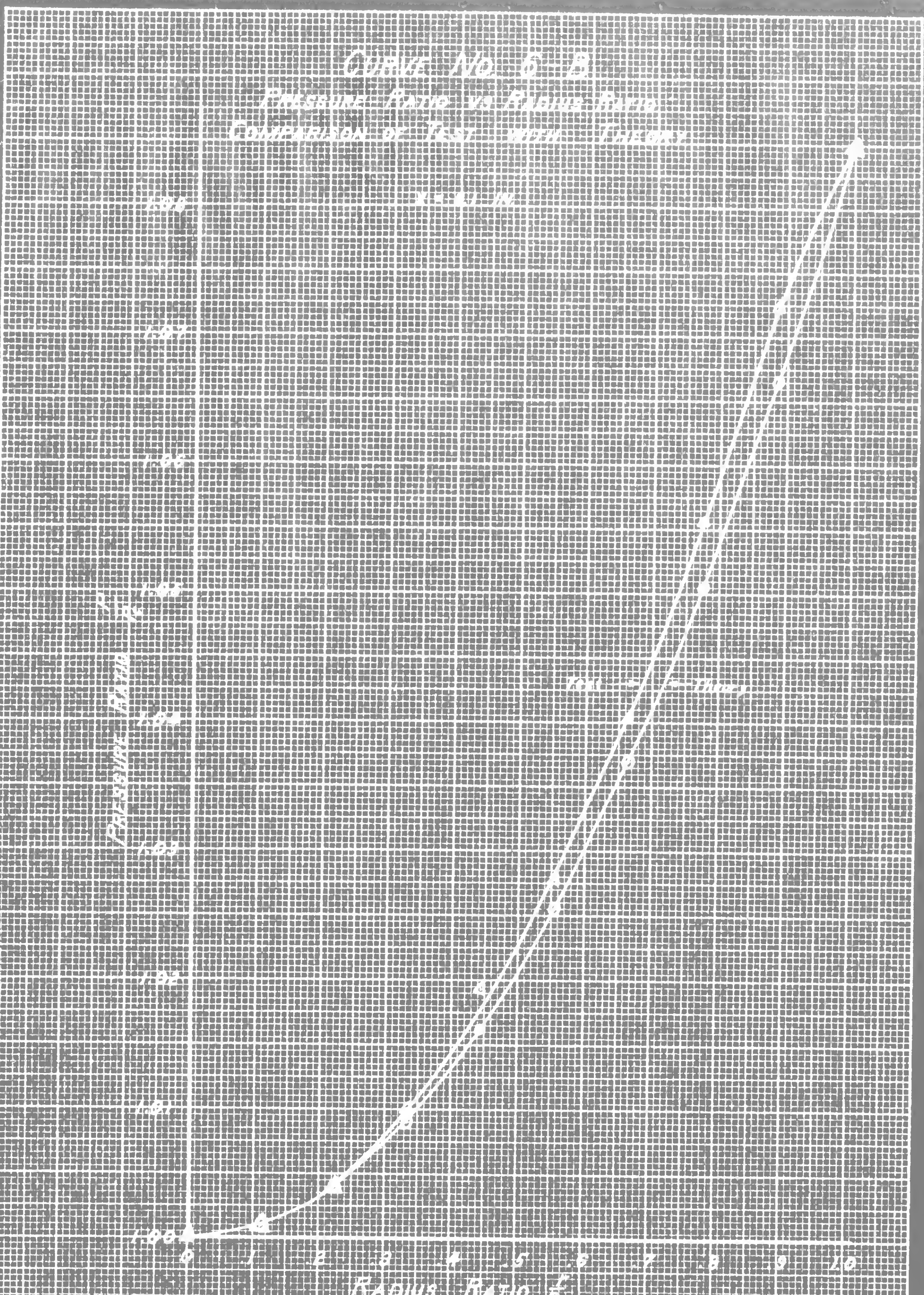
VS

RADIUS





Curve No. 6-A
Mach Number — Velocity — V/T
vs
Radius
X = 4.1 IN.
Mach Number
M
V/T
V
Velocity — Feet Per Second
V/T — Ft/Sec °R
600
500
400
300
200
100
0
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
Radius — Inches



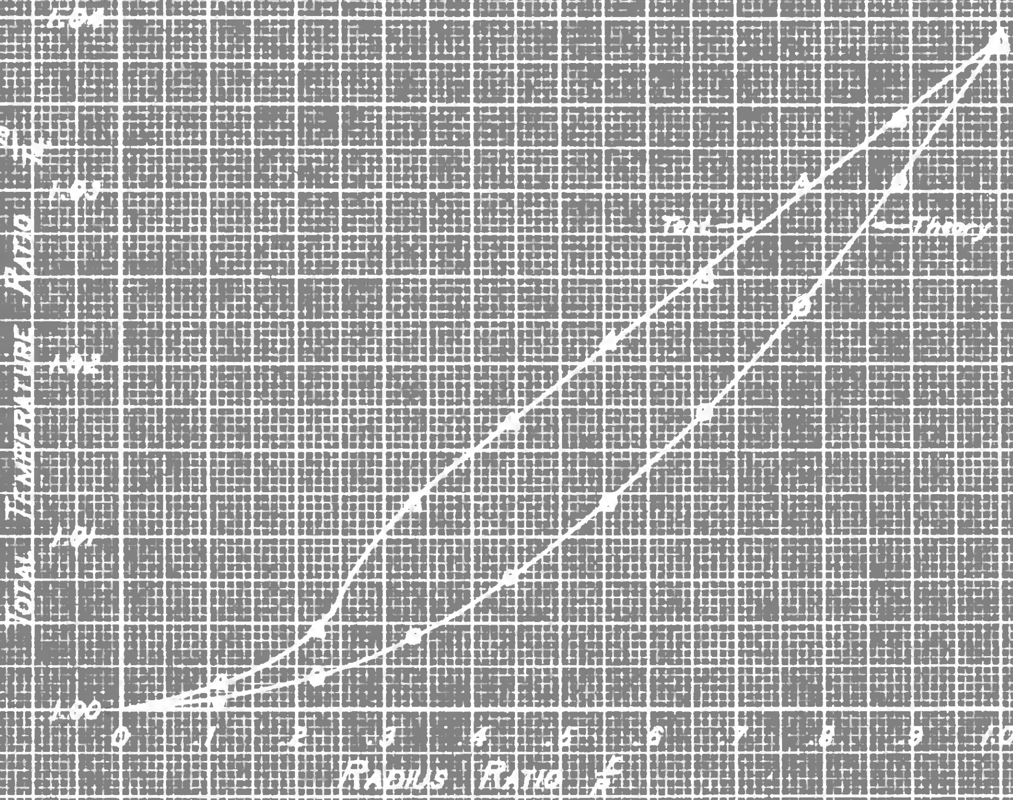
CURVE NO. 6 B
PRESSURE RATIO VS RADIUS RATIO
COMPARISON OF TEST WITH THEORY
PRESSURE RATIO
1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1.00
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
RADIUS RATIO r/R

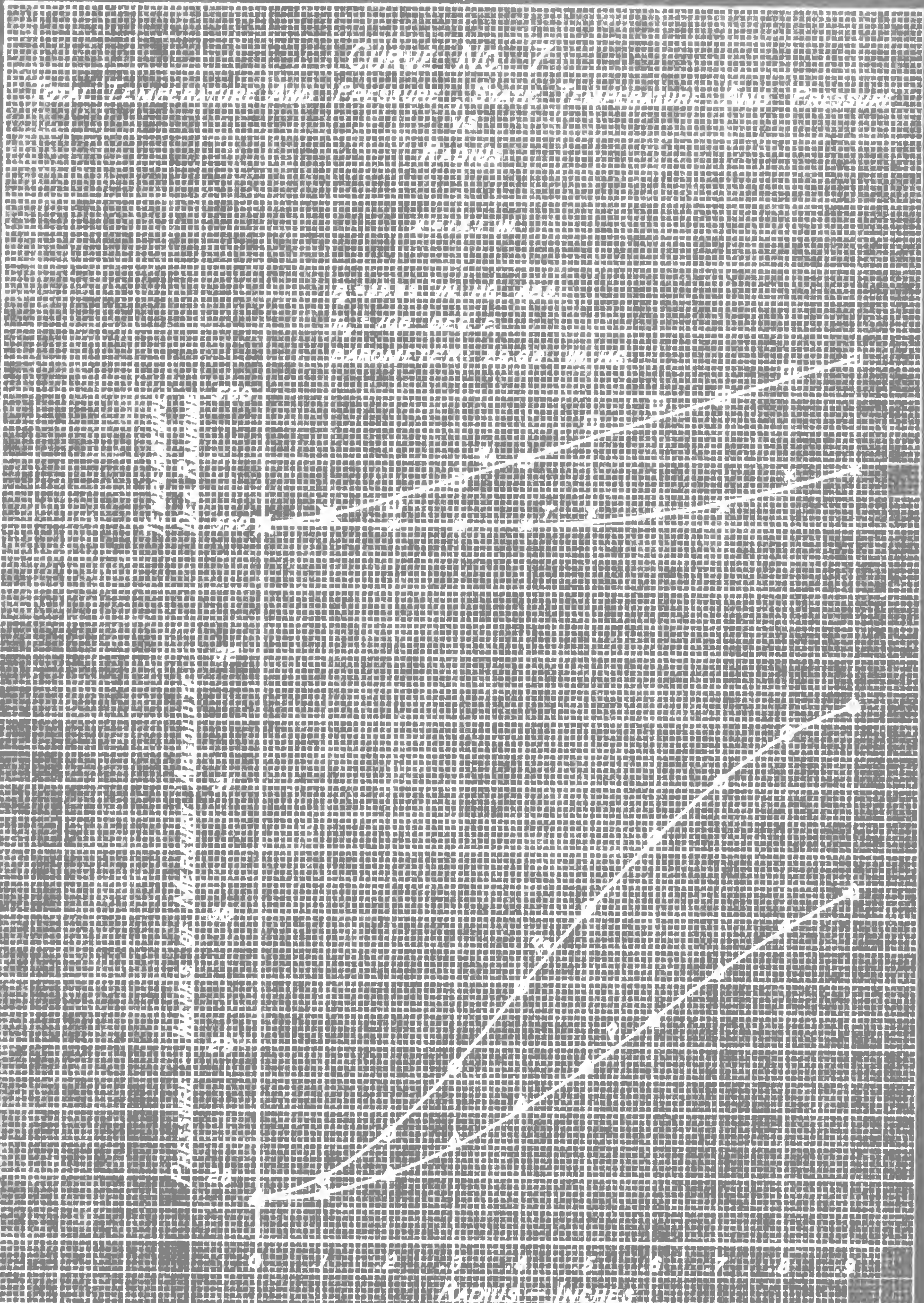
CURVE NO. 6-C

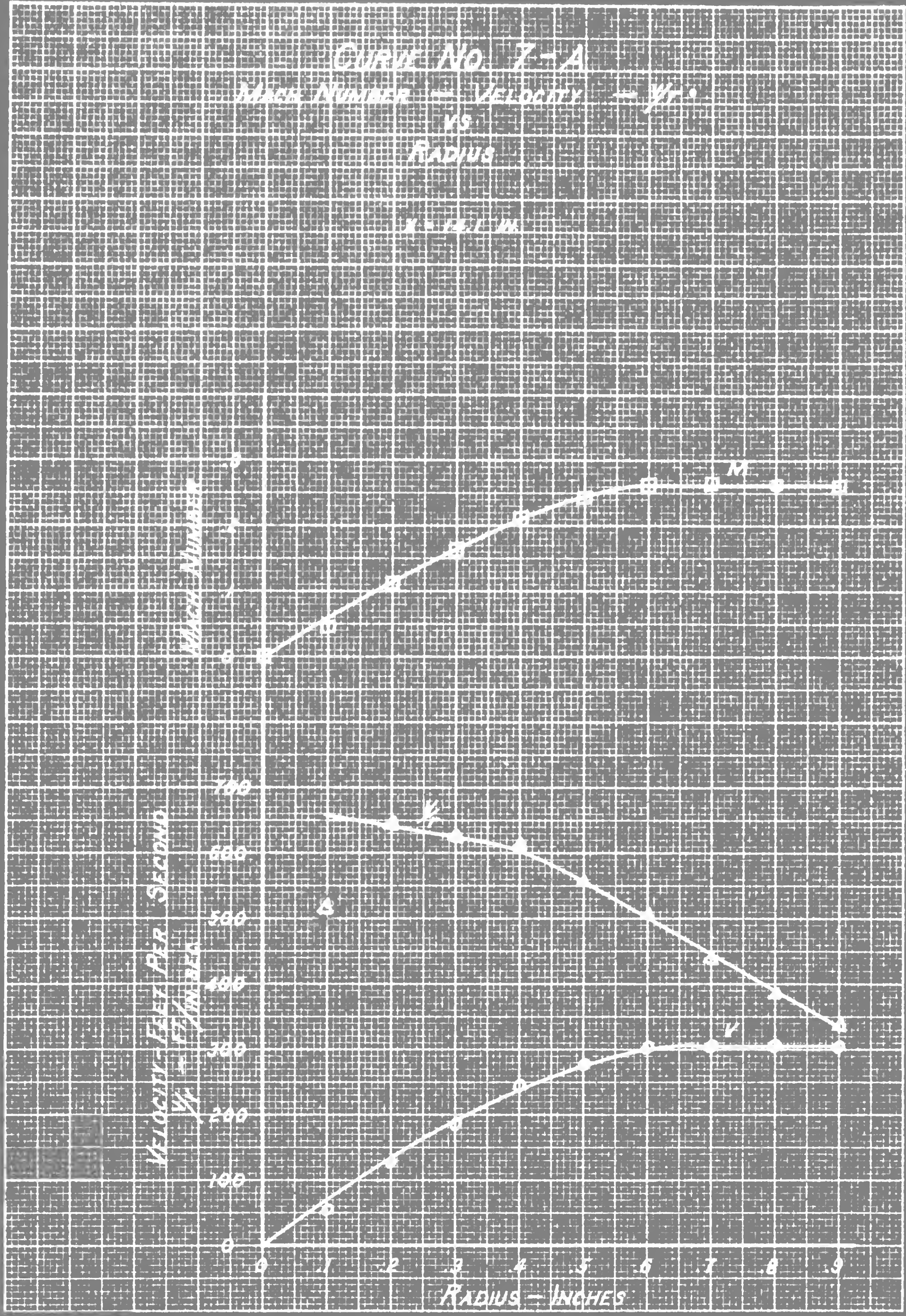
TOTAL TEMPERATURE RATIO VS RADIUS RATIO

COMPARISON OF TEST WITH THEORY

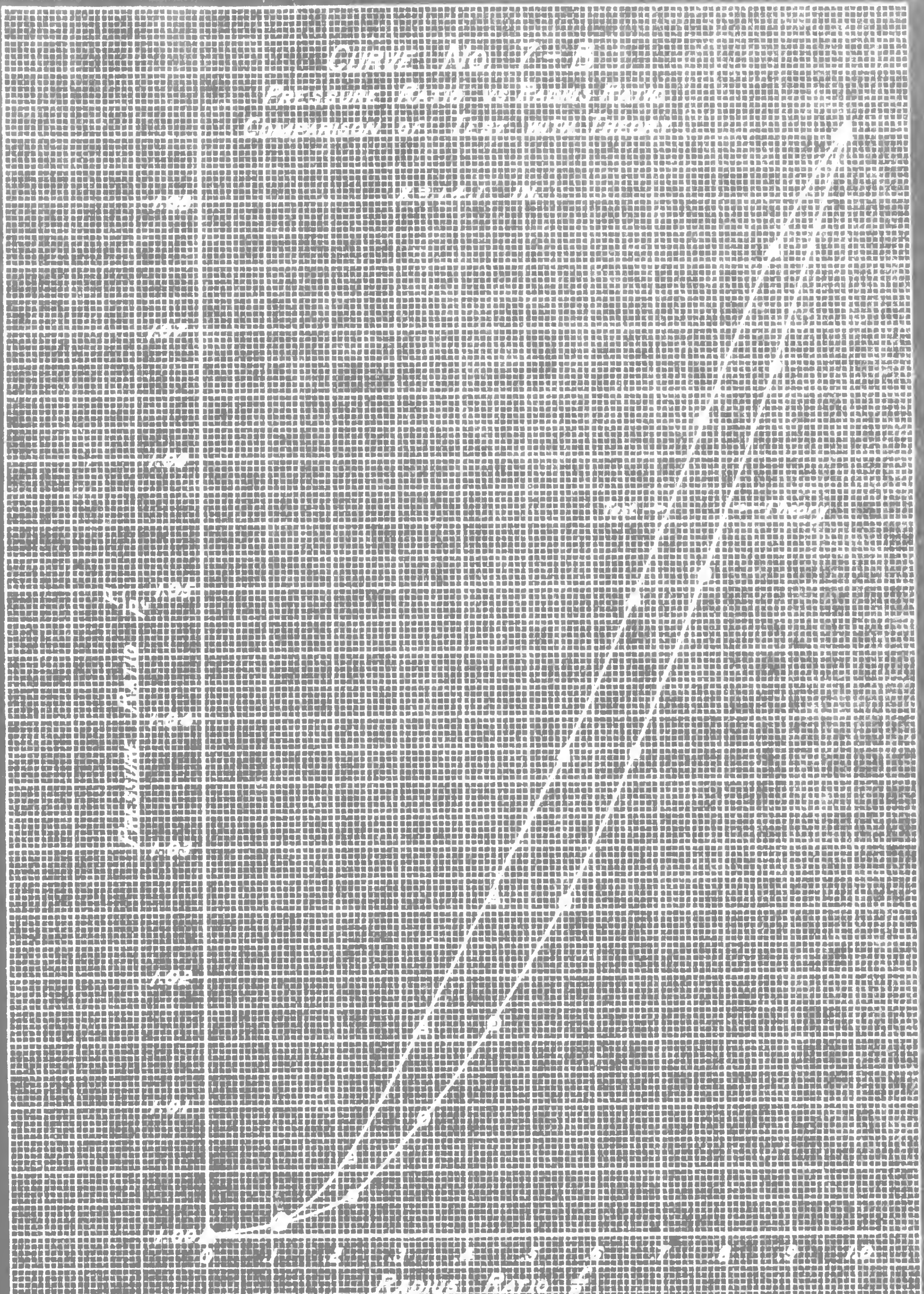
x = 6.1 IN.




CURVE NO. 7
TOTAL TEMPERATURE AND PRESSURE, STATIC TEMPERATURE AND PRESSURE
VS
RADIUS
0 1 2 3 4 5 6 7 8 9
RADIUS — INCHES



CURVE NO 7-A
MACH NUMBER — VELOCITY — V_T
VS
RADIUS
M
.8
0
MACH NUMBER
V_T
V
700
600
500
400
300
200
100
0
VELOCITY - FEET PER SECOND
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
RADIUS — INCHES


CURVE NO 7-B
PRESSURE RATIO VS RADIUS RATIO
COMPARISON OF TEST WITH THEORY
Test
Theory
PRESSURE RATIO
RADIUS RATIO
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.00
1.01
1.02
1.03
1.04
1.05
1.06
1.07
1.08

Curve No. 7-C

Total Temperature Ratio vs Radius Ratio
Comparison of Test with Theory

Z = 12.1 IN.

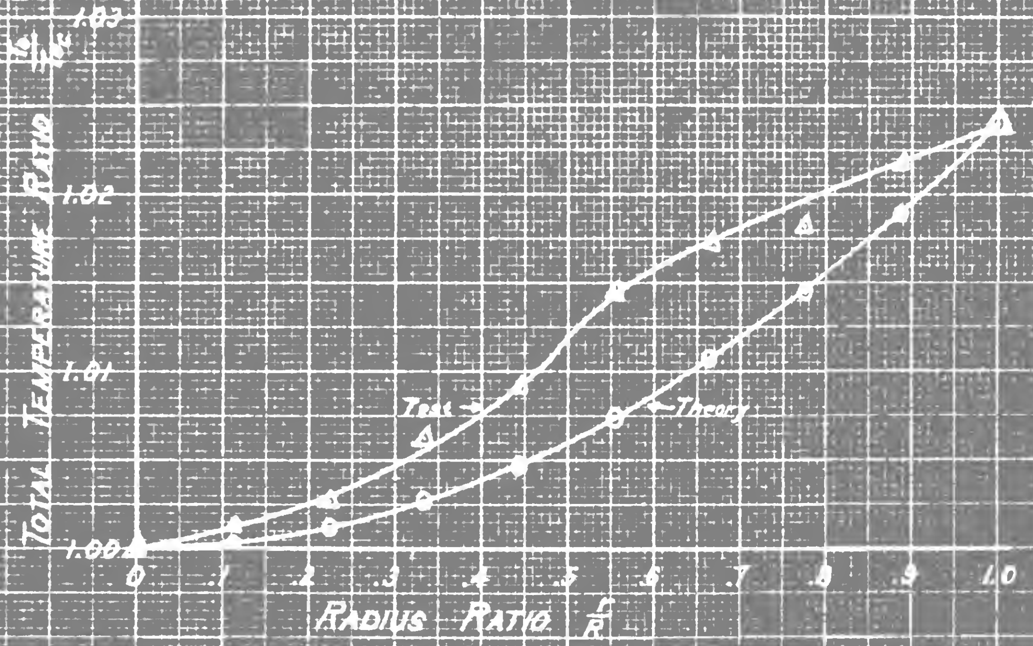


FIGURE 1

SCHEMATIC LAY-OUT OF EXPERIMENTAL SET-UP

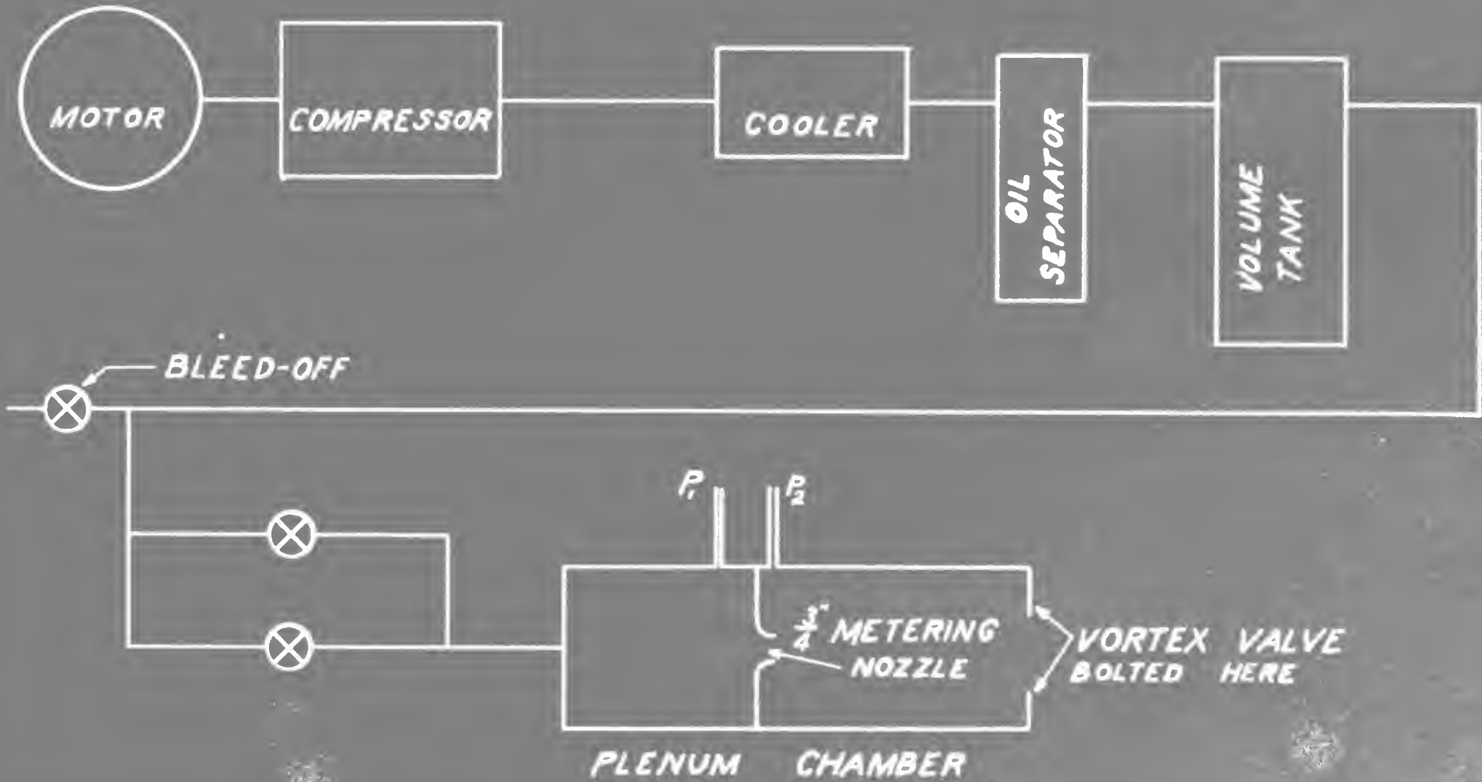
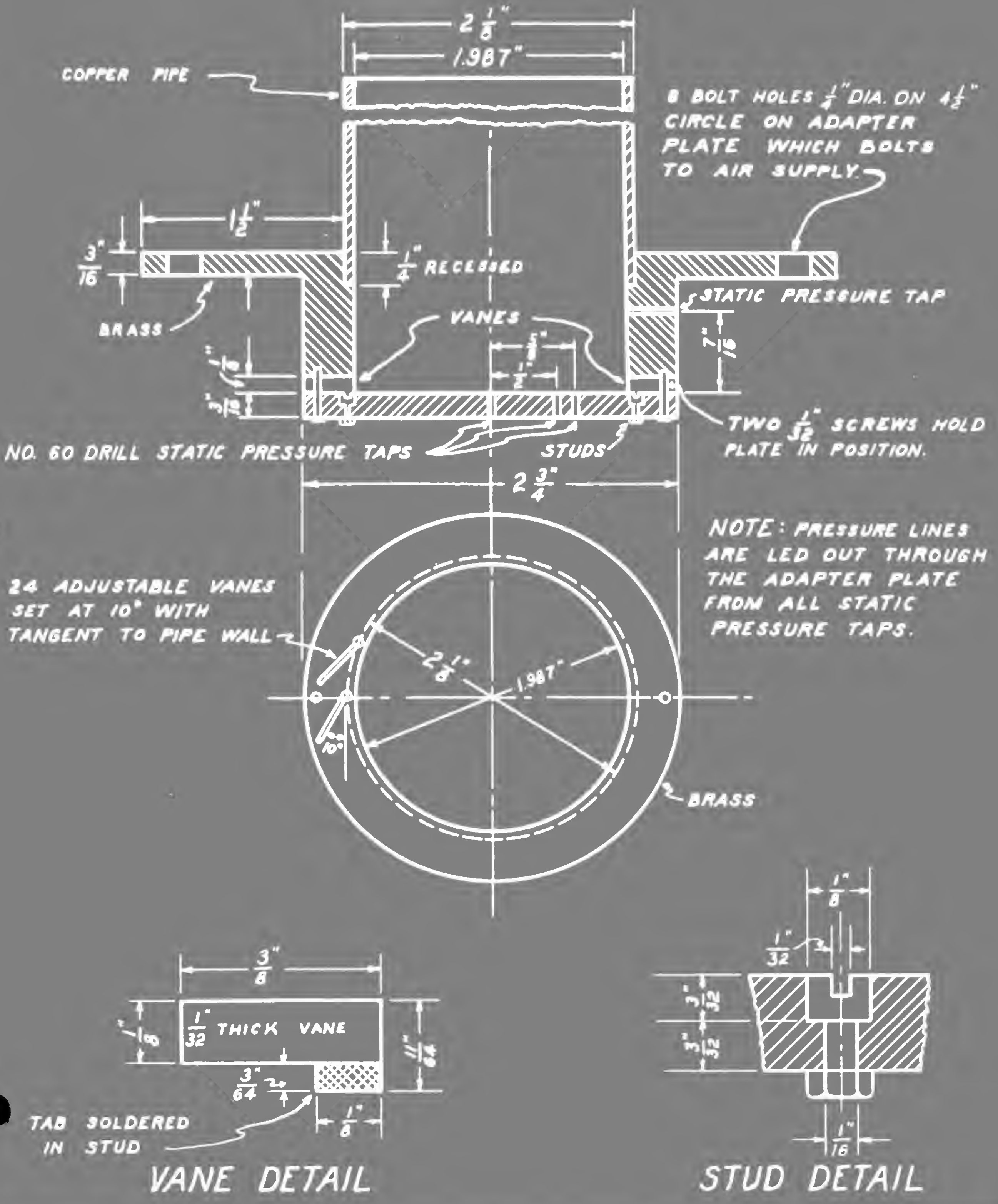


FIGURE 2
VORTEX VALVE



DATE DUE

Thesis 11260
V6 Vickrey
Vortex flow in an
actual gas.