EFFECT OF CORE SHAPES ON THE FLOW OF JETS FROM UNIT HEATER OUTLETS

by

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TABLE OF CONTENTS

INTRODUCTION

The tests described in this thesis were conducted as a part of a cooperative research project on the downward projection of heated air jets sponsored jointly by the American Society of Heating and Ventilating Engineers and the Engineering Experiment Station of Kansas State College. The Project has been in progress at Kansas State College since May, 1945, under the supervision of Professor Linn Helander, head of the department of Mechanical Engineering.

A considerable amount of work has been done at the college on the flow of jets and as a result of this, six papers have already been published. The papers are briefly reviewed in the section on Survey of Literature. The present report is the result of studies suggested in a paper by Professor Helander, Dr. Yen and L. B. Knee (1955) which indicated that basic research should be carried out to explore the possibility of advantageously modifying outlets so as to increase the initial thrust of the jet. The effect of inserting solid cores in stream at the outlet was studied. Mainly, attention was devoted to the thrust characteristics. The data are presented in the form of tables and graphs. The effect of cores on the angle of spread was studied by the smoke bomb technique. To study the effect of cores on velocity distribution, horizontal and vertical anemotherm traverses were taken. The results are presented in the form of graphs and also are summarized in the form of tables. The graphs were also used to determine the angle of spread. The results agreed well with those obtained from smoke pictures. The unit heater outlets used were:

(1) Deep cylindrical outlet 17 1/4" dia. and 13" deep

(2) Shallow diffuser outlet 17 1/4" dia. and 4" deep

As the result of the research reported, a method has been evolved to give an increased value of thrust for jets flowing out of unit heater outlets when a fan is used at the outlet.

SURVEY OF LITERATURE

The best early experimental study of free air jets under conditions pertaining to ventilation practice was reported in 1921 by Zimm. Although occasional experiments on jets have been reported at odd intervals over a span of years stretching back into the preceding century, these have all been either limited to small jets with near sonic initial velocities or have been of insufficient quantitative scope to permit useful conclusions to be drawn for ventilation practice.

The early lack of an adequate theory covering the behavior of a free jet, including its effects in forming a velocity field containing large amounts of entrained fluid from the surrounding space, necessitated an entirely experimental approach. Zimm proceeded by making thorough velocity surveys over the entire region influenced by the free jet. His experimental installation was located in a room 11.5 feet wide by 26.25 feet long; room air was drawn into a blower and discharged through a cylindrical pipe 1.97 in. I.D. by 5.91 in. long whose outlet was in free space. Velocity measurements were made with a pitot tube in the region near the outlet and with a heated wire instrument in the farther regions of the jet. Silk threads were used to indicate the flow direction. Initial outlet velocities ranged from 590 to 2360 ft./min. and jet velocities were read to as low as 20 ft. per min. with hot wire instrument. Zimm described the cross section of the fully developed jet as comprising three regions:

(1) A central region in which the measured mean velocity remained essentially steady at all times.

(2) An intermediate region in which the measured mean velocity attained a characteristic value which was not exceeded but where irregular and brief variations to lower velocities were encountered.

(3) An outer region where the measured mean velocity underwent continual but moderately slow oscillations of relatively large amplitude which made it difficult to obtain data.

His work covered only one particular set of conditions which would be helpful to further investigations. There was an unfilled need, however, for a valid analytical theory to simplify the entire treatment of jet problems.

Tollmien (1945), while carrying through the suggestions of Prandtl, marked the threshold of a new quantitative although semiempirical viewpoint in the practical treatment of jet problems.

Three different systems were treated by Tollmien namely (1) mixing at a free stream boundary (2) a plane (two dimensional) jet, and (3) an axially symmetrical jet. The surroundings were considered to be at rest, isothermal conditions were assumed to prevail, and the fluid density was assumed to be the same throughout the entire mixing region. The static pressure was also assumed constant throughout entire mixing length which was later varified by calculation to be substantially true.

An important consequence of the constant static pressure assumed to exist throughout the jet region was the requirement that the total momentum of the jet flow (by jet is meant both primary and the entrained fluid) be a constant along the trajectory. This leads to the condition that velocity along the jet axis, U_{max}, varies in inverse proportion to the distance from the origin.

In applying the above rules, it is to be noted that "origin" is not at the outlet plane but, is a "point source" located back up the outlet a distance determined by the angle of the jet expansion and the outlet dimensions.

Tollmien estimated by calculations that the difference between the static pressure in the surroundings and at the center of a fully turbulent cylindrical jet was of the order of .075 per cent of the velocity head on the jet axis.

Tollmien's work mainly centered around conical jets, but it laid the ground for velocity field calculations and experimentation.

For several years following Tollmien's contribution, no particular advances were made in the analytical fundamentals of the jet problem.

According to the simple momentum theory, Tollmien predicted that the temperature and velocity distributions across a heated jet should be represented by the same curve when expressed in corresponding dimensionless coordinates. Tollmien's experiments were in part undertaken to establish the validity of the theory or, at least, within the limits of practical requirements.

Ruden (Hottage, 1952) was the first to study the jet velocity field and he came up with a conical jet core which extended about four outlet diameters down from the outlet (Tollmien observed a similar one). The core was surrounded by a region of turbulent mixing which expanded with increasing distance from the outlet. The cores seem to disappear at four outlet diameters below the outlet. He also took some data on temperature distribution but disagreement was great. Ruden's conclusion was that heat and momentum evidently followed different mechanisms of turbulent exchange.

Forthmann (1936) obtained experimental data on the velocity distributions in free airstream with turbulent mixing for comparison with the predictions of the momentum-transfer theory. The systems investigated were (1) a free jet from a long narrow slot (2) a free stream boundary with surrounding air at rest, and (3) a jet formed by confined expansion from a slot into a rectangular channel of large cross section.

Forthmann was unable to solve in a satisfactory manner the practical difficulty of measuring static pressure in a region of highly turbulent action. Ordinary probes of the pitot tube type were felt to be quite unsatisfactory. Forthmann's work established that for the case of a jet coming out of a slot the velocity varies inversely as the square root of the downstream distance measured from the point origin.

It may be recalled at this stage that Tollmien's theory was developed for the region of a turbulent jet which was sufficiently far from the outlet to allow characteristic turbulence conditions to develop and for a surrounding fluid at rest.

Most of Tollmien's (1945) work was done in the form of a study of various phases of turbulence. It was only in 1935 that ventilation jets were isolated as a constituent problem in air distribution research.

Jordan was the first to report on the trajectories of air jets from various outlets. He employed a smoke generator in the air supply to a succession of jet outlets and traced the contours of the smoke field as defining the boundaries of the jet. Observations were made as far as 16 feet from the outlet. The following outlet types were used: (1) a bell mouth converging nozzle 5.0" dia. (2) a flat plate orifice 5" dia. (3) a square duct 7.1" on side with various vane arrangements at the open end. Jet air was maintained successively at room temperature and at 3°F and 10°F below room temperature. Initial jet velocities ranged from 500 to 3,000 ft. per min.

The test results were presented as jet contour sketches only, with no further quantitative analysis.

Among his important conclusions were the following:

(1) The introduction of turbulence at the point of outlet tends to cause good diffusion at the point of outlet.

(2) On a vaned outlet, the vane angle will not increase the spread of the air if the velocity head is insufficient.

(3) A high velocity results in an induced circulation of the surrounding air which aids in the distribution of the air.

(4) If the outlet velocity is low, temperature differences become the main factor causing the air either to fall or rise within 16'.

Additional studies on ventilation jets were contributed by Greenlaw and Hart (Nottage, 1951). These authors emphasized the importance of air distribution control in producing draftless ventilation and undertook to develop empirical relations for the throw and drop of jet with different types of Grilles. Both isothermal and cooled jet behavior was observed. The following empirical formula was derived:

$$\text{Throw} = K \frac{(\text{cfm})}{\text{open area}}$$ when K is an experimental constant determined for each grille type.

The brief tests were summarized in tabular form, as no analysis seemed practicable.

General observations of Greenlaw and Hart were studied by Tuve in a discussion which pointed out great need for careful research. As an initial requirement for test work, accurate instrumentation suitable for air jet readings at low velocities was emphasized.

Then came Mackey who offered a discussion of air distribution and jet behavior. For want of something better, an approximate method was developed for an "ideal jet" based on postulates: (1) that a jet from a straight flow outlet took a straight sided shape with an included angle of 14 degrees, (2) that the total jet momentum remained constant along the throw, (3) that the jet velocity was uniform across any section. With these specific conditions, and defining throw as the jet travel to where velocity became 50 fpm. A simple expression was developed for throw estimates:

$$\text{Throw} = 0.0816 \quad U_o\sqrt{A_o}$$

For ideal jets A_o is the outlet area, sq. ft. U_o is the initial jet velocity in fpm and the throw is in feet.

Data of Greenlaw and Hart showed that actual jets had a throw of about 80% of the ideal prediction. The considerations advanced served to indicate that an approximate form of equation for empirically reporting jet throw data would be, throw = $K_1\ Q/\sqrt{A_o}$. K_1 is an empirical constant. Q in cfm is the discharge.

Mackey stated that more data are needed to support or disprove what he had presented.

Further observations on ventilation jets were reported by Tuve and Priester in 1944. The jets from rectangular outlets were observed to take on an essentially circular cross section at distances beyond two slot widths. This is of practical value, for, as a consequence, the behavior of jets from different outlet forms may be represented by similar equations.

The average included angle from rectangular outlets was found to be 22.5 degrees.

The Tuve and Priester data were limited to isothermal conditions and large free spaces. Madison and Elliot have constructed useful charts, based on Tuve and Priester data, which give a rapid solution for throw, entrainment ratio and residual velocity for circular as well as rectangular outlets.

The preceeding discussion pertains to horizontal jets.

DOWNWARD PROJECTION OF HEATED JETS

Exploratory studies of the downward projection of heated jets were reported in 1948 by Professor Helander and Jakowartz, (1948). This paper was in the nature of a progress report. It dealt with the results of a preliminary study of jets from two outlets, and presented a tentative equation for the downward throw of the type studied. This equation had the form:

$$\frac{L_{max}}{D_o} = \frac{1}{a}\left(\left[a(\overline{B}_o)+1\right]^{\frac{1}{2}} - 1\right) \quad \ldots\ldots\ldots\ldots (1)$$

Where $\overline{B}_o$ is denoted as the cross stream average buoyancy number at the outlet:

a = dimensionless entrainment factor

D_o = orifice diameter of outlet

L_{max} = distance from outlet to the bottom of the jet, feet.

Five papers have been presented as the result of the work carried out under the supervision of Professor Helander at

Kansas State College in cooperation with the American Society of Heating and Air Conditioning Engineers.

The second paper dealt with the downthrow of approximately free jets from long radius A.S.M.E. nozzles attached to the base of a plenum chamber. In this paper, an extensive amount of data on downthrows greater than approximately eight orifice diameters and less than forty eight orifice diameters was presented. The data were correlated by the empirical equation:

$$\frac{L_{max}}{D_o} = 1.66\ B_o^{\frac{1}{2}} \quad . . . . (2)$$

Here, B_o is the buoyancy number evaluated at the center of the outlet. For the range of conditions for which equation (2) applies, B_o may be set equal to 1.04 $\overline{B}_o$. Making this substitution:

$$\frac{L_{max}}{D_o} = 1.70\ \overline{B}_o^{\frac{1}{2}} \quad . . . . (3)$$

The third paper gave approximately determined data on downthrows of the jets from the commercial heater. For throws in excess of eight orifice diameters, these data were correlated with data presented in the previous paper by means of the following modification of equation (3):

$$\frac{L_{max}}{D_o} = 1.70\ f\ \overline{B}_o^{\frac{1}{2}}$$

wherein f is an arbitrarily introduced empirical throw factor.

Values of f were determined for each of the three differently matched unit heater fans. The magnitude of f was found to depend on the downthrust or force of the jet as it issued from the outlet. This downthrust, in turn, was related to the horsepower of the jet as it left the outlet. Empirical performance factors in addition to f were therefore introduced. These were:

(1) Downthrust ratio, defined as the ratio of the downthrust of the actual jet to that of a standard jet which produced the same throw in feet as the actual jet produces, and

(2) Jet efficiency ratio, defined as the ratio of the outlet air horsepower of the standard jet to that of the actual jet.

Values of these ratios and of f together with other pertinent data were reported in this paper. Several important conclusions were arrived at and some of them are given below:

(1) The fan had a pronounced effect on the outlet conditions.

(2) The shallow diffuser developed the largest angle of spread, i.e., 28 degrees approximately for unheated jet. Conical and annular outlets developed about the same angles of spread in degrees.

(3) A fundamental type of research should be pursued to determine the separate effects of β_1, β_2, etc. (See Nomenclature).

Some supplementary conclusions were drawn and are noteworthy:

(a) Unit heater fan combination should be carefully matched to the outlet.

(b) The outlet and fan combination should be designed for over all effectiveness, that is, with regard for both the resistance offered by the outlet to the flow and pattern of flow developed.

(c) The less the whirl, dead area, and irregularity of distribution of flow at the outlet, the more effective will be the jet utilization of outlet downthrust and outlet air horsepower.

(d) The throw of the jet may be increased by increasing the velocity of the jet at the outlet and thereby increasing the outlet downthrust and outlet air horsepower. This may be done, for example, by artificially reducing the effective area of the outlet area. Whirl because of its effect on the effective area may produce the same result.

(e) Increasing f in the foregoing manner may entail an increase in power consumption out of proportion to effect produced on throw.

As the result of this paper, which has been briefly described above, it was recommended that fundamental research be planned to obtain data applicable to design and operation of practical outlets and determine the effect of:

(1) reducing the effective area of an outlet

(2) modifying the velocity profile

(3) enlarging the spread of the jet angle

(4) artificially introducing whirl.

The fourth paper presented the characteristics of jets discharged from vertical discharged unit heater, equipped with either an annular outlet or a shallow diffuser. The following experimentally determined data were presented:

(1) Velocities and temperatures along the vertical axis of the jet discharged from the heater.

(2) Velocities and temperatures in the fully developed region of the fully developed flow.

(3) Temperatures in the space surrounding the jet.

As a result of this paper a nomograph for finding downward throw of jets was prepared and published by the Barber Colman Company.

Here again, the authors recommended a means for measuring directly the momentum of a jet issuing from an outlet.

To carry out the forementioned fundamental research, a setup was designed at Kansas State College and as a result came the fifth paper which:

(1) described a simple means for directly measuring the thrust or projective force developed by outlets of type used in practice.

(2) gave data on the flow characteristics at outlet for:

(a) four inch long radius A.S.M.E. nozzle with and without inserted cores;

(b) a unit heater with

1. a deep cylindrical outlet, with and without core,

2. a shallow diffuser without vanes and with and without cores,

3. a shallow diffuser with adjustable guide vanes;

(3) gave data on the velocity distribution downstream from the face of A.S.M.E. nozzle with and without cores of various shapes;

(4) gave data on the influence of a plate against

which jet was allowed to impinge.

However, no study was made of full nozzle length cylindrical cores. Only small cores were used.

No effort was made to show the effect of various shapes of cores on the jets coming out of various outlets. The present study was undertaken with the purpose of continuing the work done in the last paper and checking some of the data already presented.

PROBLEM BRIEFLY OUTLINED

While studying the jets issuing from unit heater outlets with fan at the outlets, it must be kept in mind that a unique situation arises due to the operation of the fan which creates, due to whirl, a region of negative pressure in front of the outlet.

A considerable amount of energy which could have been usefully employed is thus wasted to maintain this zone of negative pressure. This energy, if made available, would improve the performance of the jets. The negative pressure zone can be filled with a solid core of suitable shape and part of this energy might thereby be made available to increase the propulsive force. Thus, one phase of the present research was to determine as far as possible core shapes which would give the maximum thrust by eliminating or reducing the region of negative pressure.

The second phase naturally follows the first; having found a suitable core size for a particular outlet, the effect of

EXPLANATION OF PLATE I

View of Experimental Equipment

Reference numbers:

(1) Micromanometers

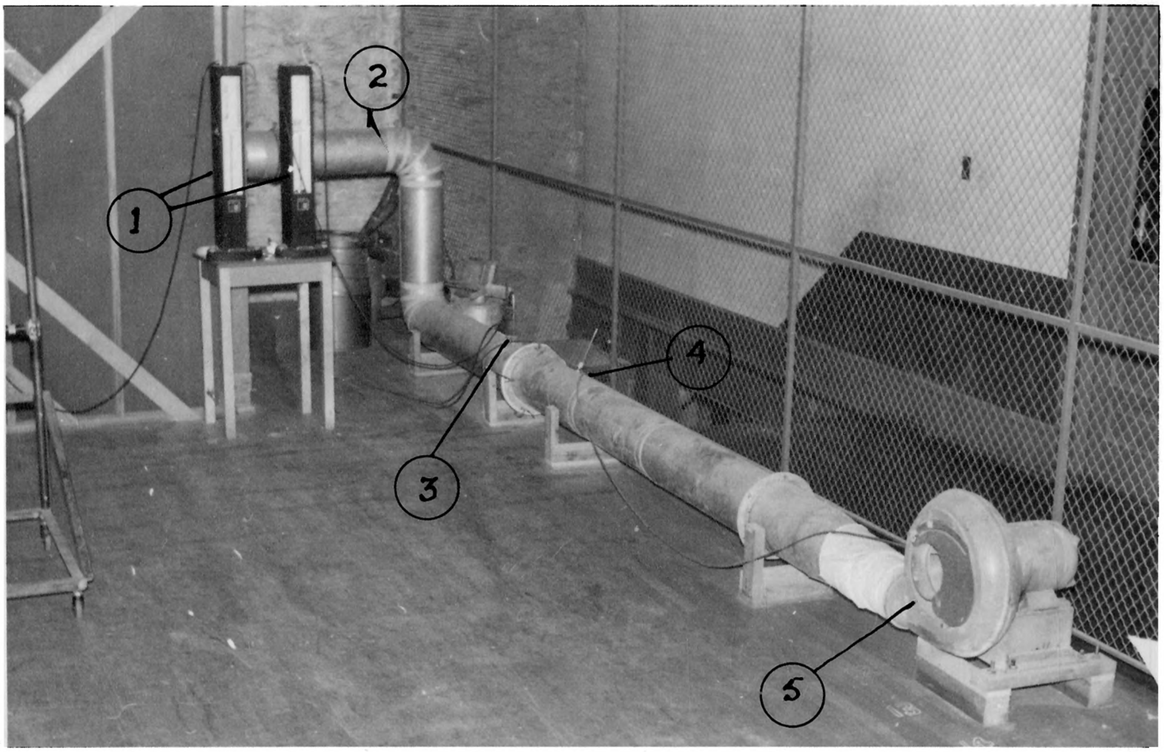
(2) The air carrying duct

(3) Pitot tube and impact tube combination for the measurement of flow rate

(4) Thermometer for temperature measurement

(5) The fan to supply air to the plenum chamber.

PLATE I



core on the velocity profile and shape of jet was observed.

The effect of the core shapes on the jet characteristics has been reported here in the form of tables, graphs and various plates.

EQUIPMENT AND PROCEDURE

Plates 1 through 5 show various views of test station. The housing encloses the thrust measuring equipment. Part of the equipment inside the housing is a swing platform upon which was mounted a unit heater. (Shown in schematic drawing not attached here.) Atmospheric pressure was maintained in the housing by an external air supply fan when the unit heater characteristics were studied. The air flow to the housing from this external fan was measured by the metering nozzle as shown in the schematic diagram (Figs. 1 and 2, see appendix). Unit heater discharged the air from the housing

The thrust imparted by the unit heater to the swing platform was determined by means of a thrust measuring device. Plate II shows a front view of the device. Plate III shows the external arrangement of the thrust measuring instrument in the test setup. Plate II shows a view of the device, which consisted of a 6" x 1/2" x 1/8" aluminum cantilever beam equipped with two SR 4 type A5 strain gages. The two strain gages used were located on each side of the cantilever beam near the fixed end in such a manner that the effects of strain were additive.

The thrust imparted by the swing platform was applied at the upper end of the cantilever beam.

EXPLANATION OF PLATE II

Head On View of Thrust Measuring Device.

Reference numbers:

(1) the line of contact between swing platform and the cantilever beam

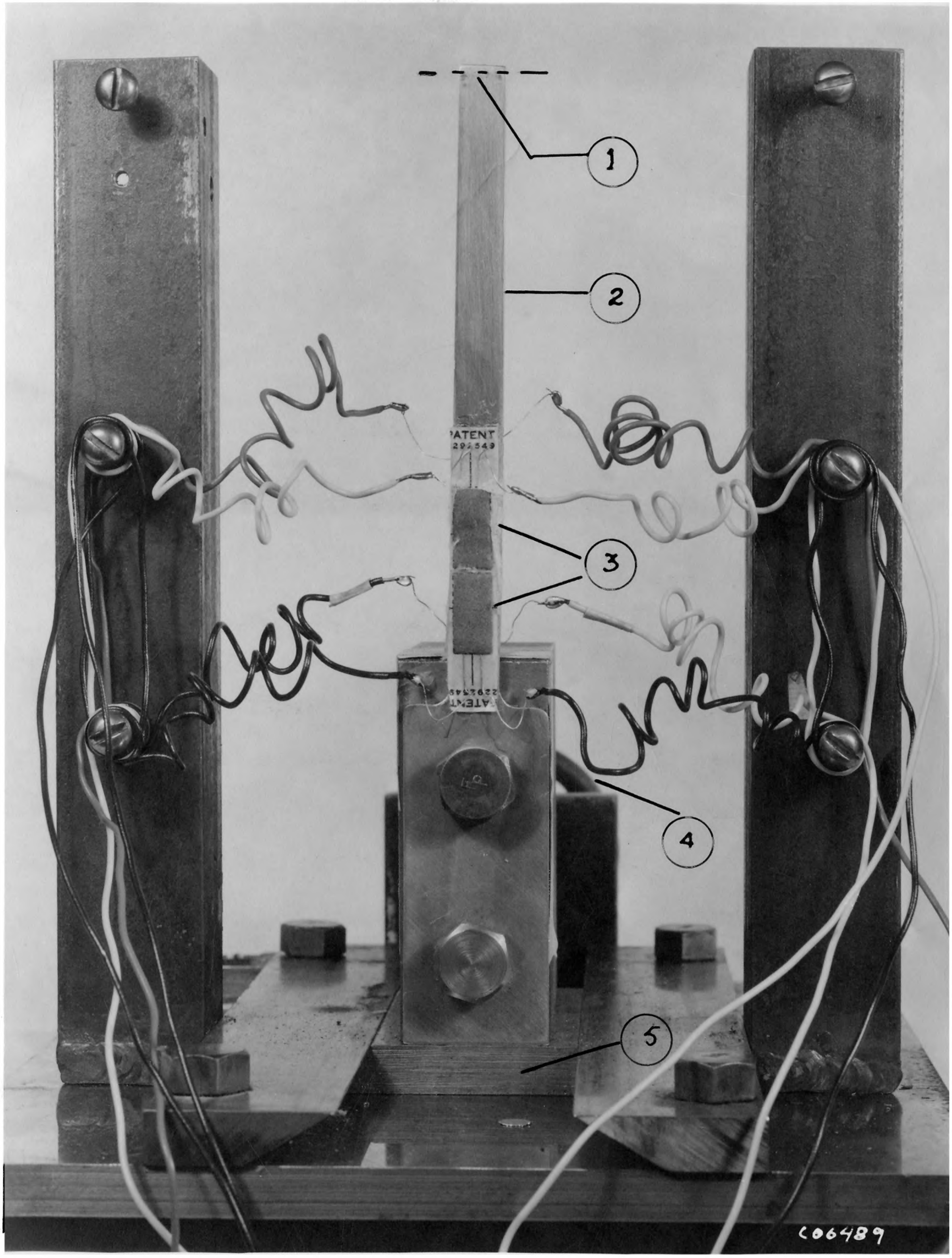
(2) 6" x 1/2" x 1/8" aluminum cantilever beam

(3) 4 Sr_4 type A_5 strain gages (two on back)

(4) adjusting wheel

(5) base adjustable in line parallel to the direction of thrust.

PLATE II



The output of the strain gages was measured by SR 4 type M strain indicator. The thrust measuring device was calibrated by means of weights (Plate III). During a test, when vibrations were present, the thrust measuring device was sensitive to a change in weight of one gram.

A position indicating switch connected to two external lights (Plate III) was used to reestablish the plumb position of the swing before taking a thrust reading. The swing was plumb when the lights fluctuated with equal frequency.

To bring the swing to its plumb position, the restraining force exerted by the thrust sensing cantilever beam on the saddle of the swing was altered by means of a hand operated screw.

The instrument carriage (Plate IV) could be moved horizontally in the direction of the flow. It was used to carry all the static and impact pressure tubes whenever they were used. It was also used to carry the anemotherm probe for velocity measurements along the axis of the stream. The carriage could be moved as far as 12 feet from the outlet and as close as 1 1/2 feet to the outlet. While taking the thrust readings the cores were attached directly to the unit heater by means of a bracket. This made it possible to obtain a direct reading of thrust.

The cores were held in place with bracket as shown in Plate IV.

The cores were mounted on a 1/2 inch pipe by drilling and threading a hole in the face of each core. The pipe, in turn, was passed through another pipe which was welded to the bracket. A screw was run through this pipe to hold the 1/2 inch pipe in position. By loosening this screw the core could be moved backward or forward.

The following cores were used:

(1) cores of same length (2 feet long) and different diameters (2", 3", 4", 5", 6", and 8"),

(2) cores of same length (1 1/2 feet long) and different diameters (2", 3", 4", 5", 6", and 8"), and

(3) cores of same length and different shapes.

The outlets used were (1) shallow diffuser (17 1/4" diameter, 4" deep) and (2) a deep cylindrical outlet (17 1/4" diameter and 13 1/2" deep).

To start the test the supply fan (Plate I) was started and the plenum chamber was closed and checked against air leakage. Then the inside pressure reading of the plenum chamber was taken and the inlet opening of the fan was adjusted until atmospheric pressure was established in the plenum chamber. Before starting the fan, the strain gage-cantilever swing platform combination was calibrated by applying known forces to the platform, simulating reactive forces, and noting the strain gage indicator reading. Thereby the equilibrium position of the platform was established and the positioning switch was set.

To set the positioning switch, the following procedure was adopted:

(a) Central contact arm was set between terminal

EXPLANATION OF PLATE III

View Showing Instrument Room

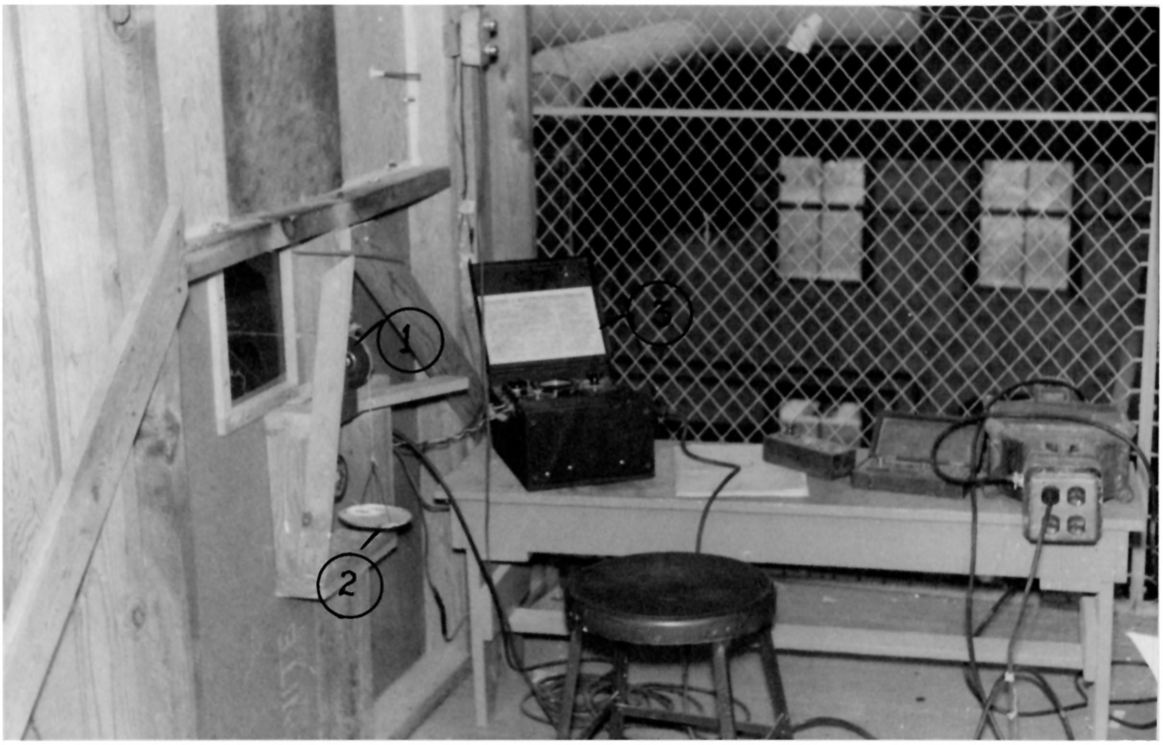
Reference numbers:

(1) Pulley.

(2) Pan used for thrust calibration.

(3) Baldwin sensitive strain gage indicator.

PLATE III



EXPLANATION OF PLATE IV

Front View of Experiment Station

Reference numbers:

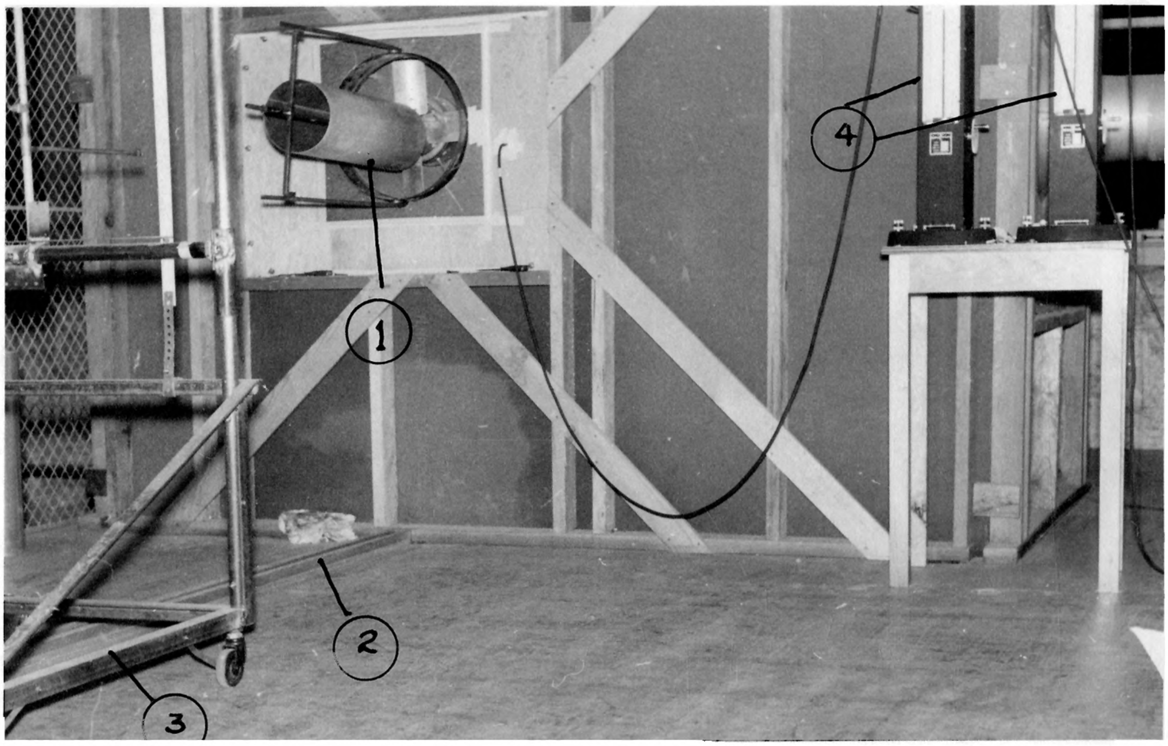
(1) Cylindrical core shown held in place by a bracket which mounted on the shallow diffuser.

(2) Instrument carriage guide railing.

(3) Instrument carriage with two guide rods to keep its path fixed and wheels on four ends of the frame to make it move more easily.

(4) Micromanometers for measuring pressures in the plenum, duct and the jet.

PLATE IV



contacts of the positioning switch.

(b) Position lights were plugged in.

(c) The terminal contacts on the position indicator were adjusted until the lights fluctuated with equal intensity. This marked the reference position of the platform and the central contact arm.

Having set the positioning switch, the fan was turned on with no core in the outlet. The original plumb position of the platform was restored and thrust was measured.

A similar procedure was employed when cores were inserted. In each test the plumb position with the core in place and the (fan not in operation) was established. With the fan in operation, this plumb position was reestablished before the thrust reading was taken.

The static pressures in the stream were measured by using a pitot static tube although only static part of it was used. The instrument carriage was used to move the pitot tube backwards and forwards and to the sides.

The static pressures along the cylinder were taken by drilling fine holes along the length of the cylinder and inserting small hypodermic tubes. Pressure was conveyed to a micromanometer by small sized rubber tubing. The hypodermic tubes were held in place by hard rubber collars, 1/4 inch thick, glued along the inside of the cylinder. The collars were glued in such a manner that they were leak free. Six

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Enough vibrations were present so it could be easily seen when the lights fluctuated with equal intensity.

holes were drilled 2 inches apart on four sides (each row of holes being 90° apart). Regular aluminum cylinders were used as cores and they were always turned on the lathe so as to make them perfectly smooth. Other cores were also turned on the lathe and finished to a perfectly smooth surface. Smoothness was judged by feel of hand or eye and no attempt was made to determine the smoothness by any other means.

Merriam micromanometers were used to measure the pressure readings. They could be read to the third decimal place.

A hot wire anemometer and an anemotherm were used besides the conventional pitot tubes to measure velocity readings.

A three-legged stand was used to hold the anemotherm. The floor was divided by lines into square sections six inches on a side so as to form a coordinate system for the jet. Two appropriate legs of the anemotherm stand were aligned on a line parallel to the jet axis, the anemotherm measured velocity parallel to the axis.

The anemotherm could read velocities in three ranges, (a) 0-100 fpm, (b) 100-1000 fpm, and (c) 1000-8000 fpm. Before use, the zero was corrected. Then the anemotherm was calibrated in each range to get dependable readings. The calibration procedure was a simple vernier adjustment described in the anemotherm corporation's pamphlet for this model 60 anemotherm airmeter. The instrument was calibrated against a standard pitot static tube in a high speed duct. The agreement between the readings was within $\pm$ 2 per cent in high range and $\pm$ 1 per cent in low ranges. Smoke was used to make the jet visible and to study jet characteristics near

EXPLANATION OF PLATE V

Front View of Experiment Station

Reference numbers:

(1) Stand carrying anemotherm probe for measuring velocity in the stream.

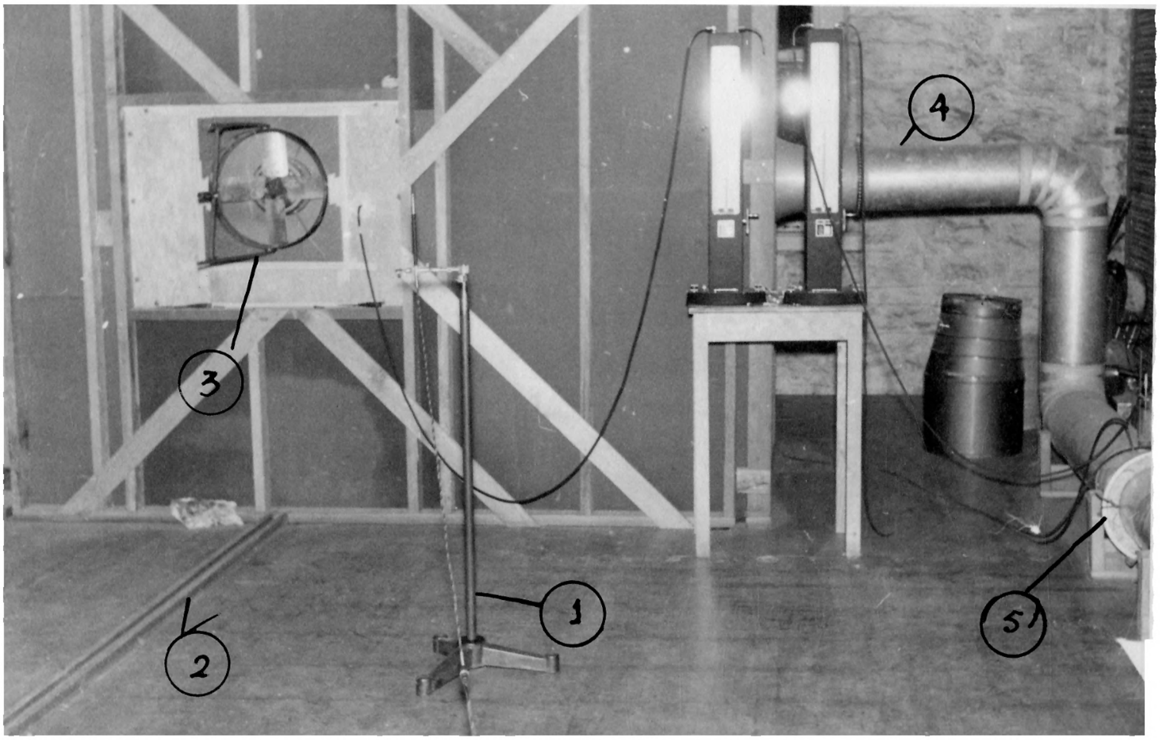
(2) Guide railing for the instrument carriage which was used to carry conventional pitot tube.

(3) Core frame mounted on the shallow diffuser outlet.

(4) Air carrying duct shown entering the plenum between the two micromanometers.

(5) Pitot static tube and impact tube arrangement for measuring flow at the outlet of 6" A.S.M.E. nozzle which was mounted in the duct.

PLATE V



the outlet.

Smoke was introduced at the inlet of the fan by firing two smoke bombs at a time. Besides eye view observation, moving pictures were taken to analyze the flow characteristics.

NEGATIVE PRESSURES AT OUTLET

It was thought that the region of negative pressure in the vicinity of the outlet was caused by whirl. Whirl also was regarded as a chief source of energy loss. Static pressure readings were taken to determine the distribution of pressure in the vicinity of the outlet. Plate VI shows the pressure distribution at different distances below and above the axis of the jet. This plate gives a good picture of what may be expected in the way of negative pressures when a unit heater of the type under study is used. It was thought that the insertion of a core would cause the jet to converge, due to the formation of a boundary layer, and that it would cause a decrease in the negative pressures. A cylindrical core 1 foot long and 6 inches diameter was introduced with its upstream face 2 inches from the fan. Readings were taken along the cylindrical surface of the core. These showed that negative pressures decreased downstream along the surface of the core. This indicated that if a long enough core was used probably at some point on its surface atmospheric pressure would exist.

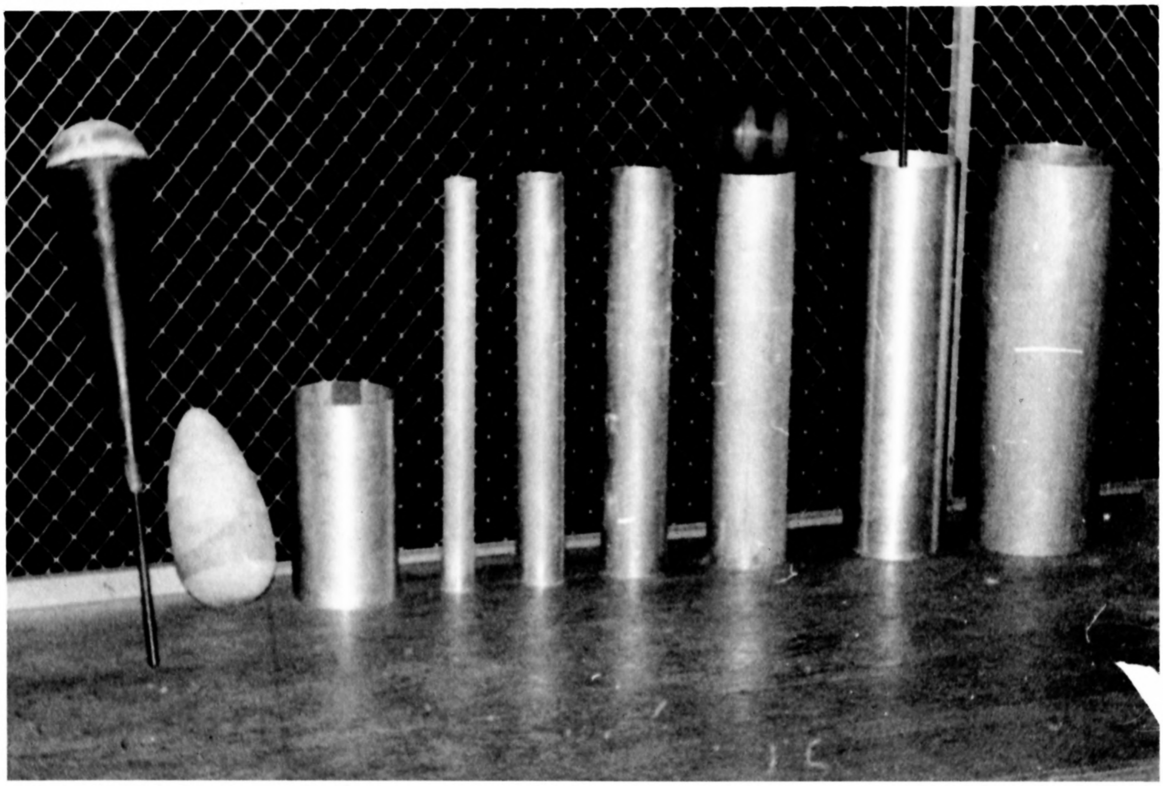
The static pressure distribution along the core walls is shown in Plate VII. The above procedure was used to show that a negative pressure exists and that a core decreases the negative pressure.

EXPLANATION OF PLATE VI

View of Core Shapes

This plate shows some of cores used for the tests in the present research. Besides the cylinders of various diameters, the large egg-shaped core and the long conical core are also shown resting on the floor. Placed on one of the cylinders is the small egg-shaped core.

PLATE VI



ANALYSIS OF DATA

Effect of Cores on Thrust

Case 1.

<u>Full Length Cores Used With A Deep Cylindrical Outlet.</u>

The full length cores were introduced into the stream and a considerable increase of thrust was noted. The flow rate decreased as the diameter of the cores was increased, but the decrease in thrust due to the decrease in flow rate was more than offset by the reduction in negative pressure. Plate IX shows the plot of T_c/T_o no core V_s $\frac{D_c}{D_o}^2$. On the same plate a plot of Q_c/Q_o no core V_s $\frac{D_c}{D_o}^2$ has been plotted showing how flow decreased with increase in core diameter as the thrust increased.

Plate X shows the plot of β_2/β_2 no core V_s $\frac{D_c}{D_o}^2$. This indicates how the relative thrust increases with increase of core diameters, core lengths being the same. These plots are based on the maximum measured thrust readings which were observed when the upstream core face was 2 inches from the fan, that is when the core extended axially 11 inches into the deep cylindrical outlet as shown on plot. The deeper the core was moved into the outlet the greater was the thrust or relative thrust (in all cases).

The decrease of measured thrust as the core was moved outward, that is farther from the fan, is shown in Plate XI The data using 2 foot long cylindrical cores with deep cylindrical cores with deep cylindrical outlets are shown in Table 1. The data reported in this table have been reduced

EXPLANATION OF PLATE VII

This plate shows the negative pressure distribution at a distance 23 inches downstream.

Curve A. Pressure variation along horizontal and vertical chords in the plane of traverse 5 inches from the center line of the jet.

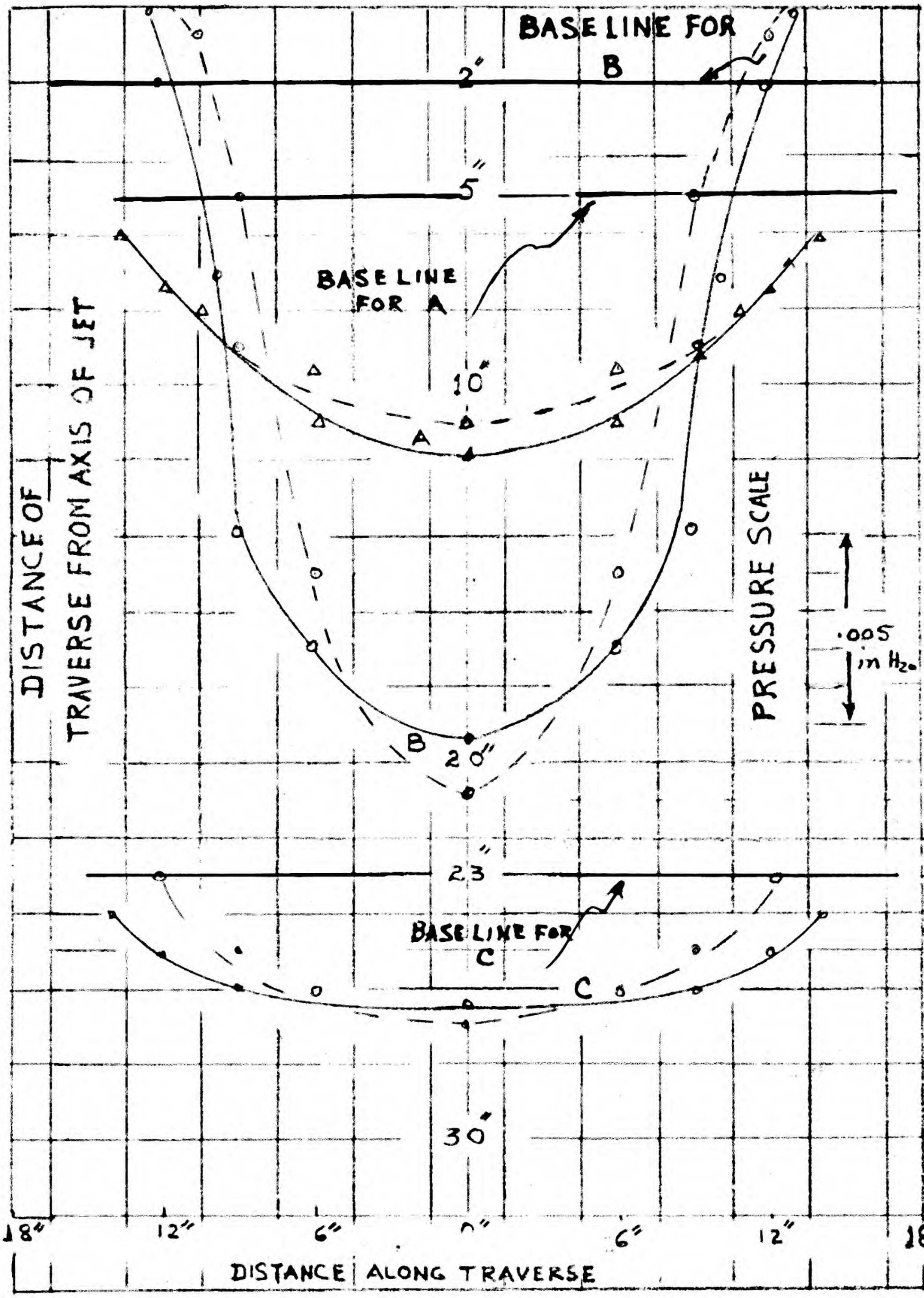
Curve B. Pressure variation along horizontal and vertical cords in the plane of traverse and 2 inches from the center line of the jet.

Curve C. Pressure variation along horizontal and vertical chords in the plane of traverse 23 inches from center line of the jet.

-------- dotted curves show traverse in the vertical plane

________ bold curves show traverse in the horizontal plane

PLATE VII



NEGATIVE STATIC PRESSURE DISTRIBUTION
WITH NO CORE AND SHALLOW DIFFUSER OUTLET
IN HORIZONTAL AND VERTICAL PLANE AT A
DISTANCE OF 23" DOWNSTREAM

EXPLANATION OF PLATE VIII

Negative Pressure Distribution

Plate shows:

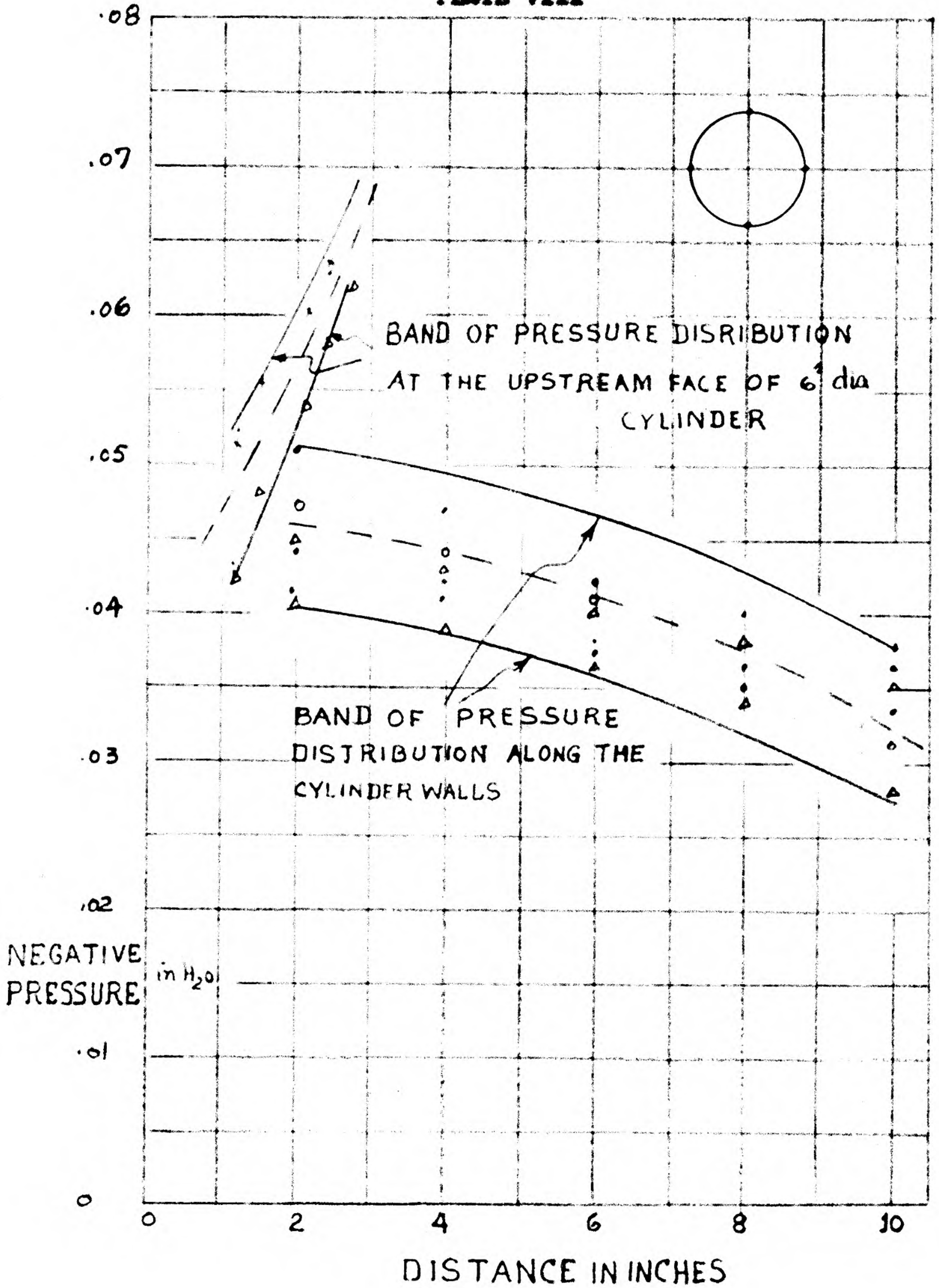
(a) Band of pressure distribution at the upstream face of 6 inches diameter cylinder (1 foot long).

Distance is measured from axis of cylinder radially along the face of the cylinder, therefore perpendicular to the axis of the jet.

(b) Band of pressure distribution along the cylinder walls. Distance is measured from upstream face of core along the cylinder walls, therefore parallel to the axis of the jet. Upstream face of core was located 2 inches from fan.

Bands were drawn because each reading was distinctly different but all readings fell in the range shown.

PLATE VIII


.08
.07
.06
.05
.04
.03
.02
.01
0
BAND OF PRESSURE DISRIBUTION
AT THE UPSTREAM FACE OF 6" dia
CYLINDER
BAND OF PRESSURE
DISTRIBUTION ALONG THE
CYLINDER WALLS
NEGATIVE
PRESSURE
in H_2O
0
2
4
6
8
10
DISTANCE IN INCHES

to a dimensionless form.

For values of $\left(\frac{D_c}{D_o}\right)^2$ up to .084, the curve of T_o/T_o no core $V_s\left(\frac{D_c}{D_o}\right)^2$ has a considerably smaller slope than that for values of $\left(\frac{D_c}{D_o}\right)^2$ between .084 and .121. This may be explained by studying the drag effects of bodies in the stream. (See Appendix). For $\left(\frac{D_c}{D_o}\right)^2$ between .084 and .121. The per cent increase in thrust due to the reduction in negative pressures increased more rapidly than the per cent reduction in thrust due to the increased surface drag. This accounts for the steeper slope. This was not true for values of $\left(\frac{D_c}{D_o}\right)^2$ less than .084. From Plate XI, which shows thrust as a function of distance in inches from the fan, it is clear that thrust increases as core is brought nearer the fan.

Case 2.

Full Length Cores Used With A Shallow Diffuser Outlet.

The technique described was again used to measure the thrust developed by the shallow diffuser. The increase in measured thrust was again recorded for this case. Plate XII shows the plot of T_o/T_o no core $V_s\left(\frac{D_c}{D_o}\right)^2$ and Q_o/Q_o no core $V_s\left(\frac{D_c}{D_o}\right)^2$ is also plotted on the same curve.

The measured thrust increases with increase in diameter of the core as is evident from the dimensionless plot. With each increment of $\left(\frac{D_c}{D_o}\right)^2$ up to 0.22 the thrust increased, but at a progressively smaller rate with each increase in $\frac{D_c}{D_o}$. This is evident from the slope of the plot of T_o/T_o no core $V_s\left(\frac{D_c}{D_o}\right)^2$.

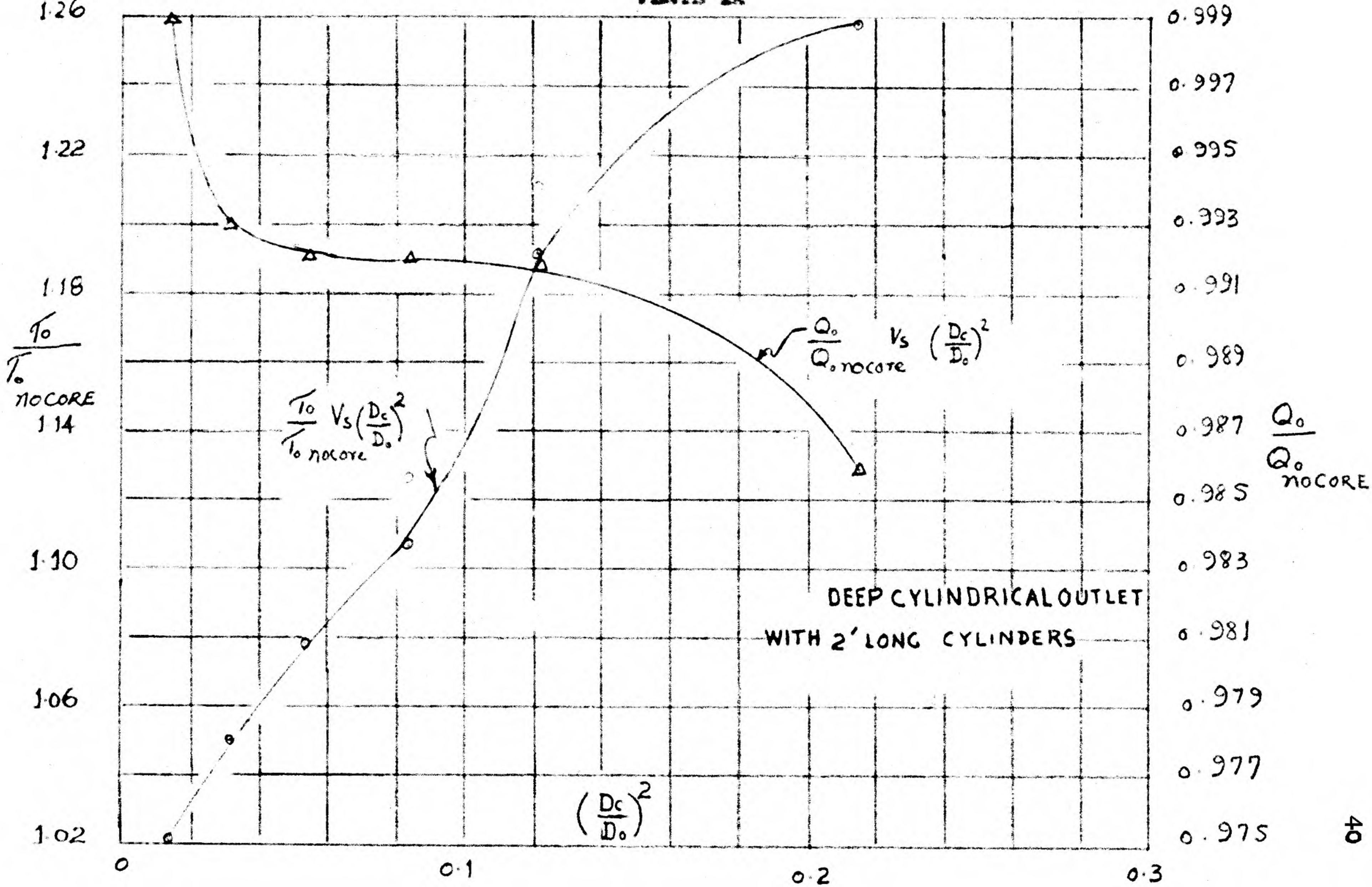
EXPLANATION OF PLATE IX

This plate shows the plot of $\frac{To}{To\ no\ core}$ $V_s\left(\frac{D_c}{D_o}\right)^2$ and $\frac{Qo}{Qo\ no\ core}$ $V_s\left(\frac{D_c}{D_o}\right)^2$ when the deep cylindrical outlet was used and when 2 foot long cylinders were used as cores.

This curve is based on the values of Q_o and T_o when cores were axially placed, and extended 11 inches into the cylindrical outlet, i.e., to within 2 inches of the fan.

At this location T_o was a maximum for all cores.

PLATE IX


1.26
1.22
1.18
1.14
1.10
1.06
1.02
$\frac{T_o}{T_{o\,NOCORE}}$
0.999
0.997
0.995
0.993
0.991
0.989
0.987
0.985
0.983
0.981
0.979
0.977
0.975
$\frac{Q_o}{Q_{o\,NOCORE}}$
0
0.1
0.2
0.3
$\left(\frac{D_c}{D_o}\right)^2$
$\frac{Q_o}{Q_{o\,nocore}}$ Vs $\left(\frac{D_c}{D_o}\right)^2$
$\frac{T_o}{T_{o\,nocore}}$ Vs $\left(\frac{D_c}{D_o}\right)^2$
DEEP CYLINDRICAL OUTLET
WITH 2' LONG CYLINDERS

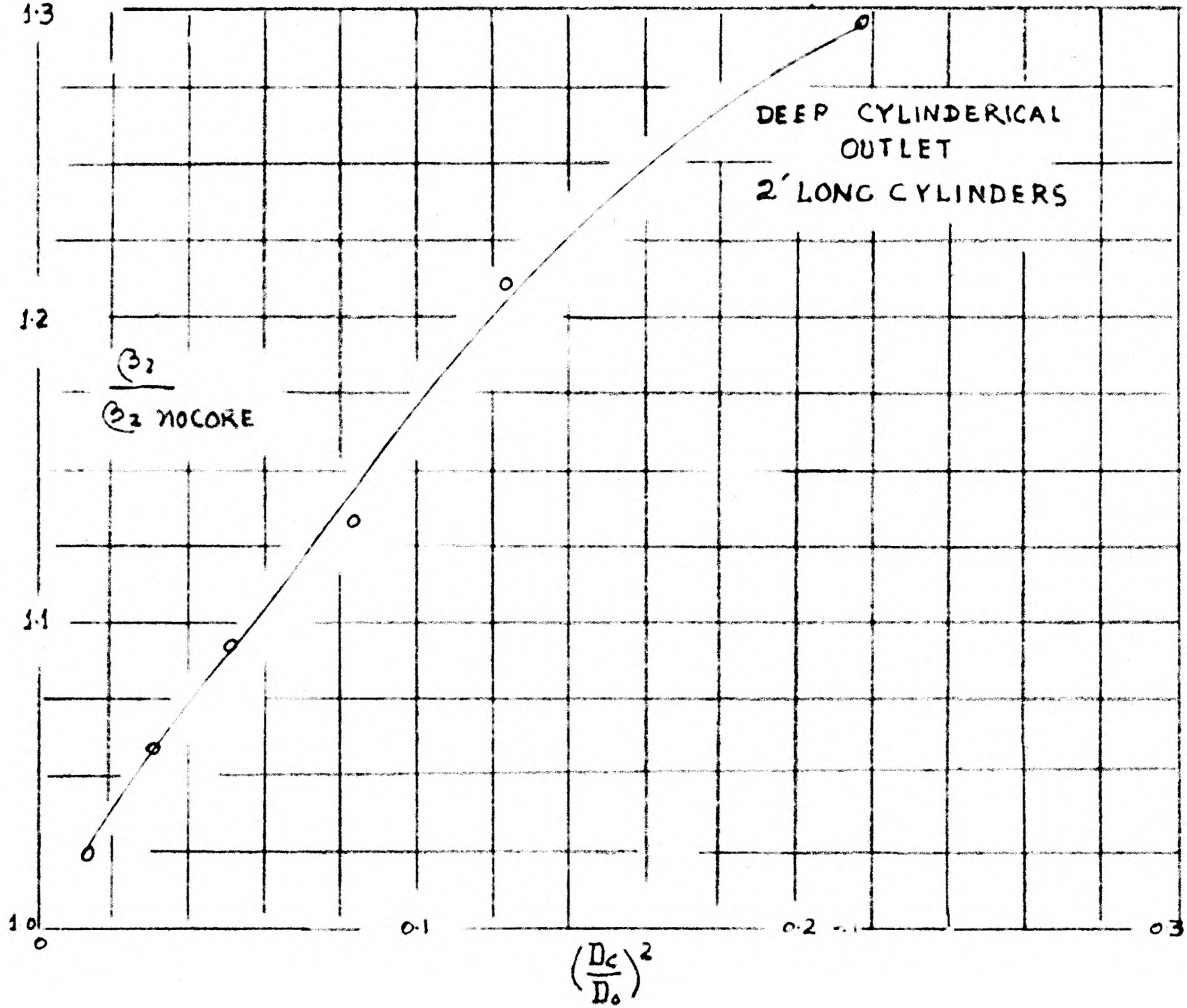
EXPLANATION OF PLATE X

This plate shows plot of $\frac{\beta\ 2}{\beta\ 2 \text{ no core}}$ $V_s \left(\frac{D_c}{D_o}\right)^2$ when the deep cylindrical outlet was used and 2 foot cylinders were used as cores.

β_2 was based on the values of T_o as in Plate IX.

Cores were axially placed and extended 11 inches into the cylindrical outlet, i.e., to within 2 inches of the fan.

PLATE X



1·3
1·2
1·1
1·0
0
0·1
0·2
0·3
$\frac{\beta_2}{\beta_2 \text{ NOCORE}}$
DEEP CYLINDERICAL
OUTLET
2' LONG CYLINDERS
$\left(\frac{D_c}{D_o}\right)^2$

EXPLANATION OF PLATE XI

This plate shows the increase in thrust above To no core when the cores are placed axially inside the deep cylindrical outlet.

Increase in thrust above To no core is shown plotted as a function of distance of the upstream core face from the fan.

Cores used in this test were 2 foot long cylinders of different diameters.

PLATE XI

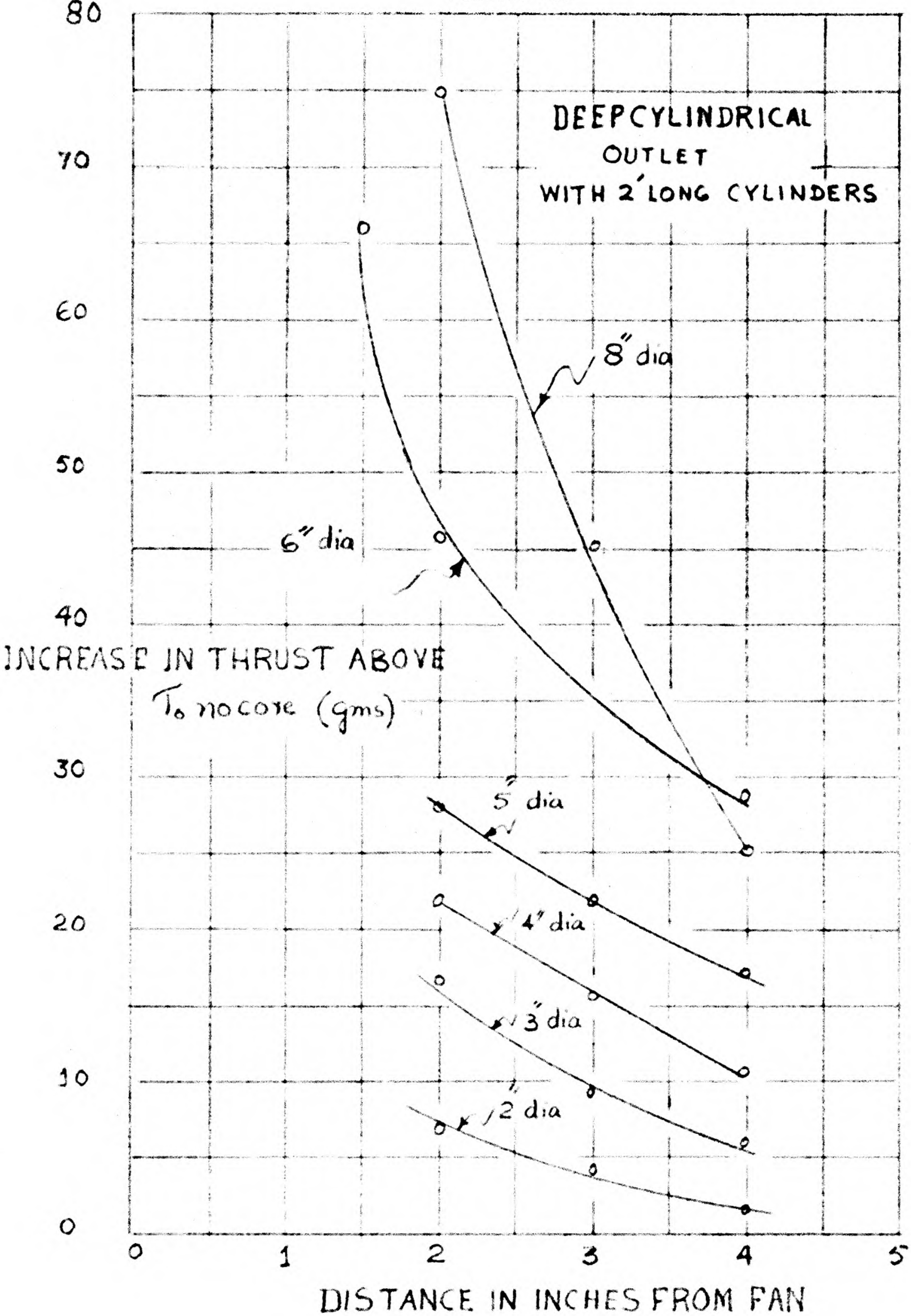

DEEPCYLINDRICAL
OUTLET
WITH 2' LONG CYLINDERS
8" dia
6" dia
5" dia
4" dia
3" dia
2" dia
INCREASE IN THRUST ABOVE
T₀ no core (gms)
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
DISTANCE IN INCHES FROM FAN

Table 1. Outlet Data for Unit Heater. Deep Cylindrical Outlet 17" diameter 13 1/2" deep, using 2' long cores which extended 11" into outlet, that is to within 2" of fan.

$\left(\frac{D_c}{D_o}\right)^2$	Cores Used	$\frac{Q_o}{Q_o \text{ no core}}$	$\frac{T_o}{T_o \text{ no core}}$	$\frac{\beta_2}{\beta_2 \text{ no core}}$
0.215	8" diameter cylinder	0.986	1.258	1.295
0.121	6" diameter cylinder	0.992	1.191	1.21
0.0840	5" diameter cylinder	0.992	1.105	1.133
0.0538	4" diameter cylinder	0.992	1.074	1.092
0.0302	3" diameter cylinder	0.993	1.050	1.064
0.01346	2" diameter cylinder	0.999	1.021	1.024

Plate XIII, shows the increase in relative thrust, B_2, plotted as a ratio of the relative thrust without core. This plot shows that increase in relative thrust for a shallow diffuser was less than the value observed when the deep cylindrical outlet was used. Centrifugal forces still predominated in the case of the shallow diffuser and the straightening of the jet was much less pronounced. The negative pressure zone existed to a certain extent despite the cores in the stream. Its effect was noticeable to a greater extent when the shallow diffuser was used than it was when the deep cylindrical outlet was employed.

The straightening effect was caused by the formation of a boundary layer along the core which tended to increase in thickness downstream from the fan. Due to the presence of a centrifugal component of velocity, the air particles, as soon as they formed the boundary layer, were thrown out radially. The result was a very complex flow pattern. Regardless of the destruction of the boundary layer, it still helped to decrease the centrifugal forces and thus the negative pressure caused due to whirl. The thrust again decreased as the core was moved away from the fan. It was also noticed, as in the case of deep cylindrical outlet, that the thrust decreased at a greater rate when large diameter cores were used.

From the curves for the shallow diffuser and deep cylindrical outlet for the 2 feet long, different-diameter cores it was evident from Plate XI and Plate XIV that cores of small diameters do not contribute much in the way of increased thrust. It was also deen that an increase in thrust was

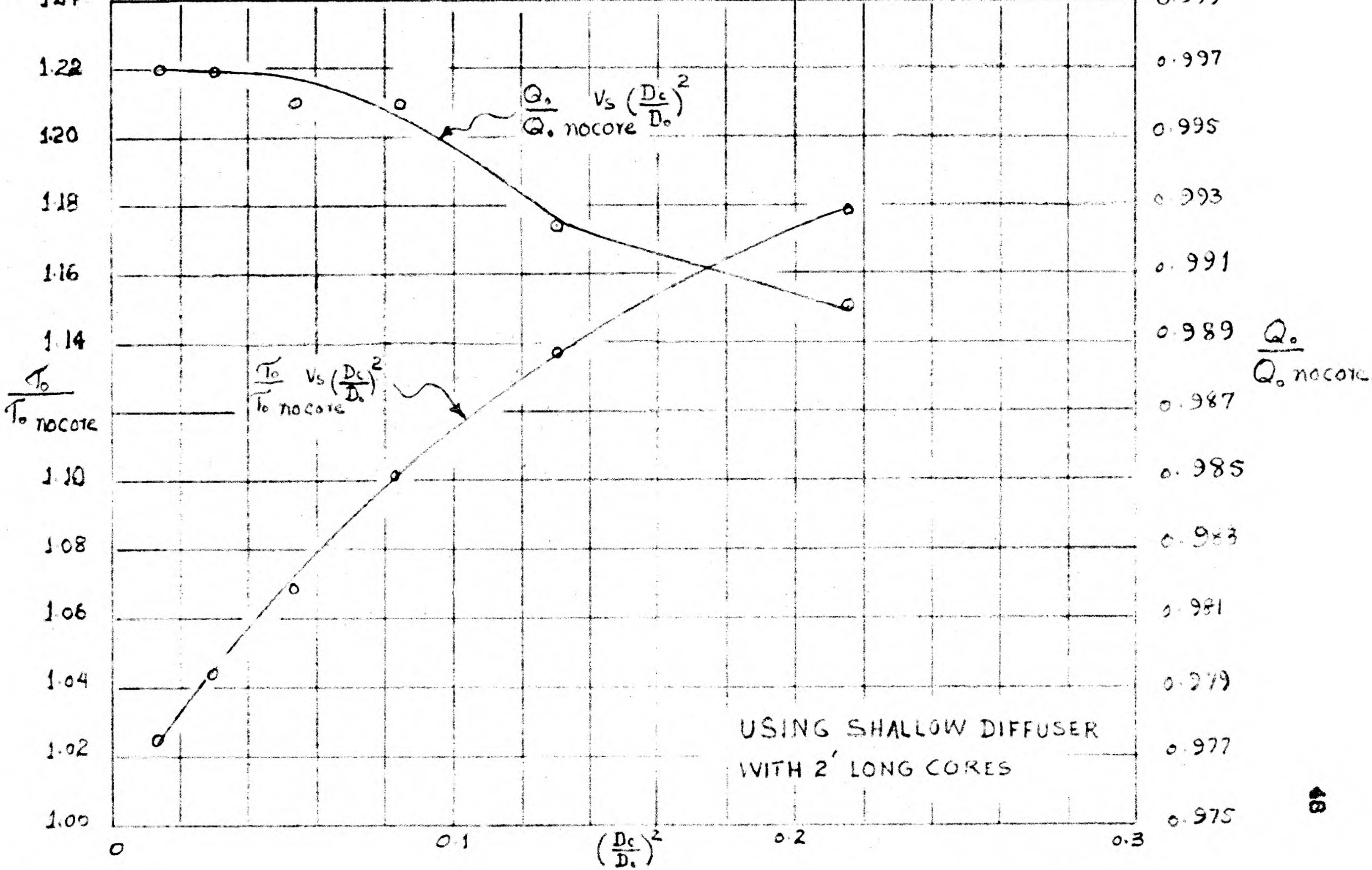
EXPLANATION OF PLATE XII

This plate shows the plot of $\frac{T_o}{T_{o\ \text{no core}}}$ $V_s\left(\frac{D_c}{D_o}\right)$ and $\frac{Q_o}{Q_{o\ \text{no core}}}$ $V_s\left(\frac{D_c}{D_o}\right)^2$ when the shallow diffuser was used as an outlet and when 2 feet long cylinders were used as cores.

This curve is based on the values of Q_o and T_o when cores extended axially 2 inches into shallow diffuser, i.e., to within 2 inches of the fan.

At this location T_o was a maximum for all cores.

PLATE XII



1.24
1.22
1.20
1.18
1.16
1.14
1.10
1.08
1.06
1.04
1.02
1.00
0.999
0.997
0.995
0.993
0.991
0.989
0.987
0.985
0.975
0
0.1
0.2
0.3
$\frac{T_0}{T_0 \text{ nocore}}$
$\frac{Q_0}{Q_0 \text{ nocore}}$
$\left(\frac{D_c}{D_0}\right)^2$
$\frac{Q_0}{Q_0 \text{ nocore}}$ Vs $\left(\frac{D_c}{D_0}\right)^2$
$\frac{T_0}{T_0 \text{ nocore}}$ Vs $\left(\frac{D_c}{D_0}\right)^2$
USING SHALLOW DIFFUSER
WITH 2′ LONG CORES

EXPLANATION OF PLATE XIII

This plate shows plot of $\frac{\beta_2}{\beta_{2\ no\ core}}$ $V_s \left(\frac{D_c}{D_o}\right)^2$ when the shallow diffuser was used as an outlet and 2 feet long cylinders were used as cores.

β_2 is based on the value of T_o used in Plate XIV.

Cores were extended 2 inches into the diffuser, i.e., within 2 inches of the fan.

PLATE XIII

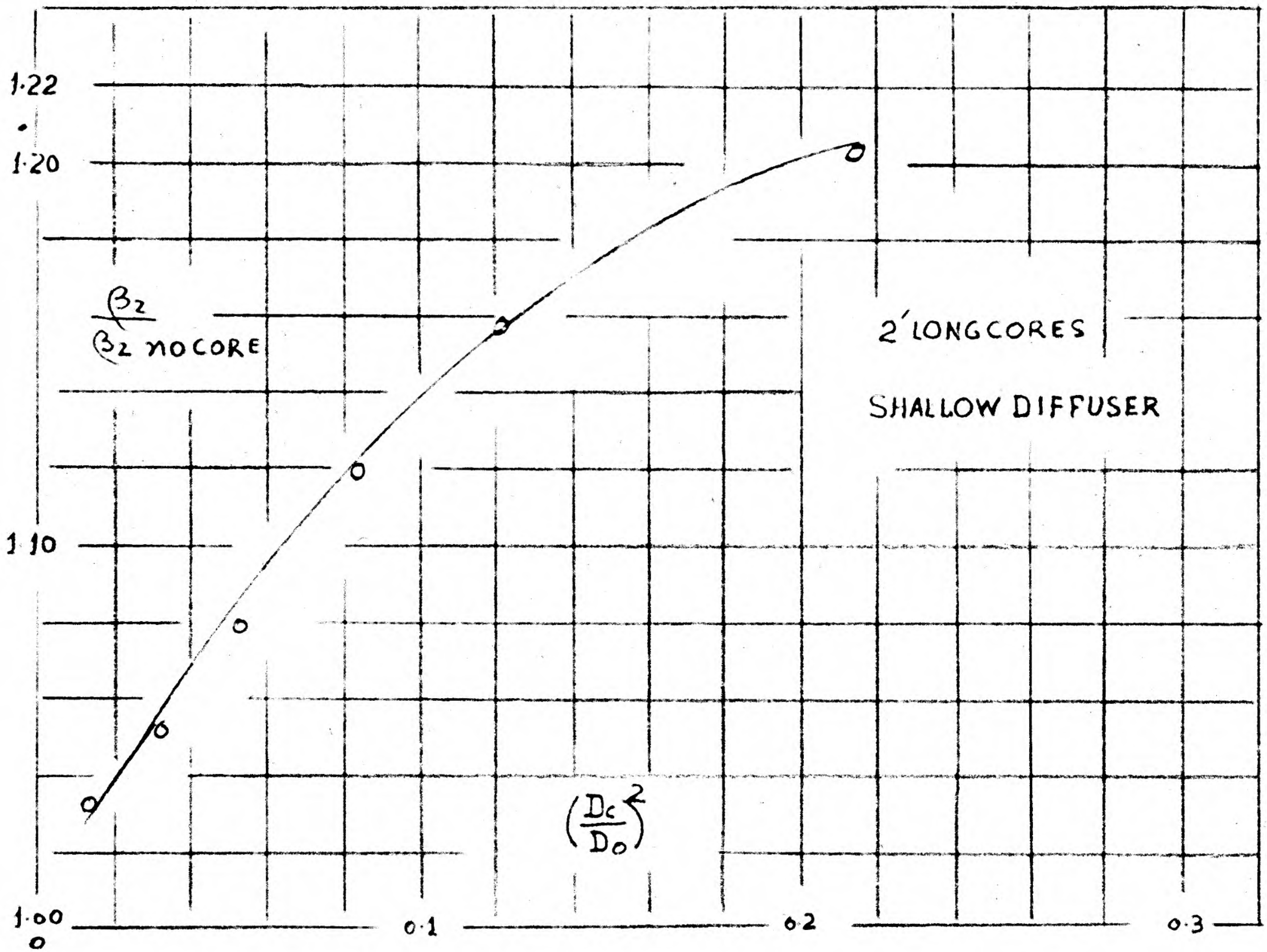
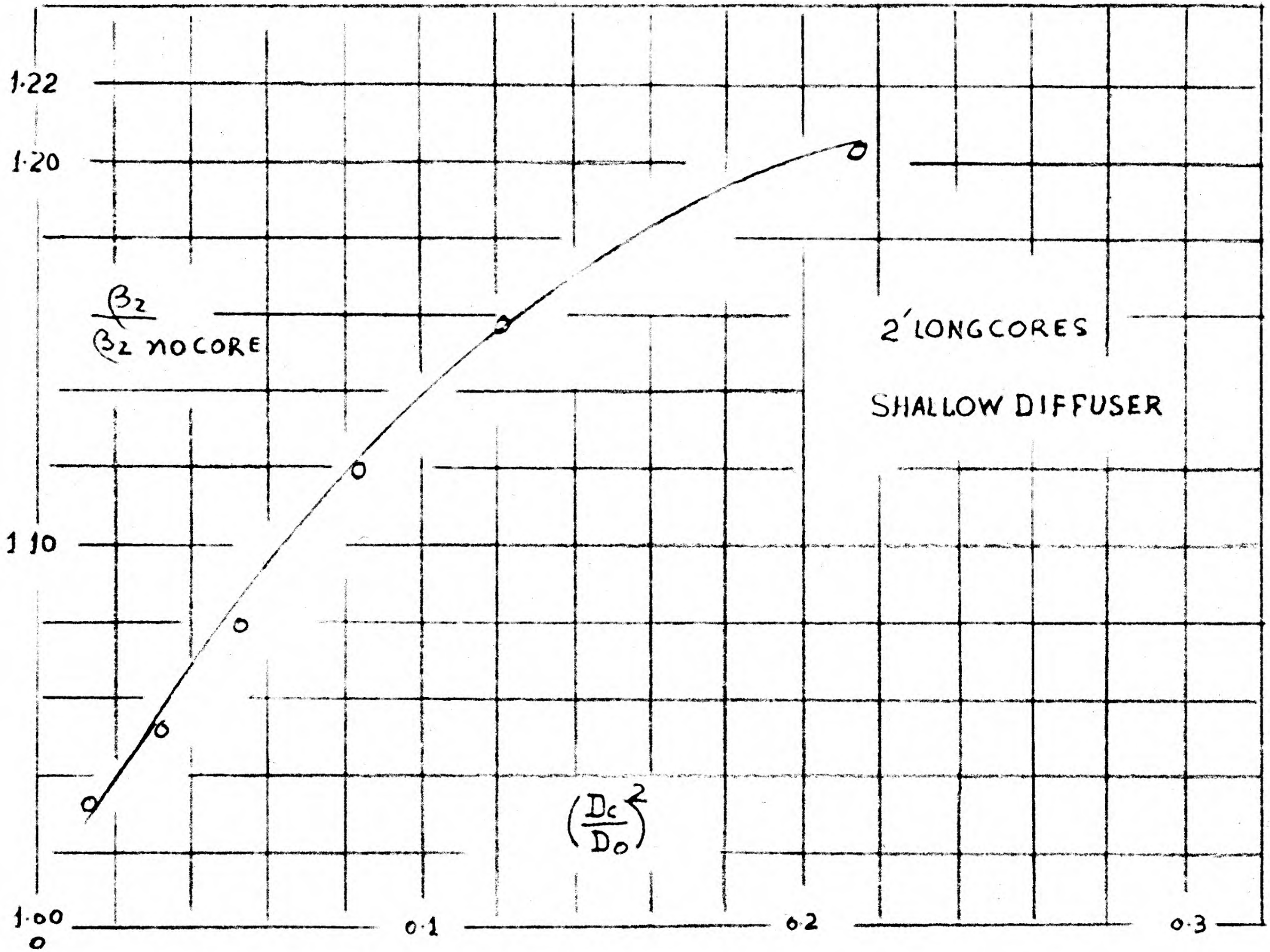

1.22
1.20
1.10
1.00
0
0.1
0.2
0.3
$\frac{\beta_2}{\beta_2 \text{ no core}}$
2' LONG CORES
SHALLOW DIFFUSER
$\left(\frac{D_c}{D_o}\right)^2$

PLATE XIII



1.22
1.20
1.10
1.00
0
0.1
0.2
0.3
$\frac{\beta_2}{\beta_2 \text{ no core}}$
$\left(\frac{D_c}{D_o}\right)^2$
2' LONG CORES
SHALLOW DIFFUSER

PLATE XIV

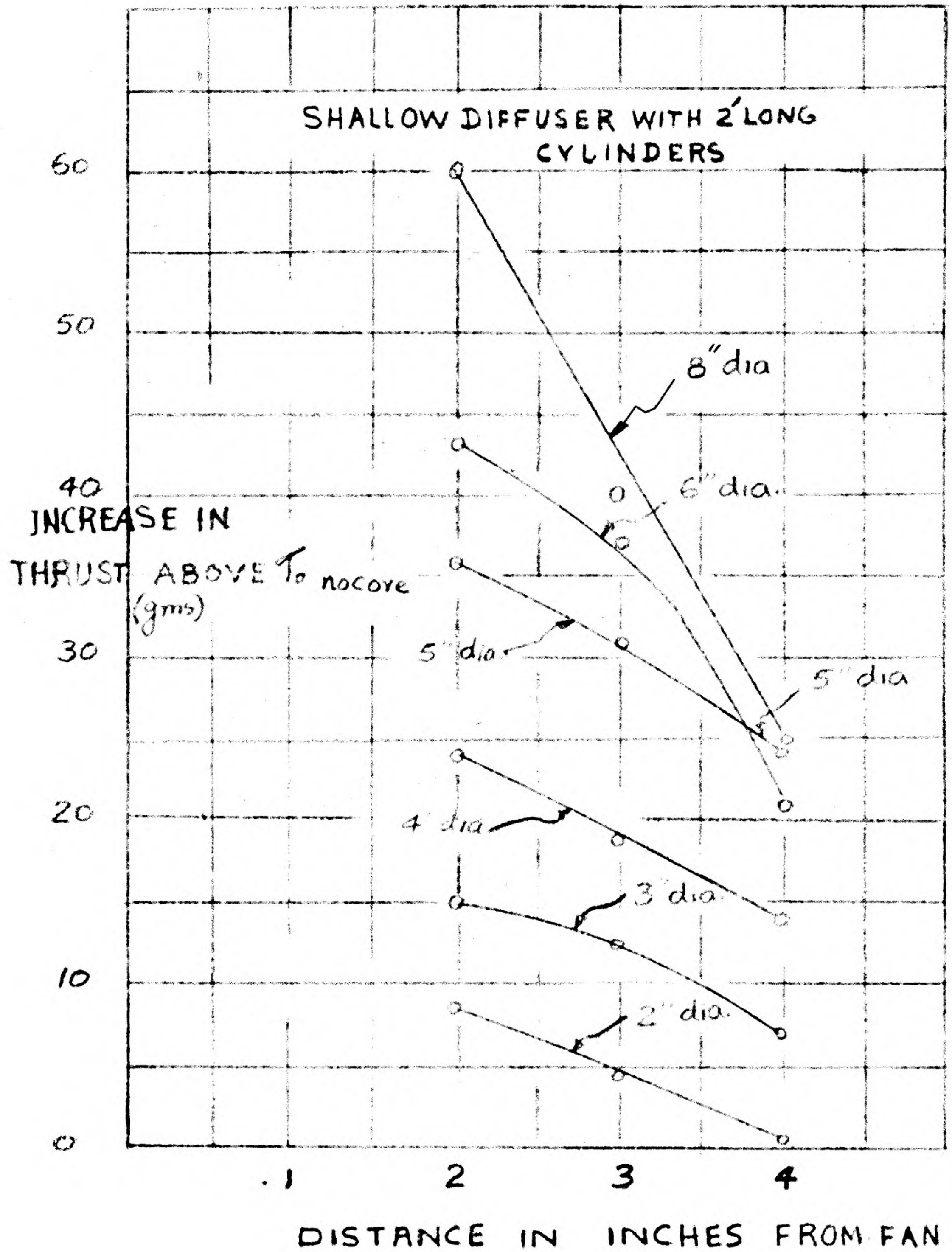

SHALLOW DIFFUSER WITH 2' LONG CYLINDERS
INCREASE IN THRUST ABOVE To nocore (gms)
DISTANCE IN INCHES FROM FAN
8" dia
6" dia
5" dia
5" dia
4" dia
3" dia
2" dia
60
50
40
30
20
10
0
.1
2
3
4

Table 2. Reduced outlet data for unit heater outlet using shallow diffuser and 2' long cores when cores extended axially 2" into the shallow diffuser, i.e., to within 2" of the fan.

$\frac{D_c}{D_o}$	Cores Used	$\frac{Q_o}{Q_o \text{ no core}}$	$\frac{T_o}{T_o \text{ no core}}$	$\frac{\beta_2}{\beta_2 \text{ no core}}$
0.215	8" diameter 2' long cylinder	0.990	1.179	1.202
0.121	6" diameter 2' long cylinder	0.992	1.137	1.157
0.0840	5" diameter 2' long cylinder	0.996	1.110	1.119
0.0538	4" diameter 2' long cylinder	0.996	1.069	1.078
0.0302	3" diameter 2' long cylinder	0.997	1.044	1.052
0.01346	2" diameter 2' long cylinder	0.997	1.025	1.032

pronounced only when:

$$0.236 < \frac{D_c}{D_o} < 0.463$$

The trend of the data would seem to indicate that beyond $\frac{D_c}{D_o} = 0.463$ the decrease in flow rate would be considerable and would offset the advantage of an increased thrust. This would be consistent with data on guide vanes, which previously were found to increase the thrust but decrease the flow rate. This was reported by Helander and associates (1956).

Case 3.

<u>Using 1 1/2' Long Cylindrical Cores With Deep Cylindrical Outlet And Shallow Diffuser.</u> Plate XV shows the plots between T_o/T_o no core $V_s \left(\frac{D_c}{D_o}\right)^2$, Q_o/Q_o no core $V_s\left(\frac{D_c}{D_o}\right)^2$ and $B_2/B2$ no core $V_s\left(\frac{D_c}{D_o}\right)^2$, for the deep cylindrical outlet.

The dimensionless ratios are also summarized in Table 3.

In Plate XV, length being the same, again the important factor under consideration was the diameter of the core. One can see from this plot of the increased thrust versus distance from the fan that the rate of change of thrust with distance from the fan was the more rapid as the diameter of the core was increased. For smaller values of $\frac{D_c}{D_o}$ the rate of change was more or less uniform. When values of $\left(\frac{D_c}{D_o}\right)^2$ lay between .0538 and .084 the change in thrust was not noticeable but the flow rate decreased sharply. This, in terms of $\frac{D_c}{D_o}$, corresponds to a range of 0.232 to 0.289. Increase in thrust was pronounced only when $0.374 > \frac{D_c}{D_o} > 0.289$.

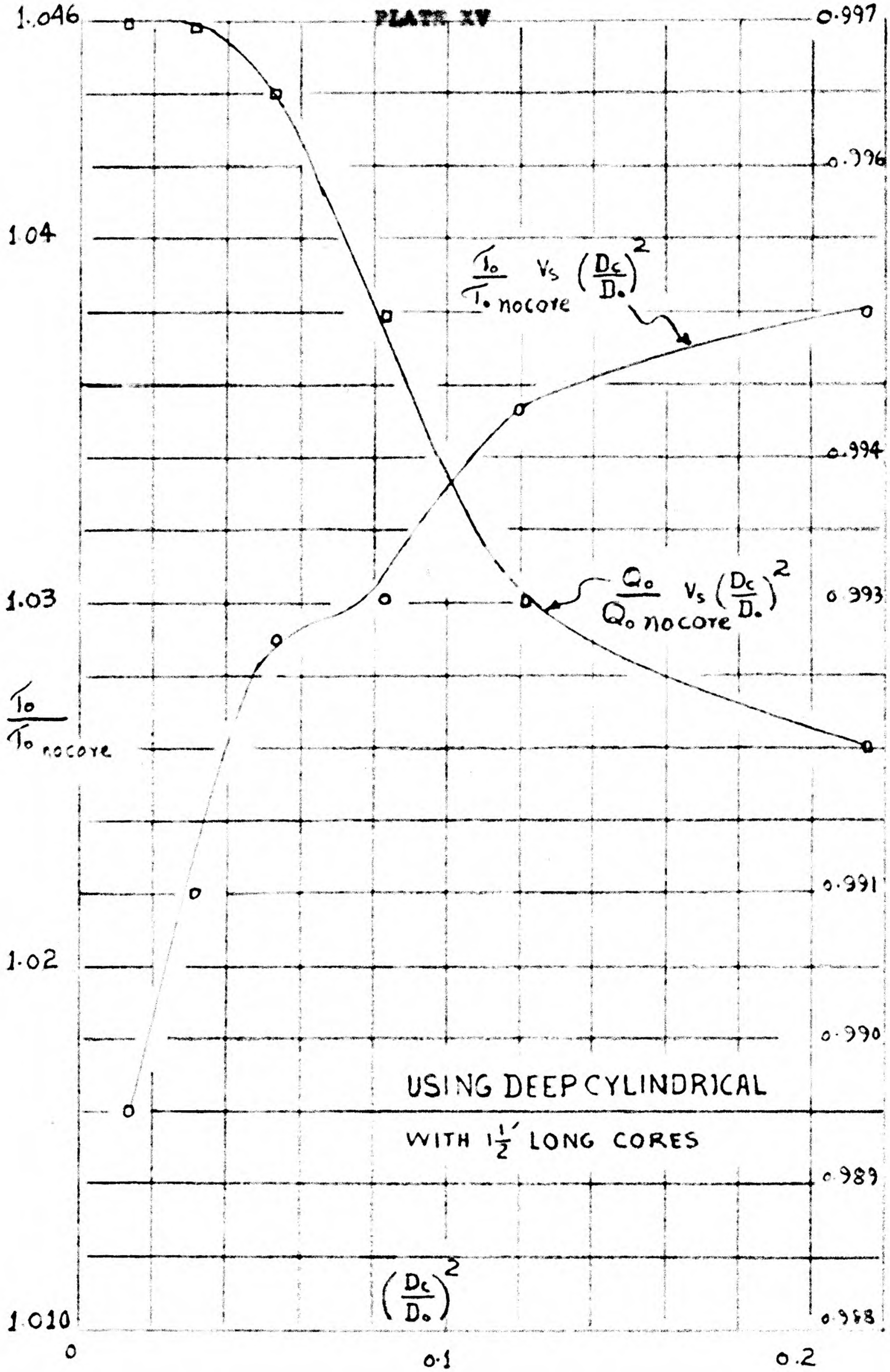
EXPLANATION OF PLATE XV

This plate shows the plot of $\frac{T_o}{T_{o\ no\ core}}$ $V_s\left(\frac{D_c}{D_o}\right)^2$ and $\frac{Q_o}{Q_{o\ no\ core}}$ $V_s\left(\frac{D_c}{D_o}\right)^2$ when the deep cylindrical outlet was used and when 1 1/2' long cylinders were used as cores.

This curve is based on the values of Q_o and T_o when cores extended axially 11" into the cylindrical outlet, i.e., 2" within the fan.

At this location T_o was a maximum for all cores.

PLATE XV



1.046
1.04
1.03
1.02
1.010
0.997
0.996
0.994
0.993
0.991
0.990
0.989
0.988
0
0.1
0.2
$\frac{T_o}{T_{o\ nocore}}$ Vs $\left(\frac{D_c}{D_o}\right)^2$
$\frac{Q_o}{Q_{o\ nocore}}$ Vs $\left(\frac{D_c}{D_o}\right)^2$
$\frac{T_o}{T_{o\ nocore}}$
$\left(\frac{D_c}{D_o}\right)^2$
USING DEEP CYLINDRICAL
WITH $1\frac{1}{2}'$ LONG CORES

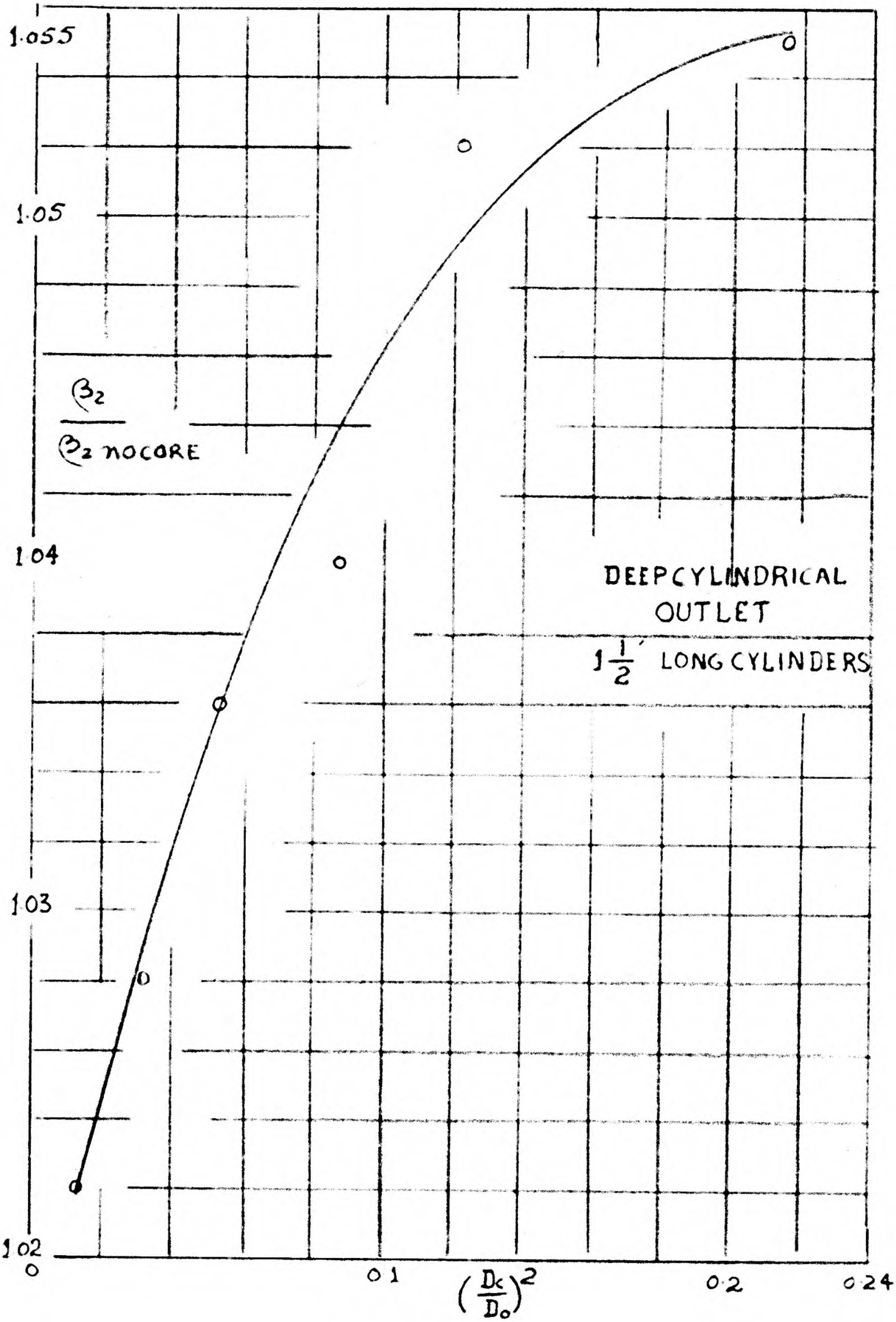
EXPLANATION OF PLATE XVI

This plate shows plot of $\frac{\beta 2}{\beta 2 \text{ no core}}$ $V_s \left(\frac{D_c}{D_o}\right)^2$ when the deep cylindrical outlet was used and 1 1/2' long cylinders were used as cores.

β_2 was based on T_o as used in Plate XV.

Cores were extended 11" into the outlet, i.e., within 2" of the fan.

PLATE XVI


1.055
1.05
1.04
1.03
1.02
$\frac{\beta_2}{\beta_2 \text{ no core}}$
DEEP CYLINDRICAL OUTLET
$1\frac{1}{2}'$ LONG CYLINDERS
0
0.1
0.2
0.24
$\left(\frac{D_c}{D_o}\right)^2$

EXPLANATION OF PLATE XVII

This plate shows the increase in thrust above To no core when the cores are placed axially inside the deep cylindrical outlet.

Increase in thrust above $T_{o\ no\ core}$ is shown plotted as a function of distance of the upstream core face from the fan; cores used in this test were 1 1/2' long cylinders of different diameters.

PLATE XVII

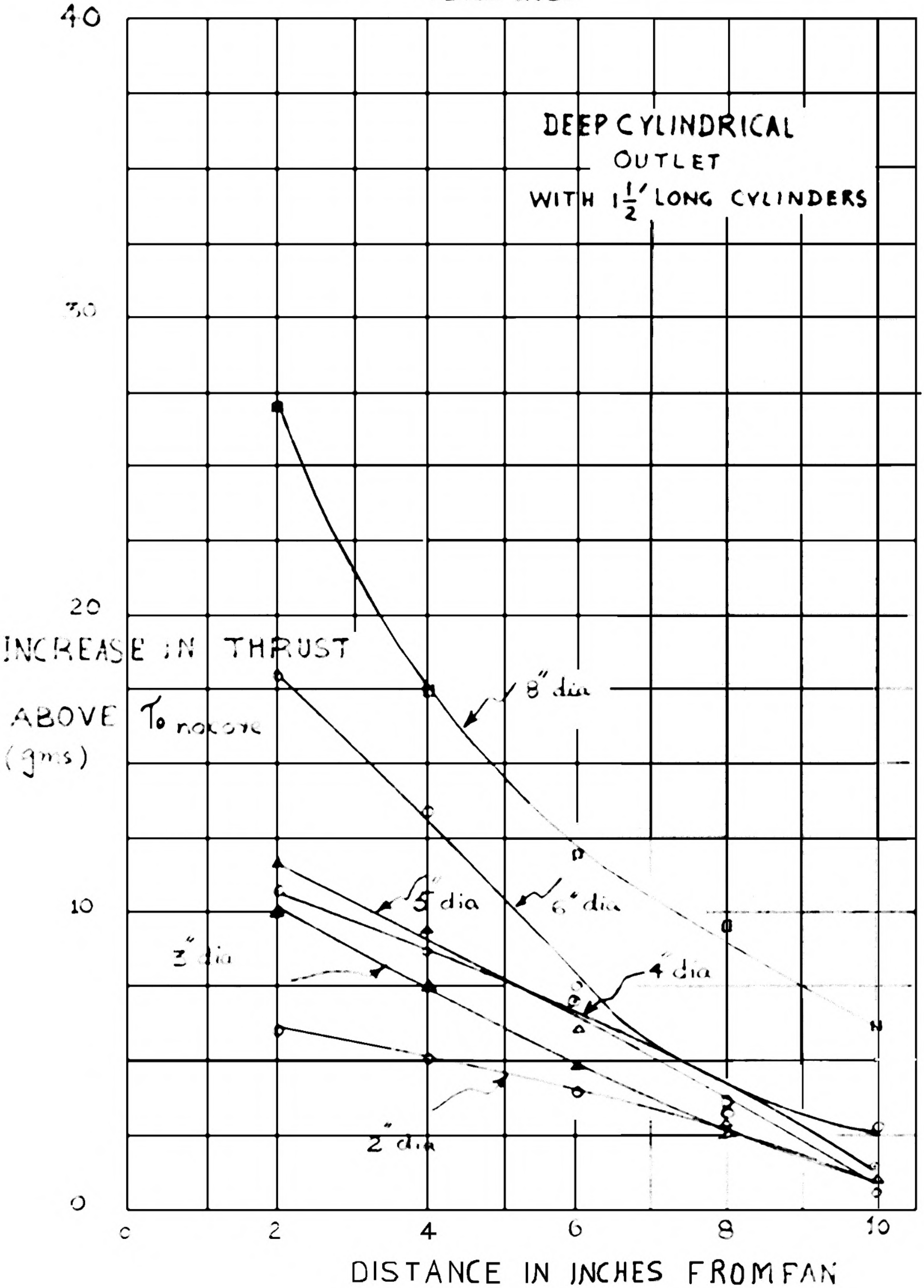

DEEP CYLINDRICAL
OUTLET
WITH 1 1/2' LONG CYLINDERS
40
30
20
10
0
INCREASE IN THRUST
ABOVE To nozzle
(gms)
8" dia
6" dia
5" dia
4" dia
3" dia
2" dia
0
2
4
6
8
10
DISTANCE IN INCHES FROM FAN

Table 3. Reduced outlet data for unit heater with deep cylindrical outlet using 1 1/2' long cores when extended axially 11" into deep cylindrical outlet, i.e., 2" from fan.

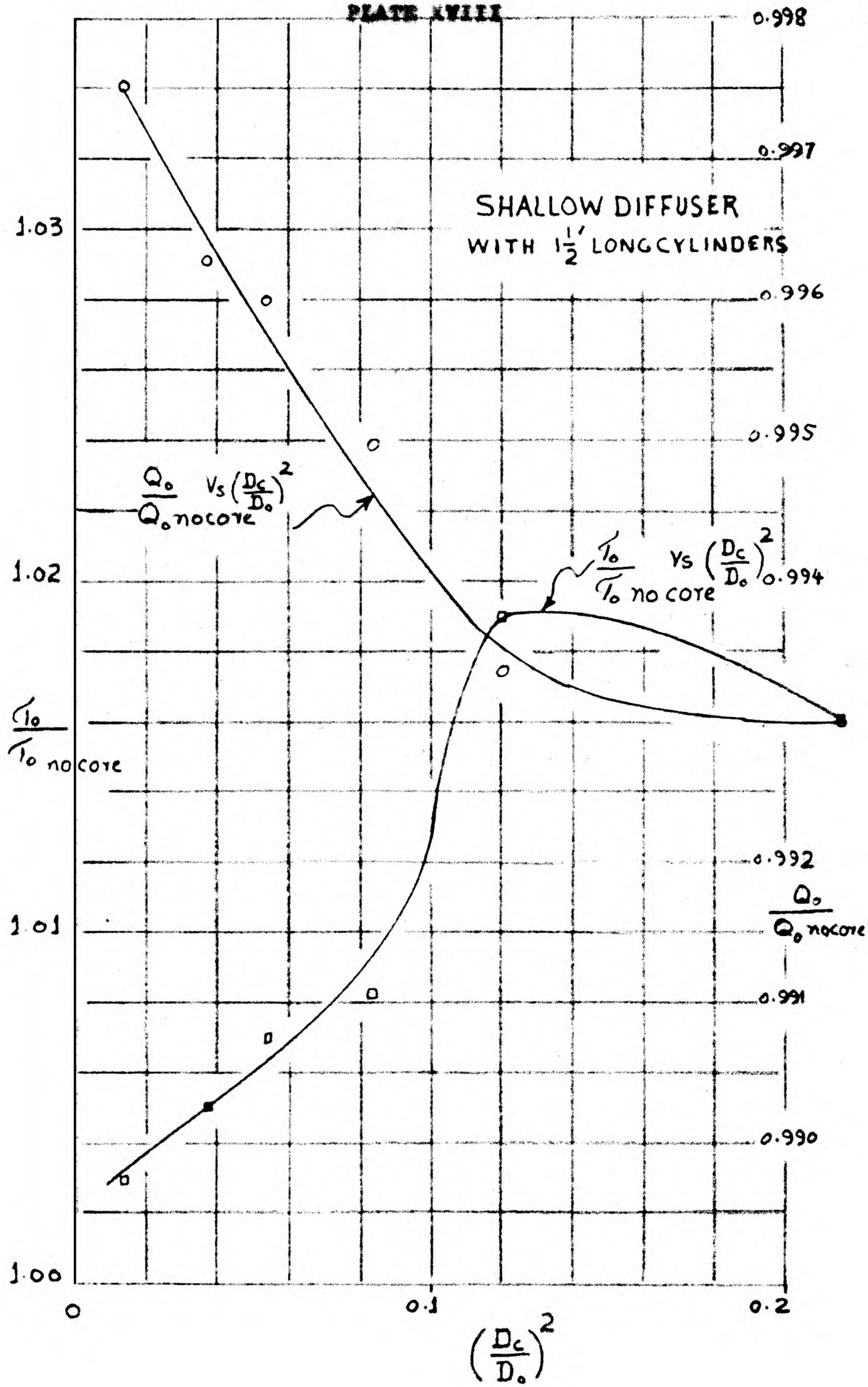
$\frac{D_c^2}{D_o}$	Cores Used	$\frac{Q_o}{Q_{o\ no\ core}}$	$\frac{T_o}{T_{o\ no\ core}}$	$\frac{\beta_2}{\beta_{2\ no\ core}}$
0.215	8" diameter 1 1/2' long cylinder	0.992	1.038	1.055
0.121	6" diameter 1 1/2' long cylinder	0.993	1.0355	1.052
0.0840	5" diameter 1 1/2' long cylinder	0.995	1.030	1.04
0.0538	4" diameter 1 1/2' long cylinder	0.9964	1.029	1.036
0.0302	3" diameter 1 1/2' long cylinder	0.997	1.022	1.028
0.01346	2" diameter 1 1/2' long cylinder	0.997	1.015	1.022

EXPLANATION OF PLATE XVIII

This plate shows the plot of $\frac{T_o}{T_{o\ no\ core}}$ Vs $\left(\frac{D_c}{D_o}\right)^2$ and $\frac{Q_o}{Q_{o\ no\ core}}$ Vs $\frac{D_c}{D_o}^2$ when the shallow diffuser was used as an outlet and when 1 1/2' long cylinders were used as cores.

This curve is based on the values of Q_o and T_o when cores extended axially 2" into the shallow diffuser, i.e., to within 2" of the fan.

At this location T_o was a maximum for all cores.



SHALLOW DIFFUSER
WITH 1½' LONGCYLINDERS
Qo / Qo nocore Vs (Dc/Do)^2
To / To no core Vs (Dc/Do)^2
To / To no core
Qo / Qo nocore
1.03
1.02
1.01
1.00
0.998
0.997
0.996
0.995
0.994
0.992
0.991
0.990
0
0.1
0.2
(Dc/Do)^2

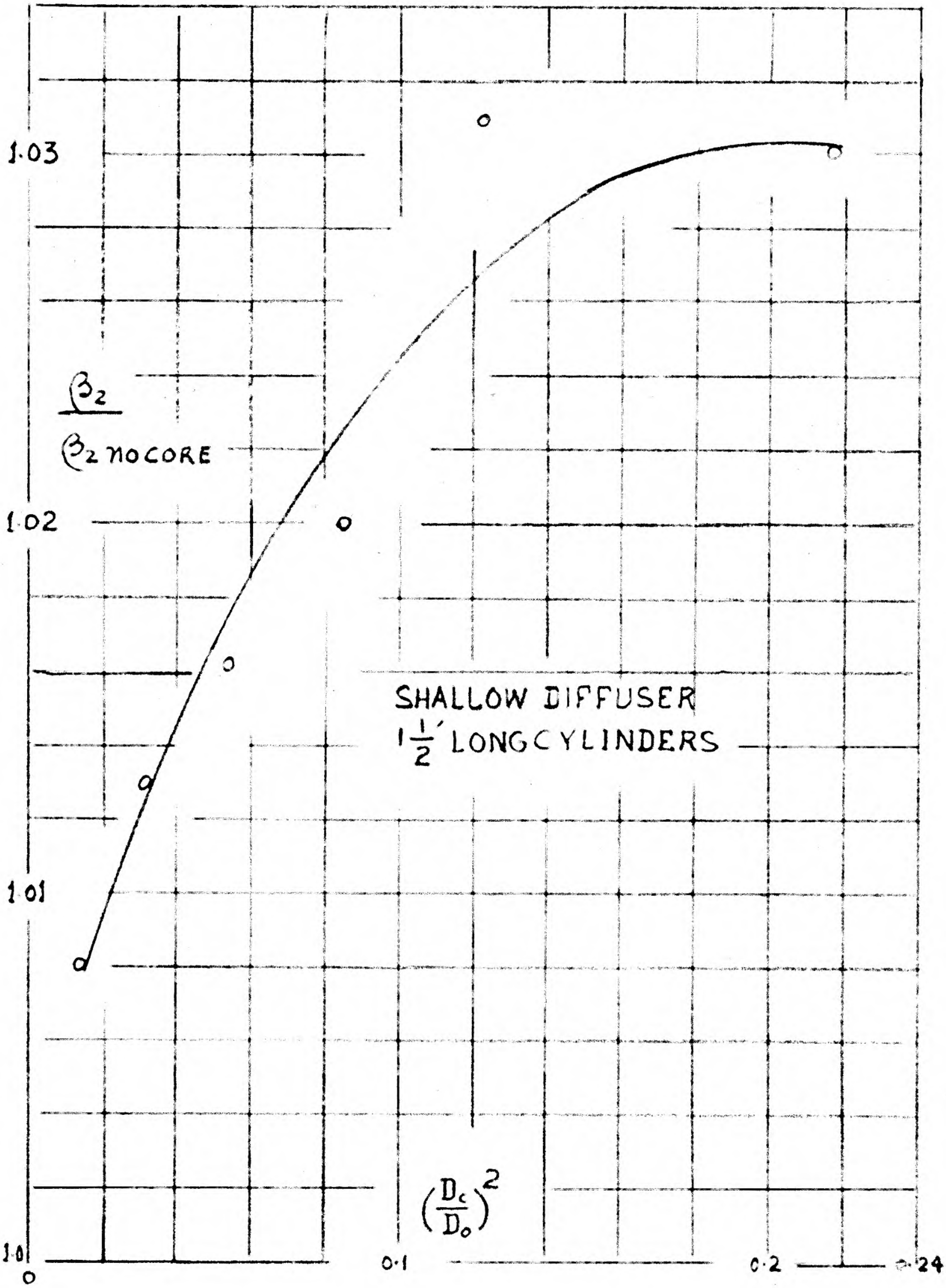
EXPLANATION OF PLATE XIX

This plate shows plot of $\frac{\beta_2}{\beta_{2\ \text{no core}}}$ $V_s \left(\frac{D_c}{D_o}\right)^2$ when the shallow diffuser was used as an outlet and 1 1/2' long cylinders were used as cores.

β_2 is based on To as used in Plate XVIII.

Cores were extended 2" into the diffuser, i.e., within 2" of the fan.

PLATE XIX


1.03
1.02
1.01
1.0
$\frac{\beta_2}{\beta_{2\ no\ core}}$
SHALLOW DIFFUSER
$1\frac{1}{2}'$ LONG CYLINDERS
$\left(\frac{D_c}{D_o}\right)^2$
0
0.1
0.2
0.24

EXPLANATION OF PLATE XX

This plate shows the increase in thrust above To no-core when the cores are axially placed inside the shallow diffuser outlet.

Increase in thrust above To no core is shown plotted as a function of distance of the upstream core, face from the fan.

PLATE XX

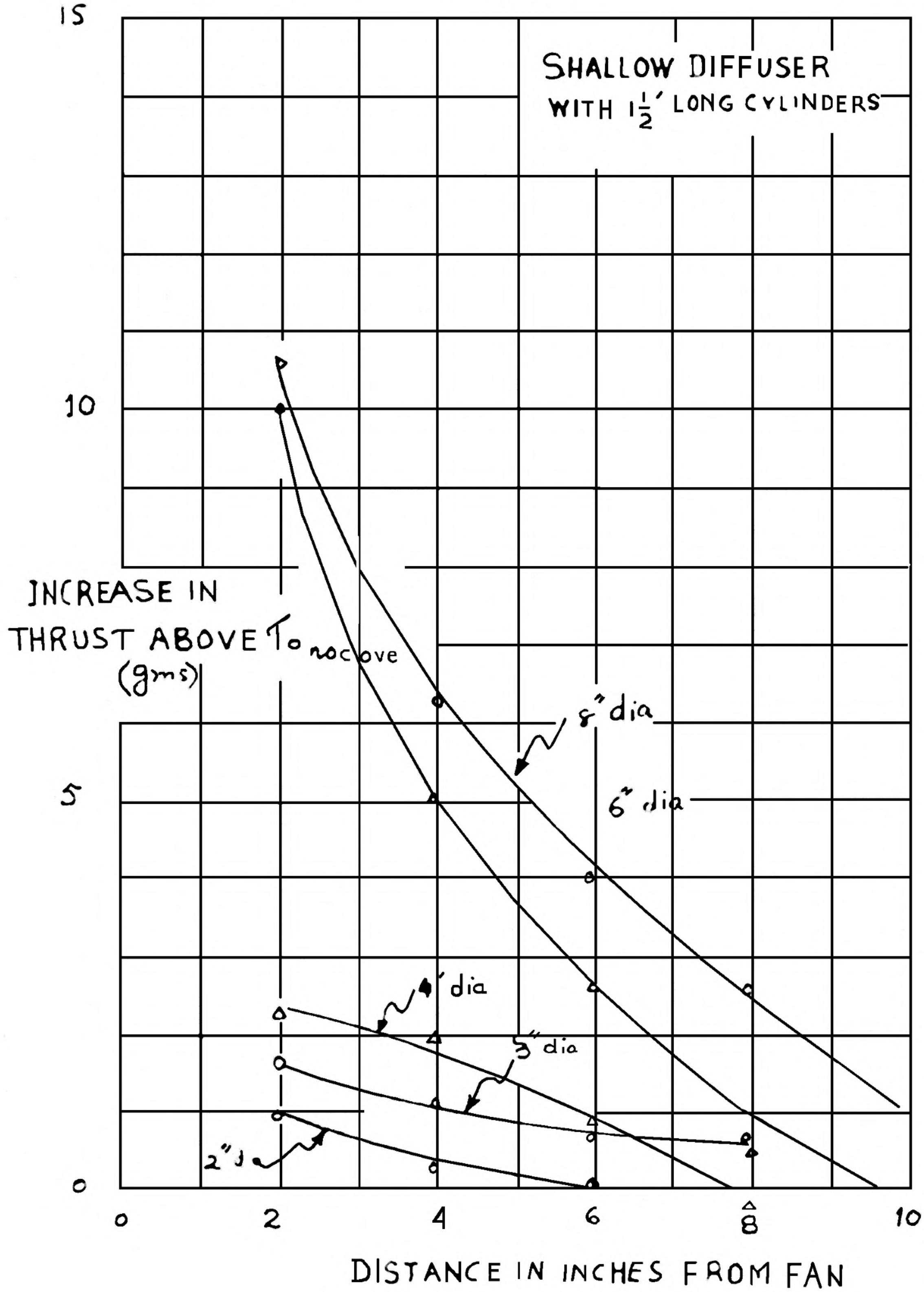

SHALLOW DIFFUSER
WITH $1\frac{1}{2}$' LONG CYLINDERS
15
10
5
0
INCREASE IN THRUST ABOVE To nozzle
(gms)
8" dia
6" dia
4" dia
3" dia
2" dia
0
2
4
6
8
10
DISTANCE IN INCHES FROM FAN

Table 4. Reduced outlet data on unit heater with shallow diffuser when 1 1/2' long cores were moved 2" inside the diffuser, i.e., 2" from the fan.

$\left(\frac{D_c}{D_o}\right)^2$	Cores Used	$\frac{Q_o}{Q_o \text{ no core}}$	$\frac{T_o}{T_o \text{ no core}}$	$\frac{\beta_2}{\beta_2 \text{ no core}}$
0.215	8" diameter 1 1/2' long cylinder	0.993	1.016	1.03
0.121	6" diameter 1 1/2' long cylinder	0.9933	1.019	1.031
0.0840	5" diameter 1 1/2' long cylinder	0.995	1.008	1.02
0.0538	4" diameter 1 1/2' long cylinder	0.996	1.007	1.016
0.0302	3" diameter 1 1/2' long cylinder	0.9963	1.005	1.013
0.01346	2" diameter 1 1/2' long cylinder	0.9975	1.003	1.008

For values of $\frac{D_c}{D_o}$ greater than 0.374 the flow rate decreased rapidly and offset the advantage due to increased thrust.

Plates XVIII and XIX show the plots for the shallow diffusor. The data for the diffuser are summarized in Table 4.

The behavior of the curves for the shallow diffusor is very much the same as that in the curves for cylindrical outlet, except that $T_c/T_{o\ no\ core}$ when plotted against $\left(\frac{D_c}{D_o}\right)^2$ increased until $\left(\frac{D_c}{D_o}\right)^2$ had a value of .121. There was no further increase in measured thrust for larger values of $\left(\frac{D_c}{D_o}\right)^2$. Instead, the curve showed a steadily decreasing rather than an increasing thrust. Furthermore, the flow rate and measured thrust ratio both decreased simultaneously. The useful zone corresponded to a range of $\left(\frac{D_c}{D_o}\right)^2$ between 0.084 to 0.121. Within this range maximum thrust for small decrease in flow rate was realized.

Case 4.

Stream Line Core Shapes With Deep Cylindrical Outlet and Shallow Diffuser. Results of some other core shapes used with shallow diffuser and deep cylindrical outlets are noted in Table 5 and 6. Of these four streamlined cores, two are of comparable size. It can be seen that both the egg shaped core and the small cylinder give almost the same values for the dimensionless ratios; therefore, they do not suggest any advantage in favor of streamlined bodies. The smaller egg shaped core caused less decrease in flow but it produced an increase in thrust small compared to that developed by a core of larger size. The thrust ratios $B_2/B_{2\ no\ core}$ for comparison are noted below:

B2/B2 no core with Streamlined Cores

	Shallow Diffuser	Deep Cylindrical Outlet
2' long cylinder	1.153	1.184
21" long core	1.076	1.110
1 1/2" long cylinder	1.033	1.053

Results for the 21 inches long cone are better than those for the 18 inch cylinder of the same face diameter. Much more data would be needed to prove or disprove the usefulness of this streamlined core over the cylinder of the same size.

Thrust characteristics with cylinders are almost as good or better than with the streamline bodies reported herein.

Any body with a smooth surface that fills most of the volume containing negative pressure would probably prove satisfactory.

Frictional drag will most probably be the deciding factor in the selection of a core. In streamlined bodies, although the pressure drag would be low, frictional drag might be large because a stream lined body having the same diameter as a cylinder would have to be much longer than the cylinder to fill the same volume.

The economic point of view might be a decisive factor in selection of final shape with everything else being the same. Based on present information, it seems the cylinder is a suitable core shape to use.

Effect of Cores on Angle of Spread

Case 1.

<u>Shallow Diffuser</u>. Plate XXV shows the velocity profiles taken from the shallow diffuser with and without core. The cores used were a 2 feet long, 6 inches diameter cylinder which, of all the cores tested, gave the maximum measured thrust and a 6 inch face diameter streamlined cone 21 inches long.

When no core was used, for two to three outlet diameters downstream from the outlet, the jet came out like a partly opened umbrella. Going farther downstream the angle of spread was almost constant. Here half the angle of spread was about sixteen to seventeen degrees, defined as the slope of the ray over which the local velocity was 1/2 the axial velocity. After eight to nine outlet diameters the angle of spread started decreasing.

On the curve showing velocity profile with cores in the diffuser, the angle of spread was uniform. For two to three outlet diameters downstream from the outlet, the angle of spread with core in the diffuser was more than the corresponding angle of spread when no core was employed. Farther downstream the angle of spread was same with and without the core, i.e., between sixteen and seventeen degrees.

The angle of spread, with core, decreased after eight to nine outlet diameters downstream. From here on, the spread could be determined from velocity readings, based on half the maximum velocity, as readings were more or less uniform.

The region beyond eight to nine outlet diameters was highly turbulent and better instrumentation is needed to explore into

EXPLANATION OF PLATE XXI

This plate shows the increase in thrust above $T_{o\ no-core}$ when the cores are placed axially inside the deep cylindrical outlet.

Increase in thrust above $T_{o\ no\ core}$ is shown plotted as a function of distance of the upstream face of core from the fan.

Cores used in this test include:

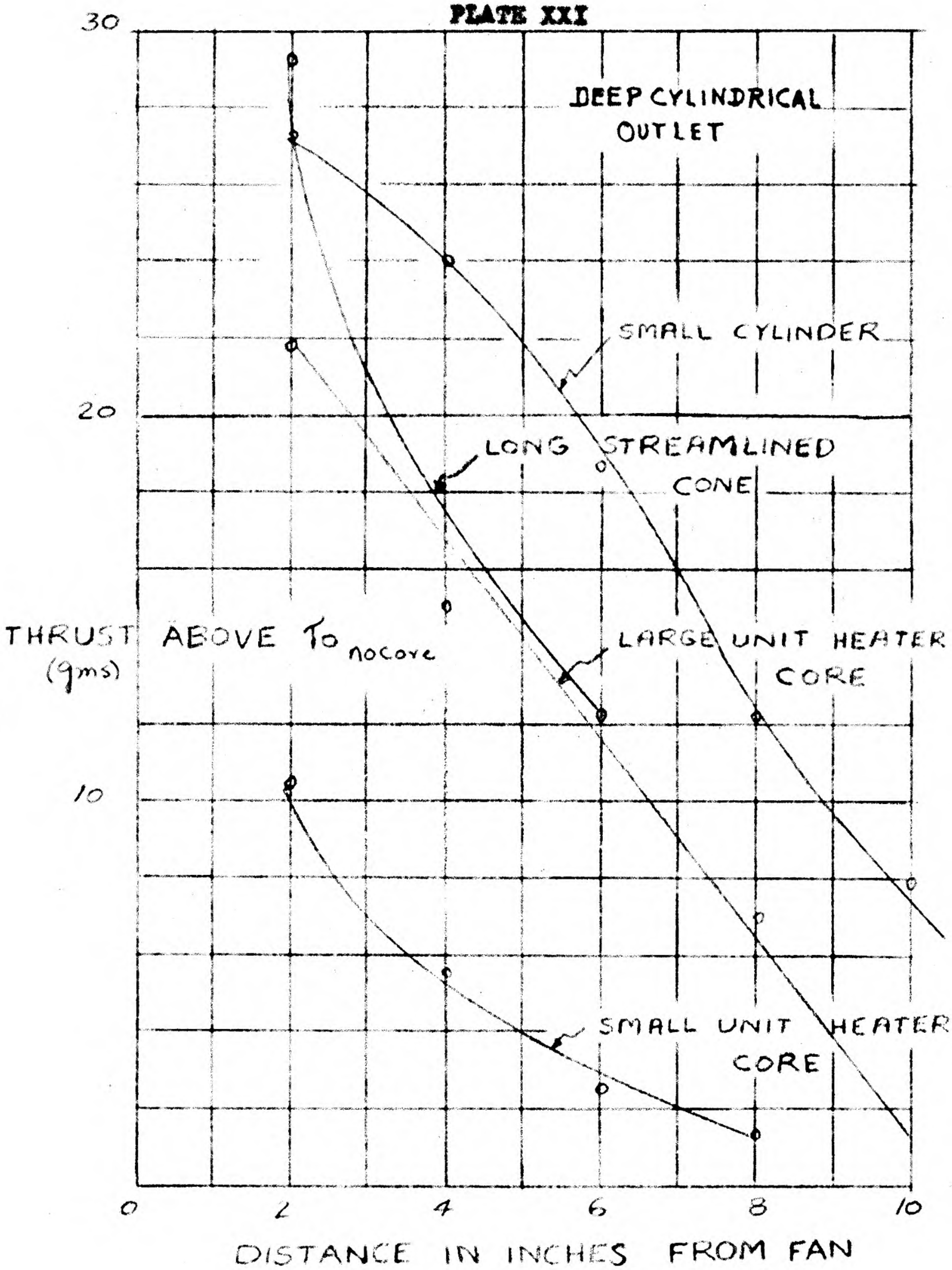
(1) a 6" diameter 1' long cylinder (small cylinder)

(2) a streamlined cone 6" diameter and 21" long (long streamlined cone)

(3) a large unit heater core 6" diameter and 11 1/2" long

(4) a small unit heater 4 1/8" diameter and 8 1/2" long

PLATE XXI


30
20
10
0
2
4
6
8
10
DEEP CYLINDRICAL
OUTLET
SMALL CYLINDER
LONG STREAMLINED
CONE
LARGE UNIT HEATER
CORE
SMALL UNIT HEATER
CORE
THRUST ABOVE To no core
(gms)
DISTANCE IN INCHES FROM FAN

EXPLANATION OF PLATE XXII

This plate shows the increase in thrust above To no core when the cores are placed axially inside the shallow diffuser outlet.

Increase in thrust above T_o no core is shown plotted as a function of distance of the core from the fan.

Cores used in this test include:

(1) a 6" diameter, 1' long cylinder (small cylinder)

(2) a streamlined core 6" diameter and 21" long (large streamlined core)

(3) a large unit heater core 6" diameter, 11 1/2" long (large unit heater core)

(4) a small unit heater 4 1/8" diameter, 8 1/2" long (small unit heater core)

PLATE XXII

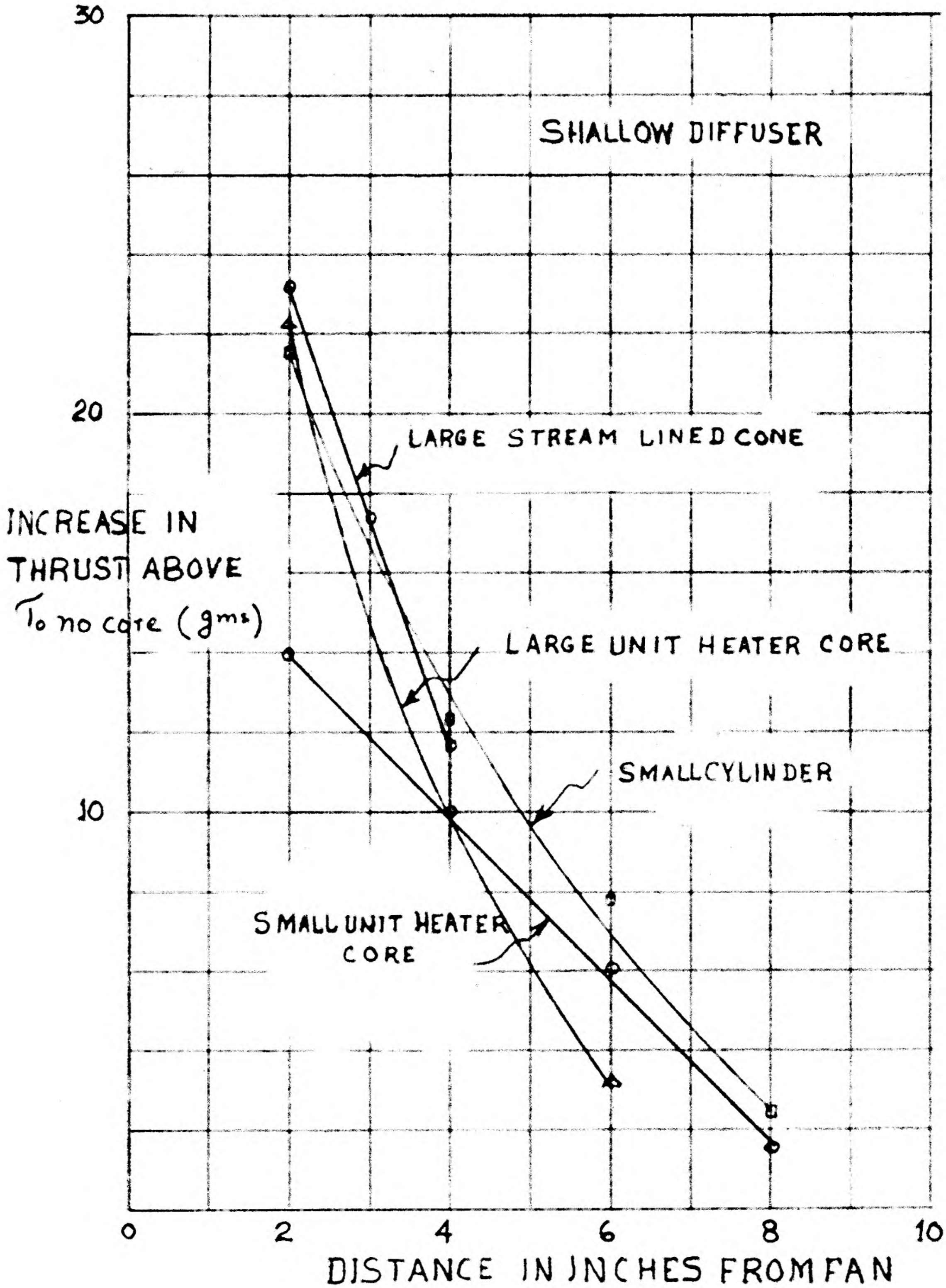

30
20
10
0
2
4
6
8
10
SHALLOW DIFFUSER
LARGE STREAM LINED CONE
INCREASE IN THRUST ABOVE To no core (gms)
LARGE UNIT HEATER CORE
SMALLCYLINDER
SMALL UNIT HEATER CORE
DISTANCE IN INCHES FROM FAN

Table 5. Outlet data on unit heater with shallow diffuser outlet when cores were placed axially 2" inside the diffuser, i.e., 2" from the fan.

$\frac{D_c}{D_o}$	Cores Used	Shape of Cores	$\frac{Q_o}{Q_{o\ \text{no core}}}$	$\frac{T_o}{T_{o\ \text{no core}}}$	$\frac{\beta_2}{\beta_{2\ \text{no core}}}$
0.0586	Small unit heater core	8 1/2 " long	0.9973	1.057	1.064
0.121	Large unit heater core	11 1/2" long	0.9966	1.081	1.088
0.121	Small cylinder	12" long	0.995	1.082	1.091
0.121	Long stream-lined cone	21" long	0.983	1.076	1.088

Table 6. Outlet data on unit heater with deep cylindrical outlet when cores were placed axially 11" inside the deep cylindrical outlet, i.e., 2" from the fan.

$\frac{D_c 2}{D_o}$	Cores Used	Shape of Cores	$\frac{Q_o}{Q_o \text{ no core}}$	$\frac{T_o}{T_o \text{ no core}}$	$\frac{\beta_2}{\beta_2 \text{ no core}}$
0.0586	Small unit heater core	8 1/2" long	0.997	1.037	1.043
0.121	Large unit heater core	11 1/2" long	0.990	1.104	1.124
0.121	Small cylinder	12" long	0.991	1.084	1.102
0.121	Long stream-lined cone	21" long	0.991	1.111	1.13

this region. Plate XXIII shows the pictures taken of the jet profile made visible by the smoke bomb technique (Nottage, 1952). The angle of spread measured from these pictures checks well with the angle of spread determined by velocity profile method shown in Plate XXVI. Compared to angle of spread of 16-17 degrees of the mediam velocity ray $\frac{V}{Vc} = 1/2$ reported herein, an angle of 16 degrees was reported earlier in papers by Helander and associates (1956).

Case 2.

Deep Cylindrical Outlet. Plate XXV shows the velocity profiles at various distances downstream with core (2 feet long cylinder, 6 inches diameter) placed axially inside the deep cylindrical outlet. Also shown in this plate are the profiles at various distances downstream when no core was used. From the velocity profiles as shown in this plate, the point of half the maximum velocity was located for each profile. The locus of all these prints gave the approximate angle of spread.

This, when compared with pictures of the jet made visible by smoke gave almost identical values. The angle of spread (determined by the locus of mediam velocities) when no core was used was approximately 15 degrees at the outlet. Angle of spread increased downstream. At about 3 feet downstream the angle was 19 degrees.

The angle constantly increased between 3 feet to 8 feet downstream. The range was from 19 degrees to 28 degrees.

After 7 feet to 8 feet downstream the angle decreased and at 10 feet downstream it was noted to be 16 degrees again. From here on, it was difficult to determine the angle of spread because of turbulence.

When streamlined core and long cylinder were used, the jet tended to converge around the cores and the angle at outlet was only 9 degrees. Two feet to three feet downstream the angle was about 16 degrees to 17 degrees. This angle was almost constant until about 9 feet downstream when the angle started to decrease slightly. Streamlined core gave same angle of spread as the long cylinder.

Effect of Cores on Whirl

The jets were allowed to come out of the outlets mentioned in the foregoing discussion. Smoke puffs were introduced at the boundary of the jet and a viewer could see the smoke travel in almost an elliptical path and notice roughly the angular speed of the smoke. This rotation of smoke, which is present due to whirl, can also be noticed with a regular smoke test. When the core was introduced and same procedure was repeated, the rotation seemed to have been slowed down considerably. This indicated that cores tend to reduce whirl and thus increase the axial component of flow. The straightening effect of cores was discussed while discussing the thrust characteristics of long cores. This effect also accounts for the decrease in whirl as noticed above.

It may be stated here that the core was not intended to destroy negative pressure completely. (Without negative pressure, the jet would split at the outlet like an umbrella.) A zone of negative pressure has value in limiting the angle of spread and keeping the jet together.

SUMMARY OF TEST RESULTS

From the results presented in the foregoing paragraphs it is clear that as the diameter of core increases the measured thrust increases and flow decreases.

The relative thrust B_2 also increases with increase in diameter. Between $a\left(\frac{D_c}{D_o}\right)^2$ range of .054 to 0.121 the maximum increase in measured thrust as well as relative thrust ratios is realized. Change in flow rate in this range is also less significant. From there data it seems probably that the best core diameters to use would be in the $\frac{D_c}{D_o}$ range of 0.289 to 0.374.

From the measured thrust and relative thrust values of 2 feet long core in comparison to 1 1/2 feet long cores it can be seen clearly that the increased length had considerable effect on thrust values. T_o increased with length when diameter was kept the same. $T_o/T_{o\ \text{no core}}$ also had a better value with the longer cores. This, of course, is true only for a certain range outside which increase in thrust caused by a decrease in negative pressure region would be nullified by the frictional drag due to increase in surface area.

It was noticed that change in angle of spread with cores

EXPLANATION OF PLATE XXIII

Shows spread of the jet with shallow diffuser as outlet

Fig. 1.

Reference numbers

(1) Front wall of plenum chamber

(2) Shallow Diffuser

(3) The frame used to support the cores.

Fig. 2.

Reference numbers

(1) Shallow Diffuser

(2) Cylindrical Core

(3) Frame used to support the core.

PLATE XXIII

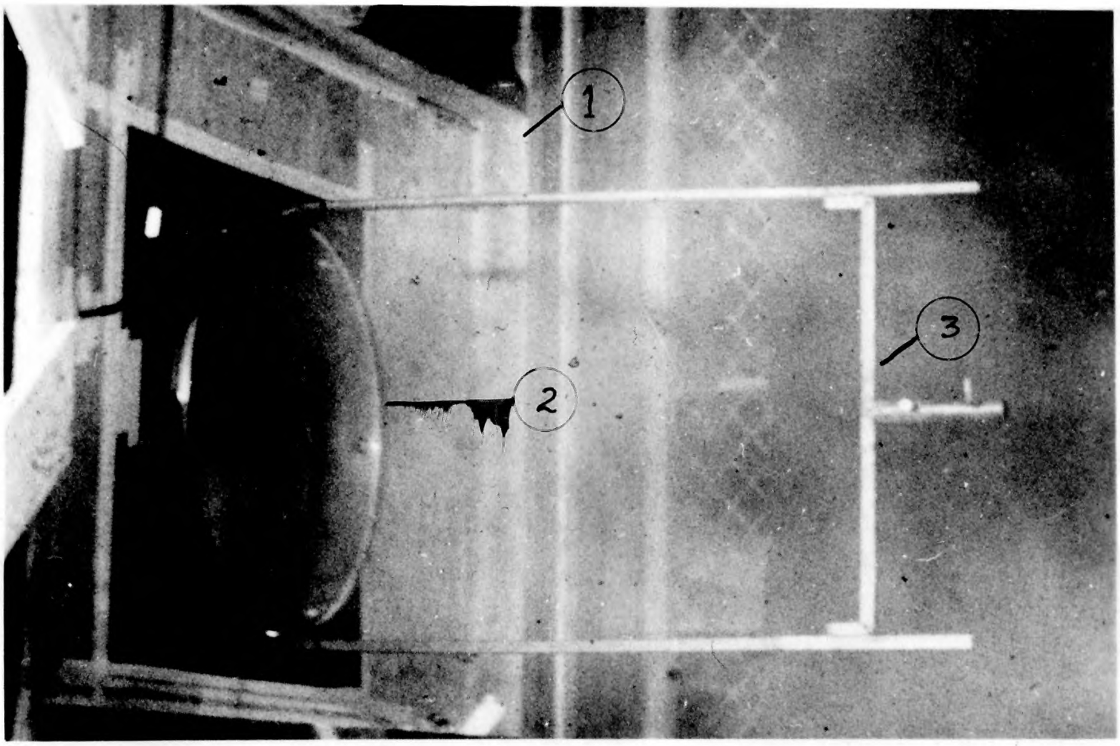


Fig. 1

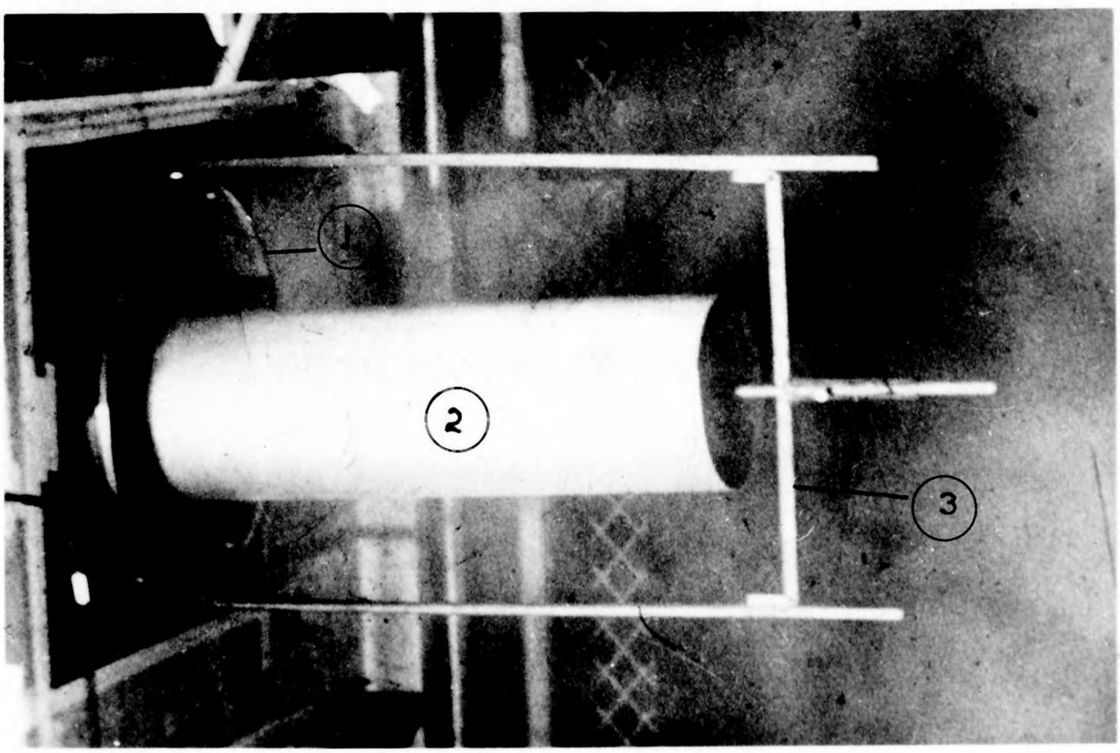


Fig. 2

EXPLANATION OF PLATE XXIV

Shows spread of the jet made visible by smoke when deep cylindrical outlet was used.

Fig. 1.

Reference numbers

(1) Deep cylindrical outlet

(2) Front wall of plenum chamber

(3) Frame for supporting cores

Fig. 2.

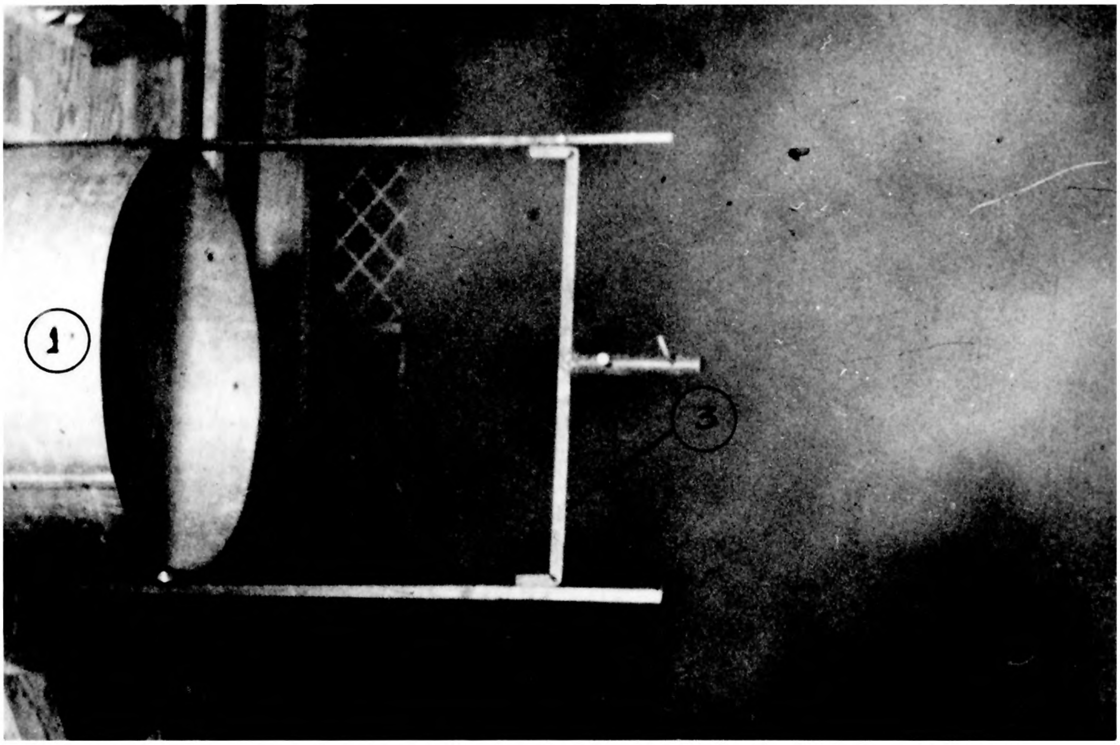
Reference numbers

(1) The front wall of plenum chamber

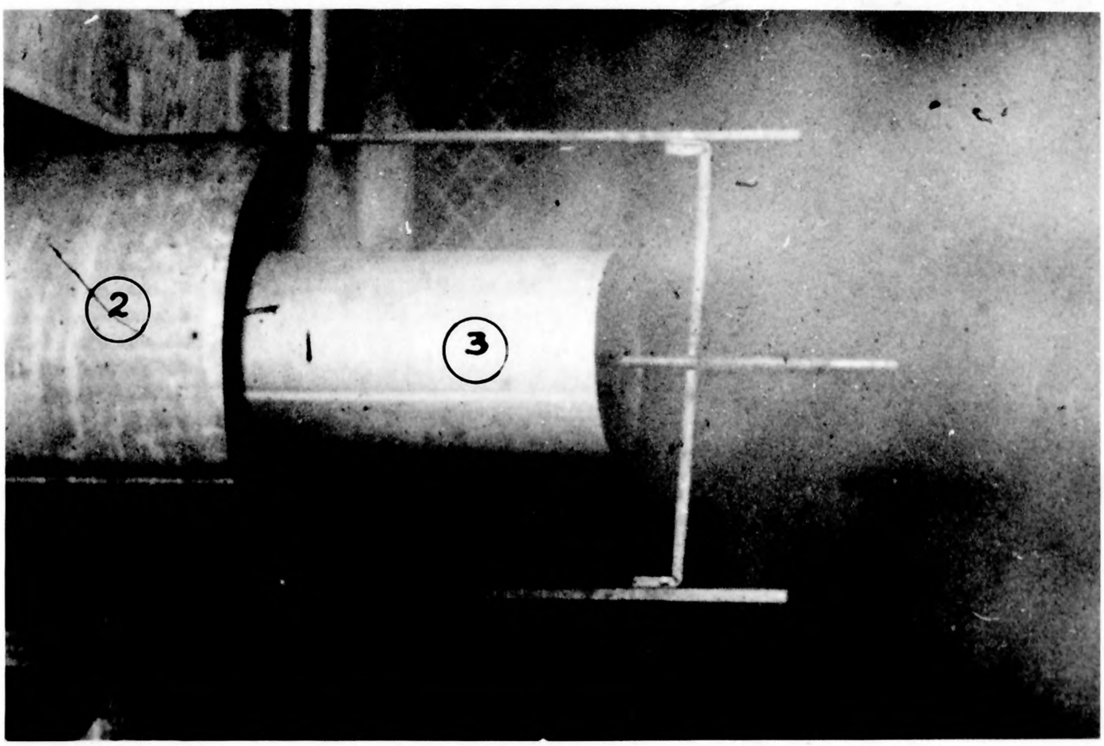
(2) Deep cylindrical outlet

(3) Cylindrical core

PLATE XXIV



Figs. 1



Figs. 2

EXPLANATION OF PLATE XXV

Angle of Spread

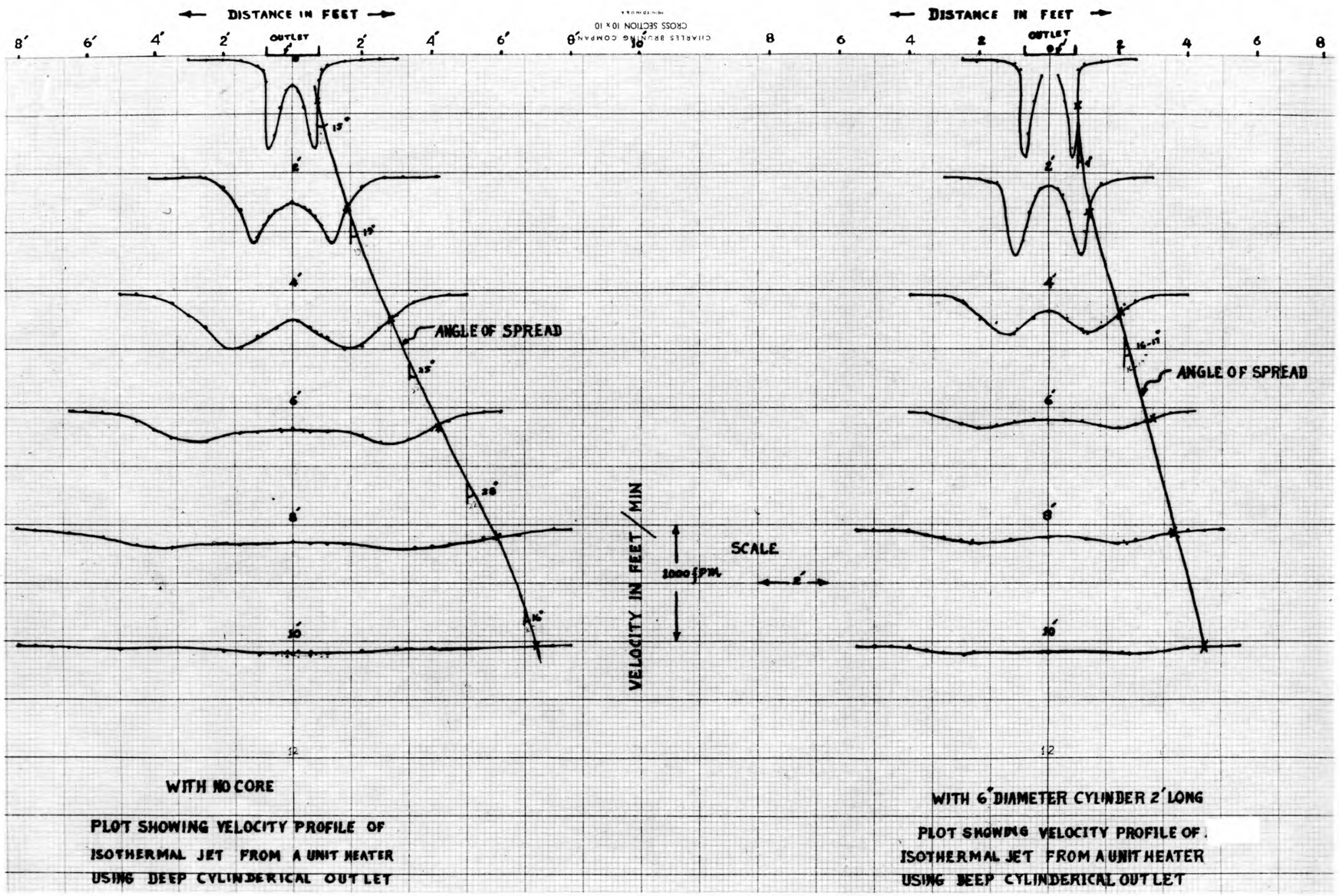
A. This plate shows the velocity profile of the jet when deep cylindrical outlet was used with no core.

Velocity profiles are shown at various distances downstream. Angle of spread determined on the basis of half the maximum velocity is shown on the curve.

B. This plate shows the velocity profile of the jet when deep cylindrical outlet was used and a 2' long cylinder (6" diameter) was used as a core.

Velocity profiles are shown at various distances downstream. Angle of spread determined on basis of half the maximum velocity is shown on the curve.

PLATE XXV


DISTANCE IN FEET
OUTLET
ANGLE OF SPREAD
VELOCITY IN FEET/MIN
1000 FPM
SCALE
WITH NO CORE
PLOT SHOWING VELOCITY PROFILE OF
ISOTHERMAL JET FROM A UNIT HEATER
USING DEEP CYLINDERICAL OUTLET
WITH 6" DIAMETER CYLINDER 2' LONG
PLOT SHOWING VELOCITY PROFILE OF
ISOTHERMAL JET FROM A UNIT HEATER
USING DEEP CYLINDERICAL OUTLET

EXPLANATION OF PLATE XXVI

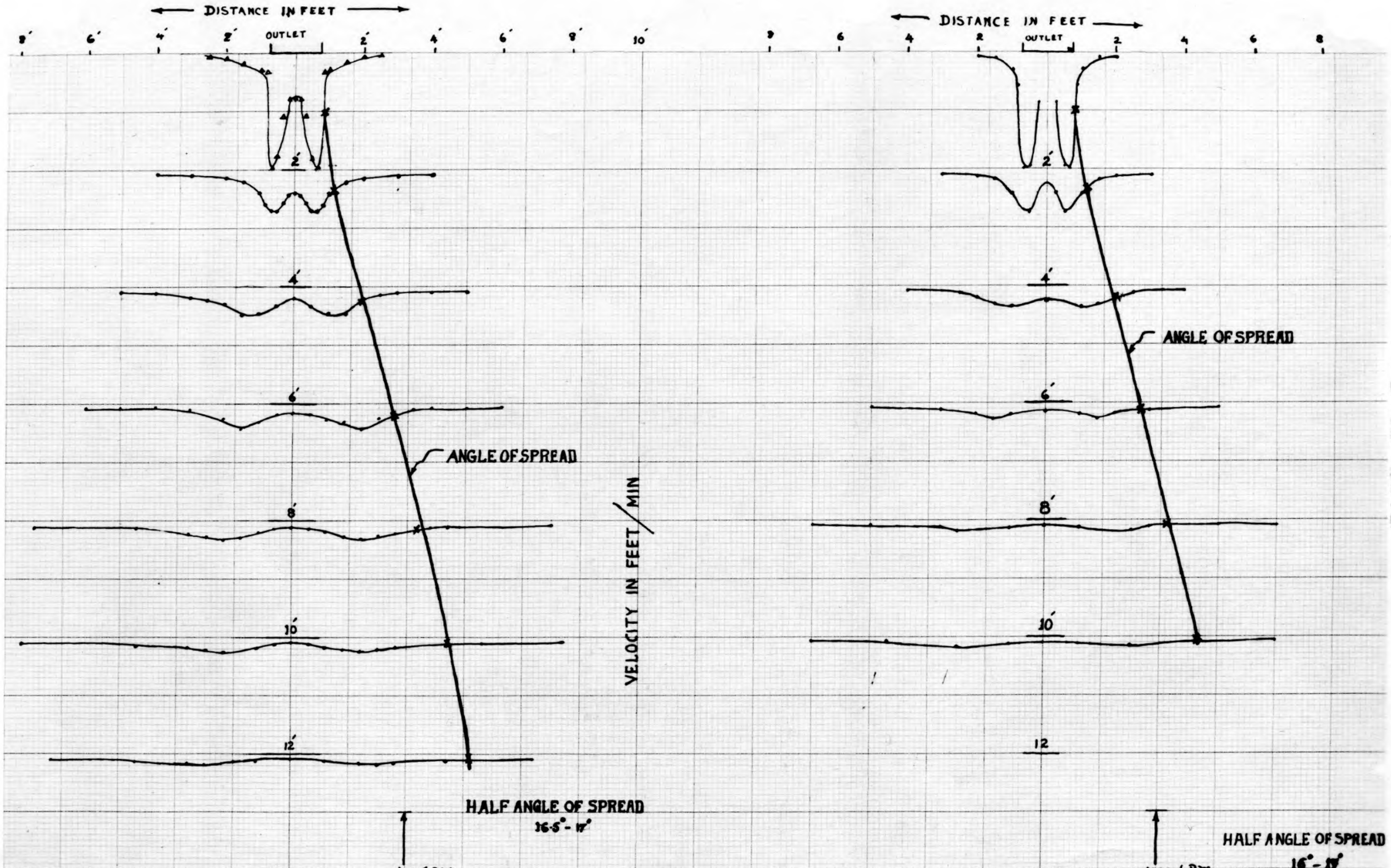
Angle of Spread

A. This plate shows the velocity profile of the jet when shallow diffuser outlet was used with no core.

Velocity profiles are shown at various distances downstream. Angle of spread determined on the basis of half the maximum velocity is shown on the curve.

B. This plate shows the velocity profile of the jet when shallow diffuser outlet was used and a 2' long cylinder (6" diameter) was used as a core.

Velocity profiles are shown at various distances downstream. Angle of spread determined on basis of half the maximum velocity is shown on the curve.



WITH NO CORE

PLOT SHOWING VELOCITY PROFILES OF ISOTHERMAL JET FROM A UNIT HEATER USING SHALLOW DIFFUSER AS OUTLET

WITH 6″ DIA CYLINDER 2′ LONG

PLOT SHOWING VELOCITY PROFILES OF ISOTHERMAL JET FROM A UNIT HEATER USING SHALLOW DIFFUSER AS OUTLET

PLATE XXVI

was only noticeable up to 2 to 3 out diameters downstream. In the principal zone the angle remained unchanged. Beyond 8 to 9 outlet diameters the stream was highly turbulent and angle of spread could not be determined graphically for lack of better instrumentation.

With large cores, the optimum value of the measured thrust was almost 14.2 per cent greater than the thrust with no core. The corresponding decrease in flow rate was always less than 2 per cent. The decrease of flow rate outside the range of optimum thrust was as high as 5 per cent.

CONCLUSIONS AND RECOMMENDATIONS

To the knowledge of the author, there is nothing in literature to suggest that work with the purpose of present research has been undertaken before. As the result of experiments with about thirty different cores and some 400 readings, it has been established that thrust can be significantly increased by introducing cores with $\frac{D_c}{D_o}$ ratio in the suggested range whenever a unit heater outlet is used with fan at the outlet.

It was pointed out by Helander, Yen and Tripp (1956) that greater angle of spread may be desirable for certain applications. In this report the cores did not affect the angle of spread except in the primary zone. After trying large number number of cores with different size, shape and diameter, it is now clear that other means will have to be devised to increase the angle of spread.

Cylinders with the suggested $\frac{D_c}{D_o}$ ratios of 0.289-0.374 may be used in unit heater designs to increase the projective force of the jets (downthrow in case of downward projection).

With the results of tests in view, $L_c/D_c = 4$ is suggested for maximum throw: L_c = length of core and D_c = diameter of core. For a greater ratio of L_c/D_c nothing can be said until tests are run in that higher range.

It is suggested that air from the intake may be bled into the negative pressure region to fill the zone of negative pressure. Since this would decrease the negative pressure, the jet would tend to spread. This method may also overcome the disadvantage of drag which the cores have. At the same time a separate means may have to be used to supple this bled air and its use may not be ~~may~~ not be feasible economically.

It is suggested that more sensitive hot wire instruments should be used to analyze the angle of spread beyond 8 to 9 outlet diameters when the flow becomes excessively turbulent.

A pressure recording device may give more dependable data in view of the fluctuating pressure readings which are caused due to the presence of the core at the outlet.

While taking zero readings, vibrations were artificially introduced to get the positioning lights to fluctuate with the same intensity. Some mechanical means could have been used to check this zero position. This should be investigated to permit better reference point adjustment.

NOMENCLATURE

a = dimensionless entrainment factor

A_o = outlet area, square feet

$\bar{\beta}_o$ = cross stream average buoyance number at outlet = $\dfrac{U_o^2}{gD_o} \Big/ \left(\dfrac{T_o}{T_a} - 1\right)$

D_c = diameter of core, feet

D_o = diameter of outlet, feet

f = arbitrarily introduced empirical throw factor

f_j = empirical factor to compensate for the deviations in the distribution of the temperature in the room into which the jet is projected.

f_o = empirical factor to compensate for other effects, principally effects due to dynamically established forces and pressure differentials at the boundaries of the space into which the jet is projected.

Q_o = rate of flow at outlet, cfs

L_{max} = distance from outlet to the bottom of the jet, feet

ρ_o = mass density at outlet pounds per cubic feet

T_a = reference room temperature, °F abs

$\bar{T}_o$ = mean temperature at outlet, °F abs

$\mathcal{F}_o$ = directly measured thrust, pounds force

$\bar{U}_o$ = cross stream average velocity at the outlet, feet per sec. = Q_o/A_o

$$\beta_1 = \frac{\text{outlet momentum force (flux)}}{\left(\frac{Q_o}{A_o}\right)^2 \left(\frac{\rho_o}{g_c}\right) A_o} = \frac{\oint_{A_o} \frac{\rho_o U_o^2}{g_c} \, dA}{\left(\frac{Q_o}{A_o}\right)^2 \left(\frac{\rho_o}{g_c}\right) A_o}$$

$$\beta_2 = \frac{\text{measured thrust of jet}}{\left(\frac{Q_o}{A_o}\right)^2 \left(\frac{\rho_o}{g_c}\right) A_o}$$

ACKNOWLEDGMENTS

The writer is very grateful to Professor Linn Helander for his approval to work on this problem, and for his helpful suggestions and encouragement during the course of the research work. He is also grateful to Dr. Ralph G. Nevins, head of the department of Mechanical Engineering, Dr. Wilson Tripp and Professor R. E. Crank for their generous help at all occasions. The writer wishes to express also his gratitude to Mr. Harve Rose, department of Mechanical Engineering for his valuable and sincere assistance with equipment.

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APPENDIX A

Practical Significance of Relative Outlet Thrust Factor β_2

Two significant factors that affect the downthrow of a heated jet must be evaluated before the throw can be predicted. The first of these is the distribution of velocities and pressures at the face of the outlet. This distribution determines the projective force or downthrust of heated jets.

The second factor is the distribution of temperatures in the space into which the jet is projected. This distribution determines the total buoyancy force that opposes the downward thrust of the jet.

Other factors are involved, such as frictional forces and dynamically established pressure differentials at boundaries of space into which jets are projected.

In view of the foregoing, the factor f, in the throw equation in a previous paper for jets having a throw in excess of 8 orifice diameter may be represented as the product of three factors.

$$\frac{L_{max}}{D_o} = 1.7\ (f_o)(f_j)(f_s)(\overline{B}_o)^{\frac{1}{2}} \quad . \ . \ . \ . \ . \ . \ . \ \text{IV}$$

Each factor will have a value of unity for the conditions that prevail when the jet is projected from a long radius A.S.M.E. nozzle into a room, the boundaries of which are remote from the jet.

For an equation of the form of equation IV wherein

$\frac{L_{max}}{D_o}$ = constant $(\bar{B}_o)\frac{1}{g}$, f_o may be set equal to square root of the downthrust factor, B_2, defined as ratio of downthrust or projective force at the outlet to the downthrust or projective force that would have been developed had the velocity been uniform $\bar{U}_o = \frac{Q_o}{A_o}$, and the gage static pressure uniformly zero. f_j will depend upon the angle of spread of the jet, the extent of whirl present, and the magnitude of the frictional forces acting at the inner surface between the downwardly moving jet and the ambient stream of upwardly moving jet and the ambient stream of upwardly moving air. f_s will principally depend upon the geometry and structure of space into which the jet is projected. Anything that increases the degree of non-uniformity of velocity at the outlet without altering the outlet static pressure distribution will augment f_o. Anything that flattens the profile of temperature plotted against radial distances from the jet axis, will reduce f_j.

B_2 can be evaluated by directly measuring outlet thrust T_o of a jet, using means described herein, thus

$$B_2 = \frac{\text{measured thrust in pounds force}}{\left(\frac{Q_o}{A_o}\right)^2 \left(\frac{\rho_o A_o}{g_c}\right)}$$

Here Q_o = rate of flow at the outlet. A_o = outlet area. Some values of B_2 determined from tests reported herein had the following values.

Core Size	Deep Cylindrical Outlet	Shallow Diffuser
2' long, 6" diameter cylinder	1.291	1.442
2' long, 5" diameter cylinder	1.200	1.436
2' long, 4" diameter cylinder	1.171	1.396

B_2 for 1 1/2" long cores.

Core Size	Deep Cylindrical Outlet	Shallow Diffuser
6" diameter, 21" long cone	1.217	1.220
6" diameter, 1' long cylinder	1.182	1.172
6" diameter large unit heater core	1.144	1.245

Values of measured thrust and flow rate are reported in Appendix B.

Flow Around Immersed Bodies

Viscous action may produce three essentially different types of resistance. At very low Reynolds numbers inertial effects caused by steady movement of a body are completely secondary to those of viscous stress, the latter then extending a great distance into the surrounding flow and causing more or less widespread distortion of the flow pattern. This type of resistance is known as "deformation drag".

At much higher Reynolds numbers the region in which appreciable deformation occurs is limited to a thin fluid layer surrounding the body, the resulting shear along the boundary surface (regardless of whether boundary layer is laminar or turbulent) then producing what is called "surface drag".

Finally, if the form of the body is such that separation occurs, the low intensity of pressure in the wake leads to a resultant force which opposes the motion. Since the magnitude of this force varies with the shape of the body, it is customarily called "form drag".

The latter is, however, a somewhat misleading term, for the form and position of a body also determine to some extent the magnitude of the other two types of resistance.

Under favorable conditions form drag itself may reach such proportions as to reduce viscous stresses to relative insignificance.

Fundamentally, drag is caused by the components of the normal and tangential forces transmitted from the fluid to the surface elements of the solid object. The normal forces are those of pressure which in general may be calculated by applying the Bernouli's principle to the stream tube adjacent to the object. The tangential forces are those of shear at the surface of the object arising from viscous effects in the boundary layer.

$$D = \int_0^S p\,dA \sin\theta + \int_0^S \tau_0 \, dA \cos\theta$$

Integral over the surface of the object. Pressure drag + frictional drag.

Pressure drag for streamlined bodies is small but frictional drag is many times the pressure drag. Since stream lining has brought more area in contact with the flow.

CONVENTIONAL HOT WIRE ANEMOMETER EQUATION

The following is the King's semiempirical form which is assumed for the rate of heat loss from a wire immersed in a flowing fluid. For the time rate of increase of heat energy in the wire this gives

$$\frac{dH}{dt} = i^2 R - (A' + B' \quad u)(T - T_a \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where the physical makeup of A' and B' as deduced by King is $A' = a\,lk$, $B' = b\ell\sqrt{dc\rho\, k}$. Here a and b are regarded as numerical constants, although they are dimensional, and should show some variation if a wide enough temperature range is considered.

The term $A'\ (T - T_a)$ presumably represents heat loss due to free convection and radiation. Therefore, it is clear that the constant must include such physical quantities as the acceleration of gravity, the thermal expansion coefficient of the fluid, the specific heat of the fluid, a temperature function, a radiation constant and so forth.

The term $B' \sqrt{u}\ \ (T - T_a)$ represents forced convection, and, after K has been factored out, the term can be written as proportional to the product of a Reynolds member and a Prandtl member.

$$\frac{4\ 2\ ms}{R_o \propto}\ \frac{dR}{dt} = i^2 R - (A \quad B\sqrt{u}) \quad (R - Ra) \quad . \quad . \quad . \quad (1a)$$

and if equilibrium conditions are considered such that $\frac{dR}{dt} = 0$ writing the equilibrium value of Ras R_o, the following equation is obtained

$$\frac{i^2R_c}{R_c - R_a} = A + B\sqrt{u}$$

where $A = \frac{a\ell}{R_o \propto} K$

$$B = \frac{b\ell}{R_o \propto}\sqrt{dc_p \rho k} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (2)$$

In consideration of averaged or steady state operation R_c (Equation 2) may be replaced by $\bar{R}$, and this equation is the usual mean velocity calibration of the hot wire.

King deduced his equation for steady state operation, and a primary assumption of hot-wire anemometer theory is that this rate of heat loss is independent of acceleration. A convenient alternative form of equation (2) is

$$\frac{i^2R}{R - R_a} = A - i^2 + B\sqrt{u}$$

MEASUREMENT OF MEAN VELOCITY AND TEMPERATURE IN AIR

In application of King's equation of thermal equilibrium

$$\frac{i^2\bar{R}}{R - \bar{R}_a} = \bar{A} \quad \bar{B}\sqrt{\bar{u}}$$

where $\bar{A} = \frac{a\ell}{\bar{R}_o \propto} \bar{k}$; $\qquad \bar{B} = \frac{b\ell}{R_o \propto}\sqrt{d\,\bar{c}_p\,\bar{\rho}\,\bar{k}}$

to the measurement of mean velocity and temperature in flow with a temperature gradient, the only change from the first part of preceeding section is that $\bar{A}$ and $\bar{B}$ now vary from point to point in the flow. These variations are determined from the changes in the physical constants of the fluid.

Since air very nearly a perfect gas

$$\frac{\rho}{\rho_r} = \frac{T_r}{T_a}$$

where subscript corresponds to an approximate reference temperature.

From international critical tables the thermal conductivity of air can be approximated for temperatures up to a few hundred degrees centigrade by empirical equation

$$\frac{K}{K_r} = \frac{T_r + 125}{T_a + 125}\left(\frac{T_a}{T_r}\right)^{3/2}$$

where K is the conductivity of air at T_a and K_r is conductivity at T_r.

K can be approximated by a straight line over a fairly wide temperature range.

Variation of C_p with temperature can be neglected from 0 to 300°C. Thus

$$\frac{\bar{A}}{\bar{A}_r} = \frac{\bar{K}}{\bar{K}_r}$$

$$\frac{\bar{B}}{\bar{B}_r} = \sqrt{\frac{\bar{K}\rho}{\bar{K}_r\rho_r}}$$

or

$$\frac{\bar{A}}{\bar{A}_r} = \frac{T_r + 125}{T_a + 125}\left(\frac{T_a}{T_r}\right)^{\frac{3}{2}}$$

$$\frac{\bar{B}}{\bar{B}_r} = \sqrt{\frac{T_r + 125}{T_a + 125}\left(\frac{T_a}{T_r}\right)^{\frac{1}{2}}}$$

In practice, it is convenient to have these equations in terms of resistances

$$R_a = R_o \left[1+\alpha(T_a - 273)\right]$$

$$R_r = R_o\left[1+\alpha(T_r - 273)\right]$$

By using above equation we end up with the following equations for the case of platinum with = .0037 or = 270 where

$$\frac{\bar{A}}{A_r} = \frac{T_r + 125}{\frac{\bar{R}_a}{R_r} T_r + 125} \left(\frac{\bar{R}_a}{R_r}\right)^{\frac{3}{2}}$$

$$\frac{\bar{B}}{B_r} = \left(\frac{T_r + 125}{\frac{\bar{R}_a}{R_r} T_r + 125}\right)^{\frac{1}{2}} \left(\frac{\bar{R}_a}{R_r}\right)^{\frac{1}{4}}$$

α = thermal coefficient of change of resistance of wire.

Accuracy of results depends upon the accuracy of physical form of cooling terms in King's equations. Linear variation of $\frac{i^2 \bar{R}}{\bar{R} - \bar{R}_a}$ with $\bar{U}^{\frac{1}{2}}$ has been checked with considerable accuracy by many experiments.

REMARKS ON KING'S EQUATION

As pointed out by McAdams book on heat transmission the forced-convection term in King's equation can be written in terms of the product of a Reynold number and a Prandtl number so that rate of heat loss from the wire is

$$i^2R = K(T - T_a)\,(a' + b'\sqrt{R\sigma})$$

R = Reynolds number.

Inserting an extra d and introducing a heat transfer coefficient h and the Nusselt number $= \frac{hd}{K}$, McAdams writes this in the form

$$= K_1 + K_2 \sqrt{R\sigma}$$

Conventionally the first term in King's equation is described as including radiation and free convection, while second term is due to forced convection.

The latter appears to be quite reasonable, but it is apparent that free-convection effects, if appreciable, cannot enter the heat transfer equation simply additively. The free convection phenomena is complex and in most current applications the direction of buoyancy induced velocity is perpendicular to the main flow. The form of A, is given by King and gives no clue as to its physical origin, although it is physically obvious that radiation must be included.

l = length of hot wire

ρ = specific density

c_p = specific heat at T_a

K = thermal conductivity of fluid

u = velocity of fluid

d = diameter of hot wire

T = temperature.

T_a = it is meant to indicate the instantaneous absolute temperature of gas and T_r = absolute value of reference medium e.g. air at rest, for a free jet.

α = thermal coefficient of resistance of wire material.

Table 7. Average velocity readings nature of outlet shallow diffuser, no core used, velocity pressure in duct, 2.150" H_2O, room temperature, 80°F.

Distance from outlet, feet	Velocity along geometrical axis, fpm	Distance from geometrical axis of the jet																											
		1"	2"	3"	4"	5"	6"	7"	8"	9"	10"	11"	12"	1.5'	2.0'	2.5'	3.0'	3.5'	4.0'	4.5'	5.0'	5.5'	6.0'	6.5'	7.0'	7.5'	8.0'	8.5'	9.0'
0	400		400		550		910		1000		170		150	85	45	43	43												
2		208	225	250	290		360		360		310		205	104	80	83	77	71	70	77		73	53	50		43			
4		106					170						235	245	105	74	67	65	58	58	53	53	53	53					
6		83					90						132	153	220	125	105	60	53	48	48	54	58	53		46			
8		60					63						90	135	155	135		120		53		47		56		50		50	
10		54					60						58		125	110	100		93	85		52		52		53			
12		50					53						55	60	80	96	85	78		67		57		52		46			

Table 8. Average velocity readings, height of jet axis above ground level, type of outlet, 13" deep, 17 1/2" diameter, type of core, long cylinder 24" long, 6" diameter, velocity pressure in duct, 2.180, room temperature 79°F.

Distance from outlet, feet	Velocity along geometrical axis, fpm	Distance from geometrical axis of the je																											
		1"	2"	3"	4"	5"	6"	7"	8"	9"	10"	11"	12"	1.5'	2.0'	2.5'	3.0'	3.5'	4.0'	4.5'	5.0'	5.5'	6.0'	6.5'	7.0'	7.5'	8.0'	8.5'	9.0'
0					430			970	1000		280		145	43	35	35	35												
2'				210			370			350			210	84	62	52	52	48	42										
4'		125					127						175	155	103	62	62	53	53	51	46	46							
6'		75					82						97	135	92	68	66	48	45	42	42	42	39						
8'		54					56						65	68	87	93	58	48	47	47	45	45		45					
10'		52					55						58	61	73	77	74	55		48		43		40		38			

Table 9. Average velocity readings, deep cylindrical outlet, 13" deep, 17 1/2" diameter, velocity pressure in duct, 2.295" H_2O, duct temperature, 80°F.

Distance from outlet, feet	Velocity along geometrical axis, fpm	Distance from geometrical axis of the jet																											
		1"	2"	3"	4"	5"	6"	7"	8"	9"	10"	11"	12"	1.5'	2.0'	2.5'	3.0'	3.5'	4.0'	4.5'	5.0'	5.5'	6.0'	6.5'	7.0'	7.5'	8.0'	8.5'	9.0'
0	265	275	300	365	450	600	675	735	700	215	128	107	85	57	46	42	37	17	23										
1'	215		230		245		330		560		725		740	103	57	40	30	27	31	36									
2'	250		265		295		310		370		450		550	310	117	49	45	41	38	26	32	36	39	35	34				
3'	235		250		270		315		350		400		450	570	250	130	60	44	37	33	31	34	40	37	35				
4'	225		260		265		310		350		365		375	500	475	315	210	100	55	46	39	32	37	39	33	32			
5'	190		205		215		230		240		250		245	265	340	360	250	160	83	60	40	25	23	28	32	29			
6'	175		180		185		170		185		190		180	185	240	300	310	260	190	105	53	43	29	35	30	29			
7'	160												135	145	150	200	210	255	150	135	73	60	57	43	38	35	30	32	
8'	145						160						165	170	135	130	120	195	180	170		110		95		43	35	37	35
9'	130						150						125	115		120		140		180		120		90		45	53	46	37
10'	115		140		155		135		115		130		130		80		52		65		75		65		30		45		28
11'	107		125		135		150		150		160		125		90		82		80		75		60		43		32		26

Table 10. Average velocity readings, type of outlet, deep cylindrical core, 13" deep, 17 1/2" diameter, type of core, long streamlined cone, 21" long, 6" diameter, velocity pressure, 2.275" H_2O, duct temperature, 85°F., barometric pressure, 29.04.

Distance from outlet, feet	Velocity along geometrical axis, fpm	Distance from geometrical axis of the jet																											
		1"	2"	3"	4"	5"	6"	7"	8"	9"	10"	11"	12"	1.5'	2.0'	2.5'	3.0'	3.5'	4.0'	4.5'	5.0'	5.5'	6.0'	6.5'	7.0'	7.5'	8.0'	8.5'	9.0'
0	265		270		470		760	820	880		240	92	66	37	32	32													
1'		238	245		300		550		750	700	620	480	400	100	44	37	42	32	32										
2'	235	238	245		270		315		440		590		670	370	102	80	38	32	30	32									
3'	220	230	235		256		295		345		390		430	580	330	140	59	43	34	32	34								
4'	215	220	230		250		270		280		310		315	455	490	310	212	90	62	43	37	37	35						
5'	200	200	205		190		210		206		210		210	270	380	390	310	180	75	67	40	35	30						
6'	195		185		235		245		245		235		235	235	260	365	380	290	250	135	107	64	41	34	32				
7'	165		160		180		180		185		185		165	165	160	200	240	235	235	200	103	95	60	38	30				
8'	160	160	165		175		180		180		185		175	140	120	120	120	200	215	235	175	145	73	58	55	40	35		
9'	125	130	130		130		130		130		130		130	105	95	75	75	75	125	115	100	85	45	93	38	35			
10'	150	145	145		145		150		150		135		145	145	110	75	70	70	75	65	105	95	60	45	42	38	35		

Table 11. Average velocity readings, type of outlet, deep cylindrical outlet (diffuser) 13" deep, 17 1/2" diameter, type of core, large cylinder, 6" diameter, 2' long, room temperature, 82°F.

Distance from outlet, feet	Velocity along geometrical axis, fpm	Distance from geometrical axis of the jet																					
		1"	2"	3"	4"	5"	6"	7"	8"	9"	10"	11"	12"	1.5'	2.0'	2.5'	3.0'	3.5'	4.0'	4.5'	5.0'	5.5'	6.0'
1'				180		440		650	790	760		104		57	46	38							
2'				140		210		325		580		680	500	100	60	53	43	37					
3'																							
4'	172						205						355	320	120	65	48	45	40	38			
5'																							
6'	103						110						120	150	210	140	80	58	43	40	38		
7'																							
8'	98						100						89	110	152	125	100	65	60	55	42		
9'																							
10'	95												85		85	105	98	73	46	39	38		

Table 12. Summary of thrust results, deep cylindrical outlet 13" deep, 17 1/4" dia.

No. of Reading	Type of core	Thrust reading in gms core face locations stated below: 2" from fan	3" from fan	4" from fan	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units	Q_o no core Units
1	2" dia. cylinder 2' long	273	270	267	266	19.92	2.232	86	2.237	19.95
2	2" dia. cylinder 2' long	275	273	271	270	19.92	2.232	84	2.235	19.94
3	2" dia. cylinder 2' long	271	269	265	263	19.86	2.207	83	2.209	19.87
4	2" dia. cylinder 2' long	287	284	282	280	19.63	2.187	84	2.200	19.85
5	3" dia. cylinder 2' long	280	277	275	270	19.88	2.228	85	2.235	18.90
6	3" dia. cylinder 2' long	288	281	278	268	19.88	2.228	86	2.237	19.95
7	3" dia. cylinder 2' long	277	272	268	265	19.63	2.187	84	2.20	19.85

Table 12. (cont.)

No. of Reading	Type of core	Thrust reading in gms core face locations stated below: 2" from fan	3" from fan	4" from fan	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units	Q_o no core Units
8	3" dia. cylinder 2' long	290	285	280	275	19.63	2.191	84	2.209	19.87
9	4" dia. cylinder 2' long	295	287	282	280	19.63	2.191	85	2.209	19.87
10	4" dia. cylinder 2' long	285	277	273	265	19.63	2.187	86	2.200	19.85
11	4" dia. cylinder 2' long	293	285	280	269	19.88	2.228	86	2.237	19.95
12	4" dia. cylinder 2' long	292	287	282	270	19.80	2.218	84	2.235	19.90
13	5" dia. cylinder 2' long	297	292	287	270	19.72	2.208	85	2.935	19.90
14	5" dia. cylinder 2' long	296	291	286	265	19.88	2.224	86	2.237	19.95

Table 12. (cont.)

No. of Reading	Type of core	Thrust reading in gms core face locations stated below: 2" from fan	3" from fan	4" from fan	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units	Q_o no core Units
15	5" dia. cylinder 2' long	300	293	288	275	19.64	2.184	84	2.200	19.85
16	5" dia. cylinder 2' long	290	285	277	270	19.75	2.186	84	2.209	19.87
17	6" dia. cylinder 2' long	288		273	252	19.82	2.215	96	2.222	
18	6" dia. cylinder 2' long	292		277	250	19.83	2.223	98	2.232	
19	6" dia. cylinder 2' long	310		290	270	19.90	2.208	100	2.216	
20	6" dia. cylinder 2' long	277		265	237	19.80	2.218	97	2.236	
21	6" dia. cylinder 2' long	410		395	370	19.90	2.280	96	2.296	

Table 12. (cont.)

No. of Reading	Type of core	Thrust reading in gms core face locations stated below: 2" from fan	3" from fan	4" from fan	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units	Q_o no core Units
22	6" dia. cylinder 2' long	273		255	230	19.92	2.08	103	2.148	
23	6" dia. cylinder 2' long	288		278	247	19.80	2.255	92	2.27	
24	6" dia. cylinder 2' long	308		296	270	19.67	2.181	85	2.209	
25	6" dia. cylinder 2' long	310		291	267	19.64	2.184	86	2.20	
26	6" dia. cylinder 2' long	335		318	277	19.80	2.220		2.37	
27	6" dia. cylinder 2' long	327		317	270	19.80	2.205	84	2.235	

Table 12. (concl.)

No. of Reading	Type of core	Thrust reading in gms core face locations stated below: 2" from fan	3" from fan	4" from fan	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units	Q_o no core Units
28	8" dia. cylinder 2' long	345	320	287	270	19.55	2.173	85	2.209	
29	8" dia. cylinder 2' long	340	300	285	265	19.25	2.095	86	2.200	
30	8" dia. cylinder 2' long	353	326	306	275	19.85	2.210	86	2.237	
31	8" dia. cylinder 2' long	342	315	302	270	19.85	2.190	84	2.235	

Table 13. Summary of thrust results, deep cylindrical outlet 13" deep, 17 1/4" dia.

No. of Reading	Type of core	Thrust reading in gms core face locations stated below, inches from fan 2"	4"	6"	8"	10"	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
32	8" dia. cylinder 1 1/2' long	400	388.3	385	380		375	16.35	1.541		1.556
33	8" dia. cylinder 1 1/2' long	395	390	383	382	378	375	16.30	1.524	78	1.538
34	8" dia. cylinder 1 1/2' long	423	411	405	401.5	397.5	387	16.35	1.541	76	1.550
35	6" dia. cylinder 1 1/2' long	388	385	380.5	377	376.7	375	16.40	1.545		1.556
36	6" dia. cylinder 1 1/2' long	386	382	376	373	372	375	16.33	1.527	78	1.538
37	6" dia. cylinder 1 1/2' long	417	410	402	397	397	387	16.35	1.546	76	1.550

* The strain gages were suspected to be out of order when these readings were taken.

Table 13. (cont.)

No. of Reading	Type of core	Thrust reading in gms core face locations stated below, inches from fan 2"	4"	6"	8"	10"	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
38	5" dia. cylinder 1 1/2' long	387	385	382	380	377	375	16.47	1.547		1.556
39	5" dia. cylinder 1 1/2' long	382	380	376	375	373	375	16.33	1.529	78	1.538
40	5" dia. cylinder 1 1/2' long	403	400	397	390	389.7	387	16.40	1.546	76	1.550
41	4" dia. cylinder 1 1/2' long	383	382	380	378.5		375	16.41	1.549	78	1.556
42	4" dia. cylinder 1 1/2' long	386	383	381	378	376	375	16.35	1.531	78	1.538
43	4" dia. cylinder 1 1/2' long	400	398	397	390.5	389.5	387	16.40	1.596	76	1.550

* The strain gages were suspected to be out of order when these readings were taken.

Table 13. (concl.)

No. of Reading	Type of core	Thrust reading in gms core face locations stated below, inches from fan. 2"	4"	6"	8"	10"	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
44	3" dia. cylinder 1 1/2' long	182	180	379.5	377		375	16.47	1.551	78	1.556
45	3" dia. cylinder 1 1/2' long	385	382	380	378	376	375	16.35	1.533	78	1.538
46	3" dia. cylinder 1 1/2' long	398	397	392	390	388	387	16.43	1.597	76	1.550
47	2" dia. cylinder 1 1/2' long	380	379	377	377		375	16.49	1.553	78	1.556
48	2" dia. cylinder 1 1/2' long	383	382	381	380	375	375	16.35	1.536	78	1.538
49	2" dia. cylinder 1 1/2' long	392	391	390.5	390	388	387	16.43	1.548	76	1.550

* The strain gages were suspected to be out of order when these readings were taken.

Table 14. Summary of thrust results, shallow diffuser, 17 1/4" diameter, 4" deep.

No. of Reading	Type of core	Thrust reading in gms core face locations stated below: 2" from fan	3" from fan	4" from fan	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
50	8" dia. cylinder 2' long	380	370	358	320	19.92	2.25	81	2.285
51	8" dia. cylinder 2' long	405	374	356	344	19.92	2.267	82	2.280
52	8" dia. cylinder 2' long	378	366	357	320	19.92	2.232	84	2.245
53	6" dia. cylinder 2' long	315		300	280	19.9	2.20	98	2.32
54	6" dia. cylinder 2' long	300		292	265	19.95	2.229	95	2.32
55	6" dia. cylinder 2' long	330		307	290	19.95	2.219	98	2.237

Table 14. (cont.)

No. of Reading	Type of core	Thrust reading in gms core face locations stated below: 2" from fan	3" from fan	4" from fan	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
56	6" dia. cylinder 2' long	316		297	273	19.95	2.218	98	2.237
57	6" dia. cylinder 2' long	318		292	280	19.88	2.203	95	2.235
58	6" dia. cylinder 2' long	317		292	280	19.80	2.213	89	2.235
59	6" dia. cylinder 2' long	375		359	320	19.84	2.260	81	2.285
60	6" dia. cylinder 2' long	382		362	345	19.90	2.271	82	2.280
61	5" dia. cylinder 2' long	376	370	363	346	19.95	2.273	82	2.280
62	5" dia. cylinder 2' long	363	358	352	320	19.93	2.267	81	2.285

Table 14. (cont.)

No. of Reading	Type of core	Thrust reading in gms core face locations stated below: 2" from fan	3" from fan	4" from fan	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
63	5" dia. cylinder 2' long	366	361	354	330	19.90	2.271	82	2.280
64	4" dia. cylinder 2' long	348	343	337	320	19.93	2.270	81	2.285
65	4" dia. cylinder 2' long	366	362	358	347	19.93	2.274	82	2.280
66	4" dia. cylinder 2' long	355	350	345	330	19.88	2.228	86	2.237
67	3" dia. cylinder 2' long	362	360	353	347	19.95	2.276	82	2.280
68	3" dia. cylinder 2' long	335	332	328	320	19.93	2.277	81	2.285

Table 14. (concl.)

No. of Reading	Type of core	Thrust reading in gms core face locations stated below from fan	from fan	from fan	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
69	3" dia. cylinder 2' long	343	341	337	330	19.92	2.232	84	2.235
70	2" dia. cylinder 2' long	328	323	320	320	19.9	2.283	81	2.285
71	2" dia. cylinder 2' long	353	352	347	346	19.93	2.278		2.280
72	2" dia. cylinder 2' long	338	335	331	330	19.93	2.233	84	2.235

Table 15. Summary of thrust results, shallow diffuser, 4" deep, 17 1/4" diameter.

No. of Reading	Type of cores	Thrust reading in gms core face locations stated below, inches from fan 2"	4"	6"	8"	10"	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
73	8" dia. cylinder 1 1/2' long	450	443				440	16.74	1.625	66	1.635
74	8" dia. cylinder 1 1/2' long	422	420	418	415	414	413	16.70	1.526	80	1.536
75	8" dia. cylinder 1 1/2' long	420	416	414	413	408	407	16.69	1.526	78	1.538
76	6" dia. cylinder 1 1/2" long	440	430	427			425	16.74	1.627	66	1.635
77	6" dia. cylinder 1 1/2' long	417.5	415	414	412		413	16.70	1.529	80	1.536
78	6" dia. cylinder 1 1/2' long	415	413	410	407	405	405	16.69	1.529	78	1.538

*The strain gages were suspected to be out of order when these readings were taken.

Table 15. (cont.)

No. of Reading	Type of cores	Thrust reading in gms core face locations stated below, inches from fan 2"	4"	6"	8"	10"	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
79	5" dia. cylinder 1 1/2' long	420	417.5	425	425	425	425	16.76	1.628	66	1.635
80	5" dia. cylinder 1 1/2' long	415.4	414				414	16.74	1.531	80	1.536
81	5" dia. cylinder 1 1/2' long	414	413	411.5	408	405	405	16.70	1.531	78	1.538
82	4" dia. cylinder 1 1/2' long	423	423	423			424	16.80	1.630		1.635
83	4" dia. cylinder 1 1/2' long	414	414	414			414				
84	4" dia. cylinder 1 1/2' long	413	412	408.5	407	405	405	16.70	1.533		1.538

*The strain gages were suspected to be out of order when these readings were taken.

Table 15. (concl.)

No. of Reading	Type of cores	Thrust reading in gms core face locations stated below, inches from fan 2"	4"	6"	8"	10"	T no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
85	3" dia. cylinder 1 1/2' long	424	424	424			424				
86	3" dia. cylinder 1 1/2' long	414	414	414			414	16.76	1.628		1.635
87	3" dia. cylinder 1 1/2' long	412	408.5	407.5	407	405	405	16.74	1.535		1.538
88	2' dia. cylinder 1 1/2' long	424	424	424			424				
89	2" dia. cylinder 1 1/2' long							16.76	1.628		1.635
90	2" dia. cylinder 1 1/2' long	408	406	405			405	16.80	1.537		1.538

*The strain gages were suspected to be out of order when these readings were taken.

Table 16. Summary of thrust results, deep cylindrical outlet, 13" deep, 17 1/4" dia.

No. of Reading	Type of cores	Thrust reading in gms core face locations stated below, inches from fan: 2"	3"	4"	6"	8"	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
91	Long stream lined cone, 21" long	300	295	285			268	19.80	2.220	88	2.237
92	Long stream lined cone, 21" long	307	296	287			270	19.80	2.220	86	2.237
93	Long stream lined cone 21" long	292	287	280			275	19.60	2.181	85	2.209
94	Long stream lined cone, 21" long	285	278	275			260		2.12		2.200
95	Long stream lined cone, 21" long	395		387	332		370	20.20	2.285	96	2.296
96	Long stream lined cone, 21" long	267		260	253		235	19.94	2.220	97	2.236
97	Long stream lined cone, 21" long	297		277	270		265	19.96	2.210	100	2.216

Table 16. (concl.)

No. of Reading	Type of cores	Thrust reading in gms core face locations stated below, inches from fan. 2"	3"	4"	6"	8"	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
98	Long Stream lined cone, 21" long	280		276	255		245	19.95	2.222	98	2.232
99	Long stream lined cone, 21" long	283		273	267		250	19.93	2.216	96	2.222
100	Large unit heater core	283	280	277			268	19.85	2.224	86	2.237
101	Large unit heater core	295	288	282	275	270	270	19.70	2.205	86	2.235
102	Large unit heater core	290	285	280	277	275	275	19.60	2.181	85	2.209
103	Large unit heater core	258	251	241	240	235	236	19.50	2.12		2.200
104	Large unit heater core	289		284	279	272	265	20.23	2.221	97	2.236
105	Large unit heater core	275		265	255	250	250	19.93	2.206	100	2.216

Table 17. Summary of thrust results, deep cylindrical outlet, 13" deep, 17 1/4" dia.

No. of Reading	Type of cores	Thrust reading in gms core face locations stated below, inches from fan: 2"	4"	6"	8"	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
106	Small unit heater core	280	277	275		275	19.60	2.191	85	2.209
107	Small unit heater core	235	230	227		227	19.93	2.122	101	2.148
108	Small unit heater core	250	245	242	237	235	20.0	2.230	97	2.236
109	Small unit heater core	270	265	263	260	260	20.0	2.212	100	2.216
110	Small unit heater core	252.5	245	242.5		242.5	20.0	2.227	98	2.232
111	Small unit heater core	255	250	247		247	19.93	2.218	96	2.222

Table 18. Summary of thrust results, deep cylindrical outlet, 13" deep, 17 1/4" dia.

No. of Reading	Type of cores	Thrust reading in gms core face locations stated below, inches from fan 2"	3"	4"	6"	8"	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
112	Small cyl. 1' long 6" dia.	305	300	293	287	283	275	20.2	2.181	85	2.209
113	Small cyl. 1' long 6" dia.	262	257	253	247	243	230	19.83	2.08	101	2.148
114	Small cyl. 1' long 6" dia.	400		395	387	382	370	20.2	2.28	96	2.296
115	Small cyl. 1' long 6" dia.	255		250	245	240	235	19.93	2.218	97	2.236
116	Small cyl. 1' long 6" dia.	297		290	285	280	267	20.0	2.208	100	2.216
117	Small cyl. 1' long 6" dia.	273		267	257	250	247.5	20.06	2.223	98	2.232
118	Small cyl. 1' long 6" dia.	275		265	257	255	250	19.93	2.215	96	2.222

Table 19. Summary of thrust results, shallow diffuser, 17 1/4" diameter, 4" deep.

No. of Reading	Type of cores	Thrust reading in gms core face locations stated below, inches from fan					T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
		2"	3"	4"	6"	8"					
120	Large stream lined cone 21" long 6" dia.	305		295			280	19.86	2.216	89	2.235
121	Large stream lined cone 21" long 6" dia.	308		300			280	19.84	2.205	93	2.225
122	Large stream lined cone 21" long 6" dia.	290		273			273	19.86	2.219	93	2.239
123	Large unit heater core 11 1/2" long 6" dia.	365	360	355	350		345	19.93	2.267	82	2.280
124	Large unit heater core 11 1/2" long 6" dia.	305		287	285		280	19.80	2.216	89	2.235

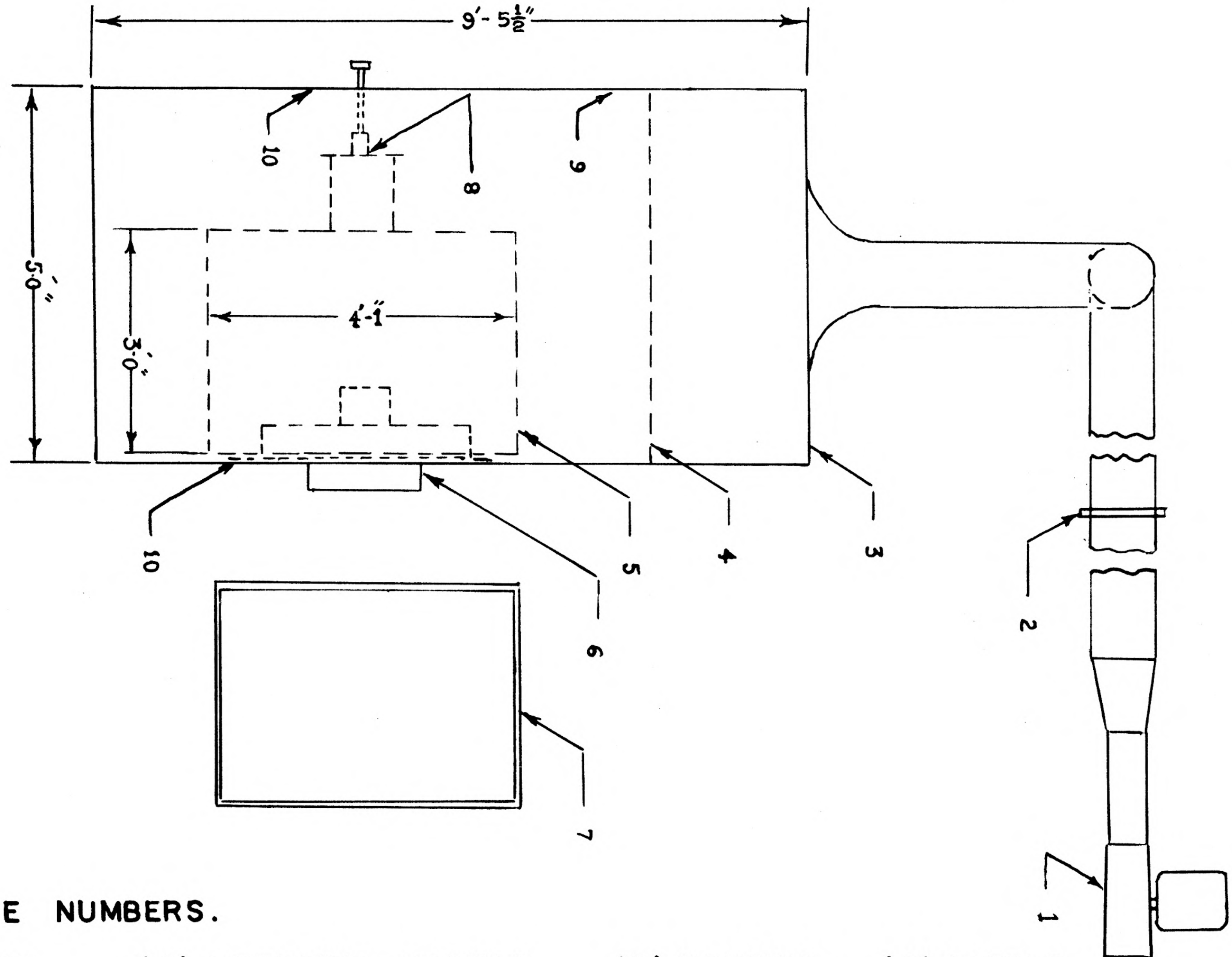
Table 19. (cont.)

No. of Reading	Type of cores	Thrust reading in gms core face locations stated below, inches from fan 2"	3"	4"	6"	8"	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
125	Large unit heater core 11 1/2" long 6" dia.	307		292	282		280	19.80	2.208	93	2.225
126	Large unit heater core 11 1/2" long 6" dia.	292	270	283	270		270	19.85	2.214	93	2.239
127	Small unit heater core 8 1/2" long 4 1/2" dia.	295		293	287	283	280	19.91	2.223	89	2.235
128	Small unit heater core 8 1/2" long 4 1/2" dia.	300		387	380		380	19.90	2.22	93	2.225
129	Small unit heater core 8 1/2" long 4 1/2" dia.	283		278	275	270	270	19.96	2.234	93	2.239

Table 19. (concl.)

No. of Reading	Type of cores	Thrust reading in gms core face locations stated below, inches from fan 2"	3"	4"	6"	8"	T_o no core gms	Volume rate of flow, Q Units	Velocity pressure reading Units	Temp. in duct °F	Velocity pressure no core Units
130	1' long 6" dia. cylinder	305		295	292	285	280	19.90	2.228	89	2.235
131	1' long 6" dia. cylinder	305		292	287	280	280	19.12	2.04	93	2.225
132	1' long 6" dia. cylinder	288		283	280	275	273	19.90	2.219	93	2.237

DIMENSIONS AND SCHEMATIC ARRANGEMENTS OF THE EQUIPMENT (PLAN VIEW) FOR MEASURING OUTLET THRUST OF UNIT HEATERS. (TO SCALE)

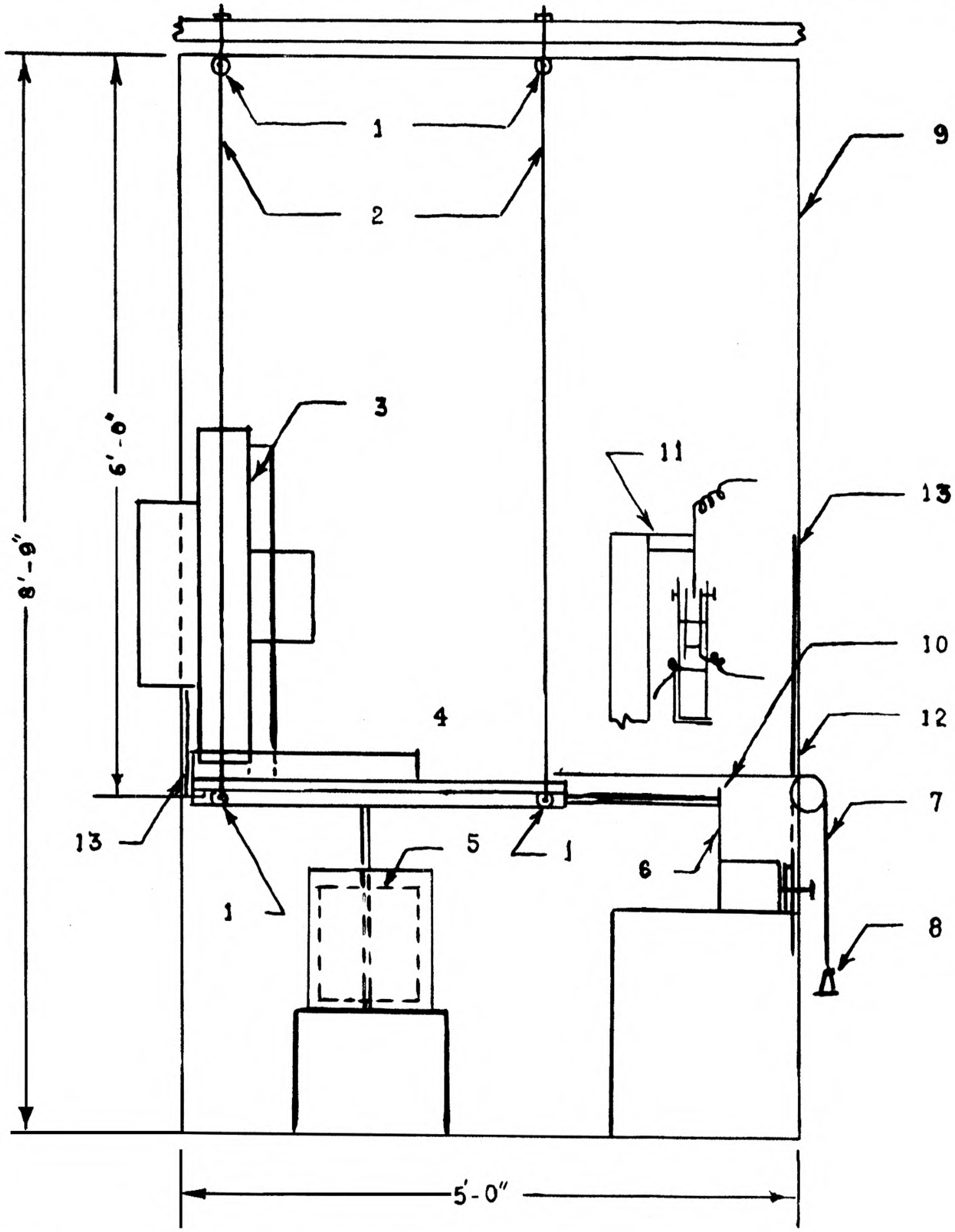


REFERENCE NUMBERS.

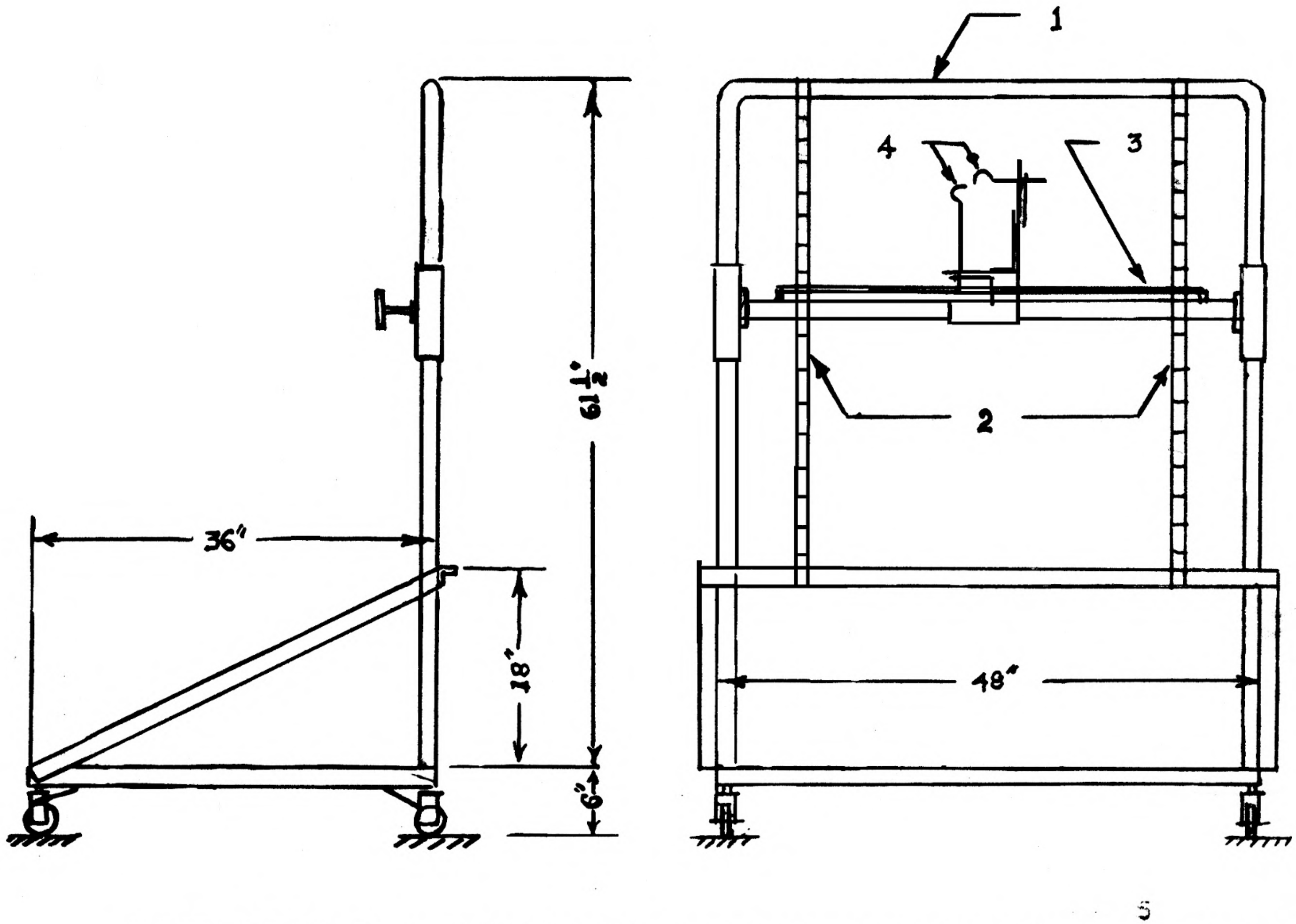
(1) BLOWER (2) METERING NOZZLE (3) HOUSING (4) BAFFLE
(5) SWING PLATFORM (6) UNIT HEATER (7) INSTRUMENT CARRIAGE
(8) THRUST MEASURING DEVICE (9) DOOR (10) WINDOWS.

Figure 1

DIMENSIONS AND SCHEMATIC ARRANGEMENT OF EQUIPMENT FOR MEASURING OUTLET THRUST OF UNIT HEATERS (SIDE ELEVATION)



REFERENCE NUMBERS (1) BALL BEARING (2) SUPPORT RODS (3) UNIT HEATER (4) SWING PLATFORM (5) VIBRATION DAMPER (6) THRUST MEASURING DEVICE (7) SKING (8) CALIBRATION PAN (9) HOUSING (10) POSITION INDICATING SWITCH (11) ENLARGED TOP VIEW OF POSITION INDICATING SWITCH (12) DOOR (13) WINDOWS.



DIMENSIONS AND SCHEMATIC ARRANGEMENT OF INSTRUMENT CARRIAGE

REFERENCE NUMBERS (1) CARRIAGE FRAME (2) VERTICAL SCALE (3) HORIZONTAL SCALE (4) IMPACT TUBES (5) GUIDE RAIL

Figure 3

EFFECT OF CORE SHAPES ON THE FLOW OF JETS FROM UNIT HEATER OUTLETS

by

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ABSTRACT

The tests described in this report were conducted as a part of a cooperative research project on the downward projection of heated air jets sponsored jointly by the American Society of Heating and Ventilating Engineers and the Engineering Experiment Station of Kansas State College.

This report is the result of suggestions contained in a paper by Professor Helander, Dr. Yen and L. B. Knee (1954) who suggested that basic research be carried out to explore the possibility of increasing thrust of the jet. Present research concerns itself with the unit heater outlet characteristics. Outlets used were; (1) deep cylindrical outlet, 17 1/4" diameter, 13" deep, and, (2) shallow diffuser 17 1/4" diameter, 4" deep.

When a unit heater fan is operating, due to whirl, a zone of negative pressure is created in front of the outlet. A considerable amount of energy is lost in maintaining this zone of negative pressure. It was thought that if this zone could be filled out by placing a smooth solid core in the stream, part of the energy would be made available for increasing the propulsive force of the jet.

Apparatus was available to measure the thrust directly.

This consisted of a plenum chamber to which air was fed by an external supply fan. Part of the equipment was a swing platform upon which was mounted a unit heater. The thrust imparted by the unit heater to the swing platform was determined by means of a strain gage thrust measuring device.

The following combinations of cores were used:

(1) Two feet long cylinders of different diameters.

(2) One and one-half feet long cylinders of different lengths.

(3) Same diameter stream line bodies of different lengths.

(4) Same diameter stream line bodies of same length.

These solid cores were introduced into the jet stream and their effects on the characteristics of the jets were studied. Major consideration was given to the study of the effect of core shapes on the thrust characteristics of the jet stream and the results have been reported in the form of dimensionless graphs and tables. Effect on the angle of spread and whirl was also studied. Pitot static tube traverses were taken to determine the velocity distribution and a hot wire instrument was also used to measure velocities. On the basis of velocity distribution, angle of spread was found. This was checked by taking smoke pictures of the jet stream. Effect on whirl was studied visually by smoke bomb technique.

As a result of the present work it was found that as the diameter of the core is increased the measured thrust, as well as relative thrust, increases. An optimum range was determined in which maximum increase in thrust, as well as relative thrust, would be realized without appreciably affecting the flow rate. Comparing the effects of long cores with smaller cores of the same diameter, it was established that length has a considerable effect on thrust values. With large cores mentioned above the measured thrust was nearly 14.2% greater than the thrust obtained when no core was used. Maximum decrease in flow rate was about 2%. The cores did not affect angle of spread except in primary zone. Whirl was greatly decreased when long cores were used. For core diameters larger than the optimum range reported in this report, flow rate decreases rapidly and offsets the advantage due to gain in thrust. For smaller values of core diameters the effect on thrust is insignificant.