The Effect of Pressure on the Propagation Rate of Bunsen Flames in Propane-Air and Ethylene-Air Mixtures

by R. E. Cullen

Project MX-833
USAF Contract W33-038-ac-21100

Willow Run Research Center
Engineering Research Institute
University of Michigan
UMM-81. December 1950

en 3n

UMR 6685

FOREWORD

This report is part of the program of research conducted at the University of Michigan for the United States Air Force under Contract W-33-038-ac-21100.

This research was carried out under the direct supervision of R. B. Morrison and under the faculty supervision of E. T. Vincent and J. W. Luecht.

The author wishes to express his appreciation to Mr. R. B. Morrison for his technical aid and personal encouragement, to D. P. Roseman who determined the surface areas of the Bunsen flames observed in this report, and to C. F. Riley, a co-worker, who was not present at the completion of the investigation.

ABSTRACT

The observed effect of pressure on the normal flame speed of Bunsen flames burning in propane-air and ethylene-air mixture concentrations of .067 pound propane/pound air and .0836 pound ethylene/pound air at pressures from atmospheric to about one inch Hg absolute is described. The effect of the temperature of the inlet fuel-air mixture on the normal flame speed of Bunsen flames burning in a propane-air mixture concentration of .067 pound propane/pound air from room temperatures to 550° F. is also described.

The dependency of flame speed on the burner size at various pressures is investigated with four burners of 3/8-inch, 1/2-inch, 5/8-inch and 1 1/4-inch diameters.

It is concluded that flame speed is an inverse logarithmic function of pressure for both propane and ethylene within the range of pressures that flames were observed if the burner diameter were chosen large enough.

A non-dimensional parameter, viz., the Peclet number, based upon the observed flame speed and the burner diameter, is established to correlate the experimental results. It is concluded that the Peclet number must be kept large if a true flame speed is desired.

The introduction of a heat sink into the development of the Mallard and LeChatelier flame speed relation is examined. It is concluded that the heat conduction theory alone possibly does not describe the observed effects of pressure and burner size on flame speed. Further experiments are suggested which could substantiate or disprove the heat sink theory based on thermal conduction.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (continued)

INTRODUCTION

A more complete understanding of the mechanism of flame propagation is basic to the design of jet-propelled devices. An important contribution in this respect is the study of the factors affecting the propagation rates of flames burning in combustible mixtures.

Various experimenters in the past have investigated many of the factors, e.g., temperature of the unburned mixture, ambient pressure, type of fuel, fuel-oxidant ratio, turbulence, humidity, imposed electromagnetic fields, and so forth, affecting the flame propagation rate. The effects of many of the variables have been fairly well established. However, because of the discrepancies in the literature concerning the effects of ambient pressure on the propagation rates of flames, and because of the importance of this variable in the operation of jet combustion chambers at altitude conditions, it is the purpose of this report to investigate in particular the effect of pressure on the propagation rates of flames in propane-air and ethylene-air mixtures.

GENERAL REMARKS

1. SOME BASIC DEFINITIONS

From the great amount of work done in the past on the propagation of flames in gaseous mixtures, it might be well to review some of the more important and established considerations and definitions.

A flame front can be defined as the rapid chemical change occurring in a thin layer, generally accompanied by luminosity. The factors which determine the rate at which this flame front propagates into the unburned mixture can be grouped into two categories. One includes factors which can be considered as properties of the unburned mixture itself, i.e., the type of fuel, the fuel-oxidant ratio, and the state (pressure and temperature) of the combustible gases. The second is very broad and includes factors resulting from any influence of the system in which the flame burns on its propagation rate; this category is composed of such things as wall effects, turbulence and other flow disturbances, electromagnetic fields, and so forth.

The "Normal Velocity of Combustion" can be defined as follows:* an explosion which is initiated by a point source of ignition, namely a spark, in a sufficiently large quantity of combustible mixture so that the boundaries of the system are far removed, propagates into the unburned mixture at a certain velocity. The velocity with which the borderline between the unburned and the burned gases moves normal to itself into the unburned mixture at rest in the immediate proximity of the combustion surface is called the "Normal Combustion Velocity", V_n. The "Normal Flame Speed", V_f, can be considered as the more complicated phenomenon which is influenced by the external conditions imposed by the system in which the flame burns. With reference to the flame propagation rates observed in this report, the external effects have been minimized in many cases so that the flame propagation rates can be said to approach closely the normal velocity of combustion. However, since these effects have never been completely removed, the flame propagation rates observed have been accordingly called normal flame speed.

*This is essentially the definition given by Jost in Reference 1.

Normal combustion velocities can range from about one foot per second to approximately thirty feet per second, depending on the fuel and oxidant used and the state of the unburned gases. Normal flame speeds on the other hand can range from even lower values up to several hundred feet per second. In extreme cases, flames can initiate a different phenomenon which proceeds with velocities up to several times the speed of sound.* It is a process which, unlike flame speed, is not affected by many external influences. With reference to these two processes, the slow burning phenomenon is generally termed a "deflagration" while the extremely rapid process is called a "detonation". According to Chapman and Jouget,** these two combustion processes are the only ones compatible with the conservation laws of mass, momentum and energy. A detonation always proceeds at a velocity which is supersonic with respect to the unburned gases, while both the pressure and the density increase across the reaction zone. The deflagration always proceeds at a velocity which is subsonic with respect to the unburned gases while the pressure and density decrease across the reaction zone. It can be concluded, therefore, that concerning a detonation, the state of the unburned gases is unaffected by the process itself, i.e., by heat transfer from the combustion zone due to molecular motion.*** In contrast to this, concerning a deflagration, the unburned gases are affected by the process which is occurring in the combustion zone. It is the deflagration process with which this report will deal. As was stated earlier, the flame propagation rates observed will be called "normal flame speed".

2. DEVELOPMENT OF THE EQUATION OF MALLARD AND LE CHATELIER

An explanation of the mechanism by which a flame front propagates into the unburned gases was first introduced by Mallard and Le Chatelier.**** They reasoned that since a flame generally proceeded at velocities relative to the unburned gases of the same order of magnitude as the

*This phenomenon is presently being studied at this facility by R. B. Morrison and J. A. Nicholls (Ref. 2).

**See Reference 3.

***The effect of radiation has not been studied in great detail. The effect, however, is believed small.

****See Reference 4.

rate of thermal conduction, the process could be considered solely from the standpoint of heat conduction from the flame into the unburned mixture.

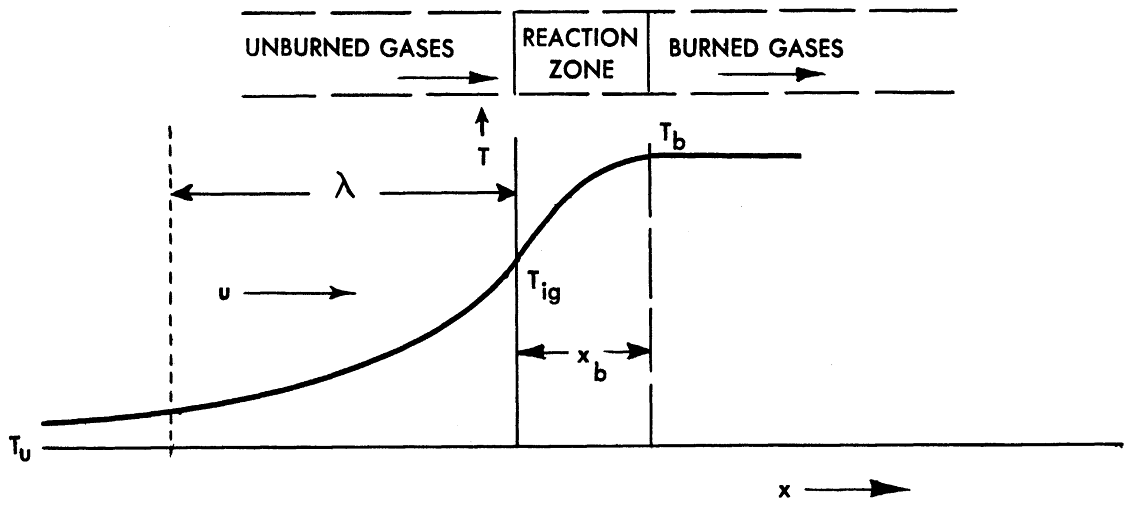


FIG. 1 TEMPERATURE VARIATION THROUGH REACTION ZONE BASED ON HEAT CONDUCTION THEORY.

Consider now, as in Figure 1, a stream tube in a small portion of a large combustible mixture moving with linear velocity, u, so that the flame front is stationary with respect to a fixed coordinate system. Assume now that the gases moving from the left are at some temperature, T_u, and are heated by conduction to some temperature, T_{ig}. At this point chemical reaction commences and the gases burn to some temperature, T_b, at which point the combustion is completed. This infers a finite flame zone thickness, x_b.

Confining our attention to the zone immediately upstream of T_{ig} where the usual heat conduction relations are applicable, consider a two-dimensional element in space through which the gases are flowing with variable velocity u, as in Figure 2.

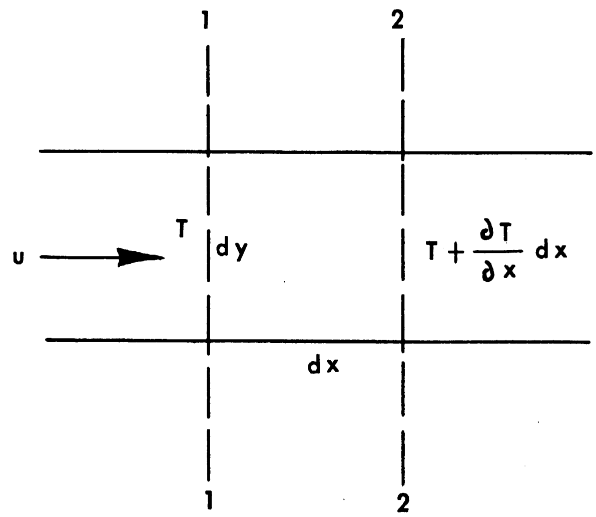


FIG. 2 ELEMENTAL AREA IN UNBURNED GASES

Heat conduction on face 1-1 is $k\,dy\,\frac{\partial T}{\partial x}$ (where k is the coefficient of thermal conductivity).

Heat conduction on face 2-2 is $k\,dy\,\frac{\partial}{\partial x}\left(T + \frac{\partial T}{\partial x}dx\right)$

The net heat transport due to conduction is therefore:

$$k\,\frac{\partial^2 T}{\partial x^2}\,dx\,dy$$

Heat convection through face 1-1 is $\rho u\,C_p\,T.dy$ (where ρ is the density and C_p the mean specific heat).

Heat convection through face 2-2 is $\rho u\,C_p\,T dy + \frac{\partial}{\partial x}(\rho u\,C_p\,T dy)dx$

The net heat transport due to convection is therefore:

$$\rho u\,C_p\,\frac{\partial T}{\partial x}\,dx\,dy \left(\begin{array}{l}\text{for } \rho u = \text{const.}\\ \text{and } \frac{\partial}{\partial x}\rho u = 0\end{array}\right)$$

If the temperature at any one point is to remain constant with time, i.e., if the flame front is stationary, then the net heat transport by conduction must be equal to the net heat transport by convection or

$$k \frac{\partial^2 T}{\partial x^2} dx\, dy = \rho u C_p \frac{\partial T}{\partial x} dx\, dy \qquad (1)$$

This is a second order linear partial differential equation in the form

$$\frac{\partial^2 T}{\partial x^2} - \frac{\rho u C_p}{k} \frac{\partial T}{\partial x} = 0 \qquad (2a)$$

Since T is assumed a function of x only, this can be written as a total differential equation

$$\frac{d^2 T}{dx^2} - \frac{\rho u C_p}{k} \frac{dT}{dx} = 0 \qquad (2b)$$

Which solves by operators to

$$T = C_1 + C_2\, e^{\frac{\rho u C_p x}{k}} \qquad (3)$$

Putting in the following boundary conditions:

$$T = T_u \text{ at } x = -\infty$$

and

$$T = T_{ig} \text{ at } x = 0$$

and solving for the constants C_1 and C_2, (3) reduces to

$$T = T_u + (T_{ig} - T_u)\, e^{\frac{\rho u C_p x}{k}} \qquad (4)$$

Since with the case of a stationary flame, $u = V_f$ (the normal flame speed) Equation (4) can be put in the form

$$V_f = \frac{k}{\rho C_p x} \ln\left(\frac{T - T_u}{T_{ig} - T_u}\right) \qquad (5)$$

Equation (5), however, does not allow for the explicit solution for V_f unless the temperature T is known at some finite distance x in advance of the flame front. Differentiating Equation (4) with respect to x and putting in the condition that $T = T_{ig}$ at $x = 0$:

$$\left(\frac{dT}{dx}\right)_{T_{ig}} = \frac{\rho V_f C_p}{k} \left(T_{ig} - T_u\right) \qquad (6)$$

Equation (6) represents the slope of Equation (4) at $T = T_{ig}$.

Assuming with Mallard and LeChatelier that the temperature is a linear variation with distance through the flame front, from Figure 1

$$\left(\frac{dT}{dx}\right)_{T_{ig}} = \frac{T_b - T_{ig}}{x_b} \qquad (7)$$

Assuming continuity of slope at T_{ig}, (6) and (7) can be equated and solved for V_f.

$$V_f = \frac{k}{\rho C_p x_b} \left(\frac{T_b - T_{ig}}{T_{ig} - T_u}\right) \qquad (8)$$

Equation (8) is the classical relation of Mallard and LeChatelier. It predicts several experimentally verified trends, including an increase in flame speeds with an increase in the temperature of the unburned gases, rich and lean ignition limits, greater values for flame speeds with gases having larger differences between flame temperatures and ignition temperatures, and a variation in flame speeds that is at least qualitatively correct for gases having various values of k and C_p.

However, the theory has many limitations, one of which is the inadequate concept of an ignition temperature as an entity of unburned gases. It has been shown that an ignition temperature as such is not a physical reality because the length of the induction period (the interval during which the mixture is held at the ignition temperature before the ignition actually commences) greatly affects the so-called ignition temperature. The theory also predicts infinite flame speeds at $T_u = T_{ig}$ which experimentally has been proven erroneous. Also, the assumption of a linear temperature variation in the reaction zone is highly simplified. The theory has been developed further by Crussard, Daniel, Nusselt and others incorporating the chemical reaction rate in the combustion zone. Their results can be reduced essentially to the form:

$$V_f = \sqrt{\frac{K}{\rho C_p} \left(\frac{T_b - T_{ig}}{T_{ig} - T_u} \right)}$$

where K is proportional to a reaction velocity factor as well as the thermal conductivity.

3. SOME OTHER MECHANISMS OF FLAME PROPAGATION

Many investigators visualize other processes than pure thermal conduction playing an important part in the mechanism of flame propagation. Among these, Landau* postulates a turbulent convective process. Concerning the deflagration process, he derives a relation indicating that the flame front is inherently unstable, and in the burning zone the movement of the gases is turbulent. This greatly increases the heat transfer to the unburned gases by convective mixing. He concludes that the flame propagation velocity is increased over that velocity predicted by thermal conduction alone. Damköhler** states that in the extreme limiting case of fine-scale turbulence, the ratio of the turbulent to the laminar flame speed is:

$$\frac{V_{ft}}{V_f} = \sqrt{\frac{\epsilon}{\nu}}$$

*See Reference 5.
**See Reference 6.

where ϵ is the Prandtl turbulent exchange quantity and ν is the kinematic viscosity.

Another process postulated by many investigators* is diffusion into the unburned zone ahead of the flame front by active species such as monatomic hydrogen and hydroxyl radicals which are liberated in the combustion process. The large variation in the propagation velocity of flames in $CO + O_2$ mixtures with the introduction of small amounts of water vapor is believed to result mainly from this active species diffusion.

Obviously, a more complete understanding of the phenomenon of flame propagation will be realized only by carrying out more thorough investigations in the future, both experimentally and theoretically.

4. METHODS OF FLAME SPEED MEASUREMENT

The methods of measuring normal flame speed can be grouped into two general categories: one in which the flame is moving with respect to some fixed point in space; the other in which the flame is stationary.

In the first group, perhaps the most important is the constant pressure soap-bubble method first used by Stevens** and later by Fiock and Marvin***. With this method a flame is ignited in the center of a soap bubble filled with a combustible mixture, the flame moving from the center of the bubble into a region of constant pressure. If the soap-bubble is large enough, this method probably represents the closest approximation to the normal combustion velocity that can be measured experimentally. Only one dynamic condition need be considered; viz., the rate of increase of the spherical flame front with respect to the rate of increase of the soap-bubble to determine the flame speed with respect to the unburned mixture. The main limitation of this method is its inability to show the effect of many variables on flame speed. Another method employing a constant-volume bomb has been used by other investigators. This method, however, introduces the undesirable effect of an increasing pressure of the

*See Reference 7.
**See Reference 8.
***See Reference 9.

unburned gases during the combustion process. A flame propagating in a tube filled with combustible mixture has been studied by many. Its limitations include those of the constant-pressure soap-bubble method with the introduction of various undesirable wall effects.

In the second group, the most important is the so-called Bunsen flame method, which was first begun by Bunsen and Gouy and later continued by Mache and Michelson. With this method the combustible mixture flows through a tube and burns in the form of a cone on the end of the tube. The shape of the flame surface is determined mainly by the velocity distribution of the unburned gas at the exit of the tube, and the distribution of normal flame speed over the flame surface.

An analysis of the relationship between the flow of the unburned gases and the area and normal velocity of the flame surface was first given by Gouy (Fig. 3). If we assume a constant flame speed over the whole flame surface normal to the surface, the following continuity relation must apply:

$$\rho_o A_o \bar{V}_o = \rho_f A_f V_f$$

where the area of the exit of the tube is given by A_o and the average velocity of the unburned gases above the exit of the tube $\bar{V}_o$. The quantity of gas flowing, $A_o \bar{V}_o$, must be burned in the flame surface A_f. If the density of the unburned gases at the exit of the tube, ρ_o, is assumed equal to the density of the gases, ρ_f, immediately up-stream of the flame front then the normal flame speed, V_f, is given by:

$$V_f = \frac{A_o \bar{V}_o}{A_f}$$

The main error introduced by the Gouy method is that the normal flame speed is not constant over the surface of the flame. At the base of the flame cone the flame speed is lowered due to the effect of the presence of the tube itself on the reactions occurring in the combustion zone. At the tip of the cone the flame speed is increased due to the

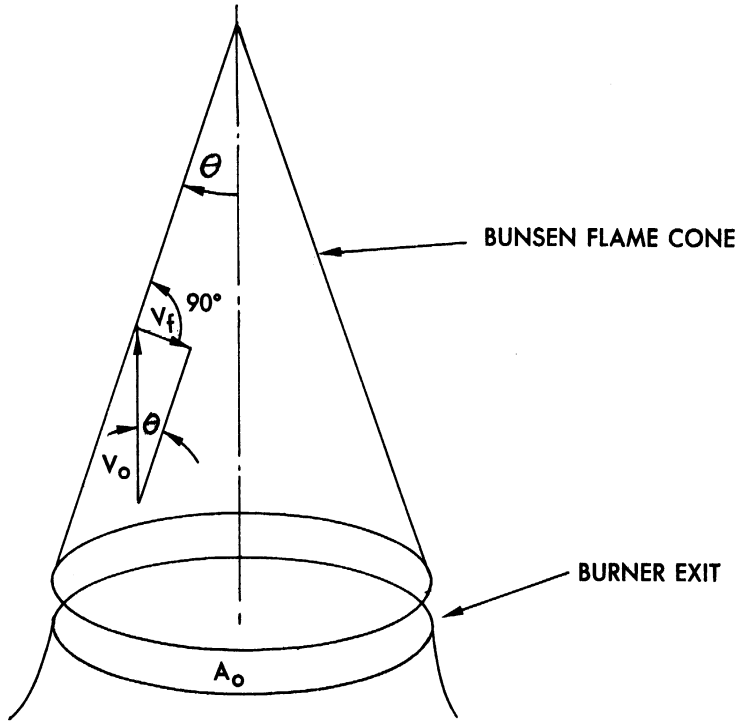


FIG. 3 DIAGRAM OF BUNSEN FLAME

preheating effect of the convergent flame surface on the unburned gases. If the tube is chosen large enough with respect to the thickness of the reaction zone, these errors are generally negligible. Similarly, the error due to the assumption of $\rho_o = \rho_f$ is negligible if the burner diameter is kept large, because the assumption is justified completely if ρ_f is taken immediately upstream of the "preparatory zone" in the unburned gases. This zone is believed to be of the same order of magnitude as the thickness of the flame zone.*

If the velocity distribution in the unburned gases is rectilinear at the exit of the burner, the flame surface closely resembles a right cone of revolution. The Gouy method then reduces to

$$V_f = \bar{V}_o \sin \theta$$

where θ is the half angle of the flame cone.

*See Reference 6 for Damköhler's estimated thickness of the preparatory zone. Also see Appendix II.

DESCRIPTION OF EQUIPMENT AND EXPERIMENTAL PROCEDURE

In order to carry out an investigation of the pressure effects on normal flame speed, the Bunsen burner flame using the Gouy area method for flame speed determination was selected because of its obvious advantages when dealing with flames burning at widely varying pressures, where the flame surface departs considerably from the form of a cone.

Two types of Bunsen flames were studied; both resulting from the burning of a flow developed in a tube of circular cross section. The first was a flame resulting from the burning of a fully developed parabolic flow, the second a flame closely representing a true cone at atmospheric pressure, resulting from the burning of a flow having a rectilinear velocity distribution at the exit of a convergent nozzle.

A brass tube with a circular cross section 1/4 inch in diameter and 23 inches long was utilized for the study of the first type of Bunsen flame (Fig. 4a). It was made long purposely to insure a fully developed Poiseuille flow. The tube was surrounded by a steam jacket to keep the tube exit at a sufficiently high temperature to prevent condensation of water vapor in the products of combustion.

For the second type of flame, a circular stainless steel tube with an internal diameter of 1 5/8 inches and a length of 24 inches was used (Fig. 4b and 5). At the exit of the tube one of four interchangeable, convergent nozzles with exit internal diameters of 3/8, 1/2, 5/8 and 1 1/4 inches was installed. With each of the three smaller burners the radius of curvature of the contracting section was made equal to the diameter of the exit section of the nozzle. The radius of curvature of the contracting section of the 1 1/4-inch diameter burner was made 4 1/2 inches because of the size limitation imposed by the 1 5/8-inch tube. This burner is not included in Figure 5. Immediately upstream of the contracting section of each burner, several layers of 100-mesh copper screens were placed to damp out flame oscillations, which were especially noticeable with the larger burners. These screens, because of their extremely fine structure, caused no observable turbulence in the flame front.*

*The measured flame speeds at atmospheric pressure are in good agreement with the laminar flame speeds appearing in the literature.

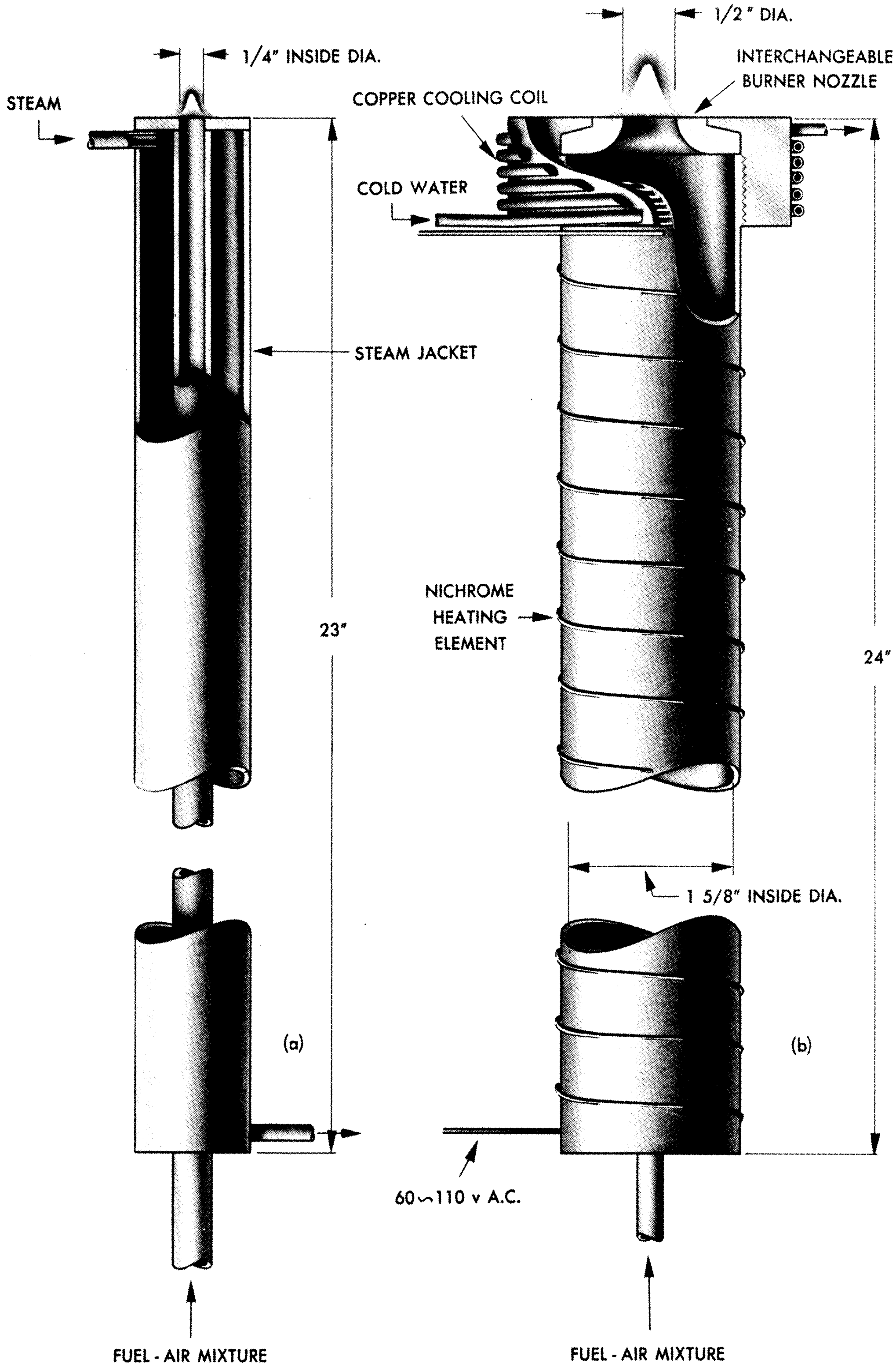


FIG. 4 LOW PRESSURE BURNER ASSEMBLIES.

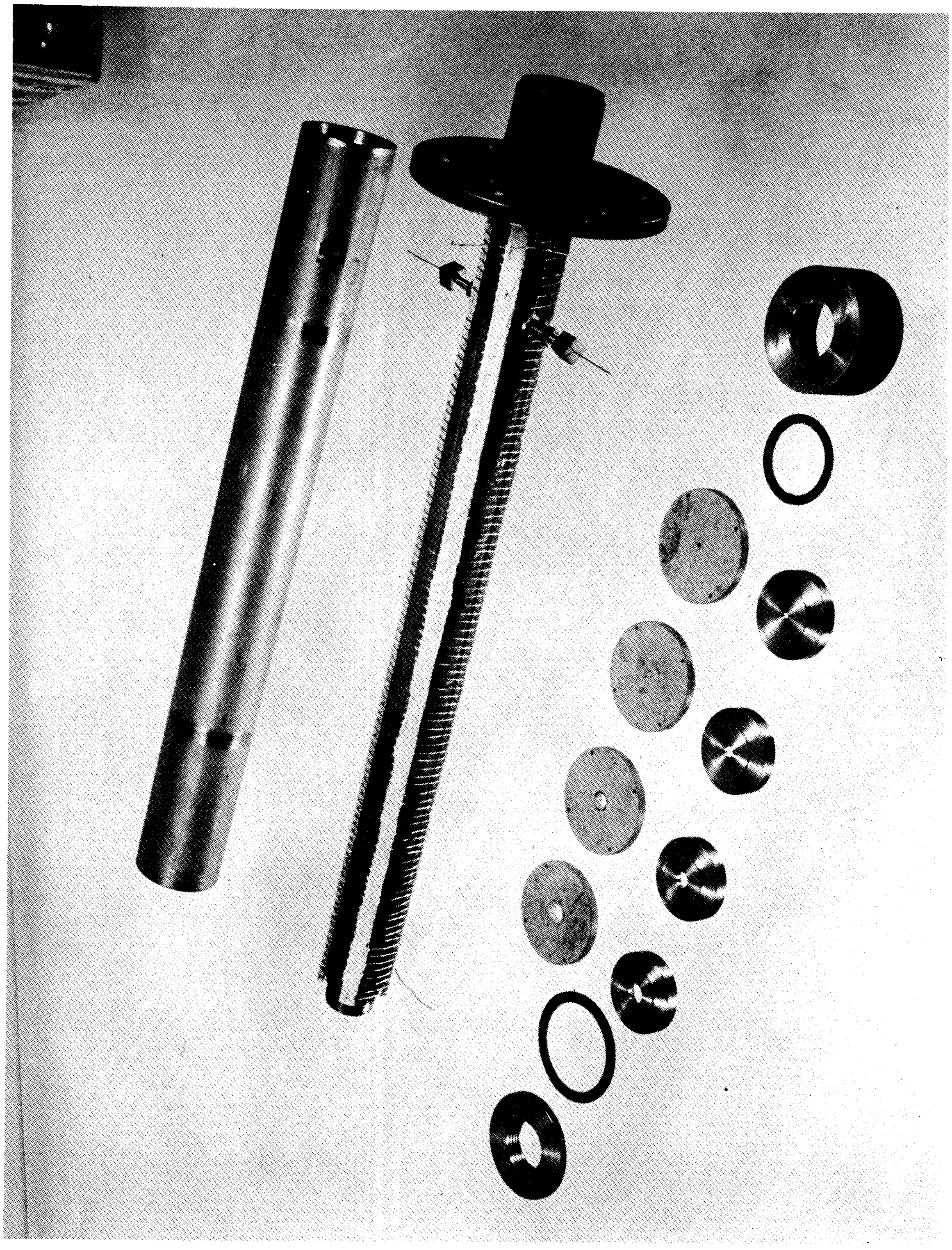


FIG. 5 BURNER TUBE AND NOZZLES.

The flames burning from these burners were nearly conical in shape at atmospheric pressure. With the flames burning above the interchangeable burners, in contrast to the flames burning above the 1/4-inch Bunsen tube, the heat supplied to the burner exit by the flame proved to be more than sufficient to evaporate the moisture deposit. Moreover, the temperature of the burner exit increased with time, causing the temperature of the inlet mixture to vary in the same manner. This effect was undesirable for the experiments in which the temperature of the inlet mixture was to be held constant. Therefore, a series of copper cooling coils through which cold water circulated was employed to keep the temperature of the burner exit constant. The rate of flow of the cooling water was adjusted so that the burner exit reached a temperature just above that of the dew point of the burned gases.

The variation of flame speed with temperature was studied using flames burning from the 1/2-inch burner. The 1 5/8-inch diameter stainless steel tube was wrapped with a heating element of nichrome wire and a lagging of asbestos was placed over the wire. The desired temperature of the mixture was obtained by varying the current through the heating element with a variable transformer.

The 1/4-inch tube was mounted in the bottom of a pressure vessel constructed of 1/2-inch welded mild steel. The dimensions of the vessel were 10 x 10 x 10 inches. The flame was observed through two 1 1/2-inch thick, laminated plate-glass windows. The surfaces of the windows on the inside of the pressure vessel were kept free of moisture by means of intermittent heating with an infra-red lamp. The flames were ignited with a high voltage spark to the tube exit from a movable electrode. The voltage was supplied from a 6-volt dry cell through a 10,000-volt induction coil.

To observe the larger flames burning from the convergent nozzles, it was necessary to construct a larger pressure vessel 10 x 12 x 20 inches, since the small vessel caused the flame to burn unsteadily (Fig. 6). In all other respects the large vessel was similar to the smaller one.

To obtain reduced pressures in the small pressure vessel a water aspirator was used. With the large pressure vessel a vacuum pump of the Nash Hytor type was employed because of its greater evacuating capacity.

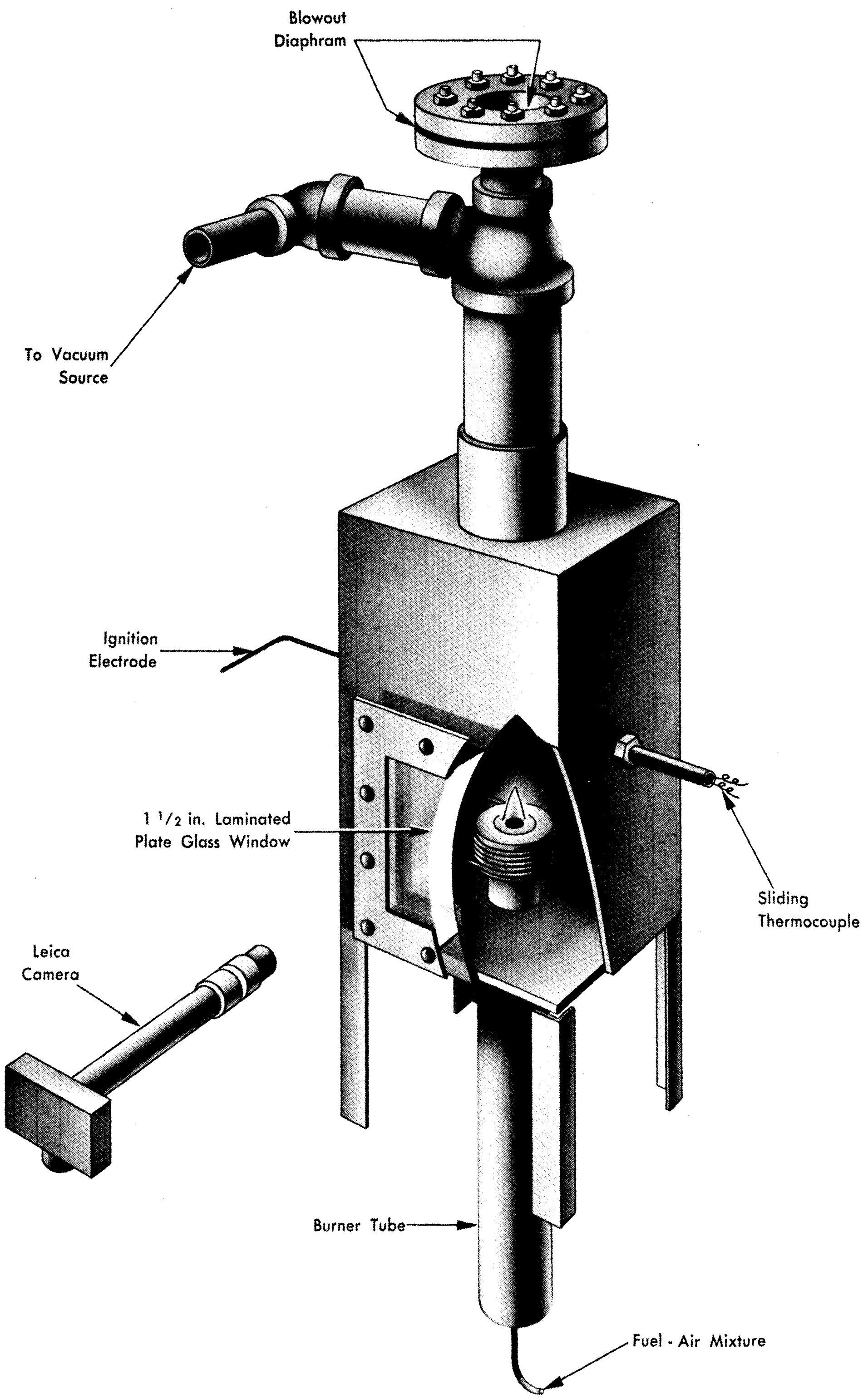


FIG. 6 LARGE PRESSURE VESSEL

To obtain the lowest pressures at which flames were observed, i.e., about 1 inch Hg absolute, a high pressure air-ejector operating between 1500 and 2000 psi was used in conjunction with the vacuum pump.

The fuels used were commercially pure propane and medical ethylene. The air was first dried to a very low humidity and then pre-mixed with the fuel in storage bottles of about three cubic feet capacity at known mixture concentrations and at a pressure of 240 psig. The bottles were stored for safety reasons in a sand-bagged building fifty feet from the laboratory. To prepare a given fuel-air mixture, the bottles were first evacuated to about 0.5 inches Hg absolute with the water ejector. Then, they were filled with the fuel to about atmospheric pressure to scavenge all but an insignificantly small amount of the air originally in the bottles and evacuated again to 0.5 inches Hg. They were then filled to a pre-calculated pressure with the fuel and then filled with air to 240 psig. The compressibility factors for propane, ethylene, and air were taken from Reference 10. This method of pre-mixing the air and fuel, while tedious, served two important purposes. It made manual control of the rate of flow to the flame much simpler because one control valve was used instead of two. Secondly, it insured that a constant fuel-air mixture was flowing at all times through the apparatus. It is doubtful if the experiments could have been carried out without considerably more elaborate equipment if a pre-mixed combustible were not used. At the initiation of the studies a separate fuel-air system was attempted. However, it was found practically impossible to maintain a constant mixture concentration at the flame for a sufficiently long period of time to insure that the fuel-air mixture at the flow measuring instruments was identical to that at the flame when the photograph of the flame was taken. Sometimes severe oscillations of the fuel-air mixture were observed which exceeded the rich and lean limits, causing the flame to blow out. With the pre-mixed gas the flow burned steadily, greatly facilitating observations.

Three Fisher and Porter rotameters and one Schutte and Koerting rotameter of different flow capacities were used to meter the flow. These were calibrated for air against standard flow meters at a standard density of 0.073 lb/ft^3. The two smaller rotameters were also calibrated by a positive displacement method using a fuel-air mixture. The calibration by the positive displacement was in good agreement with that obtained by calibration with the standard flow meters.

The pressure at the rotameters and in the pressure vessel was recorded by two 117-inch Meriam type mercury manometers. The temperature at the rotameter was obtained by a mercury thermometer with the bulb immersed in the line carrying the fuel-air mixture immediately downstream of the rotameter. The temperature of the combustible mixture at the nozzle exit was obtained by means of a chromel-alumel (22 gauge) sliding thermocouple assembly with an O-ring seal. A Leeds and Northrup potentiometer was used to record the temperature. A schematic drawing of the complete apparatus appears in Figure 7.

A Leica 35 mm camera was used to photograph the flame. A copying attachment and a Hektor f 4.5 telephoto lens with a focal length of 135 mm was utilized to increase or decrease the flame size on the negative, depending on the size of the flame being used. In all cases, the image on the film was kept as large as possible. The film used in all the experiments was Ansco Supreme, a moderately fast film with fine-grain characteristics.

The photographs of the flames were mounted in glass slides and projected on white tracing paper to between ten to fifteen times natural size. The inner surface of the flame cone was traced including all of the fillet at the bottom of the flame cone. At atmospheric pressures this fillet was a very small portion of the total flame area. However, at lower pressures the fillet area became increasingly larger with respect to the total flame surface, so that in the vicinity of the minimum pressure attained with each burner the fillet area became as much as 30% of the total flame area. Also, due to the diffuse appearance of the flame surface at low pressures, as is evident in Figures 9 to 14, it was difficult to select the exact lower limit of the flame front. To establish a uniformity in measurement, the furthest visible extent of the flame surface on the negative was used as this limit with all of the flame photographs. In conjunction with this, the exposures given the flames varied, depending upon the pressure. Over-exposures were taken at low pressures to insure that the entire visible surface was included. The method of surface area determination of the flame projections appears in Appendix I.

The test runs at reduced pressures for the 3/8-inch, 1/2-inch, and 5/8-inch burners were made in the following manner. A photograph of a

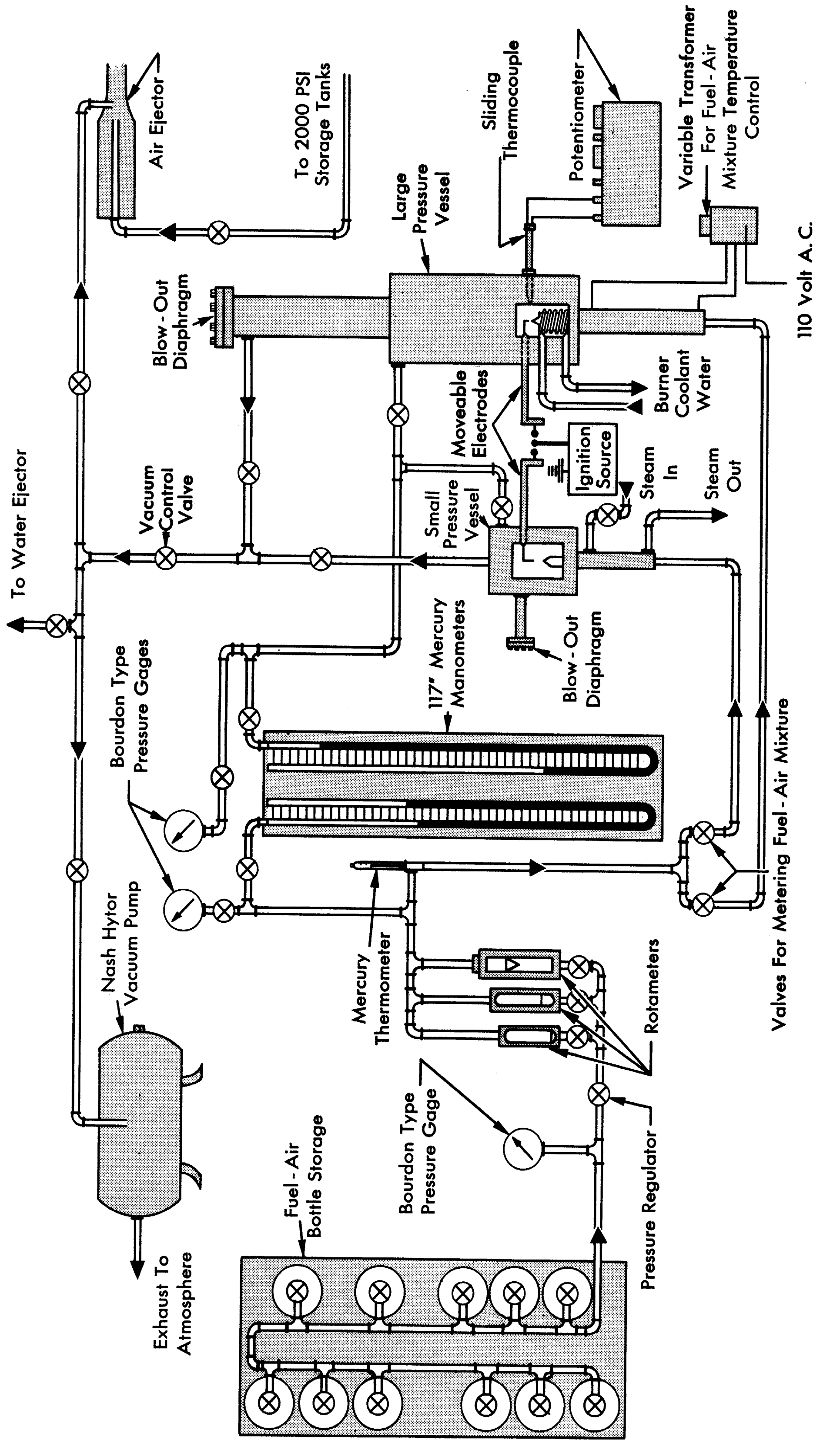


FIG. 7 SCHEMATIC DRAWING OF COMPLETE APPARATUS

scale placed at the axis of the burner was first taken to determine the scale size of the flame. The burner was then ignited and allowed to burn at atmospheric pressure for 10 to 15 minutes, during which time the coolant flow around the burner exit was adjusted so that the temperature of the exit was just above the dew point. When this temperature was stabilized, the flame was blown off and the sliding thermocouple was moved over the burner exit and the temperature of the unburned gases was measured. The flame was then reignited and photographed with simultaneous readings taken of all the necessary quantities, i.e., rotameter flow, temperature and pressure at rotameter, and the pressure in the pressure vessel. The valve to the vacuum source was then partially opened and the vent valve to the pressure vessel was closed. The pressure at the rotameter was held to a fairly constant value slightly above atmospheric pressure by means of a pressure regulator. The flow to the flame was controlled by a metering valve downstream of the rotameter. As the pressure slowly decreased, the photographs of the flame were taken at the desired pressures. The flow rate to the flame for a given size burner was kept fairly constant down to a pressure below which the flow had to be continually reduced to prevent blowoff.* After the lowest pressure was attained, the flame was again blown off and the temperature of the mixture at the burner exit was taken. The variation in temperature for the four propane-air pressure runs was from 82° to 87° F. and for the ethylene-air runs from 84° to 91° F. These temperature variations proved to have a negligible effect on flame speed.

With the 1 1/4-inch diameter burner the pressure runs were initiated at 10-inch Hg absolute for the ethylene-air mixtures and 13-inch Hg absolute for the propane-air mixtures. These pressures represented the upper pressure limit at which flames could be burned from the 1 1/4-inch burner without distortion of the flame cone due to turbulence. In other respects the runs were made in a manner similar to the runs made with the smaller size burners.

*This limiting flow rate was used rather than a constant flow rate at all pressures, because the blowoff of the flame at low pressures and snap back of the flame at high pressures limited the range of pressures that could be investigated.

At elevated temperatures, a propane-air mixture and the 1/2-inch diameter burner were used. The flame was ignited and the current to the heating element increased until the temperature of the combustible mixture in the 1 5/8-inch tube reached the ignition temperature at the tube walls. At this point spontaneous ignition occurred in the mixture, causing the flame at the burner exit to be extinguished. The current to the heating coils was then turned off, the temperature of the mixture at the burner exit was measured, the flame was reignited and a photograph with the simultaneous aforementioned readings was taken. During the cooling process, which lasted for longer than an hour, photographs were taken at decreasing temperatures. The flame was blown out and the temperature of the mixture taken each time alternately before and after each photograph to equalize the slight temperature decrease in the short period of time between the two operations. This experiment was conducted from high to low temperatures because it was noticed during the heating process that the addition of heat to the gas mixture caused large fluctuations in the flame. These fluctuations were not present during cooling.

The initial reduced pressure runs were made in the small pressure vessel with the 1/4-inch Bunsen tube. The only data with the 1/4-inch Bunsen tube included in this report, however, were the runs made at atmospheric pressure with several different mixture concentrations of propane and air. In the earlier runs made with the small 1/4-inch Bunsen tube at different pressures, the flow was metered upstream of the rotameter, with the rotameter pressure assuming a value very close to the reduced pressure at the flame. While this extended the range of the rotameters, the standard rotameter density correction factor was found to be considerably in error at low pressures. For this reason with all later experiments in the large pressure vessel the gas density at the rotameter was kept approximately equal to that value used during the rotameter calibration, i.e., atmospheric density of .073 $lb./ft.^3$ Since any correction to the reduced pressure data with the 1/4-inch Bunsen tube was questionable, the data are not included.

For all the runs made using propane-air as a combustible, the fuel-air mixture for maximum flame speed was used, i.e., .067 pound propane/pound air obtained from Figure 8. For the ethylene-air flames a fuel-air ratio of .0836 pound ethylene/pound air was used. This value was taken as the approximate average mixture of ethylene-air for maximum

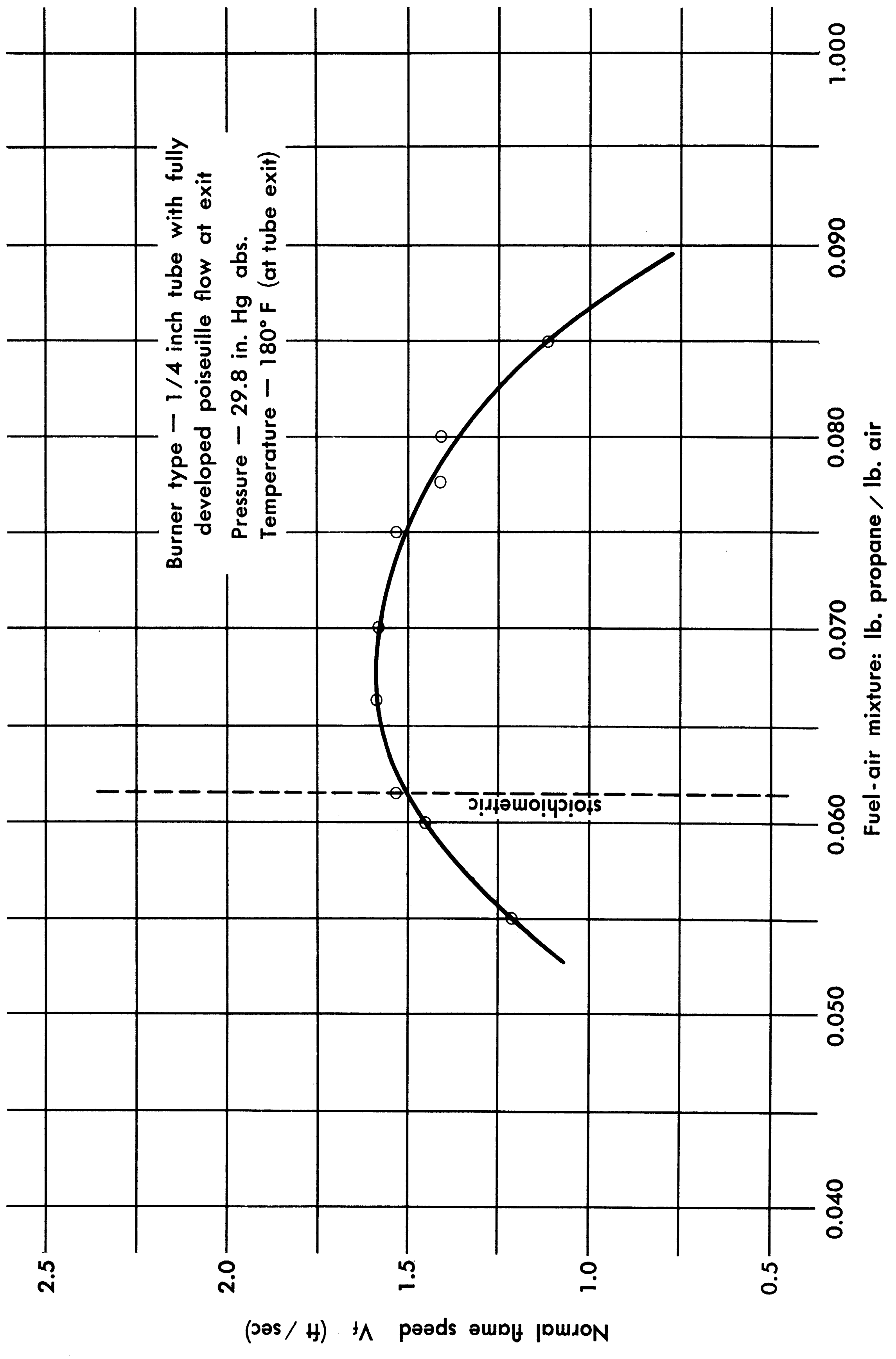


FIG. 8 THE EFFECT OF FUEL - AIR RATIO ON NORMAL FLAME SPEED FOR PROPANE AIR BUNSEN FLAMES

flame speed appearing in the literature.* The mixtures for maximum flame speed were used instead of stoichiometric mixtures in order to attain the lowest possible pressures before blowoff. One filling of the four storage bottles for propane-air and the three storage bottles for ethylene-air was sufficient for all the observed data in this report. This eliminated any effect of small variations in the fuel-air ratio and the humidity on the observed flame speed.

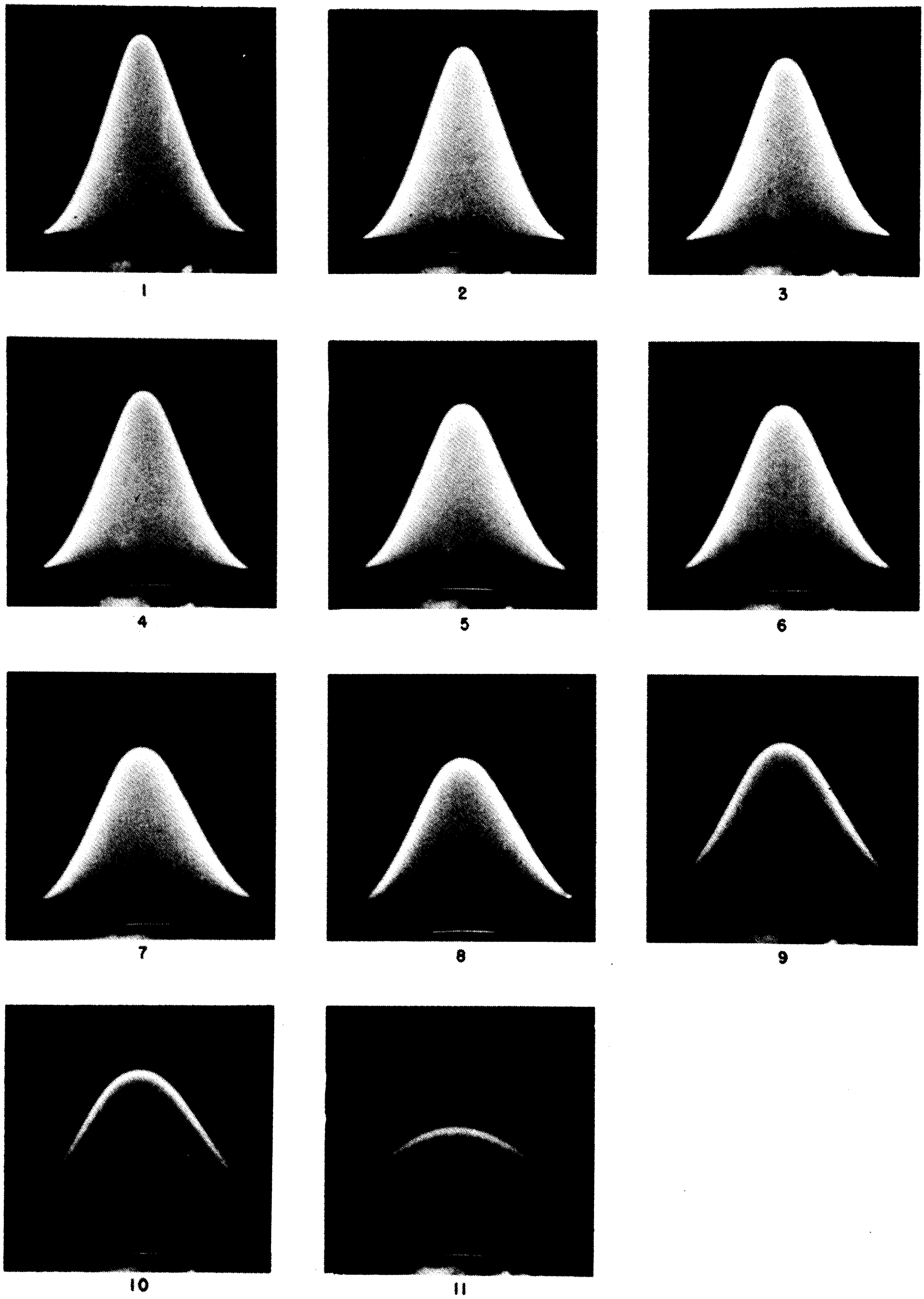
*It is believed, however, that this value was chosen too large, because upon later investigation it was found that the average was closer to 7% ethylene.

RESULTS AND DISCUSSION

1. DISCUSSION OF FLAME PHOTOGRAPHS

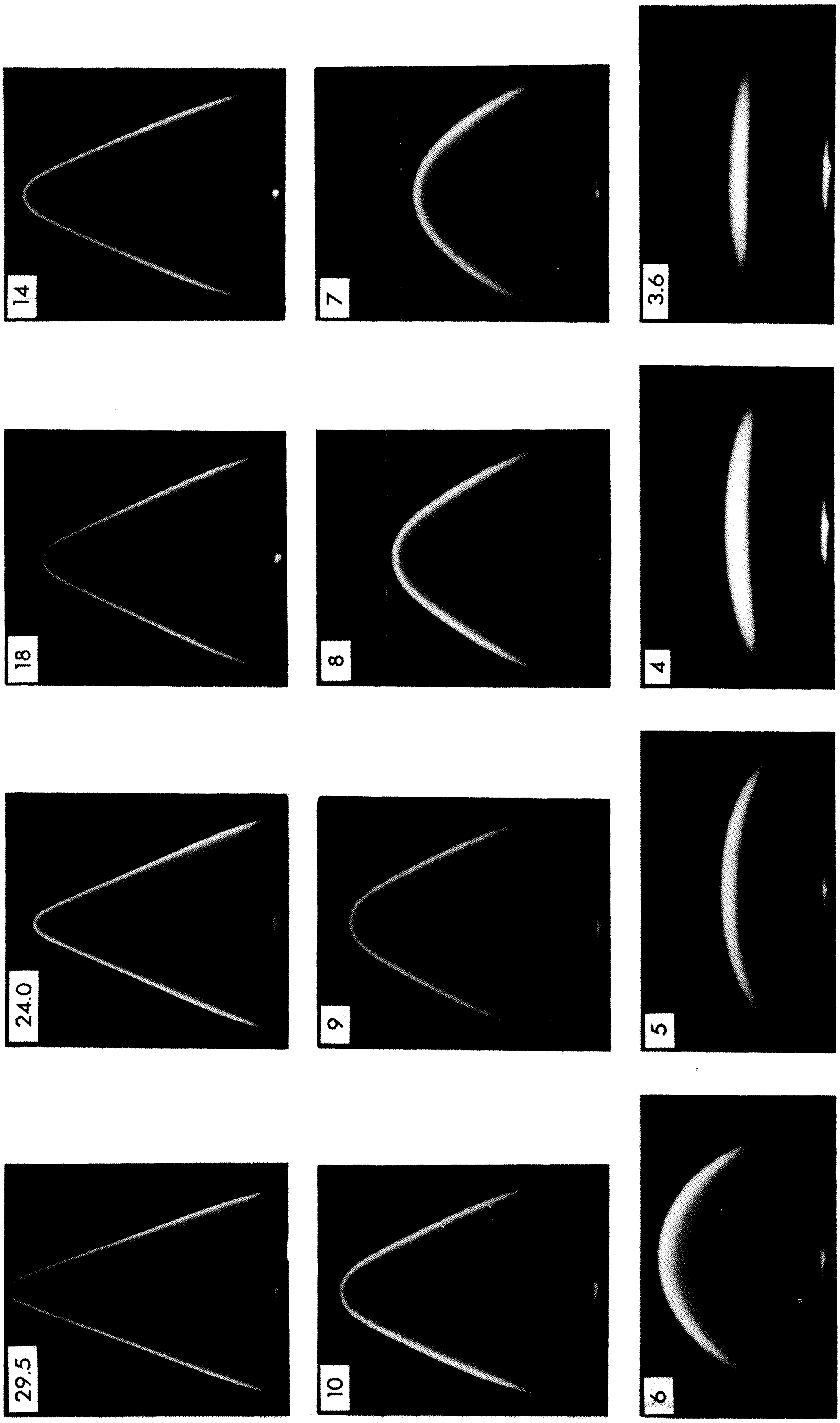
Photographs of flames burning from the various size burners and at different pressures appear in Figures 9 through 14. Figure 9 shows a propane-air flame burning from the 1/4-inch Bunsen tube at pressures ranging from atmospheric to 9.6 inches Hg absolute. At atmospheric pressure the flame surface is characteristic of the type observed with a fully developed Poiseuille flow at the tube exit, while at lower pressures the flame surface becomes practically flat with the thickness of the luminous flame front becoming much greater. Figure 10 shows the same effect with an ethylene-air flame burning from a 3/8-inch burner, having a convergent exit section, at pressures varying from atmospheric to 3.6 inches Hg absolute. At atmospheric pressure the flame surface approximates a right cone of revolution, the result of a nearly rectilinear flow distribution at the burner exit. Similarly, as in the case with the 1/4-inch Bunsen tube, the flame surface becomes nearly flat at low pressures. Figure 11 shows an ethylene-air flame burning above the 1 1/4-inch burner. At 8 inches Hg absolute the flame resembles a right cone of revolution although not as closely as in the case of the 3/8-inch burner at atmospheric pressure, undoubtedly due to the departure of the flow at the exit of the 1 1/4-inch burner from a rectilinear type distribution. This was not objectionable, as mentioned earlier in the report, because the normal flame speed was obtained by determining the surface area of the flame cone.

Comparing the flame photographs in Figures 10 and 11, an interesting fact is apparent. The flames burning from the 1 1/4-inch burner closely resemble the flames burning from the 3/8-inch burner throughout the range of pressures shown in each case, i.e., the flame front thickness, the radius of curvature of the apex of the cone, and the "dead space" vary in the same manner with pressure. In both cases, the lowest pressure is about one-eighth of the highest value. The absolute pressures at the upper and lower limit of the range of pressures for the 3/8-inch burner is about 3.5 times the corresponding pressures with the 1 1/4-inch burner. The burner sizes are different by a factor of about 3.3. In other words, to establish similarity in flames burning at pressures differing by a certain factor, the burner diameter for the flames at the lower pressure



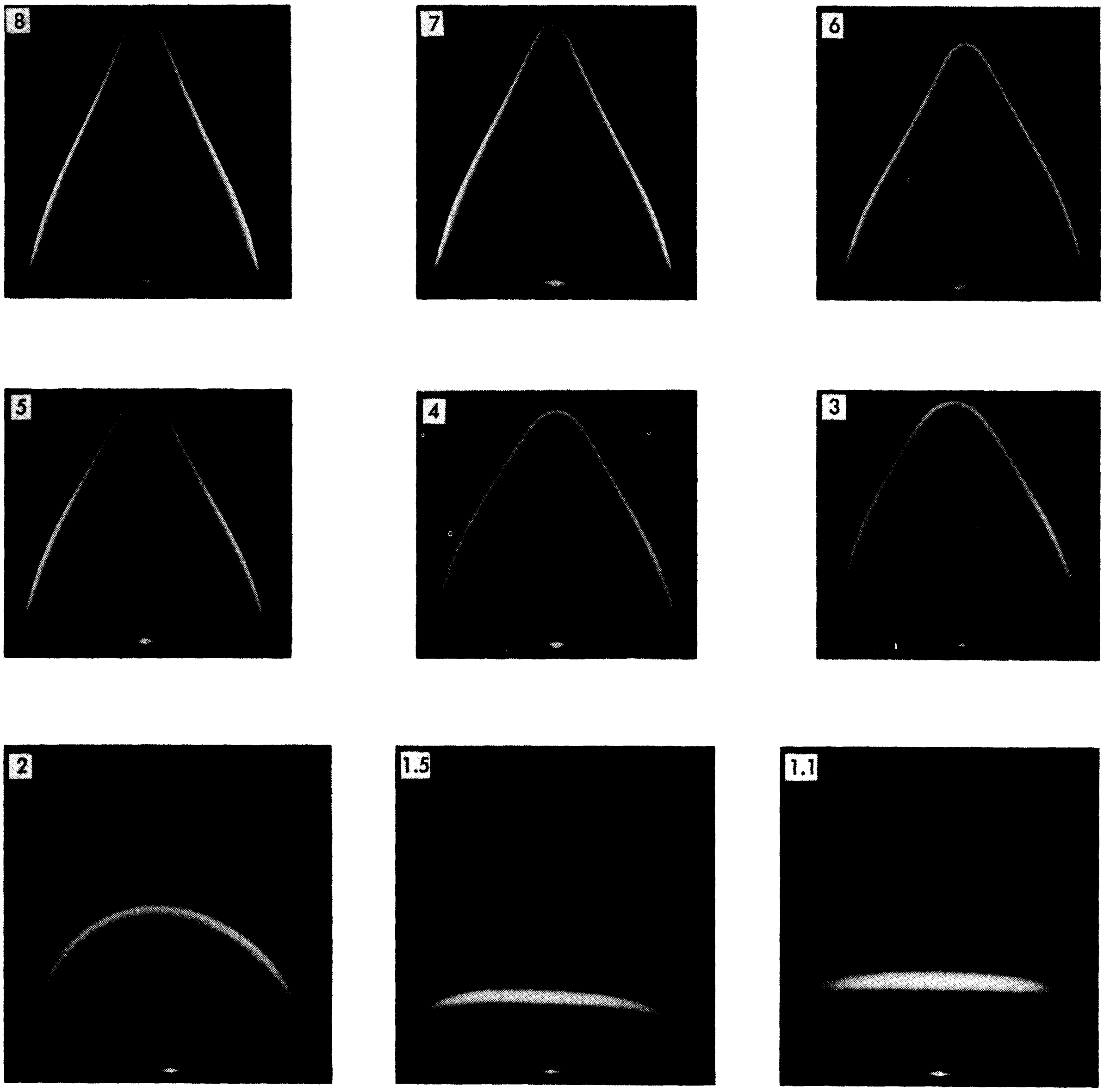
PROPANE — AIR MIXTURES F / A (BY WEIGHT) 0.067 BURNER TUBE DIA. 0.25" CONSTANT VOLUMETRIC FLOW RATES FOR RUNS 1 - 9 RANGE OF PRESSURES FROM 14.5 PSIA FOR RUN 1 TO 4.7 PSIA FOR RUN 11 IN PRESSURE INCREMENTS OF 1 PSIA

FIG. 9 BUNSEN FLAMES AT REDUCED PRESSURES



Fuel - Air Ratio 0.0836 lb. Ethylene/lb. Air
Diameter of Burner Exit 3/8 Inch
Numbers Under Photographs Indicate Pressure in Inches of Hg abs.

FIG. 10 ETHYLENE - AIR BUNSEN FLAMES AT REDUCED PRESSURES WITH THE 3/8 INCH BURNER.



Fuel - Air Ratio 0.0836 lb. Ethylene / lb. Air
Diameter of Burner Exit 1 1/4 in.
Numbers Under Photographs Indicate Pressure in Inches of Hg abs.

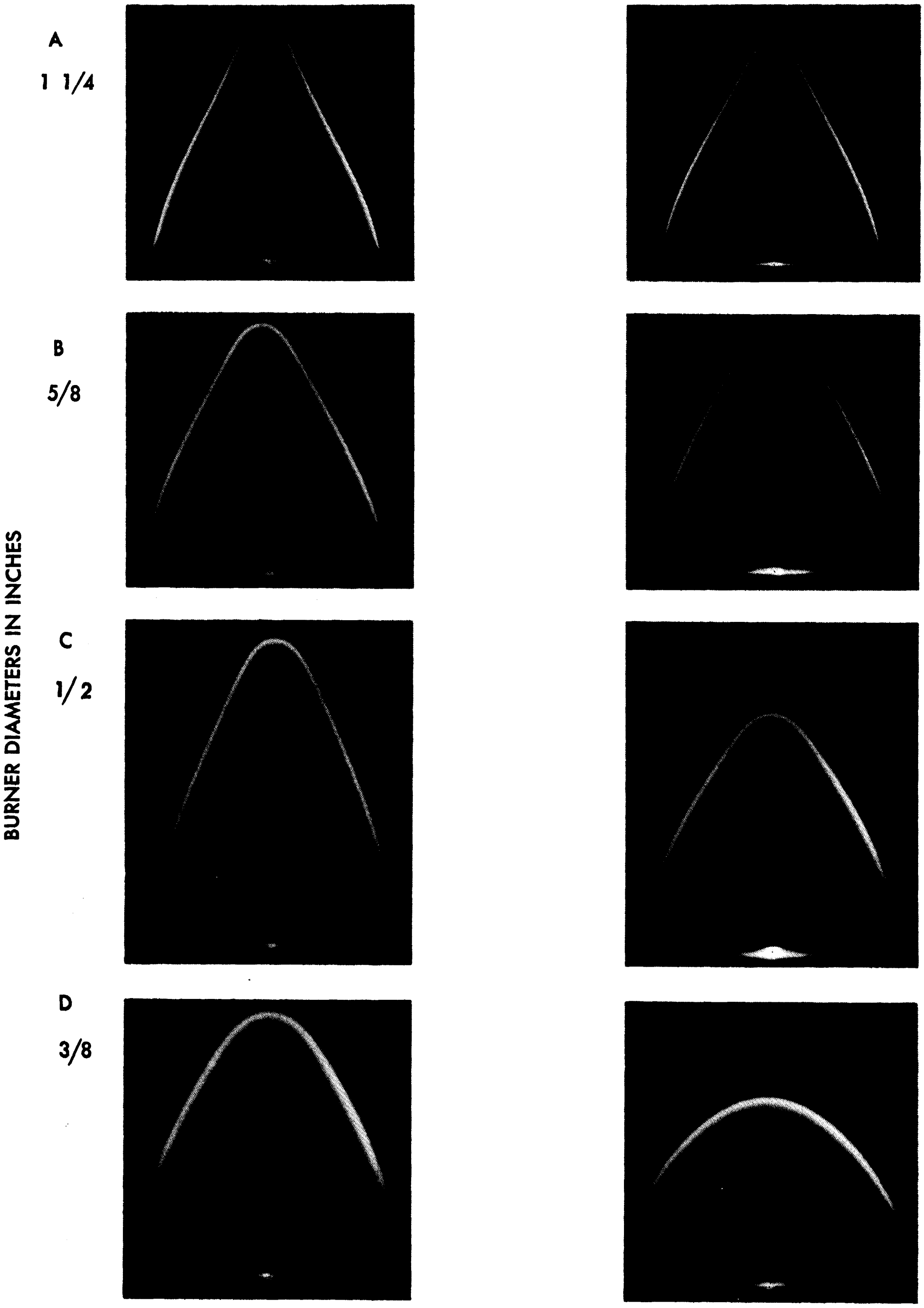
FIG. 11 ETHYLENE - AIR BUNSEN FLAMES AT REDUCED PRESSURES WITH THE 1 1/4 INCH BURNER.

must be greater than the burner diameter of the flames at the higher pressure by that same factor. The importance of this fact on the variation of the flame speed at various pressures is brought out later in this the report.

Figures 12 and 13 compare ethylene-air and propane-air flames burning from the four different size burners at various pressures. Figure 12 shows ethylene-air flames at 8 inches Hg absolute and propane-air flames at 10 inches Hg absolute. Figure 13 shows ethylene-air flames at 4 inches Hg absolute and propane-air flames at 6 inches Hg absolute. It is again of interest to note that at any given pressure the non-similarity between the flames burning from the four burners is quite evident. It must be remembered that in all cases the flames burning from the smaller burners have been enlarged so that all the flames appear approximately the same size. Figure 14 shows the effect of varying flow velocities on the shape of the flame surface at low pressures with ethylene-air and propane-air flames burning from the 1 1/4-inch burner. The velocity gradients in the flow are such that the flame surface can be made concave downward without the flame snapping back in the burner. With this size burner it was possible to reduce the flow even lower than in the photographs, to a point where the bottom of the flame surface was considerably below the burner rim without the flame snapping back. The fuel-air mixture used with the flames pictured in Figures 9 through 14 was .067 pound propane/pound air and .0836 pound ethylene/pound air, i.e., the mixtures for maximum flame speed.

2. EXPERIMENTAL RESULTS

Figure 15 shows the variation in normal flame speed with pressure for propane-air flames with four burner sizes at a mixture concentration of .067 pound propane/pound air and with a variation of inlet mixture temperatures from 82° F. to 87° F. Figure 16 is a similar plot showing the variation in normal flame speed with pressure for ethylene-air flames at a mixture concentration of .0836 pound ethylene/pound air and with inlet mixture temperatures varying between 84° F. and 91° F. From the results it appears that the burner size has a marked effect on the observed normal flame speed. Especially noticeable is a sharp decrease in flame speed near the lower pressure limit for each burner. However, it also appears that there is an increasing trend in flame speeds with



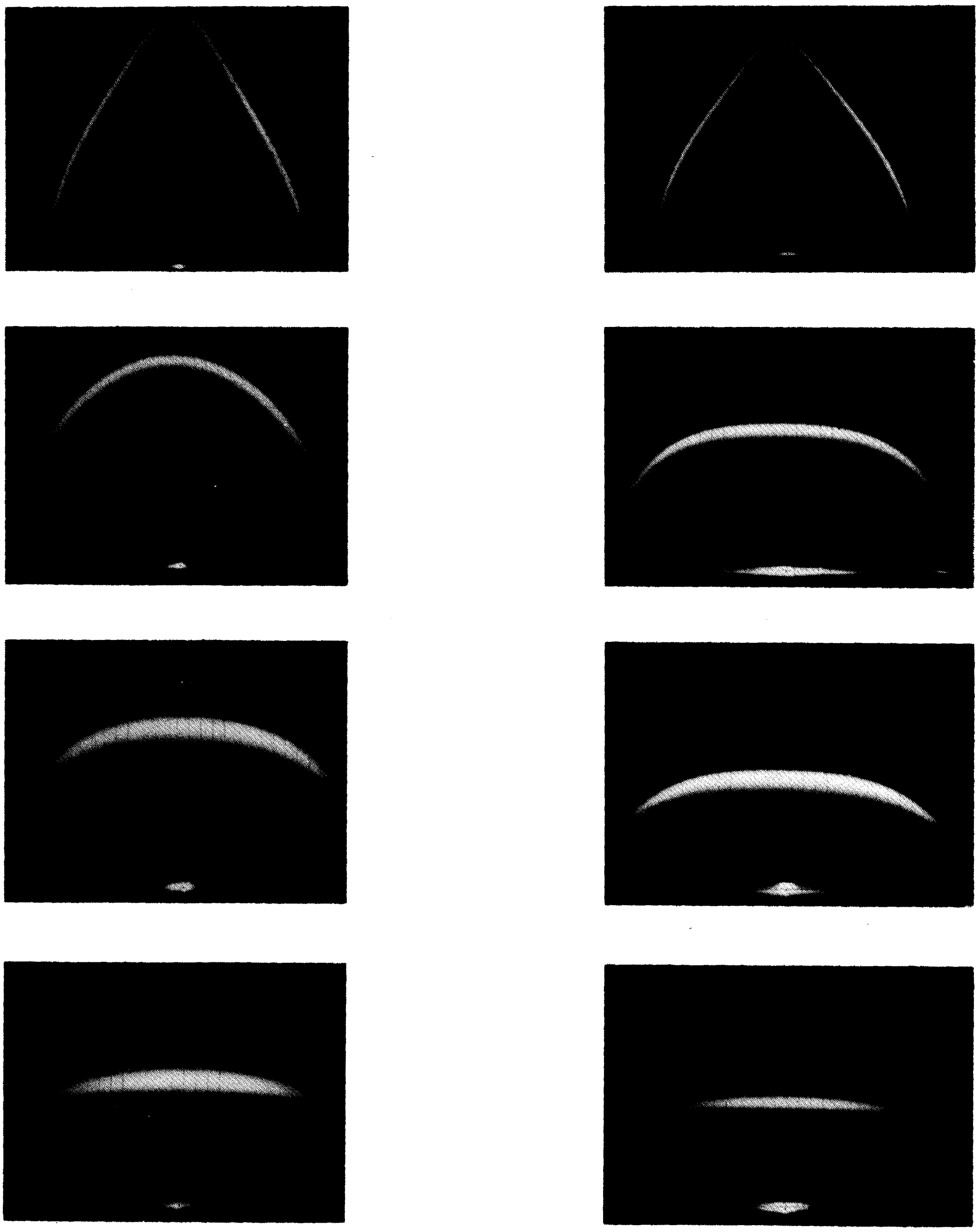
ETHYLENE - AIR FLAMES

Fuel - Air Ratio 0.0836 lb. Ethylene/lb. Air
Pressure 8 in. Mercury, abs.

PROPANE - AIR FLAMES

Fuel-Air Ratio 0.067 lb. Propane/lb. Air
Pressure 10 in. Mercury, abs.

FIG. 12 PROPANE - AIR FLAMES AND ETHYLENE - AIR FLAMES BURNING FROM THE FOUR DIFFERENT DIAMETER BURNERS AT 10 IN. Hg ABS. & 8 IN. Hg ABS.



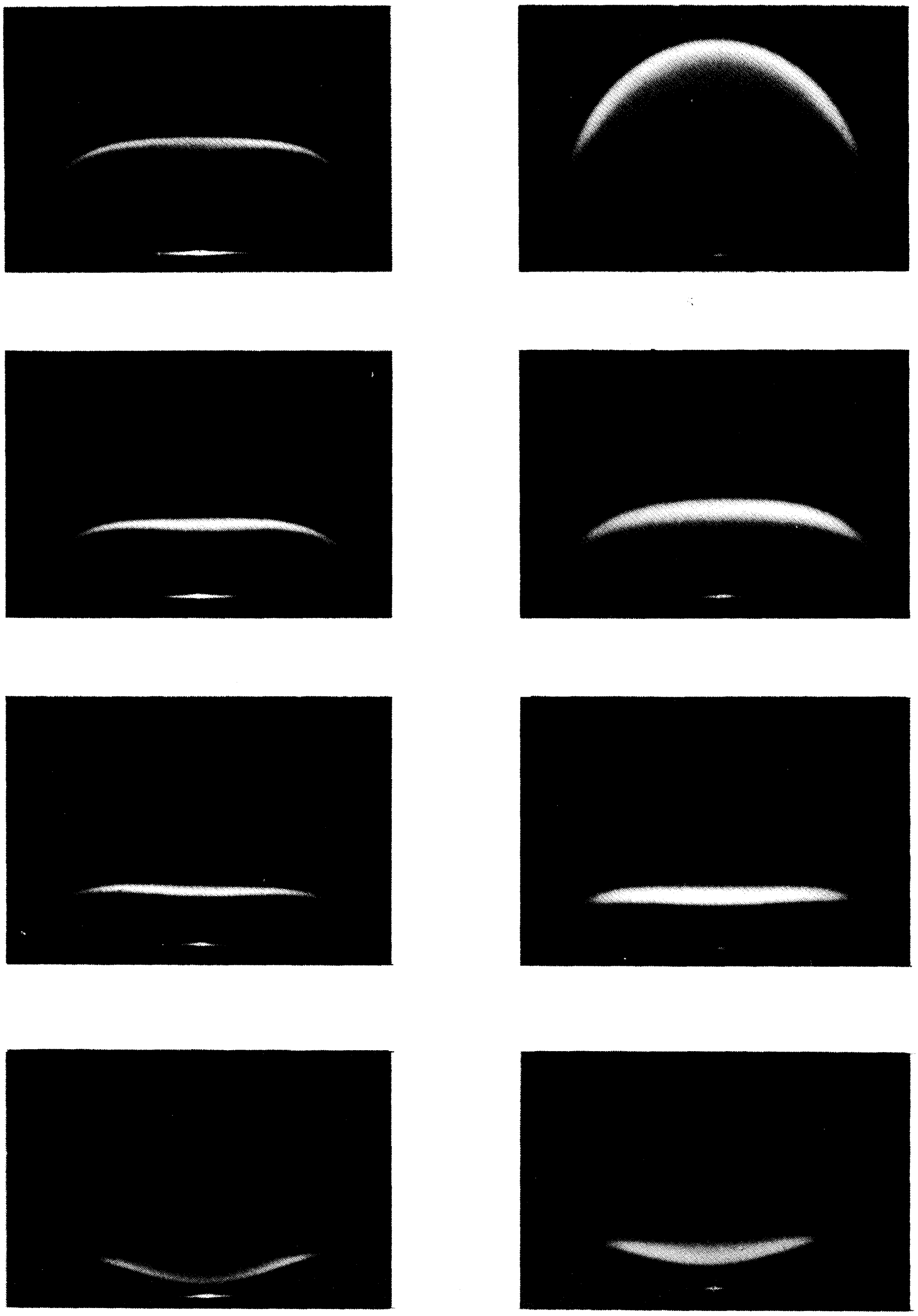
ETHYLENE - AIR FLAMES

Fuel - Air Ratio	0.0836 lb. Ethylene/lb. Air
Pressure	4 in. Mercury, abs.

PROPANE - AIR FLAMES

Fuel -Air Ratio	0.067 lb. Propane/lb. Air
Pressure	6 in. Mercury, abs.

FIG. 13 PROPANE - AIR FLAMES AND ETHYLENE - AIR FLAMES BURNING FROM THE FOUR DIFFERENT DIAMETER BURNERS AT 6 IN. Hg ABS. & 4 IN. Hg ABS.



PROPANE - AIR FLAMES

Fuel - Air Ratio 0.067 lb. Propane / lb. Air
Pressure 2.5 in. Mercury, abs.

ETHYLENE - AIR FLAMES

Fuel - Air Ratio 0.0836 lb. Ethylene / lb. Air
Pressure 1.5 in. Mercury abs.

Decreasing Flow Rates From Top to Bottom

FIG. 14 EFFECT OF VARIATION OF FLOW RATE ON PROPANE - AIR AND ETHYLENE - AIR FLAMES AT REDUCED PRESSURES WITH THE 1 1/4 INCH BURNER.

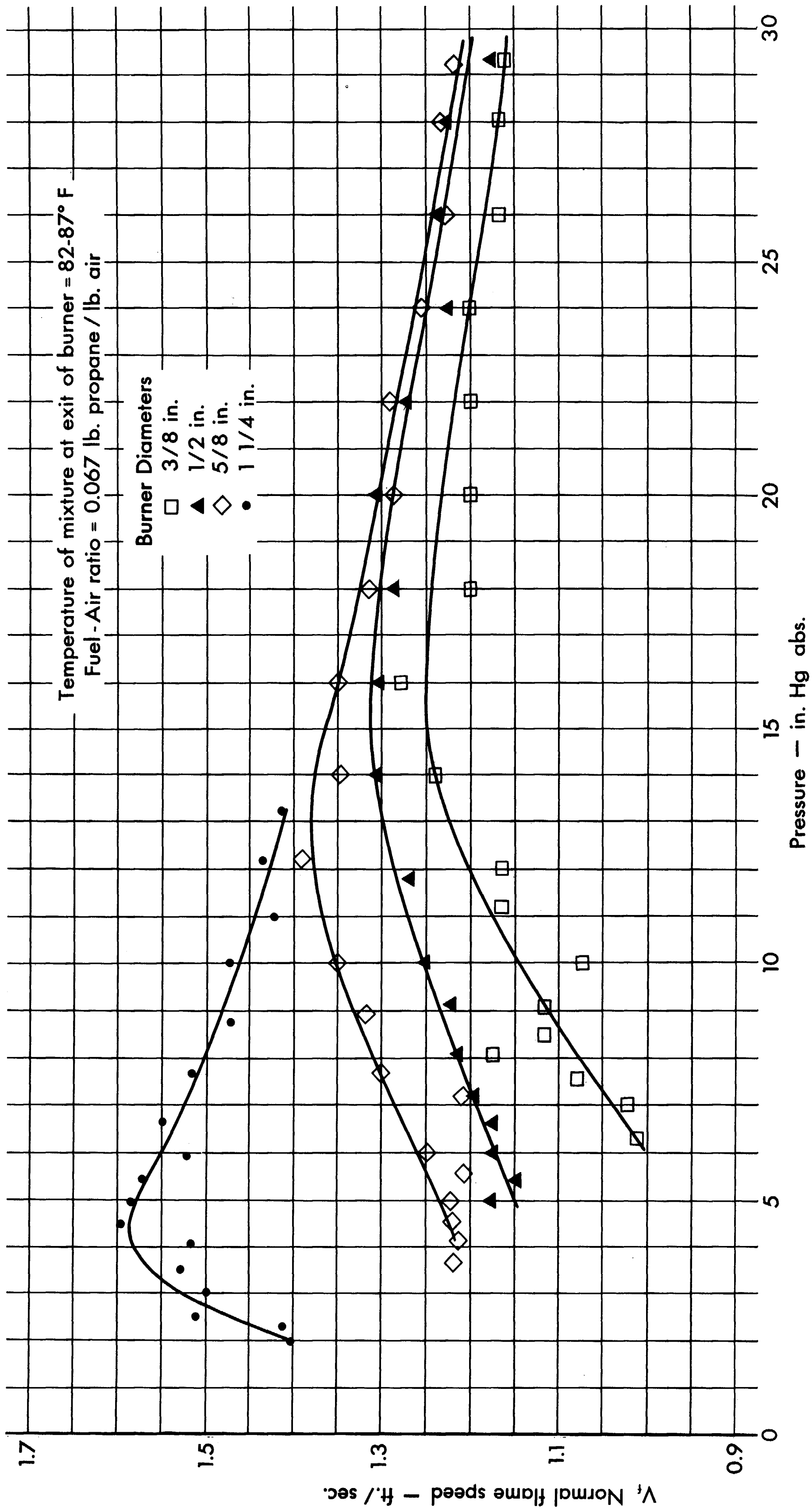


FIG. 15 VARIATION OF NORMAL FLAME SPEED WITH PRESSURE FOR PROPANE — AIR BUNSEN FLAMES WITH FOUR BURNER SIZES

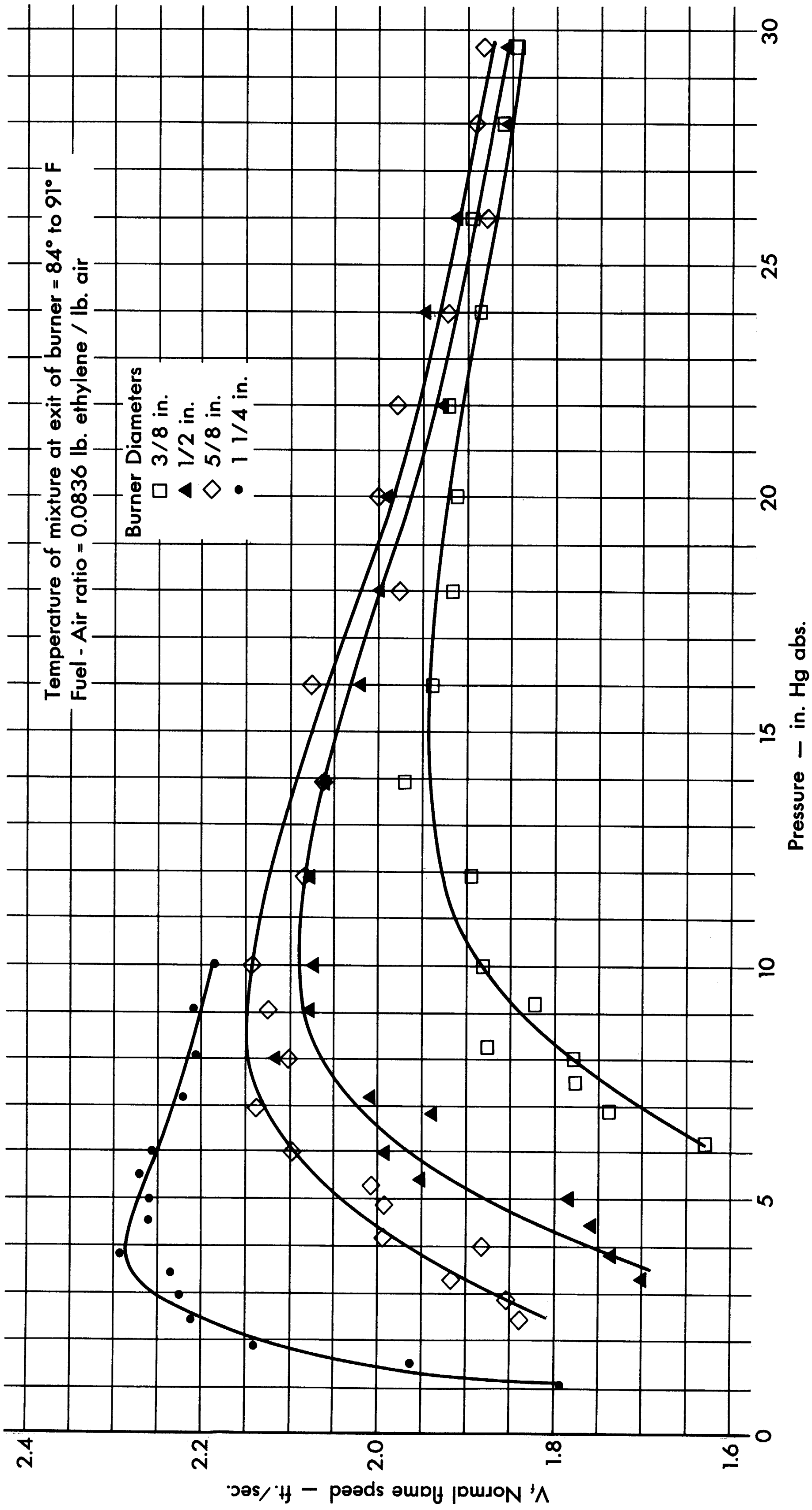


FIG. 16 VARIATION OF NORMAL FLAME SPEED WITH PRESSURE FOR ETHYLENE—AIR BUNSEN FLAMES WITH FOUR BURNER SIZES

decreasing pressure for both fuels if an upper envelope of the curves representing the flame speeds observed from the four burners is considered.

The variation with pressure of the "dead space", which can be defined as the vertical distance between the lower limit of the visible reaction zone and the rim of the burner, is shown in Figure 17. It should be stated that the absolute values are only qualitative since the photographs used for the determination of this distance were the same photographs used for the determination of the flame speed. The axis of the photographs was taken through a point about one-third of the distance from the bottom of the cone to the apex, thus tending to cancel any effects of distortion of the flame surface from the desired vertical cross section. At higher pressures, the actual "dead space" is slightly greater than that shown, while at lower pressures where the bottom of the flame cone approaches the photographic axis, the values shown approach closely the actual distances. Figure 18 shows the variation of "dead space" with the flow rate for propane-air flames burning from the 5/8-inch diameter burner at a pressure of 6 inches Hg absolute. It is evident that for low flow rates the variation in "dead space" is negligible. However, shortly before blowoff there is a definite increase in the measured values of "dead space".

The variation in the thickness of the luminous flame zone with pressure is shown in Figure 19. The values are an average of the thickness taken at two points on the flame surface. Figures 17 and 19 show, in a qualitative way at least, that there is a similar trend to the variation with pressure of both the thickness of the luminous flame zone and the "dead space".

Figure 20 is a plot of normal flame speed versus temperature for a propane-air flame burning above the 1/2-inch burner. The mixture concentration used, as in the reduced pressure experiments, was .067 pound propane/pound air. The normal flame speed appears to vary directly with temperature to a power that is just slightly greater than unity.

The five points that appear above the curve at the lowest temperatures were ignored in fairing the curve. Instead the curve was drawn through a point at 82° F. which was obtained at atmospheric pressure during the reduced pressure experiments with the 1/2-inch burner (Fig. 15). The five points were discarded because, during the cooling

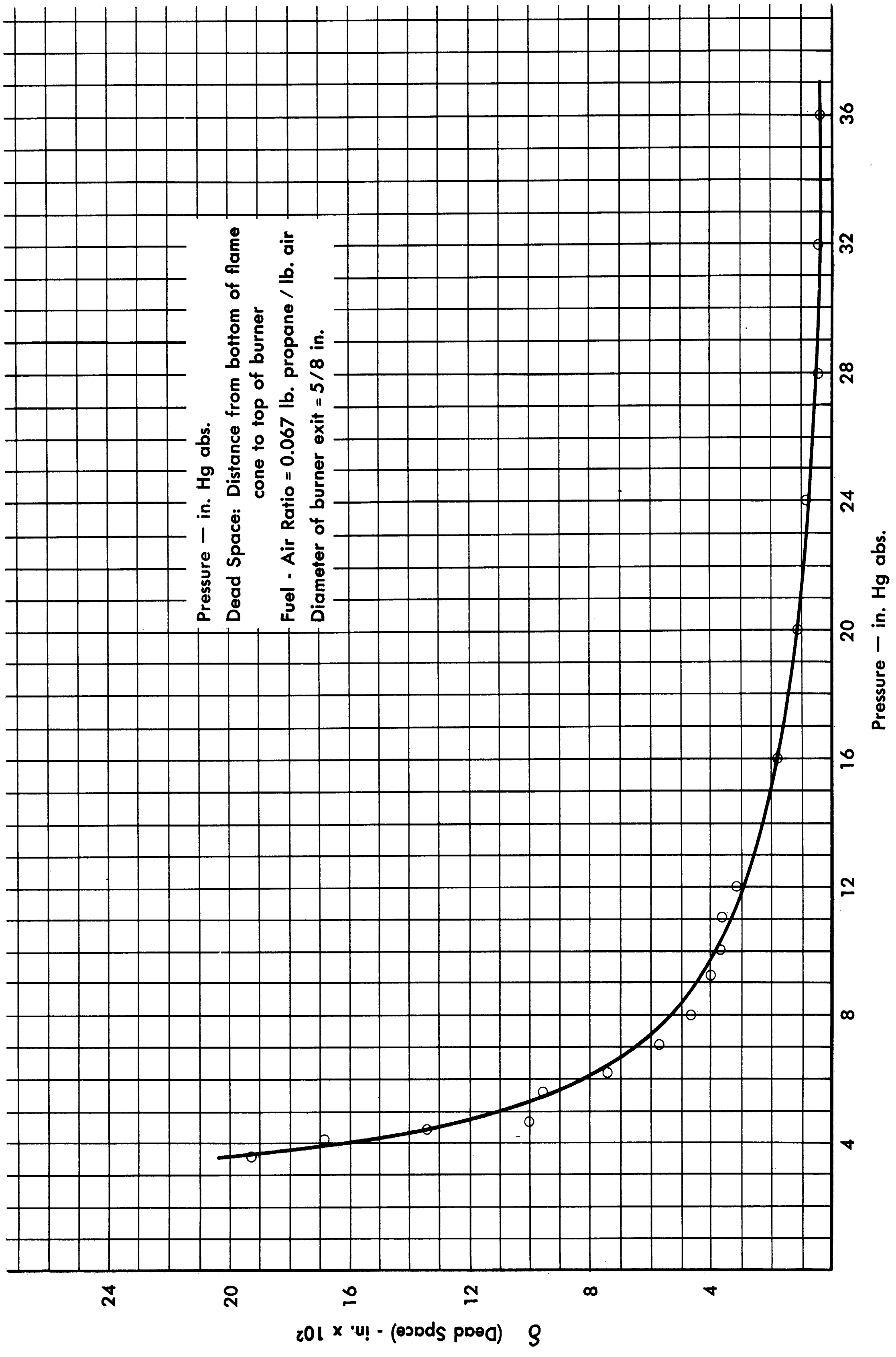


FIG. 17 VARIATION OF DEAD SPACE WITH PRESSURE FOR PROPANE—AIR BUNSEN FLAMES

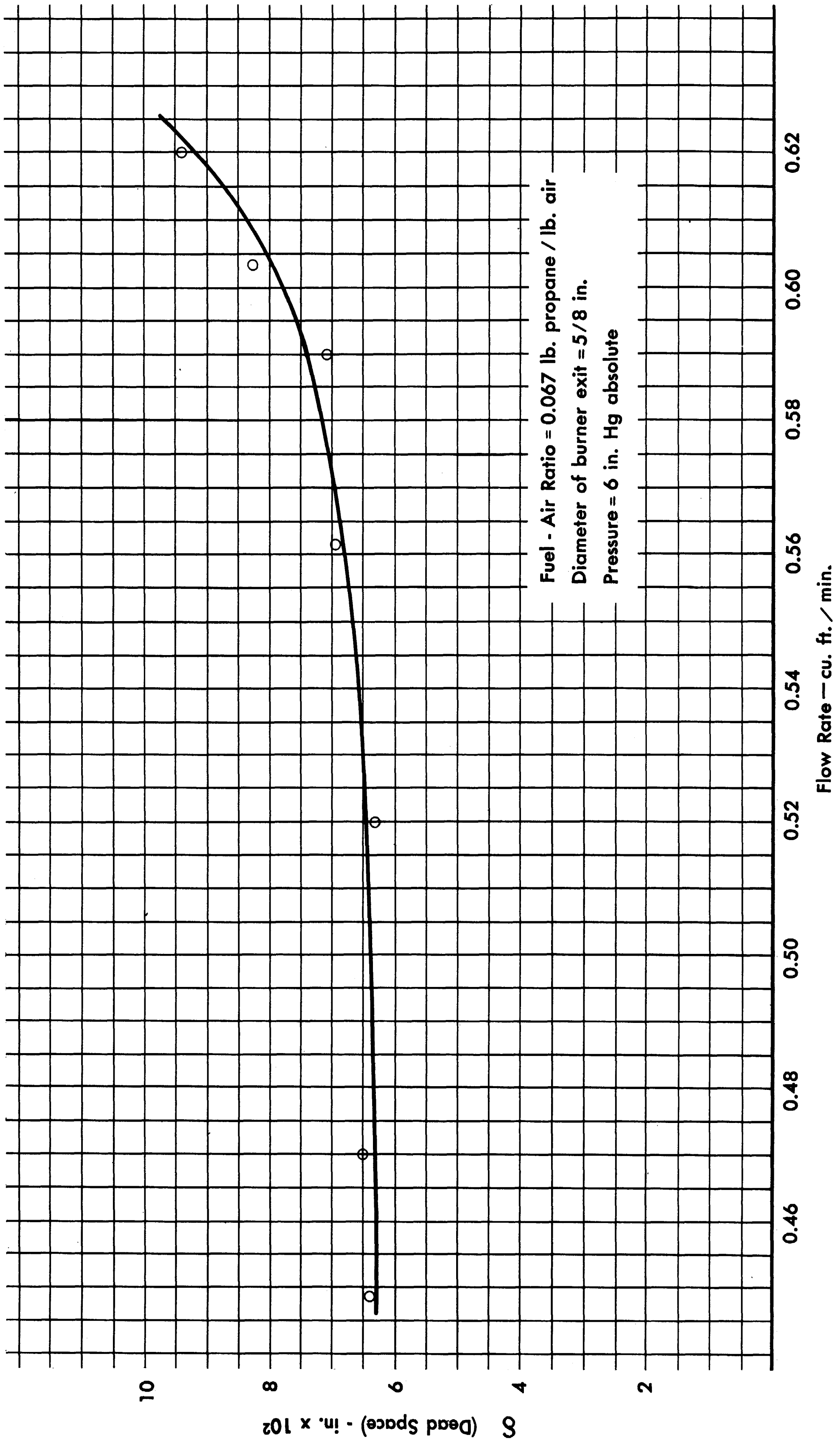


FIG. 18 VARIATION OF DEAD SPACE WITH FLOW RATE FOR PROPANE—AIR BUNSEN FLAMES

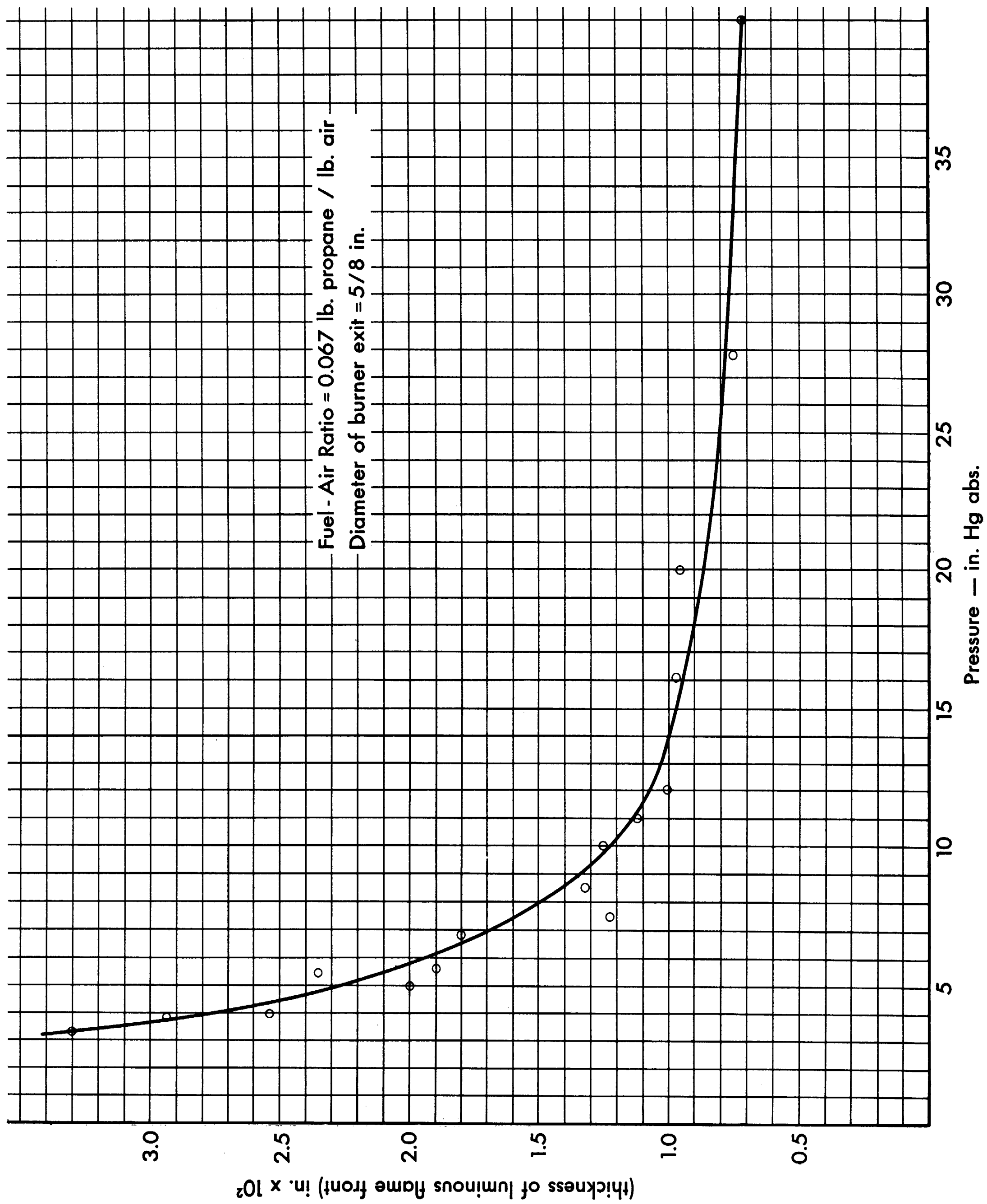


FIG. 19 VARIATION OF THE THICKNESS OF THE LUMINOUS FLAME FRONT WITH PRESSURE

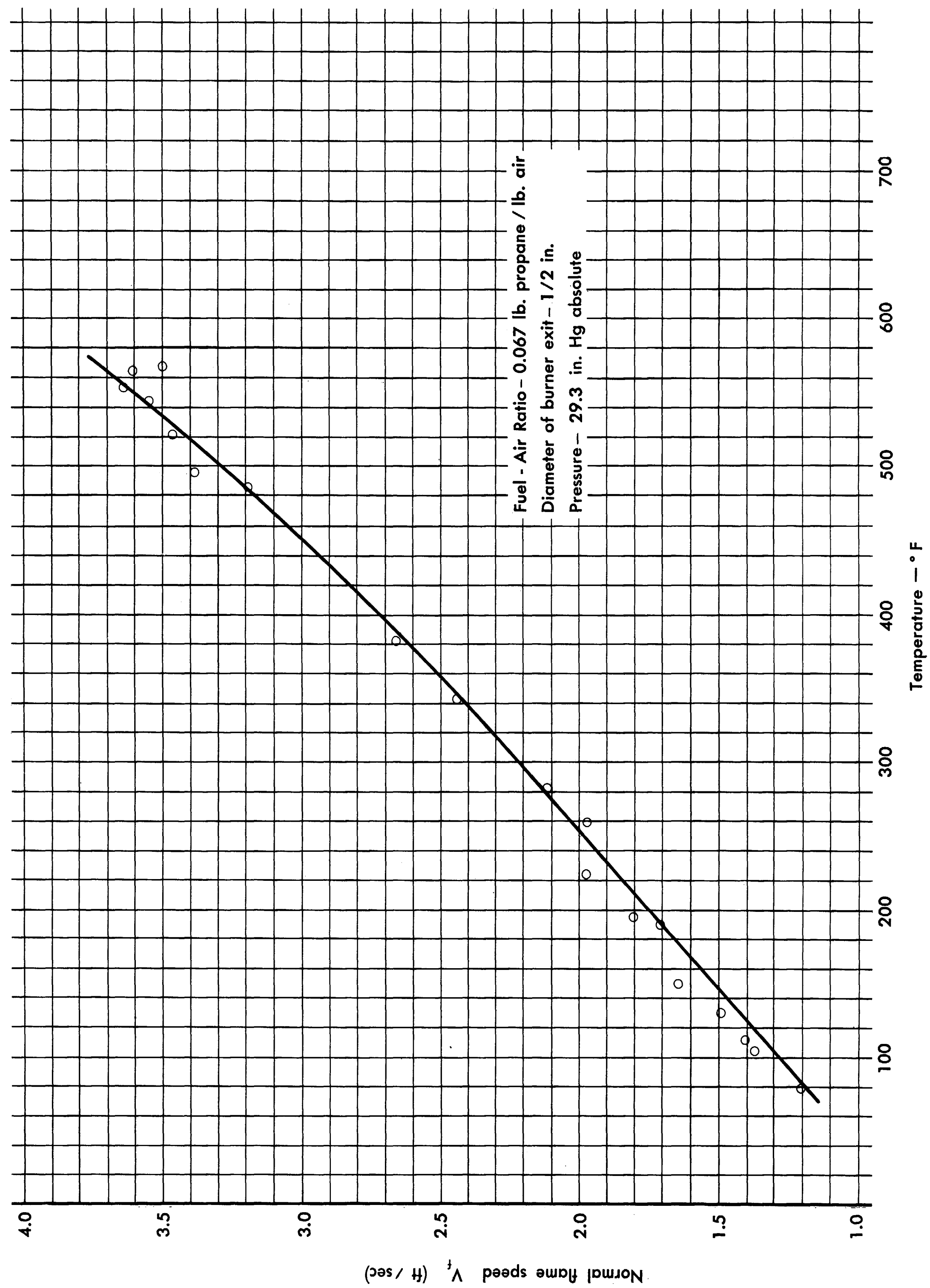


FIG. 20 VARIATION OF NORMAL FLAME SPEED WITH TEMPERATURE OF MIXTURE AT EXIT OF BURNER, FOR PROPANE - AIR BUNSEN FLAMES.

process in the temperature experiment, the screens upstream of the burner became distorted, causing the flame cone to become distorted also. The other points are considered reliable, because at higher temperatures the flame cones were symmetrical.

3. VARIATION OF NORMAL FLAME SPEED INVERSELY WITH THE LOGARITHM OF THE PRESSURE

From a consideration of Equation (5) and the Mallard and LeChatelier relation, Equation (8), the variation of flame speed with pressure from the standpoint of thermal conduction can be inferred. With the more general relation, Equation (5), the temperature of the unburned gases must be known at some finite distance ahead of the reaction zone. Experimentally, this is extremely difficult, because at atmospheric pressures it is believed the distance is very small through which the temperature rises from a value very close to that of the unburned gases far removed from the flame front to the ignition temperature.* Low pressures, where this distance is much greater, afford a much better opportunity for this measurement. The introduction of dense white smoke tracers that decompose at some known temperature below the ignition temperature of the gases has been suggested by some investigators. Optical methods, such as the shadowgraph, schlieren, and interferometric techniques hold much promise for a determination of the temperature distribution in the preparatory zone and the reaction zone. The latter method is especially attractive for quantitative measurements of the density and, therefore, the temperature in these zones. However, lacking such knowledge, it is of interest to to note that the Mallard and LeChatelier relationship, Equation (8), with the much simplified assumption of a linear temperature variation in the reaction zone, can be used to predict a qualitative trend in flame speed variation with pressure. With the additional assumption that $(T_b - T_{ig})/(T_{ig} - T_u)$ and k/C_p remain constant with pressure, only the value of the thickness of the reaction zone at different pressures must be known. Figure 19 has shown the variation of thickness of the luminous flame zone with respect to pressure. Whether or not the luminous zone coincides with the actual reaction zone is still a question;** however, it is probable

*See Appendix II.

**See Reference 6, Damköhler.

that the variation in the thickness of the luminous zone with pressure agrees qualitatively, at least, with the variation of the reaction zone thickness with pressure. The following simplified relation, then, gives the normal flame speed as a function of ρ and x_b.

$$V_f = \frac{K_b}{\rho x_b} \qquad (9)$$

where K_b is a constant, making the value of V_f from Equation (9) agree with the observed propane-air flame speeds at atmospheric pressure.

To establish a more precise upper envelope of the curves of Figures 15 and 16, the same data are represented in Figures 21 and 22 where the normal flame speed is plotted against the logarithm of the pressure. It appears from these plots that the upper envelope of the curves can be represented by a straight line within the limits of pressure throughout which the flames were observed. This variation so predicted must be incorrect in the limits, since it would predict an infinite flame speed at zero pressure, and a flame speed equal to zero at a large finite pressure. However, at least within the region in which the flames were observed, it is reasonable to believe that the variation of normal flame speed with pressure, for both propane-air ethylene-air flames at the mixture concentration used, is logarithmic. Certainly, within the range of pressures from 10 inches Hg absolute to atmospheric pressure, the trend in flame speed is well established to within the limits of accuracy of the Bunsen burner method. A further substantiation of this logarithmic trend in flame speed at higher and lower pressures using propane and ethylene as fuels would have to be conducted with smaller and larger size burners, respectively.

Figure 23 is a comparison of the experimental variation in flame speed with pressure, and the variation as predicted by the Mallard and LeChatelier relation from Equation (9). The values of the thickness of the luminous flame front, x_b, are the experimental values. The values of normal flame speed are taken from the envelope of the curves of Figure 21. As noted, it has been assumed that the term $(T_b - T_{ig})/(T_{ig} - T_u)$ is constant with pressure. However, the greater dissociation of the combustion products at lower pressures than at atmospheric pressure may

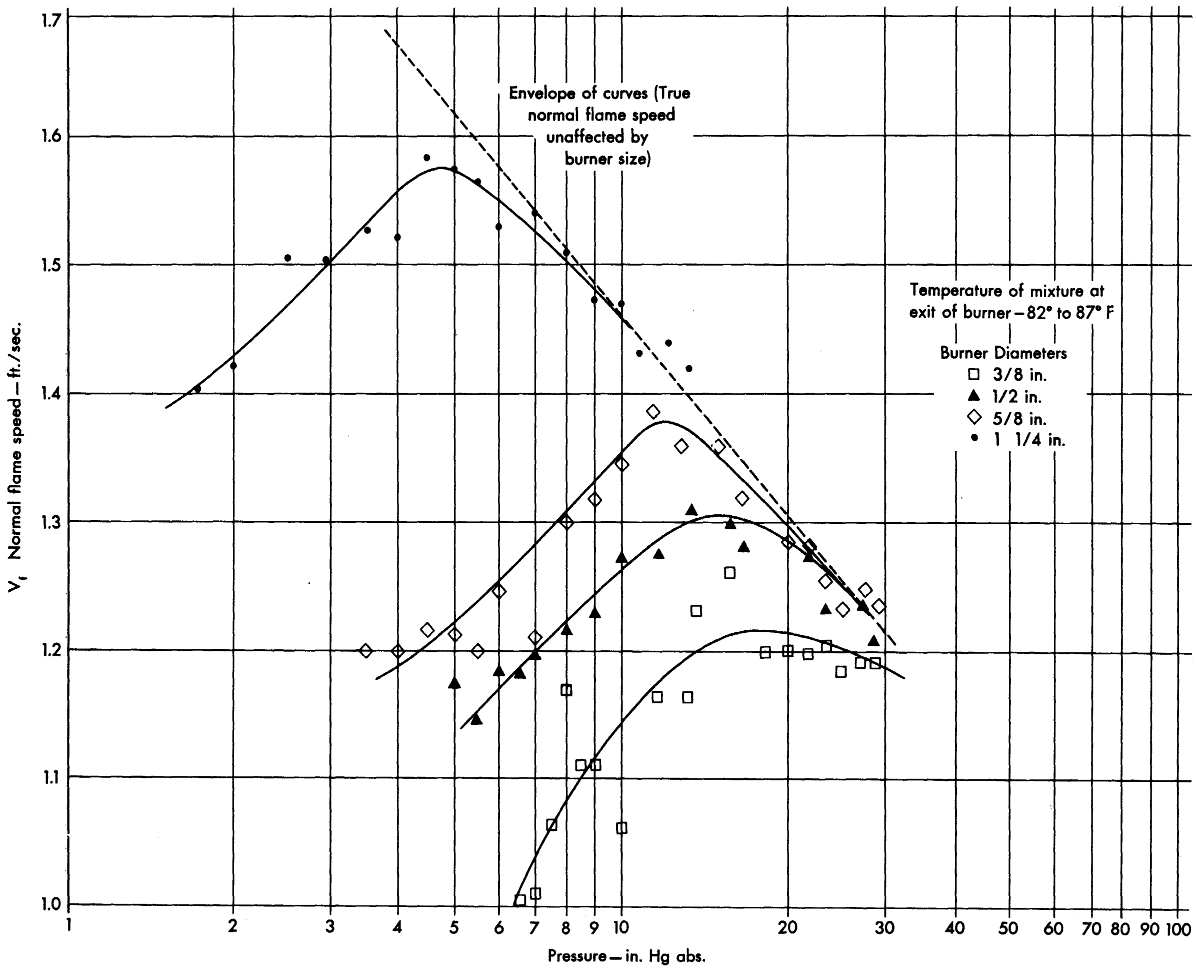


FIG. 21

VARIATION OF NORMAL FLAME SPEED WITH THE LOGARITHM OF THE PRESSURE FOR PROPANE-AIR BUNSEN FLAMES WITH FOUR BURNER SIZES.

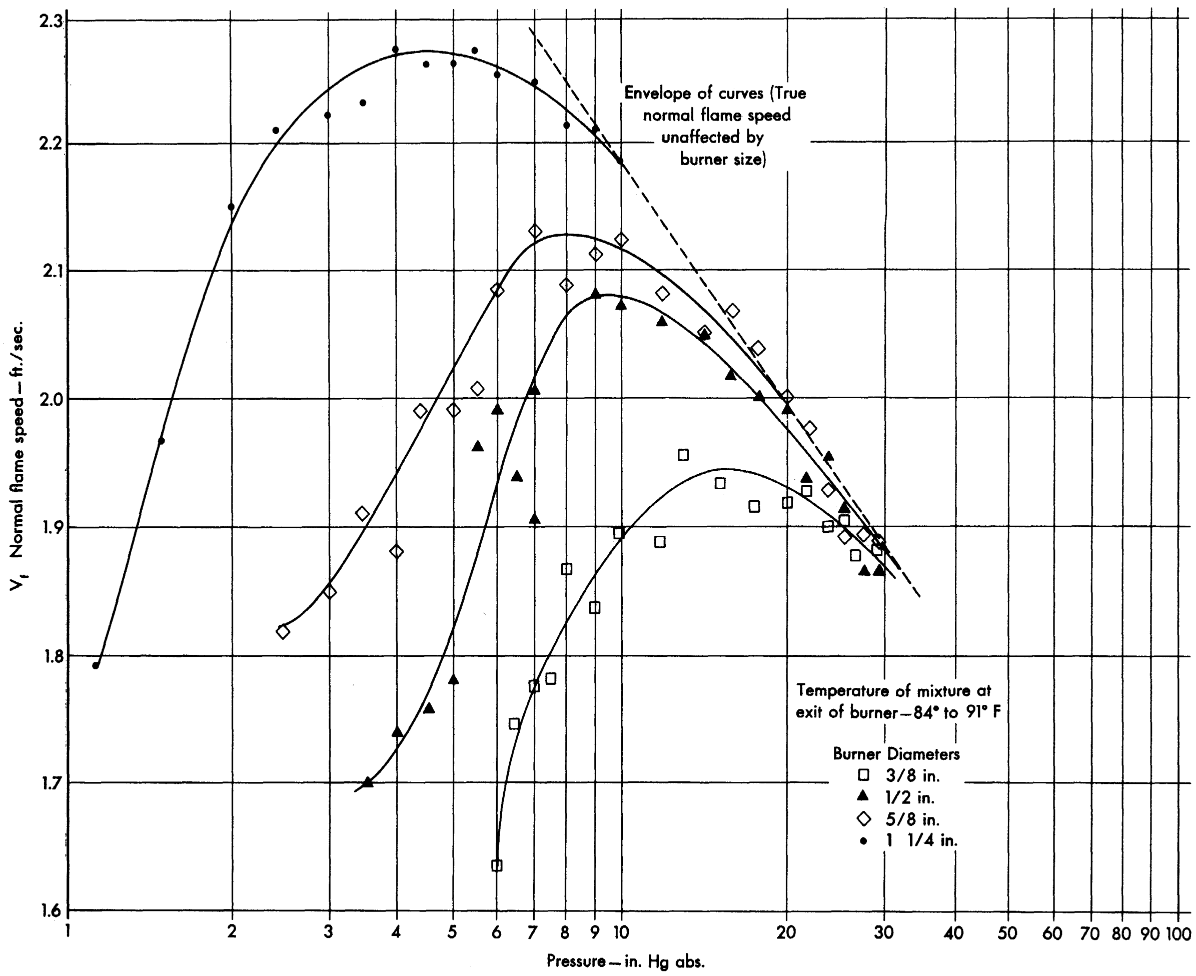


FIG. 22

VARIATION OF NORMAL FLAME SPEED WITH THE LOGARITHM OF THE PRESSURE FOR ETHYLENE - AIR BUNSEN FLAMES WITH FOUR BURNER SIZES.

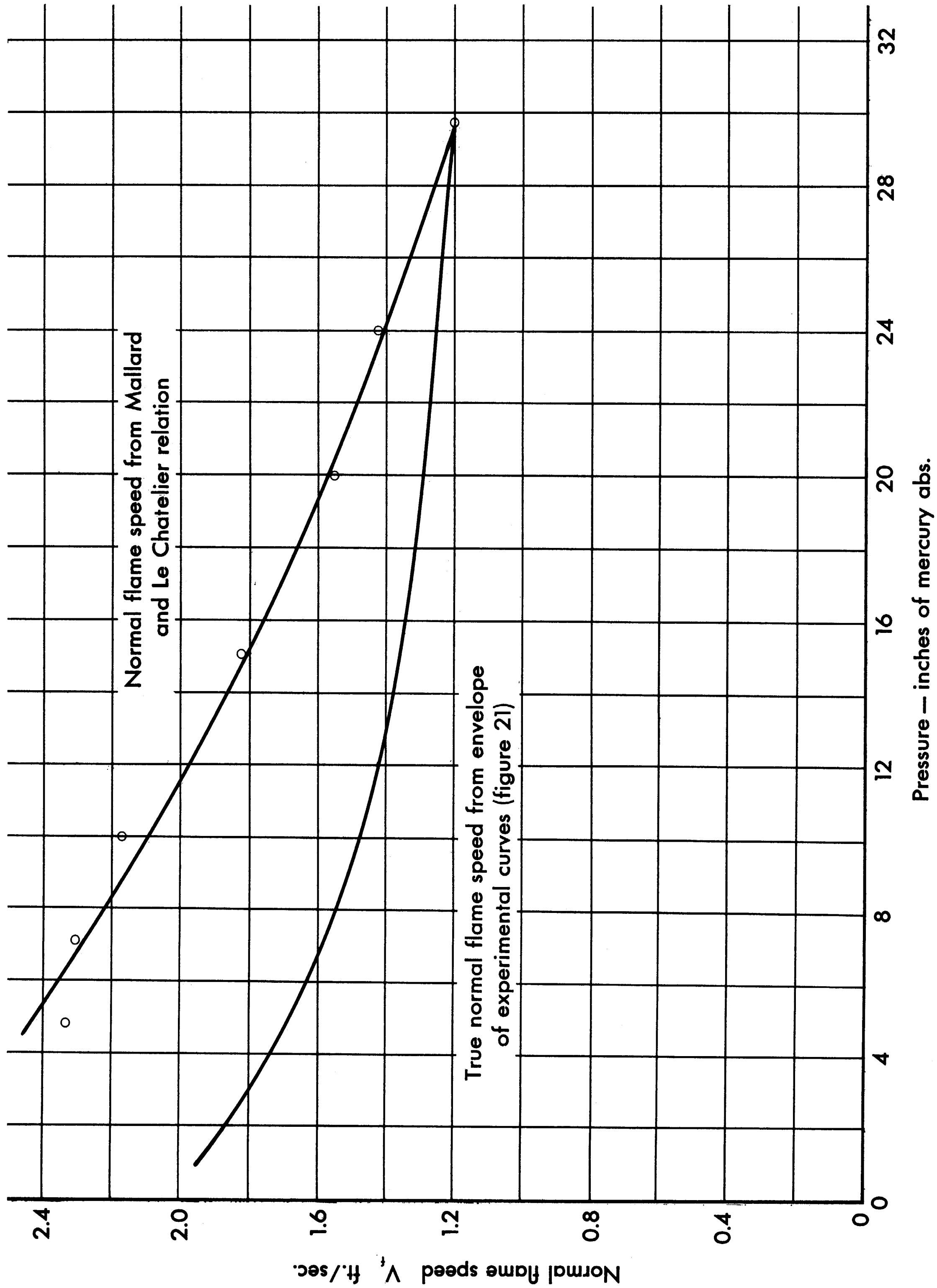


FIG. 23 NORMAL FLAME SPEED VARIATION WITH PRESSURE FROM MALLARD AND LE CHATELIER RELATION, USING EXPERIMENTAL VALUES OF x_b (Luminous Flame Zone Thickness)

lead to a lower value of the temperature of the burned gases, T_b. Thus, the factor $(T_b - T_{ig})/(T_{ig} - T_u)$ could possibly be a decreasing function at reduced pressures causing the theoretical curve to coincide more closely with the experimental. It has been pointed out earlier in this report that the concept of an ignition temperature in the relation leaves much to be desired. Nevertheless, it is interesting that the heat-conduction theory, using the experimental determination of the luminous flame front thickness, does predict a variation in flame speed, with certain assumptions, that agrees qualitatively with the normal flame speed measured experimentally.

4. INTRODUCTION OF A HEAT SINK INTO THE RELATION OF MALLARD AND LE CHATELIER

It has been shown that the burner size itself has a marked effect on flame speed as is evident by a sharp decrease in flame speeds at certain reduced pressures for each burner size. This effect of burner size on flame speed has been noticed by many investigators and has led to the term "critical burner size". This term can be defined briefly as follows: if, for a given fuel, and fuel-oxidant concentration, and for a given ambient pressure and temperature, the burner diameter is decreased from a size that represents the largest commensurate with laminar Bunsen type flames, the resulting measured flame speed is relatively constant to a certain burner diameter below which the measured flame speed drops off sharply. The critical burner size, then, is the smallest diameter burner from which Bunsen flames can be burned, with measured flame speeds agreeing closely with the flame speeds observed with the largest possible burner. It follows, then, from the observed data with flames burning from the four different size burners, that the critical burner size is also a function of pressure. This is reasonable since it has been shown in the photographs of flames burning at various pressures, Figures 9 through 14, that the scale of the flame itself, i.e., the luminous flame front thickness, the radius of curvature of the apex of the cone, and the "dead space", is considerably greater at lower pressures. It has been shown previously, that the size of the burner must be continually increased at lower pressures to establish similarity of the flames. Thus it can be postulated, then, that the critical burner size must be continuously increased at lower pressures to obtain a true value of the flame speed unaffected by any influence from the burner itself.

Concerning the mechanism by which the flame propagation rate is affected by the burner, some explanations have been offered. It is believed that the burner exit above which the flame is situated provides a heat sink which alters both the temperature gradient in advance of the flame front about the base of the flame cone and the temperature of the burned gases in the reaction zone. It also provides a source of termination of the active species that are diffusing into the preparatory zone from the primary reaction zone. This "quenching" effect of the tube exit on the adjacent reaction zone has been studied by many investigators in relation to the "snap back" phenomenon with Bunsen burners.*

With this in mind, and from a pure thermal-conduction standpoint, the effect of a heat sink on the development of normal flame speed relation will be investigated.

Using the same model used previously in the development of the equation of Mallard and LeChatelier, assume that a heat sink exists at some distance λ in advance of the flame front (Fig. 1). Assume further that the heat sink transports away the heat conducted to it from the flame front by some means so that the temperature of the unburned gases at a distance λ ahead of the flame front is equal to the temperature of the unburned gases far removed from the flame front, i.e., at infinity.

Taking Equation 3

$$T = C_1 + C_2 e^{\frac{\rho u C_p x}{k}} \tag{3}$$

and putting in a new boundary condition that

$$T = T_u \quad at \quad x = -\lambda$$

with the previous boundary condition that

$$T = T_{ig} \quad at \quad x = 0$$

*See Reference 11, Lewis and Von Elbe.

then

$$T_u = C_1 + C_2 \, e^{\frac{-\rho u C_p \lambda}{k}} \tag{10}$$

$$T_{ig} = C_1 + C_2 \tag{11}$$

Combining Equations (10) and (11) and solving for the constants C_1 and C_2.

$$C_1 = T_{ig} - \frac{T_{ig} - T_u}{1 - e^{\frac{-\rho u C_p \lambda}{k}}}$$

$$C_2 = \frac{T_{ig} - T_u}{1 - e^{\frac{-\rho u C_p \lambda}{k}}}$$

and finally putting the values of C_1 and C_2 into Equation (3)

$$T = T_{ig} - \frac{T_{ig} - T_u}{1 - e^{\frac{-\rho u C_p \lambda}{k}}} + \frac{T_{ig} - T_u}{1 - e^{\frac{-\rho u C_p \lambda}{k}}} \left(e^{\frac{\rho u C_p x}{k}} \right) \tag{12}$$

Differentiating Equation (12) with respect to x

$$\frac{dT}{dx} = \left(\frac{T_{ig} - T_u}{1 - e^{\frac{-\rho u C_p \lambda}{k}}} \right) \frac{\rho u C_p}{k} \, e^{\frac{\rho u C_p x}{k}} \tag{13}$$

and putting in the conditions that $T = T_{ig}$ at $x = 0$, and $u = V_{fa}$ where V_{fa} is the normal flame speed in the presence of a heat sink at a distance λ in front of the reaction zone

$$\left(\frac{dT}{dx}\right)_{T=T_{ig}} = \frac{T_{ig} - T_u}{1 - e^{\frac{-\rho V_{fa} C_p \lambda}{k}}} \left(\frac{\rho V_{fa} C_p}{k}\right) \tag{14}$$

Equation (6) from the development of the Mallard and LeChatelier relation

$$\left(\frac{dT}{dx}\right)_{T=T_{ig}} = \frac{\rho V_f C_p}{k} \left(T_{ig} - T_u\right) \tag{6}$$

represents the slope of Equation (4) at x = 0 where V_f is the normal flame speed without a heat sink, i.e., $T = T_u$ at $x = -\infty$ was the imposed boundary condition.

Relating Equation (14) and Equation (6) with the assumption that the temperature gradient at x = 0 for the case of the heat sink is the same as that of the case without the heat sink,

$$\left(T_{ig} - T_u\right) \frac{\rho V_f C_p}{k} = \left(\frac{T_{ig} - T_u}{1 - e^{\frac{-\rho V_{fa} C_p \lambda}{k}}}\right) \left(\frac{\rho V_{fa} C_p}{k}\right) \tag{15}$$

which reduces to

$$\frac{V_{fa}}{V_f} = 1 - e^{\frac{-\rho V_{fa} C_p \lambda}{k}} \tag{16}$$

Equation (16), then, represents the ratio of the normal flame speed V_{fa} in the presence of a heat sink to the normal flame speed V_f without a heat sink. It predicts an exponential variation of the ratio of the two flame speeds as a function of the Peclet number $\rho V_{fa} C_p \lambda / k$. It indicates that for large values of this parameter V_{fa} approaches V_f, and for small values V_{fa} approaches zero. An examination of the variables that make up the Peclet number shows that it is simply the product of the Reynolds number and the Prandtl number. The Prandtl number, $C_p\mu/k$, is practically independent of pressure for gases sufficiently removed from the critical pressure. The coefficient of viscosity, μ, is also independent of pressure for perfect gases and for real gases below the critical pressure. Therefore, at pressures lower than the critical for a given gas, C_p/k is practically independent of pressure. Thus, the only pressure-dependent variables appearing in the Peclet number are ρ, V_{fa} and λ.

In an attempt to establish whether a heat sink from a pure thermal-conduction standpoint might be responsible for the reduction in flame speeds observed at low pressures, the data obtained with flat flames burning from the four burners will be used in Equation (16). The observed normal flame speed will be used to represent V_{fa} and the "dead space" δ will represent λ. Obviously, this is only a crude approximation to the conditions postulated in the derivation of Equation (16). For the flat flames burning at low pressures the streamlines in the unburned gases diverge above the rim of the burner and are not normal to the flame front throughout the flame surface. Furthermore, only about one-half of the total flame surface extends over the rim of the burner.

In Figure 24 are tabulated the experimental values of the quantities necessary for the determination of V_{fa}/V_f for a propane-air mixture of .067 pound propane/pound air. The values of the specific heat and thermal conductivity were obtained from Reference 10 based on a temperature of 85° F. for the unburned mixture.

Burner Size	Pressure in.Hg abs.	ρ lb./cu.ft.	V_{fa} ft./sec.	λ (δ)ft.	C_p/k ft.sec./lb.	V_{fa}/V_f
3/8"	7.0	0.0176	0.926	0.00696	6.217×10^4	0.999
1/2"	6.5	0.0164	1.11	0.00544	6.217×10^4	0.998
5/8"	4.5	0.0113	1.19	0.00971	6.217×10^4	0.999
1 1/4"	2.0	0.0050	1.42	0.02190	6.217×10^4	0.999

FIG. 24 DETERMINATION OF V_{fa}/V_f

The predicted reduction in flame speed from Figure 24 is in the order of one-tenth of one percent. If we base the values of C_p and k on the average temperature in the preparatory zone as Damköhler did in Reference 6, assuming the ignition temperature of the mixture to be 500° C. and the average temperature in the preparatory zone to be 250° C., then the value of C_p/k for a propane-air mixture of .067 pound propane/pound air is equal to 3.88×10^4 ft.sec./lb. The combustible mixture used by Damköhler was a mixture of 15% propane and 85% oxygen. However, since the concept of ignition temperature is somewhat vague,* it is believed sufficient to assume that the average temperature in the preparatory zone is qualitatively the same for propane-oxygen and propane-air mixtures. With this value for C_p/k instead of the value of 6.217×10^4 ft.sec./lb. used in Figure 24 the values of V_{fa}/V_f are in the order of 0.98. With either assumption for the magnitude of C_p/k, the reduction in flame speed predicted by Equation (16), then, is no more than two percent while the actual reductions measured experimentally are from 23% to 35%.** It should be borne in mind that while this discrepancy appears somewhat large, the value of V_{fa}/V_f from Equation (16) is an exponential function of the Peclet number. The value of the Peclet number for the case of the 1/2-inch burner, using the value of 3.88×10^4 ft.sec./lb. based on the average temperature in the preparatory zone, is 3.84 (Fig. 24). The solution of Equation (16) for this case gives $V_{fa}/V_f = .98$. If, however, the Peclet number were one-third of 3.84, the solution of Equation (16) would give $V_{fa}/V_f = .72$, i.e., a reduction in flame speed of 28%. This would be in agreement with the order of magnitude of the reduction in flame speed observed experimentally. This discrepancy in the value of the Peclet number by a factor of three might be explained by the following considerations. First of all, as mentioned previously, the model used for the derivation of Equation (16) assumed a heat sink that established a temperature equal to T_u at a distance λ from every point on the flame surface. This certainly was not the case for the flat flames used for

*Damköhler postulates the possibility of ignition temperatures of 500° C. and 200° C. for the same mixture, depending on whether the reaction zone coincides with the luminous zone.

**This can be seen from Figure 21 with the envelope of the curves representing the value of the flame speeds V_f, unaffected by the burner exit, with V_{fa} taken from the experimental curves for the four burners.

this comparison. Furthermore, there is some doubt whether the values of C_p and k based on a mean temperature in the preparatory zone is valid. Lower values of C_p/k, i.e., C_p and k based on a higher temperature, would give reductions in flame speed that agree more closely with the experimental reductions. Also, the values of the "dead space" used for the distance λ could be in error since it was difficult to establish exactly the lower limit of the flame front.* From these considerations, i.e., the uncertainty of the experimental values used for λ (in this case the "dead space", δ), and the values of C_p/k based on an average temperature of 250° C. in the preparatory zone, it is likely that the agreement of the Peclet number computed from the above values of C_p/k and λ to within one order of magnitude is all that can be expected. It was mentioned previously that there is a factor of three by which the observed Peclet numbers disagree with the values of the Peclet number that would give solution of Equation (16) agreeing with the experimental values of the reduction in flame speed. This agreement, then, is well within one order of magnitude.

In order to verify whether the heat conduction theory and the assumptions made in the derivation of Equation (16) are valid, it would be necessary to duplicate experimentally as closely as possible the conditions set up in the above derivation. To this end, some sort of uniform heat sink, perhaps a porous body of high thermal conductivity through which the flow could issue, might be used to establish a heat sink that would not alter the assumed rectilinear flow distribution yet would affect the flame front equally at every point. If this were accomplished and a normal flame front established, measurements could be made of all the necessary quantities, viz., the distance λ of the flame front from the heat sink, the observed normal flame speed, the density, and the values of C_p/k (determined more accurately possibly from a mean temperature obtained from an investigation of the temperature distribution in the preparatory zone). In conjunction with this, if the true normal flame speed unaffected by any burner influence were known for the same conditions of pressure, temperature, and fuel-oxidant concentration, then the validity of Equation (16) could be checked.

*It was found that the "dead space" varied with the photographic exposure given the flames.

If the results of the above experiments indicated that there were definite discrepancies in the heat-conduction theory or in the assumptions made in the derivation of Equation (16), then, referring again to Damköhler,* it might be fruitful to treat the problem (taking into account the diffusion of active species) by including, in the development of a pure heat-conduction theory, the diffusion coefficients instead of the thermal conductivity, and the concentrations of the atom-type instead of the temperature. With certain assumptions, this would lead to an equation, similar to Equation (16), the validity of which could be checked experimentally.

5. THE PECLET NUMBER AS A NON-DIMENSIONAL PARAMETER FOR THE CORRELATION OF THE EXPERIMENTAL DATA

In order to correlate the effect of burner diameter and pressure on flame speed, it is reasonable to believe that some non-dimensional parameter exists that contains the variables ρ, V_{fa} and D_j where ρ is the density, V_{fa} is the apparent (measured) normal flame speed, and D_j the exit burner diameter, which would describe the phenomenon. In the preceding section, it was shown that the Peclet number based on experimentally determined quantities agreed as to order of magnitude with the Peclet number required, to give solutions of Equation (16) for V_{fa}/V_f that agreed with the experimentally determined values of V_{fa}/V_f. If, instead of basing the Peclet number on a characteristic distance that is a measure of the distance of an ideal heat sink from a normal flame front, we base it on the burner diameter, then Equation (16) can be rewritten as follows:

$$\frac{V_{fa}}{V_f} = 1 - e^{-\frac{\rho V_{fa} C_p (\beta D_j)}{k}} \qquad (17)$$

where β = Const. with $\lambda = \beta D_j$

*See Reference 6.

From Equation (17) we see that there is an exponential relationship between V_{fa}/V_f and the Peclet number whereby V_{fa}/V_f approaches zero as either D_j or ρ approach zero. Since this is in accordance with the trends of the curves of Figures 21 and 22, a plot of the values of V_{fa}/V_f (determined experimentally) against the Peclet number* logically follows. Figure 25 is a plot of this relationship for all the data appearing in Figures 21 and 22. The trend of the experimental points seems to substantiate this supposition reasonably well. An exponential curve fitted to the experimental data which agrees well within the limits of the data is $V_{fa}/V_f = 1 - .628e^{-0.01809P_e}$. This empirical curve, however, predicts a finite value of $V_{fa}/V_f = .372$ at $P_e = 0$, i.e., with either D or ρ equal to zero. This means that a simple exponential curve cannot be fitted to the data that will satisfy both intuitive end conditions, i.e.,

$$\frac{V_{fa}}{V_f} = 0 \text{ at } P_e = 0 \text{ and } \frac{V_{fa}}{V_f} = 1 \text{ at } P_e = \infty$$

It is believed, however, that in view of the fact that the observed data correlate reasonably well with Bunsen flames burning with two different fuels over a wide range of pressures and with different burner diameters, that there exists a convenient non-dimensional parameter, i.e., the Peclet number. The magnitude of this parameter, then, gives an indication of how closely the observed normal flame speed, V_{fa}, agrees with the true normal flame speed, V_f. It means, then, in order to measure normal flame speeds experimentally by the Bunsen burner method with the values of flame speed approaching that of the normal combustion velocity, which is a property only of the state and composition of the unburned mixture, that large values of the Peclet number are required. If flames at low densities are being observed, the burner diameter must be kept large and fuels with high flame speeds are desirable. The upper limit on the Peclet number for laminar type Bunsen flames would be the Peclet number corresponding to the critical Reynolds number of the burner. Since the two fuels used, i.e., propane-air and ethylene-air mixtures, have values of C_p/k that differ by only 1.5%, this variable appearing in the Peclet number is not tested thoroughly. Only further

*The Peclet number based on the diameter of the burner, D_j, as the characteristic distance, is used in Figure 25.

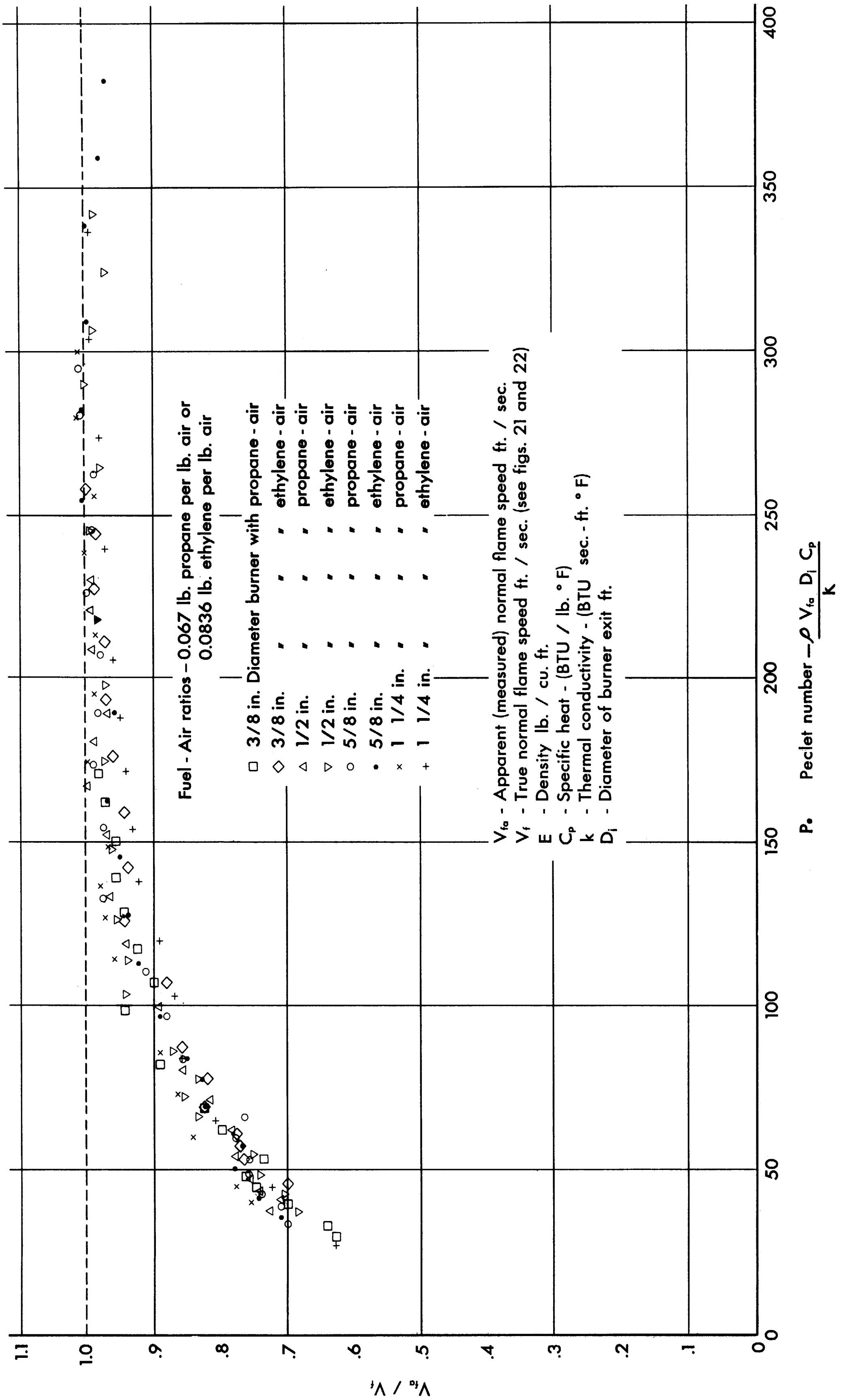


FIG. 25 CORRELATION OF NORMAL FLAME SPEED DATA WITH THE PECLET NUMBER FOR PROPANE - AIR AND ETHYLENE - AIR BUNSEN FLAMES FOR FOUR DIFFERENT BURNER SIZES.

experiments using fuel-oxidant mixtures with markedly differing values of C_p/k can prove whether or not the Peclet number does accurately describe this phenomenon. In this respect also, fuels with much higher normal flame speeds, e.g., acetylene and hydrogen, should be tested. The results of these experiments, as with the experiments suggested in the preceding section, should indicate whether the Peclet number, derived from the heat conduction theory of flame propagation, does accurately describe the reduction in normal flame speed from the true value for flames of the Bunsen burner type.

6. COMPARISON WITH RESULTS OF OTHER INVESTIGATORS

A survey of the literature showed two other investigators, Ubbelohde* and Wolfhard** whose experiments were of a similar nature, i.e., the investigation of flame speeds at pressures less than atmospheric. Ubbelohde observed that the normal flame speeds with carbon monoxide and air mixtures increased with decreasing pressures down to a pressure of 330 mm Hg absolute. At lower pressures, he observed a sharp reduction in flame speeds similar to reductions observed in this report. In his experiments one burner size was used for pressures less than atmospheric. Wolfhard observed flames burning at pressures as low as 5 mm Hg absolute. His conclusions were that the normal flame speed for stoichiometric mixtures of acetylene with oxygen was independent of pressure down to extremely low pressures, although there were indications of decreasing flame speeds. In these experiments several different size burners were used.

At pressures higher than atmospheric, the results of several investigators are in agreement. It is concluded by Khitrin,*** Stevens,**** and Ubbelohde·· that for several different fuels in combination with air, the normal flame speed decreases with increasing pressure up to four atmospheres. Khitrin used two different methods for flame speed determination: the Bunsen burner and the Stephens soap-bubble techniques. There is

*See Reference 12.
**See Reference 13.
***See Reference 14.
****See Reference 15.

agreement, also, between the results of Khitrin and Stephens using different fuels in combination with oxygen. They found, by using the two different techniques for flame speed determination, that normal flame speed for mixtures of fuels with oxygen was independent of pressure. This is in agreement with the results of Wolfhard who studied flames at pressures lower than atmospheric.

The results of several more recent investigations* pertaining to the effect of pressure on flame propagation rates, show considerable disagreement. It is possible that the variation in measured flame speed with burner size, as observed in this report, might be responsible for some of these discrepancies.**

---

*See Reference 17, 18, and 19.

**For a discussion of other errors in flame speed measurement, see Appendix II. For a comparison of the flame speed variation with pressure as observed in this report, with the variation predicted by Tanford, see Appendix III. Also see Reference 16.

REFERENCES

No. Title

1 Jost, W., translated by Croft, H. O., "Explosion and Combustion Processes in Gases" McGraw-Hill Book Co., New York, 1946.

2 Morrison, R. B. and Nicholls, J. A., Progress Reports No. 1, 2, and 3, Detonative Combustion, University of Michigan to USAF Air Materiel Command AF-33-038-12657.

3a Jouget, E., "Mechaniques des Explosifs", O. Doin et Fils, Paris, 1917.

3b Jouget, E., Proceedings of the International Congress for Applied Mechanics, 1926, pp. 12-22 (As reported in Courant, R. and Friederichs, K. O., "Supersonic Flow and Shock Waves" Interscience Publishers, Inc., New York, 1948, pp. 206-218.)

4 Mallard and LeChatelier, Ann. Mines, 4, 274, 1883.

5 Landau, L., Acta. Physicochimica, URSS, Vol. 19, No. 1, 1944.

6 Damköhler, G., Zeit. für Electrochemie, 46, 11, November 1940 as translated in NACA-TM-1112, April 1947.

7 Jost, W. and VonMuffling, V., Zeit. für Physik Chem. SECA, 181, 208, 1938.

8 Stevens, F. W., NACA Report 305, 1929.

9 Fiock, E. F., and Marvin, C. F., Chem. Rev., 21, 267, 1937.

10 Perry, J. W., "Chemical Engineers' Handbook" Third Ed., McGraw-Hill Book Company, New York, 1950.

11 Von Elbe, G. and Lewis, B., "Third Symposium on Combustion and Flame and Explosion Phenomena", The Williams and Wilkins Co., Baltimore, 1949, p. 68.

12 Ubbelohde, L., Koelliker, E., J. Gasbeleuchtung, 59, 49, 1916. Ubbelohde, L. Andwandter, R., ibid., 60, 255, 1917.

13 Wolfhard, Zeit. für Tech. Physik, 23-24, 206, 1942-1943.

14 Khitrin, L., Tech. Phys. USSR, 3, 926, 1028, 1934; 4, 110, 121, 1936.

REFERENCES (continued)

No. Title

15 Stevens, F. W., NACA Report 373, 1930.

16 Tanford, C., "Third Symposium on Combustion and Flame and Explosion Phenomena" The Williams and Wilkins Co., Baltimore, 1949, p. 140.

17 Culshaw, G. W., and Garside, J. E., "Third Symposium on Combustion and Flame and Explosion Phenomena" The Williams and Wilkins Co., Baltimore, 1949, p. 204.

18 Wohl, Kurt and Kapp, Numer M. Meteor Report UAC-42, U. S. Navy Bureau of Ordnance, Contract NOrd 9845, 1949.

19 Johnston, W. C., "Flame Propagation Rates at Reduced Pressures" for presentation at the SAE Summer Meeting, French Lick, Indiana, June 1-6, 1947, Westinghouse Electric Corporation, Research Laboratories, East Pittsburgh, Pennsylvania.

LIST OF SYMBOLS

V_n	Normal combustion velocity
V_f	Normal flame speed
V_{ft}	Normal turbulent flame speed
V_{fa}	Normal apparent (measured) flame speed
$\bar{V}_o$	Average velocity of exit gases at burner exit
u	Velocity of unburned gases
T_b	Temperature of burned gases in reaction zone
T_{ig}	Ignition temperature of combustible mixture
T_u	Temperature of unburned gases far removed from reaction zone
x_b	Thickness of luminous reaction zone
δ	"Dead space" (Distance between bottom of luminous flame cone and top of burner)
λ	Distance of ideal heat sink from reaction zone
ρ_o	Density of unburned gases far removed from reaction zone
ρ_f	Density of unburned gases at inner limit of luminous reaction zone
A_o	Area of burner exit
A_f	Surface area of inner limit of luminous reaction zone
θ	Half angle of Bunsen flame cone
C_p	Specific heat at constant pressure

LIST OF SYMBOLS (continued)

k	Coefficient of thermal conductivity
ϵ	Prandtl turbulent exchange quantity
ν	Coefficient of kinematic viscosity
K	Constant (proportional to reaction velocity and thermal conductivity)
β	Constant (where $\lambda = \beta D_j$)
P_e	Peclet number $\rho V_{fa}(C_p/k)D_j$
D_j	Internal diameter of burner exit
K_b	An emperical constant in Equation (9)

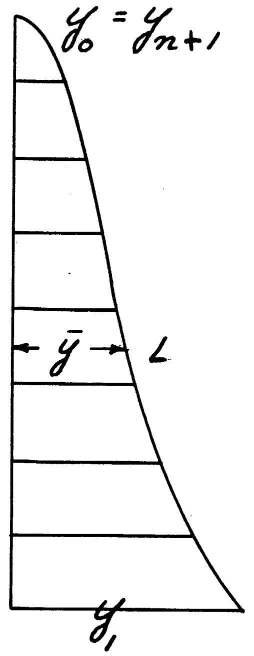
APPENDIX I

METHOD OF FLAME SURFACE AREA DETERMINATION

The surface areas of the flames were first obtained by means of graphical integration by conical sections. Since this proved very long and tedious, a different and much simpler method was employed instead. The method is described in detail because it eliminated much of the laborious time-consuming work entailed by other methods, yet was equally accurate.

The method is based on the theorem of Pappus* which states that the area of a surface of revolution generated by revolving a plane curve about any non-intersecting axis in its plane is equal to the product of the length of the curve and the circular path of the curve centroid, i.e.,

$$A = \int 2\pi y \, dL = 2\pi \bar{y} L$$



The steps involved in the procedure derived from the theorem are listed below:

1. The axis of symmetry is determined on the flame picture.

2. The length of curve, L, is carefully taped off on ticker tape and measured. This length is divided into a suitable even number of n equal intervals with the use of a piece of coordinate paper. The number of ordinates to be selected varies with the complexity and change of curvature, from 4 to 10 intervals being sufficient.

3. The intervals are taped on the curve L, thus defining a series of n + 1 ordinates y_1 to y_{n+1}.

*Damköhler, Reference 6.

4. The ordinates are measured and integrated by Simpson's Rule to determine the centroidal distance $\bar{y}$, in the manner shown:

y_1 - 1

y_2 - 4

y_3 - 2

y_4 - 4

y_5 - 2

⋮

y_{n+1} - 1

Σ

$$\bar{y} = \frac{\Sigma\,(h/3)}{L}$$

Σ = sum of the Simpson's Rule products

h = length of interval = L/n

5. Area is determined as:

$$A = 2\pi\bar{y}L$$

$$= 2\pi \frac{\Sigma}{L} \frac{h}{3} L$$

$$= \frac{2\pi}{3} \Sigma h = 2.0944\, \Sigma h$$

In a short time, facility with the method allows flame area calculations to be made in less than one-half of the usual time required by the conical section method and with equal accuracy. Moreover, in the case of the nearly flat or "saucer" type flames at low pressures, the conical method was extremely tedious and inaccurate while the above method remained equally as accurate for the flat flames as for the conical flames.

APPENDIX II

SYSTEMATIC ERRORS IN THE GOUY AREA METHOD FOR FLAME SPEED DETERMINATION

In order to obtain an estimate of the thickness to within an order of magnitude, of the preparatory zone ahead of the reaction zone, i.e., the distance through which the temperature rises from a value close to T_u of the unburned gases at infinity to T_{ig} at the reaction zone, Equation (5) from the development of the heat conduction theory of flame propagation can be used:

$$V_f = \frac{k}{\rho C_p x} \ln\left(\frac{T - T_u}{T_{ig} - T_u}\right) \tag{5}$$

Solving for the distance x

$$x = \frac{k}{\rho C_p V_f} \ln\left(\frac{T - T_u}{T_{ig} - T_u}\right) \tag{5a}$$

The factor $(T - T_u)/(T_{ig} - T_u)$ is a measure of the magnitude of the temperature in the preparatory zone. At $T = T_u$ the value of the factor is zero and at $T = T_{ig}$ the value is unity. If instead of assuming a value for the ignition temperature, the factor $(T - T_u)/(T_{ig} - T_u)$ is given values from 1/100 to 1, then a temperature plot in percent $(T - T_u)/(T_{ig} - T_u)$ against distance can be constructed from Equation (5a). Figure IIa shows this relationship for both ethylene-air and propane-air mixtures at pressures of 29.5 and 1.8 inches of Mercury absolute. The values of C_p/k and ρ are based on an average temperature of 85° F. of the unburned gases. If we use the values of C_p/k based on an average temperature of 250° C. in the preparatory zone then the resulting distance obtained from Equation (5a) is somewhat larger. The values of V_f taken from the envelope curves of Figures 21 and 22 represent the true normal flame speed for the two mixtures at 29.5 and 1.8 inches of Mercury absolute. If the actual flame speeds measured in the experiments at 1.8 inches of Mercury absolute were used instead of the flame speeds from the envelope curves, the distances from Equation (5a) would be also somewhat larger than indicated in Figure IIa. However, in order to obtain a qualitative estimation of these distances predicted

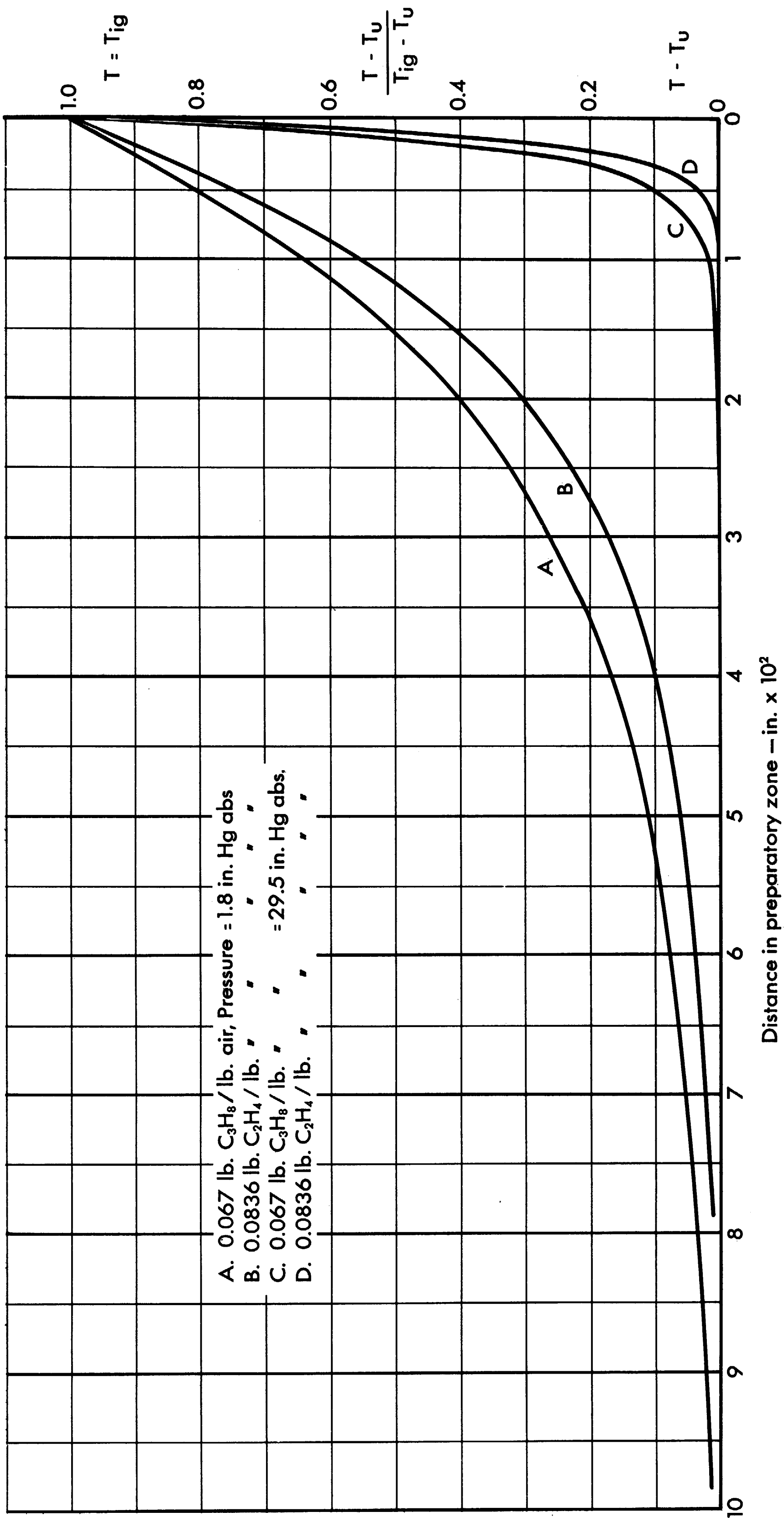


FIG. IIa VARIATION OF TEMPERATURE IN PREPARATORY ZONE, ACCORDING TO THE HEAT CONDUCTION THEORY, FOR PROPANE - AIR AND ETHYLENE - AIR MIXTURES FROM $T \cong T_U$ to $T = T_{ig}$ FOR TWO DIFFERENT PRESSURES.

by the heat-conduction theory, the following values are tabulated in Figure IIb for a value of $(T - T_u)/(T_{ig} - T_u) = 1/100$, i.e., a temperature in the preparatory zone that is one per cent of the value from T_u to T_{ig}. The use of the value 1/100 for $(T - T_u)/(T_{ig} - T_u)$ then, is a convenient definition for the boundary of the preparatory zone.

FIG. IIb THICKNESS OF PREPARATORY ZONE

Mixture	Pressure in.Hg abs.	V_f ft./sec.	Distance inches
Propane-air	29.5	1.217	9.82×10^{-3}
Propane-air	1.8	1.868	10.5×10^{-2}
Ethylene-air	29.5	1.890	6.66×10^{-3}
Ethylene-air	1.8	2.668	7.8×10^{-2}

Thus, it can be seen that by using the inner limit of the luminous reaction zone for the measurement of the flame areas at atmospheric pressures, the error introduced by the Gouy area method is apparently small if the burner size is made sufficiently large. A check of the actual magnitude of this discrepancy was made for the case of the 1/2" burner at atmospheric pressure with a propane-air mixture. The areas selected from several flame projections were taken at a distance of 9.82×10^{-3} inches inside the inner limit of the visible reaction zone. The normal flame speeds determined by this method were ca. 5% greater than the value determined from the area based on the inner limit of the visible reaction zone. These larger values for flame speeds agree closely with values obtained by other investigators using the schlieren cone instead of the visible cone for the determination of flame speed by the Gouy area method. It is believed, then, that by using sufficiently large burners, the variation in measured flame speeds by the Gouy method is within 5% regardless of what area is selected, i.e., the area based on the visible cone, the schlieren cone, or the area predicted by the heat-conduction theory using a point in the preparatory zone where the temperature is one percent of the value from T_u to T_{ig}.

However, it would appear from Figure IIb at pressures of 1.8 inches of Hg absolute, where the thickness of the preparatory zone is about ten times as large as at atmospheric pressure, that the variation of the measured flame speeds, depending upon the point selected for the surface area determination, would check to within 5% only if the burner size were made ten times as great as at atmospheric pressure. This then brings up the point that possibly some of the reduction in flame speeds noted at lower pressures with a given size burner might be due to the systematic error in the method of flame speed measurement. As the flame becomes progressively flatter at lower pressures for a given size burner, the "dead space" and also the distance the flame surface overhangs the burner rim becomes much greater. Due to the divergence of the flow in the "dead space", the point at which the surface area is determined becomes much more critical for these flat flames than for the conical flames at higher pressures.

It is concluded, then, that the reduction in measured normal flame speed at low pressure might be due to actual reduction in flame speed because of the quenching effect of the burner exit; to systematic errors in the method of flame speed measurement using the inner limit of the visible reaction zone; or to a combination of both effects.

The use of the Peclet number for the correlation of this effect is still of significance regardless of what the actual reasons are for this measured flame speed reduction. Future experiments for the determination of the temperature distribution and flow pattern in the preparatory zone at extremely low pressures would prove beneficial to the solution of these problems.

APPENDIX III

VARIATION OF FLAME SPEED INVERSELY WITH THE FOURTH ROOT OF THE PRESSURE

It has been shown in Figures 21 and 22 that the normal flame speed for the fuel-air mixtures observed in this report vary inversely with the logarithm of the pressure if the upper envelopes of the curves are considered. Tanford* concludes that flame speed should vary inversely with the fourth root of the pressure. This conclusion is based on an equation of flame propagation derived by Tanford and Pease which takes into account the role of active species such as monatomic hydrogen and the hydroxyl radical. Figure IIIa shows that the variation of the normal flame speed (taken from the envelope of the curves of Figure 21) with the reciprocal of the fourth root of the pressure is nearly linear. This seems to bear out reasonably well the conclusions of Tanford that the burning velocity should vary approximately inversely with the fourth root of the pressure.

Tanford also concludes, concerning the reduction in flame speeds at low pressures in a discussion of the data obtained by Ubbelohde, that at some sufficiently low pressure, which is dependent on the size burner used, the influence of the burner rim will be felt, and a reduction in flame speed should occur because of chain termination at the burner rim. This is essentially in agreement with the conclusions made in this report.

*See Reference 16.

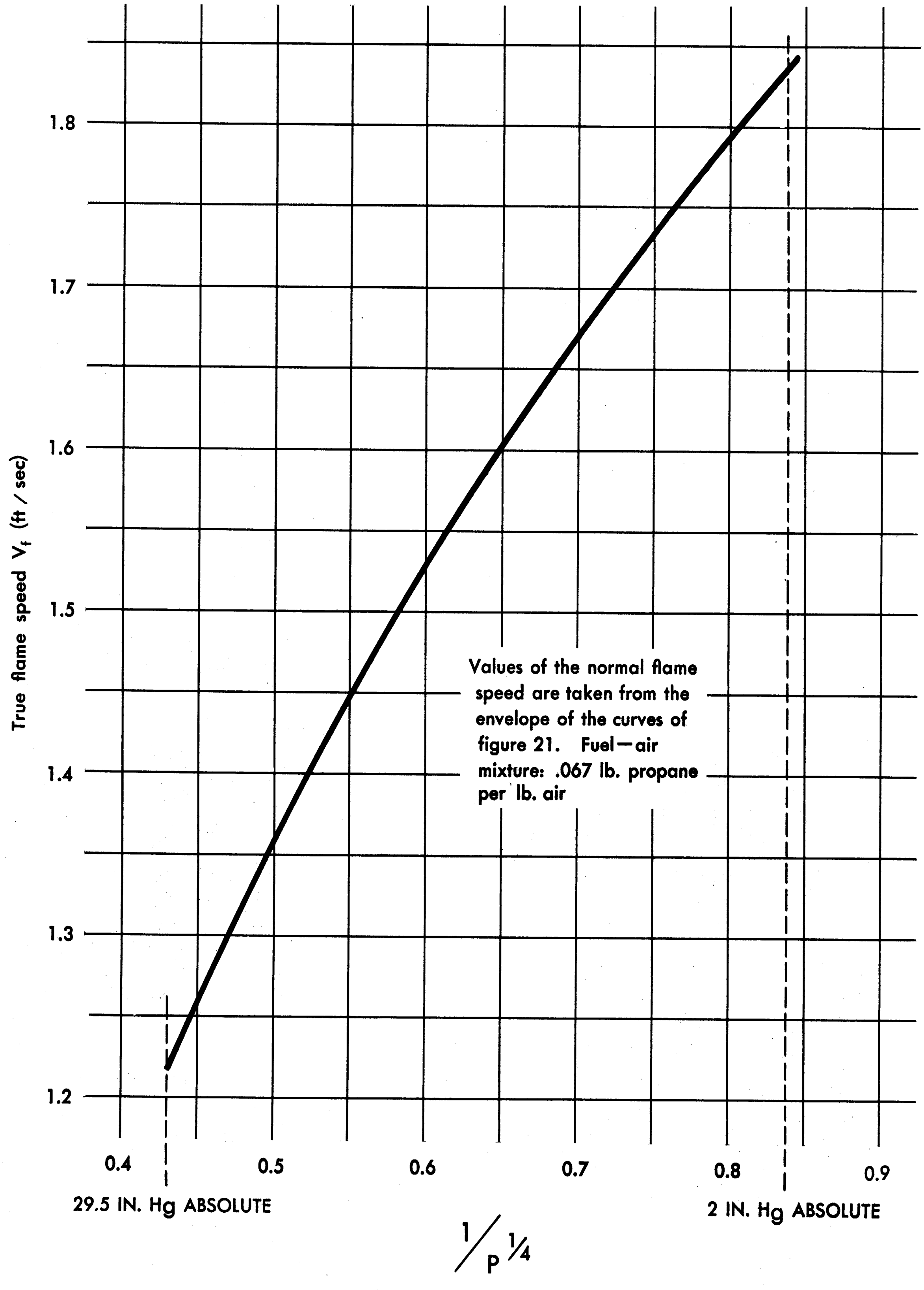


FIG. IIIa VARIATION OF FLAME SPEED INVERSELY WITH THE FOURTH ROOT OF THE PRESSURE

DISTRIBUTION

Distribution of this report is made in accordance with the AMC letter, dated 8 April 1949.