FLAME STABILIZATION ON BLUFF BODIES AT LOW AND INTERMEDIATE REYNOLDS NUMBERS

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ABSTRACT

The problem of attaining stable combustion in ramjet power plants and in afterburners of turbojet engines has led to rather extensive studies of the processes involved in stabilizing flames on bluff bodies. One of the results of these studies was to indicate that the flame stabilization mechanism changes significantly at low Reynolds Numbers; the velocity at which flames may be stabilized drops abruptly as the Reynolds Number is decreased, and the mixture ratio for which maximum velocity of flame holding occurs shifts markedly from the stoichiometric value.

This abrupt change in the mechanism of flame stabilization is investigated through photographic studies of the flame front near the flame holder. A transition from a laminar to a turbulent surface of the flame front immediately downstream from the flame holder is shown to account for the change in flame stabilization characteristics. This transition was found to occur independently of fuel type and flame holder geometry.

The behavior of the low Reynolds Number stabilization limits is attributed to a diffusion process; in particular, the shift found for the mixture ratio corresponding to the maximum blowoff velocity is explained on the basis of the difference in the diffusion rate of fuel and oxygen. Detailed experiments including blowoff results, chemical analysis of gas taken from the flame holder wake, and measurements of wake temperatures are shown to confirm the suggested diffusion mechanism.

Once the transition phenomenon is appreciated, re-examination of high Reynolds Number blowoff data is found possible. The results of previous experiments are found to show that the blowoff velocity depends on the square root of the characteristic dimension if the transition Reynolds Number is exceeded and if the flame holder is a bluff body of small fineness ratio.

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LIST OF SYMBOLS

(C/N)	Ratio of moles of carbon to moles of nitrogen for a gas mixture
D	Characteristic flame holder dimension
P	Combustion chamber static pressure
T	Combustion chamber static temperature
U	Approach gas speed
α	Exponent for the correlation $U \sim D^{\alpha}$
λ	Exponent for the correlation $U \sim P^{\lambda}$
Λ	Ratio of: $(C/N)_{approach\ stream} / (C/N)_{wake}$
ϕ	Fuel-air ratio, fraction of stoichiometric value
ϕ_m	Approach gas fuel-air ratio, fraction of stoichiometric, corresponding to maximum blowoff velocity for a particular flame holder size
ϕ_c	Approach gas fuel-air ratio, fraction of stoichiometric, corresponding to a stoichiometric value of wake gas mixture ratio
ϕ_t	Approach gas fuel-air ratio, fraction of stoichiometric, corresponding to the maximum value of the temperature of the wake gases
μ	10^{-6}

I. INTRODUCTION

In air breathing jet propulsion devices it is necessary to maintain a steady continuous combustion process in gas streams moving at speeds greatly exceeding the normal burning velocity. Such a combustion process may be achieved by stabilizing the flame through continuous ignition at some point of the flow; the combustion front then propagates into the high speed gas stream at an angle fixed by the ratio of flame speed to gas speed. The fact that a flame may be stabilized or "held" in the wake of a bluff body placed in a high speed gas stream is well known; the present interest in the phenomenon arises from the fact that bluff body flame holders have been found useful in ramjet combustion chambers and in turbojet afterburners.

Early experiments showed that, for a particular shape and size of bluff body, stabilization of a flame in the wake was possible over a range of values of gas speed and mixture ratio. Outside this range it was impossible to stabilize the flame and the flame was said to "blow off" from the flame holder. The values of gas speed and mixture ratio at which the combustion process ceased were designated blowoff limits and the locus of such points the blowoff curve. In general, the maximum velocity at which a flame could be maintained - the maximum blowoff velocity - was found to occur very near the stoichiometric fuel-air mixture ratio.

Visual exploration of the flow field near the flame holder disclosed that a zone existed, just downstream of the body, in which the hot combustion products recirculated strongly. When viewed along the axis of a cylindric flame holder, the stabilized flame appears to the eye similar to the photograph shown in Figure 1. Here the recirculation zone in the cylindric wake is clearly seen as a dark area separated from the combustible main gas stream by a not too well defined burning region. Under certain conditions this recirculation zone and attendent burning region was found to exist even when the flame failed to propagate downstream.

Facts of particular engineering interest are the dependence of blowoff limits upon size and geometry of the flame holder, inlet temperature and pressure of the combustible mixture, and characteristics of the fuel. For a variety of simple isolated flame holders in idealized approach stream, this dependence has been investigated experimentally by J. P. Longwell(1) and A. C. Scurlock(2) at the Massachusetts Institute of Technology, by A. Weir, R. E. Cullen, and D. Rogers(3) at the University of Michigan, E. A. De Zubay(4) of the Westinghouse Research Laboratories, G. H. Haddock(5) at the Jet Propulsion Laboratory, and O. L. Olsen(6) at the U. S. Bureau of Standards. Although these results exhibited wide differences, certain definite trends appear general. For high approach speeds of the combustible mixture, an increase in flame holder size was always accompanied by an increase in blowoff speed at any mixture ratio, while the opposite was true for rich mixtures at very low gas speeds. For large flame holder sizes, the maximum blowoff velocities were always observed to occur near the stoichiometric fuel-air ratio while for very small flame holders, the experiments of references 2, 3, 5, and 6 indicated that the maximum blowoff velocity shifted sharply to rich mixtures. At any fuel-air ratio the blowoff velocities of cylindric flame holders was found to increase at a rate proportional to some value between the square root and first power of the cylinder diameter.

The results of Haddock and of Olsen on the effect of inlet gas temperature are in close agreement while the variations of blowoff limits with pressure, investigated by Weir et al and by De Zubay, agree remarkably well in spite of geometric differences. Scurlock's results indicate a strong dependence of blowoff limits on the type of fuel employed.

Although this great amount of work has been done to determine the blowoff limits for various conditions little investigation of the nature of the wake region itself has been carried out. H. M. Nicholas and J. P. Field,[7] and Longwell, et al,[1] have shown that a recirculation zone existed in the wake region and Nicholas, et al, found that the gas speeds in this region were an appreciable fraction of the inlet gas speed. Static pressure surveys on the surface of cylindric flame holders held perpendicular to the gas stream show that while the pressure level of the downstream face of the cylinder was considerably higher under conditions of burning, the general shape of the pressure distribution was unchanged. No information concerning the temperature and size of this region has been reported.

The previous investigations of flame stabilization yield, however, very little information concerning the mechanism of flame stabilization itself, for the good reason that experimental investigations of the wake are extremely difficult. However in view of the considerable uncertainty in proper interpretation to be given to various sets of experimental results, it seems that a point has been reached at which this confusion can be reduced only by undertaking the detailed investigation despite its experimental difficulties.

The present work begins with an investigation of flame stabilizing characteristics of bluff bodies at low Reynolds Numbers. The cause for the change in the flame stabilization mechanism which occurs as the Reynolds Numbers was reduced was first investigated, and then a study of the low Reynolds Number flame stabilization regime was made. This study was undertaken not only with the purpose of determining the cause of the anomalous behavior of the small diameter flame holders mentioned above, but with the hope that the investigation would indicate mechanisms, perhaps hidden at higher Reynolds Numbers, which would be of help in interpreting the high Reynolds Number flame stabilization results. Because any real understanding of the stabilization process requirea a knowledge of the phenomena taking place in the recirculation region, a series of experiments were carried out to determine as much as possible concerning the temperature and the chemical composition of this region. As a direct result of these two lines of investigation, it has been found possible to reinterpret the available information obtained at high Reynolds Number and to clarify, in a large part, the inconsistencies noted by previous authors.

II. EXPERIMENTAL APPARATUS

A schematic diagram of the principal features of the flow systems used in the experimental work is given in Figure 2. A controlled quantity of air was drawn from a well regulated supply and was heated to a fixed temperature by a heat exchanger system. Fuel was injected into the hot air stream some distance upstream from the plenum chamber to insure that the mixture entering the combustion chamber was uniform and homogeneous. A smoothly converging nozzle connected the plenum chamber to the combustion chamber; the contraction ratio of this nozzle and the size of the plenum chamber were sufficient to give a uniform flow of low turbulence level at the combustion chamber inlet. Thus the combustible mixture at the entrance to the combustion chamber was of uniform mixture strength, velocity and temperature, and of low turbulence level.

The experiments were carried out in a rectangular combustion chamber with a 2" x 4" cross-section. Vycor glass windows were provided for all four walls to allow visual and photographic observation of the flame front for a distance 5 inches downstream from the flame holder.

Air Supply and Control. The service air supply for this system was furnished by two reciprocating pumps with a total capacity of 3.7 lbs/sec at a pressure of 100 lbs/in^2. The mass flow rate of the air was regulated through a remote controlled sonic-throat valve located upstream from the fuel injector and heat exchanger. This arrangement allowed the mass flow of air to be held at a constant value despite changes in fuel injection rates, mixture temperatures, and changes in combustion chamber static pressure.

Air-Temperature Control. Unless otherwise specified, a mixture temperature of approximately 610°R was used in all experiments. This is the minimum temperature which safely assures complete vaporization of all the components of the gasoline fuel. The air was heated in a shell-and tube- type heat exchanger whose hot air supply was furnished by a turbojet can burner. Two butterfly valves operated by a commercial temperature control system fixed the combustion chamber mixture temperature by shunting a fraction of the air around the heat exchanger. The vapor bulb sensing element for the control unit was located in the air supply line downstream of the fuel injection point. This arrangement gave a quick response to fluctuations in the gas mixture temperature caused by changes in the fuel-air ratio and therefore changes in the heat necessary to vaporize the fuel.

Combustion Chamber. The combustion chamber was a 9 inch long rectangular duct with a 2" x 4" cross-section flow passage. The duct was constructed (Cf. Figure 3) from cold rolled mild steel and was strongly water cooled to prevent deformation due to heating effects; the inside surfaces of the duct walls were film cooled over a 1.5 inch section at the exit. Because this cooling was sufficient to keep the chamber at room temperature even after prolonged operation, the temperature of the chamber walls was not a variable of the experiments. Vycor glass walls were used on all four sides of the chamber and for most of the experiments, the flame holders were mounted through 1/8 inch holes drilled in these glass side walls. The glass windows allowed a view of the duct extending from just upstream from the flame holder to a position 5 inches downstream from the holder. The discontinuities in the wall surface at the connection between the combustion chamber and the nozzle, and between the glass walls and the combustion chamber proper were kept less than 0.002 inches.

Flame Holders. The cylindric flame holders were constructed from stainless steel tubing, steel ball bearings were used for the spherical holders, and the V-gutters, disks and flat plates were machined from mild steel stock. The holders were mounted through 1/8 inch holes drilled in the walls of the combustion chamber and were located 7 inches upstream from the exit of the combustion chamber on the center line of the 4 inch wall. The spherical holders were held on 0.010 inch diameter nichrome wire, and the disks were held on 1/8 inch struts. Figure 4 shows the type of mounting used and the construction details for the large and small cylindric holders. Water cooling was sufficient to keep the temperature at the downstream stagnation point of the cooled flame holders well below 150°F.

Fuel Systems. The gasoline fuel used in the experiments was commercial paint thinner (Thinner Number 1, Union Oil Company) whose chemical properties have been described in detail in Reference 5. The mean molecular weight of the fuel is 89 and it is composed of roughly 36% by volume naphthenes, 58% paraffins, and 6% aromatics. The gaseous fuels were commercial grade methane and hydrogen. The methane fuel was composed of 92% by volume methane, 6% propane and 2% nitrogen. The gasoline fuel, Figure 2, was drawn from tanks pressurized to 100 lbs with nitrogen and injected through a constant pressure variable area nozzle 30 feet upstream from the plenum chamber. The gaseous fuels were taken from sets of 40 high-pressure gas cylinders; the gas, initially at 1500 lbs/in^2 pressure, was regulated by two Grove Dome Gas Regulators in series before being metered at 115 lbs/in^2

pressure. The gaseous fuels were injected into the hot gas stream at the same point as the liquid fuel. For the gaseous fuels, both temperature and pressure measurements were obtained just downstream from the flowmeters.

Ignition System. Ignition was obtained by producing a high voltage spark between the back edge of the flame holder and a remotely positioned ignitor rod. With a 10,000 volt power supply ignition was possible near the stoichiometric fuel-air ratio for gas speeds up to 100 ft/sec; the larger flame holders were easiest to ignite, and a spark gap between 1/16 and 1/8 inch wide was found to give the best ignition results.

Plenum Chamber and Nozzle. The plenum chamber was a pipe section 15 inches in diameter and 5 feet long (Cf. Figures 2 and 5. An 8 inch diameter perforated baffle was used at the upstream entrance of the chamber to break up the high speed air stream entering the chamber from the 4 inch air supply line and in addition, 6 stainless steel 200-mesh calming screens were located at 6 inch intervals in the plenum chamber to reduce the turbulence level of the gas stream. A 12 inch diameter rupture diaphragm was built into the upstream end of the chamber to allow a quick reduction of plenum chamber pressure in event of a blow-back.

The nozzle was 18 inches long and reduced the flow cross-section area from a 15 inch diameter circle to a 2" x 4" rectangular opening. This gives a contraction ratio of about 22:1. Pressure surveys showed that this nozzle furnished a flat velocity profile at the combustion chamber entrance for all operating conditions. From these surveys it also appeared that the boundary layer on the duct walls at the plane of the flame holder had begun transition for gas speeds of 100 ft/sec or higher.

Pressure and Temperature Measurements. Plenum chamber pressure and combustion chamber static pressure were measured by a water and mercury manometer. The lines connecting these pressure sources were equipped with remote controlled cutoff valves which allowed the pressure taps to be blown clear of any trapped oil or water before readings were taken. The plenum chamber pressure was obtained from an ordinary total head tube located on the center line of the plenum chamber downstream of the last screen. The combustion chamber static pressure tap was located on the center line of one of the 2 inch wide walls of the combustion chamber 3-1/8 inches upstream from the location of the flame holder and 2 inches downstream from the end of the converging section of the nozzle. The gaseous fuel static pressure was measured with a 0 - 200 lb/in^2 test gage calibrated before use. Temperatures were measured by use of chromel-alumel thermocouples and a Brown Automatic Potentiometer.

Sampling Apparatus. Sampling flame holders were constructed in a similar manner to the cooled flame holders, except that the cooling passages were used in removing the gas sample rather than for cooling purposes. For 0.125 and 0.049 inch diameter flame holders the sample was exhausted through 20 - 0.010 diameter holes located at the downstream stagnation point. A slit .003 x 0.600 inches was used as an inlet for the 0.031 inch diameter flame holder. The holes were located over a one inch length of the flame holder and the ratio of hole diameter to cylinder diameter was kept below 1/5.

Schlieren Equipment. The schlieren system was of the conventional double mirror type; a BH-6 lamp light source was used, and the focal length of the two 6 inch diameter concave mirrors was 54 inches. Since the electrical circuit and the physical layout of the optical system were conventional, no diagrams will be given here. The spark and shutter, which was used to keep the film from being fogged by the light from the flame, were synchronized by use of several relays arranged in series to furnish the proper time delay between the firing of the shutter mechanism and the schlieren spark. Super XX film was used for all pictures and the duration of the spark was shown to be less than 7 μ seconds.

III. TRANSITION PHENOMENON IN STABILIZED FLAME

Existing Evidence of Transition. The large difference which exists in the stabilizing characteristics of flame holders operating at high and at low Reynolds Numbers is most clearly illustrated by the extensive set of blowoff curves for circular cylinders obtained by G. Haddock.[5] For the larger cylinders, and hence for high Reynolds Numbers, the blowoff curves are geometrically similar, Cf. Figure 6; for a given rod size the maximum blowoff velocity lies near the stoichiometric fuel-air ratio and increases regularly with increasing flame holder size. The three smallest flame holders however do not conform to this pattern; the maximum blowoff velocities are relatively constant for large variations in flame holder size and occur at mixture ratios above the stoichiometric value. This behavior suggests that the Reynolds Numbers of these rods are sufficiently low that they operate in a different flow regime. Some conformation of this conjecture may be obtained by replotting the data of Haddock so as to exhibit the variation with Reynolds Number of the maximum blowoff velocity and the fuel-air ratio at which it occurs. Figure 7 indicates quite distinctly that abrupt changes take place in both of these quantities for values of the Reynolds Number in the neighborhood of 10^4. (The Reynolds Number is based on gas properties of the approaching stream and flame holder diameter.) Data obtained under comparable conditions by Olsen,[8] have been included in this figure to indicate the generality of the transition. These two sets of data cover a range of Reynolds Numbers wide enough to indicate clearly the transition phenomenon; other experimentors such as Scurlock,[2] and Weir, Rogers and Cullen,[3] were able to observe only that the peaks of low Reynolds Number blowoff curves were shifted from the stoichiometric fuel-air ratio.

Examination of spark schlieren photographs of the flame front stabilized behind cylindric holders suggest that one difference between the high and low Reynolds Number regimes may be connected with transition in the flame front bounding the recirculation zone. Photographs of the flame front taken by Scurlock,(2) Haddock,(5) and Shonerd,(9) give some indication that for Reynolds Numbers as high as 10^4, the flame front near the flame holder is laminar while at higher Reynolds Numbers the flame front appears to be turbulent. Such a deduction is hardly justified, however, since photographs of the flame edge may be very misleading due to non-uniformity in the thin flame zone along the line of sight.

Consequently a detailed photographic investigation of the flame front near the flame holder was undertaken with the purpose of determining definitely whether the change observed in the blowoff characteristic resulted from a transition from laminar to turbulent flame front. Further, the dependence of the transition phenomenon on fuel type, mixture temperature, and flame holder geometry, temperature and size was investigated.

Flame Schlieren Photographs and Their Interpretation. Spark schlieren photographs were taken using the 2" x 4" combustion chamber, described previously, which was constructed so that it was possible to photograph the flame front looking down on the plane of the flame holder axis and gas flow direction, (Cf. Figure 8), as well as from the conventional view along the axis of the cylindric flame holder. Pictures taken in the former view make possible an accurate determination of the magnitude of the three dimensional effect at the walls of the combustion chamber, and hence make the determination of the true condition of the flame front more certain. A schlieren system is sensitive to density gradients, and for the pictures shown here, the only visible gradients are caused by the sudden change in density associated either with a flame front, or with mixing of hot and cool gases without combustion taking place.

Interpretation of schlieren pictures of flames held on two dimensional flame holders is difficult because of the need to differentiate between the two dimensional effects which are of interest, and the three dimensional effects which arise from interaction between the flame front and the wall boundary layer. A typical "side view", i.e., a view looking along the flame holder axis, is given in Figure 9a . The direction of gas flow is from left to right and the flame holder is just hidden from view by the black area projecting from the left side of the picture. The wavy flame surfaces are clearly defined but the detail shown between the flame fronts is caused by three dimensional effects. The schlieren system is sensitive to density gradients parallel to the gas flow direction so that a dark region indicates that the density decreases in the direction of flow. The light area at the right side of the photograph is caused by temperature gradients in the glass side walls. A photograph taken from the same view but with the schlieren system sensitive to gradients perpendicular to the flow direction is given in Figure 9b. The great apparent thickness of the flame front shown in this picture is due to the fact that the flame front is not completely two dimensional. The temperature gradients in the glass darken the top of the picture and lighten the bottom.

In Figure 9c is given a "top view" of the flame front, i.e. a view looking down on the plane of the axis of the flame holder and the flow direction. The flow is again from left to right and the flame holder is visible as a black strip spanning the tunnel at the left edge of the picture. In photographs taken from this view the complete flame holder, or at least the downstream edge of the flame holder, will always appear at the left hand edge of the picture and the walls of the combustion chamber will appear as dark strips down either side. This view demonstrates that the wavy structure of the flame front (Cf. Figures 9a and 9b) is two dimensional except near the side walls where there is some interaction between the flame front and the boundary layer. The detail shown in the top view results from a simple refraction of the light beam as it enters and leaves the hot layer of gas enclosed between the flame fronts. Thus the top view pictures may be interpreted as a contour map of the flame surface illuminated by a light coming from the right hand side of the picture. This artifice is also helpful in interpreting the photographs taken from the side view when the flame front is strongly three dimensional. Figure 9d presents such a photograph; the details shown here are almost entirely due to the refraction of the light beam on entering and leaving the three dimensional bursts of hot gas rather than to bending of the light rays by density gradients in a two dimensional flame.

Schlieren Study of the Flame Surface. Spark schlieren photographs were taken of the flame front behind circular cylinders with Reynolds Number, cylinder diameter and fuel-air ratio used as parameters. Top view schlieren photographs illustrating the dependence of the flame front geometry on Reynolds Number and fuel-air ratio for a 0.035 inch diameter cooled cylinder are given in Figures 10 and 11. For all values of the Reynolds Number at which this flame holder could operate, the flame front, (Cf. Figure 10), is laminar for at least 30 diameters downstream from the holder. At very low Reynolds Numbers, the only disturbance of the laminar flame front is a regular wave pattern. Although with an increase in Reynolds Number these waves break up into cells some distance away from the flame holder, the scale of the distortion is large and never takes on a turbulent character. For the highest Reynolds Numbers, the flame is residual, i.e., a flame exists near the flame holder but does not propagate into the free stream gases and the nonburning flow downstream from the residual flame forms a turbulent wake which quickly develops into a typical Kàrman vortex street. Time exposure photographs confirm the conclusion of visual observation that the luminous portion of the flame front stops before the development of this turbulent asymmetric wake begins. The photographs given in Figure 10 were taken for a value of the fuel-air ratio approximately 1.4 of stoichiometric. In Figure 11 is shown the dependence of the flame front geometry on fuel-air ratio at a Reynolds Number value of 830. Here again, for all the conditions observed, the flame front appears to be laminar. Even the asymmetric wake downstream of the residual flame (fuel-air ratio 2.82 of stoichiometric) is laminar for this low Reynolds Number. The most important fact shown by these pictures is that the flame front is always essentially laminar in nature. This general description of the flame front was found to be typical of all flame holders with diameters less than 0.100 inch for both gasoline and methane flames.

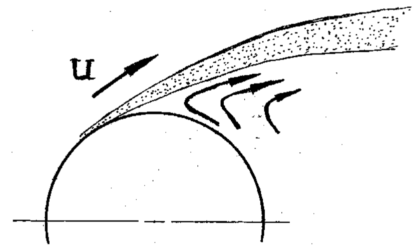
Similar sets of photographs for 1/8 inch and 1/2 inch cylindric flame holders are given in Figures 12a, 12b, and 13. These flame fronts are laminar at only the lowest Reynolds Numbers. As the Reynolds Numbers increase, the surface structure shows a strong tendency to break down into smaller distortions although the original wave structure may still be discerned. The photographs at the highest Reynolds Numbers show a complete transition to what may reasonably be interpreted as a turbulent flame front. These photographs were taken at very nearly the stoichiometric fuel-air ratio and it is of interest to note that the approach mixture speeds at the highest Reynolds Number are much less than the maximum blowoff velocity at this fuel-air ratio. Photographs showing the dependence of the flame front shape on fuel-air ratio are given in Figure 14 for a 1/8 inch diameter flame holder operating at a Reynolds Number of 3.3×10^3. Photographs such as this show that for low enough Reynolds Number the flame front is completely laminar even at the rich and lean blowoff limits. For the richest mixture shown the flame is residual and the Kármán vortex street is clearly seen.

Studies such as these were made of the flame fronts stabilized on cylindric flame holders for diameters ranging from 0.020 inches to 0.75 inches. The photographs of the flame surface in the vicinity of the respective maximum blowoff velocities for various flame holders revealed that the flame front was turbulent when the Reynolds Number exceeded 10^4 and was laminar for Reynolds Numbers less than this value. This transition agrees, moreover, with that shown by the curves of Figure 7 and hence it seems clear that the sharp change in the blowoff characteristics observed in the direct result of transition in the flame front separating the recirculation zone from the unburned gas stream.

The effect of flame front transition has been illustrated through its influence on maximum blowoff velocity only because this point of the blowoff curves is unambiguously defined. However, if any other set of blowoff velocities, say the set defined by some particular value of the fuel-air ratio, is plotted as a function of the Reynolds Number, a characteristic break is found in the curve similar to that shown in Figure 7. Schlieren pictures likewise confirm that this break corresponds to the change from laminar to turbulent flame front.

Fluid Mechanical Interaction of Flame Surface and Wake. The occurrence of laminar flames for Reynolds Numbers as high as 10^4 appears to contradict the fact that the isothermal wake of a cylinder is turbulent at these Reynolds Numbers. It is therefore of interest to review briefly the important changes which occur in the isothermal wake of a cylinder with increasing Reynolds Number and to try to determine if there is any connection between the isothermal wake structure and the transition observed in the flame front. At Reynolds Numbers between 1.0 and about 30, a stable vortex pair exists in the wake of the cylinder; the flow is completely laminar, and no appreciable wake is produced. For Reynolds Numbers between 30 and 150, the boundary layer and the separated boundary layer, or vortex layers as they are usually called, are still laminar, but the vortex layers now roll up to form the familiar Karman vortex street. As the Reynolds Number is increased above 150, vortices are still shed regularly from the cylinder, but a transition to turbulent flow in the vortex layers now occurs some distance downstream from the cylinder. With further increase of the Reynolds Number this transition region moves upstream toward the surface of the cylinder, and for Reynolds Numbers near

10^4, transition begins at the separation point itself. For Reynolds Numbers greater than 2×10^5, the transition to turbulence precedes the boundary layer separation. The nature of this flow near the separation point is shown in the sketch at right.(10) Much more detailed surveys of the flow behind bluff bodies are given by H. L. Dryden,(11) S. Goldstein,(12) and A. Roshko.(13)



In general, this picture of the flow about circular cylinders fits very well the behavior of flows about other bluff bodies of small fineness ratio such as spheres and flat plates or disks held perpindicular to the air stream. However, the values of the Reynolds Numbers at which the various transitions occur are affected by the geometry of the body. For instance, comparison of the drag curves of cylinders and spheres indicates that the Reynolds Numbers at which transition to turbulence in the vortex-layers occurs at the separation point is about 1.50×10^4 for cylinders and 3.0×10^4 for spheres.(14)

In view of these facts concerning the isothermal wake flow, it is rather more surprising that a laminar flame front is found at all, than that a transition between laminar and turbulent flames takes place. That laminar flame fronts are observed for Reynolds Numbers greater than 10^2, strongly suggests that the process of combustion is responsible for preventing the transition to turbulence in the vortex-layers. In attempting to compare the isothermal wake characteristics with the diabatic characteristics account must be taken of the fact, that due to conduction and mixing effects at the interface between the hot recirculation zone gases and the gases of the vortex-layers, the temperature of the vortex-layer will increase with distance from the separation point. An increase of temperature of the order to be expected from the combustion temperatures of the fuels used in the present experiment could cause a change in local Reynolds Number by a factor of from 10 to 20. Consequently, if the heating of the vortex-layers is rapid enough to increase appreciably their temperature before transition occurs, the local Reynolds Number may be reduced sufficiently to prevent transition. Thus, at low Reynolds Numbers the transition to turbulence in an isothermal wake will occur several diameters downstream from the flame holder; with sufficient heat transfer from the wake, the vortex-layers may be stabilized for large distances downstream of the cylinder. However, as the Reynolds Number is increased, the transition region of the vortex-layers will move toward the flame holder in spite of the effects of heating. Furthermore, because of the quenching action of the cooled cylinder, heating of the gases in the neighborhood of the separation point will be small. Finally, therefore, when the Reynolds Number is high enough to insure transition to turbulence near the separation point, the flame surface should be turbulent regardless of the heating effects. Isothermal studies mentioned above indicate that transition near the separation point occurs for Reynolds Numbers of the order of 10^4, which is precisely the Reynolds Number range for which transition to turbulence is actually observed in the flame front.

The fact that the flame front must, at some point downstream of the flame holder, burn through the vortex-layers suggests an alternative cause for the onset of turbulence. When this vortex-layer is turbulent the flame front should exhibit a turbulent structure as it passes through the layer. The location of this intersection is influenced directly by the flame propagation speed and consequently is strongly affected by the fuel-air ratio. Photographs for both methane and gasoline fuels show conclusively that the development of turbulence is completely independent of fuel-air ratio. Therefore, the transition in the flame front can not be attributed to the passage of the flame front through the unstable vortex-layers.

The foregoing discussion implies that the transition to turbulence in the flame front is influenced by the structure and the stability of the boundary layer on the surface of the flame holder upstream of the point of flame attachment. If this is true, one would expect that the flame front would be turbulent when the boundary layer on the flame holder body was turbulent. Experiments were carried out in which the flame holder boundary layer was tripped by various means and it was found that in all these experiments, the flame was turbulent whenever the boundary layer was turbulent regardless of the Reynolds Number. This tripping of the boundary layer was discovered to have a large effect on the general nature of the blowoff curves. If the boundary layer of the flame holder normally operating completely in the low Reynolds Number regime were tripped, the maximum blowoff velocity was found to be shifted from its normally rich value to a point near the stoichiometric value. This result confirms the statement made earlier that the advent of turbulence in the flame front is responsible for the change in the character of the blowoff curves shown in Figure 7. It was also found possible to delay the transition to turbulence in the flame front by increasing the boundary layer thickness on the cylindric holder. This result is quite reasonable since for isothermal flow, the distance to the transition point in the vortex-layers increases with the thickness of the boundary layer at the separation point.

On the basis of the suggested mechanism of transition, the temperature of the flame holder should have a significant effect through its influence on the quenching distance and also on the local value of the Reynolds Number. Photographs demonstrating the behavior of the flame front behind a 1/8 inch cylinder as a function of the temperature of the flame holder are given in Figure 15. Such pictures indicate, as would be expected, that high flame holder temperatures can cause the flame front to remain laminar for an appreciable distance downstream from the flame holder, but that even for the flame holder temperatures as high as 2000°F, the transition Reynolds Number is increased by only 20%.

The chief characteristics of fuels which would be expected to affect the transition phenomena are the quenching distance, the adiabatic flame temperature, and the flame speed. The effect of the flame speed will be principally important in fixing the time required for the flame to burn through the vortex-layers. It was shown earlier that, for the fuels investigated, this interaction is of no importance in fixing the point of transition. Likewise, the small variation in the adiabatic flame temperature for these three fuels will have little influence on the transition phenomenon. The quenching distances reported for hydrogen flames are smaller by a factor of ten than those reported for methane and gasoline flames and consequently, the transition phenomena for the hydrogen flame would be expected to occur at slightly higher Reynolds Numbers than that for methane or gasoline flames. Comparison of schlieren photographs illustrating the transition regime for these three fuels, (Cf. Figures 16, 17, and 13), completely corroborate this conjecture.

Investigation of Generality of the Phenomenon. To determine whether the transition phenomenon observed with circular cylinders occurs for flame holders of other geometric shape, schlieren photographs of the flame surfaces were made for flames stabilized on spheres, circular disks, flat plates and V-gutters. The effects of the flame holder shape are illustrated in Figures 18 and 19 in which are shown the development of turbulence in gasoline flames stabilized on 1/2 inch spheres, and disks. As was found for the flame stabilized on cylindric flame holders, the low Reynolds Number flame fronts for the various geometries are characterized by a distinct wavy structure. As the Reynolds Number is increased, smaller distortions are superimposed on these waves, and for the highest Reynolds Numbers shown, the flame fronts are clearly turbulent. These pictures and others for flat plates and V-gutters not shown demonstrate conclusively that the general phenomena occurring in the transition regime are similar regardless of the geometry of the flame holder.

In the following table are given the Reynolds Numbers for which the transition to turbulence in the flame front is judged to be complete for the various flame holder geometries studied. It should be noted that the judgment of "complete" is subjective, and that the gradual advent of turbulence and the limited number of pictures taken for any flame holder geometry further restrict the accuracy of the results. Unless otherwise specified, gasoline is used as fuel.

Flame Holder Geometry, Size and Mounting	Cross Section of Duct	Inlet Gas Temperature	Reynolds Number for Transition
3/4" cylinder, cooled	2" x 4"	610°R	4.3 x 10^4
1/2" cylinder, cooled*	2" x 4"	610°R	2.8 x 10^4
1/2" cylinder, cooled	2" x 4"	860°R	2.7 x 10^4
1/4" cylinder, cooled	2" x 4"	610°R	2.0 x 10^4
1/4" cylinder, cooled	2" x 4"	860°R	1.9 x 10^4
3/16" cylinder, cooled	2" x 4"	610°R	1.8 x 10^4
1/8" cylinder, cooled*	2" x 4"	610°R	1.3 x 10^4
1/8" cylinder, uncooled	2" x 4"	610°R	1.4 x 10^4
1/8" cylinder, heated to 2400°R	2" x 4"	610°R	1.5 x 10^4
1/10" cylinder, cooled	2" x 4"	610°R	1.25 x 10^4
1/2" sphere, wire supported, uncooled	2" x 4" 1" x 4"	610°R 610°R	6.0 x 10^4 6.0 x 10^4
1/2" sphere, sting mounted from downstream, uncooled	1" x 4"	610°R	5.4 x 10^4
1/4" sphere, wire supported, uncooled	2" x 4"	610°R	3.5 x 10^4
1/2" disk, sting mounted from upstream, uncooled	2" x 4"	610°R	6.0 x 10^4
1/2" disk, sting mounted from downstream, uncooled	2" x 4"	610°R	6.5 x 10^4
1/2" flat plate, cooled	2" x 4"	610°R	5.8 x 10^4
3/4" V-gutter, uncooled	2" x 4"	610°R	6.8 x 10^4
3/8" V-gutter, uncooled	2" x 4"	610°R	4.3 x 10^4

* Gasoline, hydrogen and methane fuels were used for these conditions.

For cylinders and spheres sufficient data were obtained to show that the transition to turbulence depends on the size of the flame holder. The dependence is definitely of the form $Re_t \sim D^{\frac{1}{2}}$ for cylinders and appears to be the same for spheres. Influence of the cylinder diameter independent of the Reynolds Number is substantiated by the fact that the transition Reynolds Number obtained for 1/4 and 1/2 inch diameter cylinders was found to be unchanged when the approach gas temperature was increased by 40 per cent. This dependence on $D^{\frac{1}{2}}$ clearly indicates that some other characteristic length associated with the phenomenon is of importance in fixing the transition Reynold Number. The most important length, on the basis of the model suggested earlier, is the quenching distance. Because little is understood about the quenching distance in general, and even less about the distance pertinent to this particular problem, nothing can be said at this time concerning the dependence of this distance on the characteristic dimension of the flame holder.

For cylinders and spheres, the Reynolds Number at which the transition to turbulence takes place ranges between 1 to 4×10^4, and 4 to 6×10^4 respectively while the isothermal flow Reynolds Number for which turbulence first appears in the vortex-layers at the separation point are approximately 1.5×10^4 and 3×10^4 respectively. The agreement between the two "critical" Reynolds Numbers, and the constant factor by which they differ, gives support to the ideas developed earlier concerning the cause of the transition in the flame front.

Conclusions. The results of schlieren studies of the surface of flames stabilized by bluff bodies show conclusively that the flame front undergoes a transition from a laminar to a turbulent character for Reynolds Numbers of the order of 10^4. This transition was found to occur in the same range of Reynolds Number in which the flame stabilizing characteristics of bluff body flame holders change abruptly and experiments showed that the appearance of turbulence in the flame front near the flame holder was the phenomenon responsible for this change in blowoff characteristics.

The transition Reynolds Number was found to depend on the size and the geometry of the flame holder, but the transition phenomenon itself was demonstrated to be independent of these quantities. The transition Reynolds Number increases weakly with increasing flame holder temperature and laminar flame speed but was not affected by an increase in temperature of the approaching gas stream. The flow condition which influences the transition Reynolds Number most strongly is the state of the boundary layer upstream of the separation point. If this boundary layer is either naturally turbulent or is artificially tripped, the flame front is always found to be turbulent.

FLAME STABILIZATION AT LOW REYNOLDS NUMBERS

Since it is clear that the abrupt changes observed in the blowoff characteristics of flames stabilized on bluff bodies result from transition in the flame front separating the fresh gas from the wake, it is now proposed to examine more closely the detailed processes involved in flame stabilization below transition. One of the most striking changes associated with transition is that, while the maximum blowoff velocity occurs near the stoichiometric mixture ratio for high Reynolds Number, it shifts to very rich values as the Reynolds Number is reduced below the transition point. The only exception to this behavior is reported by Scurlock[2] who observed no shift at low Reynolds Numbers when "Cambridge City Gas" was employed as fuel.

It is to be expected that the high Reynolds Number blowoff curves peak near the stoichiometric fuel-air ratio in view of the fact that the maximum rate of heat release for a combustible mixture occurs near the stoichiometric ratio. Since there is no reason to believe that changes in the Reynolds Number will seriously alter this fact, it seems reasonable to conjecture that near the maximum blowoff velocity for low Reynolds Number conditions, some vital zone of the combustion process is actually operating near the stoichiometric ratio in spite of the rich free stream gas mixture. The shift in maximum blowoff velocity is commonly attributed to the fact that diffusion may become a significant influence at low values of the Reynolds Number; the difference in diffusion velocities of oxygen and hydrocarbon fuel may then produce the local change of mixture ratio in the wake. However, this picture has necessarily remained quite nebulous since no flow details were known for any values of Reynolds Number.

Diffusion as Influenced by Transition. The information obtained in the present investigation, concerning the nature of the transition between high and low Reynolds Number regions, now allows a more nearly precise picture to be formulated. Combustible material enters the recirculation zone through some transfer process across the interface of the free stream gases and the recirculation zone. For low Reynolds Numbers, it has been shown that this interface is laminar and consequently molecular processes will dominate the transfer phenomena. In particular, diffusion of fuel and oxygen across the interface will contribute materially to the transfer of combustible matter into the burning zone. The diffusion velocity depends strongly on the chemical species and is markedly larger for light molecules than for heavy. Therefore, in a mixture of ordinary gasoline with air, oxygen (being of the order of one third the molecular weight of the gasoline) will diffuse much more rapidly into the burning zone than will the gasoline. Hence, the effective fuel-air ratio of the burning gases may be considerably smaller than that of the free stream. Since the generation of a propagating flame is strongly dependent upon the initiation of combustion near the flame holder, it may be expected that the maximum blowoff velocity will occur when flame initiation takes place at the stoichiometric mixture. The fact that Scurlock's experiments with Cambridge City Gas exhibit no shift may be explained on the basis of this hypothesis. The mean diffusion velocity of this fuel is very close to that of oxygen[15] so that the differential diffusion effect, and therefore the shift in the blowoff curves, would be expected to be negligible.

The diffusion hypothesis is further supported by some chemical sampling of the recirculation zone gases carried out by Williams and Shipman.[16] Their work indicates that, as predicted on the basis of the differential diffusion hypothesis, the carbon content of the gases in this zone is appreciably lower than that which would be expected from complete combustion of the free stream gases. Visual observation of the color of the interface separating the recirculation zone from the free stream gases also suggests that the fuel-air ratio at this interface is considerably leaner than that of the free stream gases. Finally, observations of Scurlock,[2] that an increase in stream turbulence causes the peaks of low Reynolds Number blow-off curves to return toward stoichiometric, support the important role of transition.

Since the chief function of a flame stabilizer is that of igniting the free stream gases, it is of interest to inquire whether results of experiments on spark ignition of combustible mixtures exhibit some of the phenomena observed in the flame stabilization process. Although the maximum rate of heat release for a combustible mixture occurs near the stoichiometric fuel-air ratio, Lewis and von Elbe[17] found that for heavy hydrocarbon fuels the minimum spark ignition energy occurred for fuel-air ratios considerably above the stoichiometric values, and that for methane, a fuel which is slightly lighter than oxygen, the minimum point occurred below the stoichiometric value. Lewis and von Elbe suggested that some differential diffusion mechanism accounts for this behavior. To investigate more thoroughly this conjecture, diffusion coefficients of fuels employed by Lewis and von Elbe were calculated from the tables and numerical values given in Reference 17. In Figure 20 is given a plot of the fuel-air ratio for the minimum spark ignition energy as a function of the ratio of the diffusion coefficients of the fuel and oxygen in air. The good correlation of the data shown here, together with the fact that the ignition of the free stream gases by the hot gases of the recirculation zone is similar to this spark ignition process, strengthens the belief that diffusion is important in the flame stabilization at low Reynolds Numbers. It should be noted that the mixture ratio for minimum ignition energy is not shifted for hydrogen in spite of the fact that the diffusion coefficient for this fuel is much greater than that of oxygen. This result suggests that the differential diffusion phenomenon is not the only significant process but that other influences, such as, for example, the very large thermal conductivity of hydrogen, are important.

It is now clear how specific experiments may be constructed to determine definitely whether the diffusion mechanism is indeed the governing process. For example, the blowoff curves for some low molecular weight fuel should show a shift toward lean mixtures at low Reynolds Numbers. Also, systematic chemical sampling in the wake close to the flame holder should disclose a trend toward stoichiometric mixture ratios at the maximum blowoff velocity ragardless of the free stream mixture ratio. Consequently, a detailed experimental program was carried out to determine definitely the validity of the diffusion hypothesis. These experiments were:

1. Determination of blowoff curves for fuels with diffusion velocities greater and less than that of oxygen.
2. Examination of spark schlieren photographs to determine the effect of fuel characteristics on the flame front geometry.

3. Chemical sampling of the wake gas over a range of Reynolds Numbers wide enough to allow a detailed comparison with the results of the blowoff measurements.
4. Determination of wake gas temperatures for a range of Reynolds Numbers wide enough to allow a detailed comparison with the results of the blowoff measurements.

Determination of Flame Blowoff. The limiting values of the mixture velocity and the fraction of the stoichiometric fuel-air ratio for which a flame could be stabilized behind circular cylindric flame holders were determined for diameters ranging between 0.020 to 0.250 inches. The fuels used were gasoline, methane, and hydrogen, and the flame holders were water cooled. Similar curves were also obtained for 0.125, 0.049, 0.031 and 0.020 inch diameter uncooled flame holders. The flame holder sizes were picked to give a complete picture of the low speed regime and hence only two large flame holders are included in this study. The smallest cylinders used were the smallest flame holders on which a flame could be ignited at gas speeds exceeding 50 ft/sec.

The flame stability limit was usually determined by first setting the air flow at a fixed value and then slowly reducing or increasing the fuel flow until the flame was blown off. For the points near the peaks of the blowoff curves, this method was not possible and it was necessary to blow off the flame by slowly increasing the gas speed.

The accuracy of the determination of the values of fuel flow at blowoff was determined by the steps in which the fuel flow was increased or decreased as well as the errors in the meter calibrations. For the work reported in this paper, the percentage change in fuel reading at blowoff was usually less than 2 per cent, so that the estimate of the meter reading at the flame blowoff was of the order of 1 per cent. It was possible to increase the total pressure of the plenum chamber by steps of only 0.4 cm of water; for gas speeds greater than 150 ft/sec this corresponds to errors in gas speeds at blowoff of 1 per cent or less. Then the net error in measurement of gas speed and fuel flow rate due to the fact that the blowoff point was approached in steps and not by a continuous change in gas speed or fuel-air ratio was of the order of 1 per cent or less.

Errors due to inaccuracies in meter readings and to inaccuracies in the meters themselves were estimated at 1 per cent for both the liquid fuel and air mass measurements. Further errors due to gas temperature measurements were of the order of 1/2 per cent or less. This leads to total maximum errors of 2.5 per cent in air measurements and 2 per cent in fuel flow measurements at the blowoff point. The maximum error, then, in calculation of gas speed is of the order of 2.5 per cent while that for the fuel-air ratio is 4.5 per cent.

The meters used to measure the gaseous fuel flows were calibrated with air, and corrections were applied to these calibrations to correct the curves for the two gaseous fuels. Because the errors introduced by this procedure may be appreciable the error in the reported values of the fuel-air ratios for the methane and hydrogen experiments may be greater than 4.5 per cent.

Residual flames, i.e., flames which did not propagate into the high speed mixture, were included within these blowoff curves. Such residual flames are commonly found near the blowoff limits for holder diameters less than 0.100 inches and less frequently for larger flame holders at very low speeds near the rich or lean blowoff limits. The extent of the residual flame for small flame holders is indicated by the curves of Figure 21 The outer curve in this figure is the extinction limit for the residual flame, while the inner curve represents an estimate of the point at which continuous flame propagation from the recirculation zone into the unburned gas stopped. Because this point was very difficult to determine consistently, extinction of the residual flame was defined as the blowoff limit.

Examination of the blowoff curves (Figure 22) obtained with gasoline fuel shows that as the flame holder diameter is increased, the curves shift toward smaller values of the fuel-air ratio and that for diameters of 1/8 inch or larger, the peaks of the curves lie approximately at the stoichiometric fuel-air ratio. In contrast to this behavior, the curves obtained using methane as fuel, Figure 23,* show a shift toward larger fuel-air ratios as the diameter of the flame holders is increased. It is again of interest to examine these trends by plotting the values of the maximum blowoff velocity and the fuel-air ratio at which it occurs as a function of the Reynolds Number. (This value of the fuel-air ratio will, in the future, be referred to as ϕ_m.) Figures 24 and 25 give plots of the data obtained in the present experimental program as well as the data of Haddock, discussed earlier; for the purpose of comparison with the gasoline data, the values of ϕ_m for methane have been normalized by dividing by the value of ϕ_m for the 1/8 inch diameter flame holder. While there is a consistent difference between the values of the maximum blowoff velocity obtained by Haddock(5) and those of the present experiments, the general shape of the three curves is quite similar, and the transition Reynolds Numbers indicated by the curves are the same. Except for the change from a 1" x 4" to a 2" x 4" combustion chamber the conditions employed in the experiments of Haddock and in the present experiments were identical. Since the flame front near the blowoff point is not completely two dimensional, it is felt that the differences in the level of the blowoff velocities for the two sets of data may be attributed to the difference in the importance of this three dimensional effect for the two duct geometries. The conclusions drawn here are in no way based on the level of the blowoff velocities; therefore, for present purposes these three dimensional effects can be neglected. This is particularly true in view of the fact that the values of ϕ_m on which conclusions are based agree very closely for the two sets of data. The effects of flame holder cooling, also illustrated in Figure 24, is to reduce the level of the blowoff velocity at low Reynolds Numbers. The values found for ϕ_m are not affected by cooling the flame holders.

The most interesting fact shown in Figure 25 is the difference in the behavior of the values of ϕ_m for the blowoff curves obtained using methane and the gasoline fuels. For methane fuel, the shift in the value of ϕ_m with decreasing Reynolds Number, though small, is definitely toward lean values of the fuel-air ratio; in direct contrast with this behavior is the large shift in ϕ_m toward rich values of the fuel-air ratio observed with gasoline fuel. No values of ϕ_m were obtained when hydrogen was used as fuel because with this fuel the maximum blowoff velocity for even a 0.010 inch diameter flame holder occurred at supersonic speeds. However, examination of the lean blowoff limits obtained with hydrogen (Cf. Figure 26) shows that the curves corresponding to the small diameter flame holders (and hence the curves corresponding to the flame holders operating at low

Reynolds Number) are strongly shifted toward lean fuel-air ratios. But this behavior is precisely that predicted by the diffusion hypothesis suggested earlier. Even the magnitudes of the shifts of the blowoff curves are easily understood on the basis of this hypothesis. The diffusion coefficients of hydrogen and gasoline differ greatly from that of oxygen and hence the blowoff curves in the laminar regime should be strongly affected by the diffusion process. However, because the diffusion coefficient of methane differs only slightly from that of oxygen, the methane curves will be affected only slightly by the diffusion mechanism. A comparison of the values of ϕ_m obtained for methane and gasoline fuels shows that the difference in the magnitude of the shift from the stoichiometric value is roughly proportional to the difference between the diffusion coefficients for these two fuels and oxygen. It is also of interest to note that the relative magnitudes of the shifts from the stoichiometric fuel-air ratio of the values of ϕ_m for methane and gasoline fuels are in good agreement with the shifts found by Lewis and von Elbe (Cf. Figure 20) for the shifts in the fuel-air ratio corresponding to the smallest value of the minimum spark ignition energy.

Therefore, the observed results are in complete agreement with the corresponding predictions based on the diffusion hypothesis.

<u>Schlieren Photographs</u>. Visual observation of the flame demonstrated that there was a considerable difference in the shape of the flame front at the two blowoff limits. This difference was most obvious at very low Reynolds Numbers for gasoline flames; for these conditions the rich flame front was always a very stable two dimensional residual flame while the

lean flame front was much less stable and was usually three dimensional in character. Spark schlieren photographs taken of the flame front behind 1/32 inch and 1/8 inch flame holders (Cf. Figures 11 and 14) clearly substantiate this conclusion. In these figures the dependence of the flame front geometry for gasoline on the fuel-air ratio is given for a constant gas speed of approximately 70 ft/sec. For both cylinder sizes the flame near the rich blowoff limit is residual; the hot wake discharged from the residual flame quickly forms a turbulent Kármán vortex street and no sign of combustion is found downstream from the residual flame. On the other hand, the flame front near the lean blowoff limit is characterized by a discharge of gas from the recirculation zone in discrete three dimensional bursts. Because these bursts have a sharply defined boundary and because they continue to grow in size as they move downstream, it is clear that they are still burning.

On the basis of the diffusion hypothesis this difference in the shape of the flame front at the rich and lean blowoff limit is quite reasonable. Consider the effect of diffusion in the immediate neighborhood of the flame front near the flame holder. Due to differences in diffusion rates, the fuel-air ratio at the interface separating the recirculation zone from the unburned gas is lower than that in the free stream. Because the diffusion phenomena will be of less importance as we move downstream from the flame holder, it would be expected that the fuel-air ratio at the flame front would increase in a downstream direction. A situation then arises which is asymmetric with respect to the stoichiometric fuel-air ratio, since an increase in fuel-air ratio for a lean mixture corresponds to an increase in the ease of ignition, in heat release and in flame speed, and for a rich mixture, to a decrease in these quantities. Now, if near the rich blowoff limit, the recirculation zone is not able to ignite the unburned gas, the hot gases discharged from this zone will be even less able to do so because of the increase in fuel-air ratio of the unburned gases as they move downstream. However, near the lean blowoff limits, the hot gases discharged from the recirculation zone may be able to cause ignition even when the recirculation zone is not able to do so because of this increase in fuel-air ratio.

If this explanation is at all correct, the behavior of the flame front at the blowoff limits when methane fuel is used should be just the reverse of that found when gasoline fuel is used. This follows from the fact that for methane-air mixtures, the oxygen diffuses less rapidly than the fuel and hence the conditions at the blowoff limits are reversed. A comparison of schlieren pictures (Figure 27) showing the dependence on the fuel-air ratio of the flame front geometry for both gasoline and methane fuels shows conclusively that this reversal actually does take place. A similar comparison of pictures obtained with turbulent flame fronts shows, as would be expected, no difference between the shape of the flame front at lean and rich mixtures.

Some indication of the distance downstream from the flame holder over which diffusion effects are important can be gained by examining the rate at which the flame front propagates into the unburned medium. Since this rate is governed by the laminar flame speed, some indication of the local value of the fuel-air ratio at the flame front can be found by comparing the inlet fuel-air ratio for maximum flame spreading with the known value of the fuel-air ratio corresponding to the maximum flame speed. (For gasoline fuels, the maximum flame speed occurs for fuel-air ratios approximately 10 per cent above the stoichiometric value.) Photographs, such as those given in Figure 14, indicate that the maximum spreading rate occurs near the stoichiometric fuel-air ratio and hence show that, though diffusion may have a large influence in fixing the conditions in and about the recirculation zone, this influence is small further downstream.

Chemical Sampling. Perhaps the most critical examination of the diffusion hypothesis is furnished by chemical sampling experiments. In these experiments, the ratio of the number of carbon atoms to nitrogen atoms is determined for a gas sample taken from the recirculation zone in the immediate neighborhood of the flame holder and at the same time a similar ratio is determined for the unburned gas. Comparison of these ratios gives a direct indication of the importance of diffusion, because a diffusion process is the only mechanism which could cause a difference between the ratios.

Chemical samples of the wake gas were obtained by applying suction to openings at the downstream stagnation point of several sizes of flame holders. The suction was obtained by slowly draining mercury from a collecting bottle which was attached to the flame holder by plastic tubing. The sampling system was operated with a collecting rate less than 100 cc/minute of cooled gas and a comparison of blowoff limits determined under the conditions of no sampling and sampling at the rate of 1000 cc/minute of cooled gas indicated that the sampling process had no measurable effect on the blowoff point. Schlieren photographs taken under these two conditions also showed no noticeable difference.

The sampling system was carefully checked for leaks and before each sample was obtained, 500 cc of gas was flushed through the system. This volume of gas was about ten times the total volume of the system exclusive of the collecting bottle.

The gas was passed through a copper oxide furnace before being collected to insure that no unoxidized hydrocarbons were present in the sample. The furnace consisted of an 8 inch long tungsten heating element, and a Vycor glass tube 1 cm in diameter packed with cupric and cuprous oxide. Under normal operating conditions the temperature of the tube was held at 600°C or higher, and the total time required for the gas sample to pass through the furnace was approximately 10 seconds. Chemical analysis showed that these conditions were sufficient to cause complete oxidation of the gas samples.

Analysis of the sample for the CO_2, O_2, and N_2 content was made by use of a commercial Orsat Gas Analyzer. The quantity reported in this paper is the ratio of the number of carbon atoms to nitrogen atoms which is just twice the ratio of the percentage of carbon dioxide to nitrogen for the gas samples, i.e., $2(\%\ CO_2)/(\%\ N_2)$. The carbon dioxide content of a typical sample might be as low as 8 cc for a 100 cc sample; since the inaccuracies of the Orsat system were of the order of $\pm$ 0.1 cc, this makes the error in calculating the ratio 2 per cent or less.

In Figure 28, the carbon to nitrogen ratio for the wake gas is plotted against the ratio for the unburned gas for a typical group of samples and, in Figure 29, the quotient of the ratios, i.e., the quantity:

$\Lambda = \left[\left(\frac{C}{N}\right)_{\text{free stream}} / \left(\frac{C}{N}\right)_{\text{wake}} \right]$ is given as a function of the Reynolds Number for data obtained for three sampling flame holders with 0.125, 0.049, and 0.031 inch diameters. At most points, data taken at more than one value of the approach gas fuel-air ratio are given. With no further analysis, these data when compared with the values of ϕ_m obtained for a similar Reynolds Number (Cf. Figure 29) show that the range of Reynolds Number in which diffusion is of importance in fixing the chemical composition of the wake gases is the same as that in which the values of ϕ_m become significantly different from the stoichiometric values. Furthermore, although Λ depends strongly on the approach gas mixture ratio, the dependence of Λ and ϕ_m on the Reynolds Numbers are quantitatively similar. It is also of interest to note that the dependence of Λ on the Reynolds Number is not greatly influenced by the flame holder size.

If the assumption is made that the chemical composition of the gas entering the recirculation zone is the same as that of the gases in the burning zone separating the recirculation zone from the unburned gases, then it is possible to make a more direct comparison of the results of the chemical sampling experiments with the results of the blowoff studies. Given the chemical composition of the fuel and the experimentally determined values of the (C/N) ratio, it is possible to calculate the fuel-air ratio of the gases entering the recirculation zone. Then from plots of this wake gas fuel-air ratio as a function of the corresponding approach gas fuel-air ratio, a determination can be made of the approach gas fuel-air ratio furnishing a stoichiometric wake mixture. (Call this value of the approach gas fuel-air ratio ϕ_c.) However, it was noted previously that the maximum blowoff velocity would be expected when the fuel-air ratio of the burning zone was near the stoichiometric value; hence, the values of ϕ_m and ϕ_c determined for the same Reynolds Number should be equal. That this is true for the low Reynolds Number regime is indicated by a comparison of the values of ϕ_m and ϕ_c given in Figure 30. The qualitative agreement shown for the chemical data and the curve obtained from the blowoff data is excellent, and the quantitative agreement is quite good for Reynolds Numbers below 4×10^3.

For Reynolds Numbers above 4×10^3, the values of ϕ_c determined for the 0.049 inch holder drop rapidly to the stoichiometric value. This change occurs at the same value of the gas speed at which the flame front first takes on a residual character. For the highest Reynolds Number at which samples were obtained for the 0.049 inch holder, the flame front was a steady residual flame and ϕ_c was very nearly unity. In spite of these facts, the maximum blowoff velocity was found to occur at 1.30 of the stoichiometric fuel-air ratio. This behavior suggests that the critical region for the flame stabilization process is not the entire recirculation region, but just the burning zone separating the recirculation region from the unburned gas. That this result is not restricted to residual flames is shown by the behavior of the values of ϕ_c obtained for the 1/8 inch flame holder. Examination of schlieren photographs (Cf. Figure 12) shows that as the turbulence in the flame front becomes more pronounced with increasing Reynolds Numbers, ϕ_c decreases quickly to unity. However, the transition Reynolds Number defined by the chemical data is considerably lower than that defined by either the blowoff data or the schlieren pictures. This result is easily understood if the important region to the flame stabilization mechanism is the burning region and not the entire recirculation zone. As long as some critical length of the burning zone is laminar, the ignition process will be strongly influenced by differential diffusion effects, but because some of the gas entering the recirculation zone must come from further downstream (a region less effected by diffusion effects) the chemical composition of the recirculation zone gases will be considerably closer to that of the free stream than will be the gases of the burning zone itself. Hence, the transition as defined by the chemical sampling data will occur at lower Reynolds Numbers than it will for the blowoff data. These results indicate that the chemical composition of the recirculation region, and hence any chemical reaction taking place in this region, is not of governing importance in the stabilization mechanism.

It should also be pointed out that diffusion of CO_2 and CO from the recirculation zone will tend to reduce the carbon content of this region and therefore will cause an increase in the value of ϕ_c. While a correction for this effect might substantially reduce the value found for ϕ_c, no qualitative change in the dependence of ϕ_c on the Reynolds Number is to be expected.

Temperature Measurements. Another indication of the correctness of the diffusion hypothesis is offered by measurements of the temperature of the wake gases. The suggestion was made previously that ϕ_m and ϕ_c correspond to the values of the approach stream mixture ratio which furnishes a stoichiometric fuel-air ratio to the gas in the burning zone. If we again assume that the material in the wake near the flame holder comes exclusively from the burning zone, then because the adiabatic flame temperature is a maximum near the stoichiometric fuel-air ratio, the maximum temperature of the wake gas should occur at approach stream mixture ratios roughly equal to ϕ_m or ϕ_c.

Temperature measurements were made to determine the temperature of the wake gases as a function of fuel-air ratio with the approach gas speed used as a parameter. Because the results were only to be used to obtain the fuel-air ratio corresponding to the maximum temperature, it was not necessary to accurately determine the gas temperature so long as the errors neglected were not functions of the fuel-air ratio. The errors due to using unshielded thermocouples in low speed wake gas streams are connected with the fact that due to heat loss from the junction by conduction and radiation, the thermocouple temperature will be considerably below the gas temperature. The heat losses from the thermocouple will increase monotonically with the junction temperature and so may be neglected. However, convective heat transfer to the junction will depend strongly on the gas speed in the wake; because visual observation indicated that the recirculation pattern in the wake region and hence the gas speed was a function of the fuel-air ratio, it was necessary to take account of this effect. This was done by locating the thermocouple inside the flame holder, and by maintaining a constant flow of the wake gas over the thermocouple junction. Apparatus similar to that used in the chemical sampling experiments was used to furnish this gas flow. Using this type of instrumentation, it was possible to obtain reproducible data for a 0.049 and 0.125 inch diameter cylindric flame holders. However, the data obtained with the smaller flame holder were not reliable due to the fact that the fuel-air ratio for maximum temperature is very poorly defined.

Typical temperature versus fuel-air ratio plots for various gas speeds are given in Figure 31 for temperatures measured in the wake of a 1/8 inch uncooled flame holder by the technique defined above; gasoline was used as fuel. The peaks of the temperature curves all lie to the rich side of the stoichiometric mixture ratio even for the highest gas speeds, but the shift from the stoichiometric ratio increases strongly for the lower Reynolds Numbers. The behavior for the higher values of the Reynolds Number is to be expected, since, due to disassociation effects, the maximum adiabatic flame temperature occurs for fuel-air ratios between 1.05 and 1.10 of stoichiometric. Comparison of the dependence of the fuel-air ratio corresponding to the maximum wake gas temperature with the dependence of ϕ_m on the Reynolds Number for the data obtained with the 0.125 and the 0.049 inch flame holders is given in Figure 32. In comparing the data to the curve, it should be kept in mind that $\phi_t = 1.05$ for the adiabatic flame temperature. The two sets of data agree well in general shape and also in the relative magnitudes of the deviation from the "normal" high Reynolds Number values. As was found to be the case for the chemical data, the transition Reynolds Number defined by the temperature data occurs at slightly lower values of the Reynolds Number than that defined by the values of ϕ_m.

Conclusions. The results of the four experiments reported here demonstrate clearly that diffusion processes are of governing importance in the flame stabilization mechanism at low Reynolds Numbers. In particular, it has been shown that differences in the diffusion rates of oxygen and fuel satisfactorily account for the shift of maximum blowoff velocity from the stoichiometric value.

Comparison of the results obtained from the blowoff experiments with those obtained in the chemical sampling and temperature measurements indicates that the important region to the flame stabilization process is the burning zone and not the recirculation zone itself.

V. HIGH REYNOLDS NUMBER FLAME STABILIZATION

The present interest in a theoretical attack on the problem of flame stabilization by bluff bodies emphasizes a need for re-examination of experimental information which can serve as a check on the gross behavior of the results deduced from an assumed model. Of particular importance is the dependence of stability limits upon flame holder size, and temperature and pressure of the approach stream. Although this situation has recently been reviewed by J. P. Longwell in his survey paper for the Fourth (International) Symposium on Combustion,[18] sufficient advance in understanding the problem has been made during the interim to merit a reconsideration. It is appropriate, therefore, to discuss such reliable experimental results as pertain to the problem and to observe 1) What behavior or trends can be substantiated with sufficient certainty to guide analytical investigations, and 2) What relation do these investigations of flame holding bear to the engineering problem of ramjets and afterburners.

It is intended to examine the available experimental results, which are applicable to the blowoff problem, for the following behavior:

(1) Variation of flame blowoff velocity with size of flame holder at stoichiometric mixture ratio (approximately the maximum blowoff velocity) for constant values of temperature and pressure of the approach stream.

(2) Variation of flame blowoff velocity with size of flame holder at mixture ratios differing from stoichiometric for constant values of temperature and pressure of the approach stream.

(3) Variation of flame blowoff velocity with pressure and temperature of the approach stream for constant values of flame holder size at stoichiometric mixture ratio.

The information examined in the review is that of A. C. Scurlock,[2] J. P. Longwell, et al,[1] E. A. De Zubay,[4] G. H. Haddock,[5] and L. O. Olsen.[6] Although this selection is by no means exhaustive, it contains most of the available information obtained under conditions related to the blowoff problem, and contains all data which have previously been cited[18] as leading to divergent results or being actually inconsistent.

Blowoff Velocity vs Flame Holder Size, Stoichiometric Mixture Ratio. It will be convenient to re-examine the experimental results of Haddock[5] and the low Reynolds Number results reported earlier in the present paper. Examination of the blowoff curves reported by this author, Figure 6, indicates that the maximum blowoff velocity for a given flame holder diameter increased with the square root of the holder diameter when the Reynolds Number was sufficiently high. However, when flame holder diameters were used which operated below some "critical" Reynolds Number, the dependence of the maximum blowoff speed on the diameter of the flame holder was greatly weakened. In Section I it was shown that this change in the flame stabilizing mechanism was associated with a change from a laminar to turbulent flame front and further that this change definitely occurred for the flame holder geometries used in the experiments to be discussed here.

With these facts in mind, it is interesting to compare the results of experiments from the various Laboratories. Figure 33 gives the data published by Olsen of the National Bureau of Standards[6] and Haddock,[5] and shows the two results to be in essential agreement. These experiments of Olsen were carried out with flame holder sizes having blowoff velocities which occurred at values of the Reynolds Number exceeding the critical. Consequently the transition is not in evidence. Other experimental data are reported by the National Bureau of Standards group, but the blowoff speeds involved were so high that the critical Mach Number for the flame holders was exceeded. The resulting blowoff curves were severely altered by this fact and hence are not comparable with the results reported here. Also data obtained by this group showing the transition regime have been discussed previously in Section III and is illustrated in Figure 7. It is of particular interest to examine the rather extensive data of E. A. De Zubay for circular disk flame holders since these data are often cited[18] as indicating inconsistency of other results. This information is plotted in Figure 33 for the four pressure levels used by De Zubay. It is clear that the general shape of the curves defined by these data agrees well with that of the other investigators cited. The transition from laminar to turbulent flame front is distinctly shown by data taken at a pressure of 0.47 atmosphere and occurs in the same range of Reynolds Number as it does for the data obtained using circular rods. Furthermore a study of this plot resolves the previous confusion surrounding values of the slope of the blowoff curve reported by different experimenters. A portion of the previous apparent inconsistency arose from the fact that the transition region in De Zubay's data was impossible to recognize because there were so few points in this range. Consequently the reasonable attempt to correlate all data by a single straight line led to an excessive value of the slope; it is only when this information is viewed in conjunction with further experiments covering the transition range that the true consistency of the data appears. Therefore it may be stated that, without exception, all available blowoff data at the stoichiometric mixture and Reynolds Numbers above the transition regime indicate that the blowoff velocity vary approximately as the square root of the characteristic dimension of the flame holder. It may be inferred from the appearance of $D^{\frac{1}{2}}$, that laminar processes play a significant role in some phase of the flame stabilization process.

The disagreement in absolute values of the blowoff velocities observed by various experimenters may be attributed to the differences in temperature and pressure of the approach mixture, and the type of fuel employed. Furthermore, the geometric configurations of both flame holder and combustion chamber will exert a strong influence upon the blowoff limits as is indicated by the observations from References 2, 5 and 6 which are summarized in Figure 34.

Blowoff Velocity vs Flame Holder Size, below Stoichiometric Mixture Ratios. Several investigators have suggested that the dependence of blowoff velocity upon flame holder size changes as the mixture ratio deviates from the stoichiometric. This trend was due in part, to the fact that some of the experimental measurements[3] were carried out at such low values of the Reynolds Number that the results lie, at best, in the transition region. Longwell,[18] after examination of the blowoff data of Haddock at the stoichiometric and seven tenths of the stoichiometric fuel-air ratio, also concluded that the exponent α in the correlation $U \sim D^{\alpha}$ varied as the mixture ratio was changed. Although this conclusion was in part, based on data which were in error (the $\frac{1}{2}$ inch flame blowoff data reported in Reference 5 were slightly in error due to leaks in an ignition system) a detailed examination of the value of α as a function of the fuel-air ratio suggests that the exponent does increase as the fuel-air ratio is reduced from the stoichiometric value. This behavior indicated by Haddock's data is clearly shown in Figures 35a and 35b in which the dependence of blowoff velocity on flame holder diameter is given for various constant values of the fuel-air ratio.

Figure 35 shows that as the fuel-air ratio departs from the stoichiometric value the data become more scattered, and that for large departure from stoichiometric the character of the curve seems to change completely. A break appears in these curves for fuel-air ratios far from the stoichiometric value because, for these mixture ratios, the blowoff velocity is greatly reduced and hence the flame holders operate in the laminar flow regime. To a great extent the scatter appears to be due to the fact that for fuel-air ratios far from the stoichiometric value a very small change in fuel-air ratio produces a large change in blowoff velocity and this sensitivity makes the determination of slopes extremely difficult. In view of these facts it seems unjustifiable, on the basis of Haddock's data alone, to determine whether or not the observed increase of α, as the fuel-air ratio is reduced from the stoichiometric value, is a real effect. Moreover, examination of the data from Reference 6, analyzed similarly in Figure 36, indicates that for these experiments α was constant.

Figure 37 gives a summary of the values of α as a function of the fuel-air ratio for all experimental results reported in References 1, 2, 4, 5 and 6. As was found from Haddock's results, the data of De Zubay are badly scattered on the lean side and the value of α shows a tendency to increase. The few points taken from the results of Scurlock show little scatter and indicate a constant value of the slope.

Except for the results of Longwell, the data of Figure 37 indicate that is approximately one-half and that the increase in α is slight as the fuel-air ratio is reduced below stoichiometric. The results obtained by Longwell do not agree with those of the other experiments discussed in this paper since the values of α determined by his data are greater by nearly a factor of two. Because this difference is well within the accuracy of combustion experiments, a physical basis for this discrepancy must be sought. Results of some recent experiments indicate that the blowoff phenomena may be strongly affected when the boundary layer on the flame holder becomes turbulent upstream from separation. It is probable that this turbulent boundary layer exists for Longwell's experimental conditions in contrast with those of the other experiments discussed here. If this boundary layer transition proves to be of the importance indicated, then a third significant region of flame stabilization exists in addition to the two described here.

Dependence of Flame Blowoff Velocity with Pressure and Temperature. In Reference 4 De Zubay has investigated the dependence on pressure of the flame blowoff velocities for Reynolds Numbers greater than the transition value. As is indicated by his published data, this relation, Figure 38, varies from $U \sim P^{0.8}$ at stoichiometric fuel-air ratios to $U \sim P^{0.6}$

for lean fuel-air ratios. This exponent of P is slightly lower than that reported by De Zubay because his determinations included all the data rather than only that part having Reynolds Number above the transition value. This dependence does not seem to be entirely consistent for different diameters of disk-shaped flame holder.

Haddock and Olsen investigated the dependence of blowoff velocity on inlet temperature of the combustible mixture. The data of Olsen were obtained for a 1/4 inch cylindric flame holder with inlet temperatures of 200, 300, 400, and 500°F. Although the dependence on temperature was influenced slightly by changes in the fuel-air ratio, a good correlation of the complete blowoff curve was obtained by use of the relation $U \sim T^{1.4}$. Similar curves obtained by Haddock gave $U \sim T^{1.2}$ and again the exponent for best correlation of the data was found to depend slightly on the fuel-air ratio.

Concluding Remarks. The foregoing examination of the available experimental information concerning the flame blowoff limits from bluff bodies show predominantly the results that, near the stoichiometric mixture ratio, the blowoff velocity varies approximately as the square root of the flame holder is sufficiently high. In the range of engineering such behavior is well substantiated for a variety of flame holder geometries. This feature implies that a laminar, (i.e., a molecular), transfer process is of controlling importance at some stage of the fluid mechanics or chemistry of the process. The sole exception to a behavior of $U \sim D^{\frac{1}{2}}$ is the result obtained by J. P. Longwell. It can not be clearly ascertained whether this difference is attributable to the gross difference in the physical configuration of the flame holder or to the approach conditions employed in his experiment.

It should be observed further that there is a very real question regarding what may be inferred from the data concerning the direct influence of flame holder dimension upon the blowoff limits in actual turbojet afterburners and ramjet engines. This doubt arises, in part, from the strong influence of duct length and size on the observed blowoff limits and the probable infleunce on these limits of non-uniformaties of flow and fuel distribution. From both experimental and analytical viewpoints caution should be exercised to insure that future refinement in studies of "isolated" flame holders contribute significantly to solutions of the engineering problem.

VI. CONCLUDING REMARKS

The experiments which have been described demonstrate that the available results concerning flame stabilization on bluff bodies may be differentiated into low and high Reynolds Number regimes. The physical difference between the two lies in the fact that the thin burning region separating the zone of recirculation from the combustible main stream is laminar at low values of Reynolds Number and turbulent at high values. The laminar flow at low Reynolds Numbers allows the different diffusion rates of fuel and oxygen to displace the mixture ratio at maximum blowoff velocity from the stoichiometric value. The fact that for normal stabilized flames the maximum blowoff velocity occurs when the recirculation zone operates at nearly a stoichiometric mixture ratio, irrespective of the corresponding free stream mixture, was conclusively demonstrated by chemical analysis of the wake material. The behavior of stabilized flames at Reynolds Numbers above transition has definitely been clarified by recognizing the existence of transition. In particular, the dependence of blowoff velocity on flame holder size is now a matter of agreement for all applicable experimental information.

These results permit a greatly clarified picture of structure of the recirculation zone. The importance of diffusion at low Reynolds Numbers confirms the belief that the reaction takes place largely in the thin mixing zone separating the recirculating wake gases from the main stream. These products of combustion then constitute the material of the recirculation zone. Although this fact is shown definitely only for low Reynolds Number, it is certainly the case also for high Reynolds Number since the residence time in the mixing zone is changed by a factor of not exceeding ten. The only element now that obstructs a complete picture of the stabilization zone is lack of factual evidence on the length of this region and factors which lead to its determination. This question is now under investigation at the Jet Propulsion Laboratory by the present author.

There are strong indications, and some experimental evidence, that a third regime of flame stabilization exists at Reynolds Numbers higher than those investigated with circular cylinders. The transition observed takes place in the free vortex-layer and the transition moves to the point of boundary layer separation and remains relatively fixed for a considerable range of Reynolds Number. However if the Reynolds Number is increased sufficiently the boundary layer of the flame holder itself will become turbulent before separation and strong modifications of the flame stabilization characteristics are to be expected. This is particularly the case for flame holders with long forebodies on which the boundary layer may develop. In this regime it seems possible that strict turbulent consideration will obtain, that is, that only one characteristic length exists, the flame holder dimension, and therefore the blowoff velocity will be directly proportional to this length. The validity of this conjecture is also under investigation.

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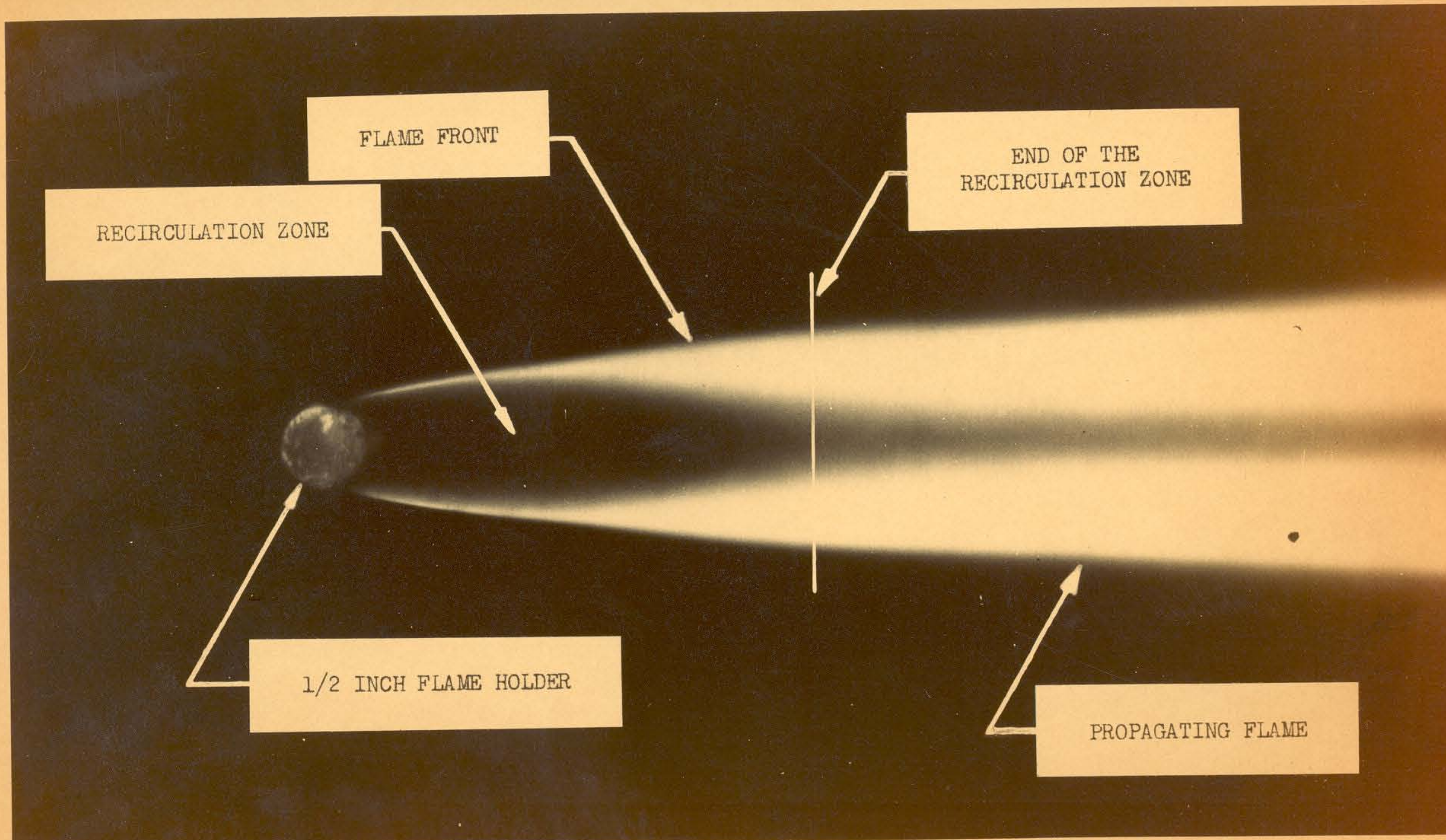


Figure 1. Time Exposure Picture of Flame Stabilized on 1/2-Inch Diameter, Cylindric Flame Holder

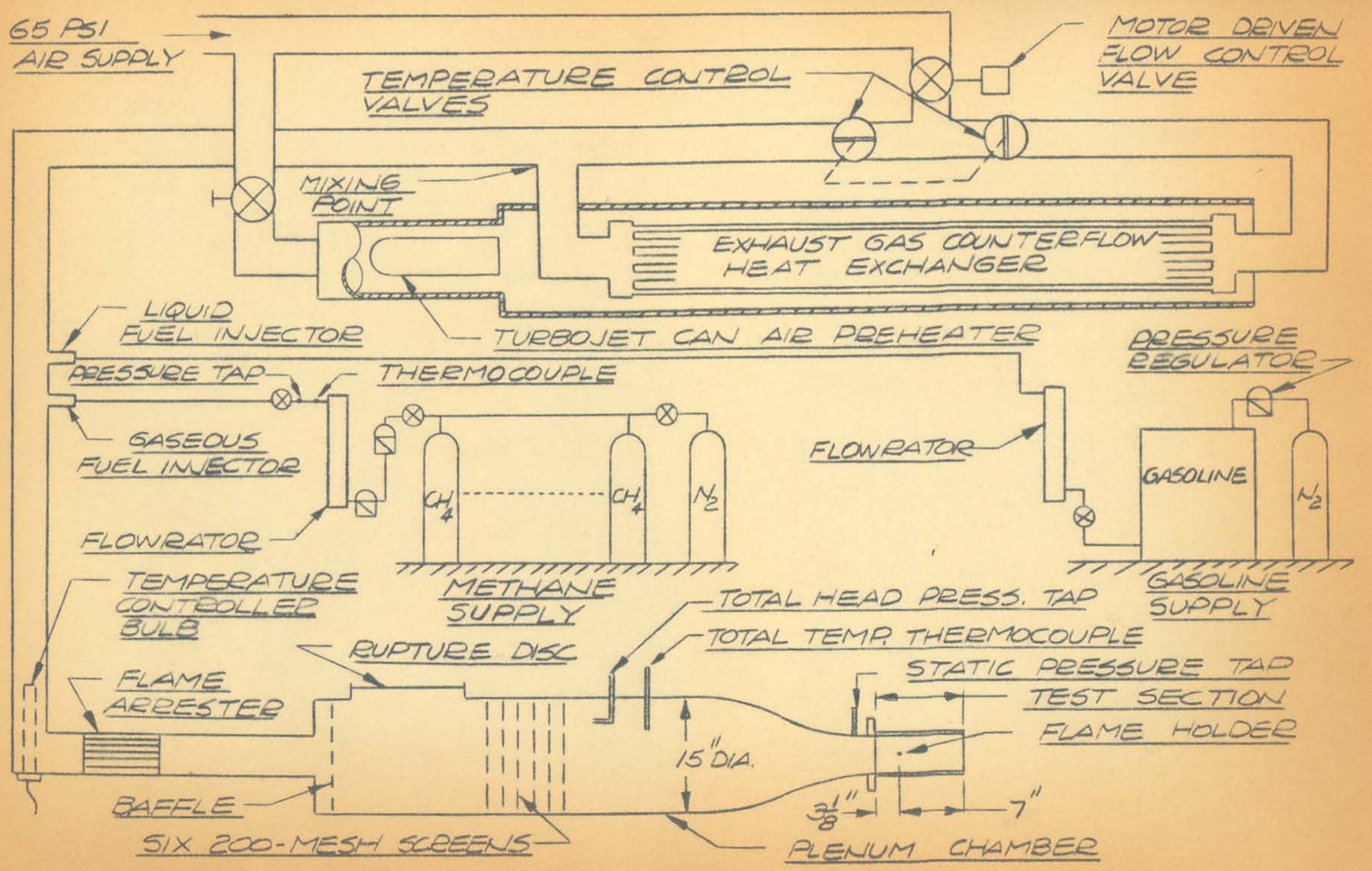
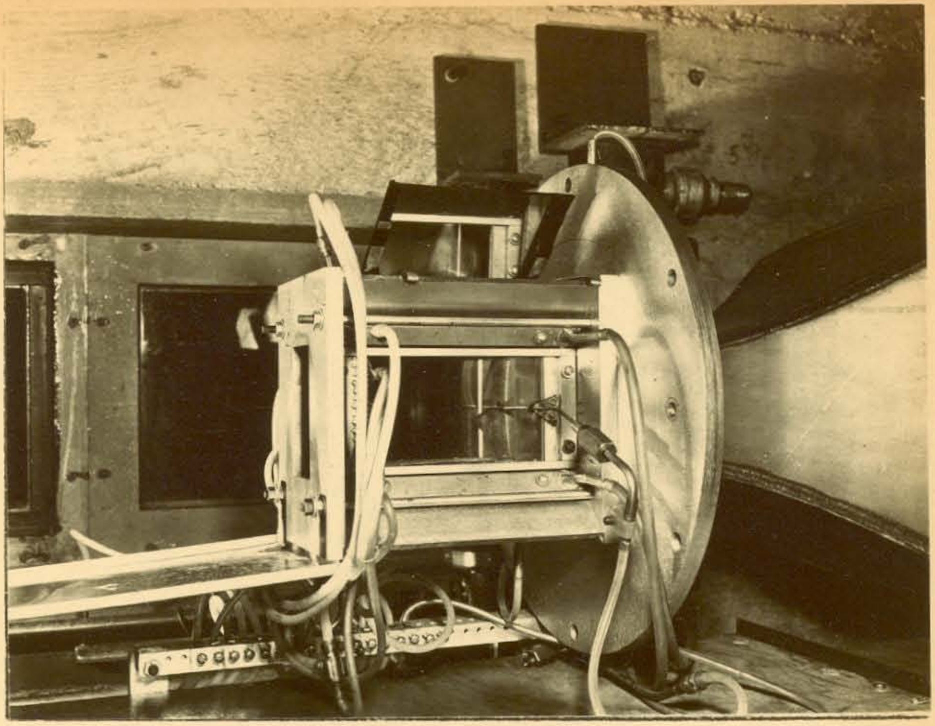


FIGURE 2. SCHEMATIC DIAGRAM OF FLOW SYSTEMS



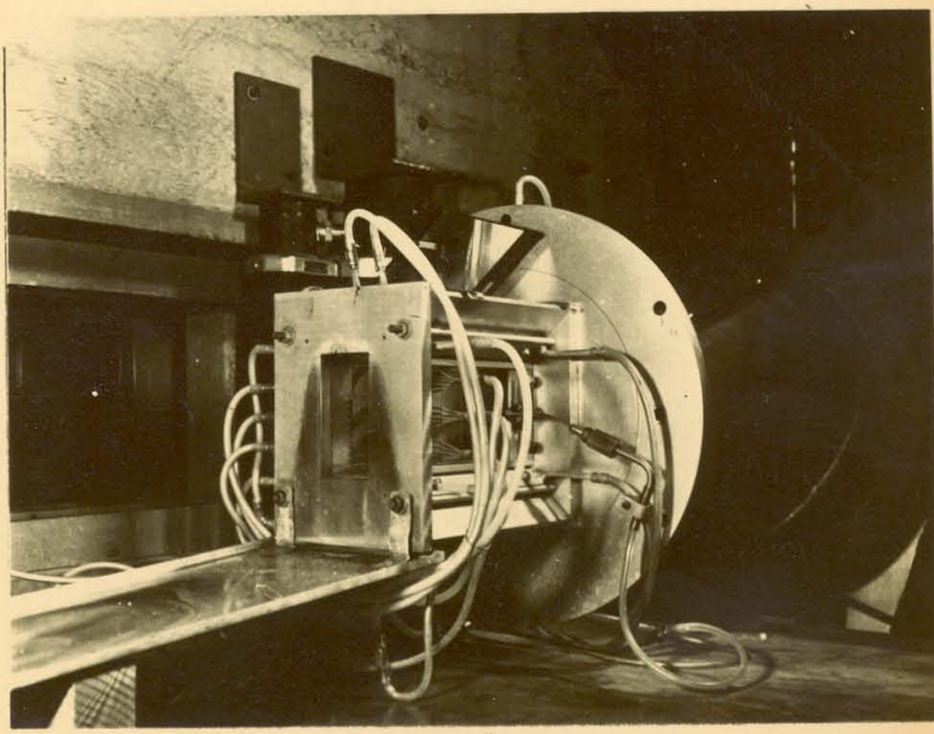


FIGURE 3. SIDE AND THREE-QUARTER VIEWS OF COMBUSTION CHAMBER

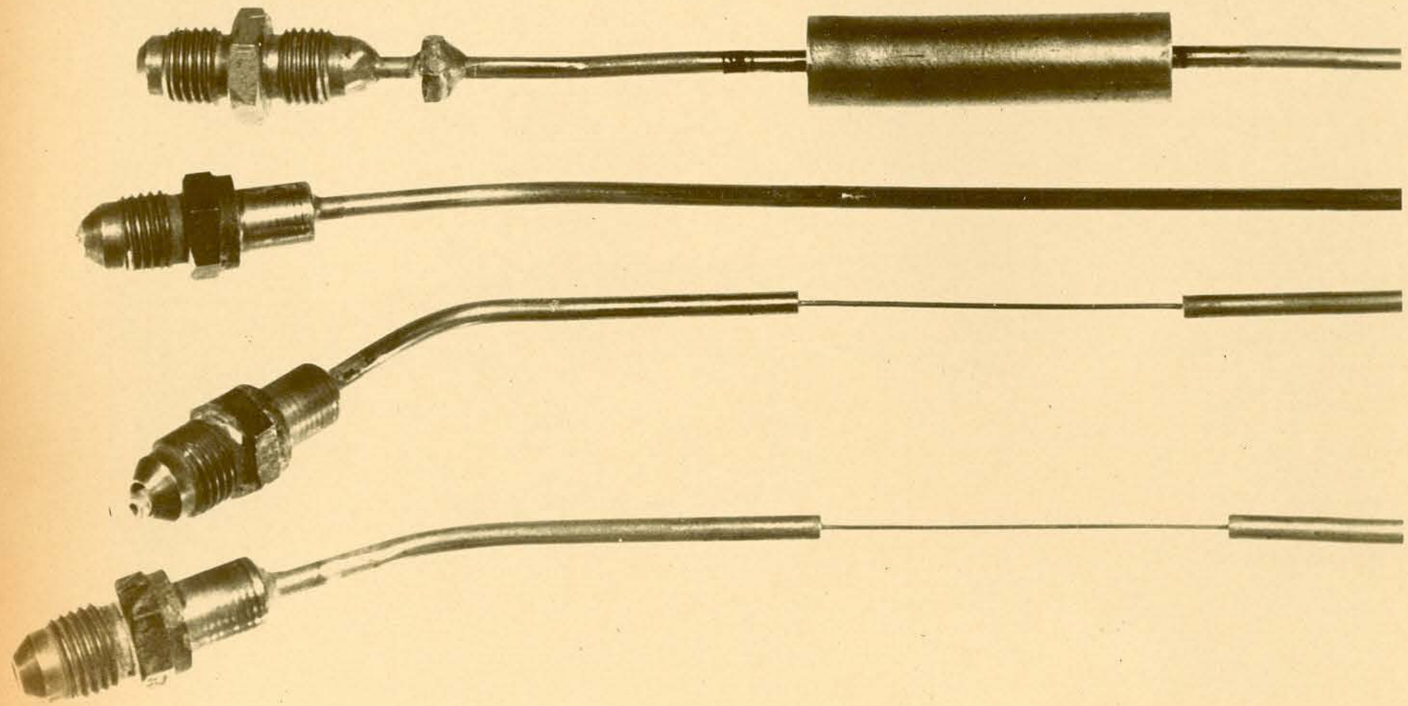


FIGURE 4. SOME EXAMPLES OF WATER COOLED FLAME HOLDERS

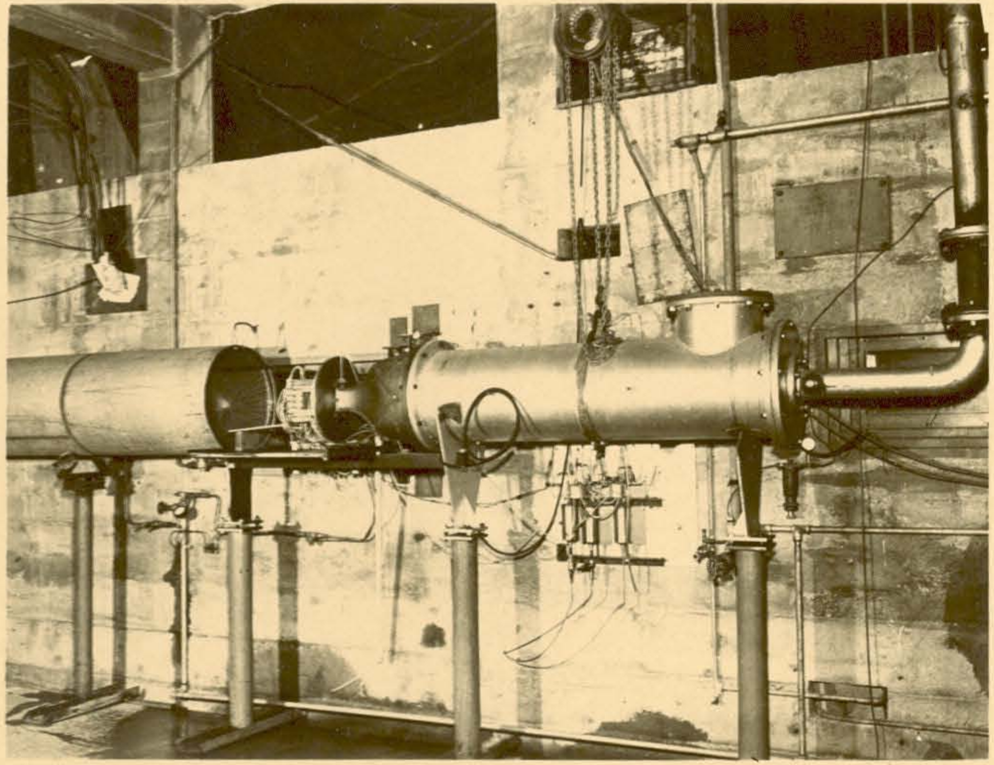


FIGURE 5. GENERAL VIEW OF COMBUSTION CHAMBER, NOZZLE, AND PLENUM CHAMBER

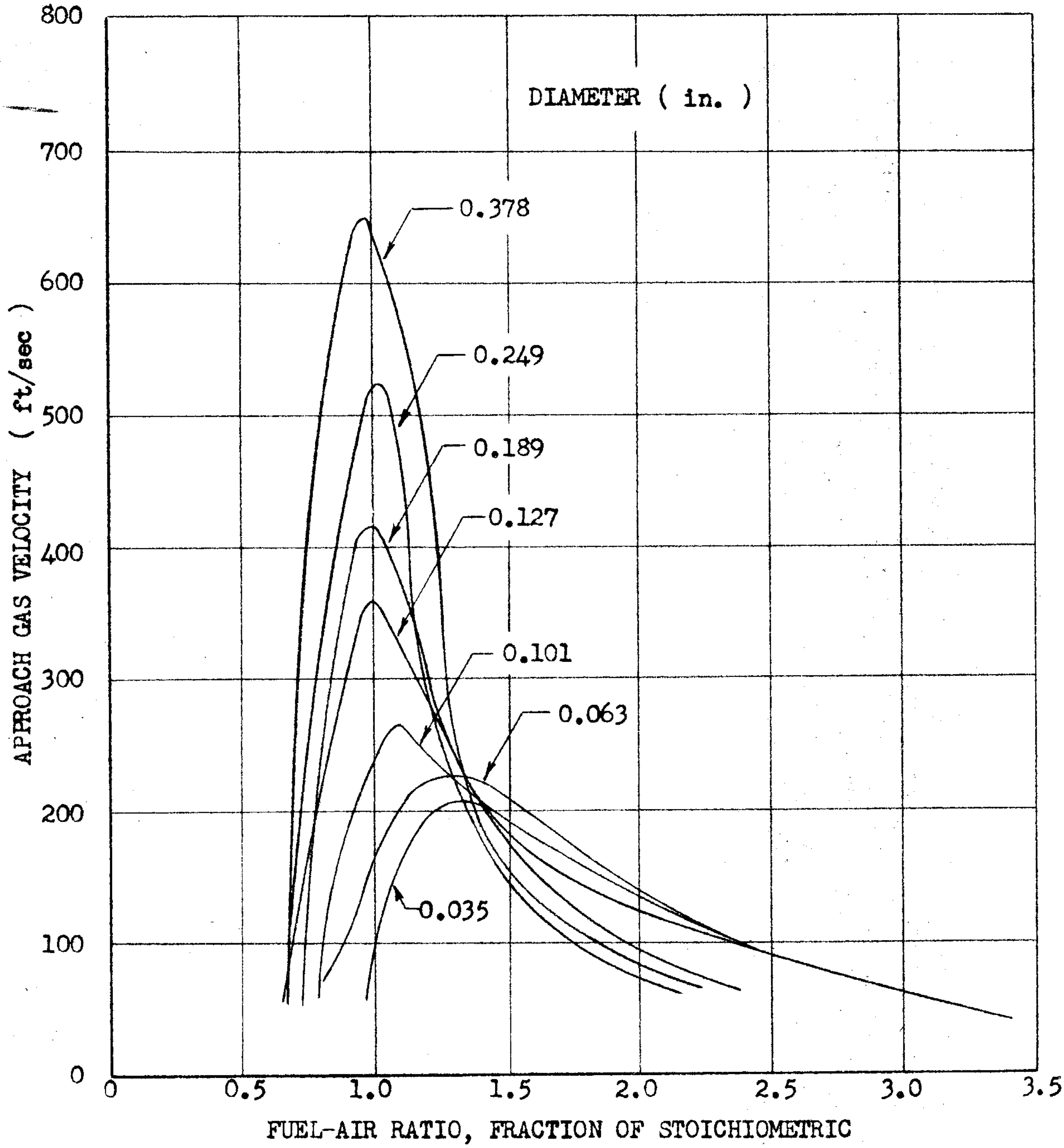


FIGURE 6 . DEPENDENCE OF BLOWOFF VELOCITY ON FUEL-AIR RATIO FOR CYLINDRIC FLAME HOLDERS

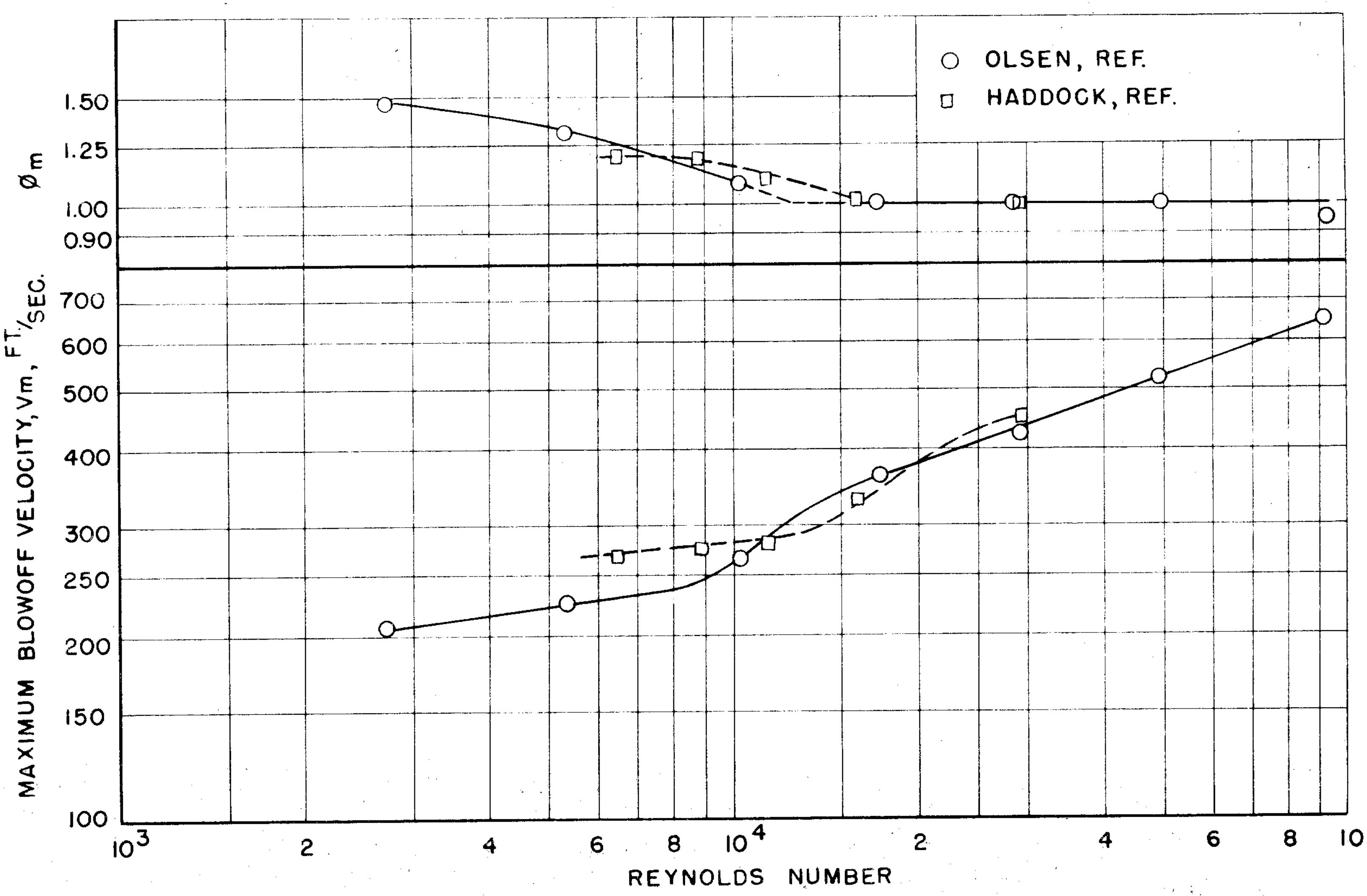


FIG. 7 THE MAXIMUM BLOWOFF VELOCITY AND THE FUEL-AIR RATIO CORRESPONDING TO THE MAXIMUM BLOWOFF VELOCITY AS A FUNCTION OF THE REYNOLDS NUMBER

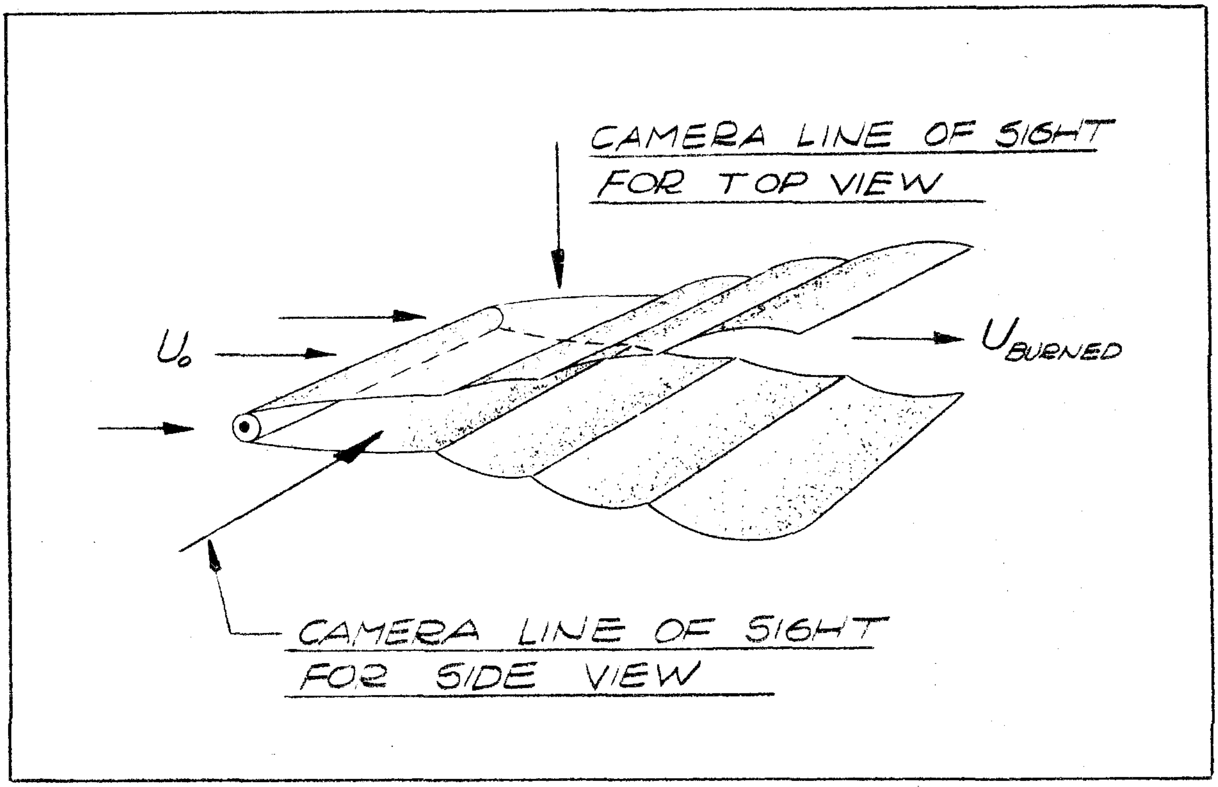
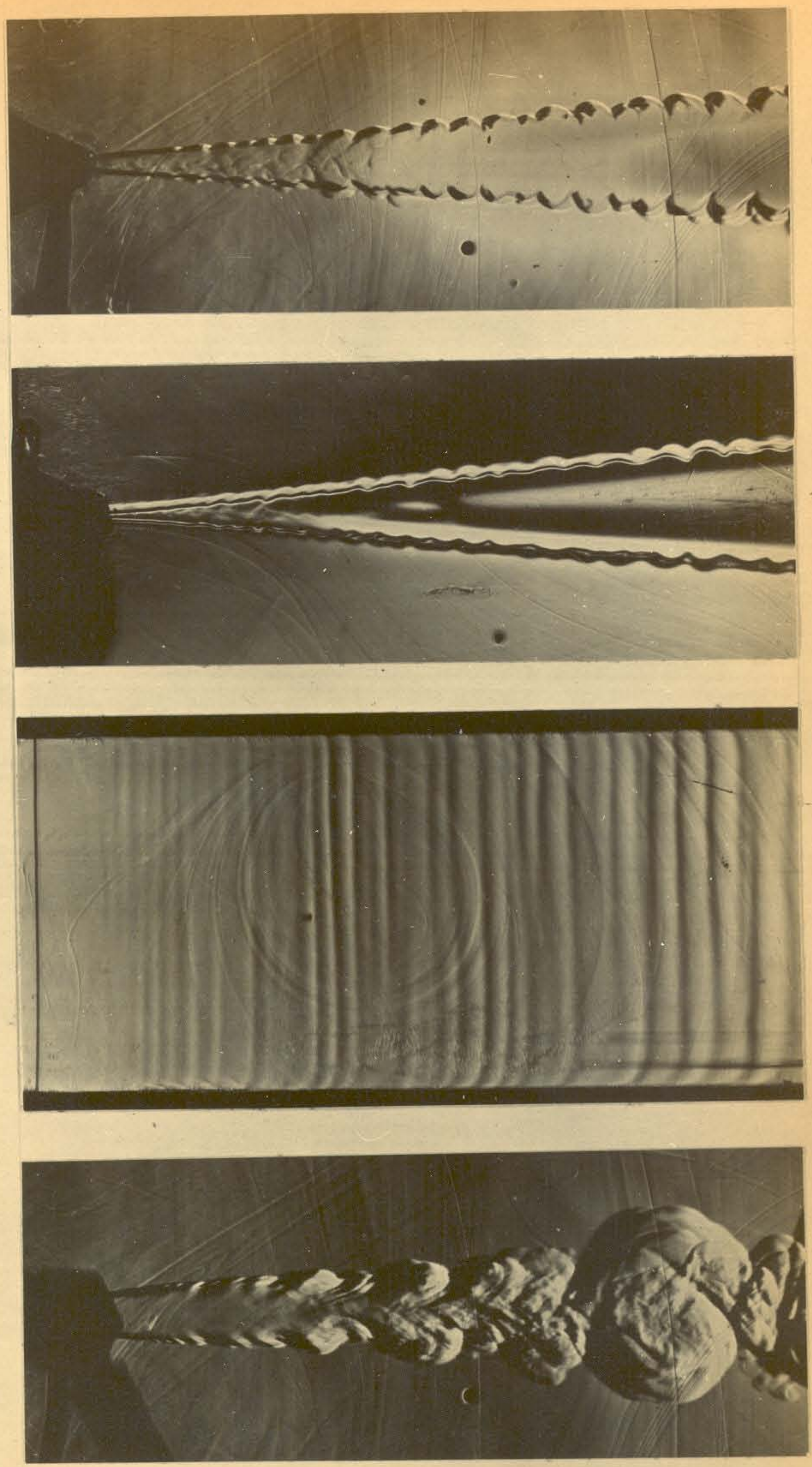


FIGURE 8. SCHEMATIC DIAGRAM ILLUSTRATING THE TWO CAMERA VIEWS OF A FLAME STABILIZED ON A CYLINDRIC HOLDER



a

b

c

d

Figure 9. Examples of Schlieren Pictures of Flame Fronts Stabilized on Circular Cylinders

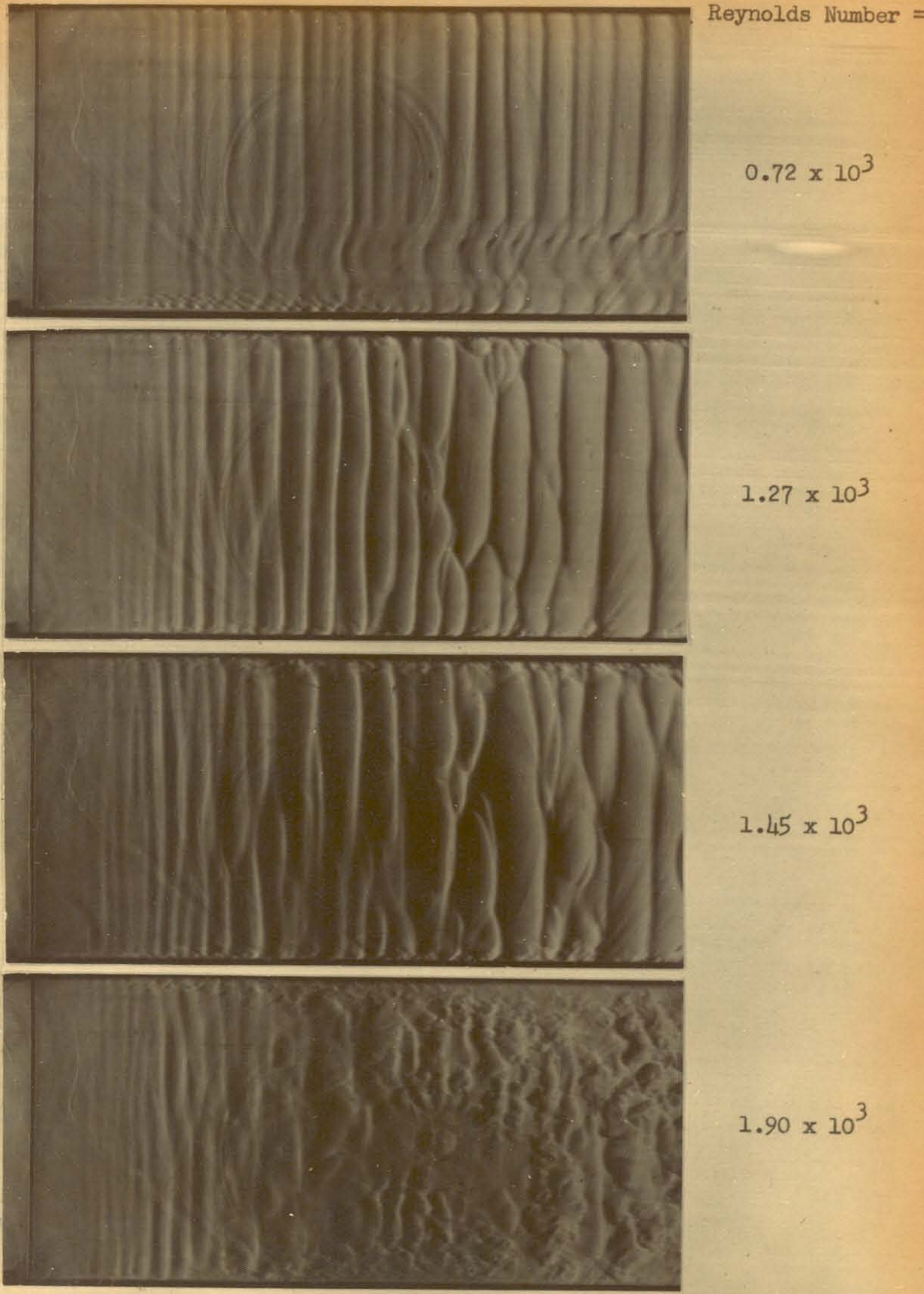
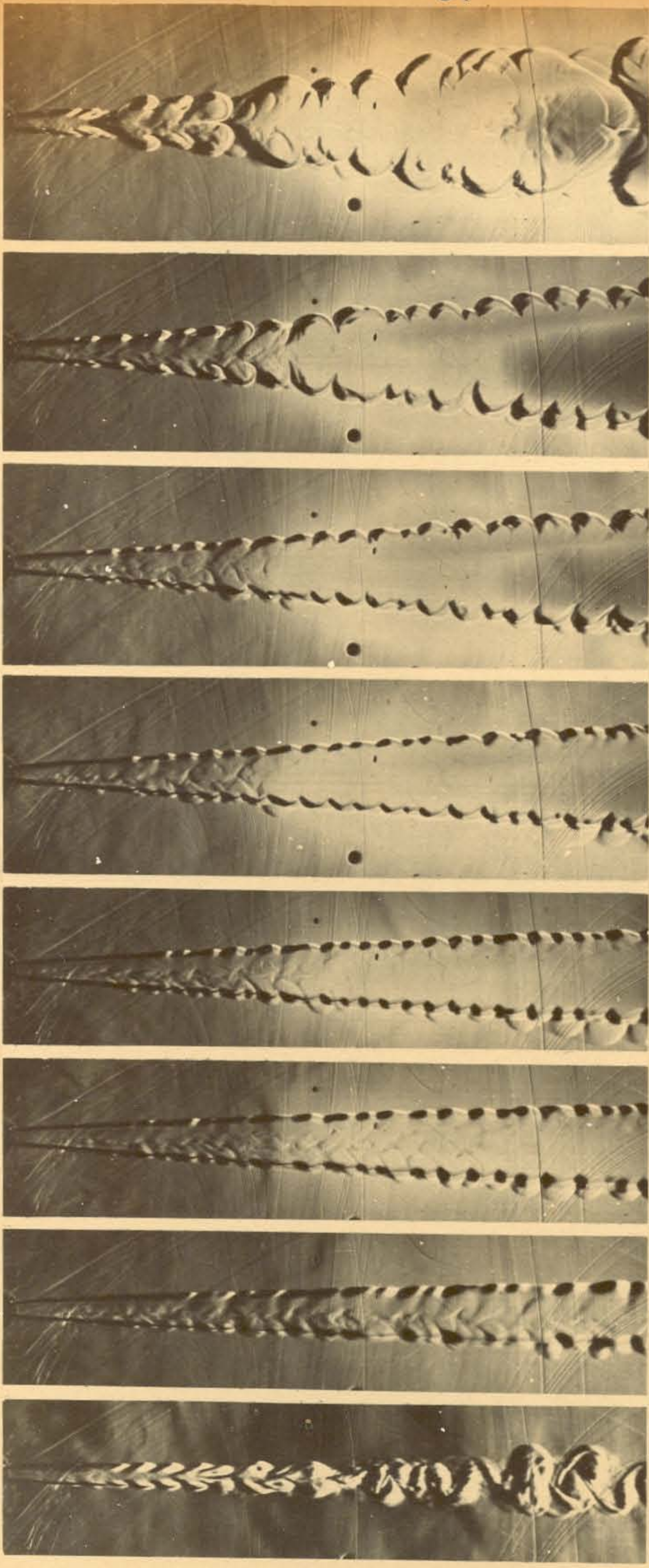


Figure 10. Schlieren Photographs of Flame Front Stabilized on a 1/32-Inch Diameter, Cylindric Flame Holder.

Fuel-Air Ratio, Fraction of Stoichiometric



1.10

1.20

1.29

1.37

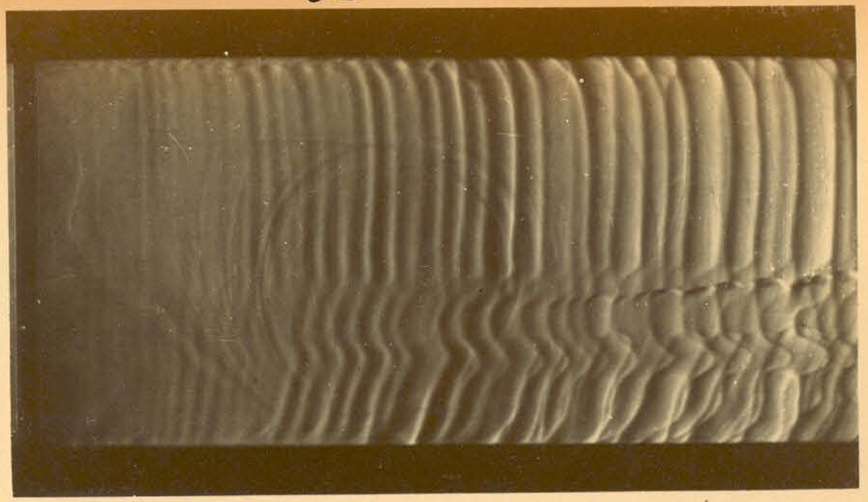
1.46

1.55

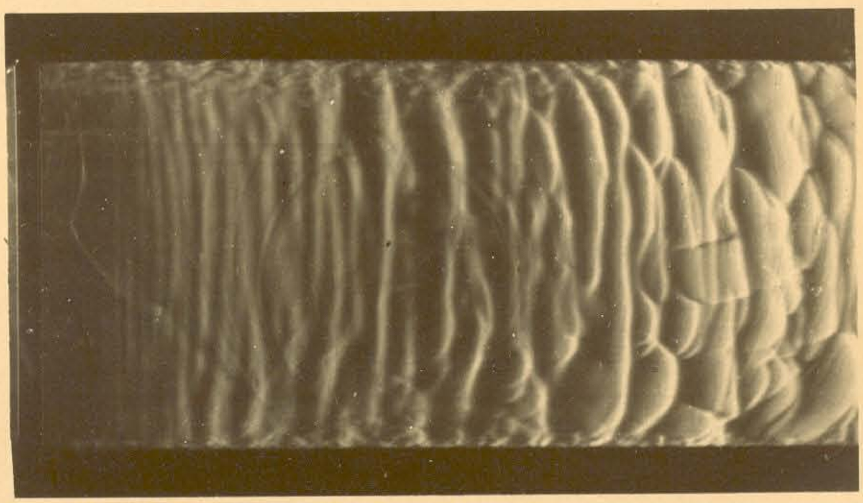
1.80

2.82

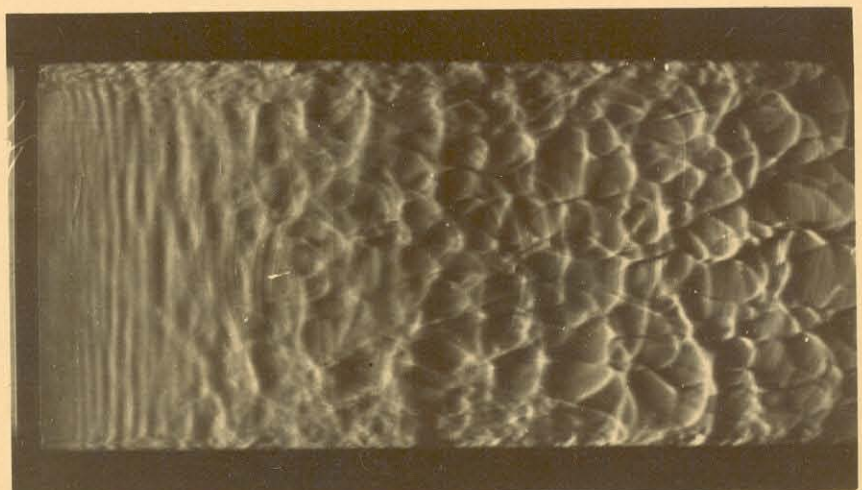
FIGURE 11. Variation of Flame Front Geometry with Changing Fuel-Air Ratio for a Flame Stabilized on a 0.031 Inch Diameter Cylindric Flame Holder at a Reynolds Number of 820.



Reynolds Number = 0.32×10^4

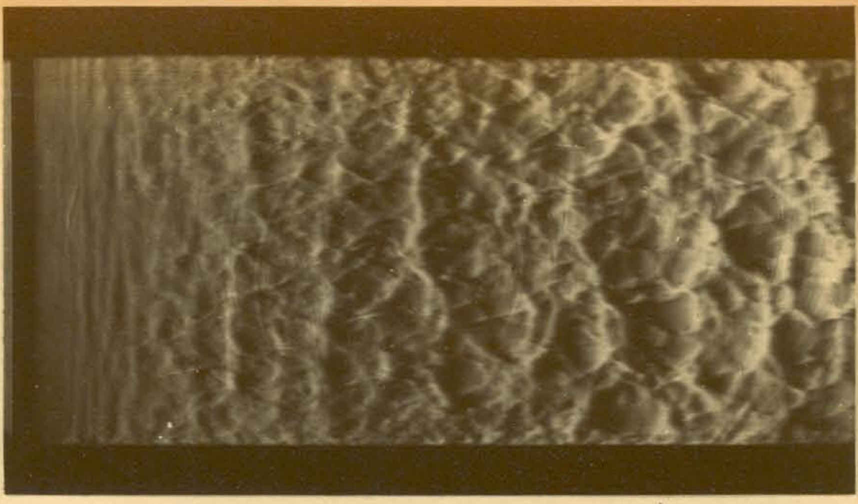


Reynolds Number = 0.51×10^4

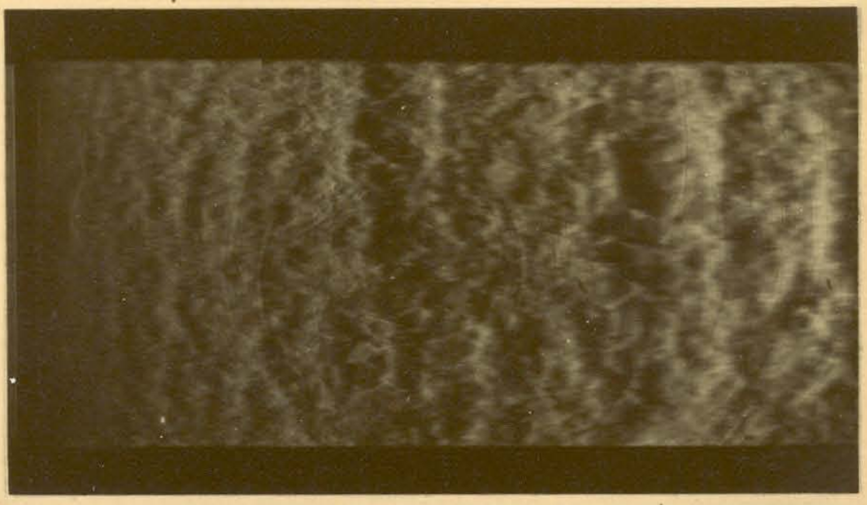


Reynolds Number = 0.77×10^4

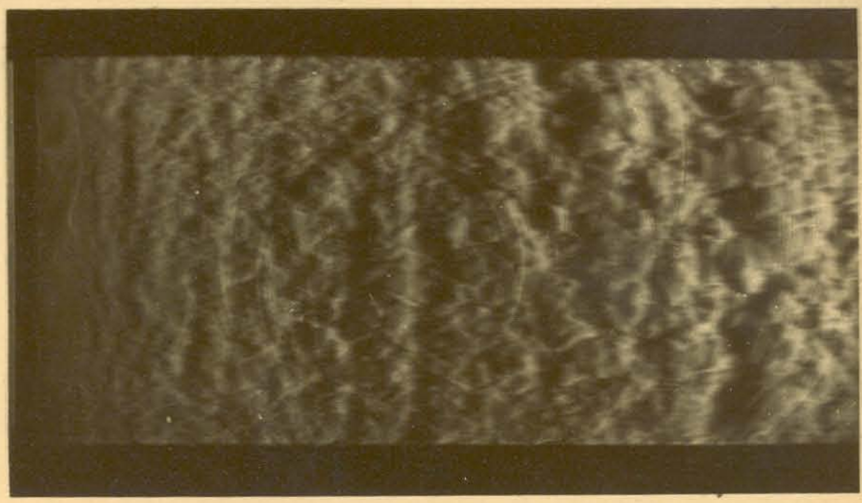
Figure 12a. Development of Turbulence in the Flame Front Stabilized on a 1/8-Inch Diameter, Cylindric Flame Holder



Reynolds Number = 1.00 x 10^4

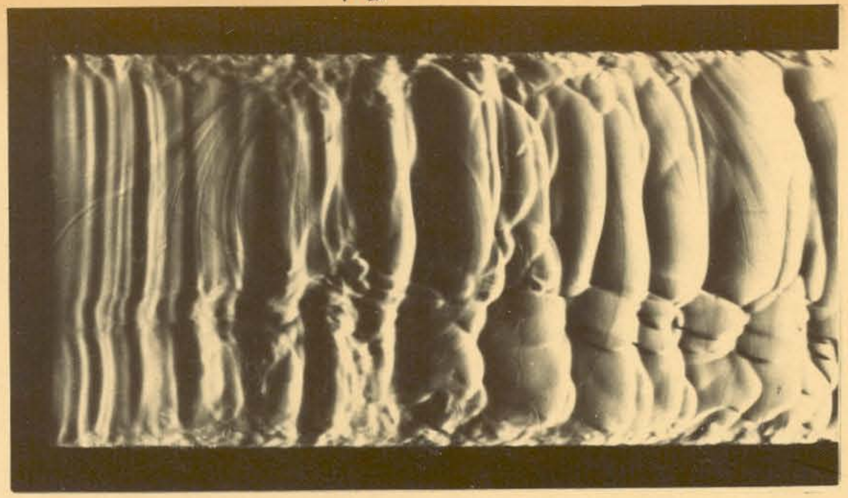


Reynolds Number = 1.30 x 10^4

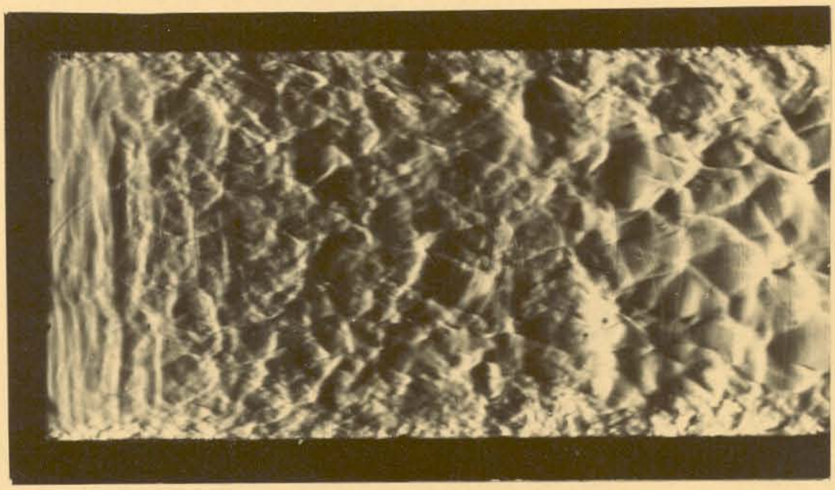


Reynolds Number = 1.70 x 10^4

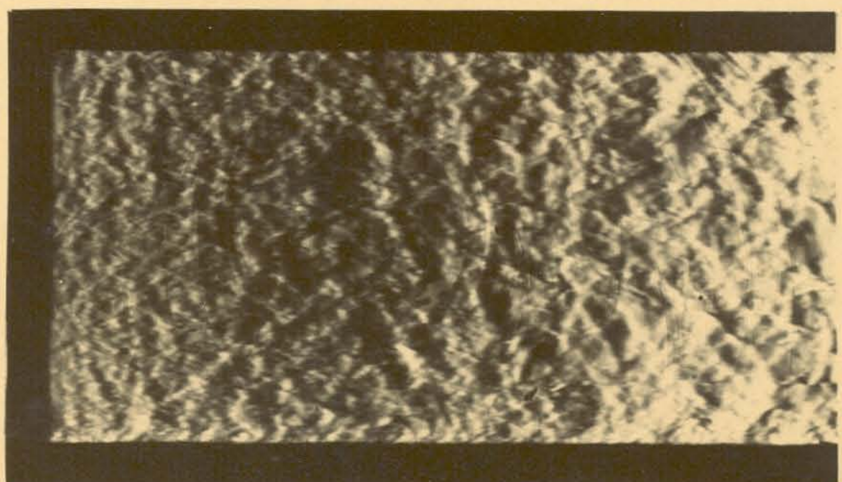
Figure 12b Development of Turbulence in the Flame Front (Continued)



Reynolds number = 1.3×10^4

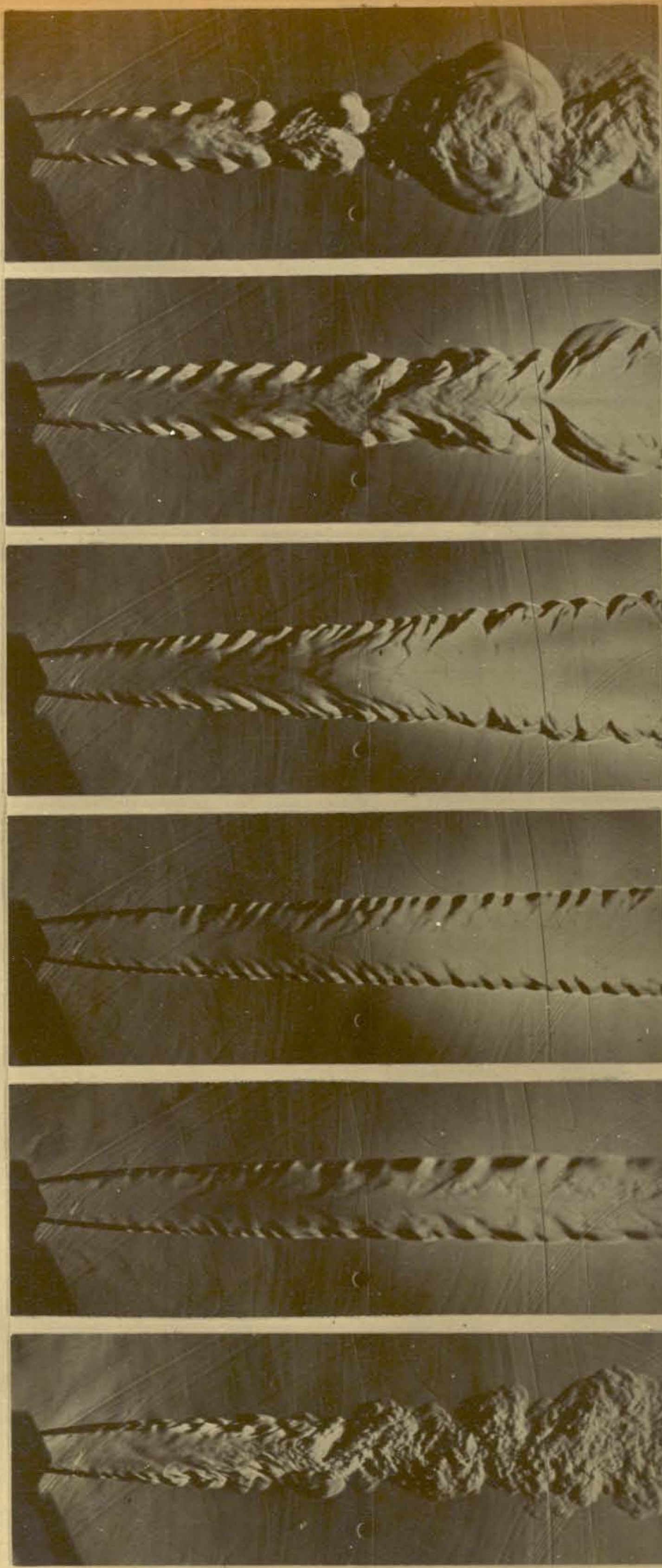


Reynolds number = 2.2×10^4



Reynolds number = 2.9×10^4

Figure 13. Schlieren Photographs of Flame Front Stabilized on 1/2-Inch Diameter, Cylindric Flame Holder.



Fuel-Air Ratio, Fraction of Stoichiometric

0.71

.82

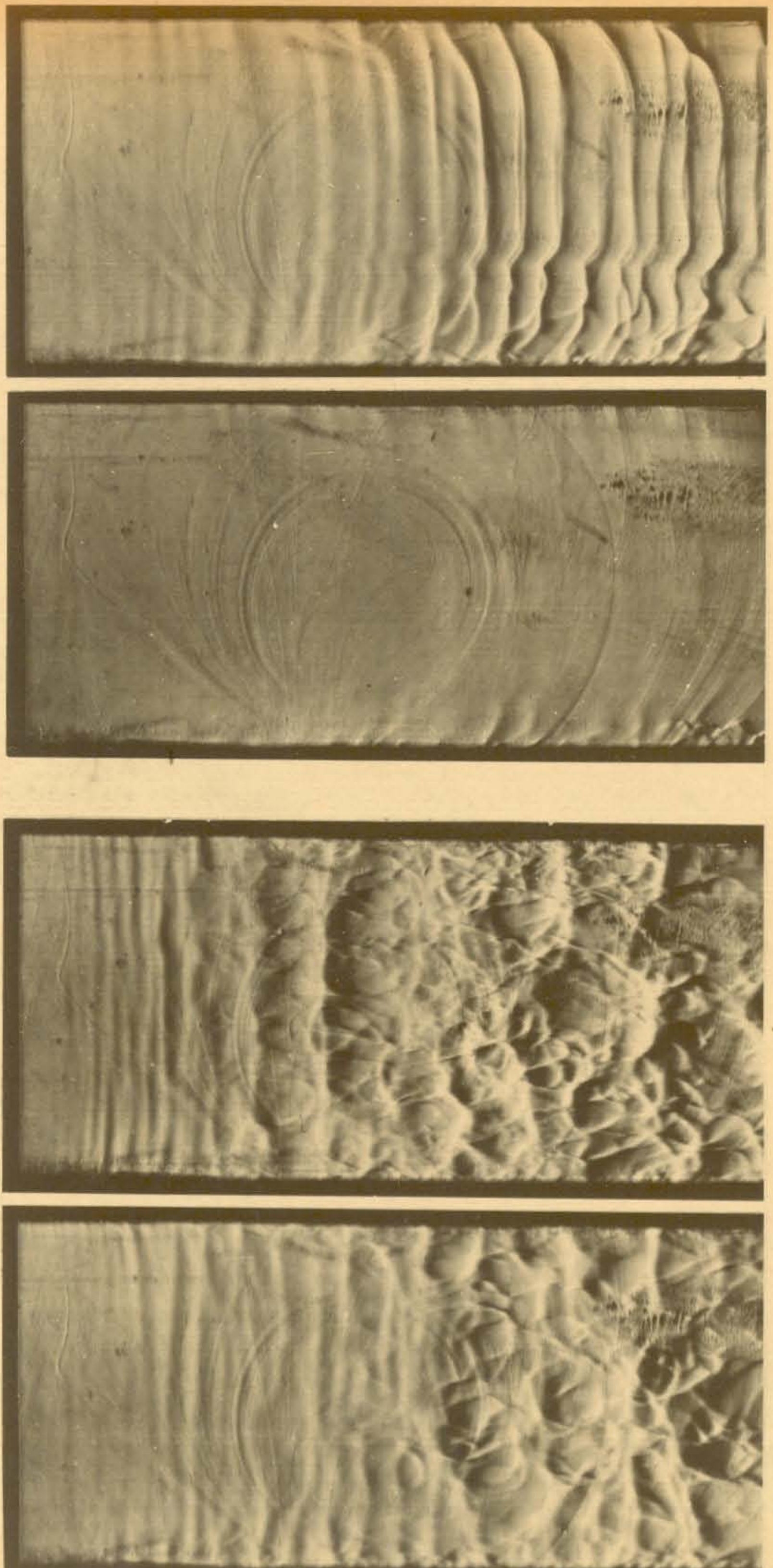
1.09

1.45

1.82

2.45

Figure 14. Dependence of the Flame Front Geometry on the Fuel-Air Ratio for a Gasoline Flame Stabilized on a 1/8-Inch Diameter, Cylindric Flame Holder.



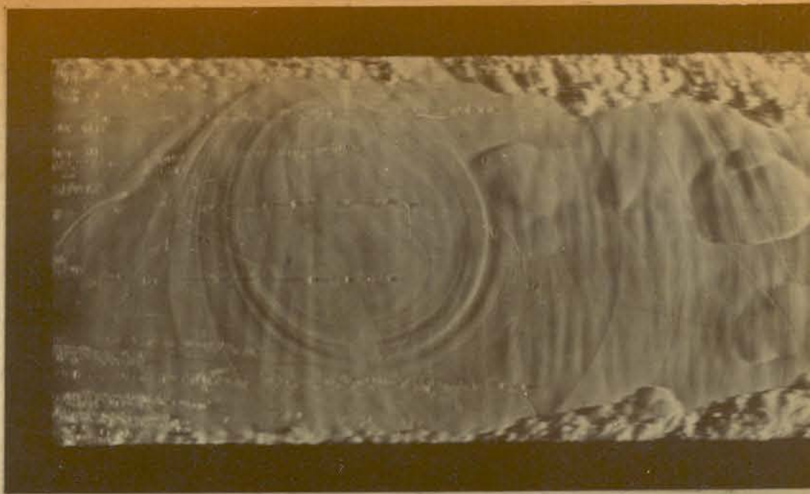
V = 67
Ø = 1.2
Temperature of
Flame Holder: 800°F

V = 67
Ø = 1.2
Temperature of
Flame Holder: 2000°F

V = 180
Ø = 1.2
Temperature of
Flame Holder: 800°F

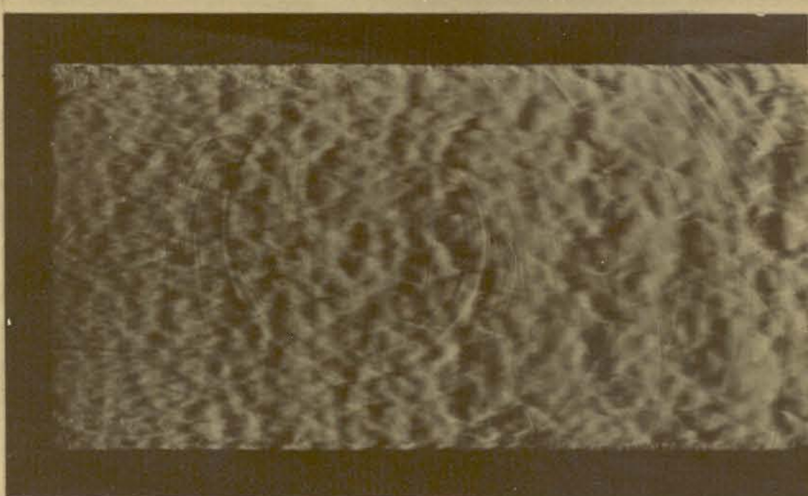
V = 180
Ø = 1.2
Temperature of
Flame Holder: 2000°F

FIGURE 15. Gasoline Flame Front Stabilized Behind 1/8 inch Circular Cylinder.



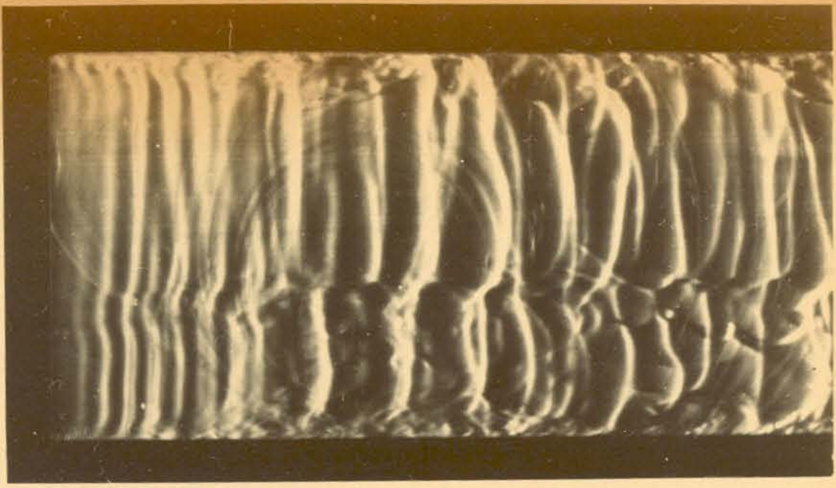
Reynolds Number = 1.9 x 10^4

Reynolds Number = 2.5 x 10^4

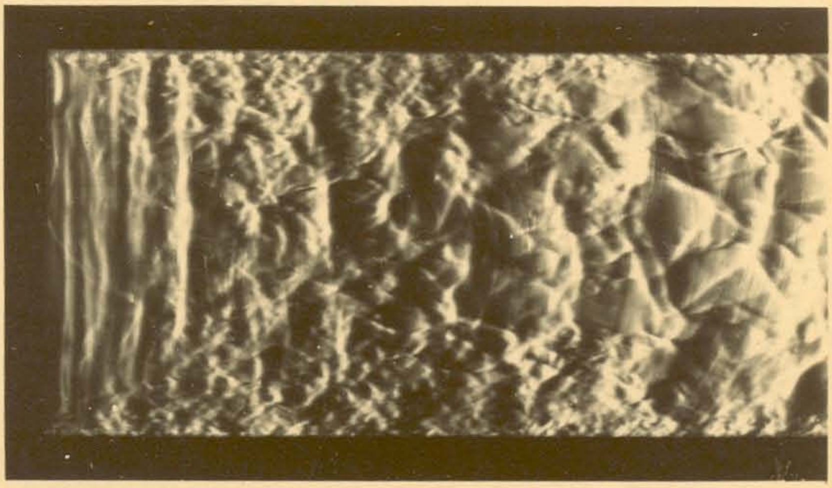


Reynolds Number = 3.2 x 10^4

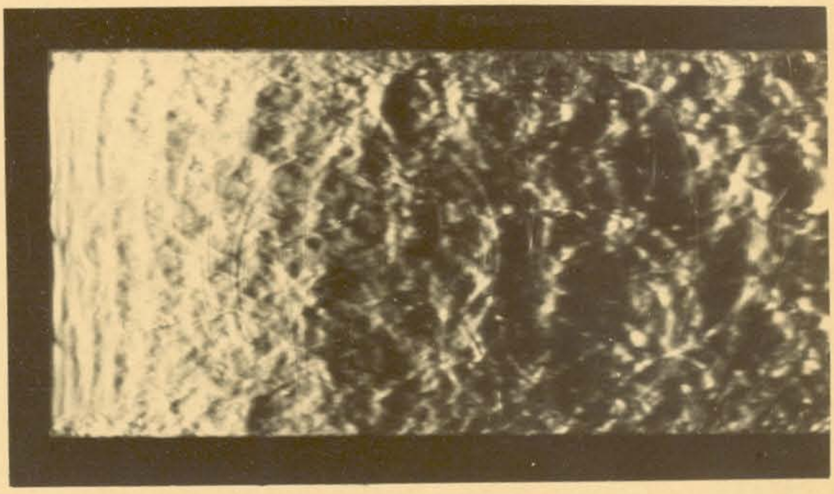
Figure 16. Schlieren Photographs of Hydrogen Flame Front Stabilized on a 1/2-Inch Diameter, Cylindric Flame Holder



Reynolds number = 1.25×10^4



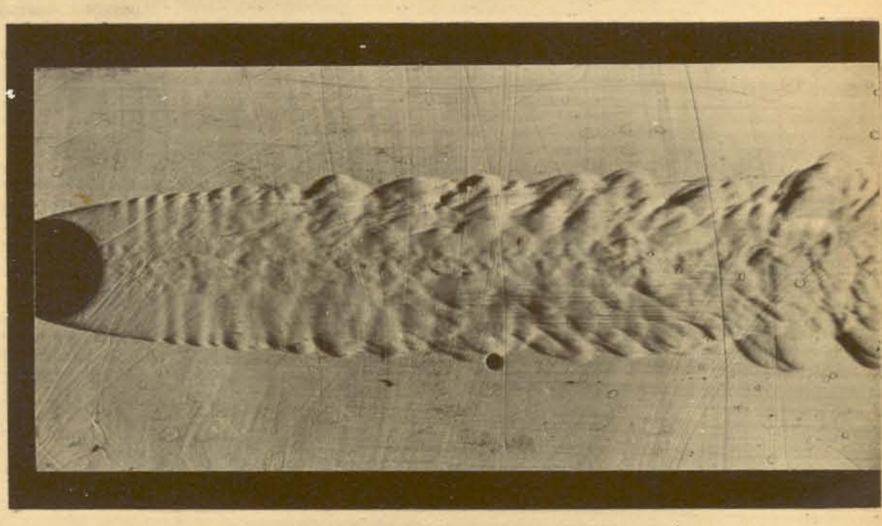
Reynolds number = 1.95×10^4



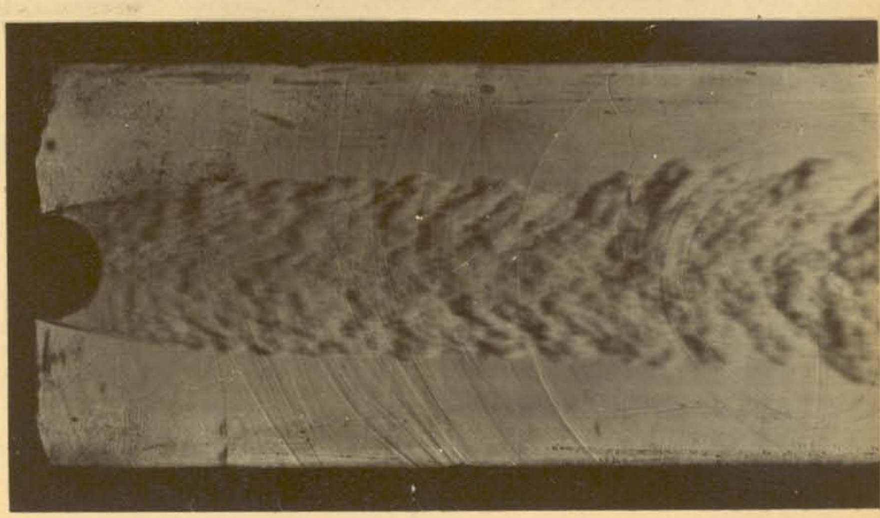
Reynolds number = 2.80×10^4

Figure 17. Schlieren Photographs of Methane Flame Front Stabilized on 1/2-Inch Diameter, Cylindric Flame Holder.

Reynolds Number = 1.9×10^4

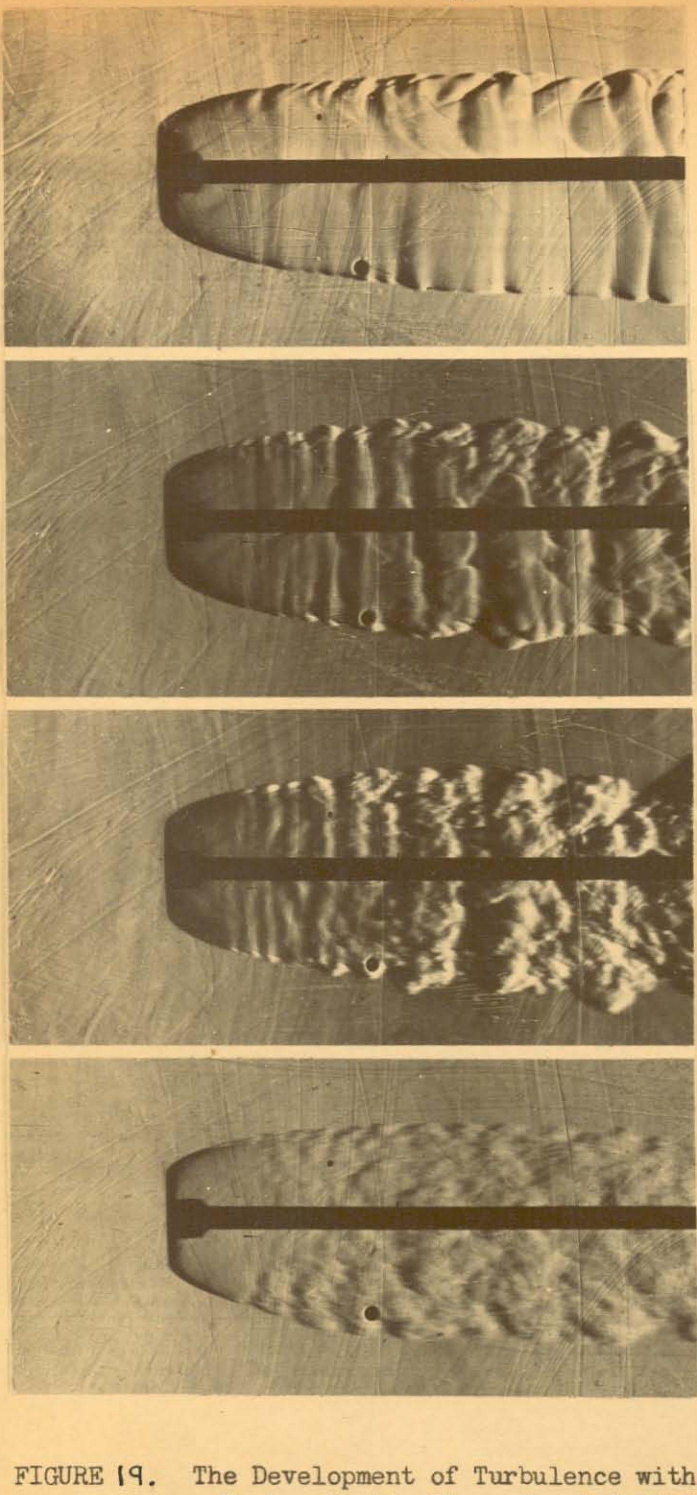


Reynolds Number = 3.6×10^4



Reynolds Number = 6.7×10^4

Figure 18. Schlieren Photographs of Flame Front Stabilized on 1/2-Inch Diameter Sphere



Reynolds Number = 1.3×10^4

Reynolds Number = 3.75×10^4

Reynolds Number = 5.00×10^4

Reynolds Number = 7.50×10^4

FIGURE 19. The Development of Turbulence with Increasing Reynolds Number in the Flame Front Held Behind a 1/2 Inch Uncooled Disk.

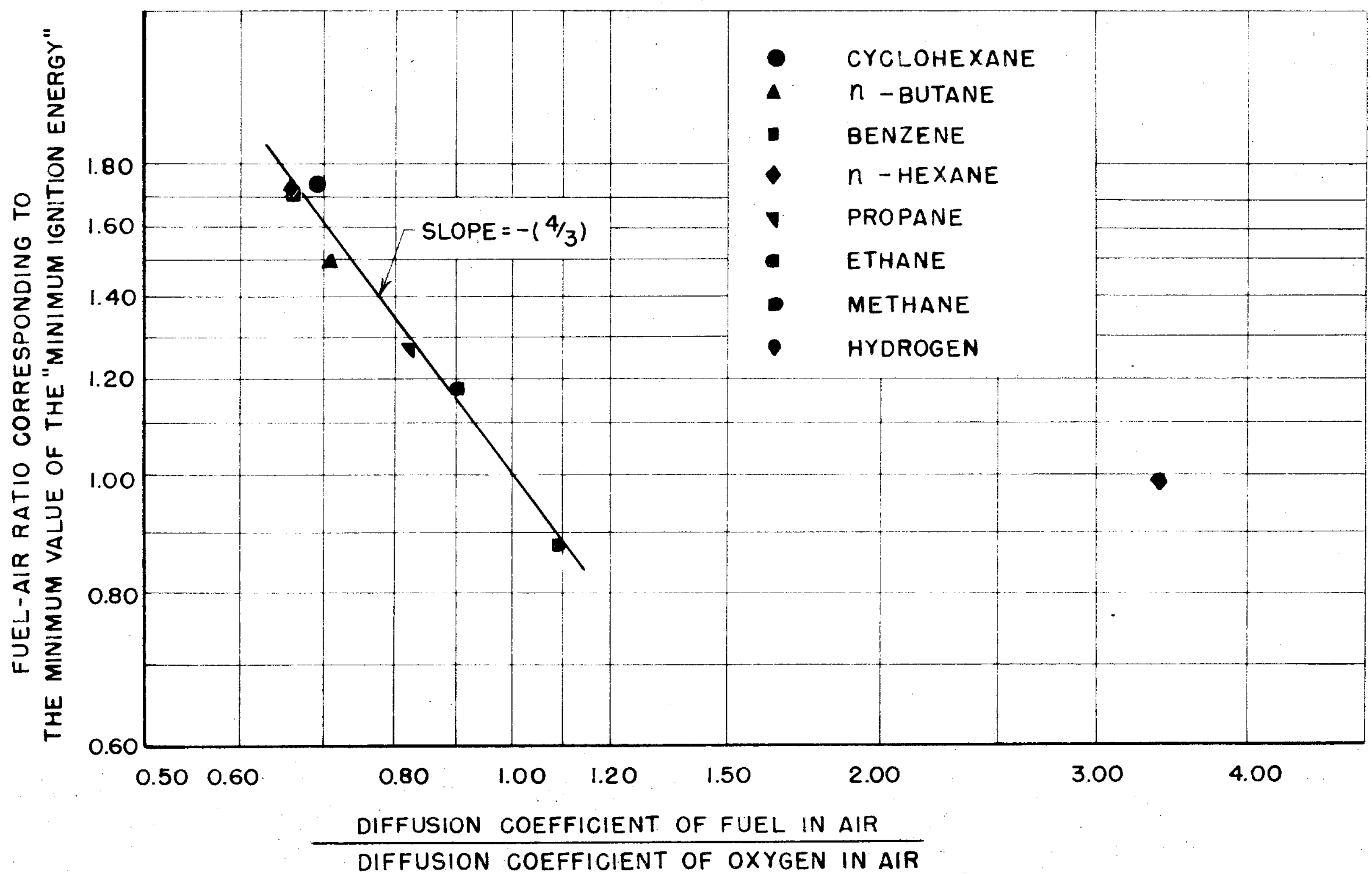


FIG.20 DEPENDENCE OF THE FUEL-AIR RATIO CORRESPONDING TO THE MINIMUM VALUE OF THE "MINIMUM IGNITION ENERGY" ON THE RATIO OF THE DIFFUSION COEFFICIENTS OF FUEL AND OXYGEN IN AIR

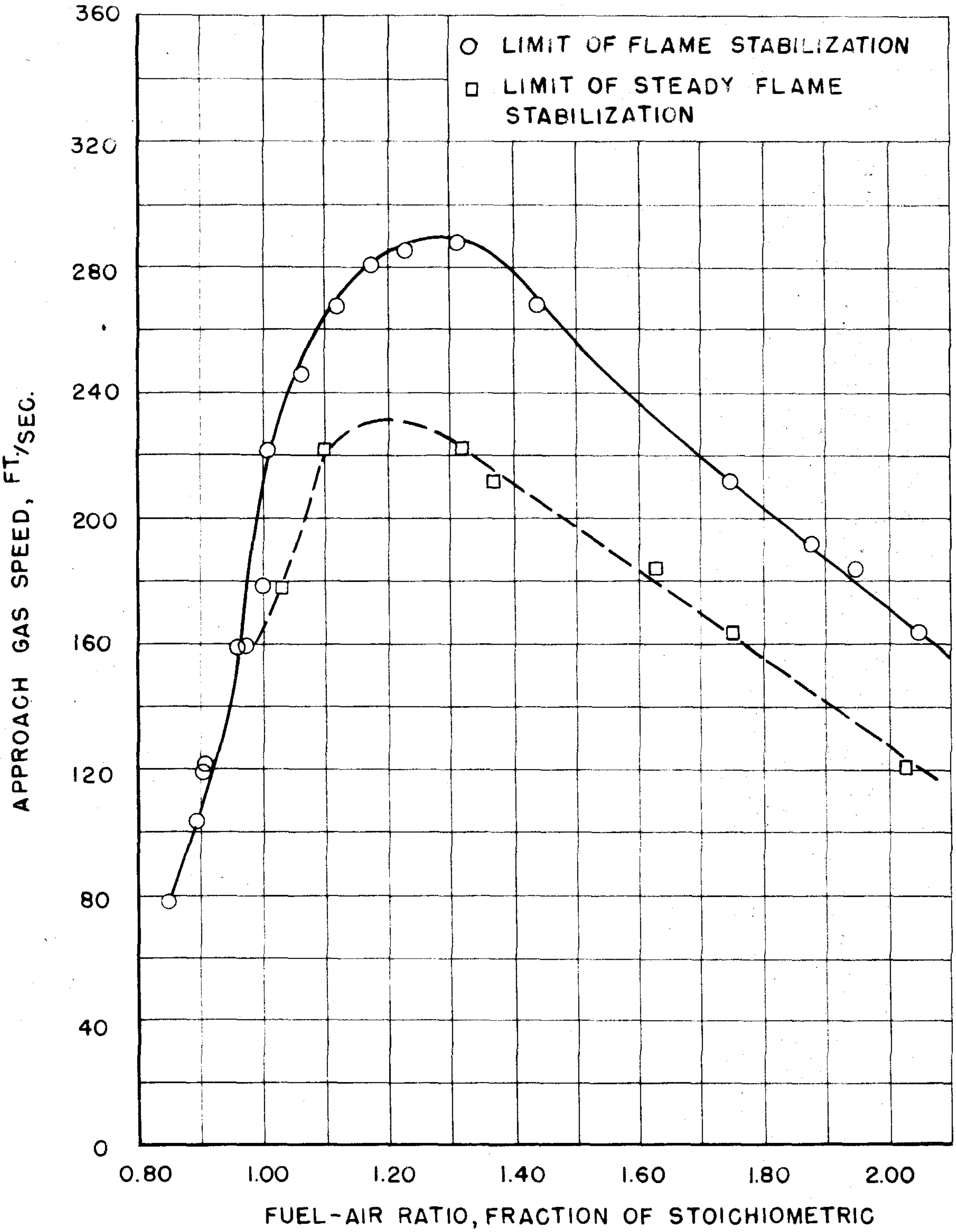


FIG.21 BLOWOFF CURVE FOR 0.049 INCH COOLED FLAME HOLDER SHOWING THE LIMIT OF STEADY FLAME STABILIZATION AS WELL AS THE BLOWOFF LIMIT CURVE

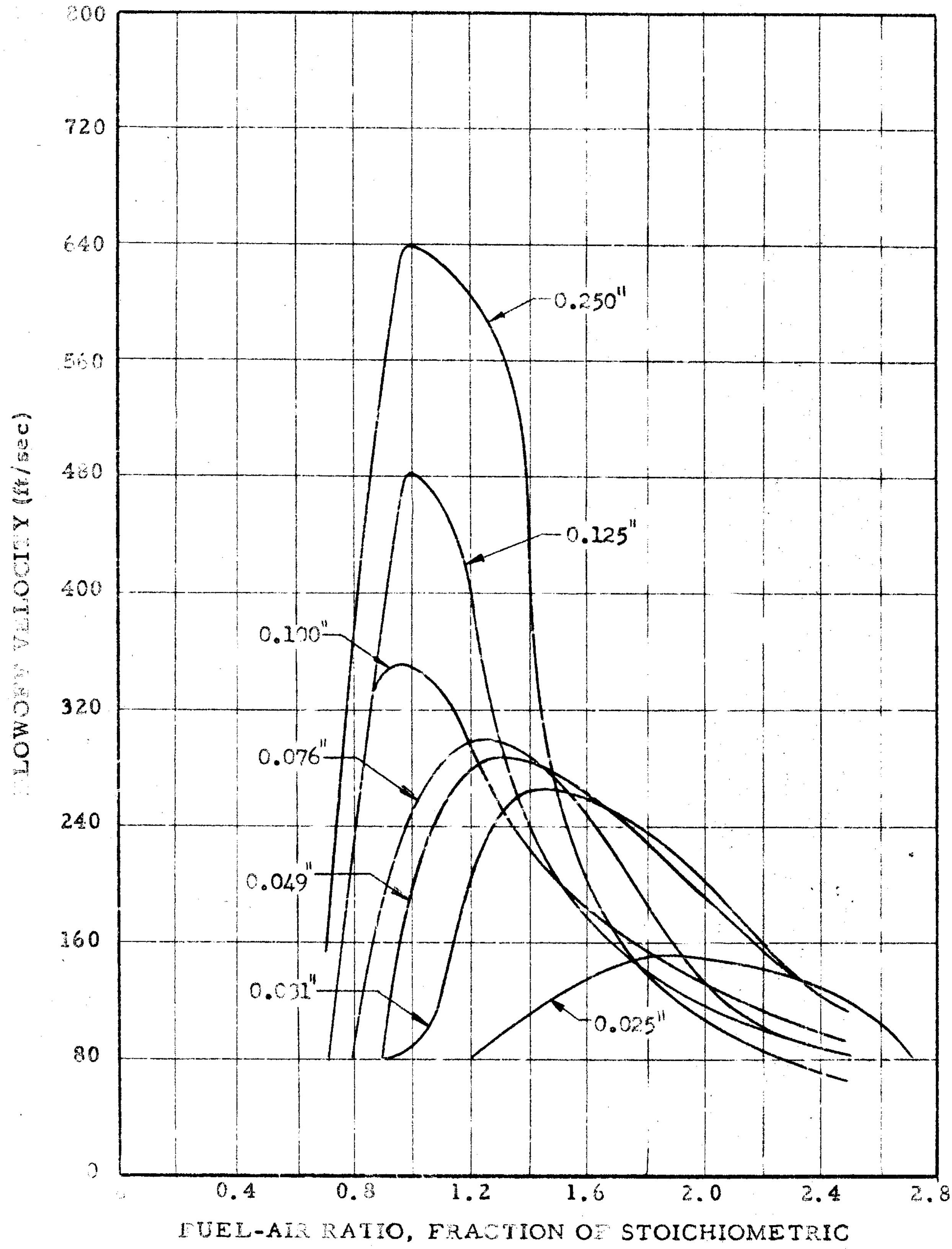


FIGURE 22 - DEPENDENCE OF BLOWOFF VELOCITY ON FUEL-AIR RATIO

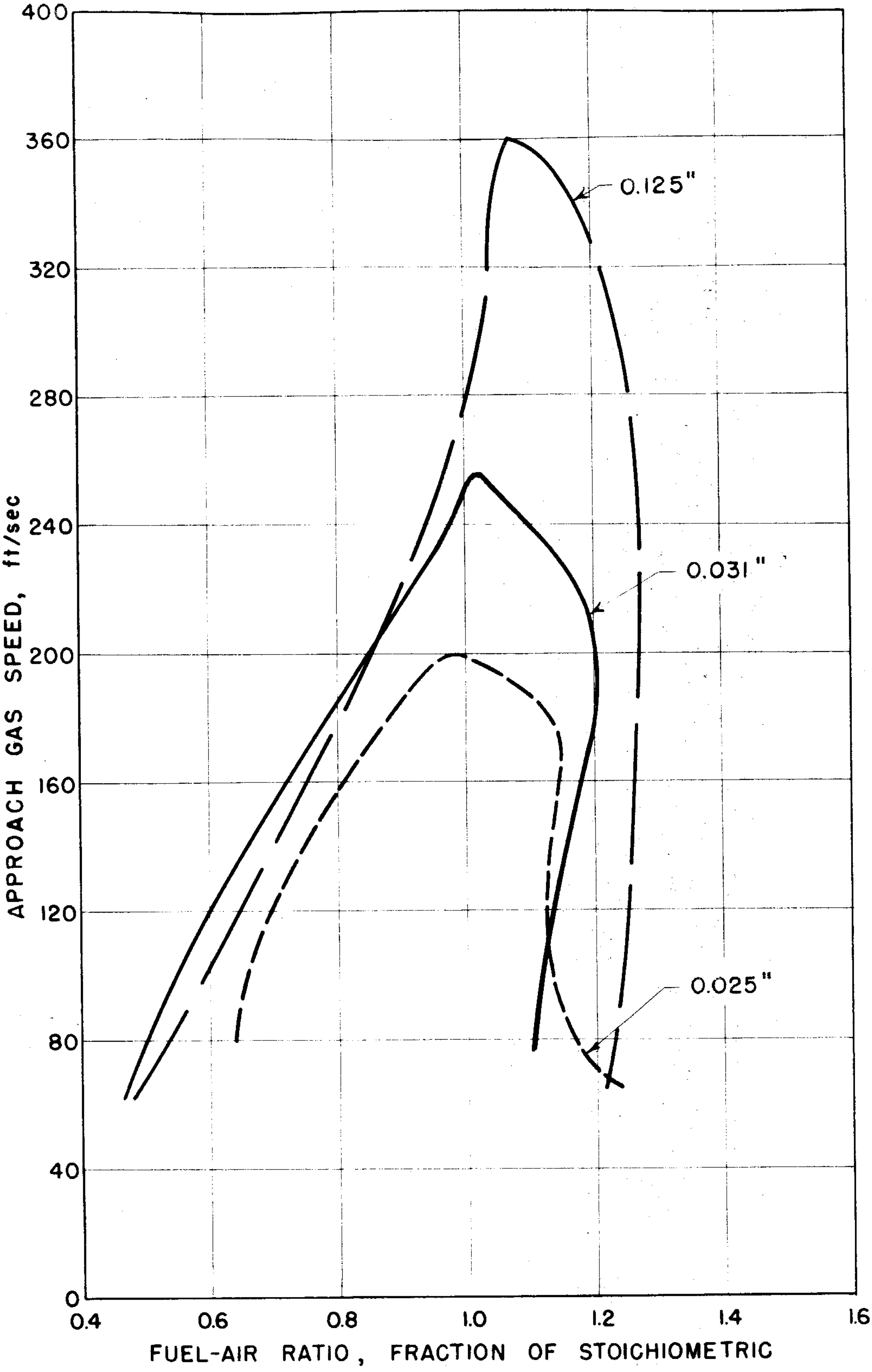


FIG.23 BLOWOFF CURVES FOR METHANE FUEL

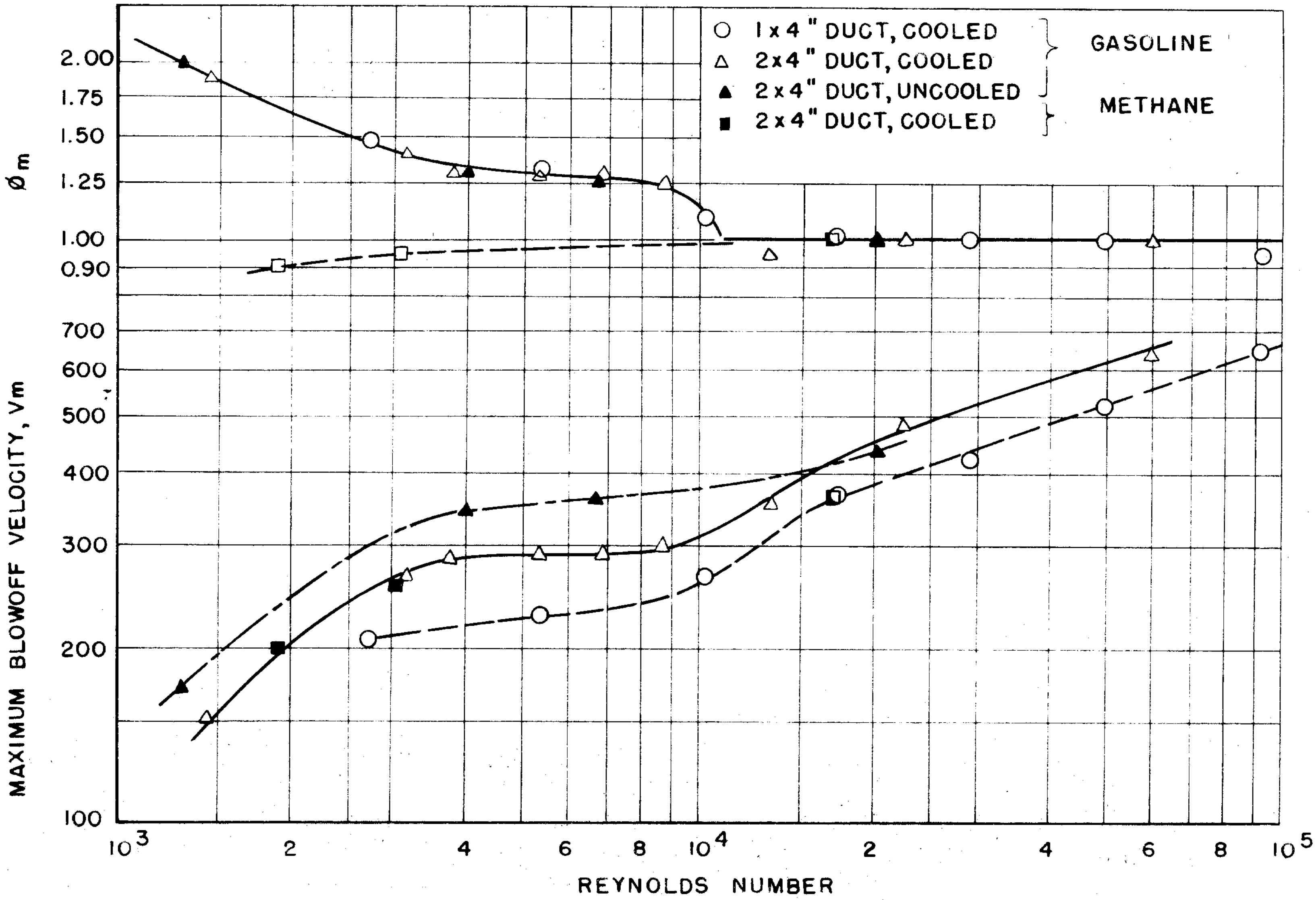


FIG.24 MAXIMUM BLOWOFF VELOCITY AND FUEL-AIR RATIO CORRESPONDING TO THE MAXIMUM BLOWOFF VELOCITY AS A FUNCTION OF THE REYNOLDS NUMBER

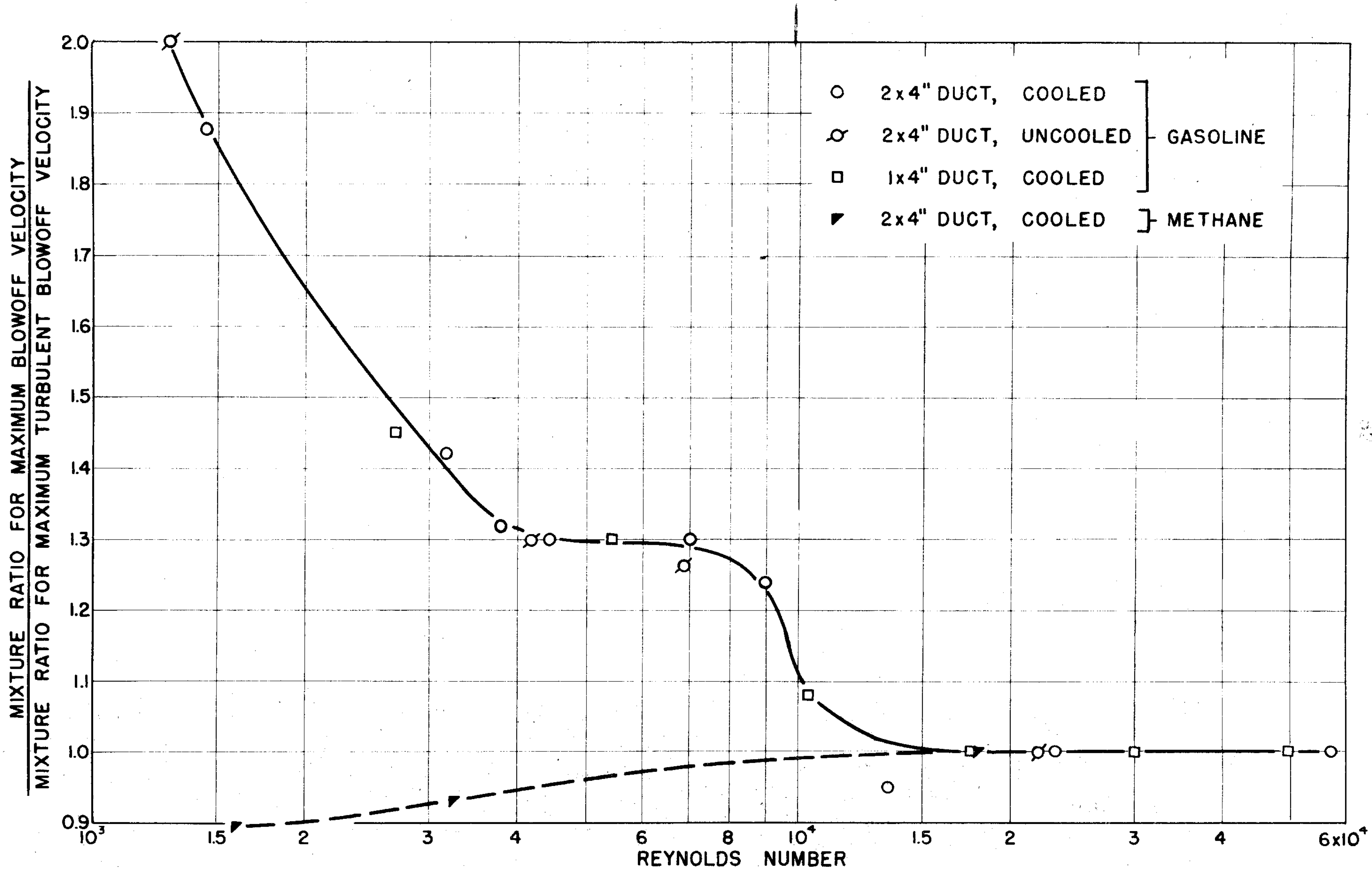


FIGURE 25 – DEPENDENCE OF MIXTURE RATIO CORRESPONDING TO MAXIMUM BLOWOFF VELOCITY ON REYNOLDS NUMBER

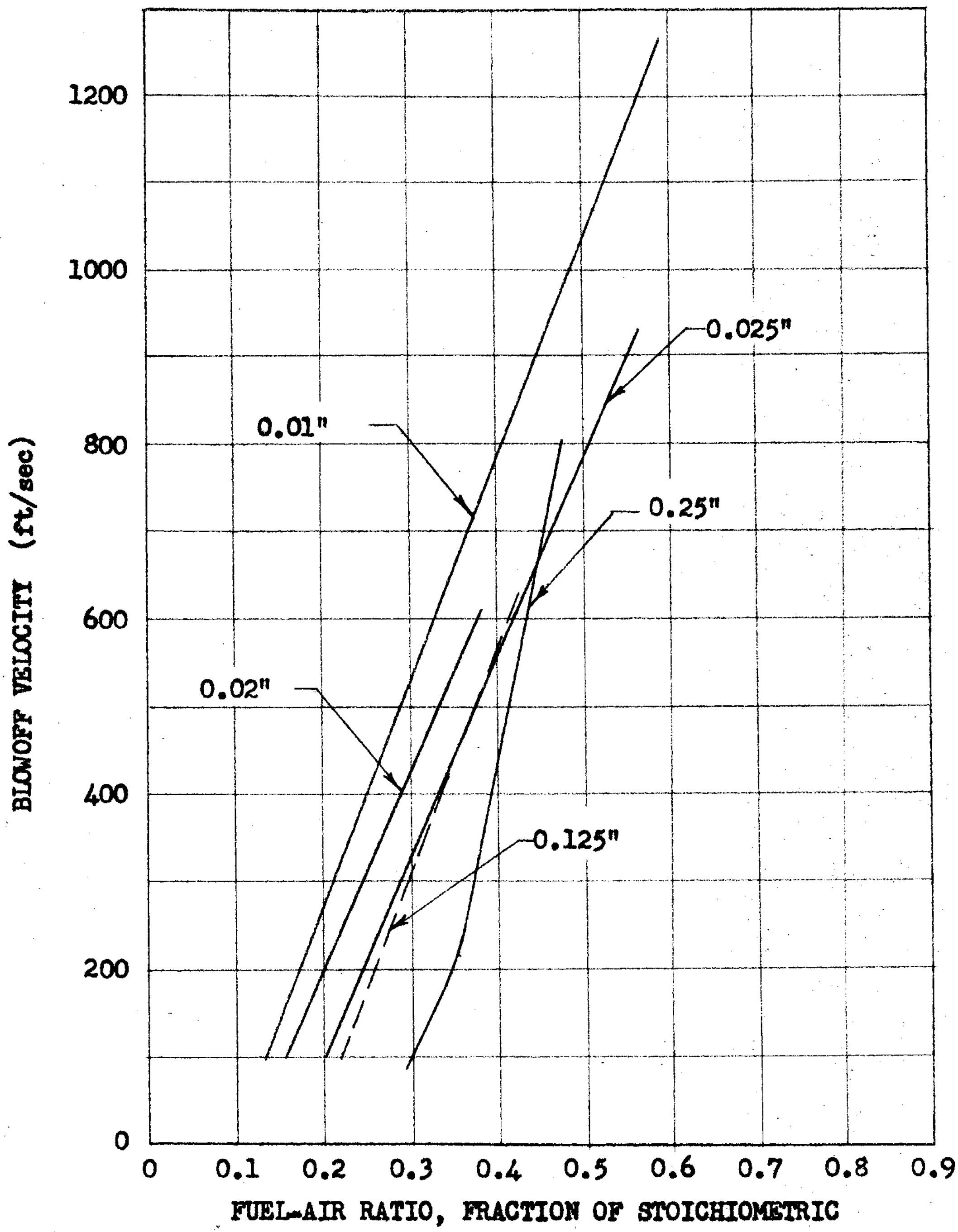


FIGURE 26 - BLOWOFF CURVES FOR HYDROGEN FUEL

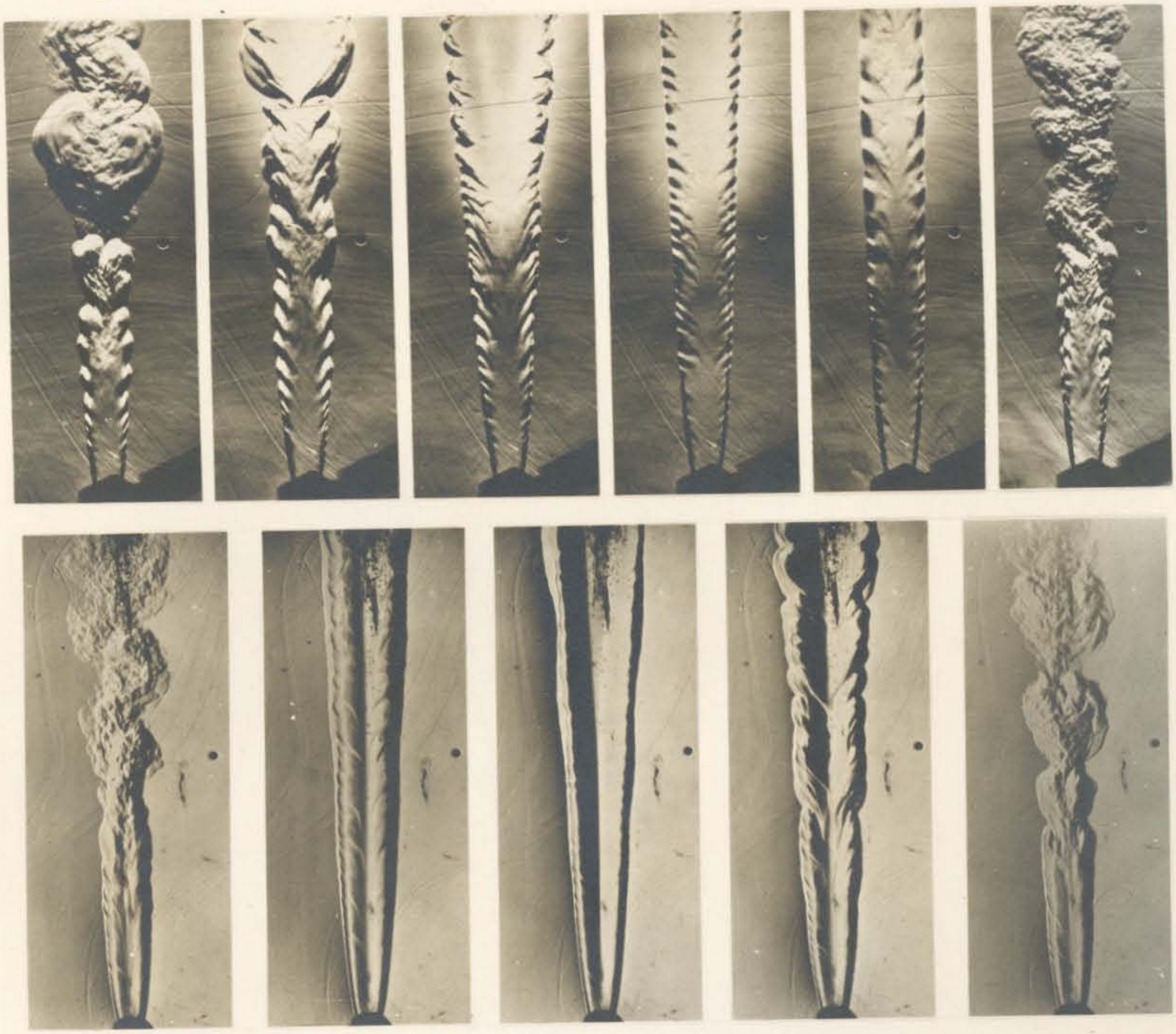


FIGURE 27. COMPARISON OF THE DEPENDENCE OF FLAME FRONT GEOMETRY ON THE FUEL-AIR RATIO FOR GASOLINE AND METHANE FUELS

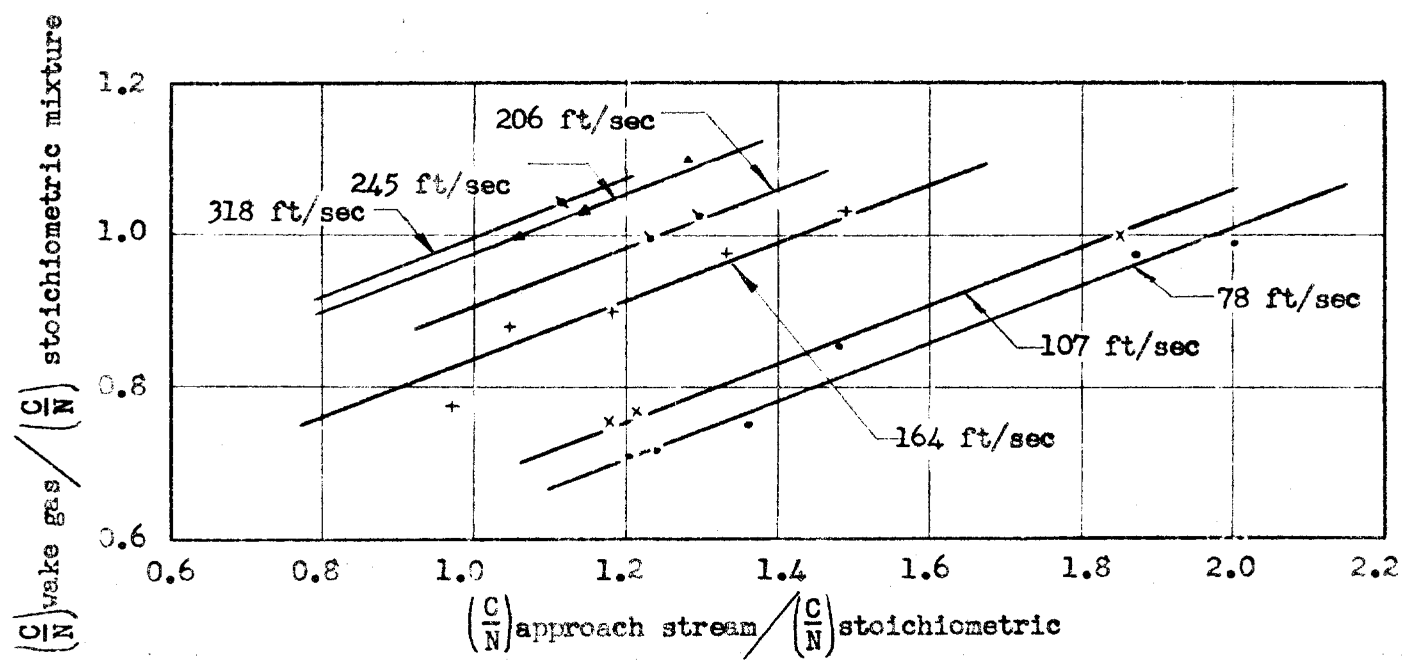


FIGURE 28. DEPENDENCE OF $\left(\frac{C}{N}\right)$ Wake gas ON $\left(\frac{C}{N}\right)$ Approach stream AND APPROACH STREAM VELOCITY FOR A 0.049-in. CYLINDRIC FLAME HOLDER

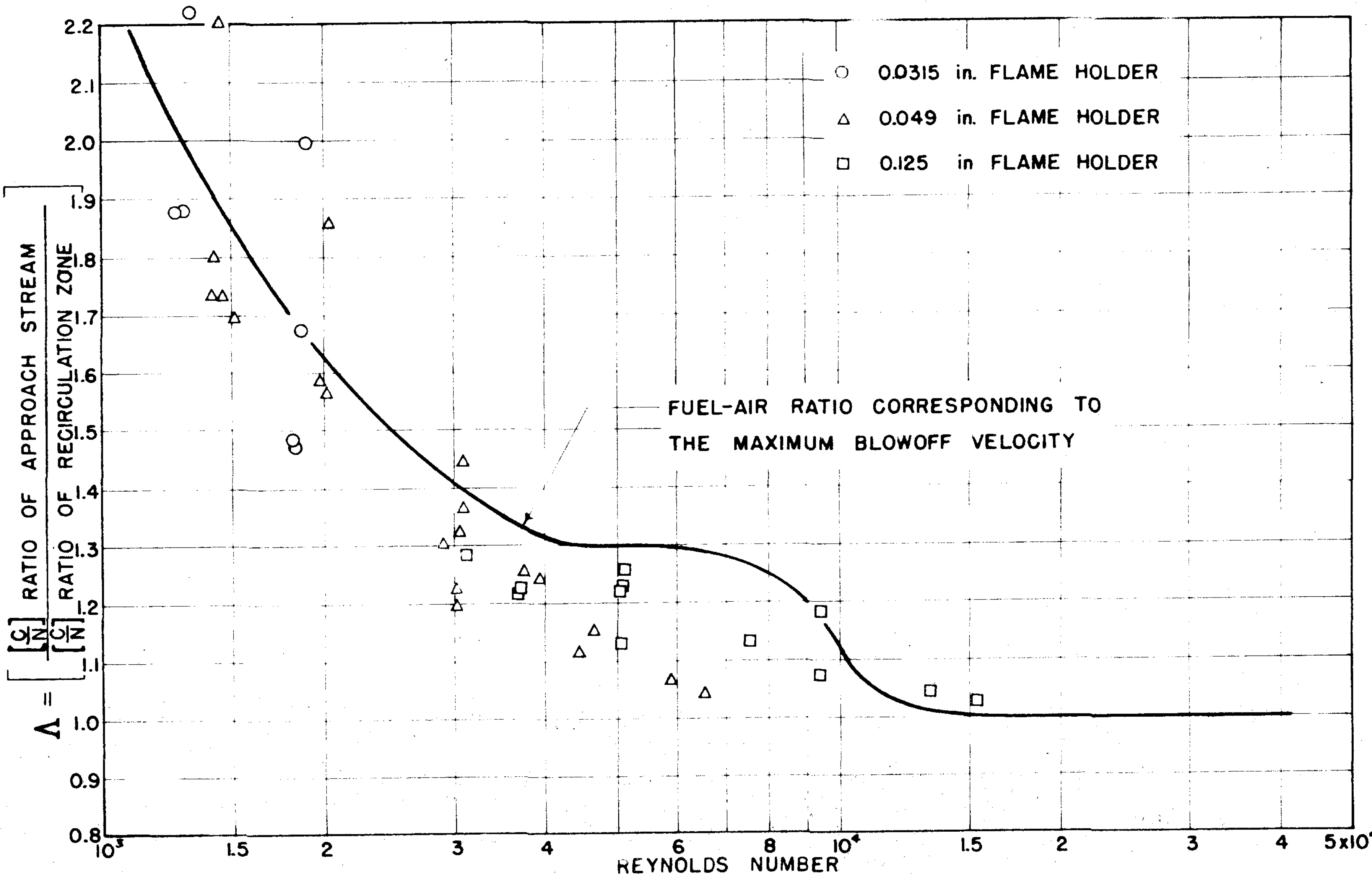


FIGURE 29 -DEPENDENCE OF Λ ON REYNOLDS NUMBER

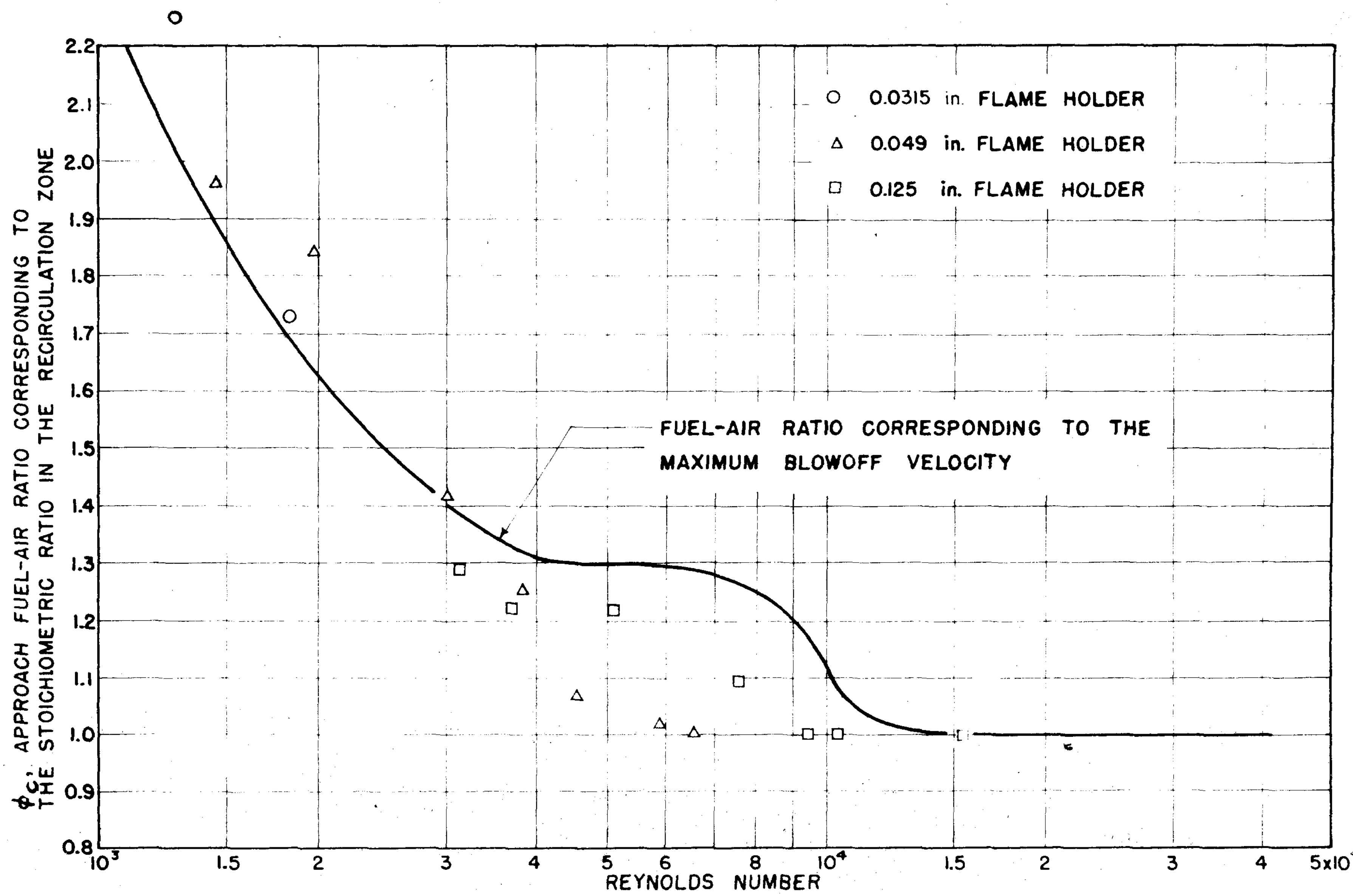


FIGURE 30 - DEPENDENCE OF ϕ_c ON REYNOLDS NUMBER

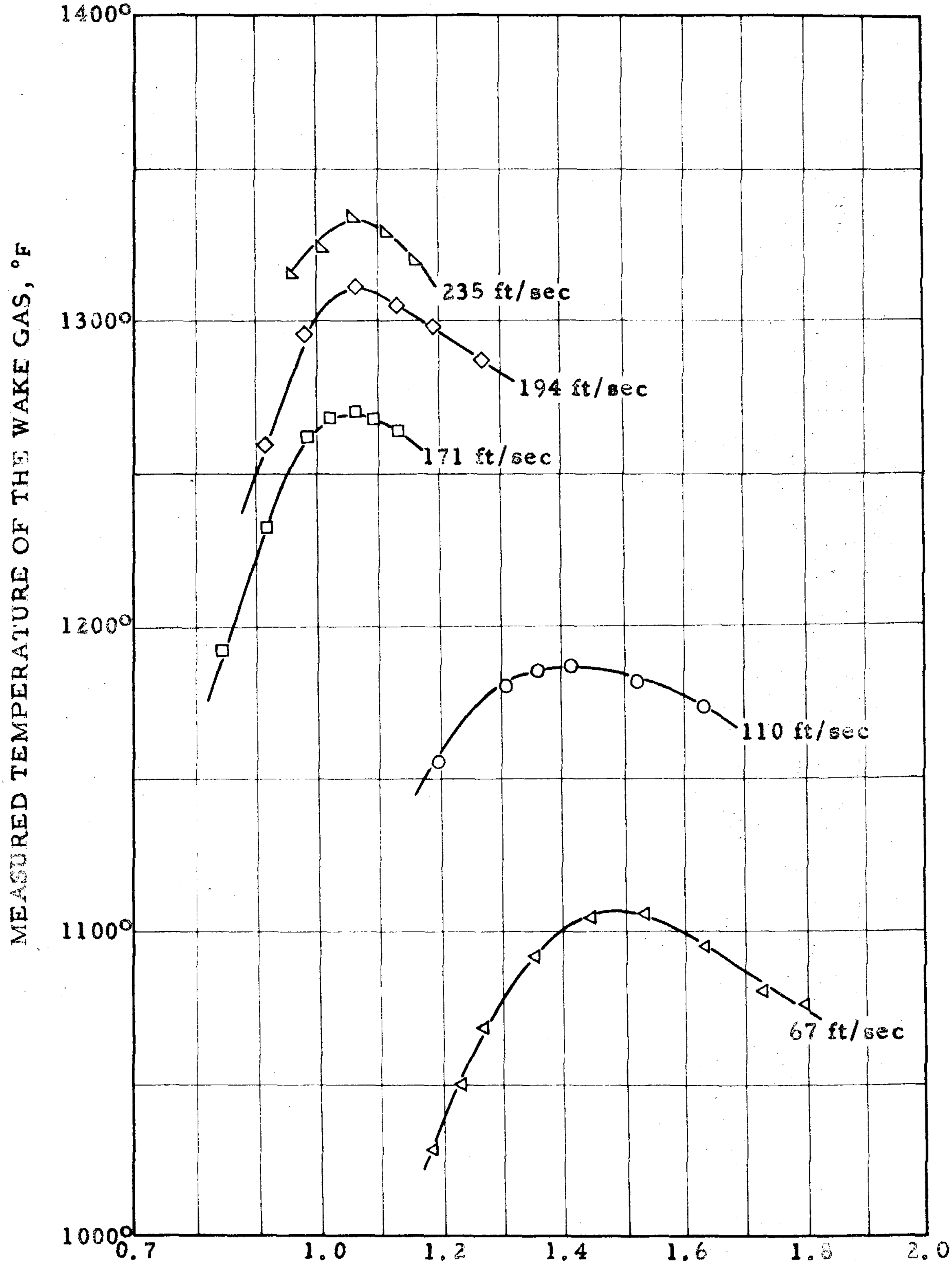


FIGURE 31 - DEPENDENCE OF WAKE GAS TEMPERATURE ON FUEL-AIR RATIO AND APPROACH VELOCITY FOR A ONE-EIGHTH INCH DIAMETER FLAME HOLDER

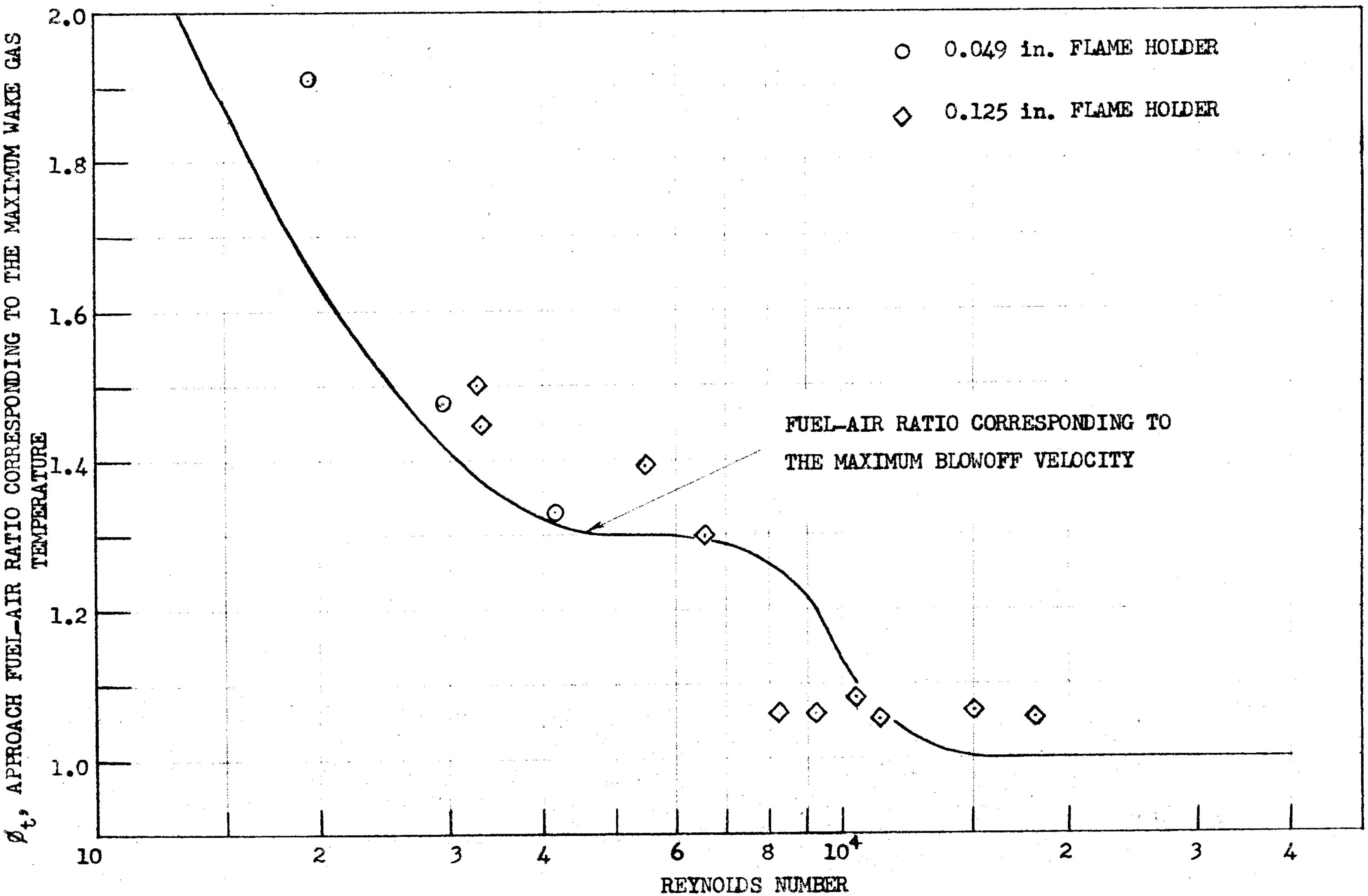


FIGURE 32. DEPENDENCE OF ϕ_t ON THE REYNOLDS NUMBER

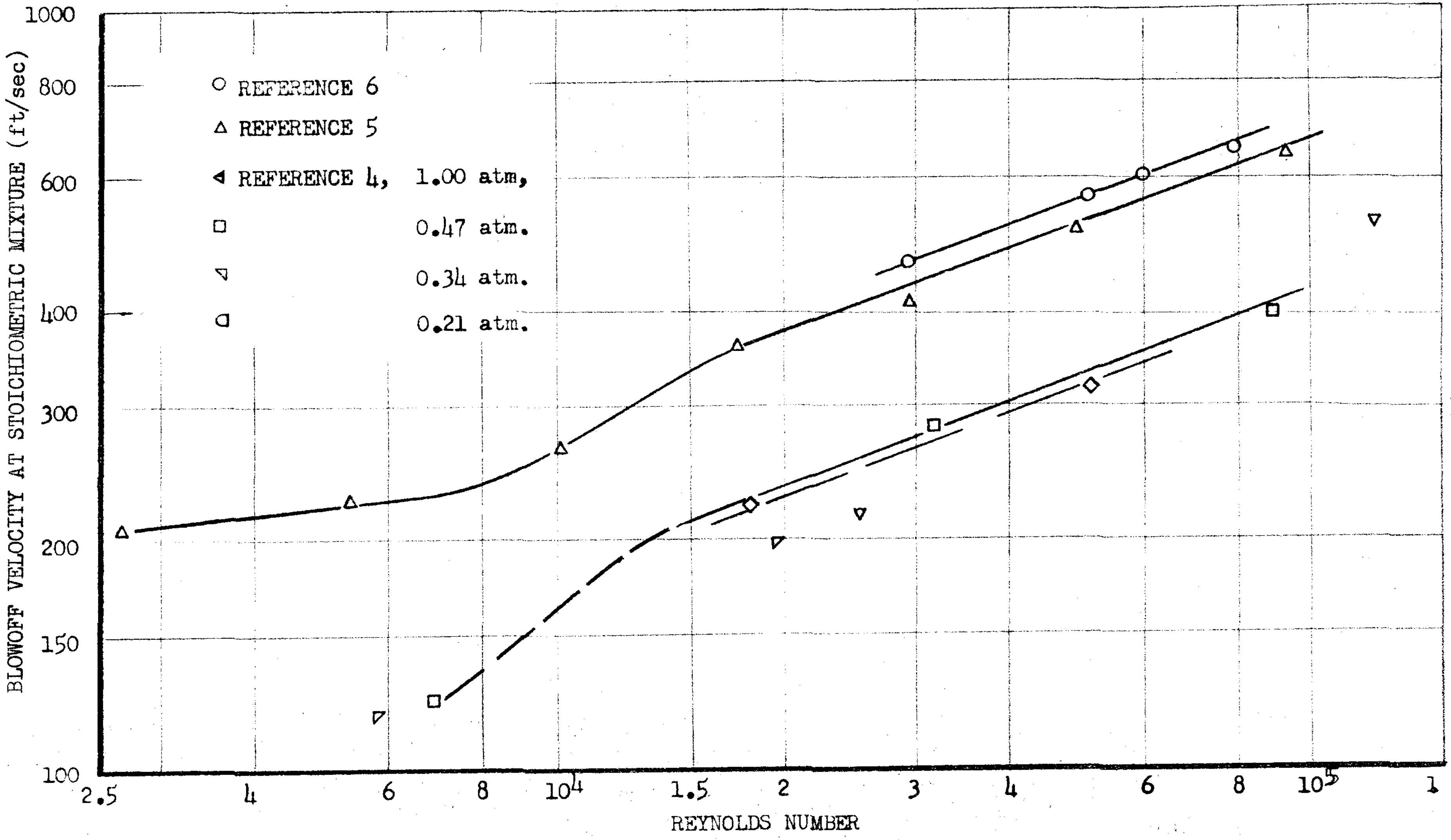


FIGURE 33. VARIATION OF THE BLOWOFF VELOCITY AT THE STOICHIOMETRIC FUEL-AIR RATIO WITH REYNOLDS NUMBER

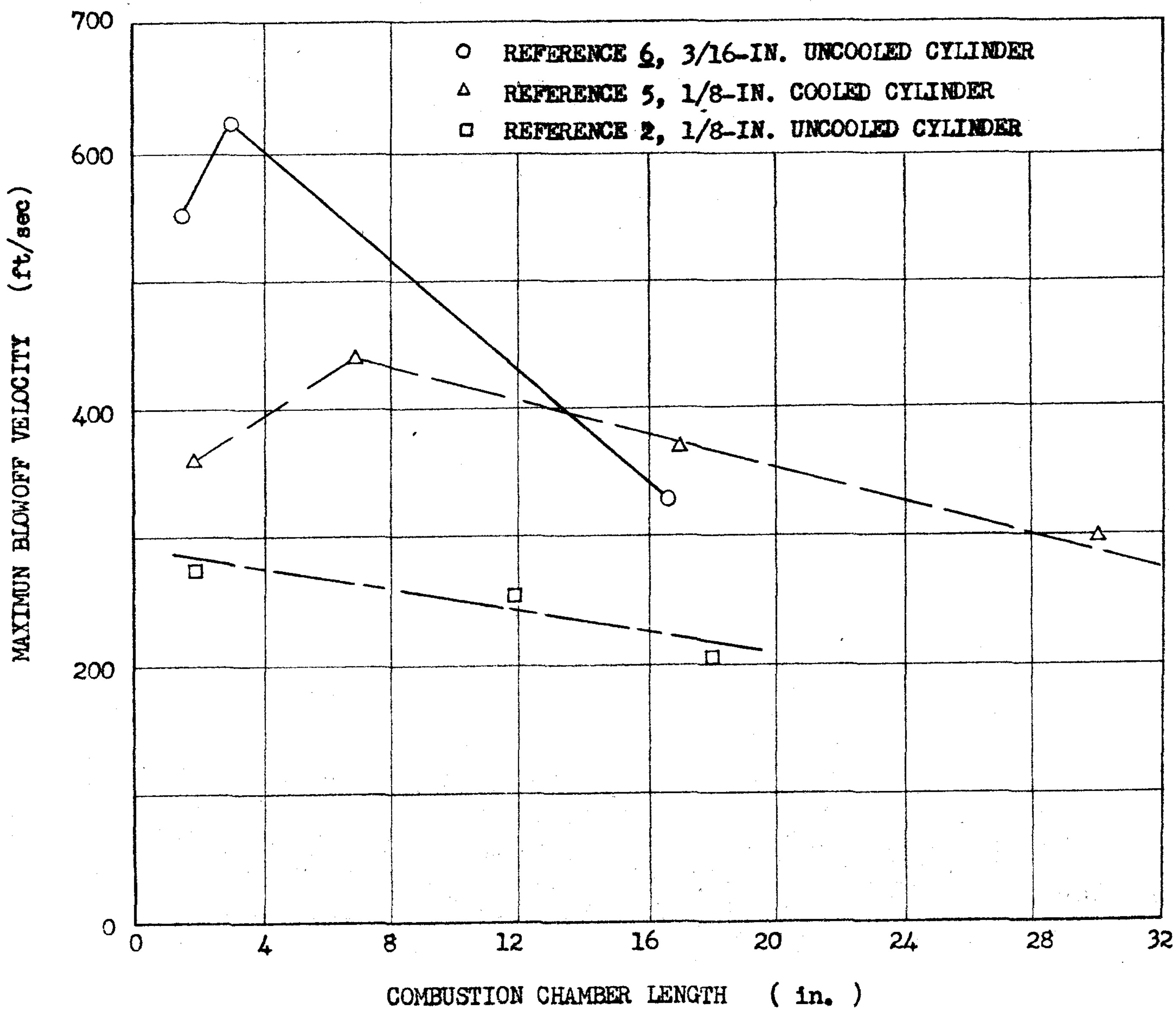


FIGURE 34. DEPENDENCE OF MAXIMUM BLOWOFF VELOCITY ON COMBUSTION CHAMBER LENGTH

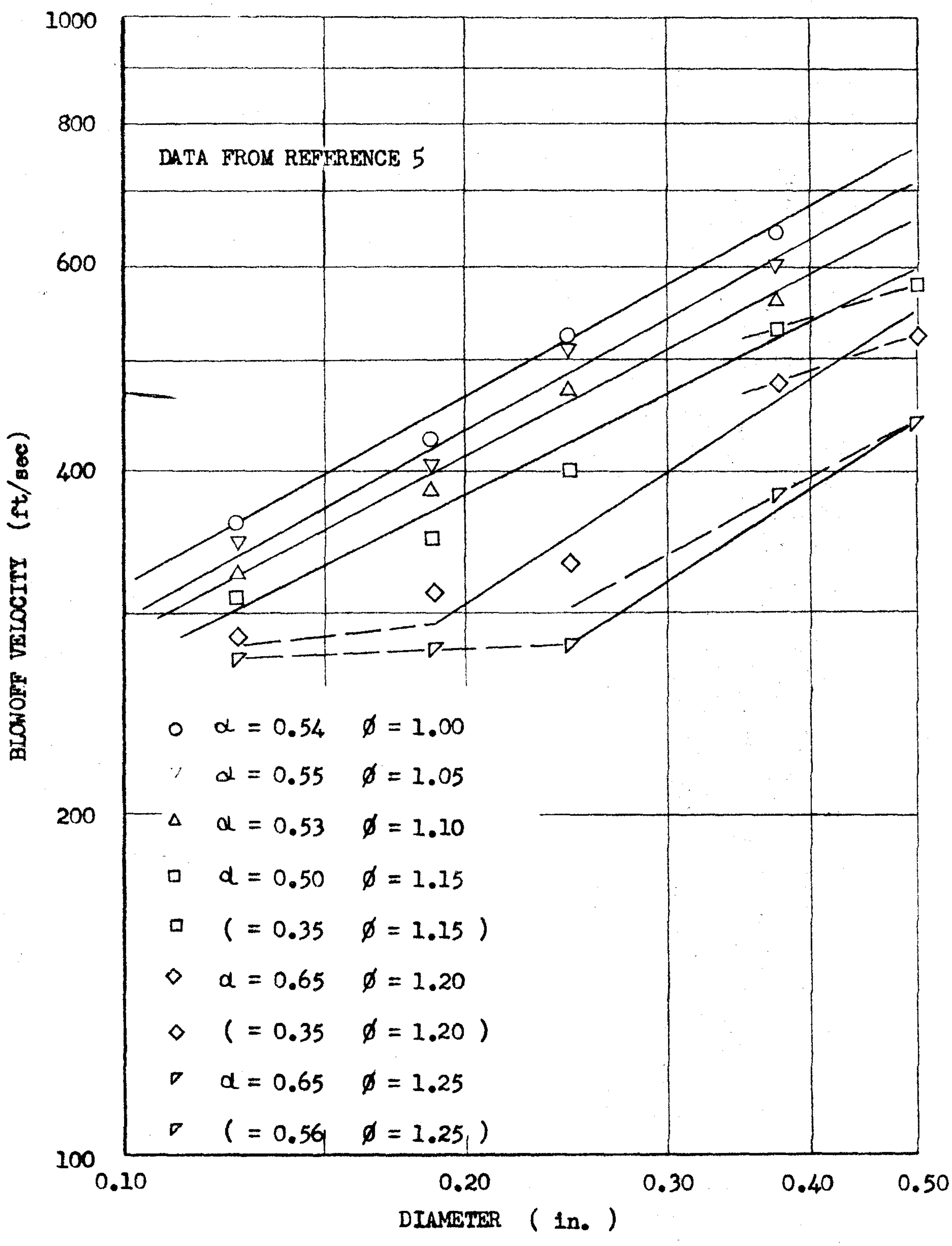


FIGURE 35_a. CROSSPLOT OF BLOWOFF VELOCITY VS FLAME HOLDER DIAMETER FOR VARIOUS FUEL-AIR RATIOS

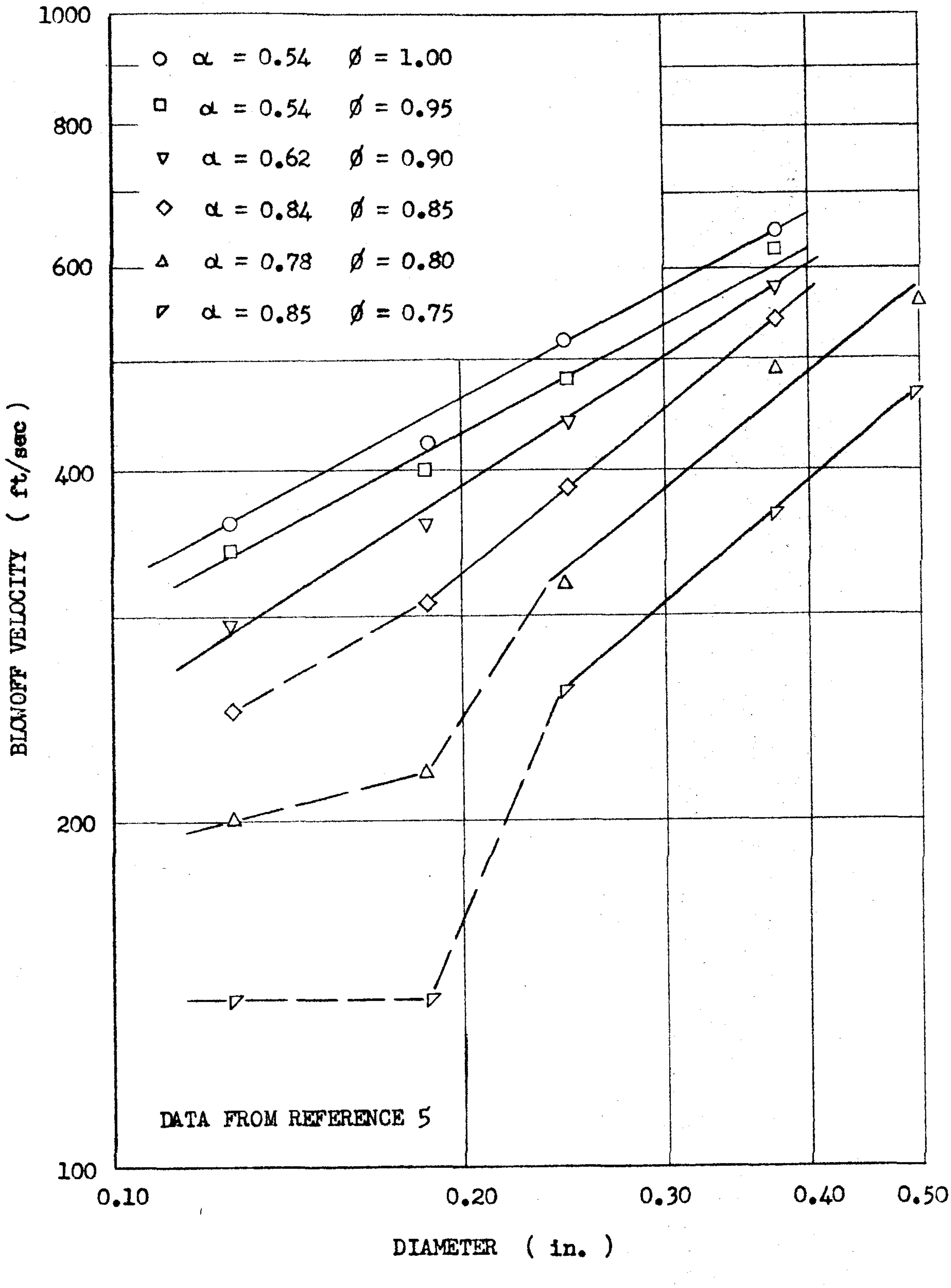


FIGURE 35_b. CROSS PLOT OF BLOWOFF VELOCITY VS FLAME HOLDER DIAMETER FOR VARIOUS FUEL-AIR RATIOS

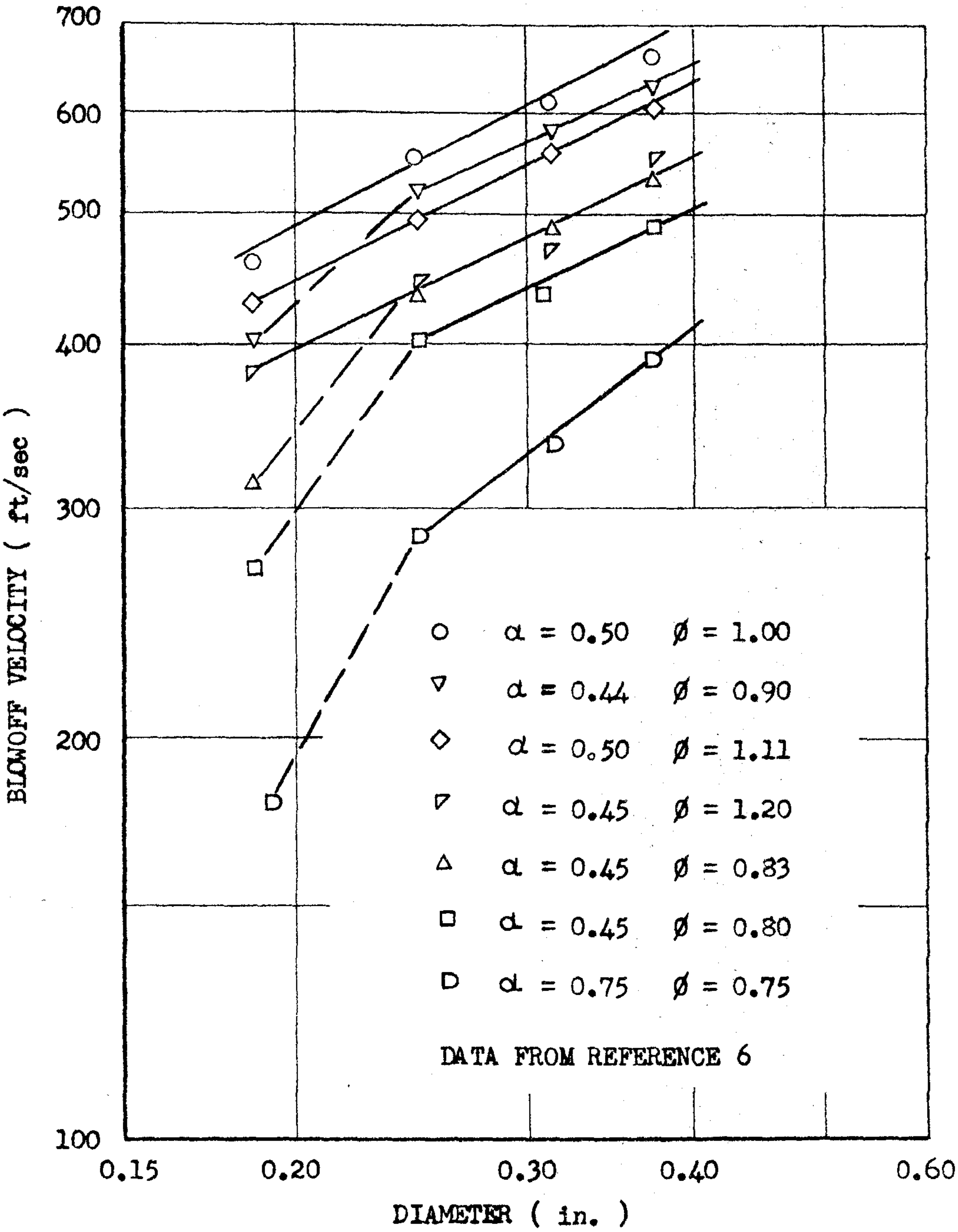


FIGURE 36. CROSSPLOT OF BLOWOFF VELOCITY VS FLAME HOLDER DIAMETER FOR VARIOUS FUEL-AIR RATIOS

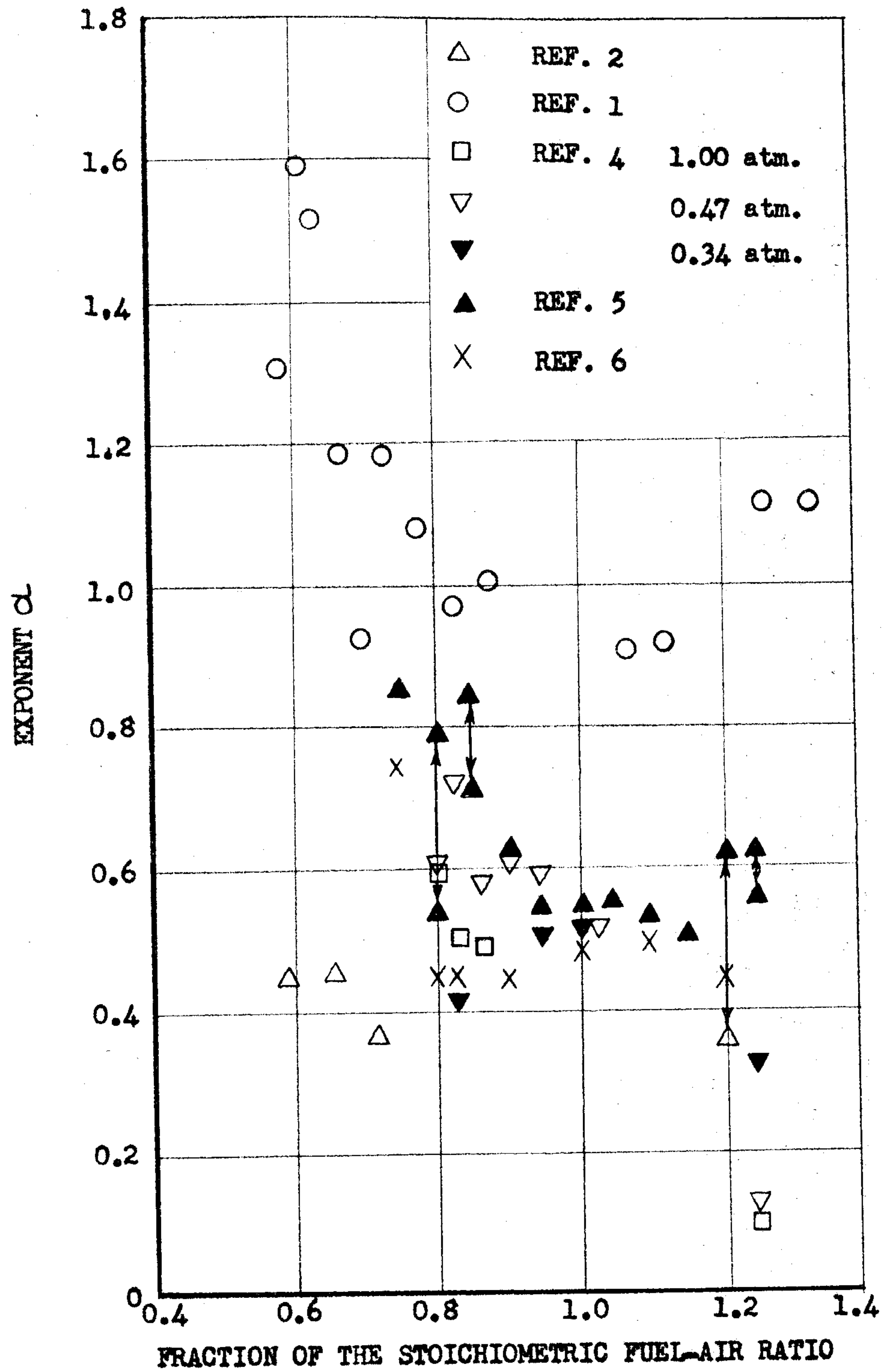


FIGURE 37. CROSSPLOT OF VALUES OF EXPONENT α AS A FUNCTION OF THE FUEL-AIR RATIO

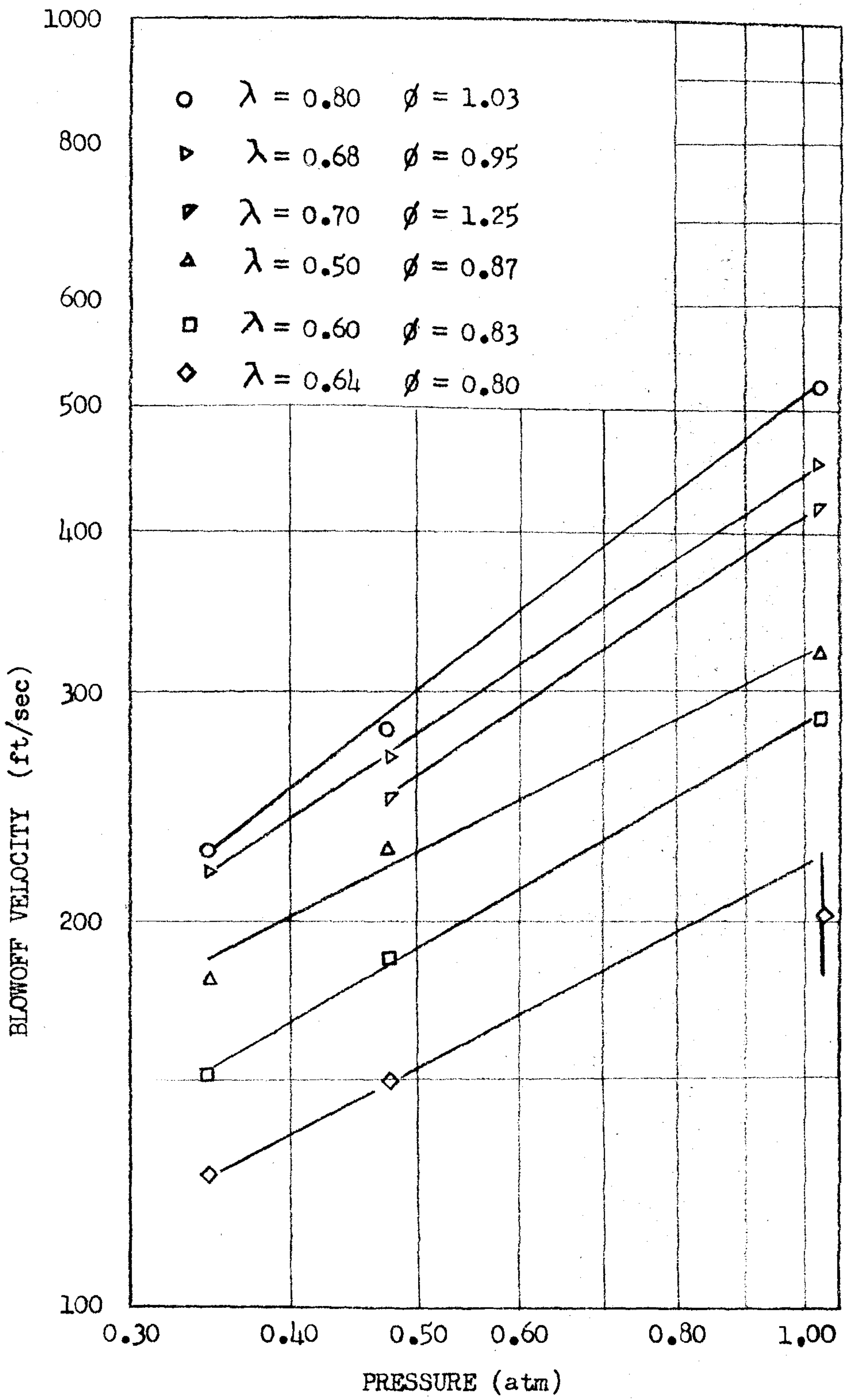


FIGURE 38 DEPENDENCE OF BLOWOFF VELOCITY OF 1/2-INCH DISK FLAME HOLDER ON COMBUSTION CHAMBER PRESSURE LEVEL