INTERFERENCE EFFECTS BETWEEN MULTIPLE BLUFF BODY FLAMEHOLDERS

Thesis by

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ABSTRACT

A general program was undertaken to determine the interference effects between multiple bluff body flameholders. The flameholders used for these experiments were 1/4 inch diameter water cooled cylinders tested in a 1 by 4 inch combustion chamber. Stability limits, flame geometry, and relative combustion efficiency were determined as functions of flameholder spacing and number.

The results of the tests showed that the maximum blowoff velocity decreased as the number of flameholders increased. This reduction was primarily due to the increase in the blockage ratio. In addition, a reduction in maximum blowoff velocity occurred when the flameholders were moved from the symmetrical arrangement in the duct.

A combustion instability characterized by a loud, high frequency noise occurred over well defined ranges of fuel air ratio, gas velocity, and flameholder spacing.

The recirculation zone length and flame widths were primarily functions of blockage ratio, modified slightly by flameholder separation. No large scale interaction occurred between the wakes of adjacent flameholders. Combustion efficiency increased with the number of flameholders and was little affected by flameholder separation.

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INTRODUCTION

In air breathing jet propulsive devices such as ram jets and turbojet afterburners a flame must be stabilized in a combustible gas mixture whose speed may be several hundred feet per second. This has frequently been accomplished by placing bluff bodies such as cylinders or "V" gutters in the gas stream and stabilizing the flame in the low velocity eddy region formed behind such bodies. The choice of size, shape, positioning, and number of flameholders for a particular application has been somewhat arbitrary due to the limited knowledge of the exact mechanism of the flame holding process.

Figure 1 is a photograph of a flame stabilized on a cylindrical flameholder, viewed along the longitudinal axis. The low velocity eddying region immediately behind the cylinder is known as the recirculation zone and is seen as the non luminous dark area. Longwell (Ref. 1) and Nicholson (Ref. 2), early established the recirculating character of the flow in this zone. In the mixing zone, between the recirculation zone and the unburnt gas, the hot recirculation zone gases mix with the unburnt material. If a sufficient quantity of the cool material is ignited a propagating flame will result; thus the residence time of the material in the mixing zone will be an important parameter of the problem. Since the length of the mixing zone is related to the length of the recirculation zone the latter becomes an important parameter.

Previous investigations have shown that for a particular size and shape of flameholder, flame stabilization can be accomplished for a given range of mixture ratio and gas velocity, and that outside these limits the flame will "blow off". When the limiting mixture ratio is plotted versus gas velocity the resulting curve is designated as the blowoff curve.

Many investigations have been carried out in an effort to determine the effect on the stabilization process of varying such parameters as size, geometry, and temperature of the flameholder; fuel characteristics; temperature and pressure of the combustible mixtures; and length of the combustion chamber. Such studies have been conducted by J. P. Longwell (Ref. 1), A. C. Scurlock (Ref. 3), G. Williams (Ref. 4), G. W. Haddock (Ref. 5), E. E. Zukoski (Ref. 6), and others. However, with the exception of a limited amount of work with small diameter flameholders operating at large spacings, no systematic studies have been made of the interference effects between multiple flameholders. Since most practical applications use two or more closely spaced flameholders, it seemed of interest to investigate the interference effects found when flameholders are operated in close proximity to each other or to the walls of the combustion chamber.

The purpose of the present work was to determine the magnitude and characteristics of such interference. Because of the complexity of the flame stabilization process for even a single flameholder, neither a detailed quantitative nor a rigorous analytical approach was considered applicable at this time to the study of multiple flameholders. In order to pursue the problem of interference effects some of the more tangible characteristics of flameholder operation were determined for various separations and numbers of holders; among these characteristics were blowoff velocity curves, recirculation zone lengths, relative combustion efficiencies, and wake geometries. The experiments determined the variation of these characteristics while keeping the size and shape of the flameholders constant but varying the separation and number of flameholders in a fixed area combustion chamber. Numerous Schlieren photographs were taken to aid in determining the extent of mixing of the turbulent wakes and to assist in explaining the overall results of the experiments conducted.

All work was accomplished at the California Institute of Technology, Jet Propulsion Laboratory, Pasadena, California using existing equipment designed by Dr. F. H. Wright.

EXPERIMENTAL APPARATUS

Compressed air was drawn from a controlled supply and heated to a fixed temperature; fuel was injected into the heated air well up stream of the plenum chamber to insure complete and uniform mixing. The homogeneous mixture passed from the plenum chamber through a smoothly converging nozzle into the 1 by 4 inch combustion chamber. The geometry of the plenum chamber, nozzle, and combustion chamber was such that a homogeneous mixture at a fixed temperature, controlled velocity, and low turbulence level was available. A schematic diagram of the system is given in Figure 2. Vycor glass windows on the sides of the combustion chamber allowed visual observation and photographs of the flame front in the vicinity of the flameholders.

Air was supplied by a reciprocating compressor system with a capacity of 3.5 lbs/sec. at a regulated pressure of 65 psig. The mass flow rate was controlled by a sonic throat regulating valve upstream of both the heat exchanger and the fuel injector thereby insuring a constant mass flow regardless of changes in air temperature or fuel injection rate. Mass flow and hence velocity was measured by a sharp edged orifice flow meter located downstream of the heat exchanger and upstream of the fuel injector. The flowmeter utilized both water and mercury manometers to cover the range of required pressures while the temperature at the orifice was determined by a chromel-alumel thermocouple read by a Brown Automatic Potentiometer.

A mixture temperature of 610^{o}R was used in the experiments to insure complete vaporization of all the fuel components. The temperature of the air was controlled by passing a fraction of the total flow through a shell and tube type heat exchanger. This arrangement allowed the heat exchanger to be operated at a constant temperature while permitting rapid adjustment to the overall temperature of the air.

The calming chamber was 15 inches in diameter and 5 feet long. Six 150 mesh screens were mounted in the calming chamber to reduce the initial turbulence. A 10 inch rupture disc was placed in the wall of the calming chamber and a flame arrestor was located upstream of the chamber to prevent flashback from traveling up the supply lines. A total pressure tap was located in the calming chamber 2 feet upstream of the combustion chamber entrance and a static pressure tap was placed 1/2 inch downstream from the entrance in the 1 by 4 inch cross section of the combustion chamber.

The converging nozzle developed smoothly from the 12 inch diameter to the 1 by 4 inch cross section of the rectangular combustion chamber in an axial distance of 18 inches. The length of the combustion chamber was 9 inches when the 4 by 6 inch Vycor glass sidewalls were used and 6 inches when the 4 by 3 inch glass sidewalls were used. The flameholders were mounted perpendicularly across the 1 inch dimension of the chamber, and nearly tangent to the upstream edge of the glass sidewall. Photographs of the combustion chamber and a general view of the apparatus are shown in Figure 3.

From one to five 1/4 inch diameter water cooled flameholders were used. The flameholders were made of stainless-steel tubing with 1/8 inch inlet and exit water tubes passing through the sidewalls of the test section. The combustible mixture was ignited by a high voltage alternating current spark passing from an ignitor rod to the flameholder.

The fuel used was commercial paint thinner (Thinner No. 1), Union Oil Co., Los Angeles, Calif.) with a molecular weight of approximately 91. A detailed chemical and physical property analysis is given in Table I. The fuel was drawn from nitrogen pressurized tanks and injected into the heated air upstream of the calming chamber. The fuel was metered by Fisher Porter Flowrators and injected through 24 gal/hr. turbojet injectors.

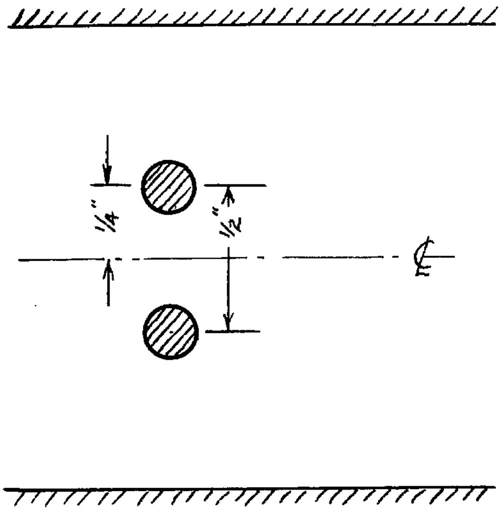
The Schlieren equipment used was a conventional double mirror system using two 6 inch diameter concave mirrors with a 50 inch focal length. The light source used was a BH-6 lamp which was synchronized with the camera shutter by a series of relays which furnished the required delay. The BH-6 furnished a spark of less than 7 microseconds duration. Photographic film was Eastman Super XX.

PROCEDURES AND RESULTS

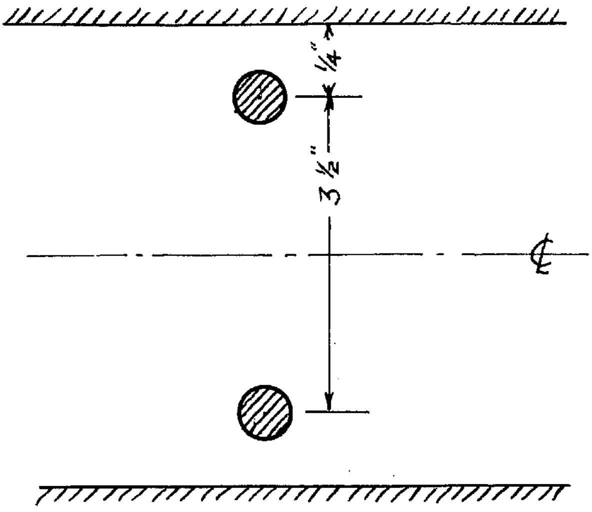
A. Blowoff Limits.

To obtain the blowoff limits at the lower velocities (below 250 ft/sec.) the desired gas velocity was set, ignition accomplished and the fuel quantity varied until blowoff occurred either at the rich or lean limit. Direct ignition of the mixture was impossible for velocities above 250 ft/sec. therefore making it necessary to light off at a lower velocity, then increase the velocity and fuel until the desired value was reached. Following this the procedure was similar to that used at the lower velocity, that is, increasing or decreasing the fuel flow rate until blowoff occurred. Points near the peak of the blowoff curve required the fuel flow to be set at a given value and then increase the air flow until blowoff. The criterion used in all tests for determining the blowoff curve was that blowoff occurred when the flame was extinguished on any one of the flameholders of a multiple configuration. This was necessary due to the added complexities in the flow field caused by the Kårmån vortex street produced behind a cold flameholder. It was found that ignition was more readily accomplished if the spark was struck slightly aft of the top or bottom position on the flame holder rather than the point directly behind or downstream.

In all the tests conducted 1/4 inch diameter water cooled flameholders were used. The blowoff limits for two flameholders at 3/8, 1/2, 3/4, 1.3, 1 1/2, 2, 2 1/2, 3, 3 1/4, and 3 1/2 inch separations were determined. For a duct 4 inches wide a separation of 3 1/2 inches places each flameholder 1/4 inch from the wall and would correspond to the 1/2 inch separation between flameholders if the center streamline between the two flameholders were replaced by a solid wall. This is illustrated in the following sketch.



1/2" Separation



3 1/2" Separation

Similarly the 3/4 and 1 inch separation correspond to 3 1/4 and 3 inch separation respectively. Experiments showed that the velocity profile of the duct was very flat and the boundary layer thickness was not in excess of .020 inches; therefore, no compensations were made for the boundary layer in these tests.

The first blowoff curves, cf Figure 4, were obtained using Vycor glass walls 6 inches long with the surface of the flameholder nearly tangent to the upstream edge of the glass wall. With a 3/8 inch separation the blowoff curve shown in Figure 4 was obtained. Near the rich and lean blowoff velocities and for all mixture ratios at velocities above 252 ft/sec. it was impossible to completely stabilize the flame on both holders at once; one flameholder became dominant and pinched the flame off the other. Schlieren photographs of this phenomenon are shown in Figure 5. Because of this unstable situation no well defined blowoff curve could be obtained for this separation.

At the 1/2" separation and the 6" glass walls no unusual events occurred during the determination of the blowoff curves. The results of these tests are given in Figure 4, and it may be seen that a maximum blowoff velocity of 380 ft/sec. was obtained. As previous investigators had found, the blowoff occurred by pinching off or necking down, slightly aft of the recirculation zone. Typical Schlieren photographs of flames at the 1/2 inch separation are shown in Figure 6.

With the 3/4 inch separation (6 inch walls) at velocities above 250 ft/sec., an extremely high intensity noise was heard near the rich blowoff limit; as the velocity increased, the mixture ratio limits covered by this noise increased until at velocities above 420 ft/sec. the noise extended over the entire range of mixture ratios from the rich to the lean blowoff limits. The maximum blowoff velocity was found to be 445 ft/sec.

The 1, 1.30, and 2 inch separations gave results similar to the 3/4 inch separation, cf Figure 4, however the noise covered an increasingly large portion of the blowoff curve. It was found that the maximum blowoff velocity for the 1 inch separation was lower than that at the 3/4 inch separation thereby deviating from the general trend of increasing blowoff velocity with separation. However, the high intensity noise previously mentioned covered a much greater range of fuel air ratios and velocities at the 1 inch separation than was the case for the 3/4 inch. It was therefore felt that, whatever the cause of the noise, it was instrumental in reducing the maximum blowoff velocity. That is, at this point, the detrimental effects of the noise overpowered the beneficial effects of increased separation. A more detailed discussion of the noise and some justification for this supposition is given in Section B.

The results plotted in Figure 4 show that the maximum blowoff velocity for two flameholders in a duct increased with increasing separation up to 2 inches. At the 2 inch separation the flameholders were spaced so as to effectively divide the duct into two ducts of 1 by 2 inches with the flameholders centered in each of these two smaller areas. This is again based on the concept that the center streamline can be replaced by a solid wall. With this symmetrical configuration, the reduction in the maximum blowoff velocities as compared to a single flameholder in the 1 by 4 inch duct may be primarily attributed to an increase in the blockage ratio. For comparison purposes results obtained with a single 1/4 inch diameter flameholder are included.

As the separation increased beyond 2 inches the flameholders were closer to the walls of the duct than to the centerline; therefore the 3, 3 1/4, and 3 1/2 inch separations corresponded to the 1, 3/4, and 1/2 inch separations respectively if effects such as heat conduction through the walls and interference between wakes are neglected. The upper portions of the blowoff curves for the 3 1/2, 3 1/4, and 2 1/2 inch separations are plotted with the 1/2, 3/4, and 1 1/2 inch separations in Figure 7 while Figure 8 is a plot of the 3 and 1 inch separations. To better visualize the results, the maximum blowoff velocity is plotted as a function of the separation in Figure 9. If there were no interference between the flame fronts or wakes of the two flameholders the maximum blowoff velocities should begin to decrease as the separation increases beyond 2 inches. Furthermore, for corresponding separations under the divided duct concept, such as 3 inch and 1 inch separations, blowoff velocities should be the same. It is apparent from Figure 9 that in addition to the "wall effects" some interaction between the flame fronts occurs causing a further reduction in maximum blowoff velocity. The maximum difference, as may be expected, is found with the flameholders at the minimum separation (1/4 inch from the centerline) as compared with the flameholders at 3 1/2 inch separation (1/4 inch from walls). The reduction in maximum blowoff velocity for corresponding separations is twice as great for flameholders approaching each other than when approaching the wall. This indicates that the effect on blowoff velocity of wake interaction alone is of the same order of magnitude as the "wall effect". The "wall effect" may be thought of as an effective blockage ratio, that is the condition arising when the effects caused by the decrease in flow area on one side of the flameholder are not relieved by the increase in the flow area on the opposite side. However, even under the most adverse conditions, that is when comparing the 3 1/2 and 1/2 inch separations, the difference in blowoff velocities is only 60 ft/sec. or approximately 15 per cent of the total blowoff velocity. Furthermore, the difference between comparable separations is considerably less as the configuration approaches the symmetrical situation at the 2 inch separation. It is interesting to note that the dip in the blowoff velocity at the 1 inch separation also occurred at the 3 inch position and that range of velocities and fuel air mixture ratios over which the noise occurred was similar for comparable separations. Thus when the separation reached 3 1/2 inches (1/4 inch from the walls) the noise disappeared completely as was the case when the flameholders were 1/4 inch from the centerline of the duct. Once the disturbance was well established, that is for separations between 1 and 3 inches, the maximum blowoff velocity increased nearly linearly up to the 2 inch spacing and decreased linearly from 2 to 3 inches, but at a different rate.

In addition to the investigation carried out with two flameholders, blowoff velocities were also determined for three and five flameholders at both 1/2 and 3/4 inch separations. For the 1/2 inch separation a well defined curve could not be established for either the three or five flameholders. For three holders the maximum velocity which could be obtained was approximately 139 ft/sec. while for five flameholders it was 124 ft/sec. At velocities above these values a flame could not be stabilized on all flameholders simultaneously. For these multiple configurations the blowoff occurred in such a manner as to give the maximum separation between adjacent flames, that is for the three flameholders the center would blowoff first; and for the five flameholders the center and two outermost would remain lit while the numbers "2" and "4" would blowoff. The flameholders are numbered consecutively from the top to the bottom of the duct to aid in identification. Schlieren photographs of five flameholders at the 1/2 inch separation are presented in Figure 10 with the bottom picture clearly showing the diminishing flame on number "2" and "4" flameholders just before lean blowoff occurs.

The same sequence of flameholder blowoff described for the 1/2 inch separation was noted for the 3/4 inch separation when testing three and five holders. The blowoff curves for two, three, and five flameholders at this separation are plotted in Figure 11 and show the drastic decrease in maximum blowoff velocity with an increasing number of flameholders. Typical Schlieren photographs of both three and five flameholders at the 3/4 inch separation are shown in Figure 12.

B. Combustion Instability.

A combustion instability characterized by a loud, high frequency noise occurred over well defined combinations of fuel air ratios and mixture approach velocities. Accompanying the noise was a fuzzy appearance of the burning wake and a drop in the settling chamber pressure. For two flameholders in the duct, especially at the 2 inch separation, the noise occurred over a large range of operating conditions. As the separation increased or decreased from 2 inches, the range of fuel air ratios and gas velocities at which the noise appeared decreased. At both the 1/2 and 3 1/2 inch separations and noise disappeared completely. The exact range of coverage for the 2, 1, and 3/4 inch separations using the 6 inch glass sidewalls are given in Figure 13, Figure 14, and Figure 15 respectively. The noise was also present for three and five flameholders at both the 1/2 and 3/4 inch separations under certain conditions of operation. For three flameholders at 1/2 inch separations, the noise occurred after the center flameholder blew off; while, for the 3/4 inch separation the noise disappeared when the center flameholder blew off. Similarly, for five flameholders at 1/2 inch separations the noise started when the number "2" and "4" flameholders blew off, however for the 3/4 inch separation the noise which was normally present would cease as the number "2" and "4" flameholders blew off. It is somewhat difficult to explain the reason behind this complex action since an adequate explanation for the variation of noise limits for two flameholders has not been developed.

Tests were made with 3 and 9 inch long sidewalls in addition to the normal test configuration of 6 inch walls to more clearly establish the relation between the disturbance and the duct length. Both frequency measurements and Schlieren photographs were obtained during conditions of noise and no noise.

Blowoff curves were determined with the 3 inch walls at flameholder separations previously used for the 6 inch walls and the results plotted in a manner similar to those in Figure 7 and Figure 8. The maximum blowoff velocities in each case were plotted versus separation in Figure 16. Comparison of Figure 16 for the 3 inch walls with Figure 9 for the 6 inch walls shows 1) an overall drop in maximum blowoff velocities and 2) an alleviation of the drop in the curve when going from the 3/4 to the 1 inch separation. The overall reduction in maximum blowoff velocities with a decrease in duct length is in agreement with the results previously reported by Haddock (Ref. 5) when testing the effects of this parameter on the stability limits. No noise or other indications of combustion instabilities were present while using the 3 inch walls. Study of Schlieren photographs taken with the 3 inch walls at various operating conditions showed little indication of disturbances which might have initiated the previously experienced unstable burning. However, the variation in the smooth curve of Figure 16 between the 3/4 and 1 inch separation indicates that some type of instability still becomes important at this particular separation.

Schlieren photographs taken at conditions of noise and no noise using 6 inch walls show conclusively the relationship between combustion instability and the noise produced. Figure 17 and Figure 18 are typical photographs taken under such conditions for the case of the 2 inch separation. Figure 13 shows the operating conditions for these photographs. In Figure 19 are given photographs of stable and unstable combustion for the 3 inch separation. All photographs taken, and in particular those of five flameholders, of Figure 20, show absolute symmetry in the longitudinal position of the bursts. This implies that the periodic disturbance causing the instability is longitudinal in nature.

The photographs show that the flame pinches down periodically. This pinching down occurs at a point near the end of the recirculation zone in a manner similar to that observed during normal blowoff. In addition to the photographic evidence, the drop in settling chamber pressure indicates that the flame is oscillating between a point near blowoff and steady burning. Other investigators have found combustion instabilities of this nature when testing single flameholders; among these are Nicholson (Ref. 2), Scurlock (Ref. 3), Blackshear (Ref. 7), and Dunlap (Ref. 8).

To further investigate the nature of the disturbance the sound was recorded on a Stancil Hoffman tape recorder using a crystal microphone pickup located 15 1/2 inches downstream and 9 inches below the duct exit. The recording was analyzed for frequency and amplitude by a Hewlett Packard Spectrum Analyser. Frequency measurements were made for both the 6 and 9 inch walls. A typical example of the frequency trace from the spectrum analyser is shown in Figure 21 for a 2 inch separation during conditions of noise and no noise using the 6 inch glass sidewalls on the combustion chamber. For the 6 inch duct, a pronounced peak is present at approximately 1000 cycles while lower amplitude noise is found in the 30-400 cycle range. In addition to the fundamental frequency of 1000 cycles, 2nd, 3rd, and in some cases the 4th harmonics were clearly visible. Since Figure 21 has been reduced from a size of 28 by 22 inches some of the finer details have been lost and the higher harmonics are not as apparent as on the original. Experiments were also carried out for the 1 inch separation and although the curves were nearly identical the relative amplitude of the major sound peak is somewhat more pronounced with the 2 inch separation. The amplitude and frequency of the peak depended slightly on the fuel air ratio and gas velocity. Two runs were made with the 6 inch walls with no combustion taking place to determine the noise made by the Kårmån vortex street. The vortex shedding produced a high frequency sound, approximately 2500 cycles per second, with an amplitude on the order of one-tenth that found during combustion instability. The frequency of 2500 cycles is in close agreement with that calculated by the well-known relation $f = \frac{VS}{d}$, where V is the approach speed of the gas, d is the diameter of the flameholder and S the Strouhal Number which for circular cylinders is approximately 0.192.

Test made with the 9 inch walls show in addition to the lower frequency noises two prominent peaks of higher frequency. One peak occurs at a frequency which would be expected if the length of the duct were the controlling parameter, that is on the order of 700 cycles, while another more prominent peak is found at approximately 1400 cycles. It is of interest to note that the frequencies between 1000 and 1500 cycles are those that are amplified the most even though in the case of the 9 inch duct this appears to be the 2nd harmonic rather than the fundamental.

It is reasonable to assume that the acoustic waves producing the noise during combustion instability are driven by the periodic bursts of flame shown in the photographs. Furthermore, the bursts of flame are caused by the pressure and velocity fluctuations of the acoustic waves, thereby resulting in a regenerative, closed cycle. If the point at which the pinching down occurs, that is the end of the recirculation zone, lies outside or near the end of the duct, the pressure, hence the velocity fluctuations are relieved, and reinforcement from duct resonance does not occur. When duct resonance does not occur the noise and combustion instability do not appear.

Since the end of the recirculation zone occurs near the end of the duct for the 3 inch walls the instability would not be expected to appear; results of the tests with 3 inch walls show that this is true.

A few measurements of velocity fluctuations were made during combustion instability. From these measurements the variation of velocity in the flame was estimated to be of the order of ± 20 ft/sec. Just how the velocity and pressure variations enter into the instability process is not known. There are several possibilities which may explain, partially at least, the observed results. For instance, it may be postulated that the end of the recirculation zone has a velocity which is essentially zero for stable combustion. The superposition of the negative phase of the velocity fluctuation on this zero velocity may shorten the length of the recirculation zone. This sudden shortening will cause vortices to be formed in the mixing zone at the aft end of the recirculation zone. If these vortices are sufficiently strong, unburnt material will be swept in towards the center of the wake, and hence the flame will be pinched off. The positive phase of the velocity fluctuation relieves this adverse condition and allows the flame to propagate. Thus the velocity fluctuations cause periodic bursts of flame to appear in the wake.

C. Investigation of Flame Geometry.

The importance of the recirculation zone in the flame stabilization process has long been recognized. Previous investigators have conducted extensive studies of the temperature, composition, pressure, and more recently the length of this zone. Zukoski (Ref. 6) has shown a direct correlation between blowoff velocities and the length of the recirculation zone. It is therefore of interest to determine, the effect of flameholder separation on flame geometry.

Lengths of the recirculation zone were obtained for various velocities and fuel-air ratios. These tests were conducted by observing the yellow sodium flame produced by injecting a small stream of salt water into the flame in the vicinity of the recirculation zone. The salt water was piped through a small metal tube mounted on a lathe compound. This arrangement allowed the tube to be moved both in an axial and transverse direction with the amount of movement indicated by a pointer and scale. The length of the recirculation zone was determined by finding the farthest point downstream at which the yellow sodium flame from which the salt water entered the low velocity eddy region. At distances farther from the flameholder than the end of the recirculation zone the yellow flame would appear only downstream of the injection point, while for distances closer to the flameholder than this end point, the sodium would be carried upstream. Although the scale on the lathe compound could be read to 0.01 inches the overall accuracy of the procedure was somewhat in doubt due to the visual evaluation required by the observer. However, the excellent reproduceability of measurements showed that the relative values of the lengths were accurate.

The lengths of the recirculation zones were determined for both a single flameholder and for two flameholders at 3/8, 1/2, 3/4, and 2 inch separations with the results plotted in Figure 22 and Figure 23. For Reynolds numbers low enough to produce essentially laminar mixing zones, the length of the recirculation zone increases rapidly with an increase in fuel-air ratio. However, for turbulent mixing zones, that is for velocities above approximately 200 ft/sec. for the 1/4 inch diameter cylinder, the length of the recirculation zone was less sensitive to variation in fuel air ratio but increases with increases in mixture velocity. Figure 24 shows the variation in recirculation zone length with mixture velocity at various separations for a stoichiometric mixture ratio. For all separations tested the recirculation zone length varied nearly linearly with the mixture velocity once this velocity was above that required to produce a turbulent flame. It can be seen from Figure 24, that the rate of variation of recirculation zone length with mixture velocity for the single flameholder, the 2 inch, and 3/4 inch separations was approximately 0.15 inches per 100 ft/sec. while for the 3/8 and 1/2 inch separation it was 0.30 inches per 100 ft/sec. of mixture velocity. Zukoski (Ref. 6) has shown that the lengths tend to become constant as the mixture approach velocity increases beyond the values shown in Figure 24.

J. R. Foster (Ref. 9) studying the effects of blockage ratio on flame geometry found a decrease in recirculation zone lengths as the per cent blockage, that is the ratio of flameholder area to duct area, was increased. The results of tests by Foster using a 1/4 inch diameter water cooled cylindrical flameholder in a 2 by 4 inch rectangular duct are plotted along with the results of this author in

Figure 25. Foster tested a 1/4 inch diameter cylinder with the flameholder across both the 2 inch dimension and across the 4 inch dimension of the duct giving a 1/16 and 1/8 blockage ratio respectively. These blockage ratios correspond to the single 1/4 inch diameter cylinder and two 1/4 inch diameter cylinders across the 1 inch dimension of the 1 by 4 inch duct. Figure 25 shows good correlation of recirculation zone lengths with blockage ratio and indicates that reduction in length with increasing the number of flameholders can be attributed primarily to blockage effects.

Additional variations in recirculation zone length may be caused by localized velocity variations and changes in blockage ratio. It is known from Figures 24, and Reference 9 that the length of the recirculation zone varies directly with mixture approach velocity and inversely with blockage ratio. Since the rapid rise in recirculation zone length for the single 1/4 inch cylinder can be associated with a Reynolds number known to be in the transition range from laminar to turbulent flow, it is postulated that similar rapid variations in the curves for each separation indicates a similar transition. Figure 24 shows a shift of this transition zone to lower mixture approach velocities as the separation decreases thereby suggesting a higher local velocity between the flameholders. It is therefore possible that as the flameholder separation was decreased from 2 inches, the velocity between the flameholders in the vicinity of the recirculation zone increased. Furthermore, the effective blockage ratio increased due to the proximity of the flameholders to each other. Effective blockage has previously been defined as the condition arising when the effects caused by the decrease in flow area on one side of the flameholder are not relieved by the increase in the flow area on the opposite side. If such was the case, the two conditions, conflicting in their effect on the length of the recirculation zone, would cause variations in the lengths from the values obtained at the 2 inch separation. Such variations are shown in figure 24.

To further investigate the effect of separation on flame geometry the width of the flame front downstream of the flameholder was measured and plotted for various separations in Figure 25; the results plotted are averages of several photographs of each separation. Figure 26 indicates that the total flame width varies slightly with flameholder separation, with the total width decreasing with decreasing separation. Since Foster (Ref. 9) has shown that flame width is virtually independent of mixture approach velocity and fuel air ratio, but varies inversely with blockage ratio, the results of Figure 26 tend to substantiate the concept of an "effective" blockage increase previously discussed.

D. Wake Interaction.

In order to determine the extent of wake interaction between two or more flameholders a large number of Schlieren photographs were studied. When the flameholders are closely spaced, as in Figure 5 and Figure 6, the wakes interlace along the visible wake length. However, each wake maintains its identity without large scale mixing or rolling up. The photographs shown in Figure 10 and especially Figure 27 further exemplify this interlacing without mixing. Figure 27 is a photograph of the flame stabilized on the center three flameholders of a five flameholder array. The Kårmån vortex streets behind the two outer flameholders produce large scale disturbances in the unburnt gas. This external disturbance caused the normally straight wakes on the center flameholders to distort, however, even under these extreme conditions the identity of the individual wakes was preserved.

The results previously presented in Figure 9 and Figure 16 show that the maximum blowoff velocity is reduced more drastically as the flameholders approach each other than when they approach the walls. Therefore, the interlacing or interference of the wakes must have some effect on the stability limits. However, as previously determined, this effect is relatively small except when the flameholder separation is less than approximately three diameters.

E. Combustion Efficiency.

In general, good combustion chamber design requires that the fuel be burned in the smallest possible space with minimum drag losses. In addition to this requirement the stability limits both in fuel air ratio and mixture velocity should not be restrictive. Therefore it is of interest to see what effect both number and spacing of flameholders has on combustion efficiency.

It can be shown from the continuity, momentum, and energy equations that the static pressure ratio across a constant area duct in which uniform combustion is taking place can be expressed as:

$$\frac{P_2}{P_3} = 1 - \gamma M_2^2 \left[\left(\rho_2/\rho_3 - 1 \right) + C_D/2 \right]$$

or approximately as:

$$\frac{P_3}{P_2} \approx 1 - \frac{2}{\rho_2 R T_{2_t}} \left[\frac{H}{C_p T_{2_t}} + C_D/2 \right] q \qquad (1)$$

Here the subscripts 2 and 3 refer to the combustion chamber entrance and exit respectively. H is the total enthalpy and C_D the flameholder drag coefficient. Since, for low M_2

$$\rho_2/\rho_3 \approx T_{3_t}/T_{2_t} \approx 1 + \frac{H}{C_p T_{2_t}}$$

and

$$q = \tfrac{1}{2} \rho_2 V_2^2$$

equation (1) may be reduced to:

$$\frac{P_2 - P_3}{q} = 2 \left[\frac{H}{C_p T_{2_t}} + C_D/2 \right] \qquad (2)$$

Although the above equations did not apply directly to the duct and flameholder configurations tested, the rise in the pressure upstream of the flameholders did provide a qualitative value for combustion efficiency, η_b, since η_b is related to the total enthalpy, H, through the relation H = $\eta_b$fh where f is the fuel weight, and h is the fuel heating value. In the apparatus used for these experiments the duct was vented to the atmosphere therefore P_3 was a constant and equal to the atmospheric pressure. Since the total head in the settling chamber, P_t, was conveniently measured, equation (2) was rewritten in the form

$$\frac{P_t}{q} = 1 + \frac{P_2 - P_3}{q} = 1 + 2\left[\left(\frac{fh}{C_p T_{2_t}}\right)\eta_b + C_D/2\right] \qquad (3)$$

with the aid of the identity: $P_t \equiv P_{2_t} - P_3$

Drag due to the flameholders with combustion is not exactly known, however it is known that the drag of a flameholder with a stabilized flame is less than that of the same body with no flame due to the change in the nature of the flow field behind the bluff body. The normal Kármán vortex street, characteristic of adiabatic flow behind a bluff body, is not present when a flame is stabilized. The drag coefficient drops from the adiabatic value, of the order of 1.2 to a value of approximately 0.75 when the flame is attached. It is therefore concluded, that whatever the drag may be during combustion, it is never more than that which is measured for the flameholder without combustion; hence, the total rise in settling chamber total pressure minus the rise due to cold flameholder drag is a conservative value for the measurement of relative combustion efficiency.

The value P_t/q was determined for one, two, three, and five flameholders at both the 1/2 and 3/4 inch separations as a function of fuel air ratio. The results of these tests are plotted in Figure 28 and show 1) a definite increase in combustion efficiency as the number of flameholders increases and 2) little change in combustion efficiency as the separation is varied. Figure 29 presents a plot of an average value of P_t/q for a stoichiometric mixture as a function of the number of flameholders. In this figure an indication of cold drag, P_t/q with no combustion, is also plotted, showing the relatively small effect of flameholder drag as compared to the overall rise of P_t/q due to the increased amount of fuel burned in the duct.

Reference to Figure 11 and Figure 29 shows that although the combustion is improved by increasing the number of flameholders from one to five the blowoff velocity is radically reduced, therefore for any particular application there is an optimum configuration determined by the relative importance of these two factors.

CONCLUSION

A general investigation of the interference effects between multiple bluff body flameholders has been carried out.

In general the maximum blowoff velocity is reduced by the addition of more than one flameholder; this is primarily due to the increased blockage ratio. For the configurations tested an additional reduction in the blowoff velocities, or stability limits, occurs as the separation is varied from the symmetrical arrangement. This additional reduction is due to "wall effect" or "effective blockage" as the flameholders approach each other or the walls of the duct, and also to the interference between the wakes of adjacent flames.

Combustion instability will occur over certain ranges of fuel air ratios and mixture approach velocities. The greatest range of instability occurs for symmetrically spaced flameholders; the instability can be alleviated or eliminated by moving the flameholders from this configuration while maintaining the actual blockage ratio constant. As a result of this combustion instability, the practical blowoff limits are greatly reduced from actual or absolute case where the flame is completely extinguished. The cause of the instability appears to be a longitudinal flame driven oscillation with the frequency controlled by the duct length. However, the frequency which is most amplified is not necessarily the duct fundamental frequency.

Variations in recirculation zone length and flame width are determined primarily by the blockage ratio.

There is no strong interaction between the wakes such as large scale mixing or rolling up. Each wake retains its identity even though considerable distortion may be induced by the unburned free stream.

Combustion efficiency increases and maximum blowoff velocity decreases with the number of flameholders. Furthermore combustion efficiency appears to be little affected by the separation between flameholders or the velocity of the approach mixture providing the range of unstable combustion is avoided.

REFERENCES

1. Longwell, J. P., Chenevey, J. E., Clark, W. W., and Frost, E. E., "Flame Stabilization on Baffles in a High Velocity Gas Stream, Part I", Third Symposium on Combustion, Flame and Explosion Phenomena, Baltimore: Williams and Wilkins Company (1949) pp 40-44.

2. Nicholson, H. M., and Fields, J. P., "Some Experimental Techniques to Investigate the Mechanism of Flame Stabilization in the Wake of Bluff Bodies, Part I", Third Symposium on Combustion, Flame and Explosion Phenomena. Baltimore: Williams and Wilkins Company (1949), pp. 44-68.

3. Scurlock, A. C., "Flame Stabilization and Propagation in High Velocity Gas Streams", Meteor Report No. 19, Cambridge: Massachusetts Institute of Technology, May (1948).

4. Williams, G. C., and Shipman, C. W., "Some Properties of Rod-Stabilized Flames of Homogeneous Gas Mixtures", Fourth Symposium (International) on Combustion. Baltimore: Williams and Wilkins Company, (1953), p. 736.

5. Haddock, G. W., "Flame-Blowoff Studies of Cylindrical Flame Holders in Channeled Flow", Progress Report No. 3-24. Pasadena: Jet Propulsion Laboratory, May 14, 1951.

6. Zukoski, E. E., "Flame Stabilization on Bluff Bodies at Low and Intermediate Reynolds Numbers", Report No. 20-75. Pasadena: Jet Propulsion Laboratory, June 30, 1954.

7. Blackshear, P. L., Jr., "Driving Standing Waves by Heat Addition", Technical Note 2772, Washington: National Advisory Committee for Aeronautics, August (1952).

8. Dunlap, R. A., "Resonance of a Flame in a Parallel-walled Combustion Chamber", Aeronautical Research Center, University of Michigan, Ann Arbor: March (1950).

9. Foster, J. R., "Effects of Combustion Chamber Blockage on Bluff Body Flame Stabilization", Ae. E. Thesis. California Institute of Technology, Pasadena, June (1956).

TABLE I

FUEL SPECIFICATIONS

Gravity (°API at 60°F)	61.4
Gravity, specific (60/60°F)	0.7335
Reid vapor pressure (lb)	4.0
Heat of combustion (Btu/lb)	
Gross	20,130
Net	18,793
ASTM distillation	
Initial (°F)	160
Maximum (°F)	220
Acid solubility (°/o)	7.0
Bromine number	0.003
Percentage of carbon	85.69
Percentage of hydrogen	14.23
Proximate analysis:	
Cyclopentane	1
Isohexane	14
n-Hexane	15
Methylcyclopentane	10
Cyclohexane	17
Benzene	2

TABLE I (cont'd)

FUEL SPECIFICATIONS

Isoheptane	14
n-Heptane	12
Methylcyclohexane	8
Toluene	3
C_8 paraffins	3
Ethylbenzene	1
Xylenes	1

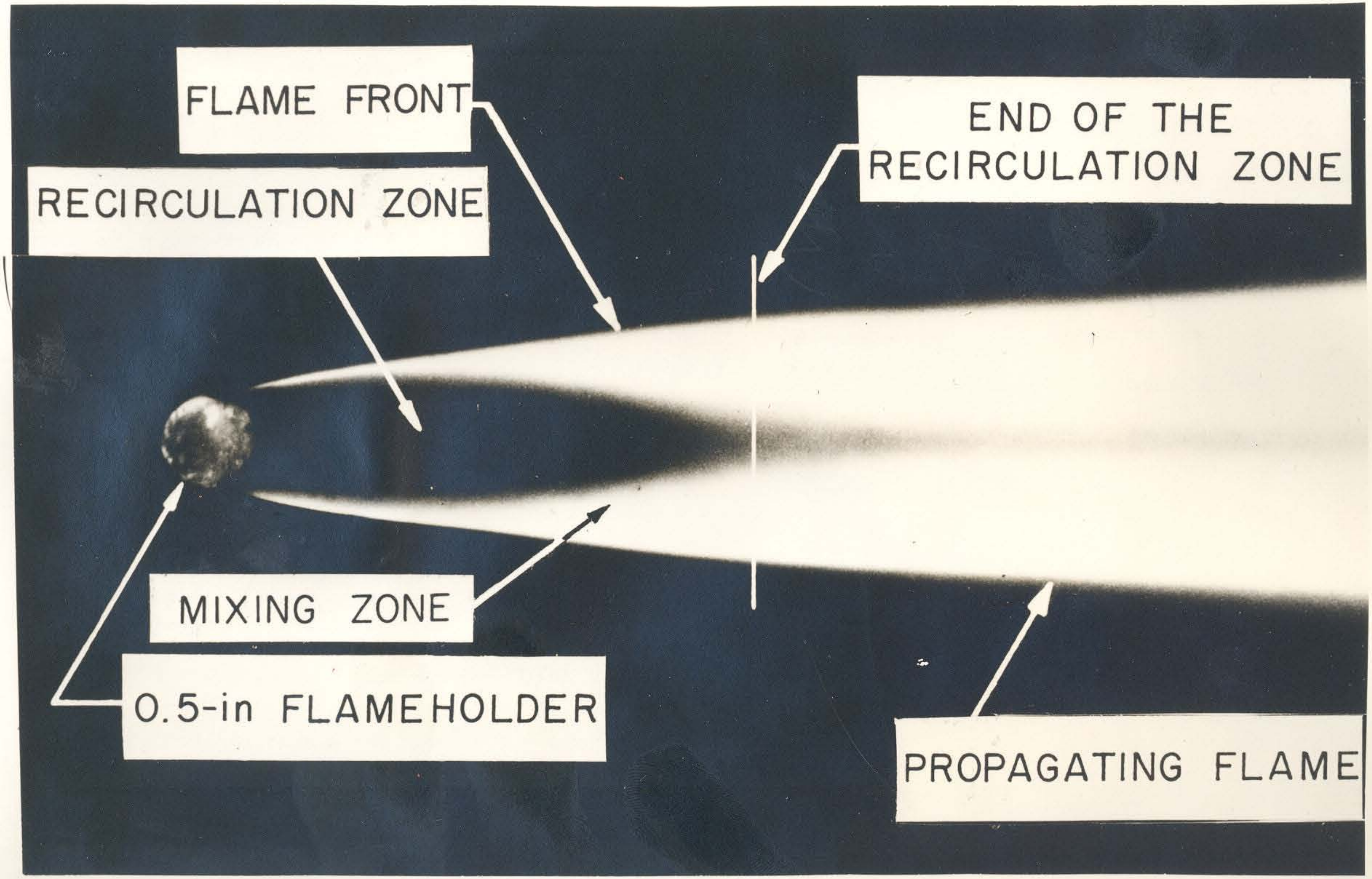


Fig. 1 - Time Exposure Photograph Showing Significant Flame Zones

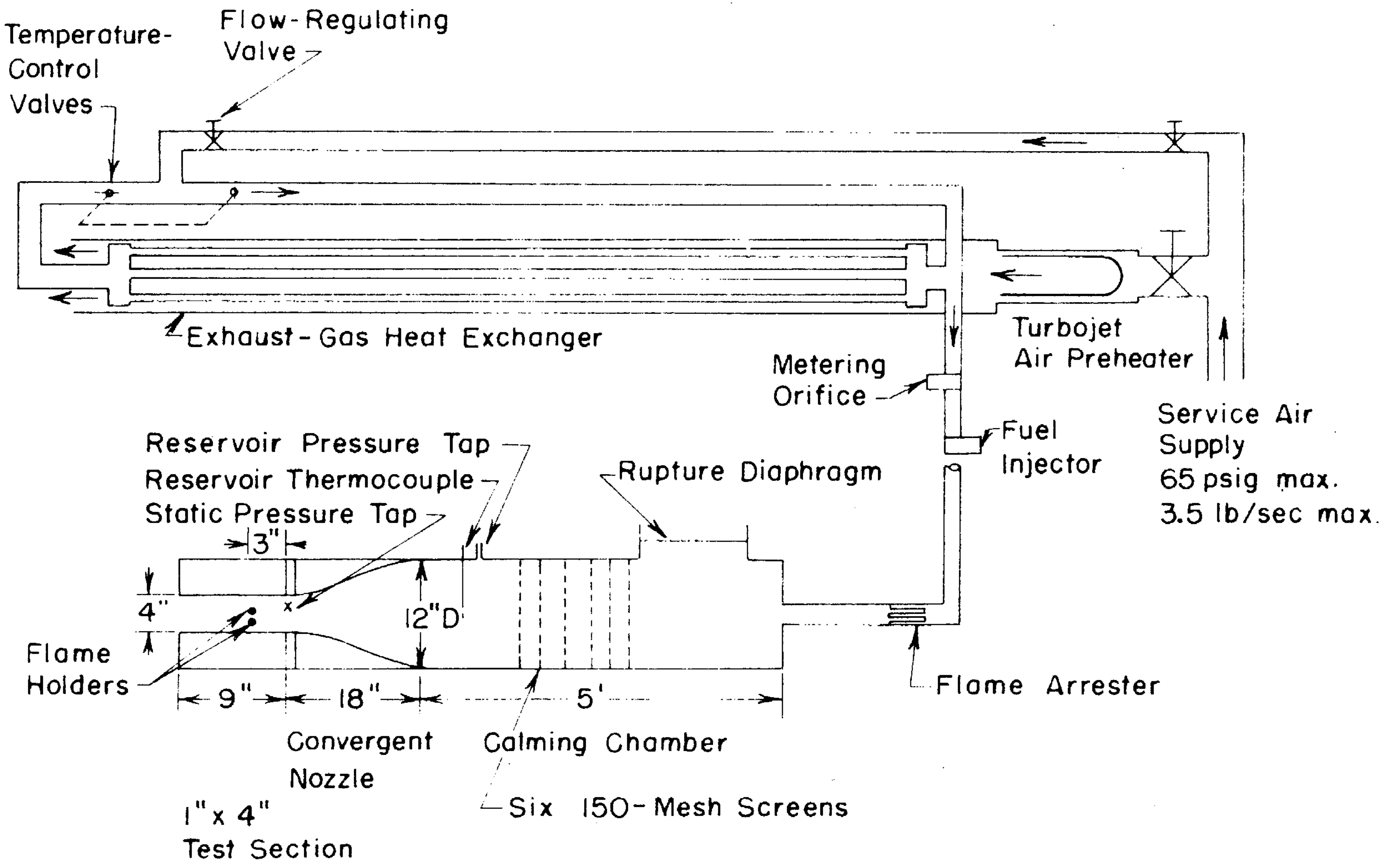
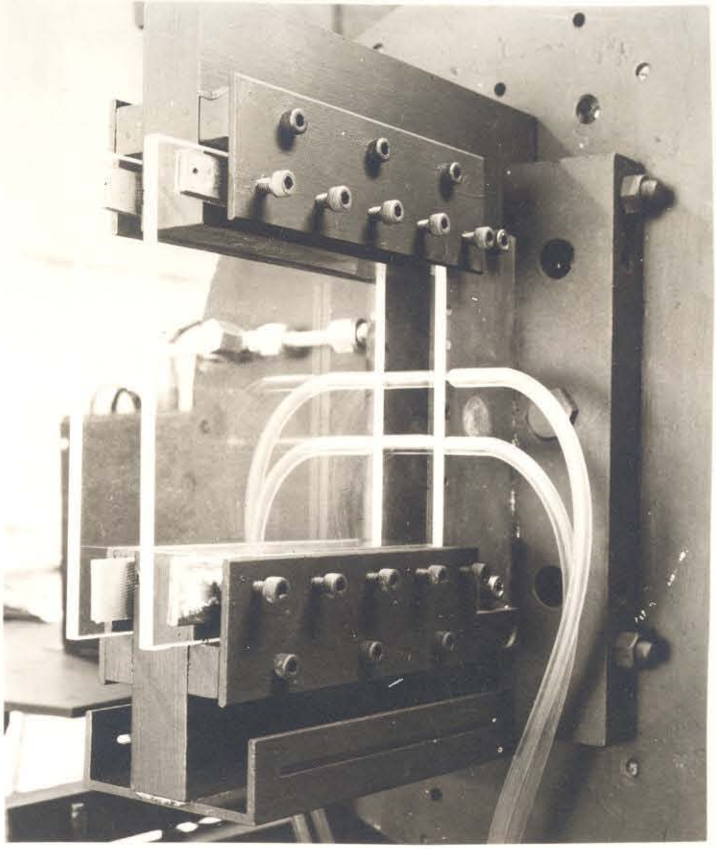
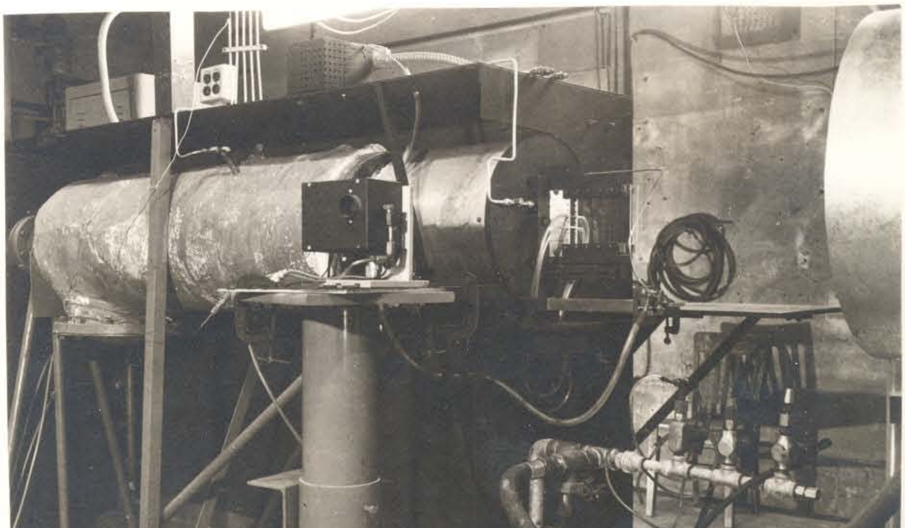


FIG. 2 - SCHEMATIC DIAGRAM OF APPARATUS



Three-Quarter View of Combustion Chamber



General View of Settling Chamber and Combustion Chamber

Figure 3 — Photographs of Experimental Apparatus

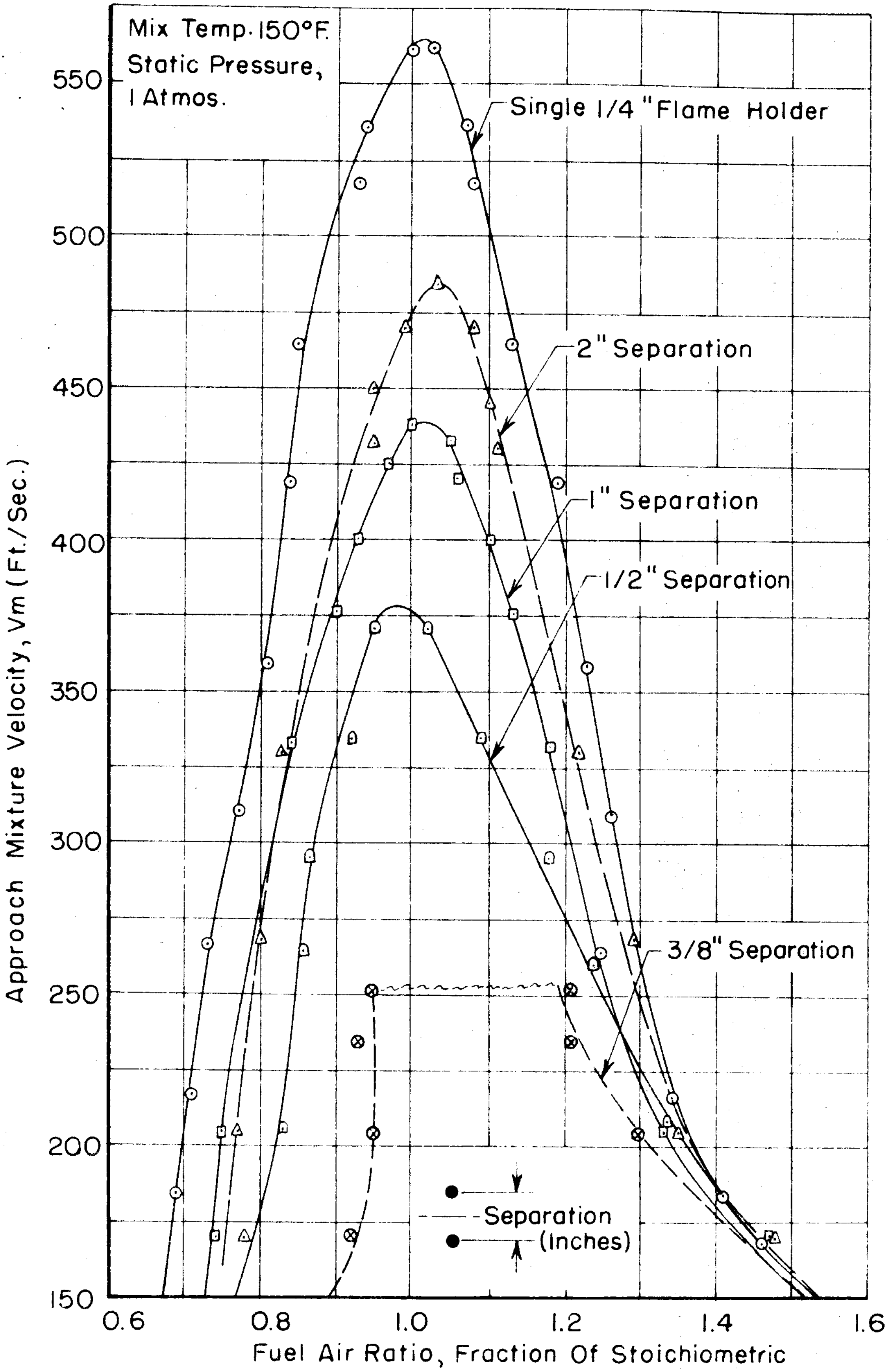


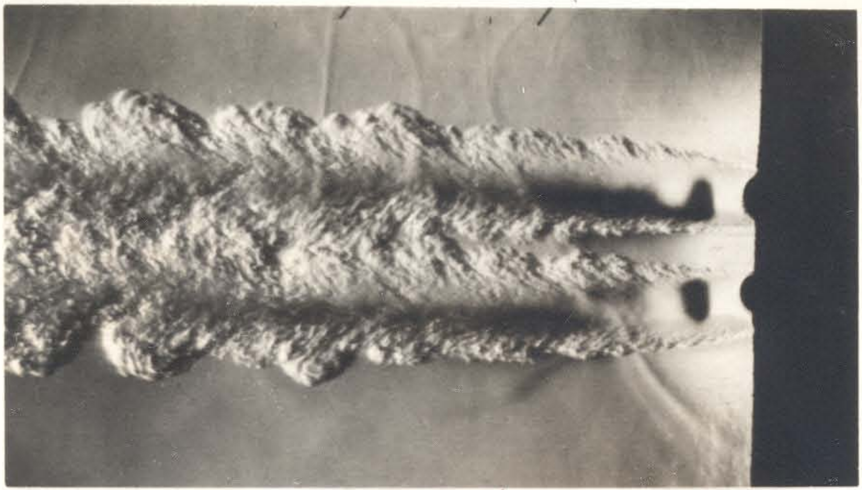
FIG. 4 – BLOWOFF LIMITS FOR TWO 1/4" DIA. CYLINDERS AT VARIOUS SEPARATIONS

Mixture Velocity 220 ft/sec, 0 = 1.01

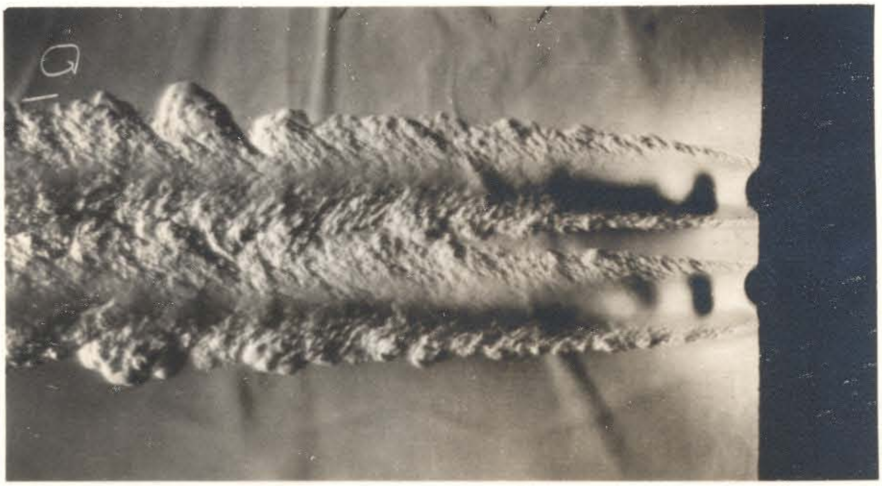
Mixture Velocity 220 ft/sec, 0 = 1.19

Mixture Velocity 220 ft/sec, 0 = 1.26

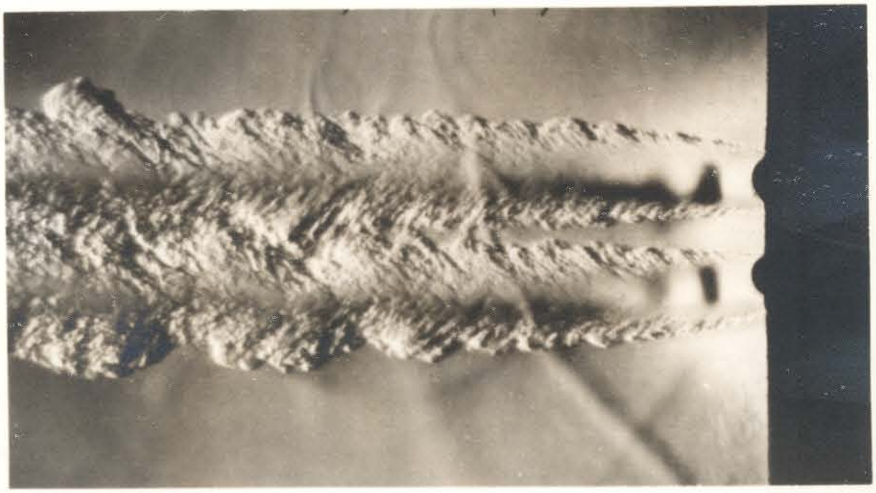
Figure 5 – Schlieren Photographs Showing Flame Blowoff Sequence on Two 1/4 inch Diameter Cylindrical Flameholders with 3/8 inch Separation.



Mixture Velocity 370 ft/sec, 0 = 1.00



Mixture Velocity 337 ft/sec, 0 = 0.98



Mixture Velocity 295 ft/sec, 0 = 1.01

Figure 6 – Schlieren Photographs Showing Flame Stabilized on Two 1/4 inch Diameter Cylindrical Flameholders With 1/2 inch Separation.

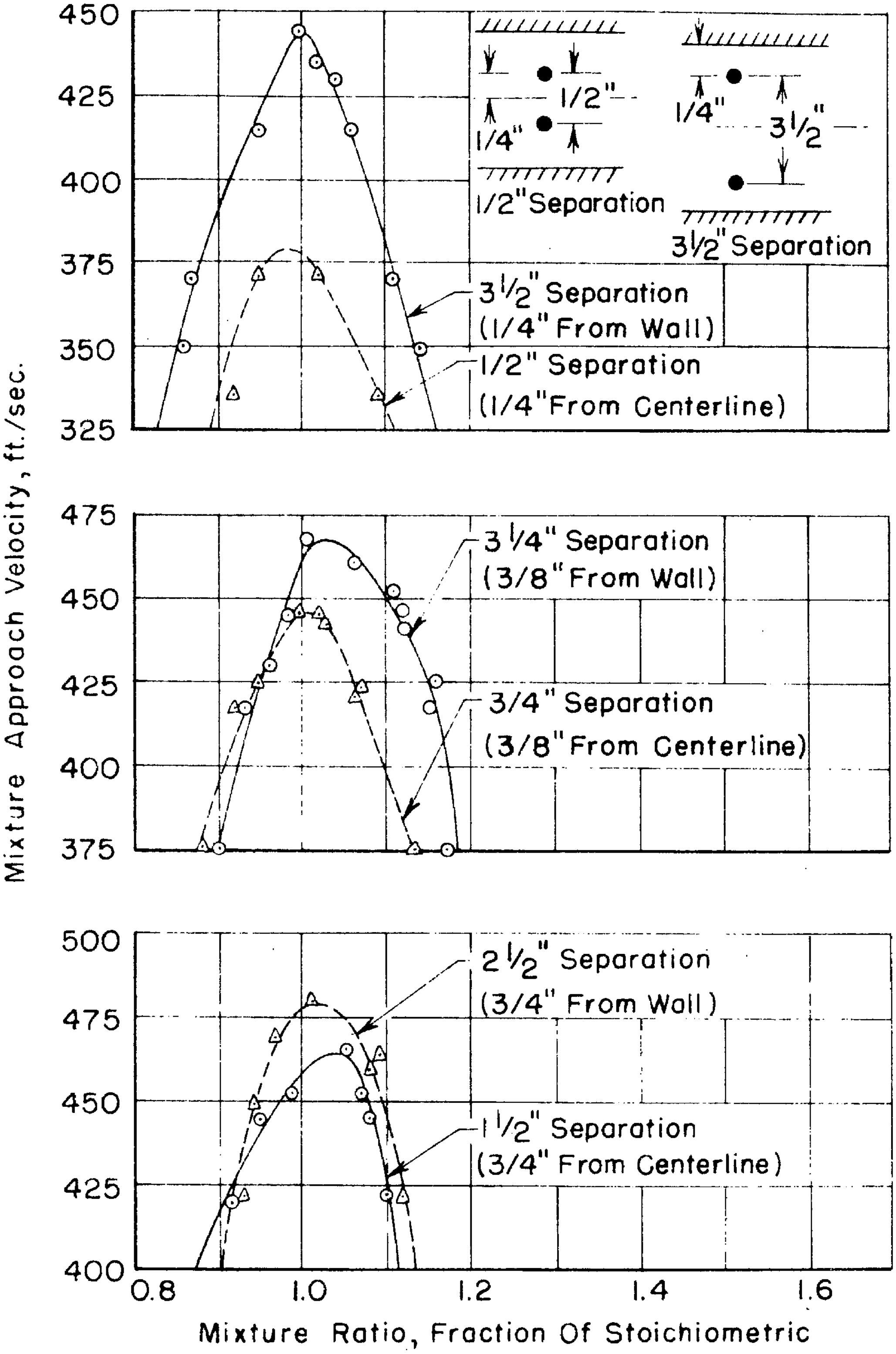


FIG. 7 - BLOWOFF LIMITS FOR TWO 1/4" DIA. CYLINDERS

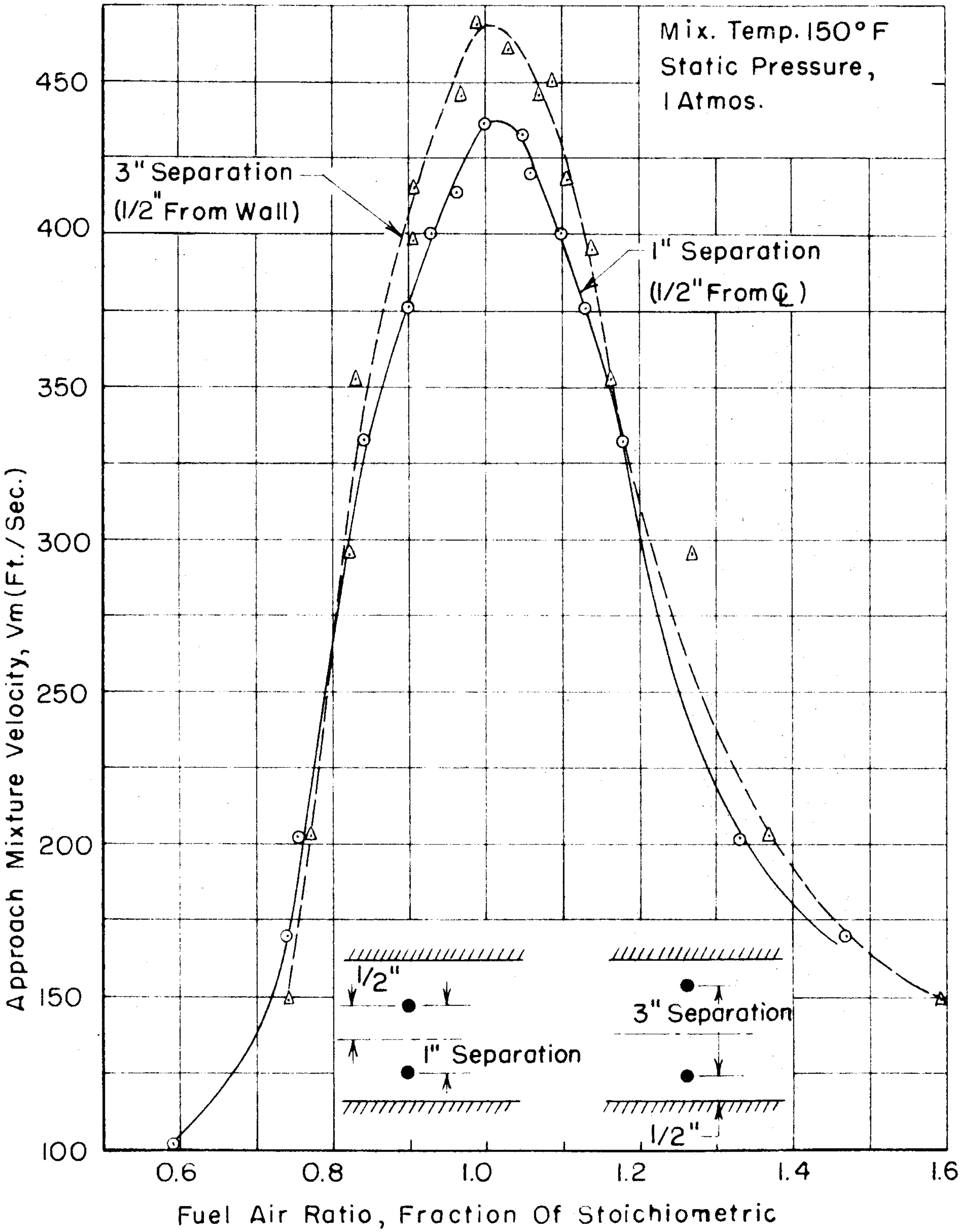


FIG. 8 - BLOWOFF LIMITS FOR TWO 1/4" DIA. CYLINDERS

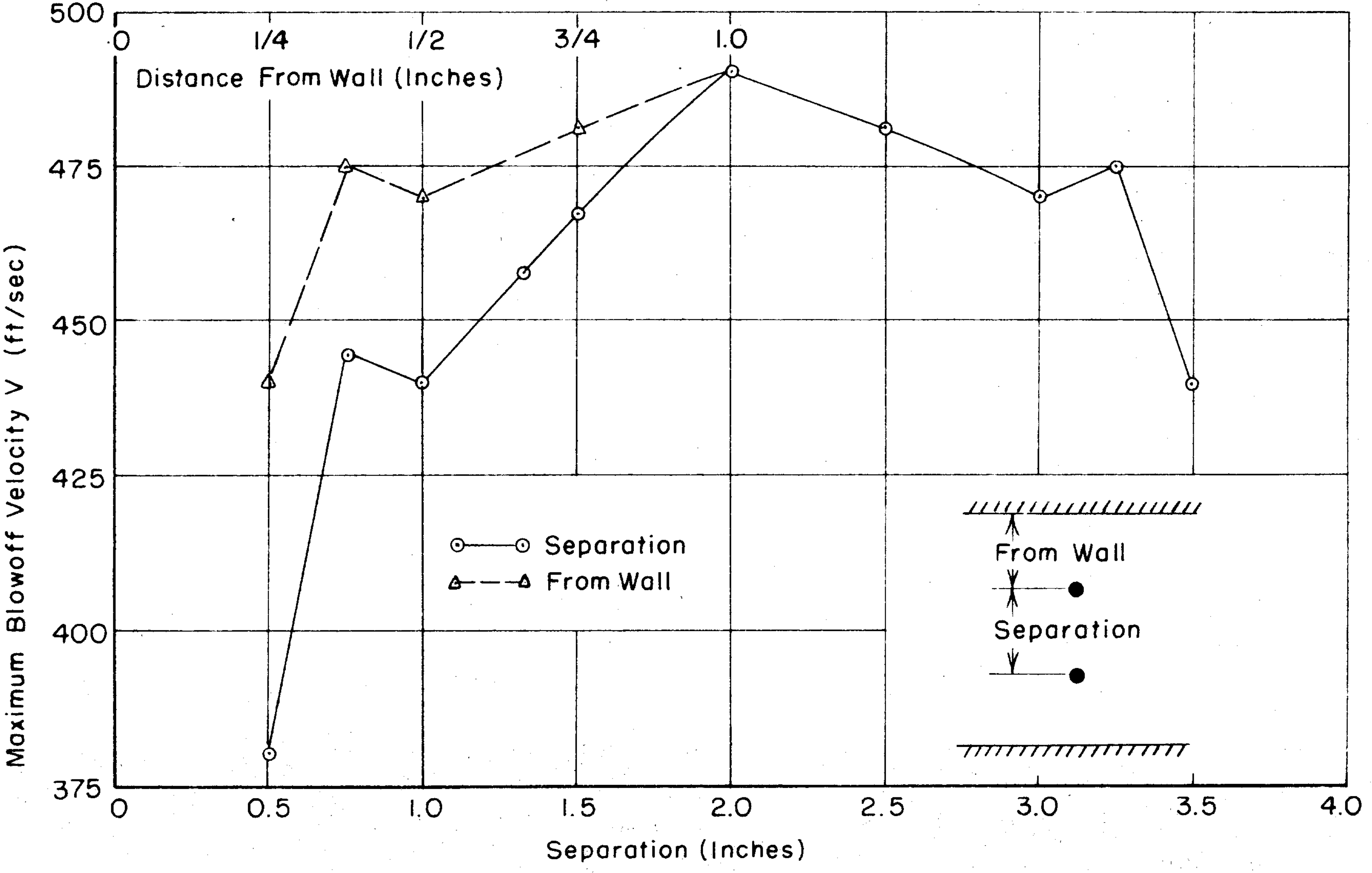


FIG. 9 - MAXIMUM BLOWOFF VELOCITIES FOR TWO 1/4" DIA. CYLINDERS AT VARIOUS SEPARATIONS

Mixture Velocity 80 ft/sec, 0 = 1.61

Approaching rich blowoff

Mixture Velocity 80 ft/sec, 0 = 0.88

At lean blowoff

Figure 10 - Schlieren Photographs Showing Flame Stabilized on Five 1/4 inch Diameter Cylindrical Flameholders with 1/2 inch Separations.

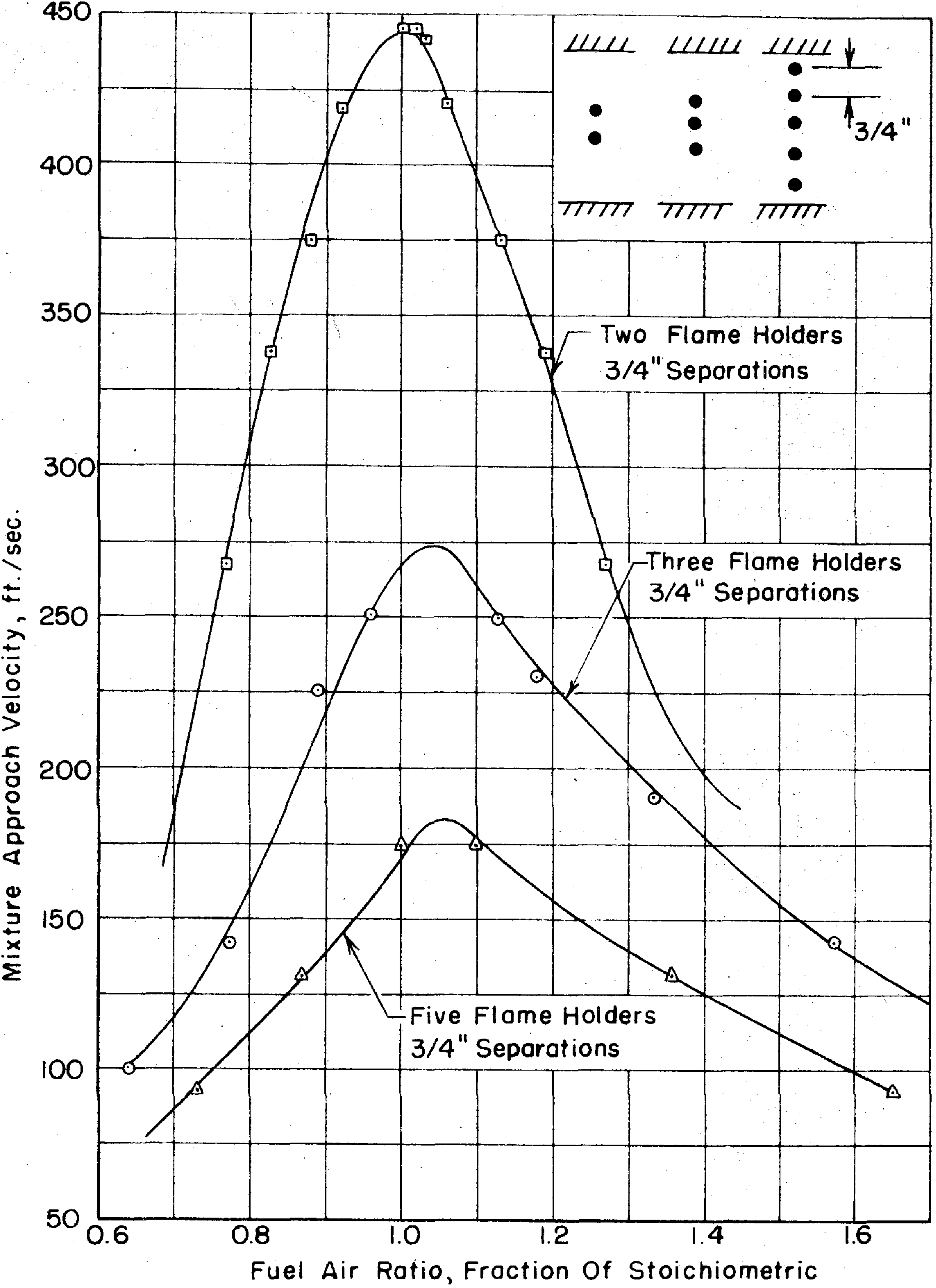


FIG. 11 - BLOWOFF LIMITS FOR MULTIPLE 1/4" DIA. CYLINDERS AT 3/4" SEPARATIONS

Mixture Velocity 138 ft/sec, 0 = 1.50

Mixture Velocity 173 ft/sec, 0 = 1.07

Figure 12 – Schlieren Photographs Showing Flame Stabilized on Three and Five 1/4 inch Diameter Cylindrical Flameholders with 3/4 inch Separations.

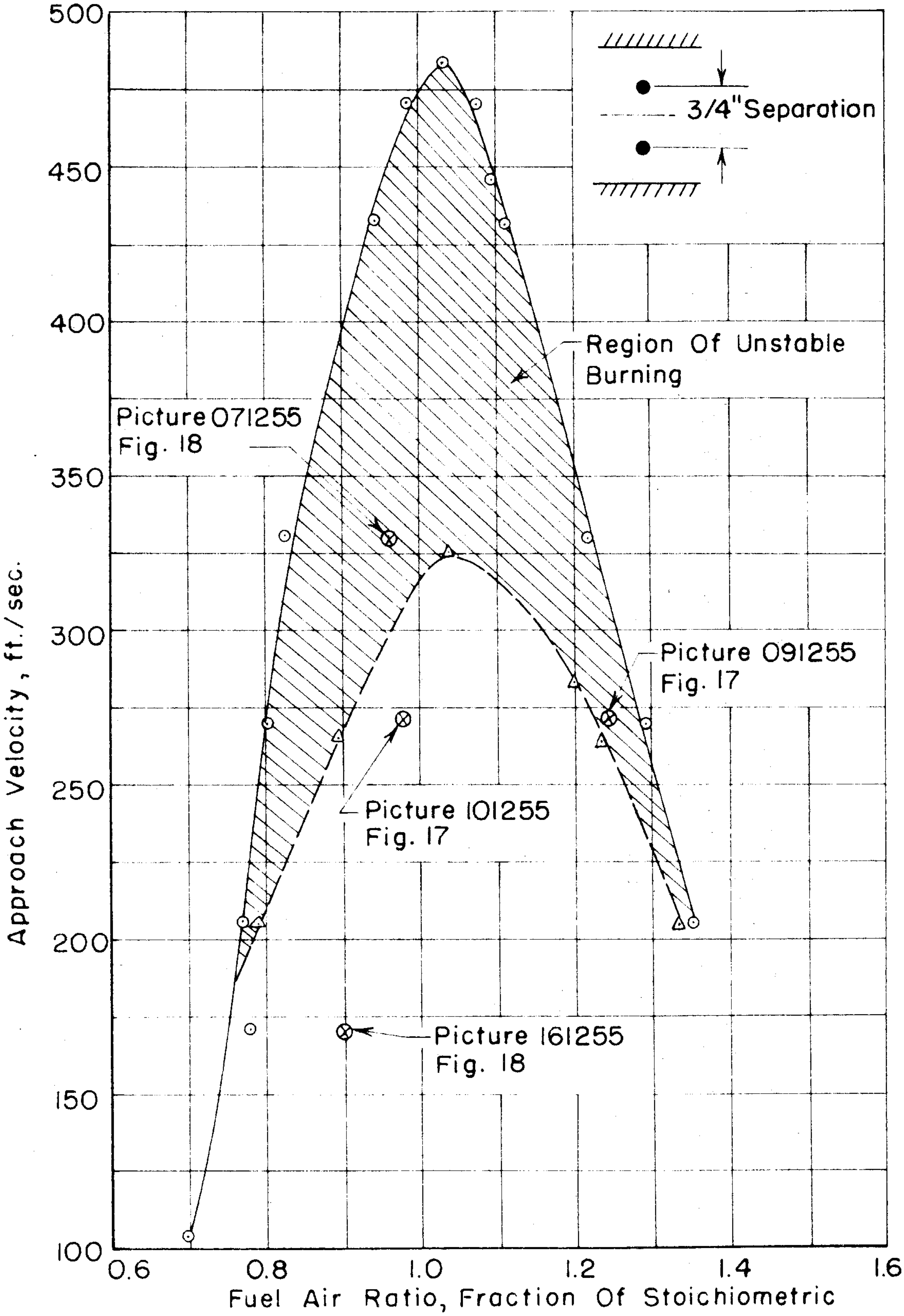


FIG. 13 - BLOWOFF LIMITS FOR TWO 1/4" DIA. CYLINDERS WITH 2" SEPARATION, SHOWING REGION OF UNSTABLE BURNING

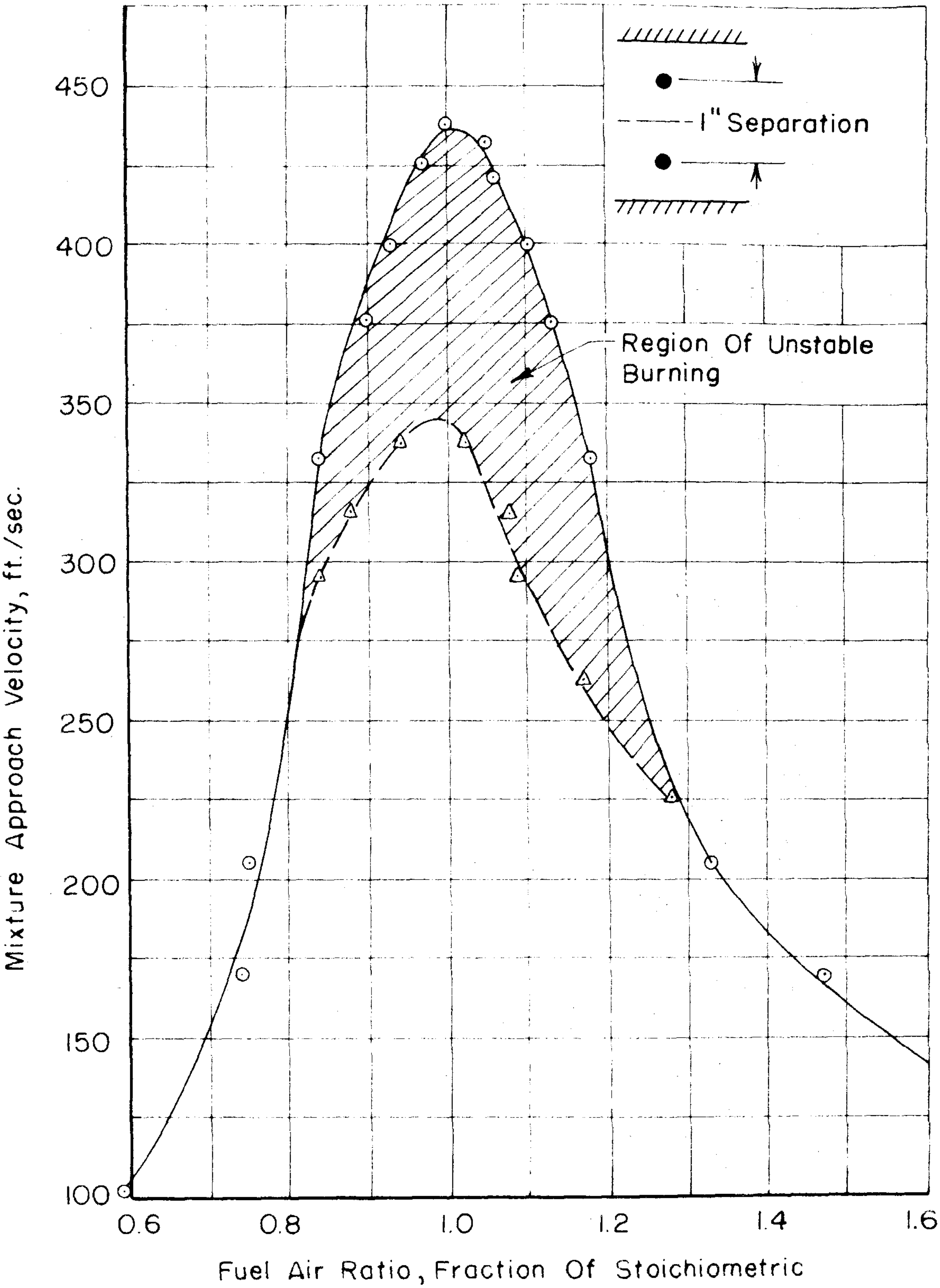


FIG. 14 - BLOWOFF LIMITS FOR TWO 1/4" DIA. CYLINDERS WITH 1" SEPARATION SHOWING REGION OF UNSTABLE BURNING

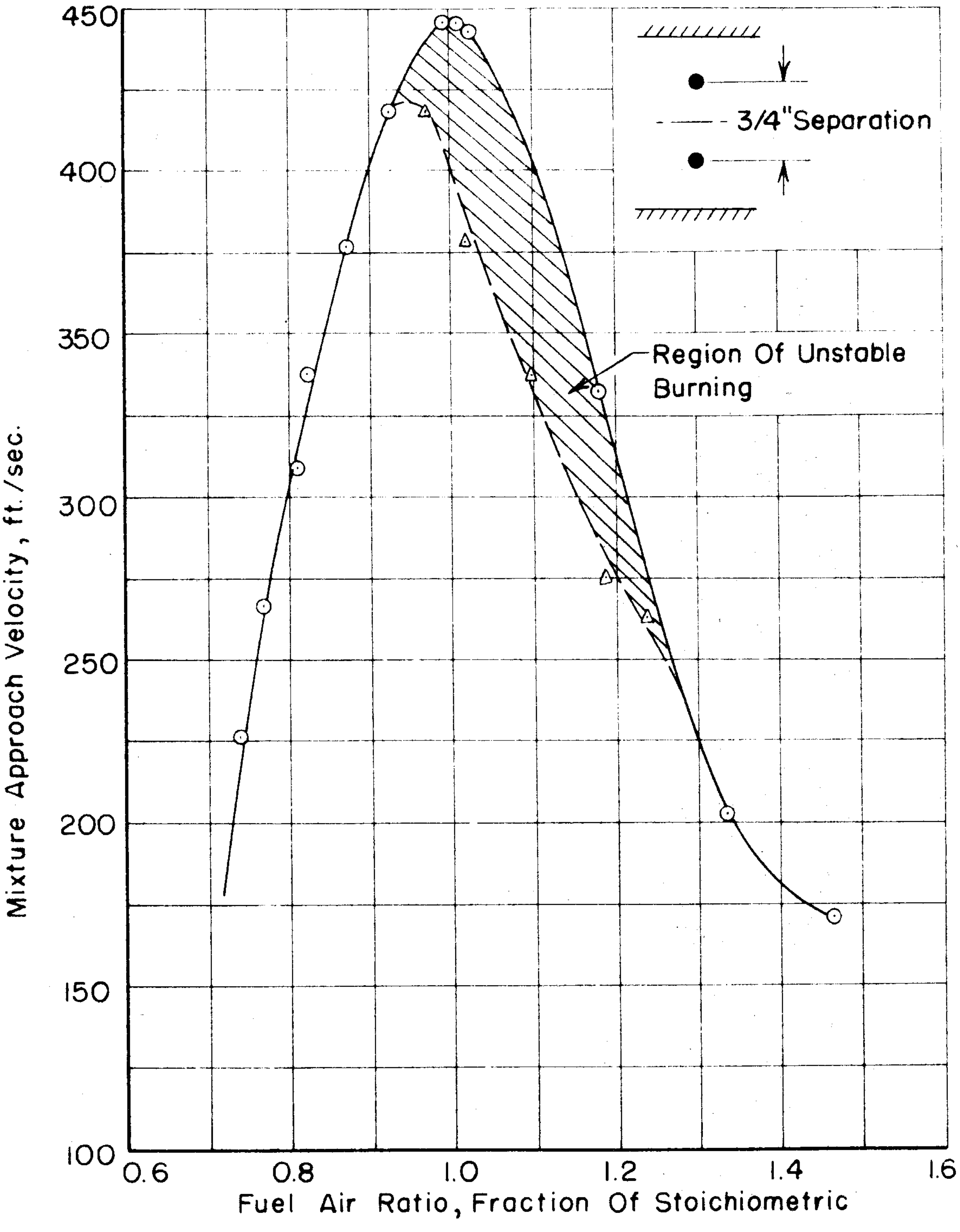


FIG. 15 – BLOWOFF LIMITS FOR TWO 1/4" DIA. CYLINDERS WITH 3/4" SEPARATION, SHOWING REGION OF UNSTABLE BURNING

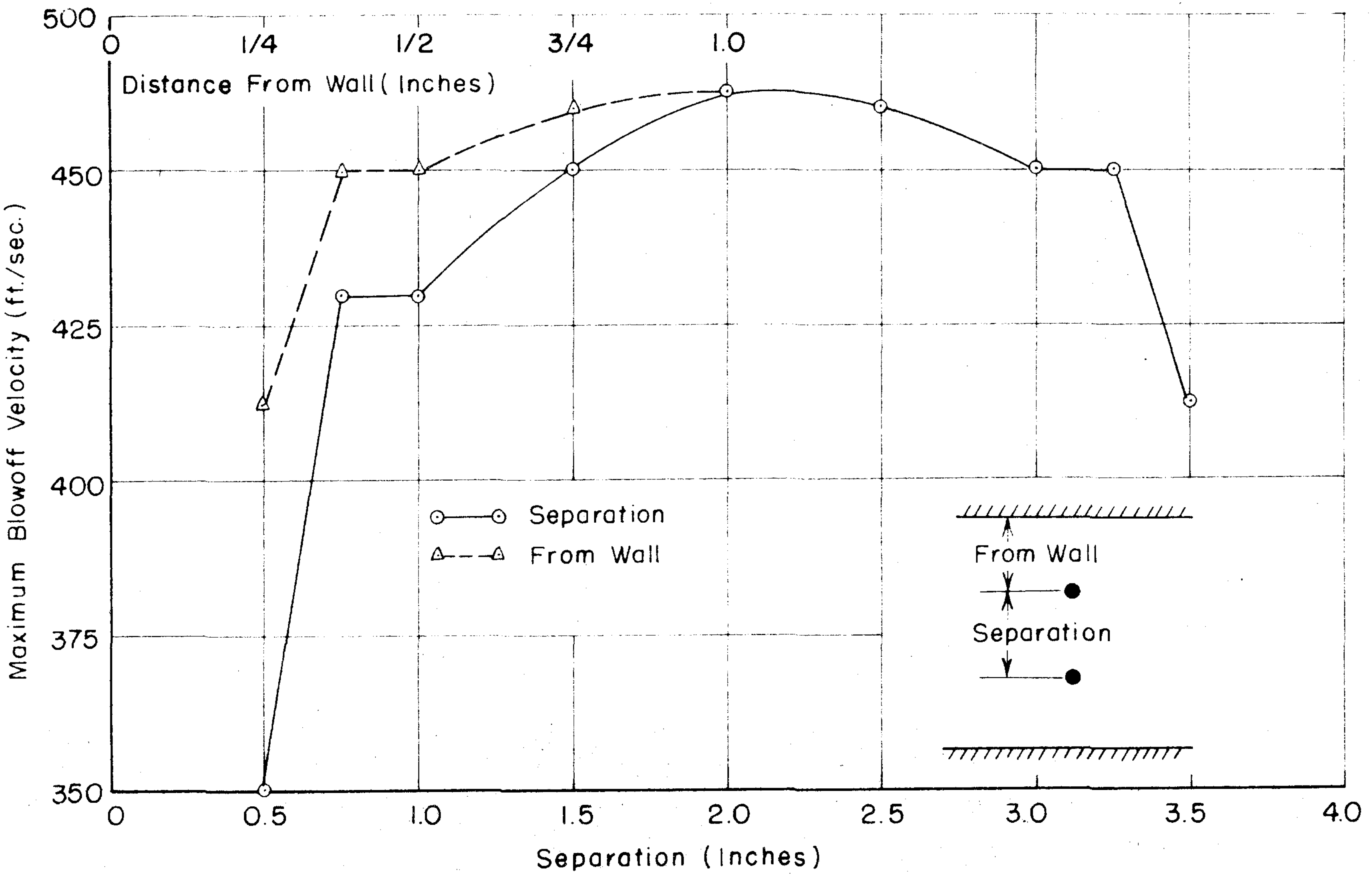
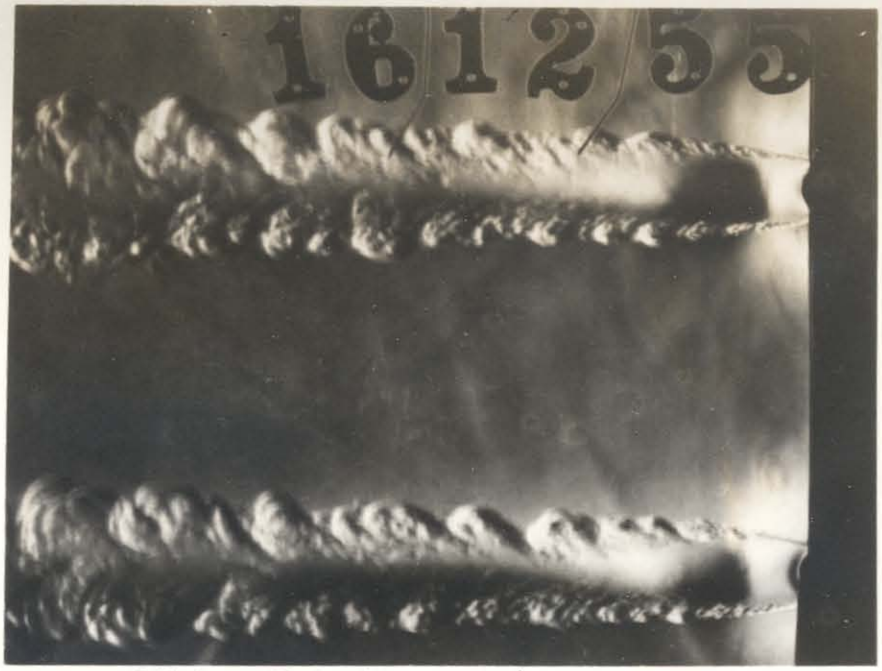


FIG. 16-MAXIMUM BLOWOFF VELOCITIES FOR TWO 1/4" DIA. CYLINDERS AT VARIOUS SEPARATIONS, USING SHORT (3") SIDES ON COMBUSTION CHAMBER

Mixture Velocity 270 ft/sec. 0 = 0.98
No Noise

Mixture Velocity 270 ft/sec. 0 = 1.24
with Noise

Figure 17 – Schlieren Photographs Showing Relationship Between Noise and Combustion Instability for Two 1/4 inch Diameter Cylinders with 2 inch Separation.

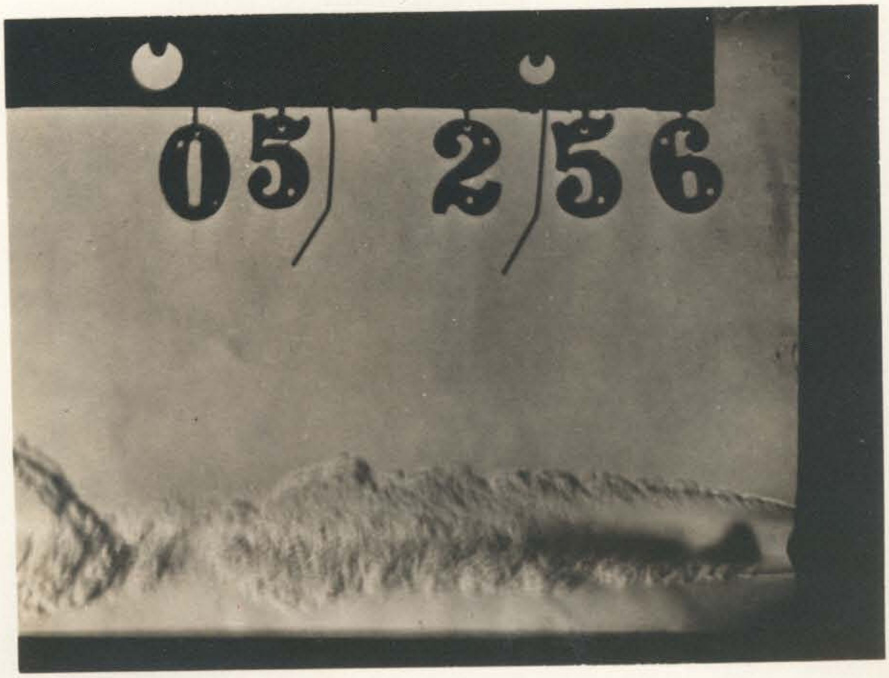


Mixture Velocity 170 ft/sec. 0 = 0.90
No Noise

Mixture Velocity 330 ft/sec. 0 = 0.96
With Noise

Figure 18 — Schlieren Photographs Showing Relationship Between Noise and Combustion Instability for Two 1/4 inch Diameter Cylinders with 2 inch Separation.

Mixture Velocity 297 ft/sec. 0 = 0.86
No Noise



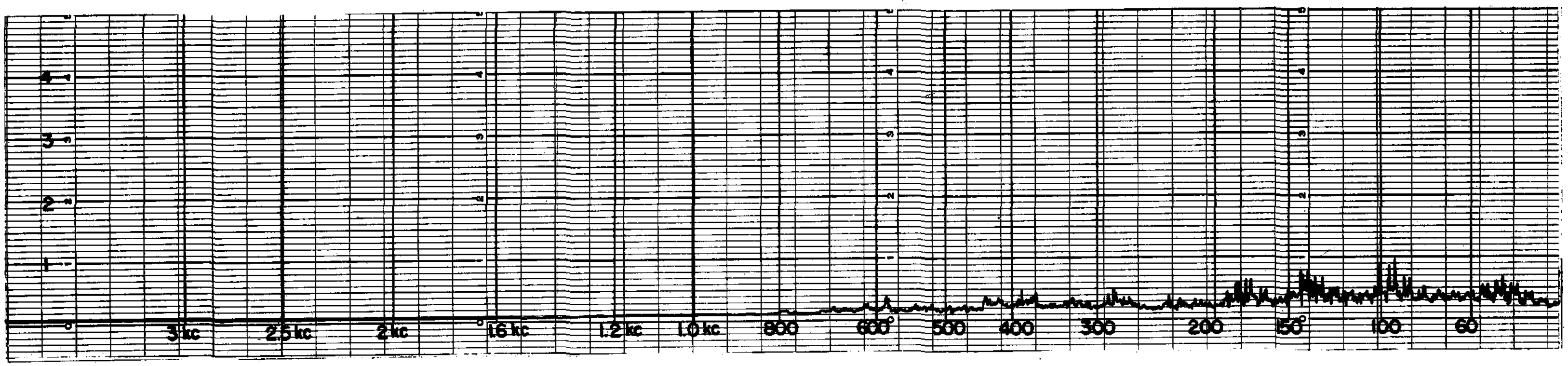
Mixture Velocity 297 ft/sec. 0 = 1.21
With Noise

Figure 19 – Schlieren Photographs Showing Relationship Between Noise and Combustion Instability for Two 1/4 inch Diameter Cylinders with 3 inch Separation.

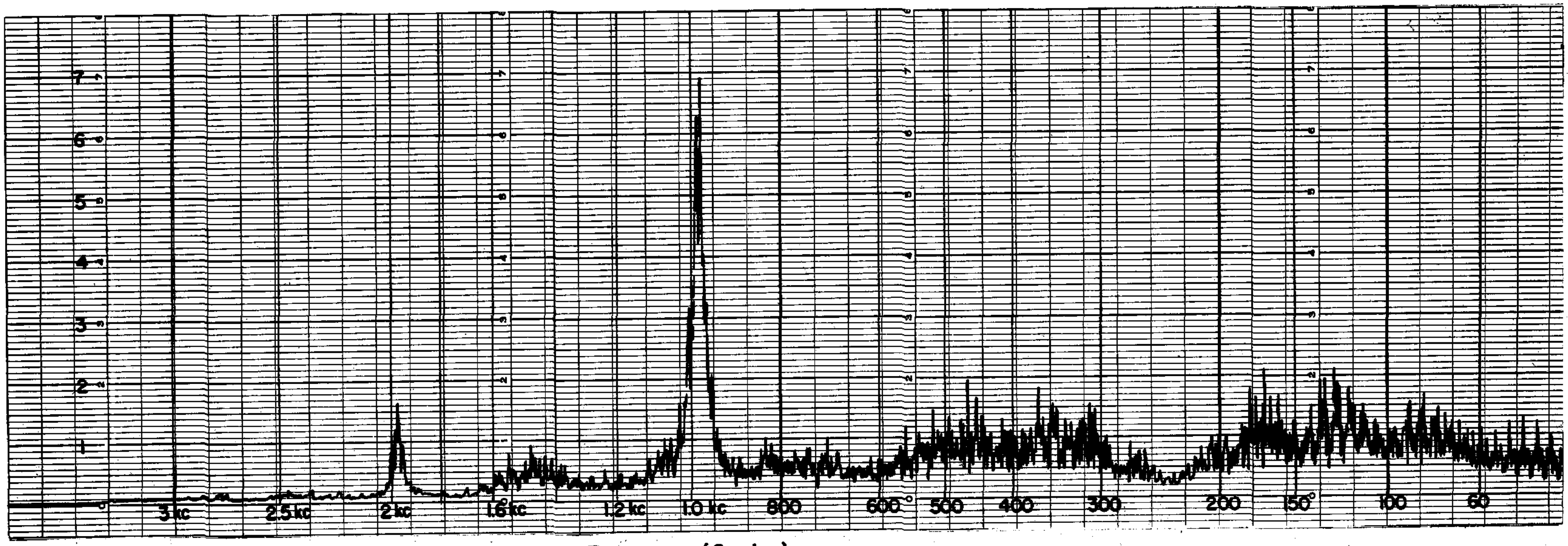
Mixture Velocity 86 ft/sec. $\phi = 1.64$

Mixture Velocity 86 ft/sec. $\phi = 1.64$

Figure **20** - Schlieren Photographs of Flame Stabilized on 5 Flameholders at 1/2 inch Separation Showing Longitudinal Symmetery of Bursts.



No Noise, Mixture Approach Velocity 245 Ft./Sec., $\phi = 1.14$



With Noise, Mixture Approach Velocity 325 Ft./Sec., $\phi = 1.02$

FIG. 21 - FREQUENCY ANALYSIS FOR TWO 1/4" DIAM. CYLINDERS WITH 2" SEPARATION

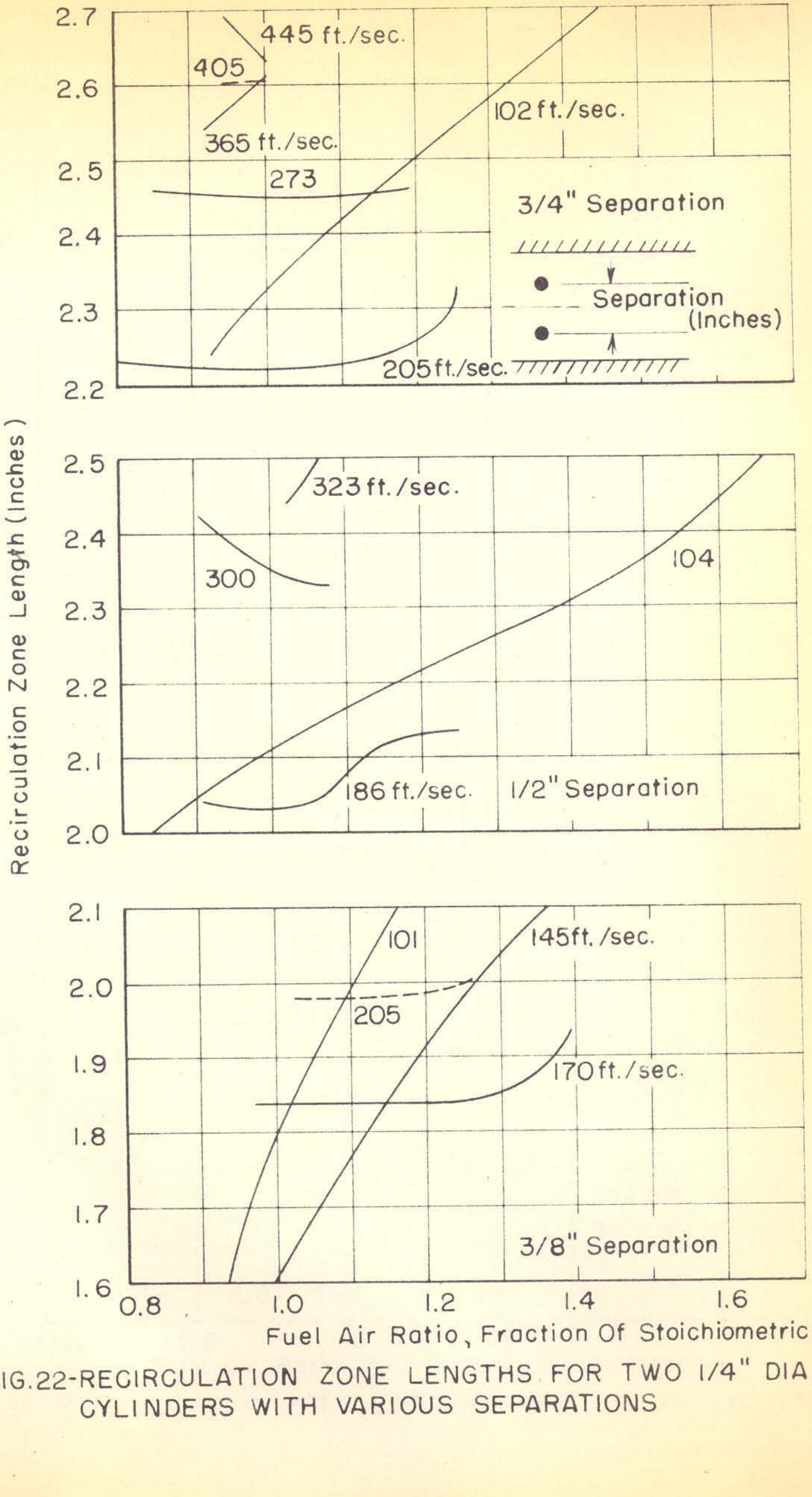


FIG.22-RECIRCULATION ZONE LENGTHS FOR TWO 1/4" DIA. CYLINDERS WITH VARIOUS SEPARATIONS

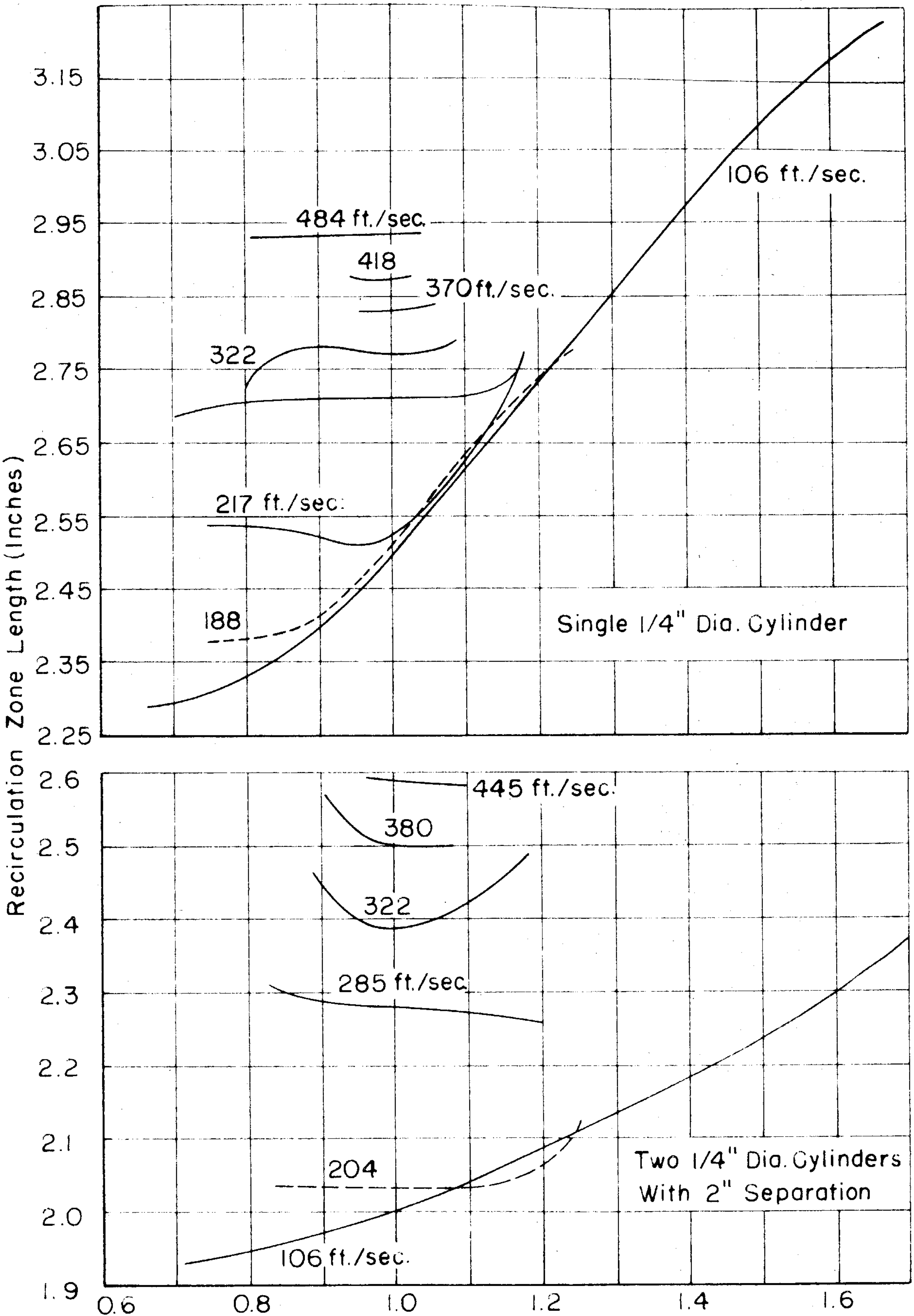


FIG.23-RECIRCULATION ZONE LENGTHS FOR 1/4" DIA. CYLINDERS

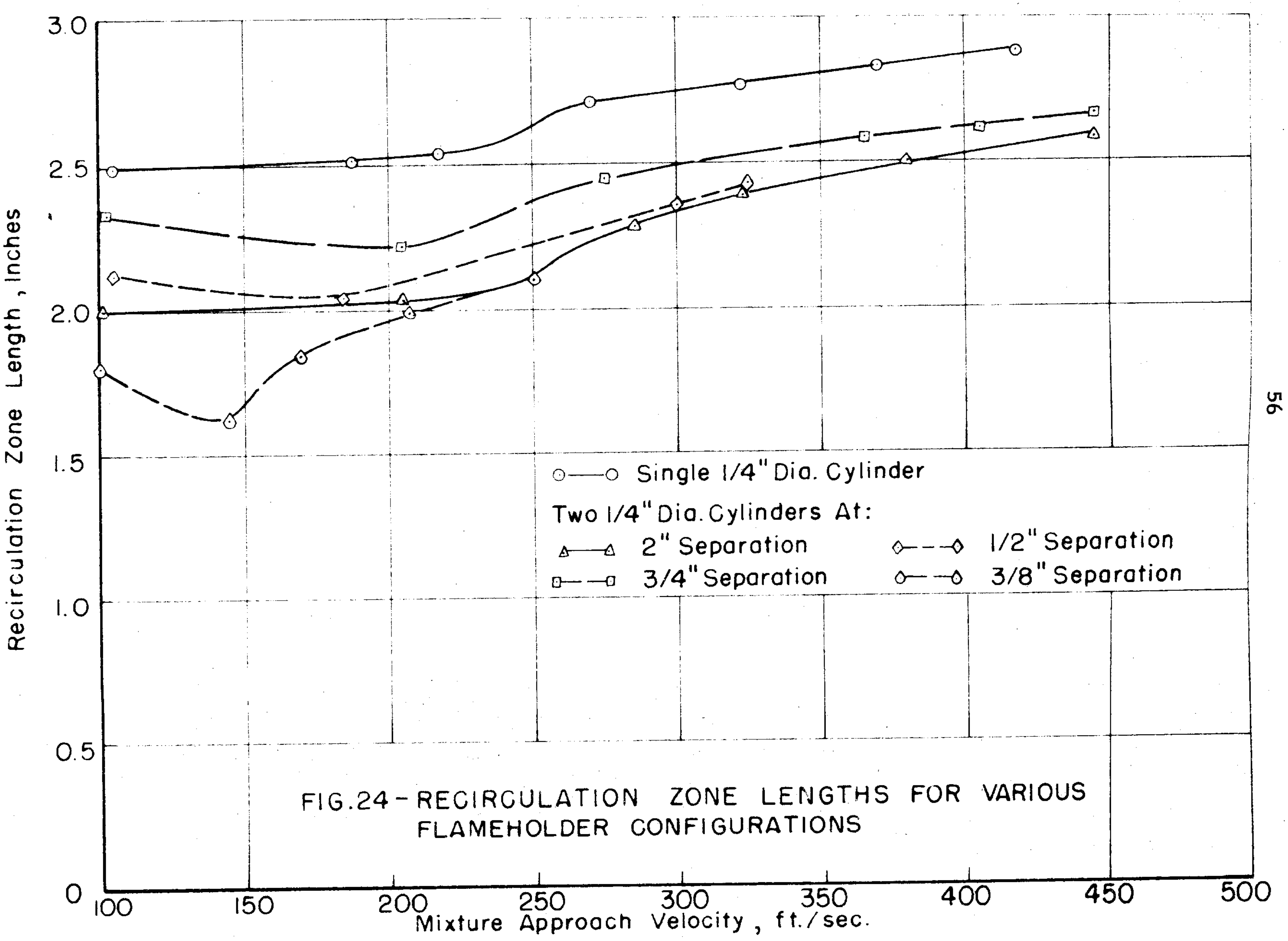


FIG. 24 - RECIRCULATION ZONE LENGTHS FOR VARIOUS FLAMEHOLDER CONFIGURATIONS

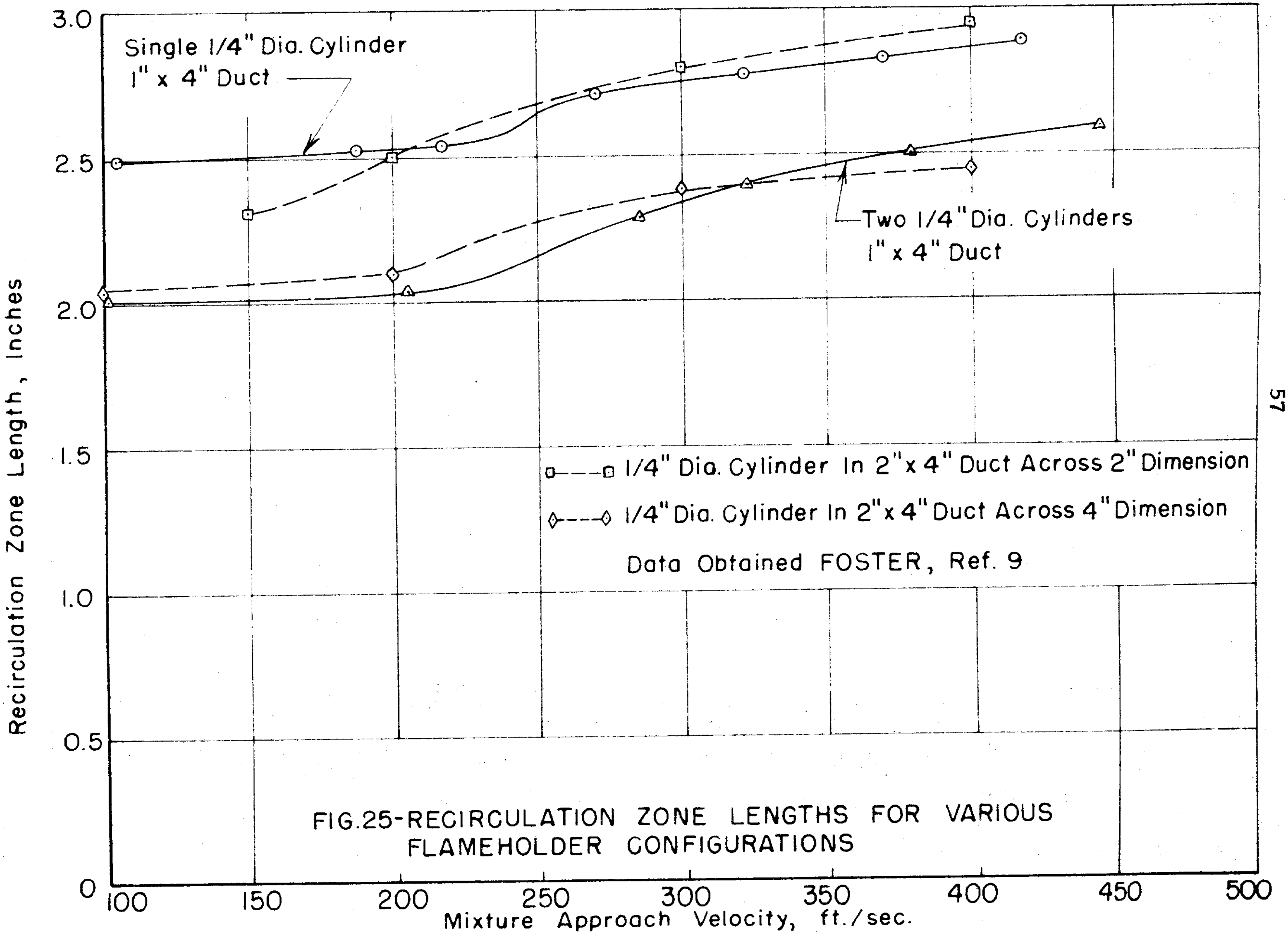


FIG.25-RECIRCULATION ZONE LENGTHS FOR VARIOUS FLAMEHOLDER CONFIGURATIONS
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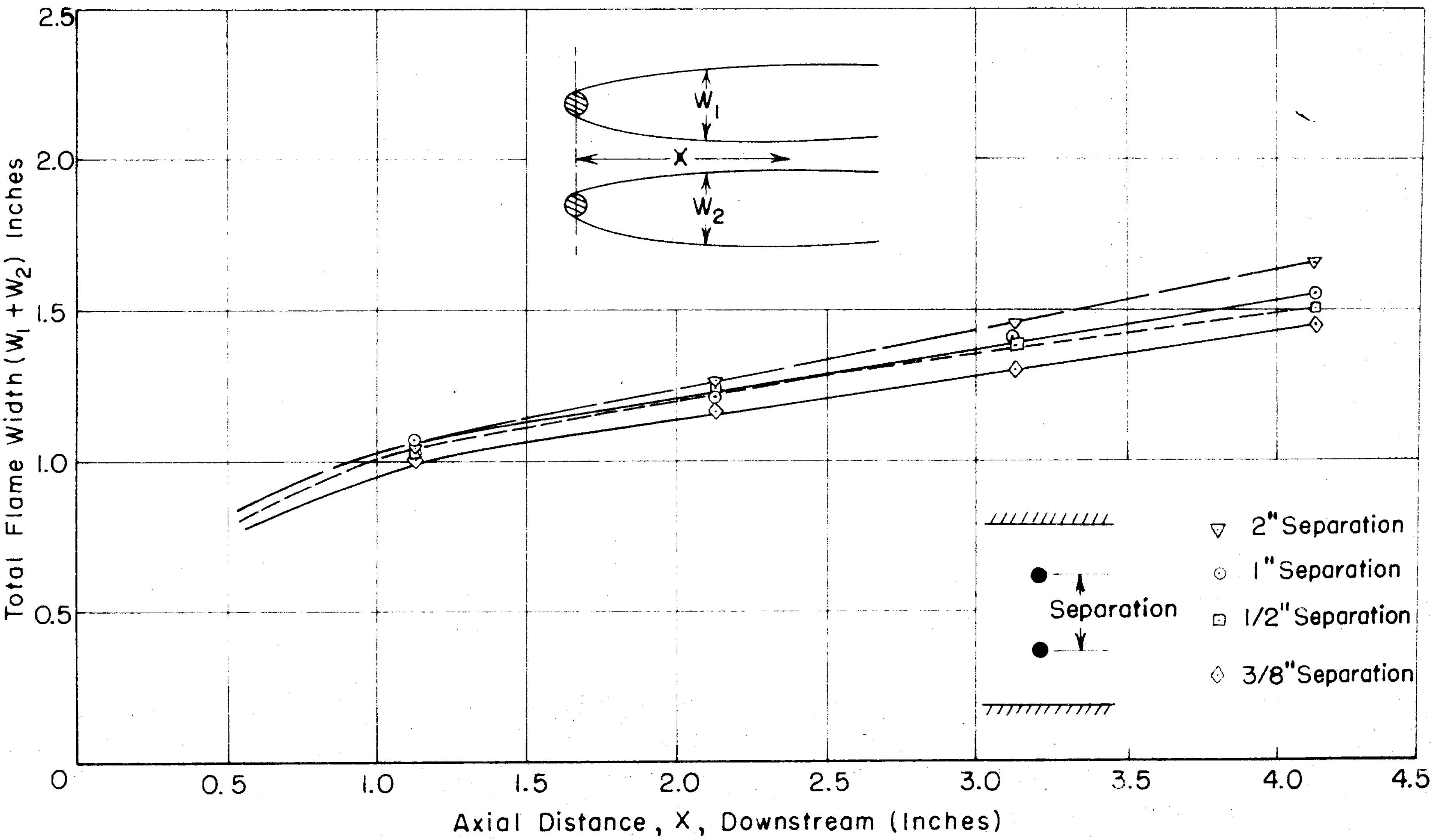
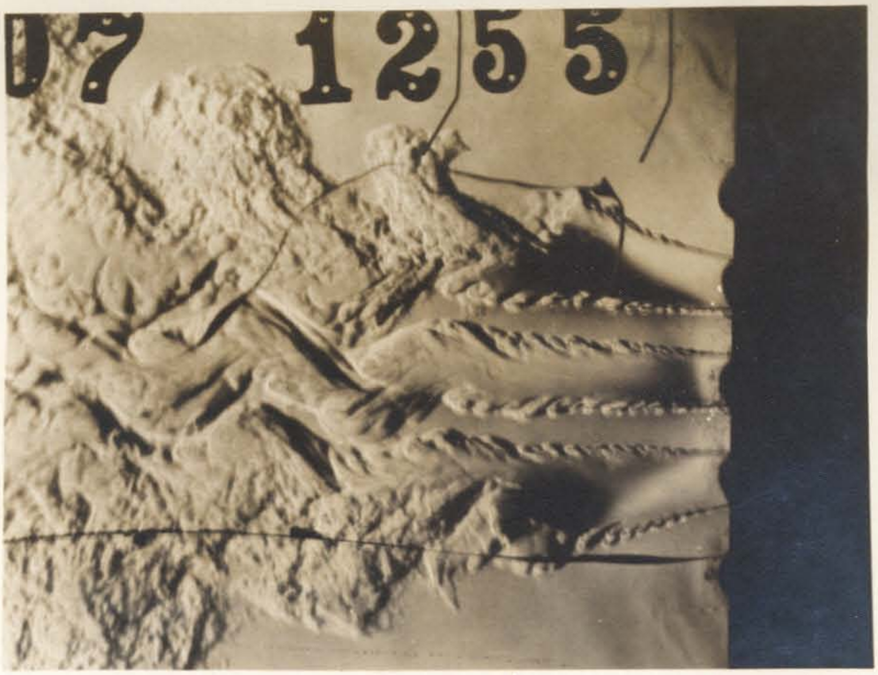


FIG.26-TOTAL FLAME WIDTHS FOR TWO 1/4" DIA. CYLINDERS AT VARIOUS SEPARATIONS



Mixture Velocity 80 ft/sec. 0 = 1.62

Mixture Velocity 80 ft/sec. 0 = 1.17

Figure 27- Schlieren Photographs Showing Extent of Wake Mixing for Flame Stabilized on Three of Five 1/4 inch Diameter Flameholder at 1/2 inch Separations.

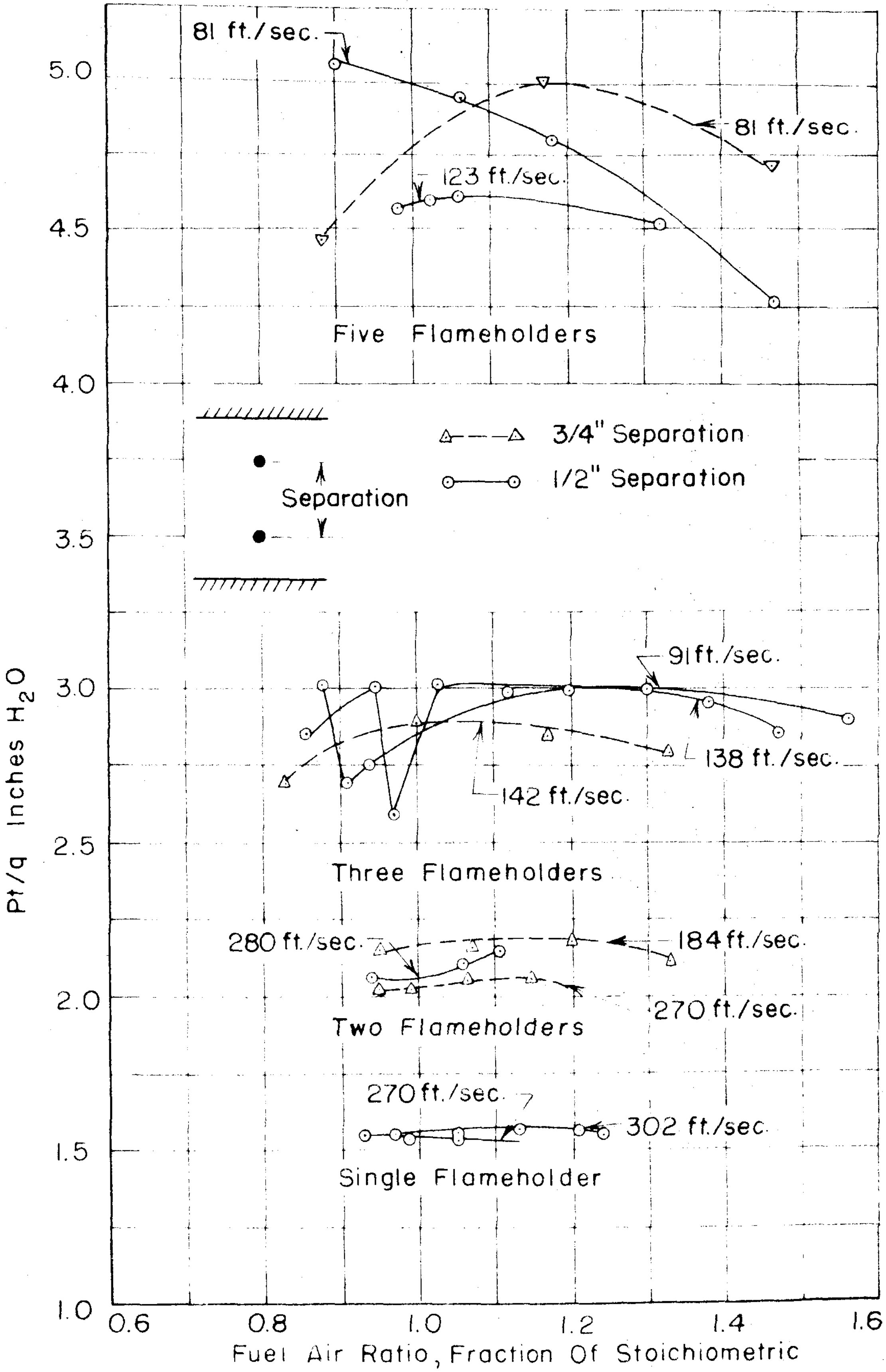


FIG. 28 - Pt/q vs. FUEL AIR RATIO FOR VARIOUS FLAMEHOLDER CONFIGURATIONS

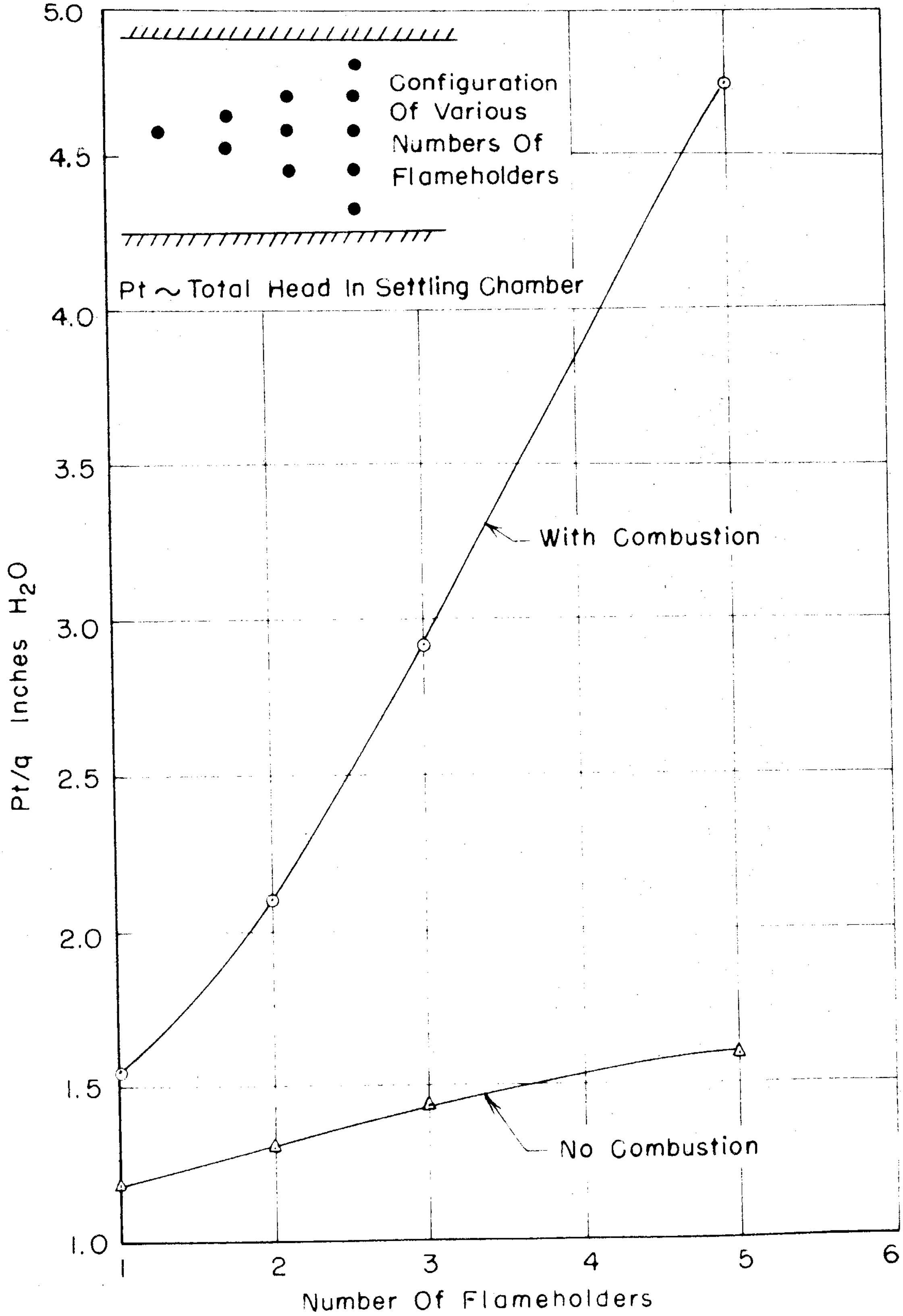


FIG.29-AVERAGE Pt/q WITH AND WITHOUT COMBUSTION FOR VARIOUS NUMBERS OF FLAMEHOLDERS