

AN EXPERIMENTAL INVESTIGATION OF  
THE RECIRCULATION ZONE OF  
LAMINAR FLAMES STABILIZED ON BLUFF BODIES  
AT LOW REYNOLDS NUMBERS

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## ABSTRACT

As part of a program to explain the shift in the maximum blow-off velocity from stoichiometric mixture ratio for small flame holder sizes, laminar flame stabilization studies were made using cylindrical flame holders of 0.031 to 0.125 inches in diameter at Reynolds numbers in the range of  $10^3$  to  $10^4$ . Chemical samples of the gases in the recirculation region behind the flame holders were taken and analyzed to determine the composition of the burning gases at the flame front. Maximum temperature measurements were taken of this same region. It was found that at these low Reynolds numbers, the composition was different than in the unburned approach mixtures, and that this was apparently due to the difference in molecular diffusion of the fuel and air across the flame front. The variation in the composition of the burning gases appears to be a direct function of the approach fuel-air mixture ratio for each diameter and approach mixture velocity.

## TABLE OF CONTENTS

PART	TITLE	PAGE
	Acknowledgement	i
	Abstract	ii
	Table of Contents	iii
I.	INTRODUCTION	1
II.	EQUIPMENT	4
III.	PROCEDURES AND RESULTS	7
	A. Blowoff Limits	7
	B. Chemical Sampling	8
	C. Recirculation Zone Temperature Measurements	11
IV.	CONCLUSIONS	14
	References	15
	Table	16
	Figures	17

## I. INTRODUCTION

Previous studies by G. Haddock,<sup>(1)</sup> E. Zukoski,<sup>(2)</sup> and G. Williams,<sup>(3-4)</sup> on the stability limits of two-dimensional ducted flames stabilized on round cylindrical flame holders have shown that there is a change in their behavior when the diameter of the flame holder is less than approximately 1/8 inches. These flames are essentially laminar in nature. For the larger diameters, the stability limit or blowoff curves "peak" (maximum stable velocity) near the stoichiometric fuel-air mixture. With the smaller diameter flame holders, the curves no longer peak at this ideal mixture ratio, but tend to depart from stoichiometric and peak farther away as the diameter is reduced.<sup>(1-4)</sup>

A time exposure picture, taken by Haddock at the Jet Propulsion Laboratory, of a flame stabilized on a cylindrical flame holder is shown in Figure 1. A 1/2-inch flame holder is shown, but a time exposure using a smaller diameter would be similar. As the unburned fuel-air mixture flows around the flame holder it encounters the flame front. The luminous regions extending from the edges of the rod downstream are zones of mixing and chemical reaction. These zones are laminar immediately behind the flame holder, and gradually become turbulent some distance downstream. It has recently been demonstrated conclusively by Zukoski that an increase in cylinder diameter causes this transition to shift toward the flame holder.<sup>(2)</sup>

Immediately behind the flame holder and between the two laminar mixing layers is a non-luminous recirculation zone of burned gases. The recirculating character of this zone has been shown by Longwell,<sup>(5)</sup>

Nicholson,<sup>(6)</sup> and Zukoski.<sup>(2)</sup> The downstream extent of this region was determined for this flame by Zukoski, by injecting salt water into the flame.

It was shown by Nicholson that material from the laminar mixing layers enters this recirculation zone. This was done by tracing the paths of aluminum particles from the unburned approach mixture, through the flame front and finally downstream through the wake. In tracing the path taken by 40 particles, picked at random from those introduced into the approach fuel-air mixture, it was found that:

"... 24 recirculated, 9 up the center and 15 up the edges of the recirculation zone; 21 of the 24 reached the flame holder and only 3 turned back downstream without touching; 8 crossed the wake diagonally and passed downstream; 9 paused in a downstream eddy near the limit of recirculation; and 8 passed directly through the flame with only small deviation."<sup>(6)</sup>

It has been postulated, in explanation of the shift of the blowoff curves, that molecular diffusion across the flame front can significantly change the composition of the material burning in the laminar mixing layers from that of the approach stream. The argument is based upon the difference between the molecular diffusivities of the fuel and oxygen. The result expected is that a mixture burning in this region would be leaner in fuel than the entering mixture for hydrocarbon fuels of molecular weights greater than that of air, and richer for fuels of molecular weights less than that of air. Diffusion would be relatively unimportant in turbulent flames due to the preponderant effect of turbulent mixing in the burning region. This turbulent mixing would maintain the burning mixture at essentially the same fuel-air ratio as the inlet stream.

In support of this postulate, it has been found that for flame holders less than 1/8 inch in diameter, the blowoff curves for mixtures of hydrocarbon fuels of molecular weights greater than that of air all show a tendency to peak on the fuel-rich side of stoichiometric. The shift is to the richer mixtures as the diameter decreases. <sup>(1-4)</sup> The opposite is true for methane where the peaks shift to mixtures leaner than stoichiometric as the diameter of the flame holder decreases. <sup>(2)</sup> Further indication of this effect is given by Williams when samples taken from the recirculation region showed a different carbon to nitrogen ratio than that in the unburned stream. <sup>(4)</sup>

The present studies, using a gasoline-like hydrocarbon fuel, were undertaken as part of an extensive investigation to show how the fuel-air mixture ratio in the recirculation zone might vary with changes in flame holder diameter, fuel-air mixture ratio and velocity of the approach stream while other parameters are held constant. An attempt also is made to correlate temperature measurements of the recirculation zone to these items. Numerous chemical samples were taken from the recirculation region and analyzed to determine the carbon to nitrogen ratio. Temperature measurements were made in the region next to the downstream face of the flame holder.

All work was accomplished at the California Institute of Technology Jet Propulsion Laboratory, Pasadena, California using existing equipment designed by E. E. Zukoski.

## II. EQUIPMENT

A schematic diagram of the facilities used in these flame studies is shown in Fig. 2. The air first passed through a heat exchanger to provide a constant temperature air supply. A liquid hydrocarbon fuel was then injected into the air stream where it was completely vaporized and mixed before this fuel-air mixture entered a calming chamber. This homogeneous mixture then passed through a 22 to 1 converging nozzle into the 2 by 4 inch duct used as a combustion chamber. The uncooled, round cylindrical flame holders were mounted in this duct perpendicular to the stream axis, and across the short dimension.

Air was supplied from a reciprocating compressor system at 65 psig with a maximum capacity of 4.0 lbs/sec. The mass flow was regulated by means of a remotely controlled regulating valve, located upstream of the heat exchanger and fuel injectors. This arrangement provided a constant air-mass flow rate independent of changes in temperature and fuel flow.

A portion of the air passed through a conventional shell and tube, reverse flow type heat exchanger. Temperature control was provided by pneumatically controlled, interconnected butterfly valves which allowed more or less air to bypass the heat exchanger. The temperature sensing element was located approximately 4 feet upstream of the calming chamber. The system thus provided a means for compensating any temperature change of the stream due to varying the fuel flow. This gave a very positive temperature control, and enabled a constant temperature of 150°F to be maintained within very close limits.



The calming chamber was 5 feet long and 15 inches in diameter. Five 200-mesh screens were mounted inside to reduce initial turbulence. The converging nozzle developed smoothly from the 15-inch diameter to the 2 by 4-inch rectangular cross section of the combustion chamber in an axial length of 16 inches. This allowed a 2-inch length of the same cross section as the duct immediately prior to entering the combustion chamber. A copper rupture diaphragm was provided as a safety feature; the diaphragm was designed to rupture at a pressure slightly greater than would be encountered during any of the tests. A flame arrester was located immediately upstream of the chamber to prevent the flame from accidentally traveling back up the air supply lines. A total head pressure tube was placed in the calming chamber 3 feet upstream of the combustion chamber. A static pressure orifice was positioned 1 inch upstream of the combustion chamber. A thermocouple to measure the fuel-air mixture temperature was installed diametrically opposite the total head pressure tube.

The combustion chamber was in the form of a uniform 2 by 4 inch cross section duct,  $8\frac{7}{8}$  inches in length. The uncooled cylindrical flame holders were positioned perpendicularly across the 2 inch dimension on the centerline of the chamber, 7 inches from the downstream end. This 7 inch dimension was selected so that results could be compared with previous work by Haddock. Interchangeable Vycor glass or watercooled, steel panels, 6 inches in length, were provided for all four sides of the duct to allow flexibility in flame observations. The last  $\frac{3}{4}$  inches of the downstream end were provided with film cooling. The combustible mixture was ignited by means of an electric arc from a remotely positioned, ignitor rod to the flame holder. The

voltage was controlled by a variac potentiometer.

The fuel used was a volatile liquid hydrocarbon, molecular weight approximately 89, commercially used as a paint thinner (Thinner No. 1, Union Oil Co., Los Angeles, Calif.). This was selected on the basis of its ready supply in large quantities, rigidly controlled production, ease of metering and vaporization, and the fact that its chemical and thermodynamic properties closely resemble the fuel of Reference 7. The chemical and physical properties are listed in Table I.

This fuel was supplied from a nitrogen pressurized tank, metered by calibrated Fischer Porter Rotameters, and injected into the heated air stream approximately 20 feet upstream from the calming chamber. This allowed ample time for complete vaporization and mixing. The fuel was injected by means of four 60°, 24 gal/hr turbo-jet injectors.

### III. PROCEDURES AND RESULTS

Since a velocity distribution survey of the duct had previously been made, approach velocity could be computed from water manometer reading of static pressure at duct entrance and total head pressure and temperature in calming chamber. These calculated velocities were corrected for the mass effect of fuel injected as measured by calibrated rotameters. From these values, the fuel-air ratio of the approach mixture was calculated. Throughout this study only three different diameter flame holders were used. These three uncooled flame holders were made of stainless steel tubing 0.0315, 0.049, and 0.125 inches in diameter.

#### A. Blowoff Limits

For each of the three flame holders, with their open ends sealed, effort was concentrated upon obtaining complete blowoff curves for approach velocities greater than 100 ft/sec. For velocities at which direct ignition was possible, the lean and rich blowoff limits were determined by reducing or increasing fuel-flow rate until blowoff occurred. For greater velocities where ignition could not be directly obtained, ignition was accomplished at lower velocities. The velocity was then raised to that desired, maintaining a fuel-air mixture ratio of approximately 1.3 times stoichiometric; the blowoff limits were then obtained in a similar manner. For velocities near the maximum blowoff velocity, ignition was again accomplished at a lower velocity. The fuel-flow rate was set for the desired blowoff point, and the air-flow rate increased until blowoff occurred.

The resulting blowoff curves are given in Figure 3. As was expected the curve for the 0.125-inch flame holder gave a maximum velocity at the stoichiometric mixture. The maximum velocity for the 0.049-inch cylinder was at 1.26 times stoichiometric while for the 0.0315-inch cylinder the maximum velocity point was at 1.30 times the stoichiometric fuel-air ratio.

The approach fuel-air mixture ratios, as a fraction of the stoichiometric,  $\phi$ , are plotted in Figure 4 versus Reynolds number for the maximum blowoff points. The Reynolds number calculations were based upon the kinematic viscosity for 50 percent relative humidity at one atmosphere, as given by the U. S. National Bureau of Standards since this was the average humidity at the test location. It can be seen that these blowoff points lie on a curve drawn through similar points obtained by Haddock<sup>(1)</sup> and Zukoski<sup>(2)</sup>.

#### B. Chemical Sampling

The same three flame holders were again used for the experiments on chemical sampling in the wake. The two larger diameter holders now had a series of 19 holes, each 0.010-inch in diameter, drilled through the tubing wall. These holes were spaced in a line parallel to the tube axis and were in the central 1-inch of the holders length. The 0.0315-inch diameter holder had an opening 0.003-inch wide and approximately 0.50-inch long, cut through its wall in a similar location to give the same sampling area as on the larger flame holders. When installed in the duct, these openings were positioned directly downstream.

With one end of the flame holder sealed, samples of the gases found in the recirculation zone were drawn from the open end of the tube, through a cupric oxide furnace and collected in 500 cc pipettes over mercury. Care was taken to purge the system before each sample was taken. The furnace, which was maintained at  $700^{\circ}\text{C}$ , insured that all of the carbon present was oxidized to  $\text{CO}_2$ . The sampling was accomplished at a rate of 100 cc per minute to obtain a good overall, average sample of the gases in this turbulent recirculation zone. Some 45 samples were taken during which the approach mixture and velocity were varied while the temperature was maintained constant at  $150^{\circ}\text{F}$ .

These samples were analyzed by the standard Orsat method, and the percentage of  $\text{CO}_2$ ,  $\text{O}_2$ , and  $\text{N}_2$  was determined. From these values the carbon to nitrogen ratio found within the recirculation zone was computed. The Orsat results were reproducible within one percent. The error in accuracy of this sampling technique was established to be under four percent.

From the known fuel-air ratio of the approach mixture, the carbon to nitrogen ratio was also determined for each run. It was found that the carbon to nitrogen ratio in the recirculation zone varied greatly from that in the approach mixture at all velocities where the mixing layers were essentially laminar in nature. This variation is given in Figure 5 where the comparison of the carbon to nitrogen ratio of the approach mixture to that in the recirculation zone is given versus Reynolds number. The curve from Figure 4 is reproduced for comparison.

Samples were not taken for the 0.0315-inch holder beyond a Reynolds number of  $2 \times 10^3$  as the flame separated seriously from the

walls of the duct and the significance of the sample was in question. With the 0.049-inch flame holder the mixing layer became turbulent at a Reynolds number of  $4.3 \times 10^3$  and rapidly advanced to a residual flame. As can be seen, there is a wide scattering of points at the various velocities.

A clearer understanding of these data can be derived from Figure 6 where the fuel-air mixture ratio of the recirculation zone as a fraction of stoichiometric is plotted against a similar fuel-air ratio of the approach mixture for each approach velocity and cylinder diameter. In this figure, the fuel-air ratio of the recirculation zone appeared to be a direct function of the mixture ratio of the approach stream for each velocity. From these curves, the approach fuel-air mixture that should give a stoichiometric mixture in the recirculation zone may be determined. Schlieren photographs of flames under these determined conditions were taken and are shown in Figure 7. Also these determined approach mixture fuel-air ratios are plotted against Reynolds number in Figure 8. The condition for each of the Schlieren pictures is indicated by small letters. The curve from Figure 4 is again repeated for comparison purposes.

By comparing the Schlieren photographs of Figure 7 with the data of Figure 8, it can be seen that for the 0.0315-inch flame holder, the approach mixture ratio estimated to give a stoichiometric mixture in the recirculation zone corresponds closely to the curve of approach mixture ratio of maximum blowoff velocities, and that the mixing layer is definitely laminar.

For the 0.049-inch cylinder, these points also follow the curve at

the lower Reynolds numbers. At a Reynolds number of about  $3.2 \times 10^3$  these points begin to fall below the curve, and at a Reynolds number  $4.5 \times 10^3$  there is a sharp drop to approximately a stoichiometric mixture. From the Schlieren photographs it can be seen that the drop away from the curve is accompanied by more turbulence in the mixing layer. Where the sudden drop occurs at a Reynolds number of  $4.5 \times 10^3$ , the transition to a turbulent layer has been achieved.

Parallel results are obtained with the 0.125-inch flame holder except that the mixing layer has not reached the turbulent transition by  $1.03 \times 10^4$ .

From these results, conclusions on the mechanics involved may be drawn. At low approach Reynolds numbers the mixing layer is completely laminar and the recirculation zone is composed mainly of material from this layer. This shows that molecular diffusion at the flame front causes the burning mixture to be much leaner than the unburned approach stream. As the Reynolds number and velocity increase, the mixing layer gradually becomes more turbulent so that this diffusion has a smaller effect. The recirculation zone now also receives material from farther down the wake.

From other Schlieren pictures it has been found that for a 0.125-inch uncooled flame holder the transition from a laminar to a turbulent flame occurs at approximately a Reynolds number of  $1.5 \times 10^4$ . (2)

### C. Recirculation Zone Temperature Measurements

An effort was made to establish at which fuel-air ratio, for various approach mixture velocities, the maximum temperature

occurred in the recirculation zone. No quantitative temperature measurements were attempted, and radiation effects were not considered.

For the 0.125-inch flame holder, two different thermocouple arrangements were used. Chromel and Alumel thermocouple wire, 0.010-inch in diameter, encased in ceramic tubing was inserted through opposite ends of the cylinder. These were joined at a small hole cut through the wall of the flame holder at the mid-point of its length. The hole was filled with silver solder around the thermocouple wires, and the whole assembly filed down to the original shape of the cylinder. In the second arrangement, the hole was filled with Sauereisen cement and filed down. For the 0.049-inch holder, the Chromel-Alumel thermocouple wires were welded to the inner face of the tubing wall one inch from either end. No internal thermocouple could be installed in the 0.031-inch flame holder.

To take the temperature readings, the flame holders were installed so that the thermocouple junction was facing directly downstream. Attempts were made to measure temperatures immediately behind the 0.0315-inch cylinder, and to make a temperature survey across the recirculation zone perpendicular to the flow. These attempts were unsuccessful in that the flame front was disturbed and moved away from the thermocouple when it was inserted in this region. During all measurements the approach velocity was held at some constant value and the fuel-air ratio varied.

Temperature measurements for the largest flame holder were successful, and typical curves are given in Figure 9. It can be seen



that these curves are well defined, and give a good indication of the maximum temperature fuel-air ratio. The maximum points are at an approach fuel-air mixture ratio of 1.05 times stoichiometric for the higher velocities, and they shift to richer mixtures as the velocity is reduced.

Temperature readings with the 0.049-inch flame holder were not as successful in that the curves were not well defined. In some cases maximum temperature points were found in both the lean and rich rough burning regions. Only those maximum points falling within the smooth burning regions are considered.

The approach fuel-air mixture ratio, as a fraction of stoichiometric for maximum temperature points of the 0.125-inch cylinder are given as a function of Reynolds number in Figure 10. Since it is known that the maximum flame temperatures occur at 1.05 to 1.10 times stoichiometric, due to dissociation, it can be seen that these points, if reduced by 5 to 10 percent, would agree fairly well with the sampling results.

#### IV. CONCLUSIONS

Assuming that the composition of the recirculation zone gives a representative picture of the composition in the burning zone for flames stabilized on bluff bodies at low Reynolds numbers, it was found that the combustion associated with the recirculation zone is taking place at a fuel-air mixture much leaner than that in the unburned stream when a heavy hydrocarbon fuel is employed. This evidence is in direct support of the postulate that molecular diffusion controls the mixture ratio of the recirculation zone. This effect is dominant at Reynolds numbers below  $10^4$ . At these values of Reynolds number, where the burning region is completely laminar, diffusion causes the maximum stability limits to be attained at an approach fuel-air mixture ratio rich enough to give stoichiometric conditions in the recirculation region. As the burning region becomes more turbulent, turbulent mixing dominates the process so that by the time a turbulent flame appears, the burning region is of the same composition as the unburned mixture. This seems to explain the shift in the maximum stability limits from a stoichiometric fuel-air mixture for the 1/8-inch diameter flame holder to much richer mixtures as the diameter is reduced.

The variation of the mixture ratio in the burning region appears to be a direct function of the mixture ratio in the unburned stream for each diameter and approach stream velocity. Further studies are indicated to determine the exact relation. When this exact relation is found, it will enable exact fuel-air mixture ratios to be calculated in order to derive maximum benefit of flame stabilization under all operating conditions.

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TABLE I. Fuel Specifications<sup>(1)</sup>

Gravity ( $^{\circ}$ API at 60 $^{\circ}$ F)	61.4
Gravity, specific (60/60 $^{\circ}$ F)	0.7335
Reid vapor pressure (lb)	4.0
Heat of combustion (Btu/lb)	
Gross	20,130
Net	18,793
ASTM distillation	
Initial ( $^{\circ}$ F)	160
Maximum ( $^{\circ}$ F)	220
Acid solubility (o/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
Isoheptane	14
n-Heptane	12
Methylcyclohexane	8
Toluene	3
C <sub>8</sub> paraffins	3
Ethylbenzene	
Xylenes	1

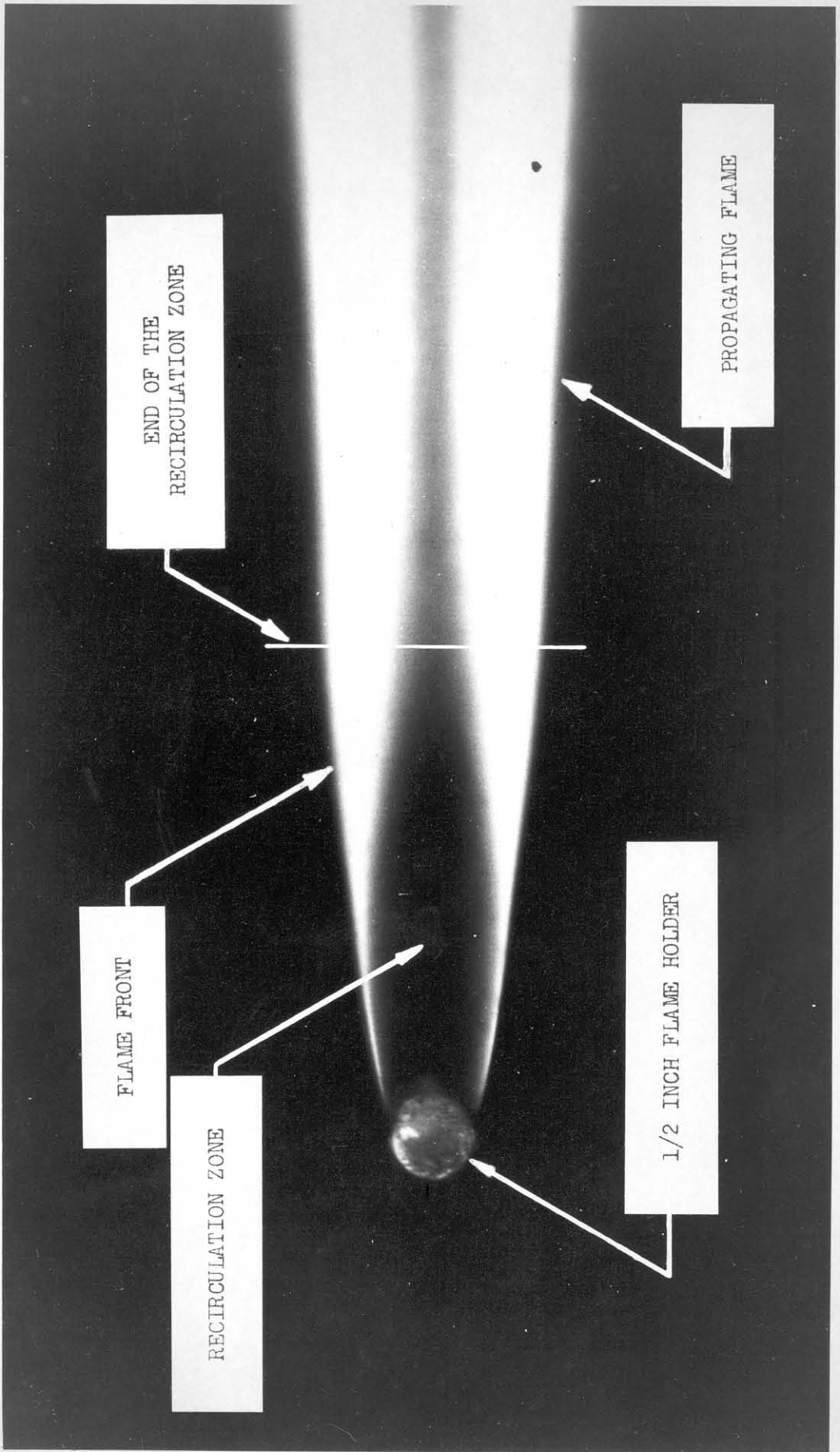


Figure 1. Time Exposure Picture of Flame Stabilized on 1/2-Inch Diameter, Cylindric Flame Holder

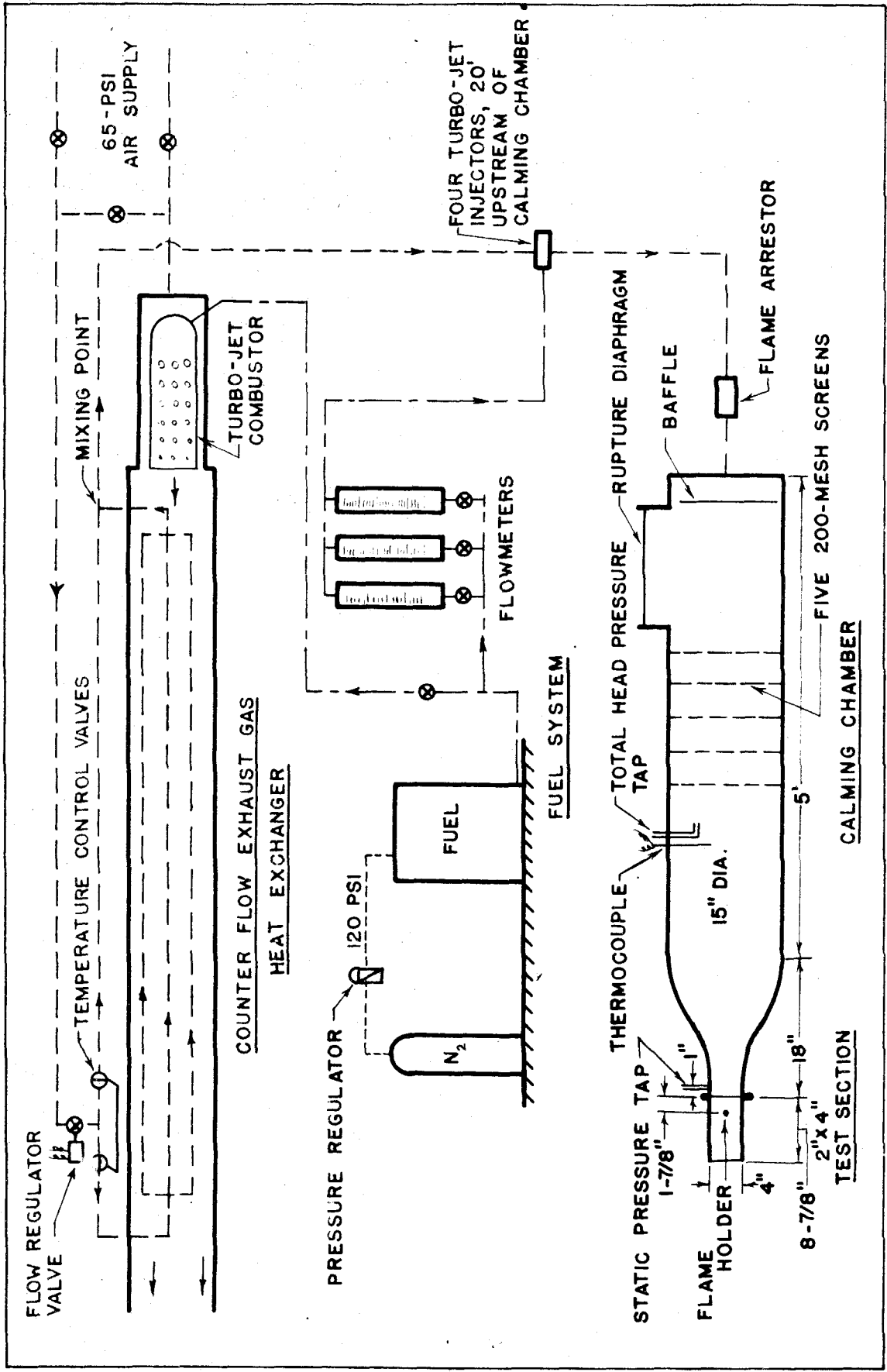


FIGURE 2. SCHEMATIC FLOW DIAGRAM OF EQUIPMENT

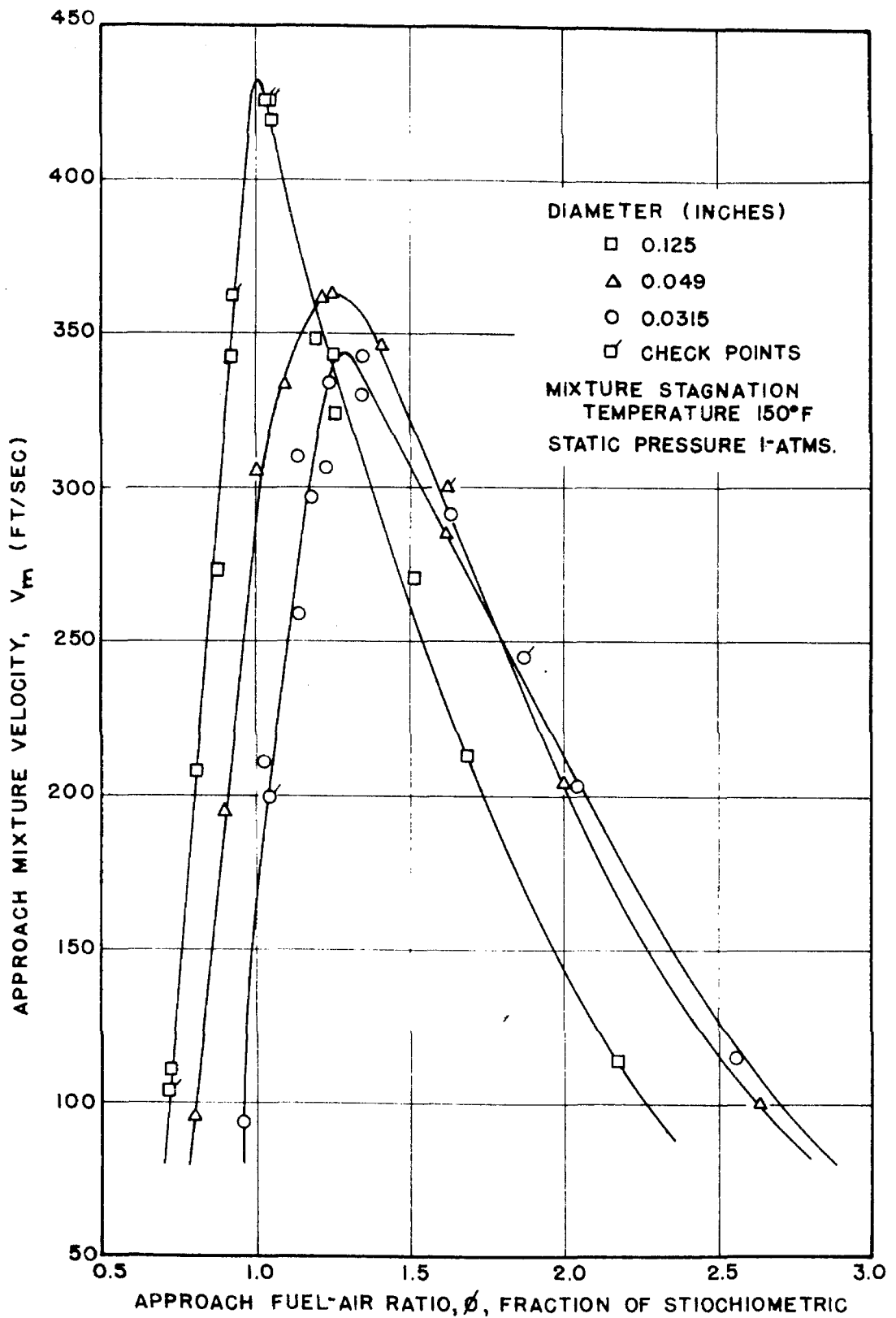


FIGURE 3. FLAME BLOWOFF LIMITS FOR CYLINDER SIZES 0.0315 TO 0.125 INCH IN DIAMETER

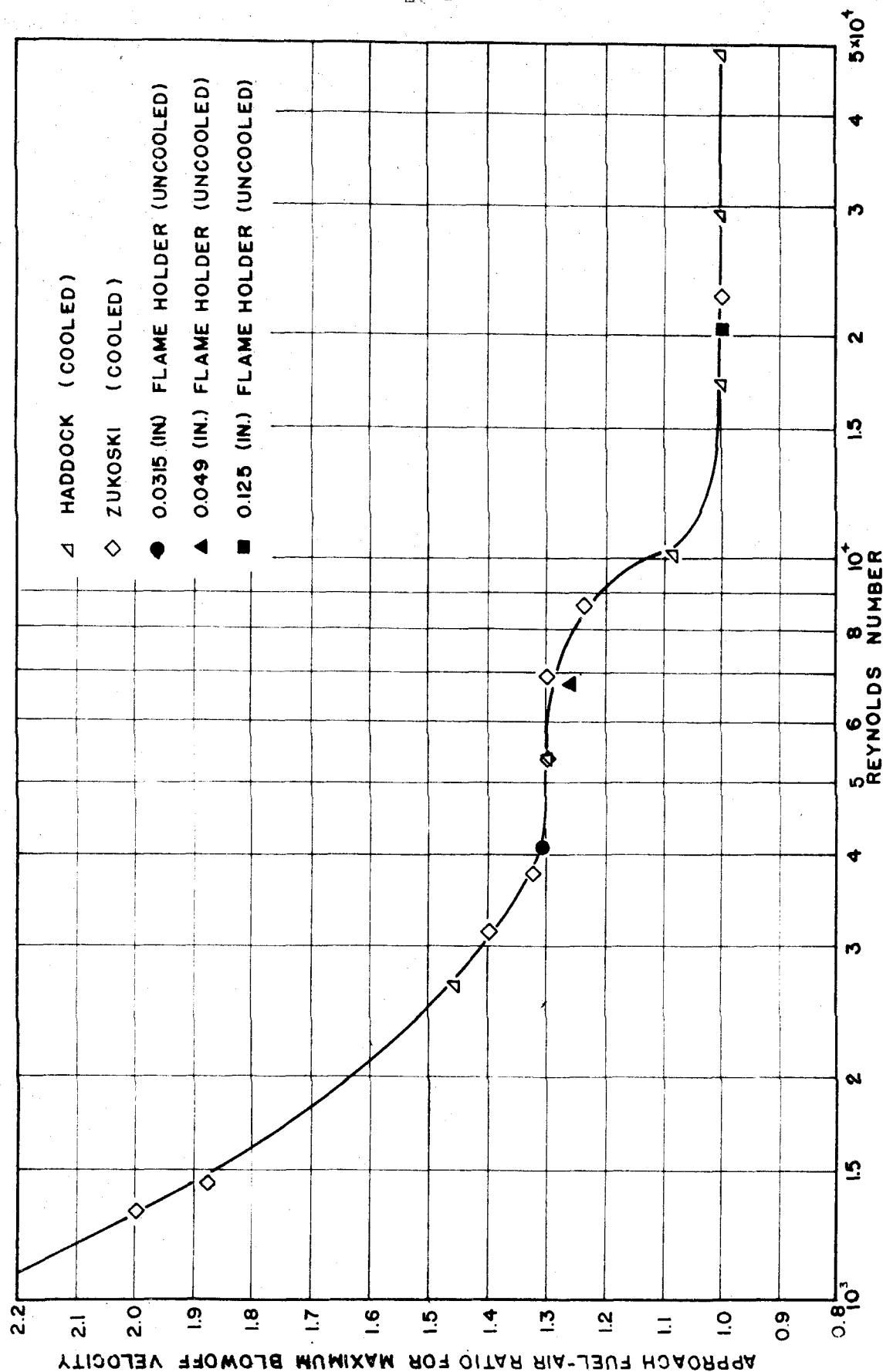


FIGURE 4. APPROACH FUEL-AIR RATIO CORRESPONDING TO THE MAXIMUM BLOWOFF VELOCITY AS FUNCTION OF REYNOLDS NUMBER



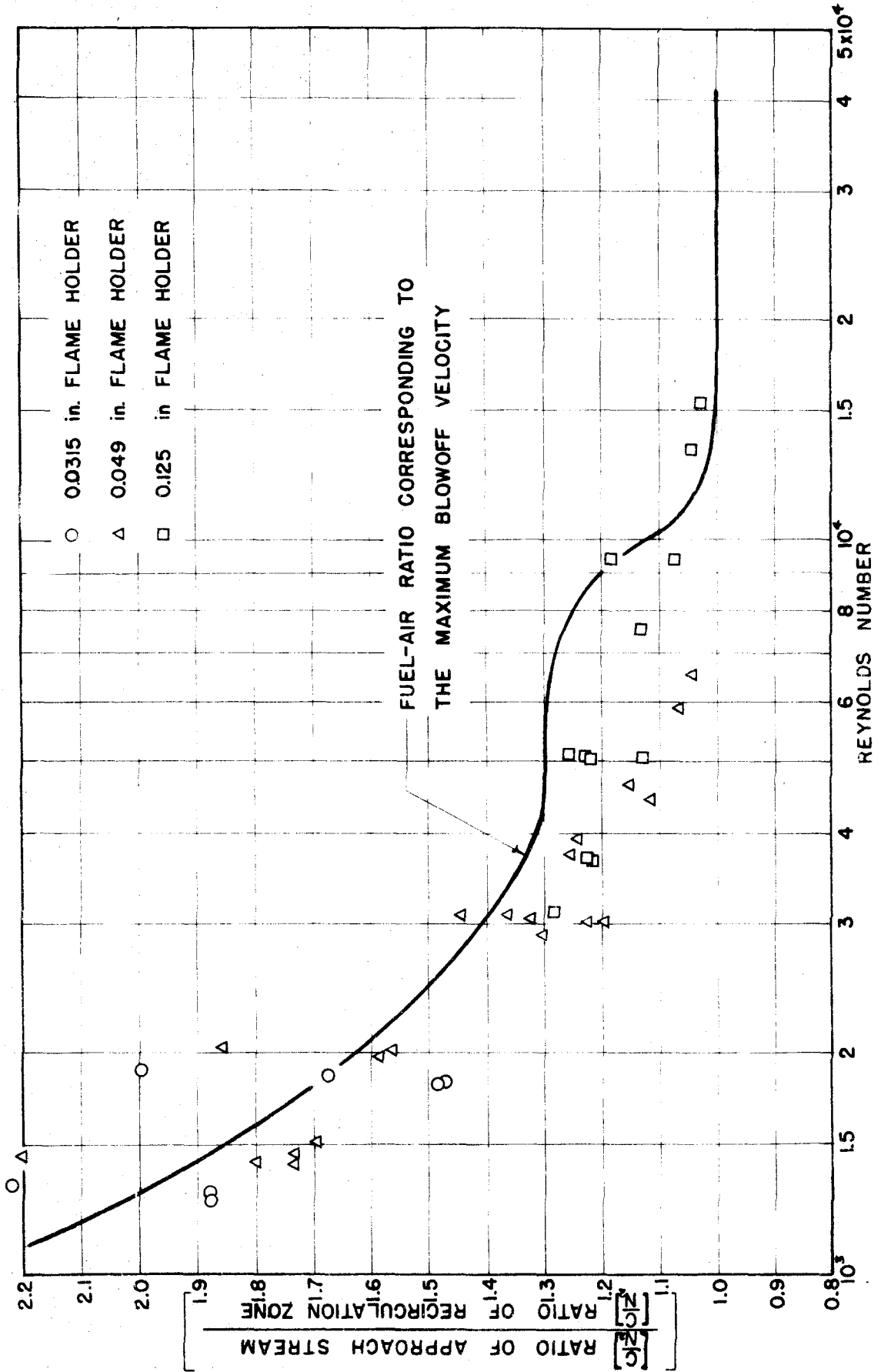


FIGURE 5. RATIO OF CARBON TO NITROGEN OF APPROACH MIXTURE TO CARBON TO NITROGEN OF THE RECIRCULATION ZONE AS A FUNCTION OF REYNOLDS NUMBER

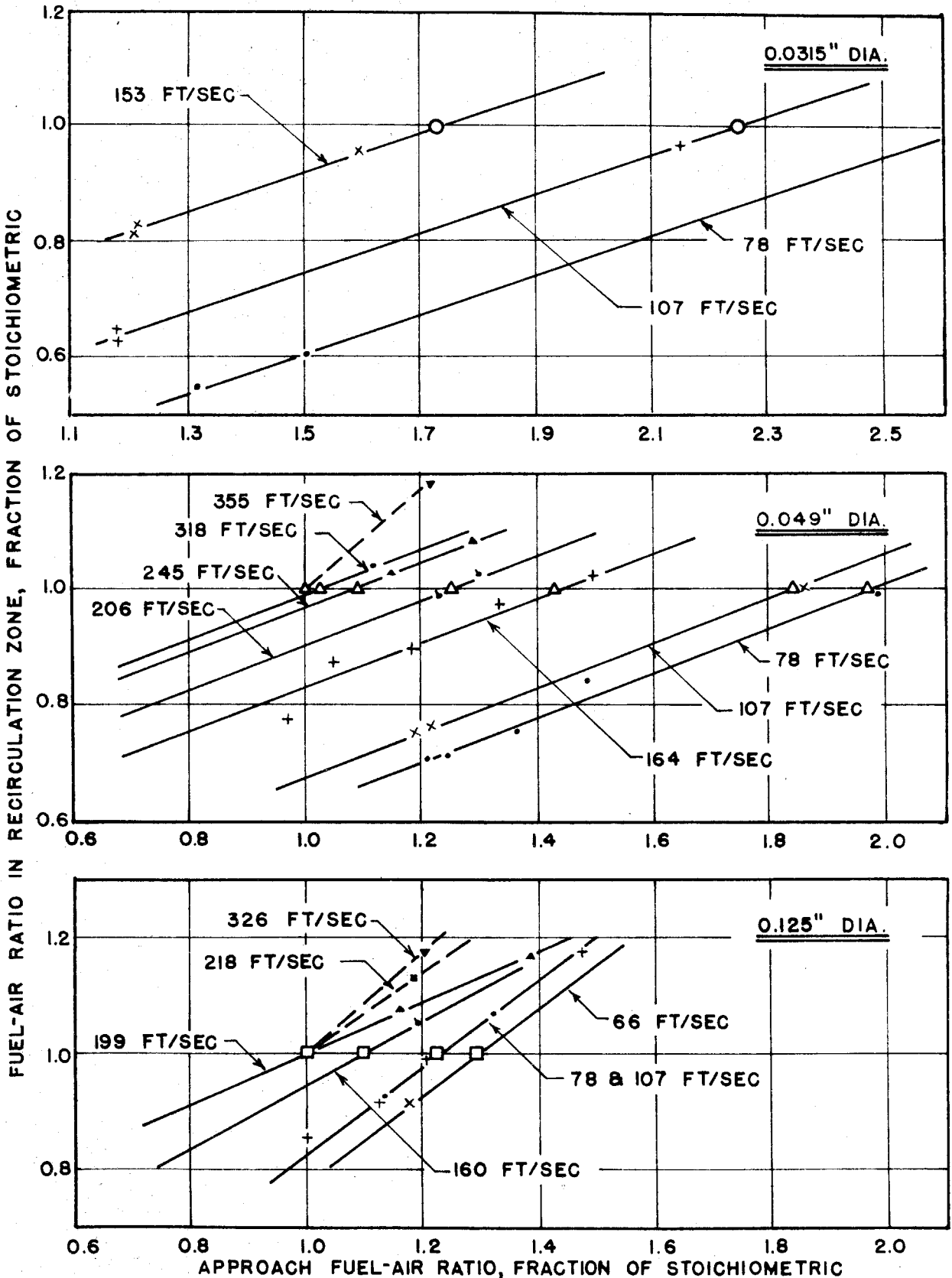
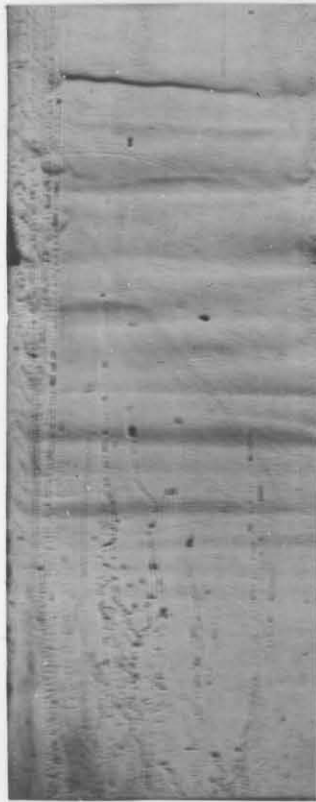
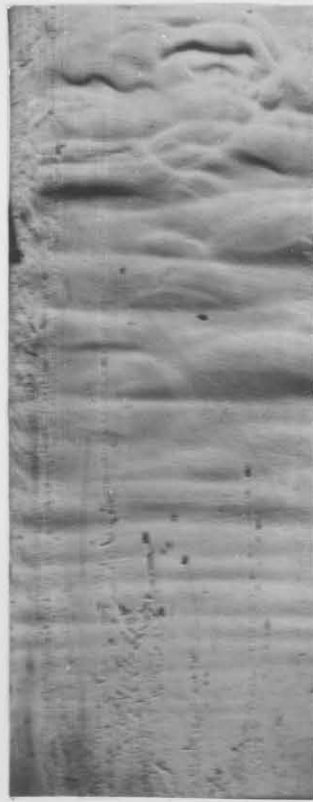


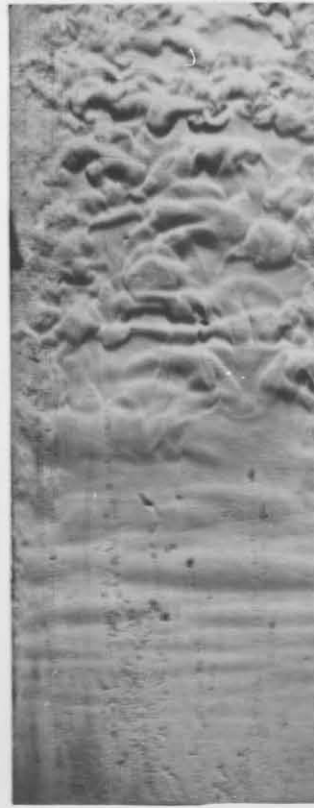
FIGURE 6. FUEL-AIR RATIO OF APPROACH MIXTURE AND RECIRCULATION ZONE FOR DIFFERENT CYLINDER DIAMETERS AND VELOCITIES



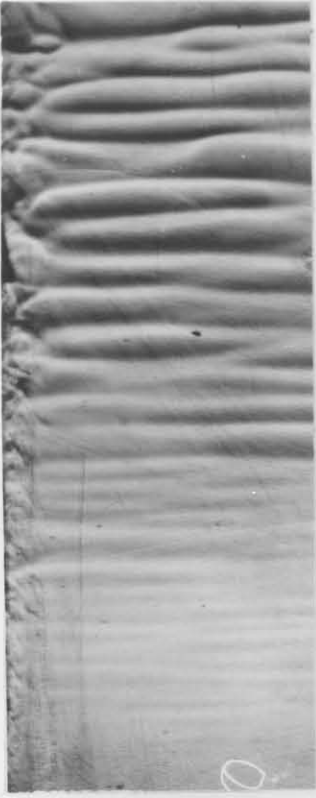
(a) .031 Inch  $Re = 0.932 \times 10^3$   $\phi = 2.60$



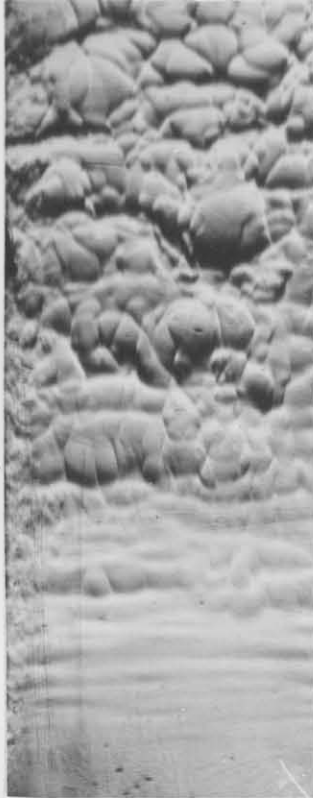
(b) .031 Inch  $Re = 1.30 \times 10^3$   $\phi = 2.24$



(c) .031 Inch  $Re = 1.83 \times 10^3$   $\phi = 1.75$



(d) .049 Inch  $Re = 2.00 \times 10^3$   $\phi = 1.78$

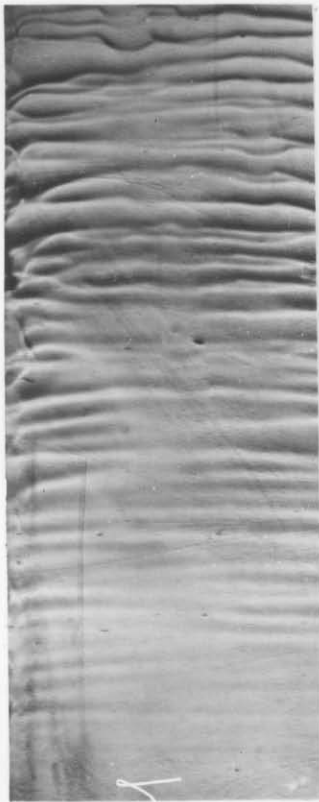


(e) .049 Inch  $Re = 3.82 \times 10^3$   $\phi = 1.25$

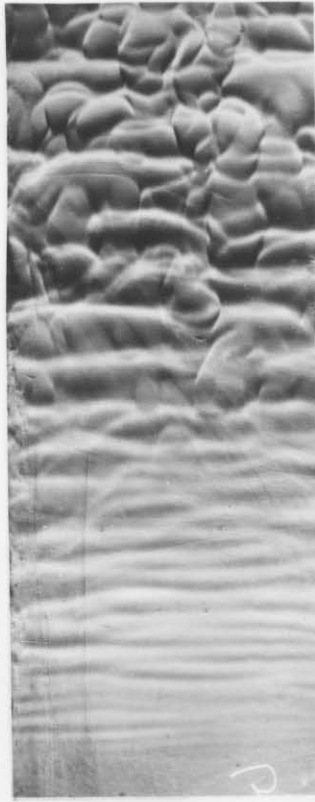


(f) .049 Inch  $Re = 4.55 \times 10^3$   $\phi = 1.10$

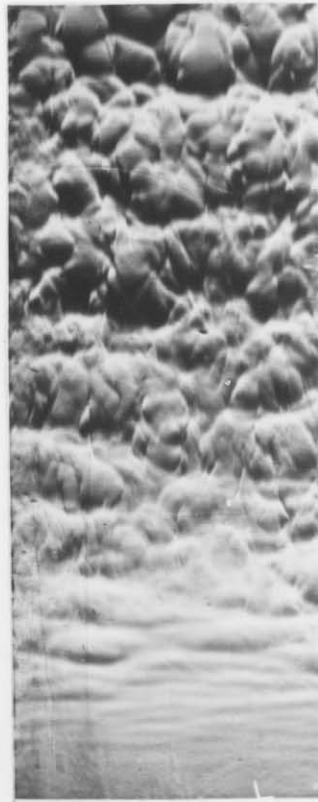
Figure 7. Schlieren Pictures at Conditions to Give Stoichiometric Mixture in Recirculation Zone



(g) .125 Inch  $Re = 5.10 \times 10^3$   $\phi = 1.22$



(h) .125 Inch  $Re = 7.58 \times 10^3$   $\phi = 1.09$



(i) .125 Inch  $Re = 1.03 \times 10^4$   $\phi = 1.02$

Figure 7. Schlieren Pictures at Conditions to Give Stoichiometric Mixture in Recirculation Zone (Continued)

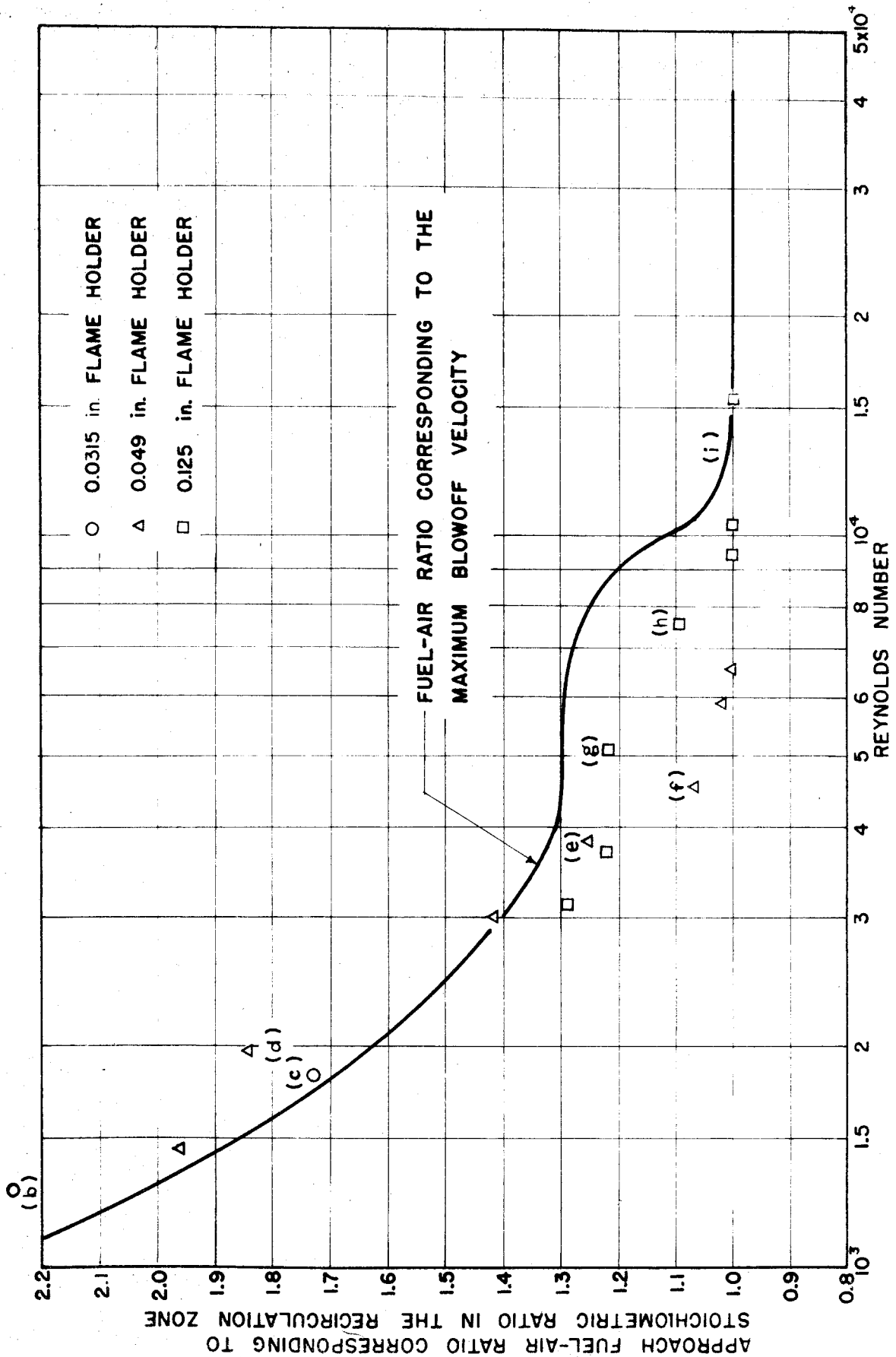


FIGURE 8. ESTIMATED APPROACH FUEL-AIR RATIO TO GIVE A STOICHIOMETRIC MIXTURE IN THE RECIRCULATION ZONE AS A FUNCTION OF REYNOLDS NUMBER

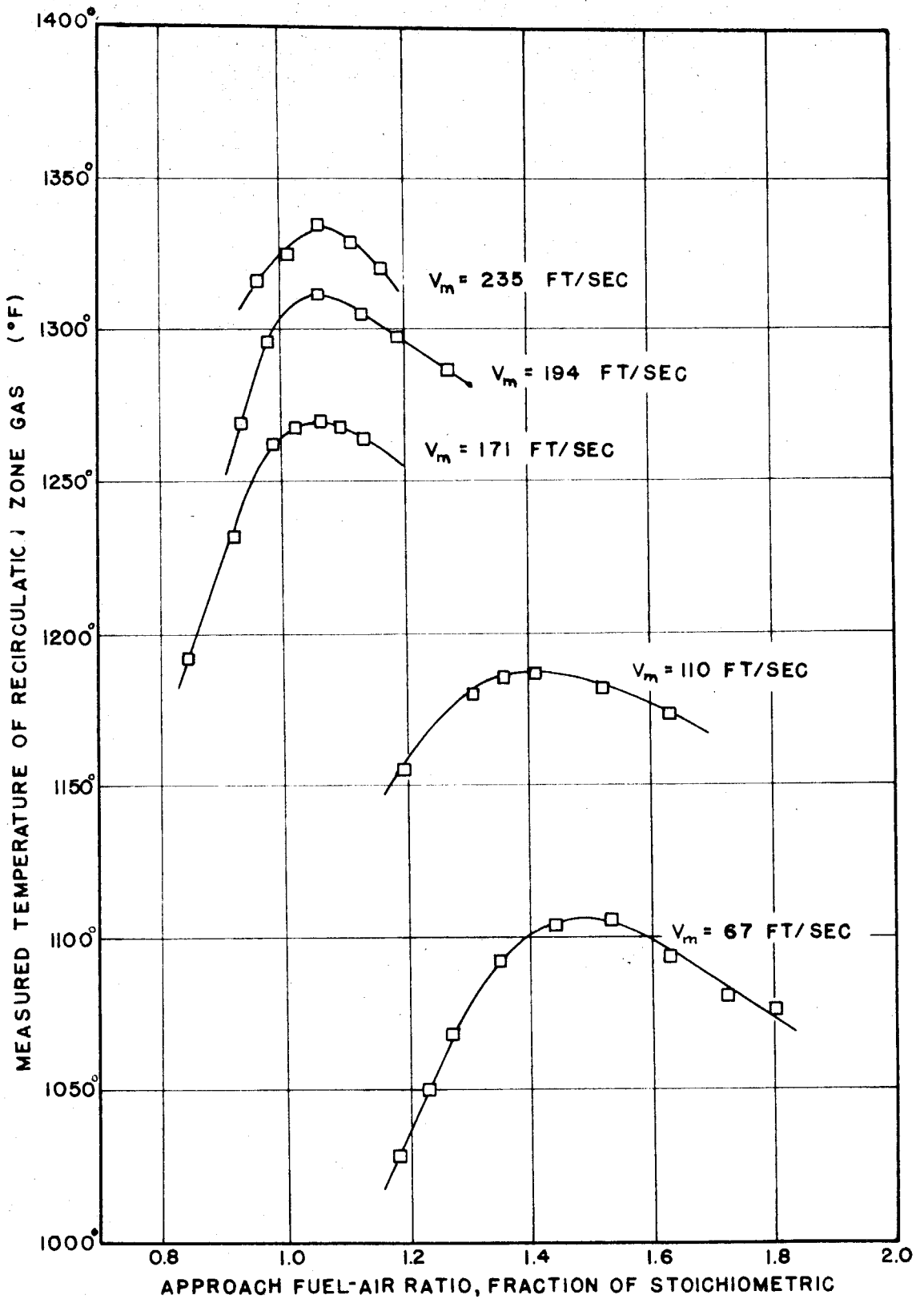


FIGURE 9. TEMPERATURE OF RECIRCULATION ZONE GAS AS FUNCTION OF APPROACH FUEL-AIR RATIO AND VELOCITY, 0.125 INCH HOLDER

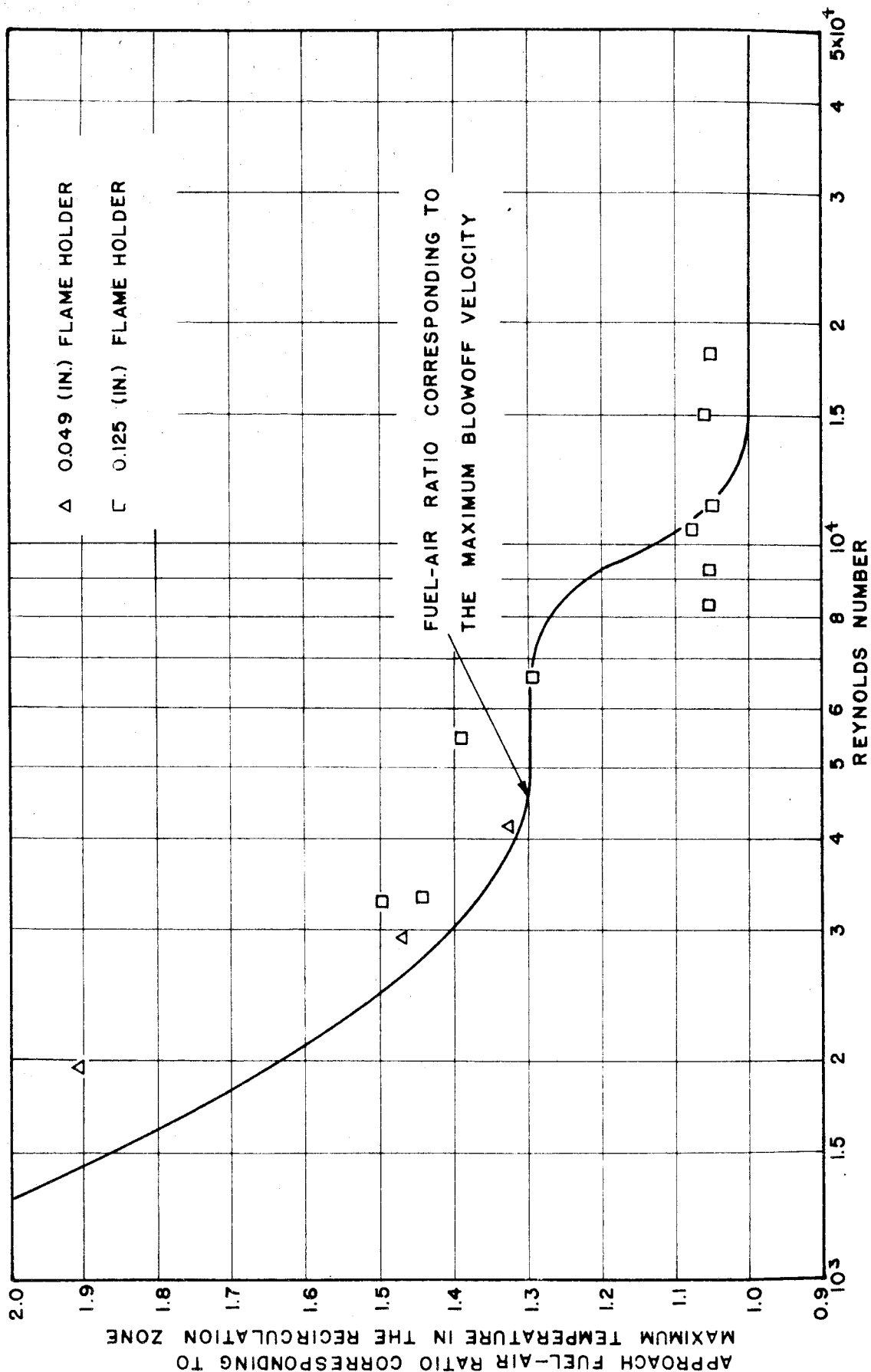


FIGURE 10. APPROACH FUEL-AIR RATIO CORRESPONDING TO THE MAXIMUM TEMPERATURE IN THE RECIRCULATION ZONE AS A FUNCTION OF REYNOLDS NUMBER