STABILIZED FLAMES IN HIGH - VELOCITY STREAMS OF PROPANE AND AIR

by

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Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

From the Massachusetts Institute of Technology
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Professor Joseph S. Newell
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Dear Sir:

Inclosed is the thesis entitled "Stabilized Flames in High-Velocity Streams of Propane and Air," which is submitted in partial fulfillment of the requirements for the Degree of Master of Science.

Respectfully,

Raymond F. Baddour

Lee D. Carr

ACKNOWLEDGMENTS

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A	air flow rate
C	proportionality constant
C_o	concentration of reacting materials
$\bar{C}_p$	average specific heat of gas
D	flame holder diameter
F	fuel flow rate, or fraction of gas burned
k_i	thermal conductivity
l_1	scale of turbulence, Lagrangean
l_2	scale of turbulence, Eulerian
n	characteristic flame holder dimension, or exponent on D
R	ratio of gas densities, burned to unburned
s	flame length
S_T	flame speed
S_L	laminar flame speed
T_b	temperature of burned gas
T_i	ignition temperature
T_o	inlet temperature
U	mean stream velocity
u, v, w	fluctuating velocity components in x, y, z directions
$\frac{u'}{2}, \frac{v'}{2}, \frac{w'}{2}$	turbulence intensity
$\overline{u^2}, \overline{v^2}, \overline{w^2}$	turbulence intensity
V_o	gas velocity at combustion chamber entrance
$V_{B.O.}$	gas velocity at combustion chamber entrance at blow-out
W_4	flame width at 4 inch station
W_t	chamber width
x, y, z	components of direction
Y_T	1/2 flame width
β	average reaction rate
[illegible]	thickness of flame front
σ	function
ν	kinematic viscosity
ρ_o	density of unburned gas

SUMMARY

Experiments were conducted to:

1. Determine the effects of the combustion chamber walls on the stability limits of blunt flame holders.
2. Extend the data of Scurlock on propane-air combustion using an improved propane feed-system.
3. Study flame stabilization and propagation using spherical flame holders and compare the results with those obtained using rod flame holders.

The tests were performed by burning homogeneous mixtures of vaporized propane and air in a combustion chamber of rectangular cross-section. The mixtures entered the chamber with a practically flat velocity profile and low turbulence level at velocities ranging from 25 to 300 feet per second. Stability limits and flame photographs were obtained using as stabilizers (a) rods which extended to the sidewalls, (b) shortened rods with hemispherical ends of length to diameter ratios from two to ten, and (c) spheres.

Over the range of diameters studied, the stability limits of rod flameholders were unaffected by the walls or the length of the flame holder so long as the length was at least twice the diameter. The spheres had stability limits appreciably lower than those of the rods. Propagation was the same for a rod extending to the sidewalls,

shortened rods, and a sphere, all at the same diameter.

The data for all of the rods were correlated satisfactorily by plotting $V_{B.O.}/D^{0.45}$ versus A/F. For spheres, correlating factors of the form $V_{B.O.}/D^{n}$ were not entirely satisfactory; however, a value of n equal to one was taken as a good average.

Diffusion of unburned gas into the flame front immediately behind the stabilizer appears to play an important part in the stabilization. Further studies of a fundamental nature on this phenomenon are recommended. Further investigations using three dimensional stabilizers, such as spheres and cones, should also prove valuable.

INTRODUCTION

THE PROBLEM

Modern high-output combustion chambers, such as the ram-jet and the turbo-jet, have presented a new and difficult problem in flame studies. The operation of these chambers requires the maintenance of a stable flame in a gas stream of relatively high velocity, the order of magnitude of which is several hundred feet per second. The conditions met in operation of the ram-jet are especially rigorous. Here the stabilizer is required to maintain in a high velocity gas stream a flame that will propagate to give essentially complete combustion in the chamber while providing a maximum pressure drop across the flame front consistent with a low frictional pressure drop due to the presence of the stabilizer. Until very recently, information of the most fundamental nature required to attack the problem was all but completely lacking. Work done lately, notably by Longwell (9) and Scurlock (13), has provided a sufficiently clear picture of the mechanisms of combustion involved in these high-output chambers to guide further investigations.

The general problem is the prediction of the results to be expected for a given fuel under specified conditions of operation with a given flame holder, or the choice of flame holder to operate satisfactorily under given operating conditions. Obviously, this requires the presentation of data in terms of variables that are not peculiar to any given fuel or flame holder. While correlations of results obtained thus far with properties considered to be the critical ones have not been entirely satisfactory, they indicate that the investigations were proceeding in the right direction.

COMBUSTION PROCESSES IN GENERAL

The term flame is applied to a rapid chemical change occurring in a thin layer separating burned gas from unburned gas, and almost always accompanied by luminosity. For practical purposes, distinction is made between two types of flames: the diffusion flame, in which the combustion process and the mixing process occur simultaneously; and the flame of premixed gases, resulting from the combustion of fuel mixed with the oxidant gas prior to entrance in the combustion chamber. This discussion is limited to the combustion of premixed gases.

Once a combustion process has been initiated, its propagation through the mixture proceeds with a velocity determined by two major factors. One is the factor of the gas flow depending on prevailing external conditions. The other is an entity characteristic of the gas mixture, i.e., the factor of flame propagation which remains after all influences on the flow have been eliminated. This is termed the normal velocity of flame propagation, or simply the flame velocity. If no turbulence exists in the region of combustion, this velocity is the laminar flame velocity.

A stabilized flame is one which is held stationary in space relative to some object. This object may be termed the flame stabilizer or flame holder. A familiar example of a flame stabilizer is the ordinary Bunsen burner. While a Bunsen tube will not stabilize a flame if the average velocity of the gases passing through the tube exceeds 5 to 10 feet per second, and the stabilizers to be investigated must operate in gales of several hundred feet per second, the underlying principles by which a Bunsen tube stabilizes a flame are essentially those operating in all stabilizers. It seems desirable, therefore, to discuss the relatively simple method by which a Bunsen burner tube stabilizes before proceeding to the more difficult stabilizer types.

THE BUNSEN BURNER

From previous discussions, it may be seen that for an object to stabilize a flame, it must provide a region in which the velocity of the gas does not exceed the flame velocity in that region. This low-velocity region is produced in a Bunsen tube by the natural velocity gradient which exists in a gas flowing through a tube. Thus, a stabilized Bunsen flame is obtained when the gas velocity at some point near the burner rim and just above the orifice is equal to the flame velocity at this point. On either side of this region, the gas velocity exceeds the flame velocity (except at the burner rim where they both approach zero but at different rates). The combustion which occurs in this region where gas and flame velocities are equal serves as a constant source of ignition for the adjacent gas of higher velocity, and a stabilized flame is produced. Using this reasoning, Lewis and von Elbe (8) successfully correlated both blow-out limits and flash-back limits over a range of tube sizes with gas composition and the velocity gradient at the burner rim. It is possible to stabilize flames with a Bunsen tube only in a range of low gas velocities. By mounting a rod in the axis of a cylindrical burner tube, Lewis and von Elbe were able to stabilize flames at velocities higher than these critical for the tube alone. Attempts to correlate blow-out limits of this system with velocity gradient at the wire surface were not satisfactory, however, indicating a different mechanism is operative in producing the region where flame velocity and gas velocity are equal. It is believed that in this case, the region where flame and gas velocities are equal is in the vortices immediately behind the blunt end of the axially mounted rod.

From these data, two important facts are manifest. For a stabilizer to operate successfully, it must maintain a region in which the gas velocity does not exceed the flame velocity; the method by which a Bunsen burner produces this region is different from that by which an obstruction placed in a gas stream does so.

LAMINAR FLAME PROPAGATION

In the case of a laminar flame, propagation proceeds due to the transfer of heat by conduction and the diffusion of active atoms and free radicals from the combustion zone into the unreacted gases. There have been many attempts to relate the laminar flame velocity to the fundamental chemical and physical properties of the gas mixture involved. At best, the relations derived so far have just succeeded in providing a guide to making qualitative predictions about the changes to be expected in the laminar flame velocity when the quantities involved in these expressions are varied. The difficulty is due primarily to the complicated nature of the kinetics of almost all combustion reactions. Combustion nearly always involves a chain reaction with unstable intermediate products. These intermediate products are the active species which, combined with the heat energy of the gases, are the heart of the propagation mechanism. Unfortunately, the detailed knowledge of the formation and dissipation of these active species which is required to obtain an accurate expression for propagation rates has not been obtained. Previous workers, therefore, have been forced to derive expressions considering only the thermal aspects of combustion. That the results are qualitatively correct is due to the fact that both heat and molecular diffusion follow the same type of law.

The earlier equations derived from purely thermal considerations involve a quantity called the ignition temperature, T_i, which is some temperature intermediate between the inlet gas temperature, T_o, and the temperature of the burned gases, T_b. Below this temperature, the rate of reaction is presumed to be negligible, but once the gases reach the ignition temperature, it is assumed that combustion proceeds at a constant rapid rate which is dependent only on the initial condition of the gas and its fundamental chemical and physical properties. Bringing the active species theory into the argument would necessitate writing an equation for the condition of the gas when both the temperature and the concentration of active species have reached the point where reaction rate proceeds at some constant high value. Neglecting the active species is equivalent to assuming that the gas approaches the temperature and the concentration of active species critical for combustion at the same rate. Although this assumption is questionable, the equation derived using it will be discussed because experiments check it qualitatively.

The equation presented below is a form similar to that derived originally by Mallard and LeChatalier (10) and modified by Damkohler (4). The derivation is included in Scurlock's work and will not be presented here. Referring to Fig. 1, the gas approaches the flame front with the laminar flame speed, S_L. In the preignition zone, the temperature rises from the approach stream temperature, T_o, to the ignition temperature, T_i, by conduction of heat from the flame front into the unreacted gas. In the reaction zone, the temperature of the gas rises from the ignition temperature to the temperature of the burned gases,

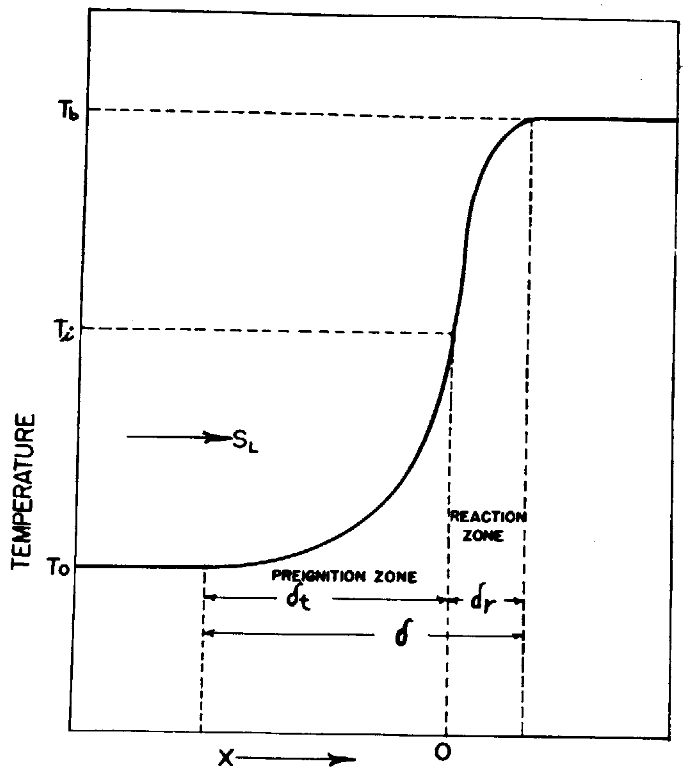


Fig. 1
Temperature Distribution in a Laminar Flame Front

T_b, by the combustion reaction itself which proceeds at an average rate $\overline{\beta}$. The remaining expressions involved are: k_i, the thermal conductivity of the gas at T_i, $\overline{C}_p$, the average heat capacity of the gas between T_o and T_i; ρ_o, the density of the unburned gas; b, a proportionality constant; and C_o, the concentration of reacting material. The equation for the laminar flame speed derived on the basis of strictly thermal considerations, then, is:

$$S_L = \left[\frac{(k_i) \quad (b)\overline{\beta} \quad (T_b - T_i)}{(\overline{C}_p \rho_o) \quad C_o \quad (T_i - T_o)} \right]^{\frac{1}{2}} \qquad (1)$$

The following general conclusions may be made on the basis of equation (1), and they have been verified experimentally (2), (3):

(1) The flame velocity increases with an increase in flame temperature, and drops to zero when the flame temperature is as low as the ignition temperature.

(2) The flame velocity increases with an increase in the inlet gas temperature.

(3) Flame velocity decreases with an increase in the heat capacity of the gas mixture.

(4) Flame velocity increases with an increase in the thermal conductivity of the gas mixture.

THE EFFECTS OF TURBULENCE ON FLAME PROPAGATION

Combustion in high velocity gas streams almost always occurs in the presence of turbulence. Since equation (1) contains the factors which affect the laminar flame speed, the effect of turbulence may well be illustrated by comparing the flame speed in a turbulent stream with the laminar flame speed for the same gas.

It is well known that turbulence serves to increase the rate of transfer of heat, mass, or momentum under conditions of fixed driving forces. The mechanism by which it does so is not so well known. The first difficulty met in a study of turbulence is obtaining a clear picture of turbulence itself. It is usual in the study of turbulence to separate the actual flow of the fluid into a steady flow and a superimposed turbulent flow. The method of separation is arbitrary and is performed in a manner that permits the simplest analysis of the case being studied. Turbulence, then, may be defined as the presence of random fluctuations of the velocity of the particles composing a fluid stream about an arbitrarily chosen steady velocity, usually the average stream velocity.

Reynolds (12) made the first detailed study of turbulence, and his work was later followed by that of Prandtl (11). The theory of turbulence which is in the most advanced stage at present is that based on a statistical approach. This statistical theory of turbulence was developed mainly by Taylor (15), von Karman (16), and Dryden (5). Since the present investigation is not concerned with quantitative turbulence studies, the following discussion of the results of the analysis of turbulent motion by statistical mechanics will be limited to a presentation of material sufficient to permit the use of the terms necessary to describe turbulent motion.

Turbulence is described quantitatively by two factors: intensity and scale. Assigning a mean velocity, U, in the x direction to the fluid in turbulent motion, the intensity of the turbulence is measured by the instantaneous deviations in velocity from U at any point. This deviating velocity has components u, v, and w in the x, y, and z directions, respectively. The root-mean-square values of these fluctuating components, $\sqrt{\overline{u^2}}$, $\sqrt{\overline{v^2}}$, and $\sqrt{\overline{w^2}}$ are referred to as the intensity of the turbulence and are generally designated as u', v', and w'. In the case of isotropic turbulence, these quantities are equal. Turbulence intensities are usually reported as per cent turbulence, which is equal to (u'/U)(100).

Turbulence scale is a measure of the size or duration of the fluctuations and is more difficult to define. There are two common definitions used. The first method involves the introduction of the mixing length concept, the mixing length being analogous to the molecular mean free path of the kinetic theory of gases. This scale, l_1, is defined mathematically using the Lagrangian manner of describing flow by following the paths of fluid particles. Its value lies in the fact that for many cases it lends itself more readily to mathematical handling than does the scale defined by the second method. This second scale, l_2, is defined in the Eulerian system and may be thought of as proportional to the average diameter of an eddy. Taylor (15), who suggested both these methods for defining scale, also deduced that $l_1 = l_2/2$ merely by comparing values of the two reported in the literature. In practice, l_2 may be determined with relative ease, so that often derivations are made using l_1, and the experimentally determined value of l_2 substituted in the expression using the approximate relationship given above.

Expressions for the effect of turbulence on flame velocity have been derived for two limiting cases. The first equation is derived for the case when the scale of the turbulence is very small in comparison with the thickness of the flame front. In this case, the only effect of turbulence should be to increase the rate of transfer of heat and active species through the preignition and reaction zones. From equation (1), S_L was found to be proportional to the square root of the thermometric conductivity:

$$\sqrt{\frac{k_i}{\bar{C}_p \rho_o}}$$

The introduction of turbulence increases this molecular transfer coefficient by an amount equal to the coefficient of eddy diffusivity, E, where E has been shown to be equal to $u\, l_1$ (15). The ratio of flame velocity in the turbulent stream, S_T, to the laminar flame velocity, S_L, may be expressed as:

$$\frac{S_T}{S_L} = \sqrt{\frac{\frac{k_i}{\bar{C}_p \rho_o} + u' l_1}{\frac{k_i}{\bar{C}_p \rho_o}}} = \sqrt{1 + \frac{u' l_1}{\frac{k_i}{\bar{C}_p \rho_o}}} \qquad (2)$$

The other limiting case is the one in which the scale of the turbulence is very large compared with the thickness of the flame front. Here the effect of turbulence on the flame velocity should be to increase the total area of the flame front by its distortion due to the fluctuating velocities in the turbulent stream. By assuming the distortions to be cone-shaped indentations in the flame front, the following expression was derived for the ratio of the turbulent flame speed to the laminar flame speed, which is equal to the ratio of the area of the cone to the area of its base:

$$\frac{S_T}{S_L} = \sqrt{1 + \left(\frac{u'}{2S_L}\right)^2} \qquad (3)$$

Actually, of course, neither of these extreme cases is realized in practice; a fluid in turbulent motion possesses a continuous range of scale sizes. Scurlock has combined both the above expressions into one which may be applied to the general case; this expression contains correction factors for the intermediate scale sizes where the radius of curvature of the cone tips is important:

$$\frac{S_T}{S_L} = \sqrt{\left[1 + \left(\frac{u'}{2S_l}\right)^2 \left(\frac{\frac{l_2}{\delta}}{K_1 \quad l_2/\delta}\right)\right]\left[1 + \left(\frac{\frac{k_i}{\bar{C}_p \rho_o}}{c u' l_2}\right)\left(\frac{1}{1 + \frac{l_2}{K_2 \delta}}\right)\right]} \qquad (4)$$

S_L

In this expression, K_1 and K_2 are constants, δ is the thickness of the preignition and reaction zone, and cl_2 has been substituted for l_1.

SUMMARY OF RECENT WORK

Flame studies may be conveniently divided into studies of flame stabilization and of flame propagation. Both Longwell and Scurlock have made studies of a fundamental nature on stabilization, and Scurlock has also studied flame propagation.

Work on Flame Propagation by Scurlock

Scurlock has studied the flames of high speed gases under carefully controlled conditions to obtain information of a fundamental nature about the mechanisms of propagation and stabilization. His experiments were performed with a homogeneous mixture of air and a gaseous fuel, either Cambridge city gas or commercial propane. He studied the effects of varying:

1. Air-fuel ratio
2. Combustion chamber entrance velocity
3. Turbulence in the entering gas stream
4. Flame stabilizer size and shape

Considering just the hydrodynamics involved in the flow of gases through the chamber during combustion, differential equations were set up for mass and force balances across the flame front. Although the equations could not be solved analytically, they were resolved by stepwise calculations. All the terms involved in the final equations were put on a reduced basis, so that by specifying just the ratio of the density of the unburned gas to that of the burned gas, a complete set of calculations could be made giving flow conditions throughout the chamber. The calculations were performed for a range of density ratios, and from the results the flame fronts were constructed showing gas flow into and out of the flame front for both the case of a rectangular chamber with combustion proceeding from a line and the case of a cylindrical chamber with combustion proceeding from a point. While a number of simplifying assumptions were necessary to permit solution of the problem, undoubtedly the one warranting the most critical consideration when applying the results obtained in the theoretical calculations to an actual case of combustion of high velocity gases is that no momentum transfer occurs normal to the direction of flow. As stated previously, combustion in these cases is nearly always accompanied by turbulence with a rapid momentum transfer. Several important general conclusions may be drawn from the calculations, however, concerning the flow in the chamber during combustion:

1. Velocity gradients are generated due to the combustion process itself. Assuming no pressure gradient to exist in the chamber cross-section normal to the gas flow, this would be due to the fact that the less dense burned gases are accelerated more rapidly than the denser unburned gases surrounding them. This velocity difference in adjacent gas streams was manifest experimentally in many cases by

the severe turbulence generated in the flame front.

2. Pressure drop across the chamber for a given heat release rate is greater when combustion proceeds downstream from a stabilizer than if heat is added uniformly across the cross-section. This fact should be considered in designing a combustion chamber or in using the pressure drop across a chamber as a measure of the completeness of combustion within the chamber.

3. The gas flow lines have a velocity component away from the flame front before entering it, and a component toward the center of the chamber after passing through the flame front; after combustion is complete, the flow lines become parallel to the axis of the chamber.

It is also possible from these calculations to determine the fraction of the gas burned, F, from the flame width, W_r, measured at some point above the stabilizer and from this to calculate the flame velocity by means of the following equation in the case of a rectangular chamber:

$$S_f = \frac{V_o Y_t F}{s} \qquad (5)$$

In this case, S_f is an average flame velocity over the length of flame front between the stabilizer and the point where the flame width was measured; Y_t is one-half the flame width and s is the flame length measured along the flame front between the stabilizer and the point where the flame width was measured.

Using the results of the stepwise calculations combined with those obtained from a study of flames by various photographic methods, Scurlock obtained a picture of the structure of a propagating flame downstream from the stabilizer. Referring to Fig. 2, the flame is divided into three major regions for the purpose of this analysis. The first is a region of relatively small extent just downstream of the stabilizer. The size of this region varies somewhat with the gas mixture, the chamber entrance velocity, and the stabilizer size, but its length is of the order of an inch and is effected but slightly by the size of the stabilizer over the range studied; the width is approximately that of the stabilizer. This is a region of low-velocity gases and contains the recirculating eddies which act to stabilize the flame. Therefore, when this region is turbulent, the eddies loop inward toward the region of lower velocity, forming what Scurlock has termed reverse eddies. The flame front in this region is laminar over a wide range of conditions, irrespective of the condition of the flame front farther downstream. The conditions which affect the stability of the flame front in this region, then, are those which affect the velocity gradient at the front and the distance over which this gradient acts, this distance being known as the fetch. An increase in the chamber entrance velocity would increase the velocity gradient; low values of R_ρ and of the laminar flame speed tend to increase the fetch since this would decrease the acceleration of the burned gases, which acceleration produces the velocity gradient. Approach stream turbulence also has a noticeable effect in hastening the generation of turbulence in this first region.

As combustion proceeds downstream from the stabilizer and the burned gases are accelerated, the velocity gradient generated in the

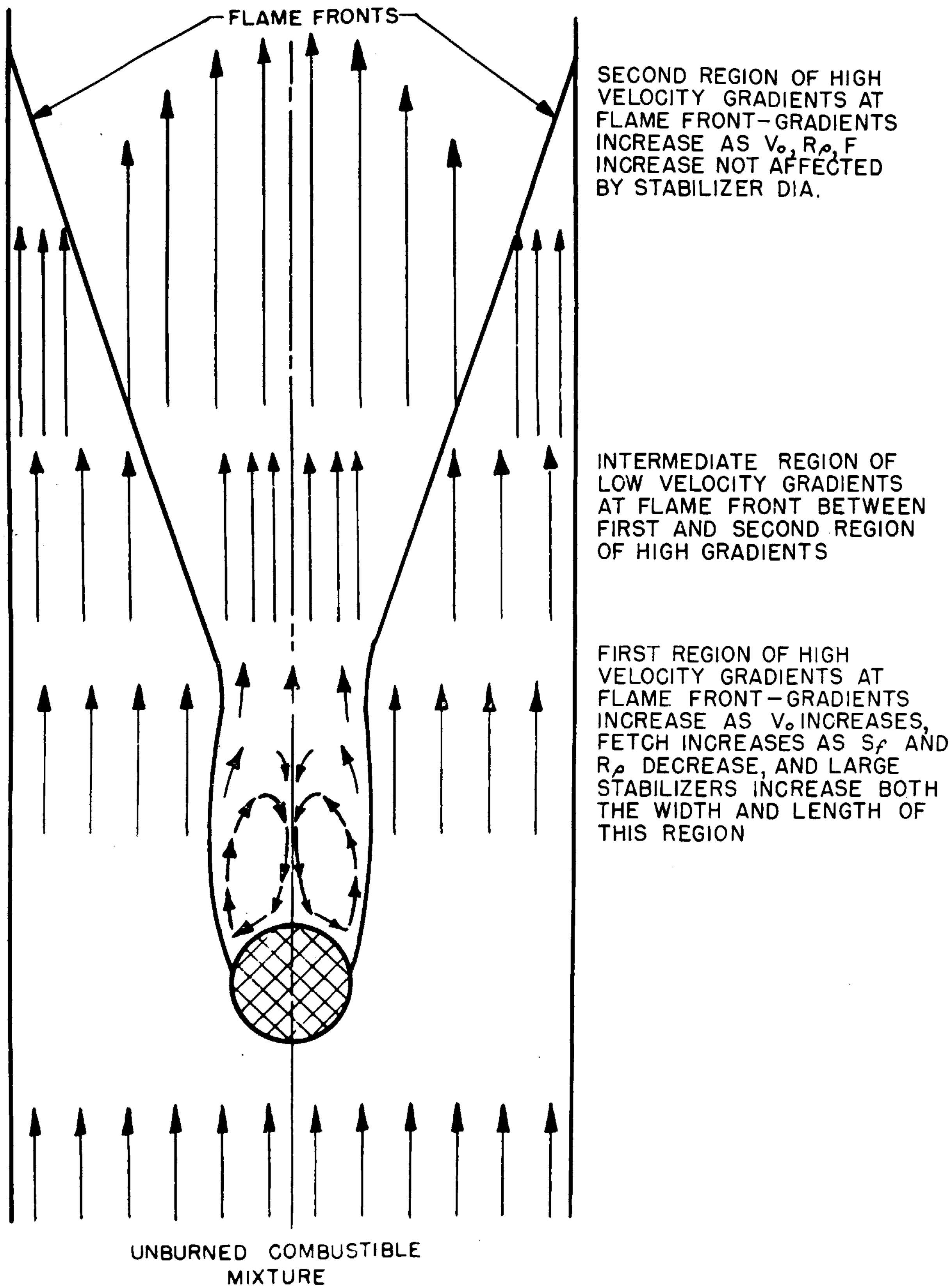


Fig. 2

Schematic Representation of Regions of High Velocity Gradient at Flame Front first region reaches a minimum at some intermediate point; as combustion proceeds beyond this point, a velocity gradient is generated in the reverse direction due to the acceleration of the burned gases to a velocity exceeding that of the surrounding unburned gases. When this gradient is of sufficient magnitude, eddies are formed which loop outwards, away from the flame front; these are termed regular eddies. The conditions favorable for increasing the instability in this second region of high velocity gradient are those which tend to cause an increased velocity of the burned gases relative to the unburned gases and an increased fetch. Higher relative velocities of these burned gases obtain at high values of R_ρ and of F, the fraction burned. An increased fetch was observed to exist at high values of V_o/S_1. The width of the chamber, W_t, and the entrance velocity, V_o, would also be expected to have an effect on the formation of turbulence in this region. No effect of stabilizer size on the formation of gradients in this region was detected. The aforementioned effects are of such a high magnitude in determining the condition of the flame front in this region that the effects of approach stream turbulence are all but completely masked by them. Only in the case of closed-edge gutter stabilizers could an effect of approach stream turbulence be definitely established.

Flame Stabilization (Scurlock)

Using a 3 x 1 inch rectangular combustion chamber, Scurlock studied the stabilization characteristics of blunt objects in city gas and propane-air streams. Blow-out limits of flames stabilized on cylindrical rods, V-gutters, and flat plates of various diameters and widths were determined as a function of gas stream velocity (chamber entrance velocity), stabilizer characteristic dimension, and stream composition (air-fuel ratio, pounds per pound). Stabilizers were mounted wall-to-wall with the major axis normal to the stream of gas. The apparatus was constructed to permit accurate control of the turbulence level.

By a heat balance across the eddy boundary the following equation was derived for the velocity at blow-out:

$$\frac{V_{B.O.}}{n\left(\frac{e'}{e'-g'}\right)} = \left[\frac{K'S_L\ (T_b-T_o)}{\gamma^{g'}\ (T_i-T_o)}\right]^{\frac{1}{e'-g'}} = \phi'\left(\frac{A}{F}\right) \qquad (6)$$

From the results of his investigation, Scurlock made the following conclusions on stabilization:

1. Equation (6) applies when the stabilized flame blows off the holder.

2. The mechanism of flame stabilization behind bluff objects is different from that of Bunsen flames. When a stabilized flame is present, the eddy region behind the bluff stabilizer is filled with hot combustion products which furnish a continuous source of ignition for the unburned approach gases coming

into contact with them. Because of the absence of an eddy region a flame will not stabilize on a streamlined object at approach gas velocities in the range of interest for high-output systems.

3. In accordance with Eq. (6), blow-out limit data obtained with stabilizers ranging in characteristic dimension from 0.016 to 0.5 inches were found to correlate fairly well when $V_{B.O.}/n^{0.45}$ was plotted against air-fuel ratio. The points scattered slightly on the lean side at low velocity, however, and this was attributed to the cooling action of the stabilizer on the eddy region. It has been suggested that a second term be added to the left-hand side of Eq. (6) to take this effect into account by correcting for conduction through the stabilizer. If the stability-limit data of Longwell and of Lewis and von Elbe are plotted as $V_{B.O.}/n^{0.45}$ versus generalized oxidant fraction, correlations thought to be as satisfactory as those originally obtained by these investigators using other methods of correlation were obtained.

4. The effect of stabilizer shape on the stability limits is negligible for the bluff stabilizers employed: rods, 30^{o} open and closed edge gutters, and flat plates.

5. Heating or cooling the stabilizer greatly influences the stability limits. Electrical heating of the stabilizer extends the stability limits considerably, and these limits are narrowed when the stabilizer is cooled by circulating water through it.

6. The stability limits for a given size stabilizer are unaffected by chamber width over the range of simulated chamber width to stabilizer characteristic dimension ratios studied (78.9 to 9.87) as long as the flow remains steady.

7. Values of $V_{B.O.}/n^{0.45}$ are apparently a direct function of S_L and (T_b-T_o), as indicated in Eq. (6). However, at least one of the other quantities on the right-hand side of Eq. (6) must also vary with different fuels, since correlation of the city gas-air and propane-air stability-limit data is not obtained by plotting $V_{B.O.}/n^{0.45}$ (S_L) (T_b-T_o) versus generalized oxidant fraction.

8. Increasing turbulence intensity decreases the stability limits, with the effect of turbulence of a given scale and intensity becoming less as the ratio of stabilizer diameter to scale increases.

Flame Stabilization (Longwell)

Longwell, using Napthalene gas and air, studied flames stabilized on symetrically shaped bluff objects mounted on the axis of a 6 inch cylindrical pipe. His system differed, essentially, from that of Scurlock in three ways:

1. Stabilizers were symetrical disks, cones, etc. which did not reach the walls of the combustion chamber.

2. Fully developed turbulent flow was at all times present upstream of the stabilizer.

3. The stabilized flame exhausted into free air and never reached the combustion chamber walls.

The data were plotted and correlated with the same variables as were used by Scurlock. All of Longwell's data correlated fairly with the plot

$$\frac{V_{B.O.}}{n} = \phi\ (A/F)$$

OBJECT OF THE INVESTIGATION

Attempts made to correlate the data of Longwell and Scurlock on the same basis were not successful. Opinions were advanced by each author to account for the discrepancies but concrete evidence was lacking.

In all of the tests made by Scurlock, stabilizers were used which extended to both the Vycor glass sidewalls of the combustion chamber. There was a possibility, then, that the slow moving film attached to these walls might have an appreciable effect on the stability limits obtained. The hot gases in the eddy zone downstream of the stabilizers were also subject to a possible quenching effect, loss of heat and destruction of active species, by the glass walls. One of the main purposes of the present investigation was to evaluate the effect of the sidewalls on the flame stabilization.

The commercial propane (PANESSO) used in Scurlock's work was of a rather low purity. It was obtained from the Colonial Beacon Oil Company and an analysis by the Boston Esso Laboratory of a sample from one of the bottles used gave the following composition by volume:

Propane	83.8%
Propylene	13.3%
Ethane	2.4%
Butane	0.5%

Propane was admitted into the apparatus by permitting it to distill from the containers. Although only about the top 15% was used from each bottle, the composition from run to run might have changed sufficiently to account for the more erratic results obtained with propane compared with those obtained with Cambridge city gas. Another purpose, then, was to check Scurlock's work with an improved propane feed system.

In an effort to gain a more complete understanding of the mechanism of stabilized combustion, a third program was initiated to compare stabilization and propagation characteristics of spheres, so-called three dimensional stabilizers, with those of rods, comparably denoted as two dimensional stabilizers.

PROCEDURE

The two dimensional type rod stabilizer used by Scurlock was shortened by a series of length increments from a 1 inch rod to a sphere, a shape similar to that used by Longwell. A series was composed of rods, 1, 7/8, 3/4, 5/8, and 3/8 inches in length, and a sphere of a diameter equal to that of the rods. Fig. A-5 illustrates the configuration and method of mounting for each test stabilizer. Each of the shortened rods was subjected to blow-out tests over a range of velocities and air-fuel ratios to determine the characteristic stabilization limits curves. Two rod series, 0.1005 and 0.188 inch diameter, and two additional spheres, 0.210 and 0.510 were thus tested in streams of low turbulence level.

Photographs of the stabilized rich, lean and stoichiometric flames on the 0.188 inch rod series were taken at velocities of 25, 50, 100, 150 and 200 feet per second. The negatives used were in the determination of flame width at the 4 inch station downstream of the stabilizer.

Prior to the experimental work, it was believed that:

(a) The data obtained in this manner would reveal the presence, effect, and extent of influence of the wall boundary layer interaction and the quenching of eddy zone;

(b) Comparison of the data of Scurlock for equal sized rods might indicate the effect of varying fuel composition;

(c) Study of photographs and plots might throw light on a possible explanation for the discrepancies between two and three dimensional stabilizers.

The experimental apparatus used is schematically illustrated in Fig. 3. The system was essentially the same as that used by Scurlock, modified, however, to insure fuel feed of a constant composition. Following the flow diagram from left to right, air and propane under pressure were metered and piped to a common control point. The streams were then mixed and fed through a calming section to the combustion chamber. Flame was initiated on the stabilizer by a sparking device and the burned gases exhausted through a stove pipe duct to the test cell ventilation system. Fig. 4 is a composite photograph of main elements of the apparatus. Details of the apparatus and experimental technique are located in the Appendix.

No external control was exercised over the humidity of the inlet air. However, interstage and outlet surface coolers in the compressor were maintained at about the same temperature throughout all the experimental runs. Pressure and temperature levels, therefore, remained fairly constant in the air surge and storage tank at all times and a blow-down of the sump at the end of each operating period revealed condensate. For this reason it is believed that the variation in feed air humidity was small.

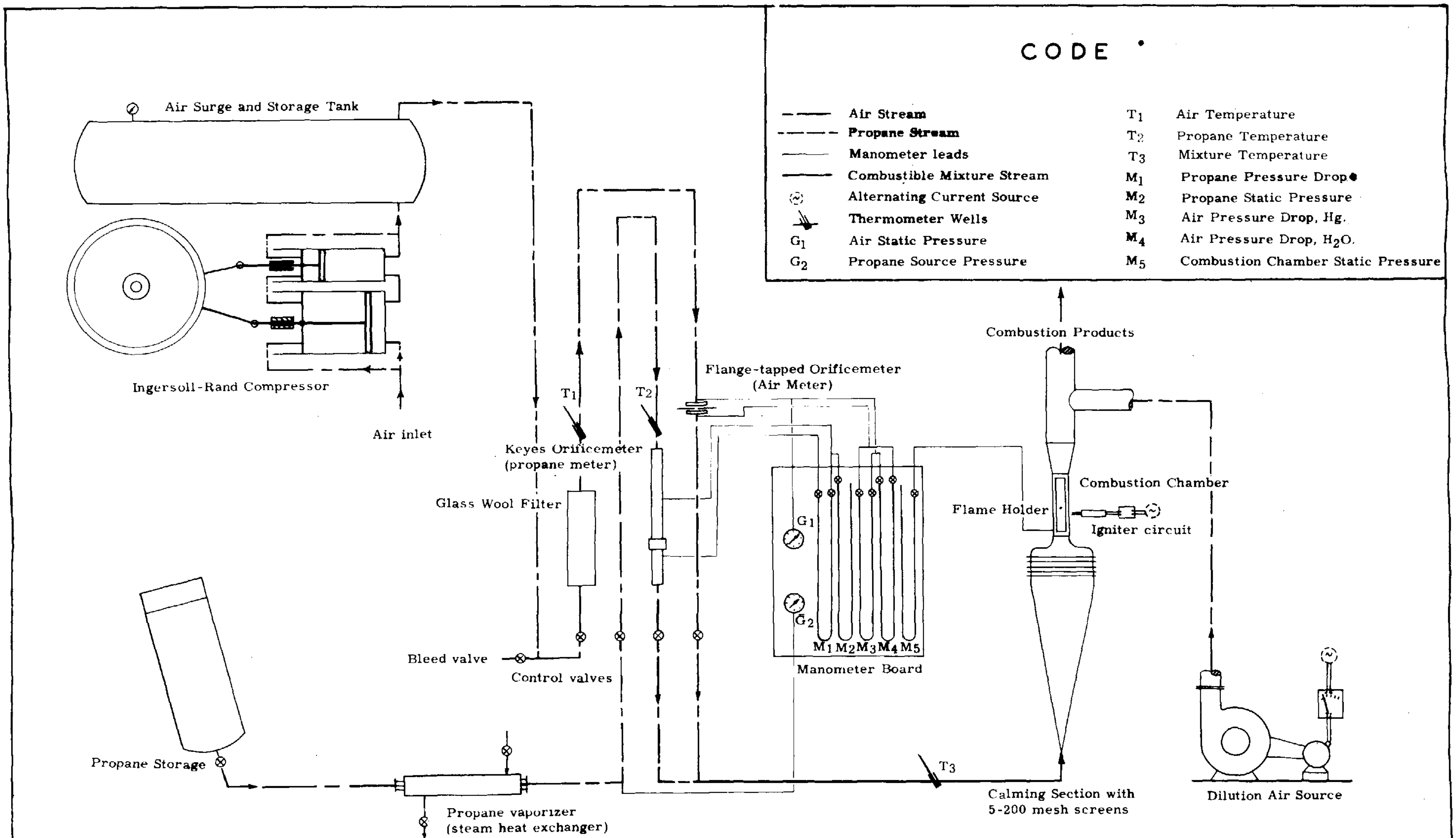
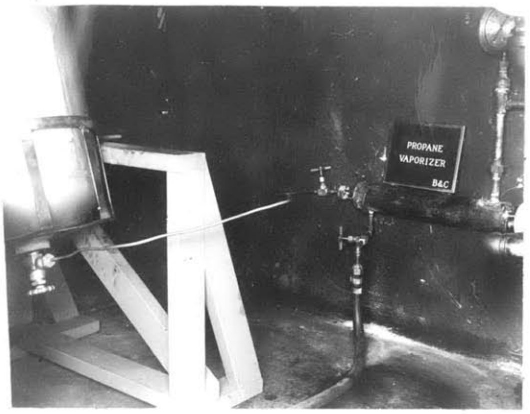
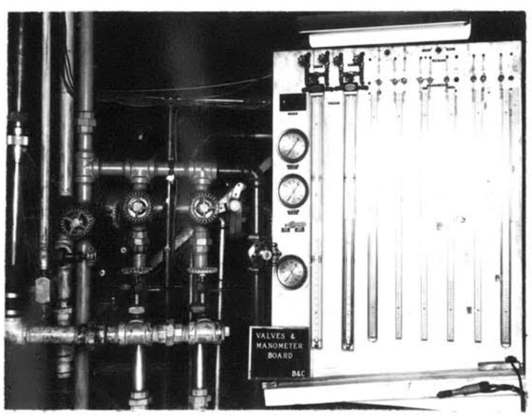


Fig. 3

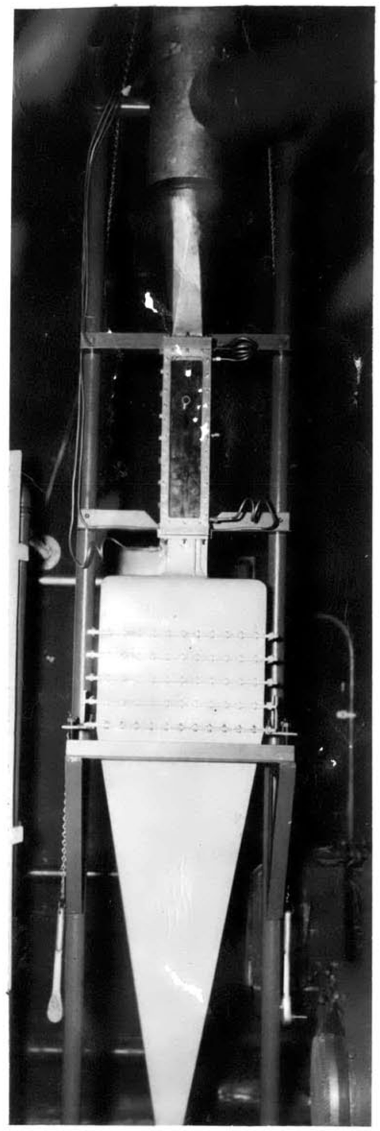
SCHEMATIC DIAGRAM OF APPARATUS



(b)
Propane Vaporizor



(a)
Valves and Manometer Board



(c)
Calming Section and
Combustion Chamber

Fig. 4
The Main Apparatus

RESULTS AND DISCUSSION OF RESULTS

Blow-out Limits for the Two Series

In Figs. 5 and 6 are presented the stability limits for the two stabilizer series, the 0.100 inch diameter rod series and the 0.188 inch diameter rod series, respectively. In Fig. 5, there is no detectable difference in the trends of the stability limits for the shortened rods and the rod which extends to both glass sidewalls, in the rich range. At stoichiometric, the limits peak at slightly different velocities and air-fuel ratios for the different rods, but the difference is not entirely systematic, for the two shortened rods of intermediate length have the highest stability limits. On the lean side, the trends again come together except for the 3/8 inch rod which is displaced slightly to the left over most of the range. For the 0.188 inch series, the trends are much the same for the different rod lengths except for the 3/8 inch rod which has a slightly but consistently lower stability limit. The line for the 1 inch rod on the lean side is dotted because it is based on two points only and the accuracy of its location is doubtful. On this basis, it is concluded that over the range of length to diameter ratios covered, from ten to two, there is no appreciable difference between the stability limits for a rod flame holder which extends to the sidewalls and a shortened rod of the same diameter; a consistent and detectable slight lowering of the stability limits appears, however, at a ratio of two. These data would indicate that the glass sidewalls

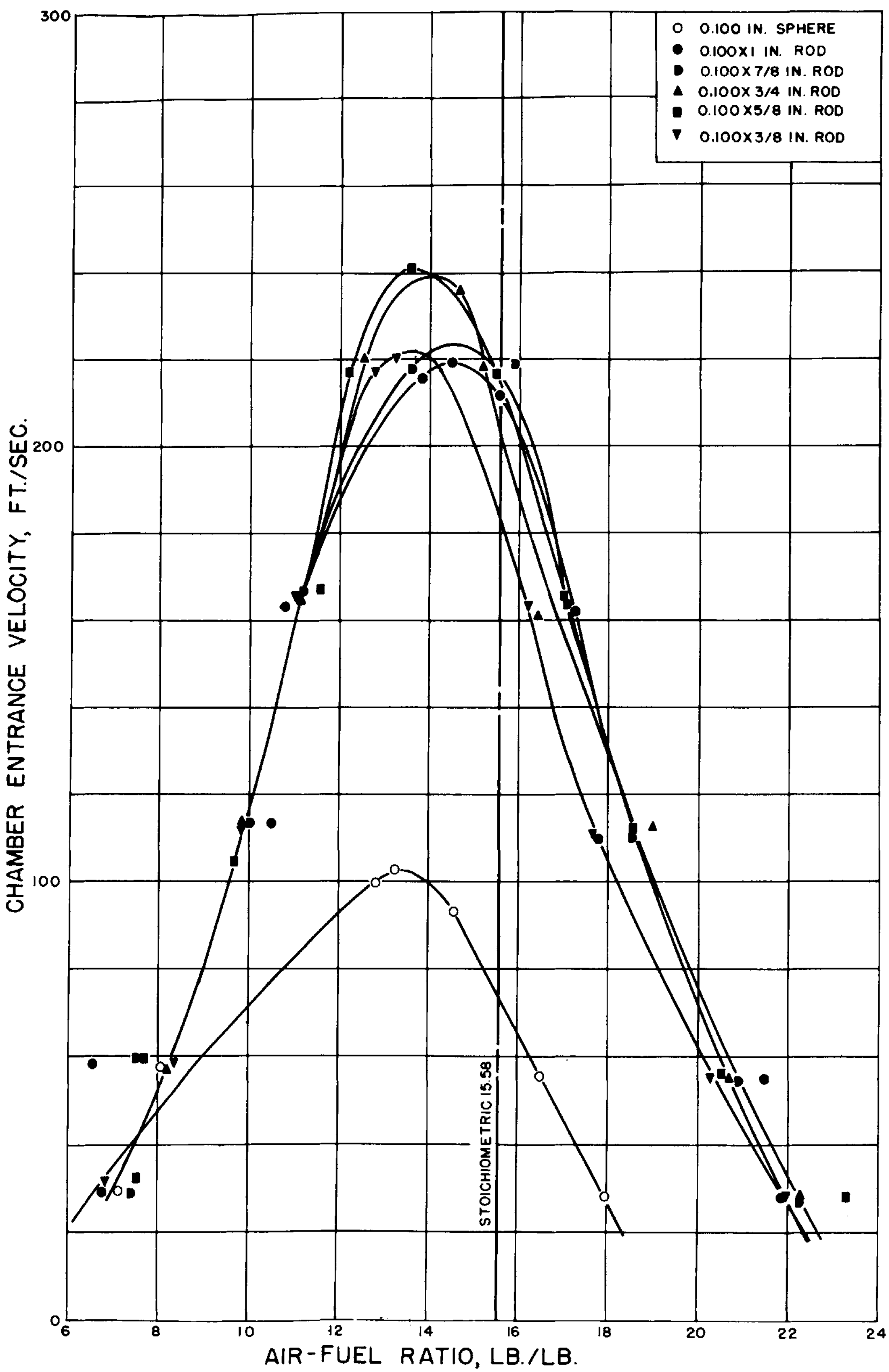


Fig. 5

Stability Limits for 0.100 inch Rod Series

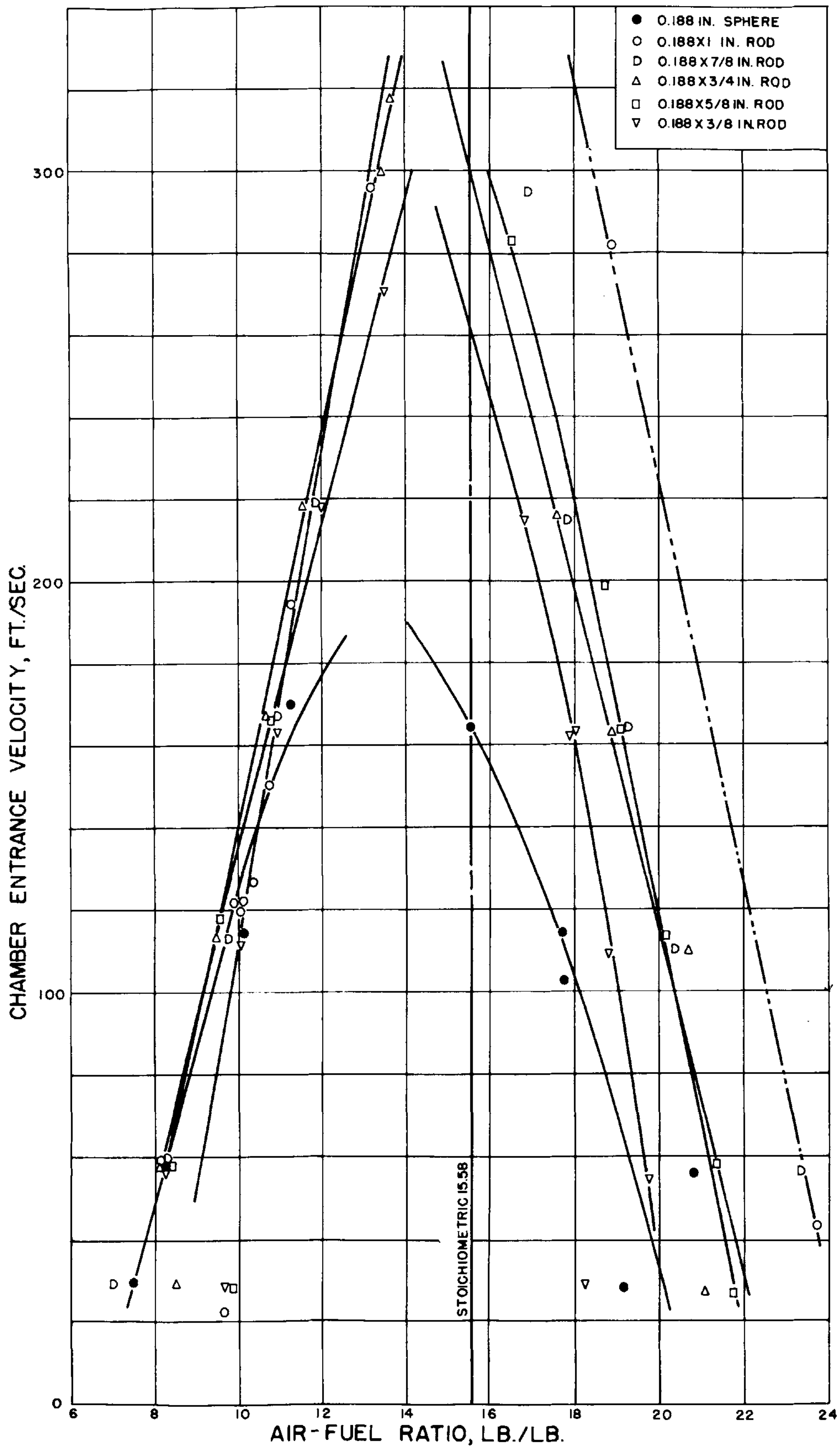
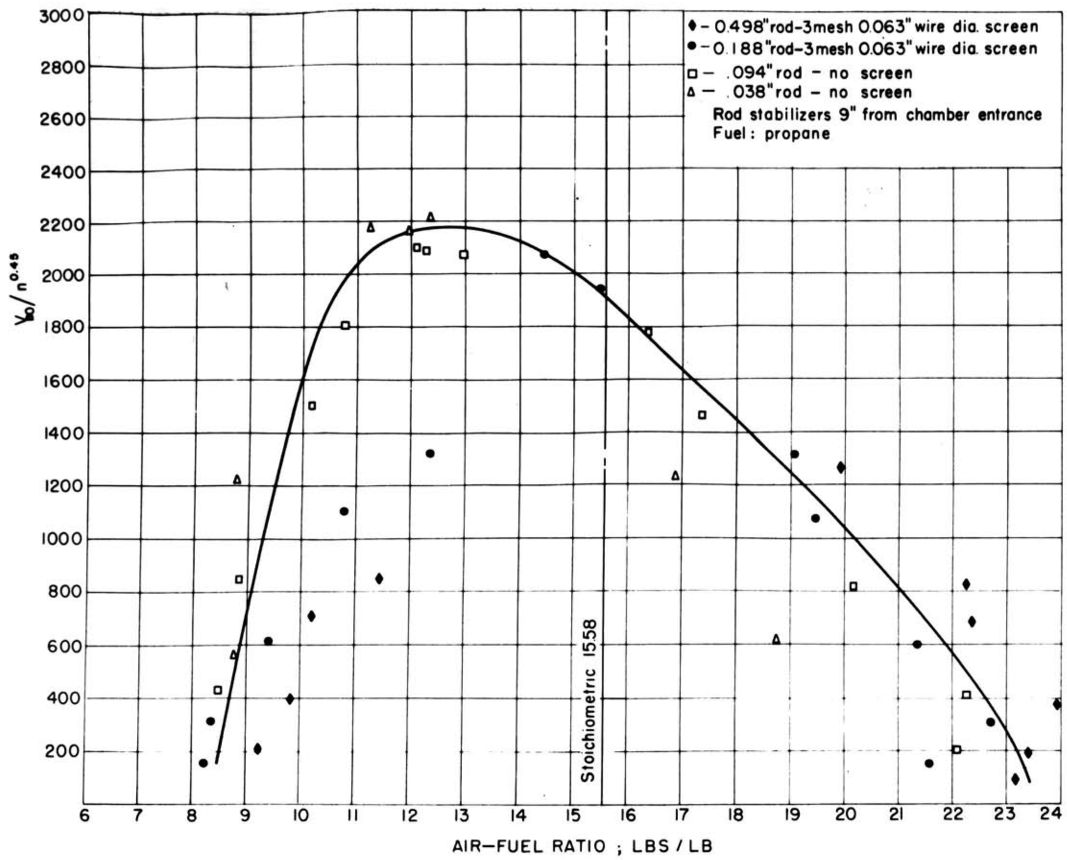


Fig. 6
Stability Limits for 0.188 inch Series

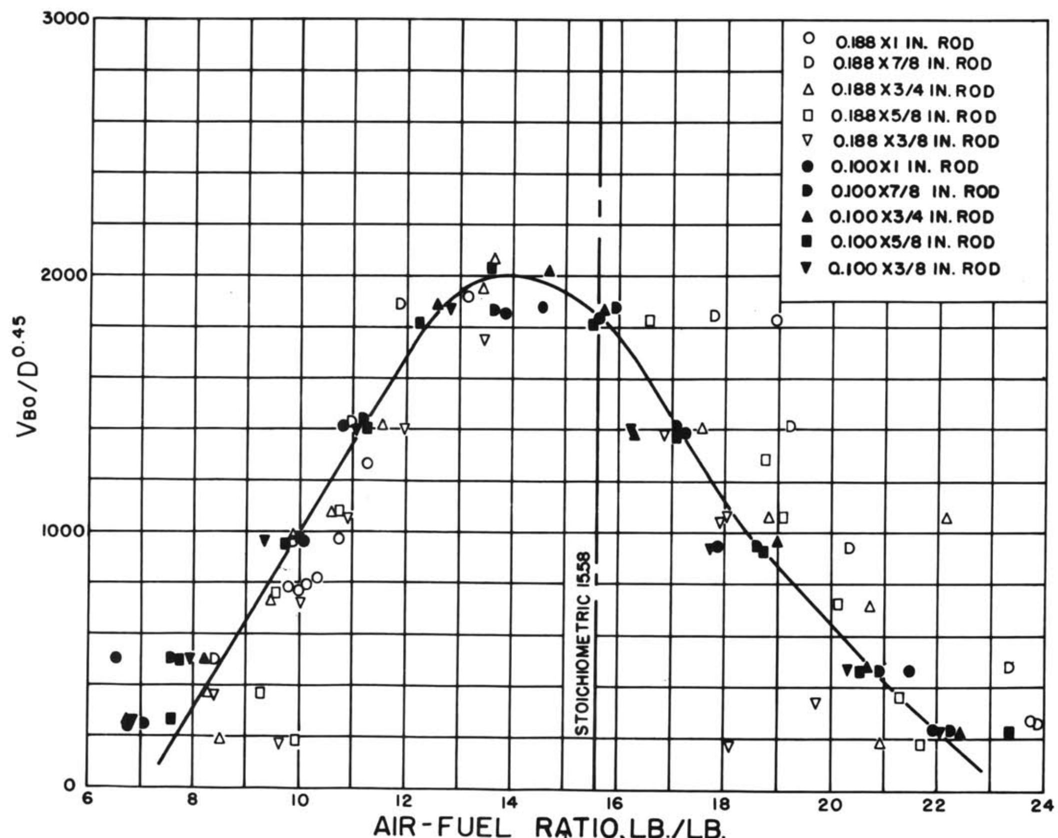
have no significant effect on the stability limits of flame holders mounted flush against their sides. The slightly higher stability limits of the 0.100 inch series shortened rods might be attributed to the removal of the eddy zone from the quenching effect of the wall. Doubt as to the exact location of the curves at the peaks precludes a positive statement. Another possibility is that the walls do have an effect which is exactly equal to the end effects of the shortened rods used for this test. This seems unlikely, since the magnitude of the end effects would be expected to vary with the rod diameter while the effect of the wall should remain relatively constant.

The generalized correlation which Scurlock obtained for rods of various diameters by plotting $V_{B.O.}/n^{0.45}$ versus air-fuel ratio is shown in Fig. 7a. In Fig. 7b is shown the correlation of data obtained in this investigation for 1 inch rods and shortened rods using the same parameters. In both plots, the points for the larger diameter rods are lower on the rich side and higher on the lean side than those of the smaller diameter rods. Obviously this spreading cannot be resolved merely by changing the exponent of the rod diameter; for example, while increasing the exponent would group the points on the lean side, it would scatter still more the points on the rich side. This indicates that, although the correlation is satisfactory, a more exact correlation might be obtained if a factor were included containing both the diameter and the air fuel-ratio

The stability limits as plotted in Fig. 7a are generally higher than those in 7b. This discrepancy may be accounted for by the fact



a.



b.

Fig. 7

Generalized Correlation for Rods

that propane used in Scurlock's test consisted of the lighter ends which have a higher flame speed.

Stability Limits for Spheres

Spheres have a lower stability limit than rods of the same diameter, as illustrated by Figs. 5 and 6. The relative difference between the limits of the rods and the spheres is less for the 0.188 inch series than for the 0.100 inch series. It is not surprising that an increase in diameter should produce different results in the stability limits of rods and of spheres. From the discussion of flame stabilization already presented, it seems probable that both the volume of the eddy region immediately downstream from the stabilizer and the area of the flame front in this region are important in maintaining a stabilized flame. Whereas increasing the diameter of a rod increases essentially only the diameter of the eddy region, increasing the diameter of a sphere increases both the diameter of the eddy region and its circumference, providing a relatively greater increase in the area of the flame front in this region. Thus, an increase in the stabilizer diameter produces a greater change in surface area per unit volume of eddy for spheres than for rods. That the spheres act differently is illustrated graphically in Fig. 9, which presents the correlation of the blow-out limits, shown in Fig. 8, obtained for spheres of four different sizes. In Fig. 9b, $V_{B.O.}/D^{0.45}$ is plotted versus air-fuel ratio, the same parameters used successfully in correlating the data for rods. Several different trends are distinguishable. In Fig. 9a, $V_{B.O.}/D$ is plotted versus air-fuel

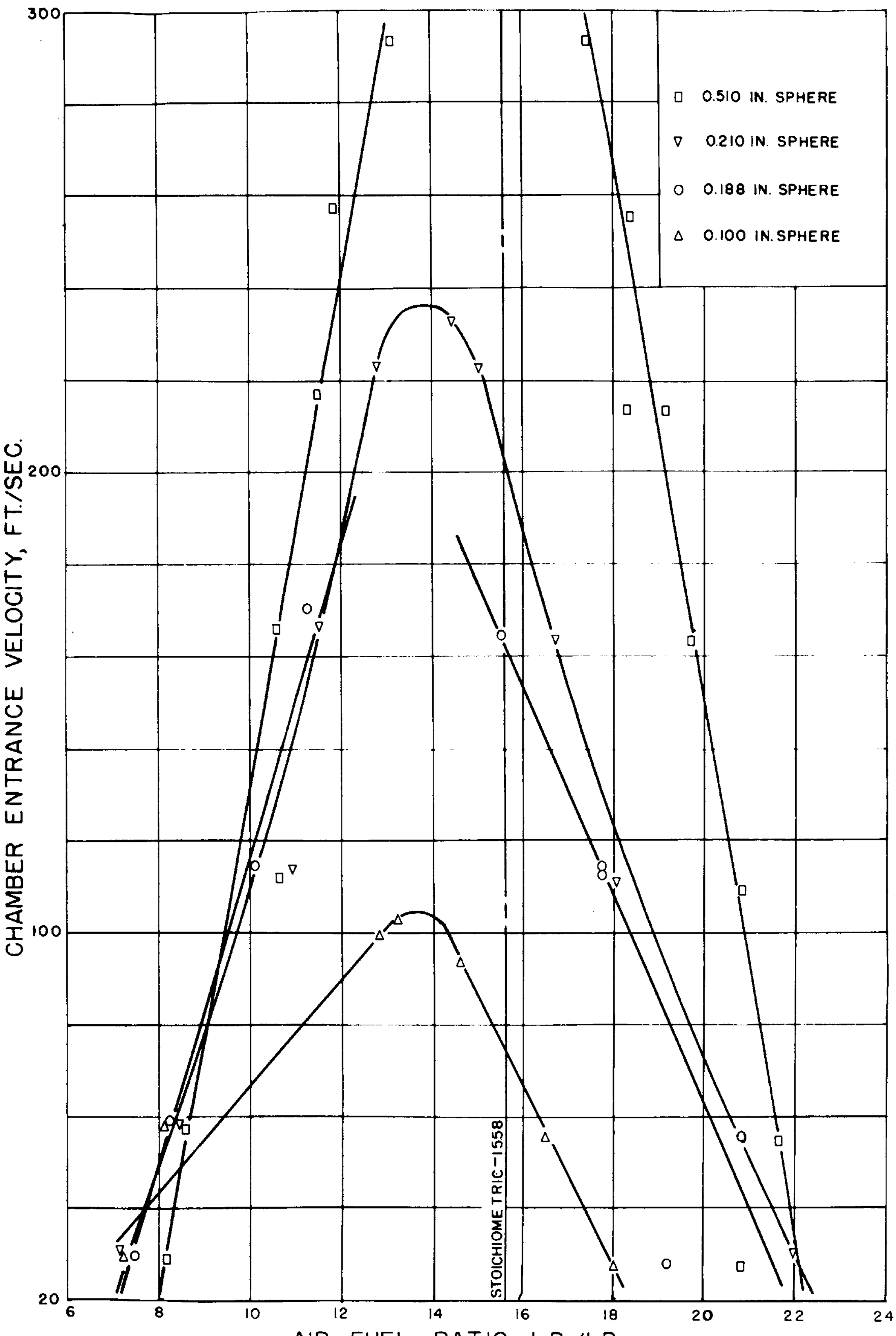
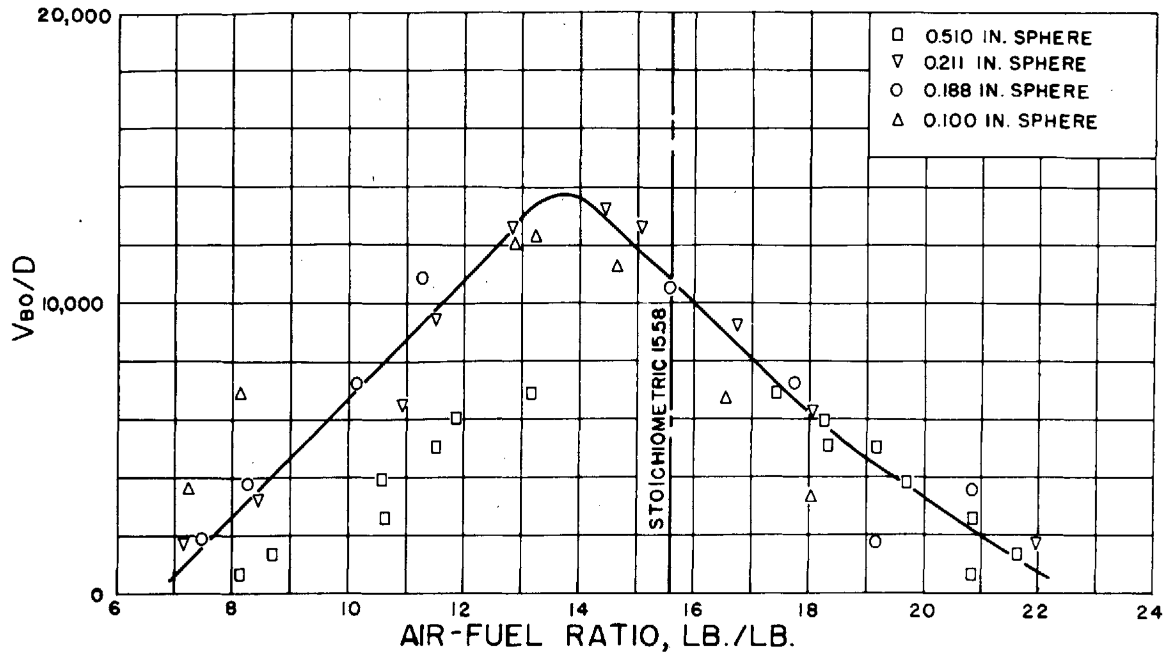


Fig. 8
Stabilization Limits for Spheres



a.

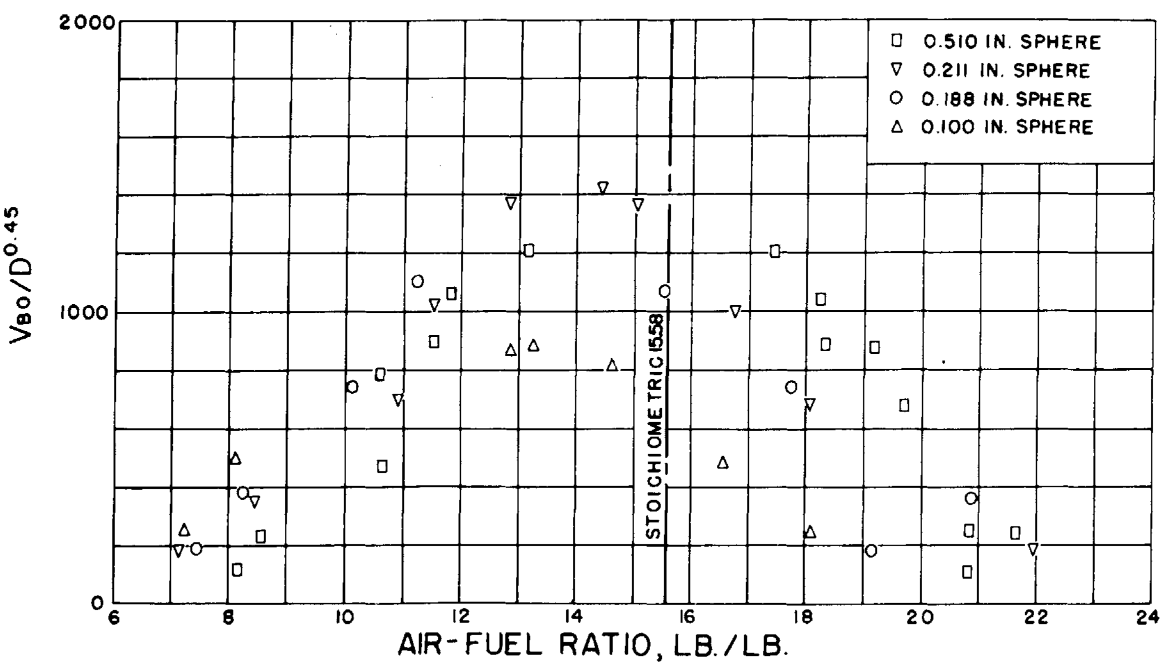


Fig. 9 b.

Comparison of Two Generalized
Correlations for Spheres

ratio, and the correlation is improved, especially in the stoichiometric and lean region. Actually, the first power for D was used as a compromise, for it was found that the 0.75 power best correlated the rich side and the 1.25 power best correlated the lean.

Flame Propagation Behind Rods and Spheres

In Fig. 10 are presented a series of flame width curves for the 0.188 inch diameter shortened rods and the 0.188 inch diameter sphere at different stream velocities. On the same plots are shown the points obtained by Scurlock for the 0.188 inch diameter rod extending to the glass sidewalls. From the discussion of flame propagation in the Introduction, it was shown that the flame width is a measure of the completeness of combustion and, hence, of the flame propagation. From the curves in Fig. 10, it may be seen that flame propagation is unaffected by shortening the rod flame holder even to the point where it becomes a sphere.

That the points for the 1 inch rod fall beneath the curves may be explained by two factors. The first is that the propane used in Scurlock's test was the lighter ends of the mixture contained in the tanks and possibly exhibited a smaller $R\rho$, the effect of which is to reduce the turbulence in the flame front and lower the turbulent flame speed. The second is a difference in technique used to measure the flame widths. Scurlock measured flame widths directly on the negatives, whereas in this investigation the flame photographs were projected to full size and the flame width measured from the projection.

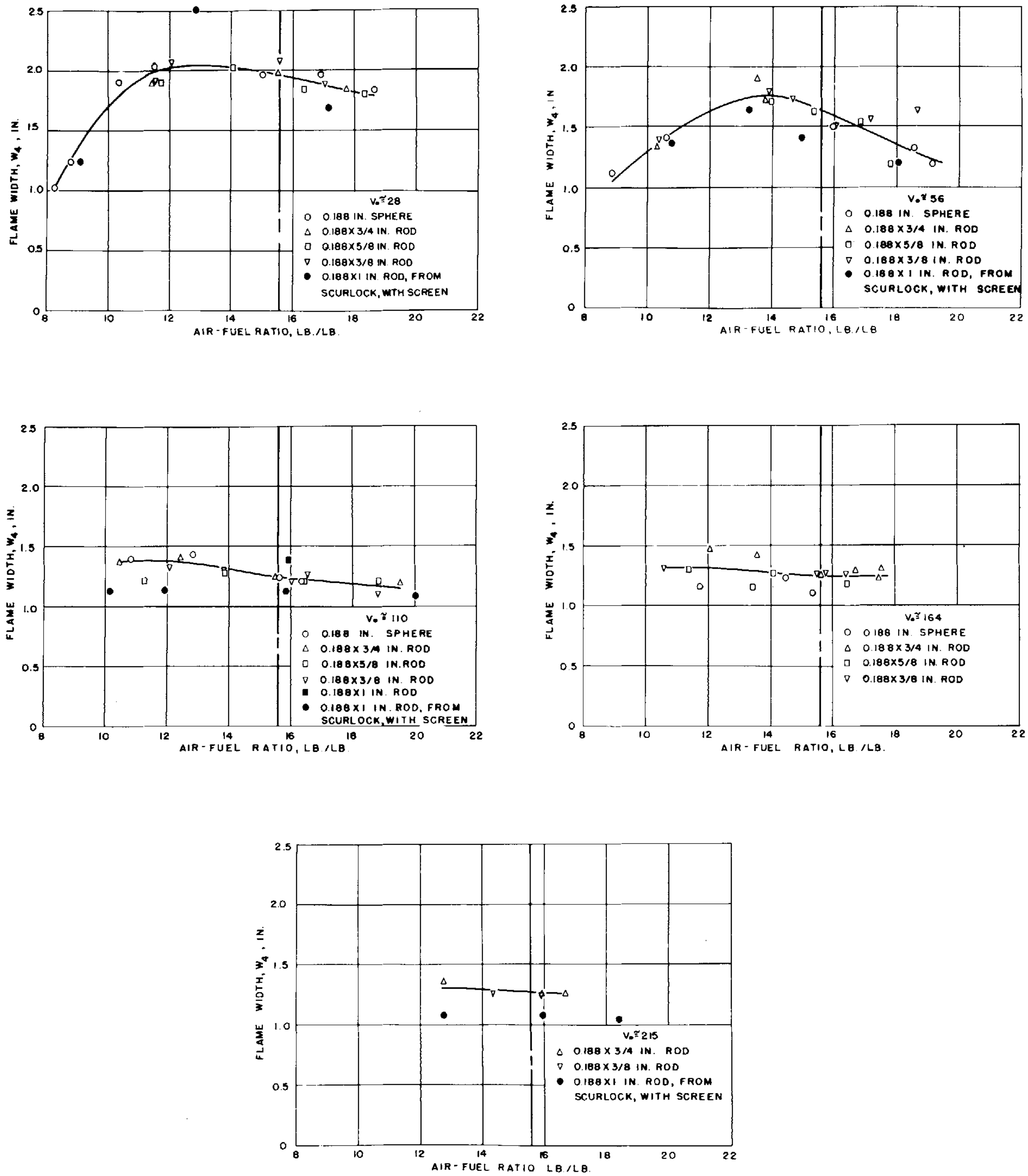


Fig. 10

Flame Width Curves for Rod Series and Spheres at Different Stream Velocities

Discussion of Gas Flow Into The Flame Front

If a combustible gas mixture should enter the combustion chamber with a flat velocity profile and burn in a flame front perpendicular to the direction of flow, all of the gas which entered the flame front would do so by flowing into it and its composition would be identical with that of the gas entering the chamber.

However, should the gas flow past a laminar flame front parallel to it, all of the gas that entered the flame front would do so by molecular diffusion and its composition would be determined by the concentration of the components of the gas adjacent to the front and their relative rates of diffusion into the front. At any point along the flame front, then, the composition of the gas entering the front would be different from the composition of the gas entering the chamber.

In the actual case of combustion behind a blunt object, the gas entering the laminar flame front immediately downstream from the stabilizer has one velocity component perpendicular to and the other parallel to the flame front so that its composition lies somewhere between that for the two hypothetical cases cited above. Since the gas burning in the recirculating eddy region behind the stabilizer is believed to be the source of continuous ignition for the flowing gas stream, it is the composition of the gas entering this region and not the composition of the gas entering the chamber, which is important in defining the stability limits. The argument that molecular diffusion of the unreacted gas into the flame front plays an important part in flame stabilization is supported by several observations, listed and discussed below.

Case 1. The Location of the Peaks of the Stability Curves

From Figs. 7 and 9, it may be readily observed that the highest blow-out velocities occur at gas mixtures richer than stoichiometric. This is inconsistent with the fact that higher laminar flame velocities are obtained at stoichiometric, as shown in Fig. 12. Since it is believed that at least a portion of the flame front just downstream from the separation point at the stabilizer is laminar over the entire operating range of velocities, this shift of the stability curve to the rich side appears to be a result of the entrance into this laminar front of a gas mixture leaner than that of the mixture entering the chamber. This is attributed to the fact that an appreciable portion of this gas enters the front by molecular diffusion, and the relatively high molecular weight propane diffuses slower than oxygen.

Case 2. Shift of the Stability Limits Curves With The Introduction of Turbulence in the Gas Stream Entering the Combustion Chamber

The effect of turbulence in the main stream on the laminar flame immediately downstream of the separation point is to shorten the flow distance over which the flame

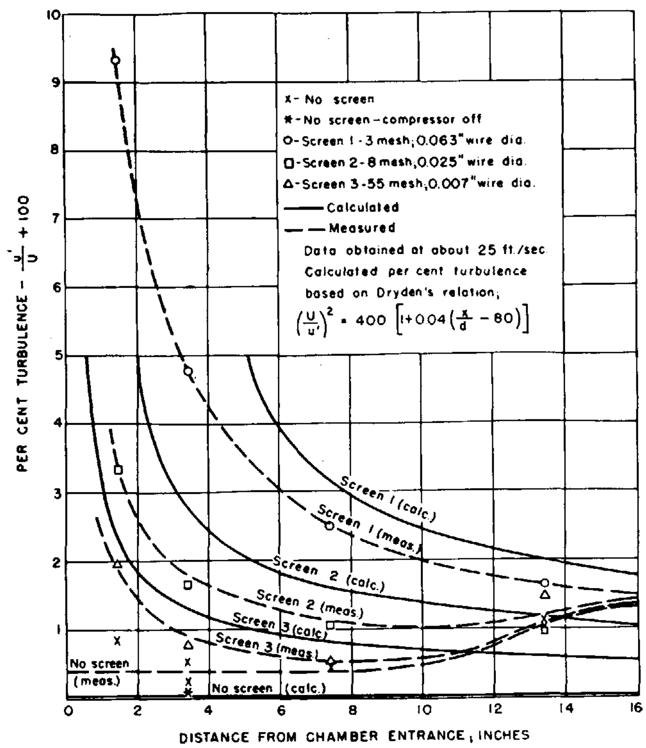


Fig. 11

Turbulence Intensity in Chamber With No Combustion Taking Place, From Scurlock

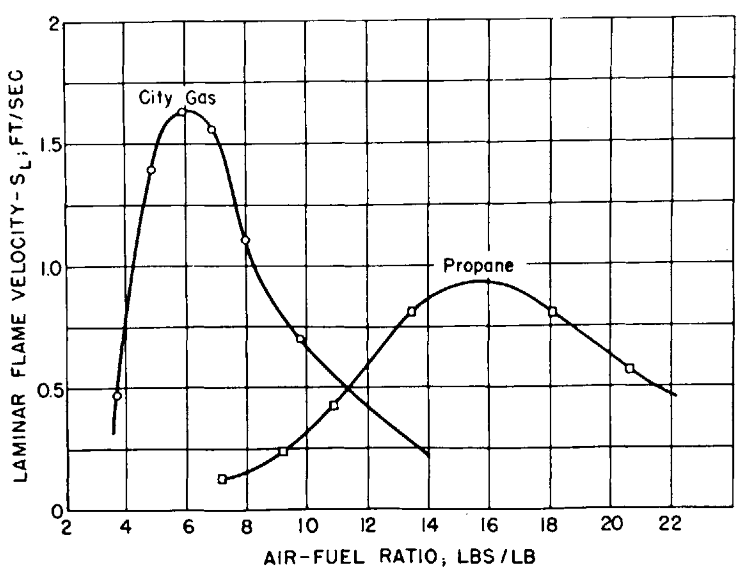


Fig. 12

Laminar Flame Velocities, City Gas-Air and Propane-Air Mixtures, From Scurlock front is transformed from that of a laminar to a turbulent front. This action reduces the region over which molecular diffusion has an appreciable effect. Eddies in the turbulent flame front transport slugs of unburned gas of the same composition as the main stream into and through the flame front. If the eddy zone is adjacent to this turbulent region, it will receive some of these slugs of unburned gas and be replenished by this gas of the same composition as the main stream. The temperature of the gas in the eddy zone would be definitely influenced by the combustion of the eddy transported gas from the main stream.

The above-described effect should move the stabilization curves toward stoichiometric. Examination of Fig. 13 reveals a definite transition of the curve peaks toward stoichiometric when turbulence is introduced into the main stream.

Case 3. Residual Flames

A residual flame is a small flame attached to the stabilizer which fails to propagate through the main body of the gas mixture. Scurlock observed residual flames only while approaching the lean limit blow-out for city gas air mixtures. In this investigation, however, they were observed only while approaching the rich limit blow-out for propane-

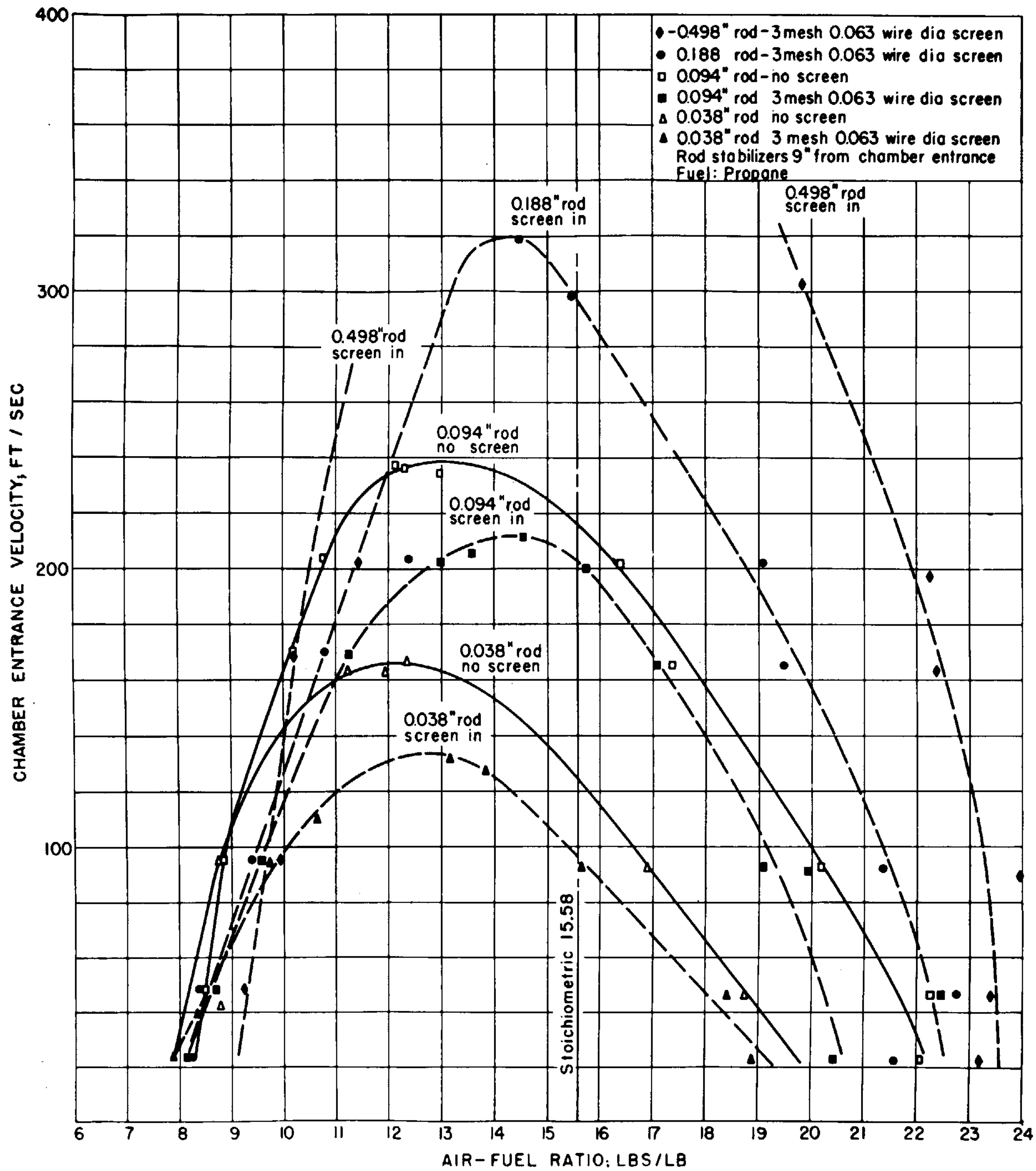


Fig. 13

Stability Limits of Rods With and Without Turbulence Generating Screens Present, from Scurlock air mixtures. The flame front appeared to be laminar.

These facts are an indication that: (1) For city gas, which has a high concentration of low-molecular constituents such as hydrogen, a residual flame was maintained behind the stabilizer, despite the fact that the gas entering the chamber was of a composition too lean to maintain a propagating flame. This resulted from a gas entering the flame front which was richer, because of the relatively higher rate of diffusion of the fuel, than the gas entering the chamber. (2) For propane, which has a relatively high molecular weight, a residual flame was maintained behind the stabilizer when the main gas stream was too rich to permit propagation through it. In this case the flame was maintained because the gas entering the flame front was poorer in slow-diffusing propane than the main stream.

Case 4. Observation of Flame Color

The flame temperature and the flame color vary with the composition of the burning gas mixture. For a rich propane-air mixture, the flame was observed to be dark green well downstream from the stabilizer. Immediately behind the stabilizer, however, the flame was a light green color, the color for a flame of a leaner mixture.

These four observations support the belief that the gas which burns in the recirculating eddies behind blunt stabilizers is different in composition from that in the entering gas stream, the difference resulting from molecular diffusion of the unburned gas into the laminar flame front in this region.

Based on the results of previous work and the observations made during this investigation, the following explanation of flame stabilization on blunt objects is postulated.

Consider the calmed premixed air and fuel stream as it approaches a rod stabilizer. At bottom center of the stabilizer the stream divides and flows around the surface, forming a relatively slow moving layer of gas immediately adjacent to the stabilizer surface. Heat is transferred from the surface of the hot rod to the adjacent gas layer. Because of viscosity, the rapidly flowing main stream keeps the boundary layer moving around the stabilizer until it is met by a reverse flowing layer induced by the recirculating eddies downstream of the rod. Separation of the slow moving lamina of unburned gas from the stabilizer occurs at this point, denoted the separation point.

The unburned gas layer feeds off the stabilizer in laminar flow but at this point is adjacent to the recirculating, high-temperature gas in the eddy zone. Over a short distance from the stabilizer a laminar interface exists between the hot eddy zone gases and the unburned gas layer. Across this interface heat is transferred and active species diffuse into the heated unburned gas. Simultaneously, oxygen and fuel diffuse into the hot eddy zone. Extremely rapid heating and activating of the diffusing gases occur at and immediately within the interface of the eddy zone. Perhaps the first visible indication of flame is the reaction of these diffusing gases as they are carried away from the stabilizer along the stream lines of the recirculating eddy. The diffusing gas serves to replenish the heat content of the eddy zone but the resulting temperature of the eddy is characterized by a gas composition quite different from that of the main stream. A correction for the relative diffusivities of the components of the main stream gas should indicate the true composition of the gas entering the eddy by diffusion.

Heating and activating of the unburned gas adjacent to the interface rapidly raises the temperature of the gas to the ignition temperature, whereupon combustion initiates. Contact of the eddy zone boundary with the now burning gas, further serves to replenish the depleted eddy with heat and active species. The flame, initiated in this layer, has the appearance of a laminar flame, and starts to propagate into the unburned main gas stream in a direction normal to the plane of the flame front.

The high temperature eddy recirculates and sweeps along the top of the flame stabilizer where it transfers heat to the stabilizer and generates the continuously moving reverse flow layer adjacent to the top stabilizer surface.

Turbulence in the approach stream and the diameter of the stabilizer have a marked influence on this stabilization picture. Turbulence contributes to a rapid disintegration of the laminar flow pattern of the layer which separates from the stabilizer. Depending on the scale and intensity of turbulence, finite slugs of unburned gas can be carried into and through the turbulent flame front, which is generated by a breakdown in the laminar pattern, and into the eddy zone. That portion of the eddy which is adjacent to the turbulent flame front will also be heated by the turbulent flame, the temperature of which is characterized by the main stream gas composition. Since the eddy extends only a short distance downstream from the stabilizer, the magnitude of the influence of the turbulent flame on the eddy zone is inversely dependent on the length of the laminar flame front. Should the laminar flame pattern exist over the entire length of the eddy, the eddy zone temperature will be characterized by a gas composition which is enriched with the more rapidly diffusing components in the main stream. Conversely, a short laminar flame front will have little opportunity to affect the eddy, and the gas of the main stream composition will play a major role in determining the temperature level of the eddy zone.

Sensible heat requirements of slugs of unburned gas which are carried into the eddy zone will reduce the final temperature level and heat content of the eddy zone. Consider, too, the intense fluctuations in the flow pattern of the eddy zone caused by this externally induced turbulence. This effect may be sufficient to decrease the stability of the eddy zone and cause eddy shedding. Small three dimensional stabilizers would be more vulnerable to this effect. These factors may account for the reduced stability limits, Fig. 13, observed by Scurlock when turbulence was generated in the inlet stream.

For a given flow rate, contact time of the slow moving boundary layer with the upstream side of the hot stabilizer is a direct function of the stabilizer diameter. The heat transfer process at this point can be measured as a function of this contact time. Large diameter rods should, therefore, accomplish a higher degree of the required heat transfer than smaller diameter rods and reduce the heat demand on the eddy in contact with the separated layer. Obviously, a shorter time or length of contact with the eddy will be required if a greater fraction of the required heat has already been transferred to the layer. If this reasoning is correct, the visible flame should appear at a point closer to the stabilizer.

Goldstein has shown how the slow moving boundary layer increases in thickness as it moves downstream from the initial contact point. With increasing thickness, the stability of the laminar flow layer decreases and eventually the layer transforms to a thinner, turbulent boundary layer. An increase in stabilizer diameter produces an increase in the flow path of the layer.

If the layer attains the critical thickness and velocity, at which transition occurs, before leaving the rod surface, it will separate from the stabilizer with a flow pattern characteristic of turbulent boundary layer, a thin laminar film adjacent to the rod surface followed by a buffer and turbulent layer. The life of this thin laminar film is undoubtedly very short and turbulent flow rapidly results. Under such conditions only a very small amount of mass will be transported into the eddy zone by pure molecular diffusion and the major transfer will take place by eddy diffusion. The eddy zone will, therefore, assume a temperature characterized by the gas composition in the main stream.

To be correct, this postulation should explain the various phenomena observed by all investigators. Scurlock's observation of the position of the visible flame on various sized rod stabilizers appears to fit this picture. Stability limits curves, Figs. 8 and 13, reveal a definite transition of the peaks toward stoichiometric with increasing degree of turbulence and stabilizer diameter. Scurlock's correlation curve, Fig. 7a, exhibits a definite trend when turbulence inducing screens were used. From Fig. 11, the turbulence at the stabilizer was $\cong$ 3%. The flow photographs taken by Goldstein and Prandtl and Tietjents, and the spark photographs of Scurlock appear to confirm the existence of laminar flow in the layer leaving the stabilizer at the separation point. The existence of the residual flame further confirms the validity of this postulation.

An approximation of the composition of the diffused mixture relative to that of the main stream reveals a correction of the proper magnitude and sign, $(A/F)\ 1.10 = (A/F)_{eddy\ zone}$. The derivation of this correction is located in the Appendix, A-2. If this factor is applied to the generalized correlations, Fig. 7b and 9, a shift of the curve to the right results and the peak value of $A/F \cong 14$ as read from the curve becomes $A/F \cong 15.4$, which is in fair agreement with the expected peak at stoichiometric, $(A/F)_{stoich.} = 15.58$.

CONCLUSIONS

1. The flame stabilizing characteristics of a rod are unaffected by its length so long as the length is at least twice the diameter.

2. The walls of the combustion chamber have no significant effect on the stability limits of the stabilizer.

3. Over the range of diameters investigated, a sphere has a lower stability limit than a rod of the same diameter.

4. Flame propagation, as determined by the flame width measured 4 inches downstream from the stabilizer, is the same for rods extending to the sidewalls, shortened rods with hemispherical ends, and spheres, all of the same diameter.

5. In the combustion of premixed propane and air, the gas which burns in the recirculating eddy region behind blunt stabilizers is leaner than that in the entering stream, the difference resulting from molecular diffusion of unburned gas into the laminar flame front of this region.

6. A plot of $V_{B.O.}/D^{0.45}$ versus air-fuel ratio satisfactorily correlated the stability limit data for 1 inch rods and shortened rods.

7. Plots of $V_{B.O.}/D^{n}$ were not entirely satisfactory for correlating the stability limit data for spheres, although an n of one gave a better correlation than an n of 0.45.

RECOMMENDATIONS

1. A continued study of the fundamentals of flame stabilization behind three-dimensional stabilizers, such as spheres and cones, should provide a better understanding of the relative importance of the area of the flame front of the recirculating eddy region behind the stabilizer and its volume. This might lead to a correlating factor more satisfactory than $V_{B.O.}/D$.

2. The extent of the influence of diffusion of unburned gas into the region just downstream from the stabilizer should be checked with fuels of low and high molecular weights relative to the molecular weight of air; the affect on this diffusion of the introduction of turbulence upstream from the stabilizer should also be determined.

3. The state and thickness of the slow moving film of unburned gas on the stabilizer for different conditions should be determined and the magnitude of their effect on stabilization evaluated.

4. A study of the effects of stabilizer temperature on the eddy region, in particular on the location of the point at which the visible flame starts, should prove valuable.

5. To determine if the gas composition, at which a residual flame is maintained, is outside the limits of combustion, an experiment might be performed to attempt ignition of a gas mixture under the conditions at which a residual flame has been observed to exist.

APPENDIX

APPENDIX A

CALCULATIONS

1. Method of Flow Rate Calculation

The quantities determined from experimental measurements were air rate, in pounds per second, fuel rate in pounds per second, and velocity of the gas mixture at the entrance to the combustion chamber in feet per second.

Calculation of Air Rate, Propane Rate

The air rate to the combustion chamber was determined by means of a 3/4 inch standard Foxboro orifice plate mounted in standard 2 inch pipe with flange taps. The orifice was calibrated with the standard orifice meter of Professor Keyes and the calibration curves, shown in Fig. A-1, were calculated using the method and data presented in Fluid Meters (1).

Propane was metered by means of the standard orifice meter. Three different orifice plate sizes were required to accommodate the range of flows used and calibration curves for the three sizes are shown in Fig. A-2.

From information given in Fluid Meters, the error for the curves is estimated to range from ± 0.2% to ± 2%, decreasing as the differential pressure increases.

Deviations from the upstream temperatures and pressures used in calculating the calibration curves were accounted for by correction factors determined from Fig. A-3.

Calculation of Velocity at Entrance to Combustion Chamber

V_o, the velocity of the mixed gases entering the chamber, was calculated using the following equation:

$$V_o = \frac{(A + F/1.54)\ (359/29)\ (T/492)(13.6 \times \text{Barometer}/P + 13.6 \times \text{Barometer})}{3/144}$$

A - Air Rate, pound/second

F - Propane rate, pound/second

1.54 - Ratio of molecular weight of propane mixture to molecular weight of air

T - Temperature of gas mixture entering chamber, ^{o}R

Barometer - Barometric pressure, cm. Mercury

P - Static pressure on chamber, cm. Water

3/144 - Cross-sectional area of chamber, square feet

Substituting the values obtained from Run 12:

$$V_o = \frac{(0.1528 + 0.009749/1.54)(359/29)(536/492)(13.6 \times 75.92/11.6 + 13.6 \times 75.92)}{3/144}$$

$= 101.8$ feet per second

2. Method of Diffused Gas Composition Approximation

Let the mol fraction of each component represent its concentration in the gas stream and consider the concentration of nitrogen everywhere the same in the system. Consider the fuel to be propane. Assume complete combustion occurs in the eddy zone gases. The concentration driving force for diffusion will, therefore, be the mol fraction of each component.

$$\frac{A}{F}\frac{44}{29}\frac{21}{100} = \frac{[O_2]}{[C_3H_8]} = \frac{A'}{F'}$$

$$\frac{A'/F'}{1 + A'/F'} = \text{mol fraction of } O_2$$

$$\frac{1}{1 + A'/F'} = \text{mol fraction of } C_3H_8$$

D_O = Diffusion coefficient of O_2 through Nitrogen

D_C = Diffusion coefficient of C_3H_8 through Nitrogen

$\frac{A'/F'}{1 + A'/F'} D_O$ = A rate of diffusion of O_2 into the eddy zone

$\frac{1}{1 + A'/F'} D_C$ = A rate of diffusion of C_3H_8 into the eddy zone

Division of the two above rates yields:

$A'/F' \frac{D_O}{D_C}$ = Mols of O_2 per mol of C_3H_8 into the eddy zone

but $A'/F' \times \frac{29}{44} \times \frac{100}{21}$ = $\#O_2$ per $\#C_3H_8$

$\therefore$ $A/F \frac{D_O}{D_C}$ is a measure of the composition of the diffusing gas and eddy zone composition may be determined from the values on the given plots, corrected by the diffusivity ratio.

Using the equations of Sherwood (14) for the calculation of Diffusion Coefficients and considering each component diffusing through nitrogen,

$$D = 0.0043 \frac{T^{3/2}}{P(V_A{}^{1/3}+V_B{}^{1/3})^2} \sqrt{\frac{1}{M_A} + \frac{1}{M_B}}$$

Where

D = Diffusion coefficient Cm^2/sec.

T = Absolute temperature ^oK

M_A, M_B = Molecular weights of the two gases

P = Total pressure

V_A, V_B = Molecular volumes

Dividing the coefficients and substituting the necessary values in the above equation:

$$\frac{D_O}{D_C} = 1.10$$

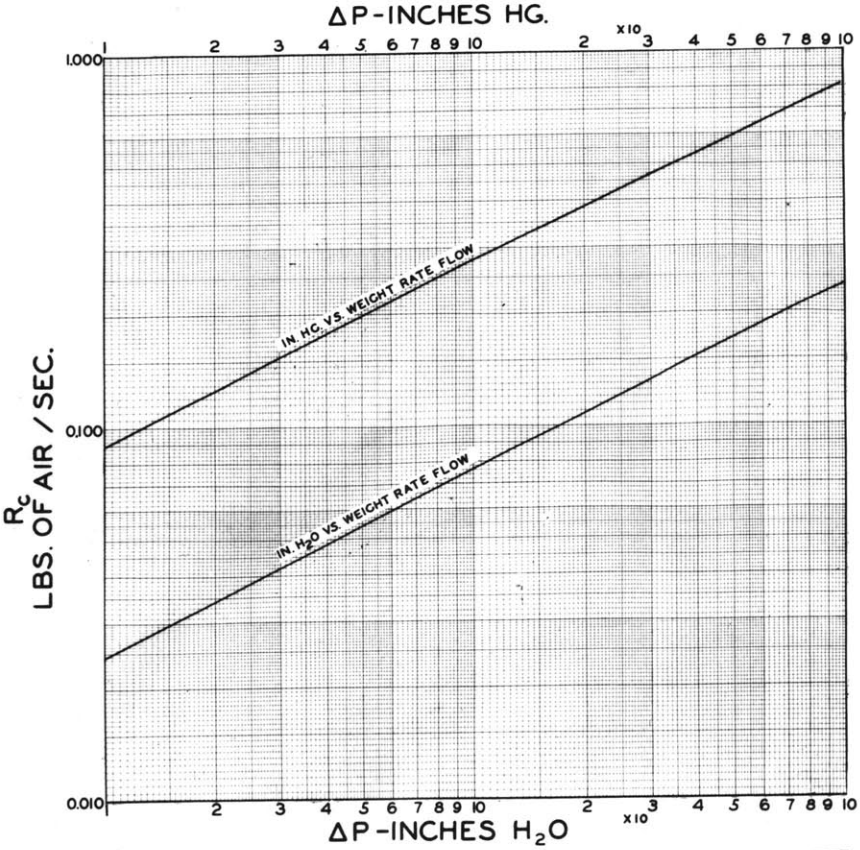


FIG. A-1

CALIBRATION CHART FOR AIR ORIFICE METER. BASIS FOR CALCULATION: AIR AT 308° R. AND 104.7 P.S.I.A.
RATE CORRECTION:
$R_{ACT.} = R_{CHART}\left[\frac{P_A}{P_C} \times \frac{T_C}{T_A}\right]^{\frac{1}{2}}$

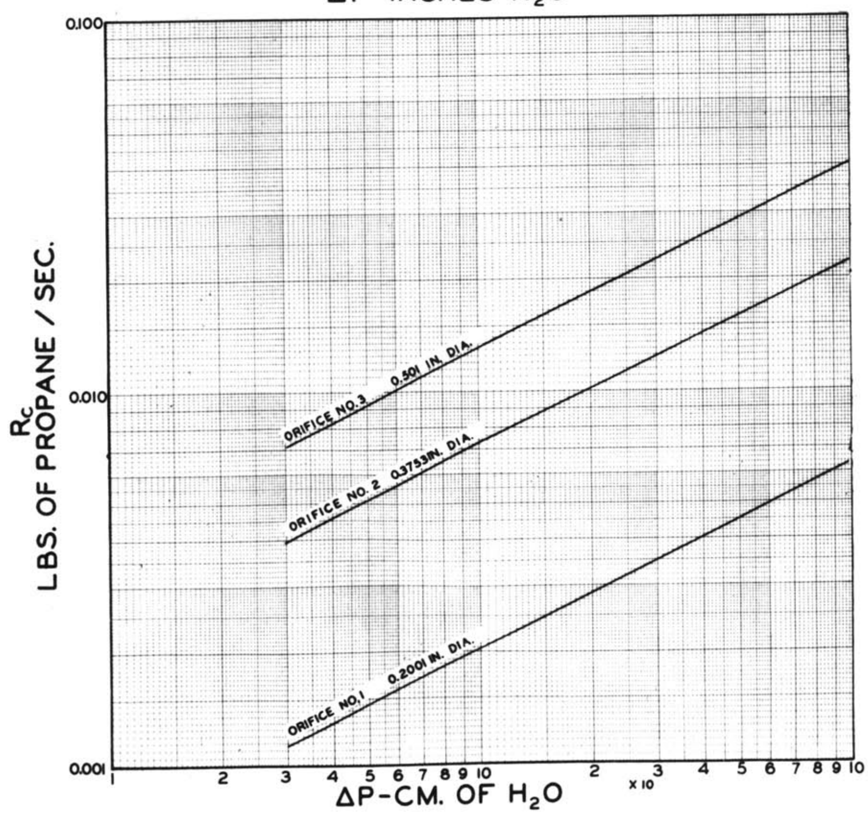


FIG. A-2

CALIBRATION CHART FOR PROPANE ORIFICE METER-KEYES STAND. BASIS FOR CALCULATION: PROPANE AT 298° AND 116 CM. PRESSURE, MERCURY, ABSOLUTE.
RATE CORRECTION:
$R_{ACT.} = R_{CHART}\left[\frac{P_A}{P_C} \times \frac{T_C}{T_A}\right]^{\frac{1}{2}}$

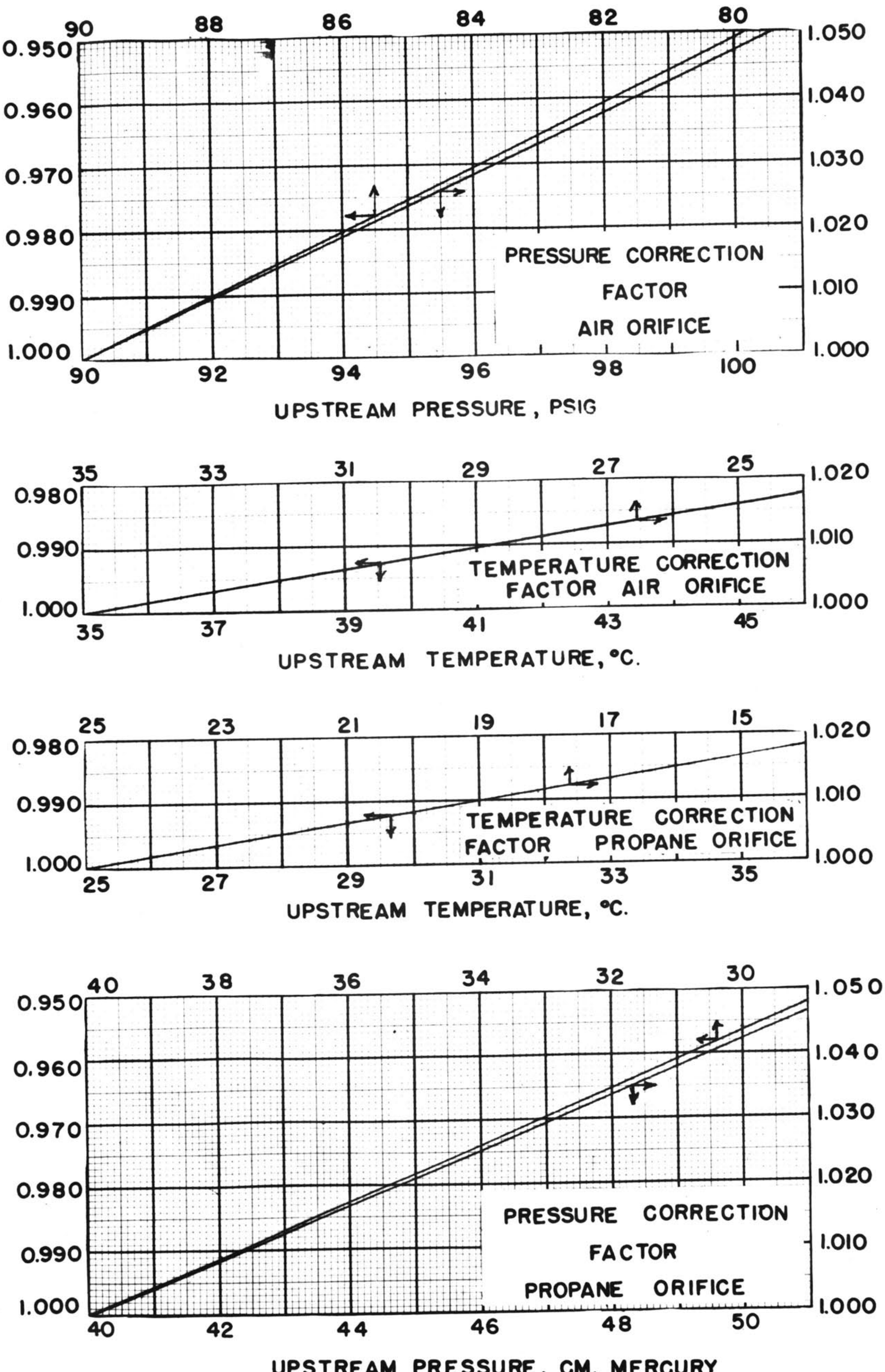


Fig. A-3
Correction Factors

APPENDIX B

DETAILS OF THE APPARATUS

Air System

Air was supplied by an Ingersoll-Rand carbon ring piston type compressor. The twin, two stage compression cycle with interstage cooling provided 0.5 pounds per minute of oil-free air to the surge and storage tank at 100 p.s.i.g. and about 80^{o}F. The compressed air was, then, piped through a large glass wool filter to the"control point." A bleed-valve was located at the filter entrance to aid in the control of a steady air flow rate to the apparatus during each run. Use of two throttling valves in series interspaced by a sharp-edged orifice permitted rate and static pressure control of the air feed to the system. Downstream of the second throttling valve, the air mixed with the fuel.

Propane Fuel System

Commercial propane in the liquid state was fed from inverted storage bottles to a steam heat exchanger. The propane was sprayed through small distributing tubes into copper heat-exchanger tubes, which were externally in contact with steam. Tubes and steam were contained in a 3 inch iron pipe to which feed and condensate lines had been brazed. The vaporized propane was piped to a similar series of two throttling valves interspaced with a Keyes standard orifice meter. Immediately downstream of the second valve the propane was mixed with air and the mixture piped to the calming section.

Calming Section and Combustion Chamber

Fig. A-4 presents an isometric sketch of the calming section and combustion chamber, showing dimension and construction details. The gas mixture, fed in at the base, flowed up through the diffuser section decreasing in velocity and turbulence intensity. As it passed through the five 200 mesh screens in series, the scale of turbulence was successively reduced. The calmed mixture then flowed through a smooth nozzle and entered the combustion chamber with a flat velocity profile. Rod and sphere stabilizers were mounted between the Vycor glass walls of the combustion chamber 8 inches downstream from the chamber entrance. The shortened rods and spheres were suspended by 2 mil tungsten wire which extended from the axis at each end of the stabilizer through 1 mm holes drilled in the Vycor glass walls.

Ignitor

Ignition of the gas mixture was accomplished by sparking across the gap of a two wire probe, which was inserted into the combustion chamber, slightly below the stabilizer. The probe was connected to the high voltage terminals of a 110-15,000 Volt transformer.

Modification of the ignitor system was recommended at the conclusion of the experimental work. By using the glass-wall-supported metal stabilizer for one electrode, a retractable single electrode probe extending from, and grounded to the metal wall would comprise a spark circuit. This arrangement made possible

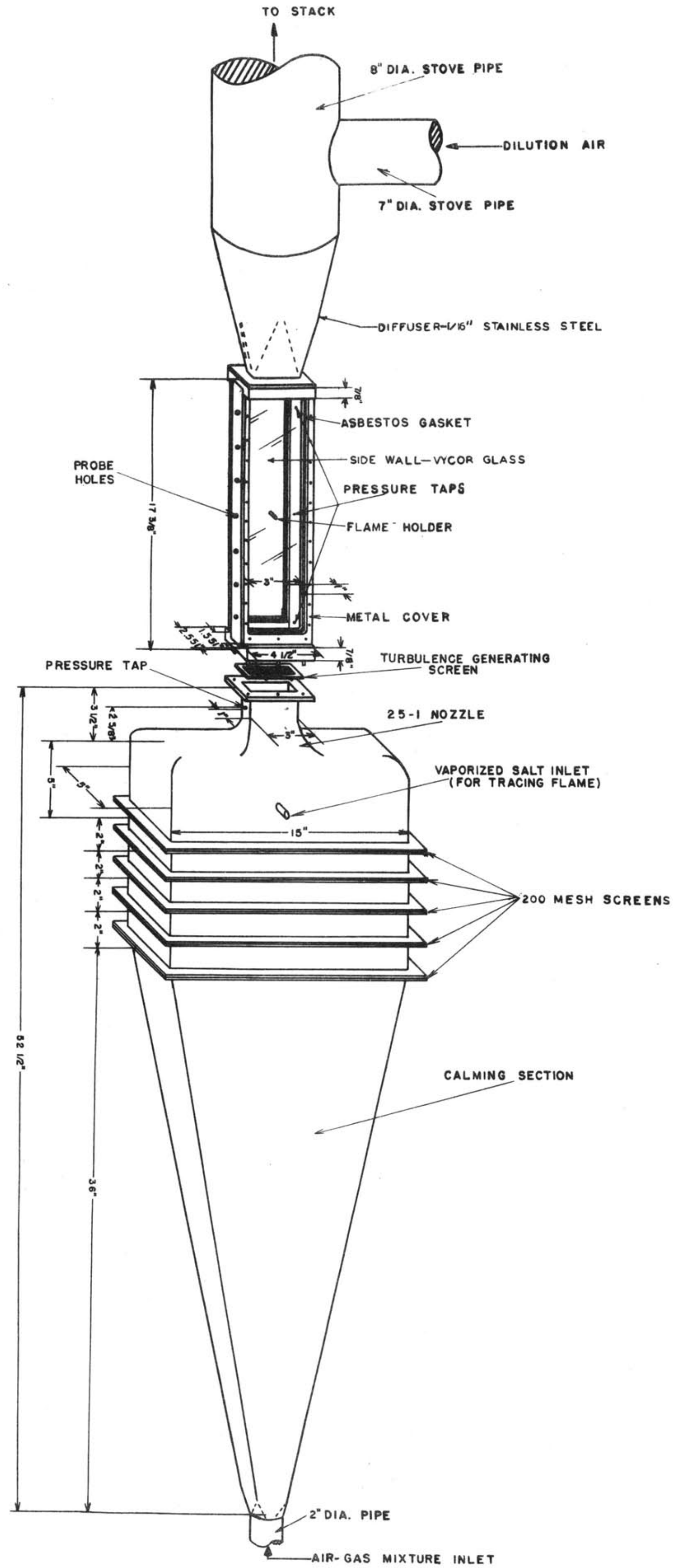


FIGURE A-4

COMBUSTION CHAMBER AND CALMING SECTION

the release of energy in the gas zone immediately downstream of the stabilizer, practically eliminated flash-back and prevented burn-out of the thin tungsten wire supports.

Exhaust System

Burning gases from the combustion chamber entered a 9 inch stove pipe stack, where it was diluted with air taken from the room. The stack gases were piped to the exhaust system of the combustion test cell in which the apparatus was assembled.

Considerable trouble with burn-out of the exhaust stack was experienced during test runs. The use of an open system, large diameter stack is recommended for further work of this type.

APPENDIX C

EXPERIMENTAL PROCEDURE

The sequence of operations by which data were obtained may be summarized as follows:

1. The test stabilizer was mounted in the combustion chamber.
2. Steam was admitted to the propane vaporizer.
3. Manometer lines and cocks were inspected and adjusted.
4. Dilution air was fed to the exhaust stack.
5. Feed air from the compressor was adjusted to 90 pounds static pressure at the orifice plate and a velocity of approximately 35 feet per second in the chamber.
6. The ignitor was inserted into the combustion chamber slightly below the stabilizer and intermittently sparked.
7. Propane was fed through the vaporizer to the system and allowed to attain a static pressure of about 10 cm. of Mercury at the orifice plate. At this pressure, it was slowly fed to the combustion chamber.
8. Propane static pressure was slowly increased until the air-fuel mixture entering the combustion chamber ignited and stabilized on the ignitor insulation. By intermittently playing this flame over the test flame holder, a flame was stabilized on the holder.

9. The ignitor was removed from the chamber and a machine screw turned into the ignitor probe hole.

10. The propane and air feed rates were increased at approximately a stoichiometric ratio until the desired velocity in the combustion chamber was attained. The stoichiometric ratio was maintained by adjusting the control valves of the air and fuel streams so that a blue flame was observed. Green and purple tinged flames characterized rich and lean gas mixtures, respectively.

11. Photographs of rich, lean, and stoichiometric flames were taken at this velocity.

12. The supply of propane was, then, either increased or decreased to obtain a rich or lean limit blow-out. While one operator adjusted valve settings a second operator measured manometer readings by moving adjustable tabs on each manometer leg to the position of the meniscus. This technique made possible rapid and accurate recordings of pressure at blow-out.

13. After blow-out all of the manometer tab readings and stream temperatures were recorded, and the sequence then repeated for the next desired velocity.

APPENDIX D

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APPENDIX E

SERIES: 0.188 inch Diameter Rod, 1 inch long

DATE: July 5, 1948

Run No.	A lb/sec.	F lb/sec.	T_o °R	P_o Cm. water above bar.	A/F. lb/lb.	V. ft/sec.	W_4 in.	PHOTO NO.	REMARKS
1.	0.186	0.0179	540	17.0	10.36	126.6	-	-	RLBO
2.	0.174	0.0173	544	13.8	10.04	120.0	-	-	RLBO
3.	0.177	0.0175	544	15.2	10.15	122.1	-	-	RLBO
4.	0.176	0.0180	543	14.0	9.81	121.7	-	-	RLBO
5.	0.0330	0.0331	543	2.8	9.99	23.0	-	-	(1)
6.	0.0636	0.00268	542	3.3	23.74	42.6	-	-	LLBO
7.	0.288	0.0255	544	28.1	11.28	194.8	-	-	RLBO
8.	0.220	0.0204	544	16.7	10.74	150.6	-	-	RLBO
9.	0.429	0.0227	544	34.8	18.91	282.2	-	-	LLBO

bar. = 76.06 cm. Hg.
(1) Flutter. At low velocities, the flame front appeared rippled. No noticeable effects of glass walls on flame.

SERIES: 0.188 inch, Diameter Rod, 1 inch long, 0.188 inch Sphere

DATE: July 7, 1948

RUN NO.	A lb/sec.	F lb/sec.	T_o °R	P_o Cm. water above bar.	A/F lb/lb.	V. ft/sec.	W_4 in.	PHOTO NO.	REMARKS
10.	0.452	0.0343	538	43.3	13.19	295.8	-	-	RLBO (1)
11.	0.157	0.00987	538	11.5	15.93	105.1	1.39	1-1-11	
12.	0.153	0.00975	536	11.6	15.66	101.8	1.24	2-1-12	(2)
13.	0.173	0.00975	536	11.6	17.73	114.7	-	-	LLBO

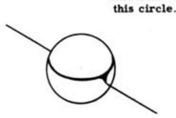
bar. = 75.92 cm. Hg.
(1) Rod installed (2) Sphere installed

SERIES: 0.188 inch Sphere

DATE: July 8, 1948

RUN NO.	A lb/sec.	F lb/sec.	T_o °R	P_o Cm. water above bar.	A/F lb/lb.	V. ft/sec.	W_4 in.	PHOTO NO.	REMARKS
14.	0.246	0.0170	540.5	19.3	14.49	164.9	1.23	3-1-14	
15.	0.264	0.0158	542	17.8	15.52	164.8	-	-	BO
16.	0.169	0.0103	540	11.2	16.38	113.6	1.21	4-1-16	
17.	0.160	0.0125	542	13.8	12.81	108.8	1.43	5-1-17	(1)
18.	0.160	0.0148	542	14.2	10.82	109.5	1.39	6-1-18	(1)
19.	0.166	0.0164	544	11.1	10.11	114.8	-	-	RLBO
20.	0.167	0.00938	543	4.0	17.77	112.8	-	-	LLBO
21.	0.0421	0.00280	540	3.9	15.01	28.5	1.95	7-1-21	(2)
22.	0.0421	0.00366	540	4.1	11.51	28.9	2.03	8-1-22	(3)
23.	0.0423	0.00408	541	3.8	10.37	29.2	1.91	9-1-23	(4)
24.	0.0414	0.00472	541	3.8	8.78	29.0	1.24	10-1-24	(5)
25.	0.0415	0.00504	541.5	3.2	8.24	29.2	1.02	12-1-25	
26.	0.0424	0.00566	541.5	3.2	7.48	30.0	-	-	RLBO (1)

bar. = 80.75 cm. Hg.
(1) Vibrating flame
(2) Screen cleaned
(3) Slight flutter
(4) Marked flutter
(5) Marked flutter, turquoise flame
(6) At conclusion of this series, the ball stabilizer had a sharply defined ring slightly above the horizontal axis with a stream line leading to the wire support (see figure below). The flame seemed to originate from this circle.



SERIES: 0.188 inch Sphere

DATE: July 9, 1948

RUN NO.	A lb/sec.	F lb/sec.	T_o °R	P_o Cm. water above bar.	A/F lb/lb.	V. ft/sec.	W_4 in.	PHOTO NO.	REMARKS
28	0.0416	0.00246	541	3.2	16.93	28.1	1.95	3-2-27	
29	0.0415	0.00217	542	2.6	19.16	28.0	-	-	LLBO
30	0.0419	0.00224	542	3.5	18.67	28.3	1.83	4-2-29	
31	0.0833	0.00522	545	7.8	15.97	56.7	1.50	5-2-31	
32	0.0849	0.00457	543	5.2	18.56	57.3	1.32	6-2-32	
33	0.0834	0.00436	543	5.0	19.13	56.3	1.19	7-2-33	
34	0.0833	0.00399	543	5.0	20.86	56.0	-	-	LLBO
35	0.0840	0.00793	544	6.8	10.60	58.2	1.42	8-2-35	
36	0.0833	0.00937	546	4.8	8.88	58.7	1.13	9-2-36	
37	0.0833	0.0101	547	3.2	8.24	59.2	-	-	RLBO
38	0.2477	0.0161	548	18.6	15.38	167.8	1.10	10-2-38	
39	0.2475	0.0211	549	19.1	11.71	170.1	1.16	11-2-39	
40	0.2475	0.0220	549	19.1	11.27	170.4	-	-	RLBO

Barometer - 76.86 cm. Hg.

SERIES: 0.188 inch Diameter Rod, 5/8 inch long

DATE: July 13, 1948

RUN NO.	A lb/sec.	F lb/sec.	T_o °R	P_o Cm. water above bar.	A/F lb/lb.	V. ft/sec.	W_4 in.	PHOTO NO.	REMARKS
42	0.243	0.0181	546	22.0	13.45	164.4	1.16	1-3-42	(1)
43	0.244	0.0214	548	22.6	11.39	167.0	1.28	3-3-43	
44	0.244	0.0227	545	22.6	10.76	166.7	-	-	RLBO
45	0.243	0.0173	546	23.9	14.04	163.9	1.265	4-3-45	
46	0.244	0.0149	548	21.1	16.42	164.7	1.18	5-3-46	
47	0.244	0.0127	548	14.1	19.10	164.1	-	-	LLBO
48	0.297	0.0158	548	22.6	18.76	198.8	-	-	LLBO
49	0.425	0.0257	552	40.2	16.52	283.3	-	-	BO (2)
50	0.168	0.0102	551	12.6	16.45	114.8	1.19	6-3-50	(3)
51	0.167	0.0120	551	13.3	13.87	114.9	1.27	7-3-51	
52	0.168	0.0150	552	13.6	11.24	117.0	1.21	8-3-52	
53	0.168	0.0175	552	11.6	9.57	117.9	-	-	RLBO
54	0.168	0.00891	552	10.1	18.86	114.7	1.21	9-3-54	
55	0.166	0.00825	552	5.8	20.17	113.9	-	-	LLBO
55a	0.0720	0.00517	540	6.3	13.91	48.8	1.71	10-3-55	(4)
56	0.0869	0.00515	540	6.3	16.87	58.5	1.54	11-3-56	
57	0.0868	0.00488	540	6.3	17.80	58.3	1.19	12-3-56	
58	0.0868	0.00567	542	6.8	15.31	58.8	1.625	1-4-58	
59	0.0868	0.00407	542	6.8	21.31	58.1	-	-	LLBO
60	0.0435	0.00266	540	3.6	16.33	29.4	1.83	2-4-60	
61	0.0416	0.0296	541	3.9	14.06	28.3	2.01	3-4-61	
62	0.0416	0.00354	542	3.9	11.74	28.6	1.89	4-4-62	(5)
63	0.0416	0.00418	542	3.9	9.95	28.9	-	-	RLBO (6)
64	0.0416	0.00226	542	3.2	18.37	28.1	1.58	5-4-64	
65	0.0416	0.00192	542	3.8	21.63	27.9	-	-	LLBO
66	0.0818	0.00993	542	3.8	8.24	57.5	-	-	RLBO

(1) Bar. = 75.95 cm. Hg.
(2) New tank of Propane
(3) At conclusion of this run, stack partially disintegrated. After repairs, by pass value used instead of inspirators to control air flow; reduced flashback on ignition.
(4) Bar. = 75.84 cm. Hg.
(5) Bordering on flutter region
(6) Violent flutter. Flame left stabilizer and fluttered at mouth of diffuser.

SERIES: 0.188 inch Diameter Rod, 3/4 inch long

DATE: July 15, 1948

RUN NO.	A lb./sec.	F lb/sec.	T_o °R	P_o Cm. water above bar.	A/F lb/lb.	V. ft/sec.	W_4 in.	PHOTO NO.	REMARKS
67	0.0831	0.00605	539	7.1	13.74	56.3	1.725	6-4-67	
68	0.0820	0.00796	540	5.8	10.30	56.5	1.335	7-4-68	
69	0.0829	0.0100	540	3.4	8.29	58.1	-	-	RLBO
70	0.163	0.0105	541	13.1	15.52	109.6	1.27	8-4-70	
71	0.163	0.0131	542	15.0	12.44	110.7	1.41	9-4-71	
72	0.163	0.0156	543	12.1	10.45	112.2	1.38	10-4-71	
73	0.163	0.0172	544	11.8	9.48	113.1	-	-	RLBO
74	0.164	0.00839	544	9.8	19.55	110.3	1.19	11-4-74	
75	0.164	0.00792	544	9.8	20.71	110.1	-	-	LLBO
76	0.247	0.0158	543	23.6	15.63	165.0	1.26	12-4-76	
77	0.244	0.0180	544	24.9	13.56	164.1	1.42	1-5-77	
78	0.245	0.0204	545	24.8	12.01	166.0	1.47	2-5-78	
79	0.245	0.0230	545	21.2	10.65	167.7	-	-	RLBO
80	0.244	0.0139	543	19.9	17.55	162.8	1.31	3-5-80	(1)
81	0.244	0.0110	545	16.4	22.18	162.7	-	-	LLBO
82	0.325	0.0204	544	31.0	15.93	215.8	1.25	4-5-82	
83	0.323	0.0239	545	35.3	13.52	215.5	-	-	
84	0.323	0.0253	546	35.6	12.77	216.4	1.38	6-5-84	
85	0.325	0.0281	545	37.1	11.57	218.2	-	-	RLBO
86	0.324	0.0194	545	30.4	16.70	215.3	1.26	7-5-86	
87	0.325	0.0185	545	27.5	17.57	216.1	-	-	LLBO
88	0.458	0.0340	546	57.7	13.47	299.9	-	-	RLBO
89	0.486	0.0357	546	59.4	13.61	317.6	-	-	RLBO

Bar. = 76.53 cm. Hg.
(1) New tank of Propane

SERIES: 0.188 inch Diameter Rods, 3/4 inch and 3/8 inch long

DATE: July 18, 1948

RUN NO.	A lb/sec.	F lb/sec.	T_o °R	P_o Cm. water above bar.	A/F lb/lb.	V. ft/sec.	W_4 in.	PHOTO NO.	REMARKS
90	0.246	0.0147	542	21.9	16.74	163.8	1.29	8-5-90	(1)
91	0.245	0.0140	544	20.3	17.50	163.7	1.22	9-5-91	
92	0.245	0.0130	544	20.3	18.85	163.3	-	-	LLBO
93	0.0420	0.00271	544	3.9	15.56	28.6	1.98	10-5-93	
94	0.0420	0.0311	544	4.1	13.50	40.7	1.90	11-5-94	
95	0.0420	0.00368	544	3.8	11.41	29.1	1.89	12-5-95	
96	0.0416	0.00489	544	3.3	8.50	29.2	-	-	RLBO (2)
97	0.0416	0.00234	544	3.3	17.74	28.2	1.83	1-6-97	
98	0.0416	0.00198	544	3.3	20.94	28.0	-	-	LLBO
99	0.0408	0.00265	542	3.5	15.55	27.8	2.08	2-6-99	(3)
100	0.0408	0.00342	542	4.1	12.03	28.1	2.08	3-6-100	
101	0.0408	0.00356	542	3.9	11.56	28.1	1.92	4-6-101	(4)
102	0.0408	0.00426	542	3.0	9.68	28.4	-	-	RLBO (5)

(1) Bar. = 76.43 cm. Hg., 3/4 in. long rod installed
(2) Bar. = 76.46 cm. Hg.
(3) Bar. = 76.30 cm. Hg., 3/8 in. long rod installed
(4) Bordering on flutter
(5) Violent flutter

SERIES: 0.188 inch Diameter Rod, 3/8 inch long (cont.)

DATE: July 20, 1948

RUN NO.	A lb/sec.	F lb./sec.	T_o °R	P_o Cm. water above bar.	A/F lb/lb.	V. ft/sec.	W_4 in.	PHOTO NO.	REMARKS
103	0.0427	0.00250	540	3.9	17.05	28.5	1.89	5-6-103	(1) (2)
104	0.0435	0.00240	540	3.9	18.11	29.0	-	-	LLBO
105	0.0827	0.00515	541	5.5	16.04	55.4	1.51	6-6-105	
106	0.0827	0.00565	542	7.2	14.63	55.6	1.74	7-6-106	
107	0.0827	0.00481	542	6.0	17.17	55.4	1.57	8-6-107	
108	0.0822	0.00440	542	5.7	18.67	54.9	1.64	8-6-108	
109	0.0822	0.00416	542	5.0	19.76	54.8	-	-	LLBO
110	0.164	0.0103	543	11.7	16.00	109.9	1.20	10-6-110	
111	0.165	0.0119	543	14.4	13.87	111.0	1.31	11-6-111	
112	0.164	0.0136	545	15.3	12.07	111.2	1.33	12-6-112	
113	0.164	0.0163	540	12.0	10.07	111.7	-	-	RLBO
114	0.162	0.00979	548	12.0	16.55	109.2	1.27	1-7-114	
115	0.163	0.00866	548	9.3	18.84	109.7	1.10	2-7-115	
116	0.0829	0.00597	546	7.2	13.89	56.4	1.80	3-7-116	
117	0.0829	0.00805	546	5.7	10.31	57.3	1.42	4-7-117	
							1.41	5-7-117	
118	0.0829	0.00994	546	4.8	8.34	58.2	-	-	RLBO
119	0.244	0.0136	546	6.5	18.02	164.3	-	-	LLBO
120	0.241	0.0153	544	21.1	15.74	160.4	1.28	6-7-120	(3)
121	0.241	0.0229	546	24.5	10.51	163.5	1.32	7-7-121	
122	0.241	0.0212	546	22.7	11.36	163.0	1.31	8-7-122	
123	0.241	0.0220	545	23.7	10.96	163.2	-	-	RLBO
124	0.247	0.0159	545	22.3	15.50	164.2	1.27	9-7-124	
125	0.245	0.0149	547	19.9	16.41	163.8	1.28	10-7-125	
126	0.242	0.0135	549	16.7	17.91	162.1	-	-	LLBO
127	0.322	0.0203	549	29.1	15.91	215.6	1.23	11-7-127	
128	0.322	0.0191	549	29.1	16.87	215.0	-	-	LLBO
129	0.323	0.0225	549	31.5	14.36	216.0	1.28	12-7-129	
130	0.322	0.0269	550	32.9	12.00	218.0	-	-	RLBO
131	0.410	0.0303	547	38.0	13.51	271.3	-	-	RLBO (4)

(1) Bar. = 76.30 cm. Hg
(2) Verging on flutter
(3) New tank of Propane
(4) Bar. = 75.92 cm. Hg

SERIES: 0.510 inch Sphere, 0.1 inch Diameter Rod, 1 inch long

DATE: July 21, 1949

RUN NO.	A lb/sec.	F lb/sec.	T_o °R	P_o Cm. water above bar.	A/F lb/lb.	V. ft/sec.	W_4 in.	PHOTO NO.	REMARKS
132	0.0413	0.00198	544	3.0	20.82	27.8	-	-	LLBO (1) (2)
133	0.0413	0.00404	544	3.0	8.18	29.0	-	-	RLBO
134	0.0822	0.00380	544	4.7	21.63	55.0	-	-	LLBO
135	0.0822	0.00957	545	4.7	8.58	57.6	-	-	RLBO
136	0.163	0.00782	545	9.4	20.85	109.0	-	-	LLBO
137	0.164	0.0154	545	15.9	10.62	112.2	-	-	RLBO
138	0.246	0.0125	546	16.1	19.70	163.7	-	-	LLBO
139	0.246	0.0232	546	27.6	10.60	166.4	-	-	RLBO
140	0.324	0.0177	540	25.2	18.32	213.4	-	-	LLBO (3)
141	0.327	0.0284	541	37.0	11.51	217.1	-	-	RLBO
142	0.386	0.0211	543	31.0	18.28	254.0	-	-	LLBO
143	0.387	0.0327	544.5	43.8	11.86	257.0	-	-	RLBO (4)
144	0.448	0.0257	544.2	38.5	17.41	293.5	-	-	LLBO
145	0.448	0.0340	545.1	52.2	13.18	293.5	-	-	RLBO
146	0.323	0.0168	543.5	23.4	19.19	213.5	-	-	LLBO (5)
147	0.0422	0.00192	540	0.7	21.90	28.2	-	-	LLBO (6)
148	0.0416	0.00611	540	0.6	6.80	29.6	-	-	RLBO
149	0.0822	0.00382	540	2.3	21.50	55.0	-	-	LLBO
150	0.0819	0.0126	540	1.2	6.52	58.5	-	-	RLBO
151	0.165	0.00925	539	9.3	17.81	109.9	-	-	LLBO

(1) 0.510 in. sphere
(2) Bar. = 76.0 cm. Hg
(3) Bar. = 75.9 cm. Hg
(4) New tank of Propane
(5) Stank fell, no diffuser
(6) Installed 0.1 in. diameter rod, 1 inch long

SERIES: 0.1 inch Diameter Rod, 1 inch long

DATE: July 23, 1948

RUN NO.	A lb/sec.	F lb/sec.	T_o °R	P_o Cm. water above bar.	A/F lb/lb.	V. ft/sec.	W_4 in.	PHOTO NO.	REMARKS
152	0.165	0.0164	538	11.0	10.06	113.1	-	-	RLBO
153	-0.244	0.0141	540	17.3	17.27	162.1	-	-	LLBO
154	0.242	0.0223	540	22.4	10.84	163.6	-	-	RLBO
155	0.319	0.0204	543	30.7	15.60	211.8	-	-	BO

Bar. = 75.6 cm. Hg

SERIES: 0.1 inch Diameter Rod, 1 inch long
0.1 inch Diameter Rod, 7/8 inch long

DATE: July 26, 1948

RUN NO.	A lb./sec.	F lb./sec.	T_o °R	P_o Cm. water above bar.	A/F lb./lb.	V. ft./sec.	W_4 in.	PHOTO NO.	REMARKS
156	0.329	0.0237	540	35.4	13.89	215.5	-	-	RLBO (1)
157	0.334	0.0230	541	35.5	14.52	219.1	-	-	RLBO
158	0.330	0.0207	541	23.8	15.99	218.2	-	-	LLBO (2)
159	0.330	0.0242	542	35.3	13.62	217.5	-	-	RLBO
160	0.248	0.0220	543	23.0	11.25	166.9	-	-	RLBO
161	0.246	0.0144	543	18.3	17.07	163.5	-	-	LLBO
162	0.165	0.0165	544	10.2	10.01	113.4	-	-	RLBO
163	0.165	0.00887	545	8.2	18.58	110.7	-	-	LLBO
164	0.0835	0.0110	545	0.9	7.55	59.2	-	-	RLBO
165	0.0822	0.00392	542	2.2	20.96	55.0	-	-	LLBO
166	0.0413	0.00586	542	1.4	7.04	29.3	-	-	RLBO
167	0.0413	0.00184	543	0.9	22.36	27.6	-	-	LLBO

Bar. = 76.1 cm. Hg
(1) 0.1 in. diameter rod, 1 inch long (2) 0.1 in. diameter rod, 7/8 inch long

SERIES: 0.1 inch Sphere

DATE: July 27, 1948

RUN NO.	A lb./sec.	F lb./sec.	T_o °R	P_o Cm. water above bar.	A/F lb./lb.	V. ft./sec.	W_4 in.	PHOTO NO.	REMARKS
168	0.0415	0.00230	538	1.6	18.01	27.9	-	-	LLBO
169	0.0420	0.00483	538	0.2	7.21	29.7	-	-	RLBO
170	0.0826	0.00500	539	4.0	16.52	55.6	-	-	LLBO

Bar. = 76.0 cm. Hg

SERIES: 0.1 inch Sphere, 0.1 inch Diameter Rod, 3/8 inch long
0.1 inch Diameter Rod, 5/8 inch long

DATE: July 28, 1948

RUN NO.	A lb./sec.	F lb./sec.	T_o °R	P_o Cm. water above bar.	A/F lb./lb.	V. ft./sec.	W_4 in.	PHOTO NO.	REMARKS
171	0.0810	0.0100	545	0.5	8.10	57.7	-	-	RLBO (1)
172	0.137	0.00935	546	6.9	14.61	93.7	-	-	RLBO
173	0.145	0.0112	546	8.3	12.87	99.8	-	-	RLBO
174	0.149	0.0112	547	8.8	13.29	102.9	-	-	RLBO
175	-	-	-	-	-	-	-	-	(2)
176	0.0424	0.00192	540	1.0	22.02	28.05	-	-	LLBO (3)
177	0.0829	0.00408	541	2.4	20.32	55.9	-	-	LLBO
178	0.0833	0.0105	541	1.1	7.91	59.0	-	-	RLBO
179	0.0444	0.00645	542	0.6	6.89	31.9	-	-	RLBO
180	0.163	0.00921	543	7.9	17.73	110.4	-	-	LLBO
181	0.161	0.0171	544	7.7	9.39	112.3	-	-	RLBO
182	0.242	0.0149	545	16.4	16.23	163.3	-	-	LLBO
183	0.242	0.0220	545	20.3	11.01	165.7	-	-	RLBO
184	0.328	0.0247	545	28.8	13.27	220.6	-	-	RLBO
185	0.323	0.0251	545	28.7	12.85	217.5	-	-	RLBO
186	0.244	0.0144	547	17.1	17.02	165.2	-	-	LLBO (4)
187	0.165	0.0888	546	7.6	18.62	112.2	-	-	LLBO

Bar. = 75.82 cm. Hg
(1) Sphere installed
(2) Glass walls broken, no data
(3) 3/8 in. long rod installed
(4) 5/8 in. long rod installed (0.1065 in. in diameter)

SERIES: 0.1 inch Diameter Rod, 5/8 inch long

DATE: July 29, 1948

RUN NO.	A lb./sec.	F lb./sec.	T_o °R	P_o Cm. water above bar.	A/F lb./lb.	V. ft./sec.	W_4 in.	PHOTO NO.	REMARKS
188	0.163	0.0168	545	7.6	9.70	114.1	-	-	RLBO
189	0.0837	0.0108	545	1.0	7.75	59.6	-	-	RLBO
190	0.0458	0.00604	546	0.6	7.59	32.9	-	-	RLBO
191	0.0413	0.00177	546	1.0	23.33	28.1	-	-	LLBO
192	0.0832	0.00405	546	2.8	20.53	56.6	-	-	LLBO
193	0.245	0.0217	546	22.3	11.30	167.6	-	-	RLBO
194	0.324	0.0209	545	29.2	15.50	216.3	-	-	BO
195	0.323	0.0264	545	32.6	12.24	217.5	-	-	RLBO
195A	0.361	0.0266	547	37.9	13.60	241.8	-	-	RLBO

Bar. = 75.82 cm. Hg

SERIES: 0.1 inch Diameter Rod, 3/4 inch long
0.188 inch Diameter Rod, 7/8 inch long, 0.211 inch Sphere

DATE: July 30, 1948

RUN NO.	A lb./sec.	F lb./sec.	T_o °R	P_o Cm. water above bar.	A/F lb./lb.	V. ft./sec.	W_4 in.	PHOTO NO.	REMARKS
196	0.244	0.0218	540	22.6	11.17	165.0	-	-	RLBO (1)
197	0.242	0.0148	540	20.6	16.37	161.0	-	-	LLBO
198	0.331	0.0263	542	35.4	12.57	220.1	-	-	RLBO
199	0.329	0.0210	542	30.7	15.70	217.8	-	-	LLBO
200	0.359	0.0244	542	37.5	14.68	236.2	-	-	RLBO
201	0.166	0.0168	542	9.6	9.88	114.7	-	-	RLBO
202	0.168	0.00884	543	8.0	19.01	113.0	-	-	LLBO
203	0.0835	0.0102	544	7.3	8.21	58.7	-	-	RLBO
204	0.0427	0.00632	543	0.6	6.76	30.6	-	-	RLBO
205	0.0427	0.00190	543	1.0	22.41	28.7	-	-	LLBO
206	0.0836	0.00405	543	2.7	20.66	56.4	-	-	LLBO
207	0.0839	0.00360	543	2.2	23.31	56.3	-	-	LLBO (2)
208	0.0403	0.00168	543	0.9	23.99	27.1	-	-	LLBO
209	0.246	0.0225	544	24.0	10.94	167.1	-	-	RLBO
210	0.246	0.0128	544	16.0	19.29	164.3	-	-	LLBO
211	0.328	0.0276	544	35.9	11.87	219.1	-	-	RLBO
212	0.324	0.0182	546	28.1	17.80	215.3	-	-	LLBO
213	0.448	0.0264	548	47.5	16.98	294.5	-	-	LLBO
214	0.162	0.0166	547	10.0	9.74	112.9	-	-	RLBO
215	0.164	0.00805	546	8.1	20.37	110.6	-	-	LLBO
216	0.0825	0.00999	547	1.9	8.26	58.6	-	-	RLBO
217	0.0422	0.00597	547	0.5	7.06	30.4	-	-	RLBO
218	0.0436	0.00608	546	0.3	7.16	31.3	-	-	RLBO (3)
219	0.0827	0.00976	546	1.3	8.47	58.5	-	-	RLBO
220	0.165	0.0151	547	10.7	10.93	114.2	-	-	RLBO
221	0.164	0.00906	547	7.2	18.09	111.3	-	-	LLBO
222	0.0455	0.00207	547	0.8	21.99	30.9	-	-	LLBO
223	0.840	0.00314	547	2.5	26.74	56.6	-	-	LLBO
224	0.245	0.0212	547	19.8	11.54	167.5	-	-	RLBO
225	0.244	0.0145	547	18.6	16.76	163.9	-	-	LLBO
226	0.330	0.0258	549	26.9	12.81	223.6	-	-	RLBO
227	0.330	0.0219	549	23.6	15.09	222.7	-	-	RLBO
228	0.345	0.0239	549	26.0	14.47	233.1	-	-	RLBO

(1) 0.1 in. diameter rod, 3/4 in. long installed (0.1005 in. diameter)
(2) 0.188 in. diameter rod, 7/8 in. long installed
(3) 0.211 in. sphere installed

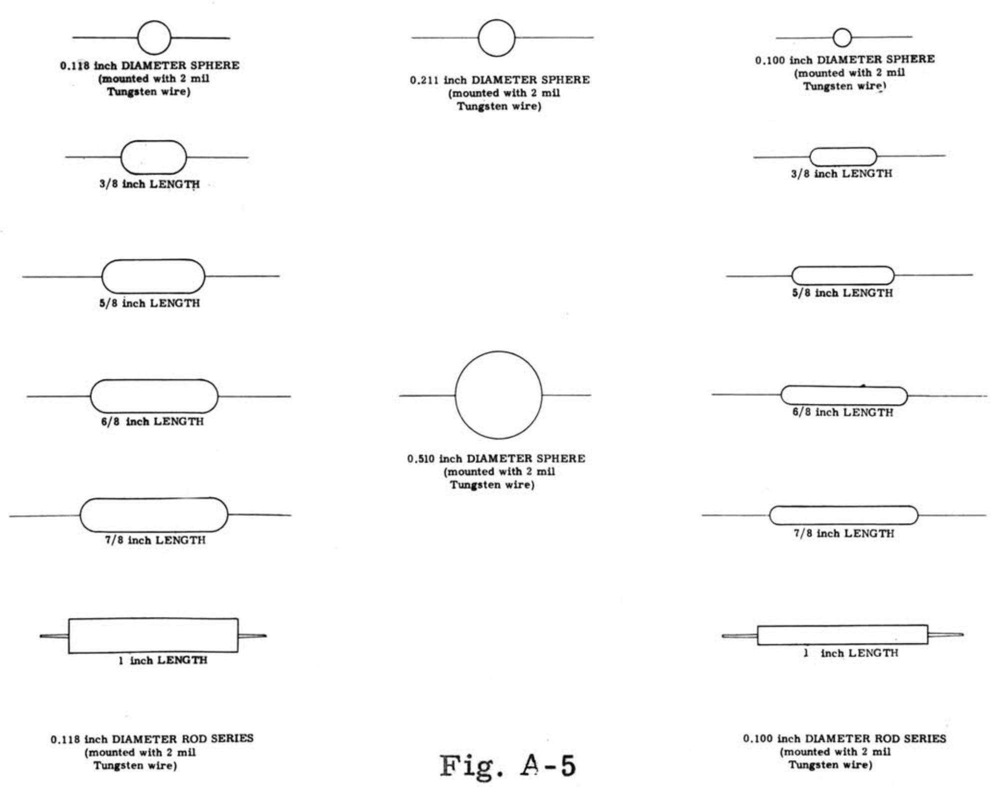


Fig. A-5

FLAME STABILIZERS