FLAME STABILIZATION AND PROPAGATION IN
HIGH-VELOCITY GAS STREAMS

by

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Cambridge, Massachusetts
March 5, 1948

Professor Joseph S. Newell
Secretary of the Faculty
Massachusetts Institute of
Technology
Cambridge, Massachusetts

Dear Sir:

In partial fulfillment of the requirements for the degree of Doctor of Science in Chemical Engineering, I herewith submit a thesis, entitled, "Flame Stabilization and Propagation in High-Velocity Gas Streams".

Respectfully yours,

Arch Chilton Scurlock

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TABLE OF NOMENCLATURE

A	area of flame front
A_r	reduced area of flame front (= A/cross-sectional area of duct)
a', b', c', d'	constants
a'', b'', c'', d''	constants
B	a constant
b	a proportionality constant believed to be not far from one
C	concentration of reacting material
C'	a constant
C_0	initial concentration of reacting material
C_p	heat capacity
c	a constant that relates l_1 to l_2 which has a value near $1/2(l_1 = 1/2 l_2 = cl_2)$
$\bar{C}_p$	average heat capacity of gases in preignition zone
D_r	reduced flame diameter for cylindrical duct (= flame diameter/diameter of duct)
d	screen wire diameter
E	coefficient of eddy diffusivity
E'	activation energy
e', f', g', h'	constants
F	fraction that has burned of total gas flowing through any cross section of duct
f	fuel-air ratio
h	slant height of cone

K_1, K_2	constants appearing in the generalized equation for St turbulence
K'	proportionality constant thought to be a function of air-fuel ratio
K''	a constant
k	thermal conductivity
k_1	thermal conductivity of gases at T_1
l_1	$u'^2 \int_0^{\infty} R_t dt$ - scale of turbulence defined in the La- grangian manner by following a single fluid particle (analogous to mean free path of the kinetic theory)
l_2	$\int_0^{\infty} R_y dy$ - scale of turbulence defined in the Eulerian manner by observing velocity fluctuations at points separated by a variable distance y (often thought of as the average diameter of an eddy)
n	characteristic dimension of flame stabilizer
Og	generalized oxidant fraction
P	static pressure
P_0	static pressure at combustion chamber entrance
R	gas law constant
Ra	resistance of hot-wire used for turbulence measure- ment at air stream temperature
Rr	reduced radius of flame in cylindrical duct (= radius of flame front/radius of duct)
R_t	$(\overline{u_{out}})/u'^2$ - correlation coefficient employed in the description of scale in the Lagrangian manner by following the paths of fluid particles
R_y	$(\overline{u_y u_y})/u'^2$ - correlation coefficient employed in the description of scale in the Eulerian manner by correla- tion of velocity fluctuations taking place in the fluid at the same time but at points separated by a distance ($y - y_0$)
R_ρ	ρ_0/ρ_b - ratio of unburned gas density to density of the completely burned products

r	radius of curvature of spherical flame front
r_1	radius of curvature of eddy region in plane normal to axis of cylindrical combustion chambers employed by Longwell, Lewis and von Elbe.
S_f	flame velocity
$S_f(\max)$	maximum flame velocity calculated on basis of minimum flame length, $s_t(\min)$
$S_f(\min)$	minimum flame velocity calculated on basis of maximum flame length, $s_t(\max)$
S_L	laminar flame velocity
S_T	turbulent flame velocity
s	length of flame front
s_r	reduced length of flame front ($= \frac{\text{length of flame front}}{1/2 \text{ chamber width}} = s/y_t$)
s_{rt}	total length of flame front
$s_t(\min)$	total minimum length of flame front (for calculation of maximum flame velocity)
$s_t(\max)$	total maximum length of flame front (for calculation of minimum flame velocity)
T	temperature
T_b	theoretical flame temperature of gases after combustion
T_{er}	temperature of the eddy region
T_i	temperature of gases in flame front at which reaction rate becomes appreciable
T_o	temperature of gases at combustion chamber entrance
t	time
U, V, W	steady component of flow velocity in the x, y, and z directions
u, v, w	fluctuating component of velocity in the x, y, and z directions

u', v', w'	the root-mean-square values of u, v, w often referred to as the intensity components of turbulence
u_0, u_t	fluctuating velocity components in the x direction of a particle at zero time and time t , respectively
u_{y0}, u_y	the fluctuating velocity components in the x direction measured along the y axis of y_0 and y , respectively
V	local velocity (also used to designate V_0 under each flame photograph)
V_{B0}	velocity at blow-out
V_0	average velocity at the combustion chamber entrance
V_r	reduced gas velocity ($=$ gas velocity/ V_0)
U_{rb}	reduced gas velocity for burned gas
V_{ru}	reduced gas velocity for unburned gas
W	width of flame
W_2, W_4, W_6, W_n	width of flame at a distance measured along the flame front of 2 inches, 4 inches, 6 inches and n inches
W_r	reduced flame width ($= W/W_t$)
$W_r-2.67$	reduced flame width at a distance measured along the flame front, on a reduced basis, s_r , of 2.67
W_t	width of rectangular duct
w_a	weight rate of flow of air into combustion chamber
w_f	weight rate of flow of fuel into combustion chamber
x	distance measured in the direction of flow
X	the displacement in the x direction from some zero reference point of a small mass of material
Y	half width of flame ($= W/2$)
Y_r	reduced half width of flame ($= W_r/2$)
Y_t	half width of duct: ($= W_t/2$)

y	distance from the combustion chamber center line measured normal to the direction of flow and parallel to the plane of the chamber front wall
z	distance measured normal to the x and y directions
β	reaction rate at any point x in reaction zone of laminar flame front
$\bar{\beta}$	average reaction rate in reaction zone of laminar flame front
Δ	the quenching distance
δ	total thickness of the preignition zone plus reaction zone ($= \delta_t + \delta_r$)
δ_r	thickness of reaction zone of laminar flame front
δ_t	thickness of preignition zone of a laminar flame front (the preignition zone is defined here as beginning in the unburned gas at a point where the temperature has risen one per cent of its total rise to T_1)
ν	kinematic viscosity
ρ_b	density of burned products
ρ_o	density of unburned gas entering combustion chamber
$1/f$	air-fuel ratio
ΔP	static pressure drop
ΔP_c	static pressure drop across combustion chamber
ΔP_t	static pressure drop for complete combustion calculated by stepwise method
ΔP_{to}	static pressure drop for complete combustion calculated assuming heat addition to be uniform across chamber ($= \rho_o V_o^2 (R_p - 1)$)
$\Delta(\Delta P_o)$	finite increment of ΔP
$\Delta(V_o^2)$	finite increment of V_o^2
Δs_r	finite increment of s_r
$\frac{k}{C_p \rho}$	thermometric conductivity

$(u'/U) \times 100$ per cent turbulence

$\phi(1/f)$ a function of air-fuel ratio

$\phi'(1/f)$ a function of air-fuel ratio

Subscripts:

a	air
b	burned
B0	blow-out
c	combustion chamber
f	flame
i	ignition
L	laminar
o	inlet conditions or initial conditions
T	turbulent
t	overall dimension or value
u	unburned
1 to 22	denotes segment in stepwise integration for obtaining velocity field through combustion chamber
-1 to -22	denotes step in stepwise integration for obtaining velocity field through combustion chamber
1/4, 1/2, 3/4, 1	 12 - denotes distance in inches from upstream extremity of flame measured along flame front where flame width measurement is taken

I. ABSTRACT

The purpose of this investigation was to study the characteristics of flames of homogeneous mixtures of gaseous fuel in air stabilized in a constant cross section duct as they are affected by:

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

Data were obtained with two different fuels, - Cambridge city gas and propane. Special emphasis was placed not only upon learning the effects of these variables on the flame, but also upon gaining a knowledge of the mechanism of flame stabilization and the method of propagation of the flame downstream from the stabilizer. Some thought has been devoted to development of a tentative explanation of the resonance and rough burning phenomena which occur in nearly all high-output combustion systems.

A stabilized flame may be defined as a flame held stationary in space relative to some reference system, - the Bunsen burner flame is a familiar example. If the velocity of the gases passing up the Bunsen tube is increased above 5 or 10 feet per second; however, the flame blows away from the burner tube and is extinguished.

Modern high-output combustion chambers such as those of the ram-jet and turbojet engines, on the other hand, often

require maintenance of stable combustion at velocities of the gas entering the chamber of over 300 feet per second. It is further required that this stabilized flame propagate through, and burn substantially, the entire body of the combustible air-fuel mixture before being exhausted; and that the whole burning process take place in a steady manner, free from resonance or rough burning effects and with a minimum of friction pressure drop.

To develop a turbojet or ram-jet combustion chamber of optimum design, information of a rather fundamental nature regarding the mechanism of flame stabilization in high velocity streams and a knowledge of the manner of propagation of the flame downstream from the stabilizer are highly desirable. Almost none of this fundamental information existed prior to this investigation.

In a field so sparsely explored as the one chosen for study, it has been considered best to search widely in a manner such that numerous frontiers might be opened, rather than to devote the entire effort to a detailed exploration of a single phenomenon. The tendency in this work was, however, to emphasize primarily hydrodynamic considerations rather than chemical kinetics and reaction mechanisms.

The experimental apparatus employed for the investigation was constructed so that a homogeneous mixture of air and gaseous fuel was introduced into the combustion chamber of constant cross section, air-fuel ratio $1/f$ could be varied over a wide range, and combustion chamber entrance velocities V_0 from 20 to

350 feet per second were readily obtained. A calming section and nozzle preceding the combustion chamber served to maintain a turbulence intensity in the gases entering the chamber of considerably less than 0.5 per cent*, and to produce a velocity profile at the chamber entrance that was essentially flat. Pressures near atmospheric and temperatures T_0 between 300° and 340°K were maintained at the chamber entrance. Screens of varying mesh and wire diameter were often placed at the combustion chamber entrance to raise the turbulence entering the chamber to some desired higher level. The combustion chamber itself was rectangular, being 3 inches by 1 inch in cross section. Two of its opposing walls were constructed of Vycor glass which allowed continuous observation of the flame and the application of various photographic techniques to its study. Flame stabilizers of simple shape and of various sizes were supported with their axes normal to the direction of flow between the opposing glass side walls. When the stabilized flame was viewed along the axis of a stabilizer, an appearance of two-dimensionality was obtained.

FLAME PROPAGATION

As an aid in interpreting the experimental results on flame propagation, and to obtain a better visualization of the flow conditions through the combustion chamber in the presence of

* A turbulence intensity of about 3% exists at the center of a pipe carrying a fluid in fully developed turbulent flow. (14)

a stabilized flame, a method has been developed for estimating this flow by hydrodynamic calculations. Many of the conclusions reached on the basis of these calculations also apply qualitatively to high output combustion chambers in general.

By using the results of these calculations with flame width data obtained in the rectangular combustion chamber, estimates of effective flame velocities in the chamber can be obtained, and interesting comparisons of calculated and experimental results can be made. The following important general conclusions are obtained from these stepwise calculations:

1. Velocity gradients are generated due to the combustion process itself even when no gradients either in velocity or air-fuel ratio exist prior to combustion. This occurs because the light burned gases in the wake of the stabilizer are accelerated more rapidly than are the surrounding unburned gases.

2. Pressure drop across the chamber for a given heat release rate is greater when combustion proceeds downstream from a stabilizer than if the heat is added uniformly across the cross section. The ratio of these pressure drops increases with the ratio, R_ρ , of the unburned to burned gas density.

3. A parcel of unburned gas before entering the flame front has a small velocity component in a direction normal to the chamber axis, and away from the flame front. After passing through the flame front and burning, the parcel has a velocity component in the reverse direction which becomes zero when combustion is complete.

Visual observation of flames stabilized on simple bluff objects of various size and shape including rods, 30° closed and open edge gutters, flat plates, and multiple rods, and study of flame pictures including time exposures, spark shadow photographs, and high speed movies lead to the following general conclusions:

1. No classical Karman vortex trail due to eddy shedding from the stabilizer is present during combustion. Instead, the two recurrently forming eddies behind the stabilizer are thought to shorten and become symmetrical during combustion just as occurs in isothermal flow around a bluff object when the Reynolds number is reduced to below about 30.

2. The flame propagation velocity is increased over the laminar flame propagation velocity, S_L , by three different types of disturbance:

(a) Generation of turbulence due to velocity gradients across the flame front present in the region just downstream of the flame stabilizer. This type of disturbance is most likely to appear when the value of the following expression is large:

$$\left(\frac{v_o n}{\nu}\right)^{0.1 \text{ to } 0.3} \left[\frac{v_o}{S_L (R_f - 1)} \right] \quad (43)$$

Frequently no disturbance due to instability of this first region is present. Under these conditions no effect of stabilizer characteristic dimension n (for a rod n is the diameter) on flame propagation is observed. (ν is kinematic

viscosity of the gases, V_0 is the velocity of the gases entering the chamber).

(b) Generation of turbulence due to velocity gradients across the flame front produced by the pressure drop resulting from the combustion process itself which accelerates the low-density burned gases more rapidly than the high density unburned gases. This type of disturbance is most likely to appear when the following expression is large:

$$\frac{V_0 W_t}{\nu} (F) (R_p - 1) \left(\frac{V_0}{S_L} \right) \quad (45)$$

(F is fractional completion of combustion, W_t is chamber width).

(c) The approach stream turbulence: The effect of approach stream turbulence intensity, u' , on flame velocity is, under most conditions, masked by the effect of the other disturbances. Its effect is comparatively quite small even at approach stream turbulence intensities as high as 3 per cent of the mean entrance velocity V_0 , and is in most cases still somewhat smaller than the effect due to internally generated disturbances at turbulence intensities as high as 6.5 per cent. The following equation was found to describe the effect of approach stream turbulence on the ratio of turbulent flame velocity to laminar flame velocity*:

$$\frac{S_T}{S_L} = \sqrt{1 + \left(\frac{u'}{2S_L} \right)^2} \quad (21)$$

* Laminar flame speeds were measured at various air-fuel

3. Propagation of the flame downstream of stabilizers of the same characteristic dimension but of differing shape is in most cases the same. However, at the higher velocities at very lean mixtures when turbulence generation in the first region of velocity gradients controls the rate of flame propagation, for the 30° gutters and flat plates, $(n \times 0.37)$ and $(n \times 1.5)$, respectively, should be employed as the effective characteristic stabilizer dimension to put these shapes on a basis comparable with rods for flame width comparisons.

4. The flame velocity in general increases with distance downstream from the stabilizer.

5. From observation of residual flames it is concluded that under certain conditions there may exist near the stabilizer a stable flame which fails to propagate into the main body of the combustible gas stream, but instead is quenched.

FLAME STABILIZATION

From theoretical considerations regarding flames stabilized on bluff, nonconducting objects it was concluded that the following equation applies at blow-out: (V_{BO} = Blow-out velocity)

$$\frac{V_{BO}^{e'-g'}}{n^{g'}} = \frac{K' S_L (T_b - T_o)}{(\nu)^{g'} (T_i - T_o)} = \phi \left(\frac{1}{f} \right) \quad (50)$$

(where T_b = temperature of completely burned fuel-air mixtures, T_o = approach gas stream temperature, and T_i = ignition temperature, all exponents are constants).

 ratios for both city gas and propane in a Bunsen cone apparatus. Measurements of turbulence intensity and scale existing in the chamber were made with a hot-wire anemometer type meter for unobstructed gas entry, and with screens of various meshes and wire diameters at the chamber entrance.

An additional term, $K''(n/S_L)^{h'}$, added to the left-hand side of equation (50) is suggested to allow for conductivity of the stabilizer and the resultant cooling of the eddy region by the stabilizer.

The flame near the stabilizer was studied by visual and photographic means, and blow-out limit data obtained with stabilizers of various size and shape, with both city gas and propane as fuel. The effect on stability of heating and cooling the stabilizer and of turbulence in the approach stream was investigated.

The following conclusions regarding flame stabilization were arrived at primarily from experimental results:

1. The mechanism of flame stabilization behind bluff objects is different from that for stabilization of flames of the Bunsen type. The eddy region present behind the bluff stabilizer is filled with hot combustion products when a stabilized flame is present and these recirculating hot gases furnish a continuous source of ignition for the unburned approach gases coming into contact with them. Due to absence of an eddy region, a flame will not, on the other hand, stabilize on an unheated streamlined object in a high velocity gas / stream.

2. In accord with equation (50), blow-out limit data obtained with stabilizers ranging in characteristic dimension from 0.016 to 0.5 inches were found to correlate fairly well for a given fuel when $V_{BO}/n^{0.45}$ was plotted versus air-fuel ratio. The points scattered slightly on the lean side at low velocity, however.

This was attributed to the cooling action of the stabilizer on the eddy region. The addition of a second term to the left-hand side of equation (50) has been suggested to take into account this effect by correcting for heat conduction by the stabilizer. By plotting the stability limit data of Longwell, and of Lewis and von Elbe as $V_{BO}/n^{0.45}$ versus generalized oxidant fraction, the correlations which were obtained are thought to be as satisfactory as those originally obtained by these investigators using other methods of correlation.

3. The effect of stabilizer shape on the stability limits is negligible for the bluff stabilizers employed - rods, 30° open and closed edge gutters, and flat plates.

4. Heating and 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.

5. The stability limits for a stabilizer of given size 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.

6. Values of $V_{BO}/n^{0.45}$ are probably a direct function of S_L and $(T_b - T_o)$, as indicated in equation (50). At least one of the other quantities on the right-hand side of equation (50) apparently also varies with different fuels, since no correlation of the city gas-air and propane-air stability limit data is obtained by plotting $V_{BO}/n^{0.45} (S_L)(T_b - T_o)$ versus

generalized oxidant fraction.

7. Increasing turbulence intensity decreases the stability limits. The effect of turbulence of the same scale and intensity becomes less as the ratio of stabilizer diameter to scale increases.

UNSTEADY BURNING PHENOMENA

On the basis of theoretical considerations and a few experimental observations, the following conclusions in regard to unsteady burning phenomena have been reached:

1. Rough burning is due to random fluctuations about a mean value of the fraction burned, F . Fluctuations in F cause similar fluctuations in ΔP_c , the static pressure drop across the combustion chamber. Since for atmospheric discharge the exhaust pressure remains constant, changing ΔP_c causes changes in pressure of the approach stream and thus results in random increases and decreases in V_o . Burning tends to be roughest when F is large and when it fluctuates most in absolute value with time.

2. Unsteady burning phenomena of a periodic nature, differentiated by frequency ^{as} resonance or flutter, occur when an unstable equilibrium exists. They are most likely to appear when F is very near unity and when the flame velocity at the chamber exit is large, but should not appear when combustion is complete. Resistance to flow produced by the chamber walls, the stabilizer, or a screen placed at the chamber entrance, reduces the likelihood of appearance ^{of} periodic unsteady burning.

3. During resonance or flutter the period of the vibra-

tion is the resonant frequency of some portion of the apparatus. Resonance during this investigation occurred at the fundamental resonant organ-pipe frequency of the combustion chamber, (about 300 cps) and flutter occurred at the fundamental resonant organ-pipe frequency of the combustion chamber and calming section together, (about 40 cps).

II. INTRODUCTION

A. General Discussion

A stabilized flame may be defined as a flame held stationary in space relative to some reference system. The Bunsen burner flame resting stationary just above the burner tube as the combustible gases flow up through it and burn is a familiar example of a stabilized flame. Here the burner tube itself acts as the flame stabilizer. If the velocity of the gases passing up the tube is increased above 5 or 10 feet per second, however, the flame blows away from the burner and is extinguished. The velocity at which this blow-off occurs is a function of the fuel properties, the air-fuel ratio, the diameter and temperature of the burner tube, the pressure and temperature of the unburned gases, and the degree of mixing that has been achieved between the fuel and primary air.

Recently there has been considerable interest in the development of radically new power plant types requiring heat release rates per unit of combustion chamber volume one hundred to one thousand times the volumetric heat release rates encountered in a modern industrial furnace. Foremost among these both in terms of interest and in difficulty of design are the jet propulsion type. These high output power plants include the turbo-jet, pulse-jet, ram-jet, and rocket engines.

We are concerned here with the two of these power plant

types which use as the oxidant air taken in during flight and which, further, maintain steady state combustion without re-ignition in the combustion chamber - the turbojet and ram-jet power plants. Of these two, the one in the least advanced stages of development and whose combustion chamber design requirements from the standpoint of high heat release rates per unit of volume are the most severe is the ram-jet. From a theoretical design standpoint it would often be desirable to maintain stable combustion in a ram-jet combustion chamber at velocities of the gas entering the chamber of over 300 feet per second. For the turbojet, combustion chamber entrance velocities desirable from theoretical design considerations are less than for the ram-jet, but are still in the neighborhood of 50 to 100 feet per second.

In ram-jet and turbojet combustion chambers, then, it is desirable to maintain a stabilized flame in gases up to above 300 feet per second. It is further required that this flame propagate through the entire body of the combustible air-fuel mixture before being exhausted in order that a high percentage completion of combustion will obtain, and that the whole burning process take place in a steady manner free from resonance or rough burning effects and with a minimum of friction pressure drop.

To develop a turbojet or ram-jet combustion chamber of optimum design, information of a rather fundamental nature regarding the mechanism of flame stabilization in high velocity

streams and a knowledge of the manner of propagation of the flame downstream from the stabilizer are highly desirable. Knowledge should further be available regarding the causes of rough burning and resonance so that these instability effects can be avoided.

At present, almost none of this fundamental information exists. Attempts to extrapolate the very scanty available data related to laminar and turbulent flame propagation and to low velocity stabilization of flames of the Bunsen cone and inverted Bunsen cone type into a velocity range higher by several orders of magnitude have been for the most part unsuccessful. The absence of this much-needed information from the literature can perhaps be attributed both to the recent origin of the need, and to the difficulty of separating the individual effects of the many independent variables which affect the combustion chamber performance of a turbojet or ram jet. Parameters on the basis of which combustion chamber performance is evaluated include the air-fuel ratio range over which a stabilized flame can be maintained, the completeness of combustion, the friction pressure drop through the chamber, and the presence or absence of resonance or rough burning phenomena. Important among the independent variables controlling combustion chamber performance are:

1. Air-fuel ratio
2. Completeness of mixing of air and fuel
3. Combustion chamber entrance velocity, temperature, and pressure

4. Type of fuel and additives employed
5. Turbulence in the entering air-fuel stream
6. Combustion chamber configuration
7. Size, shape, and temperature of the flame stabilizer

Attempts to isolate satisfactorily the individual effects of these variables by studying directly the operation of a turbo-jet or ram-jet combustion chamber have proved unsuccessful. Therefore, it seemed desirable to choose certain of these independent variables for study and to devise experiments in a way such that the remaining variables are either eliminated completely or held constant.

The purpose of this thesis has been to carry out a fundamental study of flames stabilized in a constant cross section duct as they are affected by:

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

Data have been obtained with two widely different types of fuel - Cambridge city gas and propane. Special emphasis has been placed not only upon showing the effects of these variables on the flame but also upon gaining a thorough knowledge of the mechanism of flame stabilization and the method of propagation of the flame downstream from the stabilizer. Some thought stimulated by a few experimental observations has been devoted to development of a theoretical explanation of resonance and rough burning phenomena.

The apparatus employed for the investigation was constructed so that a homogeneous mixture of air and gaseous fuel was introduced into the combustion chamber, air-fuel ratio could be varied over a wide range, and combustion chamber entrance velocities from 20 to 350 feet per second were readily obtained. A calming section and nozzle preceding the combustion chamber served to maintain a turbulence level in the gases entering the chamber of less than 0.5 per cent* and to produce a velocity profile at the chamber entrance that was essentially flat. Pressures near atmospheric and temperatures in the neighborhood of 300 to 340°K were maintained at the chamber entrance. Screens of varying mesh and wire diameter were often placed at the combustion chamber entrance to raise the turbulence entering the chamber to some desired higher level. The combustion chamber itself was rectangular, being 3 inches by 1 inch in cross section. Two of its opposing walls were constructed of Vycor glass which allowed continuous observation of the flame and the application of various photographic techniques to its study. Flame stabilizers of simple shape and varying size with their axes normal to the direction of flow were supported between the opposing glass side walls. When the stabilized flame was viewed looking along the axis of a stabilizer an appearance of two-dimensionality was obtained. The combustion chamber was rather short so that only under special conditions did combustion approach completion

* The turbulence at the center of a pipe carrying a fluid in fully developed turbulent flow is approximately 3 per cent (14).

before the gas left the chamber. Thus, the pressure drop across the combustion zone was held at a relatively low level. Pressure fluctuations and their effect on the inlet gas velocity were consequently reduced. This assured a smooth flow of gases past the stabilizer and a steady flame essentially free, except in certain special cases, from any resonance or rough burning effects.

Upon reviewing briefly the literature related to flame propagation and stabilization in the low velocity range, it may occur to the reader that little can be gained by pursuing a program aimed at obtaining data in the high velocity region when as yet only a beginning has been made at the development of a quantitative theory of laminar flame propagation; that is, one properly taking into account the individual effects of heat transfer, molecular diffusion, and, most difficult of all, chemical reaction rate and mechanism. It may appear that a more profitable approach would be first to attack and solve the problem in the low-velocity, laminar flow region before investigating phenomena at higher velocities.

Although continued studies in the low velocity region are highly recommended, it is believed that in the high velocity range a very enlightening study can be made with primary emphasis placed only on hydrodynamic considerations. The present investigation has tended in that direction. It was on a similar basis that investigators such as Burke and Schumann (9) working with diffusion flames, and Hawthorne (20) studying high

velocity gas jets were successful. The development of a satisfactory detonation theory was achieved entirely from hydrodynamic and thermodynamic considerations without reference to chemical reaction rates. Further, the present rudimentary theory of turbulent flame propagation predicts that hydrodynamic considerations should be controlling in many instances where turbulent flames are the subject of study.

In a field so sparsely explored as the one chosen for this investigation, it has been considered best to explore widely in a manner such that numerous frontiers might be opened, rather than to devote the entire effort to a detailed exploration of a single phenomenon. Consequently, perusal of this work by the researcher in the field of combustion will, it is believed, suggest a number of interesting avenues for further research.

B. Work of Previous Investigators - Technical Background

1. Laminar Flame Propagation

The following discussion is limited to slow combustion (deflagration) in homogeneous gas mixtures.

When an explosive gas mixture burns the combustion takes place in a narrow zone (separating burned and unburned gas) which propagates as a Huygens wave in a direction normal to itself into the unburned gas. Within this zone, in the layers adjacent to the completely burned gas, heat is released and atoms and free radicals are formed by the chemical reaction. A part of the heat and active species (chain carriers) is transferred by conduction and diffusion to the adjoining layers of unburned gas which in turn become activated to rapid chemical reaction. In this way, the combustion zone progresses against the unburned gas at a definite velocity. The rate of progress of this zone relative to the unheated, unburned gas is the normal flame propagation velocity, or simply the flame velocity*. If no turbulence exists in the region of combustion this velocity is the laminar flame velocity.

It has not proved possible to observe this velocity directly as conditions where the unburned gas is at rest have not been realized experimentally**. The velocity of propagation must be

* Also variously referred to in the literature as the burning velocity, transformation velocity, flame speed, ignition velocity and normal velocity.

** The nearest approach to this ideal situation is obtained by igniting at its open end a tube filled with combustible gases and closed at the other end. Unfortunately, however, the flame surface does not remain normal to the tube axis due, as pointed out, by Jost (22), to movement of the unburned gas induced by the approaching flame front. It, therefore, becomes necessary to photograph the moving flame after known time intervals to determine its rate of

(continued on next page)

calculated either as the vector difference of the observed velocity of flame movement and the velocity of flow of the unburned gas, or as total mass flow through the flame front divided by the surface of the flame front and by the initial density.

The former method is typified by the soap-bubble technique of flame velocity determination of Stevens (44), used extensively and discussed in detail by Flock and Marvin (17). With the soap-bubble method, photographs equally spaced in time are taken of a growing soap bubble filled with an explosive gas mixture of known composition that has been ignited at its center by means of an electric spark. Analysis of these photographs yields the velocity both of the flame front and the unburned gas. The difference between these two quantities is the laminar flame propagation velocity characteristic of the explosive mixture. The method is limited to mixtures that are saturated with water vapor and is subject to the error that diffusion of gases through the soap film is a fairly rapid process, so that the mixture composition is often not well defined.

The latter method is typified by the Bunsen cone technique developed by Gouy (19) and Michelson (35), and discussed in detail by Mache (32), and more recently by Lewis and von Elbe (31)

(continued from previous page)

movement and to obtain the total flame area. This is a rather difficult procedure due to the asymmetrical shapes generally assumed by the flame front and to changes in flame front area and velocity with time which often occur. Because of these difficulties this method of experimentally determining laminar flame velocity is not widely used. Careful measurements of flame velocity obtained using this method, however, by Coward and Hartwell (10) agree closely with those obtained by other, more widely used, methods.

and von Elbe and Mentser (16). Since the Bunsen burner flame is stationary in space, to determine laminar flame velocity, it is only necessary to divide the volumetric flow rate through the tube by the total flame surface determined by analysis of a flame photograph. This simple method is widely used. Criticism of the method has been based (22) primarily on the effect on flame velocity of diffusion of air (or other surrounding gases) into the explosive gas mixture near the burner rim, and increase in flame velocity due to increased diffusion of heat and chain carriers from all sides into the unburned gas at the flame tip. Since the Bunsen cone method is based on the assumption of constant flame velocity over the entire flame surface, this criticism is valid and has been given considerable attention. It has been shown by Ubbelohde (48) and more recently by Jost (22) and von Elbe and Mentser (16) that the use of a sufficiently large burner tube reduces any error due to anomalous flame velocities near the burner rim or flame tip to a low value. Another excellent method of reducing rim diffusion errors encountered with rich mixtures is the split tube method of Ubbelohde (48). This method allows separation of the inner Bunsen cone from the outer diffusion flame in a manner such that the inner cone is surrounded with combustion products instead of air.

For over fifty years investigators have attempted to develop a quantitative method for calculation of laminar flame

velocity based on the fundamental physical and chemical properties of the combustible mixture. The problem is still far from solution, and what has been achieved is of little value for practical applications. This failure can be attributed primarily to the complicated nature of the kinetics of almost all combustion reactions. These reactions often take place by chain mechanisms involving unstable intermediate products. A detailed knowledge of the great majority of these reactions has not yet been obtained. Since exact equations taking into account the actual reaction mechanism cannot be developed without a more thorough knowledge of these mechanisms, investigators have for many years worked with equations involving questionable simplifying assumptions.

All the earlier theories were based on the assumption that the mechanism of flame propagation was entirely thermal; that is, diffusion of chemically active species was neglected. This assumption was justified on the basis that both diffusion of heat and of active species obeyed the same type of law. Therefore, any equations derived on the basis of thermal diffusion alone could be made to apply, even if transfer of active species was quite important, simply by multiplying through by the proper constant. Furthermore, all of these older thermal theory equations are based on the assumption of an ignition temperature, T_1 , intermediate between the approach gas temperature, T_0 , and the temperature of the burned products, T_b , and below which the reaction rate is very low. Once this ignition temperature is

reached the reaction is assumed to proceed at a constant rate determined only by initial conditions.

Mallard and Le Chatelier (33) in 1883 first developed a theoretical equation based on these assumptions. Employing the same assumptions, a number of other investigators including Jouget (23), Daniell (13), and Damköhler (12), have developed equations improved only slightly over that of Mallard and Le Chatelier. Since this type of equation is still the most useful yet developed for qualitative application to general problems, the derivation of a form similar to that obtained by Damköhler is included here.

Referring to Figure 1, consider a flame front fixed in space with the approaching unburned gases moving in the positive x direction toward it at the laminar flame velocity, S_L . This approaching explosive gas mixture, as it nears the reaction zone, enters a preparatory zone where it receives heat by conduction and active species by diffusion from the reaction zone until it reaches a temperature, T_1 , at which reaction rate becomes appreciable. The reaction then proceeds rapidly to completion and the gas leaving the reaction zone reaches the maximum temperature of the burned gases, T_b . The origin is fixed at the boundary between preignition and reaction zone.

Since no appreciable amount of heat has been released within the explosive gases before reaching the reaction zone,

FIG. 1

TEMPERATURE DISTRIBUTION IN A LAMINAR
FLAME FRONT

all the heat in the gas entering this zone must have been supplied from the reaction zone by conduction. The following heat balance can therefore be written for the boundary between the preignition and reaction zone:

$$\bar{C}_p \rho_0 S_L (T_1 - T_0) = k_1 \left(\frac{dT}{dx} \right)_1 \quad (1)$$

where $\bar{C}_p$ is the average heat capacity between T_0 and T_1 , ρ_0 is the density of the unburned gas, k_1 is the thermal conductivity of the gases at T_1 and $\left(\frac{dT}{dx} \right)_1$ is the temperature gradient at T_1 .

Since the entire reaction takes place in the reaction zone of thickness, δ_r , the following balance equating the rate of entry of combustible material into the reaction zone to the material reacting in that zone can be written:

$$C_0 S_L = \int_0^{\delta_r} \beta dx = \bar{\beta} \delta_r \quad (2)$$

where C_0 is the concentration of reacting material, β is the reaction rate at any point x , and $\bar{\beta}$ is the average reaction rate in the reaction zone.

An additional relation can be written as follows:

$$\left(\frac{dT}{dx} \right)_1 = \left(\frac{T_b - T_1}{\delta_r} \right)^b \quad (3)$$

where b is a constant of proportionality believed to be not far from unity. Combining equations 1, 2, and 3, and solving for S_L :

$$S_L = \left(\frac{k_1}{C_p \rho_0} \frac{b\beta}{C_0} \frac{T_b - T_1}{T_1 - T_0} \right)^{1/2} \quad (4)$$

Equation 4, derived on the basis of strictly thermal considerations, can be employed to arrive at several general conclusions agreeing remarkably well with those experimentally obtained. The flame velocity according to equation 4, becomes greater as T_b increases, becomes smaller as T_b decreases, and drops to zero when T_b becomes equal to T_1 . Maximum flame velocities are observed when flame temperature is also near a maximum, and ignition limits where the flame no longer propagates have been found to exist. High flame velocities are predicted for gases possessing a high reaction rate, other things being equal. This corresponds to experiment since acetylene-air flames, for example, propagate a great deal faster than carbon monoxide-air flames. It is further predicted that flame velocity will increase with increasing T_0 . This is found to be the case, but the increase is less marked than might at first be expected. Flame velocity is approximately proportional to the unburned gas temperature, the exact relation varying considerably for different fuels. This experimental observation leads us to the tentative conclusion that $(T_1 - T_0)$ is quite large. This is also suggested by the fact that the temperature of the gases approaching the flame front can be raised well above minimum temperatures for spontaneous ignition of stagnant mixtures in a heated vessel (preceded by an induction period). This suggests

that T_1 is well above ignition temperatures obtained by this method.

Equation 4 further predicts changes in S_L resulting from changes in $\bar{C}_p$ and k_1 . Substituting CO_2 for N_2 in a methane-air mixture, thus raising $\bar{C}_p$ but holding k_1 approximately constant, reduces the combustion velocity considerably and narrows the inflammability limits as predicted by equation 4. If, conversely, argon is substituted for nitrogen (10) the combustion velocity rises to several times its original value. CO_2 , N_2 and argon cannot, however, be compared on the basis of heat capacity effects alone since T_b also is considerably modified by replacing one of these gases with another.

If mixtures are compared in which first helium then argon, both of which have the same heat capacity, are substituted as the inert gas, a difference in S_L should appear due only to a difference in k_1 . Coward and Jones (11), using methane as a fuel, found that the flame velocity with helium is 15 per cent higher than with argon while the conductivity of pure helium is about eight times that of argon. This last experiment points out the inadequacy of equations derived on the basis of thermal considerations alone, and emphasizes the large roll played by diffusion of active species. These active particles should continue to diffuse at about the same rate in mixtures diluted with either argon or helium, and therefore, would tend to hold

the flame velocity relatively constant.

Nusselt (37) and Jahn (21) derived equations based on assumptions similar to those employed in the derivation of equation 4, but further specialized the equations obtained for application only to hydrogen-oxygen, hydrogen-oxygen-nitrogen, or hydrogen-oxygen-carbon dioxide mixtures.

A more advanced thermal theory relating reaction rate to temperature, assuming the classical relation of Arrhenius,

$$\beta \propto e^{-\frac{E}{RT}} \quad \text{for zero order}$$

$$\beta \propto e^{-\frac{E}{RT}} \quad \text{for first order, etc.}$$

and finally eliminating T_1 entirely from the final expression has been developed by Zeldovich (50), Frank-Kamenetsky (49), and Semenov (42). This equation has been applied, thusfar, only to combustion of carbon monoxide, the restriction being due to doubt by the authors that the theory applies to fast reactions of the branched chain type, particularly to combustion of hydrogen and the hydrocarbons.

Lewis and von Elbe (29), (30), have made the first successful attempt to take into account the kinetics of a chain reaction in their treatment of the decomposition of ozone. Their calculated propagation velocities coincide remarkably with experimental

values. This coincidence, however, is due to the relative simplicity of the ozone decomposition reaction and is based on a knowledge of the reaction mechanism. Extension of this treatment to more complicated and less understood combustion reactions is not considered feasible at present.

Referring now back to equation 1, this relation, which has been written for the specific point where $x = 0$ and $T = T_1$, can be written, by removal of subscripts, as a general differential equation relating T to x in the preignition zone as follows:

$$\bar{C}_{p_{T_0 \rightarrow T}} \ell_0 S_L (T - T_0) = k_T \left(\frac{dT}{dx} \right) \quad (5)$$

where $\bar{C}_{p_{T_0 \rightarrow T}}$ is the average heat capacity of the gases between T_0 and T , and k_T is the thermal conductivity at T .

If the thickness of the preignition zone, δ_t , is now more exactly defined as the distance from the point where $T = T_1$ back to where T has increased above T_0 by an amount one one-hundredth of the total increase between T_0 and T_1 , if $\bar{C}_{p_{T_0 \rightarrow T}}$ is replaced by $\bar{C}_p$, which is approximately the average heat capacity across δ_t and k_T is replaced by $\bar{k}$ which is the average thermal conductivity across δ_t , equation 5 can be integrated between the limits of T , and δ_t can be solved for directly.

$$\delta_t = \frac{4.606}{S_L} \frac{\bar{k}}{\bar{C}_p \rho_0} \quad (6)$$

The thickness of the preignition zone is seen to be inversely proportional to laminar flame velocity, S_L , and directly proportional to the thermometric conductivity, $\bar{k}/\bar{C}_p\rho_o$. By assuming an S_L of 1.0 foot per second and a $\bar{k}/\bar{C}_p\rho_o$ of 0.001 square feet per second, both reasonable values, δ_t , is found to be 0.012 inches in thickness.

Returning again to equation 1, if the average value of dT/dx through the reaction zone is assumed equal to its value at the boundary of the zone where the temperature is T_1 , then $(dT/dx)_1$ can be replaced by $(T_b - T_1)/(\delta_r)$. The equation can then be solved for δ_r . If the ratio $(T_b - T_1)/(T_1 - T_o)$ is further assumed to be unity* and the equation combined with equation 6, the following expression results:

$$\begin{aligned}\delta_r &= \left(\frac{T_b - T_1}{T_1 - T_o}\right) \frac{k}{S_L \bar{C}_p \rho_o} = \frac{1}{S_L} \frac{k}{\bar{C}_p \rho_o} \\ &= \frac{\delta_t}{4.606}\end{aligned}\tag{7}$$

Substituting the previously calculated value of $\delta_t (= 0.012 \text{ inches})$ into the above expression, δ_r , is found to be 0.0026 inches or about 0.1 millimeters - a commonly observed thickness of the luminous reaction zones.

*The ratio $\left(\frac{T_b - T_1}{T_1 - T_o}\right)$ probably decreases to values considerably below unity near the rich and lean ignition limits. This assumption, can, therefore, only be considered a rough approximation.

3. The Effects of Turbulence on Flame Velocity

It is well known that the transfer of heat, mass or momentum through a gradient by conduction, molecular diffusion, or viscosity forces, respectively, in a fluid in laminar flow can be greatly increased by the introduction of turbulence.

Turbulent motion was first studied in detail by Reynolds (39) who proposed an analogy between the transfer of heat and momentum. Prandtl (38) later introduced the concept of a "mixing length" and contributed to the development of a theory for momentum transfer in fully developed turbulent flow in a pipe. G. I. Taylor (45), von Karman (24), and Dryden (15) are generally credited with development of the statistical theory of isotropic turbulence. Other contributors to the development of this theory include among others, Burgers (8), Noether (36), Tollmien (46). The statistical theory has been developed in a manner similar in many respects to the treatment of conduction, viscosity, and diffusion in laminar flow based on the kinetic theory, and it represents at present the most advanced state of turbulence theory. The following discussion is based on the statistical approach.

Turbulent motion is characterized by the random motion of the particles constituting the fluid stream, and in general makes its appearance in fluids when they flow past solid surfaces or when neighboring streams of the same fluid flow past or over one another. In true turbulent motion, it is essential

that the fluctuations be irregular. When a cylinder is immersed in an isothermal fluid stream, under certain circumstances a regular vortex system appears at the downstream side, and the vortices break away from the cylinder with a regular periodicity. In the Karman "vortex trail" the fluctuations of speed at any point with time are periodic. This vortex motion does not produce turbulent mixing and should not be designated as turbulent motion. With increasing distance behind the cylinder the regular pattern gradually disappears, and the vortex motion gradually changes into a turbulent motion in which the fluctuations are no longer periodic.

It is convenient to think of a fluid in turbulent motion as having a mean velocity, U , in the x direction, with a superimposed random motion resulting in instantaneous deviations from U at any point. This instantaneous deviating velocity at any point has components, u , v , and w , in the x , y , and z directions*. The root-

* As pointed out by Dryden (15), the separation of the actual flow into a steady flow and a superimposed turbulence cannot be made in any unique manner. Thus, even the so-called laminar flow appears non-turbulent merely because the instruments used do not respond to the motions of the individual molecules. The concept of turbulence, therefore, depends on the purpose of the study as has been well illustrated in the case of atmospheric turbulence, where there are at least three possibilities. The general circulation of the atmosphere may be regarded as the steady flow, in which case the wind movement near the "highs" and "lows" on the weather map constitute the superimposed turbulence. The second possibility is to regard the motion described on the ordinary weather map as the steady flow. In this case the gusts constitute the superimposed turbulence. The final possibility is to consider the gust as the steady flow, in which case the superimposed turbulence is on a small scale similar to that studied in wind tunnels.

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' , respectively.

It is evident that the effect of turbulence cannot be satisfactorily correlated with the single property, intensity. It is necessary to introduce some statistical measure of the size or duration of the perturbations.

The earliest attempt to describe the spatial characteristics of turbulence was the introduction of the mixing length concept, the mixing length being analogous to the molecular mean free path of the kinetic theory of gases. Difficulties arise because there are no discrete fluid particles in the turbulent flow which retain their identity. A method of avoiding these difficulties was suggested by Taylor (45). He showed that the diffusion of particles starting from a point depends on the correlation, R_t , between the velocity of a fluid particle at any instant and that of the same particle after a time interval, t . If the relationship between R_t and t is such that R_t falls to zero at some value of t , and remains so for greater intervals, it is possible to define a length, l_1 , by the relation:

$$l_1 = u' \int_0^{\infty} R_t dt \quad (8)$$

where:

$$R_t = \frac{\overline{u_t u_t}}{\sqrt{\overline{u_0^2}} \sqrt{\overline{u_t^2}}} = \frac{\overline{u_0 u_t}}{u'^2}$$

and u_0 and u_t are the fluctuating velocity components in the x direction of a particle at zero time and time t , respectively.

This method of assigning a scale to turbulence is based on the Lagrangian manner of describing flow by following the paths of fluid particles. This scale, l_1 , is in many ways analogous to the mean free path of the molecules in the kinetic theory and is of special value in the consideration of turbulent diffusion.

In practice, use of a scale defined in the Eulerian manner is more common, since this type of scale can readily be determined by the widely used hot-wire anemometer type turbulence measuring instrument. Taylor (45) suggested that scale might be defined in the Eulerian system based on the variation of the correlation coefficient, R_y , between the values of the component u at two points, separated by the distance y in the direction of the y coordinate, as y varied. If R_y falls to zero at some value of y and remains at zero for larger y values, a length, l_2 , may be defined by the relation:

$$\begin{aligned} l_2 &= \int_0^{\infty} \frac{u_{y_0} u_y}{u'^2} dy \\ &= \int_0^{\infty} R_y dy \end{aligned} \quad (9)$$

where u_{y_0} and u_y are the fluctuating velocity components in the x direction measured simultaneously at a distance along the y axis of y_0 and y , respectively. This scale, l_2 may be thought of as proportional to the average diameter of an eddy - an

eddy being a region of neighboring particles which for a moment exhibits a common fluctuating velocity vector. Although no theoretical equation which relates l_1 and l_2 has yet been developed, Taylor (45) by comparing experimental values in the literature of both quantities, deduced that $l_1 \cong l_2/2$. It is often found convenient in practice to derive equations for turbulent diffusion using l_1 and then, because of the relative ease of its experimental determination, to substitute, l_2 .

The simplest type of turbulence for theoretical or experimental investigation is that in which the intensity components in all directions are equal. This specialized type is known as isotropic turbulence and is more accurately defined by the condition that the mean value of any function of the fluctuating velocity components and their derivatives at a given point is independent of rotation or reflection of the axes of reference. Changes in direction and magnitude of the velocity fluctuations at a given point are wholly random and there is no correlation between the components of the fluctuations in different directions.

There is a strong tendency toward isotropy in all turbulent motions. The turbulence at the center of a pipe in which the flow is eddying or in the natural wind at a sufficient height above the ground is approximately isotropic. A screen of uniform mesh and wire diameter placed in a fluid stream sets up a more or less regular eddy system of non-isotropic character which very quickly transforms into a field of uniformly distributed isotropic turbulence.

The assumption of isotropy introduces many simplifications in the statistical representation of turbulence. The two quantities, intensity and scale, are sufficient to give a description of the statistical properties of the turbulent field.

The kinetic energy of the turbulent fluctuations per unit of volume is equal to $1/2 \rho (\bar{u}^2 + \bar{v}^2 + \bar{w}^2)$ which becomes for isotropic turbulence $3/2 \rho \bar{u}^2$. The rate of kinetic energy dissipation then, is $-3/2 \rho d(\bar{u}^2)/dt$. If the turbulence is superimposed on a stream of uniform velocity, U , we may write $dt = dx/U$. The rate of decay with respect to distance, x , then becomes $-3/2 \rho U d(\bar{u}^2)/dx$. In a fully developed turbulent flow the Reynolds stresses are proportional to the density and the square of the turbulent fluctuations. The work done against these stresses, which must come from the kinetic energy of the system may be written as proportional to $\rho u'^3/l_2$ which has the dimensions of a rate of change of energy. Equating these two expressions and introducing a constant B , we obtain:

$$- \left(\frac{3}{2}\right) \rho U \frac{d(u'^2)}{dx} = 3 \frac{B u'^3}{l_2}$$

or

$$l_2 \frac{d(U/u')}{dx} = B \quad (10)$$

Integrating between limits of x_0 and x :

$$\frac{U}{u'} - \frac{U}{u'_0} = B \int_{x_0}^x \frac{dx}{l_2} \quad (11)$$

where U/u'_0 is the value of U/u' at $x = x_0$. $u'/U \times 100$ is generally referred to as the per cent turbulence. This equation has been found by Dryden to give a very good representation of the experimental data. To evaluate the integral, l_2 , must be known as a function of x .

Dryden (15) has developed two related semi-theoretical equations describing the scale and intensity of turbulence downstream from screens with ratio of mesh to wire diameter of 5 to 1 placed in an air stream. These equations were obtained by fitting a theoretically developed equation of the type of equation (11) to intensity and scale data obtained in the National Bureau of Standards low turbulence wind tunnel behind screens with a ratio of mesh to wire diameter of 5 to 1 (corresponding to a blocked area of 36 per cent). These equations can be written as follows:

$$(U/u')^2 = 400 \left\{ \left[1 + 0.04 \left(\frac{x}{d} - 80 \right) \right] \right\} \quad (12)$$

$$\left\{ \frac{l_2}{d} \right\}^2 = 0.264 \left\{ \left[1 + 0.04 \left(\frac{x}{d} - 80 \right) \right] \right\} \quad (13)$$

where d is the screen wire diameter and x the distance downstream from the screen. The choice of screen wire diameter instead of some other grid parameter such as mesh width as the characteristic dimension of the grid determining the scale at a given distance downstream was dictated by experimental results obtained by von Karman (24). The equations apply only at distances at least 80 wire diameters from the screen.

According to Dryden, however, it requires about that distance to establish isotropic turbulence to which the equations apply. A turbulence pattern considerably different from that predicted by the above equation may be obtained if turbulence is present in the air stream before passage through the screen. This already existing turbulence is only partly modified by passage through the screen and thus remains to reinforce that generated by the screen. By eliminating x/d between equations 12 and 13, it is readily seen that for any initial condition of isotropic turbulence the quantity $u'^2 l_2$ remains constant as decay proceeds. $\frac{u'^2 l_2}{\nu}$, where ν is the kinematic viscosity, is often referred to as the Reynolds number of turbulence.

The description of isotropic turbulence in terms of intensity and scale resembles the description of the molecular motion by molecular velocity and mean free path. Other statistical properties might be employed for the description of turbulence such as, for example, the distribution of turbulent energy with frequency. Taylor (45), however, has shown that this spectrum may be computed from the correlation curve (R_y vs y) so that no new information is obtained.

The introduction of a filament of smoke into a gas stream presents an excellent method of determining the nature of the flow. If laminar flow prevails, the smoke filament will be observed to retain its identity whereas if the flow is turbulent the smoke is rapidly diffused over the entire cross section of

the stream. Diffusion coefficients in turbulent streams are often several orders of magnitude above those encountered with molecular diffusion. It is interesting to examine why this is so.

Let us consider the introduction from a point source of a small mass of material at a time t_0 into a uniform field of isotropic turbulence. We shall then determine a relation for the average movement of this small mass in the turbulent field. Denote the displacement of the mass from its source due to turbulent diffusion as X and the instantaneous fluctuating velocity as u both measured in the direction of the arbitrarily selected x axis. Let u_{t_0} and u_t be the values of u at t_0 and t , respectively, and consider the definite integral:

$$\int_{t_0}^t u_{t_0} u_t dt$$

Now putting the equation on a statistical basis by averaging* and substituting the correlation coefficient, R_t , we obtain:

$$\int_{t_0}^t \overline{u_{t_0} u_t} dt = \overline{u^2} \int_{t_0}^t R_t dt \quad (14)$$

but:

$$\int_{t_0}^t \overline{u_{t_0} u_t} dt = \overline{u_{t_0} \int_{t_0}^t u_t dt} = \overline{u_{t_0} X} = \overline{uX} \quad (15)$$

* Obviously the movement of any one particle after a time, t , cannot be predicted since in any one case the movement is random. The problem is subject to treatment only if the average movement which would result if many similar masses were introduced under the same conditions is desired.

Therefore:

$$u'^2 \int_{t_0}^t R_t dt = \overline{u\bar{x}} = 1/2 \frac{d(\bar{x})^2}{dt} = E \quad (16)$$

where E is the coefficient of eddy diffusion. If t is taken to be large so that R_t drops to zero then:

$$u'^2 \int_{t_0}^t R_t dt = u' l_1 = E \quad (17)$$

The eddy diffusivity, E, is then found to be equal to the product of the scale, l_1 , and the intensity u' . l_2 may be introduced for l_1 if the proper constant is also included, as:

$$u' l_1 = c u' l_2 = E \quad (18)$$

where c, as previously stated is approximately 1/2.

The assumption for one point source of a time of diffusion, t, large enough for R_t to drop to zero made to obtain equation 17 corresponds to the assumption of an infinite number of point sources releasing masses at different times with the masses continuously diffusing across a plane under a concentration gradient. In this latter case the rate of diffusion across the plane is constant with time. This transfer may be thought of as the sum of the transfers of mass from many point sources releasing masses at different times. If in this case then, diffusion proceeds for a differential time, but the masses are considered to have been diffusing for different periods of

time some of which are long, $E = u'l_1$ continues to apply. Diffusion across a plane surface under a uniform concentration gradient, as in a laminar flame front is analogous to the latter case.

It is interesting to note that equation 16, if applied for the case of diffusion times so short that R_t may be considered unity yields the expression:

$$u'^2 (t - t_0) = E \quad (19)$$

which means that for diffusion from point (or line) sources when the time of diffusion of the material from the source is smaller than the time l_1/u'^* , the eddy diffusivity is no longer a function of scale, but of $u_1'^2$ and the time of diffusion Δt . This anomolous behavior of the eddy diffusion coefficient for diffusion from sources approximating a point and from fine line sources as, for example, a hot wire, has been well established experimentally by Towle and Sherwood (47), and Schubauer (41).

Since eddy diffusion is a bulk mixing process, the coefficient of eddy diffusion, E , has the same value for the transfer of heat, mass, or momentum as contrasted to the varying values of these transfer coefficients under non-turbulent

*The time must be somewhat smaller than that required for an eddy to traverse a mean free path which may be approximated by l_1/u' .

conditions.

Damköhler (12) and later Shchelkin (43) considered in a rather preliminary fashion the effects of turbulence on the propagation velocity of flames. Theoretical equations for two broad categories of turbulence neither of which have yet been satisfactorily proven experimentally result from the discussions of these authors.

The first equation applies when the scale of the turbulence is very small in comparison with the flame front thickness, δ . 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 4, S_L was found to be proportional to the square root of the thermometric conductivity:

$$\sqrt{\frac{k_1}{\bar{c}_p \rho_0}} *$$

The introduction of turbulence increases this molecular transfer coefficient by an amount equal to the coefficient of eddy diffusivity, E , where E equals $u'l_1$ as shown in equation 17. The ratio of flame velocity in the turbulent stream, S_T , to laminar flame velocity, S_L , may then be written as:

*It should be noted here that the thermometric conductivity is roughly equal to the molecular diffusion coefficient, D , in most gases, the quantities being equal in a perfect gas. Both quantities have the dimensions of length square over time and are often used interchangeably in the literature.

$$\begin{aligned}
 \frac{S_T}{S_L} &= \sqrt{\frac{\frac{k_1}{\bar{c}_p \rho_o} + u'^2 l_1}{\frac{k_1}{\bar{c}_p \rho_o}}} \\
 &= \sqrt{1 + \frac{u'^2 l_1}{\frac{k_1}{\bar{c}_p \rho_o}}} \quad (20)
 \end{aligned}$$

The second relation is derived for the case in which the scale of turbulence is a great deal larger than the thickness of the flame front. Here the only effect of the turbulence upon flame velocity is to increase the total area of the flame front by distortion produced by the fluctuating velocities of the turbulent stream. Figure 2 demonstrates schematically how this distortion might take place. The velocity component u is assumed to create rapidly changing cone-shaped indentations in the flame front. The area of the base of these cones is proportional to l_2^2 , the cone altitude being proportional to the product of u' and the length of time during which this velocity can be considered operative, l_2/S_L^* . The ratio of the cone surface to that of the base, which is equal to the ratio of S_T to S_L , if the only effect of turbulence were that of flame front distortion, is then solved for and the following expression results:**

$$\frac{S_T}{S_L} = \sqrt{1 + \left(\frac{u'}{2S_L}\right)^2} \quad (21)$$

* l_2/S_L is the time required for a flame propagating with a velocity, S_L to proceed across an eddy of diameter, l_2 .

** $\frac{\text{cone area}}{\text{base area}} = \frac{\pi r h}{\pi r^2} = \frac{h}{r} = \frac{\sqrt{(1/2 l_2)^2 + (u' l_2 / S_L)^2}}{1/2 l_2} = \sqrt{1 + \left(\frac{u'}{2S_L}\right)^2}$
 where h is the cone slant height.

FIG. 2

FLAME FRONT IN A TURBULENT STREAM
WITH LARGE SCALE TURBULENCE

For values of u' large in comparison with S_L equation 21 reduces to the following:

$$S_T = u'/2 \quad (22)$$

Shchelkin (43) discusses the appearance of the flame front shown in Figure 2 when turbulence of extremely high intensity is present. His picture of the combustion zone under these conditions is a ragged continuous flame front in the central portion of the combustion zone with detached parcels of unburned material being present on the downstream side of this front. These parcels are visualized as being formed by the rapid thrust of eddies of unburned gas through the continuous flame front into the burned gas. They grow progressively smaller and finally disappear entirely as the distance from the continuous flame front increases. It is concluded by Shchelkin (43) that equation 21 is still applicable for this case of very high turbulence intensity. The reasoning which leads him to this conclusion, and his picture of the combustion zone under these conditions are, however, open to considerable question.

Referring again to Figure 2 and considering the flame velocity near the tip of the conical protrusion of unburned gas into the flame front it is seen that a situation exists here which is similar in many respects to that existing at the tip of a Bunsen flame. In this tip region, the flame velocity is increased many times over that for a normal flame

front due to an increase in the rate of transfer of heat and active species to the unburned gas. Again neglecting diffusion of active species in the calculation of flame velocity and assuming a flame front of spherical shape the following equation written for a differential annulus within the preignition zone relating flame velocity, S_f to the sphere radius, r , is easily obtained:

$$S_f = \frac{r^2}{r_0^2} \frac{k}{\bar{c}_p \rho_0} \left(\frac{2}{r} + \frac{\frac{\partial^2 T}{\partial r^2}}{\frac{\partial T}{\partial r}} \right) \quad (23)$$

where r_0 is the radius of curvature at the beginning of the preignition zone and r the radius of curvature at any location within that zone. r is positive when the flame front is concave toward the unburned gas and negative when concave toward the burned gas. For large values of r , the equation reduces to that for normal flame propagation from which equation 5 can be obtained by a single integration. When $2/r$ is of the same order as:

$$\left[\frac{\frac{\partial^2 T}{\partial r^2}}{\frac{\partial T}{\partial r}} \right]$$

then the effect of flame front curvature on flame velocity is large. Since for a normal flame front equation 23 yields:

$$\left[\frac{\frac{\partial^2 T}{\partial r^2}}{\frac{\partial T}{\partial r}} \right] = \frac{S_L}{\frac{k}{\bar{c}_p \rho_0}} \quad (24)$$

or, substituting from equation 6*:

$$\left[\frac{\frac{\partial^2 T}{\partial r^2}}{\frac{\partial T}{\partial r}} \right] = \frac{S_L}{\frac{k}{\bar{C}_p \rho_0}} = \frac{4.606}{\delta_t} \quad (25)$$

Therefore, when

$$\frac{2}{r} = \frac{\frac{\partial^2 T}{\partial x^2}}{\frac{\partial T}{\partial x}} = \frac{4.606}{\delta_t}$$

$r = \delta_t / 2.303$. For a negative r of this value S_f equals zero and flame propagation ceases. If, on the other hand, r is positive and of this value, S_f would be increased considerably over S_L . The effect of flame front curvature on flame velocity becomes less as r increases. Assuming $\delta_t = 0.012''$ as previously calculated the term $2/r$ is only about one twentieth the value of

$$\left[\frac{\frac{\partial^2 T}{\partial r^2}}{\frac{\partial T}{\partial r}} \right]$$

when $r = 0.1''$. Since l_2 may be considered an average eddy diameter, an approximate value of r for a turbulent flame front is obtained by setting $r \cong l_2/2$. This effect of flame front curvature on flame velocity is not allowed for in the derivation of equation 21. This opens to some doubt its applicability for turbulent flame fronts of intermediate scale where the curvature might introduce considerable error. The effect of small radii of curvature in the flame front is to reduce the flame front distortion by increasing flame velocity in fast eddies protruding

*There is an assumption introduced when equation 24 is substituted back into the equation for small values of r .

into the hot gas, and decreasing flame velocity in slow eddies lagging back in the cold gas.

Returning to a consideration of equations 20 and 21, it is believed that only seldom do conditions exist such that either of these equations alone can be applied. A fluid in turbulent motion actually possesses an entire spectrum of eddy sizes, l_2 representing only some sort of an averaged linear dimension of these eddies. A certain percentage of the smallest eddies present, therefore, might conform to the conditions prescribed for the derivation of equation 20 while the action of some of the larger eddies may best be described by a relation similar to equation 21. It would be desirable, therefore, to combine these two relations into a generalized equation in such a way that when l_2/δ is small the equation reduces to equation 20, and when l_2/δ becomes very large an expression essentially equal to equation 21 results. A generalized equation of this type may be written as follows:

$$\frac{S_T}{S_L} = \sqrt{\left[1 + \left(\frac{u'}{2S_L}\right)^2 \left(\frac{l_2}{\delta}\right)^{\frac{K_1}{K_1 + l_2/\delta}}\right] \left[1 + \left(\frac{K_1/\sqrt{C_p \rho_0}}{cu' l_2}\right) \left(\frac{1}{1 + \frac{l_2}{K_2 \delta}}\right)\right]} \quad (26)$$

where K_1 and K_2 are constants and $c l_2$ has been substituted for l_1 .

3. Flame Stabilization

The stability of flames of the Bunsen burner type has been studied extensively and in detail by Lewis and von Elbe (31) and von Elbe and Mentser (16), and the mechanism of this type of stabilization has been well established.

In the combustible gas stream issuing from the burner tube if there exists a point where flame velocity equals flow velocity, and if at no place does flame velocity exceed flow velocity then at that point a flame front will exist normal to the direction of flow and the flame will stabilize. If the flow velocity is increased until it everywhere exceeds flame velocity, blow-off occurs. On the other hand, if the flow velocity is progressively decreased stability occurs nearer and nearer the tube entrance until finally a flow velocity exists in the burner tube itself which is below flame velocity, and the flame flashes back down the tube.

The flame velocity near the rim of a burner tube is greatly affected by the quenching action of the relatively cold tube walls. It is essentially reduced to zero for a short distance measured from the wall, but rises rapidly to a constant flame velocity when this short distance, Δ , known as the quenching distance is exceeded. The flame velocity near the tube rim is further affected by mixing of the outside air (or any other gases that surround the tube) with the explosive gas mixture by molecular

diffusion. These quenching and diffusion effects near the rim determine the stability limits for any one fuel and air mixture.

Correlation of gas composition at blow-off and flash-back for tubes of diameter varying over a considerable range is obtained when this data is plotted against velocity gradient at the tube wall. This result might have been anticipated from the foregoing discussion by recalling that the velocity gradient, dV/dy , at a tube wall maintains almost the same value at a short distance out from the wall, and by assuming that Δ is small and constant for any one gas composition. This reasoning would lead to the following expression relating the critical stream velocity V_{BO} (equal to S_L at blow-off or flash-back) to the velocity gradient:

$$V_{BO} = \frac{dV}{dy} \Delta = S_L \quad \left(\begin{array}{l} \text{a function of gas} \\ \text{composition only} \end{array} \right) \quad (37)$$

The quenching distance, Δ , has been found to remain relatively constant with varying tube diameter for any one gas composition and wall temperature, and its magnitude is of the same order as the thickness of the preignition zone, δ_t . Δ is considerably reduced, however, by heating of the burner tube.

If an obstruction such as a rod or other unstreamlined object is placed in a gas stream, vortices are formed on its downstream side. If the stream is composed of a combustible gas mixture, then a flame initiated in this mixture which would

otherwise be carried away often attaches itself to this eddy region behind the obstruction. Velocities exist in this region of recirculation which are much less than that of the stream itself, thus forming a possible zone of self-ignition. It is this type of flame stabilizer that appears most promising and is at present most widely used for flame anchoring in the high velocity streams of ram-jet combustion chambers.

Mahe (32) noted such a stabilization effect for the case of a wire mounted centrally in a burner tube with its axis corresponding to that of the tube and its blunt end protruding slightly above the tube rim. The eddy region forming downstream of this wire serves to stabilize a flame. This inverted Bunsen flame has been studied in some detail by Lewis and von Elbe (31). These authors have attempted to correlate blow-off limit data for this type of flame with velocity gradient at the wire surface, in a manner that proved so successful with upright burner flames. The correlation is less satisfactory than with the upright flames, indicating, as might be expected, that effects other than wall velocity gradient must be present. Since the eddy region downstream of the wire contains hot recirculating combustion products which are continuously being brought into contact with fresh unburned material, a constant source of ignition is maintained. This stabilization mechanism, therefore, is of a different nature from that found at the rim of a Bunsen burner where at one point flame velocity equals stream velocity

and a flame anchor is thus simply obtained.

Lewis and von Elbe (31) observed that the flow around the wire tip of the inverted Bunsen apparatus is considerably different from that obtained with isothermal flow when a stabilized flame is present. Figure 3 is reproduced from reference (31) by these authors. The flow lines were obtained by photographing the tracks of magnesium particles illuminated stroboscopically as they moved with the flowing gas. Figure 3 shows that the eddy region to the rear of the wire is considerably decreased in size when combustion takes place. It would be expected that the eddy region behind any blunt object would be similarly affected by combustion. This effect of combustion on the eddy region, as well as the blow-off limit data of Lewis and von Elbe for inverted cone type flames, is discussed at greater length in Section V.

FIG. 3

STREAMLINES ABOVE WIRE WITH FLAT END
SHOWING VORTEX. WIRE DIA. 0.211 CM.
(AFTER LEWIS & VON ELBE —31)

4. High-Output Combustion Chamber Development - Its Contribution to This Investigation

During the last few years a number of technical groups throughout the country have been working on the development of high output combustion chambers of improved design. The large amount of experience gained by these groups while operating a wide variety of high output combustion chamber types on test stands and in flight has been invaluable. The considerable volume of empirical and exploratory data that has been obtained serves as a guide for workers entering the field, and allows a definition of the problems involved.

This data has proved very useful for orientation purposes. It was studied carefully while planning the research program and has been often referred to during the course of the investigation. Space and time, however, do not permit inclusion of a complete bibliography of this work, much of which has been reported only in monthly progress reports or short memorandums issued by the working groups and given only a very limited distribution. References are restricted, therefore, only to a very limited few of these reports.

Among those that have recently contributed to high output combustion chamber development are groups at the Massachusetts Institute of Technology (1) (2), Johns Hopkins Applied Physics Laboratory (4)(6), Esso Laboratory (5) (7) NACA,

University of California, National Bureau of Standards, Experiment Incorporated, California Institute of Technology, the Marquart Aircraft Company, and a number of others.

Only rarely can data taken under conditions existing in actual high output combustion chambers be compared directly with the results of this work. The great majority of data obtained by these development projects is of this kind. Recently, however, some of these projects have begun investigations of a more fundamental sort.

Longwell (7) of the Esso group has obtained data under well-controlled conditions on blow-out limits of flames stabilized in a short 6¹/₄ inch diameter cylindrical duct burning a homogeneous, gaseous air-fuel mixture. Stabilizers of varying diameter and cross section, such as cones, blunt-ended rods, and tubes open at one end have been employed with the stabilizer axis coinciding with that of the duct. Over the range of average chamber entrance velocities investigated, 300 to 800 feet per second, a single curve was drawn through all these data when air-fuel ratio at blow-out was plotted versus the ratio of flame stabilizer radius to gas entrance velocity. A cross plot, therefore, would show entrance velocity at blow-out to be a straight line function of stabilizer diameter. These data will be discussed at greater length in Section V.

III DESCRIPTION OF APPARATUS

Briefly, the main apparatus consists of a rectangular combustion chamber with two opposing transparent side walls into which a homogeneous mixture of air and gaseous fuel is introduced with a flat velocity profile under various known conditions of velocity, air-fuel ratio, and turbulence; and in which a flame can be held by means of a flame stabilizer.

The apparatus was constructed for the purpose of studying flame stabilization and flame propagation in high velocity gas streams with a view toward gaining a better understanding of the fundamental mechanisms involved.

It was decided that in order to accomplish best the purpose of the investigation the effect of a few important variables on flame stability and propagation would be studied. The apparatus was so designed that any one of these chosen parameters could be easily varied over a wide range while holding the others essentially constant. In this way, the effect of each variable on flame stability and propagation could be directly determined.

The variables chosen and the approximate range over which they were varied are as follows:

1. Air-fuel ratio -
lean limit to rich limit blow-out
2. Combustion chamber entrance velocity -
20 - 350 feet per second

3. Turbulence in the entering gas stream -
Intensity: less than 0.5 per cent to about
8 per cent.
Scale: 0.01 inches to about 0.8 inches.
4. Flame stabilizer size and shape -
Size: 0.016 inches to 0.5 inches in width
normal to the flow.
5. Shapes: single rods, 30° closed edged and
open edged gutters, flat plates,
multiple rods.

In addition, data were obtained with two widely different types of fuel; Cambridge city gas, and propane.

An attempt was made to simplify the system as much as possible by eliminating other variables not desired for study. For example, the apparatus was designed so that a homogeneous, gaseous mixture of air and fuel with essentially uniform velocity entered the combustion chamber, thus eliminating any fuel distribution, mixing, or vaporization problems, or unpredictable velocity gradient effects.

Figure 4 is a schematic diagram of the apparatus. Figure 5 is a photograph showing the entire apparatus as it stood at the south end of combustion cell Number 1 on the second floor of Building 31-A. Figure 6 is a drawing of the calming section, contraction nozzle, and combustion chamber assembly.

A. The Main Apparatus

Referring to Figure 4 the flow through the apparatus as described below may be easily followed.

FIG. 4
SCHEMATIC DIAGRAM OF APPARATUS

THE MAIN APPARATUS

COMBUSTION CHAMBER AND CALMING SECTION

Air was supplied during the major part of the investigation from an Ingersoll-Rand Diesel powered compressor located outside of the building. The compressor supplied a maximum of about 0.5 pounds of air per second at approximately 90 pounds per square inch gage. During the last third of the investigation, air was supplied from an electrically driven Ingersoll-Rand carbon-ring, oil-free compressor which had roughly the same capacity as the Diesel powered compressor. It proved more satisfactory, however, since it delivered air more nearly free from oil and condensed moisture, and at a more nearly constant temperature. (See Appendix D, Figures 138a and 138b for photographs of these compressors.)

Air from the compressor flowing through 2" pipe passes through a centrifugal oil separator and into a large surge and storage tank. From this tank the air passes out through a glass wool filter to the air metering orifice. Since the air compressor operated at only two speeds it was necessary to employ an air bleed valve which allowed air in any desired quantity to be vented to the atmosphere. Proper manipulation of this bleed valve in conjunction with the other air regulating valves eliminated air rate variations due to periodic automatic pumping rate changes. This bleed valve is attached to the glass wool filter.

The orifice meter is a standard $3/4$ -inch in diameter sharp-edged orifice installed after a 50 diameter straight section of 2" pipe and equipped with flange taps. Pressure drop across the orifice is determined by means of either a

water or mercury manometer, depending on the air rate. Total pressure upstream of the orifice is determined by means of a calibrated Bourdon gage, and temperature is obtained by reading a thermometer in a well just preceding the 50 diameter straight section.

Air leaving the orifice meter can be made to pass through any one of three globe valves, the first leading to the large inspirator (#1), the second leading the small inspirator (#2) and the third serving as an inspirator by-pass. These inspirators pump low pressure city gas (Cambridge city gas pressure is approximately 8" of water above atmospheric) into the air stream, utilizing the excess air pressure in so doing. The inspirators are designed to operate at constant air rates and although they function reasonably well at lower than design rates they act as chokes at higher rates. Consequently, to obtain air rates to the combustion chamber higher than can be passed through the inspirator, additional air is introduced through the by-pass. (See Appendix D for details related to the design and construction of the inspirators.)

Cambridge city gas was employed as a fuel for the major part of the work. Its average composition as determined in the gas company laboratory by Orsat type analysis was as follows:

CO ₂	7.3 per cent
Illuminants	9.8 per cent
O ₂	0.6 per cent
CO	21.8 per cent
CH ₄	14.7 per cent
H ₂	26.8 per cent
N ₂	19.0 per cent

From day to day the percentage composition varies by about 1 or 2 per cent of the values given.

City gas enters the apparatus through a 2" pipe from a large gas main just outside the building. This gas then passes through a gas company meter, a check valve, a plug valve, and finally through one of two globe valves to either the high rate or low rate gas metering venturi. Both of these venturis were calibrated by placing a standard orifice in the line in series (See Appendix E for further details of this calibration procedure). The pressure differential across the venturis and the total upstream pressure above atmospheric are obtained as readings on water manometers. Gas temperature is obtained from a thermometer in a well located in the line ahead of the venturi meters. The gaseous fuel passes from the venturi meters through one of the two globe valves leading to the large or small inspirator and used for fine adjustment of the gas rate.

The air-fuel mixture passes from the inspirator and by-pass system *through a 200 mesh screen filter, then* past a thermometer well where temperature of the

gases entering the calming section and combustion chamber is obtained, ~~then through a 200 mesh screen filter~~, and, finally, into the calming section. The gases then pass up through a 25 to 1 contraction ratio nozzle and into the combustion chamber where combustion is stabilized on a flame-holding shape. The combustion products then pass up into the exit diffuser. Dilution and cooling air is blown into the stream just above the exit diffuser and the mixture passes upward through an 8" stove pipe to the exhaust stack.

Figure 7 is a photograph of the calming section, contraction nozzle, and combustion chamber assembly, and Figure 8 is a photograph showing them *disassembled*. Figure 9 is a photograph of the combustion chamber partially disassembled.

1. Details of the Test Section

Referring to Figure 6, a detailed description of the working portion of the apparatus follows.

The calming section consists of a diffuser followed by five 200 mesh screens. The diffusion section is 36" in length and expands the flow cross section from that of a 2" standard pipe to a 5" by 15" rectangular section. The five 200 mesh screens which follow the diffuser are spaced at 2" intervals. These screens serve to smooth the flow and reduce the turbulence to a very low level*. Following the 200 mesh screens after

* The screens remove large scale turbulence and introduce a turbulence of very small scale which decays at a high rate, and is thus reduced to a low intensity upon entering the approach nozzle.

FIGURE 7

**Calming Section, Contraction Nozzle,
and Combustion Chamber Assembly**

FIGURE 8

**Calming Section, Contraction Nozzle,
Combustion Chamber, An Exit Diffuser
Disassembled**

FIGURE 9

**Combustion Chamber Partially
Disassembled**

FIGURE 10

Manometer and Gage Panel

a five inch long straight section is a 25 to 1 contraction ratio nozzle where the flow cross section is reduced from 5 x 15 inches to 1 x 3 inches. Passage of the gases through this contraction nozzle produces a stream of uniform velocity in which the per cent turbulence is reduced to a very low level*. Care has been taken in obtaining a smooth nozzle inside surface, and a smooth junction between the nozzle and combustion chamber.

From the contraction nozzle the gases enter the combustion chamber itself. The combustion chamber is rectangular with a 3 x 1 inch inside cross section and is 17.375" in length. The two 3" wide side walls are made of 1/8" thick transparent Corning Vycor glass** which resists thermal shock and high temperature almost as well as quartz. Initially Pyrex plates were employed but they broke very quickly due to extreme temperature effects. These Vycor plates are easily removable, being held in place by metal flanges attached to the chamber by screws. The plates contain holes 1 millimeter in diameter spaced at one inch intervals along the plate center lines and drilled only half way through the plates. The lowest hole on both plates is 2" above the combustion chamber entrance. A pin on each end of the flame

*The value of u' remains essentially constant upon passage through the nozzle assuming isotropy continues, but, since the stream velocity is increased 25 times, the per cent turbulence is decreased by this same amount.

** Vycor is made from pyrex glass by leaching out all of the oxides other than SiO_2 and refusing the remainder. It contains more than 98 per cent SiO_2 and therefore may be described as a cheap grade of quartz. Its price is roughly one-fifth that of quartz.

stabilizers fits into these holes. Thus, a method of anchoring the flame stabilizers in the combustion chamber is obtained.

The combustion chamber is equipped with seven probing holes situated along its length on one of the one inch wide metal walls and through which probes for pitot and turbulence traversing were introduced. These holes are spaced 3 inches apart, the lowest hole being 2.65" from the combustion chamber entrance. These probe holes, when not in use, are closed with bolts which fit flush against the inside chamber wall. Pressure taps are located at the chamber entrance, at its center, and near its exit in order that chamber static pressure and pressure drop across the combustion zone may be obtained. The chamber inside walls have been carefully made so that no rough spots or protrusions into the stream exist, and the steel from which the chamber is fabricated was thoroughly annealed before machining. (See Appendix D, Figures 136 and 137 for more detailed drawings of the calming section, nozzle, and combustion chamber).

The combustion products leaving from the combustion chamber pass up through a stainless steel exit diffuser and into an 8" stove pipe through which they are carried up into the stack. Dilution air at the rate of approximately 1000 cubic feet per minute is mixed with the hot gases just above the top of the exit diffuser. This dilution air is obtained from an electrically driven low pressure centrifugal blower installed in the corner of the combustion cell opposite the air tank.

This air reduces the exit gas temperature by a considerable amount thus protecting the stove pipe from excessive heating. Further- it eliminates any fire hazard present due to accumulation of explosive gases in the stack since the gases are diluted to an air-fuel ratio that is no longer explosive.

A ventilator located at the other end of the combustion cell from the apparatus introduces a large volume of air at low pressure into the cell from outside the building. This air moves at an average rate of about five feet per second through the cell and up the large stack situated above the apparatus. This flow of air produces continuous ventilation, and eliminates any hazard that might otherwise be present due to city gas accumulation in the combustion cell or stack.

2. Instrument Panel

Figure 10 is a photograph of the manometer and gage panel from which all pressure measurements were obtained. Referring to Figure 10 and going from left to right the top Bourdon gage at the left reads upstream pressure at the air orifice. The bottom Bourdon gage reads upstream pressure at the inspirators. Pressure at either inspirator is obtained by manipulation of the three-way valve just below this gage. The first two manometers are of the pressure type and contain water and mercury respectively. They are read to obtain the pressure drop across the air orifice. The water manometer is used at low air rates and the mercury manometer is employed for high air rates. By

proper manipulation of the valves above these manometers either the water or the mercury manometer can be cut out of the system.

The next two water-filled manometers read the upstream pressure above atmospheric at the gas venturi meters, and the pressure drop across these meters. By manipulation of the two three-way valves mounted at the top of the board, readings for either the high-rate or low-rate gas venturi meters may be obtained.

From the next water-filled manometer can be obtained the pressure drop across the turbulence generating screen often placed at the combustion chamber entrance. The two mercury-filled manometers further to the left yield the pressure drop across the combustion chamber and the pressure above atmospheric at the chamber entrance, respectively. The last upright water-filled manometer on the left is a spare, and was used extensively for pitot traverse measurements.

By proper manipulation of the gas and air rate, homogeneous mixtures of air and city gas can be introduced into the combustion chamber at measured velocities from about 20 feet per second to above 350 feet per second, and air-fuel ratio can be varied over a wide range.

3. Turbulence-Generating Screens

The turbulence in the gases entering the combustion chamber can be raised from its initially low level to higher levels by

placing screens of varying mesh and wire diameter at the chamber entrance. Figure 11 is a photograph of the three screens used for modifying the chamber turbulence during combustion. The screen dimensions are as follows:

	mesh (wires/inch)	wire diameter (inches)	blocked area
Screen 1	3	0.063	0.3424
Screen 2	8	0.025	0.3600
Screen 3	55	0.007	0.6294

4. Flame Stabilizers

Flame stabilizers of various size and shape were mounted in the combustion chamber between the Vycor glass side walls and normal to the flow as previously described. The stabilizers could be mounted at various distances from the combustion chamber entrance.

Figure 12 is a photograph of the stabilizers used during the course of this investigation. Figure 12(a) shows the nine steel rod stabilizers studied. The rod diameters are from top to bottom; 0.498 inches, 0.311 inches, 0.188 inches, 0.126 inches, 0.094 inches, 0.038 inches, 0.026 inches and 0.016 inches.

Figure 12 (b) shows the closed edge 30° gutters employed as stabilizers. The gutters are made from 0.008 inch thick sheet steel. The angle between the two metal surfaces of the gutter measures 30°. These gutters were mounted in the chamber by means of pins in a manner similar to that employed for

FIGURE 11

The Three Screens Used for Modifying
Chamber Turbulence During Combustion

FIGURE 12

Fig.12(a)

Fig.12(b)

Fig.12(c)

Fig. 12(d)

Fig. 12(e)

Flame Stabilizers Used During Investigation

mounting the rods. Protruding pins at the gutter apex fitted into holes in the glass side walls. It was, however, necessary to anchor the gutters further by placing porcelain cement on the gutter edges where they contacted the glass walls so that they could not rotate about the axis of the anchoring pins. In the case of the symmetrical rods, this type of rotation was, of course, unobjectionable. The gutters were mounted with their apexes pointed upstream. Referring to Figure 12(b) from top to bottom the gutter widths are; 0.5 inches, 0.25 inches, 0.10 inches, 0.05 inches and 0.025 inches.

Figure 12(c) is a photograph of the two open edged 30° gutters used as flame stabilizers. The top gutter is 0.5 inches wide and is viewed from the side. The ratio of its open area to the total blocked area is 100 to 1. The lower gutter is viewed from its apex. It is also 0.5 inches wide, but the ratio of its open area to the blocked area for a closed edge gutter is 25 to 1.

Figure 12 (d) shows the 0.5 inch wide flat plate used as a flame stabilizer. It was made from a piece of 0.008 inch thick sheet steel and was anchored in the combustion chamber with pins and porcelain cement in the same manner as were the gutters.

Figure 12(e) is a photograph of two of the three multiple rod stabilizers used during this investigation, the eight rod and the four rod stabilizers. The stabilizer having only two

rods is not shown. These stabilizers were made by mounting 0.038 inch rods on thin, steamlined pieces of sheet steel. The rods are so spaced that when the stabilizer assembly is mounted in the tunnel, each rod is at the center of its combustion zone. This amounts to saying that the tunnel is divided into 2, 4, and finally 8 equal smaller chambers, the number corresponding to the number of stabilizing rods, and at the center of each of these smaller chambers a rod stabilizer is situated. For anchoring purposes, each of these multiple rod stabilizers have two pins attached to the center of their outside surfaces, one on each side. The procedure for mounting these stabilizers in the combustion chamber is similar to that employed for the gutters.

5. Ignition

Combustion is initiated in the chamber by inserting a spark rod through one of the probe points and firing the spark intermittently while gradually increasing the fuel rate. It was found that if ignition was attempted at velocities much over 50 feet per second, flashback of the flame into the calming section almost always occurred. This flashback sometimes damaged the turbulence generating screen and nozzle. Therefore, to avoid flashback, ignition was always carried out at velocities between 20 and 50 feet per second. The spark rod assembly was supplied with 10,000 volts from the secondary of a transformer whose primary was activated from the 110 volt building power supply. Power entered the transformer only when a push-button type switch was closed. The spark thus was made to flash in the

combustion chamber by pressing this button.

The spark rod consists of a handle made of high dielectric material with a glass tube running through it and extending a few inches beyond it. This glass tube extension is passed through the probe hole into the combustion chamber. A high-voltage line from the transformer enters the butt end of the spark rod handle and there connects with a wire extending to the end of the glass tube. Another high voltage line, which is grounded to the apparatus, is attached to the side of this handle and connected to a thin metal strip that extends along the outside of the glass tube to its end. A spark occurs between the strip and the axial wire at the end of the glass tube when the push-button switch is closed.

Upon ignition the flame usually first attaches itself to the spark rod. If the spark rod is in the near vicinity of the flame stabilizer the flame will then also attach itself to the stabilizer. When this occurs, the spark rod is withdrawn and the bolt reinserted in the probe hole.

In order to get the flame to attach itself to the very small stabilizers it was usually necessary to insert the spark rod under the stabilizer and allow the flame attached to the spark rod to play over the stabilizer until attachment occurred.

6. Camera

A permanent camera mount was erected in front of the

combustion chamber in order that photographs of flames in the chamber could be obtained. A Voightlander camera using 9 x 12 centimeter film pack and having an f-4.5, 13.5 centimeter focal length lens was thus mounted at the proper distance from the chamber to a 4 to 1 reduction from full scale on the photographic negative (distance from camera lens to combustion chamber about 27 inches). Kodak Super-X film pack was used exclusively.

B. Adaption to Propane

It was thought desirable to obtain some data with a gaseous fuel other than Cambridge city gas. Propane was chosen because of its easy availability, its adaptability for use with the apparatus, its reasonable price, and the similarity of its properties to the higher saturated hydrocarbons which have been widely used as fuels in turbojet and ram-jet combustion chambers.

Referring again to Figure 4, the propane installation is shown schematically with dotted lines.

Seven cylinders each initially containing 100 pounds of liquid propane were manifolded together and employed as a source of propane gas. The withdrawal of gaseous propane from a cylinder at high rates results in considerable cooling of the cylinders with an attendant drop in cylinder pressure, discharge rate, and discharge temperature. Use of seven manifolded cylinders as a propane source allows the gas to be withdrawn at a high rate from the system without an excessive withdrawal rate from any one cylinder. Extreme cooling effects

are therefore eliminated.

The propane gas from the manifolded cylinders passes through a pressure-type needle valve, a single setting type regulator valve of simple construction, and finally through the testing air inlet globe valve into the lines previously described for city gas. The large plug valve in the city gas inlet line was kept closed during runs with propane so that no city gas could enter the system. The propane gas passes through the gas venturi meters (which are ~~not~~ satisfactory for metering propane because of their size) and then through the standard orifice earlier installed in the line for calibration of the gas venturis with city gas. (See Appendix G for a description of this orifice meter.)

This standard orifice meter was used directly for measurement of propane flow rate. A water manometer 200 cm. in height was temporarily installed to obtain the pressure differential across the orifice meter, and the upstream pressure was obtained from the spare water manometer on the manometer panel. Upstream temperature was obtained at the point previously described for obtaining city gas temperature. The rate of propane gas introduction into the system was regulated just as was the city gas rate by manipulation of the globe valves just preceeding the air inspirators.

The propane used was obtained from the Colonial Beacon Oil Company. This grade of bottled propane is sold under the trade-

mark name of PANESSO, and is a rather low purity product. Its per cent composition by volume obtained at the Boston Esso Laboratory by analysis of a sample taken from one of the bottles used is as follows:

Propane	83.8 per cent
Propylene	13.3 per cent
Ethane	2.4 per cent
Butane	0.5 per cent

C. A Controlled Temperature Stabilizer

Blow-out limit data were obtained with a flame stabilizer whose temperature could be held constant.

A stainless steel tube 0.032 inches in outside diameter and with a wall thickness of 0.006 inches was installed as a stabilizer 9 inches above the combustion chamber entrance. For this installation, holes were drilled all the way through the Vycor glass side walls. The tube passed entirely through the chamber and extended out on either side for about one inch.

Heating current was passed through the tube from a 10 to 1 step-down transformer fed from the 110 volt building power supply through a 10 ampere General Radio Variac. The tube heating current, and therefore its temperature, was easily varied by simply turning the Variac control knob.

During a run the tube in the combustion chamber was viewed

through an optical pyrometer and the tube temperature was held constant by manipulation of the Variac control knob so that the optical pyrometer filament, which was previously set at a known constant temperature, always appeared to merge with the tube.

In order to hold the tube temperature constant at a low level, cooling water from the city main was passed through the tube at a high rate. The water entered the tube from one side, passed through it, and was allowed to shoot into a beaker on the other side. The temperature of the collected water in the beaker was measured by means of a thermometer. This measured temperature was assumed to be that of the outside surface of the water-cooled tube.

D. High-speed Movies

High-speed movies of the flame were taken with an Eastman High Speed Camera capable of taking pictures at a maximum rate of 3000 frames per second. This camera was mounted on a tripod a few feet from the combustion chamber and was operated at 1500 frames per second with Kodak Super XX film.

Since the flame itself did not emit sufficient light to register on the film, it was necessary to introduce finely divided sodium chloride into the gases entering the combustion chamber so that more light would be emitted by the hot gases. This resulted in a considerable increase in flame liminosity and satisfactory pictures were obtained at air-fuel ratios

near stoichiometric where flame temperature is highest and the light emission of sodium ions is therefore greatest. Movies at higher film speeds or at air-fuel ratios very far removed from stoichiometric could not be obtained due to a deficiency of light resulting in underexposure of the film.

The most serious difficulty arising with the introduction of sodium chloride was its effect on the Vycor glass side walls. A considerable amount of NaCl, both in liquid and vapor form, reached these walls in the region where the flame impinged on them. This NaCl immediately fused with the hot glass and after about two or three minutes of NaCl introduction the transparency of the walls was seriously impaired. After taking a few reels of high speed movies, it was always necessary to put in new glass walls. The expense entailed and the time required for replacement of the walls greatly limited the number of high speed movies obtained.

The finely divided NaCl particles introduced into the gas stream entering the combustion chamber were produced in an NaCl vaporizer. Figure 13 is a schematic diagram of this vaporizer. It consists of two carbon electrodes, one of which is immersed in a salt bath. A carbon arc is produced between those two electrodes and the resulting heat vaporizes some of the NaCl. The whole assembly is placed inside a 5 inch section of pipe, capped at both ends. A stream of air is passed through the vaporizer and over the salt bath and the vaporized NaCl

FIG. 13

recondenses in this cool air stream forming a finely divided dispersion of NaCl particles in air. This air containing finely divided NaCl particles is then introduced into the system at a point just preceding the contraction nozzle as indicated in Figure 6. Current was supplied to the vaporizer from a 10 to 1 step down transformer run from the 110 volt building power supply.

E. Stroboscopic Equipment

The high speed movies revealed that a fairly periodic motion existed in the flame above the stabilizer. It was decided to build a stroboscope disc by means of which this motion, if it were sufficiently periodic, could be observed and photographed.

An aluminum disc 20 inches in diameter and 1/16 inch thick was made, and 64 equally spaced slits 2 inches long and 1/8 inch wide beginning 1/8 inch from its outer perimeter were milled in it. The disc was then balanced and put on the shaft of a one horsepower variable speed motor which revolved it at rates that could be varied from zero to 3500 revolutions per minute. The motor and disc assembly was mounted on a stand a few feet from the combustion chamber and the rate of revolution of the disc was varied by manipulation of a 10 ampere Variac in series with the motor. The flame was observed by standing with the stroboscope near the eye between the chamber and the observer and manipulating the Variac knob to change the rate

of the disc.

F. Shadow Photograph Apparatus

In order to obtain pictures of the stabilized flame in which the eddying motion within the flame was stopped, it was decided to employ a shadow technique with a high speed spark as a light source.

Figure 14 is a schematic diagram of the set-up employed for taking shadow photographs, and Figure 15 is a photograph of the spark apparatus in place and ready for operation.

The spark furnishes essentially a point source of light which persists for a very short time. This light passes through the flame and is distorted. It then strikes a photographic film and leaves an image. Since the flame itself emits light, the photographic film can only be uncovered for a very short time or it will be completely and uniformly exposed by the flame, and no impression due to the light from the spark will be observable on the developed negative.

To avoid this over exposure by the light from the flame, a shutter was constructed which completely uncovered the film for approximately $1/200$ of a second. The spark discharge circuit was automatically closed when the film was completely uncovered, and a shadow photograph was thus obtained.

The spark is produced by discharge of an 8.5 microfarad

FIGURE 14

SCHEMATIC DIAGRAM OF SHADOW PHOTOGRAPH SET-UP

FIGURE 15

Apparatus in Place for Taking Spark
Photographs

FIGURE 16

Libessart Spark Discharge Apparatus

condenser charged to approximately 3000 volts. The discharge takes place through a thyatron type tube, and is triggered by the closing thyatron grid circuit when the film shutter exposes the photographic film. The effective spark discharge time is estimated to be slightly less than one ten-thousandth of a second. (See Appendix D, Figure 14 for a circuit diagram of the charging and spark discharge circuit.)

A Libessart type discharge gap was employed. Figure 16 is a photograph of the Libessart apparatus. The discharge takes place between two bolts whose ends are pointed. A small hole is drilled along the axis of one of these bolts and it is through this hole that the bright light of the spark is emitted. A strip of Bakelite is placed between the two bolts and a small hole is drilled through it. This hole forms a passage between the pointed ends of the two bolts, and the spark discharge takes place through this small hole. The buildup of pressure is greater within the hole than would be the case if the Bakelite strip were not present. Higher maximum temperatures are therefore obtained during the spark discharge. This results in a spark with increased light intensity. The Libessart apparatus itself is mounted on the permanent camera mount about 30 inches in front of the combustion chamber as shown in Figure 15.

For obtaining shadow photographs, the optical requirements of the glass combustion chamber walls are very much more severe than is the case when direct photographs of the flame are taken.

Two plates of Vycor glass, 1/4 inch thick, 5 inches in length, and 3.5 inches in width were polished until they approached optical flats*. These two plates were installed opposite one another with plates of ordinary 1/4 inch thick Vycor above and below them to make up the rest of the chamber walls. A flame stabilizer was supported 7 inches above the combustion chamber entrance between these two polished plates.

The shutter, which is triggered manually when a shadow photograph is desired, is shown in Figure 17. Figure 17(a) shows the shutter cocked and ready to be triggered. By pushing the small metal arm at the far left of Figure 17(a), the shutter is released and is drawn rapidly to the other side by means of springs. Figure 17(b) shows the shutter in the uncocked position. The film pack, fitted into a holder, is supported on the back of the stationary shutter frame. Kodak Plus X 9 x 12 centimeter film pack was used for taking the shadow photographs.

When the shutter has completed about half of its journey from the cocked to the uncocked position, the photographic film is completely uncovered. At this time, the spark circuit is closed. When these contact strips seen at the top of the shutter assembly touch, the thyatron grid circuit is completed, the primary circuit is closed, and a spark photograph is obtained.

* The original Vycor contains a number of flaws throughout its mass and is not entirely homogeneous. Therefore, perfect optical properties were never obtained and a number of imperfections remained even after careful polishing.

FIGURE 17

Fig. 17 (a)

Fig. 17 (b)

Shutter Assembly Employed for Taking
Shadow Photographs of Flames; (a) cocked,
(b) uncocked

The shutter assembly is mounted on an angle iron frame by means of clamps as shown in Figure 15. For adjustment purposes, this frame can be moved vertically on the main apparatus frame, and the shutter assembly can be moved horizontally in any direction on this frame by loosening the clamps.

G. Apparatus for Taking Shadow Photographs with High Speed Movie Camera

In order to obtain high speed movies of the flame at blow-out the apparatus shown schematically in Figure 18 was employed. Light from a continuous source cast a shadow of the flame on a ground glass screen. This screen was photographed with a high speed camera.

A seven ampere carbon arc served as a bright, continuous light source. This light was collimated by means of a convex lens and the resulting beam passed through the flame. The carbon arc itself was mounted on the same angle iron frame used for mounting the shutter assembly for taking the previously described shadow photograph stills. The polished, high quality Vycor glass used for taking the other shadow photographs was also employed.

A piece of ground glass was supported about one foot in front of the combustion chamber, its position being so adjusted that the flame shadow fell upon it.

FIG. 18

SCHEMATIC DIAGRAM FOR TAKING HIGH SPEED
SHADOW MOVIES

The previously discussed Eastman High Speed Camera was again used, with the same type of film. The camera was mounted on a tripod a few feet in front of the ground glass screen and photographs of the screen were taken at the rate of 1000 frames per second.

To obtain pictures of blow-out, the fuel rate was slowly decreased. The camera was started just before blow-out, and before the whole 100 foot reel of film was exposed blow-out usually would occur.

H. Pitot Traversing Apparatus

A number of pitot traverses were made to determine the velocity cross section, the thickness of the boundary layer, and the ratio of central stream velocity to average velocity at various distances from the combustion chamber entrance.

The first set of traverses were made with a pitot tube which measured impact pressure only. The static pressure was measured by means of static pressure taps at the combustion chamber wall. The pitot tube was moved across the chamber by means of a traversing device. After making an initial setting, the location of the pitot head from the combustion chamber far wall was read directly from a scale. This distance was varied by means of a screw mechanism so adapted that it could be mounted on the chamber side and be held in place by a bolt fitting into a chamber probe hole. A small

hole only slightly larger in diameter than that of the pitot tube passed axially through this bolt. Through this hole the pitot tube passed, and the part of the tube extending out of the chamber into the traversing device was clamped to the moving portion of this device. After making an initial setting, the location of the pitot head measured from the far wall of the chamber was read directly and this distance was varied by means of a screw mechanism.

This pitot tube was bent into different shapes so that traverses could be obtained at different distances from the front glass wall. Total pressure was read from the spare upright water manometer on the manometer panel, and static pressure was obtained from a short upright water manometer made especially for this purpose. Since it was necessary to obtain the velocity head by taking the difference between two manometer readings, the absolute accuracy of the calculated velocities is not considered to be very good. On the other hand, the data are satisfactory for purposes of relative comparison.

In order to obtain more accurate absolute velocity measurements from which accurate values of the ratio of central velocity to average velocity could be obtained, central traverses were made with a pitot tube having both static and impact taps. The traversing device used with this pitot tube was similar to that employed with the other tube except that

it had no screw mechanism for traversing. A rider firmly clamped to the pitot tube fitted over a small metal scale calibrated in hundredths of an inch. The tube and rider were pushed back and forth manually, and, after making an initial setting, a direct reading of the distance of the pitot head from the far wall of the chamber could be made. It was necessary to use a split screw to attach this traversing device to the chamber and to pass the pitot tube through, since the pitot tube had a side arm extending out from it and therefore would not pass through the hole.

Velocity head measured with this pitot tube was read on the spare upright water manometer, and static pressure above atmospheric was measured on the short upright water manometer used previously.

All pitot traverses were made with no screen at the combustion chamber entrance.

I. Turbulence Measuring Apparatus

A detailed description of the apparatus used for the measurement of turbulence and the procedure for its operation is given in a recent report by Levine (27). Only a brief description of this apparatus will therefore be included here.

The hot wire anemometer method was employed for measuring the scale and intensity of turbulence. The meter was constructed

by Levine on the basis of considerations outlined in a report by Levine, May, and Scurlock (28).

Briefly, the method consists of suspending a platinum wire with its axis normal to the direction of flow in a turbulent air stream. A heating current is passed through this wire which raises the wire temperature substantially above that of the air stream. If the heating current is held constant, it is seen that the wire temperature is a function of the air velocity past the wire. If the wire is small then its time constant is low enough so that it is always at equilibrium temperature as the turbulent eddies pass across it at varying velocities. This means that the wire temperature must constantly vary. Platinum has a high temperature coefficient of resistivity and since the temperature of the wire is varying and the current remaining constant, the voltage across the wire varies. If this fluctuating voltage is amplified and measured, it is easily related to the turbulent velocity fluctuations in the air stream provided that the constants of the wire, the stream, and the amplifier, are known with sufficient accuracy. Even if the wire is so large that it always lags a short distance from equilibrium, this can be corrected for by the proper setting of a compensating circuit, provided again that the necessary system constants are well enough known for the time constant of the wire to be determined.

For the measurement of scale, two probes which can be moved relative to one another in a direction normal to the

direction of flow and normal to the probe axes are required. Further, a switching circuit is required by means of which the fluctuating voltage from both probes can be read when the probe outputs are added or when these probes are made to buck one another. Figure 19 is a photograph of the turbulence meter. This meter includes an amplifier, switching circuit, variable compensating circuit, and probe power supply circuit. Figure 20 is a photograph of the turbulence traversing device in place. The double probe can be plainly seen facing downward toward the combustion chamber entrance.

The traversing device, adapter, and axially drilled bolt employed for supporting and moving the impact pitot tube previously described were again used with the turbulence probe assembly. Turbulence measurements were made at four stations in the chamber. Measurements of both intensity and scale behind the three screens shown in Figure 11, and with no screen in place, were carried out.

The small platinum wires used as probes were of the Wollaston type with a diameter of 0.0001186 inches. This diameter was determined by measuring the resistance of a known length of wire at room temperature by passing a very small measured current through the wire, measuring the voltage drop across this wire, and calculating the wire resistance by means of Ohms law. Since the resistivity of platinum is known, a knowledge of the wire resistance and length allows the wire

FIGURE 19

The Turbulence Meter

FIGURE 20

The Turbulence Traversing Device in Place

diameter to be easily calculated. The actual probes used were made in lengths ranging from 0.015 to 0.30 inches.

J. Bunsen Cone Apparatus for Measuring Laminar Flame Velocity

The apparatus used for measuring laminar flame velocities in mixtures of air and Cambridge city gas, and air and propane was of standard construction. The burner tube had an inside diameter of 0.37 inches, an outside diameter of 0.539 inches, and was six feet in length*. The tube was tapered at the burner end so that its rim was very thin.

A homogeneous mixture of fuel and air was allowed to flow from the combustion chamber entrance nozzle of the main apparatus through a wet-test meter and finally into the long burner tube. The air-fuel ratio of the gas mixture was determined by the same means previously described for obtaining air and fuel rate through the main apparatus. The volumetric rate of flow through the burner tube was obtained by reading the wet-test meter. The difference between two meter readings taken one minute apart yielded the volumetric flow rate. Temperature and gage pressure in the wet-test meter were obtained from a thermometer and manometer mounted on the meter. The gas rate through the burner tube was adjusted by manipulation of a pinch clamp on the rubber tubing leading from the main apparatus

*Initially a tube with an inside diameter of 0.15 inches was employed, but the rim diffusion errors were too large to tolerate and the limits of flame stability were much narrower than with the larger tube.

nozzle outlet to the wet-test meter. The air-fuel ratio was regulated in the manner previously described for the main apparatus.

The burner tube was mounted in an upright position with its tip extending a few inches up into a square cardboard box open at the top and about 8 inches on an edge. This box served to shelter the flame from air gusts. A plate of glass was installed in one wall of this box which allowed the Bunsen flame and the upper portions of the burner tube to be viewed and photographed. The camera and film used for photographing these Bunsen flames were the same previously described for photographing flames in the combustion chamber of the main apparatus.

K. Apparatus for Analysis of Cambridge City Gas

The analyses of Cambridge city gas furnished by the Cambridge Gas Company were not completely satisfactory since the composition of the constituents reported as "illuminants" and " CH_4 " were not determined. "Illuminants" include all the unsaturated hydrocarbons, and " CH_4 " includes all the paraffin hydrocarbons.

It was desirable to know what mixture of air and city gas corresponded to stoichiometric. Further, for the calculation of theoretical flame temperature it was necessary to determine the total carbon in a known quantity of city gas.

A Fisher Precision Gas Analysis Apparatus was employed

for these determinations. This apparatus is of the Orsat type with a slow combustion attachment. The detailed description is contained in a pamphlet obtainable from the Fisher Scientific Company.

A known volume of city gas was drawn into the apparatus with a known volume of air more than sufficient for complete combustion. The mixture was thoroughly reacted in the slow combustion attachment and the CO_2 and O_2 in the remaining products was determined. From the O_2 remaining, calculation of the stoichiometric air requirements for complete combustion was easily carried out. All initially present carbon is in the form of CO_2 in the completely reacted city gas and air mixture, therefore, the total carbon in city gas can be easily calculated from the CO_2 determination.

Three analyses were carried out and their results averaged to obtain final values.

IV EXPERIMENTAL PROCEDURE

Included in this section is a description of the procedure followed in obtaining data. The outline used in the preceding section on the description of apparatus is again followed here.

A. The Main Apparatus

The majority of runs were those made to obtain blow-out limits and photographs of the flame at various air-fuel ratios and combustion chamber entrance velocities with different sizes, shapes, and locations of the flame stabilizer, and for different turbulence levels. Most of these runs follow a set pattern, although in special instances there was considerable deviation from this pattern.

A "run" generally included the collection of all routine blow-out and photographic data for one flame stabilizer located in one position, and for one turbulence condition. If all these data were not obtained during one day's operation, another "run" was started the next day.

A "run" is begun by starting the air compressor, turning on the combustion cell ventilator, switching on the dilution air blower, and obtaining a barometric reading. Air is allowed to flow into the combustion chamber at about 30 feet per second. The city gas line is opened and a small amount of gas is allowed to enter the combustion chamber. The probe-hole bolt nearest to the flame stabilizer is removed and the

spark ignition rod inserted. The spark circuit is closed intermittently while the city gas rate is slowly increased. Finally, ignition takes place and a flame stabilizes, first on the spark rod, then on the flame stabilizer itself. The spark rod is then withdrawn and the probe hole bolt reinserted. Figure 21 shows combustion being initiated in the combustion chamber by means of the spark rod.

Figure 21

Combustion Being Initiated in the Chamber by Means of the Spark Rod

Gas velocity at the combustion chamber entrance is set at the desired value, and steady-state flow conditions are obtained by manipulation of the air bleed valve until the pressure upstream of the air orifice remains constant.

In making a regular "run", data are generally obtained, if possible, at velocities of approximately 25, 50, 100, 180, 220, 320 feet per second. Data at the lowest velocity are first obtained and the velocity is progressively increased. Lean limit blow-outs for air and city gas obtained with the previously described metering facilities at 25 feet per second were found to be very unreliable since they were determined from very small manometer readings. These data were therefore not retained. Using propane as a fuel, on the other hand, a different gas meter was employed and good data were obtained at this low velocity. At 120 feet per second only blow-out data and no photographs were obtained, and at velocities above 220 feet per second data were taken at no standardized velocity level, points being obtained at the most convenient conditions. Data at velocities as low as 280 feet per second or as high as 380 feet per second sometimes were obtained.

To demonstrate how data were usually taken, consider operation of the apparatus at the 50 feet per second condition. The air rate is maintained at a constant value by holding a constant 8" reading on the water manometer reading pressure drop across the air orifice, and by manipulation of the air bleed valve so

that the air orifice upstream pressure remains constant. A considerable volume of city gas is introduced into the system to burn with the air, and this gas has some effect on the combustion chamber entrance velocity. Consequently, when obtaining data at a constant air rate, but at different air-fuel ratios, the actual velocity of the explosive mixture entering the combustion chamber increases somewhat as the entering mixture becomes richer in fuel. This effect is present, but to a lesser degree, when propane replaces city gas as fuel.

At 50 feet per second lean limit blow-out is first obtained. This is done by slowly decreasing the fuel rate until the flame blows off from the stabilizer. A complete set of readings is then taken and these data recorded in the data book. Essentially, no change takes place in the air or gas rate at blow-out. The combustion chamber entrance pressure at blow-out does change, however. This pressure, therefore, cannot be read after blow-out but must be estimated on the basis of other data. It is usually assumed to be the same as that of the reading later obtained very near to blow-out at the same velocity. After obtaining the lean limit blow-out, combustion is again initiated in the chamber by means of the spark rod as previously described. As already stated when blow-out data are obtained at velocities higher than about 50 feet per second, it is always necessary in order to avoid flashback to reduce the velocity before reigniting.

After reignition the fuel rate is set just slightly above

that found for blow-out and a photograph is taken. A complete set of temperature and pressure readings are then obtained for this condition. The fuel rate is now increased slightly and another photograph is taken. Only gas venturi meter readings and combustion chamber readings are taken for this new condition since the air rate remains unchanged. After obtaining these conditions, the fuel rate is again increased, another photograph is taken, and another set of readings are obtained. Usually, about six photographs are obtained at each velocity.

Finally, the fuel rate is increased to so large a value that rich limit blow-out occurs. At rich limit blow-out another complete set of readings is taken.

Often at the two lowest velocities, 25 and 50 feet per second, "flutter"* begins before rich limit blow-out occurs, or frequently even before a stoichiometric mixture is obtained. When flutter begins there is always danger of flashback. Furthermore, the photographs are of doubtful value for purposes of determining flame width. Consequently, no more data are generally taken at a velocity when "flutter" begins.

With the multiple rod flame stabilizers combustion approached nearer to completion before the gases exhausted

* "Flutter" may be described as a low frequency, periodic pulsation in the flow which is initiated when combustion nears completion in the combustion chamber. It is present in this apparatus when the angle between the two flame fronts increases and decreases periodically at about 40 cycles per second. The phenomenon is further discussed in another portion of this report.

from the chamber. Often severe "resonance"* effects accompany this more nearly complete combustion. This high-frequency periodic pulsation often becomes severe and is accompanied by extreme vibration of the entire apparatus and a very loud noise in the form of an almost pure note. The flame often detaches itself from some, or all, of the stabilizer rods when resonance begins. Since the data are no longer reproducible after resonance begins, and are not comparable with the data taken without resonance, only very little data have been obtained while resonance is taking place.

Difficulty arose in obtaining data with flat plates. The plates would not anchor satisfactorily and would blow out of the chamber as entrance velocity was increased. The 0.5 inch wide flat plate remained in place best and data up to about 200 feet per second were obtained with this plate. Smaller plates blew out at very low velocities and no data were obtained with them.

At velocities above 220 feet per second it is not possible to obtain rich limit blow-out data since the gas rate required is greater than can be safely handled without danger of collapse of the gas company meter.

*"Resonance" as here referred to is a periodic pulsation in the flow quite similar to "flutter" except that its frequency is considerably higher, being in the neighborhood of 300 - 400 cycles per second.

In going from lean to rich mixtures at 100 feet per second, it is necessary to shift from the small gas venturi to the larger one. In order to meter velocities above 100 feet per second, it is necessary to close off the water manometer and use only the mercury manometer for measurement of pressure drop across the air orifice.

Occasionally pieces of metal or metal oxide from the stove pipe exhaust stack would dislodge and fall through the combustion chamber into the calming section. These objects would lodge on the top 200 mesh screen and disturb the flow entering the combustion chamber. The presence of asymmetrical flow in the combustion chamber was easily detected since the stabilized flame (which was always under observation) would become asymmetrical. When this was observed, the calming section and nozzle were taken down and thoroughly inspected and cleaned.

B. Adaption to Propane

The runs with propane used as a fuel were carried out in the same manner as those with city gas previously described except that the method of metering the gas was different.

A standard orifice was placed in the gas line for metering the propane, and it was necessary to change orifice plates during a run. One plate served at low gas rates and another plate with a larger hole was employed for higher gas rates.

C. Controlled Temperature Stabilizer

Blow-out limits were obtained with the controlled temperature flame stabilizer, in the same routine manner previously described, for obtaining blow-out limits with other stabilizers.

D. High Speed Movies

To obtain high speed movies, the high speed camera previously described was loaded with a 100 foot roll of film, properly focused on the combustion chamber, and set to operate at 1500 frames per second. The main apparatus was then started up just as though a regular run were to be made. A flame was initiated in the combustion chamber and attached to the flame stabilizer. The chamber entrance velocity and air-fuel ratio were adjusted to the desired values and a set of pressure and temperature readings were taken. The NaCl vaporizer was then put into operation and air was allowed to enter. A cloud of finely divided NaCl particles suspended in this air passed from the vaporizer into the combustion chamber and caused the flame to become luminous. When the flame appeared to be uniformly luminous, the high speed camera was switched on and a reel of film was exposed.

E. Stroboscopic Equipment

An explanation of the operating procedure for the stroboscope apparatus is included in the Section III, Description of Apparatus.

F. Shadow Photograph Apparatus

Shadow photographs were taken following an operating schedule the same as that described for obtaining photographs during a regular run.

All lights in the combustion cell were turned off while shadow photographs were being taken to avoid exposure of the film. Two men were required to operate this apparatus most satisfactorily. One man cocked and tripped the shutter, operated the spark apparatus, and pulled the film pack tabs to expose new film. The other man operated the main apparatus and took pressure and temperature readings between photographs.

G. Apparatus for Taking Shadow Photographs with High Speed Movie Camera

The procedure followed in taking these pictures has already been described in Section III.

H. Pitot Traversing Apparatus

The pitot traverses were carried out in a standard manner which requires no explanation in addition to that included in Section III.

I. Turbulence Measuring Apparatus

A detailed description of the procedure followed in obtaining measurements of the intensity and scale of turbulence

with the hot-wire apparatus is included in reference (27). Only a brief discussion will therefore be included here.

After putting the turbulence probe in place at a station in the combustion chamber and plugging in the amplifier leads, the resistances of the two probe wires at air stream temperature are determined. These resistances are found by passing a very small current (0.002 amperes) through the wires and measuring the voltage drop across them. The probe resistances are then calculated using Ohm's law. This measurement is carried out with air flowing through the combustion chamber for cooling purposes. It is estimated that the wires are elevated above air-stream temperature due to heating action of the small current by less than two-tenths of a degree centigrade.

A potentiometer is employed for measurement of the voltage drop across the probes. This same instrument is used for determining probe current by measuring the voltage drop across a standard 10 ohm resistance in series with the probe and applying Ohm's law.

After determining the probe resistances at air stream temperature the air velocity entering the combustion chamber is set at about 25 feet per second, and pressure and temperature readings at the air metering orifice and the combustion chamber are recorded. The probe heating current is now set at 0.025 amperes, and the probe to be used for obtaining turbulence intensity measurements is moved to the center of the combustion

chamber by manipulation of the traversing device screw. Turbulence intensity measurements are now taken.

In order to calibrate the probes, it is necessary to obtain probe resistance as a function of local air velocity. The calibration data for both probes are obtained at the same time that turbulence intensity measurements are obtained. At 25 feet per second and with a heating current of 0.025 amperes the resistances of the two probes are found in the same manner as were these probe resistances at air-stream temperature. These measured resistances of the hot-wire are employed with other wire constants previously determined to calculate the wire time constant. The probe compensating circuit of the amplifier is set in accordance with the value of this calculated time constant, and a measurement of the turbulence intensity is obtained. This measurement is a reading representing the root-mean-square value of the fluctuating voltage across the hot wire after compensation for lag in accordance with the wire time constant, and after considerable amplification. The amplifier gain is also recorded. A turbulence intensity measurement is obtained with each of the three screens shown in Figure 11 in place at the combustion chamber entrance, and when no screen is in place.

The velocity is now increased to about 50 feet per second and probe calibration resistances and turbulence intensities are again obtained. At 50 feet per second, and at this velocity only, scale measurements are also taken. These measurements

are obtained by first setting the two probe wires very close together by manipulation of the micrometer screw built into the probe assembly. An add and a buck reading are then obtained, and the distance between the probes as indicated by the micrometer scale is recorded. The probes are then separated by a larger distance, add and buck readings are again obtained and the probe separation distance recorded. The probes are separated by increasing distances and data taken until the buck and add readings are essentially the same.

The velocity of the air entering the combustion chamber is increased by increments and turbulence intensity measurements obtained until a velocity of about 200 feet per second is reached, or until both probes have broken.

At 100 feet per second traverses are made of the chamber between the center and the far wall, with turbulence measurements being taken at a number of points between these points.

At each probing station, and with no screen at the combustion chamber entrance, the probe is placed near the far wall in the boundary layer and air velocity is slowly increased while observing the probe output meter. When the boundary layer becomes turbulent, the meter reading generally increases about ten times. Air orifice and combustion chamber data are recorded when this occurs.

Turbulence measurements were obtained at four stations

along the length of the combustion chamber.

Turbulence intensity measurements were also obtained while combustion was taking place in the chamber, and during conditions of "flutter". During these measurements the probe was located at the station nearest to the chamber entrance, and the measurements were not corrected for the presence of city gas in the entering stream.

J. Bunsen Cone Method of Measuring Laminar Flame Velocity

The procedure for using the Bunsen cone method for measurement of laminar flame velocity was to take photographs of the flame at different air-fuel ratios for later analysis.

Before taking a photograph at a new air-fuel ratio a short period of burning at the new condition was allowed during which the wet-test meter and burner tube became thoroughly purged of old gas mixtures and equilibrium conditions were obtained.

After all the flame photographs for a run had been taken, a light was placed over the burner tube, and, with the camera and burner tube still in the same relative position, a photograph of the burner tube was obtained. Since the dimensions of the tube are known, this last photograph establishes the scale of the flames in the other photographs.

K. Analysis of Cambridge City Gas

This analysis was performed in a routine manner, the

procedure being described in detail in a pamphlet accompanying the apparatus issued by The Fisher Scientific Company.

V EXPERIMENTAL AND CALCULATED RESULTS AND DISCUSSION

In order to simplify the presentation, this section has been divided into five parts:

- A. Nature of the flow through the combustion chamber when no combustion is taking place.
- B. Characteristics of the fuels, and fuel and air mixtures investigated.
- C. Propagation of a stabilized flame.
- D. Flame stabilization.
- E. A discussion of unstable burning phenomena.

In the last three sections, the problem is first attacked from a theoretical standpoint. These theoretical considerations are then followed by experimental results and discussion.

A. NATURE OF THE FLOW THROUGH THE COMBUSTION CHAMBER WHEN NO COMBUSTION IS TAKING PLACE.

1. Pitot Traverses

A series of pitot traverses were obtained at three stations along the length of the combustion chamber when no combustion was taking place. The purpose of these was: (1) to determine the velocity distribution at different distances downstream from the chamber entrance, (2) to obtain a knowledge of the boundary layer build-up at the chamber wall, and (3) to find

the relation between chamber central velocity and average chamber entrance velocity.

Figure 22(a), (b) and (c) are velocity profiles obtained at 1.65, 7.65 and 13.65 inches, respectively, from the combustion chamber entrance with an impact pressure tube. The traverses show the velocity profile to be remarkably flat in the central portion of the chamber cross section.

All of the velocity profile data shown in Figure 22 were obtained at a combustion chamber entrance velocity of approximately 140 feet per second. The traverses 0.465 inches from the chamber center, and the point in each traverse obtained nearest the far wall were taken with the impact tube resting against the chamber wall and are therefore subject to greater error than the other points. Measurements of impact pressure only were not considered of sufficient accuracy* for use in obtaining the ratio of chamber central velocity to average chamber entrance velocity. A question regarding the constancy of this ratio with varying average entrance velocity was also raised.

Additional traverses of greater absolute accuracy were obtained with a pitot tube at velocities of approximately 50, 100, 200 and 300 feet per second.

*Static pressure read from a mercury manometer connected to a pressure tap in the chamber wall is subtracted from total pressure read on a water manometer to obtain pressure head. The readings of static pressure from the mercury manometer are of doubtful accuracy.

FIGURE 22
PITOT TRAVERSES OBTAINED WITH STATIC PRESSURE TUBE

Figure 23 shows the results of these traverses plotted as the ratio of local velocity measured by the pitot tube to average chamber entrance velocity, V/V_0 , versus distance from the near wall. (The near wall is the wall upon which the traversing device is mounted.) These traverses show the same sort of flat velocity profile previously obtained.

From Figures 22 and 23, the boundary layer thickness is estimated to be about one-eighth of an inch at the first station near the chamber entrance, three-sixteenths of an inch at the second station near the center of the chamber, and one-fourth of an inch at the third station near the chamber exit. No systematic change in boundary layer thickness or V/V_0 is found with changes in V_0 over the range of velocities covered.

Figure 24 is a cross plot of the curves in Figure 23 of V/V_0 versus distance downstream from the chamber entrance. It is seen that velocity along the chamber axis increases linearly with distance downstream from the chamber entrance; velocity one-eighth of an inch from the wall increases at first and then becomes nearly constant; and velocity one-twentieth of an inch from the wall decreases almost linearly.

All pitot traverse data are included in Appendix E, runs 6, 53, 54, and the method of calculation is outlined in Appendix B.

FIGURE 23

PITOT TRAVERSES OBTAINED WITH
STATIC PRESSURE TUBE

FIGURE 24

RATIO OF LOCAL VELOCITY TO CHAMBER ENTRANCE VELOCITY
VERSUS DISTANCE DOWNSTREAM FROM CHAMBER ENTRANCE
AT DIFFERENT DISTANCES FROM CHAMBER WALL

2. Turbulence Determinations

Calculation of the scale and intensity of the turbulence existing in the combustion chamber when no combustion is taking place was carried out for 3 different screens at the combustion chamber entrance, and with no screen in place. Equations 12 and 13 proposed by Dryden (/5) for calculation of the turbulence downstream of screens with a mesh width to wire diameter of 5 to 1 were used. These equations apply only at distances downstream from the screen greater than 80 screen wire diameters. Turbulence measurements were also performed using the hot-wire method (27), (28), but the accuracy of the measurements proved to be poor. The measurements do, however, serve as a rough check on the calculations.

The three screens employed for turbulence generation are described as follows:

<u>Screen No.</u>	<u>Mesher per Inch</u>	<u>Wire Diameter</u>	<u>Blocked Area</u>
1	3	0.063"	0.3423
2	8	0.025"	0.36
3	55	0.007"	0.6294

Screens 1 and 2 have a mesh width to wire diameter ratio of 5.29 and 5, respectively, therefore, use of Dryden's equations with these screens is easily justified. Screen 3 has a mesh width to wire diameter ratio of 2.89 which is

smaller than that for which Dryden's equations were obtained. The unmodified equations were, however, applied for estimation of the turbulence scale and intensity behind screen 3.

Calculation of the turbulence existing in the chamber with no screen at the combustion chamber entrance is carried out using Dryden's equations by assuming the turbulence in the chamber to be that existing 6 inches downstream from a 200 mesh screen (such a screen is located in the calming section just upstream of the converging nozzle). The turbulence intensity is assumed to remain constant upon passage through the contracting nozzle, with the per cent turbulence being reduced 25 fold. The scale is assumed to be unaffected by passage through the nozzle, and no allowance is made for decay of the turbulence during passage through the chamber.

Figure 25 is a plot of the per cent turbulence in the central portion of the combustion-chamber versus the distance from the chamber entrance. All the calculated results are given, and the measured results at a V_0 of approximately 25 feet per second (which are considered the most accurate) are shown. It is seen that due to decay, the per cent turbulence falls rapidly as the distance from the turbulence generating screen increases. At any one location in the chamber, the per cent turbulence is highest behind the screen with the

largest wire diameter, since decay proceeds at a slower rate when the wire diameter, and therefore the scale, is large. For orientation purposes it should be recalled that the turbulence intensity at the center of a pipe in which fully developed turbulent flow exists is about 3 per cent (14).

The measured per cent turbulences fall below the calculated values for all three screens except near the exit end of the chamber where the measured values begin to increase due to diffusion out into the main stream of turbulence generated in the boundary layer. Dryden's equations, of course, do not allow for the effect of turbulence generation near the walls. This effect of wall generated turbulence is small, however, in the short 16 inch chamber, with turbulences being increased a maximum of about 1 per cent at the chamber exit.

With no screen at the combustion chamber entrance, the measured values of per cent turbulence are considerably above the calculated values, the measured values being about 0.4 per cent compared with the calculated value of about 0.02 per cent. The probable reason for this large discrepancy is found by comparison of the per cent turbulence reading with the air compressor turned off (with air being supplied to the chamber from the hold-up in the large surge tank) with a

reading obtained under the same conditions except with the compressor on. It is seen that a per cent turbulence of 0.07 per cent is obtained when the compressor is off which is of the same order as the calculated value. The hot-wire anemometer measures vibrations and reports them undistinguished from turbulence. Apparently, then, vibrations caused by operation of the Diesel compressor are responsible for between 0.3 and 0.4 per cent of the measured per cent turbulence values. The effect of the compressor as it changes speed or is turned on and off is easily noted by observation of the oscilloscope screen connected across the hot-wire output circuit.

Figure 26 is a plot of turbulence scale versus distance from the chamber entrance, and includes both calculated and measured values with screens 1, 2 and 3 in place, and with no screen in place. The measured values were obtained near the center of the chamber at V_0 of about 50 feet per second. Scale measurements were only obtained at three of the four stations at which turbulence measurements were made, and measurements were not obtained with no screen in place because of the high hum level of the probe power supply when the probes were in the buck position. This hum served to mask almost completely the low level turbulence present in the chamber with no screen in place. Also, because of this

FIGURE 26

TURBULENCE SCALE IN CHAMBER WITH NO COMBUSTION TAKING PLACE

hum, no satisfactory measurements were obtained at the station near the chamber exit where the turbulence level is also low.

The measured values of scale are in every case larger than the calculated values.

Comparison of the measured and calculated values of scale and intensity in Figures 25 and 26 suggests that the hot wire was not sufficiently compensated for time lag. If the wire were insufficiently compensated, the output voltage due to the high frequency velocity pulsations at the wire would be reduced below its value if the wire had no lag (or if the wire were properly compensated), thus reducing the entire output signal and resulting in measured per cent turbulences lower than those actually present. The effect of the high frequency velocity pulsations (associated with small scale) would again be reduced in the scale measurements and the measured scale would be predominantly determined by the low frequency velocity pulsations. This would result in measured values of the scale of turbulence larger than the true values. This is apparently exactly what has occurred.

Further, if V_0 is increased and the actual per cent turbulence remains constant, as it does approximately behind screens (45), (24), (15), frequencies to which the probe is

subjected will increase proportionately. As V_0 is increased the insufficiently compensated probe should, therefore, yield lower and lower values of measured per cent turbulence. Examination of the turbulence measurement data included in Appendix C, runs 62, 63, 64 and 65 show that considerable reduction in per cent turbulence actually does occur with increasing velocity.

In spite of considerable precaution to avoid it, there was still a very small amount of finely divided oil droplets entrained in the air. The effect of these droplets upon striking the hot wire is not precisely known, but it is presumed that the presence of oil on the wire surface would reduce the wire temperature and increase its heat capacity. This would tend to decrease the sensitivity of the wire and to increase its time constant to a value above that calculated. It is believed that the presence of these small oil droplets plus the vibratory effects of the air compressor were primarily responsible for the relatively poor turbulence measurements obtained.

The critical velocity at which the boundary layer becomes turbulent was determined at 3 locations along the chamber length. Reynolds numbers were calculated based on the distance from the end of the converging section of the

nozzle (distance from the combustion chamber entrance plus 2 inches). Figure 27 presents the results of the measurements and calculations. The Reynolds number at which the boundary layer becomes turbulent is about 1.1×10^6 . It is interesting to note that at all velocities over about 20 feet per second the boundary layer in the major portion of the chamber is turbulent. The turbulence was measured and found to be about 3 to 5 per cent in this turbulent boundary layer.

A few turbulence measurements obtained at the chamber entrance with combustion proceeding further downstream are discussed in section IV-E.

All turbulence measurement data are included in Appendix D, runs 61, 62, 63, 64, 65 and 66, and the method of calculation is discussed in Appendix B.

FIGURE 27
CRITICAL VELOCITIES AND REYNOLDS NUMBER
FOR BOUNDARY LAYER TURBULENCE IN
CHAMBER

B. CHARACTERISTICS OF THE FUELS; AND FUEL AND AIR MIXTURES
INVESTIGATED.

Two fuels, Cambridge city gas and propane, were employed during the course of this investigation. Of the two, Cambridge city gas was used most extensively.

The average per cent composition by volume of the Cambridge city gas as determined in the gas company laboratory by Orsat type analysis is as follows:

CO ₂	7.3 per cent
Illuminants	9.8 per cent
O ₂	0.6 per cent
CO	21.8 per cent
CH ₄	14.7 per cent
H ₂	26.8 per cent
N ₂	19.0 per cent

The "illuminants" include all of the unsaturated hydrocarbons. All saturated hydrocarbons are reported as "CH₄". From day to day the percentage composition varies by about 1 or 2 per cent of the values given. The gas has a specific gravity based on air of 0.73 ± 0.004 . The stoichiometric air requirements to burn the gas completely to CO₂ and H₂O is 6.51 pounds of air per pound of city gas (see Appendix C, run 95 for data).

The propane used was obtained from the Colonial Beacon Oil Company. The grade of bottled propane employed is sold under the trade-mark name of PANESSO, and is a rather low purity product. Its per cent composition by volume obtained at the Boston Esso Laboratory by analysis of a sample taken from one of the bottles used is as follows:

Propane	83.8 per cent
Propylene	13.3 per cent
Ethane	2.4 per cent
Butane	0.5 per cent

The stoichiometric air requirement to burn the gas completely to CO_2 and H_2O is 15.58 pounds of air per pound of Panesso.

Figure 28 presents the results of laminar flame velocity measurements obtained by the Bunsen cone method with city gas-air and propane-air mixtures. In Figure 28(a) laminar flame velocity, S_L , is plotted versus air-fuel ratio. In Figure 28(b) curves for the two fuels are presented on a more nearly comparable basis by plotting S_L versus the generalized oxidant fraction. The generalized oxidant fraction, O_g , is obtained by dividing the weight of oxidant (in this case air) by the sum of the weight of oxidant and the weight of fuel put on an air basis. Thus O_g always has a value of 0.5 for a stoichiometric mixture, 1 for pure oxidant, and

FIGURE 28

LAMINAR FLAME VELOCITIES CITY GAS-AIR AND PROPANE-AIR
MIXTURES (INITIAL TEMP. -27°C; PRES.-1 ATM.)

zero for pure fuel. It is observed that S_L for the propane is approximately half that for Cambridge city gas. The maximum S_L for city gas is about 1.6 feet per second and that for propane is about 0.8 feet per second.

Photographs of the Bunsen flames from which S_L values were obtained are presented in Figures 130 and 131 of Appendix A, and a brief discussion of the Bunsen method of measuring laminar flame velocity is also included. The laminar flame speed data are included in Appendix C, runs 32 and 80.

Figures 29(a) and 29(b) are plots of the theoretical flame temperature of city gas-air and propane-air mixtures versus air-fuel ratio and generalized oxidant fraction, respectively. The two curves are seen to be remarkably similar. Figures 30(a) and 30(b) are plots of the ratio of mols of gas after complete combustion to mols of air plus fuel before burning for city gas-air and propane-air mixtures, versus air-fuel ratio and generalized oxidant fraction, respectively. Figures 29 and 30 were calculated by the method of Satterfield, Hottel and Williams (40).

Figures 31(a) and 31(b) present plots of the ratio of unburned gas density to burned gas density for city gas-air

FIGURE 29

THEORETICAL FLAME TEMPERATURE OF CITY GAS-AIR AND PROPANE-AIR
MIXTURES (INITIAL TEMP -15.6°C; PRES. -1 ATM.)

FIGURE 30

CHANGE IN NUMBER OF MOLS. DURING COMBUSTION OF CITY GAS-AIR AND
PROPANE-AIR MIXTURES (INITIAL TEMP-15.6°C; PRES-1 ATM.)

FIGURE 31

CHANGE IN DENSITY OF CITY GAS-AIR AND PROPANE-AIR MIXTURES
(A) ON COMBUSTION (INITIAL TEMP.-15.6°C; PRES.-1 ATM)

and propane-air mixtures, versus air-fuel ratio and generalized oxidant fraction, respectively. These plots were constructed by assuming the unburned gas to have the same initial conditions as those assumed for the calculation of Figures 29 and 30, and by using the results shown in these figures with the aid of the perfect gas law to estimate the gas density after completion of combustion.

C. PROPAGATION OF A STABILIZED FLAME

1. Theoretical Calculations

As an aid in interpreting the experimental results on flame propagation and in order to obtain a better visualization of the flow conditions through the combustion chamber in the presence of a stabilized flame, a method has been developed for estimating this flow by hydrodynamic calculations. Many of the conclusions reached on the basis of these calculations also apply qualitatively to high output combustion chambers in general.

By using the results of these calculations with flame width data obtained in the rectangular combustion chamber previously described, estimates of effective flame velocity in the chamber can be obtained, and interesting comparisons of calculated and experimental results can be made.

A stepwise method of calculating the flow through a rectangular combustion chamber while combustion is taking place is outlined below, and the results of the calculation are presented.

Referring to Figure 32 consider the combustion of an explosive, homogeneous mixture flowing in a rectangular duct of constant cross section having a width W_t , a half

FIGURE 32

width, Y_t , ($Y_t = W_t/2$), and a thickness of unity. The following simplifying assumptions are made:

1. Steady-state flow conditions prevail.
2. The unburned gases enter the chamber with uniform velocity V_0 , density ρ_0 , and pressure P_0 .
3. No momentum transfer takes place normal to the direction of flow.
4. The flame is initiated along a mathematical line oriented normal to the gas flow and normal to the forward chamber wall.
5. The flame front is a mathematical surface and the unburned gas, upon passing through it, burns completely and assumes the properties of the burned material with a density ρ_b .
6. Incompressible flow prevails.
7. The static pressure is uniform across any cross section normal to the chamber axis.

A necessary corollary to these assumptions is that there are no heat transfer, friction, catalytic, or quenching effects caused by the chamber walls, but that the walls act only to confine the flowing fluid.

A discussion of the validity of these assumptions is reserved until the end of this section.

The nomenclature used in the mathematical treatment is as follows:

A	area of flame front
A_r	reduced area of flame front ($= A/\text{cross-sectional area of duct}$)
D_r	reduced flame diameter for cylindrical duct ($= \text{flame diameter}/\text{diameter of duct}$).
F	fraction that has burned of total gas flowing through any cross-section of duct.
P	static pressure.
P_0	static pressure at combustion chamber entrance.
R_r	reduced radius of flame in cylindrical duct ($= \frac{\text{radius of flame front}}{\text{radius of duct}}$)
R_p	ρ_0/ρ_b - ratio of unburned gas density to density of the completely burned products.
S_f	flame velocity
s	length of flame front.
s_r	reduced length of flame front ($= \text{length of flame front}/1/2 \text{ chamber width} = s/Y_t$)
s_t	total length of flame front.
s_{rt}	total length of flame front on a reduced basis
V	local velocity

V_o	average velocity at the combustion chamber entrance
V_r	reduced gas velocity
V_{ru}	reduced gas velocity for unburned gas
V_{rb}	reduced gas velocity for burned gas
W	width of flame
W_r	reduced flame width ($= W/W_t$)
W_t	width of rectangular duct
Y	half width of flame ($= W/2$)
Y_r	reduced half width of flame ($= W_r/2$)
Y_t	half width of duct ($= W_t/2$)
ΔP	static pressure drop
ΔP_t	static pressure drop for complete combustion calculated by stepwise method
ΔP_{to}	static pressure drop for complete combustion calculated assuming heat addition to be uniform across chamber.
ΔS_r	increment of reduced flame front length.
ρ_b	density of burned gas
ρ_o	density of unburned gas

Subscripts:

b	burned
o	inlet conditions
r	reduced parameter
t	overall dimension

1 - 22 denotes segment in the stepwise integration

-1 to -22 denotes step in stepwise integration

Since the flow is symmetrical about the center line of the combustion chamber, it is necessary only to consider half of the chamber. If a differential amount of the entering combustible mixture adjacent to the combustion chamber center line is permitted to burn, a static pressure drop dP will result. The velocity of the unburned gases will increase by an amount dV_u , and the burned gases will be moving at a velocity dV_b higher than before burning. We can now write an overall mass balance, an overall momentum balance, and a force balance for the unburned gas, for the flow conditions before and after combustion of this differential amount of material.

Overall mass balance:

$$\rho_o V_o Y_t = \rho_o (V_o + dV_u)(Y_t - dy) + \rho_b (V_o + dV_b) dy \quad (28)$$

Overall force balance:

$$P_o Y_t + \rho_o V_o^2 Y_t = (P_o + dP) Y_t + \rho_o (V_o + dV_u)^2 (Y_t - dy) + \rho_b (V_o + dV_b)^2 dy \quad (29)$$

Force balance on the unburned gas:

$$-dP = \frac{\rho_o d(V_u^2)}{2} \quad (30)$$

In order to generalize the above equations and put them on a dimensionless basis in such a way that they apply for any entrance velocity, entrance density, or duct width, the reduced parameters $Y_r = y/Y_t$,

$$V_r = \frac{V}{V_0} \quad \text{and} \quad R_p = \frac{\rho_0}{\rho_b} \quad \text{are introduced.}$$

Equation 28 is divided by $\rho_0 V_0 Y_t$, equation 29, by $\rho_0 V_0^2 Y_t$ and equation 30 by $\rho_0 V_0^2$ and the symbols for the reduced parameters are substituted.

No method has been found for integrating these equations analytically. Consequently, it was necessary to solve them by the use of finite increments. These are now introduced for all differentials. Dimensionless equations employed for solution of the first step of the combustion process are obtained as follows:

Overall mass balance:

$$1 = V_{r1}(1 - \Delta Y_{r1-1}) + \frac{V_{rb1} - 1}{R_p} \Delta Y_{r1-1} \quad (31)$$

Overall force balance:

$$\begin{aligned} \frac{-\Delta P_1}{\rho_0 V_0^2} &= V_{r1}^2 (1 - \Delta Y_{r1-1}) \\ &+ \frac{V_{rb1}^2 - 1}{R_p} \Delta Y_{r1-1} - 1 \end{aligned} \quad (32)$$

Force balance on the unburned gas:

$$\frac{-\Delta P_1}{\rho_0 V_0^2} = \frac{V_{r1}^2 - 1}{2} \quad (33)$$

where V_{r1} is the reduced velocity of the unburned gases after

the first combustion step, and V_{rbl-1} is the velocity of the first burned segment at the end of the first step.

A solution of these simultaneous equations for the first step can easily be made by assuming either a:

$$\frac{\Delta P}{\rho_0 V_0^2} \quad \text{or a } \Delta Y_r$$

and determining the remaining unknowns. The solution of the problem for additional steps, however, becomes difficult if values of ΔY_r are assumed since the number of simultaneous equations that must be solved increases with each step. On the other hand, the assumption of equal increments of:

$$\frac{\Delta P}{\rho_0 V_0^2}$$

for each step results in a readily solvable problem even when small increments are chosen since the new equations introduced for additional steps may be solved directly and only three equations must be solved simultaneously for each step.

After a value of:

$$\frac{\Delta P}{\rho_0 V_0^2}$$

has been assumed and the first-step equations solved, the

width of the first burned segment and its velocity are known. The width and velocity of this segment can then be found for additional drops in pressure independently by solution of a force balance for the burned gases in the segment. For the second step then, the following equations are written:

Force balance in the burned material:

$$\frac{-\Delta P-2}{\rho_b V_o^2} = \frac{V_{rb1-2} - V_{rb1-1}}{2} \quad (34)$$

Overall mass balance:

$$1 = V_{ru2}(1 - \Delta Y_{r1-2} - \Delta Y_{r2-2}) + \frac{V_{rb1-2}}{R\rho} \Delta Y_{1-2} + \frac{V_{rb2-2}}{R\rho} \Delta Y_{2-2} \quad (35)$$

Overall momentum balance:

$$\frac{-\Delta P-2}{\rho_o V_o^2} = V_{ru2}^2(1 - \Delta Y_{r1-2} - \Delta Y_{r2-2}) + \frac{V_{rb1-2}^2}{R\rho} \Delta Y_{r1-2} + \frac{V_{rb2-2}^2}{R\rho} \Delta Y_{r2-2} \quad (36)$$

Force balance in the unburned material:

$$\frac{-\Delta P}{\rho_o V_o^2} = \frac{V_{ru2} - 1}{2} \quad (37)$$

In these equations, as stated above, the width of the first burned segment at the end of the second step, ΔY_{r1-2} , and the velocity in the first segment after completion of

the second step, V_{rbl-2} , are determined independently by equation 34 and an equation of continuity, so that the second step equations and the equations of all additional steps reduce, like those of the first step, to the solution of a quadratic equation.

The problem has been solved for three values of the density ratio, R_ρ , namely 4, 6 and 8. This covers the density ratio range encountered with different air-fuel ratios when burning Cambridge city gas and air. In each solution approximately twenty steps of equal

$$\frac{\Delta P}{\rho_o V_o^2}$$

were taken. The magnitude of these steps was decided upon by dividing the calculated value of:

$$\frac{\Delta P}{\rho_o V_o^2}$$

for uniform heat addition to the stream* by 20. The pressure drop produced by completing combustion in the stepwise manner, of course, is always greater than that for uniform heat addition; therefore, more than 20 pressure steps obtained in the above manner were always necessary to burn all of the material. The pressure drop increment chosen for the last step, in which combustion is just completed is obtained by trial and

* $\frac{-\Delta P}{\rho_o V_o^2} = R_\rho - 1$. This equation can be easily obtained by combining a mass balance, $\rho_o V_o = \rho_b V_b$ with a force balance, $\Delta P = \rho_b V_o^2 - \rho_b V_b^2$

error.

The results of the calculations are shown in Figures 33 through 37, and Figures 38 and 39 demonstrate how the calculations can be employed to construct flame fronts and lines of flow for any special case. The numerical results of these calculations are included in Appendix A. The calculations can be very easily converted to apply to the case of combustion in a duct of cylindrical cross section with the flame attached to a point stabilizer located at its center. This conversion has been performed for the $R_p = 6$ calculation and these results are included on the Figures.

Figure 33 shows velocity profiles for the three values of R_p chosen for calculation. These profiles were obtained by plotting segment velocity versus the distance from the chamber center to the segment center at a fixed fraction burned. Smooth curves were then drawn through these points. The part of the velocity profile representing the velocity in the unburned gas always remains flat as is indicated. Profiles are shown for several fractions of the total gas burned. It is at once noted that even though no velocity gradients existed before combustion began, upon initiation of combustion, such gradients very rapidly appear. The burned products at the center, because of their low density, increase in velocity more than do the unburned gases when accelerated across

FIGURE 33

VELOCITY PROFILES CALCULATED BY STEPWISE METHOD
ASSUMING A FLAT APPROACH VELOCITY PROFILE

FIGURE 34

FLAME WIDTH VS. FRACTION BURNED
CALCULATED BY STEPWISE METHOD

FIGURE 35

PLOT OF FRACTIONAL PRESSURE DROP VS. FRACTION
BURNED CALCULATED BY STEPWISE METHOD

PLOT SHOWING DEVIATION OF PRESSURE DROP ACROSS COMBUSTION
 ZONE FOR COMPLETE COMBUSTION CALCULATED BY
 STEPWISE METHOD FROM THAT ASSUMING UNIFORM
 HEAT ADDITION

FIGURE 37

WIDTH OF FLAME VS. FRACTIONAL PRESSURE
DROP CALCULATED BY STEPWISE METHOD

FIGURE 38

FLAME FRONT CONFIGURATION FOR THE
CASE OF ENTRANCE VELOCITY TO FLAME
VELOCITY EQUAL TO 10 CALCULATED
BY STEPWISE METHOD.

FIGURE 39

LINES OF FLOW IN THE NEIGHBORHOOD
OF THE FLAMEFRONT FOR THE CASE
 V_0/S_f EQUAL TO 10 CALCULATED
BY STEPWISE METHOD

a given pressure drop. The resulting velocity profile after combustion has begun resembles somewhat that of a jet of gases issuing into a lower velocity fluid stream. The maximum velocity gradients exist at the flame front and increase in the fraction burned. The largest gradients are found with the highest $R\rho$, other things being equal. Larger gradients of velocity near the flame front are produced in a cylindrical chamber than in the rectangular one as seen by comparing the slope of the dotted profiles for a cylinder with the solid ones for the rectangular duct.

Figure 34 presents plots of flame width, W_r , versus the fraction burned, F , for three values of $R\rho$, in a rectangular duct, and D_r versus F for the cylindrical duct at $R\rho = 6$. The flame diameter, D_r , for the cylindrical chamber is very simply related to the flame width, W_r , for the rectangular chamber by the following relation:

$$D_r = \sqrt{W_r}$$

These plots point out how rapidly the flame width increases initially with fraction burned and how slowly the increase proceeds as F approaches 1.

The curves are useful for calculation of flame velocity, S_f , from measurements of flame width. W_r at a known distance, s ,

along the flame front from the stabilizer can be determined directly from photographs of stabilized flames, and by referring to Figure 34, the fraction burned can be obtained. A flame velocity, which is actually an average S_f over the length of flame front between the flame stabilizer and the cross section where W_r is measured, can be calculated then in the case of the rectangular chamber by means of the following equation:

$$S_f = \frac{V_o Y_{tF}}{s} \quad (38)$$

Figure 35 shows the effect of fraction burned on fractional pressure drop.

Figure 36 shows the effect of R_ρ for $F = 1.0$ on the ratio of pressure drop for non-uniform exit velocity to that for uniform exit velocity. The curves in Figures 35 and 36 apply to either the rectangular or the cylindrical chamber.

It is seen that the assumption of uniform heat addition (resulting in uniform velocity across any cross section) gives overall pressure drops which are considerably smaller than those calculated by the stepwise method, and that this difference increases as R_ρ increases. Figures 35 and 36 should prove of interest to those workers who have employed pressure drop measurements for estimation of the completion

of combustion in ram jet combustion chambers. The fact that greater pressure drops across the combustion zone are produced for the same heat release by a progressive combustion than for uniform heat addition as shown in Figure 36 means, of course, that increased thrusts are also obtained when heat is added progressively across the chamber*.

Figure 37 is a plot of flame width, W_r , as ordinate versus fractional pressure drop as abscissa for the three R_p values calculated and for the cylindrical case for $R_p = 6$. These curves may be used with the experimental data to check independently the density ratio value obtained on the basis of theoretical flame temperature and change in the number of mols. This density ratio value is important for use with Figure 34 to obtain a value of F for use in equation 35 for calculation of S_f . This check is made by measuring both the fractional pressure drop and the flame width, W_r , plotting these values on the graph and interpolating between R_p lines to determine what R_p line the point falls on.

* This statement applies exactly only for the case of uniform entrance velocity and a uniform air-fuel ratio in the combustion chamber. In general, pressure drops will differ from those calculated for uniform heat release whenever the combustion spreads progressively through the flowing mixture, or the entrance velocity is non-uniform, or the air-fuel ratio is non-uniform, and for some conditions it may actually be less than the corresponding pressure drop calculated for uniform heat release.

It has probably already been noted that in carrying out the above-described stepwise calculation no assumption of flame speed was necessary. Now it is desirable to demonstrate further the generalized nature of the calculations by applying them to the determination of flame front configuration and flow stream lines in a special case in which the flame velocity, S_f , is assumed to remain constant along the entire flame length. This would be the case if no turbulence were present. S_f would then equal the laminar flame velocity. The calculations can be as readily applied to the determination of flame front configuration and lines of flow making some other assumption regarding S_f .

It is further assumed that $V_o/S_f = 10$, and a mass balance;

$$\rho_o S_f s_t = \rho_o V_o Y_t$$

is written for one half the chamber where s_t is the total flame front length. Putting this equation on a non-dimensional basis by introducing $s_{rt} = s_t/Y_t$ the mass balance becomes:

$$s_{rt} = V_o/S_f = 10$$

(in the case under discussion)

Further, we can write a mass balance for each segment of

flame front,

$$\Delta s_r = \frac{V_0}{S_f} \cdot F = 10 \cdot F \quad (39)$$

where F is again the fraction burned.

Since a plot of W_r versus F has been calculated (Figure 34), we can easily obtain s_r versus W_r which is the relation needed to draw in the flame front.

Flame fronts have been constructed for R_p values of 4, 6, and 8 and are shown in Figure 38. The configuration for the cylindrical case is also shown for $R_p = 6$. This was found by recalling that equation 39 held also for the cylindrical case if, instead of s_r , (the flame front length, which is proportional to the flame front area in the two-dimensional duct) the reduced flame front area, A_r , is inserted. We then obtain:

$$A_r = \frac{V_0}{S_f} \cdot F = 10F$$

or:

$$\Delta A_r = 10\Delta F$$

The quantity ΔA_r can be approximated for short increments of flame front by employing the equation for the area of a truncated cone,

$$\begin{aligned}
\Delta A_r &= \frac{\text{truncated cone area}}{\text{cylinder cross section}} \\
&= \frac{\pi(R_{r1} + R_{r2})\Delta s_r}{\pi \cdot (1)^2} \\
&= (R_{r1} + R_{r2})\Delta s_r \\
&= 10F \tag{40}
\end{aligned}$$

where $R_{r1} (= R_1/Y_t)$ and $R_{r2} (= R_2/Y_t)$ are the distances from the center of the cylinder to the flame front measured normal to the cylinder axis at the top and bottom of the increment of flame front length, Δs_r .

Solving equation 40 for Δs_r , we obtain:

$$\Delta s_r = \frac{10F}{R_{r1} + R_{r2}} \tag{41}$$

Figure 34 contains a plot giving the relation between F and W_r (equal to R_r for the cylindrical case); therefore, all the information is available for construction of a flame front for the cylindrical case.

In Figure 39 is shown the streamlines in the neighborhood of the flame front for the two-dimensional case with $R_c = 6$ and $V_0/S_f = 10$. The method of construction is based on the general stepwise calculations and is very simple. It involves following an increment of combustible mixture as it flows downstream and calculating the velocity and width of its

stream tube. The flame front shown in Figure 39 was taken from Figure 38 for $R_p = 6$. The curves in Figure 39 are based on calculations for division of half the chamber into five elements. The point where each stream line enters the flame front is found easily by stepping off five equal increments along the flame front length. The angles of entry and departure from the flame front are formed by construction, since the velocity of entry can be obtained from the calculations, the velocity component of the entering gas normal to the flame front is S_f , the normal component upon leaving the flame front is $S_f \cdot R_p$, and the velocity component parallel to the flame front remains unchanged upon passage through the front. The points through which the stream lines pass after departing from the flame front are easily obtained for different fractional completions of combustion by going directly to the calculations which include, for the completion of each step, the width of each segment and the fractional mass of material each contains.

Figure 39 is especially interesting in that it gives a quantitative picture of the flow through the combustion zone. Note especially how the streamlines diverge from the chamber entrance before entering the flame front and later converge after passage through it.

Returning to the assumptions made in performing the step-wise calculations outline above, they must be viewed critically; first, as to whether calculations based on these assumptions approximate actual test conditions in the rectangular combustion chamber used in the flame stabilization studies, and second, whether the calculations give results approximately applicable to conditions in ram-jet combustion chambers in general. In the following, each assumption is restated and discussed with reference to the two applications desired:

1. Steady-state flow conditions prevail.

This is certainly an excellent assumption in the case of the rectangular test section employed for this study, as is also good for ram jet chambers in general, except, of course, when rough burning or resonance phenomena are present.

2. The unburned gases enter the chamber with a uniform velocity.

Velocity profiles obtained by pitot tube measurements and presented in Figures 22 and 23 are essentially flat at the chamber entrance. Consequently, the assumption is excellent for the apparatus employed. For ram-jet combustion chambers in general the validity of the assumption depends on the design of the section preceding the combustion chamber. In many cases, the assumption may be quite reasonable. The accuracy of the calculations would not be very greatly affected

if a velocity distribution for fully developed turbulent flow in a pipe prevailed.

3. No momentum transfer takes place normal to the direction of flow.

If molecular viscosity forces were the only ones present for the transfer of momentum (This is very nearly the case with no combustion taking place in the rectangular chamber employed when run with no turbulence generating screen in place.), the assumption would be an excellent approximation. Actually, as is later shown, in most cases considerable turbulence is generated either in the vicinity of the flame stabilizer or further downstream. When this turbulence resulting from combustion appears, it is undoubtedly true that rapid momentum transfer occurs and that the calculated velocity profile shown in Figure 33 for complete combustion never exactly obtains. Since this turbulence generation with its attendant high momentum transfer occurs in most cases both in the apparatus presently being considered, and in ram-jet combustion chambers in general, it is necessary to appreciate the fact that use of the stepwise calculations for obtaining flame velocities, velocity profiles, etc., must usually be considered only an approximation, although one which is in most cases considered fairly good.

4. The flame stabilizer is a mathematical line oriented normal to the gas flow and normal to the forward chamber wall.

The assumption is quite good for many of the small flame stabilizers (as small as 0.016" in diameter) used in the rectangular chamber. Further it has been found, as later discussed, that beyond a distance of about 8 stabilizer diameter downstream from the stabilizer the effect of stabilizer size, except at very lean and very rich mixtures, is negligible.

For ram jet chambers in general, of course, the assumption of a point stabilizer in a cylindrical duct is seldom approximated. Probably the use of a single small cone or round plate located at the center of the cylindrical combustion chamber as a flame stabilizer is the nearest approximation found in practice.

5. The flame front is a mathematical surface and the unburned gas, upon passing through it, burns completely and assumes the properties of the burned material.

This assumption is quite good as long as conditions approximating laminar flow conditions prevail. When turbulence sets in, the volume occupied by flame increases and the assumption is less valid. It is not known exactly how deviations

from this assumption would affect the calculations, but it is suspected that such deviations might have an appreciable effect under high turbulence conditions resulting in a very thick flame front. The above remarks apply both to the present apparatus and to ram jet chambers in general.

6. Incompressible flow prevails.

This assumption is quite good at chamber entrance velocities below about 100 feet per second. It remains fairly good for the earlier parts of the combustion process as studied in the present apparatus up to over 300 feet per second. In the later stages of combustion, at these high entrance velocities, however, the gases would reach high velocities and consequently large drops in static pressure would be involved. The effect on the velocity profile curves of Figure 33 due to large changes in static pressure would be considerable, although their general shape would be maintained. Both ρ_u and ρ_b would decrease as combustion proceeded and the consequent accelerations for each pressure drop increment would be increased so that the velocity profile curves would be moved up along the ordinate, and velocity gradients would become steeper.

7. The static pressure is uniform across any cross section.

This assumption only approximates actual conditions, but

it is quite good as long as V_0/S_f is greater than about 8 or 10. The ratio of the pressure drop across the entire combustion zone to the drop across the flame front is approximately $(V_0/S_f)^2$. Even when V_0/S_f is as low as 10, (this low a ratio would generally only occur at entrance velocities that are lower than are of interest for high output combustion) therefore, this pressure ratio is (100/1). That is, static pressure differences across any cross section are usually less than 1 per cent of the total pressure drop in the direction of flow.

The results of the above stepwise calculations will be often employed and referred to in the following presentation of experimental results and discussion.

2. Experimental Results

(a) Flame Photographs

Photographs of stabilized flames at different air-fuel ratios and chamber entrance velocities have been obtained with different flame stabilizer sizes and shapes, and using as fuel both city gas and propane.

A typical set of pictures taken using Cambridge city gas as a fuel is shown in Figure 40. The flame stabilizer in this case is a 0.126" in diameter steel rod which is located 9 inches from the combustion chamber entrance and no turbulence generating screen is in place. Under each photograph is given the combustion chamber entrance velocity designated as V and the air-fuel ratio designated as l/f . The three numbers on each photograph represent the film negative number, the film pack number and the run number, respectively. The photographs were all obtained using Kodak plus-X 9x12 centimeter film with a Voigtlander camera. The exposure time was two-fifths of a second* and an f-6.7 lens setting was used. The distance from the flame was so set that flame photographs one-fourth of full scale resulted. The entire series of regular flame photographs are included in Appendix A.

*Results of a series of flame width measurements obtained from negatives exposed to the same flame for different lengths of time are included in Appendix A. It is found, at least in this one case, that the exposure time in the neighborhood of two-fifths of a second could be varied by 100 per cent or more in either direction without changing the measured flame width. Slight changes in measured flame width are, however, obtained when the exposure time is varied by greater amounts.

The homogeneous city gas and air mixtures burn with a blue non-luminous flame which assumes a greenish color at air-fuel ratios on the rich side of stoichiometric. Flames which are quite similar in appearance are also obtained when propane and air mixtures are burned. A more detailed discussion of the appearance of the flame to the eye under various operating conditions, and the apparent effect of the walls on the flame is included later in this section.

Measurements of flame width, W , from the photographic negatives were made at two inch intervals measured along the flame front. These measurements are recorded in Appendix C as part of the data obtained with each picture.

Figure 41 is an enlargement of a typical flame photograph taken with the 0.038" rod stabilizer located 2 inches from the chamber entrance. Upon this picture is indicated the locations where flame width measurements were taken, and the nomenclature employed to denote the various measurements. The measurements were obtained from the photographic negative by means of a pair of dividers, a metal scale calibrated to hundredths of an inch, and a paper scale used to measure the distance along the flame front, s .

Figures 42 through 50 are plots of flame width, W_4 , at a distance downstream of 4 inches, versus air-fuel ratio for rod

FIGURE 40 - TYPICAL SET OF FLAME PHOTOGRAPHS

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FIGURE 41
ENLARGEMENT OF TYPICAL FLAME
PHOTOGRAPH SHOWING SOME OF THE
LOCATIONS WHERE FLAME WIDTH
MEASUREMENTS ARE OBTAINED

FLAME STABILIZER:

0.038" DIA. ROD

2" FROM CHAM-
BER ENTRANCE

SCREEN:

3 MESH

0.063" WIRE
DIA.

FUEL: CITY GAS

$V_0 = 97.3$ FT./SEC.

$1/f = 9.07$ LBS/LB.

PHOTO NEGATIVE
NUMBER

FILM PACK
NUMBER

RUN NUMBER

FIGURE 42

FIGURE 43

FIGURE 44

FIGURE 45

FIGURE 46

FIGURE 47

FIGURE 48

FIGURE 49

FIGURE 50

stabilizers, located 9 inches from the combustion chamber entrance and using city gas as a fuel. Rod diameters of 0.498", 0.311", 0.188", 0.126", 0.094", 0.062", 0.038", 0.026", and 0.016", were used. Data for the same rod stabilizer obtained both with and without turbulence-generating screens at the chamber entrance are shown on the same plot. Figures 42 and 43 for the 0.498" and 0.311" rods include only data obtained with the 3 mesh 0.063" wire diameter screen at the chamber entrance. Figure 44 for the 0.188" rod includes data obtained with the 3 mesh 0.063" wire diameter screen, the 8 mesh 0.025" wire diameter screen and with no screen. Figures 45 through 50 all include data taken with no screen and with the 3 mesh 0.063" wire diameter screen in place.

In each of these figures a family of curves, each curve representing a different chamber entrance velocity, V_0 , is shown. Curves are shown for V_0 values of approximately 25, 50, 100, 230, and 330 feet per second, and the exact value of V_0 for each data point is indicated beside the point. It is noted that along any one V_0 curve the velocities at which the points were obtained increase slightly toward the lower values of air-fuel ratio. This is because in obtaining the data the air rate was set at a constant value and the fuel rate was gradually increased to obtain richer mixtures. This

increase in fuel rate, since the fuel is a gas occupying considerable volume, causes the overall chamber entrance velocity to increase. This difference in velocity from rich to lean is too small to affect materially the position of the V_0 curves, and is therefore not corrected for. Dotted curves are drawn through points obtained when a turbulence generating screen was in place, and solid curves are drawn either through points obtained when no screen was used, or through points obtained both with and without a screen when they fall on the same line.

The Small Effect of Approach Stream Turbulence on Flame Width

For the moment focus attention on Figure 44, which is fairly typical of the whole group of figures from 42 to 50 and which further is based on more data both with and without turbulence generating screens than are the other plots. The first conclusion obtained by examination of Figure 44 is that the presence or absence of turbulence in the gases approaching the flame front as determined by the presence or absence of a turbulence generating screen at the combustion chamber entrance has a negligible effect on the flame width. The results of a few simple calculations are helpful in fully appreciating this observation.

Figure 51 is a series of curves at different values of V_0

FIGURE 51

ACTUAL FLAME VELOCITY COMPARED WITH FLAME VELOCITIES
CALCULATED ASSUMING APPROACH STREAM TURBULENCE
TO BE ONLY FACTOR DISTURBING FLAME FRONT

of flame velocity, S_f , versus air-fuel ratio calculated using equation 38, $S_f = V_o Y_{tf}/s$, flame width values from Figure 44 put on a reduced basis by dividing by W_t ($= 3$ inches), the calculated density ratio information found in Figure 31, and the results of the stepwise calculations included in Figure 34 to obtain F entering with reduced values of W^* . Also included as dotted curves are the values of S_f that would be expected with no screen in place, and with the 3 mesh 0.063" wire diameter screen in place, assuming approach stream turbulence to be the only factor present to increase flame velocity. Average turbulence values along the 4 inch section of flame front above the stabilizer for this last calculation are estimated from Figure 25 to be 0.4 per cent (which is thought to be safely on the high side) with no screen and 2.3 per cent with the mesh 0.063" wire diameter screen, and equation 21 is assumed to apply**. The laminar flame velocity curve for mixtures of city gas and air from Figure 28 is also included

* A number of assumptions are made in obtaining Figure 34, the validity of which has already been discussed. The major assumption involved in using Figure 31 is that complete combustion takes place upon passage through the flame front. This assumption is of doubtful validity when applied to a turbulent flame front. The values of S_f calculated by the above method are, however, believed to be relatively good approximations probably falling within 10 to 20 per cent of the actual values.

** Equation 21, $\left[\frac{S_T}{S_L} = 1 + \left(\frac{u'}{2 S_L} \right)^2 \right]$, is thought to be more nearly applicable for this calculation than is equation 20, since the scale of the turbulence under consideration is larger than the flame front thickness. The use of this equation for the calculation of values of S_T must be considered only an approximation, however, for reasons previously pointed out. The value, 2, by which S_L appearing under the radical is multiplied, must be looked upon with some doubt.

for orientation purposes. This curve corresponds to the flame velocity for zero turbulence at the flame front. Many of the lower velocity curves calculated on the basis of the presence of approach stream turbulence only, fall too near the curve for laminar flame velocity to be shown separately.

Figure 52 presents the same information as that contained in Figure 51 plotted as S_f/V_0 versus air-fuel ratio. Figure 53 is a plot of the per cent isotropic turbulence necessary to produce the S_f values indicated in Figure 51. Equation 21 is again employed for calculation of these turbulence values, and laminar flame velocities employed for carrying out the calculations are obtained from Figure 28.

Figure 51 shows that values of S_f are in most cases considerably above those for no turbulence or those calculated on the basis that approach stream turbulence is the only factor present to increase flame velocity. The calculated value of S_f at an air-fuel ratio corresponding to stoichiometric (6.51 lbs/lb) and at a V_0 of 300 feet per second is approximately 135 feet per second compared with a laminar flame velocity at stoichiometric of about 1.6 feet per second. It is rather surprising to note that flame velocities calculated at a V_0 of 50 feet per second are greater than those obtained at either 100 or 200 feet per second, and are only exceeded^{ed} by the values of S_f at 300 feet per second.

FIGURE 52

ACTUAL S_f / V_0 COMPARED WITH S_f / V_0 ASSUMING
APPROACH STREAM TURBULENCE TO BE ONLY FACTOR
DISTURBING FLAME FRONT.

FIGURE 53

Figure 53 brings out the fact that disturbances must be present in the flame front acting to increase flame velocity equivalent to turbulence levels as high as 40 per cent to produce the values of S_f obtained in Figure 51, as compared with an average turbulence present in the approach stream of 2.3 per cent with the 3 mesh 0.063" wire diameter screen in place. This calculated equivalent per cent turbulence is seen to be greater at 25 and 50 feet per second near stoichiometric than at the higher velocities. At 230 and 300 feet per second the equivalent per cent turbulence has become almost constant with velocity at a value of about 8 per cent.

Upon studying Figures 51, 52, and 53 with Figure 44, it is concluded that the most likely reason for the negligible effect of average approach stream turbulences up to 2.3 per cent on the flame width is that another source of disturbance must be present which produces an effect on the flame front equivalent to that of very severe turbulence. The presence of this intense disturbance serves to mask almost completely the turbulence in the approach stream even at values of approach stream turbulence up to 2.3 per cent. It is the presence of this disturbance which accounts for the almost constant values of flame width obtained with increasing chamber entrance velocity and varying air-fuel ratio at velocities above 100 feet per second. Equation 21, of course, predicts a flame

velocity proportional to the root-mean-square fluctuating turbulent velocity, u' , at high values of u' . If per cent turbulence remains constant above some velocity, then u' is proportional to V_0 , S_f is thus proportional to V_0 , and flame width, W , which is a function of V_0/S_f , remains constant with increasing V_0 at any one distance downstream along the flame front.

The same result regarding the negligible effect of approach stream turbulence and the presence of some other very strong disturbance which is the controlling factor in determining flame width is obtained by examination of the whole set of data included in Figures 42 through 50 taken with rod stabilizers of varying diameter.

Karman Vortex Trail Behind Stabilizers Appears Not to be Present as Turbulence Source During Combustion

An unstreamlined object such as a rod placed in an isothermal stream at Reynolds numbers above about 30 sheds eddies alternately from one side and then the other in a regular fashion, and initially these eddies are spaced on either side about 5 rod diameters apart. This eddy street is known as a Karman vortex trail and rapidly degenerates into a field of random turbulence occupying the region downstream of

the rod*. The Reynolds numbers encountered during this investigation calculated on the basis of isothermal flow around the stabilizers range from about 150 to 100,000. Certainly, then, with no combustion taking place, a vortex trail is present behind the stabilizers.

In view of the fact that a blunt object such as a rod placed in an isothermal stream serves as a strong source of turbulence, it seems logical to look to the rod stabilizers themselves as the source of turbulence having the major influence on flame width. In the case of a rod placed in an isothermal stream, the field of turbulence at a given distance downstream from the rod is increased in intensity in a manner roughly proportional to rod diameter. It would be expected, then, that if turbulence generated by the rod stabilizer were the controlling factor, as stabilizer diameter was decreased to some very small value, the flame width, too, would greatly decrease.

To get a clear picture of the effect of stabilizer diameter on flame width Figures 54 through 58 have been prepared from the plots contained in Figures 42 through 50.

* For a detailed discussion of flow around rods and other blunt objects placed in an isothermal stream, and photographs showing the lines of flow around these objects, see Goldstein (18).

FIGURE 54

FIGURE 55

FIGURE 56

FIGURE 57

FIGURE 58

They contain all of the flame width curves at 25, 50, 100, 220 and 330 feet per second respectively, and allow easy comparison of similar flame width data obtained downstream of rod stabilizers of varying diameter.

By carefully studying these plots, it is concluded that at 25, 50, and 100 feet per second the stabilizer diameter has a negligible effect on flame width at 4 inches downstream from flame stabilizers with diameters ranging from 0.498 inches to 0.016 inches, except at very lean and very rich mixtures where the flame width increases somewhat with increasing stabilizer diameter. At 230 and 300 feet per second only a very slight effect of stabilizer diameter on flame width is noted.

Focusing attention on Figure 55, which presents all of the flame width data obtained at a V_0 near 50 feet per second with rod stabilizers of various diameters, it is observed that, although there is a spread in the flame width curves of about 0.25 inches through the range of air-fuel ratios from 4.5 to about 11, there is no systematic decrease in the height of the curves with diameter. The spread in the curves in this air-fuel ratio range is attributed to experimental error. Many factors probably contribute to producing variations in measured flame width from run to run. Among these may be mentioned small changes in city gas

composition and in moisture content of the air* from run to run, differences in the temperature of the gases entering the chamber from run to run (as much as 30^o C but generally much smaller), possible slight variations in flame width obtained at the same operating condition from picture to picture due to the random nature of the flame front fluctuations and the imperfect averaging obtained on exposure of the film, and the human error involved in performing the flame width measurements**.

The flame widths on the lean side at air-fuel ratios above about 11 shown in Figure 55 do, on the other hand, show a systematic increase with increasing stabilizer diameter. This systematic increase in flame width with stabilizer diameter is also present at very rich mixtures,

*The effect of changes in moisture content of the air is believed to be only one of dilution for the combustion of either city gas or propane, with any modification of the data due to changes in humidity being of the same order as would be found if the explosive mixture were diluted with any inert gas in amounts varying from about 0.3 to 3 per cent.

** The human error which enters in carrying out measurements of flame width is estimated to be about 0.02 to 0.06 inches depending on the difficulty of locating the exact position of the often diffuse flame front. The measurements were always taken from one outside edge of the flame front to the corresponding outside edge on the other side of the flame. These outside edges were taken as the outer extremity of the exposed region on the photographic negative. The tacit assumption is made, therefore, that the outer extremity of this exposed region is the outer flame boundary.

although the effect is not nearly so pronounced as on the lean side. Further discussion of this apparently anomolous behavior of the flame at very lean mixtures is given later.

Examination of Figures 54 and 56 showing flame widths at 25 and 100 feet per second, respectively, leads to the same result obtained from Figure 55. In Figures 57 and 58 showing flame widths at 230 and 330 feet per second, respectively, there is some indication that flame width is decreasing slightly with rod diameter, especially at 330 feet per second, but the effect is very small considering the range of rod diameters covered.

It is of course obvious that if stabilizer diameter continued to be increased above 0.498 inches, a diameter would finally be reached where flame width would increase with rod diameter at 4 inches downstream of the stabilizer measured along the flame front. This would be the case even if no eddies are shed from the rod and a permanent eddy region exists behind it (as is later shown to be the case). As rod diameter and thus the size of the eddy region increases, the place of flame width measurement becomes too near the eddy region for flow to have reestablished itself properly. This apparently has not yet occurred even in the case of the 0.498 inch rod stabilizer, but would be

expected to occur soon if stabilizer diameter were increased still further*.

The observation that flame width measured at a given distance (at least 8 rod diameters) along the flame front downstream of the rod stabilizer is generally independent of rod diameter over a range of diameters from 0.498 inches to 0.016 inches leads to the conclusion that eddies are not being shed from the rod stabilizers during combustion as is the case with rods placed in an isothermal stream. Considerable additional evidence that no classical Karman vortex trail is produced by the rod stabilizers during combustion will be presented shortly.

The Apparently Anomalous Behavior of the Flame Width Curves at Very Lean Mixtures

Now focus attention on the rather odd behavior of the flame width curves on the lean side. This anomalous behavior is especially well defined in Figures 42, 43, and 44 which are flame width curves for the three largest rod stabilizers.

* This effect is found with the larger rods by comparison of the flame width measurements at 2 inches downstream of stabilizers of various diameter. These measurements are included in the data sheets in Appendix E.

Referring to Figure 43, which presents flame width data obtained with the 0.311 inch rod and is thought to be typical, it is noted that at air-fuel ratios above 12 the flame width increases with increasing velocity, being greater at a V_0 of 100 feet per second than at 25 feet per second. This is just the opposite of the result obtained at air-fuel ratios nearer to stoichiometric where the flame width decreases in a regular fashion as V_0 becomes greater.

It is further noted by following the flame width curves from stoichiometric out toward the lean side that in the 100 and the 230 feet per second curves there is at some point a definite break in the trend of the curves toward smaller flame widths followed by a rather rapid increase in flame width and then a leveling off at this higher width. The break is observed to occur at an air-fuel ratio nearer to stoichiometric (occurs at about 10 lbs/lb) at a V_0 of 230 feet per second than at a V_0 of 100 feet per second (occurs at about 11.5 lbs/lb), and it is not shown to occur at all, even at very lean mixtures, at 50 or 25 feet per second. (The data points, however, are widely separated and it can not be said with absolute certainty that a break does not occur at least at 50 feet per second.) After the break has occurred and as the curve rises and flattens off, it crosses the curves of flame width at lower velocity which either

have not yet broken or do not break at all.

Observation of the flame when this break occurs shows that the very definite widening which takes place over a rather narrow air-fuel ratio range is accompanied by a change in the flame appearance, especially in the neighborhood of the stabilizer, that indicates the presence of severe turbulence. Interpretation of flame pictures to determine qualitatively the extent and nature of the turbulence present is later *attempted*.

The significance of these breaks in the flame width curves upon going toward leaner mixtures can be better appreciated by returning to Figure 51 and observing the flame velocity curve calculated at 100 feet per second from the flame width curve of the same velocity shown in Figure 44. This curve breaks in the same fashion just discussed. The curve shows that at the break going toward leaner mixtures the flame velocity increases and then levels off in the same manner as the flame width curve from which it was calculated. An explanation of this anomalous behavior of many of the flame width curves will be presented later, but certain tentative conclusions regarding this break, rise, and leveling off can be drawn at present.

At the break and rise in the curve of flame width, and

thus flame velocity, some new disturbing influence has appeared having the same effect as would the sudden addition of more turbulence. This new disturbance is equivalent to a higher per cent turbulence at velocities of the order of 200 feet per second than at lower velocities since the flame widths at these higher velocities are greater. It will further be noted by examination of all the figures from 42 to 50 that the break and rise in the curves, if it occurs at all, is generally less pronounced and more difficult to find with the smaller rods. Apparently, then, this disturbance acting to increase flame width at very lean mixtures is more intense if the stabilizer diameter is large. In other words, this type of disturbance found at lean mixtures, in contrast to the disturbing influence acting to increase flame velocity at other air-fuel ratios already discussed briefly, is more intense with larger stabilizer diameters and thus produces wider flames when the stabilizer diameter is large. It is the influence of this type of disturbance which accounts for the increase in flame width with stabilizer diameter at very lean mixtures which was previously noted for rods in Figures 54 through 58.

Flame Width Results and Conclusions Obtained With Rod Stabilizers are Corroborated with Other Flame Stabilizing Shapes

It appeared desirable to determine what effect changing

the shape of the flame stabilizer would have on the flame widths obtained. Runs with a series of five gutters were made and flame width measurements obtained in a manner similar to that previously discussed for the rod stabilizers.

Figures 59 through 63 are plots of flame width at a distance downstream of 4 inches versus air-fuel ratio for 30° closed-edge gutter stabilizers* with widths of 0.500", 0.250", 0.100", 0.050", and 0.025", respectively, located 9 inches from the chamber entrance with city gas again being employed as a fuel. The curves are plotted in the same manner previously described for rod stabilizers.

Examination of these plots for the closed-edge gutter series leads to the same conclusion regarding the effect of approach stream turbulence arrived at by studying the rod series plots. It is observed, however, that in Figures 61, 62, and 63, which include data taken both with and without a turbulence generating screen in place, an effect of approach stream turbulence in increasing flame widths, at least at the lower velocities, can almost always be definitely established, even though the effect is relatively

* The 30° closed edge gutter was chosen as a desirable shape for study because such a shape has often been used in constructing flame stabilizers for ram-jet combustion chambers. The 30° gutter might also be considered as a 2-dimensional cone. 30° cones have also been widely used with ram-jet stabilizers (1).

FIGURE 59

FIGURE 60

FIGURE 61

FIGURE 62

FIGURE 63

small. Such a statement cannot be made in the case of the rod data where sometimes, due undoubtedly to small internal inconsistencies, the introduction of approach stream turbulence even appears to decrease flame width (see Figures 46 and 49). This definite trend found with the gutter data is encouraging and speaks well for their internal consistency since it is obvious that at least some increase in flame width, however small, must be produced by introducing turbulence into the approach stream.

The internal consistency of the rod data would not be expected to be as good as that obtained with the gutters since the rod data were collected over a considerably longer period of time. Days sometimes lapsed between runs with and without the turbulence screen in place, and the city gas composition, air temperature, and humidity had an opportunity to change considerably from run to run. With the gutters, on the other hand, all the data were taken over a period of a few days, with runs with and without the turbulence generating screen in place generally being obtained on the same day. The gutter data, therefore, must be considered internally more consistent than those obtained with rods although less were collected.

Since the diameter of the rod stabilizers was seen to

have a negligible effect on flame width at most air-fuel ratios and chamber entrance velocities, it would probably be expected that a change in shape of the flame stabilizer would also have no effect on flame width.

Figures 64 through 68 have been prepared from Figures 59 through 63. They contain all of the flame width curves at 25, 50, 100, 230, and 340 feet per second, respectively, for the closed-edge gutters. The conclusion arrived at by studying similar plots for rod stabilizers presented in Figures 54 through 58 that flame width is in most instances unaffected by stabilizer diameter is corroborated by these data obtained with gutters, and the conclusion that during combustion no eddies shed from the stabilizers in a manner such that a Karman vortex trail is formed is further substantiated.

Comparison of Figures 64 through 68, obtained with gutter stabilizers, with plots at corresponding velocities presented in Figures 54 through 58 for rods shows that corresponding plots roughly superimpose on one another. A closer examination reveals, however, that the flame widths above the rods are, on the average, slightly larger than those obtained with gutters. This is observed to be especially true at very high air-fuel ratios. A tentative explanation is later advanced for this observation.

FIGURE 64

FIGURE 65

FIGURE 66

FIGURE 67

FIGURE 68

A small amount of flame width data was obtained with two other types of flame holder - 0.50 inch wide open edge gutters, and a 0.50 inch wide flat plate - which is directly comparable with some of the rod and closed-edge gutter data.

Figures 69a and 69b present flame width data taken using 0.50 inch wide open-edge gutters with an open inlet area to total downstream area of 1 to 25 and 1 to 100, respectively, obtained under the same conditions as for the 0.50 inch closed edge gutter.

Comparison of these figures with Figure 59, which presents flame *width* data for the 0.50 inch closed-edge gutter, reveals that the three plots almost superimpose. The conclusion can therefore be drawn that opening the gutter end as much as one twenty-fifth of the total blocked area to admit unburned gases into the eddy region has a negligible effect on the width of the stabilized flame*.

* It might be expected that the open-edge gutters would yield slightly wider flames than the closed-edge gutters since combustible gases not only burn at the two flame fronts extending downstream from the gutter edges, but also within the gutter itself (as is seen by examination of the flames obtained using the open-edge gutters stabilizers included in Appendix A). This latter amount of gases burning within the gutter is that which enters through the gutter open edge. The observation that flame width is not measurably changed by opening the gutter edge as much as one twenty-fifth of the total blocked area indicates that the amount of gases entering this opened edge is very small compared with the amount burning in the first 4 inches of flame front above the stabilizer. Otherwise an increased flame width would result.

FIGURE 69 (A)

FIGURE 69 (B)

Figure 70 presents flame width data obtained under the same conditions using a 0.50 inch wide flat plate with its surface oriented normal to the direction of gas flow. The general shapes of the flame width curves for the flat plate stabilizer are similar to those obtained with the other flame stabilizers.

A comparison of flame width data obtained with the 0.498 inch diameter rod, the 0.50 inch wide closed-edge gutter, the 0.50 inch wide open-edge gutter with a total area to open area of 25 to 1, and the 0.50 inch wide flat plate is made in Figures 71a through 71e which includes flame widths for these shapes at 25, 50, 100, 230, and 340 feet per second, respectively. On the basis of this rather scanty amount of data it can be concluded that the flame widths are roughly the same (at least within the limits of error previously seen to exist with the rod and gutter series data), except at very rich and very lean mixtures where the flame width appears to be largest with the flat plate and smallest with the two gutters, the rod falling in between in flame width. A tentative explanation is later advanced for this last observation.

FIGURE 70

FIGURE 71 (A)

FIGURE 71 (8)

FIGURE 71 (C)

FIGURE 71 (D)

FIGURE 71 (E)

Additional Evidence That No Eddies Are Shed From the Flame Stabilizers During Combustion

It was stated previously that when a rod or other blunt object is placed in an isothermal stream and the Reynolds number exceeds about 30 a trail of eddies is shed from the downstream side of the rod alternately from one side and then the other. The lines of flow in the vicinity of the rod at any instant might be represented as shown in Figure 72a (/8).

Referring to this figure, the boundary layer is seen to leave the rod on either side at about 80 degrees from its front dead center, this location being known as the separation point. Behind the rod two large eddies have formed, one of which has grown larger than the other and will, after some additional growth, shed from the rod and move downstream. The shedding of these eddies alternately from the two sides proceeds in a regular fashion and gives rise to an eddy street known as a Karman vortex trail which degenerates further downstream into a high intensity field of random turbulence.

If instantaneous static pressure measurements could be obtained along the streamline indicated as A in Figure 72a, this pressure would be found, at first before the influence of the rod is felt, to decline very gradually as the rod is approached, due to the pressure drop necessary

FIGURE 72 (A)
FLOW AROUND A ROD IN AN ISOTHERMAL
STREAM (REYNOLDS NO. > 30)

FIGURE 72 (B)
STATIC PRESSURE ALONG STREAMLINE A

to overcome friction and maintain flow in the duct. The pressure then declines rapidly near the rod and reaches its minimum value in the vicinity of the separation point.

After passing the rod, the pressure again rises almost to the level obtained before the influence of the rod was felt, and, after passing through a maximum, again gradually declines. A plot of such a static pressure distribution is shown in Figure 72b.

The forces which create the eddying flow behind the rod are now considered in the light of this plot of pressure distribution along streamline A. In the zone just downstream from the two eddies where the pressure is at its maximum a stagnation region exists where gases may move under the influence of a pressure drop either back toward the rod or further downstream. This stagnant region of maximum pressure may be thought of as the downstream extremity of the eddy region, since downstream of it the gases never flow back toward the rod as part of a recirculating eddy.

A gas parcel that starts back toward the rod from this stagnant region is rapidly accelerated under the influence of a pressure drop and soon reaches the rear of the rod. The parcel then proceeds toward a region of still

FIGURE 73 (A)
THE EFFECT OF COMBUSTION ON THE
STATIC PRESSURE ALONG STREAMLINE A

FIGURE 73 (B)
FLOW AROUND A ROD IN AN ISOTHERMAL
STREAM DURING COMBUSTION

lower pressure near the separation point. Upon reaching a position near this point, viscous forces acting between this parcel and the adjacent high velocity gases flowing past the rod cause the parcel to be dragged along downstream toward regions of higher pressure. The parcel soon begins to decelerate as it moves toward higher pressures, finally arriving with a very low velocity back near its starting point in the stagnant region of maximum pressure.

We have not, for the sake of simplicity, in the foregoing discussion taken into account the effect of the eddy shedding process on the location of the stagnant region of maximum pressure, the length of the eddy region, and the movement of a parcel around the eddy. It is of course realized that unsteady state conditions actually prevail when eddies are being shed, therefore in any discussion regarding length of the eddy region, the location of the stagnant region of maximum pressure, or the path of a parcel around an eddy while shedding is taking place, we are speaking only of mean conditions.

If in Figure 72a the Reynolds number were reduced to a value below 30, the two eddies on the downstream side of the rod would tighten down nearer the rod, thus reducing the length of the eddy region. These eddies, furthermore, would

become symmetrical and would no longer shed - a steady state condition then existing with no turbulence generation downstream of the rod (18).

The eddy region can be reduced in length in a way such that eddies no longer shed by a means other than reduction of the Reynolds number. If combustion is now allowed to take place with the flame stabilized on the rod shown in Figure 72a, the static pressure along streamline A as shown in Figure 72b will be considerably altered. Figure 73a shows the pressure curve without combustion from Figure 72b drawn as a dotted line. The pressure drop due to combustion is also indicated; and the sum of the two curves, which may be thought of as the pressure drop along streamline A with combustion taking place, is indicated as a solid line. It is at once noted that by addition of the pressure drop due to combustion to the previous plot the pressure maximum to the rear of the rod is moved considerably nearer to the rod. As has already been pointed out, this pressure maximum corresponds approximately to the furthest downstream extent of the eddy region.

The introduction of combustion, therefore, has reduced the length of the eddy region considerably just as does a reduction in Reynolds number below 30, thus very likely

accounting for the observation that eddy shedding does not take place from the stabilizers during combustion.

In the discussion accompanying Figure 3 reproduced from the work of Lewis and von Elbe (31) the reduction in the length of the eddy region to the rear of a blunt ended solid rod mounted axially in a burner tube due to combustion is noted. The foregoing discussion, which should be equally applicable to this case, is offered as an explanation of the reduction in eddy length during combustion observed by these authors.

Figure 73b shows the flow which is believed to exist in the vicinity of a rod stabilizer while combustion is proceeding. The eddies have tightened down on the rod and are now symmetrical. They no longer grow and shed, steady state conditions now prevailing with the rod plus eddy region only acting to disturb the flow in a manner very similar to that of a streamlined shape with the same cross section.

Some further experimental evidence that there is no eddy shedding from the stabilizers during combustion is now presented.

At velocities near 25 feet per second with the smaller

rod stabilizers the flame appears laminar to the eye just as does a Bunsen flame when the flow up the tube is not turbulent. A laminar flame is denoted when the blue reaction zone appears as a fine line instead of a diffuse zone as in the presence of turbulence. Because of the quenching effect of the glass sidewalls on the flame (later discussed) which causes the flame to curve inward at the walls, the pictures generally do not show this laminar appearance even when it is easily seen with the eye. On some occasions, however, when the flame has a laminar appearance the photograph also indicates the presence of a laminar flame.

Figure 74a is a picture obtained using a 0.038 inch in diameter rod stabilizer located 6 inches from the chamber entrance with no turbulence generating screen in place at a V_0 of 24.3 feet per second and an air-fuel ratio of 11.34 pounds per pound. The flame shown obviously has a laminar appearance. The reaction zone is seen as a narrow band which separates the as-yet unburned gases from those in the central portion of the chamber bounded by the two flame fronts and in which combustion is essentially completed*.

* The assumption has been made throughout this investigation that the relatively high intensity blue radiation emitted from the flame registering on the photographic negative denotes the presence of reaction. Regions from which no strong radiation is emitted are thus assumed either to have not yet reacted, or to have burned completely.

FIGURE 74 - EXAMPLE OF A LAMINAR AND A TURBULENT FLAME Laminar
FlameTurbulent
Flame

Flame Stabilizer: 0.038" dia.
rod 9" from chamber entrance

Screen: None

Fuel: City Gas

	<u>74 (a)</u>	<u>74 (b)</u>
V_o -	24.3 ft/sec	213.3 ft/sec
l/r -	11.34 lb/lb	9.70 lb/lb
S_f -	0.63 ft/sec	5.48 ft/sec
S_L -	0.44 ft/sec	0.79 ft/sec

FIGURE 75 - APPEARANCE OF FLAME ON SPARK ROD BEFORE AND AFTER STABILIZATION Stabilized on
Rod OnlyStabilized on
Rod and Flame Holder

Flame Stabilizer: 0.498" dia.
rod 9" from chamber entrance

Screen: 3 mesh; 0.063" wire dia.

Fuel: City Gas

Velocity - about 40 ft/sec.
Air-Fuel Ratio - lean

To the eye the reaction zone of the flame shown appeared even thinner than the photograph implies, but the slight inward curvature of the flame near the walls due to quenching gives the appearance of some added thickness. The flame velocity calculated in the manner previously described from a flame width measurement 4 inches downstream from the stabilizer along the flame front is found to be 0.63 feet per second while the measured laminar flame velocity at this air-fuel ratio is 0.49 feet per second. This is considered fair agreement in view of the many assumptions upon which calculation of the flame velocity is based, and testifies to the laminar nature of the flame shown.

The laminar nature of the flame pictured in Figure 74a is further emphasized by comparison with the extremely turbulent flame shown in Figure 74b obtained under the same conditions at a V_0 of 213.3 feet per second and an air-fuel ratio of 9.70 pounds per pound. In this case, the entire region downstream of the stabilizer, with the exception of the eddy region itself where only burned products are seen to be present, is filled with still reacting material testifying to the violent nature of the turbulence present. The calculated flame velocity for the first four inches of flame front is in this latter case 5.48 feet per second compared with an S_L of 0.79 feet per second.

The fact that laminar flames can be obtained at all behind rod stabilizers is potent evidence that no eddy shedding is taking place at least under the conditions at which these laminar flames exist.

Even more conclusive evidence that under certain conditions laminar flames essentially free from turbulence are obtained behind rod stabilizers is found in the shadow photographs taken at low velocity with no screen which are latter presented.

It has been observed in the presence of a laminar flame such as that shown in Figure 74a that if a small glass rod is inserted through one of the chamber probe holes and moved to a position such that its tip almost touches the flame, the flame front in the region above the rod is violently disturbed by the eddies emanating from the rod. After a moment, however, if the rod is held closely enough, the flame attaches itself to the rod which now acts as a second stabilizer. When this occurs the flame is no longer violently disturbed but again appears laminar. It is quite obvious that eddies ceased to shed from the rod when the flame attached itself.

Figures 75a and 75b show an experiment somewhat similar to that just described. In Figure 75a obtained at a V_0 of

about 40 feet per second and with a lean air-fuel mixture during ignition, a flame is seen stabilized on the spark ignition rod but not yet on the 0.498 inch rod stabilizer. The curvature of the flame front as the flow passes the rod is interesting to note. At this condition the flame about half an inch above the rod (but not yet attached) is observed to be violently turbulent. This condition persists for about 30 seconds. Finally, however, the flame manages to get a start in the eddy region behind the rod thus stabilizing itself as shown in Figure 75b. The flow now becomes smooth in the near vicinity of the rod thus indicating that eddies are no longer shedding.

The last bit of evidence that no eddy shedding proceeds during combustion is found due to the existence, and unusual nature, of residual flames. Under certain conditions occasionally with rod stabilizers, but much more often with gutters, as the fuel rate is gradually decreased to obtain a lean limit blow-out the flame ceases to propagate in the chamber except in a small region just above the stabilizer. This small flame, attached to the stabilizer, but failing to propagate through the main body of the mixture is called a residual flame. This type of flame, when observed at all, persisted over only a very narrow air-fuel ratio range.

In Figure 76 is shown an enlargement of a typical residual flame stabilized on a 0.25 inch closed edge gutter located 9 inches from the chamber entrance with a 3 mesh 0.063" wire diameter screen in place. V_0 is 95.8 feet per second and the air-fuel ratio is 13.58 pounds per pound. Other residual flame photographs are also included as Figures 77a through 77e.

It is observed that the residual flames have a laminar appearance, the reaction zones appearing as fine lines instead of diffuse regions. The appearance of these residual flames to the observer is also definitely laminar with the two "ears" seen at the top of the residual flame (as contrasted to the single tip of a Bunsen type flame) holding their positions in a very steady manner. It is obvious that no such steady residual flames could exist if eddies were shedding from the rod.

It was at first suggested that the top of the residual flame corresponded to the top of the eddy region to the rear of the stabilizers. That this is not the case, however, can be shown on two counts. The first is that the residual flame is too long even to correspond to the eddy region found behind rods when no combustion takes place. It is therefore far too long to correspond to the greatly shortened eddy region present during combustion. The second is the fact that

FIGURE 76ENLARGEMENT OF RESIDUAL FLAME

Stabilizer: 0.25" Closed Edge Gutter Located 9"
from Chamber Entrance.
Screen: 3 Mesh, 0.063" wire dia.
Fuel: City Gas
 V_o = 95.8 ft/sec.
 $1/f$ = 13.58 lbs./lb.

FIGURE 77 - RESIDUAL FLAMES

<u>Picture No.</u>	<u>Stabilizer</u>	<u>V₀</u>	<u>1/f</u>	<u>Flame Height</u>	<u>Height Stabilizer Width</u>
10-2-41	0.25" C.E. Gutter	95.8	13.58	1.48"	5.94
11-2-41	0.25" C.E. Gutter	95.8	13.58	1.24"	4.96
3-2-43	0.10" C.E. Gutter	45.9	15.66	1.36"	13.6
3-3-43	0.10" C.E. Gutter	174.0	11.56	1.28"	12.8
4-3-43	0.10" C.E. Gutter	224.4	10.62	1.40"	14.0
6-2-67	0.50" C.E. Gutter	212.3	11.39	1.76"	3.92
$\left(\frac{\text{Total Area}}{\text{Blocked Area}} = 100 \right)$					

- Note: (1) Apex of all stabilizers 9" from chamber entrance.
 (2) Residual flames sometimes observed with rods, but no photographs obtained.

(a)

(b)

(c)

(d)

(e)

the ratio of residual flame height to stabilizer width is far from being a constant as would be expected approximately if the residual flame corresponded to the eddy region. Values of flame height to stabilizer width for all of the residual flames shown in Figure 77 are given in the last column of the table at the top of Figure 77. The values range from 14 for the 0.10 inch closed edge gutter to 3.92 for the 0.05 inch open edged gutter. More nearly constant for the different stabilizers is the residual flame height. This quantity varies from 1.24 inches for the 0.25 inch closed edge gutter to 1.76 inches for the 0.50 inch open edge gutter. Visual observation revealed that the residual flames decrease in height as the mixture becomes leaner, the height of the flame, and in fact even its presence, being very sensitive to changes in air-fuel ratio.

It appears, then, that the two "ears" at the peak of the residual flame where it ceases to propagate are a short distance downstream of the stagnant region of maximum pressure. There the hot gases are rapidly increasing in velocity due to the accelerating action of a pressure drop and also to the viscous drag of the high velocity neighboring gases. This region where the flame quenches and ceases to propagate will be again discussed in a later part of this section devoted to stabilization.

The Generation of Eddies Due to Velocity Gradients Across the Flame Front - High Speed Movies and Shadow Photographs of the Flame.

Eddy shedding from the stabilizers during combustion has been ruled out as a source of turbulence. The presence of turbulence up to 2.3 per cent in the approach stream has been shown to have only a very small effect on flame width, this approach stream turbulence being almost completely masked by some considerably more intense disturbing influence. The search for this disturbing influence is, therefore, continued.

It is well known that if a velocity gradient exists across a surface of discontinuity between two ideal fluid streams this discontinuity surface is unstable, differential perturbations on the surface becoming finite, developing into eddies, and thus destroying the discontinuity through mixing of the two streams.

If, however, the two fluids are real and possess finite viscosities, the discontinuity surface is stable under certain conditions and unstable under others (26). For example, a jet of gas shooting out into stagnant air remains laminar at low exit velocities but becomes turbulent as velocity is increased. The criterion for stability in the case of a jet is the Reynolds number, DV/ν , where D is some linear

dimension of the jet cross section, V is the jet velocity, and ν the kinematic viscosity. For rectangular jets of smoke-filled air issuing into stagnant air the value of this Reynolds number at the first appearance of turbulence was found by Brown (3) to be about 100, where D was taken as the narrowest dimension of the rectangular jet.

The manner in which instability develops between two adjacent fluid streams of different velocity is demonstrated in Figure 78. Steps in the growth of a small disturbance moving on a surface of discontinuity into a large, well-developed eddy are shown. Under the proper conditions these eddies rapidly degenerate into a more random type of disturbance. It is to be noted that in order for instability to develop fully, other things being equal, the length of the discontinuity surface over which the velocity gradient acts, known as the "fetch", must be greater than some minimum.

Consideration of the flow through the combustion chamber in the presence of a stabilized flame shows that two regions exist where velocity gradients are generated at the flame front. Attention has already been called to the second of these regions in Figure 33. In this figure are shown the velocity profiles produced as a result of combustion, the initial velocity profile before any combustion takes place being flat. It is seen that the burned products with their

FIGURE 78-DEVELOPMENT OF AN EDDY ON A SURFACE
OF DISCONTINUITY BETWEEN TWO FLUIDS

greatly reduced density are more rapidly accelerated under the influence of pressure drop than the unburned gases, thus generating velocity gradients at the flame front which increase as the fraction burned increases. Further, these gradients are larger for the same fraction burned the greater the value of the density ratio of the burned to the unburned gases, R_ρ . It might be expected, then, that instability of the flame front due to generation of velocity gradients of this type would be most likely to occur where the fraction burned is highest, the air-fuel ratio is near stoichiometric (corresponding to high values of R_ρ), and the chamber entrance velocity is highest. Size of the stabilizer would not be expected, on the other hand, to influence materially the generation of this type of velocity gradient.

The first region where velocity gradients exist across the flame front is clearly shown in Figure 73b. This first region is formed between the unburned main stream and the relatively stagnant hot gases present for a few diameters downstream of the stabilizer. Maximum velocity gradients and thus a greater tendency toward instability would be expected in this first region as chamber entrance velocity increases. Low flame velocities, and low values of R_ρ

would tend to delay the acceleration of the burned gases up to stream velocity, increasing the fetch and thus the tendency toward instability of the region. Further with larger stabilizers this region is increased in size and thus might be expected to become unstable more readily and after so doing to generate a more intense disturbance.

A schematic diagram of the flow through the chamber showing the relative location of these two regions of high velocity gradient across the flame front where instability is most likely to occur is shown in Figure 79. It is noted that a region of low velocity gradient exists between these two regions of high gradient where the velocity of the burned gases increases to, and then surpasses, that of the unburned gases.

In order to study the effect on the flame of velocity gradients of the first type, a series of shadow photographs of flames stabilized on rods were obtained. These pictures are presented in Figures 80a through 80h. The speed of the spark employed as the point source of light was such that motion of the burning gases is essentially stopped and eddies and turbulence, when present, are clearly seen.

All of these pictures were obtained with the flame stabilizers located 7 inches from the chamber entrance,

SCHEMATIC DIAGRAM OF FLOW THROUGH THE CHAMBER SHOWING LOCATION OF REGIONS OF HIGH VELOCITY GRADIENT AT THE FLAME FRONT

FIGURE 79

SHADOW PHOTOGRAPHS

FLAMEHOLDER:

0.038" dia. rod
located 7" from
chamber entrance

SCREEN:

none

V ---- 24.3
1/f -- 12.57

V ---- 24.3
1/f -- 12.57

V ---- 24.6
1/f -- 11.10

V ---- 24.9
1/f -- 9.74

V ---- 49.7
1/f -- 11.84

V ---- 50.7
1/f -- 9.71

V ---- 99.6
1/f -- 10.97

SHADOW PHOTOGRAPHS

FLAMEHOLDER:

0.038" dia. rod
located 7" from
chamber entrance

SCREEN:

none

8-1-91

V ---- 101.2
1/f -- 9.52

9-1-91

V ---- 104.0
1/f -- 7.65

10-1-91

V ---- 106.8
1/f -- 6.34

11-1-91

V ---- 221.4
1/f -- 8.53

12-1-91

V ---- 227.3
1/f -- 6.79

1-2-91

V ---- 230.8
1/f -- 6.09

2-2-91

V ---- 310.1
1/f -- 6.65

SHADOW PHOTOGRAPHS

FLAMEHOLDER:

0.038" dia rod
located 7" from
chamber entrance

SCREEN:

8 mesh
0.025" wire dia.

V ---- 24.7
1/f -- 11.18

V ---- 25.0
1/f -- 9.82

V ---- 50.0
1/f -- 12.67

V ---- 52.3
1/f -- 7.80

V ---- 54.0
1/f -- 6.36

V ---- 98.5
1/f -- 10.60

V ---- 104.7
1/f -- 6.58

SHADOW PHOTOGRAPHS

FLAMEHOLDER:

0.038" dia. rod
located 7" from
chamber entrance

SCREEN:

3 mesh
0.063" wire dia.

V ---- 25.2
1/f -- 11.87

V ---- 51.2
1/f -- 9.35

V ---- 53.5
1/f -- 6.74

V ---- 100.3
1/f -- 9.78

V ---- 102.5
1/f -- 8.18

V ---- 105.8
1/f -- 6.48

SHADOW PHOTOGRAPHS

FLAMEHOLDER:

0.188" dia. rod
located 7" from
chamber entrance

SCREEN:

none

V ---- 24.3
1/f -- 12.56

V ---- 24.8
1/f -- 10.32

V ---- 48.9
1/f -- 11.90

V ---- 50.4
1/f -- 9.24

V ---- 50.4
1/f -- 9.24

V ---- 53.2
1/f -- 7.14

V ---- 99.1
1/f -- 11.21

SHADOW PHOTOGRAPHS

FLAMEHOLDER:

0.188" dia. rod
located 7" from
chamber entrance

SCREEN:

none

8-1-92

V ---- 101.1
1/f -- 9.47

9-1-92

V ---- 104.4
1/f -- 7.46

10-1-92

V ---- 107.3
1/f -- 6.21

11-1-92

V ---- 219.3
1/f -- 9.30

12-1-92

V ---- 226.2
1/f -- 7.05

1-2-92

V ---- 232.1
1/f -- 5.89

2-2-92

V ---- 334.7
1/f -- 8.12

SHADOW PHOTOGRAPHS

FLAMEHOLDER:

0.498" dia rod
located 7" from
chamber entrance

SCREEN:

none

3-1-93

V ---- 24.1
1/f -- 12.50

4-1-93

V ---- 24.1
1/f -- 12.50

5-1-93

V ---- 49.1
1/f -- 11.84

6-1-93

V ---- 50.2
1/f -- 9.63

7-1-93

V ---- 52.7
1/f -- 6.78

8-1-93

V ---- 99.8
1/f -- 9.35

9-1-93

V ---- 101.1
1/f -- 8.36

SHADOW PHOTOGRAPHS

FLAMEHOLDER:

0.498" dia rod
located 7" from
chamber entrance

SCREEN:

none

V ---- 102.9
1/f -- 7.27

V ---- 105.9
1/f -- 5.99

V ---- 215.6
1/f -- 9.91

V ---- 219.3
1/f -- 8.09

V ---- 224.7
1/f -- 6.65

V ---- 331.1
1/f -- 8.17

V ---- 331.5
1/f -- 8.98

pictures being obtained with the 0.038", 0.188" and 0.498" in diameter rod stabilizers. Orientation with regard to scale of the pictures is obtained by noting that the distance from the flame stabilizer center to the dark spot about an inch from the top of each picture (this spot is the shadow of holes in the glass side walls) is two inches. The pictures are, therefore, slightly larger than full scale. These pictures were obtained using Cambridge city gas as a fuel, but unfortunately the gas company was in the process of changing to a higher heating value fuel when they were obtained. The operators of the new high BTU gas units had begun to introduce some of this gas into the old city gas holders from which the M.I.T. area was still being supplied. The composition of the gas actually in the lines at any one time, therefore, was not known precisely*. Observation of the flame structure and comparison of a few of the blow-out limits with those previously obtained with city gas of known composition indicated that this gas had a lower laminar flame velocity than that of the old city gas employed during the major part of this investigation. Comparison of the shadow photographs with the other pictures obtained under

* The runs with the stabilizer located 2" and 6" from the duct entrance, 82 through 89, the shadow photograph runs, 90, 91, 92 and 93, and the high speed movies of the flame shadow, run 94, were the last runs made and were all performed with city gas of doubtful composition.

the same conditions of V_0 and air-fuel ratio must therefore be made only on a qualitative basis.

The small inset pictures in the lower right hand corner of each shadow photograph are two-fifths of a second time exposures of flames of the same length and burning under approximately the same conditions as those for the shadow photographs. These pictures were selected from the previously discussed set, it generally being possible to find a picture that corresponded closely to the conditions of each shadow photograph.

Referring now to Figure 80a let us examine these shadow photographs with regard to their interpretation. The thin veil of white which borders the flame on either side and observed to be slightly wider in the vicinity of the flame stabilizer is to be ignored since it is a secondary effect due to the diffraction outward of light passing through the outer edges of the flame. The flame front is recognized as the very narrow region where the color changes rapidly from light to dark. It may, for simplicity, be thought of as indicated by the fine white lines. The fine striations that run from left to right across all the pictures are due to imperfections in the polished Vycor glass side-walls.

In Figures 80a and 80b are presented shadow photographs obtained with the 0.038 inch rod stabilizer and with no turbulence generating screen in place. Picture 1-1-91, the first in the series, obtained at a V_0 of 24.3 feet per second and an air-fuel ratio of 12.57 pounds per pound shows that the first stages of eddy formation, the appearance of short protrusions at the flame front, have occurred. Their appearance first takes place about three-quarters of an inch up the flame front from the stabilizer. It is then noted that further development of the eddy apparently ceases, the protrusion growing out into the unburned gases due to combustion that proceeds at its surface, becoming fatter, and showing signs of dissipating near the top of the picture.

It might be concluded from this picture that the first region of high velocity gradients extends about three-quarters of an inch above the rod. The gradient is not sufficient with such a short fetch to fully generate developed eddies. Upon acceleration of the hot central gases due to combustion, the velocity gradient is wiped out about an inch above the stabilizer and the protrusions cease to develop further as they move on up the flame front. The picture does not extend high enough to show the second region of high velocity gradients. Photograph 2-1-91 obtained under the same conditions as that of 1-1-91 shows

approximately the same phenomenon observed in the first picture except that small protrusions are present slightly nearer to the stabilizer in this picture than in the first. Comparison of these two pictures indicates the degree of reproducibility obtained from picture to picture taken under the same conditions.

It would be expected in the light of the previous discussion that going to a richer mixture, thus increasing the laminar flame velocity, would decrease the likelihood of instability in the first region. Examination of 3-1-91 obtained at approximately the same velocity as 1-1-91 but at an air-fuel ratio of 11.10 pounds per pound shows a wider flame and no sign of eddy formation. Increasing the fuel rate still further at approximately the same velocity again results in a flame that is remarkably laminar as seen in 4-1-91.

If now the velocity is increased to near 50 feet per second the tendency toward instability in the first region of high velocity gradients is increased. Thus, it is seen in 5-1-91 at an air-fuel ratio of 11.84 pounds per pound that the flame is now extremely turbulent with fully developed eddies appearing about three-quarters of an inch above the stabilizer. Again by increasing the fuel rate,

thus bringing the air-fuel ratio down to 9.71 pounds per pound the velocity gradients are so diminished and the fetch so reduced by the more rapid acceleration of the hot central gases that eddies are observed from 6-1-91 no longer to form.

At a V_0 of 100 feet per second again with a very lean mixture in 7-1-91 severe turbulence is present as might be expected. As the mixture becomes richer in 8-1-91 the intensity of the turbulence diminishes, becoming almost entirely absent in 10-1-91.

Interpretation of the shadow photographs obtained at velocities above 100 feet per second is difficult since it appears that the eddies generated become smaller as velocity increases, with the flames showing a finer structure than at lower velocity. Further, it appears that the spark was not sufficiently fast to stop completely the motion at the higher velocities. 11-1-91 obtained at a V_0 of 221.4 feet per second and an air-fuel ratio of 8.53 pounds per pound shows the presence of extreme turbulence. 12-1-91 at approximately the same velocity but at a richer mixture is observed to be less turbulent with the turbulence beginning in a region slightly further above the stabilizer. This is also true of 1-2-91

at the same velocity but at a still richer mixture. 2-2-91 taken at a V_0 of 310.0 feet per second and an air-fuel ratio of 6.65 pounds per pound is violently turbulent with eddy generation beginning about half an inch above the stabilizer.

Figure 80c presents a set of pictures taken under the same conditions except that an 8 mesh 0.025" wire diameter turbulence generating screen was placed at the chamber entrance resulting in a calculated turbulence at the stabilizer of 1.70 per cent. The results previously obtained with no screen in place are corroborated by these pictures. Figure 80d presents a set of pictures obtained under the same conditions except that a 3 mesh 0.063" wire diameter screen was placed at the chamber entrance, resulting in a calculated turbulence of 3.35 per cent at the stabilizer. These pictures show nothing new regarding the generation of turbulence in the first region of high velocity gradients, but they are remarkable since they show so well the effect of turbulence in the approach stream. It is interesting to compare 4-2-91 obtained with a relatively high turbulence in the approach stream at a V_0 of 25.2 feet per second and an air-fuel ratio of 11.87 pounds per pound with 3-1-90 obtained under approximately the same conditions but with a lower turbulence in the approach stream, and with 3-1-91 also obtained at about the same conditions but with an extremely low level of turbulence

in the approach stream. The effect of approach stream turbulence is increased over that when the flame stabilizer is located 9" from the chamber entrance by moving the stabilizer two inches closer to the screen and thus into a region of higher turbulence intensities. Further, the effect of turbulence is probably accentuated by the slightly lower laminar flame velocities of this gas compared to that of the old city gas. Such an increased effect of turbulence at lowered values of S_L is predicted by equation 21. These three pictures at different levels of approach stream turbulence, and free from other disturbances, show the marked effect of this turbulence in wrinkling the flame front and can be considered a rough qualitative check on the measured and calculated turbulence measurements previously discussed especially in regard to the existence of a very low turbulence level in the chamber when no screen is in place.

In Figures 80e and 80f are presented a series of shadow photographs obtained under conditions similar to those for the photographs previously discussed with no screen at the combustion chamber entrance and using a 0.188 inch rod stabilizer. These pictures show approximately the same result obtained with the 0.038 inch rod. It is noted that the flame width often decreases at any one velocity as the mixture becomes richer, and eddies

are no longer generated. For example the turbulent flame of 7-1-92 at a V_0 of 99.1 feet per second and an air-fuel ratio of 11.21 pounds per pound is wider than flames at approximately the same velocity but with less turbulence present due to richening of the mixture as in 8-1-92, 9-1-92, and 10-1-92.

Comparison of the pictures obtained with the two different rod stabilizers shows no effect of rod diameter on the velocity and air-fuel ratio for first generation of eddies. A hint is found, however, that some effect might exist when 8-1-92, which appears almost ready to become turbulent near the top of the picture, is compared with 8-1-91 which shows relatively little sign of becoming turbulent. On the other hand, it is noted that the turbulent disturbance, when it once begins, behind the large stabilizer extends over a wider area with no apparent reduction in intensity per unit area, the total amount of energy in the form of turbulence thus being greater above the larger rods under otherwise similar conditions.

Figures 80g and 80h present shadow photographs obtained with a 0.498 inch rod stabilizer. The results here shown are roughly the same as previously found with the smaller rods. It is again found that the flames in

which turbulence is present are wider than those at approximately the same velocity but where richening the mixture has reduced the turbulence generation. This effect is especially evident with the larger rod. Excellent examples of this effect are found by comparison of 6-1-93 with 10-1-93 and 11-1-93. It is also found that the flame widths in the pictures obtained at values of V_0 above about 200 feet per second are relatively constant.

It is now observed that in 3-1-93 and 4-1-93, both taken at a V_0 of 24.1 feet per second and an air fuel ratio of 12.50 pounds per pound, eddies are reaching a higher degree of development than found with the smaller rods under approximately the same conditions. Thus, here is finally found an effect of rod diameter on the conditions of V_0 and air-fuel ratio for instability in the first region of high velocity gradients. Again by comparison of 6-1-93, in which eddies are being generated, with 4-1-92 and 6-1-91 both obtained at approximately the same V_0 and air-fuel ratio but with small stabilizers this effect of rod diameter is shown. The effect is small, however, not being previously detected by comparison of pictures with the 0.038 inch and 0.188 inch rod stabilizer.

Before leaving the shadow photographs attention is

called to the white regions along the central axis of the flames observed in the pictures obtained at high velocities with the 0.188 inch and 0.498 inch rod stabilizers. Thought also to be associated with this phenomenon is the distorted appearance of the rod stabilizers in these pictures. No satisfactory explanation of this phenomenon has yet been attained.

High speed movies taken at 1500 frames per second of the flame, its light emission being increased by the addition of finely divided sodium chloride particles, were obtained at two conditions both favorable to the generation of velocity gradients of the second type and unfavorable to generation of gradients of the first type.

Figure 81 showing 11 consecutive frames obtained at a V_0 of 44.1 feet per second and an air-fuel ratio of 7.09 pounds per pound with the 0.188 inch rod stabilizer located 9 inches from the chamber entrance and with an 8 mesh 0.025" wire diameter screen in place demonstrates quite well the formation of eddies due to the generation of velocity gradients of this second type. These eddies will henceforth be referred to as "regular eddies" distinguishing them from the eddies generated by instability of the flame front brought about by velocity gradients of the first

Figure 81

HIGH SPEED PHOTOGRAPHS

Flameholder--0.188" dia. Steel Rod located 9" Downstream of Tunnel Entrance and Screen
 Turbulence Generating Screen--8 mesh, 0.025" wire dia. Blocked area-0.36
 Pictures are enlargements of 11 consecutive frames of film taken at 1500 frames/sec.
 Combustion Chamber Entrance Velocity, $V_e = 44.1$ ft/sec.
 Air-Fuel Ratio, $W_a/W_f = 7.09$ lbs/lb (Fuel: Cambridge City Gas 6.51 lbs/lb=Stoichiometric)

type. These latter eddies observed in the shadow photographs which on the same flame front rotate in the opposite direction from the regular eddies are henceforth referred to as "reverse eddies".

Returning to Figure 81 it is observed that the flame, which appears to the eye very much like that shown in the two-fifths of a second exposure appearing in the lower right hand corner of the figure, is actually very ragged*. It is interesting to follow the formation of an eddy or eddy pair in this series of pictures.

Referring first to the two small ripples (one on either side of the flame) in the flame fronts indicated by the arrow, the ripples can be followed as they develop. Finally in the last three pictures a definite protrusion has formed on the left flame front which grows with time and hooks downward, this direction of rotation indicating that the high velocity fluid at the discontinuity surface is the central hot gas stream. Following the developing eddy pairs just above those indicated by the arrow the appearance of a small protrusion from the left flame front in picture 4 is observed. It hooks downward and grows, this rate of growth being considerably increased by combustion, as the eddy pair moves up through the chamber. In picture

* Flame width measurements and flame velocities calculated from them in the manner previously discussed are based on the furthest extension of the turbulent flame into the unburned gas, the widths measured and the flame velocities calculated thus being maximum values.

6 a protrusion has appeared on the right flame front which in later pictures also hooks downward and grows.

Upon considering carefully this series of consecutive high speed pictures the remarkable similarity of the flame under these conditions to a jet of fluid issuing into a slower moving fluid stream is observed. This similarity is even more apparent when the high speed movie reel itself run at 16 frames per second is seen.

Figure 82 is a plot of distance of the eddy pairs from the stabilizer versus time obtained from Figure 81, the time of obtaining the first picture being taken as zero. Four eddy pairs are followed, and their location with time indicated. The curve marked eddy pair No. 2 is that for the pair indicated by the arrow in Figure 81. It is observed that, as might be expected, the eddy pairs move more rapidly as their distance from the stabilizer increases. As dotted lines on the plot are indicated the eddy pair velocities versus distance from the stabilizer for the No. 1 and No. 2 eddy pairs. These latter curves were obtained by taking the slopes of the solid lines.

The remarkable regularity of development of the eddy pairs is noted from Figures 81 and 82. So regular appeared

FIGURE 82

MOVEMENT OF "EDDY PAIRS" OBSERVED FROM HIGH SPEED MOVIE ($V_0=44.1$; $1/f=7.09$ - Flame holder 0.188" dia. rod)

the eddy development that a stroboscope disc was *constructed in order to* view the flame under various conditions of V_0 and air-fuel ratio in the hope that the motion could be visually brought to rest. The regularity of the eddy movement, however, was not sufficient to allow a stationary flame to be seen through the stroboscope disc.*

Figure 83 shows 23 enlargements of consecutive frames from a high speed movie reel obtained in the same manner as the pictures shown in Figure 81 using the 0.126 inch rod stabilizer and with no screen at the chamber entrance. V_0 is 102.9 feet per second and the air-fuel ratio is 6.71 pounds per pound. It would be expected that increasing the approach gas velocity without a proportionate increase in laminar flame velocity would tend to move the second area of velocity gradients to a location above that for the previous pictures of Figure 81. Such apparently is the case, with the development of turbulence in the pictures shown in Figure 83 being considerably less than that found at the lower velocity. Increasing the chamber entrance velocity has also resulted in considerable loss of detail

* The stroboscope disc, however, was not employed to view the flame when "flutter" or "resonance" was proceeding. Under these conditions motion, at least of the flame front, if not of the developing eddies, is believed to be sufficiently periodic to be visually brought to rest with the stroboscopic disc. Flutter and resonance are later discussed.

Figure 83

HIGH SPEED PHOTOGRAPHS

Flameholder--0.126" dia. Steel Rod located 9" Downstream of Tunnel Entrance

Turbulence Generating Screen--None

Pictures are enlargements of 23 consecutive frames of film taken at 1500 frames/sec.

Combustion Chamber Entrance Velocity, $V_0 = 102.9$ ft./sec.

Air-Fuel Ratio, $w_a/w_f = 6.71$ lbs/lb (Fuel: Cambridge City Gas 6.51 lbs/lb=Stoichiometric)

in the flame, the motion being much further from being stopped in these pictures. The fact that considerable movement of the flame obviously takes place during every exposure suggests that any conclusions obtained from these pictures regarding the development of turbulence or the actual appearance of the flame must be treated with caution.

Small protrusions on the flame fronts appearing in the pictures of Figure 83 can sometimes be followed for as many as five frames and appear to be developing in a manner similar to the protrusions observed and followed in Figure 81. The state of development of the disturbances as they go out of sight at the top of the pictures does not appear to be nearly as advanced, however, as found in the previous set of pictures at lower velocity.

Mechanism of Flame Propagation Downstream of Stabilizers - General Discussion

The mechanism of propagation of flames stabilized on unstreamlined objects placed in a confined high velocity stream of homogeneously mixed combustible gases can now be pieced together and the resulting picture employed to explain the flame width curves already discussed.

It has been shown that the flame propagation velocity,

S_f is increased over the laminar flame velocity, S_L , by three different types of disturbance.

1. Generation of reverse eddies and turbulence due to velocity gradients across the flame front present in the region just downstream of the flame stabilizer.
2. Generation of regular eddies and turbulence due to velocity gradients across the flame front produced by the pressure drop resulting from the combustion process itself, this pressure drop causing the low density burned gases to accelerate more rapidly than the high density unburned gases.
3. The approach stream turbulence.

Conditions favorable to the appearance of the first type of disturbance it has been noted are factors that increase the difference between the main stream velocity and that of the relatively stagnant low velocity burned gases to the rear of the rod, and lengthen the distance over which this velocity difference exists known as the fetch. Thus, high values of V_0 increase the velocity difference, and low flame velocities and low values of R_0 tend to delay acceleration of the burned low velocity gases thereby increasing the fetch. Further with larger stabilizers this unstable region is increased both in width and in length*,

* The width of this region should be proportional to the stabilizer characteristic dimension. The length of the region, on the other hand, would be expected to increase only slightly with increasing stabilizer characteristic dimension.

not only the fetch thus being increased but also the overall dimensions of the potentially turbulent region.

An expression based on the foregoing conclusions can tentatively be written, the magnitude of which should be a criterion for the prediction of the degree of instability of the first region. This expression, which contains three dimensionless groups, may be written as follows*:

$$\left(\frac{V_{on}}{\nu}\right)^{a'} \left(\frac{V_o}{S_L}\right)^{b'} \left(\frac{1}{R_p - 1}\right)^{c'} \quad (42)$$

where n is the stabilizer characteristic dimension, and a' , b' and c' are positive-valued constants. An increasing tendency toward instability should be found as the value of the expression increases. Sufficient data for the evaluation of the exponents a' , b' , and c' are not at hand, nor can the expression itself be considered valid over all ranges of the parameters included. For example as R_p approaches unity a value is reached below which eddies shed from the stabilizer^{and} the expression is no longer applicable.

*This expression has no group containing a characteristic dimension of the duct. The stabilizer characteristic dimension n , is thus tacitly assumed always to be small compared with W_t , the chamber walls thus having a negligible effect on the appearance of instability in the first region. This is thought to be approximately the case under conditions encountered during this investigation, the maximum ratio of n to W_t employed being 0.167 with the 0.5 inch stabilizers.

It is possible, however, to estimate roughly the values of the exponents from information obtained from the shadow photographs and from theoretical considerations previously discussed in connection with the stepwise calculations. It was observed from the shadow photographs that the effect of stabilizer diameter on the appearance of instability in the first region was very small not even being noticeable in comparing the pictures with the 0.038 inch and the 0.188 inch rod stabilizers and only becoming evident when the stabilizer diameter was increased to 0.498 inches. a' must therefore be considerably less than unity, its value being estimated to be between 0.1 and 0.3.

The shadow photographs further revealed the considerable effect of increasing velocity on the appearance of instability which indicates that b' is rather high. In fact, if S_L and R_ϕ remain constant, doubling V_0 should approximately double the fetch since twice the length of flame front will now be necessary to burn the same fraction of the total explosive mixture and thus produce a corresponding velocity profile across the duct cross section. This reasoning suggests that b' might have a value near unity. The pressure drop per unit distance downstream from the stabilizer is approximately proportional to S_L and also to $(R_\phi - 1)$ as was observed in the discussion relating to the stepwise

calculations. If b' is unity, c' also must have approximately this same value. It is thus permissible to combine these last two groups using only the single exponent, b' , which is assigned the tentative value, unity. Expression 42, thus becomes:

$$\left(\frac{V_{on}}{V}\right)^{0.1 \text{ to } 0.3} \left[\frac{V_o}{S_L(R_e - 1)} \right] \quad (43)$$

Conditions favorable to the appearance of the second type of disturbance are those which increase the difference between the rapidly accelerating burned gases and the low velocity unburned gases, and increase the fetch. The width of the region would also be expected to have an effect. Thus, high values of R_e and V_o are favorable for its appearance, and the stabilizer dimensions do not directly affect its appearance. Conditions for its appearance become more favorable as the fraction burned, F , increases. The region of instability is further removed from the stabilizer, the higher the value of V_o/S_L . High values of V_o/S_L are favorable since the fetch tends to increase as this ratio becomes larger.

An expression based on these conclusions, the value of which should be a criterion for the prediction of the degree of instability of the second region, can be written

as follows:

$$\left(\frac{V_0 W t}{\nu}\right)^{a''} (F)^{b''} (R_e - 1)^{c''} \left(\frac{V_0}{S_L}\right)^{d''} \quad (44)$$

where a'' , b'' , c'' , and d'' are positive-valued constants. Again insufficient data are available for the evaluation of the exponents but on the basis of theoretical considerations their approximate values can be estimated. By comparing the flow in the second region of high velocity gradients with that of a jet of high velocity fluid issuing into a lower velocity fluid stream it would be expected that the Reynolds number would enter as the first power, the value of a'' thus being one. The pressure drop across the combustion zone is roughly proportional to F and to $(R_e - 1)$, the difference in velocity between the burned and unburned gases increasing with pressure drop. The exponents b'' and c'' are thus believed to have a value near one, the two being approximately equal in any case. It would be expected that the tendency toward instability, other things being equal, would be proportional to the fetch, which is in turn proportional to V_0/S_L . The exponent d'' would, therefore, also be expected to equal one. By substituting the value of one for the exponents, a'' , b'' , c'' and d'' in (44), the following expression is obtained:

$$\frac{V_0 W t}{\nu} (F) (R_p - 1) \left(\frac{V_0}{S_L} \right) \quad (45)$$

The third type of disturbance, turbulence in the approach stream, which is probably the least important from the standpoint of propagation under most conditions can be independently controlled by placing grids in the approach stream. Its effect would be expected to increase as the added disturbance becomes more intense, as the laminar flame velocity, S_L , decreases, and as V_0 is increased (assuming the per cent turbulence in the approach stream to remain constant) roughly in accord with equation 21.

The mutual effect produced by these three types of disturbance is not known but some interaction would certainly be expected to exist. For example, the presence of turbulence in the approach stream might be expected to accelerate the growth of eddies and generation of turbulence in the first region by producing indentations in the flame front which are themselves unstable due to the presence of a velocity gradient. In a similar manner the presence of turbulence generated in the first unstable region, as well as approach stream turbulence, would be expected to have a considerable effect in hastening the generation of turbulence in the second region of potential instability.

The explanation for the small effect of approach stream turbulence up to values of 2.3 per cent on flame width, W_4 , is now clear. (See Figures 42 through 50 for rods and Figures 59 through 63 for closed edge gutters). On the basis of the shadow photographs and the visual appearance of the flame, it is found that only at velocities below 50 feet per second, and then only for lean mixtures and with small flame stabilizers, do laminar flames appear when no approach stream turbulence is introduced. At all other times approach stream turbulence, when introduced, is augmented and effectively masked by the generation of eddies and turbulence in at least one of the two potentially unstable regions of high velocity gradient across the flame front.

The first region was found from the shadow photographs to be stable except at very lean and very rich mixtures and at high velocities. It would be expected that the appearance of this instability would not occur until even higher velocities and even leaner mixtures were reached with the city gas with the higher laminar flame velocity (used when obtaining the flame width curves).

The high speed movies indicated, however, that the second region, in which turbulence generation is independent of rod diameter, was unstable at the lower velocities

at air-fuel ratios not too far removed from stoichiometric, with the region of instability tending to move further from the stabilizer as velocity increased. It is this second type of disturbance which accounts for the extremely high effective per cent turbulence values at 25 and 50 feet per second in Figure 53, and it is the movement of this instability region higher up the chamber as V_0 increases which accounts for the reduction in effective per cent turbulence as V_0 increases above 50 feet per second.

The break, rise, and leveling off of the flame width curves in going toward leaner mixtures at 100 and 230 feet per second, discussed with special reference to Figure 43, can now also easily be explained. The break occurs upon the appearance of instability in the first region of high velocity gradients; the rise in the curves represent the increase in flame width produced as the eddy generation and turbulence increases; and the leveling off of the curves occur when the turbulence in this first zone of high gradients has become fully developed. The high velocity curves fall above those at low velocity at very lean mixtures because this first region is not turbulent at low velocities and only becomes partly so at slightly higher velocities, the turbulence apparently becoming fully developed and the

per cent turbulence thus remaining constant at about 200 feet per second. Above this velocity the flame widths of lean mixtures do not change with further increase in velocity.

Due to the resulting larger field of turbulence, turbulence generated in this first region of high gradients produces wider flames the larger the flame stabilizer. This explains why at very lean mixtures where flame spread is almost entirely dictated by the turbulence generated in the first region, an effect of stabilizer diameter on flame width is noted. The spread of the flame width curves at these very lean mixtures is further decreased at low velocities due to the complete absence of instability in the first region with small stabilizers and its presence with stabilizers of larger dimensions.

It was also noted that a slight effect of rod diameter on flame width was present even at air-fuel ratios near stoichiometric at velocities above 200 feet per second. Such an effect would certainly be expected from the shadow photographs which indicate the presence of instability of the first type at these velocities. Very likely both the first and second instability regions account for turbulence generation at these velocities, the first region increasing

slightly in importance at the same distance above the flame stabilizer as velocity is increased, the value of effective per cent turbulence becoming essentially constant at a value of about 8 per cent above 200 feet per second as previously noted from Figure 53.

It was further noted that at very lean mixtures the flame widths observed downstream of gutters are less than those for rods of the same linear dimension, and that the 0.50 inch flat plate produced flame widths at very lean mixtures greater than those found with rods. The explanation for this observation is suggested by reference to the data on drag for various simple shapes found in the literature (18).

It is found that a flat plate placed with its maximum dimension normal to the flow has a greater drag than a cylinder of the same characteristic dimension. No data for the drag of 30° gutters was found, but it is supposed that these gutters have a lower drag than do rods of the same characteristic dimension. The size, and probably the shape, of the eddy region to the rear of these blunt objects must be somewhat different if their drags are different, the eddy region probably increasing in size as drag increases. The flat plate would thus be expected to have an eddy region larger, and the gutter an eddy region smaller, than that of

the rod of the same characteristic dimension. This might also be predicted from consideration of the lines of flow around these objects.

Figure 84 is a plot of flame width versus rod diameter at an air-fuel ratio of 13 pounds per pound and a V_0 of 100 feet per second for the rods, closed edge gutters, and the flat plate. Points were obtained from the previously discussed flame width curves, extrapolation often being necessary to obtain a point. Only points obtainable by reasonable extrapolation and those appearing to represent a flame width in the presence of turbulence generated in the first region of high velocity gradients are included. Three curves one for each type of flame stabilizer are drawn. The multiplying factors which would put the gutter and flat plate widths on a rod diameter basis obtained from these curves are approximately 0.37 and 1.5, respectively. These two factors may be employed when flame width data is obtained with gutters or flat plates to determine the diameter of the rod with which the same flame widths can be expected. The factors should also be used when comparing values of n in expression 42 and 43 in order that a fair comparison can be made between the various shapes.

In the sub-section on stability limits later included these three flame holding shapes are again compared on the basis of stability.

FIGURE 84

EFFECT OF STABILIZER CHARACTERISTIC DIMENSION AND STABILIZER SHAPE ON FLAME WIDTH AT VERY LEAN MIXTURES

of rod diameter on flame width would be expected, therefore, to be noticeable at lower velocities and at richer mixtures than with city gas.

By examination of expression 45, it will be noted that with lower values of S_L the value of F at W_4 would be expected to decrease, thus moving the location of the second region of high velocity gradients a greater distance above the stabilizer and reducing the tendency toward instability in the region upstream where W_4 is measured. This reduced F should more than counter balance the effect of increasing V_o/S_L .

It would further be expected from equation 21 that the effect of turbulence in the approach stream up to values of 2.3 per cent would now have a somewhat greater effect on flame velocity due to the lowered value of S_L .

Referring now to Figures 85 through 88 flame width curves are presented for propane in the same manner as those earlier referred to for city gas obtained with 0.498", 0.188", 0.094" and 0.038" rod stabilizers located 9 inches from the chamber entrance. It is immediately observed that the curves look quite similar to those previously obtained for city gas except that the flame widths at 25 feet

FIGURE 85

FIGURE 86

FIGURE 87

FIGURE 88

per second now occupy approximately the same relative positions previously occupied by the flame width curves for city gas at 50 feet per second, and the 50 feet per second curves now occupy roughly the same position as that of the 100 feet per second curves for city gas.

Comparison of the curves at the same velocity for the different stabilizers both with and without screen can best be achieved by referring to Figures 89 through 93 which present the flame width curves at 25, 50, 100, 200 and 300 feet per second, respectively. It is noted that at 25 feet per second no effect of stabilizer diameter on flame width is discernable except at the very lean mixtures. At 50 feet per second and at higher velocities, however, a slight decrease in flame width with decreasing stabilizer^{diameter} is present, this slight effect thus appearing at a lower velocity with propane than with city gas as was expected.

The effect of approach stream turbulence is seen by examination of Figures 87 and 89. It is noted that this effect is quite appreciable, being even greater at 100 feet per second than would be expected on the basis of equation 21. An interesting phenomenon was observed which accounts for the exceptionally large effect of approach stream turbulence at 100 feet per second in Figure 87. It was noted

FIGURE 89

FIGURE 90

FIGURE 91

FIGURE 92

FIGURE 93

that no turbulence appeared in the first region of high gradients when approach stream turbulence was absent. The region became very turbulent, however, at 100 feet per second near stoichiometric when approach stream turbulence was added. Examination of the pictures from which these flame width data were obtained, clearly shows the difference in the appearance of the flame near the stabilizer for the two cases, corroborating the visual observations. This absence of turbulence in the first region and its initiation by the introduction of approach stream turbulence is very likely an effect similar to the lowering of the critical Reynolds number of spheres and rods in wind tunnels due to the presence of turbulence (18). This effect was visually observed in only this one case, but it very likely occurred unnoticed in other instances. Its observation definitely proves that there is, at least under certain conditions, an effect of approach stream turbulence on the appearance of instability in the first region of high velocity gradients.

In a general way it can be said that the propane flame width curves taken alone corroborate the conclusions reached on the basis of the previously discussed data obtained with city gas.

It is desirable to plot the data obtained with propane and with city gas on a comparable basis for purposes of correlation. Examination of expressions 43 and 45, however, discourage any correlation on the basis of complete dimensional similarity. Two possible methods of correlation, both imperfect, present themselves. The first is to attempt a correlation on the basis of similar $(Re - 1)$ and V_o/S_f . By comparison of the data on the basis of O_g , the values of $(Re - 1)$ for propane and city gas are roughly the same. By putting the V_o for propane on a city gas basis by means of the following expression,

$$V_o(\text{city gas basis}) = V_o(\text{propane}) \frac{S_L(\text{city gas})}{S_L(\text{propane})}$$

and using this corrected velocity as that of the propane points, the requirement of similarity of V_o/S_L is satisfied. By using the same chamber of width W_t , and comparing data obtained with rod stabilizers of similar diameter, all the parameters are comparable except the Reynolds number terms, $V_o n/\gamma$, and $V_o W_t/\gamma$. It would be expected, however, that in most instances fair agreement between the propane and city gas data could be obtained on this basis. In fact, the only time agreement would not be expected is when regions unstable with propane had not become turbulent while the

comparable region in the city gas flame, due to the higher Reynolds number terms, had done so.

Figures 94 through 97 are plots prepared in the manner described in the foregoing discussion for comparison of the propane and city gas data on an almost similar basis. The solid lines are flame width curves obtained with city gas, and the plotted points are the data obtained with propane. The velocity indicated beside each point is the propane V_0 put on a city gas basis. The correlation is reasonably satisfactory. It is noted, however, that in many cases the propane points fall slightly below the corresponding curves for city gas. As already pointed out this was expected since the Reynolds number of the flow in the case of the propane data is in every case lower than that for the comparable data obtained with city gas, less turbulence and narrower propane flames thus resulting.

The second method by means of which the propane and city gas flame width data can be compared is at the same values of the Reynolds number terms and the same V_0/S_L , but with $(R_p - 1)$ not the same.

Plots comparing the data on this basis are presented in Figures 98 through 101. The solid lines represent the

FIGURE 94

COMPARISON OF PROPANE FLAME WIDTHS AT VALUES OF $V_0 \left[\frac{S_L(\text{city gas})}{S_L(\text{propane})} \right]$ WITH CITY GAS
 FLAME WIDTH CURVES AT DIFFERENT VALUES OF V_0 FOR 0.498" ROD STABILIZER

FIGURE 95

COMPARISON OF PROPANE FLAME WIDTHS AT VALUES OF $V_0 \left[\frac{S_L(\text{city gas})}{S_L(\text{propane})} \right]$ WITH CITY GAS FLAME WIDTH CURVES AT DIFFERENT VALUES OF V_0 FOR 0.188" ROD STABILIZER

FIGURE 96

COMPARISON OF PROPANE FLAME WIDTHS AT VALUES OF $V_0 \left[\frac{S_L(\text{city gas})}{S_L(\text{propane})} \right]$ WITH CITY GAS FLAME WIDTH CURVES AT DIFFERENT VALUES OF V_0 FOR 0.094" ROD STABILIZER

FIGURE 97

COMPARISON OF PROPANE FLAME WIDTHS AT VALUES OF $V_0 \left[\frac{S_L(\text{city gas})}{S_L(\text{propane})} \right]$ WITH CITY GAS FLAME WIDTH
CURVES AT DIFFERENT VALUES OF V_0 FOR 0.038" ROD STABILIZER

FIGURE 98

COMPARISON OF PROPANE FLAME WIDTHS WITH THOSE OF CITY GAS AT SIMILAR VALUES OF V_0/S_L AND REYNOLDS NUMBER FOR DIFFERENT VALUES OF V_0 FOR 0.498" ROD STABILIZER

FIGURE 99

COMPARISON OF PROPANE FLAME WIDTHS WITH THOSE OF CITY GAS AT SIMILAR VALUES OF V_0/S_L AND REYNOLDS NUMBER FOR DIFFERENT VALUES OF V_0 FOR 0.188" ROD STABILIZER

COMPARISON OF PROPANE FLAME WIDTHS WITH THOSE OF CITY GAS AT SIMILAR VALUES OF V_0/S_L AND REYNOLDS NUMBER FOR DIFFERENT VALUES OF V_0 FOR 0.094" ROD STABILIZER

FIGURE 101
COMPARISON OF PROPANE FLAME WIDTHS WITH THOSE OF CITY GAS
AT SIMILAR VALUES OF $\frac{V_0}{S_L}$ AND REYNOLDS NUMBER FOR
DIFFERENT VALUES OF V_0 FOR 0.038" ROD STABILIZER

data for city gas and the plotted points are the propane flame width data, the values of V_0 being entered beside each point. The position along the O_g axis was obtained from the curves of laminar flame velocity of propane and city gas versus O_g presented in Figure 28b by entering with the value of O_g for a propane flame width and determining the corresponding value of O_g for city gas where the value of S_L is the same. The propane flame widths plotted against these corresponding values of O_g for city gas are the data points found in the figures.

The correlation is found to be reasonably satisfactory on the lean side, the slightly smaller values of $(R_\phi - 1)$ for the propane data on this basis not causing any appreciable discrepancy. No comparison can be obtained at air-fuel ratios near stoichiometric because of the lower values of S_L for propane which make them only comparable with fairly lean or fairly rich mixtures of city gas and air on this basis. On the rich side the propane points fall at values of O_g which are very low, the city gas data not extending this far on the rich side. Part of this shift of the propane data to the rich side may be due, not to any failure in the method of correlation but to the use of inaccurate values of S_L at very rich mixtures obtained by the Bunsen cone method. Measured

values of S_L for city gas above the actual values at very rich mixtures would account for this discrepancy and is thought to be the source of error*.

The Effect of Varying the Chamber Width, W_t - Multiple Rod Stabilizers - Maximum and Minimum Flame Velocities - Completion of Combustion.

If, instead of placing a single rod stabilizer in the center of the duct, the duct is divided into 2, 4 or 8 smaller chambers of equal width and a stabilizer placed at the center of each of these, data could be obtained showing the effect of chamber width, W_t , on flame width. Flame width data have been obtained with 2, 4 and 8 rod flame stabilizers 0.038 inches in diameter so spaced across the chamber cross section that the actual division of the chamber into 2, 4 and 8 smaller chambers of equal width was simulated.

Figure 102 is an enlargement of a photograph of the flames attached to the 4 rod stabilizer located 9 inches from the chamber entrance with the 3 mesh 0.063" wire diameter screen in place at a V_0 of 26.2 feet per second and an air-fuel ratio of 7.94 pounds per pound. Indicated on the picture are the locations at which various flame width and flame length measurements are obtained with the

* See Appendix A for a discussion of errors involved in using the Bunsen cone method for obtaining values of S_L

Figure. 102

FLAME STABILIZED ON 4 ROD STABILIZER

symbols representing these measurements. The entire series of multiple rod flame pictures is included in Appendix A.

Comparison of flame width measurements obtained in chambers of varying width should be made on a reduced basis as indicated by the previously discussed stepwise calculations. Thus the distance downstream from the stabilizer measured along the flame front at which W is obtained should be measured in chamber widths, and W itself should be obtained in units of chamber width. On a reduced basis W_4 obtained downstream of a single stabilizer located in the 3 inch wide chamber becomes $W_r-1.33$. Flame width measurements of flames holding on the multiple rod stabilizers at intervals of two-thirds of a chamber width are included with the data for the multiple rod runs in Appendix C.

Comparison of the flame widths at $W_r-1.33$ for the single rod (0.038" diameter) and the 2, 4, and 8 rod stabilizers is shown in Figure 103. Examination of the curves at the various velocities shows that excellent correlation is obtained at 100 and 230 feet per second but that at 25 and 50 feet per second the points scatter somewhat especially near stoichiometric.

Returning to expressions 43 and 45, it is observed

FIGURE 103

CORRELATION OF FLAME WIDTH ON A REDUCED BASIS, $W_{r-2.67}$, FOR DIFFERENT
SIMULATED CHAMBER WIDTHS (MULTIPLE ROD FLAME STABILIZERS)

that correlation on the basis of reduced flame widths from the standpoint of dimensional similarity is satisfactory as far as expression 43 governing instability of the first region is concerned, but it is not completely satisfactory from the standpoint of expression 45 governing instability of the second region. In this latter expression W_t appears in the Reynolds number group, this group thus decreasing as W_t decreases. It would be expected, therefore, that generation of turbulence in the first region would proceed in the same manner as chamber width varied. On the other hand, the generation of turbulence in the second region would be expected to decrease as W_t decreases. This reasoning would explain the observation already noted from Figure 103. Where turbulence in the second region of instability controls the flame width, as at 25 and 50 feet per second near stoichiometric, it would be expected that turbulence would be less and the flames narrower with smaller chamber widths due to the decreased Reynolds number for the second region. On the other hand, excellent correlation should, and does, result where turbulence generated in the first region is the major factor determining the flame width*.

* The effect of interaction of the flames attached to the multiple rods on one another is not known, but is thought to be negligible. If such an effect did exist it would be opposed to the desired result of simulation of flames stabilized in chambers of smaller width.

Referring again to Figure 102 it is noted that the junction between the flame fronts at the mathematical boundaries which represent the smaller chamber walls is clearly seen. If the total length of flame front between the stabilizer and this flame front junction, $s_t(\min)$, is measured and V_0 and Y_t are also determined, by means of equation 38 in which F is in this case one*, a maximum flame velocity, $s_f(\max)$, is easily obtained. In many of the multiple rod pictures the flame fronts did meet and measurements of $s_t(\min)$ were obtained. Referring not to Table I, all measurements of $s_t(\min)$ made from the multiple flame stabilizer pictures were tabulated on column (5) with the conditions at which the pictures were obtained also included in the table. In column (6) is recorded the values of $s_f(\max)$ calculated from these flame lengths.

It is noted that these values of flame velocity are actually values averaged over the entire length of flame front. These values are in general slightly larger than the flame velocities previously obtained for the first four inches of flame front downstream of the stabilizer obtained

* No use of the stepwise calculations for a determination of F is here necessary, the flame velocities thus obtained not being dependent on any of the assumptions employed in making these calculations.

TABLE I

Flame Velocities Calculated from Multiple Rod StabilizerFlame Length Measurements on Basis of Material Balance

$(S_f = \frac{V_o Y_t}{s_t})$ 2 rods: $W_t = 1.5''$; $Y_t = 0.75''$ 4 rods: $W_t = 0.75''$; $Y_t = 0.375''$ 8 rods: $W_t = 0.375''$; $Y_t = 0.1875''$													
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Multiplier Rod Flame Stabilizer 9" From Duct Entrance	Picture Number	V_o ft. sec	$1/f$ lbs. lb.	$s_t(\min)$ in.	$S_f(\max)$ ft. sec.	$\frac{S_f(\max)}{V_o}$	$s_t(\max)$ in.	$S_f(\min)$ ft. sec	$\frac{S_f(\min)}{V_o}$	S_L ft. sec	$\frac{s_t(\min)}{W_t}$	$\frac{s_t(\max)}{W_t}$	Remarks
2 rod	11-1-71	25.8	11.17	5.6	3.46	.134	- -	- -	- -	0.48	3.57	- -	- -
2 rod	12-1-71	27.0	7.80	2.88	7.03	.260	- -	- -	- -	1.18	1.92	- -	- -
2 rod	3-2-71	51.8	8.64	5.52	7.04	.136	- -	- -	- -	0.92	3.68	- -	- -
2 rod	4-2-71	53.3	6.95	4.20	9.52	.179	- -	- -	- -	1.52	2.80	- -	- -
2 rod	5-2-71	55.2	5.66	4.08	10.15	.184	- -	- -	- -	1.58	2.72	- -	- -
4 rod	3-1-72	24.6	14.25	5.64	1.64	.067	- -	- -	- -	0.23	7.52	- -	- -
4 rod	4-1-72	25.3	10.56	3.64	2.61	.103	- -	- -	- -	0.55	4.85	- -	- -
4 rod	5-1-72	26.2	7.94	2.80	3.51	.134	6.44	1.53	.058	1.12	3.73	8.58	- -
4 rod	8-1-72	27.4	6.02	2.52	4.08	.149	6.40	1.61	.059	1.61	3.36	8.53	- -
4 rod	9-1-72	48.7	13.45	6.60	2.77	.057	- -	- -	- -	0.27	8.80	- -	- -
4 rod	10-1-72	49.9	10.35	5.82	3.52	.071	- -	- -	- -	0.58	7.09	- -	- -
4 rod	11-1-72	51.3	8.14	4.00	4.81	.094	- -	- -	- -	1.05	5.33	- -	Sharp resonance
4 rod	12-1-72	52.9	6.58	2.88	6.89	.130	- -	- -	- -	1.59	3.84	- -	Resonance
4 rod	3-2-72	96.7	11.11	6.04	6.00	.062	- -	- -	- -	0.49	8.05	- -	- -
4 rod	4-2-72	98.3	8.58	5.92	6.23	.063	- -	- -	- -	0.94	7.89	- -	- -
4 rod	5-2-72	100.3	7.43	4.08	9.22	.092	- -	- -	- -	1.35	5.44	- -	- -
4 rod	6-2-72	104.6	5.83	4.16	9.43	.090	- -	- -	- -	1.60	5.55	- -	- -
4 rod	7-2-72	168.3	8.17	4.72	13.37	.079	- -	- -	- -	1.05	6.29	- -	- -

TABLE I (Continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Multiplier rod Flame Stabilizer 9" From Duct Entrance	Picture Number	V_o ft. sec	$1/f$ lbs. lb.	$s_{t(min)}$ in.	$S_{f(max)}$ ft. sec.	$S_{f(max)}$ $\frac{S_{f(max)}}{V_o}$	$s_{t(max)}$ in.	$S_{f(min)}$ ft. sec.	$S_{f(min)}$ $\frac{S_{f(min)}}{V_o}$	S_L ft. sec.	$\frac{s_{t(min)}}{W_t}$	$\frac{s_{t(max)}}{W_t}$	Remarks
8 rod	8-1-73	24.5	11.03	3.36	1.37	.0563	5.52	0.83	.034	0.50	8.96	14.72	- -
8 rod	9-1-73	24.9	9.42	2.64	1.77	.071	5.48	0.85	.034	0.75	7.04	14.61	Slight resonance
8 rod	11-1-73	49.6	11.14	3.68	2.53	.051	- -	- -	- -	0.48	9.81	- -	- -
8 rod	12-1-73	50.8	8.97	2.80	3.40	.067	5.56	1.71	.034	0.83	7.47	14.83	Some resonance
8 rod	4-2-73	97.4	9.80	3.40	5.35	.055	- -	- -	- -	0.67	9.07	- -	- -

by means of the stepwise calculations shown in Figure 51. It is thus indicated that S_f generally increases as distance from the stabilizer increases; an observation which would have been easily predictable since instability of the second region increases progressively downstream from the stabilizer as F increases as shown by expression 45.

In Figure 102, it is observed that combustion is not complete when the flame first reaches the wall, the burning process continuing for a considerable distance downstream of this point. In a few pictures, Figure 102 being one of these, where V_0 was rather low and the mixture near stoichiometric, combustion completed itself in the chamber as indicated. It is possible in these cases to obtain another flame front length, $St(max)$, which is the distance measured along the flame front from the stabilizer to the point farthest downstream where reaction is still proceeding. Using this considerably longer flame length a minimum flame velocity, $S_f(min)$, can be calculated. In column (8) of Table I are tabulated the only measured values of $St(max)$ obtainable from the multiple rod pictures. Reaction was not completed below the top of the chamber in the other pictures, therefore, no $St(max)$ measurement could be obtained. In column (9) are found the minimum flame velocities calculated on the basis of the flame length measurements of column (8).

It is observed that these flame velocities for complete combustion are considerably less than the previously obtained maximum velocities, being roughly one-half these values. Comparison of the $S_f(\min)$ values with values of S_L found in column (11) shows remarkable agreement of the first four values. These first four values, however, were all obtained at a V_0 of about 25 feet per second. The fifth value of $S_f(\min)$ obtained at a V_0 of 50.8 feet per second is 1.71 feet per second which compares with an S_L of 0.83 feet per second.

By dividing the minimum and maximum measured flame lengths by W_t , approximate values of the chamber length to width ratio for the flame to reach the wall and for complete combustion, respectively, are obtained. These values are found in columns (11) and (12). Values of $(s_t(\min))/W_t$ as high as 9.81 are found and higher values would have been obtained if the chamber had been longer. Values of $(s_t(\max))/W_t$, which is approximately equal to the chamber length to width ratio for complete combustion, were obtained as high as 14.83, these values being in every case roughly twice that required for the flame to reach the wall. Considerably higher values of this ratio would have been obtained if the chamber had been longer

and measurements could have been obtained at distances further from the stabilizers.

In columns (7) and (10) of Table I are tabulated the values of $(S_{f(\min)})/(V_o)$ and $(S_{f(\max)})/(V_o)$, respectively. It has already been seen from Figure 103 that correlation of the W_r -1.33 flame width measurements at 25 and 50 feet per second was rather poor due, it is believed, to a lower Reynolds number in the second region of instability with smaller W_t . For the same reason, good correlation cannot be expected if the quantities in columns (7) and (10) are plotted versus air-fuel ratio. Figure 104 is such a plot and, as expected, scattering of the low velocity data for the different stabilizers is found, especially at 25 feet per second. At 100 feet per second, however, the correlation becomes reasonably good. Also clearly pointed out in this plot is the large difference between $(S_{f(\max)})/(V_o)$ based on the outer extremity of the flame, and $(S_{f(\min)})/V_o$ for complete combustion.

Effect of Very High Intensity Approach Stream Turbulence on Flame Width and Flame Velocity

It was earlier observed that the effect of approach stream turbulence intensities up to 2.3 per cent on flame

FIGURE 104

OVERALL VALUES OF S_f/V_0 vs. $1/f$ FOR MULTIPLE ROD STABILIZERS SHOWING POOR CORRELATION AT LOW VELOCITY BECOMING BETTER AT V_0 OF 100 FT./SEC.

width was rather small because disturbances of considerably higher intensity generated at the flame front itself tended to mask this lower intensity turbulence. It would be supposed, however, that if the approach stream turbulence were raised to a level comparable to that generated at the flame front a considerable effect would be observed.

In order to secure high turbulence levels in the approach gases just before entry into the flame front, the 0.038 inch rod stabilizer was mounted only 2 inches from the chamber entrance and runs were made with three different screens and with no screen at the chamber entrance. Moving closer to the screens made possible considerably higher levels of approach stream turbulence along the first four inches of flame front downstream of the stabilizer. The average turbulence level along this first four inches for these runs is estimated from Figure 25 to be 0.4 per cent with no screen, 1.25 per cent with the 55 mesh 0.007" wire diameter screen, and 6.5 per cent with the 3 mesh 0.063" wire diameter screen. These four runs, 82, 83, 84 and 85 with the stabilizer located 2 inches from the chamber entrance were made after the composition of the city gas had become somewhat questionable for reasons previously discussed. The runs should, however, be internally consistent since they were all obtained within a few hours of one another.

Presented in Figures 105, 106, and 107 are the flame width data at 25, 50 and 100 feet per second, respectively, obtained during the course of the four runs.

At all three velocities the flame is widened about 75 per cent by approach stream turbulence of 6.5 per cent. Only about a 10 per cent widening is produced by 2.80 per cent turbulence, and no noticeable widening over that observed with no screen is obtained with 1.25 per cent approach stream turbulence. The turbulence produced by the 3 mesh 0.063" wire diameter screen is for the most part nonisotropic, the part of the flame nearest the chamber being only about 32 wire diameters from the screen. Approximately 80 wire diameters, equivalent in this case to 5.04 inches is required to obtain isotropy (15). The effect of this lack of isotropy on the flame width results of Figures 105, 106 and 107 is not known.

In Table II is presented the results of calculations based on points taken from the smoothed curves of Figures 105, 106 and 107. Flame velocities calculated by means of the stepwise method from the flame width curves are tabulated in columns (4) and (9) with no screen and with the 3 mesh 0.063" wire diameter screen, respectively. Effective per

FIGURE 105
EFFECT OF EXTREME TURBULENCE ON FLAME
WIDTH AT A V_0 OF 25 FT./SEC.

FIGURE 106
EFFECT OF EXTREME TURBULENCE ON FLAME
WIDTH AT A V_0 OF 50 FT/SEC

FIGURE 107
EFFECT OF EXTREME TURBULENCE ON FLAME
WIDTH AT A V_0 OF 100 FT/SEC

TABLE II

Effect of Extremely High Turbulence Level in Approach StreamOn Flame Velocity - A Rough Check on Validity of Equation 21(Points Taken From Smoothed Curves in Figures 105, 106 & 107)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	
Estimated Turbulence in Approach Stream; 0.4%					Estimated Turbulence in Approach Stream; 6.5%						
No Screen					3 mesh 0.063" wire diam. screen						
V _o	1/f	S _L	S _f	Effective per cent turbulence disturbing flame from Equation 21	V _o	1/f	S _L	S _f	Effective per cent turbulence disturbing flame from Equation 21	S _f calculated on basis of Equation 21 by adding 6.5% to the turbulence calculated with no screen	
ft/sec	lbs/lb	ft/sec	ft/sec		ft/sec	lb/lb	ft/sec.	ft/sec.			
25	9.30	0.765	1.38	9.17	- -	- -	- -	- -	- -	2.10	
25	10.00	0.660	0.80	3.64	- -	- -	- -	- -	- -	1.42	
25	11.00	0.525	0.52	0.	25	11.00	0.525	1.23	8.89	0.97	
25	12.00	0.415	0.44	1.185	25	12.00	0.415	0.99	7.22	1.05	
25	13.00	0.315	0.44	2.46	- -	- -	- -	- -	- -	1.16	
50	8.00	1.083	3.09	11.58	- -	- -	- -	- -	- -	4.65	
50	9.00	0.825	2.06	7.55	50	9.00	0.825	4.68	18.40	3.61	
50	10.00	0.655	1.46	5.22	50	10.00	0.655	3.60	14.16	3.00	
50	11.00	0.525	1.09	3.81	50	11.00	0.525	2.83	11.50	2.63	
50	12.00	0.415	0.96	3.45	- -	- -	- -	- -	- -	2.52	
100	4.30	1.060	2.55	4.63	- -	- -	- -	- -	- -	5.67	
100	5.00	1.470	3.30	5.92	100	5.40	1.585	9.11	17.90	6.38	
100	6.00	1.630	3.68	6.60	100	6.00	1.630	9.75	19.20	6.74	
100	7.00	1.530	3.26	5.75	100	7.00	1.530	8.65	17.05	6.31	
100	8.00	1.085	2.92	5.43	100	8.00	1.085	7.83	15.05	6.06	
100	9.00	0.825	2.62	4.97	100	9.00	0.825	6.75	13.40	5.79	
100	10.00	0.655	2.29	4.39	100	10.00	0.655	6.19	12.35	5.48	
100	11.00	0.525	2.18	4.23	- -	- -	- -	- -	- -	5.39	

cent turbulences required to produce these flame velocities calculated using equation 21 are tabulated in columns (5) and (10) for no screen and for the 3 mesh 0.063" wire diameter screen, respectively.

Column (11) presents values of S_f calculated using equation 21, the per cent turbulence being obtained by adding 6.5 per cent to the effective amount present with no screen in place. It will be noted by comparing the actual values of S_f with the 3 mesh 0.063" wire diameter screen at the chamber entrance tabulated in column (9) with the calculated S_f values, that fair agreement is found, especially at the leaner mixtures, considering the numerous assumptions and possibilities for error that are present.

In Figure 108 are plotted the values of S_f in columns (4), (9) and (11) of Table II. It is observed from this figure that, although agreement is fair in most cases between the S_f calculated by adding 6.5 per cent turbulence to the effective turbulence calculated with no screen, the calculated curves in every case fall below the curves representing the actual values. Any one of three factors, acting alone or together, could account for the discrepancy. First, equation 21 may not satisfactorily describe the action of the screen generated turbulence on the flame; second, the

FIGURE 108

EFFECT ON FLAME VELOCITY OF EXTREMELY HIGH APPROACH STREAM
TURBULENCE-A ROUGH CHECK ON VALIDITY OF EQUATION 21

assumed value of 6.5 per cent for the average value of the approach stream turbulence could easily be in error by plus or minus a per cent or so; third, the approach stream turbulence could be acting to increase the intensity of the other disturbances as well as directly on the flame. Taking these possibilities of error into consideration the agreement especially at the leaner mixtures, is remarkably good and speaks well for the validity of equation 21.

Increase in S_f With Distance Downstream From The Stabilizer

Discussion thusfar has for the most part dealt with flame velocity in the first four inches of flame front downstream of the stabilizer. It is now proposed that consideration of the changes in S_f with distance downstream from the stabilizer be undertaken. Since two main regions of turbulence generation are present in the stabilized flame separated by a region of rather low velocity gradients, as is schematically shown in Figure 79, it is difficult to predict the exact nature of the relation between flame velocity and distance downstream. It would be supposed, however, that the general tendency would be toward increasing values of S_f with distance downstream. Certainly downstream of where the second region of high velocity gradients becomes turbulent, S_f would be expected to increase continuously with distance downstream from the stabilizer.

By using Equation 38, and determining values of F for each 2 inch increment of flame front from these data by means of the stepwise calculations, S_f values for each 2 inch increment of flame front can be obtained. Such calculations have been carried out for the flames photographed during runs 82 and 85 made using the 0.038 inch rod stabilizer located 2 inches from the chamber entrance. In run 85 no screen was in place and in run 82 the 3 mesh 0.063" wire diameter screen was placed at the chamber entrance resulting in extremely high turbulence levels in the first few inches of flame front downstream from the stabilizer. In Figure 109 are presented the results of these calculations, a, b, c, and d of Figure 109 presenting plots at 25, 50, 100 and 220 feet per second, respectively. The precision with which the location of any one point is determined is rather low, but general trends of the data are unmistakable. The flame velocity definitely trends toward higher values as the distance downstream from the stabilizer increases. It is interesting to compare flame velocities obtained with high approach stream turbulence with S_f values when no screen is in place. It is observed that the flame velocity not only is increased in the near vicinity of the screen where little decay of the turbulence has proceeded and the approach stream turbulence level is still high, but also at

FIGURE 109

PLOT OF FLAME VELOCITIES FOR 2" INCREMENTS OF FLAME FRONT
SHOWING GENERAL INCREASE OF S_f WITH DISTANCE DOWNSTREAM

distances further downstream where decay would be expected to have reduced the approach stream turbulence to a rather low level. This result might be expected, however, if it is appreciated that the fraction burned, F , has been increased at any one cross section due to the rapid combustion near the screen thus making conditions more favorable for turbulence generation in the second region. These curves sometimes level off or drop in S_f for short distances, as the influence of the very high approach stream turbulence becomes lower, before again rising.

The curves have been drawn through every data point not because the precision of the data necessarily warrant it, which it does not, but merely to join all the points for a single flame together so that they can easily be found and studied for definite trends. In many cases, in fact, smooth curves, or even straight lines, would probably better represent the data.

The most definite trend of an unusual nature is found in 109d where two of the curves at 200 feet per second follow one another quite closely both rising to a peak at a distance downstream from the stabilizer of about 9 inches and then falling rapidly. It is noted that the single

curve at near 300 feet per second also has this unusual shape with the maximum occurring at 9 inches downstream. It is believed that this drop in flame velocity represents the dying out of turbulence generated in the first region. It would, therefore, be expected that the curve would rise again due to increasing turbulence generation in the second unstable region. ~~There is a~~ This peak, although not nearly so marked, is also observed in most of the curves obtained with no screen in place at 100 feet per second at about 4 or 5 inches from the stabilizer.

An idea of the precision of the data points in Figure 109 is obtained by comparison of the curves at 100 feet per second for the flame with an air-fuel ratio of 10.15 and that with an air-fuel ratio of 11.00. These flame pictures are quite similar as might be expected and it is noted that the curves follow one another rather well, the probable error for each point in Figure 109 being estimated from these two curves to be about plus or minus 0.5 feet per second.

An Experimental Check on the Lines of Flow Calculated by the Stepwise Method

Attempts were made to follow the lines of flow of the gases during combustion as they passed through the chamber

by introducing titanium tetrachloride smoke into the gas stream as it entered the short approach section to the converging nozzle (with no screen at the combustion chamber entrance). It was found that even the slightest turbulence dispersed the smoke or caused its position to fluctuate. A streamer could not for this reason be photographed at chamber entrance velocities above about 10 feet per second. Below this velocity, however, the turbulence level in the chamber became so low that remarkably steady smoke streamers could be obtained. Such a streamer is seen in Figure 110a which is an enlargement to approximately full scale of a 1 second time exposure of the chamber while combustion is proceeding.

The similarity of this smoke streamline to those shown in Figure 39 obtained by calculation is to be noted. The flame shown in Figure 110a appeared quite laminar to the eye, the quenching action of the walls being so great at this low velocity, however, that a flame front appears to extend entirely around the burned gases thus accounting for the luminous appearance of the entire burned gas zone.

Unfortunately, the gas and air metering systems were not designed for rates as low as those employed in Figure 110a. Consequently, neither V_0 nor air-fuel ratio were accurately obtainable for this picture. It is estimated, however, that V_0 is about 8 feet per second, and air-fuel

FIGURE 110(A)

ratio is about 13.5 pounds per pound corresponding to an R_p of about 5. At cross section A indicated in Figure 110b the reduced flame width, W_r , equals 0.3266 and S_f/V_0 as calculated from equation 38, using Figure 33 to obtain F , is 0.327. S_f , therefore, is estimated to be 0.262 feet per second assuming a V_0 of 8 feet per second. This compares with a value of S_L at an R_p equal to 5 of 0.27 feet per second.

In Figure 110b reproduced from Figure 110a is shown as a dashed line near the position of the actual smoke streamer (shown as a solid line) and slightly nearer the flame the theoretical streamline drawn on the basis of the stepwise calculations assuming R_p to be 5. The stepwise calculations are based on the assumption that the density of the unburned material remains constant until the flame front, assumed to be a plane of zero thickness, is reached, the gases upon passing through this flame front instantaneously burning and assuming the properties of the completely burned material. Actually, however, the flame front, consisting of the preignition and reaction zones, is of finite thickness and the unburned gas begins to rise in temperature for a distance equal to the preignition zone thickness before the luminous reaction zone denoting the flame boundary in Figure 110a is reached. By means of equation 6, using an S_L of

COMPARISON OF SMOKE STREAMER FROM FIG. 110 (A), DENOTING ACTUAL LINE OF FLOW; WITH THEORETICAL STREAMLINE OBTAINED FROM STEPWISE CALCULATIONS

FIGURE 110 (B)

0.27 feet per second and a thermometric conductivity, $(\bar{k})/(\bar{c}_p \rho)$, of 0.001 square feet per second, the thickness of the pre-ignition zone is estimated to be 0.205 inches. This heating of the gases preceeding their entry into the reaction zone caused the actual streamline to be bent outward more than would be the case if no preignition heating occurred, and is believed to account for the slight discrepancy between the calculated and experimentally determined line of flow.

Stabilized Flames in the Third Dimension - Effect of Chamber Walls on Propagation and Configuration of the Flame - Ripples in the Flame Front

Visual observation of the stabilized flame under various conditions shows a number of minor deviations from absolute two dimensionality in its appearance. The major cause of these deviations is the glass side walls of the chamber, the effects of which will be first discussed.

In Figure 111a is shown schematically a front and side view of a typical stabilized flame attached to a small rod stabilizer at an air-fuel ratio near lean limit blow-out and at a velocity of over 50 feet per second. The necking down of the flame to a minimum width about half an inch above the stabilizer is to be noted. This necking down caused by the quenching action of the colder walls was often observed. It was most pronounced with the very small

stabilizers, and was not observed with those of large characteristic dimension. This is very likely due to the fact that the larger region of hot gases just to the rear of these larger ~~stabilizers~~ is able to transfer more heat to the walls without being quenched in so doing. The narrow region just downstream of the smaller rods with its lower total heat content, on the other hand, is partially quenched by the walls.

The quenching action of the glass walls on the flame throughout the length of the chamber is easily observed when no screen is in place and V_0 is about 25 feet per second. Under these conditions at lean mixtures, as has already been pointed out, essentially laminar flames are obtained. The action of the wall on these flames is to lower the flame velocity near the walls due to quenching and thus to make the flame fronts curve in toward one another at the walls. This effect, which is frequently observed is shown schematically in Figure 111b which is a cross section of the combustion chamber at about 4 inches above the flame stabilizer, with the location of the two flame fronts indicated. When this type of quenching action is present, photographs of the flame show a much wider zone of combustion than would otherwise be found. If the burning gases are made leaner, the quenching action of the

DEVIATIONS OF FLAME FROM TWO-DIMENSIONALITY

(A)

NECKING DOWN OF FLAME WITH SMALL STABILIZER NEAR BLOWOUT AT V_0 ABOVE

(B)

CROSS SECTION OF CHAMBER 4" ABOVE STABILIZER AT LOW V_0 AND HIGH $1/F$ WITH A LAMINAR FLAME PRESENT. QUENCHING ACTION OF WALLS IS SHOWN

(C)

CROSS SECTION OF CHAMBER 4" ABOVE STABILIZER. $V_0 = 50$ FT./SEC NEAR STOICHIOMETRIC WITH TURBULENT FLAME PRESENT, SHOWING SLIGHT ADDITIONAL SPREADING AT WALLS THOUGHT TO BE SEEN BY SOME OBSERVERS.

(D)

V_0 --- 30.2 FT./SEC.
 $1/F$ -- 11.45 LBS./LB.

FLAME HANGING TO HOT WALLS JUST AFTER FUEL RATE HAS BEEN REDUCED.

(E) SLOWLY MIGRATING RIPPLES IN FLAME FRONTS

CROSS SECTION OF CHAMBER 4" ABOVE STABILIZER—LAMINAR FLAME PRESENT—SHOWING RIPPLES IN FLAME FRONT

(F) SLOWLY MIGRATING WAVE IN FLAME FRONT

CROSS SECTION OF CHAMBER 4" ABOVE STABILIZER—LAMINAR FLAME PRESENT—SHOWING WAVES IN FLAME FRONT

walls increases, the flame edges then turning inward even more than shown in Figure 111b. On the other hand, richening the mixture decreases the quenching action of the walls, the distortion of the flame front sometimes being almost completely eliminated as is the case with the flame shown in Figure 74a previously discussed*.

Determination by visual observation of the effect of the walls on the flame in the presence of turbulence is difficult if not impossible. At 50 feet per second at air-fuel ratios near stoichiometric extreme turbulence is present and any conclusions regarding the effect of the walls under these conditions are of doubtful value. It appears to some observers, however, that the flame spreads slightly more near the walls than in the center of the chamber under these conditions with the average location of the flame front occupying a position such as that shown in Figure 111c. Two possible reasons for this effect, if it actually exists, could be advanced. The first is that the walls have become hot and are thus acting to increase flame velocity. An effect

* The reduction in the quenching action of the walls at mixtures nearer to stoichiometric is not surprising since it would be expected that the quenching distance would be proportional or possibly roughly equal to the thickness of the pre-ignition zone. The pre-ignition zone is, according to equation 6, inversely proportional to S_L , this zone thus becoming thicker at mixtures farthest removed from stoichiometric where S_L is high.

of very hot walls has been observed which at first gave some weight to this possibility. If at a V_0 of, say, 50 feet per second the air-fuel ratio is held at stoichiometric for a few minutes so that the glass walls adjacent to the flame become heated to a very high temperature, and if the fuel rate is then quickly reduced so that the flame width tends to become considerably less, the hot glass side walls previously heated by the wider flame act for a few seconds as flame stabilizers on which the flame hangs. A photograph of a flame of this kind in the presence of hot walls acting as stabilizers is shown in Figure 11ld. The walls rapidly cool, however, and the flame returns to its normal position. To see if cooling the walls would reduce the flame width, a stream of water was played on the chamber at a V_0 of about 50 feet per second and an air-fuel ratio near stoichiometric, the water forming into a film that completely covered the glass side walls as it ran down the outside of the chamber. No effect on the flame width due to this water cooling of the one-eighth inch thick glass side walls could be detected. The outcome of this experiment indicates that the flame width is essentially unaffected under normal steady state conditions by heating of the glass side walls by the flame.

The second effect of the walls that might tend to

increase the flame width is that due to the presence of boundary layer turbulence, the appearance of which was previously discussed. This boundary layer turbulence might directly increase flame velocity and thus flame width or it might act to increase the instability of the first region of high velocity gradients. No evidence of any effects of boundary layer turbulence on the flame was noted from the shadow photographs.

Another method of testing for the presence of boundary layer turbulence effects is the comparison of flame widths obtained under the same conditions with the stabilizer mounted at different distances from the chamber entrance. Since the boundary layer thickens as distance from the chamber entrance increases and the appearance of turbulence does not take place in the boundary layer for a short distance from the chamber entrance (See Figure 27), it might be expected that a systematic increase in flame width with distance from the chamber entrance would occur if boundary layer turbulence effects were significant. Unfortunately, really comparable data were not obtained since the runs at 2 and 6 inches from the chamber entrance were made during a period when there was some doubt as to the composition of the city gas used.

Figure 112, however, presents the flame width data for the 0.038 inch rod stabilizer mounted at 9, 6, and 2 inches from the chamber entrance with no turbulence generating screen in place. a, b, c, and d of Figure 112 show flame width data at 25, 50, 100 and 220 feet per second. It is observed that at 25 feet per second the points for 9 inches are slightly above those for both 6 and 2 inches, these latter two falling on almost the same line. At 50 feet per second there is a slight spread with wider flames obtained with the stabilizer mounted at greater distances from the chamber entrance. At 100 feet per second the flame widths are somewhat greater with the stabilizer mounted at 9 inches from the chamber entrance than at either 6 or 2 inches, these latter two curves falling almost together. At 220 feet per second the flame widths with the stabilizer at 9 inches above the chamber entrance are again slightly greater than the others but the widths for the stabilizer at 2 inches are only very slightly below these points, and the widths above the stabilizer located 6 inches from the chamber entrance are somewhat below both these other points.

On the basis of the data presented in Figure 112, in spite of its doubtful internal consistency due to doubts regarding the fuel composition, the presence of slight effects of boundary layer turbulence on flame widths must

FIGURE 112

EFFECT OF DISTANCE OF STABILIZER FROM
CHAMBER ENTRANCE ON FLAME WIDTH

be considered a definite possibility. It will be noted that even if small increases in flame width at mixtures near stoichiometric do occur due to the presence of boundary layer turbulence, the conclusions previously arrived at in regard to propagation of the stabilized flame, which are for the most part qualitative, are not altered.

In addition to the effect of the walls other deviations from two-dimensionality were observed from time to time when the flame was laminar. These had the appearance of slowly migrating waves and ripples which moved across the face of the flame front in a rather random fashion and whose appearance from day to day and from minute to minute was not predictable. Often they were not present at all. Two typical cross sections of the chamber during combustion at about 4 inches above the stabilizer showing the presence of waves and folds in the flame front are shown as Figures 111e and 111f. These deviations from two dimensionality subtract from the precision with which laminar flame velocity can be determined from flame width measurements using the stepwise calculations, since a flame width greater than that resulting if two dimensionality were maintained is obtained.

Seorlock

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D. Flame Stabilization1. Theoretical Considerations

Thusfar the discussion has been limited to consideration of the propagation of the flame downstream of the stabilizer. Attention will now be directed toward the stabilization process itself.

It is well known that for any one flame stabilizer and type of fuel, other things being equal, a stable flame can only be maintained within a certain range of entrance velocities and air-fuel ratios. The boundaries between this stable region and the region where a flame cannot be maintained are known as the stability limits. Such limits exist for all types of flame stabilizing objects including Bunsen burner tubes, cones, and rods.

The postulation of a mechanism of flame stabilization behind blunt objects based on conclusions previously arrived at should be useful in the development of a satisfactory theoretical treatment of the stability limits. Referring again to Figure 73b showing schematically the flow around a rod flame stabilizer during combustion it has been shown that no eddies shed from the stabilizer under these conditions, steady state flow thus prevailing around the rod. This flow, except for transfer of heat and chain carriers between the eddy region and the passing gas stream which

results in ignition, is in many ways analogous to the flow of fluid around a streamlined object with the same cross section as that of the stabilizer plus the eddy region.

The cold approach stream gases pass around the rod, separate from it at the separation point, and then contact the hot gases of the eddy region. Along this contact surface a rapid transfer of heat and chain carriers from the eddy region to the approach stream gases takes place and the portion of the colder unburned stream nearest the eddy region soon reaches the ignition temperature and begins to burn. During the remaining time of contact of this recently ignited approach stream gas parcel with the eddy region heat and chain carriers flow in the reverse direction back into the eddy region replenishing the previously depleted supply. This cycle is repeated continuously with hot recirculating gases of the eddy region thus furnishing a continuous source of ignition for the unburned approach stream gases.

On the basis of thermal considerations only* it would

* Molecular diffusion undoubtedly plays a large part in the stabilization process but, just as in the development of a theory of laminar flame propagation, treatment on the basis of thermal considerations only is simpler and can be partially justified on the basis that molecular diffusion rates are roughly proportional to those of heat transfer by conduction.

be supposed that the rate of heat supply necessary for ignition of the approach stream would be increased by increasing the approach stream velocity, V_0 , by increasing the difference between the ignition temperature and the approach stream temperature, $(T_i - T_0)$, by increasing the thickness of the preignition zone, δt , and by increasing the heat capacity per unit volume, ρC_p . An expression for the rate of heat supply necessary to assure continuous ignition may then be written as follows:

$$\text{heat supply rate required for continuous ignition} \propto V_0 e' [\delta t (\rho C_p) (T_i - T_0)]^{f'} \quad (46)$$

The exponent f' very likely has a value of one. The value of the exponent e' is not known. From dimensional considerations it might be supposed that e' would equal one. Its value is thought to depend among other things, however, on the ignition lag. Such a lag, if present, would tend to increase the amount of heat transferred prior to ignition per unit volume of approach gases as V_0 increased (assuming that the heat transfer coefficient increased with V_0) thus allowing the same amount of heat to be transferred in a shorter time at the higher V_0 . The value of e' , therefore, is estimated to have a value greater than one.

If into expression 46 the value of δt from equation 6

is substituted and the exponent f' is assigned the value of one, the following expression results:

$$\text{heat supply rate required for continuous ignition} \propto \frac{V_o e' k}{S_L} (T_1 - T_o) \quad (47)$$

The heat supplied to the unburned gases coming into contact with the eddy region must, at blow-out, be equal to that required. This heat supply rate would be expected to increase as the heat transfer coefficient increases, as $(T_b - T_o)$ increases*, and as the length of the transfer surface (assumed to be proportional to the stabilizer characteristic dimension, n ,) increases**.

It might be supposed that the heat transfer coefficient would be proportional to $(\frac{nV_o}{\nu})^{g'} \frac{k}{n}$ just as is the case for transfer from hot cylinders. For hot cylinders the exponent g' has a value of about 0.6(34), and it is therefore

* This assumes that the temperature of the eddy region, T_{er} , is not far from T_b and may thus be replaced by it in the actual expression for the temperature differential, $(T_{er} - T_o)$.

** The tacit assumption is here present, first that the length of the eddy region is proportional to the stabilizer characteristic dimension, n , and second that the ratio of the first portion of the transfer surface across which heat leaves the eddy region to the second portion of the transfer surface across which heat is supplied to the eddy region is constant. This latter proportionality is suspected to hold, but the proportionality constant is thought to be a function of air-fuel ratio. The overall proportionality constant, which contains this constant thought to be a function of air-fuel ratio, is later properly placed with the other quantities whose values are a function of air-fuel ratio.

suspected that g' has a value not far removed from 0.6. The temperature differential, $(T_b - T_o)$, and the length of the transfer surface, assumed to be proportional to n , probably both appear to the first power. An expression for the heat transfer rate to the unburned approach stream gases may now be written as follows:

$$\begin{array}{l} \text{heat transfer rate to unburned} \\ \text{gas from eddy region before} \\ \text{ignition takes place} \end{array} \propto \left(\frac{nV_o}{\nu} \right)^{g'} \frac{k}{n} n(T_b - T_o) \quad (48)$$

Introducing a proportionality constant, K' , at blow-out expression 47 can be equated to 48 as follows:

$$\frac{V_o}{S_L} \frac{k}{n} (T_i - T_o) = K' \left(\frac{nV_o}{\nu} \right)^{g'} \frac{k}{n} n(T_b - T_o) \quad (49)$$

Simplifying and rearranging so that all quantities thought to be ~~to~~ a function of air-fuel ratio appear on the right hand side, the following equation results:

$$\frac{V_o (e' - g')}{n g'} = \frac{K'}{(\nu)^{g'}} \frac{S_L (T_b - T_o)}{T_i - T_o} = \phi \left(\frac{1}{f} \right) \quad (50)$$

In the derivation of equation 50 no allowance for the reduction in eddy region temperature due to the cooling action of the stabilizer has been made. Actually, the temperature of the eddy region gases that come into contact with the unburned approach stream is reduced by the cooling action of the stabilizer, thus lowering the

temperature differential and increasing the surface necessary to transfer the quantity of heat required to maintain stability*. This effect would be expected to increase as the stabilizer characteristic dimension, n , increases, and should become greater the smaller the value of $(T_b - T_1)$ as does, for example, $1/S_L$. A tentative expression taking into account the effect of stabilizer cooling effects may be written as follows:

$$\frac{V_{bo}(e' - g')}{ng'} + K'' \left(\frac{n}{S_L} \right)^{h'} = \phi \left(\frac{1}{f} \right) \quad (51)$$

where the values of h' and K'' are not known.

It is interesting to note the effect on the blow-out limits of changing the pressure as predicted by equation 50. The only term on the right hand ^{side} of equation 50 which varies with pressure is $\sqrt{}$, which varies inversely with the pressure. According to equation 50, then, the blow-out velocity, V_{bo} , becomes lower as pressure decreases.

* True, all heat entering the stabilizer must again return to the approach stream but most of this returning heat is rapidly transferred far out into the main stream and is thought to help only slightly in reducing the amount of heat required from the eddy region upon contact to insure ignition.

2. Experimental Results

Appearance of the Stabilized Flame Just Downstream of the Stabilizer

As found by visual observation, completely burned gases are present in the region just downstream of the stabilizer where the eddy region is located. Figure 113a is an enlargement to approximately twice full scale of a photograph of a flame stabilized on the 0.498 inch rod at a V_o of 47.8 feet per second and an air-fuel ratio of 13.47 pounds per pound. It is observed that the flame appears to begin at the rod stabilizer about 100 degrees from front dead center. It will be recalled that the separation point for a rod placed in an isothermal fluid stream is located about 82 degrees from front dead center at Reynolds numbers between about 30 and 2×10^5 . It is not known whether the location of the separation point is modified by combustion. It is quite likely, however, that little change in the location of the separation point occurs, but that a short preignition length precedes the point where reaction begins.

Figures 113b, 113c, and 113d are enlargements to approximately full scale of flames stabilized on a 0.5 inch closed edge gutter, a 0.5 inch open edge gutter (total to open area equals 25), and a 0.5 inch flat plate under conditions similar to those for Figure 113a. In Figure 113c, combustion

ENLARGEMENT OF FLAME STABILIZED ON THE 0.498" ROD
SHOWING DETAILS OF REGION NEAR THE STABILIZER

FIGURE 113a

$V_0 = 47.8 \text{ ft/sec}$
 $1/f = 13.47 \text{ lbs/lb.}$
Fuel: City Gas

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ENLARGEMENT TO APPROXIMATELY
FULL SCALE OF REGION NEAR
STABILIZER DURING COMBUSTION
FOR DIFFERENT FLAME HOLDING
SHAPES

(Fuel: City Gas)

FIGURE 113b

0.5" Closed Edge Gutter
 $V_0 = 46.8$ ft/sec.
 $1/5 = 13.31$ lbs/lb.

FIGURE 113c

0.5" Open Edge Gutter
($\frac{\text{total area}}{\text{open area}} = 25$)
 $V_0 = 48.2$ ft/sec.
 $1/f = 14.30$ lbs/lb.

FIGURE 113d

0.5" Flat Plate
 $V_0 = 49.7$ ft/sec
 $1/f = 13.40$ lbs/lb.

inside the eddy region is proceeding due to the flow of unburned gas into the gutter through the open edge.

Figures 114a, 114b, and 114c are enlargements to approximately full scale of flames stabilized on the 0.498", 0.188" and 0.094" rods, respectively, under approximately the same conditions of V_0 and air-fuel ratio. Figures 115a through 115g are a series of enlargements of flames stabilized on the 0.498 inch rod at approximately the same V_0 but at different air-fuel ratios. It appears from examination of Figures 114a, 114b and 114c that the first evidence of reaction occurs slightly further back on the rod as the rod diameter decreases. It might be expected that the preignition distance would tend to remain constant, other things being equal, as rod diameter decreases, signs of reaction thus first appearing further back on the smaller rods. This supposition is further substantiated by visual observation of flames stabilized on very small stabilizers where the flame does not appear to begin until a very short distance downstream of the stabilizer. (See schematic drawing on data sheet for run 47 in Appendix C.)

No effect of air-fuel ratio on the location with respect to the stabilizer of the first appearance of reaction can be detected from Figures 115a through 115g. Also no effect of stream velocity on the location with respect to the rod

FIGURE 114

ENLARGEMENT TO APPROXIMATELY
FULL SCALE OF REGION NEAR
STABILIZER DURING COMBUSTION
FOR 3 STABILIZERS OF DIFFERENT
DIAMETER WITH OTHER CONDITIONS
ABOUT THE SAME

Fuel: Propane

Fig. 114 a

0.498" Rod Stabilizer
 $V_o = 46.5$ ft/sec
 $1/f = 23.40$ lbs/lb.

Fig. 114 b

0.188" Rod Stabilizer
 $V_o = 46.5$ ft/sec.
 $1/f = 22.76$ lbs/lb.

Fig. 114 c

0.094" Rod Stabilizer
 $V_o = 46.4$ ft/sec.
 $1/f = 20.81$ lbs/lb.

ENLARGEMENTS TO APPROXIMATELY FULL SCALE OF REGION NEAR STABILIZER
DURING COMBUSTION AT $V_0 \approx 100$ ft/sec. WITH DIFFERENT AIR-FUEL RATIOS

Flame Stabilizer: 0.498" Rod 9" from Chamber Entrance
Screen: 3 mesh 0.063" wire dia.
Fuel: City Gas

Fig. 115a

$V_0 = 95.9$
 $1/f = 12.61$

Fig. 115b

$V_0 = 98.0$
 $1/f = 10.16$

Fig. 115c

$V_0 = 100.7$
 $1/f = 8.02$

Fig. 115d

$V_0 = 103.1$
 $1/f = 6.81$

Fig. 115e

$V_0 = 103.6$
 $1/f = 5.94$

Fig. 115f

$V_0 = 108.4$
 $1/f = 5.23$

Fig. 115g

$V_0 = 111.7$
 $1/f = 4.59$

of the first appearance of reaction was noted within the velocity range covered. Both of these effects could exist, however, and, if small, may not have been detected.

Other interesting pictures of flames in which the region near the stabilizer can be closely examined are found in Appendix A.

It might at first be surprising to find that reaction, as denoted by the appearance of a luminous flame front, occurs so near the rod. This observation is more easily understood, however, if it is recalled that the same amount of heat is transferred initially from the eddy region across a large temperature gradient, equal approximately to $(T_b - T_0)$, that later returns to it across the relatively small temperature gradient, $(T_b - T_{er})$. The transfer lengths (proportional to the transfer surfaces) are to one another approximately as the inverse ratio of the two temperature gradients across them, thus accounting for the very short distance apparently necessary to transfer the heat required for ignition from the eddy region. It is also likely that the first appearance of reaction as denoted by the luminous appearance of the flame is not accompanied by a fully developed laminar flame velocity with temperatures as high as T_b , but that a short additional distance is necessary for full development.

Dependence on an Eddy Region for Stability

In considering the mechanism of high velocity flame stabilization to the rear of blunt objects the prime importance of the eddy region as a continuous source of ignition was emphasized. It would be expected that a streamlined object with no eddy region at its rear would not even function as well as the cold walls of the chamber as a flame stabilizer. To demonstrate this lack of ability of streamlined objects to stabilize flames at high velocity a 0.5 inch long flat plate with its long dimension oriented parallel to the flow was mounted in the combustion chamber and attempts were made to stabilize a flame on it (see run 19 data sheet, Appendix C) . As expected all attempts to make the flame attach itself to the plate met with failure.

Mechanism of Blow-out - High Speed Shadow Photographs - Residual Flames Again Discussed

It has already been postulated that blow-out of the flame takes place when the eddy region fails to regain as much heat from the newly ignited approach stream gases as is supplied initially to these gases to obtain ignition. If, for example, V_0 were held constant and the air-fuel ratio gradually increased, the amount of energy required to obtain ignition would also rise, and the average temperature of the eddy region would necessarily drop. If the air-fuel ratio

continued to increase, a point would finally be reached where continuous ignition could no longer be maintained by the eddy region. At an air-fuel ratio slightly leaner than that for blow-out the eddy region would be gradually losing more heat than it regained from the burning gases and would thus slowly cool. Stabilization of the flame would not at once cease, however, but would be expected to continue for a few revolutions of the eddy region until this region had cooled to such a low temperature that even contact with the unburned approach stream gases along its entire length does not result in sufficient transfer of heat to raise the approach gases to ignition temperature.

Figures 116a and 116b are enlargements of consecutive frames from high speed movie reels taken at 1000 frames per second of a ground glass screen upon which a shadow of the flame was made to fall during lean limit blow-out. 116a taken at a V_0 of 48.1 feet per second and 116b taken at a V_0 of 99.1 feet per second show a series of pictures obtained during the blow-out process with the first few pictures showing normal combustion proceeding, and the last few showing the flame completely out. Blow-out was made to occur by gradually reducing the fuel rate while the high speed camera was in operation. Interpretation of these pictures is difficult since they are rather indistinct and

HIGH SPEED PHOTOGRAPHS

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Flameholder--0.498" dia. Steel Rod located 7" Downstream of Tunnel Entrance
Turbulence Generating Screen--None

Pictures are enlargements of 35 consecutive frames of film taken at 1000 frames/sec.
Combustion Chamber Entrance Velocity, $V_0 = 48.1$ ft./sec.

Air-Fuel Ratio, $w_a/w_f = 12.15$ lbs/lb (Fuel: Cambridge City Gas 6.51 lbs/lb=Stoichiometric)

HIGH SPEED PHOTOGRAPHS

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Flameholder--0.498" dia. Steel Rod located 7" Downstream of Tunnel Entrance

Turbulence Generating Screen--None

Pictures are enlargements of 35 consecutive frames of film taken at 1000 frames/sec.

Combustion Chamber Entrance Velocity, $V_0 = 99.1$ ft./sec.Air-Fuel Ratio, $w_a/w_f = 11.19$ lbs/lb (Fuel: Cambridge City Gas 6.51 lbs/lb=Stoichiometric)

conclusions based on them should, therefore, be treated with caution.

As expected, blow-out occurs over a relatively long period of time estimated in both these cases at about 0.025 seconds, corresponding to 25 frames. Apparently, the last region where strong temperature gradients (and very likely a flame) are present during blow-out is near the rod. This indicates that the flame extinguishes from the top downward toward the rod with the flame first ceasing to propagate into the main stream, as is the case with residual flames, then becoming shorter and shorter until finally the eddy region temperature becomes so low that combustion is no longer supported.

At this junction it appears worthwhile to return to a discussion of residual flames. These flames were discussed previously in connection with flame propagation and some pictures of typical residual flames are shown in Figures 76 and 77.

When a stable flame is being maintained by the stabilizer and eddy region, but when this flame fails to propagate into the main stream, a residual flame results. Considerable quenching action is present when the slow moving burned gases in the region ^{*of low velocity and high pressure just to the rear of the eddy region*} are rapidly accelerated and reduced in width

as they move further downstream. This quenching action must account for the failure of the residual flame to propagate into the main stream. Apparently, then, the propagation of the flame above the stabilizer into the unburned gases, which fails to take place in the case of the residual flame, and the stabilization mechanism itself are independent of one another. In only a few instances with city gas as a fuel did residual flames appear, and they were never observed when propane was used as a fuel. With the fuels and stabilizers employed, then, it appears that failure of the flame to stabilize, rather than its failure to propagate, is in most instances the controlling phenomenon. With other fuels and stabilizers the failure of the stabilized flame to propagate might conceivably become controlling. As is later shown, this is the case over a wide range with city gas as a fuel when the stabilizer is heated to a high temperature thus widening the stability limits without greatly increasing the tendency toward improved propagation above the stabilizer.

Stability Limits of Rods

Blow-out limits of flames stabilized on 9 rods ranging in diameter from 0.016 inches to 0.498 inches - a variation in diameter of over thirty fold - were obtained using city gas as a fuel. The stabilizers were located 9 inches from

the chamber entrance and data were obtained both with and without turbulence generating screen at the chamber entrance. In Figure 117 are presented the stability limit curves for these rod stabilizers with air-fuel ratio as the abscissa and V_0 at blow-out as the ordinate. The solid curves represent the data obtained without a screen at the chamber entrance, and the dashed curves represent the data with the 3 mesh 0.063" wire diameter screen in place. This screen produces a calculated turbulence intensity at the stabilizer of 2.67 per cent.

As predicted by equation 50, the area of the stable region (the area under a blow-out limit curve) is increased by increasing the stabilizer diameter; increasing V_0 at any one air-fuel ratio finally results in blow-out; and the flame is stable at higher values of V_0 near stoichiometric where the right hand side of equation 50 is largest. It is noted that at very lean mixtures at low values of V_0 , increasing the diameter of the stabilizer actually results in reduced stability, the blow-out curves for 0.498 and 0.311 inch rods falling at richer mixtures than the blow-out limits for stabilizers of slightly smaller diameter. This effect is explained as due to the increased cooling action of the larger stabilizers, and is taken into account in equation 51 by the second term on the left hand side.

FIGURE 117

STABILIZATION LIMITS FOR FLAMES STABILIZED ON RODS

(FUEL: CAMBRIDGE CITY GAS — ENTRANCE PRESSURE — 1 ATM.; ENTRANCE TEMP 300°–340° K)

It is observed that, in contrast with the small effect of approach stream turbulence on propagation previously discussed, the reduction in stability due to approach stream turbulence is pronounced. The effect of turbulence on stability will be discussed in detail later in this section.

It became impossible with the metering devices employed to distinguish between the limits of stability with and without a screen for the two larger rods due to the smaller difference between the blow-out limits with and without a screen for these larger rods. Data were, therefore, obtained for these two rods only with a screen in place. These data are thought, however, to be comparable with the data obtained with the other stabilizers either with or without a screen.

Returning to equation 50 let us raise both sides of the equation to the $(1/e'-g')$ power. We then obtain:

$$\frac{V_0}{\frac{g'}{n^{e'-g'}}} = [\phi(1/f)]^{1/e'-g'} = \phi'(1/f) \quad (52)$$

To correlate the data presented in Figure 117 by means of equation 52, it is only necessary to find the right value for the exponent $g'/e'-g'$. A suitable value was chosen by plotting on log paper V_0 versus n values at constant air-fuel ratio obtained from the smoothed curves of Figure 117 and taking the slopes of the lines. A slope of 0.45 was decided upon as a good average value.

In Figure 118 are shown the blow-out limit data for rods replotted with air-fuel ratio as abscissa and $V_{so}/n^{0.45}$ as ordinate. Only the data obtained with no screen in place are plotted except for those obtained with the two largest rods where data are only available for runs with a screen in place. The correlation is satisfactory using only the one term, but as expected, the points scatter somewhat on the lean side at low velocity due to the absence of the second term included in equation 51 which takes into account the quenching action of the stabilizer itself.

Returning to equation 50 it might be suspected that over a rather wide range of air-fuel ratios the group

$$\frac{K'}{(\nu)g'(T_1 - T_0)}$$

would remain relatively constant. An approximate test for the constancy of this group can be made by assuming e' to be 1.45 and g' to be 0.45 in equation 50. The left hand side of the equation then becomes $V_{so}/n^{0.45}$. Solving for

$$\frac{K'}{(\nu)g'(T_1 - T_0)} \quad \text{we obtain:}$$

$$\frac{V_{so}/n^{0.45}}{S_L(T_b - T_0)} = \frac{K'}{(\nu)g'(T_1 - T_0)} \quad (53)$$

In Table III the values of the quantities appearing on the left hand side of equation 53 are tabulated for different

TABLE II

EVALUATION OF THE GROUP $\frac{V_{so}/n^{0.45}}{S_L(T_b - T_o)}$ TO

DETERMINE WHETHER IT REMAINS CONSTANT

WITH AIR-FUEL RATIO

(1)	(2)	(3)	(4)	(5)
1/f	$V_{so}/n^{0.45}$	S_L	$T_b - T_o$	$\frac{V_{so}/n^{0.45}}{S_L(T_b - T_o)}$
lbs/lb	1/sec	ft/sec	OK T_b From Fig. 29 T_o Taken as 300°K	
	From Fig. 118	From Fig. 28		
4	580	.80	1930	0.376
5	1640	1.465	2100	0.533
6	3600	1.630	2250	0.982
7	3800	1.530	2210	1.124
8	3340	1.085	2057	1.497
9	2680	0.825	1923	1.689
10	1980	0.660	1800	1.667
11	1460	0.525	1690	1.646
12	1000	0.415	1593	1.513
13	620	0.315	1513	1.301
14	340	0.220	1444	1.070

air-fuel ratios with the values of the left hand term tabulated in column 5. It is observed that this term remains relatively constant over a fairly wide range of air-fuel ratios near stoichiometric but that its value drops off considerably on both the rich and lean side. The very large drop of this term on the rich side is probably due in part to the use of measured values of S_L above actual values. (See Appendix A for discussion of errors involved in the laminar flame measurements.)

The Effect on Stability of Heating and of Cooling the Flame Stabilizer

The cooling action of the stabilizer on the hot gases of the eddy region has already been discussed and the second term on the left hand side of equation 51 was tentatively proposed to take this effect into account. It was seen in Figure 117 how this cooling action of the rod stabilizers, which becomes greater with the larger rods, causes the two largest rods to be poorer stabilizers at lean mixtures and low values of V_0 than stabilizers of slightly larger diameter. It would be expected on the basis of these considerations that heating or cooling the stabilizer by external means would have a considerable effect on the stability limits.

A stainless steel tube 0.032 inches in outside diameter with a wall thickness of 0.006 inches was mounted in the combustion chamber 9 inches from the chamber entrance in such a manner that it could be heated electrically or cooled by passing a high velocity stream of water through it as desired. The temperature of the heated tube was determined by sighting on its external surface with an optical pyrometer, and the temperature was held constant by regulating the tube heating current by means of a variac installed in the electrical circuit. Because of the water flow rates used and the ratio of length to diameter of the cooling passage, the efflux temperature of the cooling water was assumed to be that of the tube.

Figure 119 shows a plot of the blow-out limits determined using city gas as a fuel when the tube was heated to 1200°K , when cooled to 303°K , and when at equilibrium temperature; the equilibrium temperature being defined as that temperature to which the stabilizer comes when neither heated nor cooled by external means. For orientation purposes, previous equilibrium blow-out limit data for solid rods 0.038 inches and 0.126 inches in diameter are shown as dashed curves.

Comparing the blow-out velocities obtained using the 1200°K tube with those obtained using the solid rods at

FIGURE 118
CORRELATION OF ROD STABILIZER BLOW-OUT LIMIT DATA

equilibrium temperature, it is evident that heating the tube caused its efficiency as a flame stabilizer to become comparable with that of much larger unheated solid rods. In fact at an air-fuel ratio of about 9.5 pounds per pound, the 0.032 inch tube maintained at 1200°K is observed to be equivalent as a flame stabilizer to the 0.126 inch unheated rod. At air-fuel ratios richer than 9.5 pounds per pound the 0.032 inch tube maintained at 1200°K is not so effective as the 0.126 inch unheated rod since the unheated rod reaches an equilibrium temperature higher than 1200°K as mixture ratios having higher theoretical flame temperatures are reached. It is obvious that as the equilibrium temperature of the rod approaches 1200°K , less external heat must be added to maintain this temperature, and less improvement can be expected in flame stability due to this external heat addition.

It likewise follows that the 0.032 inch tube at 1200°K should become increasingly more effective as a flame stabilizer than the unheated 0.126 inch rod as the air-fuel ratio is increased beyond 9.5 pounds per pound, since the theoretical flame temperature of the combustible mixture decreases thus causing a like decrease in the equilibrium temperature of the unheated rod. At an air-fuel ratio of 15 the heated tube holds a flame at considerably higher velocities than did any of the unheated rods employed during this investigation.

On the lean side of stoichiometric at velocities below about 300 feet per second a residual flame remains on the heated tube after propagation of the flame through the main mass of the combustible gases has ceased. The air-fuel ratio range over which these residual flames persist after general propagation has ceased was generally much greater with this heated tube than was ever previously observed with unheated stabilizers.

As would be expected, the stability limits for the tube cooled to 303°K as shown in Figure 119 are narrower than for a rod of comparable diameter at equilibrium temperature. Also, as might be expected, cooling to 303°K has the greatest effect at air-fuel ratios near stoichiometric where the equilibrium temperature of an uncooled rod is the highest.

Comparing the stability limits of the 0.038 inch rod with those of the 0.032 inch tube at equilibrium temperature it is at first surprising to note that the tube, although of smaller diameter, possesses wider stability limits. Brief consideration, however, indicates that the thermal conductance from one side of a hollow tube to the other is much poorer than for heat flow from one side of a solid rod of the same material to the other, i.e., heat transfer through the gaseous core of the tube is poorer than through

FIGURE 119

the steel core of the rod*. Consequently, with the thin walled steel tube there will be less cooling of the hot combustion gases at the downstream side of the tube.

Stability Limits of Closed Edge Gutters

It was observed in Figure 119 that heating of the stabilizer to 1200°K considerably widened the stability limits. This widening is attributed, first to the preheating of the approach gases by the hot stabilizer which makes it necessary for the eddy region to supply less heat to obtain ignition on contact, and secondly to the reduced cooling action of the hot stabilizer on the recirculating gases of the eddy region.

It might be expected that substitution of a closed edge gutter for a rod of the same characteristic dimension would, other things being equal, tend to reduce the cooling action of the stabilizer on the eddy region and thus extend the stability limits of the larger rods, especially at lean mixtures and at low velocities where this cooling action is especially pronounced. This would occur since the revolving eddies in

* The reverse would be the case, however, at very high temperatures where radiation, and not conduction, becomes the controlling process in the transfer of heat between the tube walls. In fact when the tube was heated to 1200°K , at which temperature it might be supposed that radiation would be the controlling heat transfer mechanism within the tube, no difference in temperature between the upper and lower portions of the tube was noted with the optical pyrometer.

the case of the gutters are in contact primarily with a zone of relatively stagnant gas in the base of the gutter which serves partially to insulate the eddy region from the gutter itself. This is contrasted to the case of the rod stabilizers where the revolving eddy region is in direct contact with the downstream side of the rod.

In Figure 120 are presented closed edge gutter blow-out limit data obtained in a manner similar to that for rods presented previously in Figure 117. Data were obtained with 5 gutters ranging in width from 0.025 inches to 0.5 inches. Comparison of the stability limit curves for closed edge gutters shown in Figure 120 with the similar curves for rods presented Figure 117 shows that they both have the same general shape and appearance. It is noted however that on the lean side at low velocity the stability limits extend to slightly leaner mixtures with the gutters than with the rods. This is due, it is presumed, to the relatively smaller cooling action of the gutters on the eddy region. In spite of this reduced cooling effect it is found that in this region of low velocity and high air-fuel ratio narrower stability limits are found with the 0.5 and 0.25 inch gutters than with the 0.1 inch gutter. This same effect, it is recalled, was found to exist with the rods, and is thought to be due to the greater cooling action on the eddy region of the larger stabilizers as previously discussed.

STABILIZATION LIMITS FOR FLAMES STABILIZED ON 30° GUTTERS
(FUEL: CAMBRIDGE CITY GAS—ENTRANCE PRESSURE—1 ATM; ENTRANCE TEMP.— 300° — 340° K)

In Figure 121 the gutter data are plotted as $V_{ao}/n^{0.45}$ versus air-fuel ratio to test for correlation. Only the data obtained without a turbulence generating screen at the chamber entrance are plotted except for those taken with the 0.5 and 0.25 inch gutters. In this latter case only data with the 3 mesh 0.063" wire diameter screen in place were taken. The curve shown in Figure 121 is the same previously drawn through the rod blow-out data plotted on the same basis. This previously obtained curve fits the gutter data fairly well. It is observed, however, that the data points scatter a bit more on the far lean side than was found in the correlation plot for the rods shown in Figure 118. This is not clearly understood, but it might be supposed that the cooling action of the gutters on the hot gases of the eddy region, although less pronounced in any one case, varies a greater amount from the larger to the smaller stabilizers than it does with the rods.

In the discussion of flame widths for the different types of simple stabilizing shapes it was tentatively concluded that the width of the eddy region for gutters was less than that for rods of the same characteristic dimension. On the basis of the blow-out limit data it is concluded, on the other hand, that the length of the eddy region behind gutters and rods of the same characteristic dimension is

FIGURE 121
CORRELATION OF
CLOSED-EDGE GUTTER STABILIZER BLOW-OUT LIMIT DATA

approximately the same since their stability limits, thought to depend on the length of the eddy region, are about the same.

Stability Limits Obtained Using Propane as a Fuel - Attempt to Correlate the Blow-out Limit Data Obtained with Propane with that of City Gas.

Stability limits were obtained with a series of rod stabilizers of varying diameter using propane as a fuel in the same manner previously employed using city gas. These blow-out limit data for propane are presented in Figure 122.

It is observed that the stability of propane-air flames is, under similar conditions, considerably less than that found for city gas-air flames. This is not unexpected since by examination of equation 50 it is seen that lowering the value of S_L would result in lower values of V_0 at blow-out, other things being equal. Increasing $(T_b - T_0)$ should, according to equation 50, also result in increasing V_0 at blow-out, but this quantity is almost the same at the same O_g for both city gas-air and propane-air mixtures as previously noted in Figure 29.

The stability limit curves for propane do not appear to be as internally consistent as those previously obtained with city gas. These curves reach their maxima sometimes

at quite different air-fuel ratios, and apparently often are shifted somewhat throughout their whole length toward either the rich or the lean side. The cause of this apparent internal inconsistency of the propane blow-out data is not known, but one suggested cause might be the change in moisture content of the air from run to run*.

The marked reduction in stability caused by the introduction of approach stream turbulence is again noted in Figure 122 by comparison of the blow-out limits with and without a turbulence generating screen in place shown for the 0.094 and the 0.038 inch rod stabilizers.

In Figure 123 is shown the propane blow-out data plotted with $V_{so}/n^{0.45}$ as ordinate versus air-fuel ratio as abscissa. Correlation is fair, especially at air fuel ratios near stoichiometric, in view of the apparent internal inconsistency of the propane blow-out data. A single curve has been drawn through all of these data.

Returning to equation 50 let us examine the terms appearing on the right hand side which are a function of the

* If the variation of moisture content of the air from run to run is actually the cause of the apparent internal inconsistency of the propane data, then such variations in moisture content must have a relatively much smaller effect on the stability limits of city gas-air flames, since no such internal inconsistency was previously observed using city gas.

FIGURE 122

STABILITY LIMITS FOR FLAMES STABILIZED ON RODS-FUEL:PROPANE
(PRESSURE-1 ATM; ENTRANCE TEMP-300°K)

FIGURE 123
CORRELATION OF BLOW-OUT LIMIT DATA USING PROPANE AS A FUEL

composition of the fuel-air mixture. It has already been seen that $(T_b - T_o)$ is about the same at any one value of O_g for both propane and air. It might be supposed that γ would be about the same for both air-fuel mixtures since both consist for the most part of air. Values of $(K'/T_i - T_o)$ are not known, but if it were the same for both propane-air and city gas-air mixtures at the same O_g then the data obtained using both propane and city gas as a fuel could be correlated by plotting $V_{bo}/S_L n^{0.45}$ versus O_g .

By dividing the blow-out limit correlation curves previously obtained for city gas-air and propane-air mixtures by S_L and plotting these values versus O_g , the curves shown in Figure 124 were obtained. It is observed that no correlation results. It thus must be concluded that the quantity $(K'/T_i - T_o)$ is considerably different for the two types of fuel.

Attempt to Correlate the Blow-out Data of Longwell and Lewis and Von Elbe on the basis of $V_{bo}/n^{0.45}$

Longwell (7) obtained blow-out data at entrance velocities between about 300 and 1000 feet per second for a series of 4 cylindrical pipes varying in diameter between 2.88 inches and 0.75 inches having closed, streamlined upstream ends and open downstream ends mounted axially in a cylindrical

FIGURE 124

ATTEMPT TO BRING TOGETHER THE PROPANE AND CITY GAS
CORRELATION CURVES ON THE BASIS OF $V_{80}/n^{0.45}S_L$

duct 6 inches in diameter. The duct extended only a short distance downstream of the stabilizer thus assuring steady combustion. A homogeneous mixture of air and vaporized petroleum naptha was burned, with the composition of the naptha thought to be approximately $(CH_2)_x$, corresponding to an air-fuel ratio at stoichiometric of 14.80 pounds per pound. The conditions of turbulence and the velocity distribution in the duct are not known with certainty but it is thought to correspond, at least roughly, to fully developed turbulent flow in a pipe. Longwell correlated his data on the basis of V_0/n with moderate success over the narrow range of n covered.

Lewis and von Elbe (31) obtained blow-out data for 5 blunt-ended wires ranging in diameter from 0.526 centimeters to 0.0643 centimeters mounted axially in a tube 1.417 inches in diameter. Fully developed laminar flow prevailed in the tube during these runs. Values of V_0 , which are in this case taken as the average velocity of the gases up the tube*, range from about 1.5 to 6 feet per second. The fuel was natural gas composed primarily of methane with a lesser per-

* It is difficult to put the data of Lewis and von Elbe on a basis comparable with the other data since the velocity across an annulus in which the flame is laminar varies so widely. The decision to take V_0 as the average velocity of the gases up the tube was finally decided upon because of its simplicity.

centage of the higher paraffins and has an air-fuel ratio at stoichiometric of 16.81 pounds per pound. Lewis and von Elbe attempted to correlate these data on the basis of the velocity gradient at the surface of the wire at blow-out just as they had successfully done with upright Bunsen flames. The correlation for these inverted cone type flames proved to be rather poor on this basis.

In Figure 125 the data of both Longwell and Lewis and von Elbe are plotted as $V_{g0}/n^{0.45}$ versus O_g in an attempt to obtain correlation. Semi-log paper has been employed in order to show all of the data on the same plot. Also shown as dashed lines are the two previously obtained correlation curves using city gas and propane^{as fuel}. One solid curve has been drawn through the data of Longwell and another through that of Lewis and von Elbe.

The correlation of the data of Longwell and Lewis and von Elbe on this basis certainly cannot be considered entirely satisfactory. It is thought, however, to be as good as the correlations obtained previously by these investigators. It is observed that the data of Longwell falls along the propane correlation curve for a considerable range of O_g near stoichiometric. This should not be surprising considering the similarity of Longwell's fuel to that of propane. Longwell's data is found to scatter considerably even for the

FIGURE 125
 ATTEMPT TO CORRELATE THE BLOW-OUT DATA OF LONGWELL
 AND LEWIS AND VON ELBE ON THE BASIS OF $V_{BO}/n^{0.45}$

same stabilizer and because of this scattering it is difficult to determine with certainty how good the correlation is on this basis.

The data of Lewis and von Elbe are seen to fall well below the other curves. With a stabilizer of the shape employed by both Longwell and Lewis and von Elbe allowance should probably be made in expression 46 for the additional volume of approach stream gases that must be heated per unit area of eddy region due to the small radius of curvature of this region where contact with the approach stream takes place. Instead of δ_r , the following term should be employed:

$$\frac{\pi [(r_1 + r)^2 - r_1^2]}{2\pi r_1}$$

where r_1 is the radius of the eddy region, and the whole term is the area to which heat must be supplied per unit of eddy region circumference. Substituting $2r_1 \approx n$, this term becomes $\delta_t(1 + (\delta_t/n))$ which reduces to δ_t when δ_t is small compared with n , as is the case with Longwell's stabilizers.

When δ_t/n has an appreciable value compared with unity as is the case with the data of Lewis and von Elbe the whole term $(1 + \delta_t/n)$ should be used as a multiplying factor with $V_{so}/n^{0.45}$ to obtain best correlation. The use of such a term

would tend to raise the plotted data more nearly up to the other correlation curves obtained with hydrocarbon fuels and should improve the correlation. Unfortunately, Lewis and von Elbe do not report values of the laminar flame velocity, S_L , (required for the calculation of δt using equation 6) at air-fuel ratios as lean as those employed in obtaining the inverted cone blow-out data, therefore a plot of

$$\frac{V_{so}}{n^{0.45}} \left(1 + \frac{\delta t}{n}\right) \text{ vs } O_g$$

to determine whether improved correlation of the data is obtained as predicted can now be made.

not.

Blow-out Limits for Stabilizers of the Same Characteristic Dimension but of Different Shape Found to Fall on the Same Curve

It has already been shown that the blow-out limits for flames stabilized on rods and closed edged gutters were approximately the same. In Figure 126 are plotted the blow-out limit data for 5 stabilizers of different shape but having approximately the same characteristic dimension of 0.5 inches. Data obtained with a rod, a closed edged gutter, open edge gutters with a ratio of total area to open area of 100 and 25, and a flat plate are included, and a single curve is drawn through these data. It is thus concluded that the length of the eddy region for all these shapes of the same characteristic dimension is approximately the same.

FIGURE 126

BLOW-OUT LIMITS FOR STABILIZERS OF THE SAME CHARACTERISTIC
DIMENSION BUT OF DIFFERENT SHAPE

Blow-out Limits Obtained With a 0.038 inch Rod Stabilizer
Located in Chambers of Different Simulated Width Found to
be the Same

In Figure 127 are presented the blow-out limit data obtained with 0.038 inch stabilizers mounted in a chamber 3 inches in width and in chambers of simulated widths equal to 1.5 inches, 0.75 inches, and 0.375 inches. The smaller chamber widths were simulated by employing 2, 4, and 8 rod stabilizers as previously described. A single curve is drawn through the data for the three largest chambers from which it can be concluded that, as might be expected, the blow-out limits are unaffected by chamber width over this range*. It is observed, however, that for the narrowest simulated chamber width on the lean side the blow-out limits occur at mixtures nearer to stoichiometric than found with the wider chambers. The significance of this last observation is not clearly understood but it is expected that some resonance occurred when the blow-out limits with the 8 rod stabilizer (employed to simulate a chamber width of 0.375 inches) were obtained due to the high ratio of chamber length to width and the resulting high fraction burned at the chamber exhaust.

* It was found that blow-out of the flames from the multiple rod stabilizer occurred from all the rods at the same time as closely as could be determined by visual observation.

FIGURE 127

BLOW-OUT LIMITS FOR 0.038" ROD STABILIZERS MOUNTED IN
CHAMBERS OF DIFFERENT SIMULATED WIDTH

It can thus be tentatively concluded that, if no unsteady burning effects occur, the blow-out limits from any one stabilizer are independent of chamber width. This conclusion must be qualified, however, since it could not be expected to hold indefinitely as the ratio of chamber width to stabilizer characteristic dimension approached one.

It is also observed from Figure 127 that the blow-out limits were not modified for the multiple rods if some of the flames were not attached to the stabilizer at blow-out.

Effect of Turbulence on the Stability Limits

Turbulence might be expected to have two types of effect on the stability of a flame. The first, the importance of which would probably depend not only on the turbulence intensity but also on the ratio of turbulence scale to stabilizer characteristic dimension, is that due to the actual fluctuation of local velocity at the stabilizer. During these fluctuations the velocity at the stabilizer would be expected often to reach values considerably higher than the average stream velocity, V_0 , and blow-out would thus be likely to occur at a lower V_0 than if turbulence were absent.

The second effect, which very likely becomes more important with turbulence of smaller scale, is that due to

the wrinkling of the flame front and the increase in the diffusivity and thermometric conductivity as a result of increasing the eddy diffusivity. How wrinkling of the flame front and increasing the eddy diffusivity of the approach stream affects the stability limits is not immediately clear.

In equation 50 S_L in the denominator would be increased according to equations 20, 21, or 26, and $\sqrt{g'}$ in the numerator would be replaced by $(\sqrt{V} + E)g'$ where g' , as has already been pointed out, has a value near a half. Since both the numerator and denominator are increased in a rather complicated manner by the addition of turbulence it is difficult to decide in any one case what the effect of the introduction of turbulence on equation 50 would be. It would be expected, however, that the effect on the numerator and denominator would tend to cancel, making the effect of turbulence on the whole expression rather small.

It is believed, therefore, that the effect of the introduction of turbulence on the stability limits obtained during this investigation is primarily due to variation from the mean value of the local velocity at the stabilizer. For turbulence of the same scale the stability limits should, therefore, be less influenced the larger the stabilizer.

Referring to Figures 117 and 120 presenting the stability limit curves for rods and gutters, respectively, and to Figure 122 presenting data obtained using propane as a fuel instead of city gas, it is noted that the effect of placing the 3 mesh 0.063" wire diameter screen at the chamber entrance, producing a turbulence intensity of 2.67 per cent and a scale of 0.061 inches at the stabilizer, is to reduce the stability limits below those obtained with no screen in place. This reduction in blow-out velocity at any one air-fuel ratio is considerably greater on a percentage basis with the smaller stabilizers than with those of larger characteristic dimension. In fact, with the two largest rod stabilizers it was difficult to note any effect of the screen on the stability limits. Consequently, data were only obtained with these two stabilizers with a screen in place.

The 0.038 inch rod stabilizer was also placed at 6 inches and at 2 inches from the chamber entrance and blow-out limit data obtained with the 3 mesh 0.063" wire diameter, the 8 mesh 0.025" wire diameter, and the 55 mesh 0.007 inch wire diameter screens in place, and with no screen in place (runs 82 through 89). The blow-out limits obtained with the stabilizer located at 6 inches and 2 inches from the chamber entrance are presented in Figures 128a and 128b, respectively. The scale and intensity of the turbulence

FIGURE 128 (A)

EFFECT ON STABILITY LIMITS OF DIFFERENT TURBULENCE
GENERATING SCREENS PLACED 6" UPSTREAM OF 0.038" ROD

FIGURE 128 (B)
EFFECT ON STABILITY LIMITS OF DIFFERENT TURBULENCE GENERATING
SCREENS PLACED 2" UPSTREAM OF 0.038" ROD

thought to be present at the stabilizer for each curve is indicated in the legends of these two figures.

As expected the higher the turbulence level the greater the reduction in the stability limits. Some unsteady burning occurred near blow-out with the stabilizers located 2 inches from the chamber entrance due to the greater length of combustion chamber downstream of the flame stabilizer. This probably explains the somewhat anomolous shape shown in Figure 128b of the stability limit curve obtained with no screen in place.

Stability Limits for a Stabilizer Located at Different Distances from the Chamber Entrance

In Figure 129 is shown for comparison the stability limit data obtained with the 0.038 inch rod stabilizer located at 9, 6, and 2 inches from the chamber entrance with no screen in place. Some difference is seen to exist between the stability limit curves with the limits in general widening slightly as the stabilizer is moved closer to the chamber entrance. Too much significance should not be attached to these data, however, since the runs with the stabilizer at 6 and 2 inches from the chamber entrance were made when the city gas was of doubtful composition. Some rough burning was observed near blow-out with the stabilizer at 2 inches from the chamber entrance which probably further

FIGURE 129
STABILITY LIMITS FOR 0.038" ROD AT DIFFERENT
DISTANCES FROM THE CHAMBER ENTRANCE

decreases the internal consistency of these data. Further no correction has been made for the change in the ratio of central stream velocity to V_0 seen to exist at different distances from the chamber entrance from Figure 24. Making this correction would tend to bring the curves somewhat closer together.

E. A Discussion of Unsteady Burning Phenomena

Two types of unsteady burning phenomena which frequently appear in ram-jet combustion chambers were observed under certain conditions in the chamber employed during this investigation. The first, which is sometimes called "rough burning", is generally accompanied by extremely high intensity sound with a rather random frequency distribution, and is in most cases found to occur near blow-out. The second type of instability phenomenon, which includes both "resonance" and "flutter" is of a periodic nature. During resonance the flame front rapidly fluctuates between an upper and a lower limit about its steady-state position and a relatively high frequency pure note, often of extremely high intensity, is emitted. Flutter, like resonance, is observed as a periodic fluctuation of the flame front, but the period of this movement is at least an order of magnitude greater than that of resonance, and no accompanying high intensity sound is heard. During flutter the upper and lower limits of the fluctuating motion are often much more widely separated than is the case during resonance, with the lower limit of movement of the flame sometimes being an inch or more below the flame stabilizer.

Both types of unstable burning phenomena increase the tendency toward blow-out, the blow-out limits under these conditions generally becoming rather unpredictable and unrepeatable.

1. Theoretical Considerations

Rough burning is thought to be rather simply explained as due to the changes in the random fluctuations about a mean value of the fraction burned, F . Fluctuations in F cause similar fluctuations in the static pressure drop across the combustion chamber, ΔP_0 . Since the exhaust pressure remains constant, changing ΔP_0 causes changes in pressure of the approach stream and thus results in random increases and decreases in V_0 . The value of ΔP_0 is given approximately by the following equation:

$$\Delta P_0 = \rho_1 V^2 (R_p - 1) F \quad (54)$$

where V is in this case the velocity of the approach gases relative to the combustion zone and equals V_0 when this zone is stationary. (Note that Equation 54 gives the static pressure drop across the combustion zone whether the flame front is stationary or moving in space so long as the value of V is that of the cold gas relative to the flame front.)

On the basis of equation 54 it would be expected that V_0 would be most affected, the burning thus being the roughest, when the variation in F is at a maximum. For given V , ρ , R_p and combustion chamber length, F would be expected to vary most in absolute value with time when combustion is near completion. It would also be expected to vary considerably near blow-out when the propagation just above the stabilizer

is often discontinuous.

A tentative explanation of periodic unsteady burning phenomena will now be advanced.

If a tack were balanced on its point and a differential sidewise force applied, the tack would topple over; the application of the initial differential force causing additional finite gravitational forces to act on the tack augmenting the initial force. The tack when balanced on its point is said to be in a state of unstable equilibrium since it can be upset by a differential force properly applied. If, on the other hand, the tack had been standing on its head, it would not have been upset by the differential force and thus would have been in a state of stable equilibrium.

Let us continue in this same vein to a consideration of the flow through the combustion chamber while combustion is proceeding. If V_0 were by some means reduced a differential amount and the pressure drop across the combustion chamber fell, the pressure at the stabilizer would also fall (since the chamber exhaust pressure may be assumed constant) and the tendency would be for V_0 to increase because of the increased pressure drop available for acceleration of the gases. A condition of stable equilibrium would thus exist since V_0 would tend to return to its initial equilibrium

position. If, on the other hand, as V_0 decreased differentially, an increase in the pressure drop across the combustion chamber occurred, the pressure would necessarily be increased upstream of the flame and V_0 would soon be reduced by a finite amount. This latter condition, if it existed, would be one of unstable equilibrium and would very likely result in a periodic fluctuation of V_0 about the equilibrium position with the period of the fluctuation probably being some function of the apparatus.

It will now be shown that under certain conditions a differential change in V_0 will cause ΔP_0 to change in such a way that this initial differential change is made to become finite.

Considering the effect on ΔP_0 , as given by equation 54, at the instant that a differential change in V_0 , dV , takes place and assuming that the flame velocity, S_f , at all points along the flame front remains constant for an instant after V_0 is decreased, the flame would no longer remain fixed in the duct, but would advance upstream at a velocity dV . The value of V in equation 54, which is the velocity of the approach stream relative to the flame front, would thus remain unchanged. The advance of the flame front would however, cause a lengthening of the combustion zone within the

chamber, assuming that combustion was not initially complete, thus increasing F by an amount ΔF and producing the following increase in ΔP_0 :

$$\Delta(\Delta P_0) = \rho_1 V^2 (R_p - 1) \Delta F \quad (55)$$

For the change in the fraction burned, ΔF , may be substituted $(S_f/V_0)\Delta s_r$. This is obtained from a mass balance across the additional segment of flame front, Δs_r , brought down into the chamber when V_0 is decreased, and along which the flame velocity, S_f , exists. Making this substitution, equation 55 becomes:

$$\Delta(\Delta P_0) = \rho_1 V^2 (R_p - 1) \frac{S_f}{V_0} \Delta s_r \quad (56)$$

If the reasoning were carried no further it would be expected that unstable equilibrium always exists and that flutter and resonance would always appear so long as the fraction burned at the initial equilibrium condition was less than unity. An increase in F would thus always occur when V_0 decreased and the combustion zone advanced upstream. Two factors tend to modify this conclusion. First, it is necessary to add a term to equation (56) taking into account the change in pressure drop with changing V_0 . This drop is due to wall forces on the chamber wall, the flame stabilizer, and any obstruction, such as a screen, at the chamber entrance.

All of these pressure drops are approximately proportional to V_0^2 . Taking these changes in pressure drop into account by the inclusion of an additional term in equation 56, the following expression results:

$$\Delta(\Delta P_0) = C' \rho_1 \Delta(V_0^2) + \rho_1 V^2 (R_p - 1) \frac{S_f}{V_0} \Delta s_r \quad (57)$$

where C' is a constant similar to a drag coefficient and is proportional to the sum of the coefficients for the walls, the stabilizer, and the screen. As long as the first term on the right hand side is larger than the second, a stable equilibrium exists with the system tending to remain automatically at the equilibrium condition.

The picture of the entire combustion zone moving upstream at a velocity equal to dV_0 , the initial decrease in V_0 , could only be valid for a very short interval of time after the initial velocity decreased. The flame after moving upstream a short distance, would assume a new equilibrium position and would no longer continue to advance*. When this occurs a considerable decrease in ΔP_0 takes place. The

* The flame front would stop advancing even if S_f did not change, since after the flame advanced for a short distance, this advance being more retarded near the stabilizer than at a location on the flame front further downstream, a new equilibrium position, with the angle of entry of the unburned gases into the flame front adjusted to the lower V_0 , would quickly be assumed.

value of this is obtained from equation 54 by differentiating with respect to V (since the flame front is again stationary V can be replaced by V_0). The following is thus obtained:

$$\Delta(\Delta P_0) = 2V_0 \rho_1 (R_p - 1) F \Delta V_0 \quad (58)$$

At this later time, then, a drop in pressure occurs which tends to return the chamber velocity toward its original equilibrium V_0 if it was not initially returned by the change in friction pressure drop. This delayed change in pressure drop, thus, very likely accounts for the return of the fluttering flame toward its equilibrium position after it goes for a distance past this position. Although equation 58 gives the value of a delayed change in pressure drop which does not reach its full value until the combustion zone comes to rest, the effect of this term probably begins to be felt as a stabilizing influence almost immediately.

Let us now return to an examination of equation 57 keeping the probable effect of equation 58 also in mind. It is first concluded that no instability should result as long as F is unity; thus, according to equation 57, if complete combustion is being obtained, no resonance should occur. Second, when combustion is near completion the flame velocity along the additional segment of flame front brought down into the chamber, S_f , is largest; and from geometrical considerations

the length of this segment itself, Δs_r , should be longest when the initial flame length, and thus the fraction burned, is greatest. It is thus concluded that the instability term, the second term on the right hand side of equation 57, is likely to reach highest values when the fraction burned is not far from unity, but the term becomes equal to zero when F is unity since ΔF then must equal zero. The greatest likelihood of obtaining flutter and resonance, therefore, is present when combustion is almost complete at the chamber exit.

2. Experimental Observations

Flutter was observed at velocities of 50 feet per second and below when the fraction burned approached unity and the flame fronts almost reached the chamber side walls. While flutter was taking place (run 66) at a V_0 of 25.2 feet per second and an air-fuel ratio of 10.34 pounds per pound. A hot-wire probe was placed in the approach stream. The 0.188 inch rod stabilizer located 9 inches from the chamber entrance was employed with no turbulence generating screen in place. The entire column of air in the chamber changed in velocity periodically at about 30 cycles per second as seen by viewing the oscilloscope screen which was in the circuit with the hot-wire. The trace on the oscilloscope screen appeared as a perfect sine wave. The effective measured "turbulence intensity"* obtained during this flutter was 22.3 per cent the maximum velocity thus being $(25.2 \pm 0.223 \times 25.2 \times 1.41) = 33.1$ feet per second and the minimum $(25.2 - 0.223 \times 25.2 \times 1.41) = 17.3$ feet per second.

Increasing the fuel rate and obtaining an air-fuel ratio of 8.04 pounds per pound, the measured "turbulence intensity"

* As has been previously pointed out, the hot-wire anemometer yields a value of root-mean-square fluctuating velocity in the chamber which, however, need not necessarily be due to turbulence but may, as in this case, be due to some other cause.

became 23.7 per cent, the flame moved down into the chamber somewhat more than previously, and the frequency of the sine wave signal from the hot-wire as seen on the oscilloscope screen increased somewhat.

If the organ pipe frequency of the combustion chamber and calming section is calculated assuming a length of 7 feet (equal to a quarter wave length) and a speed of sound equal to about 1100 feet per second a frequency of 39 cycles per second is obtained - approximately that present during flutter. Why a slight increase in frequency should result with air-fuel ratios nearer to stoichiometric is not known, but it might be due to an increase in the speed of sound in the richer mixtures due to a higher theoretical flame temperature of the burner gases.

The range of air-fuel ratios over which flutter occurred was considerably narrowed by placing a screen at the chamber entrance as would be expected on the basis of equation 57 in which the first term on the right hand side - the term acting to stabilize the combustion process - is increased by increasing the resistance to flow. A screen was often employed during a run because of this desirable stabilizing action even when the effect of approach stream turbulence was not being studied. It was generally possible to obtain data over the entire range of air-fuel ratios at a V_0 of 50 feet per second

with a screen in place and with the stabilizer 9 inches from the chamber entrance although without a screen flutter was almost always present in the region near stoichiometric. The tendency to flutter was also reduced, as would be expected, by increasing the size of the stabilizer.

Some photographs of fluttering flames are included among the flame pictures in Appendix A and are designated by an asterisk.

Resonance was observed with a single element flame stabilizer only during the run with the 0.038 inch rod stabilizer located 2 inches from the chamber entrance and with no screen in place (run 85). Even under these favorable conditions only a rather mild resonance occurred at velocities above 200 feet per second. At lower velocities flutter, but no resonance, was observed. Extreme resonance which occurred, however, with the 4 and 8 rod flame stabilizers made it impossible to obtain flame photographs and blow-out limit data except over a limited range of chamber entrance velocities and air-fuel ratios (runs 72 and 73). With these two stabilizers combustion often neared completion at the chamber exit at higher velocities, a condition favorable to the appearance of resonance not generally realized with the single element stabilizers.

For example, at a V_0 of 50 feet per second with the 4 rod stabilizer located 9 inches from the chamber entrance and the 3 mesh 0.063" wire diameter screen at the chamber entrance, as air-fuel ratio was decreased toward stoichiometric, resonance first appeared at an air-fuel ratio of 6.58 pounds per pound. This became very severe at slightly richer mixtures. One or two of the flameholders would then lose their flames and the resonance would either stop completely or become considerably milder. At the first appearance of resonance, combustion appeared to be near completion at the chamber exit. At this same V_0 the fuel rate was increased in the same manner in five tests and resonance followed by blow-out of one or two of the flames occurred at the same air-fuel ratio in every case.

The exhaust stack was then uncoupled from the combustion chamber to find out if its presence had an effect on the occurrence of resonance. Resonance followed by blow-out of one or two of the flames occurred again at the same air-fuel ratio previously obtained with the stack in place, and no change in frequency of the pure note accompanying the resonance could be detected. It was therefore concluded that the presence or absence of the exhaust stack had no effect on the occurrence or the nature of the resonance.

At chamber entrance velocities above 50 feet per second the history of the flame is similar to that described at 50 feet per second. As richer mixtures are approached and combustion becomes more nearly complete at the chamber exit the tendency toward resonance increases. Finally, the mixture becomes sufficiently rich for resonance to occur and past this point anomolous behavior of the flame is observed with blow-out from some, or all, of the rods finally taking place at still richer mixtures. At yet higher velocities resonance occurs even at blow-out and reliable stability limit data comparable with those taken under steady burning conditions can no longer be obtained.

Some photographs of flames taken during resonance are included among the flame pictures in Appendix A and are designated by two asterisks.

It is to be noted that complete combustion was sometimes obtained at 25 feet per second (see Figure 102) with no resonance occurring.

The musical note accompanying resonance in the present apparatus has a frequency estimated at between 300 and 400 cycles per second. No noticeable change in this frequency occurs with changes in V_0 . Assuming a speed of sound equal

to 1100 feet per second and a chamber length of 1.5 feet, (equivalent to a half wave length) a calculated resonant frequency of 370 cycles per second is obtained* - a value within the range actually thought to be present.

It was further observed that removal of one of the probe hole bolts in the side of the chamber during resonance thus opening the chamber to the atmosphere, resulted in an increase in frequency of the note accompanying the resonance. Occasionally, removal of one or two of these bolts even made the resonance change in intensity or stop altogether.

The very scanty data obtained relating to unsteady burning phenomena do not conflict with the theoretical considerations here included, but the data are much too few to draw firm conclusions. The importance from the combustion chamber design standpoint of gaining a better understanding of unsteady burning phenomena is so great that a thorough investigation seems justified.

* The combustion chamber is here assumed to have an antinode at each end with the calculated fundamental frequency thus being obtained by equating the chamber length to a half wave length. For calculation of the fundamental frequency of the chamber plus calming section it was assumed, on the other hand, that an antinode exists at the open end of the chamber and a node was present at the pipe wall at the base of the calming section, the calculated fundamental frequency in this case being obtained by equating the overall length of the chamber plus calming section to a quarter wave length.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. Flame Propagation

On the basis of the stepwise calculations giving the flow theoretically present during combustion for incompressible flow in a chamber of constant cross section, and thought to approximate the actual flow, the following general conclusions are obtained:

1. Velocity gradients are generated due to the combustion process itself even when no gradients exist prior to combustion. This occurs because the burned gases in the central portion of the chamber are accelerated more rapidly than the outer unburned gases.

2. For uniform approach velocity and air-fuel ratio, a relation between flame width and fraction burned at any one cross section results from the calculations which makes it possible by means of a simple material balance, the measured flame width, and the flame length, to calculate an actual effective flame velocity thought to be fairly accurate.

3. Pressure drop across the chamber for complete combustion is greater when combustion proceeds from a stabilizer than when the heat is added uniformly across the cross section, the ratio of these pressure drops becoming greater the larger the ratio, R_g , of the unburned to burned gas density.

4. A parcel of unburned gas before entering the flame front has a small velocity component in a direction normal to the

chamber axis so that the angle of the resultant velocity vector to the flame front is reduced. After passing through the flame front and burning, the parcel has a velocity component in the reverse direction which becomes zero when combustion is completed in the chamber.

It is recommended that additional experimental work be carried out to establish how well the results of the stepwise calculations approximate actual conditions, and the validity of the assumptions made in carrying out these calculations. Such experiments should be planned with the objective of obtaining the lines of flow and the temperature distribution in the chamber during combustion. It is recommended that additional stepwise calculations be carried out without the assumption of incompressibility.

Based primarily on experimental results, the following conclusions regarding propagation of the flame downstream of the stabilizer have been reached:

1. No classical Karman vortex trail due to eddy shedding from the stabilizer is present during combustion. Instead, the region behind the stabilizer in which isothermal flow eddies are formed, and from which the Karman vortex trail is shed is thought to shorten and become symmetrical during combustion. This is similar to what occurs in isothermal flow around a bluff object when the Reynolds number is reduced to below about 30.

2. The effective flame propagation velocity is increased over the laminar flame propagation velocity, S_L , by three different types of disturbance:

- (a) Generation of reverse eddies and turbulence due

to velocity gradients across the flame front present in the region just downstream of the flame stabilizer. This type of disturbance is most likely to appear when the value of the following expression is large:

$$\left(\frac{v_o n}{\nu} \right)^{0.1 \text{ to } 0.3} \left[\frac{v_o}{S_L (R_p - 1)} \right] \quad (43)$$

Frequently no disturbance due to instability of this first region is present. Under these conditions no effect of stabilizer diameter on flame propagation is observed.

(b) Generation of regular eddies and turbulence due to velocity gradients across the flame front produced by the pressure drop resulting from the combustion process itself, this pressure drop causing the low-density burned gases to accelerate more rapidly than the high-density unburned gases. This type of disturbance is most likely to appear when the following expression is large:

$$\frac{v_o W_t}{\nu} (F) (R_p - 1) \left(\frac{v_o}{S_L} \right) \quad (45)$$

(c) The approach stream turbulence: The effect of approach stream turbulence intensity on flame velocity is, under most conditions, masked by the effect of the other disturbances. Its effect is quite small even at approach stream turbulence intensities as high as that present at the center of a pipe in which fully developed turbulent flow exists (3 per cent), and is in most cases still somewhat smaller than the effect due to internally generated

disturbances at turbulence intensities as high as 6.5 per cent. The following equation was found to describe quite well the effect of approach stream turbulence on flame velocity:

$$\frac{S_T}{S_L} = \sqrt{1 + \left(\frac{u'}{2S_L}\right)^2} \quad (21)$$

3. Propagation of the flame downstream of stabilizers of the same characteristic dimension but of differing shape is in most cases the same. However, at the higher velocities at very lean mixtures when turbulence generation in the first region of velocity gradients controls the rate of flame propagation, for the 30° gutters and flat plates ($n \times 0.37$) and ($n \times 1.5$) respectively, should be employed as the effective characteristic stabilizer dimension to put these shapes on a basis comparable with rods for flame width comparisons.

4. The flame velocity in general increases with distance downstream from the stabilizer.

5. From observation of residual flames it is concluded that under certain conditions there may exist near the stabilizer a stable flame which fails to propagate into the main body of the combustible gas stream, but instead is quenched.

Further experimental work on the subject of high velocity flame propagation is recommended. It is believed that the effect on flame propagation of the internal disturbances due to velocity gradients at the flame front, and the effect of approach stream turbulence must be studied separately. One approach to the study

of the internally generated disturbances might be to investigate the appearance of instability on a surface of discontinuity between two dissimilar fluids moving at different velocities. A study of the effect of approach stream turbulence could very likely best be carried out on a flame front across which no appreciable velocity gradients exist.

B. Flame Stabilization

From theoretical considerations regarding flames stabilized on bluff nonconducting objects, it was concluded that the following equation applies at blow-out:

$$\frac{v_{BO} e' - g'}{n g'} - \frac{K'}{(V) g'} \frac{S_L (T_b - T_o)}{(T_i - T_o)} - \phi \left(\frac{1}{f} \right) \quad (50)$$

An additional term, $K''(n/S_L)^{\frac{h}{h'}}$, added to the left-hand side of equation (50) is suggested to allow for heat conduction by the stabilizer and the resultant cooling of the eddy region.

The following conclusions regarding flame stabilization were arrived at based primarily on experimental results:

1. The mechanism of flame stabilization behind bluff objects is different from that for stabilization of flames of the Bunsen type. The eddy region present behind the bluff stabilizer is filled with hot combustion products when a stabilized flame is present and these recirculating hot gases furnish a continuous source of ignition for the unburned approach gases coming into contact with them. Due to absence of an eddy region a flame will not, therefore, stabilize on a streamlined object at approach gas velocities in the range of interest for high-output systems.

2. In accord with equation (50), blow-out limit data

obtained with stabilizers ranging in characteristic dimension from 0.16 to 0.5 inches were found to correlate fairly well when $V_{BO}/n^{0.45}$ was plotted versus 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. The addition of a second term to the left-hand side of equation (50) has been suggested to take into account this effect by correcting for conduction through the stabilizer. By plotting the stability limit data of Longwell and of Lewis and von Elbe as $V_{BO}/n^{0.45}$ versus generalized oxidant fraction, correlations thought to be as satisfactory as those originally obtained by these investigators using other methods of correlation were obtained.

3. The effect of stabilizer shape on the stability limits is negligible for the bluff stabilizers employed: rods, 30° open and closed edge gutters, and a flat plate normal to the flow.

4. 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.

5. 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.

6. Values of $V_{BO}/n^{0.45}$ are apparently a direct function of S_L and $(T_b - T_o)$, as indicated in equation (50), but at least

one of the other quantities on the right-hand side of equation (50) apparently also varies with different fuels, since correlation of the city gas-air and propane-air stability limit data is not obtained by plotting $V_{BO}/n^{0.45} (S_L)(T_b - T_o)$ versus generalized oxidant fraction.

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

It is recommended that considerable further investigation of the stabilization mechanism be undertaken. Aspects of the problem on which further study should prove especially fruitful are the following:

(a) Quantitative study of the velocity and temperature distribution in the vicinity of the stabilizer (in and around the eddy region and in the boundary layer) during combustion and at blow-out.

(b) Study of the effect of pressure on the stability limits. Equation (50) predicts a reduction in stability at lower pressures. (ν is approximately inversely proportional to pressure).

(c) Further study of stabilization on heated and cooled stabilizers.

(d) Study of the stability limits of different gaseous fuels of known properties in an attempt better to establish the mechanism of flame stabilization and to obtain a satisfactory correlation of stability limits for

fuels of various properties.

(e) A more detailed study of the effect of scale and intensity of turbulence on the stability limits.

C. Unsteady Burning Phenomena

On the basis of theoretical considerations and a few experimental observations, the following conclusions in regard to unsteady burning phenomena have been reached:

1. Rough burning is due to random fluctuations about a mean value of the fraction burned, F . Fluctuations in F cause similar fluctuations in the static pressure drop, ΔP_c , across the combustion chamber. Since the exhaust pressure remains constant, changing ΔP_c causes changes in pressure of the approach stream and thus results in random increases and decreases in V_0 . Burning tends to be roughest when F is large and when it fluctuates most in absolute value with time.

2. Unsteady burning phenomena of a periodic nature, resonance and flutter occur when an unstable equilibrium exists. They are most likely to appear when F is very near unity and when S_f at the chamber exit is large, but should not appear when combustion is complete. Resistance to flow produced by the chamber walls, the stabilizer, or a screen placed at the chamber entrance, reduces the likelihood of appearance of resonance or flutter.

3. During resonance or flutter, the period of the vibration is the resonant frequency of some portion of the apparatus. Resonance during this investigation occurred at the fundamental

organ-pipe resonant frequency of the combustion chamber, and flutter occurred at the fundamental resonant frequency of the combustion chamber and calming section together.

The importance from the combustion chamber design standpoint of gaining a better understanding of unsteady burning phenomena is so great that a thorough investigation of unsteady burning seems justified.

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A. Supplementary Results and Discussion

1. Numerical Results of Stepwise Calculations

In Table IV is presented the numerical results of the stepwise calculations of flow through a rectangular combustion chamber for an $R\rho$ of 8, 6, and 4. The velocity of the unburned gas on a reduced basis, V_{ru} , the furthest extension of the burned gases from the center of the chamber on a reduced basis, Y_r , the fraction burned after each step, F , the increase in the fraction burned after every step, ΔF , the width of each segment of burned material on a reduced basis, ΔY_r , and the velocity of each segment of burned material after each step on a reduced basis, V_{rb} , are given in the table.

STEPWISE CALCULATION OF FLOW THROUGH COMBUSTION CHAMBER DURING COMBUSTION

TABLE IV

$R_p = 8$		$R_p = 6$		$R_p = 4$		
Step	V_{r1}	V_{r2}	V_{r1}	V_{r2}	V_{r1}	V_{r2}
1	1.30384	1.28897	1.22474	1.22546	1.14018	1.17262
2	1.54919	1.44778	1.41421	1.38506	1.35491	1.30209
3	1.76085	1.54998	1.55114	1.49050	1.37940	1.30215
4	1.94326	1.62517	1.73206	1.56998	1.48524	1.48476
5	2.12133	1.68776	1.87083	1.62672	1.58114	1.58348
6	2.28035	1.72875	2.00000	1.66812	1.66951	1.66586
7	2.42899	1.75656	2.12133	1.72854	1.73653	1.72854
8	2.56905	1.78355	2.23507	1.78273	1.81628	1.79446
9	2.70185	1.80615	2.34521	1.82406	1.89462	1.86404
10	2.82843	1.82428	2.44949	1.86217	1.96951	1.93715
11	2.94958	1.83937	2.54951	1.89656	2.03951	1.99748
12	3.06594	1.85199	2.64575	1.92613	2.10621	2.05118
13	3.17805	1.86229	2.73861	1.95132	2.16951	2.09951
14	3.28634	1.87035	2.82843	1.97273	2.22951	2.14261
15	3.39117	1.87622	2.91117	1.99035	2.28621	2.18035
16	3.49285	1.88037	2.98951	1.99951	2.33951	2.21261
17	3.59162	1.88312	3.06221	1.99951	2.38951	2.23951
18	3.68782	1.88485	3.13035	1.99951	2.43621	2.26121
19	3.78158	1.88562	3.19405	1.99951	2.47951	2.27851
20	3.87285	1.88612	3.25351	1.99951	2.51951	2.29121
21	3.96162	1.88645	3.30905	1.99951	2.55621	2.30035
22	4.04850	1.88662	3.36121	1.99951	2.58951	2.30621
23	4.13384	1.88675	3.41035	1.99951	2.61951	2.30951
24	4.21785	1.88685	3.45621	1.99951	2.64621	2.31121
25	4.29951	1.88695	3.49951	1.99951	2.66951	2.31261
26	4.37885	1.88705	3.54035	1.99951	2.68951	2.31385
27	4.45621	1.88715	3.57851	1.99951	2.70621	2.31485
28	4.53162	1.88725	3.61405	1.99951	2.71951	2.31562
29	4.60594	1.88735	3.64785	1.99951	2.72951	2.31621
30	4.67885	1.88745	3.67951	1.99951	2.73621	2.31662
31	4.74951	1.88755	3.70951	1.99951	2.73951	2.31685
32	4.81785	1.88765	3.73785	1.99951	2.73951	2.31685
33	4.88384	1.88775	3.76405	1.99951	2.73951	2.31685
34	4.94785	1.88785	3.78851	1.99951	2.73951	2.31685
35	5.00951	1.88795	3.81121	1.99951	2.73951	2.31685
36	5.06885	1.88805	3.83261	1.99951	2.73951	2.31685
37	5.12594	1.88815	3.85261	1.99951	2.73951	2.31685
38	5.18085	1.88825	3.87121	1.99951	2.73951	2.31685
39	5.23384	1.88835	3.88851	1.99951	2.73951	2.31685
40	5.28485	1.88845	3.90451	1.99951	2.73951	2.31685
41	5.33384	1.88855	3.91951	1.99951	2.73951	2.31685
42	5.38085	1.88865	3.93351	1.99951	2.73951	2.31685
43	5.42594	1.88875	3.94651	1.99951	2.73951	2.31685
44	5.46951	1.88885	3.95851	1.99951	2.73951	2.31685
45	5.51162	1.88895	3.96951	1.99951	2.73951	2.31685
46	5.55285	1.88905	3.97951	1.99951	2.73951	2.31685
47	5.59384	1.88915	3.98851	1.99951	2.73951	2.31685
48	5.63384	1.88925	3.99651	1.99951	2.73951	2.31685
49	5.67285	1.88935	4.00351	1.99951	2.73951	2.31685
50	5.71085	1.88945	4.00951	1.99951	2.73951	2.31685
51	5.74785	1.88955	4.01451	1.99951	2.73951	2.31685
52	5.78384	1.88965	4.01851	1.99951	2.73951	2.31685
53	5.81885	1.88975	4.02151	1.99951	2.73951	2.31685
54	5.85285	1.88985	4.02351	1.99951	2.73951	2.31685
55	5.88584	1.88995	4.02451	1.99951	2.73951	2.31685
56	5.91785	1.89005	4.02451	1.99951	2.73951	2.31685
57	5.94885	1.89015	4.02351	1.99951	2.73951	2.31685
58	5.97884	1.89025	4.02151	1.99951	2.73951	2.31685
59	6.00785	1.89035	4.01851	1.99951	2.73951	2.31685
60	6.03584	1.89045	4.01451	1.99951	2.73951	2.31685
61	6.06285	1.89055	4.00951	1.99951	2.73951	2.31685
62	6.08884	1.89065	4.00351	1.99951	2.73951	2.31685
63	6.11385	1.89075	3.99651	1.99951	2.73951	2.31685
64	6.13785	1.89085	3.98851	1.99951	2.73951	2.31685
65	6.16085	1.89095	3.97951	1.99951	2.73951	2.31685
66	6.18285	1.89105	3.96951	1.99951	2.73951	2.31685
67	6.20384	1.89115	3.95851	1.99951	2.73951	2.31685
68	6.22385	1.89125	3.94651	1.99951	2.73951	2.31685
69	6.24285	1.89135	3.93351	1.99951	2.73951	2.31685
70	6.26085	1.89145	3.91951	1.99951	2.73951	2.31685
71	6.27785	1.89155	3.90451	1.99951	2.73951	2.31685
72	6.29384	1.89165	3.88851	1.99951	2.73951	2.31685
73	6.30885	1.89175	3.87121	1.99951	2.73951	2.31685
74	6.32285	1.89185	3.85261	1.99951	2.73951	2.31685
75	6.33584	1.89195	3.83261	1.99951	2.73951	2.31685
76	6.34785	1.89205	3.81121	1.99951	2.73951	2.31685
77	6.35884	1.89215	3.78851	1.99951	2.73951	2.31685
78	6.36885	1.89225	3.76405	1.99951	2.73951	2.31685
79	6.37785	1.89235	3.73785	1.99951	2.73951	2.31685
80	6.38584	1.89245	3.70951	1.99951	2.73951	2.31685
81	6.39285	1.89255	3.67951	1.99951	2.73951	2.31685
82	6.39884	1.89265	3.64785	1.99951	2.73951	2.31685
83	6.40385	1.89275	3.61405	1.99951	2.73951	2.31685
84	6.40785	1.89285	3.57851	1.99951	2.73951	2.31685
85	6.41085	1.89295	3.54035	1.99951	2.73951	2.31685
86	6.41285	1.89305	3.49951	1.99951	2.73951	2.31685
87	6.41384	1.89315	3.45621	1.99951	2.73951	2.31685
88	6.41385	1.89325	3.41035	1.99951	2.73951	2.31685
89	6.41285	1.89335	3.36121	1.99951	2.73951	2.31685
90	6.41085	1.89345	3.30905	1.99951	2.73951	2.31685
91	6.40785	1.89355	3.25351	1.99951	2.73951	2.31685
92	6.40384	1.89365	3.19405	1.99951	2.73951	2.31685
93	6.39885	1.89375	3.13035	1.99951	2.73951	2.31685
94	6.39285	1.89385	3.06221	1.99951	2.73951	2.31685
95	6.38584	1.89395	2.98951	1.99951	2.73951	2.31685
96	6.37785	1.89405	2.91117	1.99951	2.73951	2.31685
97	6.36885	1.89415	2.82843	1.99951	2.73951	2.31685
98	6.35884	1.89425	2.73861	1.99951	2.73951	2.31685
99	6.34785	1.89435	2.64575	1.99951	2.73951	2.31685
100	6.33584	1.89445	2.54951	1.99951	2.73951	2.31685
101	6.32285	1.89455	2.44949	1.99951	2.73951	2.31685
102	6.30884	1.89465	2.34521	1.99951	2.73951	2.31685
103	6.29385	1.89475	2.23507	1.99951	2.73951	2.31685
104	6.27785	1.89485	2.12133	1.99951	2.73951	2.31685
105	6.26085	1.89495	2.00000	1.99951	2.73951	2.31685
106	6.24285	1.89505	1.87083	1.99951	2.73951	2.31685
107	6.22385	1.89515	1.73206	1.99951	2.73951	2.31685
108	6.20384	1.89525	1.58114	1.99951	2.73951	2.31685
109	6.18285	1.89535	1.41421	1.99951	2.73951	2.31685
110	6.16085	1.89545	1.22474	1.99951	2.73951	2.31685
111	6.13785	1.89555	1.00000	1.99951	2.73951	2.31685
112	6.11385	1.89565	0.75000	1.99951	2.73951	2.31685
113	6.08884	1.89575	0.50000	1.99951	2.73951	2.31685
114	6.06285	1.89585	0.25000	1.99951	2.73951	2.31685
115	6.03584	1.89595	0.00000	1.99951	2.73951	2.31685
116	6.00785	1.89605	-0.25000	1.99951	2.73951	2.31685
117	5.97884	1.89615	-0.50000	1.99951	2.73951	2.31685
118	5.94885	1.89625	-0.75000	1.99951	2.73951	2.31685
119	5.91785	1.89635	-1.00000	1.99951	2.73951	2.31685
120	5.88584	1.89645	-1.25000	1.99951	2.73951	2.31685
121	5.85285	1.89655	-1.50000	1.99951	2.73951	2.31685
122	5.81885	1.89665	-1.75000	1.99951	2.73951	2.31685
123	5.78384	1.89675	-2.00000	1.99951	2.73951	2.31685
124	5.74785	1.89685	-2.25000	1.99951	2.73951	2.31685
125	5.71085	1.89695	-2.50000	1.99951	2.73951	2.31685
126	5.67285	1.89705	-2.75000	1.99951	2.73951	2.31685
127	5.63384	1.89715	-3.00000	1.99951	2.73951	2.31685
128	5.59384	1.89725	-3.25000	1.99951	2.73951	2.31685
129	5.55285	1.89735	-3.50000	1.99951	2.73951	2.31685
130	5.51162	1.89745	-3.75000	1.99951	2.73951	2.31685
131	5.46951	1.89755	-4.00000	1.99951	2.73951	2.31685
132	5.42594	1.89765	-4.25000	1.99951	2.73951	2.31685
133	5.38085	1.89775	-4.50000	1.99951	2.73951	2.31685
134	5.33384	1.89785	-4.75000	1.99951	2.73951	2.31685
135	5.28485	1.89795	-5.00000	1.99951	2.73951	2.31685
136	5.23384	1.89805	-5.25000	1.99951	2.73951	2.31685
137	5.18085	1.89815	-5.50000	1.99951	2.73951	2.31685
138	5.12594	1.89825	-5.75000	1.99951	2.73951	2.31685
139	5.06885	1.89835	-6.00000	1.99951	2.73951	2.31685
140	5.00951	1.89845	-6.25000	1.99951	2.73951	2.31685
141	4.94785	1.89855	-6.50000	1.99951	2.73951	2.31685
142	4.88384	1.89865	-6.75000	1.99951	2.73951	2.31685
143	4.81785	1.89875	-7.00000	1.99951	2.73951	2.31685
144	4.74951	1.89885	-7.25000	1.99951	2.73951	2.31685
145	4.67885	1.89895	-7.50000	1.99951	2.73951	2.31685
146	4.60594	1.89				

2. Pictures of the Stabilized Flame

On the following pages are presented all of the flame pictures printed using the photographic negatives from which the flame width measurements earlier discussed were obtained. Great care was taken to obtain the same detail in the print as present in the original negative from which measurements were obtained. Some loss of detail necessarily occurs, however.

Under each picture is given the chamber entrance velocity in feet per second designated as V and the air-fuel ratio designated as l/f . An asterisk beside the velocity indicates that flutter was taking place when the picture was taken, and two asterisks indicate that resonance was taking place. The three numbers in the lower part of each picture designate the negative number, the film pack number and the run number, respectively. The complete tabulation of experimental data for each picture is included in Appendix C. The stabilizer type, characteristic dimension, and distance from the chamber entrance; and the type of screen at the chamber entrance are tabulated preceeding the series of pictures to which they apply. The fuel employed is city gas unless otherwise designated.

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FLAMEHOLDER:

0.498" dia.
steel rod 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

V — 25.2
1/f — 12.36

V — 26.1
1/f — 8.98

V — 26.6
1/f — 7.66

V — 27.7
1/f — 6.10

V — 47.8
1/f — 13.47

V — 49.0
1/f — 10.41

V — 50.7
1/f — 7.92

V — 51.6
1/f — 6.92

V — 52.7
1/f — 6.09

V — 54.9
1/f — 5.02

V — 56.5
1/f — 4.44

V — 95.9
1/f — 12.61

V — 98.0
1/f — 10.16

V — 100.7
1/f — 8.02

V — 103.1
1/f — 6.81

V — 105.6
1/f — 5.94

V — 108.4
1/f — 5.23

V — 111.7
1/f — 4.59

V — 223.2
1/f — 11.01

V — 228.2
1/f — 8.49

V — 232.7
1/f — 7.31

V — 249.4
1/f — 6.21

V — 329.8
1/f — 9.50

FLAMEHOLDER:

0.311" dia.
steel rod 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

V — 25.3
1/f — 11.82

V — 26.2
1/f — 8.71

V — 27.2
1/f — 6.68

V — 48.1
1/f — 13.14

V — 49.7
1/f — 9.58

V — 51.1
1/f — 7.77

V — 52.4
1/f — 6.60

V — 54.4
1/f — 5.37

V — 56.0
1/f — 4.72

V — 54.7
1/f — 4.00

V — 93.8
1/f — 12.56

V — 96.6
1/f — 9.42

V — 98.9
1/f — 7.78

V — 101.0
1/f — 6.70

V — 103.9
1/f — 5.73

V — 108.5
1/f — 4.73

V — 223.5
1/f — 10.78

V — 229.1
1/f — 8.43

V — 233.7
1/f — 7.13

V — 238.2
1/f — 6.28

V — 243.5
1/f — 5.59

V — 338.8
1/f — 9.61

FLAMEHOLDER:

0.188" dia.
steel rod 9"
from chamber
entrance.

SCREEN:

none

5-1-11

V ---- 42.8
1/f -- 10.58

10-1-11

V ---- 41.1
1/f -- 13.46

11-1-11

V ---- 94.6
1/f -- 10.73

12-1-11

V ---- 102.3
1/f -- 7.84

1-2-11

V ---- 102.4
1/f -- 7.59

2-2-11

V ---- 95.7
1/f -- 12.94

3-2-11

V ---- 264.2
1/f -- 9.43

4-2-11

V ---- 270.5
1/f -- 8.43

2-1-12

V ---- 45.3
1/f -- 7.24

7-1-12

V ---- 47.2
1/f -- 5.47

8-1-12

V ---- 51.1
1/f -- 4.00

9-1-12

V ---- 33.0
1/f -- 6.11

10-1-12

V ---- 35.9
1/f -- 4.09

11-1-12

V ---- 30.2
1/f -- 11.45

1-1-13

V ---- 24.5
1/f -- 12.74

2-1-13

V ---- 25.0
1/f -- 10.42

3-1-13

V ---- 48.8
1/f -- 11.36

4-1-13

V ---- 49.5
1/f -- 9.61

5-1-13

V ---- 49.9
1/f -- 8.55

6-1-13

V ---- 52.1*
1/f -- 6.48

7-1-13

V ---- 56.0
1/f -- 4.52

9-1-13

V ---- 94.5
1/f -- 9.85

10-1-13

V ---- 95.9
1/f -- 8.58

V ---- 100.4
1/f -- 6.38

V ---- 107.8
1/f -- 4.51

V ---- 220.4
1/f -- 9.93

V ---- 225.5
1/f -- 8.34

V ---- 233.4
1/f -- 6.84

V ---- 303.7
1/f -- 7.55

V ---- 97.2
1/f -- 10.82

V ---- 99.1
1/f -- 9.10

V ---- 103.0
1/f -- 6.85

V ---- 101.1
1/f -- 7.78

V ---- 103.2
1/f -- 6.79

V ---- 108.5
1/f -- 5.18

V ---- 112.1
1/f -- 4.50

V ---- 114.8
1/f -- 4.11

V ---- 47.8
1/f -- 12.43

V ---- 49.0
1/f -- 9.88

V ---- 50.4*
1/f -- 8.02

V ---- 51.3*
1/f -- 7.03

V ---- 52.0*
1/f -- 6.39

V ---- 53.5
1/f -- 5.46

V ---- 55.1
1/f -- 4.78

V ---- 56.6
1/f -- 4.26

FLAMEHOLDER:

0.188" dia.
steel rod 9"
from chamber
entrance

SCREEN:

8 mesh
0.025" wire dia

V ---- 49.8
1/f -- 10.77

V ---- 51.4
1/f -- 8.02

V ---- 53.0
1/f -- 6.47

V ---- 57.2
1/f -- 4.45

V ---- 49.4
1/f -- 11.48

V ---- 25.3
1/f -- 10.85

V ---- 26.2
1/f -- 8.33

V ---- 27.1
1/f -- 6.56

V ---- 23.8
1/f -- 11.92

V ---- 24.4*
1/f -- 9.66

V ---- 24.9
1/f -- 8.28

V ---- 25.3*
1/f -- 7.28

V ---- 25.6*
1/f -- 6.77

V ---- 48.7
1/f -- 12.01

V ---- 50.5
1/f -- 8.58

V ---- 51.3
1/f -- 7.69

V ---- 52.2
1/f -- 6.73

V ---- 52.6
1/f -- 6.38

V ---- 53.1
1/f -- 6.07

V ---- 55.1
1/f -- 5.07

V ---- 56.6
1/f -- 4.54

V ---- 57.7
1/f -- 4.19

V ---- 58.6
1/f -- 4.00

V ---- 98.5
1/f -- 9.90

V ---- 101.2
1/f -- 7.88

V ---- 102.7
1/f -- 7.09

V ---- 105.2
1/f -- 6.09

V ---- 111.0
1/f -- 4.74

V ---- 207.4
1/f -- 9.20

V ---- 211.7
1/f -- 7.35

V ---- 215.5
1/f -- 6.41

V ---- 217.6
1/f -- 6.05

V ---- 293.5
1/f -- 8.90

FLAMEHOLDER:

0.188" dia.
steel rod 9"
from chamber
entrance.

SCREEN:

3 mesh
0.063" wire dia

V ---- 24.5
1/f -- 12.17

V ---- 24.8
1/f -- 10.78

V ---- 47.4
1/f -- 11.82

V ---- 48.8
1/f -- 9.10

V ---- 49.6
1/f -- 7.94

V ---- 50.6
1/f -- 6.90

V ---- 51.7
1/f -- 6.00

V ---- 53.2
1/f -- 5.22

V ---- 54.4
1/f -- 4.66

V ---- 55.8
1/f -- 4.26

V ---- 95.0
1/f -- 12.00

V ---- 97.5
1/f -- 9.49

V ---- 98.4
1/f -- 8.59

V ---- 101.5
1/f -- 6.81

V ---- 103.9
1/f -- 6.00

6-2-16

V ---- 110.1
1/f -- 4.58

7-2-16

V ---- 213.5
1/f -- 10.28

8-2-16

V ---- 218.6
1/f -- 7.96

9-2-16

V ---- 221.5
1/f -- 6.90

10-2-16

V ---- 225.5
1/f -- 6.09

FLAMEHOLDER:

0.126" dia.
steel rod 9"
from chamber
entrance

SCREEN:

8 mesh
0.025" wire dia.

6-1-20

V ---- 24.1
1/f -- 16.13

7-1-20

V ---- 24.0
1/f -- 15.09

8-1-20

V ---- 24.2
1/f -- 13.30

9-1-20

V ---- 24.9*
1/f -- 10.15

10-1-20

V ---- 25.4*
1/f -- 8.68

11-1-20

V ---- 25.9*
1/f -- 7.54

FLAMEHOLDER:

0.126" dia.
steel rod 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

12-1-20

V ---- 24.2
1/f -- 13.30

1-2-20

V ---- 47.3
1/f -- 13.31

2-2-20

V ---- 48.5
1/f -- 10.50

3-2-20

V ---- 50.3
1/f -- 7.83

4-2-20

V ---- 51.1
1/f -- 6.98

5-2-20

V ---- 52.2
1/f -- 6.19

6-2-20

V ---- 53.4
1/f -- 5.52

7-2-20

V ---- 53.8
1/f -- 5.30

8-2-20

V ---- 55.6
1/f -- 4.59

9-2-20

V ---- 56.2
1/f -- 4.37

10-2-20

V ---- 56.9
1/f -- 4.18

V ---- 54.9 1/f -- 5.54	V ---- 56.6 1/f -- 4.78	V ---- 58.8 1/f -- 4.09	V ---- 96.8 1/f -- 11.55	V ---- 99.6 1/f -- 8.97	V ---- 102.5 1/f -- 7.23

V ---- 104.1 1/f -- 6.57	V ---- 108.6 1/f -- 5.24	V ---- 113.7 1/f -- 4.31	V ---- 222.7 1/f -- 9.39	V ---- 228.1 1/f -- 7.77	V ---- 230.8 1/f -- 6.82
<p><u>FLAMEHOLDER:</u> 0.094" dia. steel rod 9" from chamber entrance</p> <p><u>SCREEN:</u> none</p>
V ---- 278.2 1/f -- 7.87	V ---- 264.8 1/f -- 6.67			V ---- 23.7 1/f -- 12.15	V ---- 48.8 1/f -- 12.71

V ---- 50.0 1/f -- 10.11

V ---- 51.4 1/f -- 8.11	V ---- 53.3 1/f -- 6.43	V ---- 54.8 1/f -- 5.44	V ---- 57.5 1/f -- 4.47	V ---- 58.6 1/f -- 4.14	V ---- 98.3 1/f -- 10.75

V ---- 101.7
1/f -- 8.11

V ---- 105.0
1/f -- 6.58

V ---- 110.8
1/f -- 5.00

V ---- 113.2
1/f -- 4.54

V ---- 222.6
1/f -- 9.83

V ---- 225.1
1/f -- 8.44

V ---- 228.0
1/f -- 7.53

V ---- 230.3
1/f -- 6.85

V ---- 235.2
1/f -- 6.05

V ---- 290.4
1/f -- 8.46

FLAMEHOLDER:
0.094" dia.
steel rod 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

V ---- 24.3
1/f -- 14.02

V ---- 24.7
1/f -- 11.69

V ---- 24.9
1/f -- 10.72

V ---- 24.2
1/f -- 15.00

V ---- 48.7
1/f -- 13.14

V ---- 49.7
1/f -- 10.50

V ---- 52.1
1/f -- 7.39

V ---- 53.1
1/f -- 6.51

V ---- 55.2
1/f -- 5.29

V ---- 57.3
1/f -- 4.50

V ---- 96.3
1/f -- 11.39

V ---- 98.1
1/f -- 9.55

V ---- 100.2
1/f -- 8.12

V — 102.7 1/f — 6.85	V — 104.1 1/f — 6.34	V — 110.8 1/f — 4.66	V — 113.0 1/f — 4.30	V — 223.7 1/f — 8.86	V — 225.7 1/f — 8.02
<p><u>FLAMEHOLDER:</u> 0.062" dia. steel rod 9" from chamber entrance</p> <p><u>SCREEN:</u> 3 mesh 0.063" wire dia</p>
V — 231.2 1/f — 6.62	V — 234.3 1/f — 6.03	V — 315.6 1/f — 8.41
V — 25.1 1/f — 13.12	V — 25.4 1/f — 11.55

V — 25.7* 1/f — 10.44	V — 48.9 1/f — 13.30	V — 49.7 1/f — 11.27	V — 51.3 1/f — 8.76	V — 52.5 1/f — 7.33	V — 53.9 1/f — 6.24

V — 55.3 1/f — 5.41	V — 58.3 1/f — 4.28	V — 96.4 1/f — 11.87	V — 97.6 1/f — 10.47	V — 99.5 1/f — 8.80	V — 101.3 1/f — 7.64

6-2-27 V --- 111.8 1/f -- 4.55	7-2-27 V --- 223.1 1/f -- 9.20	8-2-27 V --- 227.2 1/f -- 7.84	9-2-27 V --- 226.8 1/f -- 7.50	10-2-27 V --- 234.5 1/f -- 6.06	11-2-27 V --- 241.4 1/f -- 5.26
12-2-27 V --- 311.0 1/f -- 7.95	<p><u>FLAMEHOLDER:</u> 0.038" dia. steel rod 9" from chamber entrance</p> <p><u>SCREEN :</u> none</p>
	1-1-28 V --- 24.9 1/f -- 13.69	2-1-28 V --- 25.2 1/f -- 12.07	3-1-28 V --- 48.3 1/f -- 13.22	4-1-28 V --- 49.2 1/f -- 10.95
5-1-28 V --- 51.3* 1/f -- 7.82	6-1-28 V --- 52.7* 1/f -- 6.53	7-1-28 V --- 56.4 1/f -- 4.64	8-1-28 V --- 57.6 1/f -- 4.27	9-1-28 V --- 96.2 1/f -- 11.90	10-1-28 V --- 97.9 1/f -- 10.03
11-1-28 V --- 99.7 1/f -- 8.53	12-1-28 V --- 101.3 1/f -- 7.58	1-2-28 V --- 103.0 1/f -- 6.79	2-2-28 V --- 106.7 1/f -- 5.59	3-2-28 V --- 109.9 1/f -- 4.86	4-2-28 V --- 111.7 1/f -- 4.52

5-2-28

V --- 221.4
1/f --- 8.18

6-2-28

V --- 224.8
1/f --- 7.26

7-2-28

V --- 227.4
1/f --- 6.53

8-2-28

V --- 231.4
1/f --- 5.97

9-2-28

V --- 234.5
1/f --- 5.57

10-2-28

V --- 282.9
1/f --- 6.64

FLAMEHOLDER:

0.038" dia.
steel rod 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

1-1-29

V --- 24.6
1/f --- 14.28

2-1-29

V --- 25.0
1/f --- 11.87

3-1-29

V --- 25.3
1/f --- 10.91

4-1-29

V --- 48.0
1/f --- 12.89

5-1-29

V --- 48.8
1/f --- 11.01

6-1-29

V --- 49.9
1/f --- 9.19

7-1-29

V --- 51.1
1/f --- 7.64

8-1-29

V --- 52.5
1/f --- 6.29

9-1-29

V --- 53.9
1/f --- 5.49

10-1-29

V --- 56.2
1/f --- 4.58

11-1-29

V --- 99.2
1/f --- 10.79

12-1-29

V --- 100.9
1/f --- 9.31

1-2-29

V --- 102.6
1/f --- 8.04

2-2-29

V --- 105.2
1/f --- 6.82

3-2-29

V --- 107.9
1/f --- 5.91

4-2-29

V --- 111.5
1/f --- 5.04

5-2-29

V --- 113.2
1/f --- 4.71

6-2-29
V — 229.0
1/f — 7.78

7-2-29
V — 232.0
1/f — 7.10

8-2-29
V — 235.3
1/f — 6.39

9-2-29
V — 239.4
1/f — 5.75

FLAMEHOLDER:

0.026" dia.
steel rod 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

10-1-30
V — 24.0
1/f — 13.07

11-1-30
V — 24.2
1/f — 12.03

12-1-30
V — 24.4
1/f — 11.07

1-2-30
V — 47.6
1/f — 12.44

2-2-30
V — 48.3
1/f — 10.97

3-2-30
V — 49.8
1/f — 8.35

4-2-30
V — 50.8
1/f — 7.26

5-2-30
V — 52.0
1/f — 6.26

6-2-30
V — 53.3
1/f — 5.47

7-2-30
V — 54.8
1/f — 4.84

8-2-30
V — 97.6
1/f — 10.53

9-2-30
V — 99.3
1/f — 9.09

10-2-30
V — 101.0
1/f — 7.96

11-2-30
V — 103.3
1/f — 6.80

12-2-30
V — 105.1
1/f — 6.09

1-3-30
V — 109.2
1/f — 5.06

2-1-31
V — 229.1
1/f — 6.55

FLAMEHOLDER:

0.026" dia.
steel rod 9"
from chamber
entrance

SCREEN:

none

7-1-33
V — 22.7
1/f — 14.16

8-1-33
V — 23.0
1/f — 12.49

9-1-33
V — 23.4
1/f — 10.59

10-1-33
V — 48.0
1/f — 12.72

11-1-33
V — 48.6
1/f — 11.24

12-1-33
V — 49.4*
1/f — 9.72

1-2-33
V — 95.1
1/f — 11.41

2-2-33
V — 96.3
1/f — 10.19

3-2-33
V — 98.6
1/f — 8.31

4-2-33
V — 100.3
1/f — 7.25

5-2-33
V — 101.9
1/f — 6.59

6-2-33
V — 104.0
1/f — 5.86

7-2-33
V — 106.6
1/f — 5.28

8-2-33
V — 108.7
1/f — 4.54

9-1-34
V — 229.3
1/f — 6.90

10-1-34
V — 231.4
1/f — 6.45

FLAMEHOLDER:
0.016" dia.
steel rod 9" from chamber
entrance
SCREEN:
none

11-1-35
V — 47.4
1/f — 10.76

12-1-35
V — 47.9
1/f — 9.79

1-2-35
V — 94.7
1/f — 10.13

2-2-35
V — 96.6
1/f — 8.43

3-2-35
V — 98.0
1/f — 7.56

4-2-35
V — 99.7
1/f — 6.74

5-2-35
V — 101.8
1/f — 5.98

6-2-35
V — 104.5
1/f — 5.25

FLAMEHOLDER:

0.016" dia.
steel rod 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

FLAMEHOLDER:

0.500" wide
30 degree closed
edge gutter 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

1-1-40
V --- 24.1
1/f --- 13.18

2-1-40
V --- 24.6
1/f --- 10.75

3-1-40
V --- 25.1
1/f --- 9.03

4-1-40
V --- 46.8
1/f --- 13.31

5-1-40
V --- 48.4
1/f --- 9.69

6-1-40
V --- 50.0
1/f --- 7.60

7-1-40
V --- 51.1
1/f --- 6.64

8-1-40
V --- 52.5
1/f --- 5.69

9-1-40
V --- 54.1
1/f --- 4.93

10-1-40
V --- 56.3
1/f --- 4.16

11-1-40
V --- 92.8
1/f --- 12.15

12-1-40
V --- 95.6
1/f --- 9.27

1-2-40
V --- 98.9
1/f --- 7.26

2-2-40
V --- 101.3
1/f --- 6.26

3-2-40
V --- 105.8
1/f --- 5.00

4-2-40
V --- 108.8
1/f --- 4.42

5-2-40
V --- 219.8
1/f --- 11.35

6-2-40
V --- 226.1
1/f --- 8.61

7-2-40
V --- 232.9
1/f --- 6.87

8-2-40
V --- 236.8
1/f --- 6.10

9-2-40
V --- 245.9
1/f --- 5.08

10-2-40
V --- 358.9
1/f --- 10.10

FLAMEHOLDER:

0.250" wide
30 degree closed
edge gutter 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

V ---- 23.7
1/f -- 12.71

V ---- 23.9
1/f -- 11.69

V ---- 24.46
1/f -- 9.43

V ---- 24.8
1/f -- 8.50

V ---- 46.1
1/f -- 13.41

V ---- 47.0
1/f -- 11.0

V ---- 48.8
1/f -- 8.15

V ---- 50.2
1/f -- 6.73

V ---- 51.6
1/f -- 5.79

V ---- 53.1
1/f -- 5.00

V ---- 55.0
1/f -- 4.33

V ---- 95.8
1/f -- 13.58

V ---- 95.8
1/f -- 13.58

V ---- 96.2
1/f -- 12.88

V ---- 99.1
1/f -- 9.72

V ---- 101.3
1/f -- 8.15

V ---- 103.6
1/f -- 6.93

V ---- 106.3
1/f -- 5.94

V ---- 111.6
1/f -- 4.73

V ---- 114.8
1/f -- 4.21

V ---- 222.8
1/f -- 10.95

V ---- 225.3
1/f -- 9.66

V ---- 229.3
1/f -- 8.01

V ---- 235.2
1/f -- 6.66

FLAMEHOLDER:

0.100" wide
30 degree closed
edge gutter 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

V --- 247.7
1/f -- 5.08

V --- 350.2
1/f -- 9.24

V --- 23.6
1/f -- 12.69

V --- 23.86
1/f -- 11.22

V --- 24.1
1/f -- 10.31

V --- 47.0
1/f -- 14.27

V --- 47.4
1/f -- 13.19

V --- 49.2
1/f -- 9.31

V --- 50.8
1/f -- 7.28

V --- 53.1
1/f -- 5.64

V --- 55.3
1/f -- 4.68

V --- 58.6
1/f -- 3.74

V --- 94.7
1/f -- 12.89

V --- 95.7
1/f -- 11.34

V --- 98.1
1/f -- 9.03

V --- 101.0
1/f -- 7.25

V --- 103.6
1/f -- 6.21

V --- 108.4
1/f -- 4.93

V --- 111.9
1/f -- 4.33

V --- 223.4
1/f -- 9.95

V --- 228.2
1/f -- 7.88

V --- 234.4
1/f -- 6.51

V --- 240.8
1/f -- 5.63

FLAMEHOLDER:

0.100" wide
30 degree closed
edge gutter 9"
from chamber
entrance

SCREEN:

none

V ---- 248.1
1/f -- 4.87

V ---- 361.6
1/f -- 7.35

V ---- 23.3
1/f -- 13.41

V ---- 24.0
1/f -- 9.93

V ---- 45.9
1/f -- 15.66

V ---- 48.2
1/f -- 14.59

V ---- 49.0
1/f -- 12.17

V ---- 50.2
1/f -- 9.91

V ---- 95.1
1/f -- 13.15

V ---- 96.3
1/f -- 11.59

V ---- 99.3
1/f -- 8.78

V ---- 102.1
1/f -- 7.22

V ---- 104.0
1/f -- 6.41

V ---- 108.2
1/f -- 5.22

V ---- 112.1
1/f -- 4.44

V ---- 174.0
1/f -- 11.56

V ---- 224.4
1/f -- 10.62

V ---- 223.9
1/f -- 10.13

V ---- 227.9
1/f -- 8.35

V ---- 235.7
1/f -- 6.61

V ---- 243.3
1/f -- 5.46

V ---- 246.3
1/f -- 5.09

V ---- 305.8
1/f -- 8.21

FLAMEHOLDER:

0.050" wide
30 degree closed
edge gutter 9"
from chamber
entrance

SCREEN:

none

V ---- 24.2
1/f -- 13.35

V ---- 24.5
1/f -- 11.49

V ---- 49.2
1/f -- 14.08

V ---- 49.9
1/f -- 12.10

V ---- 51.1
1/f -- 9.73

V ---- 96.2
1/f -- 12.83

V ---- 97.2
1/f -- 11.44

V ---- 101.2
1/f -- 8.12

V ---- 103.4
1/f -- 6.98

V ---- 106.5
1/f -- 5.87

V ---- 109.2
1/f -- 5.17

V ---- 112.1
1/f -- 4.61

V ---- 230.3
1/f -- 9.40

V ---- 229.4
1/f -- 8.53

V ---- 235.7
1/f -- 6.84

V ---- 240.2
1/f -- 6.09

V ---- 243.6
1/f -- 5.66

V ---- 325.4
1/f -- 6.27

FLAMEHOLDER:

0.050" wide
30 degree closed
edge gutter 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

V ---- 24.46
1/f -- 14.41

V ---- 25.1
1/f -- 11.19

V ---- 48.8
1/f -- 14.13

V ---- 49.2
1/f -- 13.02

FLAMEHOLDER:

0.025" wide
30 degree closed
edge gutter 9"
from chamber
entrance

SCREEN:

none

V ---- 108.3
1/f -- 5.86

V ---- 50.7
1/f -- 11.78

V ---- 51.6
1/f -- 9.90

V ---- 99.0
1/f -- 11.64

V ---- 100.5
1/f -- 10.08

V ---- 103.3
1/f -- 7.97

V ---- 105.6
1/f -- 6.83

V ---- 109.9
1/f -- 5.49

FLAMEHOLDER:

0.500" wide
30 degree open
ended gutter 9"
from chamber
entrance

Total Area
Open Area = 25

SCREEN:

3 mesh
0.063" wire dia.

4-1-48

V ---- 24.8
1/f -- 14.21

5-1-48

V ---- 25.2
1/f -- 12.32

6-1-48

V ---- 25.6
1/f -- 10.55

7-1-48

V ---- 26.6
1/f -- 7.90

8-1-48

V ---- 48.2
1/f -- 14.30

9-1-48

V ---- 49.4
1/f -- 11.07

10-1-48

V ---- 52.3
1/f -- 7.16

11-1-48

V ---- 53.3
1/f -- 6.38

12-1-48

V ---- 55.5
1/f -- 5.16

1-2-48

V ---- 57.7
1/f -- 4.36

2-2-48

V ---- 56.7
1/f -- 3.86

3-2-48

V ---- 96.5
1/f -- 13.32

4-2-48

V ---- 98.5
1/f -- 10.88

5-2-48

V ---- 103.2
1/f -- 7.47

6-2-48

V ---- 105.9
1/f -- 6.23

7-2-48

V ---- 108.8
1/f -- 5.42

8-2-48

V ---- 111.5
1/f -- 4.86

9-2-48

V ---- 116.0
1/f -- 4.12

10-2-48

V ---- 220.3
1/f -- 11.93

11-2-48

V ---- 227.0
1/f -- 8.87

12-2-48

V ---- 235.9
1/f -- 6.47

1-3-48

V ---- 243.3
1/f -- 5.49

2-3-48

V ---- 251.0
1/f -- 4.73

FLAMEHOLDER:

0.500" wide
30 degree open
ended gutter 9"
from chamber
entrance

Total Area
Open Area = 100

SCREEN:

3 mesh
0.063" wire dia.

3-3-48

V ---- 307.3
1/f -- 9.30

4-3-48

V ---- 343.7
1/f -- 9.64

3-1-67

V ---- 24.4
1/f -- 11.01

4-1-67

V ---- 24.8
1/f -- 9.40

5-1-67

V ---- 26.3
1/f -- 6.42

6-1-67

V ---- 47.7
1/f -- 12.96

7-1-67

V ---- 49.0
1/f -- 10.14

8-1-67

V ---- 53.9
1/f -- 5.51

9-1-67

V ---- 55.3
1/f -- 4.82

10-1-67

V ---- 56.6
1/f -- 4.33

11-1-67

V ---- 58.9
1/f -- 3.73

12-1-67

V ---- 97.0
1/f -- 12.23

1-2-67

V ---- 99.8
1/f -- 9.37

2-2-67

V ---- 104.6
1/f -- 6.76

3-2-67

V ---- 108.1
1/f -- 5.60

4-2-67

V ---- 112.3
1/f -- 4.69

5-2-67

V ---- 116.3
1/f -- 4.05

6-2-67

V ---- 212.3
1/f -- 11.39

7-2-67

V ---- 215.8
1/f -- 10.97

8-2-67

V ---- 229.8
1/f -- 6.71

9-2-67

V ---- 237.1
1/f -- 5.54

10-2-67

V ---- 245.2
1/f -- 4.75

11-2-67

V ---- 345.4
1/f -- 9.48

FLAMEHOLDER:

0.500" wide
flat plate 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

V ---- 25.0
1/f -- 12.86

V ---- 25.7
1/f -- 9.97

V ---- 26.3*
1/f -- 8.23

V ---- 49.7
1/f -- 13.40

V ---- 51.0
1/f -- 10.49

V ---- 53.2
1/f -- 7.36

V ---- 54.3
1/f -- 6.41

V ---- 56.3
1/f -- 5.33

V ---- 59.4
1/f -- 4.22

V ---- 62.1
1/f -- 3.58

V ---- 98.5
1/f -- 12.49

V ---- 103.0
1/f -- 8.27

V ---- 107.4
1/f -- 6.19

V ---- 114.6
1/f -- 4.52

V ---- 118.4
1/f -- 3.96

FLAMEHOLDER:

Double 0.038"
rod holder 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

FLAMEHOLDER:

Four 0.038" rods
across tunnel 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

8-1-72
V ---- 27.4
1/f -- 6.02

9-1-72
V ---- 48.7
1/f -- 13.45

10-1-72
V ---- 49.9
1/f -- 10.35

11-1-72
V ---- 51.3
1/f -- 8.14

12-1-72
V ---- 52.9
1/f -- 6.58

1-2-72
V ---- 55.8
1/f -- 5.14

2-2-72
V ---- 55.7
1/f -- 5.08

3-2-72
V ---- 96.7
1/f -- 11.11

4-2-72
V ---- 98.3
1/f -- 8.58

5-2-72
V ---- 100.2**
1/f -- 7.43

6-2-72
V ---- 104.5**
1/f -- 5.83

7-2-72
V ---- 161.6
1/f -- 8.17

FLAMEHOLDER:

Eight 0.038"
rods across
tunnel 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

8-1-73
V ---- 24.5
1/f -- 11.03

9-1-73
V ---- 24.9**
1/f -- 9.42

10-1-73
V ---- 25.8**
1/f -- 7.79

11-1-73
V ---- 49.6
1/f -- 11.14

12-1-73
V ---- 50.8**
1/f -- 8.97

1-2-73
V ---- 51.9
1/f -- 7.77

2-2-73
V ---- 51.9
1/f -- 7.89

3-2-73
V ---- 58.4
1/f -- 4.37

4-2-73
V ---- 97.4
1/f -- 9.80

5-2-73
V ---- 98.6**
1/f -- 8.66

FLAMEHOLDER

0.038" dia.
steel rod 2"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

8-1-82
V ---- 24.6
1/f -- 11.08

9-1-82
V ---- 50.2
1/f -- 10.85

10-1-82
V ---- 50.8
1/f -- 9.76

11-1-82
V ---- 51.2
1/f -- 9.03

12-1-82
V ---- 96.6
1/f -- 9.92

1-2-82
V ---- 97.3
1/f -- 9.07

2-2-82
V ---- 100.1
1/f -- 6.78

3-2-82
V ---- 103.3
1/f -- 5.57

FLAMEHOLDER:

0.038" dia.
steel rod 2"
from chamber
entrance

SCREEN:

8 mesh
0.027" wire dia.

4-2-83
V ---- 23.6
1/f -- 12.80

5-1-83
V ---- 24.2
1/f -- 10.44

6-1-83

V ---- 49.9
1/f -- 10.68

7-1-83

V ---- 51.1
1/f -- 8.61

8-1-83

V ---- 96.0
1/f -- 9.50

9-1-83

V ---- 97.4
1/f -- 8.37

10-1-83

V ---- 99.1
1/f -- 7.10

11-1-83

V ---- 103.0
1/f -- 5.55

12-1-83

V ---- 108.0
1/f -- 4.61

FLAMEHOLDER:

0.038" dia.
steel rod 2"
from chamber
entrance

SCREEN:

55 mesh
0.007" wire dia.

1-1-84

V ---- 24.7
1/f -- 12.26

2-1-84

V ---- 24.9
1/f -- 10.84

3-1-84

V ---- 25.4
1/f -- 9.36

4-1-84

V ---- 49.7
1/f -- 11.33

V ---- 50.4
1/f -- 10.02

V ---- 51.6
1/f -- 7.98

V ---- 55.6
1/f -- 5.12

V ---- 58.4
1/f -- 4.21

V ---- 98.7
1/f -- 10.36

V ---- 100.4
1/f -- 8.82

V ---- 102.7
1/f -- 7.16

V ---- 106.1
1/f -- 5.74

V ---- 111.0
1/f -- 4.77

V ---- 217.1
1/f -- 6.46

FLAMEHOLDER:

0.038" dia.
steel rod 2"
from chamber
entrance

SCREEN:

none

V ---- 24.6
1/f -- 12.32

V ---- 25.1
1/f -- 10.22

V ---- 25.5*
1/f -- 9.17

V ---- 49.2
1/f -- 11.39

V ---- 50.7
1/f -- 8.81

V ---- 97.2
1/f -- 11.00

V ---- 98.0
1/f -- 10.15

V ---- 100.8
1/f -- 7.74

V ---- 105.0
1/f -- 5.72

V ---- 113.2
1/f -- 4.26

V ---- 213.3
1/f -- 10.07

V ---- 212.5*
1/f -- 8.80

V ---- 217.4**
1/f -- 6.62

V ---- 222.9**
1/f -- 5.69

V ---- 301.7
1/f -- 8.04

FLAMEHOLDER:

0.038" dia.
steel rod 6"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

V ---- 23.8
1/f -- 12.50

V ---- 24.1
1/f -- 11.04

V ---- 49.1
1/f -- 12.67

V ---- 49.8
1/f -- 10.96

V ---- 51.0
1/f -- 8.91

V ---- 52.0
1/f -- 7.58

V ---- 96.7
1/f -- 10.75

V ---- 98.6
1/f -- 8.70

V ---- 101.2
1/f -- 6.99

V ---- 105.4
1/f -- 5.49

V ---- 213.6
1/f -- 7.68

V ---- 216.1
1/f -- 6.86

V ---- 221.3
1/f -- 5.81

FLAMEHOLDER:

0.038" dia.
steel rod 6"
from chamber
entrance

SCREEN:

8 mesh
0.025" wire dia.

V ---- 24.3
1/f -- 12.13

V ---- 24.5*
1/f -- 11.14

V ---- 48.3
1/f -- 12.86

FLAMEHOLDER:

0.038" dia.
steel rod 6"
from chamber
entrance

SCREEN:

55 mesh
0.007" wire dia.

3-2-88
V ---- 52.0
1/f -- 6.41

4-2-88
V ---- 54.2
1/f -- 5.20

5-2-88
V ---- 55.6
1/f -- 4.69

6-2-88
V ---- 57.2
1/f -- 4.19

7-2-88
V ---- 94.8
1/f -- 12.18

8-2-88
V ---- 95.9
1/f -- 10.76

9-2-88
V ---- 99.6
1/f -- 7.79

10-2-88
V ---- 103.8
1/f -- 5.89

11-2-88
V ---- 108.1
1/f -- 4.89

12-2-88
V ---- 212.5
1/f -- 8.37

1-3-88
V ---- 217.2
1/f -- 6.85

2-3-88
V ---- 222.6
1/f -- 5.81

FLAMEHOLDER:

0.038" dia.
steel rod 6"
from chamber
entrance

SCREEN:

none

3-1-89
V ---- 24.0
1/f -- 13.18

4-1-89
V ---- 24.3
1/f -- 11.34

5-1-89
V ---- 48.1
1/f -- 12.88

6-1-89
V ---- 48.8
1/f -- 11.11

7-1-89
V ---- 49.2
1/f -- 10.22

FLAMEHOLDER:

0.498" dia.
steel rod 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

FUEL: Propane

V ---- 22.6
1/f -- 21.92

V ---- 22.8
1/f -- 17.28

V ---- 22.9
1/f -- 16.06

V ---- 46.5
1/f -- 23.40

V ---- 47.0
1/f -- 17.15

V ---- 47.0
1/f -- 15.66

V ---- 47.5
1/f -- 12.46

V ---- 48.0
1/f -- 10.13

V ---- 92.0
1/f -- 20.75

V ---- 93.3
1/f -- 13.98

V ---- 94.2
1/f -- 11.25

V ---- 94.7
1/f -- 10.16

V ---- 197.5
1/f -- 20.89

V ---- 197.9
1/f -- 17.08

V ---- 198.9
1/f -- 14.19

V ---- 200.3
1/f -- 11.96

V ---- 306.2
1/f -- 14.52

V ---- 305.4
1/f -- 16.40

V ---- 306.1
1/f -- 18.79

FLAMEHOLDER:

0.188" dia.
steel rod 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

FUEL: Propane

V ---- 23.0
1/f -- 17.88

V ---- 23.3
1/f -- 12.84

V ---- 23.7
1/f -- 9.09

V --- 46.5
1/f --- 22.76

V --- 46.8
1/f --- 18.05

V --- 47.1
1/f --- 14.95

V --- 47.3
1/f --- 13.22

V --- 47.8
1/f --- 10.73

V --- 92.1
1/f --- 20.07

V --- 92.9
1/f --- 15.88

V --- 94.0
1/f --- 11.97

V --- 94.8
1/f --- 10.19

V --- 202.5
1/f --- 18.48

V --- 201.0
1/f --- 15.96

V --- 202.8
1/f --- 12.74

V --- 279.1
1/f --- 15.19

FLAMEHOLDER:

0.094" dia.
steel rod 9"
from chamber
entrance

SCREEN:

3 mesh
0.063" wire dia.

FUEL: Propane

V --- 22.8
1/f --- 19.82

V --- 22.9
1/f --- 16.17

V --- 23.2
1/f --- 12.71

V --- 23.6
1/f --- 9.43

V --- 23.8
1/f --- 8.47

V --- 46.4
1/f --- 20.81

V --- 46.5
1/f --- 18.47

V --- 46.9
1/f --- 14.57

V --- 47.5
1/f --- 11.43

V --- 92.5
1/f --- 19.08

FLAMEHOLDER:

0.094" dia.
steel rod 9"
from chamber
entrance

SCREEN:

none

FUEL: Propane

V --- 93.0
1/f --- 14.89

V --- 93.8
1/f --- 12.32

V --- 94.9
1/f --- 10.10

V --- 201.2
1/f --- 15.27

V --- 201.6
1/f --- 13.83

V --- 46.4
1/f --- 21.47

V --- 46.6
1/f --- 18.11

V --- 47.0
1/f --- 15.04

V --- 47.6
1/f --- 11.72

V --- 48.0
1/f --- 9.84

V --- 92.4
1/f --- 17.94

V --- 93.4
1/f --- 13.75

V --- 94.6
1/f --- 10.65

V --- 95.5
1/f --- 9.15

V --- 201.3
1/f --- 16.02

V --- 200.9
1/f --- 14.40

V --- 201.6
1/f --- 13.36

V --- 202.3
1/f --- 12.47

FLAMEHOLDER:

0.038" dia.
steel rod 9"
from chamber
entrance

SCREEN:

none

FUEL: Propane

V --- 46.2
1/f --- 18.83

V --- 46.5
1/f --- 15.60

V --- 46.6
1/f --- 13.97

V --- 47.1
1/f --- 11.58

V --- 47.5 1/f -- 9.82	V --- 92.5 1/f -- 16.37	V --- 93.0 1/f -- 14.27	V --- 93.7 1/f -- 12.31	V --- 94.8 1/f -- 10.24	V --- 95.3 1/f -- 9.31
FLAMEHOLDER: 0.038" dia. steel rod 9" from chamber entrance SCREEN: 3 mesh 0.063" wire dia.

V --- 22.8 1/f -- 18.77	V --- 22.9 1/f -- 15.84	V --- 23.2 1/f -- 12.45	V --- 23.3 1/f -- 11.35	V --- 23.6 1/f -- 8.97

V --- 46.5 1/f -- 18.24	V --- 46.7 1/f -- 15.69	V --- 47.1 1/f -- 13.05	V --- 47.5 1/f -- 11.09	V --- 47.7 1/f -- 10.09	V --- 92.4 1/f -- 15.05

V --- 92.8 1/f -- 13.06	V --- 93.7 1/f -- 10.92				

FUEL: Propane

3. Effect of Exposure Time on Measured Flame Width

In Figure 130 is presented a series of pictures taken with different exposure times, of a flame at a V_0 of 202.5 feet per second and an air-fuel ratio of 18.48 pounds per pound using propane as a fuel. The stabilizer is a 0.188 inch rod located 9 inches from the chamber entrance and the 3 mesh 0.063" wire diameter screen is in place at the chamber entrance.

In the lower right hand corner of Figure 130 is shown a plot of flame width, W_4 , obtained from the photographic negatives versus exposure time. It is noted that the change of flame width with exposure time is rather small. In fact changing the exposure time by as much as 100 per cent in either direction from two-fifths of a second (the exposure time employed for taking the regular flame pictures) results in a negligible change in measured flame width. It is thus concluded that measured flame width is very insensitive to exposure time at the exposure time employed when taking the regular flame pictures.

FIGURE 130

EFFECT OF EXPOSURE TIME ON MEASURED FLAME WIDTH

Stabilizer: 0.188" Rod 9"
from Chamber Entrance

V_0 - 202.5 ft/sec.
 $1/f$ - 18.48 lbs/lb.

Screen: 3 mesh 0.063"
wire diameter

Fuel: Propane

4. Bunsen Flame Pictures Employed for Measurement of Laminar Flame Velocity

In Figures 131 and 132 are shown in full scale the Bunsen flame pictures from which laminar flame velocities were obtained for city gas - air and propane - air mixtures, respectively.

As previously stated, laminar flame velocity, S_L , was found by dividing the volumetric rate of flow of gases through the burner tube by the area of the flame*. The value of S_L thus calculated is an average value over the entire flame area*.

Criticism of the Bunsen cone method of obtaining laminar flame velocities is based primarily on the effect on flame velocity of diffusion of air (or other surrounding gases) into the explosive mixture near the burner rim, and increase in flame velocity due to increased diffusion of heat and chain carriers from all sides into the unburned gas at the flame tip. Since the Bunsen cone method is based on the assumption of constant flame velocity over the entire flame surface, this criticism is valid. It has been shown by Ubbelohde(48), and more recently by Jost (22) and von Elbe and Mentser (16) that the use of larger burners tubes tends

* The flame areas were very accurately determined by the following means. The photographic negative was first placed in an enlarger and the greatly enlarged flame boundary traced from the projected image on coordinate paper. The symmetrical flame front was then divided into a number of truncated cones, the slant height and average radius of each cone was measured, and the area of each cone calculated. The sum of these areas is equal to the total area of the flame.

BUNSEN CONE PICTURES USED FOR MEASUREMENT OF LAMINAR FLAME VELOCITY IN CAMBRIDGE CITY GAS AND AIR MIXTURES - FULL SCALE

(TEMPERATURE - 26°C; PRESSURE - 1 ATM.)

AIR-FUEL RATIO, LBS./LB. $\frac{1}{f}$
 FLOW RATE, ft./sec. V_o
 FLAME SURFACE AREA, ft.². A
 LAMINAR FLAME VELOCITY, ft./sec.

$$S_L = \frac{V_o}{A}$$

CITY GAS COMPOSITION

CO₂ 7.3%
 Illuminants . . . 9.8%
 O₂ 0.6%
 CO 21.8%
 CH₄ 14.7%
 H₂ 26.8%
 N₂ 19.0%

BURNER TUBE

12-1-32

1/f --- 9.75
 A --- .00185
 S_L --- .694

10-1-32

1/f --- 7.98
 A --- .00226
 S_L --- 1.106

7-1-32

1/f --- 6.87
 A --- .00204
 S_L --- 1.555

2-2-32

1/f --- 5.91
 A --- .00226
 S_L --- 1.604

4-2-32

1/f --- 4.85
 A --- .00175
 S_L --- 1.398

6-2-32

1/f --- 3.65
 A --- .00160
 S_L --- .470

BUNSEN CONE PICTURES USED FOR MEASUREMENT OF LAMINAR FLAME VELOCITY IN PROPANE AND AIR MIXTURES — FULL SCALE

(TEMPERATURE — 26°C ; PRESSURE — 1 ATM.)

AIR-FUEL RATIO, lbs./lb. $\frac{1}{f}$
 FLOW RATE, ft./sec. V_o
 FLAME SURFACE AREA, ft.² A
 LAMINAR FLAME VELOCITY, ft./sec.
 $S_L = \frac{V_o}{A}$

PROPANE COMPOSITION

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

BURNER TUBE

1/f --- 20.63
 A --- .000938
 S_L --- .566

1/f --- 18.06
 A --- .00151
 S_L --- .799

1/f --- 13.43
 A --- .00304
 S_L --- .804

1/f --- 10.83
 A --- .00289
 S_L --- .422

1/f --- 9.15
 A --- .00243
 S_L --- .234

1/f --- 7.10
 A --- .00165
 S_L --- .125

to reduce the error due to anomolous flame velocities to a low value.

Let us focus attention for a moment on the rim error due to mixing by diffusion of the ambient air with the explosive mixture. With lean mixtures this mixing at the tube rim would be expected to lower the flame vlocity at the rim thus hastening blow off and causing the measured value for S_L to be low. At rich mixtures, on the other hand, S_L is increased by dilution of the explosive mixture with air, and the stability limits are also increased. How considerable error in the measured values of S_L occurs due to mixing at the rim with very rich mixtures is pointed out by Jost (22). It would be expected that such errors would be considerably increased when the fuel employed is of very low molecular weight as is hydrogen, the rate of diffusion and thus the rate of mixing with the ambient air being considerably accelerated.

It is suspected, therefore, that the laminar flame velocity measurements obtained for city gas, which contains nearly 30 per cent hydrogen, are considerably in error on the high side at very rich mixtures due to mixing by diffusion at the burner rim. The error due to rim mixing at rich mixtures with propane-air flames should, on the other hand, be considerably less because of the relatively high

molecular weight of propane and the resulting low rate of mixing by molecular diffusion.

4. Effect of Uncoupling Stack on Blow-out Limits

With many combustion chambers, it has been found that the performance is greatly affected by the size, shape, and length of the chamber and exhaust system. The question arose as to whether the data obtained during this investigation were specific to the exhaust stack used or whether it would apply generally to any system where the stack was not a determining factor. It was, therefore, considered desirable to obtain a set of stability limit data with the stack on, and immediately thereafter to obtain similar data with the stack removed. Figure 133 is a plot of stability limits for the 0.032 inch diameter tube flameholder determined with stack on and stack off. All the data falls on the same line within the experimental accuracy of the measurements and it is concluded that the stack used did not affect the stability limits. Removal of the stack also had no noticeable effect on flame width.

Some interesting observations of the appearance of the flame as it issued from the combustion chamber exit and into the room were made while the stack was uncoupled. Figure 134 is a time exposure photograph of combustion with the stack removed using the 0.032 inch diameter tube as a flameholder. The velocity was 235 ft. per sec., and the air-fuel ratio was 6.71. It can be seen that the sharp outline of

FIGURE 133

Figure 134

the flame is unchanged for a short vertical distance above the chamber exit. The sudden fanning out of the flame just above this distance is due to breakover into a turbulent jet mixing action with the ambient air. The fuzziness of the flame outline in this picture is due to the large scale eddy motion produced by the jet issuing into still air.

B. Sample Calculations and Estimation of Experimental Errors

1. Calculation of Air-Fuel Ratio

The air and fuel weight rates of flow were determined independently.

In order to obtain the air rate, the pressure drop across the air orifice, the air temperature upstream of the orifice, and the total pressure upstream of the orifice were determined. A typical set of raw data used for determination of air rate, with the estimated maximum error in the readings taken from Run No. 39, picture negative number 2-3-39, are shown below:

Pressure drop across air orifice = $31.4'' \pm 0.025'' \text{ H}_2\text{O}$

Temperature upstream of air orifice = $67^\circ\text{C} \pm 0.5^\circ\text{C}$

Pressure upstream of air orifice = $86 \text{ psig.} \pm 0.2 \text{ psig.}$

Temperature in $^\circ\text{C}$ is converted to $^\circ\text{K}$ and upstream pressure is corrected according to the calibration curve for the Bourdon gage shown in Figure 146. The following final values are thus obtained from those above:

Pressure drop across air orifice = $31.4'' \pm 0.05'' \text{ H}_2\text{O}$

Temperature upstream of air orifice = $340^\circ\text{K} \pm 0.5^\circ\text{K}$

Pressure upstream of air orifice = $86 - 0.4(\text{correction})$
 $+ 14.7 = 100.3$
 $\pm 0.2 \text{ psia.}$

Referring now to the air orifice calibration curve shown in Figure 142a which gives the weight rate of flow of air in pounds per second through the orifice versus pressure drop across the orifice in inches of water, a value of $0.1359 \pm 1\%$ pounds per second is obtained for an upstream pressure of 104.7 psia. and a temperature of 308°K . The actual weight rate of flow of air is then obtained by correcting this value from the chart to the actual temperature and pressure as follows:

$$\begin{aligned}\text{actual air rate} &= \\ &0.1359 \text{ \#/sec.} \sqrt{\frac{100.3 \text{ psia}}{104.7 \text{ psia}} \times \frac{308^{\circ}\text{K}}{340^{\circ}\text{K}}} \\ &= 0.1266 \text{ \#/sec}\end{aligned}$$

and the maximum error in this final value is estimated as follows:

$$\begin{aligned}0.1266 \pm \left\{ 0.1266 \cdot 0.01 + \left[\frac{\frac{0.5}{340} + \frac{0.2}{100.3}}{2} \right] \right\} \\ = 0.1266 \pm 0.0015 \text{ \#/sec}\end{aligned}$$

$$\text{or } 0.1266 \text{ \#/sec} \pm 1.2\%$$

City gas rate was determined in a manner quite similar to that for determination of air rate. The data obtained from the gas venturi for Run 39, picture number 2-3-39 is as follows:

Pressure drop across small gas venturi = 52.2 ± 0.1 cm.H₂O

Temperature upstream of venturi = $33^\circ \pm 0.5^\circ\text{C} = 306^\circ \pm 0.5^\circ\text{K}$

Total pressure upstream of venturi = 0 ± 0.1 cm.H₂O (above
atmos.)
= 1026 ± 0.1 cm.H₂O

From the calibration curve shown in Figure 145 for the small venturi a value of $0.0196 \pm 1.5\%$ of city gas is obtained entering with a pressure drop across the venturi of 52.2 ± 0.1 cm. H₂O. This flow is then corrected from the basis of the calibration curve to obtain the actual gas flow rate as follows:

actual city gas rate =

$$0.0196 \text{ \#/sec} \sqrt{\frac{1026 \text{ cm.H}_2\text{O}}{1033 \text{ cm.H}_2\text{O}} \times \frac{277.8^\circ\text{C}}{306^\circ\text{C}}} \\ = 0.0186 \text{ \#/sec.}$$

and the maximum error in this final value is estimated as:

$$0.0186 \pm 0.0186 \left\{ 0.015 + \left[\frac{0.1}{1033} + \frac{0.5}{306} \right] \right\} \\ = 0.0186 \pm 0.0003 \text{ \#/sec.}$$

$$\text{or } 0.0186 \text{ \#/sec} \pm 1.7\%$$

The error in the determination of city gas rate is largest when the pressure drop reading across the gas venturi appears as a small reading on the water manometer. Since the

absolute error in reading this manometer remains constant; the per cent error increases as the absolute reading becomes smaller. Other errors become negligible in comparison with the error introduced by reading the manometer at these low readings. The magnitude of this error is estimated on the basis of the orifice equation, in which flow rate is proportional to the square-root of pressure differential across the orifice, as follows:

$$\text{per cent error} = \frac{\left(\frac{\pm 0.1 \text{ cm.}}{\text{absolute reading, cm.}} \right)}{2} \times 100$$

For an absolute reading of 1 cm. the per cent error thus becomes $\pm 5\%$. For an absolute reading of 2 cm., however, the error is cut in half to become $\pm 2.5\%$. It was due to this large error in obtaining gas rate at absolute values of the manometer reading near 1 cm. that no blow-out limit data at values of V_0 below about 50 feet per second were obtained.

For run 39, picture negative number 2-3-39, an air rate of 0.1266 #/sec $\pm 1.2\%$ and a city gas rate of 0.0186 #/sec. $\pm 1.7\%$ have been obtained. The air-fuel ratio in this case is then:

$$\frac{1}{f} = \frac{0.1266 \text{ \#/sec}}{0.0186 \text{ \#/sec}} = 6.81 \text{ \#/} \# \pm 2.9\%$$

2. Conversion of Air-Fuel Ratio to Generalized Oxidant Fraction, O_g

$$O_g = \frac{1/f}{1/f + (\text{Air-Fuel Ratio at Stoichiometric})}$$

For a city gas-air mixture with an air-fuel ratio of 6.81 (and a stoichiometric air requirement of 6.51 pounds of air per pound of city gas):

$$O_g = \frac{6.81}{6.81 + 6.51} = 0.5111$$

3. Calculation of Chamber Entrance Velocity, V_o

The data necessary for calculation of V_o are as follows for Run 39 picture negative number 2-3-39:

$$\text{air rate} = 0.1266 \text{ \#/sec} \pm 1.2\%$$

$$\text{gas rate} = 0.0186 \text{ \#/sec} \pm 1.7\%$$

$$\begin{aligned} \text{chamber entrance temperature} &= 43^\circ\text{C} \pm 0.5^\circ\text{C} \\ &= 316^\circ\text{K} \pm 0.5^\circ\text{K} \end{aligned}$$

$$\begin{aligned} \text{chamber entrance pressure} &= 1.6 \text{ cm. Hg. (above atmos)} \\ &\pm 0.1 \text{ cm. Hg} = 77.1 \pm 0.1 \text{ cm. Hg} \end{aligned}$$

$$\text{barometric pressure} = 75.5 \text{ cm. Hg.}$$

V_o equals the volumetric rate of flow divided by the chamber cross section. Recalling that the specific gravity of city gas is 0.730 based on air:

$$\begin{aligned}
 V_0 &= \frac{\text{Volumetric Flow Rate}}{\text{Chamber Cross Section}} \\
 &= \frac{\left[0.1266 \text{ \#/sec} + \frac{0.0186 \text{ \#/sec}}{0.73} \right] \frac{359 \text{ ft}^3/\text{mol}}{29 \text{ \#/mol}} \left(\frac{316^\circ\text{K}}{273^\circ\text{K}} \right) \left(\frac{76.0 \text{ cm.Hg}}{77.1 \text{ cm.Hg}} \right)}{\left(\frac{3 \times 1 \text{ in}^3}{144 \text{ in}^2/\text{ft}^2} \right) \text{ft}^2} \\
 &= 103.1 \text{ ft/sec.}
 \end{aligned}$$

The maximum error involved is estimated as follows, assuming that the error in air rate is controlling (since considerably more air flows through the chamber than gas.):

Error in V_0

$$= 1.2\% + \left(\frac{0.5}{273} \right) 100 + \left(\frac{0.1}{77.1} \right) \times 100 = \pm 1.5\%$$

4. Calculation of Gas Velocity from Pitot Tube Measurements

The following equation was employed for calculation of local velocity from pitot measurements:

$$V = \sqrt{\frac{2 \Delta P}{\rho}}$$

V = local velocity

ΔP = velocity head

ρ = air density

The raw data obtained in one case during Run 6 were as follows:

$$\Delta P = 12.2 \pm 0.1 \text{ cm. H}_2\text{O}$$

$$\text{Air Temperature} = 298.5^\circ \pm 0.25^\circ\text{K}$$

$$\text{Static Pressure} = 29.73 \pm 0.05 \text{ cm. Hg.}$$

$$V = \sqrt{\frac{2 \times 32.2 \frac{\text{poundals}}{\text{pound}} \times \frac{12.2 \text{ cm.H}_2\text{O}}{1033 \text{ cm.H}_2\text{O}} \times 14.7 \#/\text{in}^2 \times 144 \frac{\text{in}^2}{\text{ft}^2}}{\left[\frac{29 \#/\text{mol}}{359 \frac{\text{ft}^3}{\text{mol}} \left(\frac{29.92 \text{ in. Hg.}}{29.73 \text{ in. Hg.}} \right) \left(\frac{298.5^\circ\text{K}}{273^\circ\text{K}} \right)} \right]}}$$

$$V = 148.1 \text{ ft/sec.}$$

The maximum error involved is estimated as follows:

$$\begin{aligned} \text{Error in } V &= \pm \left[\frac{\frac{.1}{12.2} + \frac{0.25}{298.5} + \frac{0.05}{29.73}}{2} \right] \\ &= \pm 1.1\% \end{aligned}$$

5. Calculation of Turbulence Intensity, and Turbulence Scale from Hot-Wire Measurements

Turbulence intensity was obtained by a method somewhat different from those described in references (27) and (28), and, since the method is thought to have considerable merit by the author, it is briefly described here.

The major fault of the method for turbulence intensity calculation outlined in reference (28) is thought to be due to the failure of the method to take into account the error introduced by end effects of the hot-wire where it joins the unetched portion of the Wollaston wire. The method here

outlined is thought to eliminate almost completely this error.

If the air temperature and hot-wire heating current could be held at a constant value, and V at the probe held at any desired value with extreme accuracy, the method here described would be greatly simplified. The method will, therefore, be described first assuming this to be the case.

Holding the air temperature at 300°K and the probe heating current at 0.025 amperes with a velocity at the probe, V , held at exactly 25 feet per second, the resistance of the hot wire at equilibrium temperature minus the resistance of the wire at the temperature of the air stream, $(\bar{R} - R_a)_{300^{\circ}, 0.025, 25}$ is measured. $(\bar{R} - R_a)_{300^{\circ}, 0.025}$ is then obtained at other values of V . A plot of

$$\left[\frac{(\bar{R} - R_a)_{300, 0.025}}{(\bar{R} - R_a)_{300, 0.025, 25}} \right] \quad \text{vs} \quad V$$

is then made for this wire and for other wires of different lengths. All of the points for the different probes should fall on the same line and the slope of this line,

$$\frac{d\bar{R}}{dV} \frac{1}{(\bar{R} - R_a)_{300, 0.025, 25}}$$

can be used to plot another curve representing

$$\frac{d\bar{R}}{dV} \frac{1}{(\bar{R} - R_a)_{300, 0.025, 25}}$$

versus V .

Such a plot, presenting these two above described curves, based on calibration data taken for a number of hot wires of different lengths but of the same diameter (0.0001186 inches) is shown in Figure 135. The turbulence intensity can easily be calculated if V is known by merely entering Figure 135 with a value of V and obtaining:

$$u' = \frac{\frac{\text{Amplifier Voltage Output}}{\text{Amplifier Gain}}}{0.025 \left[\frac{\frac{d\bar{R}}{dV} \frac{1}{(\bar{R} - R_a)_{300^\circ, 0.025, 25}} \right] (\bar{R} - R_a)_{300^\circ, 0.025, 25}}$$

where u' is the root-mean-square fluctuating velocity in the x direction.

The above described method of hot wire calibration to obtain u' makes it possible to employ a single calibration curve for wires of different length but of the same diameter, and with the same heating current and air stream temperature. Examination of the data points plotted in Figure 135 shows that considerable scattering is present. This indicates that even this correlation method does not completely take into account the end effects of the hot wire.

In actual practice neither the air stream temperature nor the wire heating current were held at constant values. It was therefore necessary to correct the value of $(\bar{R} - R_a)$

FIGURE 135

COMPOSITE CALIBRATION CURVE FOR PLATINUM HOT-WIRES IN AIR AT 300K, 1 ATM, WIRE HEATING CURRENT-0.025 AMPS, WIRE DIAMETER-0.0001186 INCHES

to 300°K and to a heating current of 0.025 amperes, and to correct V to an air stream temperature of 300°K before the data could be plotted in Figure 135.

The correction of $(\bar{R} - R_a)$ to $(\bar{R} - R_a)_{300^\circ, 0.025}$, where it differs only slightly from this value, is approximated by means of the following equation:

$$(\bar{R} - R_a)_{300^\circ, 0.025} = \left[(\bar{R} - R_a) + \frac{\alpha_0 R_0 (T - 300^\circ)}{\bar{R}} \right] \left[1 + \left(\frac{\bar{R} - R_a}{\bar{R}} \right) \left(\bar{R} - R_a \right) \left[\frac{0.025}{i} \right]^2 \right]$$

where α_0 is the temperature coefficient of resistivity of platinum at some base temperature, T_0 , R_0 is the resistance of the wire at this temperature, T is the actual air stream temperature in degrees Kelvin, and i is the actual wire heating current in amperes. V is corrected to V_{300} as follows:

$$V_{300} = V(300/T)$$

When obtaining values of u' at the actual temperature and wire heating current the following equation with additional terms is employed instead of the one previously given.

$$u' = \frac{(\text{Amplifier Voltage Output})}{(\text{Amplifier Gain})} \div 0.025 \left[\frac{dR}{dV} \left(\frac{1}{R - R_a} \right) \right]_{300^\circ, .025, 25} \left[\frac{300}{T} \left(\frac{R - R_a}{R - R_a} \right) \right]_{300^\circ, 0.025}$$

Turbulence scale was calculated in the same manner described in reference (28) and employed previously by Dryden (15). The method of calculation will, therefore, not be included here.

6. Calculation of Laminar Flame Velocity From Bunsen Flame Photographic Negatives

The laminar flame velocity, S_L , is obtained as the ratio of the volumetric flow rate through the Bunsen tube to the surface area of the flame.

$$S_L = \frac{\text{Flow Rate}}{\text{Flame Surface Area}}$$

The data taken to obtain S_L are as follows for one air-fuel mixture (air-fuel ratio obtained as previously shown) in Run 32:

Gas rate through wet-test meter(direct reading)
 $= 11.4 \pm 0.1 \text{ ft}^3/\text{hr.}$

Absolute pressure in wet-test meter $= 1036" \pm 0.1" \text{ H}_2\text{O}$

Temperature in wet-test meter $= 297^\circ \pm 0.25^\circ\text{K}$

Barometric pressure $= 1033" \text{ H}_2\text{O}$

Photograph of flame (with scale of photograph)

$$\begin{aligned}\text{Flow rate} &= 11.4 \text{ ft}^3/\text{hr} \times 1/3600 \text{ sec/hr} \times [1036''\text{H}_2\text{O}/1033''\text{H}_2\text{O}] \\ &= 0.003176 \text{ ft}^3/\text{sec}\end{aligned}$$

$$\text{Maximum Error} = \pm \left[\frac{0.1}{11.4} + \frac{0.1}{1033} \right] \times 100 = 1\%$$

Flame area is obtained from the photographic negative. The negative is placed in an enlarger and the enlarged flame image traced on coordinate paper. The symmetrical flame front is then divided into a number of segments short enough so that they are satisfactorily represented by straight lines. The length of these straight line segments and the distance of each segment center point from the central axis of the flame is measured. By means of the equation for the area of a truncated cone:

$$\text{Truncated Cone Area} = (\text{Segment length}) \times 2\pi \times (\text{distance of segment center line to central axis of flame})$$

each segment area was computed. The sum of these areas equals the total area of the flame, and for the case in question was found to equal 0.002043 ft^2 . The error in this figure is estimated at about ± 1 per cent.

S_L may now be found:

$$S_L = \frac{0.003176 \text{ ft}^3/\text{sec}}{0.002043 \text{ ft}^2} = 1.555 \text{ ft/sec} \pm 2\%$$

7. Calculation of Theoretical Flame Temperature, Change in Number of Mols, and R_p .

The calculation of theoretical flame temperature and change in the number of mols were carried out by the method of Satterfield, Hottel, and Williams (40). The H/O, N/O and C/O ratios for city gas were obtained by using the analysis of city gas obtained from the gas company with the data shown as Run 11A in Appendix C. The heating value of city gas was obtained from the gas company.

In order to obtain R_p , the following equation, which assumes the perfect gas law, was employed:

$$R_p = \frac{T_b}{T_o} \times \frac{\text{mols after burning}}{\text{mols before burning}}$$

where T_b is the theoretical flame temperature of the combustible mixture and T_o is the temperature of the unburned gases (assumed to be 300° for calculation of Figure 31).

8. Calculation of Flame Velocity by Means of the Stepwise Calculations

Equation 39 obtained from a material balance:

$$S_f = V_o Y_t F/s$$

was employed to calculate flame velocity of segments of flames stabilized in the combustion chamber. The fraction

burned, F , was obtained from Figure 34 resulting from the stepwise calculations by entering with the reduced flame width, W_r , and the density ratio of the unburned to burned gases, R_ρ .

In one case at an air-fuel ratio of 11.34 pounds per pound, the following data necessary for the calculation of S_f were obtained:

$$V_0 = 24.3 \text{ ft/sec}$$

$$Y = 1.5''$$

$$s = 4''$$

$$W_4 = 0.72''$$

W_r is therefore $0.72''/3'' = 0.24$ and R_ρ from Figure 31 at an air-fuel ratio of 11.34 pounds per pound is 5.6. Entering Figure 34 with these values of W_r and R_ρ , F is found to be 0.069. S_f , which is in this case the flame velocity along the first 4" of flame front downstream of the stabilizer, is now found to be:

$$S_f = \frac{24.3 \times 1.5 \times 0.069}{4''}$$

$$= 0.63 \text{ ft/sec.}$$

C. Experimental Data

On the following pages are presented all of the experimental data taken during the course of this investigation.

In the remarks column the following abbreviations are employed.

LLBO - lean limit blow-out

RLBO - rich limit blow-out

LLBO(RF) - lean limit blow-out (residual flame remaining)

RFO - residual flame out

Most of the pictures taken of the flame to which a great deal of the following data apply are included in Appendix A. A few special pictures for which the data is included in the following pages, however, are not shown in Appendix A, but are presented as Figures in other portions of this report.

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Run No. 11(a) - Determination of Stoichiometric Air Requirement of Cambridge City Gas, and the Carbon Content of the Gas.

Date: January 3, 1947

Analysis Performed in a Fisher Precision Gas Analysis Apparatus

	Sample I	Sample II	Sample III	Avge Values
Vol. of Gas Sample	19.90 cc.	14.52 cc.	14.86 cc.	--
Vol. of Air Drawn In	94.98 cc.	98.32 cc.	97.48 cc.	--
Vol. After Slow Combustion	93.70 cc.	97.32 cc.	96.68 cc.	--
Vol. After Abs. in KOH	78.90 cc.	86.30 cc.	85.31 cc.	--
Vol. After Abs. in CrCl_2	78.48 cc.	80.30 cc.	79.70 cc.	--
 O ₂ Absorbed After combustion	 0.42 cc.	 6.00 cc.	 5.61 cc.	 --
 Air Corresponding to O ₂ After Combustion	 2.00 cc.	 28.57 cc.	 26.71 cc.	 --
 Air to Burn Gas Sample Completely	 92.98 cc.	 69.75 cc.	 70.77 cc.	 --
<u>Air Volume</u> at Stoichiometric <u>Gas Volume</u>	4.672cc.	4.804cc.	4.779cc.	4.752
 Air Weight/Gas Weight at Stoichiometric	 6.400cc.	 6.581cc.	 6.547cc.	 6.510
 CO ₂ After Combustion	 14.80 cc.	 11.02 cc.	 11.37 cc.	 --
<u>Mols of Carbon</u> <u>Mols of City Gas</u>	 .7437cc.	 .7590cc.	 .7651cc.	 .7559

Run No. 8 --- Pitot Traverses (Pitot tubes employed measuring impact pressure - Static Pressure measured at wall) - Pitot tube extends one inch down from center of probe hole)

DATE: January 20, 1947

SCREEN: None

Distance from near wall of chamber (inches)	P cm.H ₂ O	V			V			V			V		
		V ₀ ft/sec	T ₀ °K	at center of chamber ft/sec	V ₀ ft/sec.	T ₀ °K	0.25" from center of chamber ft/sec.	V ₀ ft/sec.	T ₀ °K	0.375" from center of chamber ft/sec	V ₀ ft/sec	T ₀ °K	0.465" from center of chamber ft/sec
Traverse 1.65" from chamber entrance													
2.965	29.73	139.3	297	139.0	141.8	303	122.3	140.0	307	118.6	139.8	308	86.8
2.930	29.73	139.3	297	145.3	141.8	308	133.7	140.0	307	124.6	139.8	308	121.1
2.900	29.73	139.3	297.3	146.6	141.8	303	144.2	140.0	307	142.6	139.8	308	121.1
2.800	29.73	139.3	297.5	147.3	141.8	303	148.0	140.0	307	149.0	139.8	308	121.1
2.700	29.73	139.3	298	148.0	141.8	303	148.0	140.0	307	149.8	139.8	308	121.1
2.600	29.73	139.3	298	148.0	141.8	304	148.2	140.0	307	149.8	139.8	308	121.1
2.000	29.73	139.3	298	148.0	141.8	304	148.2	140.0	307	149.8	139.8	308	121.1
1.800	29.73	139.3	298.5	148.1	141.8	304	148.2	140.0	307	149.8	139.8	308	121.1
1.000	29.73	139.3	298.5	148.1	141.8	304	148.2	140.0	307	149.8	139.8	308	121.1
0.800	29.73	139.3	299	148.2	-	-	-	140.0	307	149.8	-	-	-
0.300	29.73	139.3	299	148.2	-	-	-	140.0	307	149.8	-	-	-

Traverse 7.65" from chamber entrance

2.965	29.73	140.8	311	119.3	139.8	313	128.1	139.3	312	127.9	139.3	312	104.4
2.930	29.73	140.8	311	132.0	139.8	313	136.6	139.3	312	140.6	139.3	312	116.7
2.900	29.73	140.8	311	140.3	139.8	313	143.4	139.3	312	147.7	139.3	312	121.8
2.800	29.73	140.8	311	157.8	139.8	313	158.0	139.3	312	155.1	139.3	312	121.8
2.700	29.73	140.8	311	160.2	139.8	313	169.5	139.3	312	167.5	139.3	312	122.8
2.600	29.73	140.8	311	160.2	139.8	313	169.5	139.3	312	169.9	139.3	312	130.8
2.000	29.73	140.8	311	158.4	139.8	313	158.4	139.3	312	169.3	139.3	312	129.3
1.800	29.73	140.8	311	155.6	139.8	313	155.3	139.3	312	154.5	139.3	312	124.9
1.000	29.73	140.8	311	156.7	-	-	-	139.3	312	156.9	139.3	312	121.8
0.800	29.73	140.8	311	156.7	-	-	-	139.3	312	155.7	139.3	312	121.8
0.300	29.73	140.8	311	156.7	-	-	-	139.3	312	156.3	139.3	312	121.8

Traverse 13.65" from chamber entrance

2.965	29.73	139.7	314	119.9	138.7	316	120.3	138.6	313	122.0	137.8	316	99.3
2.930	29.73	139.7	314	123.8	138.7	316	130.2	138.6	313	131.0	137.8	316	114.4
2.900	29.73	139.7	314	130.8	138.7	316	133.8	138.6	313	138.0	137.8	316	117.7
2.800	29.73	139.7	314	146.2	138.7	316	147.3	138.6	313	149.8	137.8	316	119.3
2.700	29.73	139.7	314	157.4	138.7	316	158.6	138.6	313	153.5	137.8	316	120.9
2.600	29.73	139.7	314	163.3	138.7	316	163.2	138.6	313	158.9	137.8	316	125.6
2.000	29.73	139.7	314	163.3	138.7	316	163.2	138.6	313	160.1	137.8	316	124.7
1.800	29.73	139.7	314	157.4	138.7	316	158.8	138.6	313	153.5	137.8	316	124.0
1.000	29.73	139.7	314	161.0	138.7	316	163.3	138.6	313	156.6	137.8	316	119.3
0.800	29.73	139.7	314	161.6	-	-	-	138.6	313	156.6	-	-	-
0.300	29.73	139.7	314	161.0	-	-	-	138.6	313	157.2	-	-	-

Picture No.	V _a	V _r	T	P ₀	ΔP ₀	V ₀	V ₂	Q ₂	W ₂	Remarks
	lb/sec	lb/sec	°K	cm Hg	cm Hg	lb/lb	lb/lb	ft/sec	in.	in.

Run No. 11 --- City Gas and Air Combustion

DATE: February 20, 1947

SCREEN: None

FLAME STABILIZER: 0.188" diameter steel rod located 9" from chamber entrance

5-1-11	.0601	.00968	290	76.1	0.1	10.58	.6191	42.8	0.68	1.16	1.60
10-1-11	.0588	.00937	292	76.1	0.1	11.46	.6739	41.1	0.64	0.96	1.32
11-1-11	.132	.0123	293	76.3	0.2	10.73	.6224	94.6	0.64	1.08	1.44
12-1-11	.138	.0176	294	77.0	0.7	7.84	.5464	102.3	0.80	1.48	2.04
1-2-11	.135	.0178	299	(77.0)	---	7.99	.5381	102.4	0.88	1.48	2.04
2-2-11	.133	.01028	300	(76.3)	---	12.94	.6653	95.7	0.72	1.12	1.40
3-2-11	.366	.0388	301	79.0	2.6	9.43	.5917	264.2	0.80	1.12	1.48
4-2-11	.366	.0569	302	(82.0)	---	6.43	.4970	270.5	0.84	1.20	1.60

Picture No.	V _a	V _r	T	P ₀	ΔP ₀	V ₀	V ₂	Q ₂	W ₂	Remarks
	lb/sec	lb/sec	°K	cm Hg	cm Hg	lb/lb	lb/lb	ft/sec	inches	inches

Run No. 12 --- City Gas and Air Combustion

DATE: February 27, 1947

SCREEN: None

FLAME STABILIZER: 0.188" diameter steel rod located 9" from chamber entrance.

2-1-12											
6-1-12	.0595	.00823	295	(76.0)	---	7.24	.5252	45.3	1.00	2.44	Wall (1)
7-1-12	.0592	.01082	295	76.5	0.3	5.47	.4567	47.2	1.00	2.68	Wall
8-1-12	.0592	.0148	295	(76.0)	---	6.00	.3806	51.1	0.64	0.68	---
9-1-12	.0416	.00684	296	(76.0)	---	6.11	.4842	33.0	1.40	3.00	Wall
10-1-12	.0416	.01023	296	(76.0)	---	4.09	.3896	35.9	0.68	1.04	1.20 (2)
11-1-12	.0416	.00955	296	(76.0)	---	11.45	.6376	30.2	0.68	1.00	1.16 (2)

- (1) Pale Rust introduced
(2) Flame being affected by hot glass walls

Run No. 13 --- City Gas and Air Combustion

DATE: March 3, 1947

SCREEN: None

FLAME STABILIZER: 0.188" diameter steel rod located 9" from chamber entrance.

1-1-13	.0344	.0027	295	76.0	0	12.74	.6618	44.5	0.60	0.88	1.16
2-1-13	.0344	.0033	295	76.0	0	10.42	.6156	48.0	0.64	1.04	1.32 (1)
3-1-13	.0667	.00947	297	76.2	0.1	11.36	.6358	46.8	0.64	0.96	1.24
4-1-13	.0667	.00694	297	(76.2)	(0.1)	9.61	.5522	45.5	0.68	1.00	1.32
5-1-13	.0667	.00780	297	(76.2)	(0.1)	8.95	.5678	45.9	0.72	1.08	1.48
6-1-13	.0667	.0103	297	(76.2)	(0.1)	6.48	.4988	50.1	---	---	---
7-1-13	.0667	.0147	297	(76.2)	(0.1)	4.98	.4887	56.0	0.64	1.72	2.60
9-1-13	.127	.0129	303	76.7	0.3	9.85	.6080	94.5	0.60	0.92	1.24
10-1-13	.127	.0148	303	(77.0)	(0.3)	6.58	.5686	95.9	0.64	0.96	1.32
11-1-13	.127	.0199	303	(77.0)	(0.3)	6.38	.6950	100.4	0.76	1.36	2.00
12-1-13	.127	.0282	303	(77.0)	(0.3)	4.51	.4089	107.8	0.72	1.80	1.60
1-2-13	.296	.0298	309	78.1	1.8	9.93	.6041	220.4	0.76	1.04	1.28
2-2-13	.296	.0395	309	(78.1)	(1.8)	8.34	.5616	225.5	0.80	1.12	1.40
3-2-13	.296	.0483	309	(78.1)	(1.8)	6.84	.5065	233.4	0.80	1.16	1.44
4-2-13	.408	.054	301	79.0	4	7.95	.5372	303.7	0.80	1.08	1.32

Screen: --- 8 mesh; 0.025" wire diameter; - Blocked Area - 0.36

5-2-13	.0686	.00637	297	76.3	0.2	10.77	.6232	49.8	0.64	1.04	1.32
6-2-13	.0686	.00855	297	76.4	0.3	8.02	.5521	51.4	0.80	1.80	2.48
7-2-13	.0686	.0106	297	77.0	0.4	6.47	.4985	53.0	1.28	2.44	Wall
8-2-13	.0686	.0154	297	77.0	0.5	4.45	.4063	57.2	0.80	1.56	2.48
9-2-13	.0686	.00998	297	(76.3)	(0.2)	11.48	.6380	49.4	0.68	1.08	1.32
10-2-13	.0345	.00318	301	(76.5)	(0.1)	10.85	.6290	45.3	0.60	0.84	1.16
11-2-13	.0345	.00814	301	76.5	0.1	8.33	.5614	26.2	0.96	2.24	3.00
12-2-13	.0345	.00526	301	76.6	0.2	6.56	.5019	27.1	2.12	Wall	Wall

- (1) Flashed back at slightly richer mixture.
(2) Fluttering.

Run No. 14 --- High Speed Movies - City Gas and Air Combustion

DATE: March 11, 1947

SCREEN: 8 mesh; 0.025" wire diameter Blocked Area - 0.36

FLAME STABILIZER: 0.188" diameter steel rod located 9" from chamber entrance.

High Speed Movie	.0629	.00887	293	76.8	0.3	7.09	.5224	44.1			
Ball #2											
100 ft											

NaCl added to flame to furnish more light.
High Speed Camera run at 1900 frames per second.

Picture No.	V_1 lbs/sec	V_2 lbs/sec	$\frac{P}{K}$	P_0 cm. Hg.	ΔP cm. Hg.	$\frac{W_A}{W_F} = \frac{1}{f}$ lbs/lb.	$\frac{O_2}{O_1}$ lbs/lb.	V_0 ft/sec	V_2 inches	W_4 inches	V_6 inches	Remarks
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RUN NO. 15 — City Gas and Air Combustion

DATE: March 18, 1947

SCREEN: 8 mesh; 0.025" wire diameter; - Blocked Area - 0.36

FLAME STABILIZER: - 0.188" diameter steel rod located 9" from chamber entrance

Some NaCl still in Flame from last run.												
1-1-15	.0342	.00287	287	76.0	0.1	11.92	.6467	23.8	0.64	0.88	1.20	
2-1-15	.0342	.00354	287	76.0	0.1	9.66	.5974	24.4	---	---	---	(1)
3-1-15	.0342	.00413	287	76.1	0.1	8.28	.5599	24.9	1.32	2.52	Wall	
4-1-15	.0342	.00470	287	76.2	0.2	7.28	.5278	25.3	---	---	---	(1)
5-1-15	.0342	.00505	287	(76.2)	---	6.77	.5099	25.6	---	---	---	(2)
6-1-15	.0674	.00561	299	76.3	0.1	12.01	.6486	48.7	0.60	1.00	1.32	
7-1-15	.0674	.00786	299	76.5	0.2	8.58	.5684	50.5	0.80	1.76	2.44	
8-1-15	.0674	.00877	299	76.6	0.3	7.69	.5414	51.3	1.00	2.08	2.72	
9-1-15	.0674	.01002	299	76.9	0.3	6.73	.5082	52.2	1.20	2.40	2.84	
10-1-15	.0674	.01056	299	76.9	0.3	6.38	.4951	52.6	1.28	2.48	Wall	
11-1-15	.0674	.0111	299	77.0	0.4	6.07	.4826	53.1	1.28	2.52	Wall	
12-1-15	.0674	.0133	299	76.9	0.4	5.07	.4377	55.1	0.96	2.16	2.88	
1-2-15	.0674	.0144	299	76.7	0.3	4.54	.4110	56.6	0.80	1.56	2.28	
2-2-15	.0674	.0161	299	76.6	0.3	4.19	.3914	57.7	0.68	1.12	1.52	
3-2-15	.0674	.01687	299	76.4	0.2	4.00	.3803	58.6	0.72	1.20	1.52	
4-2-15	.134	.01353	301	77.1	0.7	9.90	.6034	98.5	0.72	1.20	1.52	
5-2-15	.134	.01700	301	77.4	0.7	7.88	.5477	101.2	0.68	1.16	1.72	
6-2-15	.134	.0139	301	77.5	0.8	7.09	.5213	102.7	0.76	1.32	2.00	
8-2-15	.134	.0220	301	77.7	0.8	6.09	.4834	105.2	0.80	1.36	2.08	
9-2-15	.134	.0283	301	(77.5)	---	4.74	.4211	111.0	0.80	1.28	1.56	
10-2-15	.286	.0311	303	79.4	2.0	9.20	.5855	207.4	0.76	1.04	1.36	
11-2-15	.286	.0389	303	80.3	2.5	7.35	.5304	211.7	0.80	1.20	1.48	
12-2-15	.286	.0446	303	80.7	2.5	6.41	.4962	215.5	0.80	1.24	1.60	
13-2-15	.286	.0473	303	(80.7)	---	6.05	.4815	217.6	0.80	1.24	1.60	
2-3-15	.405	.0455	311	81.9	3.5	8.90	.5776	293.5	0.76	1.04	1.32	

- (1) Flutter.
- (2) Burning in front of flame stabilizer just before flashback occurred - Extreme flutter.

RUN NO. 16 — City Gas and Air Combustion

DATE: March 19, 1947

SCREEN: 3 mesh; 0.063" wire diameter; - Blocked Area - 0.3423

FLAME STABILIZER: - 0.135" diameter steel rod located 9" from chamber entrance.

3-1-16	.0348	.00286	291	76.4	0.2	12.17	.6515	24.5	0.60	0.92	1.28	
4-1-16	.0348	.00323	291	(76.4)	---	10.78	.6234	24.8	0.72	1.08	1.40	(1)
5-1-16	.0671	.00567	293	76.6	0.2	11.82	.6451	47.4	0.64	1.00	1.36	
6-1-16	.0671	.00737	293	76.7	0.3	9.10	.5831	48.8	0.76	1.48	2.28	
7-1-16	.0671	.00845	293	76.3	0.4	7.94	.5495	49.6	0.88	2.08	2.64	
8-1-16	.0671	.00972	293	77.0	0.4	6.90	.5147	50.6	1.20	2.24	2.76	
9-1-16	.0671	.01118	293	77.2	0.4	6.00	.4797	51.7	1.24	2.40	2.96	
10-1-16	.0671	.01284	293	77.2	0.4	5.22	.4453	53.2	1.04	2.20	2.88	
11-1-16	.0671	.01438	293	77.2	0.4	4.66	.4175	54.4	0.80	1.72	2.52	
12-1-16	.0671	.01574	293	77.0	0.3	4.26	.3957	55.8	0.72	1.16	1.64	
1-2-16	.132	.0110	302	77.3	0.6	12.00	.6483	45.0	0.72	1.08	1.40	
2-2-16	.132	.0139	302	77.4	0.6	9.49	.5933	97.5	0.64	1.08	1.60	
3-2-16	.132	.01537	302	77.7	0.8	8.59	.5688	98.4	0.68	1.32	1.96	
4-2-16	.132	.01938	302	78.0	0.8	6.81	.5113	101.5	0.76	1.44	2.08	
5-2-16	.132	.0220	302	77.9	0.8	6.00	.4796	103.9	0.80	1.48	2.12	
6-2-16	.132	.0288	302	77.8	0.8	4.58	.4132	110.1	0.76	1.24	1.68	
7-2-16	.292	.0284	310	74.5	1.8	10.28	.6123	213.5	0.76	1.04	1.32	
8-2-16	.292	.0367	310	80.3	2.3	7.96	.5500	218.6	0.72	1.08	1.40	
9-2-16	.292	.0423	310	81.0	2.5	6.90	.5147	221.5	0.76	1.12	1.48	
10-2-16	.292	.0479	310	81.3	2.6	6.09	.4836	225.5	0.76	1.16	1.56	

- (1) Flashback at slightly richer mixture.

Picture No.	V_1 lbs/sec	V_2 lbs/sec	$\frac{P}{K}$	P_0 cm. Hg.	ΔP cm. Hg.	$\frac{W_A}{W_F} = \frac{1}{f}$ lbs/lb.	$\frac{O_2}{O_1}$ lbs/lb.	V_0 ft/sec	V_2 inches	W_4 inches	V_6 inches	Remarks
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RUN NO. 18

DATE: March 28, 1947

SCREEN: None

FLAME STABILIZER: 0.188" diameter steel rod located 9" from chamber entrance.

1-1-18	.1331	.01230	303	77.3	0.6	10.82	.6244	97.2	0.68	1.16	1.48	
2-1-18	.1331	.01463	303	77.4	0.7	9.10	.5829	99.1	0.64	1.12	1.56	
3-1-18	.1331	.01944	303	77.7	0.8	6.85	.5126	103.0	0.72	1.44	2.08	
4-1-18	.1331	.01711	303	77.6	0.7	7.78	.5404	101.1	0.68	1.36	1.92	
5-1-18	.1331	.0196	303	77.7	0.8	6.79	.5106	103.2	0.72	1.52	2.12	
6-1-18	.1331	.0257	303	77.7	0.8	5.18	.4431	108.5	0.72	1.32	1.92	
7-1-18	.1331	.0296	303	77.6	0.8	4.50	.4085	112.1	0.72	1.20	1.56	
8-1-18	.1331	.0324	303	77.5	0.7	4.11	.3869	114.8	0.72	1.20	1.52	
9-1-18	.0660	.00660	303	76.8	0.2	12.43	.6563	47.8	0.64	0.96	1.32	
10-1-18	.0660	.00668	303	76.8	0.3	9.88	.6028	49.0	0.72	1.40	2.20	
11-1-18	.0660	.00823	303	76.9	0.4	8.02	.5519	50.4	---	---	---	(1)
12-1-18	.0660	.00939	303	77.0	0.5	7.03	.5192	51.3	---	---	---	(1)
1-2-18	.0660	.01033	303	77.2	0.5	6.39	.4953	52.0	---	---	---	(2)
2-2-18	.0660	.0121	303	77.3	0.5	5.46	.4559	53.5	1.32	Wall	Wall	
3-2-18	.0660	.0138	303	77.2	0.4	4.78	.4235	55.1	1.00	2.52	Wall	
4-2-18	.0660	.0155	303	77.2	0.4	4.26	.3954	56.6	0.84	1.40	2.36	

- (1) Flutter
- (2) Very slight flutter

RUN NO. 19

DATE: April 3, 1947

SCREEN: 8 mesh; 0.025" wire diameter

FLAME STABILIZER: Flat plate with center 9" from chamber entrance; dimensions: -0.496" wide; 0.008" thick; 1" long.

Attempted to make flame stabilize by inserting spark rod at point 1 1/2" below flat plate, igniting, and allowing flame to stabilize on spark rod. Flame stabilizing on spark rod partially enveloped flat plate; but when rod was withdrawn, flame failed to stabilize on the flat plate. Attempts to stabilize at velocities of 20 and 40 ft/sec; and at various air-fuel ratios were made with no success.

Picture No. $\frac{V_a}{100 \text{ sec}}$ $\frac{V_f}{100 \text{ sec}}$ $\frac{T}{^\circ K}$ P_o $\frac{\Delta P}{\text{cm. Hg.}}$ $\frac{V_a}{100 \text{ lb.}}$ $\frac{V_f}{100 \text{ lb.}}$ $\frac{V_o}{\text{ft/sec}}$ V_2 V_3 V_4 V_5 Remarks

Run No. 20 --- City Gas and Air Combustion

DATE: April 7, 1947

SCREEN: 8 mesh; 0.025" wire diameter

FLAME STABILIZER: 0.126" diameter steel rod located 9" from chamber entrance.

6-1-20	.03515	.002135	293	76.5	0.1	16.13	.7166	24.1	---	---	---	LLBO (1)
7-1-20	.0347	.00230	293	76.5	0.1	15.09	.6986	24.0	0.96	0.88	1.20	
8-1-20	.0347	.00261	293	76.5	0.1	13.30	.6713	24.2	0.68	1.08	1.80	
9-1-20	.0347	.00342	293	76.6	0.1	10.15	.6092	24.9	---	---	---	
10-1-20	.0347	.00400	293	76.6	0.2	8.68	.5713	25.4	---	---	---	
11-1-20	.0347	.00460	293	76.6	0.3	7.54	.5368	25.9	---	---	---	(2)

Screen: 3 mesh; 0.063" wire diameter.

12-1-20	.0347	.00261	293	76.5	0.1	13.30	.6713	24.2	0.60	0.92	1.40	(3)
1-2-20	.0668	.00902	298	76.7	0.2	13.31	.6715	47.3	0.72	1.16	1.60	---
2-2-20	.0668	.00836	298	76.7	0.3	10.50	.6174	48.5	0.72	1.44	2.16	---
3-2-20	.0668	.00853	298	76.9	0.4	7.83	.5461	50.3	1.16	2.24	2.72	---
4-2-20	.0668	.00957	298	77.0	0.4	6.98	.5174	51.1	1.40	2.44	Wall	---
5-2-20	.0668	.0104	298	77.0	0.5	6.19	.4872	52.2	1.48	2.60	Wall	---
6-2-20	.0668	.0121	298	77.0	0.5	5.52	.4589	53.4	1.36	2.52	Wall	---
7-2-20	.0668	.0126	298	77.0	0.4	5.30	.4488	53.8	1.08	2.20	3.0	---
8-2-20	.0668	.01454	298	76.9	0.4	4.99	.4137	55.6	0.80	1.64	2.52	---
9-2-20	.0668	.0153	298	76.9	0.4	4.37	.4014	56.2	0.80	1.32	1.96	---
10-2-20	.0668	.0160	298	76.9	0.4	4.18	.3907	56.9	0.72	1.20	1.64	---
11-2-20	.131	.0107	305	76.9	0.5	12.24	.6529	95.5	0.72	1.16	1.56	---
12-2-20	.131	.0145	305	77.1	0.5	9.03	.5812	98.7	0.72	1.24	1.76	---
1-3-20	.131	.0181	305	77.5	0.7	7.24	.5265	101.4	0.84	1.56	2.24	---
2-3-20	.131	.0197	305	77.7	0.7	6.65	.5033	102.6	0.84	1.68	2.40	---
3-3-20	.131	.0214	305	77.7	0.7	6.12	.4846	104.1	0.84	1.68	2.36	---
4-3-20	.131	.0270	305	77.7	0.7	4.85	.4270	109.1	0.80	1.36	1.84	---
5-3-20	.131	.0309	305	77.7	0.5	4.24	.3944	112.5	0.80	1.28	1.68	---
6-3-20	.296	.0300	310	79.1	2.0	9.87	.6025	214.5	0.72	1.12	1.52	---
7-3-20	.296	.0350	310	79.7	2.3	8.46	.5690	221.2	0.76	1.24	1.64	---
8-3-20	.296	.0405	310	80.1	2.6	7.31	.5289	225.0	0.80	1.28	1.72	---
9-3-20	.296	.0438	310	80.4	2.6	6.76	.5093	227.0	0.80	1.32	1.76	---
10-3-20	.296	.0460	310	80.4	2.6	6.43	.4971	228.9	0.80	1.32	1.76	---
11-3-20	.399	.0461	312	81.2	3.6	8.66	.5707	293.7	0.76	1.16	1.48	---
12-3-20	.373	.0414	313	80.7	3.3	9.01	.5805	275.6	0.76	1.12	1.44	---

- (1) Flame holding on rod quite well but is extending up only an inch or so above it. Seems to be snuffed out above rod but rises in puffs at intervals.
- (2) Flashed back at slighter rich mixture.
- (3) Flutters and tends to flash back at richer mixtures.

Run No. 22 --- High Speed Movies - City Gas and Air Combustion

DATE: May 8, 1947

SCREEN: None

FLAME STABILIZER: 0.126" diameter steel rod located 9" from chamber entrance

All high speed movies taken at 1500 frames/sec; No. 01 added to increase amount of light.

High Speed												
Ball #IV	.1301	.0194	305	76.77	0.5	6.71	.5074	102.9				(1)
1500x/sec												

- (1) Fairly good film

Picture No. $\frac{V_a}{100 \text{ sec}}$ $\frac{V_f}{100 \text{ sec}}$ $\frac{T}{^\circ K}$ P_o $\frac{\Delta P}{\text{cm. Hg.}}$ $\frac{V_a}{100 \text{ lb.}}$ $\frac{V_f}{100 \text{ lb.}}$ $\frac{V_o}{\text{ft/sec}}$ V_2 V_3 V_4 V_5 Remarks

Run No. 23 --- City Gas and Air Combustion

DATE: May 12, 1947

SCREEN: None

FLAME STABILIZER: 0.126" diameter steel rod located 9" from chamber entrance.

5-1-23	.03474	.00284	295	76.2	0.1	12.23	.6527	24.7	0.72	1.20	1.48	(1)
6-1-23	.03474	.00309	295	76.3	0.1	11.24	.6333	24.9	0.84	1.32	1.68	---
7-1-23	.03474	.00381	298	76.2	0.1	12.44	.6665	34.0	0.60	1.08	1.44	---
8-1-23	.03474	.00487	298	76.3	0.1	11.37	.6358	34.3	0.72	1.28	1.72	---
9-1-23	.03474	.00515	298	76.3	0.1	9.20	.5957	35.2	1.28	2.28	Wall	(1)
10-1-23	.0674	.00535	302	76.3	0.2	12.60	.6993	48.9	0.72	1.16	1.44	---
11-1-23	.0674	.00647	302	76.3	0.2	10.42	.6154	49.9	0.72	1.28	1.68	---
12-1-23	.0674	.00843	302	76.4	0.3	8.00	.5512	51.6	1.12	2.04	2.72	---
1-2-23	.0674	.01019	302	76.5	0.3	6.61	.5040	53.1	1.24	2.40	3.00	---
2-2-23	.0674	.01216	302	76.5	0.3	5.54	.4999	54.9	1.20	2.36	2.96	---
3-2-23	.0674	.01409	302	76.5	0.3	4.78	.4236	56.6	0.96	1.76	2.56	---
4-2-23	.0674	.01647	302	76.4	0.3	4.09	.3860	58.8	0.72	1.20	1.56	---
5-2-23	.1294	.0112	311	76.9	0.4	11.55	.6396	96.8	0.76	1.24	1.56	---
6-2-23	.1294	.01443	311	77.0	0.4	8.97	.5794	99.6	0.76	1.32	1.72	---
7-2-23	.1294	.0179	311	77.2	0.6	7.23	.5262	102.5	0.84	1.52	2.00	---
8-2-23	.1294	.0197	311	77.3	0.7	6.57	.5022	104.1	0.92	1.64	2.16	---
9-2-23	.1294	.0247	311	77.3	0.6	5.24	.4459	108.6	0.88	1.48	1.96	---
10-2-23	.1294	.0300	311	77.1	0.4	4.31	.3985	113.7	0.84	1.32	1.72	---
11-2-23	.292	.0311	318	79.0	2.2	9.39	.5905	222.7	0.84	1.24	1.56	---
12-2-23	.292	.03799	318	79.2	2.3	7.77	.5441	228.1	0.88	1.32	1.68	---
1-3-32	.292	.0428	318	79.9	2.6	6.82	.5117	230.8	0.88	1.32	1.68	---
2-3-32	.362	.0460	319	80.6	3.3	7.87	.5473	278.2	0.84	1.24	1.56	---
3-3-32	.336	.0504	319	80.7	3.4	6.67	.5059	264.8	0.84	1.28	1.64	---

- (1) Flutter above here.

Run No. 24 --- City Gas and Air Combustion

DATE: May 12, 1947

SCREEN: None

FLAME STABILIZER: 0.094" diameter steel rod located 9" from chamber entrance

5-1-24	.0328	.00270	300	75.5	0.1	12.15	.6511	23.7	0.60	1.00	1.40	(1)
6-1-24	.0676	.00460	301	76.6	---	14.70	.6930	48.0	---	---	---	LLBO
7-1-24	.0676	.00531	302	76.6	0.2	12.73	.6617	48.8	0.84	1.08	1.48	---
8-1-24	.0676	.00668	302	76.6	0.2	10.12	.6085	50.1	0.68	1.32	1.92	---
9-1-24	.0676	.00832	302	76.7	0.2	8.13	.5552	51.5	1.04	2.04	2.64	---
10-1-24	.0676	.0105	302	76.8	0.4	6.43	.4972	53.3	1.32	2.40	Wall	---
11-1-24	.0676	.0124	302	76.9	0.6	5.46	.4558	54.9	1.24	2.40	Wall	---
12-1-24	.0676	.0151	302	76.6	0.4	4.48	.4075	57.6	0.72	1.44	2.40	---
1-2-24	.0676	.0163	302	76.6	0.4	4.15	.3881	58.4	0.64	1.08	1.44	---
2-2-24	.0649	.0172	306	76.6	---	3.77	.3669	58.4	---	---	---	LLBO
3-2-24	.129	.0101	311	77.1	---	12.77	.6624	95.3	---	---	---	LLBO
4-2-24	.129	.0120	315	77.1	0.6	10.75	.6228	98.3	0.72	1.12	1.60	---
5-2-24	.129	.0159	315	77.2	0.7	8.11	.5548	101.7	0.72	1.28	1.72	---
6-2-24	.129	.0196	315	77.3	0.9	6.58	.5027	105.0	0.80	1.44	2.40	---
7-2-24	.129	.0258	315	77.3	0.8	5.00	.4344	110.8	0.84	1.36	1.80	---
8-2-24	.129	.0284	315	77.3	0.7	4.54	.4110	113.2	0.80	1.32	1.72	---
9-2-24	.127	.0309	316	77.3	---	4.11	.3870	114.5	---	---	---	LLBO
10-2-24	.292	.0297	318	78.6	1.8	9.83	.6016	222.6	0.76	1.12	1.44	---
11-2-24	.292	.0346	318	79.3	2.0	8.44	.5645	225.1	0.76	1.24	1.60	---
12-2-24	.292	.0388	318	79.6	2.3	7.53	.5362	228.0	0.80	1.28	1.72	---
1-3-24	.292	.0426	318	80.0	2.5	6.85	.5129	230.3	0.80	1.32	1.72	---
2-3-24	.292	.0483	318	80.1	2.7	6.05	.4815	235.2	0.80	1.32	1.72	---
3-3-24	.2835	.0285	318	78.6	---	9.95	.6115	216.0	---	---	---	LLBO
4-3-24	.380	.0449	321	80.7	3.3	8.46	.5652	290.4	0.76	1.20	1.52	---
5-3-24	.399	.0450	321	80.7	---	8.87	.5766	303.0	---	---	---	LLBO

- (1) Flutter above here.

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Picture No. W_a W_r T P_o AP_d W_a O_2 V_o W_2 W_3 W_6 Remarks
lb/sec lb/sec $^{\circ}F$ cm. Hg. cm. Hg. lb/lb lb/lb ft/sec inches inches inches

Run No. 29 --- City Gas and Air Combustion
DATE: May 22, 1947

SCREEN: 3 mesh; 0.063" wire diameter
FLAME STABILIZER: 0.038" diameter steel rod located 9" from chamber entrance

1-1-29	.0349	.002444	297	76.4	0.2	24.28	.6869	24.6	0.32	0.60	0.88	
2-1-29	.0349	.002941	297	76.4	0.2	11.87	.6457	25.0	0.54	0.88	1.40	
3-1-29	.0349	.003199	297	76.4	0.2	10.91	.6263	25.3	0.64	1.48	2.00	(1)
4-1-29	.06675	.005063	300	(76.5)	-	13.45	.6779	48.7	-	-	-	LLBO
	.06675	.005178	301	76.5	0.2	12.89	.6645	48.0	0.48	0.72	1.04	
5-1-29	.06675	.006071	301	76.5	0.2	11.01	.6285	48.8	0.48	0.96	1.52	
6-1-29	.06675	.00726	301	76.5	0.3	9.19	.5855	49.9	0.76	1.60	2.16	
7-1-29	.06675	.00874	301	76.7	0.4	7.64	.5398	51.1	1.04	2.00	2.60	
8-1-29	.06675	.01061	301	77.0	0.5	6.29	.4915	52.5	1.16	2.28	2.80	
9-1-29	.06675	.01216	301	77.0	0.5	5.49	.4575	53.9	1.16	2.32	3.00	
10-1-29	.06675	.01456	301	76.8	0.5	4.58	.4132	56.2	0.64	1.84	2.76	
- - -	.06385	.0157	304	(76.8)	-	4.07	.3845	55.9	-	-	-	LLBO
- - -	.1296	.0115	308	(77.0)	-	11.27	.6338	96.2	-	-	-	LLBO
- - -	.1327	.01173	309	(77.0)	-	11.31	.6347	98.7	-	-	-	LLBO
11-1-29	.1318	.01221	311	77.0	0.5	10.79	.6258	99.2	0.56	0.96	1.28	
12-1-29	.1318	.01415	311	77.1	0.6	9.31	.5886	100.9	0.52	0.96	1.40	
1-2-29	.1318	.01640	311	77.3	0.7	8.04	.5525	102.6	0.56	1.20	1.68	
2-2-29	.1318	.01934	311	77.4	0.8	6.82	.5114	105.2	0.64	1.40	1.92	
3-2-29	.1318	.02232	311	77.4	0.8	5.91	.4796	107.9	0.68	1.40	1.92	
4-2-29	.1318	.02616	311	77.3	0.7	5.04	.4363	111.5	0.68	1.20	1.64	
5-2-29	.1318	.0280	311	77.3	0.6	4.71	.4196	113.2	0.64	1.16	1.56	
- - -	.1314	.02874	313	(77.3)	-	4.57	.4126	114.4	-	-	-	LLBO
- - -	.2249	.02999	316	(78.5)	-	9.38	.5902	171.6	-	-	-	LLBO
- - -	.2230	.0442	317	(78.5)	-	5.05	.4366	189.4	-	-	-	LLBO
- - -	.2926	.0365	317	(79.3)	-	8.02	.5519	228.5	-	-	-	LLBO (2)
6-2-29	.2945	.03788	317	79.3	2.2	7.78	.5443	229.0	0.64	1.08	1.44	
7-2-29	.2945	.0415	317	79.4	2.3	7.10	.5215	232.0	0.68	1.16	1.52	
8-2-29	.2945	.0461	317	79.7	2.4	6.39	.4953	235.3	0.68	1.16	1.48	
9-2-29	.2940	.0511	317	79.7	2.4	5.75	.4692	239.4	0.68	1.16	1.48	LLBO
- - -	.3318	.04744	317	(80.0)	-	6.99	.5179	260.0	-	-	-	LLBO
- - -	.3448	.0532	317	(80.0)	-	6.48	.4989	273.7	-	-	-	LLBO

- (1) Flutter above here
(2) Appearance of flame just before blow-out at 200 ft/sec at blow-out velocities above this.

Picture No. W_a W_r T P_o AP_d W_a O_2 V_o W_2 W_3 W_6 Remarks
lb/sec lb/sec $^{\circ}F$ cm. Hg. cm. Hg. lb/lb lb/lb ft/sec inches inches inches

Run No. 30 --- City Gas and Air Combustion
DATE: May 23, 1947

SCREEN: 3 mesh; 0.063" wire diameter
FLAME STABILIZER: 0.026" diameter steel rod located 9" from chamber entrance

10-1-30	.0341	.00261	294	76.4	0.2	13.07	.6674	24.0	0.32	0.56	0.88	
11-1-30	.0341	.002835	294	76.4	0.2	12.03	.6488	24.2	0.36	0.56	1.44	
12-1-30	.0341	.00308	294	76.4	0.2	11.07	.6297	24.4	0.72	1.44	1.92	(1)
- - -	.0675	.00520	297	(76.6)	-	12.98	.6660	47.8	-	-	-	LLBO
1-2-30	.0667	.00536	298	76.6	0.2	12.44	.6565	47.6	0.40	0.76	1.12	
2-2-30	.0667	.00608	298	76.6	0.2	10.97	.6276	48.3	0.52	1.08	1.56	
3-2-30	.0667	.00799	298	76.9	0.4	8.35	.5618	49.8	1.04	1.96	2.64	
4-2-30	.0667	.00919	298	76.9	0.5	7.26	.5272	50.8	1.24	2.20	2.68	
5-2-30	.0667	.01065	298	77.1	0.7	6.26	.4905	52.0	1.32	2.40	Wall	
6-2-30	.0667	.01219	298	77.1	0.7	5.47	.4567	53.3	1.32	2.40	Wall	
7-2-30	.0667	.01379	298	77.0	0.6	4.84	.4263	54.8	1.00	2.20	2.88	
- - -	.0699	.01599	300	(77.0)	-	4.12	.3877	56.6	-	-	-	LLBO
- - -	.1292	.0207	304	(77.0)	-	10.70	.6218	95.2	-	-	-	LLBO
8-2-30	.131	.0244	307	77.0	0.6	10.53	.6180	97.6	0.52	0.92	1.32	
9-2-30	.131	.0241	307	77.1	0.7	9.09	.5827	99.3	0.60	1.12	1.56	
10-2-30	.131	.0246	307	77.2	0.8	7.96	.5501	101.0	0.64	1.28	1.76	
11-2-30	.131	.0248	307	77.4	1.0	6.80	.5107	103.3	0.68	1.48	1.88	
12-2-30	.131	.0251	307	77.5	1.0	6.09	.4835	105.1	0.76	1.52	1.92	
1-3-30	.131	.0259	307	77.4	0.9	5.06	.4372	109.2	0.64	1.24	1.72	
- - -	.1287	.0273	308	(77.4)	-	4.71	.4200	109.3	-	-	-	LLBO
- - -	.220	.02585	310	(78.5)	-	8.51	.5666	166.8	-	-	-	LLBO
- - -	.2249	.0413	311	(78.5)	-	5.45	.4555	184.4	-	-	-	LLBO
- - -	.2761	.04405	312	(79.5)	-	6.27	.4905	218.4	-	-	-	LLBO
- - -	.2852	.04332	312	(79.5)	-	6.58	.5028	223.6	-	-	-	LLBO

(1) Flutter above here

Run No. 31 --- City Gas and Air Combustion
DATE: May 27, 1947

SCREEN: 3 mesh; 0.063" wire diameter
FLAME STABILIZER: 0.026" diameter steel rod located 9" from chamber entrance

2-1-31	.3054	.04666	299	79.7	2.4	6.95	.5013	229.1	0.60	1.04	1.44	
- - -	.303	.0495	300	(79.5)	-	6.97	.5169	226.3	-	-	-	LLBO
- - -	.303	.0457	302	(79.5)	-	6.63	.5046	229.7	-	-	-	LLBO
- - -	.2956	.0495	305	(79.5)	-	6.80	.5107	235.4	-	-	-	LLBO
- - -	.2886	.04633	306	(79.5)	-	6.23	.4892	224.2	-	-	-	LLBO
- - -	.2778	.0442	307	(79.5)	-	6.29	.4912	216.1	-	-	-	LLBO

Picture No. $1/2$ O_2 Gas Gas $Tube$ A B $Remarks$
lb/lb Air lb/lb Temp $^{\circ}F$ ft³/sec No. ft² ft/sec

Run No. 32 --- Laminar Flame Speed Measurements - City Gas and Air Combustion
DATE: May 28, 1947

6-1-32	7-1-32	6.87	106.5	.5134	297	.00176	797.03	.002043	1.666	
9-1-32	10-1-32	7.98	122.5	.5606	298	.002606	828.54	.002264	1.106	
11-1-32	12-1-32	9.75	149.8	.6997	298.5	.001286	322.48	.001852	.6938	
1-2-32	2-2-32	5.91	90.7	.4757	298.5	.003622	906.96	.002258	1.904	
3-2-32	4-2-32	4.86	74.5	.4270	298.5	.002449	614.58	.001752	1.396	
5-2-32	6-2-32	3.66	55.0	.3590	299.5	.007807	136.39	.001598	.4704	(1)
7-2-32	8-2-32	-	-	-	-	-	-	-	-	(2)

(1) Would not go any further on lean side without flame either blowing off or going down tube.

(2) Picture of tube alone for scale determination; - tube outside diameter - 0.539"; tube inside diameter - 0.37" large tube length - 6 ft.

Picture No.	W_a lbs/sec	W_f lbs/sec	T °K	P_{O_2} cm. Hg.	AP_{O_2} cm. Hg.	$W_a = \frac{1}{f}$ lbs/lb	O_2 lbs/lb	V_0 ft/sec	W_2 inches	W_3 inches	W_4 inches	Remarks
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RUN NO. 33 --- City Gas and Air Combustion

DATE: June 4, 1947

SCREEN: None

FLAME STABILIZER: 0.026 diameter steel rod located 9" from chamber entrance

7-1-33	.03272	.002311	295	77.1	0.1	14.16	.6850	22.7	0.28	0.60	0.72	
8-1-33	.03272	.00262	295	77.1	0.1	12.49	.6573	23.0	0.56	0.96	1.24	
9-1-33	.03272	.00399	295	77.2	0.2	10.59	.6193	23.4	0.72	1.28	1.64	(1)

At 25 ft/sec or so, flame appears very laminar; but upon careful examination it is seen that any one flame front extending from the rod is not a plane surface but is a sort of folded surface, so that at any time a cross-section of the tunnel showing the location of the flame front at 4" above the rod might look as follows:

- - -	.06745	.00503	298	(77.2)	-	13.42	.6732	47.4	-	-	-	LLBO
10-1-33	.0673	.00529	300	77.2	0.3	12.72	.6615	48.0	0.20	0.44	0.63	
11-1-33	.0673	.00599	300	77.3	0.3	11.24	.6331	48.6	0.40	0.72	1.04	
12-1-33	.0673	.00626	300	77.3	0.4	9.72	.5988	49.4	-	-	-	(2)

Could not get Rich limit; blew out from fluttering. Flame fluttering from flame stabilizer down to 2 or 3 inches below flame stabilizer. Blew out at slightly leaner than stoichiometric. In neighborhood of 40 ft/sec flame appears gradually to become turbulent from laminar. This has also been observed in all the previous runs. The flame front no longer can be identified by eye as a thin plane surface, but appears more as a thickened zone of blue beginning a short distance above rod (about height of piloting zone).

- - -	.1253	.0108	306	(77.5)	-	11.62	.6406	91.5	-	-	-	LLBO
- - -	.1289	.01104	308	(77.5)	-	11.68	.6420	95.0	-	-	-	LLBO
1-2-33	.1284	.01125	309	77.5	0.5	11.41	.6368	95.1	0.44	0.92	1.28	
2-2-33	.1284	.0126	309	77.6	0.5	10.19	.6102	96.3	0.52	1.00	1.32	
3-2-33	.1284	.01546	309	77.9	0.6	8.31	.5606	98.6	0.64	1.28	1.80	
4-2-33	.1284	.0172	309	78.2	0.9	7.25	.5268	100.3	0.76	1.52	2.00	
5-2-33	.1284	.0195	309	78.3	1.0	6.59	.5028	101.9	0.76	1.56	2.08	
6-2-33	.1284	.02191	309	78.3	1.0	5.86	.4737	104.0	0.80	1.60	2.12	
7-2-33	.1284	.02433	309	78.0	0.8	5.28	.4477	106.6	0.80	1.52	1.96	
8-2-33	.1254	.02761	312	(78.0)	-	4.54	.4110	108.7	0.64	1.28	1.68	RLBO
- - -	.131	.0253	299	78.0	-	4.63	.4156	105.2	-	-	-	RLBO
- - -	.230	.0447	303	(79.0)	-	5.14	.4415	124.7	-	-	-	RLBO

With no screen in place to furnish resistance to air flow small perturbations appear easily and change the character of the flow. After the above data were obtained and more were to be tried for a perturbation appeared and changed the shape of the flame to a wider flatter, slightly fluttering one at all velocities. The calming section will be thoroughly cleaned out before the next run to get rid of this perturbation which is very likely caused by something that has fallen into the calming section through the nozzle, and is resting on the top screen and disturbing the flow.

A small rod about 1/8" in diameter was inserted in the probe point adjacent to the flame stabilizer and slightly below it. The flame would begin to flutter down toward the rod and finally stabilize on it. This flame sheet extending from the rod appeared as a plane (but of course could not be viewed from the edge as can the flames on the flame stabilizer).

- (1) Flutter above here
- (2) Flutter

Picture No.	W_a lbs/sec	W_f lbs/sec	T °K	P_{O_2} cm. Hg.	AP_{O_2} cm. Hg.	$W_a = \frac{1}{f}$ lbs/lb	O_2 lbs/lb	V_0 ft/sec	W_2 inches	W_3 inches	W_4 inches	Remarks
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RUN NO. 34 --- City Gas and Air Combustion

DATE: June 6, 1947

SCREEN: None

FLAME STABILIZER: 0.026" diameter steel rod located 9" from chamber entrance

- - -	.282	.03464	302	(79.0)	-	6.09	.5542	208.5	-	-	-	LLBO
- - -	.2972	.03879	306	(79.0)	-	7.64	.5406	224.4	-	-	-	LLBO
- - -	.296	.04062	309	(79.0)	-	7.28	.5279	225.7	-	-	-	LLBO
9-1-34	.292	.04235	313	79.0	2.3	5.60	.5144	226.3	.56	1.08	1.44	
10-1-34	.292	.0453	313	79.2	2.3	4.45	.4975	231.4	.50	1.06	1.46	
- - -	.286	.04772	316	(79.0)	-	4.04	.4611	233.8	-	-	-	RLBO
- - -	.300	.0481	318	(79.0)	-	3.61	.4699	241.8	-	-	-	LLBO

At about 35 ft./sec. flame cross section is as shown:

RUN NO. 35 --- City Gas and Air Combustion

DATE: June 5, 1947

SCREEN: None

FLAME STABILIZER: 0.016" diameter steel rod located 9" from chamber entrance

Cannot stabilize at 25 ft./sec. without severe flutter (because flame must get too rich to stabilize)

- - -	.0687	.00685	292	(75.6)	-	11.74	.6434	48.4	-	-	-	LLBO
11-1-35	.0685	.00618	293	75.6	0.3	10.76	.6231	47.4	.46	1.00	1.32	
12-1-35	.0685	.00679	293	75.7	0.3	9.79	.6007	47.9	.55	1.12	1.46	

Fluttering above last reading. Finally fluttered so violently at stoichiometric that it blew itself out.

- - -	.0660	.00663	300	(76.7)	-	11.72	.6430	47.7	-	-	-	LLBO
- - -	.1269	.01233	303	(77.0)	-	10.45	.6133	94.9	-	-	-	LLBO
1-2-35	.1273	.01267	306	77.0	0.6	10.13	.6067	94.7	.48	1.00	1.35	
2-2-35	.1273	.0151	306	77.3	0.6	8.43	.5643	96.6	.60	1.15	1.54	
3-2-35	.1273	.01585	306	77.4	0.9	7.65	.5371	98.0	.54	1.40	1.88	
4-2-35	.1273	.0169	306	77.5	1.0	6.74	.5065	99.7	.72	1.52	2.00	
5-2-35	.1273	.0213	306	77.5	0.9	5.98	.4766	101.8	.72	1.48	2.00	
6-2-35	.1273	.02425	306	77.5	0.9	5.25	.4464	104.5	.54	1.28	1.80	
- - -	.1300	.0262	308	(77.5)	-	4.95	.4325	109.0	-	-	-	RLBO
- - -	.221	.02930	310	(78.0)	-	7.04	.5567	171.5	-	-	-	LLBO
- - -	.223	.0370	311	(78.0)	-	6.03	.4807	180.5	-	-	-	RLBO
- - -	.243	.0368	314	(79.0)	-	6.60	.5056	192.9	-	-	-	LLBO
- - -	.243	.0362	315	(79.0)	-	5.71	.5079	191.7	-	-	-	LLBO
- - -	.246	.0378	314	(79.0)	-	5.51	.4964	195.7	-	-	-	RLBO (1)

(1) Believed to be at about top of blow-out curve.

Picture No.	W_a lbs/sec	V_f lbs/sec	T °K	P_{O_2} cm. Hg.	ΔP cm. Hg.	$\frac{V_a}{V_f} = \frac{1}{f}$ lb/lb	O_2 lb/lb	V_0 ft/sec	W_2 inches	W_4 inches	W_6 inches	Remarks
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MUN NO. 36 --- City Gas and Air Combustion

DATE: June 10, 1947

SCREEN: 3 mesh; 0.063" wire diameter

FLAME STABILIZER: 0.016" diameter steel rod located 9" from chamber entrance.

---	.0695	.00602	292	(76.4)	--	11.50	.6394	49.1	--	--	--	LLBO
7-1-36	.0682	.00607	294	76.4	0.3	11.24	.6331	48.7	.48	1.12	1.56	
8-1-36	.0682	.00741	294	76.5	0.4	9.20	.5857	49.8	.92	1.72	2.24	(1)
9-1-36	.0682	.00943	294	76.8	0.6	7.23	.5263	51.4	1.36	2.24	2.48	
10-1-36	.0682	.01080	294	76.8	0.7	6.32	.4924	52.5	1.48	2.48	Wall	
---	.0682	.01321	297	(76.5)	--	4.94	.4512	53.5	--	--	--	RLBO
---	.0671	.01326	298	(76.6)	--	5.06	.4374	54.9	--	--	--	RLBO
---	.1287	.01323	304	(77.0)	--	9.73	.5991	95.9	--	--	--	LLBO
11-1-36	.129	.01356	307	77.0	0.6	9.51	.5937	97.3	.52	1.08	1.44	
12-1-36	.129	.01547	307	77.1	0.8	8.34	.5616	98.9	.68	1.32	1.72	
1-2-36	.129	.0175	307	77.2	0.9	7.37	.5310	100.8	.76	1.48	2.00	
2-2-36	.129	.0192	307	77.3	1.0	6.72	.5079	102.0	.80	1.52	2.00	
3-2-36	.129	.0216	307	77.3	1.0	5.97	.4786	104.2	.80	1.52	2.00	
---	.128	.0240	309	(77.2)	--	5.21	.4485	104.5	--	--	--	RLBO
---	.194	.0312	310	(78.0)	--	6.22	.4886	105.8	--	--	--	RLBO
---	.192	.0270	312	(78.0)	--	7.11	.5221	101.5	--	--	--	LLBO

(1) Cross-section of flame at 50 ft./sec. near stoichiometric. Walls appear to be influencing flame speed here.

MUN NO. 37 --- City Gas and Air Combustion

DATE: June 10, 1947

SCREEN: 3 mesh; 0.063" wire diameter

FLAME STABILIZER: 0.012" diameter tungsten wire located 9" from chamber entrance.

Could not get flame to stabilize on the tungsten rod even at near stoichiometric at about 50 ft./sec. Flame from spark rod holder would be allowed to impinge on wire flame stabilizer (tungsten) until it was near white heat. When lower flame was removed flame would hang on tungsten wire for a very short time only (1/2 second or less).

SCREEN: None

Could not get the flame to hold although undoubtedly there are regions within the operating limits where stabilization would occur. The difficulty is in running at such rich mixtures with spark rod in and at fairly low velocities. Flashback tends to occur in these regions. Tungsten rod finally oxidized completely and was carried away by the gas stream.

Picture No.	W_a lbs/sec	V_f lbs/sec	T °K	P_{O_2} cm. Hg.	ΔP cm. Hg.	$\frac{V_a}{V_f} = \frac{1}{f}$ lb/lb	O_2 lb/lb	V_0 ft/sec	W_2 inches	W_4 inches	W_6 inches	Remarks
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MUN NO. 38 --- City Gas and Air Combustion

DATE: June 12, 1947

SCREEN: 3 mesh; 0.063" wire diameter

FLAME STABILIZER: 0.311" diameter steel rod located 9" from chamber entrance

---	.0673	.00486	298	(76.1)	--	13.86	.6802	47.9	--	--	--	LLBO
1-1-38	.0580	.00339	299	(76.0)	--	11.21	.6326	27.7	--	--	--	(1)
2-1-38	.0346	.00292	301	75.9	0.2	11.82	.6448	25.3	.72	1.00	1.40	
3-1-38	.0346	.00396	301	76.0	0.2	8.71	.6273	26.2	.68	1.88	2.56	
4-1-38	.0346	.005188	301	76.1	0.4	6.88	.5064	27.2	1.80	2.72	Wall	
---	.0654	.00483	302	(76.1)	--	13.54	.6753	47.3	--	--	--	LLBO
5-1-38	.0661	.00503	303	76.1	0.3	13.14	.6687	46.1	.76	1.12	1.44	
6-1-38	.0661	.00690	303	76.2	0.4	9.58	.6954	49.7	.84	1.44	2.04	
7-1-38	.0661	.00851	303	76.3	0.5	7.77	.6440	51.1	.96	2.00	2.62	
8-1-38	.0661	.01002	303	76.4	0.6	6.60	.6033	52.4	1.20	2.20	2.72	
9-1-38	.0661	.0123	303	76.4	0.6	5.37	.4522	54.4	1.20	2.24	2.76	
10-1-38	.0661	.0140	303	76.3	0.4	4.72	.4204	56.0	.88	1.52	2.20	
11-1-38	.0616	.01541	305	76.2	0.4	4.00	.3804	54.7	.88	1.32	1.60	RLBO
---	.1277	.00997	307	(76.4)	--	12.81	.6650	93.9	--	--	--	LLBO
12-1-38	.1272	.01013	307	76.4	0.6	12.66	.6586	93.8	.84	1.16	1.44	
1-2-38	.1272	.0135	307	76.6	0.7	9.42	.5914	96.6	.80	1.16	1.56	
2-2-38	.1272	.01655	307	76.8	0.7	7.78	.5444	98.9	.84	1.32	1.88	
3-2-38	.1272	.0190	307	77.0	0.8	6.70	.5070	101.0	.88	1.48	2.04	
4-2-38	.1272	.0222	307	77.0	0.8	5.73	.4681	103.9	.88	1.44	2.00	
5-2-38	.1272	.0269	307	76.8	0.8	4.73	.4207	106.5	.92	1.24	1.44	
---	.1251	.0296	312	(76.8)	--	4.20	.3920	111.5	--	--	--	RLBO
---	.2225	.01921	318	(77.5)	--	11.58	.6402	158.8	--	--	--	LLBO
---	.2176	.0488	320	(77.5)	--	4.46	.4085	194.3	--	--	--	RLBO
---	.2878	.0559	324	(78.0)	--	11.25	.6334	221.8	--	--	--	LLBO
6-2-38	.2878	.0267	325	78.0	2.0	10.76	.6256	223.6	.88	1.20	1.56	
7-2-38	.2878	.05416	325	78.6	2.5	6.43	.5641	229.1	.88	1.08	1.48	
8-2-38	.2878	.04059	326	78.9	2.7	7.13	.6226	233.7	.88	1.16	1.60	
9-2-38	.2878	.0468	326	79.1	3.0	6.26	.4912	238.2	.88	1.20	1.60	
10-2-38	.2878	.0515	326	79.1	2.9	5.59	.4619	243.6	.88	1.20	1.60	
---	.2878	.0587	328	(78.6)	--	4.76	.4218	248.2	--	--	--	RLBO
---	.4561	.0432	328	(80.8)	--	10.14	.6090	333.8	--	--	--	LLBO
11-2-38	.443	.0461	327	80.8	4.6	9.61	.5961	338.8	.88	1.20	1.48	
---	.430	.04146	328	(80.8)	--	10.37	.6144	326.6	--	--	--	LLBO

(1) Picture shows flame hanging on spark rod, passing around rod without stabilization.

Picture No.	V_a lbs/sec	V_r lbs/sec	T °K	P_a cm. Hg.	ΔP cm. Hg.	$\frac{W_a}{W_r} = \frac{1}{T}$ lbs/lb	O_2 lbs/lb	V_o ft/sec	W_2 inches	W_1 inches	W_0 inches	Remarks
MUN NO. 39 --- City Gas and Air Combustion DATE: June 12, 1947 SCREEN: 3 mesh; 0.063" wire diameter FLAME STABILIZER: 0.498" diameter steel rod located 9" from chamber entrance												
12-1-39	.0347	.002807	300	75.0	0.2	12.36	.6550	25.2	.96	1.24	1.48	
1-2-39	.0347	.008865	300	75.0	0.3	8.98	.5797	26.1	1.40	2.48	2.86	
2-2-39	.0347	.00463	300	75.2	0.4	7.66	.5406	26.6	1.80	2.96	Wall	
3-2-39	.0347	.00669	300	75.2	0.5	6.10	.4837	27.7	2.04	Wall	Wall	
- - -	.0649	.00458	302	(75.0)	-	14.17	.5882	46.8	-	-	-	LLBO
4-2-39	.0656	.00487	304	75.0	0.4	13.47	.5742	47.8	1.00	1.28	1.60	
5-2-39	.0656	.00630	304	75.2	0.4	10.41	.5153	49.0	1.00	1.36	2.00	
6-2-39	.0656	.00828	304	75.3	0.5	7.92	.5489	50.7	1.12	2.16	2.68	
7-2-39	.0656	.00948	304	75.5	0.7	6.92	.5153	51.6	1.44	2.48	Wall	
8-2-39	.0656	.01077	304	75.6	0.7	6.09	.4884	52.7	1.44	2.52	Wall	
9-2-39	.0656	.01306	304	75.5	0.5	5.02	.4355	54.9	1.08	2.16	2.92	
10-2-39	.0656	.01477	304	75.4	0.4	4.44	.4056	56.5	1.04	1.96	2.12	
- - -	.0626	.01574	307	(75.2)	-	3.98	.3792	56.1	-	-	-	RLBO
- - -	.1270	.00969	311	(75.5)	-	13.11	.6681	94.3	-	-	-	LLBO
- - -	.1291	.00986	314	(75.5)	-	13.09	.6679	96.8	-	-	-	LLBO
11-2-39	.1266	.01004	316	75.6	0.6	12.61	.6596	95.9	1.04	1.32	1.90	
12-2-39	.1266	.01246	316	75.6	0.7	10.16	.6095	98.0	1.00	1.20	1.62	
1-3-39	.1266	.01579	316	75.9	0.9	8.02	.5519	100.7	1.00	1.48	2.08	
2-3-39	.1266	.0186	316	77.1	1.0	6.81	.5111	105.1	1.04	1.68	2.24	
3-3-39	.1266	.0213	316	77.1	1.0	5.94	.4773	106.6	1.04	1.68	2.28	
4-3-39	.1266	.0242	316	77.0	1.0	5.23	.4486	108.4	1.04	1.48	2.00	
5-3-39	.1266	.0276	316	75.9	0.9	4.59	.4134	111.7	1.04	1.36	1.64	
- - -	.1234	.02946	319	(75.8)	-	4.19	.3915	112.5	-	-	-	RLBO
6-3-39	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	(1)
- - -	.2254	.0188	304	(77.5)	-	11.99	.6461	162.9	-	-	-	LLBO
7-3-39	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	(2)
- - -	.2157	.06035	312	(77.7)	-	4.29	.3989	189.3	-	-	-	RLBO
- - -	.293	.0254	318	(78.0)	-	11.54	.6392	221.0	-	-	-	LLBO
8-3-39	.2928	.0286	321	78.3	2.4	11.01	.6284	223.2	1.04	1.32	1.60	
9-3-39	.2928	.0345	321	79.1	2.6	8.49	.5559	228.2	1.04	1.20	1.62	
10-3-39	.2928	.04005	321	79.5	3.1	7.31	.5290	232.7	1.08	1.32	1.64	
11-3-39	.2928	.0472	321	79.5	3.2	6.21	.4879	249.4	1.08	1.40	1.64	
- - -	.2616	.0644	323	(78.5)	-	4.37	.4018	251.7	-	-	-	RLBO
12-3-39	.433	.0456	326	81.0	5.0	9.50	.5933	329.6	1.04	1.28	1.56	
- - -	.3955	.0361	322	(80.0)	-	10.96	.6273	295.2	-	-	-	LLBO

(1) Picture shows spark rod flame coming up and around other flame behind rod. This gives some idea of streamlines; V is about 40 ft./sec.

(2) Interesting picture taken at about 40 ft./sec. upon ignition. Notice that no flame is attached to flame stabilizer but that flame is all around. Flame finally stabilized.

MUN NO. 40 --- City Gas and Air Combustion
DATE: June 21, 1947
SCREEN: 3 mesh; 0.063" wire diameter
FLAME STABILIZER: 0.500" wide 30° closed edge gutter (0.009" thick sheet steel) located 9" from chamber entrance

1-1-40	.0346	.002525	295	77.3	0.2	13.18	.6594	24.1	.76	1.04	1.44	
2-1-40	.0346	.00322	295	77.3	0.2	10.75	.6227	24.5	.88	1.28	2.30	
3-1-40	.0346	.00383	295	77.3	0.2	9.08	.5812	25.1	1.04	2.28	Wall (1)	
- - -	.0650	.004583	302	(77.4)	-	14.40	.5887	46.5	-	-	-	LLBO
4-1-40	.0656	.00492	303	77.4	0.3	13.31	.5715	46.8	.84	1.08	1.44	
5-1-40	.0655	.00675	303	77.4	0.3	9.59	.5981	48.4	.84	1.24	2.20	
6-1-40	.0656	.00862	303	77.5	0.4	7.50	.5396	50.0	.96	1.92	2.66	
7-1-40	.0656	.00987	303	77.5	0.4	6.54	.5048	51.1	1.00	2.08	2.80	
8-1-40	.0656	.01152	303	77.6	0.4	5.59	.4652	52.5	1.04	2.12	2.84	
9-1-40	.0656	.01330	303	77.5	0.4	4.93	.4307	54.1	1.04	1.72	2.56	
10-1-40	.0655	.01575	303	77.5	0.3	4.16	.3898	56.3	.84	1.12	1.68	
- - -	.0631	.01606	306	(77.5)	-	3.93	.3765	56.6	-	-	-	RLBO
- - -	.1277	.006706	309	(77.7)	-	13.16	.6690	92.7	-	-	-	LLBO
11-1-40	.126	.01037	311	77.7	0.5	12.15	.6611	92.8	.84	1.08	1.62	
12-1-40	.126	.0136	311	77.8	0.5	9.27	.5673	95.5	.84	1.04	1.56	
1-2-40	.126	.01756	311	77.9	0.6	7.26	.5272	98.9	.88	1.32	2.04	
2-2-40	.126	.02012	311	78.0	0.7	5.26	.4803	101.3	.92	1.40	2.08	
3-2-40	.126	.0232	311	78.0	0.7	5.00	.4344	105.6	.92	1.24	1.80	
4-2-40	.126	.0286	311	78.0	0.6	4.42	.4044	106.8	.92	1.20	1.60	
- - -	.1209	.0304	312	(78.0)	-	3.98	.3792	107.5	-	-	-	RLBO
- - -	.2195	.01763	322	(78.5)	-	12.26	.6532	164.9	-	-	-	LLBO
- - -	.235	.0568	322	(78.5)	-	4.14	.3886	212.2	-	-	-	RLBO
- - -	.283	.0242	327	(79.0)	-	11.69	.6424	215.4	-	-	-	LLBO
5-2-40	.2842	.02504	330	79.1	1.5	11.35	.6355	219.8	.92	1.16	1.44	
6-2-40	.2842	.0330	330	79.5	2.0	8.51	.5695	226.1	.96	1.16	1.48	
7-2-40	.2842	.0414	330	79.9	2.3	6.87	.5133	232.9	1.00	1.24	1.62	
8-2-40	.2842	.0465	330	80.2	2.4	6.10	.4837	236.8	1.00	1.20	1.62	
9-2-40	.2842	.0580	330	80.1	2.3	5.08	.4381	245.9	1.00	1.20	1.48	
10-2-40	.4656	.0461	337	82.1	4.4	10.10	.6081	359.9	.92	1.08	1.40	
- - -	.452	.0437	340	(82.0)	-	10.34	.6137	351.0	-	-	-	LLBO

(1) Slight flutter above here.

Picture No.	$\frac{W_a}{W_r}$ lbs/sec	$\frac{W_r}{W_s}$ lbs/sec	T °K	P_a cm. Hg.	ΔP cm. Hg.	$\frac{W_a}{W_r} = \frac{1}{T}$ lbs/lb	O_2 lbs/lb	V_o ft/sec	W_2 inches	W_1 inches	W_0 inches	Remarks
MUN NO. 41 --- City Gas and Air Combustion DATE: June 23, 1947 SCREEN: 3 mesh; 0.063" wire diameter FLAME STABILIZER: 0.250" wide 30° closed edge gutter (0.009" thick sheet steel) located 9" from chamber entrance												
Upon blowout the gutters hold a residual flame a little better than the rods. The flame just before blowout sheds blobs of flame only occasionally and apparently not too periodically, but there is no general combustion except just above the flame stabilizer.												
11-1-41	.0353	.00262	299	77.0	0.2	12.71	.6613	23.7	.84	.68	.96	
12-1-41	.0353	.002649	299	77.0	0.2	11.69	.6423	23.9	.80	1.08	1.72	
1-2-41	.0353	.00353	299	77.1	0.2	9.43	.5917	24.6	.92	2.20	2.76	
2-2-41	.0353	.00392	299	77.1	0.2	8.50	.5661	24.8	1.62	2.72	Wall (1)	
- - -	.0669	.00447	303	(77.1)	-	14.97	.5959	47.5	-	-	-	LLBO
3-2-41	.0641	.00476	304	77.1	0.2	13.41	.6732	46.1	.84	.68	1.12	
4-2-41	.0641	.00585	304	77.1	0.3	11.00	.6281	47.0	.86	.92	1.16	
5-2-41	.0641	.00787	304	77.2	0.4	8.16	.5658	48.8	.84	1.92	2.46	
6-2-41	.0641	.00852	304	77.3	0.5	6.73	.5054	50.2	1.16	2.20	2.80	
7-2-41	.0641	.01106	304	77.3	0.6	5.79	.4705	51.6	1.24	2.28	2.96	
8-2-41	.0641	.01281	304	77.3	0.4	5.00	.4346	53.1	.96	1.92	2.60	
9-2-41	.0641	.01461	304	77.2	0.3	4.33	.3993	55.0	.86	.88	1.60	
- - -	.06116	.01584	306	(77.2)	-	3.86	.3723	54.3	-	-	-	RLBO
- - -	.1225	.00886	313	(77.2)	-	13.54	.6601	90.3	-	-	-	RFO (2)
10-2-41	.1262	.00929	322	77.2	0.3	13.58	.6760	95.6	-	-	-	LLBO(RF)(3)
11-2-41	.1262	.00929	322	77.2	0.3	12.58	.6760	95.8	-	-	-	LLBO(RF)(4)
12-2-41	.1262	.00960	322	77.3	0.4	12.68	.6642	96.2	.52	.96	1.40	
1-3-41	.1262	.01299	322	77.4	0.5	9.72	.5988	99.1	.86	.92	1.52	
2-3-41	.1262	.01549	322	77.5	0.6	8.16	.5658	101.3	.84	1.28	1.96	
3-3-41	.1262	.01822	322	77.7	0.7	6.93	.5156	103.6	.76	1.60	2.12	
4-3-41	.1262	.02123	322	77.8	0.8	5.94	.4773	106.5	.76	1.60	2.20	
5-3-41	.1262	.02669	322	77.7	0.7	4.73	.4207	111.6	.64	1.16	1.72	
6-3-41	.1262	.03000	322	77.6	0.6	4.21	.3926	114.8	.60	1.04	1.44	
- - -	.225	.03142	325	(77.6)	-	3.94	.3769	115.5	-	-	-	RLBO
- - -	.225	.01866	325	(78.5)	-	12.08	.6492	171.7	-	-	-	LLBO (5)
- - -	.2366	.0246	331	(78.5)	-	4.33	.3996	217.0	-	-	-	RLBO (6)
- - -	.262	.0250	336	(78.5)	-	11.28	.6341	222.9	-	-	-	LLBO
7-3-41	.261	.02566	335	78.6	1.6	10.95	.6272	222.6	.84	1.00	1.40	
8-3-41	.261	.0291	335	78.9	1.9	9.66	.5973	225.3	.84	1.08	1.44	
9-3-41	.261	.0351	336	79.5	2.2	8.01	.5516	229.3	.88	1.12	1.56	
10-3-41	.261	.0422	335	79.6	2.3	6.86	.5056	235.2	.88	1.16	1.60	
11-3-41	.261	.0453	335	79.6	2.3	5.08	.4384	241.7	.76	1.16	1.56	
- - -	.277	.0616	335	(79.6)	-	4.60	.4086	257.8	-	-	-	RLBO
12-3-41	.449	.0486	336	81.6	4	9.24	.5866	350.2	.68	1.04	1.40	
- - -	.447	.0470	336	(81.6)	-	8.51	.5936	350.7	-	-	-	LLBO

Picture No. W_a W_f C_K P_{O_2} ΔP $\frac{W_a}{W_f} = \frac{1}{2}$ O_2 V W_2 W_3 W_5 Remarks
lbm/sec lbm/sec cm. Hg. cm. Hg. lbm/lb. lbm/lb. ft/sec inches inches inches

NEW NO. 42 --- City Gas and Air Combustion

DATE: June 28, 1947

SCREEN: 3 mesh; 0.053" wire diameter

FLAME STABILIZER: 0.1" wide 30° closed edge gutter (0.008" thick sheet steel) located 9" from chamber entrance

1-1-42	.0330	.00260	300	77.0	0.2	12.69	.6610	23.6	.40	.68	1.00	
2-1-42	.0330	.00294	300	77.0	0.2	11.22	.6329	23.9	.56	1.18	1.48	
3-1-42	.0330	.00320	300	77.1	0.2	10.31	.6130	24.1	1.24	2.20	2.64	
- - -	.0658	.00432	302	(77.1)	-	15.23	.7008	46.5	-	-	-	LLBO
4-1-42	.0658	.00461	304	77.1	0.2	14.27	.6868	47.0	.32	.64	.92	
5-1-42	.0658	.004987	304	77.1	0.2	13.19	.6696	47.4	.60	.88	1.08	
6-1-42	.0658	.00707	304	77.2	0.3	9.31	.5884	49.2	.68	1.56	2.12	
7-1-42	.0658	.00904	304	77.4	0.4	7.28	.5279	50.8	1.08	2.00	2.60	
8-1-42	.0658	.01187	304	77.5	0.5	5.64	.4641	53.1	1.18	2.80	2.60	
9-1-42	.0658	.01407	304	77.3	0.4	4.66	.4181	55.3	.84	1.60	2.48	
10-1-42	.0658	.01761	304	77.2	0.4	3.74	.3647	58.6	.44	.80	1.28	
- - -	.0632	.01635	308	(77.2)	-	3.97	.3728	56.5	-	-	-	RLBO
These blow outs look very similar to blow outs with rod flame stabilizers												
- - -	.1265	.00837	313	(77.2)	-	-	13.50	.6747	93.4	-	-	LLBO (1)
11-1-42	.1261	.00978	317	77.2	0.4	12.89	.6646	94.7	.40	.72	1.08	
12-1-42	.1261	.01132	317	77.4	0.6	11.34	.6353	95.7	.36	.72	1.20	
1-2-42	.1261	.01397	317	77.6	0.7	9.03	.5610	98.1	.48	1.04	1.56	
2-2-42	.1261	.0174	317	77.8	0.8	7.25	.4886	101.0	.80	1.32	1.96	
3-2-42	.1261	.02032	317	77.9	0.8	6.21	.4680	103.6	.80	1.40	2.00	
4-2-42	.1261	.02857	317	77.9	0.8	4.93	.4310	106.4	.56	1.12	1.68	
5-2-42	.1261	.02915	317	77.8	0.7	4.33	.3992	111.9	.48	.92	1.40	
- - -	.1241	.0303	320	(77.8)	-	4.10	.3862	112.4	-	-	-	RLBO
- - -	.2236	.01563	326	(76.0)	-	11.46	.6375	172.6	-	-	-	LLBO (2)
- - -	.2170	.0482	327	(78.0)	-	4.41	.4039	197.2	-	-	-	RLBO
- - -	.2854	.02863	331	(79.0)	-	9.88	.6041	223.6	-	-	-	LLBO
6-2-42	.2825	.02636	332	79.0	1.7	9.95	.6046	223.4	.82	.92	1.32	
7-2-42	.2825	.03584	332	79.8	2.3	7.86	.5477	226.2	.56	1.04	1.48	
8-2-42	.2825	.0434	332	80.1	2.6	6.61	.5000	234.4	.80	1.04	1.48	
9-2-42	.2825	.0602	332	80.1	2.6	5.63	.4636	240.8	.60	1.08	1.52	
10-2-42	.2825	.0590	332	80.1	2.6	4.87	.4280	246.1	.60	1.04	1.44	
- - -	.2766	.0591	333	(80.0)	-	4.71	.4139	247.4	-	-	-	RLBO
- - -	.4286	.0667	334	(81.0)	-	7.86	.5372	346.2	-	-	-	LLBO
11-2-42	.447	.0606	334	(81.0)	-	7.36	.5304	361.6	.60	1.00	1.40	

(1) Residual flame for very short increment of A/F ratio interval as with rods.

(2) Rough burning (shed eddies only flame in chamber except pilot some flame) just before blow out.

Picture No. W_a W_f C_K P_{O_2} ΔP $\frac{W_a}{W_f} = \frac{1}{2}$ O_2 V W_2 W_3 W_5 Remarks
lbm/sec lbm/sec cm. Hg. cm. Hg. lbm/lb. lbm/lb. ft/sec inches inches inches

NEW NO. 43 --- City Gas and Air Combustion

DATE: June 28, 1947

SCREEN: None

FLAME STABILIZER: 0.1" wide 30° closed edge gutter (0.008" thick sheet steel) located 9" from chamber entrance

12-1-43 Tested to see if laminar (essentially) flow existed in combustion chamber without screen. Tiffl, smoke was introduced into nozzle at rate corresponding to about 5 or 6 ft/sec (meter readings exposure) too inaccurate at this low rate for precise reading, but air orifice reading 0.4" HgO).

Chamber entrance velocity too low to take accurate rate measurements.

1-2-43	.0329	.002464	298	76.8	0.2	13.41	.6731	23.3	.30	.64	.80	
2-2-43	.0329	.003314	298	76.8	0.2	9.93	.6040	24.0	.60	1.04	1.36 (1)	

This picture cross-section about 4" above flame stabilizer (fairly normal situation)

3-2-42	.0651	.004157	301	76.8	0.2	15.86	.7064	45.9	-	-	-	LLBO
4-2-42	.0651	.004157	301	76.8	0.2	15.86	.7064	45.9	-	-	-	LLBO(RF)(s)
- - -	.0633	.00399	302	(76.8)	-	15.87	.7090	44.7	-	-	-	LLBO(RF)(s)
5-2-43	.06756	.00463	303	76.8	0.2	14.59	.6915	48.2	.24	.60	.68	
6-2-43	.06756	.00555	303	76.8	0.2	12.17	.6518	48.0	.36	.64	.92	
7-2-43	.06756	.006316	303	76.8	0.2	9.91	.6036	50.2	.48	.88	1.20 (4)	
- - -	.1292	.009466	306	(77.0)	-	13.66	.6773	93.4	-	-	-	LLBO
8-2-43	.1306	.009932	307	77.0	0.4	13.15	.6689	95.1	.32	.64	.88	
9-2-43	.1306	.01127	307	77.0	0.4	11.69	.6403	96.3	.32	.68	.88	
10-2-43	.1306	.01497	307	77.2	0.5	8.78	.5743	99.3	.44	.88	1.48	
11-2-43	.1306	.01609	307	77.3	0.6	7.22	.5258	102.1	.62	1.20	1.80	
12-2-43	.1306	.02039	307	77.4	0.6	6.41	.4969	104.0	.60	1.28	1.88	
1-3-43	.1306	.02608	307	77.4	0.6	5.22	.4449	106.2	.62	1.04	1.80	
2-3-43	.1306	.02942	307	77.4	0.6	4.44	.4064	112.1	.60	.72	1.08	
- - -	.1294	.03196	310	(77.4)	-	4.06	.3855	114.7	-	-	-	RLBO
3-3-43	.2313	.03001	314	77.2	0.6	11.56	.6397	174.0	-	-	-	LLBO(RF)(s)
- - -	.2306	.0190	314	(77.2)	-	12.07	.6497	172.7	-	-	-	RFO
- - -	.2294	.0538	315	(77.2)	-	4.26	.3968	204.5	-	-	-	RLBO (s)
- - -	.2286	.02740	316	77.3	0.6	10.68	.6213	223.2	-	-	-	LLBO (RF)
- - -	.2281	.02619	316	(77.3)	-	11.19	.6322	222.4	-	-	-	RFO
4-3-43	.2285	.02764	317	77.4	0.6	10.82	.6196	224.4	-	-	-	LLBO(RF)(7)
5-3-43	.2285	.02896	317	78.0	1.1	10.13	.6087	225.9	.48	.80	1.08	
6-3-43	.2285	.03515	317	78.6	1.4	8.35	.5619	227.9	.82	.92	1.32	
7-3-43	.2285	.04442	317	78.8	1.7	6.61	.5087	235.7	.48	.80	1.20	
8-3-43	.2285	.05375	317	79.1	1.8	5.46	.4661	243.3	.60	1.00	1.40	
9-3-43	.2285	.05772	317	79.3	1.8	5.09	.4386	246.3	.60	1.08	1.56	
- - -	.2212	.06324	318	(79.0)	-	4.61	.4148	251.5	-	-	-	RLBO
10-3-43	.3996	.04968	318	80.2	2.6	8.21	.5677	305.8	.56	.88	1.24	
- - -	.3984	.04215	320	(80.0)	-	9.46	.5922	301.6	-	-	-	LLBO

(1) Flutter above here.

(2) Height of residual flame - 1.36"

(3) Height of residual flame - 1.56"; one second exposure

(4) Flutter above here. Could not get RLBO because of possibility of flashback in passing through stoichiometric.

(5) Height of residual flame - 1.36"

(6) Almost got residual flame before RLBO

(7) Height of residual flame - 1.40"

Picture No. $\frac{W_a}{lb/sec}$ $\frac{W_f}{lb/sec}$ T P $\frac{dP}{dL}$ $\frac{W_a}{W_f} = \frac{1}{r}$ O_g V_o V_2 W_2 W_4 W_6 Remarks
lb/sec cm. Hg. cm. Hg. lb/lb ft/sec inches inches inches

RUN NO. 44 --- City Gas and Air Combustion

DATE: June 27, 1947

SCREEN: None

FLAME STABILIZER: 0.06" wide 30° closed edge gutter (0.006" thick sheet steel) located 9" from chamber entrance.

11-1-44	.03362	.002519	300	76.1	0.2	13.36	.6721	24.2	.24	.52	.76	
12-1-44	.03362	.002926	300	76.1	0.2	11.49	.6363	24.5	.56	.92	1.26	(1)

Cross section 4" above flame stabilizer at this condition, with slow changes in flamefront configuration.

- - -	.06936	.004539	303	(76.2)	- -	15.26	.7013	49.7	- -	- -	- -	LLBO
1-2-44	.06796	.004626	304	76.2	0.2	14.06	.6688	45.2	.20	.44	.72	
2-2-44	.06756	.006614	304	76.2	0.2	12.10	.5803	49.9	.40	.84	1.32	
3-2-44	.06796	.006982	304	76.3	0.3	9.73	.5992	51.1	.72	1.36	1.80	(1)
- - -	.1292	.009626	310	(76.3)	- -	13.42	.6733	96.7	- -	- -	- -	LLBO

Just before blow out flame looks as shown.

4-2-44	.1261	.009982	313	76.3	0.3	12.63	.6634	96.2	.20	.40	.64	
5-2-44	.1261	.01120	313	76.4	0.4	11.44	.6373	97.2	.32	.64	.96	
6-2-44	.1261	.01678	313	76.6	0.6	8.12	.5580	101.2	.66	1.12	1.60	
7-2-44	.1261	.01636	313	76.7	0.7	6.98	.5176	103.4	.64	1.36	1.86	
8-2-44	.1261	.02161	313	76.8	0.7	5.87	.4743	106.6	.66	1.40	1.92	
9-2-44	.1261	.02477	313	76.8	0.7	5.17	.4427	109.2	.66	1.20	1.68	
10-2-44	.1261	.02777	313	76.7	0.6	4.61	.4147	112.1	.60	.80	1.24	
- - -	.1268	.02867	316	(76.7)	- -	4.36	.4010	112.3	- -	- -	- -	RLBO
- - -	.2256	.02009	323	(77.2)	- -	11.22	.6329	176.1	- -	- -	- -	LLBO
- - -	.2264	.04609	324	(77.2)	- -	4.89	.4290	200.3	- -	- -	- -	RLBO
- - -	.2637	.02678	329	(76.0)	- -	9.86	.6023	226.4	- -	- -	- -	LLBO (2)
11-2-44	.2799	.02977	333	76.7	0.9	9.40	.5909	230.3	.40	.72	1.04	
12-2-44	.2799	.03261	333	76.0	1.6	6.53	.5672	229.4	.62	.92	1.28	
1-3-44	.2799	.04092	333	76.6	1.9	6.84	.5124	235.7	.62	1.00	1.36	
2-3-44	.2796	.04698	333	76.6	2.0	6.09	.4832	240.2	.66	1.00	1.36	
3-3-44	.2799	.04948	333	76.6	2.0	5.66	.4649	243.6	.66	1.04	1.40	
- - -	.2768	.06310	336	(76.6)	- -	5.26	.4465	248.8	- -	- -	- -	RLBO
- - -	.3723	.05692	336	(80.0)	- -	6.66	.5066	310.9	- -	- -	- -	RLBO
4-3-44	.3633	.06116	337	(80.0)	- -	6.27	.4904	326.4	.48	.88	1.28	LLBO
- - -	.3646	.06897	337	(80.0)	- -	6.53	.6006	324.4	- -	- -	- -	LLBO

(1) Flutter above here.

(2) Residual flame remained for narrow A/F ratio range.

Picture No. $\frac{W_a}{lb/sec}$ $\frac{W_f}{lb/sec}$ T P $\frac{dP}{dL}$ $\frac{W_a}{W_f} = \frac{1}{r}$ O_g V_o V_2 W_2 W_4 W_6 Remarks
lb/sec cm. Hg. cm. Hg. lb/lb ft/sec inches inches inches

RUN NO. 45 --- City Gas and Air Combustion

DATE: June 27, 1947

SCREEN: 3 mesh; 0.063" wire diameter

FLAME STABILIZER: 0.06" wide 30° closed edge gutter (0.006" thick sheet steel) located 9" from chamber entrance.

5-1-45	.03401	.002360	302	76.06	0.2	14.41	.6888	24.5	.20	.40	.52	
6-1-45	.03401	.003040	302	76.06	0.2	11.19	.6322	26.1	.56	1.28	1.92	(1)
- - -	.06756	.004622	304	(76.16)	- -	14.94	.6965	48.7	- -	- -	- -	LLBO
7-1-45	.06696	.004738	306	76.15	0.2	14.13	.6846	48.8	.19	.36	.46	
8-1-45	.06696	.006142	306	76.15	0.2	13.02	.6667	49.2	.32	.68	1.04	
9-1-45	.06696	.006891	306	76.15	0.3	9.72	.5988	50.8	.64	1.48	2.06	
10-1-45	.06696	.008290	306	76.35	0.6	8.06	.5557	51.9	1.04	2.00	2.64	(2)
11-1-45	.06696	.01257	306	76.35	0.6	5.33	.4500	85.8	1.04	2.08	2.72	
12-1-45	.06696	.01585	306	76.26	0.4	4.23	.3935	88.6	.44	1.00	1.76	
- - -	.06586	.01652	308	(76.26)	- -	3.99	.3798	89.1	- -	- -	- -	RLBO
- - -	.1306	.01026	313	(76.36)	- -	12.76	.6620	98.2	- -	- -	- -	LLBO
1-2-45	.1304	.01070	315	76.35	0.4	12.19	.6518	99.0	.32	.60	.92	
2-2-45	.1304	.01232	315	76.46	0.6	10.68	.6192	100.4	.44	.88	1.28	
3-2-45	.1304	.01527	315	76.66	0.6	8.54	.5674	103.0	.56	1.20	1.76	
4-2-45	.1304	.01814	315	76.75	0.7	7.19	.5248	106.4	.68	1.48	2.04	
5-2-45	.1304	.02140	315	76.75	0.7	6.09	.4835	108.4	.72	1.56	2.16	
6-2-45	.1304	.02567	315	76.75	0.7	5.10	.4393	112.3	.60	1.24	1.60	
7-2-45	.1295	.02890	317	76.75	0.6	4.47	.4073	115.4	.48	1.00	1.48	RLBO
- - -	.2329	.02214	320	(77.2)	- -	10.52	.6177	160.4	- -	- -	- -	LLBO (3)
- - -	.2356	.04627	321	(77.2)	- -	5.09	.4389	205.6	- -	- -	- -	RLBO
- - -	.2909	.03266	322	(76.46)	- -	8.91	.5777	227.6	- -	- -	- -	RLBO
8-2-45	.2909	.03453	323	78.46	2.0	8.43	.5641	230.3	.56	1.00	1.48	
9-2-45	.2909	.04163	323	78.66	2.2	6.99	.5177	235.4	.64	1.08	1.52	
10-2-45	.2909	.04607	323	79.15	2.4	6.31	.4624	238.9	.64	1.08	1.52	
11-2-45	.2909	.05148	323	79.25	2.5	5.65	.4547	243.6	.60	1.08	1.52	
- - -	.2886	.05347	324	(79.2)	- -	5.40	.4533	244.6	- -	- -	- -	RLBO
- - -	.3400	.05561	323	(80.0)	- -	5.11	.4843	277.9	- -	- -	- -	RLBO
- - -	.3477	.05659	323	(80.0)	- -	6.26	.4900	283.0	- -	- -	- -	RLBO
- - -	.3336	.05359	322	(80.0)	- -	5.23	.4888	271.8	- -	- -	- -	RLBO
- - -	.3568	.06614	323	(80.0)	- -	5.00	.4796	276.2	- -	- -	- -	RLBO
- - -	.3592	.06612	323	(80.0)	- -	5.16	.4859	276.9	- -	- -	- -	RLBO

(1) Flutter above here.

(2) Flutter above here.

(3) Residual flame observed for very narrow range of A/F ratio.

RUN NO. 46 --- City Gas and Air Combustion

DATE: July 1, 1947

SCREEN: 3 mesh; 0.063" wire diameter

FLAME STABILIZER: 0.026" wide 30° closed edge gutter (0.006" sheet steel) 9" from chamber entrance.

Could not get any satisfactory data at 20 ft/sec because blow-out occurred before flutter stopped.

- - -	.06666	.006485	304	(76.4)	- -	12.16	.5512	46.8	- -	- -	- -	LLBO
12-1-46	.06682	.006004	307	76.4	0.3	11.13	.6309	49.9	.52	1.12	1.64	
1-2-46	.06682	.006820	307	76.6	0.3	9.80	.6008	50.5	.80	1.52	2.12	
2-2-46	.06682	.006897	307	76.6	0.5	7.68	.5413	52.2	1.24	2.16	2.64	
3-2-46	.06682	.01039	307	76.6	0.5	6.43	.4970	53.7	1.40	2.40	2.80	
4-2-46	.06682	.01156	307	76.6	0.5	5.78	.4703	54.8	1.36	2.36	2.80	
- - -	.06657	.01304	308	(76.6)	- -	5.03	.4359	56.5	- -	- -	- -	RLBO
- - -	.1280	.01208	312	(76.4)	- -	10.80	.6194	97.1	- -	- -	- -	RLBO
5-2-46	.1306	.01232	314	76.8	0.7	10.59	.6194	98.6	.40	.84	1.32	
6-2-46	.1306	.01433	314	76.9	0.7	9.11	.5881	101.4	.60	1.16	1.60	
7-2-46	.1306	.01892	314	77.1	0.9	6.90	.5144	106.4	.80	1.52	2.00	
8-2-46	.1306	.02227	314	77.2	0.9	5.96	.4737	106.3	.80	1.56	2.04	
- - -	.1283	.0247	316	(76.9)	- -	5.19	.4438	110.1	- -	- -	- -	RLBO
- - -	.2168	.03330	319	(77.0)	- -	6.51	.5000	179.8	- -	- -	- -	LLBO
- - -	.2134	.03349	319	(77.0)	- -	6.37	.4946	177.6	- -	- -	- -	RLBO
- - -	.2123	.02591	320	(77.0)	- -	7.59	.5479	171.2	- -	- -	- -	LLBO
- - -	.2060	.03424	321	(77.0)	- -	6.10	.4639	176.4	- -	- -	- -	RLBO

This gutter flame stabilizer blows out just as the rod flame stabilizers do (no residual region observed).

Position of flame with respect to gutter flame stabilizer during this run

RUN NO. 48 --- City Gas and Air Combustion DATE: July 2, 1947 SIZE: 3 mesh; 0.063 wire diameter FLAME STABILIZER: 0.500" wide 30° open edged gutter; (0.009" sheet steel) located 9" from chamber entrance												total area	
												open area	= 26
4-1-48	.03456	.002431	303	76.4	0.2	14.21	.6866	24.8	.58	.96	1.24		
6-1-48	.03456	.002806	303	76.4	0.2	12.32	.6642	26.2	.68	1.20	1.68		
6-1-48	.03456	.003276	303	76.4	0.2	10.56	.6183	26.6	1.08	2.12	2.76		
7-1-48	.03456	.004372	303	76.5	0.3	7.90	.5483	26.6	1.04	Wall	Wall		
- - -	.06703	.004637	304	(76.5)	- -	14.77	.6941	48.1	- -	- -	- -	LLBO	
8-1-48	.08672	.004667	306	76.6	0.3	14.30	.6977	48.2	.80	1.04	1.28		
9-1-48	.08672	.006027	306	76.6	0.3	11.07	.6297	49.4	.92	1.16	1.68		
10-1-48	.06672	.006316	306	76.6	0.4	7.18	.5236	52.5	1.18	2.00	2.68		
11-1-48	.06672	.01046	306	76.7	0.4	6.38	.4949	53.3	1.20	2.20	2.80		
12-1-48	.06672	.012194	306	76.7	0.4	5.16	.4420	55.5	1.08	1.92	2.72		
1-2-48	.06672	.01529	306	76.6	0.4	4.36	.4013	57.7	.88	1.12	1.40		
2-2-48	.06300	.01641	307	(76.6)	- -	3.66	.3710	56.7	.78	.96	1.28		
- - -	.1314	.009463	309	(76.7)	- -	13.69	.6808	96.2	- -	- -	- -	LLBO	
3-2-48	.1306	.009800	311	76.7	0.6	13.32	.6716	96.5	.80	1.04	- -		
4-2-48	.1306	.01200	311	76.7	0.6	10.88	.6266	98.5	.88	1.08	- -		
5-2-48	.1306	.01747	311	77.0	0.7	7.47	.5345	103.2	.96	1.32	- -		
6-2-48	.1306	.02096	311	77.3	0.7	6.23	.4899	105.9	1.00	1.44	- -		
7-2-48	.1306	.02406	311	77.3	0.7	5.42	.4546	108.8	1.00	1.40	- -		
8-2-48	.1306	.02688	311	77.2	0.7	4.96	.4272	111.5	.92	1.18	- -		
9-2-48	.1306	.03165	311	77.1	0.7	4.12	.3878	116.0	.84	1.04	- -		
- - -	.1290	.03271	312	(77.1)	- -	3.94	.3773	116.3	- -	- -	- -	LLBO	
- - -	.2359	.01860	316	(77.5)	- -	12.68	.6608	176.3	- -	- -	- -	LLBO	
- - -	.2620	.03673	318	(77.5)	- -	4.62	.4150	229.1	- -	- -	- -	LLBO	
- - -	.2918	.02392	319	(78.0)	- -	12.20	.6620	219.6	- -	- -	- -	LLBO	
10-2-48	.2913	.02441	320	78.0	1.7	11.93	.6471	220.3	.84	.84	1.24		
11-2-48	.2913	.03266	320	78.4	1.9	8.87	.5766	227.0	.98	1.18	1.38		
12-2-48	.2913	.04506	320	79.2	2.3	6.47	.4983	235.9	.98	1.12	1.40		
1-3-48	.2913	.06310	320	79.2	2.4	5.48	.4573	243.3	.88	1.18	1.40		
2-3-48	.2913	.06154	320	79.2	2.3	4.73	.4210	261.0	.88	1.16	1.40	(1)	
3-3-48	.4061	.04367	319	(80.0)	- -	9.30	.5882	397.3	.80	1.00	1.20		
4-3-48	.4606	.04776	318	80.5	3.8	6.64	.5970	345.7	.78	.96	1.20		
- - -	.4710	.04286	321	(80.0)	- -	10.99	.6280	361.6	- -	- -	- -	LLBO	

No residual flame observed with this flame stabilizer.

(1) Could not quite blow out at this velocity on rich side without drawing too much of a vacuum on gas line.

Picture No.	V_1 lbs/sec	V_2 lbs/sec	C_p K	C_m H_2	C_m H_2	$V_3 = \frac{1}{2} \frac{V_1}{V_2}$ lbs/lb	V_4 ft/sec	V_5 inches	V_6 inches	V_7 inches	Remarks
RUN NO. 49 --- City Gas and Air Combustion											
DATE: July 6, 1947											
SCREEN: 3 mesh; 0.063" wire diameter											
FLAME STABILIZER: 0.186" diameter steel rod located 9" from combustion chamber entrance.											
---	.0555	.00470	304	(77.2)	---	13.94	.6816	46.6	---	---	LIBO
---	.0558	.01660	306	(77.4)	---	3.95	.3765	57.9	---	---	LIBO
---	.1265	.01009	309	(77.7)	---	12.54	.6582	92.3	---	---	LIBO
---	.1250	.0299	313	(78.0)	---	4.18	.5911	110.1	---	---	LIBO
---	.223	.02021	323	(78.7)	---	11.03	.6289	170.2	---	---	LIBO
---	.228	.0508	325	(78.7)	---	4.61	.4090	203.1	---	---	LIBO
---	.2803	.08915	331	(79.3)	---	10.72	.6221	218.5	---	---	LIBO
---	.277	.0698	333	(79.7)	---	4.73	.6207	246.9	---	---	LIBO
---	.4650	.0497	338	(81.0)	---	9.16	.5944	351.0	---	---	LIBO
SCREEN: 8 mesh; 0.025" wire diameter											
FLAME STABILIZER: 0.186" diameter steel rod located 9" from combustion chamber entrance.											
---	.0875	.00487	324	(77.2)	---	13.86	.6804	51.5	---	---	LIBO
---	.08987	.0172	323	(77.4)	---	3.91	.3754	62.7	---	---	LIBO
---	.1247	.00988	323	(77.7)	---	12.62	.6597	95.0	---	---	LIBO
---	.1244	.0299	324	(78.0)	---	4.16	.3899	113.6	---	---	LIBO
---	.226	.02031	328	(78.7)	---	11.21	.6326	175.4	---	---	LIBO
---	.229	.0510	332	(78.7)	---	4.49	.4082	206.5	---	---	LIBO
---	.2770	.0255	337	(79.2)	---	10.86	.6253	219.5	---	---	LIBO
---	.2795	.0586	341	(79.7)	---	4.73	.6207	232.4	---	---	LIBO
---	.450	.0478	343	(81.0)	---	9.41	.5912	351.0	---	---	LIBO
SCREEN: None											
FLAME STABILIZER: 0.186" diameter steel rod located 9" from combustion chamber entrance.											
---	.0558	.00464	330	(77.2)	---	14.18	.6854	51.0	---	---	LIBO
---	.0651	.0171	325	(77.4)	---	3.87	.3728	62.4	---	---	LIBO
---	.123	.00986	326	(77.7)	---	12.75	.6617	94.5	---	---	LIBO
---	.1241	.0299	326	(78.0)	---	4.11	.3870	114.4	---	---	LIBO
---	.2317	.0206	329	(78.7)	---	11.25	.6334	179.7	---	---	LIBO
---	.2313	.0523	332	(78.7)	---	4.42	.4045	211.4	---	---	LIBO
---	.285	.02505	335	(79.2)	---	10.94	.6269	224.3	---	---	LIBO
---	.2758	.0588	338	(79.7)	---	4.69	.4198	249.9	---	---	LIBO
---	.4601	.0494	340	(81.0)	---	9.31	.5886	356.4	---	---	LIBO
SCREEN: None											
FLAME STABILIZER: 0.126" diameter steel rod located 9" from combustion chamber entrance.											
---	.0549	.00463	318	(77.2)	---	14.02	.6829	46.5	---	---	LIBO
---	.0642	.01640	318	(77.4)	---	3.92	.3755	58.9	---	---	LIBO
---	.1279	.0101	318.5	(77.7)	---	12.46	.6605	96.1	---	---	LIBO
---	.2358	.0304	320	(78.0)	---	4.12	.3875	113.2	---	---	LIBO
---	.2333	.0214	324	(78.7)	---	10.90	.6261	178.6	---	---	LIBO
---	.2348	.0514	328	(78.7)	---	4.57	.4124	210.4	---	---	LIBO
---	.282	.0270	331	(79.2)	---	10.44	.6160	220.5	---	---	LIBO
---	.2799	.0578	333	(79.7)	---	4.64	.4266	248.1	---	---	LIBO
---	.465	.0524	338	(81.0)	---	8.87	.5766	370.4	---	---	LIBO
SCREEN: 3 mesh; 0.063" wire diameter											
FLAME STABILIZER: 0.126" diameter steel rod located 9" from combustion chamber entrance.											
---	.0556	.00470	328	(77.2)	---	13.96	.6819	50.6	---	---	LIBO
---	.0580	.0158	325	(77.4)	---	3.93	.3764	62.0	---	---	LIBO
---	.1285	.0103	324	(77.7)	---	12.48	.6571	96.3	---	---	LIBO
---	.1251	.0302	324	(78.0)	---	4.14	.3869	114.4	---	---	LIBO
---	.2334	.0218	328	(78.7)	---	10.71	.6219	181.3	---	---	LIBO
---	.2330	.0511	330	(78.7)	---	4.56	.4119	210.1	---	---	LIBO
---	.284	.02799	332	(79.2)	---	10.15	.6092	223.5	---	---	LIBO
---	.2796	.0575	333	(79.7)	---	4.66	.4275	247.5	---	---	LIBO
---	.456	.0622	341	(81.0)	---	8.74	.5750	367.3	---	---	LIBO

RUN NO. 53 --- Pitot Traverses (Static Pressure - Impact pressure tube employed) (Pitot tube extends 29/32" down from center of probe hole)

DATE: July 17, 1947
SCHEM: None

Distance from near wall of chamber (inches)	P cm. H ₂ O	T ₀ °K	V ₀ ft/sec	V at center of chamber ft/sec	V/V ₀
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Traverse 1.74" from chamber entrance

2.958	1034	311	44.1	46.2	1.03
2.95	1034	311	44.1	46.6	1.06
2.90	1034	311	44.1	46.0	1.09
2.75	1034	311	44.1	46.2	1.09
2.50	1034	311	44.1	46.8	1.11
2.0	1034	311	44.1	46.8	1.11
1.5	1034	311	44.1	46.8	1.11
1.0	1034	311	44.1	46.8	1.11
0.5	1034	311	44.1	47.6	1.09

2.958	1034	323	89.3	89.9	1.01
2.95	1034	323	89.3	90.7	1.06
2.90	1034	323	89.3	90.6	1.08
2.75	1034	323	89.3	90.7	1.08
2.50	1034	323	89.3	90.8	1.08
2.0	1034	323	89.3	90.4	1.08
1.5	1034	323	89.3	90.2	1.08
1.0	1034	323	89.3	94.4	1.06
0.5	1034	323	89.3	95.8	1.07

2.958	1033	344	207.2	214.7	1.04
2.95	1033	344	207.2	219.7	1.06
2.90	1033	344	207.2	219.1	1.06
2.75	1033	344	207.2	219.2	1.06
2.50	1033	344	207.2	219.5	1.06
2.0	1033	344	207.2	220.1	1.06
1.5	1033	344	207.2	221.6	1.07
1.0	1033	344	207.2	216.6	1.06
0.5	1033	314	207.2	216.3	1.04

2.958	1028	353	338.9	312.6	.92
2.95	1028	353	338.9	321.1	.95
2.90	1028	353	338.9	361.6	1.07
2.75	1028	353	338.9	363.6	1.07
2.50	1028	353	338.9	362.6	1.07
2.0	1028	353	338.9	365.1	1.07
1.5	1028	353	338.9	366.0	1.08
1.0	1028	353	338.9	360.2	1.06
0.5	1028	353	338.9	368.5	1.08

Traverse 7.74" from chamber entrance

2.958	1034	311	44.2	38.1	.86
2.95	1034	311	44.2	40.9	.93
2.90	1034	311	44.2	44.6	1.01
2.75	1034	311	44.2	46.7	1.13
2.50	1034	311	44.2	46.4	1.12
2.0	1034	311	44.2	46.6	1.10
1.5	1034	311	44.2	46.6	1.10
1.0	1034	311	44.2	46.0	1.09
0.5	1034	311	44.2	46.2	1.09

2.958	1033	321	89.3	76.6	.86
2.95	1033	321	89.3	86.1	.96
2.90	1033	321	89.3	94.0	1.06
2.75	1033	321	89.3	98.9	1.11
2.50	1033	321	89.3	99.2	1.11
2.0	1033	321	89.3	98.2	1.10
1.5	1033	321	89.3	97.1	1.09
1.0	1033	321	89.3	95.5	1.07
0.5	1033	321	89.3	95.6	1.08

2.958	1030	337	204.4	184.4	.90
2.95	1030	337	204.4	199.2	.98
2.90	1030	337	204.4	219.1	1.07
2.75	1030	337	204.4	224.5	1.10
2.50	1030	337	204.4	224.3	1.10
2.0	1030	337	204.4	223.5	1.09
1.5	1030	337	204.4	216.7	1.07
1.0	1030	337	204.4	222.6	1.09
0.5	1030	337	204.4	217.8	1.07

2.958	1025	349	337.5	301.7	.89
2.95	-	-	-	-	-
2.90	1025	349	337.5	338.1	1.00
2.75	1025	349	337.5	369.4	1.09
2.50	1025	349	337.5	369.3	1.09
2.0	1025	349	337.5	365.4	1.08
1.5	1025	349	337.5	365.3	1.08
1.0	1025	349	337.5	367.7	1.09
0.5	1025	349	337.5	365.7	1.08

RUN NO. 54 --- Pitot Traverses (Static Pressure - Impact pressure tube employed) (Pitot tube extends 29/32" down from center of probe hole)

DATE: July 17, 1947
SCHEM: None

Distance from near wall of chamber (inches)	P cm. H ₂ O	T ₀ °K	V ₀ ft/sec.	V at center of chamber ft/sec.	V/V ₀
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Traverse at 13.74" from chamber entrance

2.958	1040	306	43.5	41.3	.95
2.950	1040	306	43.5	42.4	.97
2.90	1040	306	43.5	42.6	1.00
2.75	1040	306	43.5	46.1	1.06
2.50	1040	306	43.5	46.3	1.07
2.0	1040	306	43.5	45.5	1.06
1.5	1040	306	43.5	45.7	1.06
1.0	1040	306	43.5	44.7	1.03
0.5	1040	306	43.5	44.7	1.03

2.958	1039	319	88.4	76.3	.86
2.950	1039	319	88.4	83.1	.94
2.90	1039	319	88.4	93.3	1.06
2.75	1039	319	88.4	100.7	1.14
2.5	1039	319	88.4	101.6	1.15
2.0	1039	319	88.4	96.4	1.11
1.5	1039	319	88.4	98.2	1.11
1.0	1039	319	88.4	95.6	1.08
0.5	1039	319	88.4	95.6	1.08

2.958	1034	337	203.3	166.9	.83
2.95	1034	337	203.3	195.6	.96
2.90	1034	337	203.3	227.2	1.12
2.75	1034	337	203.3	232.5	1.14
2.5	1034	337	203.3	229.6	1.13
2.0	1034	337	203.3	224.6	1.11
1.5	1034	337	203.3	227.6	1.12
1.0	1034	337	203.3	222.4	1.09
0.5	1034	337	203.3	222.6	1.10

2.958	1025	349	336.1	296.7	.88
2.95	1025	349	336.1	296.6	.88
2.90	1025	349	336.1	338.7	1.00
2.75	1025	349	336.1	361.4	1.13
2.5	1025	349	336.1	363.8	1.14
2.0	1025	349	336.1	379.5	1.12
1.5	1025	349	336.1	377.2	1.12
1.0	1025	349	336.1	379.3	1.12
0.5	1025	349	336.1	379.3	1.12

RUN NO. 51 --- Turbulence Measurements
 DATE: August 6, 1947
 PROBE LOCATION: 3.40" downstream from chamber entrance

V ft/sec	V at probe ft/sec	Screen No.	Distance of Probe from Rear Wall, in.	T ₀ °C	P ₀ mm.Hg.	U' ft/sec	% Turb.	l _z inches	Remarks
		0							Screen Dimensions
		1							No Screen
		2							0.063" wire diameter, 3 mesh; Blocked area - 0.5423
		3							0.063" wire diameter, 8 mesh; Blocked area - 0.3600
		4							0.007" wire diameter, 50 mesh; Blocked area - 0.6294
22.2	24.2	0	1.5	300	76.2	.057	.24	--	1
22.2	24.2	0	1.9	300	76.2	.085	.36	--	1
22.2	24.2	0	2.3	300	76.2	.085	.36	--	1
22.2	24.2	0	1.5	300	76.2	.024	.10	--	2
22.2	24.2	0	1.9	300	76.2	.020	.06	--	2
22.2	24.2	0	2.3	300	76.2	.018	.08	--	2
22.2	24.2	0	2.7	300	76.2	.020	.08	--	2
22.2	24.2	0	1.5	300	76.2	.021	.09	--	3
22.2	24.2	0	1.5	300	76.2	.015	.08	--	4
22.2	24.2	0	1.9	300	76.2	.018	.08	--	4
22.2	24.2	0	2.3	300	76.2	.018	.07	--	4
22.2	24.2	0	2.7	300	76.2	.019	.08	--	4

Run to determine effect of running compressor, detacking exhaust stack, and passing air
 through Inspirator Throat at some Velocity on Turbulence Readings.

- 1 - Compressor on, stack on
- 2 - Compressor off, air flowing from surge tank; stack on
- 3 - Using by-pass valve (no sonic velocities); compressor off; stack on
- 4 - Compressor off, stack uncoupled

RUN NO. 52 --- Turbulence Measurements
 DATE: August 7, 1947
 PROBE LOCATION: 12.40" downstream from chamber entrance

22.2	24.0	0	1.5	300	76.2	.272	1.09	--	
22.4	24.6	1	1.5	300	76.2	.367	1.64	--	
22.4	24.6	2	1.5	300	76.2	.218	0.97	--	
22.4	24.6	3	1.5	300	76.2	.332	1.48	--	
22.4	24.6	0	1.5	300	76.2	.230	1.03	--	
44.2	49.0	0	1.5	301.5	76.25	.252	0.47	--	
44.2	49.0	1	1.5	301.5	76.25	1.139	2.33	--	
44.2	49.0	2	1.5	301.5	76.25	.119	0.49	--	
44.2	49.0	3	1.5	301.5	76.25	.228	0.47	--	
67.3	96.8	0	1.5	303	76.25	.737	0.77	--	
67.3	96.8	0	1.9	303	76.25	.603	0.63	--	
67.3	96.8	0	2.3	303	76.25	.603	0.63	--	
67.3	96.8	0	2.7	303	76.25	.904	0.84	--	
67.3	96.8	0	2.9	303	76.25	2.742	2.86	--	
67.3	96.8	1	1.5	303	76.25	1.179	1.23	--	
67.3	96.8	1	1.9	303	76.25	1.179	1.23	--	
67.3	96.8	1	2.3	303	76.25	1.300	1.14	--	
67.3	96.8	1	2.7	303	76.25	1.208	1.25	--	
67.3	96.8	1	2.9	303	76.25	2.278	2.37	--	
67.3	96.8	2	1.5	303	76.25	.857	0.89	--	
67.3	96.8	2	1.9	303	76.25	.804	0.84	--	
67.3	96.8	2	2.3	303	76.25	.777	0.81	--	
67.3	96.8	2	2.7	303	76.25	.671	0.91	--	
67.3	96.8	2	2.9	303	76.25	1.808	1.67	--	
67.3	96.8	3	1.5	303	76.25	.976	1.02	--	
67.3	96.8	3	1.9	303	76.25	.885	.92	--	
67.3	96.8	3	2.3	303	76.25	.838	.86	--	
67.3	96.8	3	2.7	303	76.25	1.800	1.14	--	
67.3	96.8	3	2.9	303	76.25	.87	1.01	--	
200.4	222.2	0	1.5	313	76.3	1.636	0.72	--	
200.4	222.2	1	1.5	313	76.3	2.491	1.17	--	

V
ft/sec
 V
at probe
ft/sec
 Screen No.
 Distance
of Probe
from Rear
Wall, in.
 T₀
°C
 P₀
mm.Hg.
 U'
ft/sec
 % Turb.
 l_z
inches
 Remarks

RUN NO. 53 --- Turbulence Measurements
 DATE: August 8, 1947
 PROBE LOCATION: 7.40" downstream from chamber entrance

21.9	23.9	0	1.5	300.5	76.2	.104	0.44	--	
21.9	23.9	1	1.5	300.5	76.2	.098	2.60	--	
21.9	23.9	2	1.5	300.5	76.2	.106	1.07	--	
21.9	23.9	3	1.5	300.5	76.2	.127	0.53	--	
44.2	49.1	0	1.5	300.5	76.2	.160	0.33	--	
44.2	49.1	1	1.5	300.5	76.2	.076	1.41	--	.113
44.2	49.1	2	1.5	300.5	76.2	.221	0.43	--	.051
44.2	49.1	3	1.5	300.5	76.2	.183	0.34	--	.0294
66.7	94.5	0	1.5	303.5	76.2	1.178	1.26	--	
66.7	94.5	0	1.9	303.5	76.2	.924	0.99	--	
66.7	94.5	0	2.3	303.5	76.2	.214	0.83	--	
66.7	94.5	0	2.7	303.5	76.2	.484	0.13	--	
66.7	94.5	0	2.9	303.5	76.2	1.604	1.59	--	
66.7	94.5	1	1.5	303.5	76.2	.793	0.64	--	
66.7	94.5	1	1.9	303.5	76.2	.747	0.76	--	
66.7	94.5	1	2.3	303.5	76.2	.761	0.61	--	
66.7	94.5	1	2.7	303.5	76.2	.774	0.62	--	
66.7	94.5	1	2.9	303.5	76.2	1.415	1.50	--	
66.7	94.5	2	1.5	303.5	76.2	.363	0.37	--	
66.7	94.5	2	1.9	303.5	76.2	.218	0.34	--	
66.7	94.5	2	2.3	303.5	76.2	.294	0.30	--	
66.7	94.5	2	2.7	303.5	76.2	.719	0.76	--	
66.7	94.5	2	2.9	303.5	76.2	1.067	1.58	--	
66.7	94.5	3	1.5	303.5	76.2	.277	0.29	--	
66.7	94.5	3	1.9	303.5	76.2	.277	0.29	--	
66.7	94.5	3	2.3	303.5	76.2	.140	0.19	--	
66.7	94.5	3	2.7	303.5	76.2	.413	0.44	--	
66.7	94.5	3	2.9	303.5	76.2	.691	0.73	--	
159.2	173.4	0	1.5	308	76.2	1.100	0.63	--	
159.2	173.4	1	1.5	308	76.2	2.30	1.33	--	
159.2	173.4	2	1.5	308	76.2	1.040	1.07	--	
159.2	173.4	3	1.5	308	76.2	1.043	0.53	--	
16.46	--	0	2.9	308	76.2	--	--	--	(1)

(1) At this velocity boundary layer goes turbulent (increase of about 10 times in turbulence when boundary goes turbulent. Probe 0.1" from wall.

RUN NO. 54 --- Turbulence Measurements
 DATE: August 11, 1947
 PROBE LOCATION: 3.40" downstream from chamber entrance.

23.2	24.9	0	1.5	299	76.2	.134	0.54	--	
23.2	24.9	1	1.5	299	76.2	1.100	4.78	--	
23.2	24.9	2	1.5	299	76.2	.416	1.67	--	
23.2	24.9	3	1.5	299	76.2	.167	0.79	--	
44.5	47.6	0	1.5	299	76.2	.18	0.33	--	
44.5	47.6	1	1.5	299	76.2	1.308	2.72	--	0.59
44.5	47.6	2	1.5	299	76.2	.230	0.48	--	0.37
44.5	47.6	3	1.5	299	76.2	--	--	--	0.025
66.0	94.7	0	1.5	300	76.25	.366	0.63	--	
66.0	94.7	0	1.9	300	76.25	.879	0.61	--	
66.0	94.7	0	2.3	300	76.25	.996	0.63	--	
66.0	94.7	0	2.7	300	76.25	.527	0.66	--	
66.0	94.7	0	2.9	300	76.25	.992	1.14	--	
66.0	94.7	1	1.5	300	76.25	2.663	2.61	--	
66.0	94.7	1	1.9	300	76.25	2.509	2.65	--	
66.0	94.7	1	2.3	300	76.25	2.684	2.73	--	
66.0	94.7	1	2.7	300	76.25	1.684	1.78	--	
66.0	94.7	1	2.9	300	76.25	1.965	1.68	--	
66.0	94.7	2	1.5	300	76.25	.783	.83	--	
66.0	94.7	2	1.9	300	76.25	.783	.83	--	
66.0	94.7	2	2.3	300	76.25	.736	.75	--	
66.0	94.7	2	2.7	300	76.25	.614	.66	--	
66.0	94.7	2	2.9	300	76.25	1.723	1.82	--	
66.0	94.7	3	1.5	300	76.25	.348	.39	--	
66.0	94.7	3	1.9	300	76.25	.390	.38	--	
66.0	94.7	3	2.3	300	76.25	.350	.38	--	
66.0	94.7	3	2.7	300	76.25	.470	.50	--	
66.0	94.7	3	2.9	300	76.25	1.096	1.15	--	
194.5	206.3	0	1.5	301	76.35	.863	.41	--	
194.5	206.3	1	1.5	301	76.35	3.894	1.71	--	
194.5	206.3	2	1.5	301	76.35	1.707	.82	--	
194.5	206.3	3	1.5	301	76.35	0.996	.48	--	
26.1	--	0	2.9	301	76.35	--	--	--	(1)

(1) Boundary layer goes turbulent

V ft/sec
 V at Probe
 ft/sec
 Screen
 No.
 Distance
 of Probe
 from Near
 Wall, in.
 P_0
 cm.Hg.
 P
 cm.Hg.
 u'
 ft/sec
 $\%$ Turb.
 l_2
 inches
 Remarks

RUN NO. 55 --- Turbulence Measurements

DATE: August 13, 1947

PROBE LOCATION: 1.40" downstream from chamber entrance.

22.1	23.6	0	1.6	301.5	76.4	.208	.86	--	--	
22.1	23.6	1	1.6	301.5	76.4	2.195	9.31	--	--	
22.1	23.6	2	1.6	301.5	76.4	.796	3.37	--	--	
22.1	23.6	3	1.6	301.6	76.4	.463	1.96	--	--	
44.7	47.6	0	1.6	301.5	76.46	.168	.35	--	--	
44.7	47.6	1	1.6	301.5	76.46	2.29	4.79	.0615	--	
44.7	47.6	2	1.6	301.6	76.46	.855	1.79	.0456	--	
44.7	47.6	3	1.6	301.6	76.46	.259	.66	.0806	--	
76.8	82.1	0	1.5	302	76.25	.715	.87	--	--	
76.8	82.1	0	1.9	302	76.25	.977	1.19	--	--	
76.8	82.1	0	2.3	302	76.25	.977	1.19	--	--	
76.8	82.1	0	2.7	302	76.25	.761	.91	--	--	
76.8	82.1	0	2.9	302	76.25	1.966	2.03	--	--	
76.8	82.1	1	1.5	302	76.25	3.87	4.88	--	--	
76.8	82.1	1	1.9	302	76.25	4.10	4.99	--	--	
76.8	82.1	1	2.3	302	76.25	3.62	4.29	--	--	
76.8	82.1	1	2.7	302	76.25	3.52	4.29	--	--	
76.8	82.1	1	2.9	302	76.25	2.53	3.08	--	--	
76.8	82.1	2	1.5	302	76.25	1.52	1.97	--	--	
76.8	82.1	2	1.9	302	76.25	1.71	2.08	--	--	
76.8	82.1	2	2.3	302	76.25	1.43	1.74	--	--	
76.8	82.1	2	2.7	302	76.25	1.62	1.97	--	--	
76.8	82.1	2	2.9	302	76.25	3.62	4.61	--	--	
76.8	82.1	3	1.5	302	76.25	.52	.63	--	--	
76.8	82.1	3	1.9	302	76.25	.46	.58	--	--	
76.8	82.1	3	2.3	302	76.25	.43	.55	--	--	
76.8	82.1	3	2.7	302	76.25	.54	.66	--	--	
76.8	82.1	3	2.9	302	76.25	2.62	3.19	--	--	
59.5	--	0	2.9	302	76.25	--	--	--	--	(1)

(1) Boundary layer goes turbulent.

RUN NO. 56 --- Turbulence Measurements - City Gas and Air Combustion

DATE: August 14, 1947

PROBE LOCATION: 1.40" downstream from chamber entrance.

FLAME STABILIZER: 0.188" diameter steel rod located 9" from chamber entrance.

W_a lb/sec	W_f lb/sec	T_0 °K	P_0 cm.Hg.	l/r lbs/lb	O_2 lbs/lb	V_0 ft/sec.	V ft/sec.	Screen No.	Distance Inches	u' ft/sec	$\%$ Turb.	l_2 inches	Remarks
.03379	.008270	304	75.2	10.33	.6135	26.2	27.0	0	1.5	6.020	22.30	--	(1)
.03379	.004204	304	76.2	8.04	.5525	25.1	27.9	0	1.5	6.621	23.74	--	(2)

(1) About 30 cycles/second flutter - appears as nearly perfect sine wave on oscilloscope screen.

(2) About 50 cycles/second flutter as flame comes further down into chamber - nearly perfect sine wave on oscilloscope screen.

Picture
 No.
 W_a
 lb/sec
 W_f
 lb/sec
 C_F
 P
 cm.Hg.
 ΔP
 cm.Hg.
 $U_0 = 1$
 U_0
 lbs/lb.
 V_0
 ft/sec
 U_2
 inches
 U_1
 inches
 U_0
 inches
 Remarks

RUN NO. 57 --- City Gas and Air Combustion

DATE: August 21, 1947

SCREEN: 3 mesh; 0.063" wire diameter

FLAME STABILIZER: 0.500" wide 30° gutter open edge located 9" from chamber entrance; Total Area/Open Area = 100

---	.05410	.002607	297	(77.1)	--	13.08	.6577	26.0	--	--	--	--	LLBO
3-1-67	.03401	.008090	297	(77.1)	--	11.01	.6283	26.4	.80	1.04	1.52	--	
4-1-67	.03401	.008617	297	(77.1)	--	9.60	.5909	26.8	.98	1.68	2.40	--	
5-1-67	.03401	.005295	297	(77.1)	--	8.42	.4995	25.3	1.64	2.80	Wall	--	LLBO
---	.06862	.005061	298	(77.2)	--	13.46	.6745	48.3	--	--	--	--	
6-1-67	.06757	.005213	298	(77.2)	--	12.98	.6557	47.7	.58	1.08	1.48	--	
7-1-67	.06757	.005661	298	(77.2)	--	10.16	.6091	49.0	.84	1.08	1.56	--	
8-1-67	.06757	.01227	298	(77.2)	--	5.51	.4583	53.9	1.04	2.00	2.68	--	
9-1-67	.06757	.01401	298	(77.3)	--	4.82	.4256	55.3	1.00	2.00	2.68	--	
10-1-67	.06757	.01662	298	(77.4)	--	4.33	.3992	56.4	.92	1.52	2.28	--	
11-1-67	.06757	.01813	298	(77.3)	--	3.73	.3541	58.9	.75	1.00	1.40	--	RLBO
---	.06617	.01848	299	(77.3)	--	3.58	.3548	58.5	--	--	--	--	LLBO
---	.1359	.01074	301	(77.5)	--	12.65	.6608	96.7	--	--	--	--	
12-1-67	.1349	.01103	303	(77.6)	--	12.23	.6526	97.0	.72	1.00	1.40	--	
1-2-67	.1349	.01440	303	(77.6)	--	9.37	.5900	99.8	.80	1.00	1.40	--	
2-2-67	.1349	.01996	303	(77.7)	--	6.75	.5094	104.6	.84	1.44	1.96	--	
3-2-67	.1349	.02408	303	(77.8)	--	5.60	.4625	106.1	.84	1.36	1.92	--	
4-2-67	.1349	.02876	303	(77.8)	--	4.80	.4186	112.3	.88	1.20	1.60	--	
5-2-67	.1349	.03334	303	(77.8)	--	4.06	.3833	115.3	.80	1.12	1.44	--	RLBO
---	.1330	.03589	306	(77.8)	--	3.71	.3627	118.1	--	--	--	--	
---	.2401	.02066	307	(78.3)	--	11.68	.6421	173.9	--	--	--	--	LLBO(1)
---	.2424	.02275	307	(78.3)	--	3.86	.3724	212.9	--	--	--	--	RLBO
---	.2990	.02595	308	(78.8)	--	11.52	.6390	216.3	--	--	--	--	LLBO
6-2-67	.2935	.02577	308	(78.9)	--	11.39	.6363	212.3	--	--	--	--	LLBO(RF)RFO(2)
7-2-67	.2986	.02722	308	(79.3)	--	10.97	.6276	215.8	.76	1.00	1.28	--	
8-2-67	.2986	.04452	308	(79.7)	--	6.71	.5075	229.8	.80	1.04	1.40	--	
9-2-67	.2986	.05391	308	(80.0)	--	5.54	.4597	237.1	.80	1.00	1.40	--	
10-2-67	.2986	.06285	308	(79.9)	--	4.75	.4219	245.2	.84	1.08	1.40	--	

Could not get blow out on rich side at 200 ft/sec. (Went to about 40 cm. of gas.)

11-2-67	.4821	.06087	310	(61.9)	--	9.48	.5928	345.4	.76	1.00	1.28	--	LLBO(3)
---	.4821	.04915	310	(61.6)	--	10.15	.5092	342.9	--	--	--	--	

(1) Residual flame just for an instant before blow out.

(2) Height of residual flame - 1.96"

(3) No residual flame at this high velocity blow out.

RUN NO. 58 --- City Gas and Air Combustion

DATE: August 22, 1947

SCREEN: 3 mesh; 0.063" wire diameter

FLAME STABILIZER: 0.500" wide flat plate (0.008" thick steel) located 9" from chamber entrance.

---	.03490	.002594	299	(76.4)	--	13.45	.6739	24.9	--	--	--	--	LLBO
12-1-68	.03490	.002715	299	(76.4)	--	12.86	.6636	25.0	1.16	1.32	1.64	--	
1-2-68	.03490	.003502	299	(76.4)	0.2	9.97	.5049	25.7	1.24	1.80	2.68	--	
2-2-68	.03490	.004289	299	(76.5)	0.2	8.23	.5584	26.3	1.72	2.58	Wall	(1)	
---	.07021	.004889	299	(76.5)	--	14.45	.6894	49.7	--	--	--	--	LLBO
3-2-68	.05950	.006187	300	(75.5)	0.3	13.40	.6730	46.7	1.24	1.48	1.76	--	
4-2-68	.05950	.006928	300	(75.5)	0.3	10.49	.6170	51.0	1.20	1.40	1.76	--	
5-2-68	.05950	.009444	300	(76.9)	0.6	7.35	.5306	53.2	1.28	2.32	Wall	--	
6-2-68	.05950	.01084	300	(77.0)	0.6	5.41	.4982	54.3	1.28	2.48	Wall	--	
7-2-68	.05950	.01303	300	(77.0)	0.6	5.33	.4603	56.3	1.28	2.32	Wall	--	
8-2-68	.05950	.01547	300	(75.9)	0.6	4.22	.3933	59.4	1.24	1.44	2.12	--	
9-2-68	.05950	.01943	300	(75.8)	0.4	3.58	.3446	62.1	1.20	1.44	1.98	--	
---	.04911	.01643	300	(75.6)	--	3.56	.3545	61.6	--	--	--	--	RLBO
---	.1384	.01053	299	(77.0)	--	13.02	.6587	98.2	--	--	--	--	LLBO
10-2-68	.1378	.01103	300	(77.0)	0.8	12.49	.6574	96.5	1.24	1.40	1.50	--	
11-2-68	.1378	.01556	300	(77.4)	1.0	8.27	.5695	103.0	1.20	1.48	1.84	--	
12-2-68	.1378	.02225	300	(77.7)	1.1	6.19	.4875	107.4	1.28	1.56	2.24	--	
1-3-68	.1378	.03047	300	(77.7)	1.2	4.52	.4099	114.5	1.32	1.62	1.84	--	
2-3-68	.1378	.03460	300	(77.7)	1.2	3.95	.3782	116.4	1.32	1.48	1.98	--	
---	.1361	.03857	300	(77.6)	--	3.53	.3515	121.0	--	--	--	--	RLBO
---	.2460	.02096	300	(78.0)	--	11.82	.6449	175.0	--	--	--	--	LLBO

Flame stabilizer blew out of chamber while getting RLBO

(1) Slight flutter

Picture No.	w_a lbs/sec	w_f lbs/sec	T °K	P_0 cm. Hg.	ΔP_c lbs/lb.	$1/f$ lbs/lb.	O_2 lbs/lb.	V_0 ft/sec	V_1 "	V_2 "	V_3 "	V_4 "	V_5 "	Stabilizer Temp. °K	Remarks
RUN NO. 69 --- City Gas and Air Combustion															
DATE: August 21, 1947															
SCREEN: None															
FLAME STABILIZER															
---	.06919	.004211	301	(76.6)	-	15.43	.7162	46.7	-	-	-	-	-	1200 (1)	LLBO (RF)
---	.06919	.003990	302	(76.6)	-	17.47	.7266	46.6	-	-	-	-	-	1200	RFO
---	.06908	.00207	302	(75.7)	-	5.41	.3456	65.1	-	-	-	-	-	1200	RLBO
---	.1300	.01007	302	(76.7)	-	13.70	.6779	96.8	-	-	-	-	-	1200	RLBO (RF)
---	.1300	.006950	302	(76.7)	-	16.42	.7031	97.8	-	-	-	-	-	1200	RFO
---	.1074	.00612	303	(77.1)	-	3.60	.3968	121.5	-	-	-	-	-	1200	RLBO
---	.2487	.02156	303	(77.5)	-	11.54	.6392	179.9	-	-	-	-	-	1200	RLBO (RF)
---	.2487	.02038	303	(77.5)	-	12.20	.6521	176.9	-	-	-	-	-	1200	RFO
---	.2482	.00727	303	(77.6)	-	4.33	.3997	210.4	-	-	-	-	-	1200	RLBO
---	.3054	.02553	303	(77.9)	-	10.70	.6218	221.6	-	-	-	-	-	1200	RLBO (RF)
---	.3024	.02300	303	(77.9)	-	10.91	.6252	221.1	-	-	-	-	-	1200	RFO
---	.3039	.05776	303	(78.4)	-	4.48	.4078	255.5	-	-	-	-	-	1200	RLBO
---	.4649	.06710	303	(80.4)	-	6.57	.5711	357.2	-	-	-	-	-	1200	LLBO

When flame or residual flame went out rod would drop a great deal in temperature (only just glowing). This shows that a considerable amount of heat was being transferred from the hot gases in the eddy region to the rod even when the rod is at 1200°K.

No change in flame configuration could be observed when the heating current to the flame stabilizer was turned on and off.

(Cold - H₂O cooled - tube)

In order to get flame to stabilize had to cut off cooling water. After stabilizer cooling water turned back on without blowing out flame.

---	.06898	.00818	302	(76.6)	-	13.36	.6725	46.6	-	-	-	-	-	303 (2)	LLBO
---	.06898	.00802	303	(76.6)	-	15.72	.6762	46.6	-	-	-	-	-	Equil.	LLBO
---	.06898	.01736	303	(76.7)	-	3.96	.3763	60.6	-	-	-	-	-	303	RLBO
---	.06898	.01411	303	(75.7)	-	3.60	.3668	61.2	-	-	-	-	-	Equil.	RLBO
---	.1374	.01241	303	(76.7)	-	11.07	.6297	100.9	-	-	-	-	-	303	LLBO
---	.1254	.01159	303	(76.7)	-	11.94	.6472	100.8	-	-	-	-	-	Equil.	LLBO
---	.1336	.03111	303	(77.1)	-	4.46	.4066	117.9	-	-	-	-	-	303	RLBO
---	.1277	.03363	303	(77.1)	-	4.10	.3861	119.4	-	-	-	-	-	Equil.	RLBO
---	.2482	.02963	303	(77.5)	-	6.88	.6627	166.7	-	-	-	-	-	303	LLBO
---	.2482	.02590	303	(77.5)	-	9.58	.6966	162.4	-	-	-	-	-	Equil.	LLBO
---	.2479	.04757	303	(77.8)	-	5.17	.4425	202.4	-	-	-	-	-	303	RLBO
---	.2482	.05219	304	(77.6)	-	4.76	.4221	205.6	-	-	-	-	-	Equil.	RLBO
---	.3052	.03967	304	(77.9)	-	7.69	.6417	232.0	-	-	-	-	-	303	LLBO
---	.3052	.03501	304	(77.9)	-	6.72	.6725	227.9	-	-	-	-	-	Equil.	LLBO
---	.3057	.05495	304	(78.4)	-	5.66	.4607	244.5	-	-	-	-	-	303	RLBO
---	.3039	.04059	304	(78.4)	-	4.99	.4340	246.4	-	-	-	-	-	Equil.	RLBO
---	.3315	.05334	305	(78.5)	-	6.29	.4914	262.4	-	-	-	-	-	303	LLBO
---	.434	.0645	305	(80.4)	-	6.73	.5063	324.6	-	-	-	-	-	Equil.	LLBO
---	.3199	.05649	305	(78.6)	-	5.66	.4652	255.1	-	-	-	-	-	303	LLBO

No change could be observed in flame configuration when the water is turned on and off to the stainless steel tube flame stabilizer.

(Stack uncoupled) - An odd phenomenon is being observed, worthy of reporting. However, no more time will be devoted to it in this study. See below:

Picture No.	w_a lbs/sec	w_f lbs/sec	T °K	P_0 cm. Hg.	ΔP_c lbs/lb.	$1/f$ lbs/lb.	O_2 lbs/lb.	V_0 ft/sec	V_1 "	V_2 "	V_3 "	V_4 "	V_5 "	Stabilizer Temp. °K	Remarks
Run No. 69 (Continued)															
(Blow-outs with stack uncoupled)															
---	.06888	.005242	303	(76.6)	-	13.14	.6667	46.6	-	-	-	-	-	Equil.	LLBO
---	.06888	.01004	303	(76.7)	-	3.82	.3697	61.1	-	-	-	-	-	Equil.	RLBO
---	.1374	.01166	303	(76.7)	-	11.67	.6467	100.1	-	-	-	-	-	Equil.	LLBO
---	.1382	.03299	303	(77.1)	-	4.19	.3918	119.2	-	-	-	-	-	Equil.	RLBO
---	.2482	.02558	303	(77.5)	-	9.70	.6988	163.1	-	-	-	-	-	Equil.	LLBO
---	.2482	.05227	303	(77.6)	-	4.76	.4218	205.0	-	-	-	-	-	Equil.	RLBO
---	.3057	.03490	303	(77.9)	-	6.76	.6737	227.4	-	-	-	-	-	Equil.	LLBO
---	.4197	.06167	303	(80.4)	-	5.61	.6111	314.2	-	-	-	-	-	Equil.	LLBO
4-1-69	.3047	.04639	303	(78.1)	-	6.71	.6077	236.4	-	-	-	-	-	Equil.	LLBO

No observable change in flame upon uncoupling of stack. No observable change in beginning of flutter upon uncoupling.

- (1) Temperature measured by means of optical pyrometer sighting on electrically heated rod.
- (2) Rod cooled by passing water through it. Temperature of water exiting from rod assumed to be that of rod.

Picture No.	w_a lbs/sec	w_f lbs/sec	T °K	P_0 cm. Hg.	ΔP_c cm. Hg.	$1/f$ lbs/lb.	O_2 lbs/lb.	V_0 ft/sec	V_1 "	V_2 "	V_3 "	V_4 "	V_5 "	Remarks
-------------	------------------	------------------	-----------	------------------	-------------------------	------------------	------------------	-----------------	------------	------------	------------	------------	------------	---------

RUN NO. 70 --- City Gas and Air Combustion

DATE: August 26, 1947

SCREEN: 3 mesh; 0.063" wire diameter

FLAME STABILIZER: 0.500" wide flat plate (0.008" thick steel)

---	.2485	.02021	301	(76.0)	-	12.30	.6538	176.3	-	-	-	-	-	LLBO
-----	-------	--------	-----	--------	---	-------	-------	-------	---	---	---	---	---	------

RUN NO. 71 --- City Gas and Air Combustion

DATE: August 26, 1947

SCREEN: 3 mesh; 0.063" wire diameter

FLAME STABILIZER: Double 0.030" rod holder located 5" from chamber entrance

Picture No.	w_a lbs/sec	w_f lbs/sec	T °K	P_0 cm. Hg.	ΔP_c cm. Hg.	$1/f$ lbs/lb.	O_2 lb/lb.	v_0 ft/sec	w_1 in.	w_2 in.	w_3 in.	w_4 in.	w_5 in.	w_6 in.	$t_{(min)}$ in.	$t_{(max)}$ in.	Remarks
10-1-71	.03496	.002727	297	76.5	0.3	12.62	.6632	24.6	.20	.40	.52	.58	.64	.96	-	-	
11-1-71	.03580	.003206	297	76.6	0.3	11.17	.6317	28.6	.60	.64	1.00	1.24	1.40	Wall	5.60	-	
12-1-71	.03580	.004592	297	76.6	0.5	7.80	.6480	27.0	.66	1.36	Wall	Wall	Wall	Wall	2.88	-	
- -	.06962	.005156	298	(76.5)	-	13.60	.6810	46.2	-	-	-	-	-	-	-	-	LLBO
1-2-71	.06962	.005156	298	76.6	0.4	13.60	.6747	46.3	.20	.40	.56	.58	.80	.92	-	-	
2-2-71	.06962	.006180	298	76.6	0.4	11.30	.6346	50.2	.26	.48	.56	.92	1.08	1.24	-	-	
3-2-71	.06962	.008008	298	76.7	0.5	6.64	.5703	51.8	.36	.68	1.00	1.24	1.36	Wall	5.62	-	
4-2-71	.06962	.01002	298	77.1	1.0	6.95	.5153	53.3	.40	.68	1.24	1.44	Wall	Wall	4.20	-	
5-2-71	.06962	.01230	298	77.2	1.0	6.86	.4651	55.2	.44	.92	1.20	1.40	Wall	Wall	4.08	-	
6-2-71	.06962	.01543	298	77.0	0.6	4.61	.4094	56.1	.32	.56	.76	.96	1.20	-	-	-	
- -	.06907	.01575	296	(77.0)	-	4.12	.3875	56.9	-	-	-	-	-	-	-	-	RLBO
- -	.1349	.01170	296	(77.5)	-	11.53	.5391	95.0	-	-	-	-	-	-	-	-	LLBO
7-2-71	.1356	.01214	296	77.5	0.6	11.16	.5316	96.7	.28	.62	.98	.80	.92	1.04	-	-	
8-2-71	.1356	.01593	296	78.0	1.1	6.61	.5665	99.4	.28	.52	.72	.92	1.12	1.24	-	-	
9-2-71	.1356	.02046	296	78.6	1.6	6.63	.5044	102.7	.32	.50	.84	1.12	1.20	1.36	-	-	
10-2-71	.1356	.02418	298	78.7	1.7	5.60	.4626	106.5	.32	.50	.88	1.12	1.20	1.36	-	-	
11-2-71	.1356	.02906	298	78.1	1.3	4.66	.4173	110.6	.32	.56	.80	1.00	1.12	1.24	-	-	
- -	.1352	.02941	299	(78.1)	-	4.60	.4139	111.1	-	-	-	-	-	-	-	-	RLBO
- -	.2484	.02709	298	(80.0)	-	9.17	.5648	176.5	-	-	-	-	-	-	-	-	LLBO
- -	.2519	.05019	299	(80.0)	-	5.02	.4553	198.2	-	-	-	-	-	-	-	-	LLBO
- -	.3059	.03726	299	(82.0)	-	6.21	.5677	216.2	-	-	-	-	-	-	-	-	RLBO
12-2-71	.3059	.04650	299	80.2	3.1	6.56	.5021	226.0	-	-	-	-	-	-	-	-	(1)
- -	.3059	.03596	299	(79.0)	-	6.51	.5658	222.3	-	-	-	-	-	-	-	-	LLBO-(1)
1-3-71	.3059	.03913	299	82.2	4.5	7.62	.5456	216.3	.36	.50	.76	.92	1.08	1.16	-	-	
2-3-71	.3059	.04671	299	83.1	5.3	6.56	.5015	220.1	.36	.50	.80	1.00	1.12	1.24	-	-	
- -	.3059	.05367	300	(82.5)	-	5.66	.4659	226.3	-	-	-	-	-	-	-	-	RLBO
- -	.3553	.05395	300	(84.0)	-	6.59	.5029	233.6	-	-	-	-	-	-	-	-	LLBO
- -	.3413	.05693	300	(84.0)	-	6.00	.4794	247.6	-	-	-	-	-	-	-	-	LLBO

The two rods always blew out together - never one, then the other.

- (1) Flame on one rod only; single holder

5723

Picture No.	V lbs/sec	V_f lbs/sec	T °K	P_0 cm.Hg.	ΔP cm.Hg.	$W = \frac{1}{2} \frac{V}{V_f}$ lbs/lb	$\frac{V}{V_f}$ Theor. Air	O_2 lbs/lb	V_0 ft/sec	V_2 in.	V_4 in.	V_6 in.	Remarks
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MUN NO. 76 --- Propane and Air Combustion

DATE: September 2, 1947

SCREEN: 3 mesh; 0.063" wire diameter

FLAME STABILIZER: 0.188" diameter steel rod located 9" from chamber entrance

---	.03401	.001675	296	(75.7)	--	21.59	136.6	.5809	22.6	--	--	--	LLBO
2-1-76	.03401	.001902	296	75.7	0.2	17.68	114.6	.5344	23.0	.98	1.68	2.36	(1)
3-1-76	.03401	.002548	296	75.6	0.3	12.84	82.4	.4519	23.3	1.36	2.62	Wall	
4-1-76	.03401	.003741	296	75.6	0.2	9.09	58.4	.3685	23.7	.68	1.24	1.92	
---	.03407	.004129	296	(75.8)	--	8.25	53.0	.3452	23.9	--	--	--	RLBO
5-1-76	.03407	.003053	296	(75.8)	--	22.76	146.1	.5936	45.5	.68	1.08	1.36	LLBO
6-1-76	.03407	.003849	296	75.8	0.3	18.06	115.9	.5367	45.8	.72	1.20	1.64	
7-1-76	.03407	.004648	296	76.0	0.4	14.95	94.9	.4895	47.1	.80	1.40	2.04	
8-1-76	.03407	.005254	296	76.0	0.4	13.22	84.9	.4591	47.3	.80	1.64	2.24	
9-1-76	.03407	.006473	296	76.0	0.4	10.73	68.9	.4079	47.8	.68	1.36	2.04	
---	.1376	.006493	296	(75.2)	--	21.35	137.0	.5781	92.4	--	--	--	LLBO
---	.06954	.008303	296	(75.0)	--	8.56	53.8	.3496	46.7	--	--	--	RLBO
10-1-76	.1376	.008867	296	76.2	0.6	20.07	128.6	.5629	92.1	.68	1.08	1.32	
11-1-76	.1376	.008680	296	76.2	0.6	16.68	101.9	.5047	92.9	.68	1.12	1.48	
12-1-76	.1376	.01151	296	76.3	0.7	11.97	76.8	.4345	94.0	.68	1.12	1.56	
1-2-76	.1376	.01353	296	76.3	0.6	10.19	65.4	.3953	94.8	.72	1.12	1.48	
---	.1376	.01465	296	(75.3)	--	9.41	60.4	.3765	95.3	--	--	--	RLBO
---	.2489	.01277	299	(76.6)	--	19.49	125.1	.5558	165.7	--	--	--	LLBO
---	.2489	.02305	299	(76.8)	--	10.80	69.3	.4694	170.2	--	--	--	RLBO
---	.3055	.01600	299	(77.3)	--	19.09	122.6	.5507	202.3	--	--	--	LLBO
2-2-76	.3055	.01553	299	77.3	1.7	18.48	118.6	.5426	202.6	.72	1.04	1.32	
11-2-76	.3055	.01514	299	76.3	2.0	15.96	102.5	.5080	201.0	.72	1.08	1.40	
12-2-76	.3055	.02396	299	76.4	2.3	12.74	81.8	.4499	202.8	.72	1.08	1.44	
---	.3055	.02470	300	(78.4)	--	12.37	79.4	.4425	203.8	--	--	--	RLBO
1-3-76	.4306	.02835	300	79.5	3.5	15.19	97.5	.4956	279.1	.72	1.08	1.40	
---	.4500	.02975	301	(80.0)	--	15.46	99.2	.4981	298.6	--	--	--	LLBO
---	.4904	.03391	301	(80.0)	--	14.46	92.6	.4614	319.2	--	--	--	LLBO

(1) Occasional flutter above here, but not much.

MUN NO. 76A --- Propane and Air Combustion

DATE: September 2, 1947

SCREEN: 3 mesh; 0.063" wire diameter

FLAME STABILIZER: 0.188" diameter steel rod located 9" from chamber entrance

3-3-76	.3055	.01653	299	77.3	1.7	18.48	118.6	.5426	202.5	--	--	--	(1)
4-3-76	.3055	.01653	299	77.3	1.7	18.48	118.6	.5426	202.5	--	--	--	(2)
5-3-76	.3055	.01653	299	77.3	1.7	18.48	118.6	.5426	202.5	--	--	--	(3)
6-3-76	.3055	.01653	299	77.3	1.7	18.48	118.6	.5426	202.5	.64	.92	1.12	(4)
7-3-76	.3055	.01553	299	77.3	1.7	18.48	118.6	.5426	202.5	.68	1.00	1.28	(5)
8-3-76	.3055	.01653	299	77.3	1.7	18.48	118.6	.5426	202.6	.72	1.06	1.36	(6)
9-3-76	.3055	.01653	299	77.3	1.7	18.48	118.6	.5426	202.6	.72	1.08	1.36	(7)
10-3-76	.3055	.01653	299	77.3	1.7	18.48	118.6	.5426	202.5	.76	1.12	1.36	(8)

(1) Too underexposed to measure, exposure time 1/200

(2) Too underexposed to measure, exposure time 1/100

(3) Too underexposed to measure, exposure time 1/50

(4) Exposure time 1/25

(5) Exposure time 1/5

(6) Exposure time 1/2

(7) Exposure time 1

(8) Exposure time 3

Picture No.	V lbs/sec	V_f lbs/sec	T °K	P_0 cm. Hg.	ΔP cm. Hg.	$W = \frac{1}{2} \frac{V}{V_f}$ lbs/lb	$\frac{V}{V_f}$ Theor. Air	O_2 lbs/lb	V_0 ft/sec	V_2 in.	V_4 in.	V_6 in.	Remarks
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MUN NO. 76 --- Propane and Air Combustion

DATE: September 3, 1947

SCREEN: 3 mesh; 0.063" wire diameter

FLAME STABILIZER: 0.094" steel rod located 9" from chamber entrance

---	.03407	.001669	298	75.1	0.2	20.41	131.0	.5671	22.6	--	--	--	LLBO
2-1-76	.03407	.001719	298	75.1	0.2	19.82	127.2	.5599	22.8	.80	1.40	2.12	
3-1-76	.03407	.002107	298	75.2	0.2	16.17	103.8	.5093	22.9	1.00	2.08	2.54	
4-1-76	.03407	.002580	298	75.2	0.2	12.71	81.6	.4493	23.2	1.44	2.68	Wall	
5-1-76	.03407	.003515	298	75.2	0.2	9.43	60.5	.3769	23.6	.64	1.04	1.44	
6-1-76	.03407	.004021	298	75.2	0.2	8.47	54.4	.3523	23.8	.48	.80	1.12	
---	.03407	.004183	299	(75.2)	--	8.13	52.2	.3429	23.9	--	--	--	RLBO
---	.06931	.003086	299	(75.3)	--	22.46	144.2	.5904	45.3	--	--	--	LLBO
7-1-76	.06931	.003331	299	76.3	0.3	20.81	133.6	.5718	45.4	.56	1.08	1.44	
8-1-76	.06931	.003763	299	76.3	0.4	18.47	118.5	.5424	45.5	.50	1.12	1.56	
9-1-76	.06931	.004756	299	76.4	0.4	14.57	93.6	.4833	46.9	.76	1.44	2.08	
10-1-76	.06931	.006064	299	76.4	0.4	11.43	73.4	.4232	47.6	.68	1.48	2.12	
---	.06928	.007968	299	(76.4)	--	8.69	56.8	.3581	48.3	--	--	--	RLBO
---	.1376	.008848	299	(76.3)	--	19.90	127.6	.5601	91.3	--	--	--	LLBO
11-1-76	.1376	.007207	300	76.3	0.4	19.08	122.5	.5506	92.6	.60	1.04	1.40	
12-1-76	.1376	.008235	300	76.6	0.6	14.89	95.6	.4887	93.0	.68	1.24	1.60	
1-2-76	.1376	.01116	300	76.7	0.6	12.32	79.1	.4416	93.8	.66	1.28	1.68	
2-2-76	.1376	.01362	300	76.6	0.6	10.10	64.8	.3932	94.9	.72	1.20	1.36	
---	.1366	.01429	300	(76.6)	--	9.66	61.4	.3802	94.6	--	--	--	RLBO
---	.2486	.01467	300	(77.6)	--	17.06	109.5	.5226	165.3	--	--	--	LLBO
---	.2486	.02206	301	(77.6)	--	11.26	72.2	.4194	169.1	--	--	--	RLBO
---	.3040	.01936	301	(78.5)	--	15.71	100.6	.5021	201.0	--	--	--	LLBO
3-2-76	.3040	.01991	301	78.5	2.0	15.27	98.0	.4950	201.2	.64	1.08	1.44	
4-2-76	.3040	.02196	301	78.7	2.3	13.83	88.8	.4703	201.6	.68	1.12	1.48	
---	.3040	.02341	301	(78.7)	--	12.99	83.4	.4546	202.2	--	--	--	RLBO
---	.3069	.02278	301	(78.4)	--	13.56	87.0	.4653	205.8	--	--	--	LLBO
---	.3190	.02196	301	(78.4)	--	14.53	93.2	.4825	211.8	--	--	--	LLBO

MUN NO. 77 --- Propane and Air Combustion

DATE: September 4, 1947

SCREEN: None

FLAME STABILIZER: 0.094" diameter steel rod located 9" from chamber entrance.

- - -	.03401	.001540	300	(76.2)	- -	22.08	141.8	.5863	22.8	- -	- -	- -	LLBO (1)
- - -	.06919	.003109	300	(76.3)	- -	22.26	142.6	.5882	46.3	- -	- -	- -	LLBO
5-1-77	.06919	.003222	300	76.3	0.3	21.47	137.6	.5795	46.4	.52	1.04	1.44	
6-1-77	.06919	.003821	300	76.3	0.3	16.11	116.2	.5375	46.5	.60	1.08	1.52	
7-1-77	.06919	.004600	300	76.3	0.3	15.04	96.5	.4912	47.0	.72	1.32	1.84	
8-1-77	.06919	.005906	300	76.3	0.3	11.72	75.2	.4292	47.6	.64	1.40	2.00	
9-1-77	.06919	.007028	300	76.3	0.3	8.64	53.2	.3872	48.0	.52	1.00	1.56	
- - -	.1362	.008866	300	(76.6)	- -	20.16	129.4	.5641	92.6	- -	- -	- -	LLBO
- - -	.06919	.008161	300	(76.3)	- -	6.48	54.4	.3524	46.6	- -	- -	- -	RLBO
10-1-77	.1375	.007654	300	76.6	0.5	17.94	115.2	.5532	92.4	.56	1.08	1.44	
11-1-77	.1375	.010000	300	76.6	0.5	13.75	88.3	.4688	93.4	.52	.80	1.28	
12-1-77	.1375	.01291	300	76.6	0.5	10.65	68.4	.4050	94.6	.52	.80	1.12	
1-2-77	.1375	.01502	300	76.6	0.4	9.15	58.6	.3701	95.5	.52	.92	1.32	
- - -	.1373	.01553	300	(76.5)	- -	8.64	56.7	.3620	95.6	- -	- -	- -	RLBO
Some of the RLBO are fairly rough burning at blow-out													
- - -	.2475	.01425	301	(77.5)	- -	17.37	111.6	.5271	166.1	- -	- -	- -	LLBO
- - -	.2475	.02436	301	(77.6)	- -	10.16	65.2	.3947	169.4	- -	- -	- -	RLBO
- - -	.3035	.01657	301	(78.3)	- -	16.34	104.9	.5120	200.8	- -	- -	- -	LLBO
2-2-77	.3040	.01898	301	78.3	1.7	15.02	102.6	.5069	201.3	.60	.96	1.28	
3-2-77	.3040	.02111	301	78.8	1.8	14.40	92.4	.4803	200.9	.64	1.08	1.40	
4-2-77	.3040	.02275	301	78.8	2.0	13.36	86.6	.4517	201.6	.64	1.04	1.40	
5-2-77	.3040	.02438	301	78.8	2.0	12.47	80.0	.4445	202.3	.64	1.12	1.48	
- - -	.3040	.02826	301	(78.8)	- -	10.76	69.0	.4084	204.0	- -	- -	- -	
- - -	.3568	.02743	301	(78.5)	- -	12.57	83.3	.4543	234.2	- -	- -	- -	LLBO
- - -	.3581	.02917	301	(78.5)	- -	12.28	76.8	.4407	235.4	- -	- -	- -	LLBO
- - -	.3589	.02996	301	(78.5)	- -	12.10	77.7	.4371	237.1	- -	- -	- -	LLBO

Picture No. W_a W_r T P_o ΔP_o $W_a = \frac{1}{f}$ Q_g V_o V_2 V_4 V_6 Remarks
lb/sec lb/sec $^{\circ}K$ cm.Hg. cm.Hg. lb/lb Theor. lb/lb ft/sec in. in. in.

RUN NO. 78 --- Propane and Air Combustion

DATE: September 8, 1947

SCREEN: None

FLAME STABILIZER: 0.038" diameter steel rod located 9" from chamber entrance.

Too much flutter to get anything at 26 ft./sec.

---	.06892	.005878	299	(76.4)	--	18.74	120.3	.5480	46.2	--	--	--	LLBO
6-1-78	.06892	.005890	299	76.4	0.3	18.63	120.9	.5472	46.2	.56	1.08	1.62	
7-1-78	.06892	.004417	299	76.5	0.4	18.60	100.1	.5604	46.5	.58	1.32	1.80	
8-1-78	.06892	.004932	299	76.5	0.4	18.97	89.7	.4726	46.6	.72	1.40	2.28	
9-1-78	.06892	.005953	299	76.5	0.4	11.58	74.3	.4263	47.1	.68	1.56	2.24	
10-1-78	.06892	.007019	299	76.5	0.4	9.82	63.0	.3865	47.5	.48	1.08	1.54	
---	.06065	.006906	299	(76.6)	--	8.78	56.4	.3605	42.1	--	--	--	RLBO
---	.1377	.008153	299	(76.8)	--	15.69	108.4	.5202	92.2	--	--	--	LLBO
11-1-78	.1380	.008428	299	76.8	0.6	16.37	108.1	.5124	92.5	.48	.92	1.28	
12-1-78	.1380	.009569	299	76.8	0.6	14.27	91.6	.4761	90.0	.62	.92	1.32	
1-2-78	.1380	.01121	299	76.8	0.6	12.31	79.0	.4414	93.7	.52	.96	1.40	
2-2-78	.1380	.01348	299	76.7	0.5	10.24	65.7	.3965	94.8	.40	.80	1.16	
3-2-78	.1380	.01463	299	76.7	0.5	9.31	59.7	.3759	96.3	.32	.84	.96	
---	.1371	.01569	296	(76.7)	--	8.74	56.1	.3593	95.1	--	--	--	RLBO
---	.2459	.02018	299	(78.0)	--	12.33	79.2	.4419	163.3	--	--	--	LLBO
---	.2452	.02167	296	(78.0)	--	11.22	72.0	.4187	163.5	--	--	--	RLBO
---	.2428	.02035	299	(76.0)	--	11.55	75.6	.4337	162.5	--	--	--	LLBO

RUN NO. 79 --- Propane and Air Combustion

DATE: September 8, 1947

SCREEN: 3 mesh; 0.063" wire diameter

FLAME STABILIZER: 0.038" diameter steel rod located 9" from chamber entrance.

---	.05407	.001804	298	(76.3)	--	18.89	121.2	.5480	22.8	--	--	--	LLBO
4-1-79	.05407	.001855	298	76.3	0.2	18.37	117.9	.5410	22.8	.88	1.76	2.44	
5-1-79	.05407	.002181	298	76.4	0.2	18.84	101.7	.5041	22.9	1.44	2.44	Wall	
6-1-79	.05407	.002757	298	76.4	0.3	12.45	79.9	.4441	23.2	1.78	2.56	Wall	
7-1-79	.05407	.003003	298	76.4	0.2	11.35	72.8	.4214	23.3	1.56	2.56	Wall	
8-1-79	.05407	.003798	298	76.4	0.2	8.97	57.5	.3554	23.5	.62	1.04	1.76	
---	.05407	.004328	298	76.4	--	7.87	50.5	.3357	23.8	--	--	--	RLBO
---	.06959	.003781	298	(76.5)	--	18.41	118.1	.5415	46.5	--	--	--	LLBO
9-1-79	.06959	.003815	298	76.5	0.4	18.24	117.1	.5393	46.5	.68	1.28	1.72	
10-1-79	.06959	.004435	298	76.6	0.4	15.69	100.7	.5017	46.7	.80	1.52	2.04	
11-1-79	.06959	.005335	298	76.6	0.4	10.06	85.8	.4558	47.1	.84	1.72	2.28	
12-1-79	.06959	.006277	298	76.5	0.4	11.09	71.2	.4167	47.5	.78	1.56	2.12	
1-2-79	.06959	.006895	298	76.5	0.4	10.09	64.8	.3921	47.7	.66	1.12	1.68	
---	.06587	.008829	298	(76.6)	--	8.33	53.8	.3483	39.6	--	--	--	RLBO
---	.1385	.008857	298	(77.0)	--	15.64	100.4	.5009	92.4	--	--	--	LLBO
2-2-79	.1382	.009185	298	77.0	0.7	15.06	96.4	.4913	92.4	.54	1.20	1.54	
3-2-79	.1382	.01056	298	77.1	0.8	13.06	83.8	.4561	92.8	.64	1.24	1.58	
4-2-79	.1382	.01266	298	77.1	0.7	10.92	70.1	.4120	93.7	.50	1.16	1.50	
---	.1377	.01417	298	(77.1)	--	9.72	62.4	.3841	94.1	--	--	--	RLBO
---	.1632	.01536	298	(76.0)	--	10.63	68.2	.4065	109.6	--	--	--	LLBO
---	.1982	.01506	298	(78.0)	--	13.16	84.5	.4579	131.4	--	--	--	LLBO
---	.1918	.01587	298	(76.0)	--	15.83	88.8	.4702	127.0	--	--	--	LLBO

Observed no residual flames during any propane runs.

RUN NO. 80 --- Laminar Flame Speed Measurements - Propane and Air Combustion

DATE: September 8, 1947

Picture No.	W_a lb/lb	W_r lb/lb	T $^{\circ}K$	P_o cm.Hg.	ΔP_o cm.Hg.	$W_a = \frac{1}{f}$ lb/lb	Q_g Theor. lb/lb	V_o ft/sec	V_2 in.	V_4 in.	V_6 in.	Remarks
5-1-80	20.63	132.4	.5698	299	.0006312	133.30	.009378	.5534				
6-1-80	18.06	115.6	.5559	299	.001208	303.13	.001512	.7985				
7-1-80	15.43	86.2	.4626	299	.003442	512.86	.003037	.8042				
8-1-80	10.63	59.5	.4100	299	.001221	304.51	.002991	.4724				
9-1-80	9.16	50.0	.3701	299	.0006700	145.04	.002423	.2342				
10-1-80	7.10	45.5	.3181	299	.0002056	51.41	.001548	.1248				

Picture No. W_a W_r T P_o ΔP_o $W_a = \frac{1}{f}$ Q_g V_o V_2 V_4 V_6 Remarks
lb/sec lb/sec $^{\circ}K$ cm.Hg. cm.Hg. lb/lb Theor. lb/lb ft/sec in. in. in.

RUN NO. 81 --- Stroboscopic Observations - City Gas and Air Combustion

DATE: September 18, 1947

SCREEN: 3 mesh; 0.063" wire diameter

FLAME STABILIZER: 0.038" rod located 9" from combustion chamber entrance

---	.05395	.002733	297	77.9	0.2	12.42	.5561	23.8	--	--	--	(1)
Increased fuel rate at 26 ft/sec in steps and searched for any periodic motion with stroboscope. None was observed.												
---	.06910	.006334	294.5	78.0	0.2	12.96	.5655	47.7	--	--	--	(2)
Could not get really periodic motion at very lean mixture or at stoichiometric.												
---	.1374	.01056	295	78.0	0.4	12.99	.5651	95.0	--	--	--	(3)

Nothing worth anything at either 100 ft/sec or 200 ft/sec.

As far as can be determined, there is no motion in the flame that is sufficiently periodic to be stopped by stroboscope.

(1) No period could be observed.

(2) Over a range at about 810 RPM things seemed to be jumping around. This seems to be nearest thing to stopping motion, but not good or even clear.

(3) Same effect as above noted under these conditions in a range at about 1140 RPM, but nothing very good.

RUN NO. 82 --- City Gas and Air Combustion

DATE: September 19, 1947

SCREEN: 3 mesh; 0.063" wire diameter

FLAME STABILIZER: 0.038" rod located 2" from combustion chamber entrance

Picture No.	W_a lb/sec	W_r lb/sec	T $^{\circ}K$	P_o cm.Hg.	ΔP_o cm.Hg.	$W_a = \frac{1}{f}$ lb/lb	Q_g Theor. lb/lb	V_o ft/sec	V_2 in.	V_4 in.	V_6 in.	V_8 in.	V_{10} in.	V_{12} in.	Remarks
6-1-82	.03418	.003056	296	75.5	0.3	11.08	.5298	24.5	.60	1.12	1.56	1.60	2.12	2.26	(1)
---	.05985	.006020	295	(75.9)	--	11.50	.5406	45.7	--	--	--	--	--	--	LLBO
9-1-82	.06985	.006438	297	75.9	0.5	10.86	.5250	50.2	.56	1.28	1.72	2.00	2.28	2.56	
10-1-82	.06985	.007159	297	77.0	0.7	9.78	.5998	50.8	.64	1.50	2.00	2.32	2.56	2.92	
11-1-82	.06985	.007762	297	77.1	0.9	9.08	.5812	51.2	.92	1.56	2.12	2.48	2.76	Wall	- Flutter above here
---	.1367	.01358	297	(78.1)	--	9.99	.6055	97.0	--	--	--	--	--	--	LLBO
12-1-82	.1349	.01340	297	78.1	1.8	9.92	.5038	95.5	.72	1.36	1.76	2.08	2.28	2.48	
1-2-82	.1349	.01467	297	78.4	1.9	9.07	.5822	97.3	.80	1.44	1.92	2.24	2.48	2.56	
2-2-82	.1349	.01990	297	79.5	3.0	6.78	.5101	100.1	1.00	1.76	2.16	2.52	2.80	Wall	
3-2-82	.1349	.02424	297	79.9	3.3	5.57	.4509	103.3	.95	1.80	2.24	2.56	2.88	Wall	
---	.1343	.02740	297	(79.5)	--	4.90	.4295	106.2	--	--	--	--	--	--	RLBO
---	.2503	.03405	297	(80.5)	--	7.35	.5308	131.2	--	--	--	--	--	--	LLBO
---	.2503	.04390	297	(81.5)	--	5.70	.4659	137.1	--	--	--	--	--	--	RLBO
---	.2525	.04441	297	(82.0)	--	5.92	.4782	133.9	--	--	--	--	--	--	LLBO
---	.2534	.04298	297	(82.0)	--	5.14	.4652	130.0	--	--	--	--	--	--	LLBO

(1) Flutter begins above here

RUN NO. 83 --- City Gas and Air Combustion

DATE: September 19, 1947

SCREEN: 3 mesh; 0.027" wire diameter

FLAME STABILIZER: 0.038" rod located 2" from combustion chamber entrance

4-1-83	.03346	.002615	295	76.5	0.3	12.60	.5626	24.5	.40	.54	.96	1.18	1.44	1.54	
5-1-83	.03346	.003214	295	76.5	0.3	10.44	.5135	24.2	.44	.60	1.12	1.56	1.84	2.16	(1)
- - -	.06957	.006176	295	(75.5)	- -	11.27	.5337	45.5	- -	- -	- -	- -	- -	- -	LLBO
6-1-83	.06957	.006517	295	75.6	0.5	10.58	.5212	49.5	.40	.50	1.06	1.44	1.64	2.04	
7-1-83	.06957	.006938	295	77.0	0.7	8.61	.4594	51.1	.56	1.20	1.72	2.08	2.36	2.54	(1)
- - -	.1372	.01377	294	(77.7)	- -	9.96	.5048	97.7	- -	- -	- -	- -	- -	- -	LLBO
8-1-83	.1341	.01412	294	77.7	1.1	9.50	.5933	95.0	.52	.92	1.28	1.52	1.80	2.00	
9-1-83	.1341	.01600	294	77.9	1.4	8.37	.5524	97.4	.48	.96	1.40	1.72	2.04	2.24	
10-1-83	.1341	.01850	294	78.1	1.9	7.10	.5215	99.1	.56	1.08	1.52	1.82	2.20	2.36	
11-1-83	.1341	.02418	294	78.9	2.2	5.55	.4508	102.0	.50	1.20	1.58	2.00	2.40	2.52	
12-1-83	.1341	.02911	294	78.3	1.8	4.51	.4144	108.0	.56	1.04	1.40	1.56	2.00	2.15	
- - -	.1356	.02948	294	(78.3)	- -	4.51	.4145	109.4	- -	- -	- -	- -	- -	- -	RLBO
- - -	.2528	.03344	294	(80.5)	- -	7.84	.5375	150.4	- -	- -	- -	- -	- -	- -	LLBO
- - -	.2511	.04456	294	(81.5)	- -	5.54	.4540	165.2	- -	- -	- -	- -	- -	- -	RLBO
- - -	.2953	.04447	294	(82.5)	- -	5.54	.5050	207.4	- -	- -	- -	- -	- -	- -	LLBO
- - -	.2995	.04886	294	(83.5)	- -	6.17	.4555	213.1	- -	- -	- -	- -	- -	- -	LLBO

Picture No. 34 --- City Gas and Air Combustion
 DATE: September 19, 1947
 SCREEN: 55 mesh; 0.007" wire diameter
 FLAME STABILIZER: 0.036" rod located 2" from chamber entrance

1-1-44	.03496	.002852	295	76.3	0.3	12.26	.6531	24.7	.24	.49	.79	1.26	1.24	1.36							
2-1-44	.03496	.003224	295	76.6	0.3	10.84	.6249	24.9	.36	.60	.82	1.16	1.56	1.88							
3-1-44	.03496	.003734	295	76.6	0.3	9.36	.5899	25.4	.64	1.24	1.68	2.56	Wall	Wall							
-	.07021	.006196	295	(76.7)	-	11.46	.6376	40.7	-	-	-	-	-	-							
4-1-44	.07021	.006196	295	76.7	0.4	11.33	.6361	40.7	.36	.64	.96	1.20	1.48	1.68							
5-1-44	.07021	.007008	295	76.8	0.6	10.02	.6061	50.4	.44	.80	1.28	1.64	2.04	2.20							
6-1-44	.07021	.008800	295	77.2	0.9	7.98	.5607	51.6	.58	1.40	2.08	2.44	2.88	Wall							
7-1-44	.07021	.01373	295	77.6	1.2	5.12	.4399	56.6	.72	1.44	2.16	2.64	Wall	Wall							
8-1-44	.07021	.01669	295	77.2	0.8	4.21	.3925	58.4	.48	.88	1.28	1.68	2.28	2.56							
-	.07001	.01850	295	(77.0)	-	3.85	.3701	59.8	-	-	-	-	-	-							
-	.1396	.01315	295	(77.4)	-	10.57	.6189	98.2	-	-	-	-	-	-							
9-1-44	.1396	.01346	295	77.4	1.0	10.36	.6140	98.7	.40	.76	1.04	1.32	1.60	1.80							
10-1-44	.1396	.01580	295	77.7	1.2	8.82	.5782	100.4	.40	.80	1.12	1.48	1.80	2.00							
11-1-44	.1396	.01947	295	78.3	1.7	7.16	.5236	102.7	.56	1.08	1.52	1.96	2.30	2.48							
12-1-44	.1396	.02478	295	78.6	2.0	5.74	.4686	106.1	.48	.96	1.36	1.80	2.12	2.32							
13-1-44	.1396	.02920	295	78.3	1.7	4.77	.4229	111.0	.52	.92	1.28	1.64	2.00	2.16							
-	.1396	.03682	295	(78.0)	-	4.56	.4114	112.6	-	-	-	-	-	-							
-	.2652	.08153	295	(80.0)	-	8.06	.3632	178.9	-	-	-	-	-	-							
-	.2652	.04684	295	(81.0)	-	5.24	.4469	191.1	-	-	-	-	-	-							
2-2-44	.3096	.04794	295	83.6	6.1	6.46	.4982	217.1	.56	1.00	1.48	1.80	2.12	2.36							
-	.3608	.05047	295	(86.5)	-	7.15	.6234	243.7	-	-	-	-	-	-							
-	.3216	.06318	295	(84.0)	-	6.06	.4616	227.5	-	-	-	-	-	-							

(1) Flutter above here until next picture.

Picture No. 35 --- City Gas and Air Combustion
 DATE: September 19, 1947
 SCREEN: None
 FLAME STABILIZER: 0.036" rod located 2" from chamber entrance

3-1-45	.03619	.002856	295	77.0	0.3	12.32	.6883	24.6	.28	.56	.80	1.00	1.16	1.36							
4-1-45	.03619	.003446	295	77.0	0.3	10.22	.6108	25.1	.44	.80	1.20	1.60	1.88	2.16							
5-1-45	.03619	.004638	295	77.0	0.3	9.17	.5848	25.5	-	-	-	-	-	-							Slight flutter
6-1-45	.07001	.006796	295	(77.2)	-	12.08	.6498	48.9	-	-	-	-	-	-							LLSO
7-1-45	.07001	.008146	295	77.2	0.3	11.39	.6363	49.2	.36	.60	.86	1.16	1.56	1.8							
7-1-45	.07001	.007951	295	77.3	0.5	8.81	.5749	50.7	.52	1.12	1.52	1.96	2.28	2.52							(1)
8-1-45	.1396	.01243	292	(77.7)	-	11.21	.6328	97.2	-	-	-	-	-	-							LLSO
9-1-45	.1391	.01265	292	77.7	0.6	11.00	.6281	97.2	.32	.64	1.00	1.24	1.62	1.84							
9-1-45	.1391	.01371	292	77.6	0.9	10.15	.5691	98.0	.48	.80	.92	1.20	1.52	1.80							
10-1-45	.1391	.01797	292	78.4	1.5	7.74	.5452	100.6	.40	.88	1.28	1.68	2.00	2.28							
11-1-45	.1391	.02431	292	79.3	2.2	6.72	.4678	106.0	.62	1.08	1.56	1.96	2.32	2.54							
12-1-45	.1391	.03282	292	78.4	1.2	4.28	.3958	113.2	.36	.76	1.16	1.40	1.72	1.92							
- - -	.1363	.03544	293	(78.4)	-	4.14	.3886	113.8	-	-	-	-	-	-							LLSO
- - -	.2632	.02343	293	77.4	0.6	10.81	.6241	178.6	-	-	-	-	-	-							LLSO, RFO
- - -	.2616	.02684	293	(79.0)	-	4.44	.4056	203.8	-	-	-	-	-	-							LLSO

Severe resonance occurred through stoichiometric and was still present at LLSO. High note about 300-400 cycles/sec.

- - -	.3086	.02957	293	(79.6)	-	10.43	.6158	212.5	-	-	-	-	-	-	-	-	-	-	-	-	LLSO
1-2-85	.3086	.03063	293	79.6	2.5	10.07	.6074	223.3	.36	.68	1.08	1.40	1.72	2.00							
2-2-85	.3086	.03506	293	81.3	3.0	8.80	.5748	212.5	.48	1.00	1.44	1.76	2.08	2.24							(2)
3-2-85	.3086	.04661	293	83.0	5.3	6.62	.5041	217.4	.62	1.16	1.56	1.88	2.20	2.40							(2)
4-2-85	.3086	.06424	293	83.2	6.4	5.89	.4888	222.9	.64	1.20	1.60	1.96	2.20	2.40							(2)
- - -	.5060	.06572	294	(81.0)	-	4.59	.4186	234.1	-	-	-	-	-	-	-	-	-	-	-	-	RLSO
5-2-85	.4580	.06697	294	86.1	7.8	8.04	.5626	301.7	.52	.92	1.28	1.56	1.88	2.04							
- - -	.4652	.06793	294	(86.1)	-	8.03	.5523	306.5	-	-	-	-	-	-	-	-	-	-	-	-	LLSO

(1) Flutter and flashed back above here
 (2) Some resonance

Picture No. 36 --- City Gas and Air Combustion
 DATE: September 28, 1947
 SCREEN: 3 mesh; 0.063" wire diameter
 FLAME STABILIZER: 0.036" diameter steel rod located 6" from chamber entrance

1-1-46	.03489	.002767	289	77.1	0.2	12.50	.6976	23.6	.40	.72	1.08	1.40									
2-1-46	.03489	.003134	289	77.1	0.2	11.94	.6889	24.1	.52	1.16	1.58	2.08									Flutter above here
- - -	.07067	.008461	289	(75.3)	-	12.94	.6653	49.0	-	-	-	-	-	-							LLSO
3-1-46	.07067	.005580	289	76.3	0.3	12.67	.6606	49.1	.82	.92	1.40	1.58									
4-1-46	.07067	.006451	289	76.3	0.4	10.96	.6273	49.6	.52	1.16	1.64	2.00									
10-1-46	.07067	.007951	289	76.4	0.4	8.91	.5778	51.0	.76	1.54	2.24	2.60									
11-1-46	.07067	.009318	289	76.7	0.7	7.58	.5381	52.0	1.04	2.08	2.60	Wall								(1)	
- - -	.1395	.01267	289.5	(77.9)	-	11.01	.6284	96.4	-	-	-	-	-	-							LLSO
12-1-46	.1395	.01296	289.5	77.9	0.8	10.75	.6228	96.7	.90	1.04	1.48	1.75									
1-2-46	.1395	.01604	289.5	78.4	1.1	8.70	.5719	98.6	.56	1.20	1.68	2.04									
2-2-46	.1395	.01995	289.5	78.9	1.5	6.99	.5179	101.2	.72	1.62	2.16	2.36									
3-2-46	.1395	.02543	289.5	79.2	1.7	5.49	.4573	105.4	.72	1.48	2.04	2.36									
- - -	.1392	.03053	290	(78.5)	-	4.56	.4119	110.6	-	-	-	-	-	-							LLSO
- - -	.2641	.03079	290	(80.5)	-	6.25	.5560	176.6	-	-	-	-	-	-							LLSO
- - -	.2509	.04978	290	(80.5)	-	5.04	.4364	190.1	-	-	-	-	-	-							LLSO
4- - -	.3110	.03928	291	(82.2)	-	7.92	.5468	213.6	-	-	-	-	-	-							LLSO
4-2-46	.3096	.04029	291	82.2	4.3	7.68	.5414	223.6	.64	1.16	1.64	1.92									
5-2-46	.3096	.04611	291	82.7	4.7	5.86	.5132	216.1	.66	1.24	1.68	1.95									
6-2-46	.3076	.05327	291	83.2	5.1	5.61	.4717	221.3	.72	1.28	1.72	2.04									
- - -	.3976	.05678	292	(83.0)	-	5.52	.4586	223.4	-	-	-	-	-	-							LLSO
- - -	.3655	.05262	292	(85.0)	-	6.95	.5162	246.6	-	-	-	-	-	-							LLSO
- - -	.3524	.06773	292	(85.0)	-	6.28	.4909	250.8	-	-	-	-	-	-							LLSO

(1) Flutter

Picture No.	W ₁ lbs/sec	W ₂ lbs/sec	P %	ΔP ₁ cm. Hg.	ΔP ₂ cm. Hg.	1/g lbs/lb	O ₂ lbs/lb	V ₀ ft/sec	V ₁ in.	V ₂ in.	V ₃ in.	V ₄ in.	V ₅ in.	V ₆ in.	Remarks
RUN NO. 55 --- City Gas and Air Combustion															
DATE: September 27, 1947															
SCREEN: 55 mesh; 0.007" wire diameter															
FLAME STABILIZER: 0.036" diameter steel rod located 6" from chamber entrance															
9-1-86	.00335	.00502	289	77.5	0.2	13.82	.6750	25.0	.84	.64	.88	.88			
10-1-86	.00353	.00567	289	77.6	0.2	11.72	.6429	25.3	.49	.72	1.44	1.96			
11-1-86	.00382	.003143	289	77.6	0.2	10.76	.6281	25.5	.73	1.79	2.44	Wall			
- - -	.07057	.005109	289	(77.7)	-	13.88	.6900	47.8	-	-	-	-			Slight flutter above here
12-1-86	.07026	.005259	289	77.7	0.2	13.36	.6784	49.8	.82	.64	.86	1.12			LLSO
1-2-86	.07026	.006144	289	77.7	0.3	11.44	.6372	46.4	.40	1.72	1.20	1.68			
2-2-86	.07026	.006354	289	78.1	0.5	8.41	.5637	50.0	.72	1.84	2.44	2.76			
3-2-86	.07026	.01096	286	78.4	1.0	5.41	.4962	52.0	1.04	2.20	2.80	Wall			
4-2-86	.07026	.01352	286	78.3	0.6	5.20	.6459	54.2	.96	2.16	2.80	Wall			
5-2-86	.07026	.01496	289	78.0	0.6	4.69	.6188	56.6	.90	1.56	2.06	2.60			
6-2-86	.07025	.01577	289	77.9	0.4	4.19	.5915	57.2	.44	.86	1.20	1.52			
- - -	.06935	.01738	290	(77.7)	-	3.49	.5800	57.5	-	-	-	-			RLSO
- - -	.1393	.01109	290	(78.0)	-	12.56	.6592	96.0	-	-	-	-			LLSO
7-2-86	.1386	.01136	290	78.0	0.5	12.18	.6517	94.8	.24	.66	.88	1.24			
8-2-86	.1386	.01268	290	78.1	0.6	10.76	.6231	95.9	.40	.72	1.08	1.32			
9-2-86	.1386	.01779	290	78.9	1.0	7.79	.5448	97.5	.44	1.00	1.56	2.00			
10-2-86	.1386	.02564	290	78.9	1.2	5.89	.4746	103.6	.56	1.24	1.80	2.20			
11-2-86	.1386	.02632	290	78.7	1.1	4.66	.4292	106.1	.48	.92	1.28	1.60			
- - -	.1386	.03701	290	(78.5)	-	4.51	.4094	110.4	-	-	-	-			RLSO
- - -	.2514	.02570	290	(80.0)	-	9.42	.5912	172.5	-	-	-	-			LLSO
- - -	.2514	.04691	290	(80.0)	-	5.04	.4362	191.7	-	-	-	-			RLSO
- - -	.3061	.03593	290	(81.0)	-	6.80	.6692	212.2	-	-	-	-			LLSO
12-2-86	.3061	.03694	290	81.2	3.2	6.97	.6624	212.5	.52	.96	1.28	1.60			
1-3-86	.3061	.04614	290	81.5	3.7	6.06	.6128	217.2	.56	1.00	1.32	1.68			
2-3-86	.3061	.06517	290	82.3	4.0	5.81	.4717	222.6	.56	1.04	1.40	1.72			
- - -	.3061	.06822	290	(82.0)	-	5.60	.4628	226.0	-	-	-	-			RLSO
- - -	.3937	.06933	290	(84.0)	-	6.64	.5046	271.2	-	-	-	-			LLSO
- - -	.3961	.06096	290	(84.0)	-	6.48	.4989	273.3	-	-	-	-			LLSO

WPM NO. 89 --- City Gas and Air Combustion

DATE: September 27, 1947

DATE: Sep 2008
School: none

FLAME STABILIZER: 0.036" diameter steel rod located 6" from chamber entrance

[illegible]

(1) Sharp resonance just before RL30 (about 400 cycles/sec)

Picture No.	$\frac{W}{lb/sec}$	$\frac{W}{lb/sec}$	$\frac{T}{^\circ F}$	P cm. Hg.	$\frac{\Delta P}{cm. Hg.}$	$\frac{V_s - 1}{lb/lb.}$	$\frac{Q}{lb/lb.}$	$\frac{V}{ft/sec}$	$\frac{V_s}{inches}$	$\frac{V}{inches}$	$\frac{V}{inches}$	Remarks
MUR EO. 90 - - - Shadow Photograph --- City Gas and Air Combustion												
DATE: October 3, 1947												
SCREW: 5 mesh; 0.025" wire diameter												
PLATE STILL LIFE: 0.038" diameter steel rod located 7" from combustion chamber entrance.												
3-1-60	.03477	.003110	291	75.2	0.2	11.18	.6320	24.7	-	-	-	
4-1-60	.03477	.00477	291	75.2	0.25	9.82	.6013	25.0	-	-	-	
5-1-60	.07095	.006596	291	75.2	0.3	12.67	.5900	50.0	-	-	-	
5-1-60	.07095	.006828	291	76.3	0.3	10.39	.6149	80.5	-	-	-	
6-1-60	.07095	.009096	291	76.7	0.4	7.80	.5450	52.3	-	-	-	
9-1-60	.07095	.01115	291	76.9	0.5	6.36	.4943	54.0	-	-	-	
10-1-60	.1354	.01315	291	76.9	0.5	10.50	.5195	95.5	-	-	-	
11-1-60	.1354	.01680	291	77.1	0.7	8.30	.5604	101.4	-	-	-	
12-1-60	.1354	.02120	291	77.4	0.8	6.58	.5025	104.7	-	-	-	

WIK NO. 90 - - - Shadow Photograph --- City Gas and Air Combustion

DATE: October 3, 1947

SCREEN: 8 mesh; 0.025" wire diameter

FLAME STABILIZER: 0.038" diameter steel rod located 7" from combustion chamber entrance.

3-1-60	.03477	.006110	291	75.2	0.2	11.18	.5320	24.7	--	--	--	--
4-1-60	.03477	.02477	291	75.2	0.25	9.82	.5013	25.0	--	--	--	--
5-1-60	.07065	.006596	291	75.2	0.3	12.57	.5000	50.0	--	--	--	--
6-1-60	.07065	.006826	291	75.3	0.3	10.39	.5149	50.5	--	--	--	--
8-1-60	.07065	.009096	291	75.7	0.4	7.80	.5450	52.3	--	--	--	--
9-1-60	.07065	.01115	291	75.9	0.5	6.58	.4943	54.0	--	--	--	--
10-1-60	.1394	.01315	291	76.9	0.5	6.195	.90.5	--	--	--	--	--
11-1-60	.1394	.01680	291	77.1	0.7	5.30	.5604	101.4	--	--	--	--
12-1-60	.1394	.02120	291	77.4	0.8	5.68	.5025	104.7	--	--	--	--

Picture No.	V_1 lbs/sec	V_2 lbs/sec	T °K	P_0 cm. Hg.	ΔP_0 cm. Hg.	$\frac{W}{V_2} = \frac{1}{V_2}$ lbs./lb.	V_0 lbs./lb.	V_1 ft/sec	V_2 inches	V_3 inches	V_4 inches	V_5 inches	Remarks
MUN HQ. 91 - - - Shadow Photographs - - - City Gas and Air Combustion													
DATE October 6, 1947													
SCREEN: None													
FLAME STABILIZER: 0.058" diameter steel rod located 7" from combustion chamber entrance.													
1-1-01													
2-1-01	.03432	.002730	294	75.1	0.1	12.87	.6586	24.3	- -	- -	- -	- -	Very lean
3-1-01	.03432	.003092	294	75.1	0.1	11.10	.6503	24.6	- -	- -	- -	- -	
4-1-01	.03432	.003821	294	75.4	0.2	9.76	.5996	24.9	- -	- -	- -	- -	
5-1-01	.009959	.003896	295	75.4	0.2	11.64	.6462	49.7	- -	- -	- -	- -	
6-1-01	.009960	.007181	295	75.4	0.3	9.70	.5986	50.7	- -	- -	- -	- -	(1)
7-1-01	.1392	.01269	295	75.7	0.4	10.97	.6276	99.6	- -	- -	- -	- -	
8-1-01	.1392	.01463	295	75.6	0.5	9.32	.5938	101.2	- -	- -	- -	- -	
9-1-01	.1392	.01620	295	77.0	0.6	7.58	.5402	104.0	- -	- -	- -	- -	
10-1-01	.1392	.02196	295	77.3	0.8	6.44	.4935	106.8	- -	- -	- -	- -	
11-1-01	.3087	.03596	296	76.7	1.6	6.33	.5672	221.4	- -	- -	- -	- -	
12-1-01	.3087	.04619	296	75.4	2.4	6.79	.5104	227.3	- -	- -	- -	- -	
1-2-01	.3087	.05037	296	79.7	2.6	6.09	.4853	230.8	- -	- -	- -	- -	
2-2-01	.4241	.05378	297	81.0	3.9	6.65	.5053	310.1	- -	- -	- -	- -	
SCREEN: 3 mesh; 0.063" wire diameter													
4-2-01	.03513	.002960	297	76.4	0.2	11.87	.6456	25.2	- -	- -	- -	- -	
7-2-01	.00987	.007451	297	75.6	0.4	9.35	.5896	51.2	- -	- -	- -	- -	
8-2-01	.00987	.01034	297	77.0	0.7	6.74	.5086	55.5	- -	- -	- -	- -	
9-2-01	.1386	.01419	296	77.2	0.8	9.74	.6004	100.5	- -	- -	- -	- -	
10-2-01	.1386	.01696	296	77.4	0.9	8.18	.5570	102.5	- -	- -	- -	- -	
11-2-01	.1386	.02143	296	77.6	1.2	6.48	.4987	105.8	- -	- -	- -	- -	

(1) Flutter above here.

NUM. NO. 92 - - - Shadow Photographs --- City Gas and Air Combustion

DATE: October 8, 1947

DATE: October
SCREEN: None

FLAME STABILIZER: 0.188" diameter rod located 7" from combustion chamber entrance.

[illegible]

(1) Flutter above here.

MMW NO. 93 - - - Shadow Photographs --- City Gas and Air Combustion

DATE: October 9, 1947

DATE: October
SCREEN: None

FLAME STABILIZER: 0.498" diameter steel rod located 7" from combustion chamber entrance.

3-1-95	.03424	.002739	294	75.5	0.3	12.50	.5576	24.1	-	-	-	-
4-1-95	.03424	.002739	294	75.5	0.3	12.50	.5576	24.1	-	-	-	-
5-1-95	.06954	.005866	294	76.6	0.5	11.67	.6458	45.1	-	-	-	-
6-1-95	.06954	.007222	294	76.9	0.5	9.63	.5966	50.2	-	-	-	-
7-1-95	.06954	.01026	294	77.1	0.5	6.78	.51C1	52.7	-	-	-	-
8-1-95	.1386	.01481	293.5	77.2	0.6	9.35	.5896	99.6	-	-	-	-
9-1-95	.1386	.01858	293.5	77.4	0.6	8.36	.6622	101.1	-	-	-	-
10-1-95	.1386	.01904	293.5	77.6	0.9	7.27	.5277	102.9	-	-	-	-
11-1-95	.1386	.02312	293.5	78.0	1.1	6.99	.4792	105.9	-	-	-	-
1-2-95	.3086	.03113	294	78.2	2.4	5.91	.6035	215.6	-	-	-	-
2-2-95	.3086	.03615	294	80.0	2.9	8.09	.5540	219.3	-	-	-	-
3-2-95	.3086	.04636	294	60.5	3.2	6.66	.6055	224.7	-	-	-	-
4-2-95	.4899	.05947	294	64.0	6.4	8.17	.5665	331.1	-	-	-	-
5-2-95	.4899	.05454	294	82.8	5.5	8.98	.5796	331.6	-	-	-	-

RUN NO. 94 - - - Shadow High Speed Movies --- City Gas and Air Combustion

DATE: October 10, 1947

DATE: October
SCREEN: None

FLAME STABILIZER: 0.496" diameter flame stabilizer located 7" from combustion chamber entrance.

Rolls 1,2,3	.06769	.006571	294	76.2	0.3	12.15	.6511	46.1	Picture at Blow-out
4,5	.1389	.01241	294	76.5	0.6	11.19	.6323	99.1	Picture at Blow-out

D. Details of Apparatus

Figure 136 is a detailed drawing of the combustion chamber, and Figure 137 is a detailed drawing of the nozzle and calming section of the apparatus.

Figures 138a and 138b are photographs of the Ingersoll-Rand Diesel powered compressor and the electrically driven Ingersoll-Rand carbon-ring, oil-free compressor, respectively. Both of these compressors were used for supplying air during the course of this investigation. They both deliver air at a maximum rate of approximately 0.5 pounds per second and a maximum pressure of about 100 pounds per square inch gage.

Design drawings of the two inspirators employed for introducing and mixing city gas with air are presented in Figure 139. These inspirators are built into 2" pipe tees. They were designed on the basis of equations outlined by Keenan and Newmann (25) to operate with an upstream pressure of 75 pounds per square inch absolute. At this upstream pressure and with an upstream temperature of 500°R the large inspirator, no. 1, was designed to pass 0.130 pounds per second of air and to pump about nine-tenths the equivalent volume of city gas (calculated on the basis that city gas is equivalent to air). The small inspirator, no. 2, was designed to pass 0.02654 pounds per second of air at an upstream

COMBUSTION CHAMBER

NOZZLE AND CALMING SECTION

Figure 138 a

Ingersoll-Rand Diesel Powered Compressor

Figure 138 b

Electrically Driven Ingersoll-Rand Carbon-free,
Oil-free Compressor

FIGURE 139

INSPIRATOR DESIGN

ALL DIMENSIONS IN INCHES ————— SCALE: FULL SIZE

RMR NOV. 3, 1947

pressure of 75 pounds per square inch absolute and an air temperature of 500°R , and at these conditions should pump 1.4 times that amount of city gas (calculated on the basis that city gas is equivalent to air). Neither of these inspirators is able to deliver a city gas-air mixture at pressures higher than a few pounds above atmospheric at their discharge ends, but both have been found to operate satisfactorily at almost any conditions. It was generally the practice, in fact, to use only the large inspirator at all chamber entrances velocities, it being found that this large inspirator functioned satisfactorily even at very low air rates.

Figure 140 is a photograph of the inspirator installed, the small inspirator being the one on the right hand side.

In Figure 141 is shown a wiring diagram of the spark apparatus employed for taking spark photographs.

Figure 140

Inspirators Installed

FIGURE 141

SPARK APPARATUS
SOURCE AND TRIGGERING CIRCUIT DIAGRAMS

E. Flowmeter Calibrations

The air rate to the combustion chamber was determined by means of a 3/4" standard Foxboro orifice plate mounted in standard 2" pipe with flange taps. The air orifice calibration curves shown in Figures 142a and 142b were calculated using the method and data presented in "Fluid Meters- Their Theory and Application", Part I, ASME (1947).

The city gas rate was determined by means of two venturimeters, one for low rates and one for high rates. Detailed drawings of these two venturis are shown in Figure 148. These two venturimeters were calibrated against a standard orifice meter with interchangeable plates of different diameter. This standard orifice meter is built into 2" inside diameter brass pipe and is fitted with pipe taps. It was borrowed from Professor Keyes of the chemistry department. In Figure 143 are presented calibration curves for the Keyes orifice meter for 3 orifice plates of varying diameter calculated using the method outlined in "Fluid Meters" for pipe taps. The calibration curves of Figure 143 were employed with the Keyes orifice meter to calibrate the two city gas venturis. The final calibration curves thus obtained for the city gas venturis are shown in Figure 144. A photograph of the Keyes orifice meter in place in series with the gas venturis is shown in Figure 145.

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FIGURE 143

Calibration Curves for ^{KEYS} Orificemeter with
City Gas

Orifice Plate No. 2 — $D = 0.8761"$ $\beta = .43805$

Orifice Plate No. 5 — $0.501"$ $\beta = .2505$

Orifice Plate No. 6 — 0.3753 $\beta = .18765$

City Gas Constants

$$\frac{P_{\text{gas}}}{P_{\text{air}}} = S.G._{\text{gas}} = .730$$

$$\mu = .00001075 \frac{\text{lb.}}{\text{ft.} \cdot \text{sec}}$$

$$\gamma = 1.34$$

$$P_0 = 1 \text{ atm.}$$

$$T_0 = 500^\circ \text{R}$$

$$W_{\text{act.}} = W_{\text{chart}} \left[624.9 \left(\frac{S.G._{\text{act.}} \times P_{\text{act.}}}{T_{\text{act.}}} \right) \right]^{\frac{1}{2}}$$

Nov. 18, 1946 A.C.S.

hw — inches of water

FIGURE 144

Figure 145

Keys Orifice Meter Installed

When propane was used as a fuel its flow rate was metered directly with the standard orifice meter of Professor Keyes installed as shown in Figure 145. It was necessary to change orifice plates during a run with propane to accommodate both high and low flow rates. The two calibration curves for these two plates calculated as outlined in "Fluid Meters" are shown in Figures 146a and 146b.

FIGURE 146a

FIGURE 146b

The correction curves for the two Bourdon gages employed for measurement of upstream pressure at the air orifice and the inspirators are shown in Figure 147. These gages were calibrated using a dead weight tester in the laboratory of Professor Keyes.

Calibration Curves for Pressure Gages

Gage No. 296 (Air Orifice)

Correction to be added $[\text{lbs/in}^2]$

Nov. 18, 1946 - A.C.S.

Pressure $[\text{lbs/in}^2]$

FIGURE 148

GAS VENTURI METERS (SMALL & LARGE)

SCALE 1" = 2"

NOTE: MILL FLATS
FOR WRENCH

SCALE—FULL SIZE

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BIOGRAPHICAL NOTE

The author was born January 29, 1920 in Beaumont, Texas and received his preparatory education in the public schools of Beaumont. He entered the University of Texas in September 1937 and received the degree of Bachelor of Science in Chemical Engineering in June 1941 and Bachelor of Arts with a major in Physics in September 1941. He entered the Massachusetts Institute of Technology in October 1941 and received a Master of Science degree in Chemical Engineering Practice in February 1943. The author then went on active duty with the United States Navy in February 1943, and shortly thereafter was ordered to attend the University of Chicago graduate school as a student in Meteorology. Thereafter, he served eighteen months at various bases in the Pacific theater as a Navy Aerologist with the staff of Fleet Air Wing 10. Shortly before the end of World War II he returned for duty in the Planning Division of the newly organized Office of Naval Research in the Navy Department in Washington, where he later acted as head of the Propulsion Section and Assistant Head of the Guided Missile Section. Upon returning to inactive duty as a Lieutenant (senior grade) June 1946, he became a Research Associate in the Massachusetts Institute of Technology Chemical Engineering Department where he continued his studies. He submitted a thesis entitled "Flame Stabilization and Propagation in High-Velocity Gas Streams" to the Faculty in March 1948 as partial fulfillment of the requirements for the degree of Doctor of Science in Chemical Engineering.