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FINAL REPORT

BASIC RESEARCH ON CERAMIC COMBUSTION CHAMBERS

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ABSTRACT

Spectroscopic investigation of ramjet combustion chambers indicated that continuum intensity (presumably due to atomic oxygen) was much greater in a combustion chamber with a hot (3000°F) ceramic wall than in a combustion chamber containing a gutter flameholder with colder walls. The heat loss from the high temperature combustion chamber was found to be 1875 Btu/hr/in. of length at a low (0.15 lb/sec/ sq ft) mass velocity, but only increased to 2082 Btu/hr/in. of length at a mass velocity (32 lb/sec/sq ft) sufficient for thermal choking to occur.

Spectrographic tranverses of a flat, propane-air flame physically separated from any material surface were used to determine the location of C_2, CH, and OH maxima in the flame under a pressure of 2.5 in. Hg abs. By varying the size of a heat sink upstream of the flame, as well as by varying the temperature of the heat sink, it was demonstrated in several experiments that the amount of heat absorbed from the flame changed the concentration of active species in the flame.

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INTRODUCTION

The overall objective of this research program has been to investigate those factors which contribute to the successful performance of ceramic-lined ramjet combustion chambers. This type of combustion chamber is operable with high impulse efficiencies at mass velocities greater than those required for thermal choking. Alumina wall temperatures in excess of 3000°F occur during operation and combustion intensities in excess of 50,000 Btu/sec/cu ft have been obtained[1]. In this report, some experimental data are presented which supplements the material previously distributed as a Technical Report[1].

EXPERIMENTAL PROCEDURE AND RESULTS

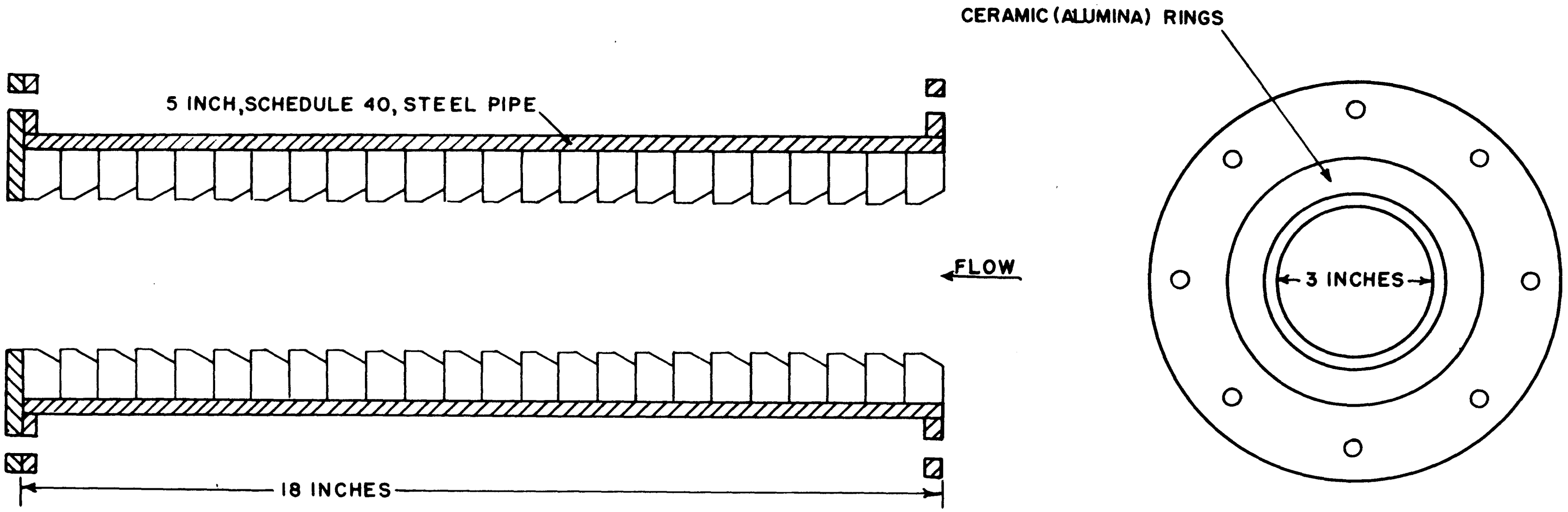
Spectroscopic Investigation of Ramjet Combustion Chambers

The combustion chambers used during these experiments are shown in Fig. 1 which is a sketch of the ceramic combustion chamber used, as well as a combustion chamber containing a gutter flameholder. An emission spectrograph was located so that a view lengthwise through the combustion chambers could be obtained.

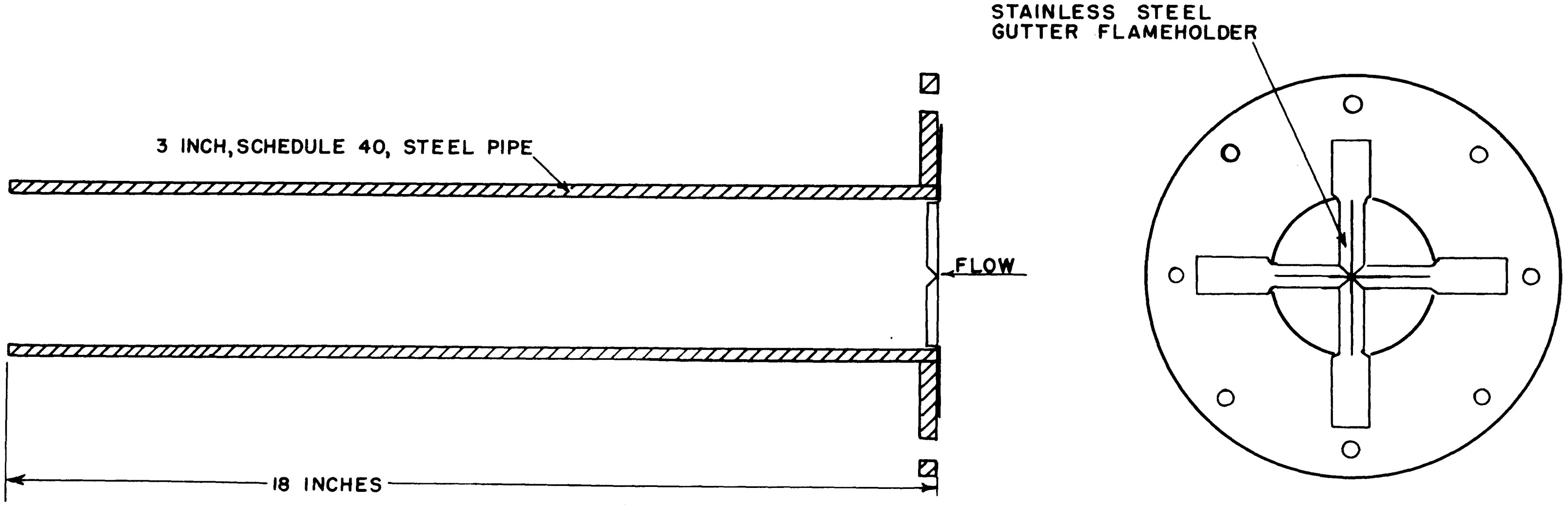
In the region from 3700 to 5700 Å, the intensities of C_2 and CH were much greater in the ceramic combustion chamber than in the combustion chamber containing a gutter flameholder[1]. In addition to the band spectra, Morrison, Weir, and Kelley[2] observed that a continuous spectrum is also emitted from the ceramic combustion chamber. The relative intensity of this continuum at 4400 Å is plotted versus propane-air ratio in Fig. 2. In Fig. 3, the relative intensity of this continuum is plotted versus mass velocity for the ceramic combustion chamber as well as for the combustion chamber containing a gutter flameholder. The greater intensity of the continuum emitted by the ceramic combustion chamber is presumably due to higher atomic oxygen concentrations.

Heat Loss From Ceramic Combustion Chamber

Some experiments[3] were performed with the ceramic combustion chamber shown in Fig. 1 in order to estimate the heat loss from the combustion chamber during operation. The temperatures obtained during one



CERAMIC COMBUSTION CHAMBER



GUTTER FLAMEHOLDER COMBUSTION CHAMBER

Figure 1. Combustion Chambers

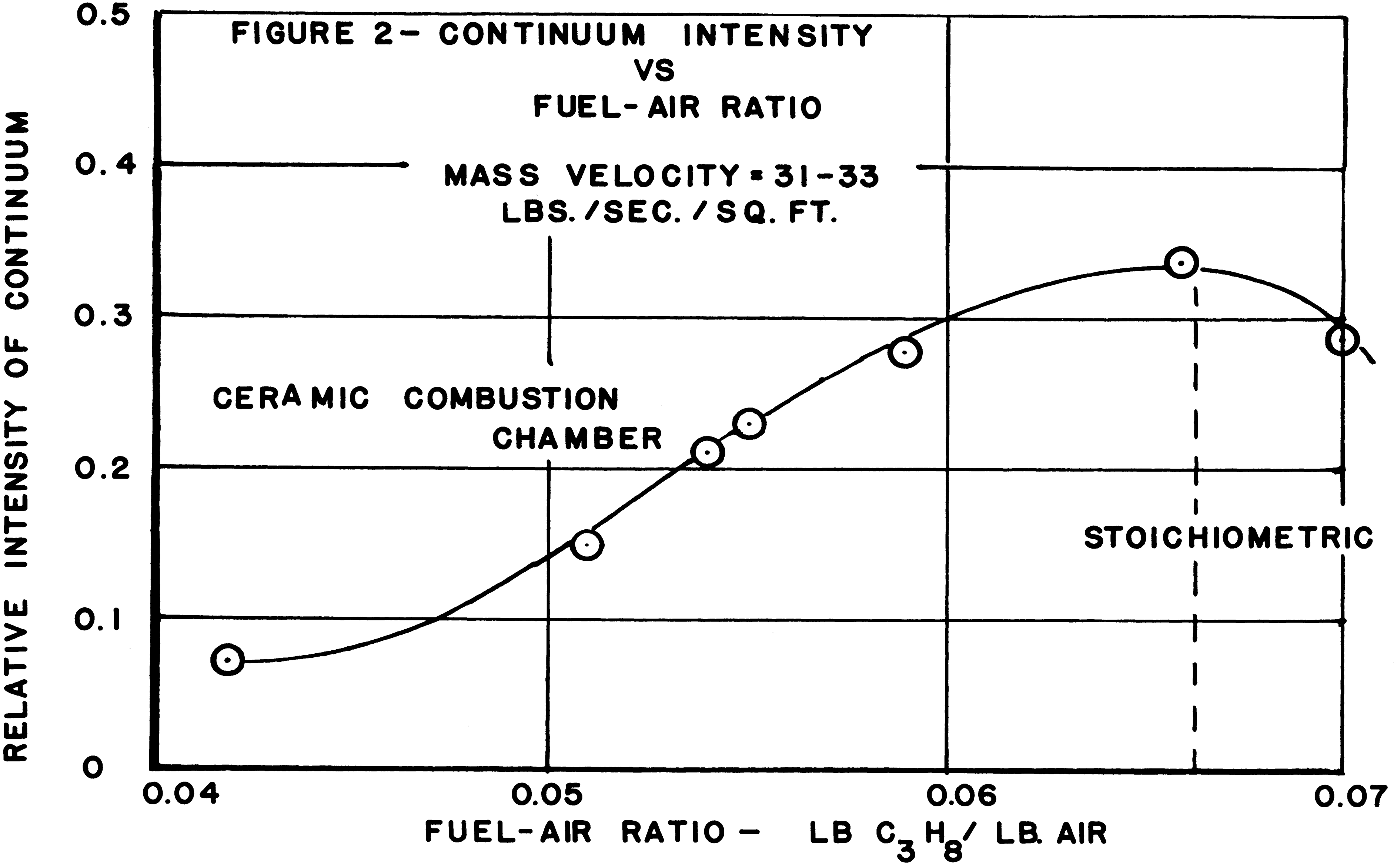


FIGURE 2- CONTINUUM INTENSITY VS FUEL-AIR RATIO

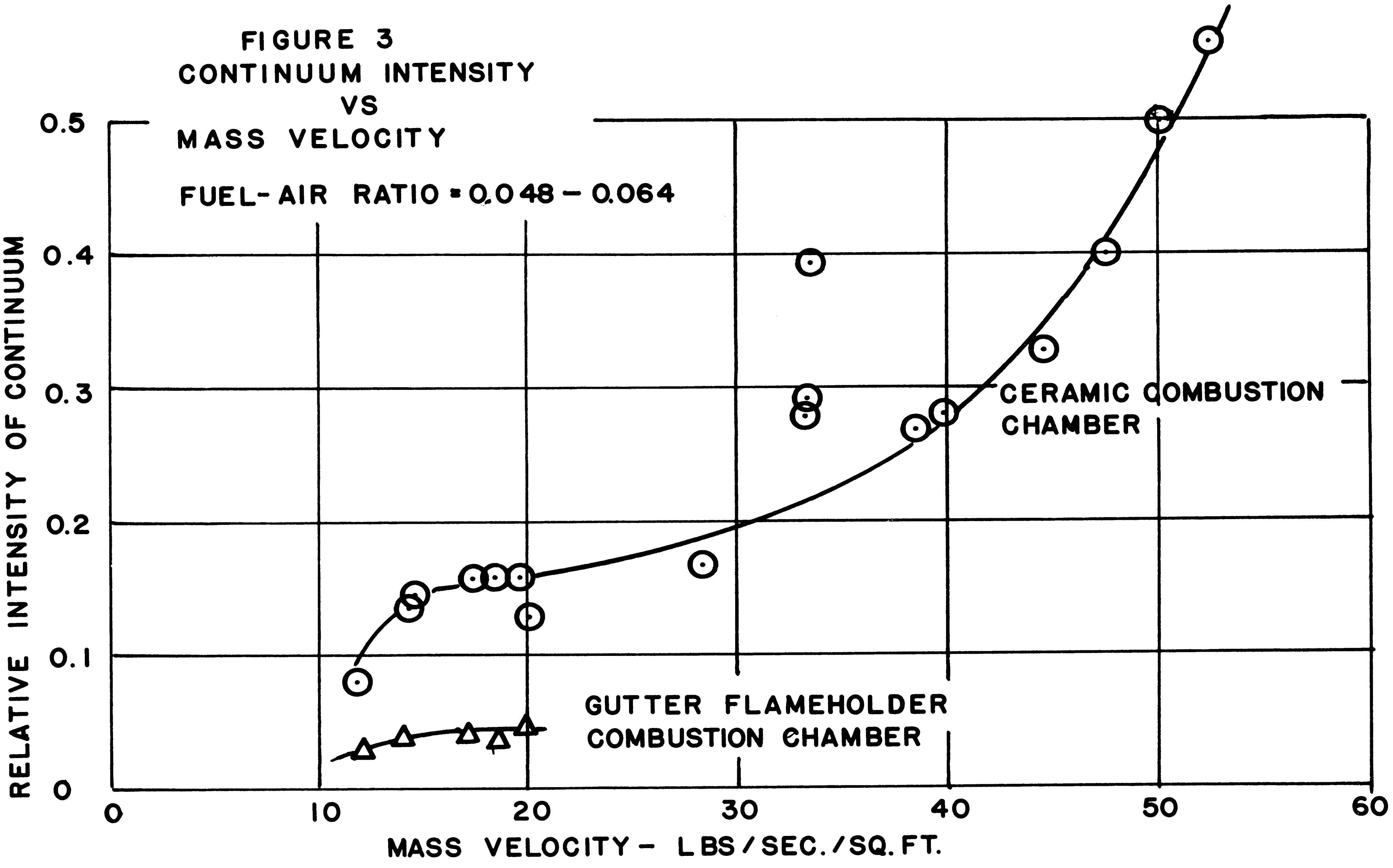


FIGURE 3
CONTINUUM INTENSITY
VS
MASS VELOCITY

FUEL-AIR RATIO = 0.048 – 0.064

such experiment at a low flow rate are shown in Fig. 4. The inside ceramic wall temperature at the exit was measured with an optical pyrometer; the other temperatures with thermocouples. The inside ceramic wall temperature at the burner inlet is difficult to obtain experimentally. The "steady state" temperatures obtained at this low flow rate and at a flow rate corresponding to thermal choking conditions are shown in Table I.

TABLE I

Ceramic Combustion Chamber Wall Temperatures

Mass Velocity (lb/sec/sq ft)	0.15	32
Inside Ceramic Wall Temperature (near exit of burner) - (°F)	2570	3000
Outside Steel Pipe Temperature (2 inches upstream from burner exit)-(°F)	680	900
Outside Steel Pipe Temperature (2 inches downstream of burner inlet)-(°F)	820	1270

These data may be used to obtain the heat loss through the burner wall, as shown in Table II. As the results of Table II indicate, about 2000 Btu/hr/in. of burner length are lost by conduction through the burner wall. The amount of radiation absorbed by the water vapor and carbon dioxide in the gases leaving the burner is in the order of 6 Btu/hr/in. of burner length when the ceramic wall temperature is 3000°F. Since about 350 pounds of propane per hour are being burned under these conditions, the heat liberated (ca. 400,000 Btu/hr/in. of burner length) is large compared to the heat conducted through the wall.

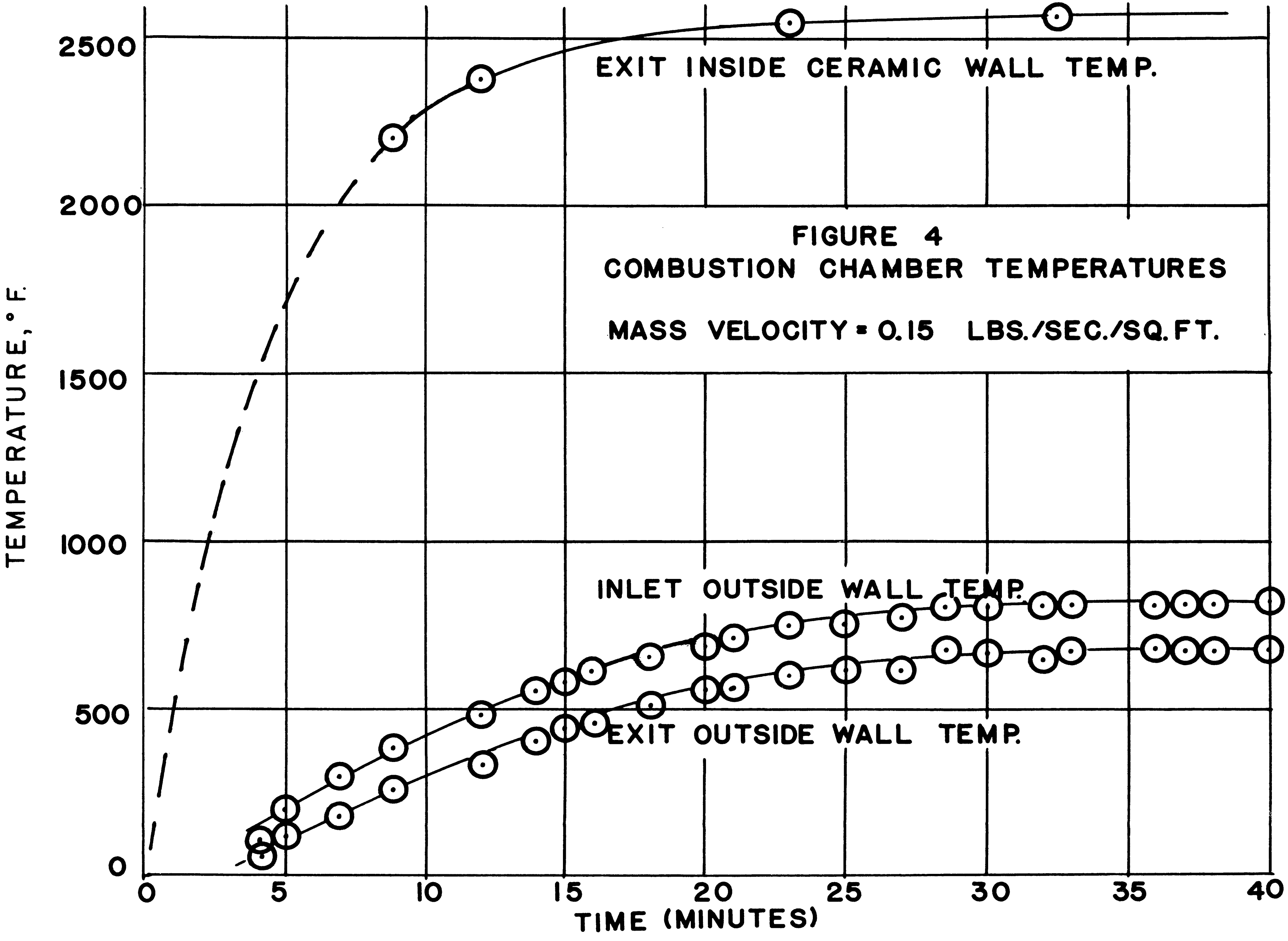


FIGURE 4
COMBUSTION CHAMBER TEMPERATURES

MASS VELOCITY = 0.15 LBS./SEC./SQ.FT.

TABLE II

Heat Loss Through Ceramic Combustion Chamber Walls

Basis: 1 inch length of combustion chamber

Mass Velocity - lb/sec/sq ft	0.15	32
Thermal conductivity of ceramic (Al_2O_3 with a porosity of 42% at 2000°F) Btu/hr/sq ft/°F/ft	1.0	1.0
Log mean area of ceramic - sq ft	0.0833	0.0833
Thickness of ceramic - ft	0.0833	0.0833
Thermal conductivity of steel pipe Btu/hr/sq ft/°F/ft	24	22
Log mean area of steel pipe - sq ft	0.115	0.115
Thickness of steel - ft	0.0214	0.0214
Thermal resistance of ceramic	1.0	1.0
Thermal resistance of steel	0.00775	0.00845
Total thermal resistance	1.00775	1.00845
Temperature Drop through steel and ceramic - °F	1890	2100
Heat conducted through burner wall Btu/hr/ 1 in. length of burner	1875	2082
Temperature drop through steel - °F	14.5	17.6

Boundary Layer Effects

The data in Table II indicated that the heat loss through the burner wall does not increase appreciably even with a twenty-fold increase in flow rate. Morrison and Weir[3] estimated the thickness of the reaction zone, or "boundary layer" necessary to supply this heat loss, by assuming that the temperature of the core gases was 600°F greater than the ceramic wall temperature and equating the sensible heat over this temperature change to the heat conducted through the burner walls. In other words, if the heat loss figure (2080 Btu/hr/in.) determined for the burner exit can be used for the entire 18 inches of burner length, the total heat loss through the burner walls is 10.4 Btu/sec and

$$10.4 = w(C_p)\ (600^\circ)$$

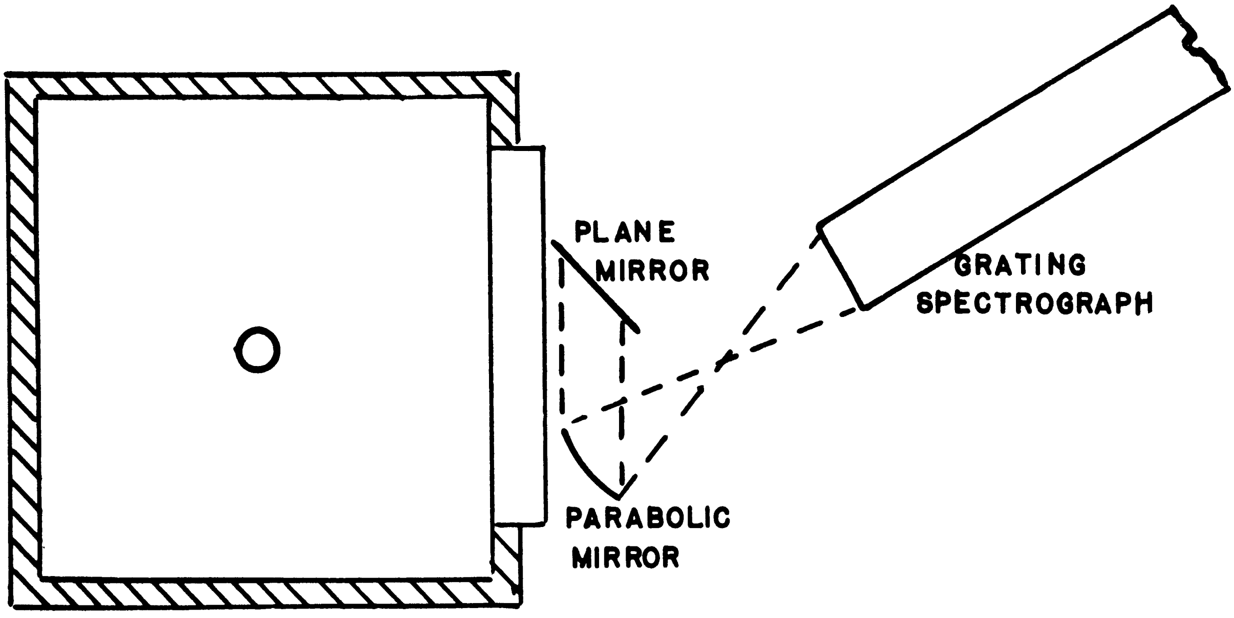
$$w = 0.0725 \text{ lb/sec}$$

This corresponds to a "boundary layer" thickness of 0.0325 in. Since the heat loss only increased 10 percent when the mass velocity was increased by a factor of 20, the 0.0325 inch dimension is relatively independent of the flow rate.

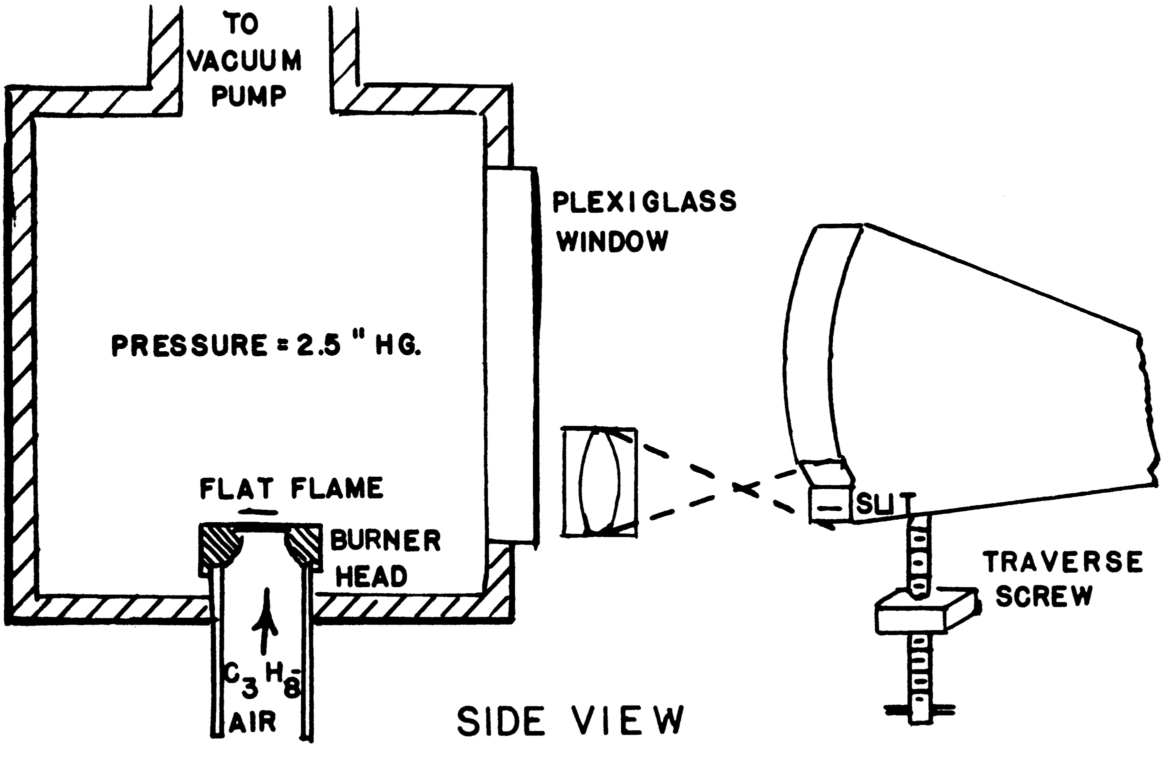
The significance of this dimension is not fully understood. However, the hypothesis has been advanced that a turbulent boundary layer of this thickness contributes to the successful operation of this type of combustion chamber, along with thermal radiation from the walls and surface catalytic effects. This might indicate that surface roughness or protuberences of this order of magnitude might be required. Experimental support of this hypothesis was obtained by comparing the performance of a burner constructed with a smooth, hard, ceramic wall (Norton Co. - RA 98) with the performance of a burner constructed with a rough, porous, ceramic surface (75% porosity - A.P. Green Co. G-25). No bevels in the wall were present in either case. In both cases, temperatures similar to those shown in Fig. 4 were obtained at low flow rates, but blowoff occurred with the hard wall burner as soon as the flow rate was increased while satisfactory performance was obtained with the porous wall burner at higher flow rates. These experiments seem to indicate that a turbulent boundary layer contributes to the successful operation of this type of combustion chamber. The important role that the boundary layer plays in the stability of flames burning from flameholders has been indicated in a previous investigation[4].

FIGURE 5

EQUIPMENT FOR FLAME TRAVERSES



TOP VIEW



SIDE VIEW

Influence of Thermal Factors on Low Pressure Flame Spectra

Another investigation was made by Robert E. Cullen in this laboratory on the effects of altitude conditions on flame propagation rate. Cullen advanced the hypothesis[5] that the presence of a heat sink was detrimental to combustion, inasmuch as the flame propagation rates at low pressures were adversely effected. Morrison, Weir, Gluckstein, and Gealer[6] modified this altitude apparatus so that a spectroscopic investigation of a flat, disk-shaped flame, physically separated from a porous ceramic surface, could be made. The results of their experiments are discussed below.

The nature of these experiments was such that effects due to a turbulent boundary layer or surface catalytic effects were presumably eliminated and only thermal factors were considered to effect the flame reactions. The equipment was arranged as indicated in Fig. 5, so that spectrographic traverses could be made of the flame image. The experiments were performed at an absolute pressure of 2.5 inches of mercury, with a propane-air ratio of 0.063 lb propane/lb air. Under these conditions, the disk-shaped flame was physically separated from the porous ceramic surface shown in Fig. 5. Experiments were also performed under the same conditions using, instead of the burner head containing the ceramic porous disk, a burner head with an open nozzle so that a flat Bunsen flame was obtained.

A photograph of a typical flat flame is shown in Fig. 6, while spectrograms obtained at different location in the flame are shown in Fig. 7. Twenty minute exposures with du Pont 428 film were used and the film negatives were examined with a recording microphotometer to obtain relative intensity measurements of the different bands.

Several sets of experiments were performed, but comparisons were made only between data recorded on the same film strip. In one experiment, the relative intensity of the 4315 A CH band in the flame was found to be about twice as great when the burner head containing the ceramic disk was maintained at 725 to 730°F, then when the burner head temperature was between 243 and 248°F. In the latter case, the 245°F temperature was maintained primarily by thermal radiation from the flame, i.e., the burner head acted as a heat sink. When heat was added to the system electrically (burner head temperature = 727°F) the doubling of CH intensity could be attributed to the combined thermal factors, i.e., the reduction of the heat sink, or the net decrease in heat transferred by radiation from the flame to the burner head, as well as the preheating of the fuel-air mixture achieved by its passage through the warmer burner head.

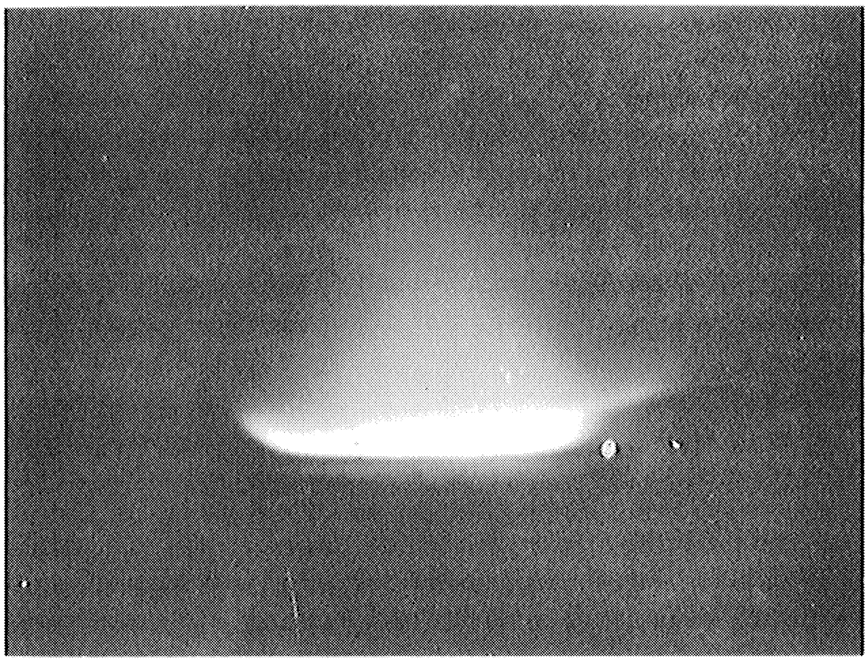


Figure 6. Typical Flat Flame Photograph

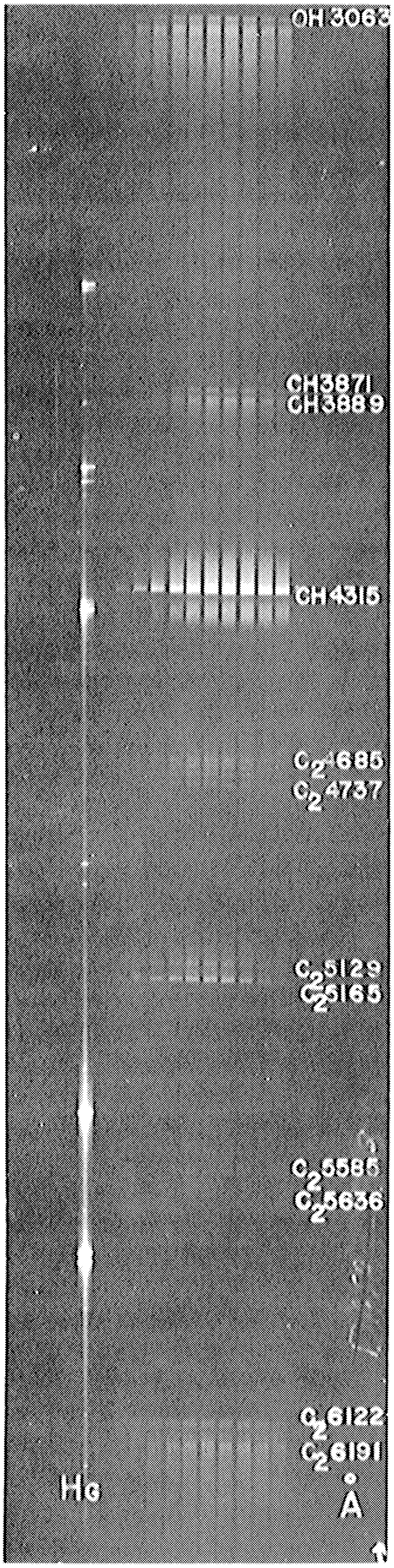


Figure 7. Typical Spectrograms

That the amount of heat absorbed from the flame change the concentration of active species in the flame was demonstrated by Morrison, Weir, Gluckstein, and Gealer[6] in several other experiments. The mass and upper surface area of the burner head used for Bunsen flames was much less than the mass and upper surface area of the burner head containing the porous ceramic disk. Therefore, for similiar shaped flames burning under the same pressure, fuel-air ratio, and flow conditions, the burner head used for the Bunsen flames should be less of a heat sink than the burner head containing the porous ceramic disk when no external heat is added to either burner head. In Table III the location in the flame where the maximum intensity of different spectral bands occurred is shown for the two cases. As may be seen, the relative intensities were greater with the smaller burner head which absorbed less heat from the flame.

TABLE III

C_2 and CH Maxima - Large and Small Heat Sink

Bunsen Burner Head (Small Heat Sink) - No External Heat
Ceramic Burner Heat (Large Heat Sink) - No External Heat (T = 245°F)
Stoichiometric Propane - Air Flame at 2.5 in Hg abs

Component	Wave Length Å	Maximum Relative Intensity		Distance of Maximum from Bottom of Flame, inches	
		Bunsen Burner Head	Ceramic Burner Head	Bunsen Burner Head	Ceramic Burner Head
C_2	4685	0.08	0.09	0.075	0.0375
C_2	4737	0.132	0.120	0.075	0.0375
C_2	5165	0.273	0.193	0.075	0.0375
C_2	5585.2	0.07	0.083	0.075	0.0375
C_2	6122.3	0.220	0.170	0.075	0.0375
CH	4315	1.46	1.28	0.075	0.0375
CH	3889	0.250	0.222	0.075	0.0375

A similar experiment was performed with these two burner heads, except that in this experiment, external heat was added to the larger burner head (containing the porous ceramic disk) so that its temperature was maintained at 380°F. No external heat was added to the smaller burner head. The locations of the maximum intensities of the various bands for this experiment are shown in Table IV. In this case, maximum intensities of the different bands were greater in all cases with the heated burner head. Thus, external heat compensated for the larger mass of this burner head.

An additional experiment[6] was performed in order to obtain relative concentration gradients in a flat flame. Since physical sampling of a flame disturbs the flow pattern in the flame, and because ordinary methods of chemical analysis are precluded because of the time required, traverses of the flame image with an emission spectrograph provide information concerning a flame which otherwise would be very difficult to obtain. The results obtained by this technique are shown in Fig. 8 where the relative intensities of C_2, CH, and OH are plotted versus the distance through a flat flame. The unheated burner head containing the porous ceramic disk was used. The thickness of the flame was 0.1 inch and the velocity of the stoichiometric propane-air mixture was about one foot per second. The atmosphere surrounding the flame was maintained at 2.9 in. Hg absolute.

Gaydon and Wolfhard[7] proposed that CH was formed from C_2 by means of the following exothermic reaction

$$C_2 + OH \quad = \quad CH + CO$$

The position of the maximum intensity of CH in the flame traverses plotted in Fig. 8 does not seem to be significantly downstream of the C_2 and OH maxima. For stoichiometric propane-air flames burning at reduced pressure, the data in Fig. 8 seem to indicate that reactions in addition to the one proposed[7] must be considered to account for the CH production.

CONCLUSIONS

C_2 and CH bands are more intense in the ceramic combustion chamber than in a gutter flameholder combustion chamber tested at the same operating condition[1]. The greater intensity of the continuum in the ceramic combustion chamber, compared to a gutter flameholder bombustion chamber, is presumably due to increased concentrations of atomic oxygen in the high temperature chamber[2]. All the experimental evidence indicates that, in addition to surface reactions occurring in a turbulent boundary layer[3], thermal

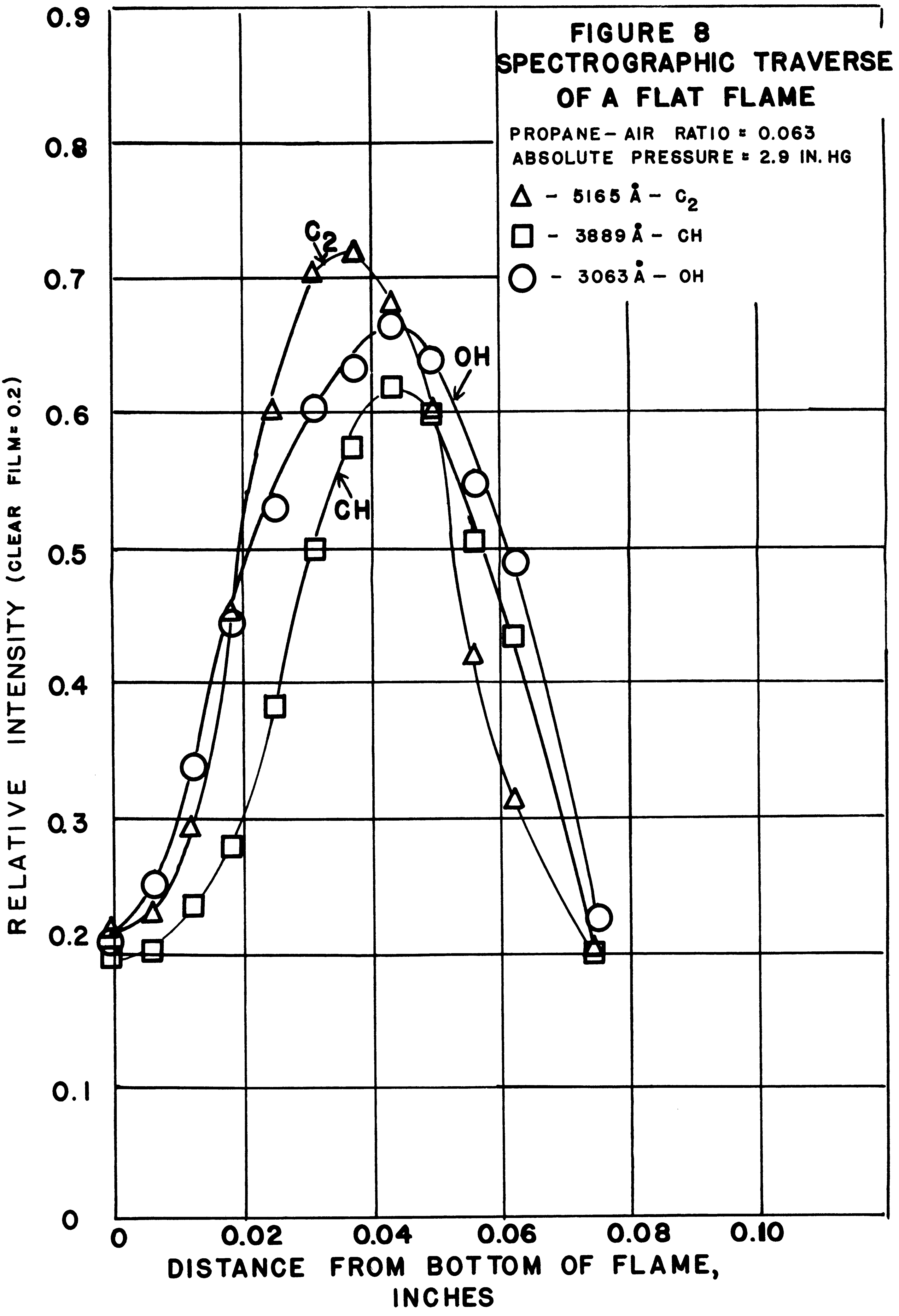


FIGURE 8
SPECTROGRAPHIC TRAVERSE OF A FLAT FLAME

TABLE IV

C_2 and CH Maxima - External Heat Added to Larger Heat Sink

Bunsen Burner Head - (Small Heat Sink) No External Heat
Ceramic Burner Heat (Large Heat Sink) - External Heat Added (T = 380°F)
Stoichiometric Propane-Air Flame at 2.5 in Hg abs.

Component	Wave Length Å	Maximum Relative Intensity		Distance of Maximum from Bottom of Flame, inches	
		Bunsen Burner Head	Ceramic Burner Head	Bunsen Burner Head	Ceramic Burner Head
C_2	4685	0.43	0.44	0.1750	0.050
C_2	4737	0.316	0.31	0.1625	0.050
C_2	5165	1.06	1.10	0.1625	0.050
C_2	5585.2	0.27	0.325	0.1625	0.050
C_2	6122.3	0.19	0.237	0.1625	0.050
CH	4315	1.7	1.7	0.1625	0.050
CH	3889	0.501	0.605	0.1625	0.050

effects due to the hot (3000°F) wall contribute greatly to burner effectiveness. Since heat absorbed from a flame reduces the concentration of active species (C_2,CH, and OH) in the flame[6], as well as the flame propagation rate[5], combustion chamber designs which allow an approach to an "adiabatic flame" would seem to be desirable.

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