UMM - 43

PROGRESS REPORT NO. 12

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Combustion Chamber Design

Ceramic-lined Combustion Chamber - The test stand has been essentially completed and some preliminary testing has been done.

Pressure and Temperature Effects on Combustion

The period was spent compiling experimental data using Bunsen flames burning at various pressures and inlet gas temperatures. Some preliminary conclusions have been reached.

Flow Associated with the V-flame

Work continued on the investigation of the resonant condition in the 1" x 1" x 24" combustion chamber. A "sensitive region" was found about one inch above the flame holder.

Detonation

Fittings were designed to measure by bursting of thin diaphragms the velocity of shock waves in the shock tube. Tests to detonate propane-air mixtures in the shock tube were not successful. Acetylene-oxygen mixtures have been detonated at low Mach numbers.

Experimental Techniques

The design of the interferometer is in the final stage. Work on the two-inch interferometer has continued. The BH-6 lamp light source has been completed.

III. PROGRESS

Effect of Pressure and Temperature on Blowoff Velocities of Flame Holders

The experimental work on the blowoff velocities of spherical flame holders in propane-air mixtures has been substantially completed. During previous periods, tests were made with nine fuel-air ratios, four flame holder diameters, five nozzle diameters, at various heights of the flame holder above the jet and with pressures from 0.4 atmosphere to 1 atmosphere. An attempt will be made to correlate this data. The correlations presented by investigators at other institutions have been inadequate when the effect of system geometry is imposed upon them. Some of the personnel on this phase of the project have been assigned to the work being done on the effect of pressure and temperature on Bunsen flames and to the work being done on the ceramic-lined combustion chamber.

Combustion Chamber Design

The test stand for the ceramic lined combustion chamber has been essentially completed and a few preliminary runs have been made. Several photographs of the test stand while the burner is in operation were taken, and these may be seen in Figures 1, 2, 3, and 4. Figure 1 is an interior view of the test stand showing the control valves, instrument panel, and observation window. The air flow and propane flow are metered with flat plate orifices and the instruments for indicating the orifice pressure, temperature, and pressure drop may be seen, as well as a pressure gage at the inlet to the burner and temperature indicators connected to the burner shell. Figures 2 and 3 are exterior views of the test stand showing the burner and the piping. Air at low flow rates is obtained from a small turbo-blower while air for high flow rates is obtained from two 80 cubic feet storage tanks at 2500 psi. The air is reduced to 500 psi, metered, and mixed with metered propane obtained from an 1100 gallon supply tank. Figure 4 is a photograph taken through the observation window of the burner operating at a high flow rate. It may be seen from these photographs that there is not a great deal of combustion occuring downstream of the burner, which might indicate that a large percentage of the fuel is burned. The burner shown in Figures 2, 3, and 4 was Burner 2, which is described in Figure 5. The annular rings on the burner inner surface described in Figure 5, may be faintly seen in Figures 3 and 4. Burner 1 was previously described[1] while a description of Burner 3 may be seen in Figure 6.

Some preliminary data was obtained with the use of Burner 3. The temperature of the ceramic at the exit of the burner was obtained by means of an optical pyrometer and this temperature is plotted versus mass velocity (for a propane-air ratio of 0.060) in Figure 7. It may be seen from Figure 7 that as the mass velocity is increased, the ceramic surface temperature approaches asymptotically the adiabatic flame temperature.[2]

Measurements of the pressure immediately upstream of the burner were obtained and these values are shown in Figure 8, as well as the calculated exit pressure. The exit pressure was calculated from the exit temperature measurements and the known mass velocity as follows:

At mass velocities below Mach = 1 at the exit, the exit pressure is assumed to be atmospheric pressure. However, at mass velocities greater than that required for Mach = 1 at the exit, the velocity at the exit is equal to the velocity of sound; hence the exit pressure may be computed by means of the conservation of mass, i.e.,

$$G = v\rho = \sqrt{\gamma g \frac{RT}{M}}\left(\frac{PM}{ZRT}\right)$$

in which

P = exit pressure to be calculated

T_s = ceramic surface temperature at exit measured by optical pyrometer assumed to be equal to the stagnation temperature of the exit gases

T = average temperature of the exit gases

$$= T_s \Big/ \left[1 + \frac{(\gamma - 1)}{2} (M_a)^2\right]$$

γ = ratio of specific heats - assumed to be equal to 1.32 (for equilibrium conditions for the fuel-air ratio and exit temperature used)

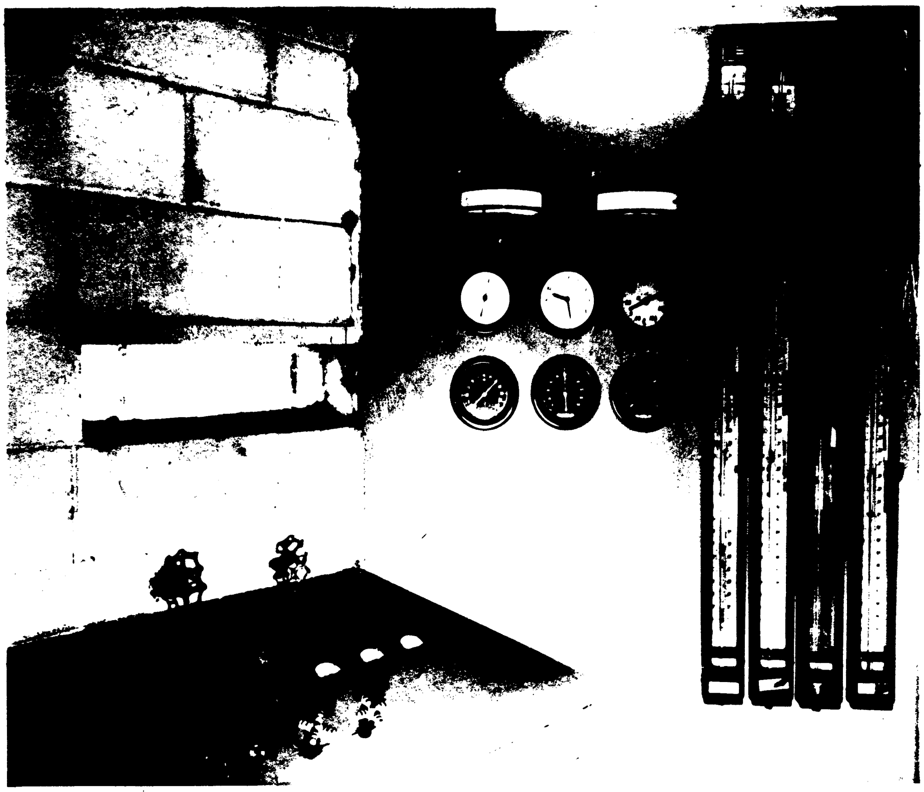

FIG. 1 INSTRUMENT PANEL BURNER TEST STAND

FIG. 2 EXTERIOR VIEW BURNER TEST STAND

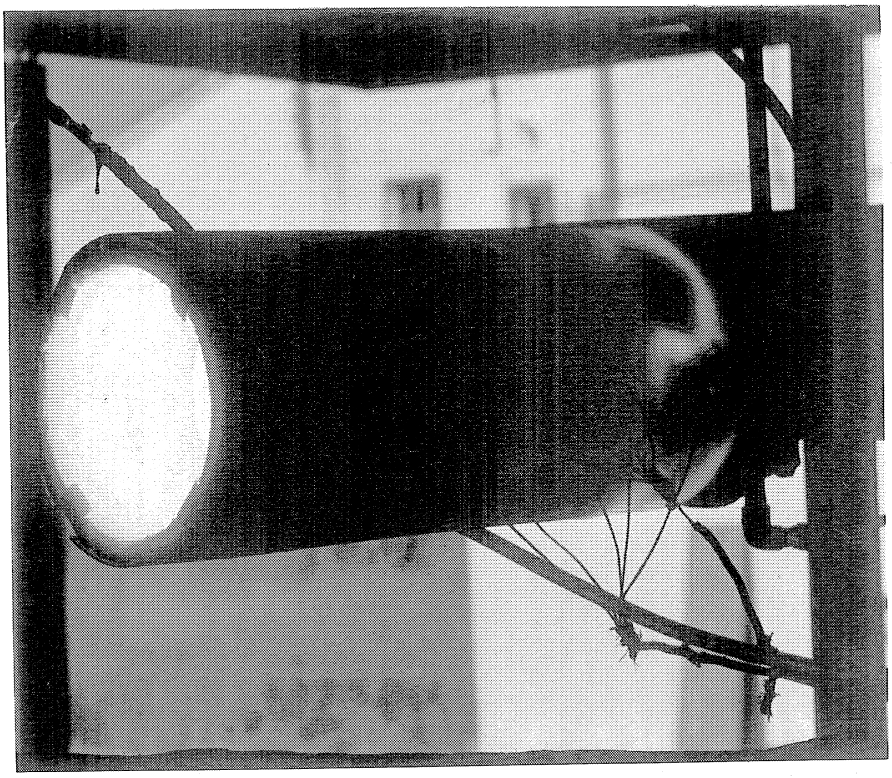

Fig. 3 - Exterior View of Test Stand - Combustion Chamber Design

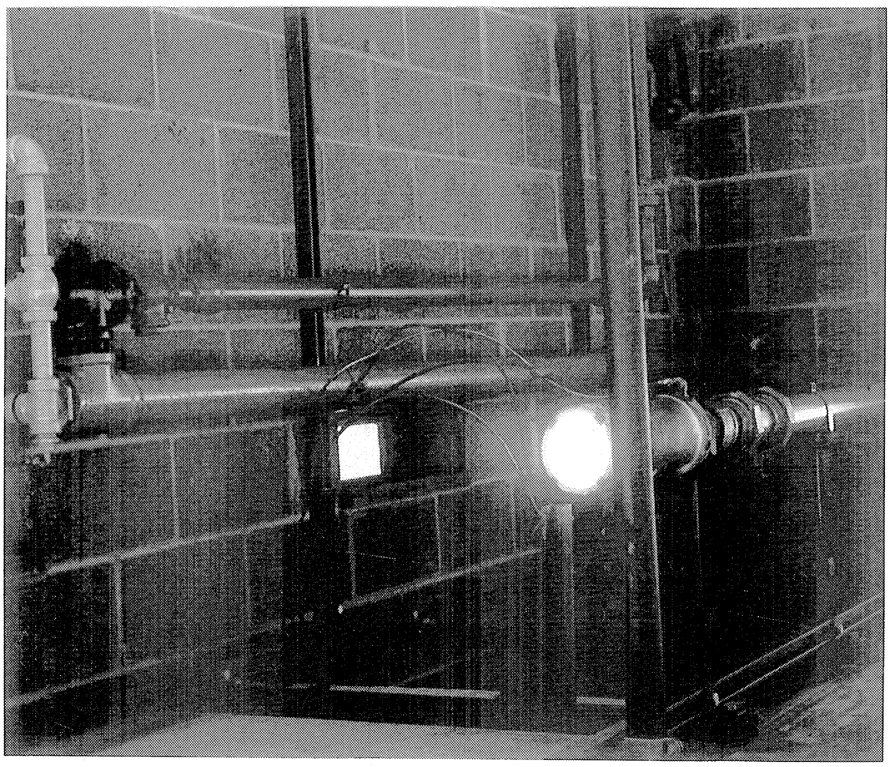

Fig. 4 - Burner viewed thru Test Stand Observation Window - Combustion Chamber Design

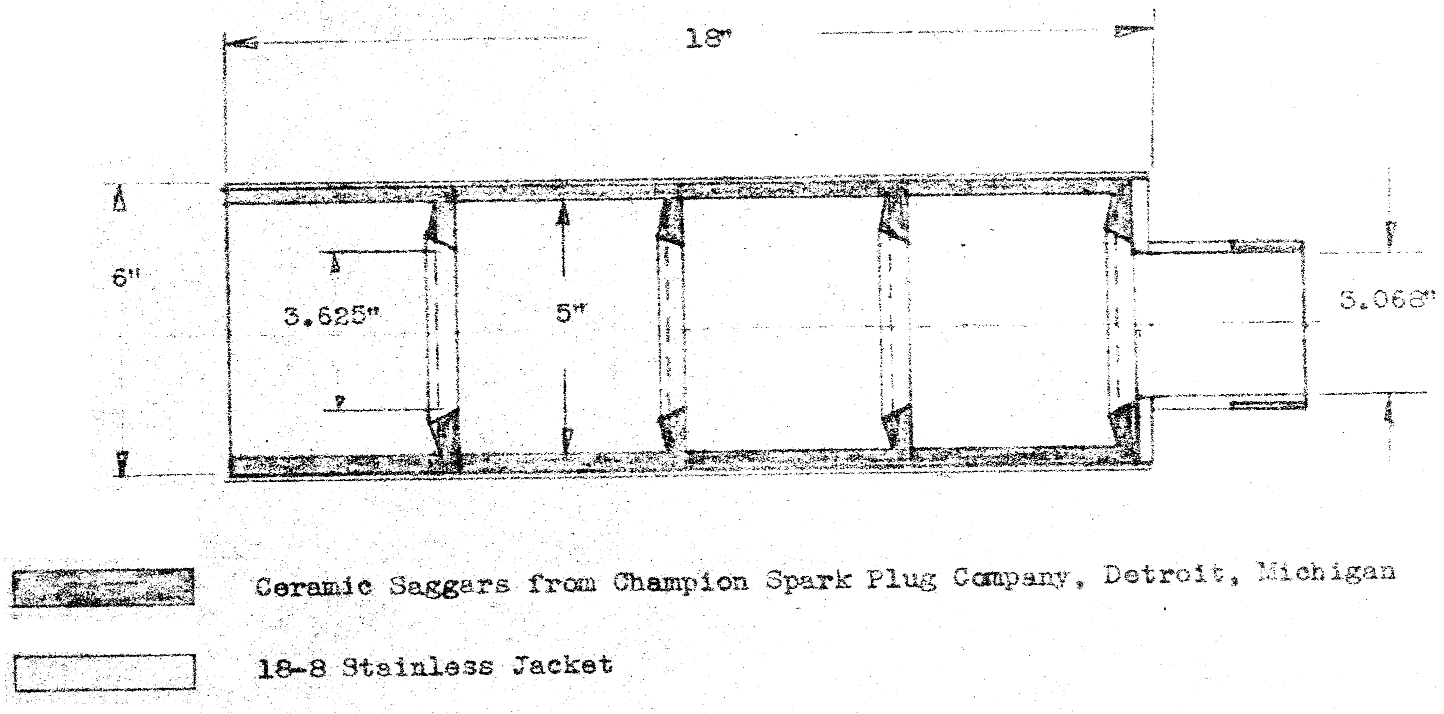

Figure 5

BURNER 2

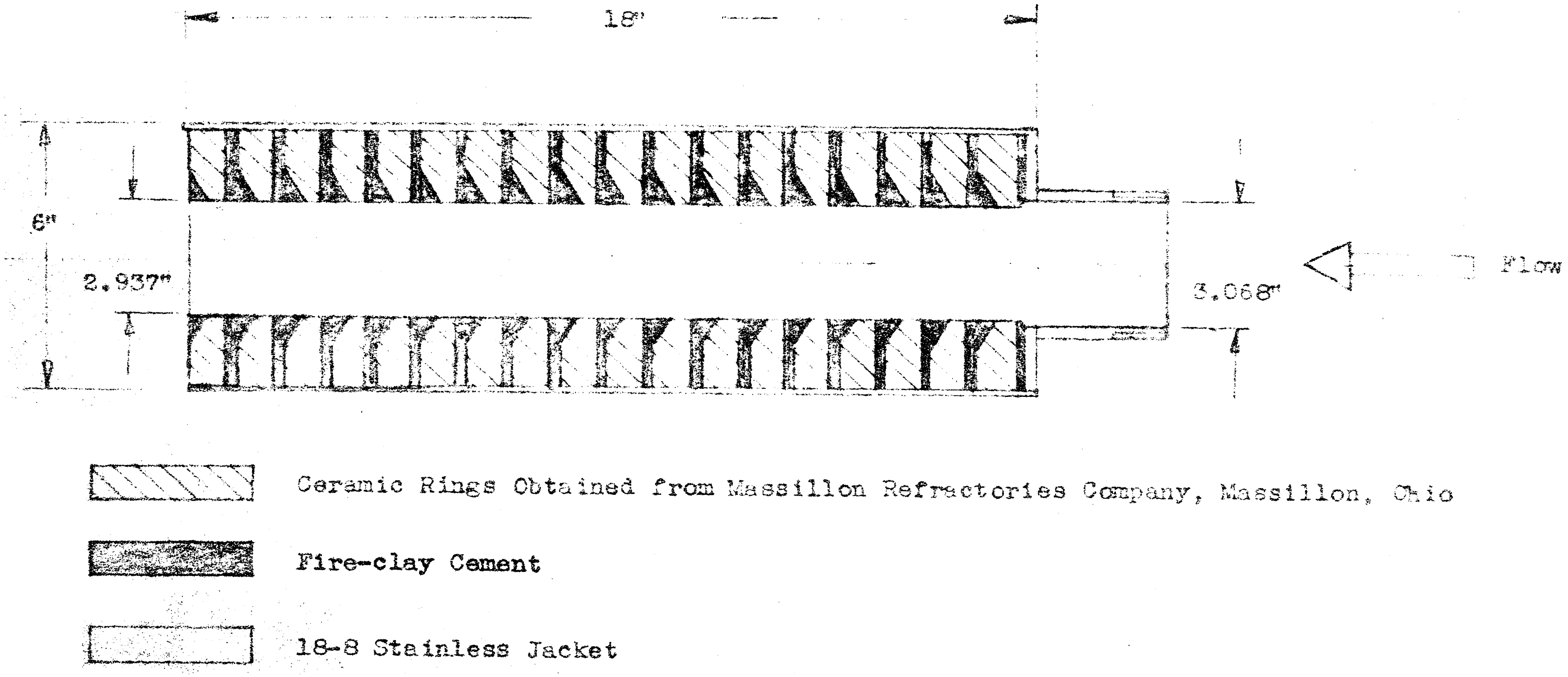

Figure 6
BURNER 3

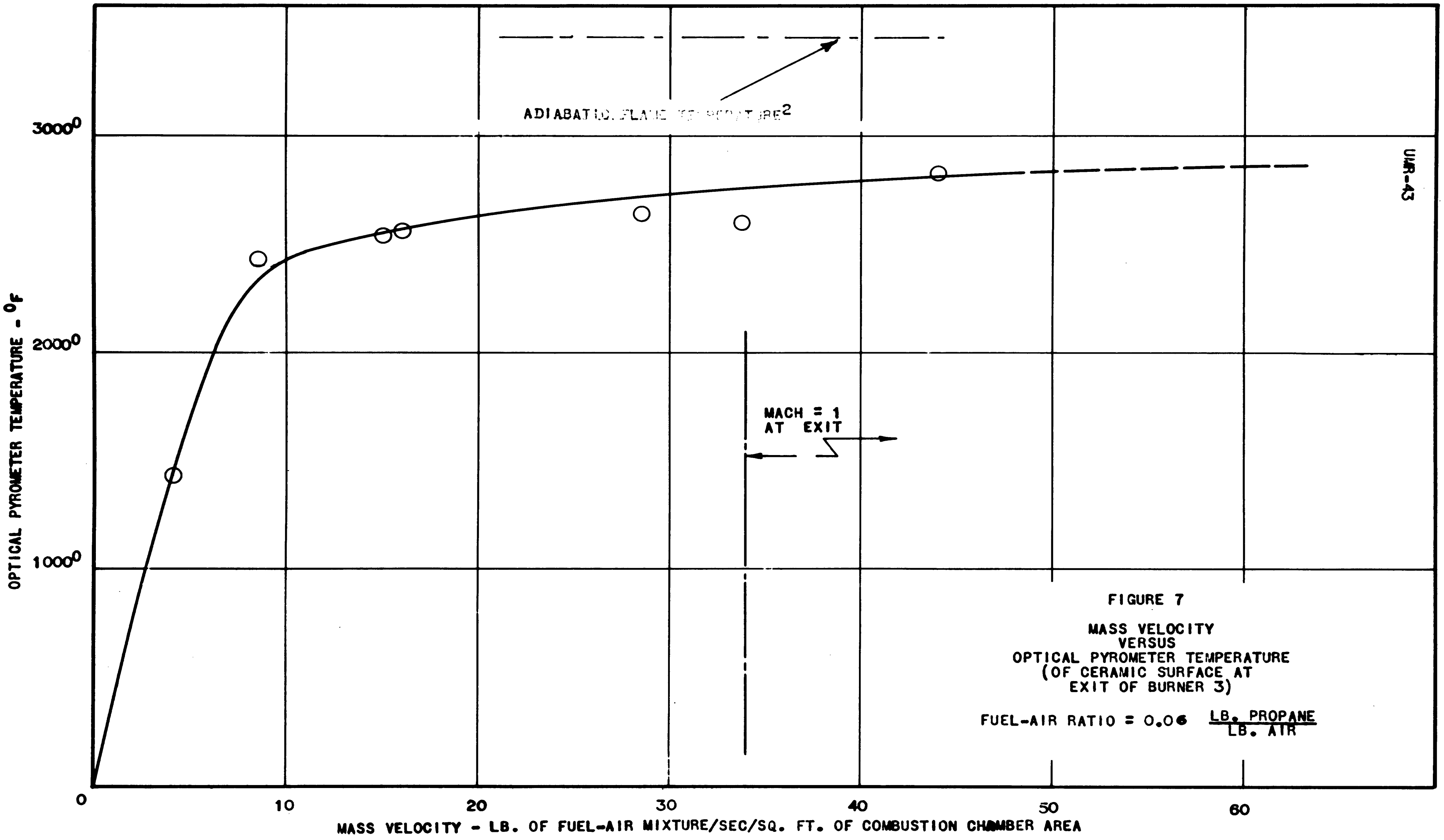

FIGURE 7

MASS VELOCITY
VERSUS
OPTICAL PYROMETER TEMPERATURE
(OF CERAMIC SURFACE AT
EXIT OF BURNER 3)

FUEL-AIR RATIO = 0.06 $\frac{\text{LB. PROPANE}}{\text{LB. AIR}}$

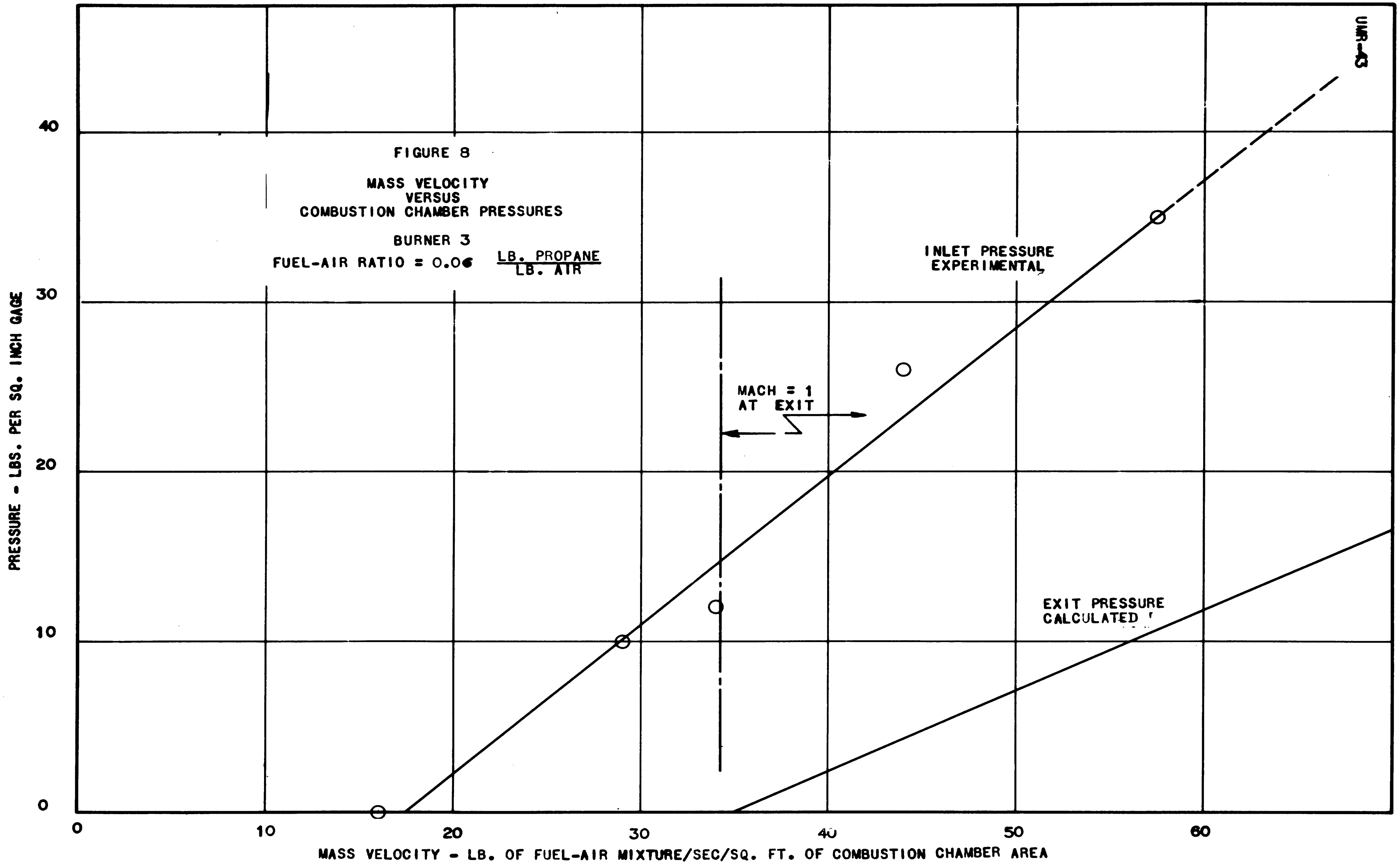

FIGURE 8

MASS VELOCITY
VERSUS
COMBUSTION CHAMBER PRESSURES

BURNER 3

FUEL-AIR RATIO = 0.06 $\frac{\text{LB. PROPANE}}{\text{LB. AIR}}$

G = mass velocity - obtained from orifice measurements

$= \frac{\text{lb. of fuel-air mixture}}{\text{sec. - sq. ft. of combustion chamber area}}$

v = exit linear velocity (ft/sec)

= velocity of sound at Mach = 1

$= \sqrt{\gamma g \frac{RT}{M}}$ if ideal gases are assumed

ρ = exit gas density (lbs. mass/cu. ft.)

$= PM/ZRT$

Z = compressability factor

= 1 for ideal gases

M = average molecular weight of exit gases - assumed to be equal to 31 (for equilibrium conditions for the fuel-air ratio and exit temperature used)

R = Universal gas constant

g = conversion factor for mass and force units

= 32.2

M_a = Mach number

$= \frac{\text{exit velocity}}{\text{velocity of sound at exit conditions}}$

Since the mass velocity and the pressure, temperature, and composition of the gases at the inlet of the combustion chamber are known, it is possible to calculate the inlet velocity by means of the same relationship, i.e.,

$$v = \frac{G}{\rho} = \frac{G}{(PM/ZRT)}$$

and it is found that the inlet velocity reaches a constant value of 215 ft/sec at a mass velocity of ca. 20 lb/sec/sq. ft.

By using the assumed equilibrium gas composition at the temperature calculated from the stagnation temperatures measured (i.e., optical pyrometer temperature of surface assumed to be equal to stagnation temperation) together with the known mass velocity and the fact that the exit pressure is at atmospheric for Mach number less than 1, it is possible to calculate the exit velocity and hence the exit Mach number by means of the relationship:

$$\text{Mach No.} = \frac{\text{exit velocity}}{\text{velocity of sound}} = \frac{G/\rho}{\sqrt{\gamma g \frac{RT}{M}}} = \frac{GZRT/PM}{\sqrt{\gamma g \frac{RT}{M}}}$$

By means of this equation, the mass velocity at which thermal choking (Mach = 1 at the exit) first occurs is found to be ca. 32 lb/sec/sq. ft. Higher mass velocities will not change the inlet velocity or the exit Mach number, but will increase the pressure at the inlet and exit of the combustion chamber and hence allow more pounds of fuel to be burned per second if blowoff does not occur.

In the preliminary runs made with these burners (1, 2, and 3) they appeared very stable with respect to blowoff velocity. Data on Burner 1 has been previously reported.[3] As may be seen in Figure 8, it was possible to burn at mass velocities of 60 lb/sec/sq. ft. (limit of air supply at that time). It is deemed significant that with the use of Burner 3 it is possible to burn at mass velocities which are twice the mass velocity required for thermal choking (Mach = 1 at exit).

A parameter which has been found useful in a comparison of ram-jet burners is the combustion chamber parameter, S_a. This parameter has been defined[4] as

$$S_a = \frac{F}{w_a \phi M}$$

and may be rearranged to

$$S_a = \frac{PA + mv/g}{w_a \phi M} = \frac{PA + \frac{GAv}{g}}{\frac{GA}{1 + f/a} \phi M} = \frac{P + \frac{G}{g} v}{\frac{G}{1 + f/a} \phi M}$$

in which:

$$M = \frac{1 + \gamma M_a^2}{M_a \sqrt{2(\gamma + 1)} \left[1 + \frac{\gamma - 1}{2} M_a^2\right]^{\frac{1}{2}}}$$

$= 1$ when Mach No. $= 1$

M_a = Mach Number

w_a = mass flow of air (lb/sec)

$= \frac{GA}{1 + f/a}$

f/a = Fuel-air ratio, by weight

F = "Stream Thrust" = $PA + mv/g$

m = total mass flow (lb/sec) = GA

G = mass velocity (lb/sec/sq. ft.)

A = area (sq.ft.)

v = linear velocity (ft/sec)

P = absolute pressure (lbs. force/sq. ft.)

g = conversion factor for mass and force units = 32.2

This combustion chamber parameter, S_a, may be evaluated from experimental measurements made at either the exit or inlet of the combustion chamber by using the above equation together with the known mass velocity. At the exit, for Mach Numbers of 1, the exit pressure is calculated, as was previously shown, from the optical pyrometer temperature, the velocity is equal to the velocity of sound which is calculated from this temperature, and since Mach Number = 1, $\phi M = 1$. At Mach Numbers less than 1, the exit pressure is atmospheric, the exit velocity is determined by the temperature, as is the exit Mach Number. ϕM is evaluated from a plot of this function versus Mach Number.[5]

At the inlet to the combustion chamber, the absolute pressure is measured. The pressure decrease between this point and the exit is due to the sum of the pressure drop caused by burning and the friction loss in the combustion chamber. The friction loss in the chamber was found experimentally to be less than 1 psi over the flow ranges used (for cold flow) and therefore was assumed to be negligible in these calculations. Since there is no flame holder in the chamber, the only friction loss is that due to the 18 inches of three-inch pipe, and it seems reasonable that this pressure loss would be small.

At Mach numbers at the exit equal to 1, $\phi M = 1$, the inlet velocity is constant, and consequently the exit S_a is determined by the inlet pressure measurement. At Mach numbers at the exit less than 1, the value of ϕM was used as determined by the exit temperature measurements, but the pressure and velocity terms were determined from the inlet pressure measurements (since the friction loss is assumed to be negligible, the "Stream Thrust" is constant at any point in a straight pipe). These values of exit S_a are plotted in Figure 9 as a function of mass velocity. It may be seen that relatively high values of S_a may be obtained with ceramic-lined burners and that these values do not decrease with increasing mass velocity as do the values of S_a obtained with the use of conventional flame holders.

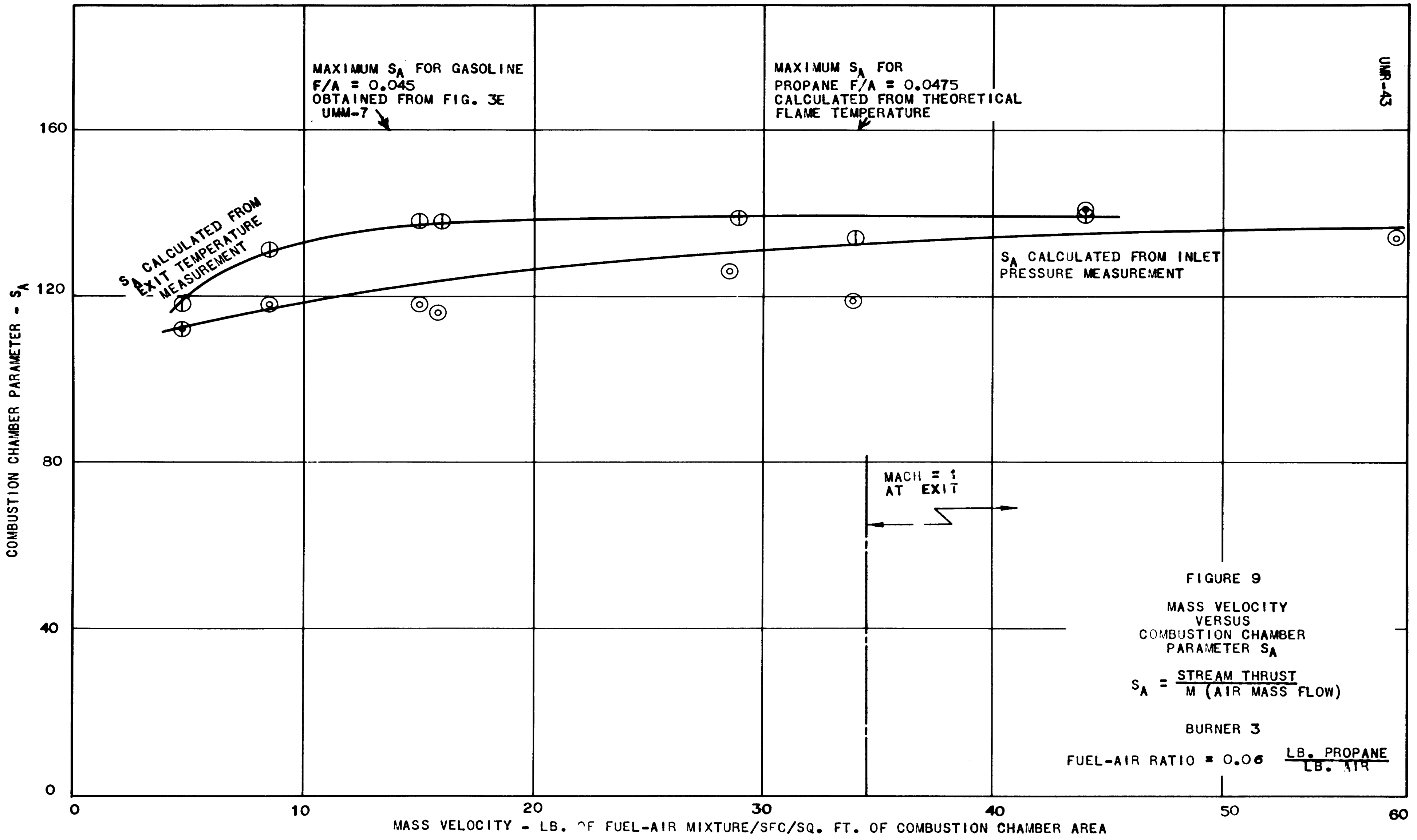

FIGURE 9

MASS VELOCITY
VERSUS
COMBUSTION CHAMBER
PARAMETER S_A

$$S_A = \frac{\text{STREAM THRUST}}{\text{M (AIR MASS FLOW)}}$$

BURNER 3

FUEL-AIR RATIO = 0.06 $\frac{\text{LB. PROPANE}}{\text{LB. AIR}}$

Pressure and Temperature Effects on Combustion

The last period was spent compiling experimental data. Bunsen flames were observed and photographs taken of flames burning at various pressures and inlet gas temperatures. The fuels employed were propane-air mixtures and ethylene-air mixtures at compositions that would give maximum flame speed (i.e., .067 lb. propane/lb. air and .0836 lb. ethylene/lb. air). Various burner diameters were used, the largest diameter of which was $1\frac{1}{4}$" and the smallest, $\frac{1}{4}$". The larger diameters were used at the lower pressures. Flames burning with inlet gas temperatures up to 400°F have been observed and photographed.

The conclusion drawn thus far for both propane-air and ethylene-air flames is that there exists an inverse dependence of flame speed upon pressure and a direct dependence of flame speed upon temperature. The latter conclusion is in good agreement with other investigators; however, the first is in disagreement with most of the relatively few investigators that have studied the effect of pressure on flame speed. For a fuel-air mixture of .067 lb. propane/lb. air, a flame speed increase from 1.2 ft/sec at atmospheric pressure to 2.4 ft/sec at 3" Hg. absolute was observed. For a fuel-air mixture of .0836 lb. ethylene/lb. air a flame speed increase from 2.2 ft/sec at atmospheric pressure to 4.3 ft/sec at 2" Hg. abolsute. It is interesting to note that the percentage increase in flame speed is about the same for propane, a single-bonded fuel, or for ethylene, a double bonded fuel. It was further noted for the smaller nozzles that the observed flame speed for both propane-air and ethylene-air mixtures is an inverse function of the jet velocity at the lower pressures. It is believed that the reason for this variation is the diffusion of exhaust products into the unburned fuel-air mixture below the flame cone through the "dead space" that separates the flame zone from the burner lip. At higher jet velocities this distance is greater, allowing more diffusion of the exhaust products into the fresh fuel-air mixture, lowering the flame speed. It is probable that a lower jet velocity, therefore, with a correspondingly smaller "dead space" gives a closer approximation to the "normal burning velocity" of the fuel-air mixture at low pressures. Further tests are being made to confirm this supposition.

Flow Associated with the V-Flame

The resonant condition in the 1" x 1" x 24" combustion chamber was previously described. An analysis of this resonant condition showed that a standing wave pattern (corresponding to an open pipe) was produced in the combustion chamber. By positioning the flame holder at the nodal point of this standing wave pattern, it was found possible to reduce the amplitude of the flame fluctuations considerably. Further investigation showed that a "sensitive region", in which any disturbance caused the flame to oscillate, was found about one inch above the flame holder. By placing this sensitive region at the nodal point, the flame fluctuations reduced until the flame was no longer observed to move about the flame holder. These results applied, however, only to low velocity flows, $V_j < 30$ 1/sec. At higher jet velocities, positioning the sensitive region at the node did not reduce the flame fluctuations. No marked increase in blowoff velocity was noted when the flame holder was in this position.

Detonation

Following a suggestion in the book by Jost, fittings were designed for the shock tube to measure velocity of shock waves by bursting of thin diaphragms.

In addition to the above electronic progress, detonation studies have been continued. In the early stages of the present detonation study[6] a bullet was fired into a stoichiometric mixture of propane and air. The shock formed at the nose of the bullet developed a temperature of 1965°R and a pressure of 225 psia but this failed to ignite the mixture. At that time it was concluded that conditions other than just temperature and pressure controlled detonation.

Since then, extensive tests have been made in the shock tube with propane-air mixtures. In the shock tube the fuel-air mixture after passage of the shock is held at the high temperature for a longer period of time. However, even with time ruled out as a factor, the propane-air mixtures have not been detonated up to shock velocities traveling at a Mach No. of 3.5 with reference to ambient mixture.

It is believed that the type of bond in the chemical chain may have some effect on the ease at which gases may be detonated. To attempt to verify this tests have been made in the shock tube with acetylene oxygen mixtures.

These two gases have been detonated successfully in the shock tube at Mach numbers as low as $M = 1.87$. In addition, a stoichiometric mixture of acetylene and air has been detonated with the same bullet test as heretofore mentioned.

Experimental Techniques

The design of the interferometer is at its last stages and will be completed entirely in the next period. Components are being simultaneously manufactured and all shop work should also be let out in the next period. A design report on the interferometer is being prepared.

Work on the two-inch interferometer and on analysis of optical records is continuing.

The light source, BH-6 lamp for continuous and flash operation, has been assembled as a complete and separate unit.

The development of a high speed light source included the calibration of the source with a synchroscope. It is estimated that a duration not exceeding 0.1 microsecond was obtained. In an effort to reduce corona on high-voltage fittings on a light source, a 60-cycle power supply was procured to replace the high frequency supply. Preliminary experimentation with a pressurized spark was performed.

REFERENCES

1) Progress Report No. 9 -- UMR-37 -- University of Michigan AAF Contract W33-038 ac-21100 -- Figure 13, page 21

2) Morrison, R. B., and Dunlap, R. A., "Measurement of Flame Speeds with the V-flame", UMM-21, University of Michigan, Figure 16, page 21

3) Progress Report No. 9 -- UMR-37 -- University of Michigan AAF Contract W33-038 ac-21100 -- Figure 14, page 22

4) Gannett, James R., "A Simplified Method of Calculating Ram-jet Performance Applicable to High Mach Numbers", UMM-7, University of Michigan, Page 15

5) ibid., Figure 4A, page 59

6) Progress Report No. 1 -- UMR-21 -- University of Michigan AAF Contract W33-038 ac-21100 -- page 8 ff.

ERRATA

Maximum S_a for gasoline and for propane - Figure 9 - the F/A ratio should read 0.06 in both cases.