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PROGRESS REPORT NO. 8
AAF CONTRACT W33-038 ac 2100
PERIOD 8
1 September to 1 November, 1949

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II. SUMMARY OF WORK CONDUCTED DURING THE PERIOD

Blowoff Velocities of Flameholders

The system used for obtaining atmospheric blowoff points was not satisfactory for vacuum operation since steady burning could not be obtained. The system designed for measuring Bunsen flame speeds under vacuum was used to obtain blowoff data for a 1/8 inch and 3/32 inch diameter spherical flame holder in a 3/8 inch diameter jet. Data was obtained for nine fuel-air ratios at pressures from 0.4 atm. to 1 atm. Photographs of a time sequence of a flame approaching blowoff under vacuum were obtained.

Combustion Chamber Design

Work for this period consisted of tests directed toward learning the effect of position of fuel injection on combustion chamber performance. Studies and experiments are also in progress toward learning more about the important basic parameters affecting the flame holder.

Pressure and Temperature Effects on Combustion

During the preceding period the large burner system was used most of the time to obtain blowoff velocities of various spheres at reduced pressures. Several photographs were made of Bunsen flames at various pressures in this larger burner system. They appear in Figure 15. It appears that the larger system has inherent advantages over the smaller system and will be used for the completion of the Bunsen flame studies in the future.

Flow Associated with the V-Flame

The experimental values for frequency of tone emitted from the confined V-Flame agree closely with the theoretical values (which were derived by assuming resonance). This agreement indicates that the tone is due to resonance of the hot and cold gases.

Detonation

Initial detonation tests were undertaken; however, no conclusions could be drawn from these tests. The spark source was triggered with the passage of the shock down the tube at reservoir pressures of 1,300 psig.

Blowdown Equipment

All components of the blowdown system have been assembled. Testing of the equipment up to the required pressures has been initiated.

Experimental Techniques and Instrumentation

Interferometer - Certain parts have been redesigned and are now being manufactured.

Shadowgraph Equipment - Thyratron control is being incorporated in a new unit.

III. PROGRESS

Blowoff Velocities of Flameholders

The system previously described for obtaining atmospheric blowoff points was modified in an attempt to obtain blowoff velocities under vacuum. A schematic diagram of this apparatus may be seen in Figure 1. Attempts to obtain steady state burning were unsuccessful and resulted in a series of explosions, the last of which badly damaged the equipment. One explanation of the inability to achieve steady burning is as follows: a stagnant zone of combustible gas accumulated in certain sections of the pyrex pipe. This accumulation was due either to the geometry of the system or the insufficient capacity of the vacuum pump (30 cfm). The sudden ignition of the mixture lowered the jet velocity from 100 ft/sec to zero and allowed the flame to burn back into the drum. Secondary air was injected, as shown in Figure 1, in an effort to dilute the combustible mixture until steady state combustion was secured. This experiment failed, as well as an experiment in which the transition section was removed, leaving the pyrex pipe open to the atmosphere. Secondary air was also used. The resulting explosion was severe enough to badly deform the drum cover.

It became apparent from these attempts to ignite the burner that major modifications were necessary to obtain low pressure stability limits. In the meantime, other members of the group had been successful in securing stable burning under vacuum, using a Bunsen tube and low jet velocities. After some extensive experimenting with the pressure and temperature equipment, it became apparent that blowoff velocities under vacuum could be obtained with the apparatus after some modification. Figure 2 is a schematic diagram of the pressure and temperature equipment converted to secure stability limits under vacuum. Accordingly, the program of obtaining Bunsen and V-flame speeds under vacuum was temporarily postponed and the combined personnel used to obtain blowoff velocities under vacuum. The essential differences between the two systems are summarized in the table below.

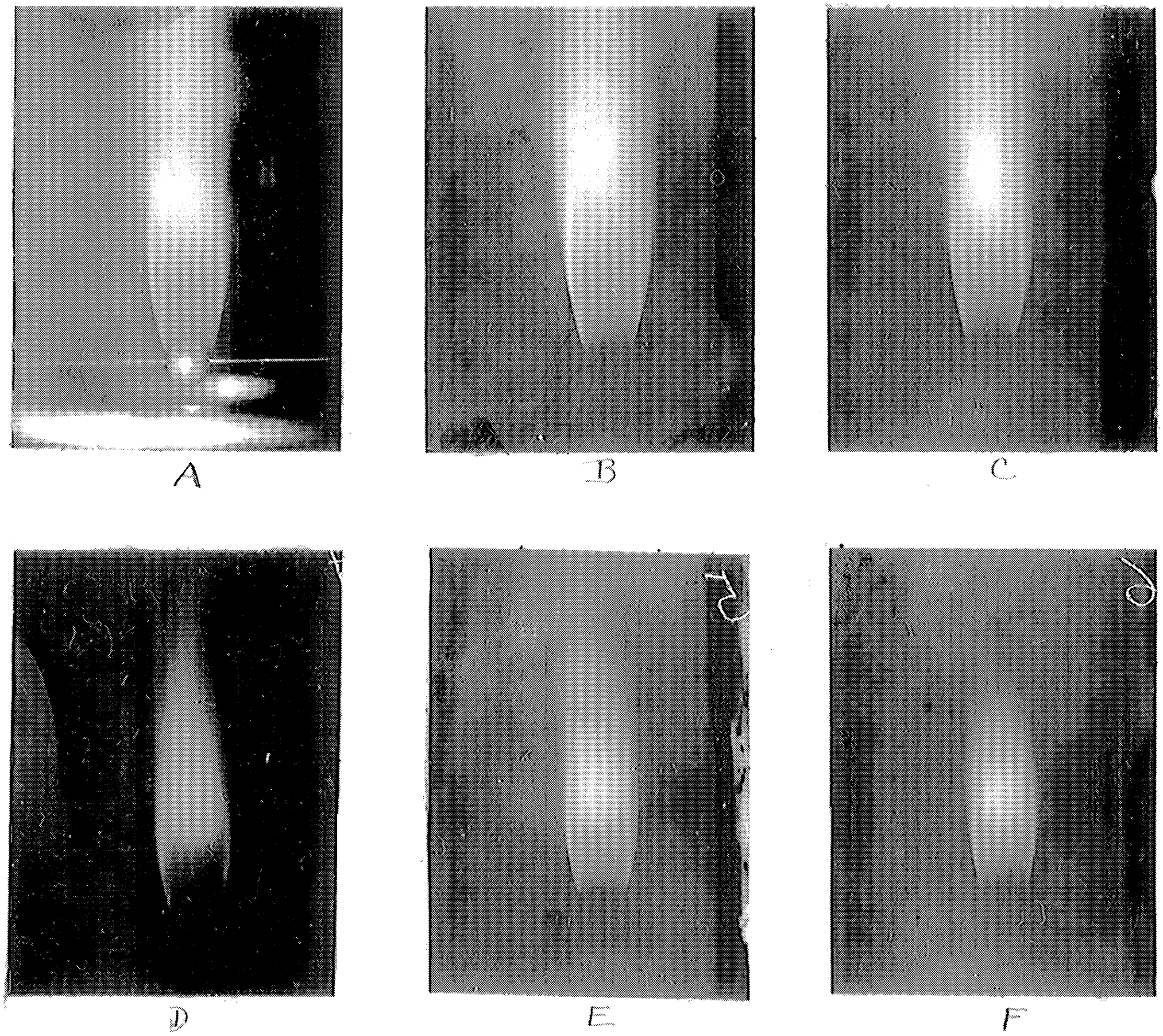
	System 1	System 2
Nozzle Diameter Used	1 inch	3/8 inch
Ratio of Area Downstream of Nozzle to Nozzle Area	36/1	1300/1
Ratio of Area Upstream of Nozzle to Nozzle Area	625/1	29/1
Method of Obtaining Fuel-Air Ratio	Fuel and Air metered separately and mixed just before drum entrance.	Fuel and Air premixed and stored in cylinder a constant F/A is always obtained.

The preliminary investigations indicated that the flame under vacuum was very sensitive to vibrations and that the system as a whole was very sensitive to pressure fluctuations. Surging of the flame itself and of the box pressure, once initiated, continued with increasing complitude until the local velocity by the holder became so high that the flame was blown out. After extensive investigations, this situation was finally alleviated by the installation of a surge tank in the vacuum line and by throttling the inlet to the vacuum pump. This eliminated the procedure of increasing the jet velocity at a constant pressure by opening the valve in the feed line--thus initiating a surge. With the surge tank installed the vent to the vacuum line was closed after an initial velocity and pressure were established in the box. The slowly decreasing pressure causes a corresponding increase in jet velocity and the blowoff point is obtained instantaneously.

A sequence of six pictures approaching the blowoff point is reproduced in Figure 3. Photographs A, B, C, D, E, & F were taken at increasing velocity and decreasing pressure from left to right with photograph F taken just prior to blowoff. This sequence illustrates a point of major importance in the investigation. It can be seen from this series of photographs that a zone of violently agitated and burning gas starts at the downstream end of the pilot ~~zone~~ flame and ~~becomes~~ increasingly larger, approaching the holder just before blowoff. (2 In every case where the velocity was great enough to allow burning ~~beyond the V-flame condition~~, the phenomena was noted before blowoff. The agitated region is very close to the holder just before blowoff and moves about quite rapidly. At the instant that this region touched the downstream side of the flameholder, blowoff occurred. This phenomena was noted during the atmospheric blowoff runs; however, there was not enough contrast between the wake and the agitated zone to allow a photograph or a close observation of the occurrence.

The technique previously described was used to obtain blowoff data in a 3/8 diameter jet for fuel-air ratios of .060, .0637, .070, .075, .080, .085, .090, .095, and .100. Two flame holders of 3/32 and 1/8 diameter were tested during this period. The holders were tested at pressures ranging from .4 atm to 1.0 atm. The absolute pressure at blowoff was plotted against mass velocity at blowoff for each fuel-air ratio and the experimental data smoothed on these plots. Typical data obtained is shown in Figures 4, 5, 6, and 7. The summary of all of these plots for the 3/32 and 1/8 spheres is shown in Figures 8, 9, 10, and 11. (3) These curves were then used to obtain a cross plot of fuel-air ratio vs. mass velocity for pressures of 750, 600, 450, and 300 mm. of Hg. The results are shown in Figures 12 and 13 for the 3/32 and 1/8 sphere respectively. This data is compared to the data previously obtained[1] using a 1 inch nozzle at atmospheric pressure. The data obtained from a 1 inch nozzle was found to be slightly in error due to a mistake in rotameter calculations. It has been recomputed and is shown in Figure 14.

Lack of time in this period prevented computation of linear velocities and a complete analysis of the data. A consideration of Figures 12 and 13 indicates the considerable effect of jet size on stability limits. An investigation of the scale effect is now underway. The stability limits for the 3/32 and 1/8 spheres as obtained in the 3/8 jet under vacuum are concurrent on the rich side. This is also characteristic of the results obtained from the 1 inch jet at atmospheric pressure.



A B C

D E F

FIGURE 3
PHOTOGRAPHS OF BURNING FROM A
SPHERICAL FLAMEHOLDER UNDER VACUUM

FUEL AIR RATIO = 0.080
Nozzle Dia. = 3/8"
SPHERE DIA. = 3/16"

PHOTOGRAPH NO.	ABS PRESSURE mm of Hg
A	680
B	465
C	412
D	359
E	333
F	307

FIGURE 4

EXPERIMENTAL DATA

MASS VELOCITY AT BLOWOFF

VS.

ABSOLUTE PRESSURE

FUEL-AIR RATIO = 0.095
SPHERE DIA. = 3/32"
NOZZLE DIA. = 3/8"

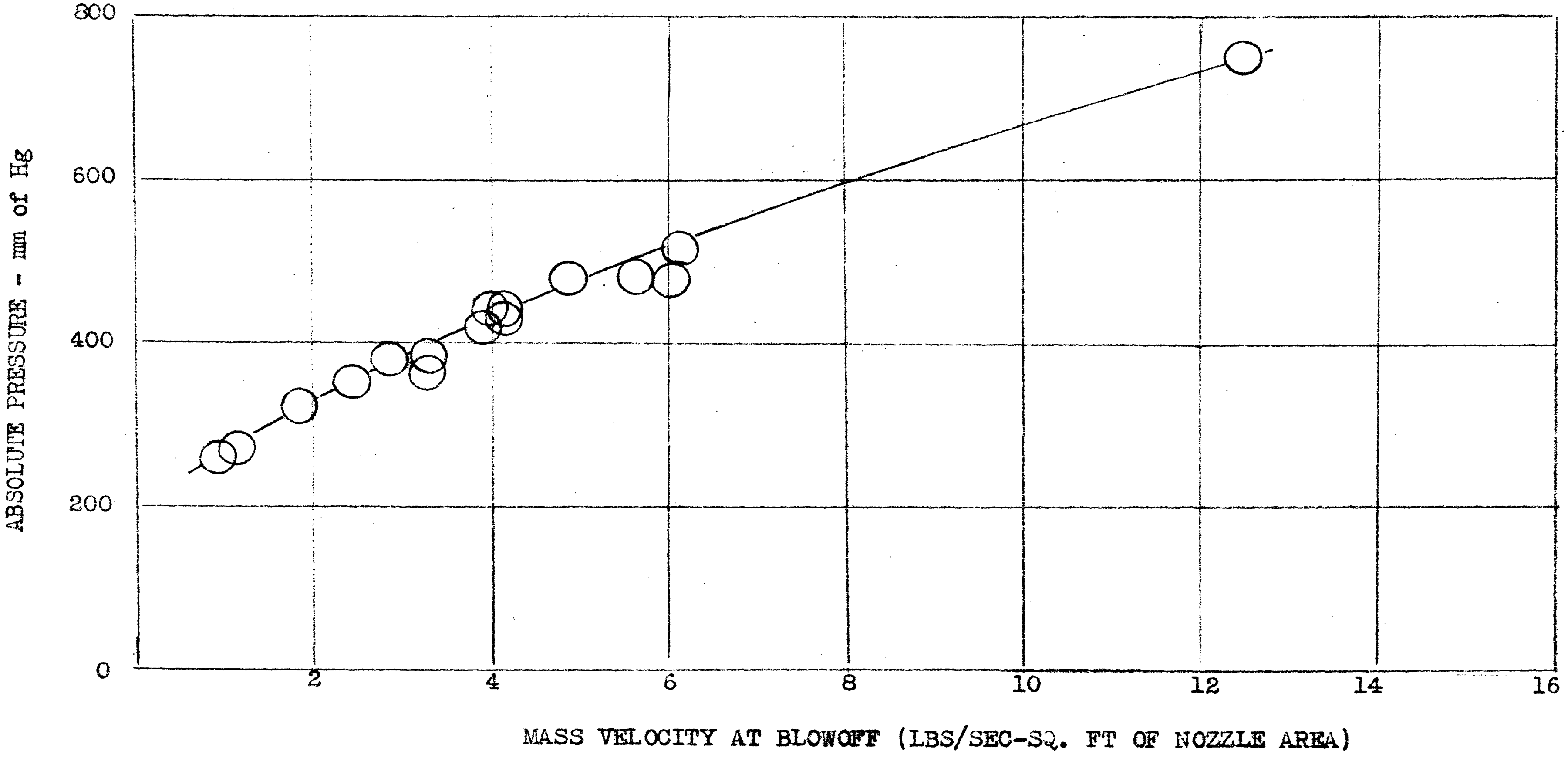


FIGURE 5

EXPERIMENTAL DATA

MASS VELOCITY AT BLOWOFF

VS.

ABSOLUTE PRESSURE

FUEL-AIR RATIO = 0.0637
SPHERE DIA. = 3/32"
NOZZLE DIA. = 3/8"

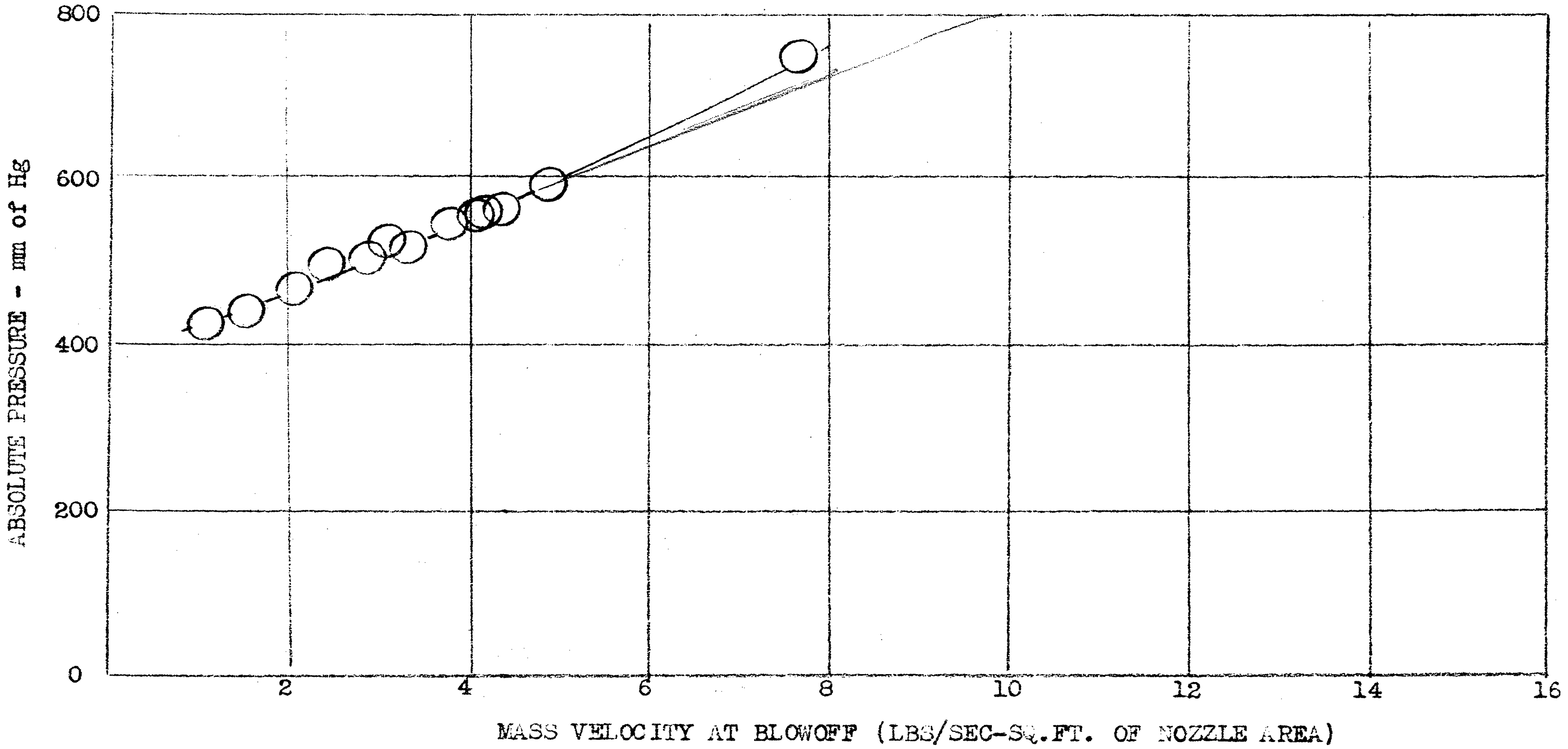


FIGURE 6

EXPERIMENTAL DATA

MASS VELOCITY AT BLOWOFF

VS.

ABSOLUTE PRESSURE

FUEL-AIR RATIO = 0.095
SPHERE DIA. = 1/8"
NOZZLE DIA. = 3/8"

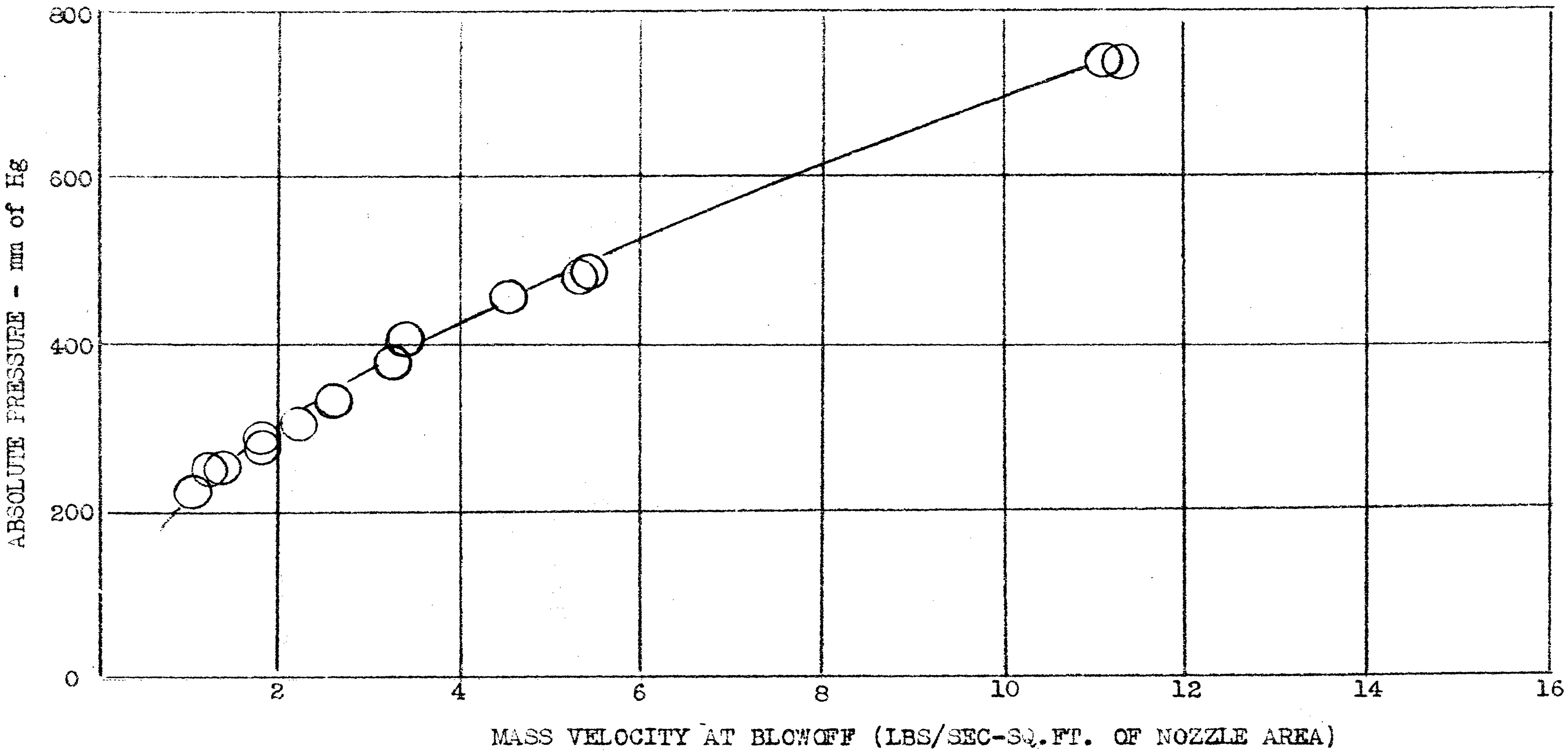


FIGURE 7

EXPERIMENTAL DATA

MASS VELOCITY AT BLOWOFF

VS.

ABSOLUTE PRESSURE

FUEL-AIR RATIO = 0.0637
SPHERE DIA. = 1/8"
NOZZLE DIA. = 3/8"

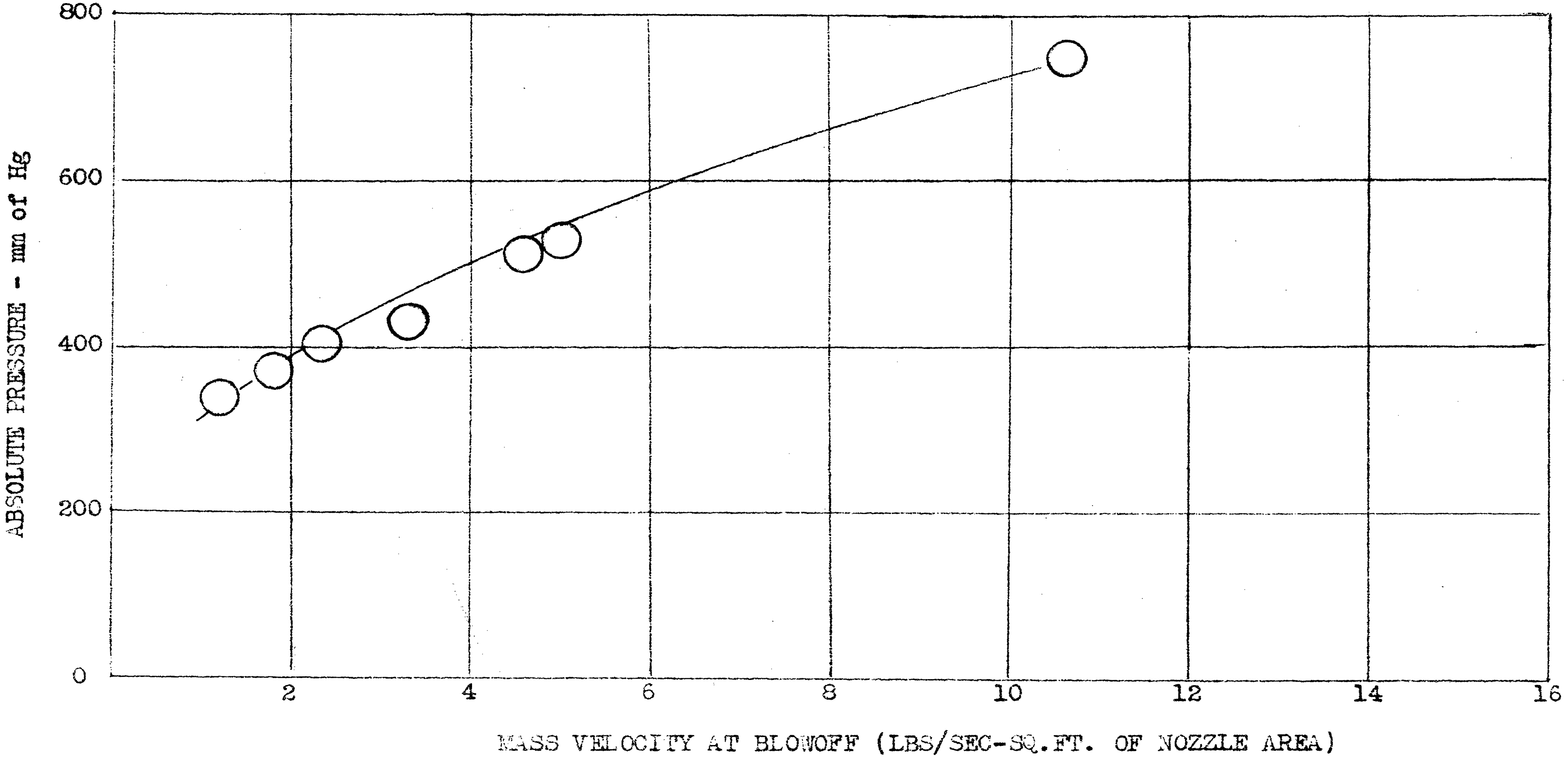


FIGURE 8

MASS VELOCITY AT BLOWOFF
VS.
ABSOLUTE PRESSURE
3/8 INCH DIAMETER JET
3/32 INCH DIAMETER SPHERICAL FLAMEHOLDER

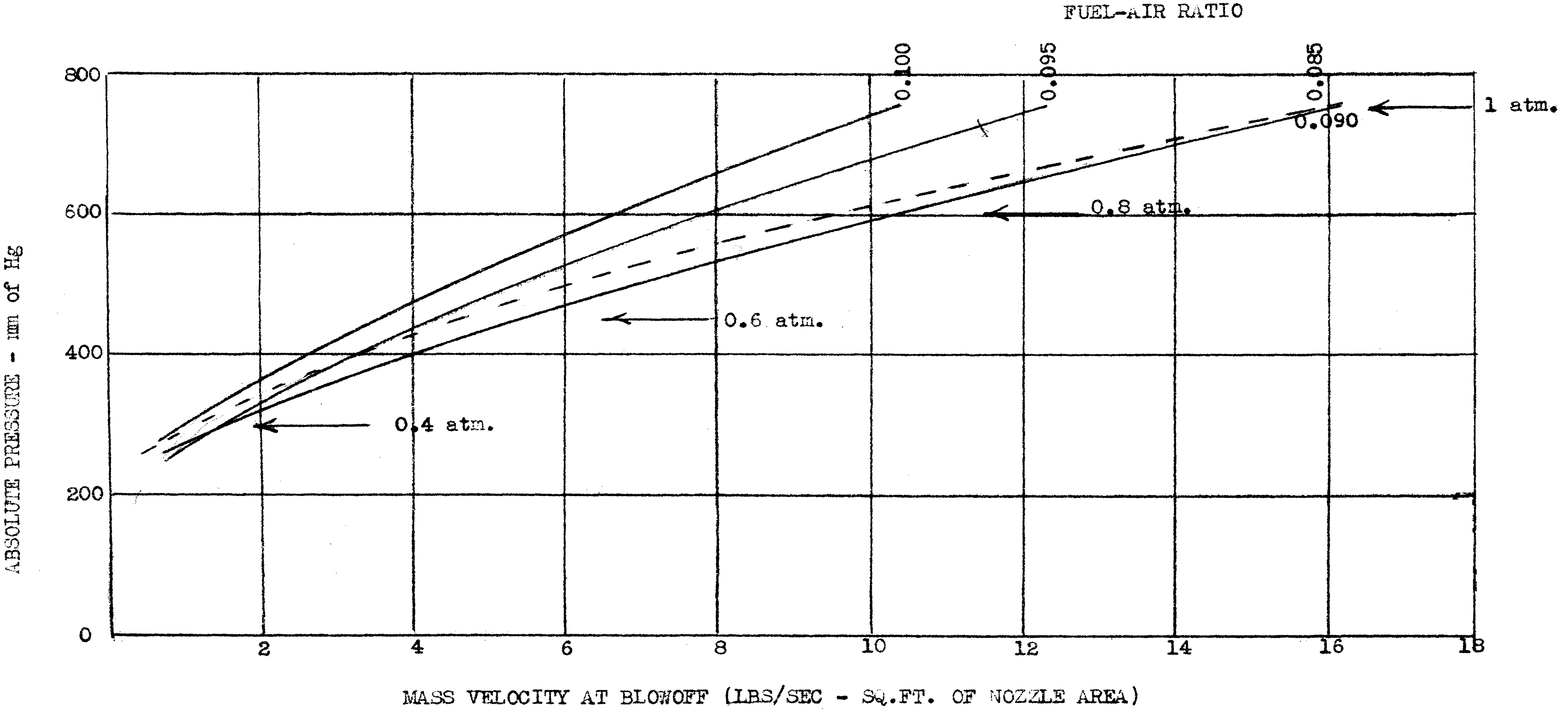


FIGURE 9

MASS VELOCITY AT BLOWOFF

VS.

ABSOLUTE PRESSURE

3/8 INCH DIAMETER JET

3/32 INCH DIAMETER SPHERICAL FLAMEHOLDER

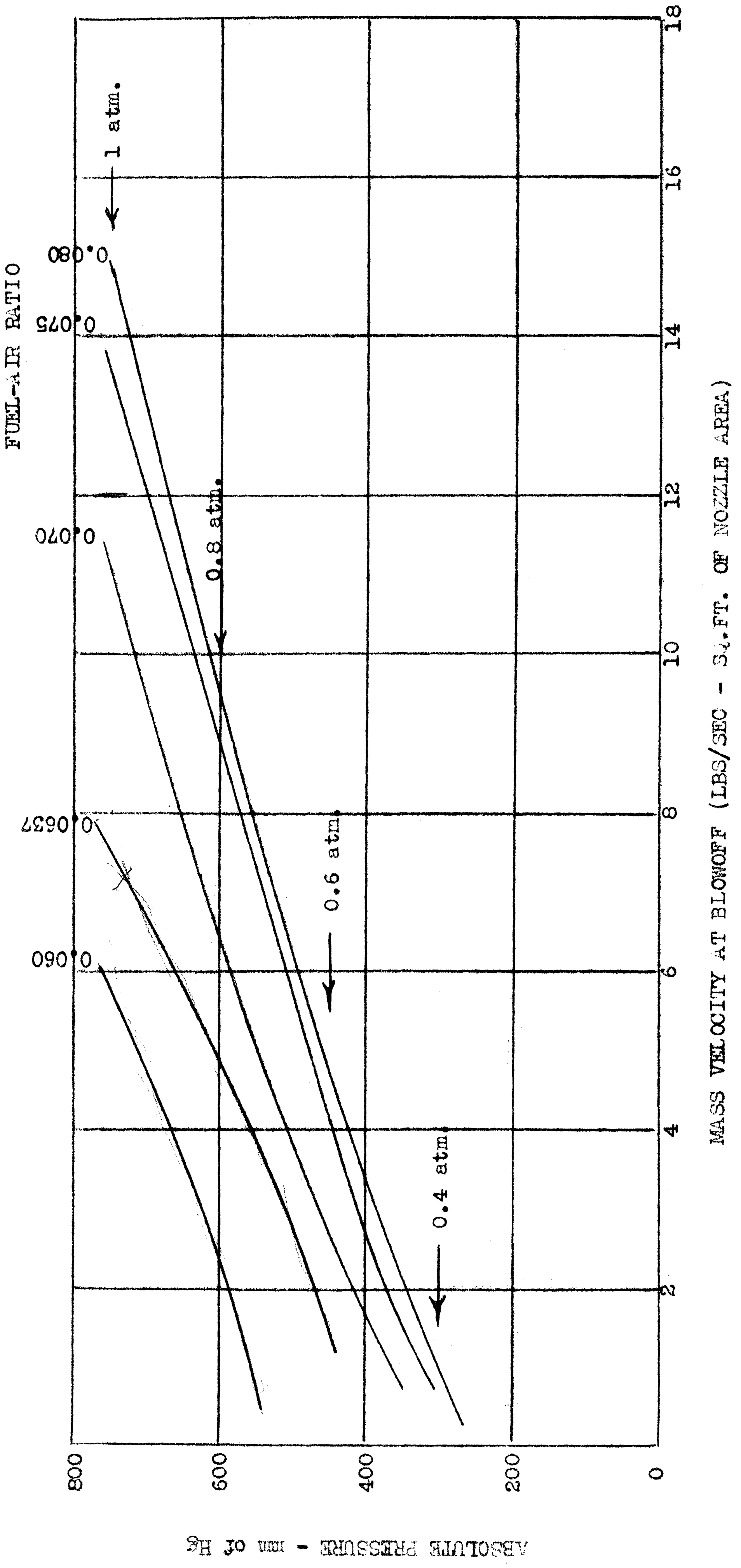


FIGURE 10

MASS VELOCITY AT BLOWOFF

VS.

ABSOLUTE PRESSURE

3/8 INCH DIAMETER JET

1/8 INCH DIAMETER SPHERICAL FLAMEHOLDER

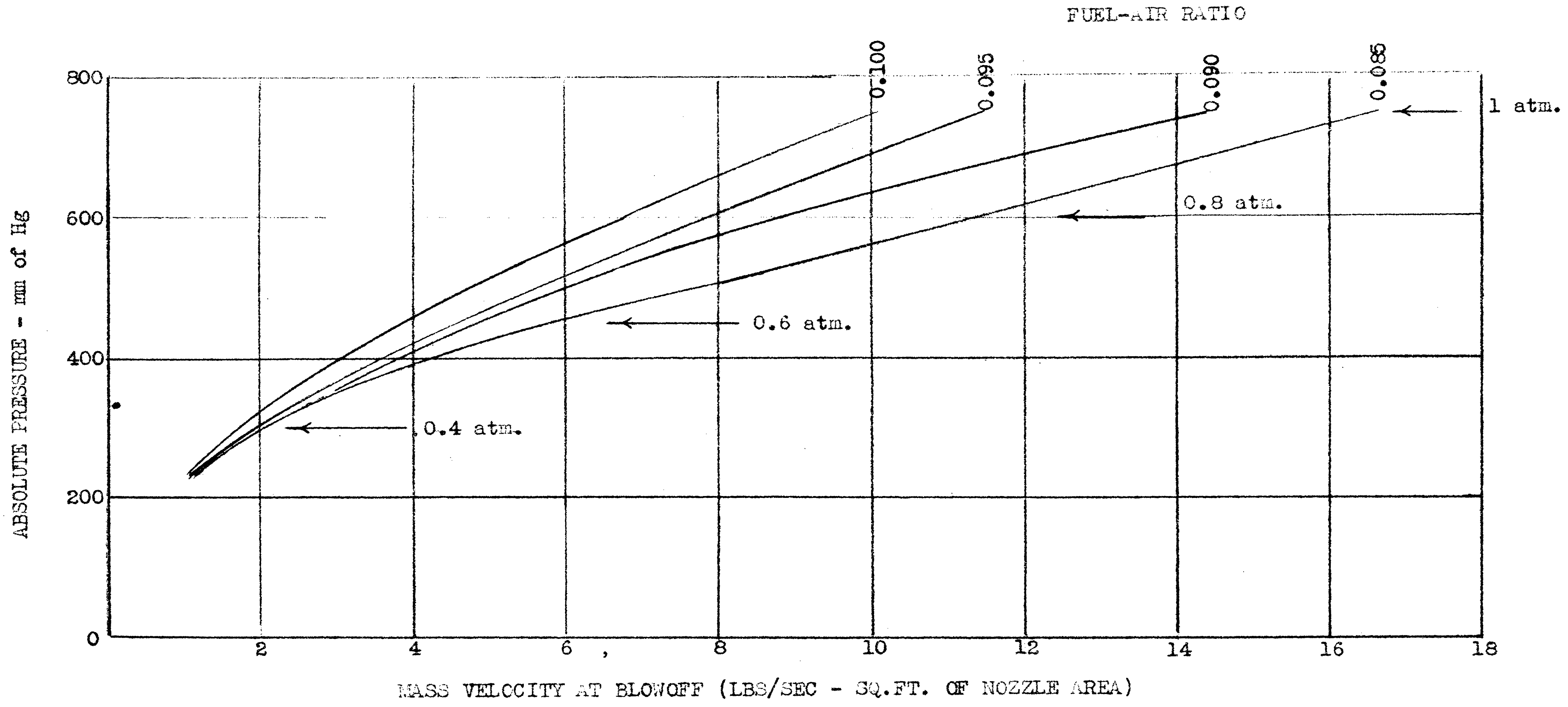


FIGURE 11

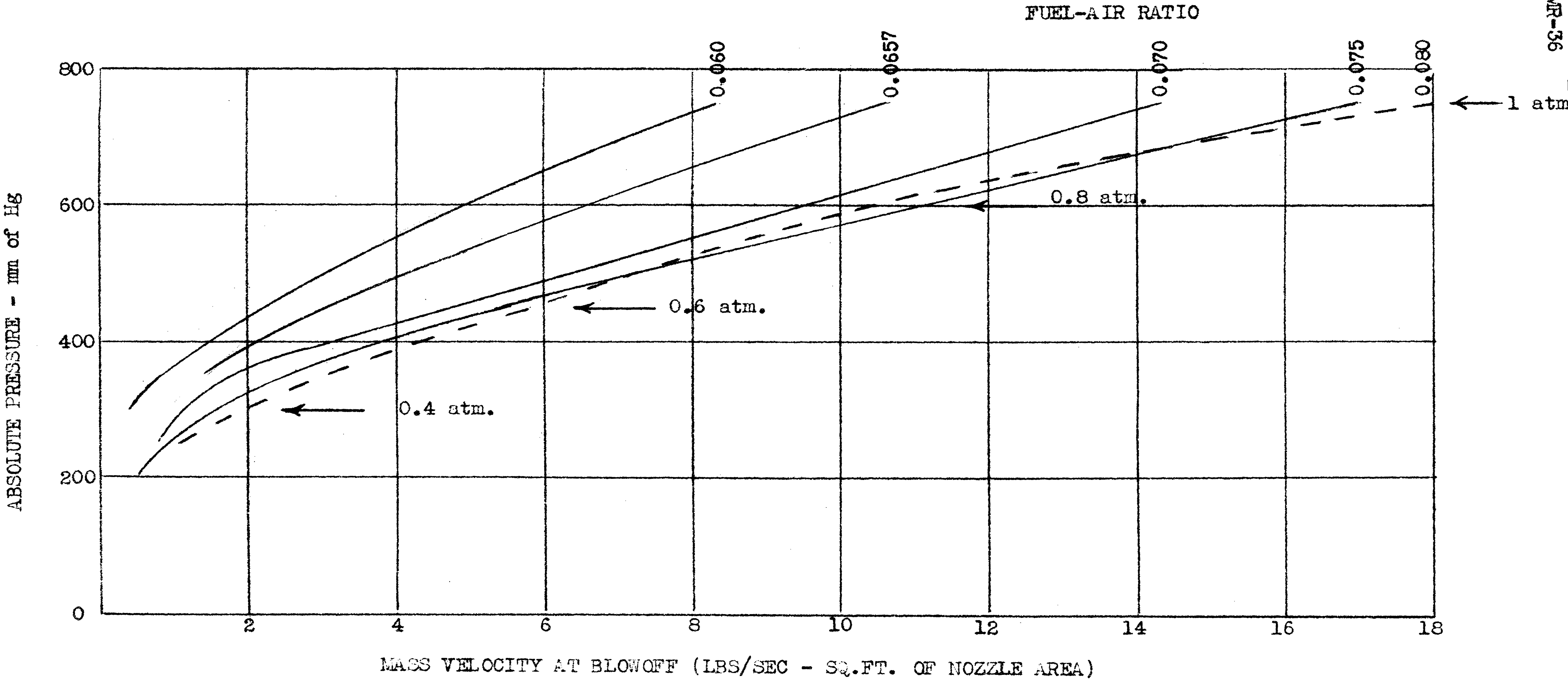
MASS VELOCITY AT BLOWOFF

VS.

ABSOLUTE PRESSURE

3/8 INCH DIAMETER JET

1/8 INCH DIAMETER SPHERICAL FLAMEHOLDER



Combustion Chamber Design

Work is being continued to more definitely establish the nature of the explosive, low frequency variety of "rough burning." The frequency of the explosions was obtained for a small scale two-dimensional combustion chamber using propane, and a simple flat plate flame holder. For the ~~three~~ few points obtained the frequency is a linear function of the air velocity which further substantiates the suggestion that this type of "rough-burning" is a blow-out and re-ignition of the fuel-air mixture. The explosions were obtained with a range of rich fuel-air ratios where the flame would not hold but would ignite after blow-out. It was possible to record the frequency of the explosions with the simple flame holder because of the singular position for re-ignition, whereas with a multi-plate holder no regular frequency is distinguishable because of local blow-out and re-ignition occurring at different parts of the holder.

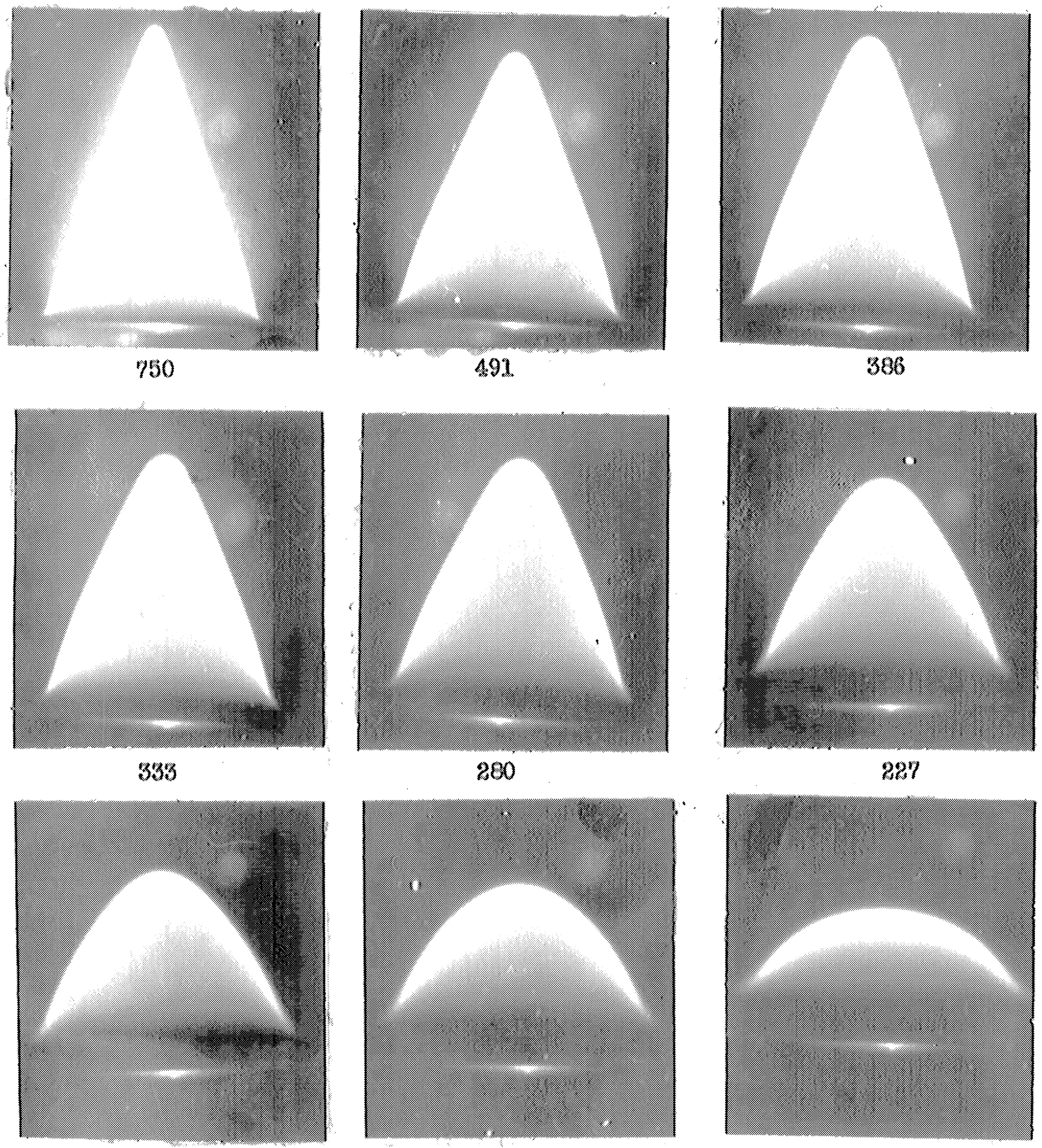
Several experiments were performed by applying suction and pressure to holes in the downstream face of a flat-plate flame holder. The stability of the holder was adversely affected by feeding air through the holes, but no effect was observed when vacuum was applied to the holes. A vacuum of 13 cm of Hg was recorded in the vacuum line thirteen inches from the holder. However, the significance of these results can not be determined until the experimental technique is further refined.

Work on the four-inch combustion chamber was concerned with observation of the performance, ignition limits, and the flame holding ability of a particular holder under various test conditions. The position and direction of the fuel-injector was varied in the four-inch combustion chamber. This should have some effect on the degree of vaporization of the liquid fuel. In order to obtain a more uniform mixture of fuel and air, a contraction in the duct in the form of a funnel was placed near the annulus section where ignition occurs. The funnel contracted to fifty per cent of the duct area and also served quite well as a flame holder. The tests are not yet complete; however, it is felt that some progress has been made in eliminating the combustion roughness by better mixing of the fuel and air and by simplifying the flame holder design. The performance with the small scale combustion chamber was similar to that of the four-inch combustion chamber, i.e., combustion was smooth except with rich fuel-air mixtures.

Pressure and Temperature Effects on Combustion Processes

In the previous progress report (Ref. 2) it was stated that the small burner appartus would be used to complete the studies of Bunsen flames at reduced and at greater than atmospheric pressures. It appears, however, due to the flexibility of the larger system that it would be advisable to conduct these experiments on the larger system. Preliminary tests made indicated that a more complete range of pressures is obtainable with the use of the large system. Bunsen flames at reduced pressures using the 1/2" nozzle proved to be more stable and seemed to give a more well-defined flame surface than did Bunsen flames in the small apparatus. The flames were stable and well-defined at pressures as low as 3 psia. With the small system it was impossible to stabilize a Bunsen flame having a large enough flame surface with which to measure flame speeds at pressures much below 5 psia. A series of photographs of Bunsen flames at various pressures burning above a 1/2" nozzle is shown in Figure 15. Furthermore, at increased pressures, the laminar Pouisselle flow in the Bunsen tube with the small system became turbulent at fairly low positive pressures. With the larger system this limitation does not exist due to the fact that the flow velocity in the larger burner tube is small enough to keep the Reynolds number below the critical value before the nozzle. This produces a well defined flame front even at fairly high pressures.

The program of obtaining Bunsen flame speeds on the large burner tube was temporarily curtailed during this period to study another phase of the contract, i.e., blowoff velocities of spheres at reduced pressures. Slight alterations in the apparatus were necessary to accommodate the larger mass flows required.



750 491 386

333 280 227

201 175 148

FIGURE 15
PHOTOGRAPHS OF BUNSEN FLAMES AT REDUCED PRESSURES

FUEL-AIR RATIO 0.080
Nozzle Dia. 1/2"
NUMBERS BELOW PHOTOGRAPHS INDICATE ABS.
PRESSURES IN mm Hg

Flow Associated with the V-Flame

It was previously stated that the confined V-Flame (one in a parallel wall combustion chamber) gives off a tone which is inherent to this type system. Associated with this tone is the wave-type flame previously shown.[3] It was thought that perhaps this tone was the result of resonance between the hot and cold gases and an expression for this tone was previously derived.[4] This expression was rearranged as shown below:

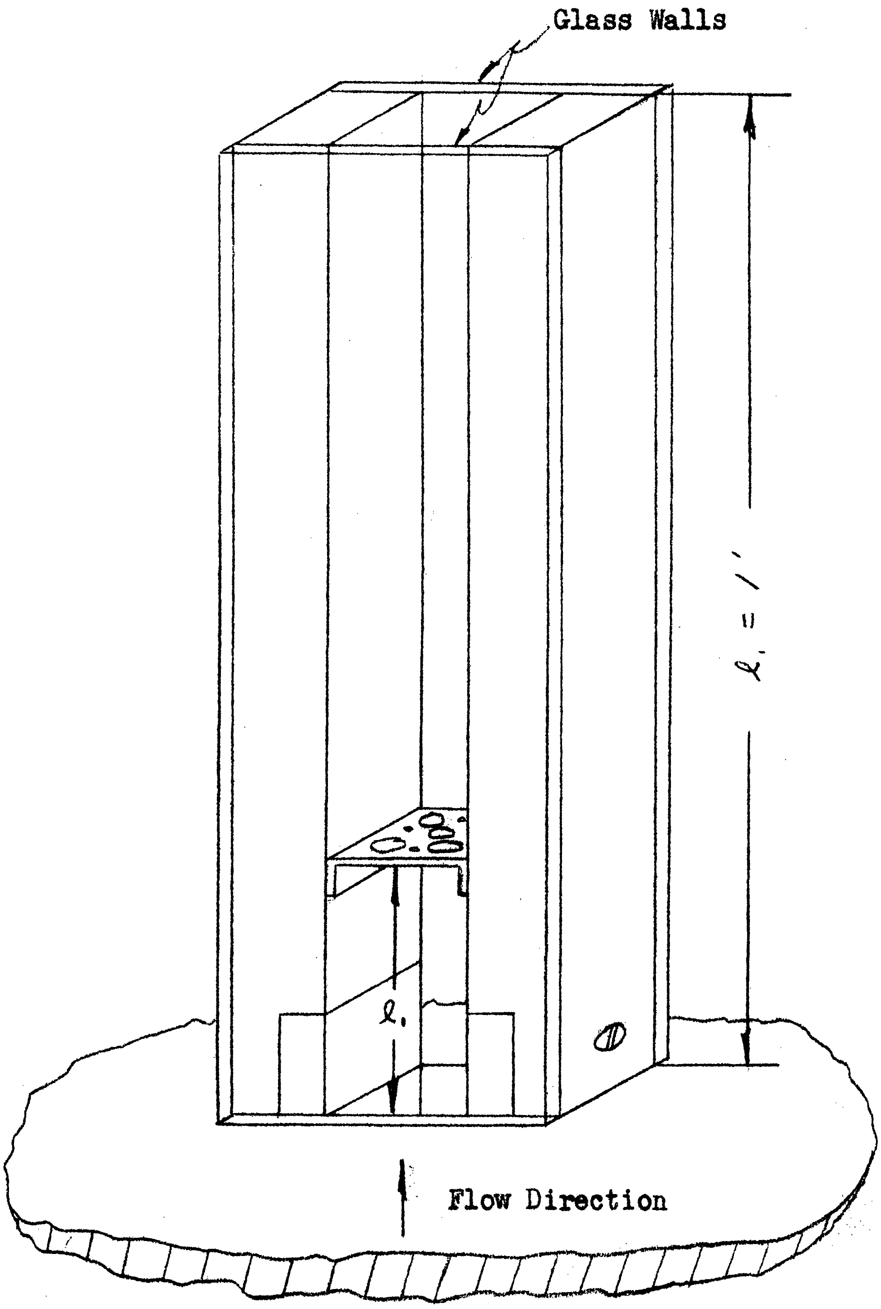
$$\tan \frac{2\pi n l_1}{\sqrt{\Gamma_1 R_1 T_1}} = -\sqrt{\frac{T_1}{T_2}} \tan \frac{2\pi n (L - l_1)}{\sqrt{\Gamma_2 R_2 T_2}}$$

(1) refers to unburned gas
(2) refers to burned gas
Γ = ratio of specific heats
T = Temperature of gas
ρ = density of gas
P = pressure of gas
$R = \frac{(\text{universal gas constant})(\text{acceleration of gravity})}{\text{average molecular weight}}$
n = resonant frequency
L = total length of combustion chamber
l_1 = length of column of unburned gas

To check this expression a multiple flameholder (Figure 16) was placed at various positions in the combustion chamber (Figure 16) and the resultant tone frequency was obtained by matching it with the tone of an audio oscillation. The following assumptions were made in the calculation:

1. $\frac{\rho_2}{\rho_1} = 0.2$ (verified by previous experimental data[5]
2. $\frac{P_2}{P_1} = 1$
3. Average molecular weight$_1$ = average molecular weight$_2$
4. Hence by perfect gas laws: $\frac{T_2}{T_1} = 5$

The theoretical and experimental results are shown in Figure 17. The calculated frequency agrees with the observed frequency very well in the range of l_1 between 0.2 and 0.5. In the higher range of l_1 the tone given off the chamber was not clearly defined and might explain the discrepancy. In the range of l_1 between 0 and .2 a low frequency oscillation of the entire flame about the flameholder began. The noise from this oscillation masked the higher frequency resonance tone, restricting all observations to a region above $l_1 = .2$. The experimental data obtained in the region l_1 = .2 to 1.0 does check closely with theoretical expectations, indicating this tone observed is one due to resonance.



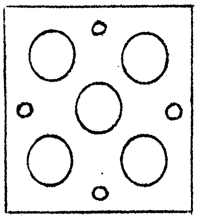
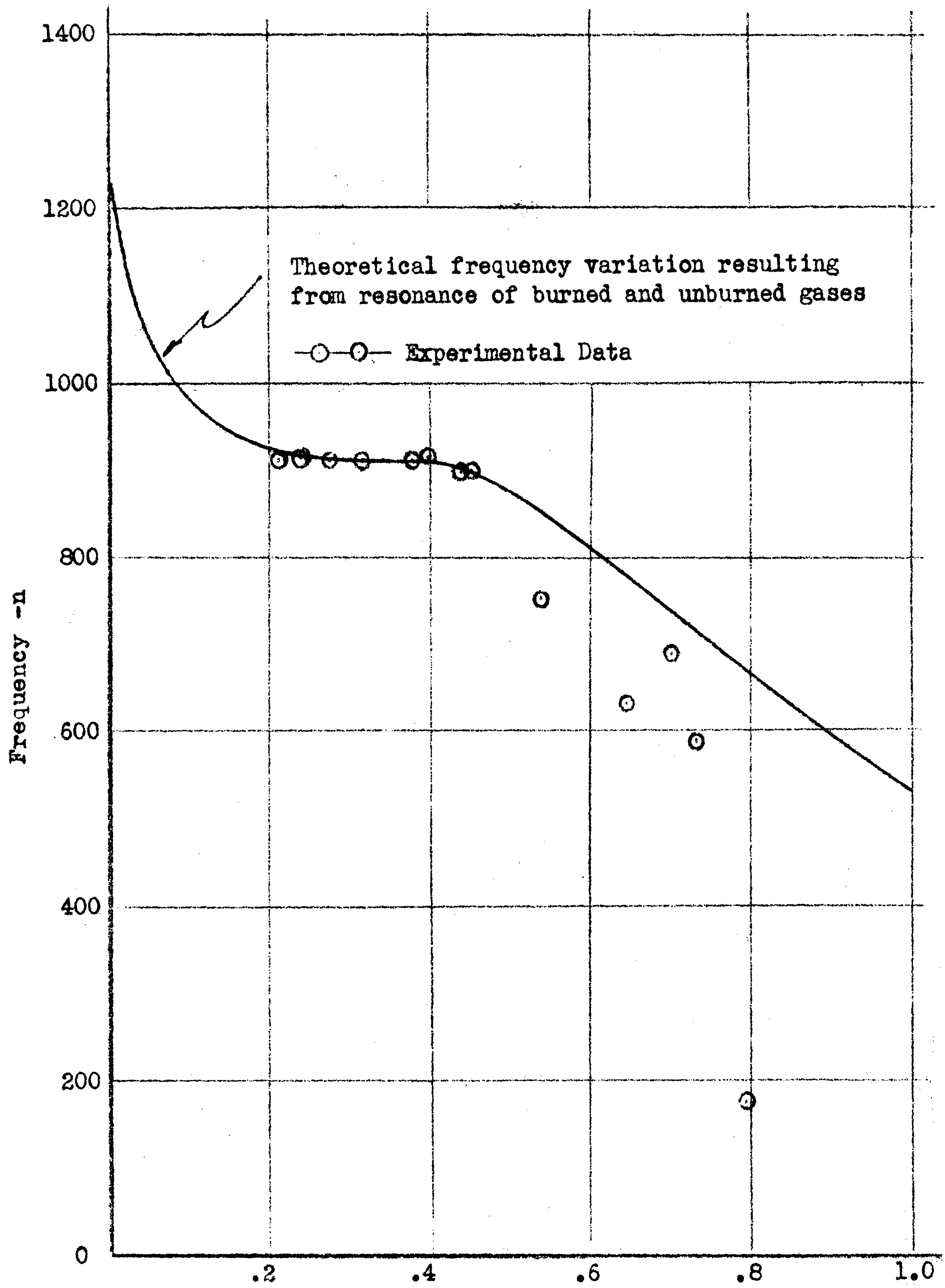


FIGURE 16

Schematic of a 1" x 1" x 12" rectangular combustion chamber showing the flame holder used in resonance tests



Frequency of tone observed from a propane-air flame burning in a 1" x 1" x 12" rectangular combustion chamber. The frequency is varied by varying the position (l_1) of the flameholder.

FIGURE 17

Detonation

14.7

The complete assembly of shock tube, reservoir, and valve housing was tested with the shock tube filled with air at 14.7 psia and the reservoir filled with helium at varying pressures up to 2,200 psia. In these first tests a 610 pound die spring pulled the slide valve open and allowed the reservoir gas to act as a contact surface and form a shock wave.

It was found that the spring could not pull the valve at the higher reservoir pressures. The area over which the reservoir pressure acted was too large, which resulted in a friction force greater than the force of the spring. The maximum reservoir pressure at which the valve would operate was 900 psia. However, initial tests were undertaken with this upper limit. The test section was filled with a stoichiometric mixture of propane and air and the valve was tripped. No photographs or shadowgraphs were taken. The experiment was performed three times, twice with a fuel air mixture in the test section and once with air in the test section. The lab was darkened for all three tests. Some observers thought they could detect a flash in the test with a fuel air mixture in the shock tube but not in the test with air in the test section.

After these preliminary experiments, attempts were made to take flash shadowgraphs to establish whether or not shock ignition actually occurred in the test section. The spark needed to take these shadowgraphs was triggered by the passage of the shock down the tube. A schematic diagram of the trigger circuit has previously been reported (Ref. 6). A narrow slit of light was focused on the center line of the shock tube. The light was then collected after passage through the test section and then the slit of light was focused on the photoelectric cell. With the passage of the shock down the tube the slit of light was deflected, causing a decrease in light intensity on the photoelectric cell. The resulting pulse from the photoelectric cell was enough to trigger the thyratron and discharge a condenser into the primary of a Plymouth induction coil. The discharge from the secondary coil was used to break down a Liebessart gap and thus allow for the discharge of a 5,000 volt condenser. The flash from the Liebessart gap was used as a light source for a shadowgraph.

It is believed that the time lag due to the induction of the circuit allowed the shock to move downstream of the test section before the Liebessart gap was broken down. To correct this the photoelectric trigger will be moved slightly upstream and a three or four foot strip film will be used instead of the small 4" x 6" photo plate.

The area of the valve seat was reduced 2/3, a 690 pound die spring was installed and the surfaces of the valve slide and seat were chromium plated. It was found after reassembly that the valve would operate at reservoir pressures up to 1,400 psig. A hydraulic system has been installed which will develop reservoir pressures up to 3,000 psig. It is believed that the slide valve with the improvements as listed above will operate successfully at reservoir pressures up to the design limit of 3,000 psig.

Blowdown Equipment

A schematic diagram of the blowdown system is shown in Figure 18. The construction work accomplished during the previous period is outlined below.

The two 80 cubic feet, 3500 psi accumulators were first prepared for operation. The tanks were sprayed inside and out with a commercial rust preventive paint. The problem of spraying the interior of the tanks posed a difficult problem, since the openings to the tanks were not large enough for a man to enter. Spraying was finally accomplished by pressurizing a steel flask and forcing the paint up through the bottom on to the tank walls.

Next the blind flanges for the bottoms of the tanks were installed. Each flange was sealed by means of a brass ring pressing against an aluminum ring which in turn pressed against the inside of the flange and against the inside of the tank opening. The rings were made to contact each other at a 30-degree pressure angle, so that tightening the flange holding nuts pushed the sealing rings upwards and outwards, making a positive seal between the tank wall and the flange.

When the installation of the bottom flanges was complete, the remaining high pressure air piping was installed. This included ½" piping from the air compressors to the accumulators, 2½" piping from the accumulators to the Foster pressure reducing regulator, 4" piping from the Foster regulator to the heat exchanger, ½" piping for the water drainage system at the bottom of the accumulators, and ½" piping for the propane heating system.

The high pressure air system was next given a hydraulic test which proceeded as follows: the accumulators were filled with water upstream of the Nordstrom on-off valve and vented at the top of the tanks. When the accumulators and air lines were filled with water, a hydraulic testing machine was connected into the closed system and the system pressure built up to 3650 psi. This pressure was held for over an hour, during which time no leakage was noted. Since maximum operation of the system would be restricted to 3000 psi, and the system designed for approximately 3500 psi working pressures, it was decided that the pressure test was satisfactory. The accumulators, incidentally, had been tested by the manufacturer in 1943 to 5500 psi.

The system has been pressurized with air to ca. 2200 psia. Several blowdown runs have been made through the Foster regulator valve with satisfactory results.

The heat exchanger is being filled with Alumite grog. It should be available for testing shortly.

Doors have been installed on the compressor shed. The exhaust lines from the engines have been piped outside of the shed. Alcohol has been added to the cooling system of the compressor-engine units. The engines have been operated satisfactorily with vaporized propane from the 1200 gallon supply tank.

During compression, it was observed that one engine overheated. The cause was ascertained to be the high temperature of the air in the compressor shed. Preliminary design of a system to remove the hot air has been started. It is planned to install a ventilator on the roof of the compressor shed.

Research Techniques and Instrumentation

Interferometer - Holders and suspension for the main glass plates have been redesigned and these parts are now being manufactured. Redesign of other parts is proceeding and individual sub-assemblies will be let out for manufacture as soon as the drawings are completed. The four main glass plates have also been manufactured.

Shadowgraph Equipment - The technique of using the spark as a light source for photography is being modified so as to utilize a thyratron tube for control. The flexibility of thyratron control makes this technique attractive. A spark unit is under construction which will utilize thyratron control. This unit will be available in addition to the unit already on hand which uses the three electrode spark gap triggered by an induction coil.

IV. PROGRAM PLANNED FOR PERIOD 9 (1 November, 1949 to 1 January, 1950)

Blowoff Velocities of Flameholders

It is planned to obtain the following experimental data during the coming period:

1. Blowoff data under vacuum for a 1/16 inch and 3/16 inch diameter sphere in a 3/8 inch diameter jet for nine fuel-air ratios.
2. Blowoff data at atmospheric pressure at a fuel-air ratio of 0.08 for 1/4 inch, 3/8 inch, and 1/2 inch diameter jet for various spheres to compare with the data obtained in a 1 inch diameter jet.
3. Blowoff velocities at various heights of the flameholder above the jet.

It is hoped that this data will enable some correlation involving jet diameter for the various spheres. It is planned to have this data, as well as the data obtained during this period, plotted not only on mass velocity plots but also plotted as fuel-air ratio versus linear jet velocity and fuel-air ratio versus the reciprocal of the square root of the Reynolds number for various pressures.

It is also planned to take Fastex pictures and shadowgraphs of the flame under vacuum in order to study further the movement of the discontinuity region toward the flame holder near blowoff.

Combustion Chamber Design

Work will be continued toward obtaining a high performance, smooth-burning combustion chamber through development of basic flame holder designs, and fuel injection systems.

Pressure and Temperature Effects on Combustion Processes

A completion of the Bunsen flame studies will be undertaken. Flame speeds will be obtained for various fuel-air ratios from as low pressures as possible with the Bunsen type flame, up to as high pressures as can be obtained. If no difficulties are encountered with the heat exchange system, the temperature effect on flame speed will be studied from room temperatures up to as close to 1000°F as is experimentally possible. A study of the variation of the zone between the visible flame and the nozzle lip will also be made in dependence upon pressure and temperature.

Flow Associated with the V-Flame

All experimental data and observation on the resonant combustion chamber will be collected and presented as an external memorandum. Analytical work will be continued to determine the cause of resonance.

Detonation

Detonation tests will be continued and further development of the photographic system will be undertaken.

Blowdown Equipment

Preliminary blowdown heating runs will be made in which general operating data will be gathered. Particular attention will be paid to a temperature survey of all parts of the heat exchanger since cracks in the exchanger lining may cause hot spots. It is expected that a preliminary design of the test section will be made, and work on instrumentation begun.

Experimental Techniques and Instrumentation

Interferometer - Sub-assemblies will be let out for manufacture as fast as drawings are completed for same.

Shadowgraph equipment - Completion of the thyratron control unit is expected within the next month. Timing circuits and photoelectric pick-ups are being designed.

ACTIVITIES VISITED

Activities Visited	Subject Discussed
Optron Laboratories Dayton, Ohio	Interferometer

BIBLIOGRAPHY

1) Progress Report No. 4 -- UMR-29 -- University of Michigan AAF Contract W33-038 ac-21100 -- Figure 1, Page 5

2) Progress Report No. 7 -- UMR-35 -- University of Michigan AAF Contract W33-038 ac-21100 -- Page 9

3) ibid. -- Figure 10, Page 15

4) ibid. -- Page 14

5) UMM-21 -- Morrison & Dunlap -- "Measurement of Flame Speeds with the V-Flame" -- AAF Contract W33-038 ac 14222 -- Page 21

6) Progress Report No. 7 -- UMR-35 -- University of Michigan AAF Contract W33-038 ac-21100 -- Figure 12, Page 20

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