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PROGRESS REPORT NO. 1

AAF CONTRACT W-33-038-ac-21100

PERIOD 1 JULY - 1 SEPTEMBER, 1948

REPORT UMR-21

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AERONAUTICAL RESEARCH CENTER

Willow Run Airport Ypsilanti, Michigan

DEFINITION OF SYMBOLS AND TERMS

Normal Flame Speed or Normal Propagation Rate is defined as the rate at which a flame front moves in a stagnant combustible mixture relative to the unburned gas in a direction normal to the front.

a = speed of sound

F/A = Fuel-air ratio by weight

M = $\frac{V}{a}$ = Mach Number

p_1 = Ambient air pressure

p_2 = Static pressure after shock

T = Ambient air temperature

T_o = Total temperature of air stream

V = velocity

V_j = jet velocity

γ = C_p/C_v = Ratio of specific heats

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I. Purpose

This contract is a basic study of the fundamentals of combustion as related to the specific variables stated in Exhibit A. In order to carry out such a study economically, the problem will first be investigated on small scale versatile equipment. Success on this equipment will dictate the procedure to be followed on the larger and more cumbersome equipment.

The purpose of Contract W 33-038 ac-21100 as stated in Exhibit "A" is reproduced here in full.

A. Determine the effects of the following conditions upon the combustion process, maximum flame temperature, and physical and chemical characteristics of the flame at various points along the combustion chamber. If possible, each condition is to be imposed upon the combustor independently while the other variables are held constant. After determining the effect of each condition separately, the cumulative effect of two or more of the conditions are to be determined. A single base fuel of petroleum origin should be used for these tests and the F/A ratio varied as required.
   (1) Inlet air temperatures up to 1000°F.
   (2) Inlet air pressures up to 200 p.s.i.a.
   (3) Inlet air velocities up to and possibly exceeding a Mach number of 1.

B. Determine the effect of turbulence upon combustion and flame characteristics. Controlled turbulence shall be introduced in the combustion chamber and each type of turbulence evaluated while other conditions are being held constant. Turbulence may be induced by the following methods:
   (1) Various designs of combustion chambers
   (2) Air jets
   (3) Flame holders of various shapes in the combustion chamber.

C. Determine the effect of various types of turbulence upon combustion superimposed upon the conditions listed in A above.

D. Determine the effects of fuel characteristics upon combustion and flame characteristics. Repeat tests under A and B above using various liquid petroleum fuels. Compare the results with those obtained with the base fuel to evaluate the effect of fuel characteristics upon combustion.

E. Using the information obtained in A and B above, attempt to correlate the data so as to obtain a combustion parameter involving all the above variables and suitable for combustion chamber design calculations.

F. Using the resulting data from investigations under D above, attempt to determine and express practical reaction rate equations for the fuels or fuel types used in the work.

G. Investigate the feasibility of maintaining a standing detonation wave in a high velocity air fuel mixture. Such an investigation may be carried on in a small bore burning tube to avoid the use of excessive amounts of air and fuel. Initial tests will be made using hydrogen and oxygen or hydrogen and air. Depending upon the success of these tests, gaseous and liquid hydrocarbons will be also used as the fuel. To assist in holding the detonation wave, the use of stratified mixtures, detonation traps or other mechanical devices should be investigated. This investigation is to be of a basic nature and does not include a study of the application of a standing detonation wave.

H. A simple combustion chamber of the Contractor's own design shall be employed with auxiliary equipment capable of delivering air to the combustion chamber at pressures up to 200 p.s.i.a., velocities at Mach number equaling, or possibly exceeding, and temperatures at 1000°F. The combustion chamber shall be constructed in such a manner that various methods of introducing turbulence may be employed.

I. The combustion chamber may be a simple burning tube of circular cross section, and of a reduced scale to avoid the necessity of excessively large auxiliary equipment. The burner should be large enough however so that results will not be adversely masked by surface-volume ratio. Present estimates indicate that burners with a two to five inch diameter may be used to obtain reliable data.

J. Investigate the effect upon flame speed of the following variables:
(1) F/A ratio
(2) Fuel characteristics and types
(3) Turbulence

(4) Ignition intensity
(5) Flame holder geometry

K. Investigate the divergent-convergent flow phenomena associated with a V-flame confined in a combustion chamber. Various shapes of combustion chambers shall be used and an attempt made to arrive at the combustion chamber form most suitable for V-flame front stability. An attempt shall be made to arrive at a mathematical analysis of the potential flow through a V-flame front in order that combustion chamber design may be placed on a more sound mathematical basis as far as fundamentals are concerned.

L. Conduct preliminary investigations of detonation phenomena in stationary charges for the purposes of finding the effect of the following variables:
(1) F/A ratio
(2) Ignition intensity
(3) Fuel characteristics and types
(4) Shock waves

M. The research program called for hereunder shall not be considered an exact guide or limitation on the work to be performed. Depending upon the results obtained during the course of these investigations, deviations and/or additions to the outline may be applied at the discretion of the Government or upon the suggestion of the Contractor with the approval of the Government.

II. Procedure to be followed on the initial phase of the Contract

Generally, combustion is accepted as a phenomenon associated with multiple diffusion processes from the burned gases to the unburned gas. The classical analysis of Mallard-Le Chatelier which is based upon the heat transfer from the burned gas to the unburned gas has been used by such investigators as Lewis and von Elbe to explain the rate of propagation of flames in gaseous mixtures. More recently, other investigators have considered the diffusion of active species such as atomic hydrogen to explain flame propagation rates. A satisfactory theory and analysis to explain flame propagation rates has not yet been proposed.

Past combustion work at the University of Michigan (Ref.1 and 2) has shown some unexpected variations in the V flames when the temperature and geometry of the holders were varied. In such cases, higher flame speeds were observed for hot holders. At high jet velocities, ca. two to three hundred feet a second, it was possible to produce a small pilot flame in the wake of the flame holder which failed to ignite the bulk of the combustible mixture. The existence of such a pilot flame as well as the foregoing mentioned phenomenon indicates that the aerodynamics associated with combustion could be as important as the chemical considerations. An understanding of the aerodynamic effects would give much insight into the phenomenon of blow off and combustion instabilities that exist at high free stream velocities. It is not unlikely that the aerodynamics could influence flame propagation in gaseous mixtures.

Accordingly, to have an understanding for the variables involved, various sizes of flame holders are being tested for blow-off speeds at various fuel air ratios. There appears to be evidence that the velocity at blow-off divided by the normal propagation speed will be a constant. (Ref. 3 and Fig. 3) Further, a correlation between blow-off velocities and the velocity gradients in the vicinity of the holder is to be investigated.

If velocity gradients prove to have an effect on blow-off speeds, it is quite possible that the flame speeds will also be a function of these gradients. In order to have a knowledge of the magnitude of the velocity gradients involved in the case of a "V" flame, a potential flow analysis of the "V" flame is in progress. Experimental verification of the latter analysis will be made on both the open "V" flame and the confined "V" flame.

The effect of inlet air temperature up to 1000° F. and inlet air pressures up to 200 p.s.i.a. will first be studied as related to the normal flame speeds. Equipment for this investigation will consist of a small Bunsen burner and "V" flame apparatus which can be subjected to air pressures from 3 to 4 p.s.i.a. to 200 p.s.i.a. With such a system the air flows required are very small and can be maintained with a small capacity air compressor. Such small scale equipment also makes it possible to easily obtain these temperatures with a small heat exchanger.

The University of Michigan has at its disposal a hot wire anemometer capable of measuring both the intensity and scale of turbulence. The effect of turbulence upon combustion will first be investigated by controlled turbulence obtained by the insertion of grids upstream of the "V" flame. Such turbulence could easily be measured with a hot wire anemometer. After the completion of this initial investigation, turbulence of a more complicated nature will be introduced by variations in combustion chamber design, introduction of air jets, and flame holders of various shapes.

The feasibility of maintaining a standing detonation wave in a duct will first be investigated by use of a shock tube capable of Mach numbers up to 5 or 6. The temperatures behind such shock waves will be well above the ignition temperatures of the fuel-air mixtures used, and therefore should produce combustion. The combustion in turn should further increase the pressure behind the shock wave which would strengthen the shock wave traversing the tube. Such a shock wave followed by combustion would then be a detonation wave. The shock tube will give sufficient data to determine the temperatures and pressures required to initiate combustion as well as final velocities obtained after the combustion has developed. In this manner, it will be possible to investigate the temperatures and Mach numbers required to initiate and maintain a standing detonation wave.

Since a detonation wave must conform to (1) the law of conservation of mass, (2) the momentum equation, and (3) the energy equation, an analysis is being made on this basis. It is possible that such an analysis will show some relation between the speed of the detonation wave and heat release.

III. Summary

A. General

A large portion of Period I was used in the design and setting up of small scale test equipment to be used in the initial investigations. The equipment is described under individual headings.

B. Blow-off Velocities

Blow-off velocities of spherical flameholders were measured for two diameters of spheres. The results, based on this limited data, indicate that a correlation between blow-off velocity and normal flame speed exists.

C. Large Scale Combustion Chamber

The major components of the large scale combustion chamber have been assembled and tested. The burner has been successfully operated with the aid of a hydrogen pilot flame. The approximate limits of the flow have been established both for the air system and fuel system.

D. Temperature and Pressure Effects on Combustion Processes

The small scale equipment required for the study of pressure effects on combustion has been assembled, and tests will proceed as soon as the flow instruments have been calibrated.

E. Detonation

Initially the phenomenon of detonation is to be investigated in a shock tube capable of Mach number equal to five or six. The equipment for such a shock tube has been partially designed. In addition theoretical work on the phenomenon of detonation has been carried out.

IV. Progress

B. Blow-off Velocities of Flameholders

The blow-off velocities of flameholders were tested in an open jet because of the simplicity of the system. Spherical flameholders were selected to eliminate errors due to orientation and because of their relatively simple flow pattern. Four spheres of the following diameters have been prepared: 0.0625, 0.125, 0.1565, and 0.178 inches. The data included in this report is based on tests conducted with 0.1625 and 0.125 inch diameter spheres. The method used to mount the flameholder is shown in Figure 1.

Figure 2 presents a schematic diagram of the equipment. The fuel was commercial propane. The propane flow was measured by a rotameter, and the total flow of the mixture was measured by means of a pressure tap in the mixing drum and a calibrated nozzle. The air flow was obtained by subtracting the propane flow from the total mixture flow. The mixture was ignited with an electric spark at a jet velocity of ca. 100 ft. per second. The jet velocity was then varied to some given value, at which point the fuel-air ratio was changed in small increments until blow-off occurred. This procedure was used on both the rich and lean sides of the blow-off.

The pilot flame which exists on both the rich and lean sides of the curve assisted in determining the blow-off region inasmuch as it appears shortly before blow-off occurs. After blow-off had occurred, an electric spark was passed through the mixture to determine whether or not it was combustible. Several trials were used to eliminate the possibility of the pilot flame having been blown out by a gust. The experimental results obtained thus far are shown in Figure 3. These curves were obtained from the 0.0625 inch and the 0.125 inch spherical flame holders. A portion of the latter curve has not yet been substantiated. Flame propagation can be maintained only within the area bounded by the curve. The maximum blow-off velocity was obtained at a fuel-air ratio of approximately .075 for the 0.0625 inch diameter sphere. There is some doubt as to the

FLAME HOLDER AND NOZZLE ASSEMBLY

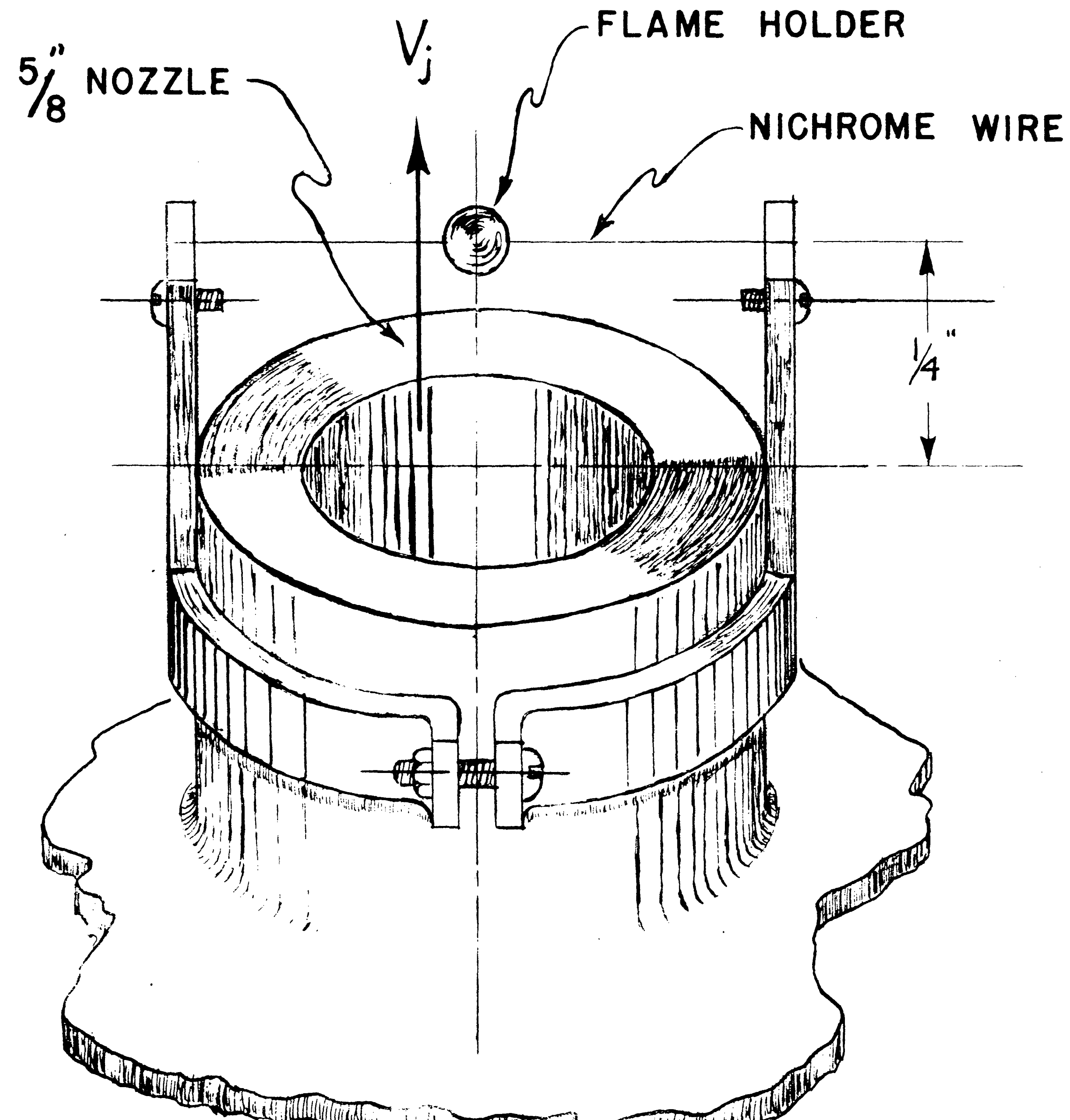
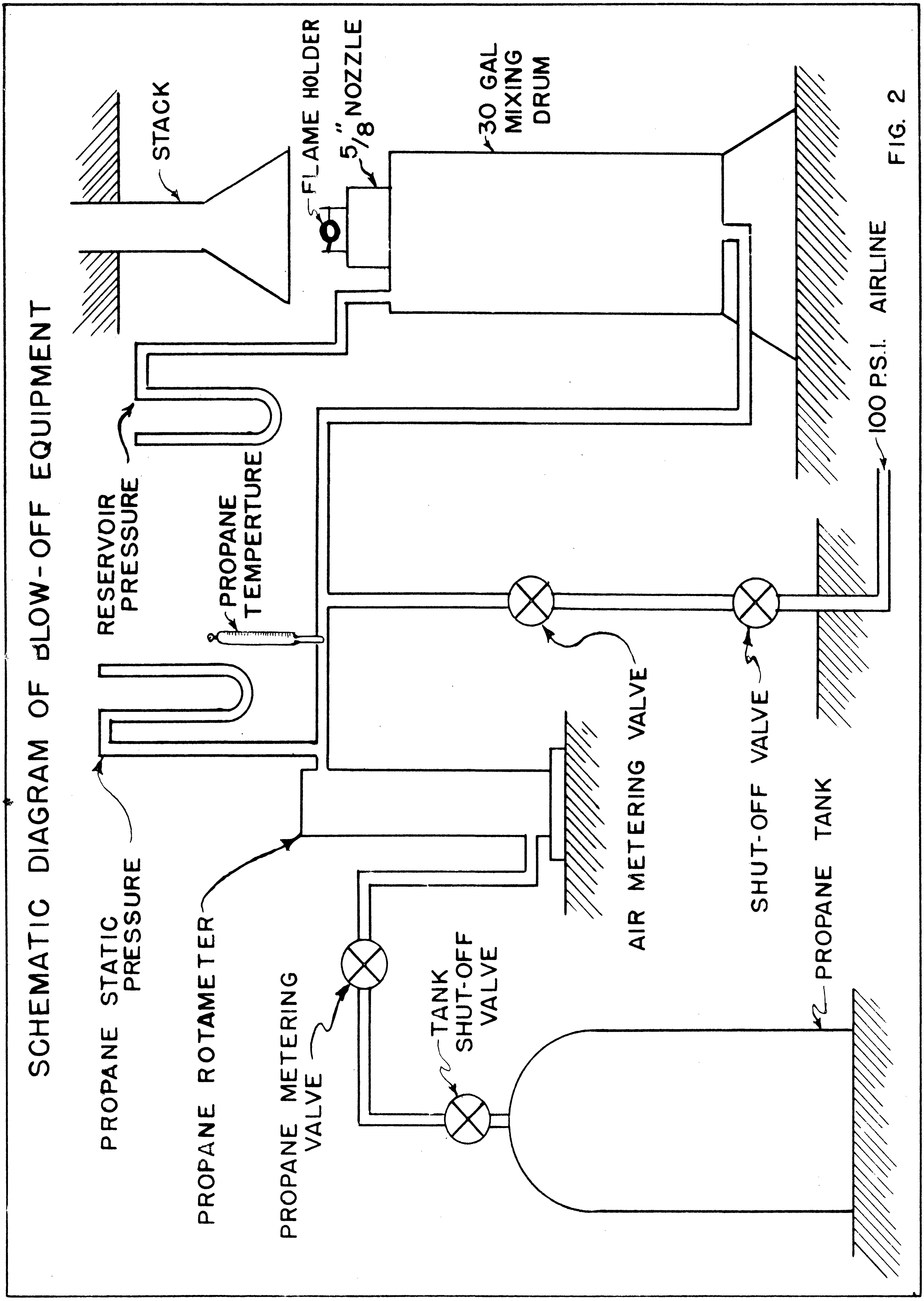


FIG. 1



SCHEMATIC DIAGRAM OF BLOW-OFF EQUIPMENT

FIG. 2

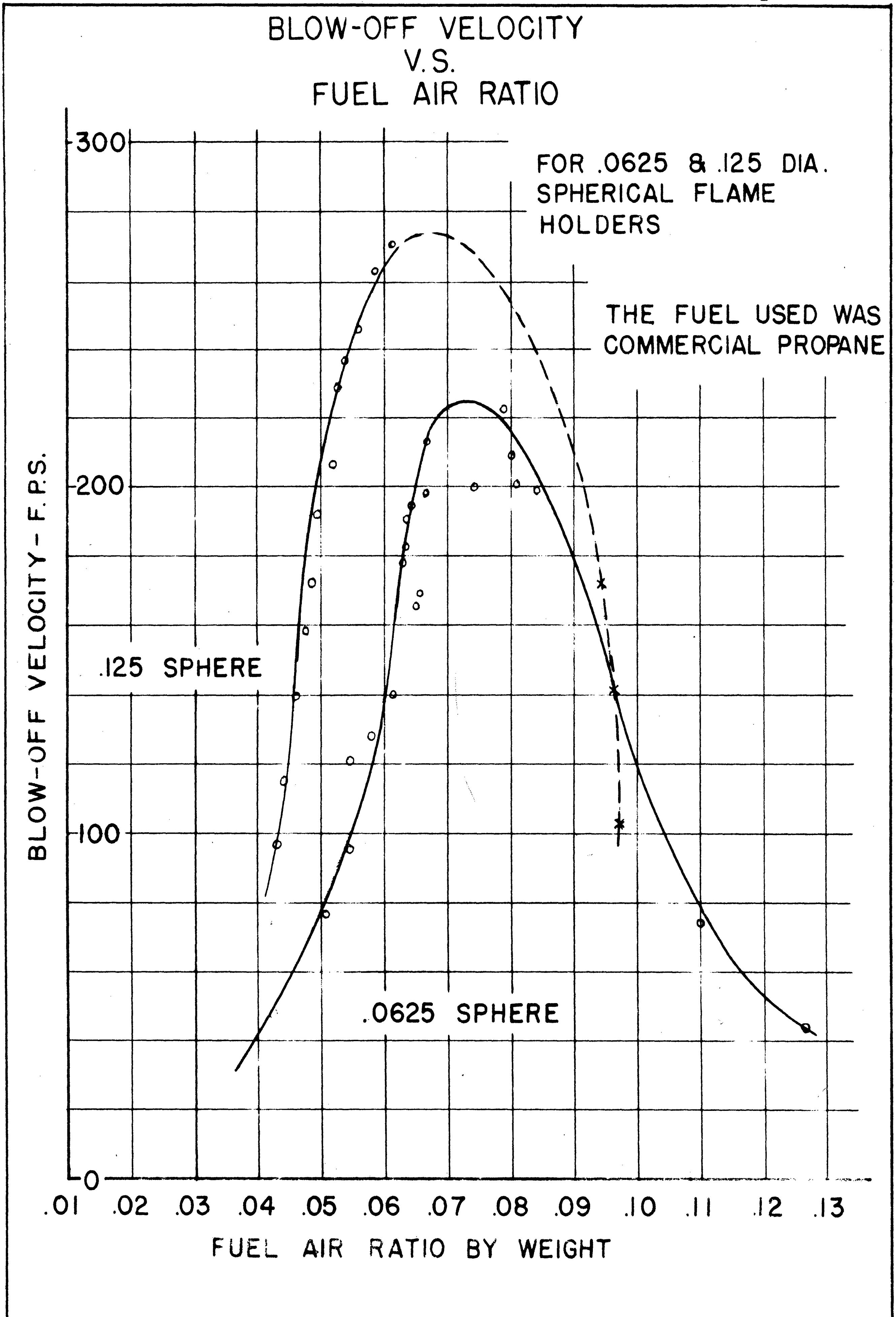
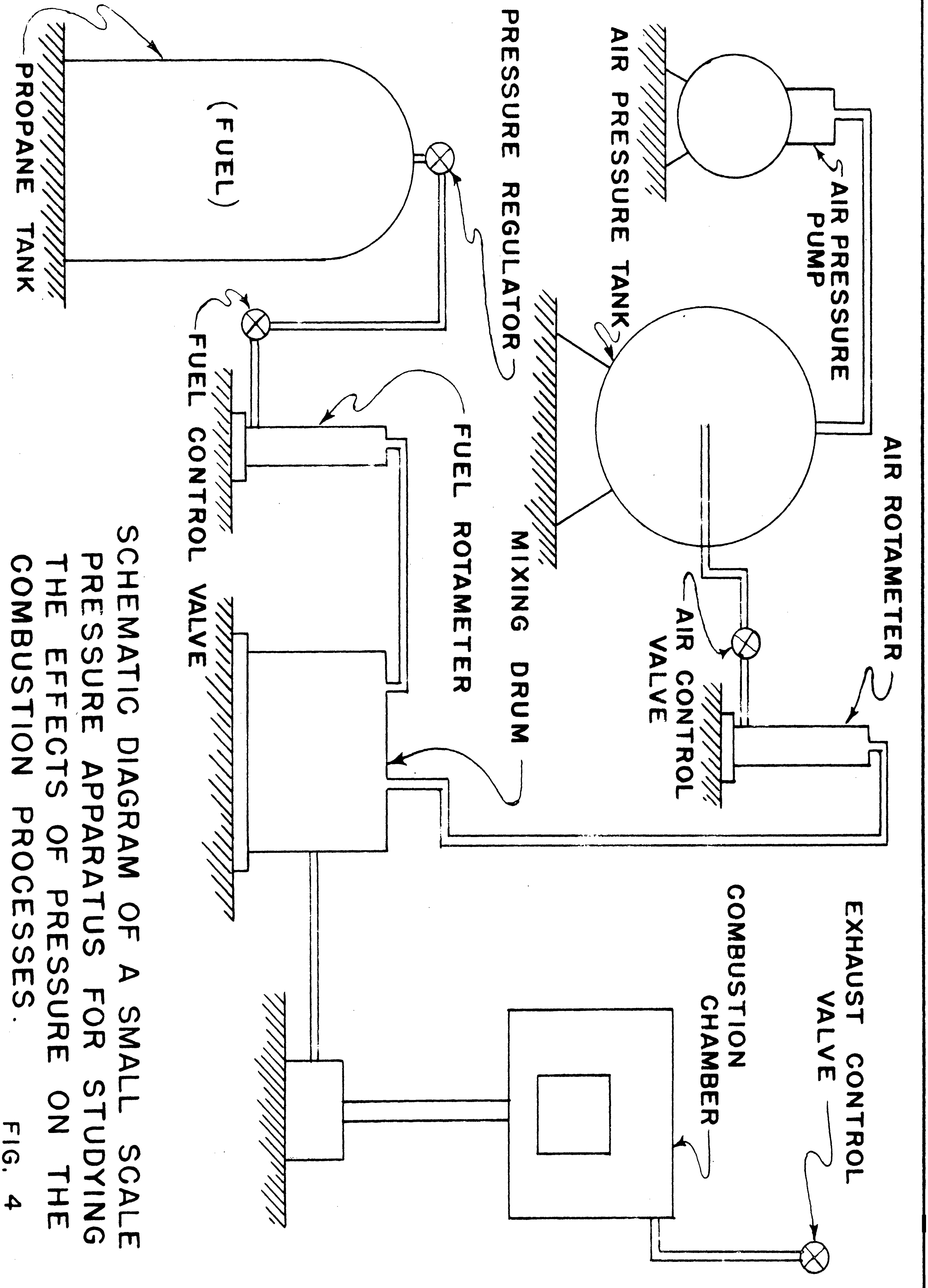

BLOW-OFF VELOCITY
V.S.
FUEL AIR RATIO
FOR .0625 & .125 DIA. SPHERICAL FLAME HOLDERS
THE FUEL USED WAS COMMERCIAL PROPANE
BLOW-OFF VELOCITY - F.P.S.
300
200
100
0
.125 SPHERE
.0625 SPHERE
.01 .02 .03 .04 .05 .06 .07 .08 .09 .10 .11 .12 .13
FUEL AIR RATIO BY WEIGHT

FIG. 3



SCHEMATIC DIAGRAM OF A SMALL SCALE PRESSURE APPARATUS FOR STUDYING THE EFFECTS OF PRESSURE ON THE COMBUSTION PROCESSES.

FIG. 4

relative position of these two curves on the rich side.

C. Large Scale Combustion Chamber

The large scale combustion chamber equipment, which consists of a naturally-aspirated Rolls Royce engine and the piping to the 4" burner section, has been put into operation and is ready to proceed with a test program. Initial tests have been made on the burner section, and all auxiliary equipment (fuel pump, ignition, and control valves) operated satisfactorily. Blanks for a series of fuel nozzles have been made up, and calibration of these nozzles at different fuel pressures is proceeding. Various means of evaluating combustion chamber performance are being studied.

D. Temperature and Pressure Effects on Combustion Processes

The first period of the contract has been spent organizing facilities and test equipment for small scale studies. A sketch of the apparatus to study effects of pressure on combustion processes is shown in Figure 4. The hydrocarbon fuel to be used is commercially pure propane. The fuel flow is controlled by a metering valve through a flow meter to the mixing drum where it is mixed with air. The air is supplied by a low capacity compressor to a large high pressure surge tank. The air flow is then throttled through a metering valve to a flow meter and then passes to the mixing drum. The fuel-air mixture flows to the pressurized combustion chamber where combustion processes can be observed through windows. The exhaust gases are controlled through a throttling valve. By using a vacuum pump and slight modifications of the system, effects of lower than atmospheric pressure on combustion phenomena can be studied. At the present, the equipment is being assembled and calibrated.

E. Detonation

Ignition of a combustible mixture with a shock wave involves other conditions than temperature and pressure. In order to confirm this, four bullets were fired through stoichiometric mixtures of propane and air at atmospheric conditions. The muzzle velocity of the bullet as specified by the manufacturer was 4140 feet per second. The nose of the bullet was ground flat (See Fig. 5) to produce a normal shock at the nose.

Theoretically the shock had a pressure ratio $\frac{p_2}{p_1}$ of 15.4 with a total temperature, T_o, at the nose of 1965°R based on the following formulas:

$$\frac{p_2}{p_1} = \frac{2\gamma M^2}{\gamma + 1} - \frac{\gamma - 1}{\gamma + 1}$$

$$T_o = T\left(1 + \left(\frac{\gamma - 1}{2}\right) M^2\right)$$

$$T = 540, \ \gamma = 1.4$$

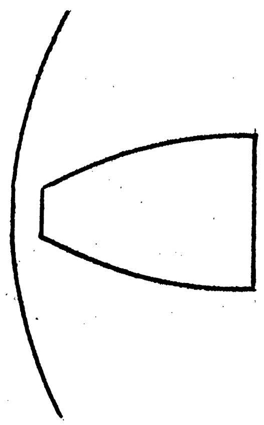


Figure 5

The propane air mixture and a spark gap were sealed in a cardboard carton into which the bullet was fired at point blank range. The mixture failed to ignite each time the bullet was fired through it. In order to prove the inflammability of the mixture, it was ignited by a spark after the bullet traversed it. This initiated combustion, blowing the carton apart.

In the bullet experiment the stagnation temperature behind the shock at the nose of the bullet was 1965° R and the absolute pressure was approximately 225 psia. The accepted ignition temperature of propane-air mixtures is 1374°R (Ref. 4). Dr. Shepherd ignited an ethylene-air mixture at 708°R to 726°R with a shock wave (Ref.5). The ignition temperature for ethylene-air mixtures is 1464°R (Ref. 4). Therefore, Dr. Shepherd ignited the ethylene-air mixture at temperatures below accepted values quoted in the reference.

The bullet experiment in which temperatures at the nose of the bullet were above the ignition temperature of the gas mixture and Dr. Shepherd's work with ethylene-air mixtures confirm the belief that conditions in addition to temperature and pressure control ignition behind a shock wave.

V. Program for Next Period

B. Blow-off Velocity

It is planned to install a Bunsen burner in the system to enable measurement of flame speed and blow-off velocity simultaneously.

C. Large Scale Combustion Chamber

The initial test program has been outlined for testing the effect of high pressure liquid fuel injection upon combustion. It is proposed that the angle of spray from the fuel nozzle as well as the fuel pressure be varied with photographs of the spray being taken while the data on each nozzle is obtained.

D. Temperature and Pressure Effects on Combustion Processes

A study of the effect of temperature on combustion processes will be commenced upon the completion of the pressure studies. At that time a study of the cumulative effect on both temperature and pressure will be initiated.

E. Detonation

At present a shock tube is being designed, and a method of photography capable of studying the shock wave and the ignition of the mixture is being developed.

F. Blow-Down Equipment

A design study of a blow-down tunnel, utilizing the high pressure storage, pumping and drying equipment available, will be made.

ACTIVITIES VISITED

Activities Visited	Subjects Discussed
Ducted Power Plant Symposium Sponsored by Project Squid Navy Department Washington, D. C.	Flame stability, ejectors, and ducted power plants.

REFERENCES

1. University of Michigan Progress Report No. 9

2. University of Michigan Progress Report No. 10

3. University of Michigan Progress Report No. 6, p. 51

4. Marks Handbook

5. Dr. W. C. F. Shepherd, Ministry of Fuels and Power, Sheffield, England. "The Ignition of Gas Mixtures by Impulsive Pressure Effects". Abstract of Papers Third Symposium on Combustion and Flame and Explosion Phenomena. September 7-11, 1948, Page 91

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