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RESEARCH MEMORANDUM

PRELIMINARY TESTS OF A BURNER FOR RAM-JET APPLICATIONS

By

Paul W. Huber

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

PRELIMINARY TESTS OF A BURNER FOR RAM-JET APPLICATIONS

By Paul W. Huber

SUMMARY

Preliminary tests have been made of a small burner to meet the requirements for application to supersonic ram jets. The principal requirements were taken as: (1) efficient combustion in a high-velocity air stream, (2) utilization for combustion of only a small fraction of the air passing through the unit, (3) low resistance to air flow, (4) simple construction, and (5) light weight.

Tests of a small burner were carried to stream velocities of nearly 150 feet per second and fuel rates such that one-eighth to one-fourth of the total air was involved in combustion. Commercial propane was selected as the fuel since its low boiling point facilitated vaporization.

Combustion which was 80 percent complete along with low aerodynamic losses was obtained by injecting the fuel evenly, prior to ignition, and allowing it to mix with the air without appreciably disturbing the stream. The pressure drop due to frictional losses around the burner and to the adjacent inside walls of the ram jet is small compared with the pressure drop due to combustion.

INTRODUCTION

There is a need for burners to meet the requirements for application to high-speed ram jets, such as the supersonic ram jet described in reference 1. Reference 1 shows that high velocities in the burning section are desirable in order to keep the fuselage slender and so give lower fuselage pressure drag. It follows that frictional losses through the burner will also become important at the high internal velocities. A system for obtaining efficient combustion when utilizing only a small

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fraction of the total air is also important for ram jets (reference 1).

The type of burner used in present turbojet units would not be applicable to a high-speed ram jet because of the high aerodynamic losses through the burner units as a result of turning, swirling, or partly blocking the air to obtain proper mixing and ignition in a short space. Various burners are now being developed for ram jets, but none have been perfected or sufficiently tested to demonstrate their suitability for a supersonic ram jet.

It was the purpose of this research to design a burner that would be applicable to a supersonic ram jet. The ultimate goal of this work was to provide a simple and light burner which would give efficient combustion with low aerodynamic losses at air stream velocities of 300 to 400 feet per second at over-all fuel-air ratios of 1/60 to 1/120. In the present work, which was of a preliminary nature, the air velocity ahead of the burner was limited to 150 feet per second due to limitations of the test facilities. Additional tests should be made at higher stream velocities and at reduced inlet air pressures and temperatures.

BURNER-DESIGN CONSIDERATIONS

Selection of fuel.- Considerable simplification in burner design may be achieved if a fuel is selected which requires no complicated means of securing vaporization. If a fuel with the proper low boiling point is selected, the partial or complete vaporization of the fuel might be accomplished at some point in the airplane or at the skin where a suitable stagnation air temperature is available. An analysis of skin-friction fuel evaporators would be necessary to determine this possibility. The fuel could be stored in flight in a light insulated tank at low temperature and at approximately atmospheric pressure. By use of such a method much of the bulky equipment in the burning air duct would be eliminated and a smooth supply of fuel to the burner that would be independent of the burner operation could be maintained.

The fuel selected for these tests was commercial propane, which is obtained in liquid form with a vapor pressure of about 120 pounds per square inch absolute at 70° F. The fuel has a vapor pressure of 1 atmosphere at -43° F. Propane has a heat of combustion slightly higher than octane (21,750 Btu/lb), and an air-fuel ratio of 15.66 is [redacted]

Mixing and efficient combustion.- An important part of any combustion process is the proper mixing of fuel and air. When a stream of gaseous fuel which has not been mixed with air is ignited, there is a strong possibility that some of the fuel may pass through the burner without being exposed to sufficient air for combustion. Combustion in an atmosphere lacking in sufficient oxygen results in the formation of free carbon, which radiates a large amount of heat to the surroundings (as in a yellow flame) and passes through as a waste of available energy. Carbon monoxide also is formed, the reaction by which it is formed having a low heat of combustion. It is important for efficient combustion, therefore, to have all the fuel exposed to sufficient air for combustion. Greatly disturbing the air to obtain this mixing causes unnecessary losses, so that it is most important to inject the fuel in such a manner that it will become evenly distributed throughout the air. It might be necessary, however, in a final burner design, to arrive at some compromise between burner losses and rapid mixing.

DESCRIPTION OF BURNER AND TEST APPARATUS

A sketch of the cross section of the burner and inner passage of the ram jet is shown as figure 1. The burner consists of a circular mixing duct surrounded by an annular igniter at the trailing edge. The area of the mixing duct is one-eighth the area enclosed by the inner passage of the ram jet, so that small fractions of the total air can be burned and the air-fuel mixtures are nearly stoichiometric.

Tests were made of a small burner $2\frac{1}{2}$ inches in diameter, 1 foot long, located in a tube of constant cross section 5 inches in diameter and 7 feet long. This tube simulated the inner passage of a ram jet and was mounted at the exit of a centrifugal blower which served as the air supply. With this blower, an air velocity of about 150 feet per second was available under conditions of operation with maximum fuel flow. A static- and a total-pressure tube were installed $2\frac{1}{2}$ inches ahead of the burner, and static orifices were placed at intervals of 4 inches along the inner passage of the ram jet to about 5 burner lengths downstream from the burner.

Mixing process.- One of the main features of the burner tested is that the fuel and air are mixed before ignition. Near the leading edge of the burner gaseous fuel is injected into the air stream that passes through the burner. The fuel is injected at right angles to the air stream at gage pressures up to 25 pounds per square inch through five holes that are 0.081 inch in diameter and located around the inner wall of the burner. The inner passage of the burner serves as a mixing duct before ignition at the trailing edge. Mixing results from diffusion of the high-pressure jet and also occurs during the time necessary to accelerate the jet in the direction of the air stream. In order to increase further the time and turbulence available for mixing, the inner duct is made diverging-converging to as large an area at the maximum section as space permits without destroying the outer streamline of the burner.

Inasmuch as the inlet area of the mixing duct is one-eighth the area of the inner passage of the ram jet, the fuel-air mixture is twice that of stoichiometric if a stream tube of ram-jet velocity fills the inlet and if one-fourth the total air is to be involved in combustion. The fuel rates covered in the tests were those necessary to involve between one-eighth and one-fourth the total air in combustion, so that the mixture in the mixing duct was always stoichiometric or richer. When the mixture leaves the burner and is ignited, therefore, turbulent spreading of the stream tube (mixing with other air) tends to keep the mixture near stoichiometric as it becomes leaner.

Ignition process.- The igniter flame is annular and surrounds the main fuel-air mixture. Air is taken into the igniter annulus by ram at the leading edge of the burner through 18 uniformly spaced holes 1/16 inch in diameter. Fuel is injected into the igniter annulus through nine holes, 0.012 inch in diameter, which are located adjacent to the inner ends of the previously mentioned 18 holes through which the air enters. Because of the diffusion of the air entering the igniter annulus, the velocity through this part of the burner is relatively low, which allows ample mixing time for the fuel and air before ignition by the spark that is provided at the downstream outlet of the annulus in question. The width of the igniter annulus is 1/2 inch. By surrounding the main mixture with igniter flame, there is less chance of fuel from the inner mixture escaping to the surrounding air without being ignited. The igniter fuel line was made separately controllable, although this separation should not be necessary in a fully developed burner. Calibrations of igniter and main fuel flows were obtained as functions of fuel-line pressures by placing the burner and the propane tank on a scale and measuring the decrease in weight per unit time at various fuel-line pressures. The separated region due to the igniter annulus constitutes the main obstruction to smooth air flow past the burner. This obstruction is 16 percent of the cross-sectional area of the inner passage of the ram jet. The fuel line and leading edge of the burner were shaped in such a way as to cause a minimum of disturbance in the air stream.

SYMBOLS

$$a = \frac{R_1 T_1}{V_1^2}$$

A	cross-sectional area, square feet
c_p	specific heat of air at constant pressure, foot-pounds per slug per °F
c_{p_T}	specific heat of air-propane mixture at constant pressure and average temperature of stations 1 and 3, foot-pounds per slug per °F
F	fraction of total air theoretically burned with propane
H	$\frac{\text{Heat added}}{\text{Unit mass}}$, foot-pounds per slug
p	pressure, pounds per square foot absolute

$\Delta p = p_1 - p_3$

q	dynamic pressure, pounds per square foot $\left(\frac{1}{2}\rho V^2\right)$
R	gas constant, foot-pounds per slug per °F
T	temperature, °F absolute
V	velocity, feet per second
ρ	density, slugs per cubic foot

Subscripts:

1	entering air
2	exit air to which no heat has been added
3	exit air to which heat has been added

ANALYSIS

Combustion efficiency as a function of static-pressure gradient.- In order to evaluate the efficiency of combustion, the static-pressure drop across the flame was measured and compared with the theoretical pressure drop to be expected for complete combustion. This method can be justified by the following analysis: It is assumed that a mixture of air and propane enters a constant-area duct at atmospheric conditions and that an amount of energy equal to the heat of combustion of the propane is added to the stream uniformly without frictional loss. The assumption that a fuel-air mixture rather than air enters the duct, as is the actual case, is made to simplify the calculations. The error in mass flow introduced by this assumption is not large, for at the maximum fuel-air ratio necessary to involve one-fourth the air in combustion, the mass of fuel injected is only $1\frac{1}{2}$ percent of the total mass. Change of c_{p_T} with temperature is included in the calculations. Calculations are based on compressible-fluid theory as follows:

$$1 \quad \left\{ \begin{array}{l} \text{Heat added} \\ \text{without} \\ \text{frictional loss} \end{array} \right\} \quad 3$$

The energy equation is

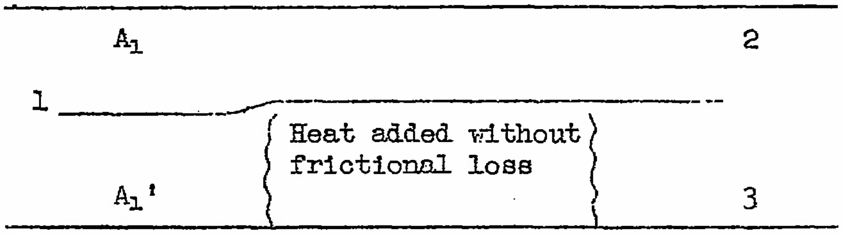
$$c_{p_T}\left(T_3 - T_1\right) + \frac{1}{2}\left(V_3^{2} - V_1^{2}\right) = H \tag{1}$$

Simultaneous solution of equation (1) with the equations of state, continuity, and conservation of momentum will yield for $\Delta p/q_1$

$$\left(\frac{\Delta p}{q_1}\right)^2\left(\frac{1}{4} - \frac{1}{2}\frac{c_{p_T}}{R_3}\right) + \frac{\Delta p}{q_1}\left(1 + a\frac{c_{p_T}}{R_3} - \frac{c_{p_T}}{R_3}\right) + 2a\frac{c_{p_T}}{R_3} - \frac{2}{V_1^{2}}\left(H + c_{p_T}T_1\right) = 0 \tag{2}$$

A plot of $\Delta p/q_1$ as a function of the fraction of total air theoretically involved in combustion with propane, as given by equation (2), is shown in figure 2. The calculations are based on an initial velocity of 100 feet per second and an initial temperature of 550° F absolute, since the initial conditions in the burner tests were near these values. It can be seen from figure 2 that for this range of fractions of total air burned, at the initial conditions given, $\Delta p/q_1$ is a linear function of the heat added. Comparison of a measured pressure drop with the calculated pressure drop is then a measure of the completeness of combustion.

Effect of nonuniform addition of heat.- In order to determine the effect of nonuniform addition of heat to the stream, pressure drops were also calculated for this case. It was assumed that heat is added without chemical reaction to one of two air streams contained in a constant-area duct, that no mixing or exchange of heat takes place between the two streams, and that the static pressures of the two streams are equal at any point. The analysis is made for compressible fluid flow.



Since the duct is of constant cross section,

$$A_1 + A_1' = A_2 + A_3 \tag{3}$$

The adiabatic relation for a stream to which no heat has been added is

$$\left(\frac{T_2}{T_1}\right)^{c_p/R} = \frac{p_2}{p_1} \tag{4}$$

The energy equation for a stream to which no heat has been added is

$$c_p(T_1 - T_2) = \frac{1}{2}\left(V_2{}^2 - V_1{}^2\right) \tag{5}$$

The equation of conservation of momentum for the whole duct is

$$(A_1 + A_1')\ (p_1 + \rho_1 V_1{}^2) = A_2(p_2 + \rho_2 V_2{}^2) + A_3(p_3 + \rho_3 V_3{}^2) \tag{6}$$

The equations of continuity between stations 1 and 2 and between 1 and 3, along with the equations of state for stations 2 and 3, are also used and from the original assumption p_3 is equal to p_2. If T_3 is assumed to be known, a solution can be obtained by combining all the equations except equation (4) into one expression with p_2 and T_2 as unknowns. When this expression is solved simultaneously with equation (4), the following equation is obtained:

$$\left(A_1 + A_1'\right)\left(1 + \frac{V_1^2}{RT_1}\right) = \frac{A_1V_1\left(\frac{p_2}{p_1}\right)^{3/7}}{\sqrt{2c_pT_1\left[1 - \left(\frac{p_2}{p_1}\right)^{2/7}\right] + V_1^2}}\left\{1 + \frac{2c_pT_1\left[1 - \left(\frac{p_2}{p_1}\right)^{2/7}\right] + V_1^2}{RT_1\left(\frac{p_2}{p_1}\right)^{2/7}}\right\}$$

$$+ \left\{A_1 + A_1' - \frac{A_1V_1}{\left(\frac{p_2}{p_1}\right)^{5/7}\sqrt{2c_pT_1\left[1 - \left(\frac{p_2}{p_1}\right)^{2/7}\right] + V_1^2}}\right\}$$

$$\left\{\frac{p_2}{p_1} + \frac{A_1'^2V_1^2T_3}{\frac{p_2}{p_1}RT_1^2\left(A_1 + A_1' - \frac{A_1V_1}{\left(\frac{p_2}{p_1}\right)^{5/7}\sqrt{2c_pT_1\left[1 - \left(\frac{p_2}{p_1}\right)^{2/7}\right] + V_1^2}}\right)^2}\right\} \qquad (7)$$

The amount of heat that has been added can be found after the solution of equation (7) by finding the value of V_3 and the stagnation value of T_3. This method was used to reduce the number of equations. A plot of $\Delta p/q_1$ as a function of the fraction of the total air involved in combustion is shown in figure 3 for cases where the heat is confined to various fractions of the total duct. The lower curve is extended with dashes to indicate that, because of the extremely high final temperatures involved, values of c_p in this region are doubtful. It is unlikely that this excessive amount of heat would remain confined to this small part of the duct for an appreciable length of time in this burning problem. Figure 3 cannot, of course, be used to provide a quantitative picture, because it is for an idealized case. This figure shows, however, that the full pressure drop due to the combustion process will not be realized unless the heat is distributed uniformly.

RESULTS AND DISCUSSION

Evaluation of results.- In all the tests of the burner with its various modifications, the combustion and results were studied mainly by comparison of measured pressure drops with the theoretical pressure drops to be expected when combustion is complete and the heat is distributed uniformly. The addition of heat could be studied over the complete length of the flame by studying the progressive static-pressure drop. A typical measured pressure distribution is shown in figure 4.

Results obtained with original burner.- The first burner tested was of the same inner and outer diameter as that shown in figure 1, was 6 inches long, and the mixing duct had no divergence. Igniter fuel was injected in the same manner as in figure 1, but the main fuel was injected in a downstream direction through a fuel nozzle located 2 inches upstream from the leading edge of the burner. The pressure drops measured indicated that the combustion was about 45 percent complete at an initial velocity of 150 feet per second at various fuel rates, although the flame was blue and very smooth. The igniter flame was about 4 inches long. Movement of the main fuel nozzle either upstream or downstream produced an adverse effect on combustion, but in every case combustion became more nearly complete as the velocity was lowered.

Modifications of original burner.- Burners of the original-burner type were then tested with igniter annuli 1/4 inch and 3/8 inch wide. Data could not be obtained at the higher velocities - above 100 feet per second - with these smaller igniters as the ignition was intermittent. The visible igniter flame extended about 1 to 2 inches beyond the trailing edge. These tests indicated that mixing was not satisfactory, inasmuch as the completeness of combustion increased as the velocity was lowered, and that the longer igniter flame obtained with the $\frac{1}{2}$-inch-wide annulus was needed for steady ignition.

Final burner design.- The burner shown in figure 1 was tested first with the main fuel nozzle used with original burner and then with the injection system shown in figure 1. Combustion was about 10 percent more complete with the fuel-injection system shown, although both configurations gave combustions much more nearly complete then those of the previous burners tested. This improvement is attributed to more satisfactory mixing.

The pressure drops measured during the tests of the burner shown in figure 1 at velocities of 100 to 130 feet per second are plotted in figure 2. It can be seen that the combustion with this burner is about 80 percent complete when the pressure-drop method of comparison is used. The pressure drop used in calculating the completeness of combustion was the pressure drop measured during burning minus the pressure drop measured at the same velocity with no burning. The latter pressure drop due to burner and wall friction was small $\left(\frac{\Delta p}{q_1} = 0.4\right)$ in comparison with the pressure drop due to combustion, but the favorable error that would be obtained when the burner and wall friction are not considered was avoided. A check on the composition of the exhaust gas as well as the unburned fuel present was obtained by a gas analyzer based on the Orsat principle. Three samples were taken simultaneously across the inner passage of the ram jet at the point where the final static pressure was measured. The average of these three analyses showed that 84 percent of the fuel was burned. Exhaust-gas samples, however, might not have been accurate, even in these comparatively low-temperature burner tests, because of surface combustion at the sampling-tube walls.

The flames were observed through a small window located a few inches downstream from the burner and were blue over the complete range of velocities and fuel rates measured. This blueness, however, is not necessarily a criterion of the best combustion efficiency. The igniter flame extended from the trailing edge of the burner to about 4 or 5 inches downstream, and the main flame extended from the trailing edge to about 3 or 4 burner lengths downstream. Burning was smooth with only small pressure fluctuations, and the main mixture could be ignited at any of the velocities and fuel rates tested. The temperature of the atmosphere was sufficient for vaporization of the fuel in these tests without the aid of a separate fuel vaporizer.

CONCLUDING REMARKS

Preliminary tests of a small ram-jet burner have been made and tests of this burner indicate efficient combustion characteristics (combustion was 80 percent complete) and low aerodynamic losses at the conditions tested. The fact that the measured combustion was so nearly complete is due mainly to the method of fuel injection and to mixing of fuel and air before ignition. The pressure drop due to frictional losses at the burner and at the inner passage of the ram jet is small, since the air is not greatly disturbed to obtain mixing and ignition.

It is believed that an investigation of the characteristics of the burner should be made at stream velocities higher than 150 feet per second, after which any desirable modifications could be incorporated. A larger burner should then be tested at the desired high velocities and reduced inlet air pressures and temperatures for application to a ram-jet airplane.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va.

REFERENCE

1. Ellis, Macon C., Jr., and Brown, Clinton E.: Analysis of Supersonic Ram-Jet Performance and Wind-Tunnel Tests of a Possible Supersonic Ram-Jet Airplane Model. NACA ACR No. L5L12, 1946.

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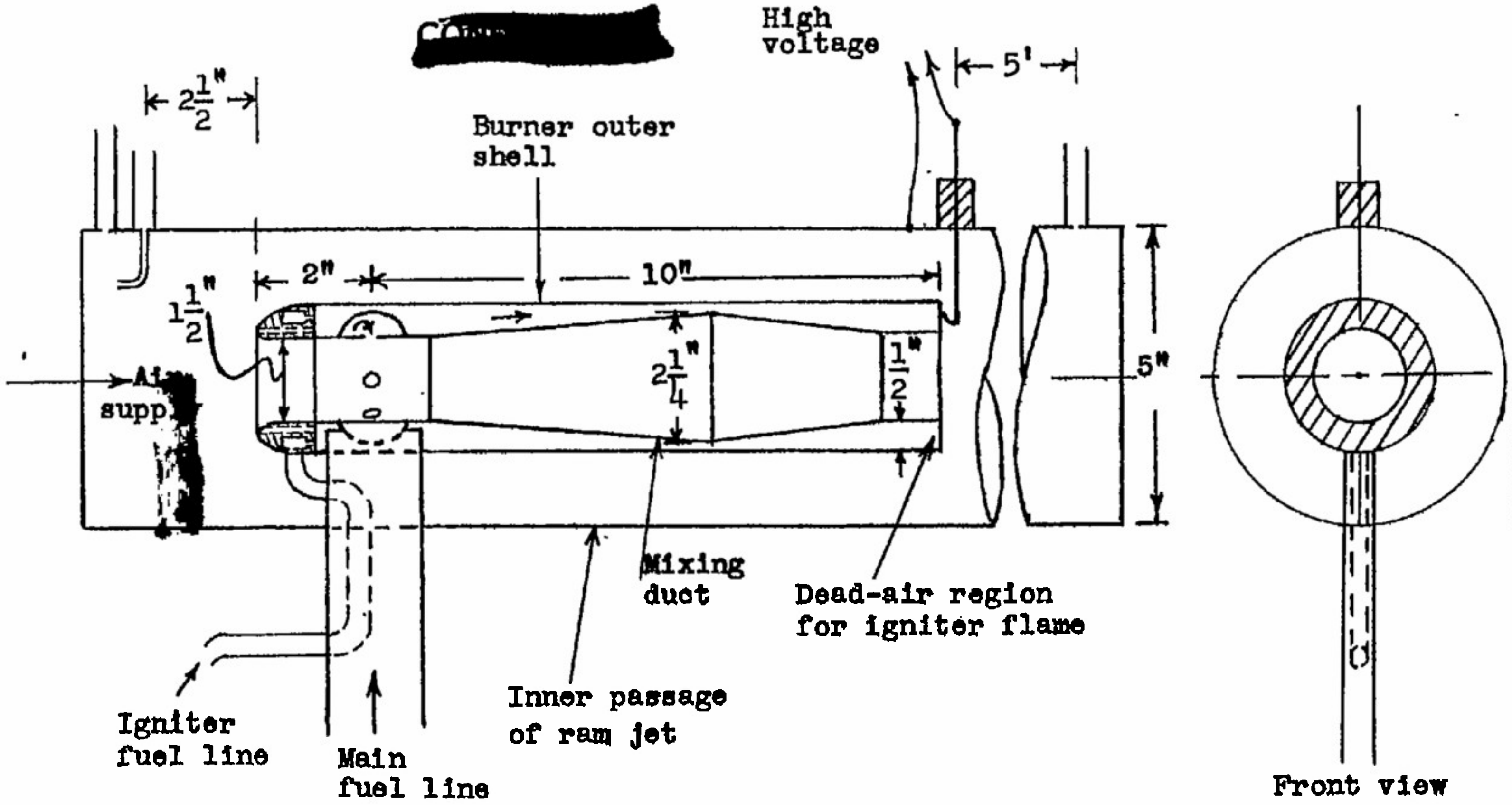

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Figure 1.- Model ram-jet burner.

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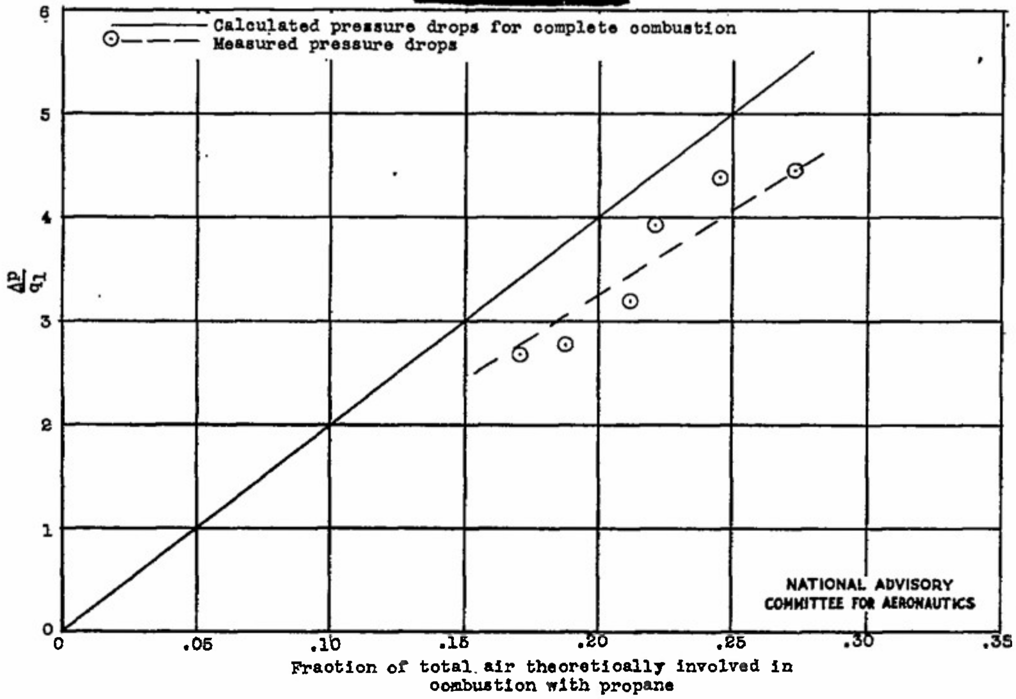

Figure 2.- Comparison of measured pressure drops across ram-jet burner with pressure drops calculated for complete combustion. Initial velocity, approximately 100 feet per second; initial temperature, approximately 550° F absolute.

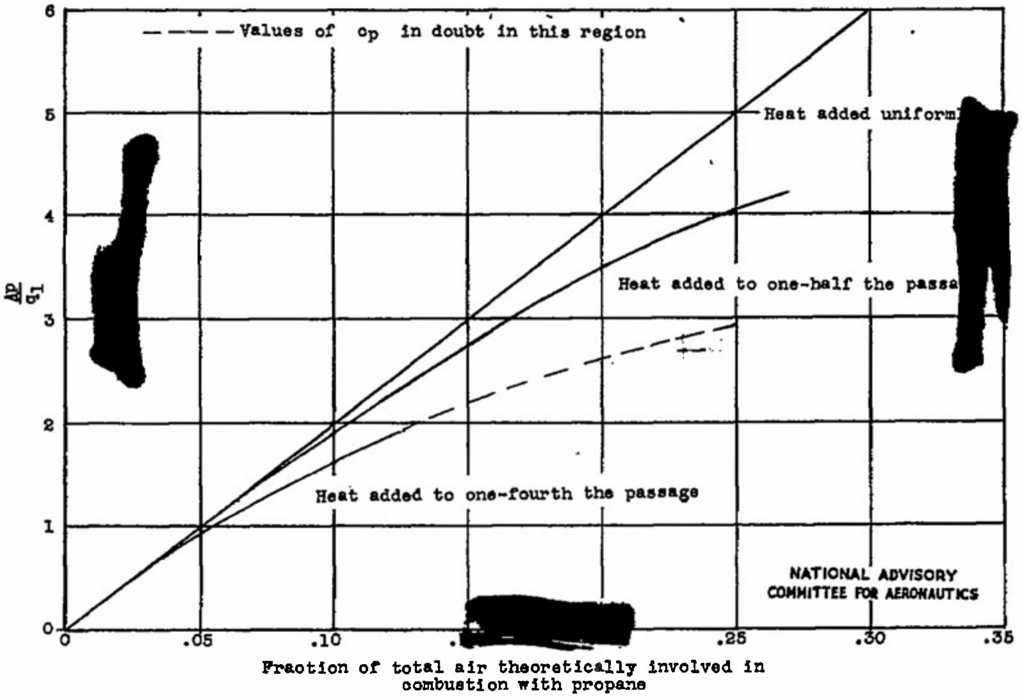

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Figure 3.- Comparison of calculated pressure drops across constant-area duct to which heat has been added uniformly and nonuniformly. Initial velocity, approximately 100 feet per second; initial temperature, approximately 550° F absolute.

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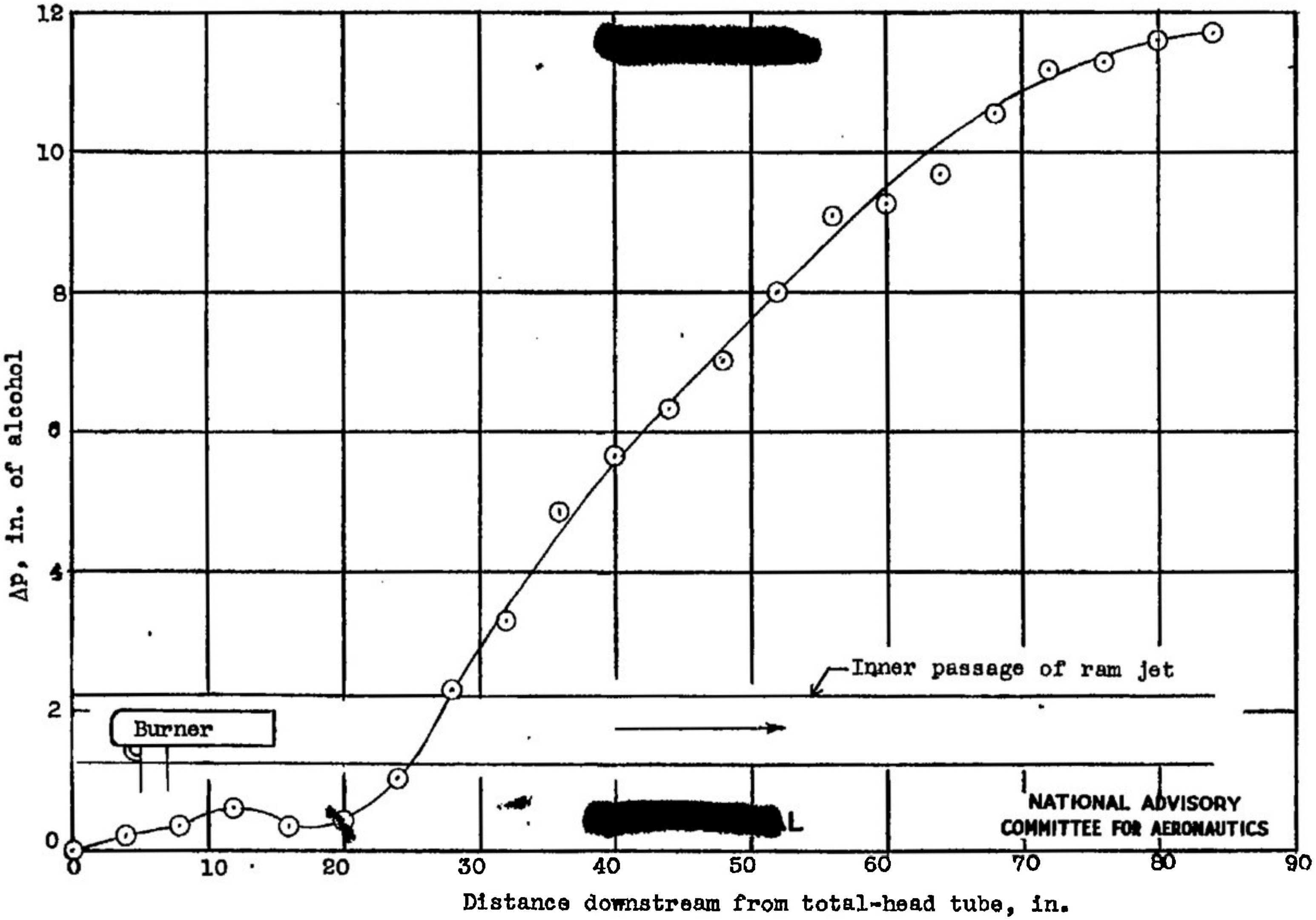

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Figure 4.- Typical measured pressure distribution along combustion tube. Initial velocity, 120 feet per second; F = 0.18.

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ABSTRACT

A small burner used to simulate the inner passage of ramjet engine was investigated to determine its possible application to supersonic flight conditions. Burner was tested at stream velocity of 150 ft/sec; fuel rates were 1/4 to 1/8 of total air used in combustion. Commercial propane was selected as fuel. Results show that because of fuel injection method and mixing of fuel and air before ignition, combustion was 80% complete. Aerodynamic losses were low, and pressure drop from frictional losses was small.

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* Combustion

ramjet engines