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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF PRESSURE FLUCTUATIONS IN 3.6-INCH RAM JET AT MACH NUMBER 1.92

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
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EXPERIMENTAL INVESTIGATION OF PRESSURE FLUCTUATIONS IN 3.6-INCH RAM JET AT MACH NUMBER 1.92

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SUMMARY

An experimental study of the pressure fluctuations at the combustion-chamber inlet of a 3.6-inch-diameter ram jet operating at a Mach number of 1.92 was conducted at the NACA Lewis 20-inch supersonic tunnel. Results based on single-point instantaneous pressure measurements in an unsteady-flow system are presented for two burner configurations of different operating characteristics in order to indicate trends in pressure magnitude, frequency, and wave form. The amplitude of the pressure fluctuations and the mean static pressure at the combustion-chamber inlet are shown as a function of fuel-air ratio for several values of outlet-inlet area ratio.

For each outlet-inlet area ratio investigated, the amplitude of the pressure fluctuations built up gradually as the fuel-air ratio was increased to the value corresponding to optimum diffuser mean static pressure (as indicated on manometers by static orifices). With further increase in fuel-air ratio, the pressure pulsations became more intense and the shock oscillated in and out of the diffuser inlet. The fundamental frequency increased from 6 to 35 cycles per second as the fuel-air ratio was increased beyond the value at optimum mean static pressure. A typical wave form is presented for this type of pressure fluctuation. With both burner configurations at conditions of optimum mean combustion-chamber static pressure, the maximum instantaneous pressure coincided (within experimental error) with the static pressure at optimum cold recovery. With the conical flame-holder configuration, the minimum instantaneous pressure at optimum mean pressure recovery approximated the cold static pressure corresponding to the particular outlet area.

A marked improvement in diffuser performance was realized with a regenerative-type burner as compared with the perforated conical flame-holder configuration.

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INTRODUCTION

A prime requisite for efficient ram-jet operation at supersonic velocities is the attainment of high total-pressure recoveries in the diffusion process. Several schemes (references 1 to 4) have been successful in attaining efficient diffusion in cold tests using steady-flow resistances (outlet-area restrictions). As shown in references 5 to 7, however, fluctuating pressures from the combustion process caused a deterioration of the optimum total-pressure recovery obtainable with three types of supersonic diffuser. These pressure fluctuations resulted in a decrease in optimum total-pressure recovery with either increasing outlet area or increasing rates of heat release. Thus the attainment of high diffuser total-pressure recoveries appears to be limited by the degree of roughness (pressure fluctuation) in the combustion process.

In order to study further the nature of these pressure pulsations and their detrimental effect on diffuser total-pressure recovery, a preliminary experimental investigation was conducted at the NACA Lewis laboratory on a 3.6-inch-diameter ram jet employing the same shock diffuser and burner configuration that had previously exhibited rough combustion characteristics (reference 5). In addition, a regenerative-type burner similar to that developed by the Research and Development Service Suboffice at Fort Bliss, Texas, was also investigated. High-speed schlieren photographs were taken of the unsteady-shock patterns at the inlet and instantaneous measurements were made of the amplitudes and frequencies of the pressure pulsations at the combustion-chamber inlet. Inasmuch as the unsteady flow produced by the burner probably set up standing waves along the duct, the single-point instantaneous measurements at the combustion-chamber inlet do not necessarily present a complete quantitative picture of the pressure fluctuations. Such data, however, should be of qualitative interest in establishing trends in pressure magnitude, frequency, and wave form.

Maximum and minimum pressures at the combustion-chamber inlet and improved diffuser performance obtained with the regenerative-type burner are presented for the operating range of fuel-air ratios and outlet areas.

APPARATUS AND PROCEDURE

Experiments were conducted in the NACA Lewis 20-inch supersonic tunnel, which was operated at a Mach number of 1.92 ±0.04. In the tunnel test section, the ambient pressure was approximately 4.0 inches of mercury absolute (pressure altitude of 47,000 ft). The total temperature of the air stream was maintained at 220° ±5° F and the dew point at -15° ±10° F. Schlieren studies were made at a Mach number of 1.91 in the 18- by 18-inch tunnel.

The 3.6-inch-diameter ram jet (fig. 1) is the same as that of reference 5, except for the outlet-area restriction. Instead of the variable outlet-area configuration, a series of fixed symmetrical nozzles was used to give the desired area ratios. The diffuser was the shock type with a triple-shock projecting cone and a curved inlet.

Two types of burner configuration were employed in this investigation. The first burner consisted of a perforated conical flame holder (references 5 to 7) used in conjunction with a liquid 62-octane-gasoline injection system and an acetylene-gas pilot. The second burner (fig. 1(b)) was the regenerative type in which the main fuel (propylene oxide) entered a 0.19-inch-diameter tube and discharged into a helical passage, where the addition of heat caused the fuel to flash into a vapor as it expanded through a 3/4-inch-diameter peripheral orifice with a gap setting of 0.005 inch. Combustion was initiated by acetylene pilot flames, which were issuing around the disk at four stations 90° apart. A photograph of the burner in combination with the acetylene pilot is shown in figure 1(c).

Instantaneous pressure data for the experiments with liquid-gasoline injection were indicated by a variable-inductance pressure pickup. This gage, which was flush-mounted to the wall at the combustion-chamber inlet, consisted basically of a twisted Bourdon tube and a variable-inductance air-gap element. The data were recorded on a three-element galvanometer, which also furnished an atmospheric reference line and timing trace.

Because of a breakdown of the variable-inductance pressure pickup, maximum and minimum pressure data were obtained for the regenerative-type burner by a balanced diaphragm gage. No frequency data were obtained with this gage.

A survey rake of 40 pitot-static-pressure tubes (fig. 1(d)) was located at the diffuser outlet. The pressures indicated on a multitube tetrabromoethane manometer board were photographically recorded.

High-speed schlieren photographs of the shock pattern at the diffuser inlet were taken with a 16-millimeter camera operating at approximately 2500 frames per second.

SYMBOLS

The following symbols are used in this report:

A_1	diffuser-inlet area with cone removed
A_4	outlet-nozzle area
P_0	free-stream total pressure
P_3	total pressure at combustion-chamber inlet (diffuser outlet)
p_3	static pressure at combustion-chamber inlet (diffuser outlet)
f/a	fuel-air ratio

RESULTS AND DISCUSSION

Perforated Conical Flame Holder

Typical of the instantaneous data taken with the variable-inductance pressure pickup is the pressure-time diagram in figure 2. The pressure ratio indicated by static tubes is superimposed on this instantaneous pressure signal. Within the accuracy of the curve, the measured mean pressure from the static-pressure tubes coincides with the integrated mean of the instantaneous pressures between points A and B.

The wave pattern (fig. 2) was the result of pressure fluctuations in the combustion chamber when the shock was oscillating in and out of the diffuser inlet. During this unstable operation, a distinct change in the slope of the wave form between the conditions of increasing and decreasing pressure was noted. As the back pressure on the diffuser increased, the normal shock moved upstream of the inlet until enough air flow was spilled that the burner presumably approached or reached the rich blow-out limit. Thereupon, the shock rapidly reentered the diffuser (as indicated by the nearly vertical slope) and the conditions again became favorable for combustion.

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Results of the instantaneous pressure measurements are presented in figure 3 for values of outlet-inlet area ratio A_4/A_1 of 0.7, 0.8, and 1.0. The ratio of combustion-chamber static pressure to free-stream total pressure p_3/P_0 is shown as a function of fuel-air ratio f/a. For each outlet area, the mean static pressure gradually increased to an optimum value and then dropped off with increasing fuel-air ratio. The instantaneous data indicated that pressure fluctuations occurred before the optimum mean static pressure. For values of f/a greater than that at the optimum mean static pressure, the pulsations became intense and the maximum instantaneous pressures in some cases exceeded the free-stream stagnation pressure and thus indicated the occurrence of explosive combustion.

With increasing values of outlet-inlet area ratio, the optimum mean static pressure decreased and occurred at a higher fuel-air ratio. The pressure fluctuations before the optimum mean static pressure increased in amplitude with increasing values of A_4/A_1 and extended over a larger range of f/a.

Values of optimum mean p_3/P_0 with the corresponding maximum and minimum data from figure 3 are plotted as a function of A_4/A_1 in figure 4. Within experimental accuracy, the maximum static pressure data coincided with the static pressure at optimum cold recovery, and the minimum static pressure data fell along the curve obtained without combustion. This correlation seemed to substantiate further the theory in reference 5 that at optimum recovery the limits of the pressure variation would correspond to conditions at blow-out and optimum heat release. It now appears that, for the perforated conical flame holder, the maximum diffuser pressure recovery in the presence of rough combustion will occur when the maximum instantaneous pressure ratio equals the optimum cold p_3/P_0.

Frequency measurements (figs. 3(a) and 3(b)) appear to be somewhat inadequate but do indicate the order of magnitude. The fundamental frequency did not remain constant but increased from 6 to 35 cycles per second as the fuel-air ratio increased beyond the value at the optimum mean static pressure. High-speed schlieren photographs of the oscillating shock indicated much the same order of frequency. For illustration, two sequences of motion pictures are shown in figure 5. The first set reveals the steady-shock pattern upstream of the diffuser inlet when the engine was operating under conditions of optimum total-pressure recovery. The second sequence (fig. 5(b)) shows that portion of the cycle where the shock was oscillating upstream of the inlet at a frequency of approximately 28 cycles per second. This pronounced change in operating conditions was effected by only a slight increase in the rate of fuel flow (from 76.5 to 78.0 lb/hr).

Regenerative-Type Burner

This investigation also included experiments on a regnerative-type burner with propylene oxide as the main fuel. High combustion efficiencies and smooth-burning characteristics were evidenced in previous experiments with this burner-fuel combination. Because of a breakdown of the variable-inductance pressure pickup, a balanced diaphragm gage was employed. This gage measured only the maximum and minimum pressures.

The resultant data are presented in figure 6 with p_3/P_0 plotted as a function of f/a. The data obtained with the regenerative-type burner show pressure fluctuations again occurring before the optimum mean p_3/P_0. Sporadic pulsing in the vicinity of and beyond the optimum mean p_3/P_0 prevented accurate measurements of the minimum pressure due to an inability to weight the effect of these intermittent fluctuations. The dashed lines indicate the conditions at which these stray pulses began to increase in frequency and intensity. The maximum static pressures were better defined than the minimum static pressures.

At the peak indicated by the static tubes, the maximum instantaneous static pressure agreed within experimental accuracy with the mean static pressure at optimum cold recovery. At the same conditions, the minimum static pressure dropped off rapidly, as shown by the dashed lines, but it could not be established whether this minimum value would coincide with the p_3/P_0 value obtained without combustion. The general trend, however, was in agreement with that presented in figure 4 for the perforated conical flame holder.

Diffuser Total-Pressure Recovery

The regenerative-type burner using propylene oxide as the main fuel gave a marked improvement in diffuser total-pressure recovery with combustion as compared with that obtained with the perforated conical flame holder using liquid-fuel injection. The relative diffuser performance with the two burners is shown in figure 7, where the optimum total-pressure recovery P_3/P_0 with combustion is presented as a function of the total-pressure recovery P_3/P_0 without combustion. Over the range investigated, improved diffuser performance in the presence of combustion is shown by the consistently higher values of optimum total-pressure recovery obtained with the regenerative-type burner. Further evidence of improved diffuser performance is indicated by the slight decrease in optimum P_3/P_0 with decreasing cold P_3/P_0 or with equivalently increasing values of A_4/A_1. Experiments using propylene oxide in conjunction with the perforated conical flame holder resulted in approximately the same curve as that obtained with 62-octane gasoline.

SUMMARY OF RESULTS

A preliminary experimental investigation of pressure fluctuations at the combustion-chamber inlet of a 3.6-inch-ram jet employing a shock diffuser and operating at a Mach number of 1.92 gave the following results for two distinct burner configurations:

1. For each outlet-inlet area ratio investigated, the amplitude of the pressure fluctuations built up gradually as the fuel-air ratio was increased to the value corresponding to optimum diffuser mean static pressure (as indicated on manometers by static orifices). With further increase in fuel-air ratio, the pressure pulsations became more intense and the shock oscillated in and out of the diffuser inlet. The fundamental frequency increased from 6 to 35 cycles per second as the fuel-air ratio was increased beyond the value at optimum mean static pressure.

2. With both burner configurations at the conditions of optimum mean combustion-chamber static pressure, the maximum instantaneous pressure coincided within experimental error with the static pressure at optimum cold recovery. With the conical flame-holder configuration, the minimum instantaneous pressure at optimum mean pressure recovery approximated the cold static pressure corresponding to the particular outlet area.

3. A marked improvement in diffuser performance was obtained with the regenerative-type burner as compared with the perforated conical flame-holder configuration.

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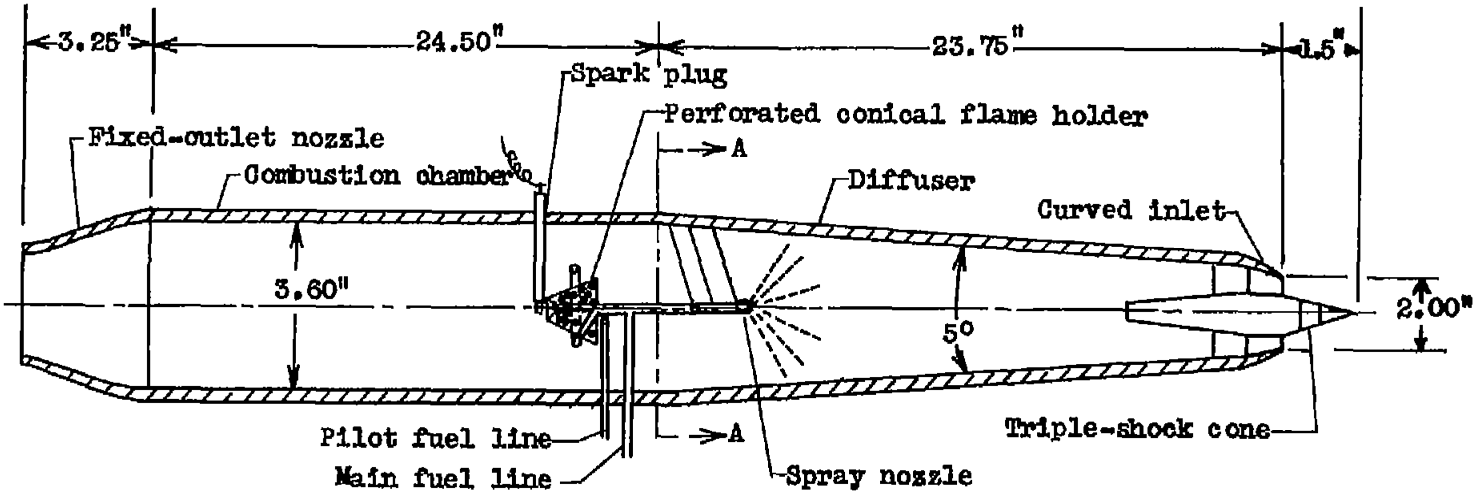
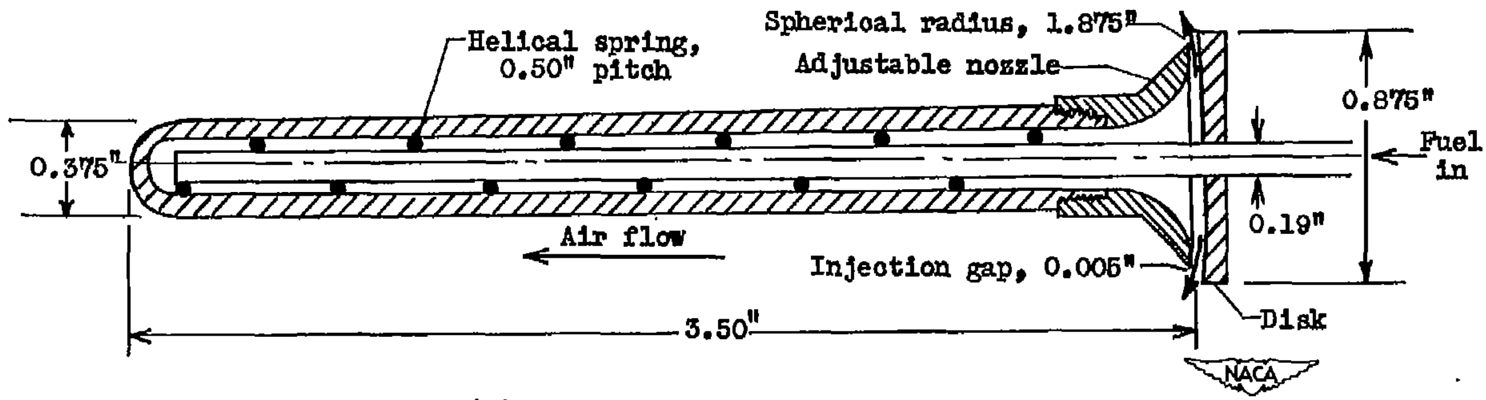
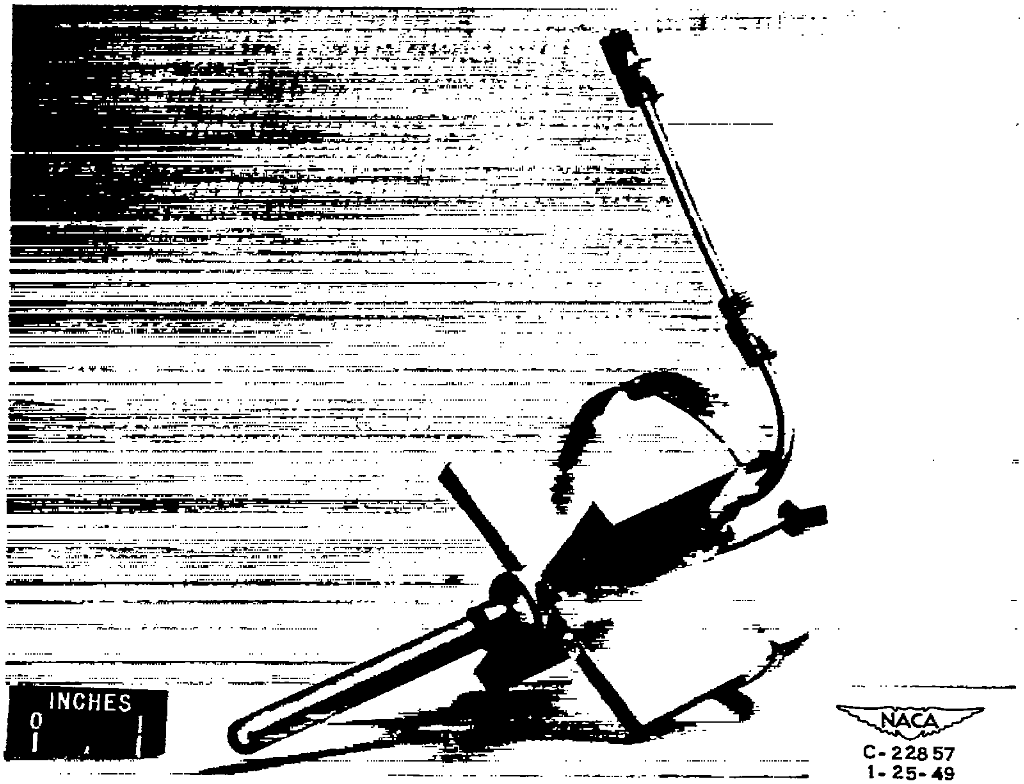


(a) Schematic drawing of combustion model with perforated conical flame holder.

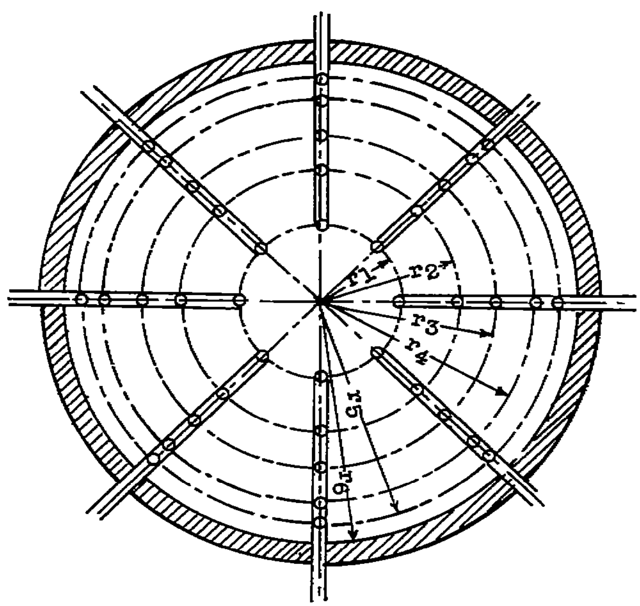


(b) Details of regenerative-type burner.

Figure 1. - Experimental ram-jet model.



(c) Regenerative burner with acetylene pilot.



	Radius (in.)
r_1	0.57
r_2	.98
r_3	1.21
r_4	1.51
r_5	1.70
r_6	1.80

(d) Pitot-static survey rake located at cross section A-A (fig. 1(a)).

Figure 1. - Concluded. Experimental ram-jet model.

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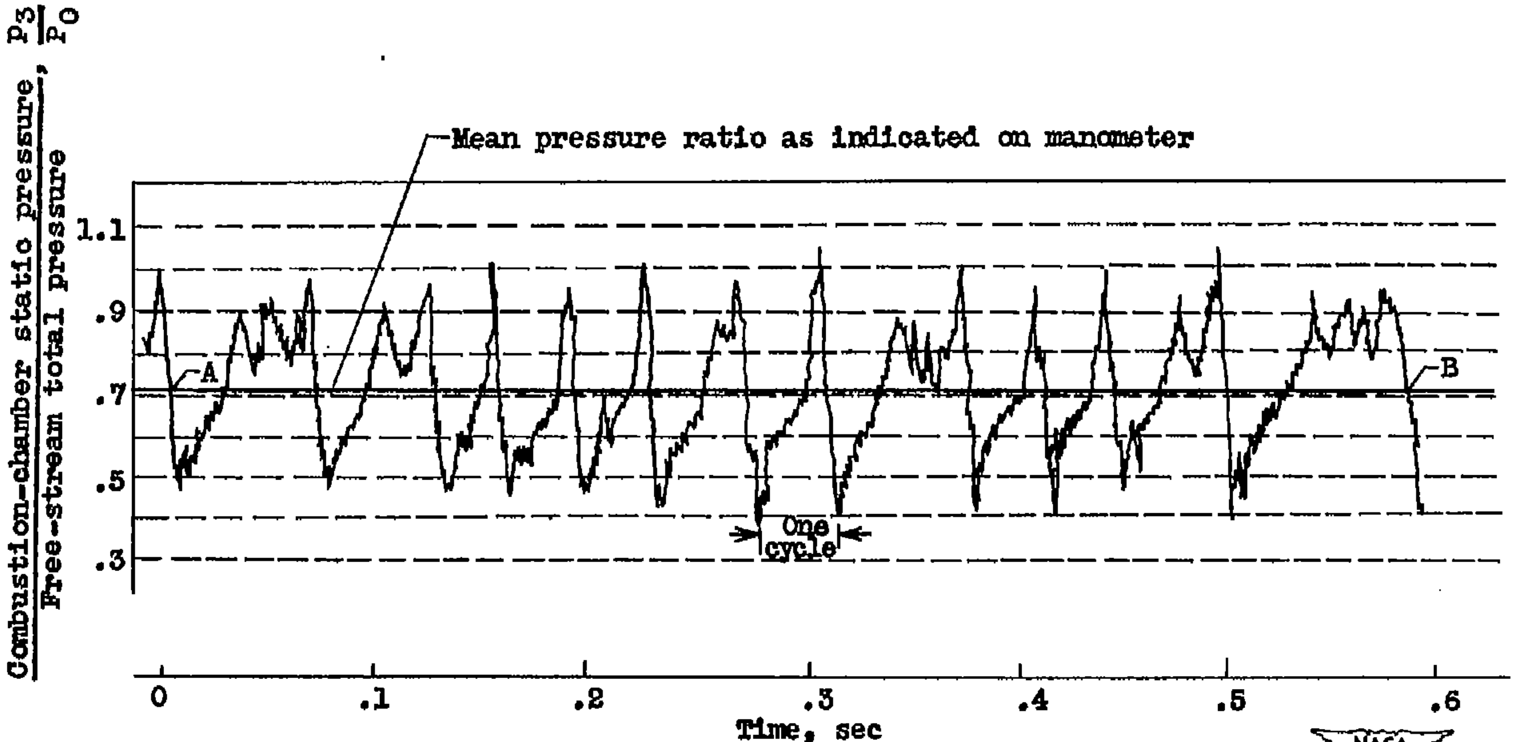
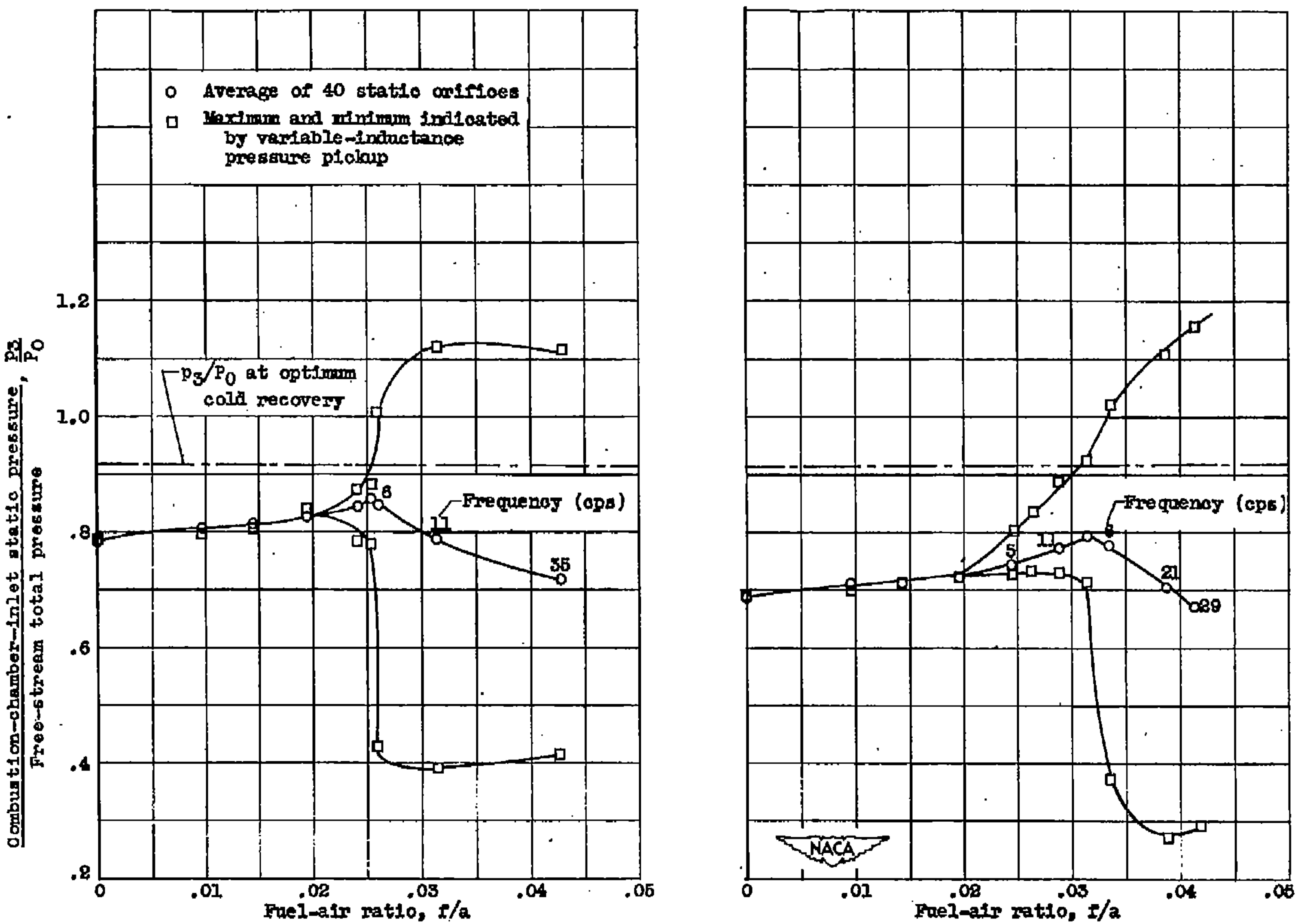


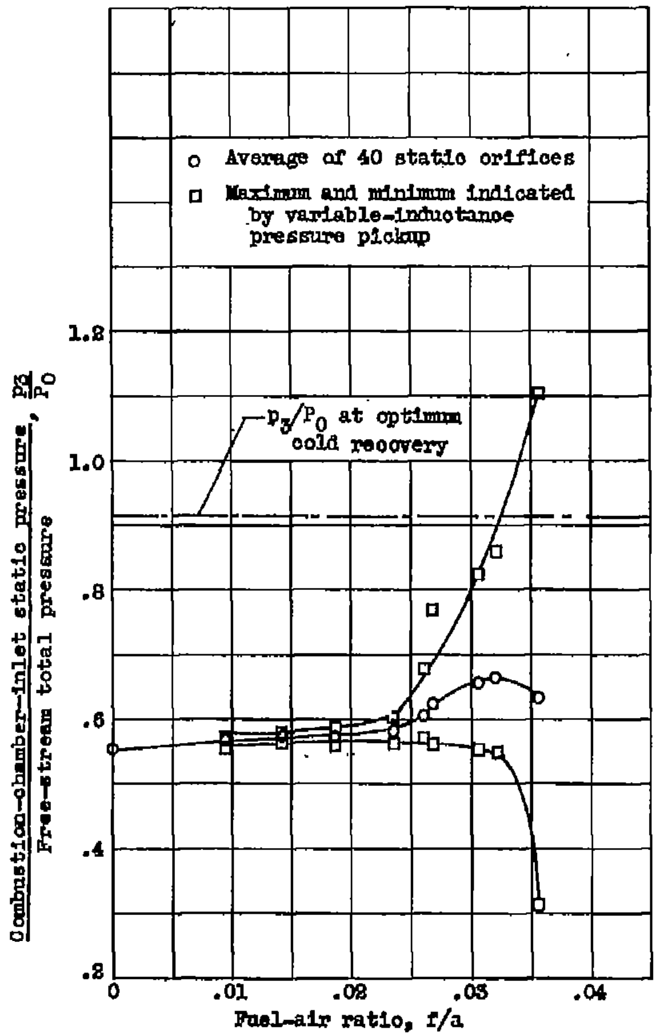
Figure 2. - Typical signal from variable-inductance pressure pickup showing wave form of pressure fluctuations at combustion-chamber inlet when ram jet is operating with shock oscillating in and out of diffuser inlet. Shock diffuser with triple-shock projecting cone; fundamental frequency, approximately 22 cycles per second.



(a) Outlet-inlet area ratio, A_4/A_1, 0.7.

(b) Outlet-inlet area ratio, A_4/A_1, 0.8.

Figure 5. - Effect of fuel-air ratio on combustion-chamber-inlet static pressure. Perforated conical flame holder.



(c) Outlet-inlet area ratio, A_4/A_1, 1.0.

Figure 3. - Concluded. Effect of fuel-air ratio on combustion-chamber-inlet static pressure. Perforated conical flame holder.

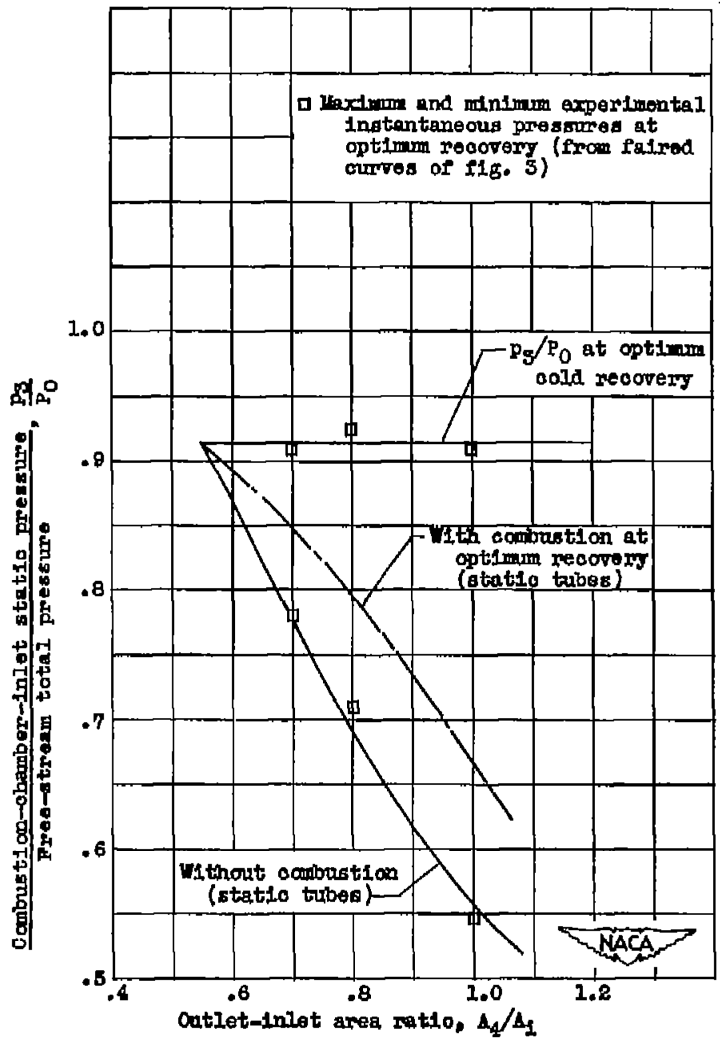
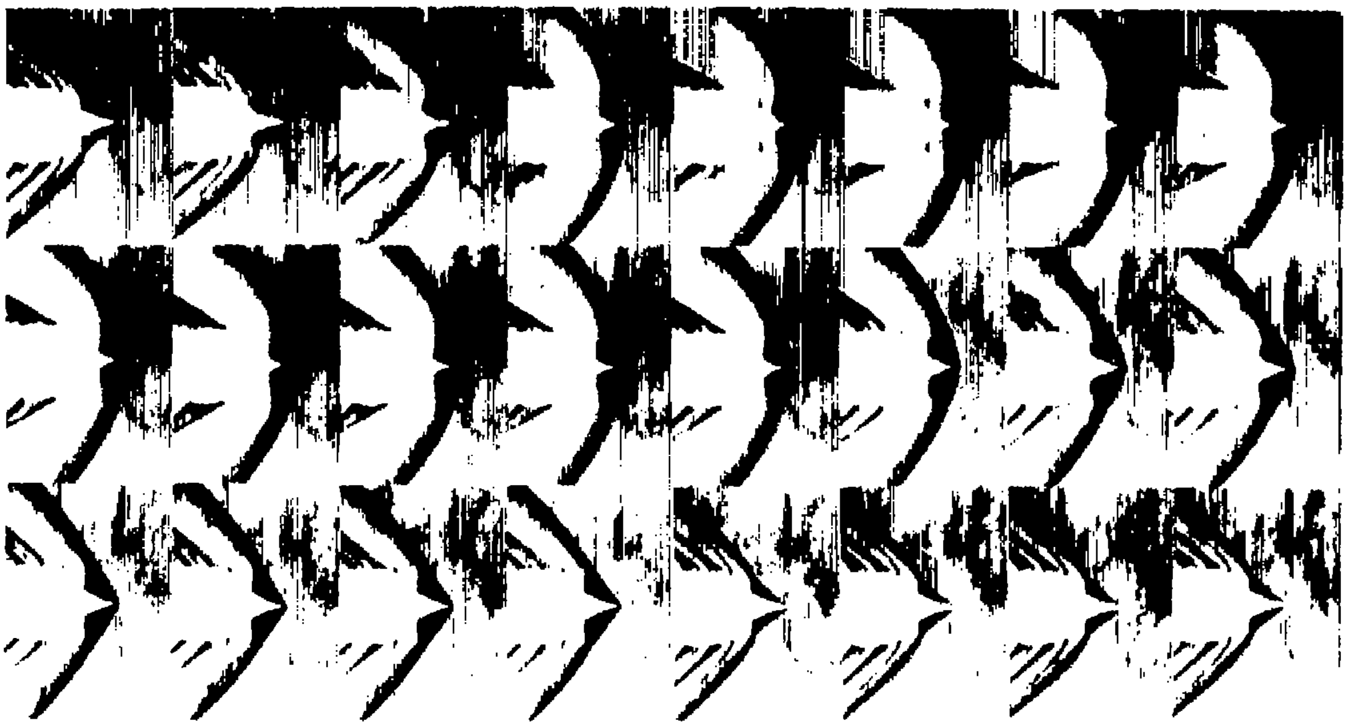


Figure 4. - Variation of maximum and minimum combustion-chamber-inlet static pressures with outlet-inlet area ratio at optimum mean static pressure. Perforated conical flame holder.

(a) Fuel flow, 76.5 pounds per hour; optimum total-pressure recovery, P_3/P_0, 0.80.



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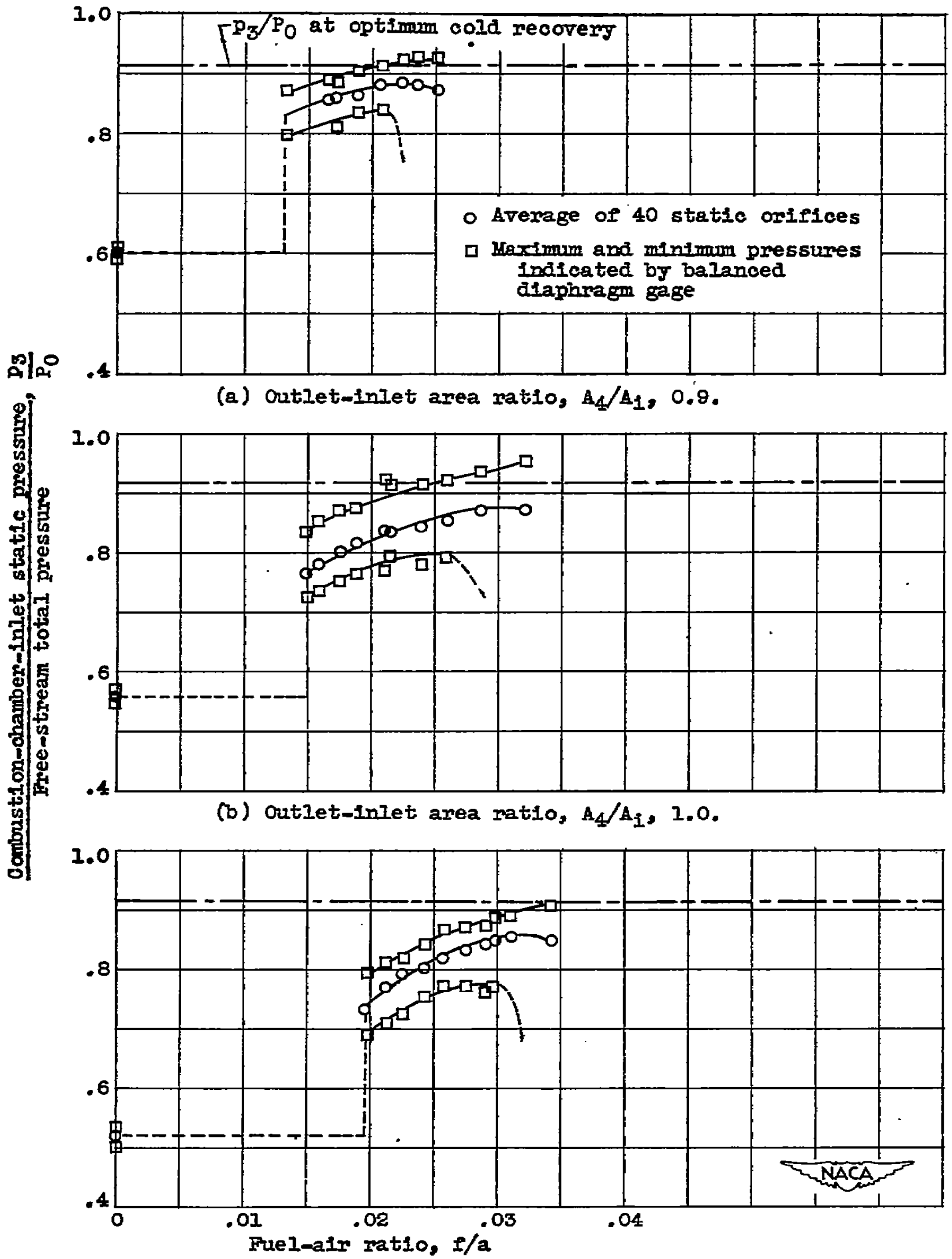
(b) Fuel flow, 78.0 pounds per hour; total-pressure recovery, P_3/P_0, 0.66; frequency, 28 cycles per second.

Figure 5. - High-speed schlieren photographs of shock pattern at diffuser inlet (approximately 2500 frames/sec). Outlet-inlet area ratio, A_4/A_1, 0.8.



(a) Outlet-inlet area ratio, A_4/A_1, 0.9.

(b) Outlet-inlet area ratio, A_4/A_1, 1.0.

(c) Outlet-inlet area ratio, A_4/A_1, 1.1.

Figure 6. - Effect of fuel-air ratio on combustion-chamber-inlet static pressure. Regenerative-type burner.

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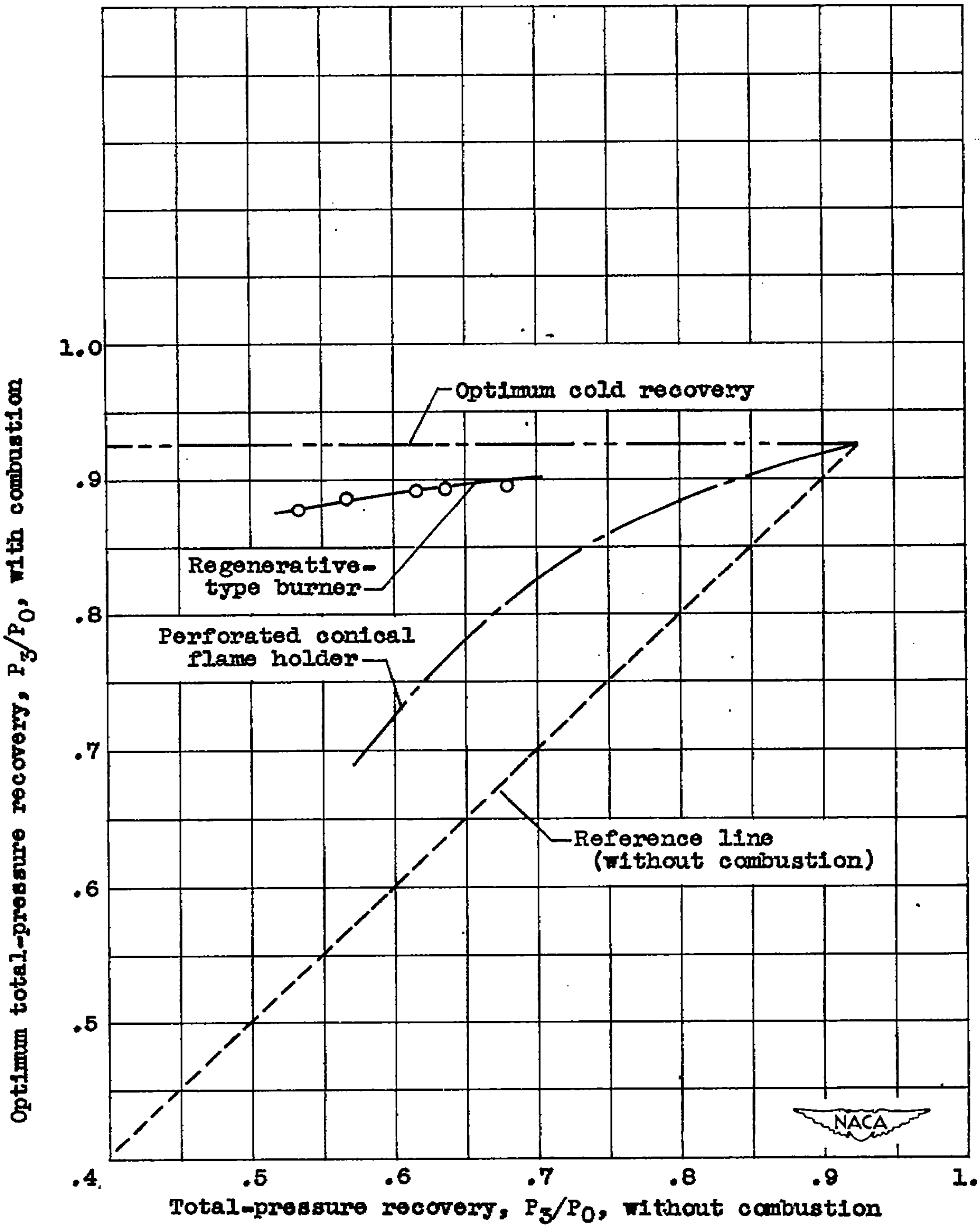

Figure 7. - Comparative diffuser performance with regenerative-type burner and perforated conical flame holder.

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