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RESEARCH MEMORANDUM

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By William H. Sterbentz and Fred A. Wilcox

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The effects of a movable exhaust-nozzle plug on the operational performance of a 20-inch ram jet were determined in an investigation conducted in the NACA Cleveland altitude wind tunnel. The results obtained at various exhaust-nozzle-plug positions over a range of fuel-air ratios, combustion-chamber-inlet velocities and static pressures, and ambient-air static pressures are presented.

The highest combustion efficiencies were attained with the exhaust-nozzle plug fully retracted into the engine. The effect of the exhaust-nozzle plug in the combustion chamber on net thrust per square foot of exhaust-nozzle area at a fixed value of gas total-temperature ratio was negligible, which indicates that the total-pressure losses over the exhaust-nozzle plug were small.

INTRODUCTION

A study of ram-jet performance characteristics indicates that control of the exhaust-nozzle-outlet area of a ram jet provides a means of obtaining optimum performance over a wide range of operating conditions. Control of the exhaust-nozzle-outlet area can be used to position the shock in a supersonic diffuser, to limit or maintain the combustion-chamber-inlet Mach number, and to vary the engine net thrust and specific fuel consumption over a range of values, even at fixed flight velocities. A movable plug located in a fixed-wall exhaust nozzle is a practical means of controlling the exhaust-nozzle-outlet area. Previous investigations of the variables that govern the performance of a ram-jet combustion chamber, however, have indicated that the performance of the combustion chamber may be markedly affected by the geometry of the combustion chamber and the flame holder. (See references 1 to 3.) An exhaust-nozzle plug, because of the supporting struts and large size and length, may greatly affect the turbulence and mixing of the gas through the combustion chamber, thereby affecting the performance of the combustion chamber.

An investigation was therefore conducted in the NACA Cleveland altitude wind tunnel to determine the effect of a movable exhaust-nozzle plug on the operational performance of a 20-inch ram jet. The results of this investigation are compared with the results presented in reference 4 for the split-injection burner operating in a ram jet with an 8-foot combustion chamber and a 17-inch-diameter exhaust nozzle. The same burner and ram jet were used in the investigation reported herein, with the exception that the exhaust-nozzle plug was added and the 17-inch nozzle was changed to a $17\frac{5}{8}$-inch nozzle. An analysis of the effect of the exhaust-nozzle plug on the combustion-chamber performance is presented in terms of the variables of exhaust-nozzle-plug position, fuel-air ratio, combustion-chamber-inlet velocity and static pressure, and ambient static pressure. The effect of the exhaust-nozzle plug on the engine net thrust and the cooling requirements are also presented.

APPARATUS AND PROCEDURE

A schematic diagram of the 20-inch ram jet used in this investigation is shown in figure 1. The diffuser has an 8° included angle, a 14-inch-diameter inlet, and a 20-inch-diameter outlet. The combustion chamber is 20 inches in diameter and 8 feet long. A fixed-wall exhaust nozzle, 2 feet long with a $17\frac{5}{8}$-inch diameter outlet, was attached to the combustion-chamber outlet. Cooling water for the combustion chamber and the exhaust-nozzle shell was circulated through helical passages constructed by seam-welding a corrugated outer shell to a smooth inner shell.

A water-cooled exhaust-nozzle plug (fig. 2), designed at the Cleveland laboratory, was mounted in the last 3 feet of the combustion chamber and extended into the exhaust-nozzle outlet. The exhaust-nozzle plug was $8\frac{1}{16}$ inches in diameter at the largest section and could be hydraulically moved a total of 11 inches from the fully retracted to the fully extended position. The rear section of the combustion chamber and the exhaust nozzle with the exhaust-nozzle plug installed are shown in figure 3. By moving the exhaust-nozzle plug forward or backward as desired, the exhaust-nozzle-outlet area could be varied from 1.34 to 1.66 square feet. The outlet areas obtained at various exhaust-nozzle-plug positions are given in figure 4.

The split-injection burner described in reference 5 was used in this investigation. The burner consisted of: (1) a flame holder (fig. 5) mounted at the combustion-chamber inlet from which a fixed amount of fuel at a temperature of approximately 80° F was sprayed in a downstream direction, and (2) a fuel injector (fig. 6) mounted upstream of the flame holder near the ram-jet diffuser inlet from which a variable amount of fuel, preheated at a temperature of 200° F $\pm 10^{\circ}$, was sprayed in an upstream direction. The fuel was preheated with the steam-heat exchanger system described in reference 5.

The ram jet was mounted below a 7-foot-chord wing attached to the wind-tunnel balance frame. Dry refrigerated air at a temperature of 20° F $\pm 10^{\circ}$ was brought directly to the ram jet by an air duct and could be throttled from approximately sea-level pressures to the desired static pressure at the combustion-chamber inlet. The engine exhausted the gases directly into the wind-tunnel test section, where the pressure altitude was varied to the desired condition. Free movement of the model was obtained by a sealed slip joint, which was inserted between the ram jet and the air duct and allowed the use of the wind-tunnel balance system to measure thrust.

From measurements of total pressures, static pressures, and indicated temperatures at the diffuser inlet and the static pressure at the combustion-chamber inlet, the air flows and the combustion-chamber-inlet velocities were computed. The fuel flows were measured with rotameters. From the measured values of jet thrust and gas flow, the combustion efficiency and the gas-temperature rise were computed by the methods presented in references 1 and 2. The heat loss to the combustion chamber and nozzle-plug cooling water was accounted for in the calculation of combustion efficiency. This heat loss was computed from cooling-water-flow and temperature-rise measurements.

The engine operational performance was investigated at various tunnel ambient static pressures, combustion-chamber-inlet static pressures, and fuel-air ratios. At each setting of fuel-air ratio and tunnel ambient and combustion-chamber-inlet static pressures, readings were taken for different positions of the movable exhaust-nozzle plug.

SYMBOLS

The following symbols are used in this report:

A	cross-sectional area, square feet
F_n	net thrust, pounds
f/a	fuel-air ratio
M	Mach number
m_g	mass gas flow, slugs per second
p	static pressure, pounds per square foot absolute
Q	heat loss, Btu per second
T	total temperature, $^{\circ}R$
V	velocity, feet per second
x	distance between exhaust-nozzle outlet and end of exhaust-nozzle plug, inches
δ	ratio of absolute tunnel ambient-air pressure to absolute static pressure at NACA standard atmospheric conditions at sea level, $p_0/2116$
η_b	combustion efficiency, percent
τ	ratio of absolute total temperature at exhaust-nozzle outlet to absolute total temperature at diffuser inlet, T_4/T_1

Subscripts:

0	equivalent free-stream condition
1	subsonic diffuser inlet
2	subsonic diffuser outlet and combustion-chamber inlet
3	combustion-chamber outlet
4	exhaust-nozzle outlet

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Parameters:

$\frac{F_n}{\delta A_4}$ net thrust per square foot of exhaust-nozzle area reduced to NACA standard atmospheric conditions at sea level

$\frac{Q}{m_g^{0.8}}$ exhaust-nozzle-plug heat-absorption parameter

RESULTS AND DISCUSSION

The sensitivity of engine combustion performance to changes in the combustion chamber is evident from a study of figures 7 to 14. The performance of the combustion chamber with the exhaust-nozzle plug in a fixed position is established in figures 7 to 9. The effects on the combustion-chamber performance of the presence of the exhaust-nozzle plug in the combustion chamber and of various settings of the exhaust-nozzle plug are presented in figures 10 to 14. Comparison is made with the data reported in reference 4 for the split-injection burner operating in a ram jet with an 8-foot combustion chamber and a 17-inch-diameter exhaust nozzle.

Performance with Exhaust-Nozzle Plug in Fixed Position

Combustion efficiency η_b is presented in figure 7 as a function of combustion-chamber-inlet static pressure p_2 and ambient-air static pressure p_0 at an exhaust-nozzle-plug setting fixed at the fully extended plug position. (See fig. 3.) Data are presented at fuel-air ratios of 0.030 ± 0.001, 0.040 ± 0.002, and 0.051 ± 0.002. Contours have been faired through the data at approximately constant values of combustion-chamber-inlet velocity V_2.

At a given value of V_2, figure 7 shows that variation in p_2 over the range investigated (1420 to 2015 lb/sq ft absolute) had little effect on η_b. Furthermore, a comparison of data having about the same value of V_2 indicates that variations in p_0 also had negligible effect on η_b. However, figure 7 does show that V_2 is an important variable affecting η_b of this engine configuration.

The strong effect of V_2 and the negligible effects of p_2 and p_0 on η_b were also observed from the results of the investigation reported in reference 4, in which the same burner was used in a similar combustion chamber without the exhaust-nozzle plug.

The data presented in figure 7 have been replotted in figure 8 to show η_b as a function of V_2. The variation of η_b with V_2 is different at each fuel-air ratio. At a fuel-air ratio of 0.030, as V_2 was increased from 119 to about 152 feet per second, η_b decreased about 6 percent (fig. 8(a)). Increases in V_b to about 152 feet per second at this fuel-air ratio caused flame blow-out. 962

At a fuel-air ratio of 0.040, an increase in V_2 from 116 to 150 feet per second caused a decrease of approximately 18 percent in η_b (fig. 8(b)). The combustion-chamber-inlet velocity could not be increased above 150 feet per second at this fuel-air ratio because of exhaust-nozzle choking.

The data for a fuel-air ratio of 0.051 show that by increasing V_2 from 117 to about 143 feet per second, a steady decrease in η_b of approximately 17 percent resulted. Exhaust-nozzle choking limited V_2 to 143 feet per second at this fuel-air ratio.

The variation of the gas total-temperature ratio across the engine τ with V_2 at any given fuel-air ratio (fig. 9) follows the pattern of variation of η_b with V_2.

Performance Effect of Exhaust-Nozzle Plug and Exhaust-Nozzle-Plug Position

The effect of exhaust-nozzle-plug position on combustion efficiency η_b and gas total-temperature ratio τ at a fuel-air ratio of 0.040 ± 0.002 is shown in figure 10. Data points are presented for the exhaust-nozzle plug in the fully retracted position (fig. 10) and are compared to the curve for the exhaust-nozzle plug in the fully extended position obtained from figures 8 and 9. At a fixed value of V_2, higher values of η_b were obtained with the exhaust-nozzle plug fully retracted. The increase in η_b is presumably due to the attendant increase in the flame-holder action of the exhaust-nozzle plug when it is fully submerged within the ram-jet combustion chamber. At a V_2 of 125 feet per second, η_b increased from about 87 percent with the exhaust-nozzle plug fully extended to about 91 percent with the exhaust-nozzle plug fully retracted (fig. 10(a)). At more pronounced increase in η_b occurred at a V_2 of 150 feet per second. At this velocity, η_b was increased from about 74 percent with the exhaust-nozzle plug fully extended to about 90 percent with the exhaust-nozzle plug fully retracted. The pattern of variation of τ with exhaust-nozzle-plug position was similar to that of η_b as shown in figure 10(b). With the exhaust-nozzle plug in the fully retracted position, flame blow-out occurred at combustion-chamber-inlet velocities greater than 160 feet per second.

A plot of η_b and τ as a direct function of exhaust-nozzle-plug position is shown in figure 11 for a fuel-air ratio of 0.050 ± 0.002 at fixed values of V_2. At a V_2 of 142 feet per second, an increase in η_b from about 69 to 80 percent was obtained by retracting the exhaust-nozzle plug a distance of 5 inches into the combustion chamber of the engine from a fully extended position. Approximately the same change in η_b occurred at a V_2 of 152 feet per second when the exhaust-nozzle plug was retracted an additional distance of 4 inches into the combustion chamber. Over these same ranges of exhaust-nozzle-plug positions, τ varied from about 5.4 to 6.3 at a V_2 of 142 feet per second and from about 5.4 to 6.1 at a V_2 of 152 feet per second. Concomitant increases in net thrust resulted from increasing both τ and the exhaust-nozzle-outlet area by retracting the exhaust-nozzle plug.

The marked improvement that incorporation of the movable exhaust-nozzle plug into the combustion chamber of the ram jet had on η_b for the engine is shown in figure 12. Replotted from figures 8, 9, and 10 are the solid-line curves showing the variation of η_b and τ with V_2 for the two extreme positions of the exhaust-nozzle plug mounted in the ram jet. The dashed curves were obtained from figure 6 of reference 4, which presents the data for the same burner operating in a similar combustion chamber without the nozzle plug.

For the condition without the exhaust-nozzle plug, as V_2 was increased from about 100 to 140 feet per second, an increase in η_b from 47 to 81 percent was obtained (fig. 12(a)). Over the portion of this range of V_2 at which data were obtained, η_b remained nearly constant at about 91 percent with the nozzle plug in the fully retracted position and at about 87 percent with the exhaust-nozzle plug fully extended. Further increases in V_2 decreased η_b for all three configurations; the sharpest drop occurred with the exhaust-nozzle plug fully extended. Although for this configuration η_b dropped below that attained without the exhaust-nozzle plug in the combustion chamber at a V_2 value greater than about 145 feet per second, some positions of the plug model always gave higher efficiencies than the single-outlet jet. A similar variation in τ can be noted.

In order to study the effect of exhaust-nozzle-plug position on η_b and τ as a function of fuel-air ratio, figures 13 and 14 are presented for the fully extended and fully retracted exhaust-nozzle-plug positions, respectively. The fuel-air-ratio range of stable combustion, which was approximately 0.029 to 0.054, was not noticeably affected by exhaust-nozzle-plug position. At a given value of V_2 and exhaust-nozzle-plug position, η_b gradually increased with fuel-air ratio until a maximum was reached at a fuel-air ratio of 0.041. Further increases in fuel-air ratio decreased the combustion efficiency. The position of the exhaust-nozzle plug did not change the fuel-air ratio at which peak η_b occurred.

The gas total-temperature ratio τ increased with fuel-air ratio for a given V_2 and exhaust-nozzle-plug position. Peak values of τ occurred at a fuel-air ratio of approximately 0.050.

Effect of Plug on Net Thrust

Reduced net thrust per square foot of exhaust-nozzle area is plotted in figure 15 as a function of equivalent free-stream Mach number M_0 for a gas total-temperature ratio τ of 6.0 ± 0.2. Data are presented for the exhaust-nozzle plug in both fully extended and fully retracted positions. The dashed curve computed from figure 12 of reference 4 is included for the split-injection burner in a ram jet with a 17-inch-diameter exhaust nozzle without the exhaust-nozzle plug. A comparison of the dashed curve with that for the fully extended plug shows that the presence of the nozzle plug in the combustion chamber had a negligible effect on the net thrust per square foot of exhaust-nozzle area. This negligible effect indicates that the total-pressure losses over the exhaust-nozzle plug were small. Higher values of net thrust per square foot of exhaust-nozzle area are obtained with the exhaust-nozzle plug fully extended because the lower combustion-chamber-inlet velocities V_2, which accompany a decrease in exhaust-nozzle-outlet area, result in lower losses in total pressure through the ram jet.

Cooling Requirements

The exhaust-nozzle-plug heat-absorption parameter $Q/m_g^{0.8}$, which is a ratio of the total heat loss to the exhaust-nozzle plug in Btu per second to the mass gas flow in slugs per second to the 0.8 power, is plotted as a function of exhaust-nozzle-outlet gas total temperature T_4 in figure 16. This parameter was chosen because the experimental data analyzed in reference 6 indicate a linear variation of $Q/m_g^{0.8}$ with T_4 for a constant wall temperature. The scatter of data in figure 16 may be attributed to variations in the specific heats of the products of combustion, to variation of the exhaust-nozzle-plug-shell temperature, and to effects of heat absorbed by radiation. Lower values of the exhaust-nozzle-plug heat-absorption parameter at a given value of T_4 were obtained when the exhaust-nozzle plug was fully retracted. The cooling-water outlet temperature was not greater than 200° F for any condition.

SUMMARY OF RESULTS

From an investigation of the effects of a movable exhaust-nozzle plug on the operational performance of a 20-inch ram jet, the following results were obtained:

1. Incorporation of the movable exhaust-nozzle plug into the combustion chamber of the ram jet had a marked effect on the combustion efficiency, which was dependent upon the exhaust-nozzle-plug

position in the combustion chamber. Over a range of combustion-chamber-inlet velocity from 100 to 140 feet per second, higher values of combustion efficiency were obtained for all positions of the exhaust-nozzle plug than for the single-outlet jet, the highest combustion efficiency being attained with the exhaust-nozzle plug fully retracted. At combustion-chamber-inlet velocities greater than 145 feet per second, when the exhaust-nozzle plug was fully extended, combustion efficiency dropped below that attained with the single-outlet jet, but higher combustion efficiencies were always obtained with the exhaust-nozzle plug fully retracted.

2. The effect of the presence of the exhaust-nozzle plug in the combustion chamber on the net thrust per square foot of exhaust-nozzle area at a fixed value of gas total-temperature ratio was negligible, which indicates that the total-pressure losses over the exhaust-nozzle plug were small.

3. The variation of combustion efficiency with combustion-chamber-inlet velocity was different at each fuel-air ratio for any fixed setting of the exhaust-nozzle plug. At a fuel-air ratio of 0.030 with the exhaust-nozzle plug in its fully extended position, as combustion-chamber-inlet velocity was increased from 119 to 152 feet per second the combustion efficiency decreased only about 6 percent. At a fuel-air ratio of 0.051, however, as combustion-chamber-inlet velocity was increased from 119 to 143 feet per second, a steady decrease in combustion efficiency of 16 percent resulted. At a given value of combustion-chamber-inlet velocity, peak combustion efficiency occurred at a fuel-air ratio of about 0.041.

4. As with the ram jet without the exhaust-nozzle plug, variations in combustion-chamber-inlet static pressure at fixed values of combustion-chamber-inlet velocity over the range investigated (1420 to 2015 lb/sq absolute) had little effect upon combustion efficiency. Similarly, variations in ambient static pressure had little effect on combustion efficiency.

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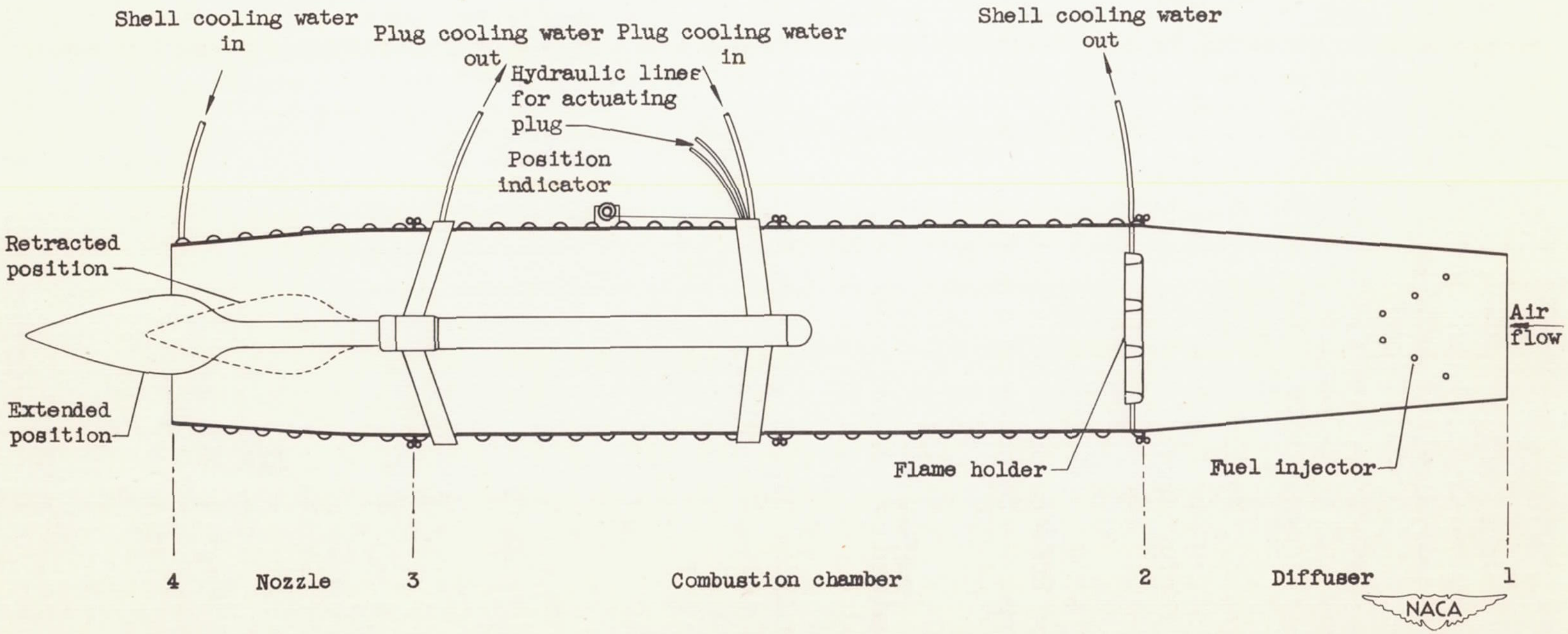

Figure 1. - Schematic diagram of 20-inch ram jet showing installation of movable exhaust-nozzle plug in combustion chamber.

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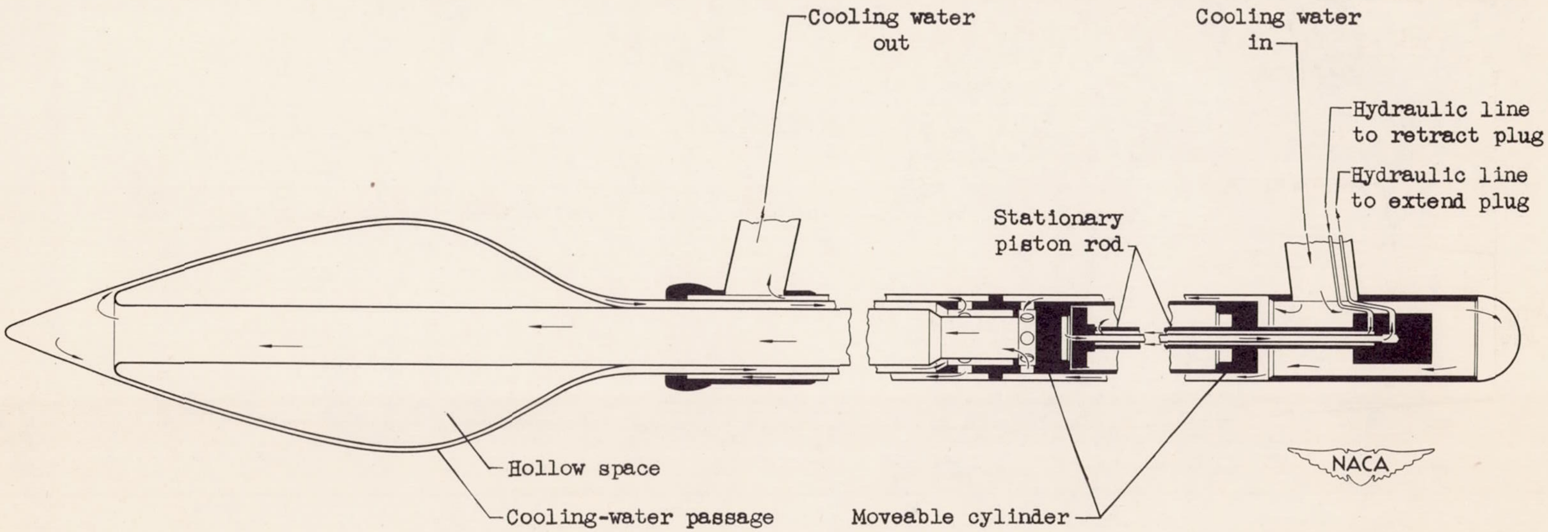

Figure 2. - Schematic diagram of exhaust-nozzle plug showing hydraulic-positioning cylinder and method of water-cooling.

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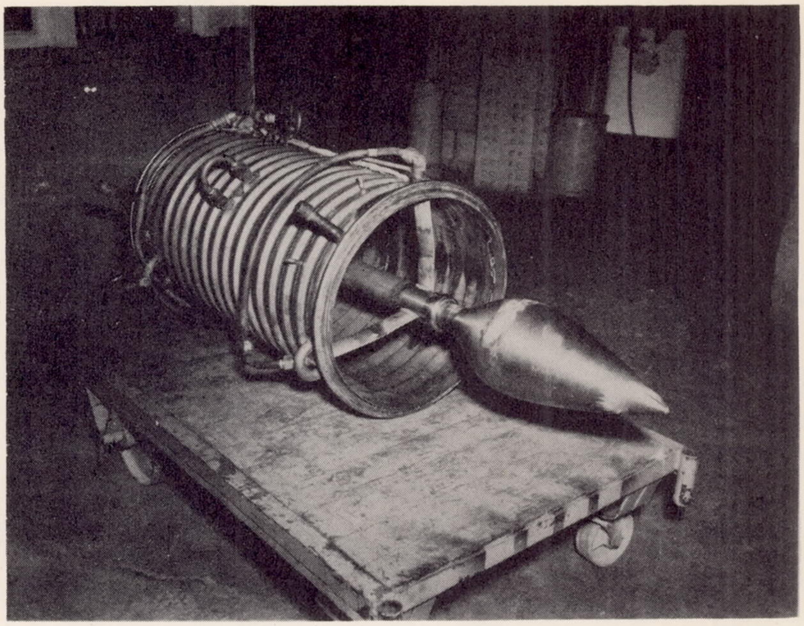
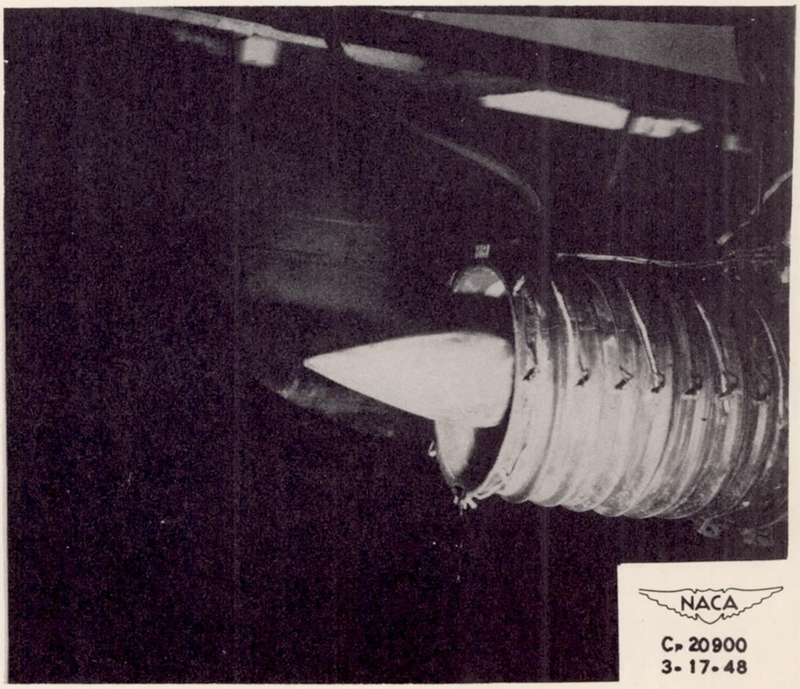


(a) Exhaust-nozzle plug in fully retracted position mounted in a 3-foot combustion-chamber section with no nozzle attached.



(b) Exhaust-nozzle plug in fully extended position mounted in combustion chamber with $17\frac{5}{8}$-inch exhaust nozzle attached.

Figure 3. - Exhaust-nozzle plug installed in combustion chamber of 20-inch ram jet.

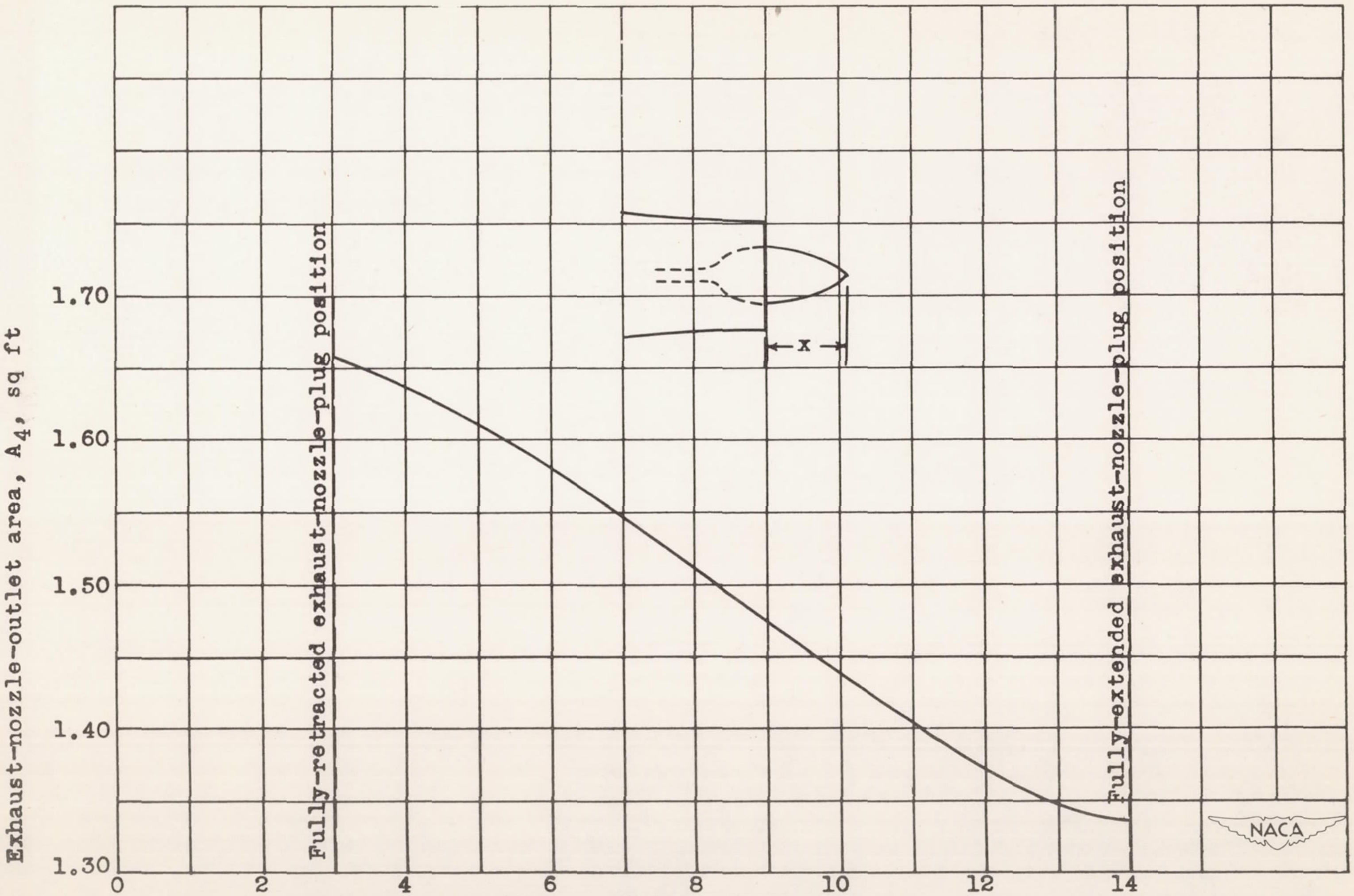


Figure 4. - Exhaust-nozzle-outlet area calibration of $17\frac{5}{8}$-inch-diameter exhaust nozzle at various exhaust-nozzle-plug positions.

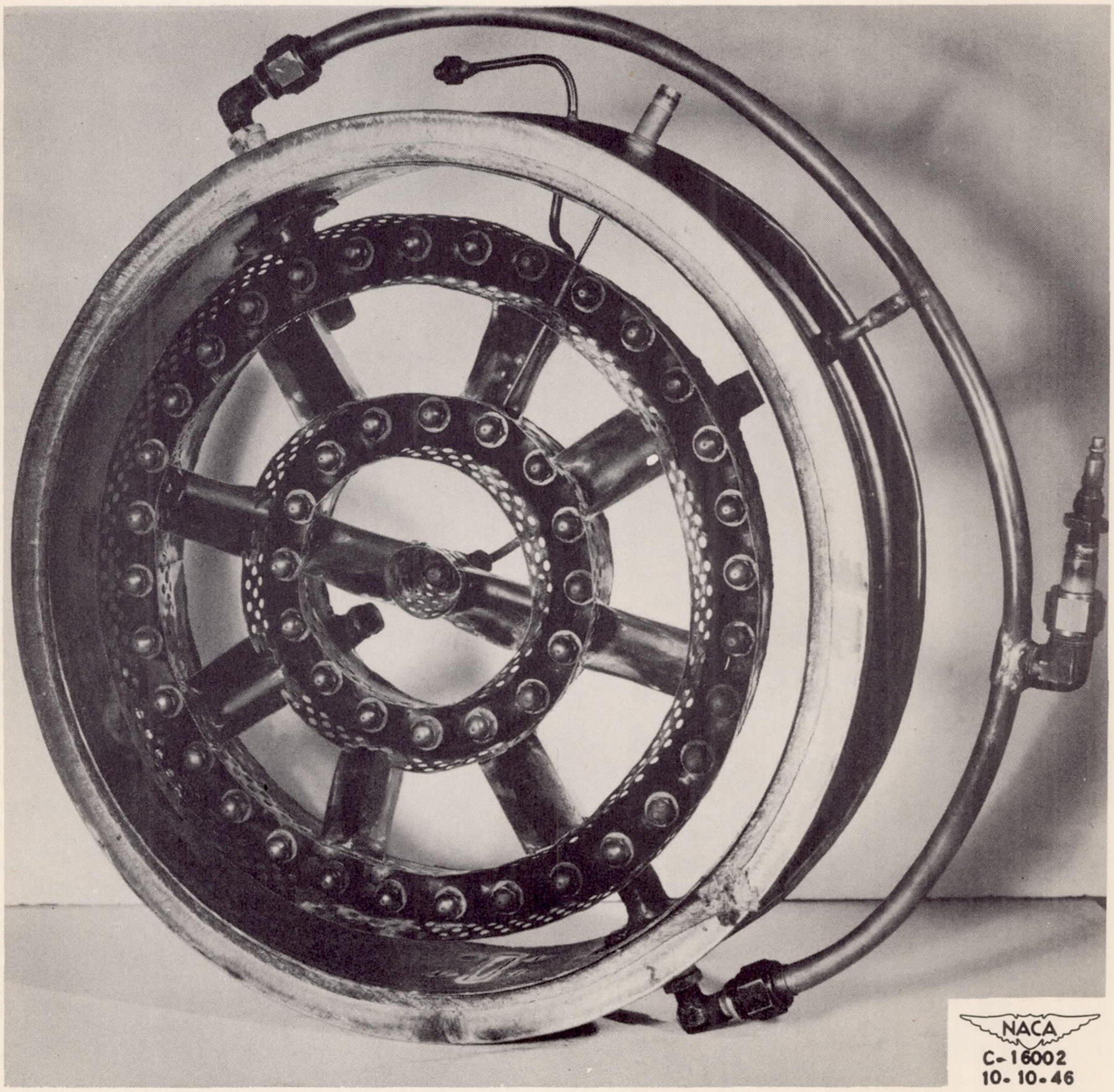


Figure 5. - Downstream view of flame holder showing fuel-spray nozzles within flame-holder gutters.

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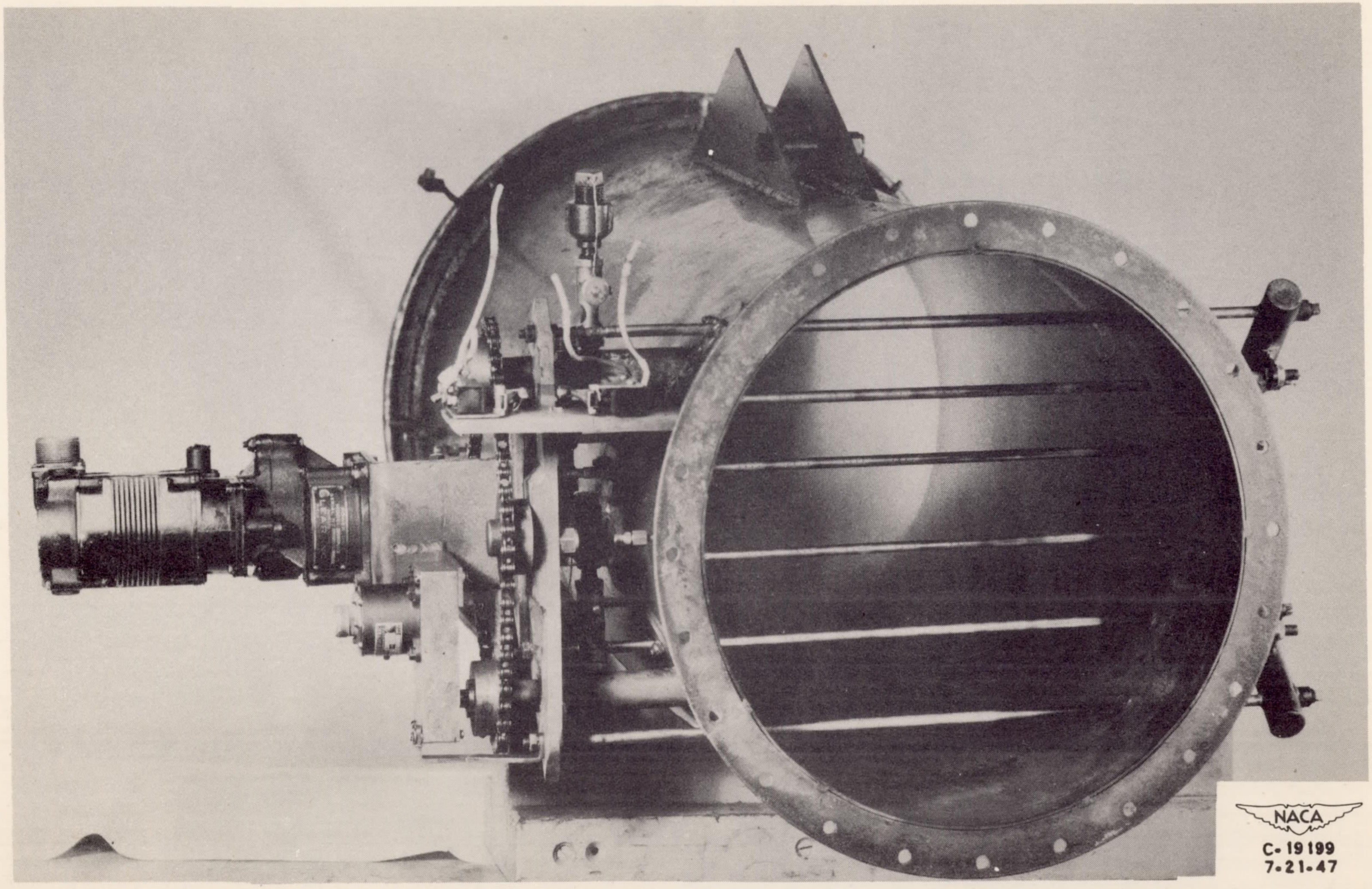

Figure 6. - Upstream view of six-tube adjustable fuel injector mounted in diffuser.

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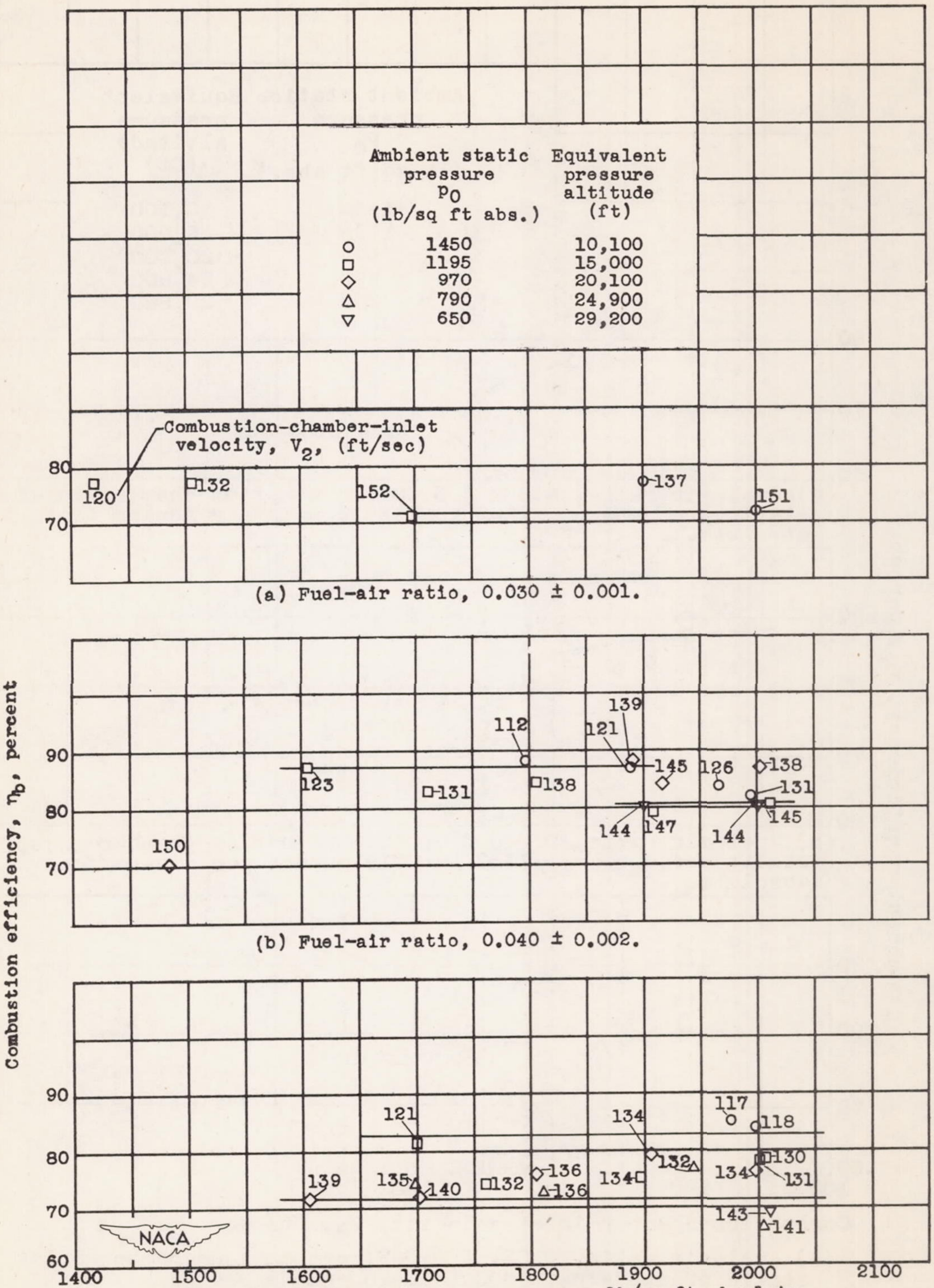
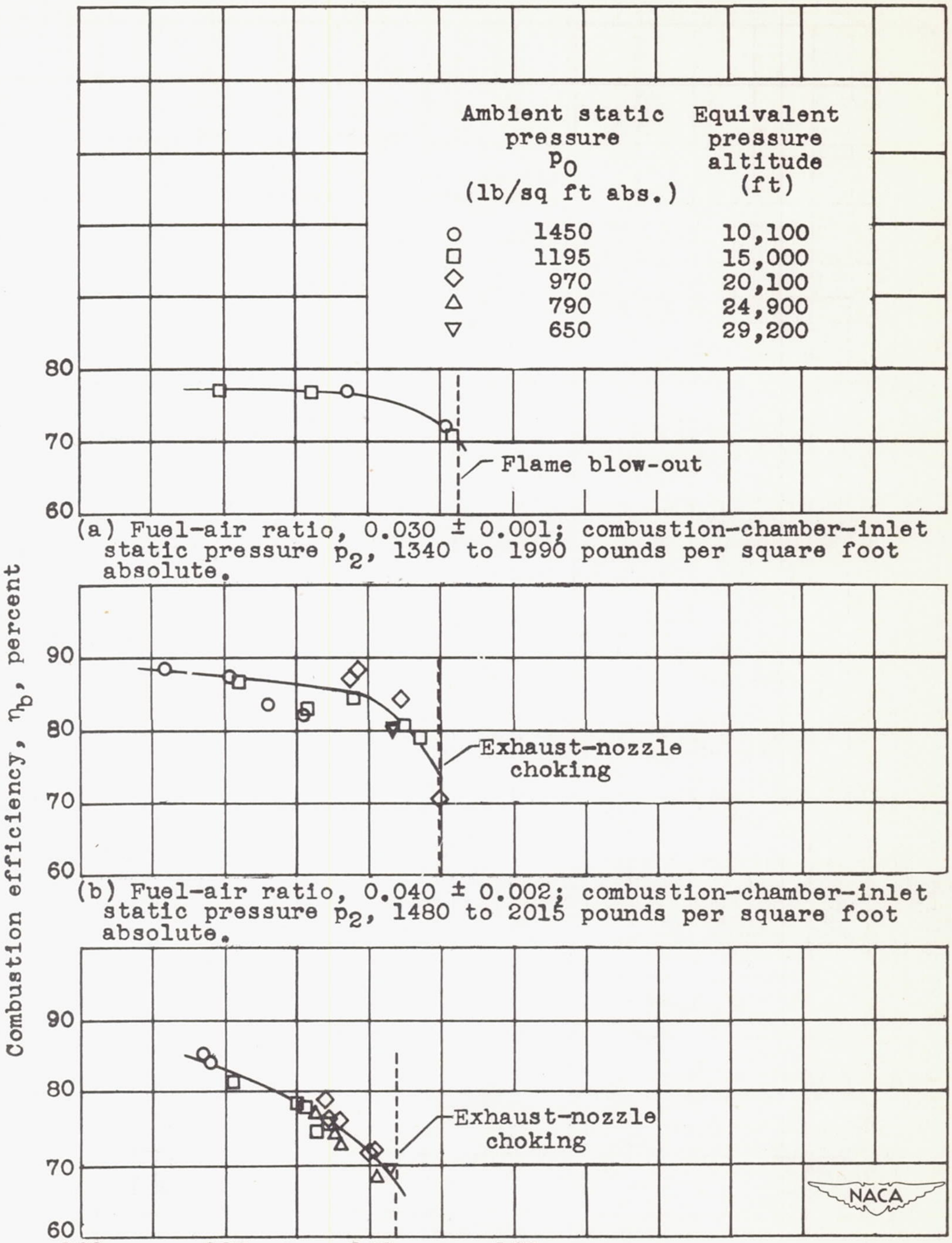


Figure 7. - Effect of combustion-chamber-inlet static pressure and fuel-air ratio on combustion efficiency at various conditions of combustion-chamber-inlet velocity and ambient static pressure. 20-inch ram jet with 8-foot combustion chamber; exhaust-nozzle plug fully extended.

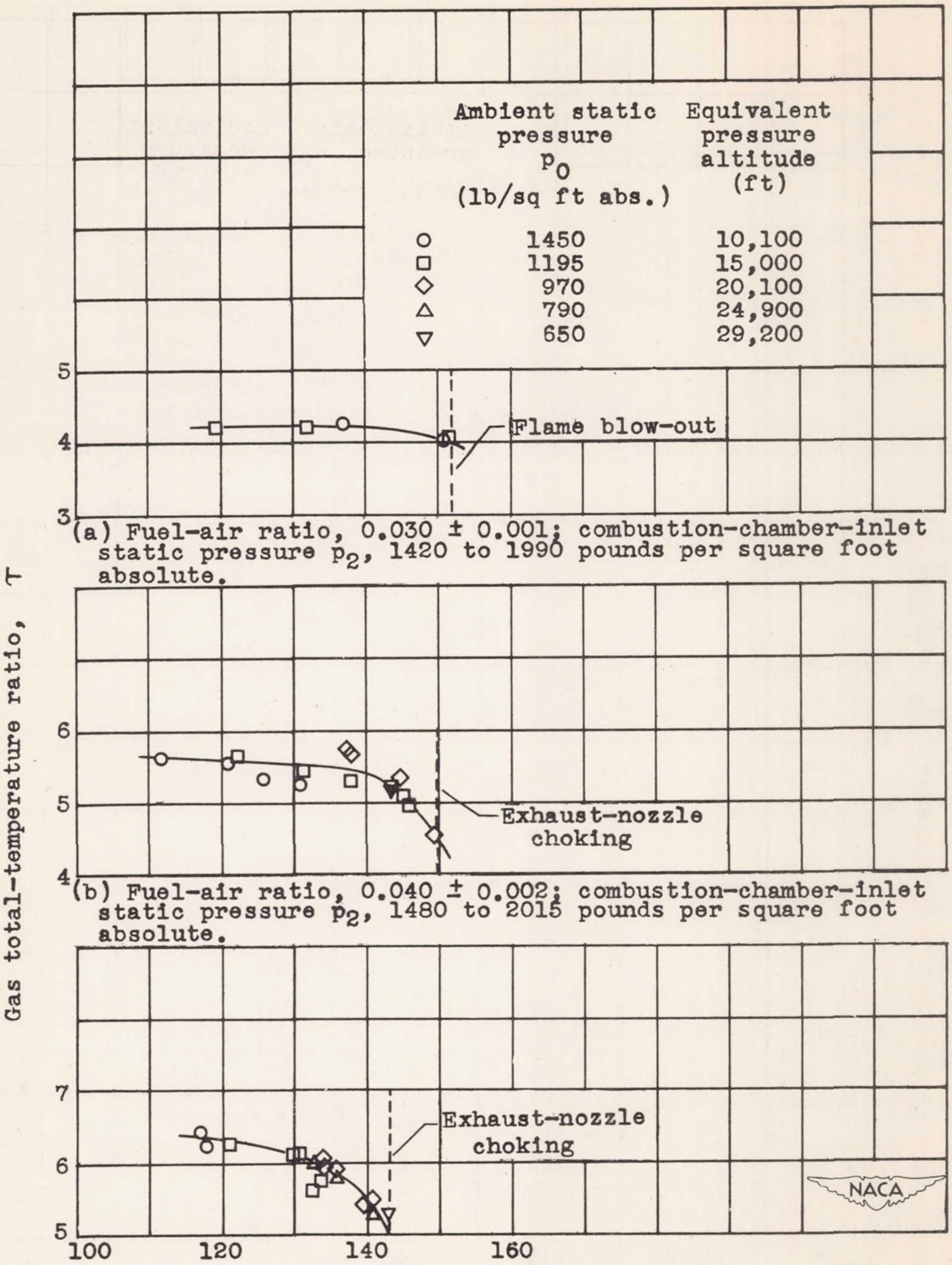


(a) Fuel-air ratio, 0.030 ± 0.001; combustion-chamber-inlet static pressure p_2, 1340 to 1990 pounds per square foot absolute.

(b) Fuel-air ratio, 0.040 ± 0.002; combustion-chamber-inlet static pressure p_2, 1480 to 2015 pounds per square foot absolute.

(c) Fuel-air ratio, 0.051 ± 0.002; combustion-chamber-inlet static pressure p_2, 1602 to 2010 pounds per square foot absolute.

Figure 8. - Effect of combustion-chamber-inlet velocity and fuel-air ratio on combustion efficiency at various conditions of combustion-chamber-inlet static pressure and ambient static pressure. 20-inch ram jet with 8-foot combustion chamber; exhaust-nozzle plug fully extended.

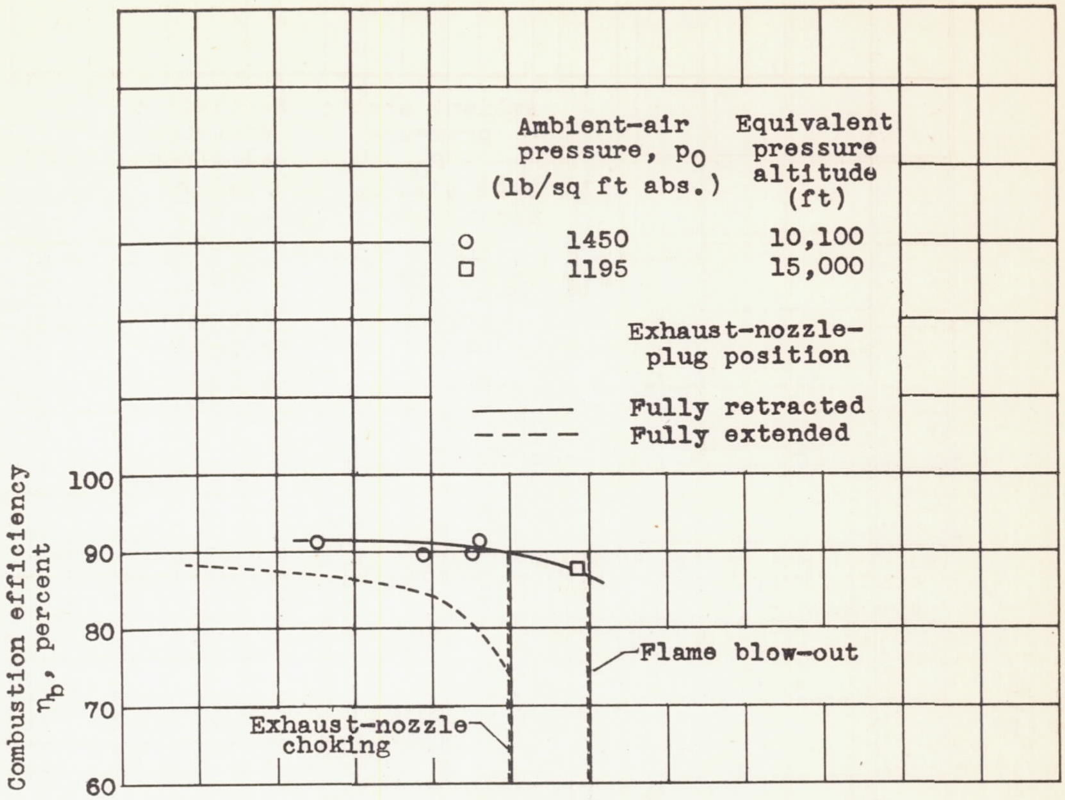


(a) Fuel-air ratio, 0.030 ± 0.001; combustion-chamber-inlet static pressure p_2, 1420 to 1990 pounds per square foot absolute.

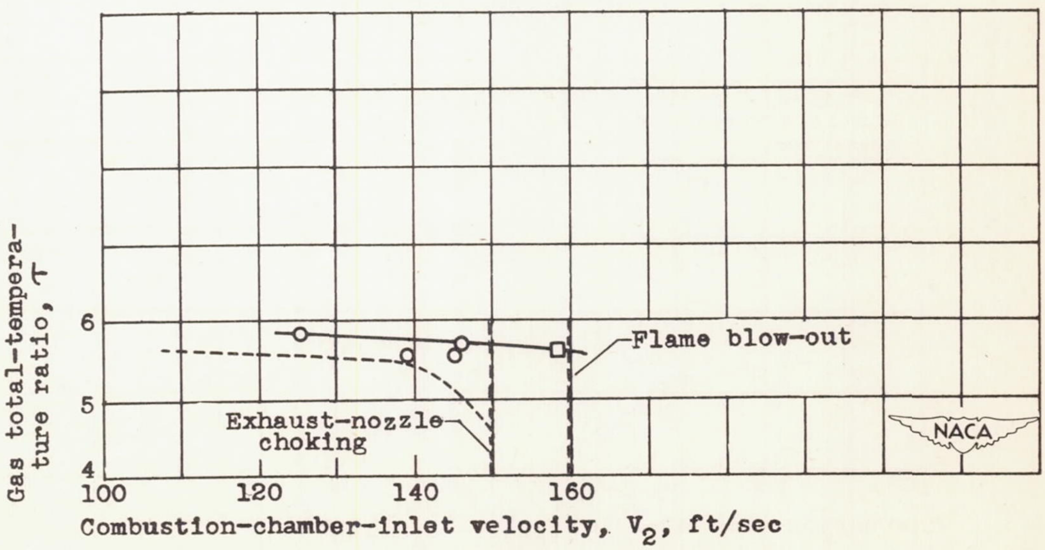
(b) Fuel-air ratio, 0.040 ± 0.002; combustion-chamber-inlet static pressure p_2, 1480 to 2015 pounds per square foot absolute.

(c) Fuel-air ratio, 0.051 ± 0.002; combustion-chamber-inlet static pressure p_2, 1602 to 2010 pounds per square foot absolute.

Figure 9. - Effect of combustion-chamber-inlet velocity and fuel-air ratio on gas total-temperature ratio at various conditions of combustion-chamber-inlet static pressure and ambient static pressure. 20-inch ram jet with 8-foot combustion chamber; exhaust-nozzle plug fully extended.

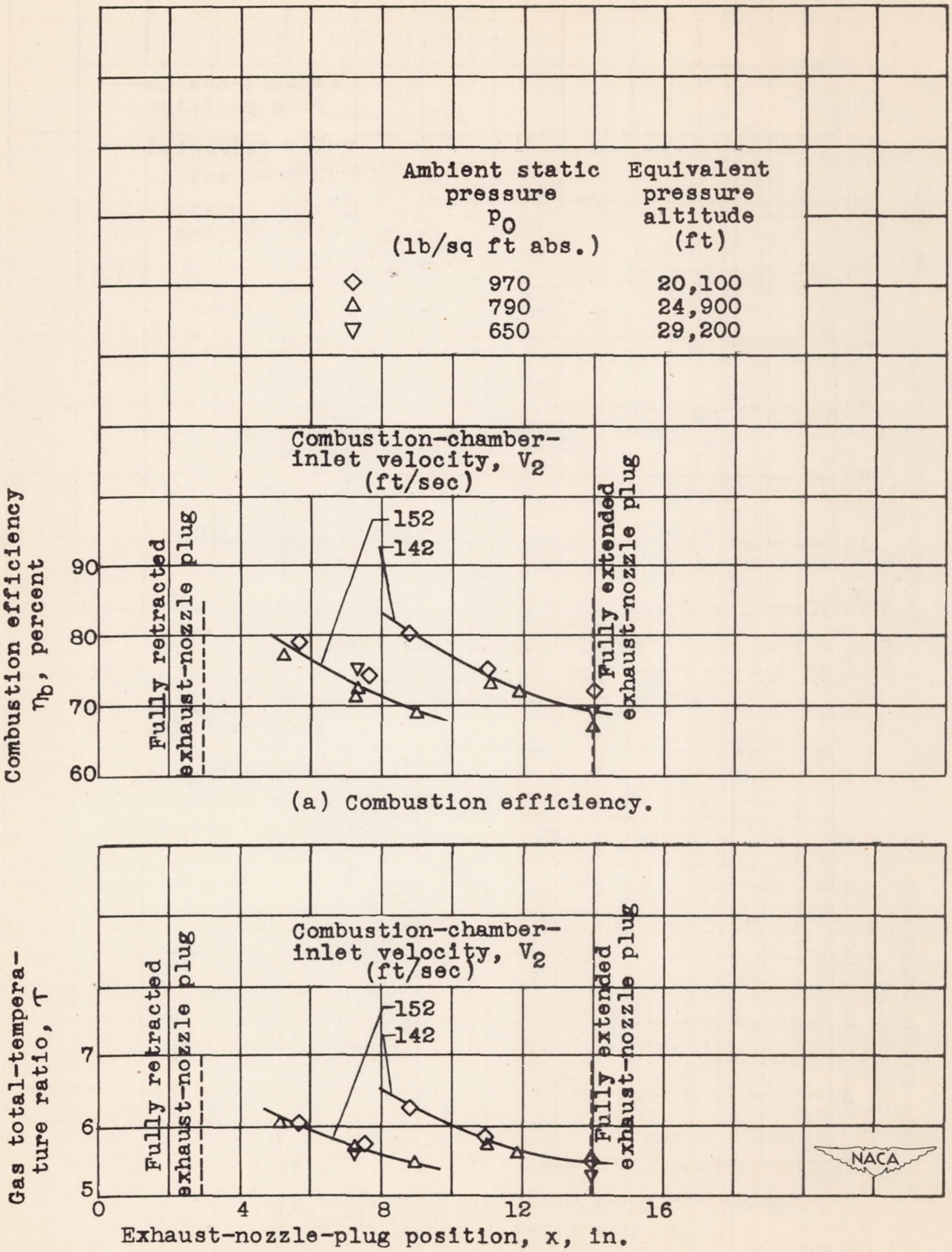


(a) Combustion efficiency.



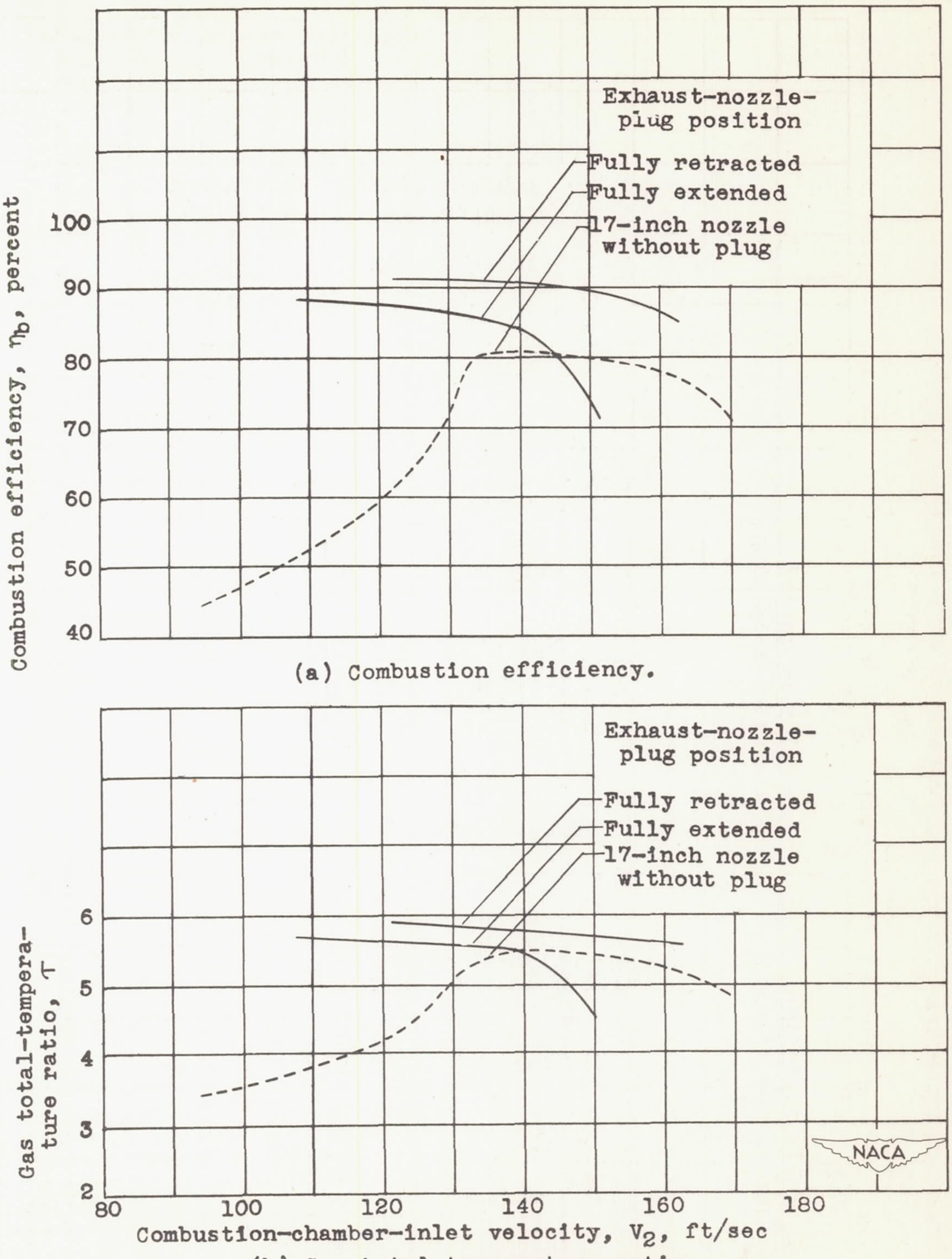
(b) Gas total-temperature ratio.

Figure 10. - Effect of combustion-chamber-inlet velocity on combustion efficiency and gas total-temperature ratio for exhaust-nozzle plug fully retracted and fully extended. 20-inch ram jet with 8-foot combustion chamber; fuel-air ratio, 0.040 ± 0.002; combustion-chamber-inlet static pressure p_2, 1795 to 2006 pounds per square foot absolute.



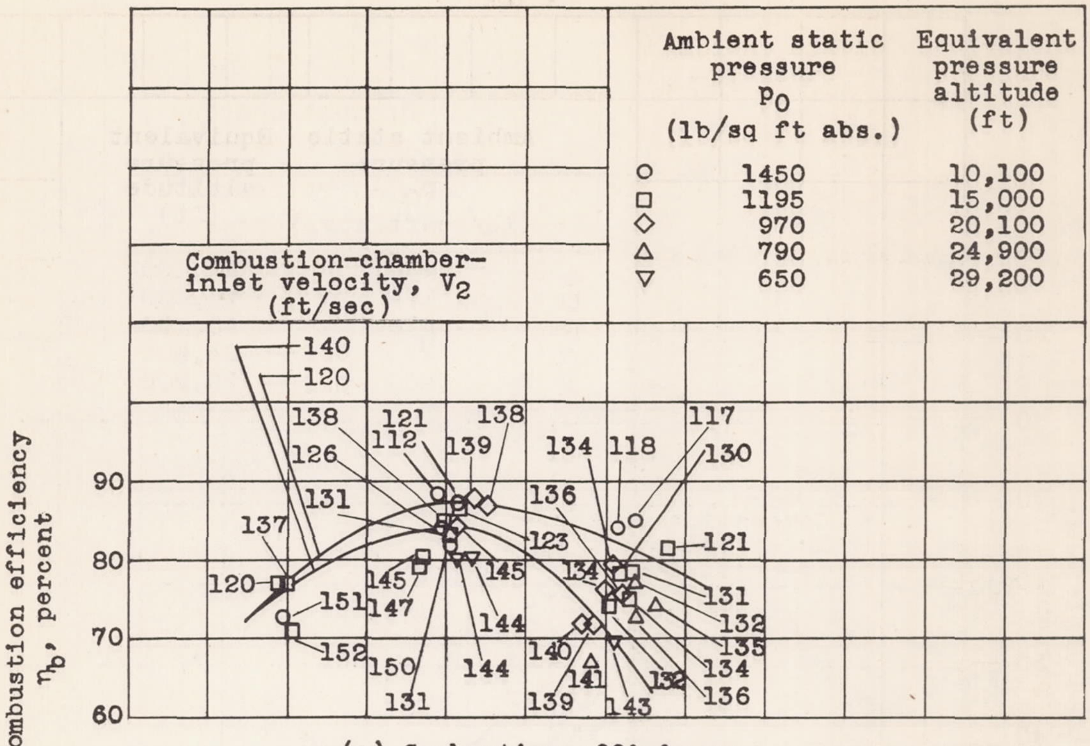
(b) Gas total-temperature ratio.

Figure 11. - Effect of exhaust-nozzle-plug position on combustion efficiency and gas total-temperature ratio. 20-inch ram jet with 8-foot combustion chamber; fuel-air ratio, 0.050 ± 0.002.

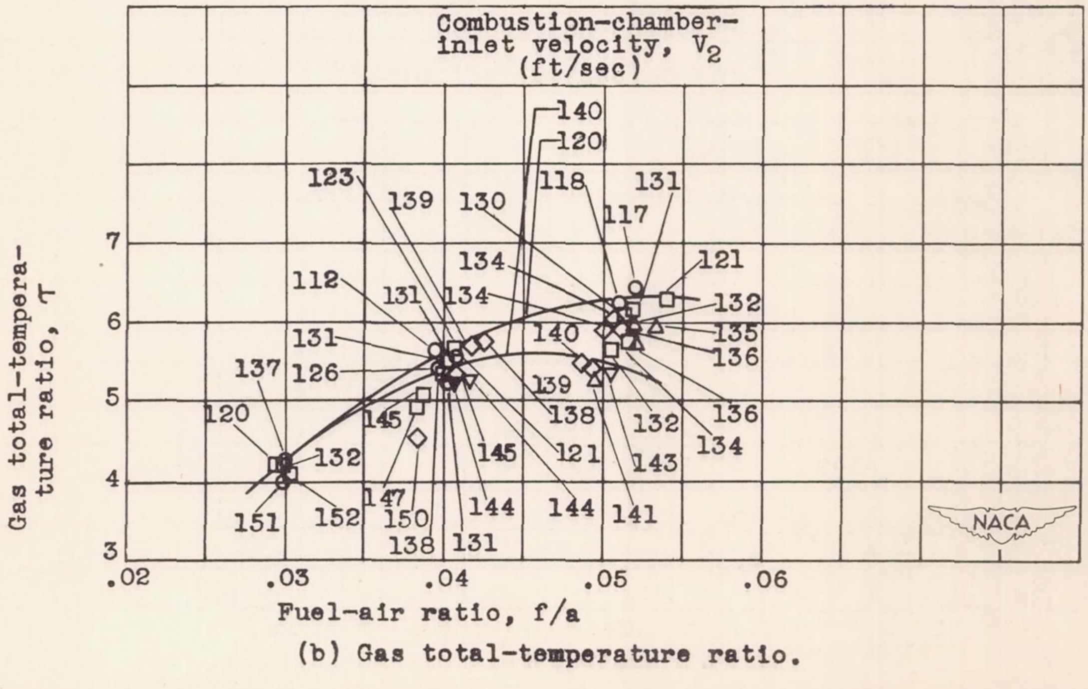


(b) Gas total-temperature ratio.

Figure 12. - Effect of combustion-chamber-inlet velocity on combustion efficiency and gas total-temperature ratio with and without exhaust-nozzle plug. 20-inch ram jet with 8-foot combustion chamber; fuel-air ratio, 0.040 ± 0.002. (Dashed curves obtained from fig. 6 of reference 4.)

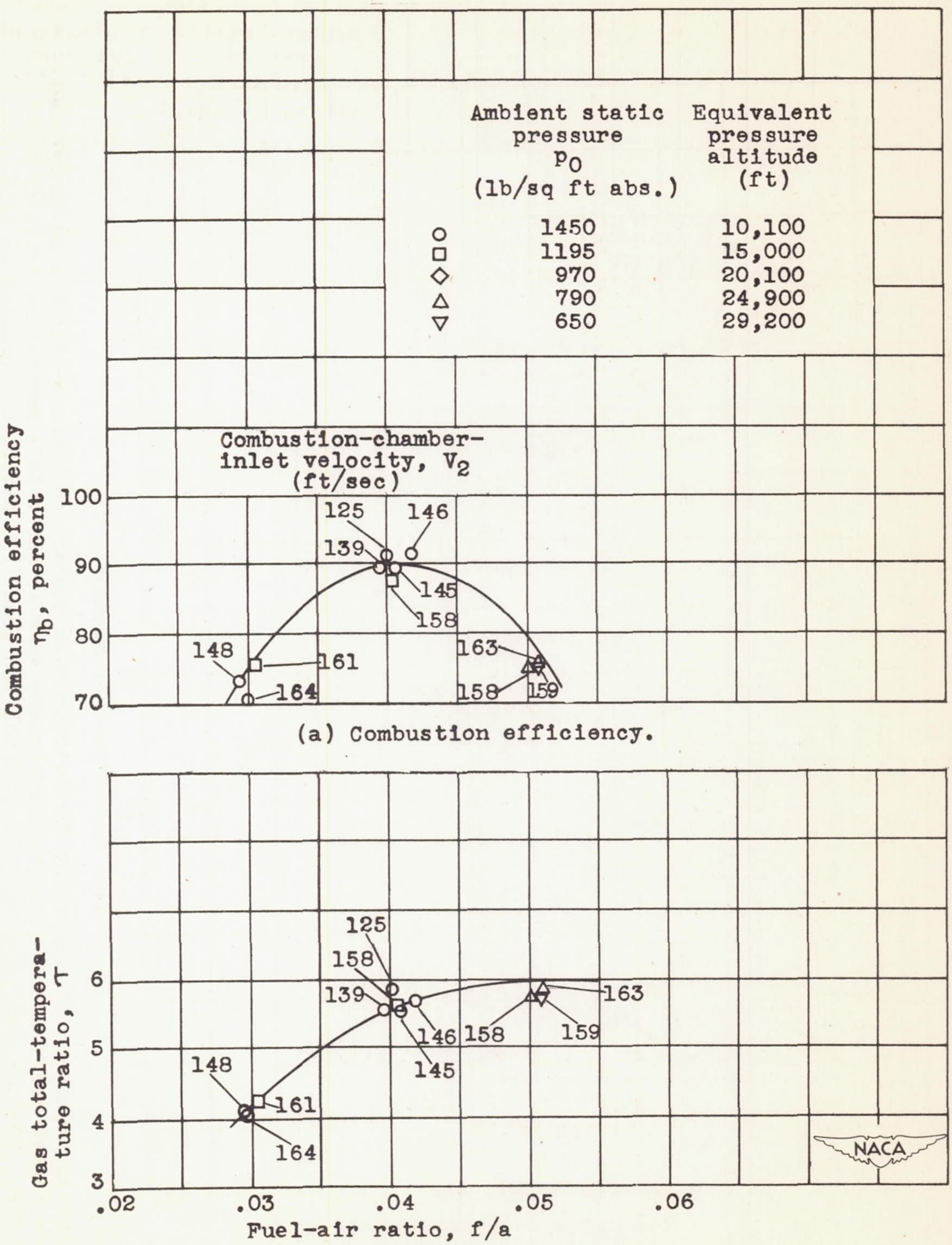


(a) Combustion efficiency.



(b) Gas total-temperature ratio.

Figure 13. - Effect of fuel-air ratio on combustion efficiency and gas total-temperature ratio over ranges of combustion-chamber-inlet velocity, static pressure, and ambient static pressure. 20-inch ram jet with 8-foot combustion chamber; exhaust-nozzle plug fully extended.



(a) Combustion efficiency.

(b) Gas total-temperature ratio.

Figure 14. - Effect of fuel-air ratio on combustion efficiency and gas total-temperature ratio over ranges of combustion-chamber-inlet velocity, static pressure, and ambient static pressure. 20-inch ram jet with 8-foot combustion chamber; exhaust-nozzle plug fully retracted.

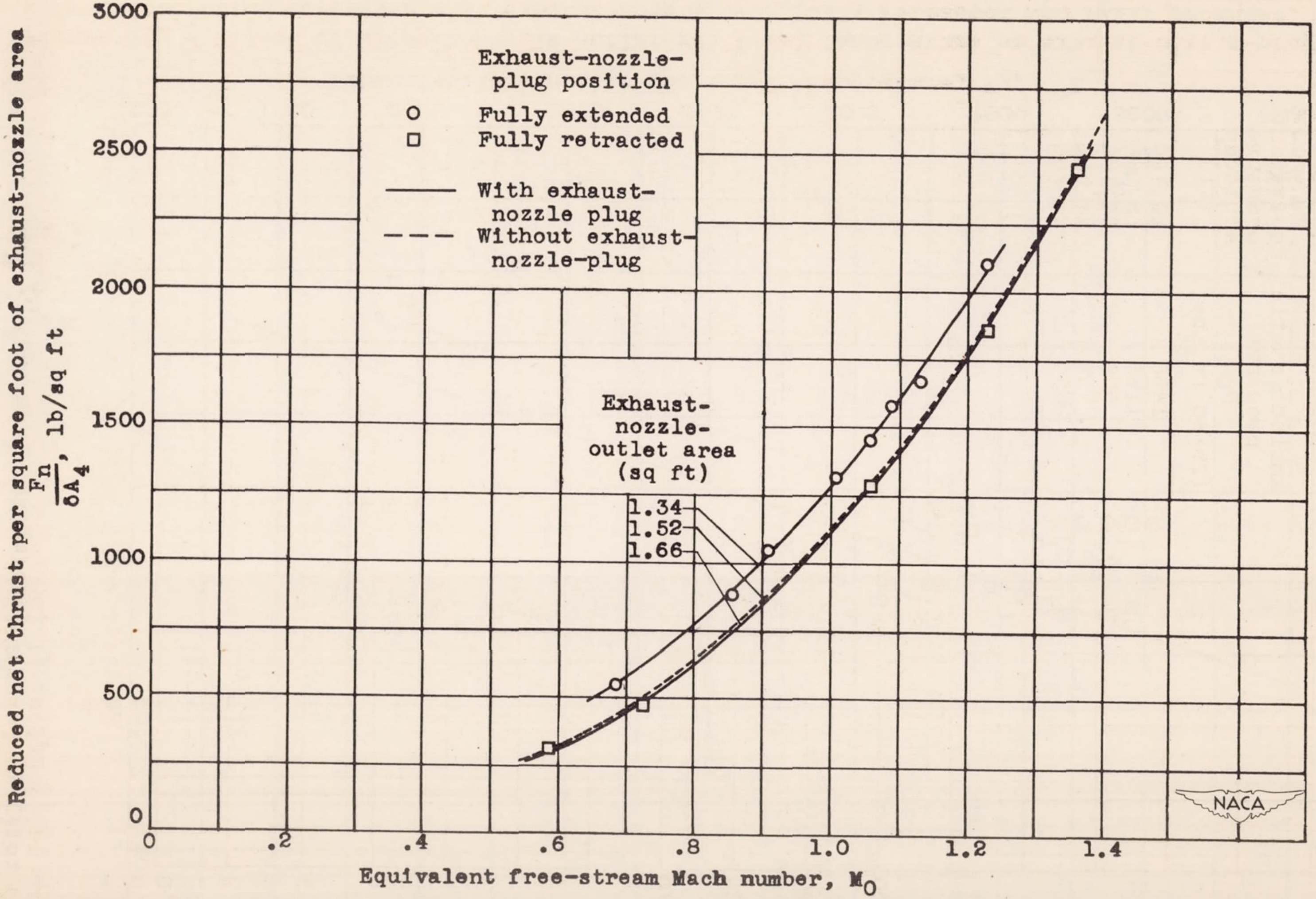


Figure 15. - Effect of equivalent free-stream Mach number and exhaust-nozzle plug on reduced net thrust per square foot of exhaust-nozzle area at gas total-temperature ratio of 6.0 ± 0.2. 20-inch ram jet with 8-foot combustion chamber. Net thrust reduced to NACA standard atmospheric conditions at sea level. (Dashed curve obtained from fig. 12 of reference 4.)

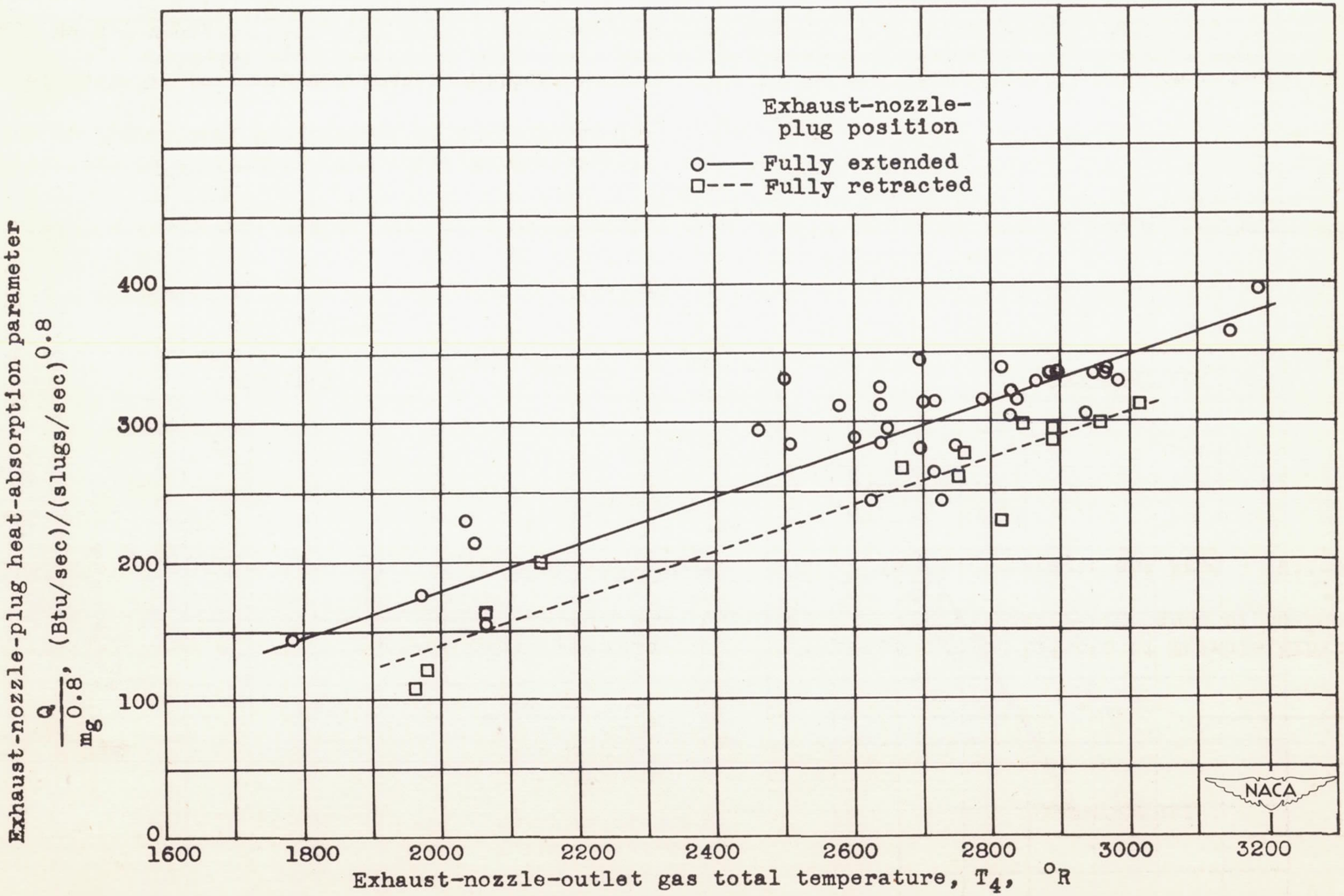


Figure 16. - Effect of exhaust-nozzle-outlet gas total temperature on exhaust-nozzle-plug heat-absorption parameter with exhaust-nozzle plug fully retracted and fully extended. 20-inch ram jet with 8-foot combustion chamber; mass gas flow, 0.44 to 0.81 slugs per second.