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RESEARCH MEMORANDUM

SOME EFFECTS OF GUTTER FLAME-HOLDER DIMENSIONS ON COMBUSTION-CHAMBER PERFORMANCE OF 20-INCH RAM JET

By Fred A. Wilcox, Eugene Perchonok, and George Wishnek

Flight Propulsion Research Laboratory
Cleveland, Ohio

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RESEARCH MEMORANDUM

SOME EFFECTS OF GUTTER FLAME-HOLDER DIMENSIONS ON COMBUSTION-CHAMBER PERFORMANCE OF 20-INCH RAM JET

By Fred A. Wilcox, Eugene Perchonok, and George Wishnek

SUMMARY

The operational characteristics of a 20-inch ram jet with four ifferent gutter-grid flame holders and a three-gutter flame holder with an adjustable gutter angle have been investigated in the NACA Cleveland altitude wind tunnel. Comparisons of the flame holders were made on the basis of operating ranges of fuel-air ratio, combustion-chamber-inlet velocity, and the combustion efficiencies obtainable. The stability of combustion with each flame holder is discussed.

The best over-all operation was obtained with a standard gutter-grid flame holder, which was operated at a maximum combustion-chamber-inlet velocity of 201 feet per second. This maximum velocity was attained with a 17-inch-diameter exhaust nozzle at an inlet-air temperature of 20° F and a fuel-air ratio of 0.038. The corresponding combustion efficiency was 50 percent. At a combustion-chamber-inlet velocity of 155 feet per second with the same nozzle and inlet-air temperature, this flame holder gave combustion efficiencies of approximately 75 percent. A double-scale-type gutter-grid flame holder gave high combustion efficiency at low combustion-chamber-inlet velocities but would not operate at combustion-chamber-inlet velocities above 150 feet per second.

Combustion efficiency was plotted as a function of Reynolds number for the standard, the double-scale, and the three-quarter-scale gutter-grid flame holders. Little scatter in these data was obtained for narrow ranges of fuel-air ratio and combustion-chamber-inlet pressure.

The results obtained with an adjustable three-gutter flame holder show that a variation of gutter angle from 25° to 53° had little effect on combustion efficiency. The minimum blocking area

of the flame holder required for choking at the exhaust nozzle for the conditions of operation and engine configuration at which these experiments were conducted appears to be approximately 50 percent.

INTRODUCTION

Investigations of a 20-inch ram jet were conducted in the NACA Cleveland altitude wind tunnel with a three-V flame holder (references 1 and 2) and with a flame holder consisting of a grid of V-shaped gutters (reference 3). The three-V flame holder was operated over a range of fuel-air ratios from approximately 0.040 to 0.098 at ram-pressure ratios corresponding to flight Mach numbers up to 1.26. The flame holder consisting of a grid of V-shaped gutters, which will hereinafter be designated a gutter-grid flame holder, was operated over a range of fuel-air ratios from approximately 0.042 to 0.051 at ram-pressure ratios corresponding to flight Mach numbers up to 1.84.

Subsequent investigations have been conducted in the Cleveland altitude wind tunnel with several versions of these two flame holders in order to obtain a flame holder that would operate over wider ranges of fuel-air ratio with high combustion efficiencies at high combustion-chamber-inlet velocities. Two of the gutter-grid flame holders investigated have approximately the same blocking area as the flame holder used in reference 3, which will be designated the standard gutter-grid flame holder, but the gutters are larger in one and smaller in the other. The third gutter-grid flame holder has the same gutter size but has greater space between the grids than the standard gutter-grid flame holder. A three-gutter flame holder similar to the three-V flame holder used in references 1 and 2 was also studied. The blocking area of this flame holder could be varied from 14 to 59.5 percent of the combustion-chamber frontal area during operation by varying the angle between the sides of the gutters from 0° to 53°.

A comparison of the performance and operational characteristics of the flame holders investigated is presented herein. Each flame holder was operated over the operable range of fuel-air ratio and combustion-chamber-inlet pressure at the tunnel pressure altitudes obtainable.

APPARATUS AND PROCEDURE

The installation of the 20-inch ram jet in the altitude wind tunnel (fig. 1) was similar to the installation reported in

reference 3. Dry refrigerated air at 20° F ±20° was supplied to the ram jet through a pipe from the wind-tunnel inlet-air duct. This air was throttled from sea-level pressure to give total pressures at the diffuser inlet that corresponded to the desired equivalent free-stream Mach numbers at various pressure altitudes. The ram jet exhausted directly into the wind-tunnel test section. A labyrinth slip joint between the inlet-air duct and the diffuser inlet permitted free movement of the model and the measurement of thrust by the tunnel balance system.

The method of investigation required only a subsonic diffuser on the ram jet. This diffuser had an 8° included angle, a 14-inch-diameter inlet, and a 20-inch-diameter outlet. A corrugated Inconel shell was seam-welded around the 20-inch-diameter combustion chamber and the exhaust nozzles. Cooling water was circulated through the corrugations.

A 5-foot combustion chamber was used with the gutter-grid flame holders. A 2-foot exhaust nozzle with a 17- or 15-inch-diameter outlet completed the engine. The combustion chamber was lengthened to 8 feet during studies of the adjustable three-gutter flame holder. The additional section (fig. 2(a)) contained a water-cooled nozzle plug that was $8\frac{1}{16}$ inches in diameter at the largest section. An exhaust nozzle with a $17\frac{5}{8}$-inch-diameter outlet was used with the nozzle plug (fig. 2(b)). The nozzle-outlet area was 1.335 square feet, the equivalent of a circular nozzle $15\frac{5}{8}$ inches in diameter.

An adjustable fuel injector was used in this investigation (fig. 3). The injector consisted of six pairs of concentric tubes arranged in an 80° V pattern and was designed to give reasonably uniform fuel distribution across the diffuser inlet. The outer tubes were fixed and contained a total of 144 drill orifices of 0.028-inch diameter arranged in 36 groups of four. The inner tubes were adjustable with respect to the outer tubes and contained a total of 36 slots. The positions of the slots with respect to the orifices were staggered in order to vary the number of orifices through which fuel was injected from 18 to 144 in eight equal steps by moving the inner tubes.

Unleaded 62-octane gasoline (AN-F-22) was used and was preheated to 200° F ±10° by the external fuel-preheating method outlined in reference 2. Fuel-injector pressures above the fuel-vapor pressure could be maintained at the lowest fuel flows required by

varying the number of fuel-injector orifices. A fuel-pressure limit of 110 pounds per square inch was imposed by the fuel-preheating system.

The gutter-grid flame holders used in this investigation are shown in figure 4 and their dimensions are listed in table I.

TABLE I

Gutter-grid flame holder	Gutter angle (deg)	Gutter width at trailing edge (in.)	Space between gutter vertices (in.)	Blocked combustion-chamber frontal area (percent)
Standard	30	$\frac{13}{16}$	$2\frac{1}{2}$	53.0
Three-quarter scale	30	$\frac{5}{8}$	$1\frac{7}{8}$	54.6
Double scale	30	$1\frac{11}{16}$	5	54.7
1.4 spaced	30	$\frac{13}{16}$	$3\frac{1}{2}$	38.5

All the flame holders were mounted in the 20-inch-diameter, 6-inch-long section shown in figure 4(a). This section was inserted between the diffuser outlet and the combustion-chamber inlet to facilitate flame-holder changes. The ignition system (fig. 4(a)) consisted of a modified aircraft spark plug that sparked to the side of one of the gutters and a propane gas line that led to a built-in pilot burner. The spark and propane were shut off when the main fuel was ignited.

The gutter angle for the adjustable three-gutter flame holder (fig. 5) could be varied from 0° to 53° during operation to give a variation in the blocked frontal area from 14.2 to 59.5 percent of the combustion-chamber area. The sides of the gutters were mounted on shafts that were rotated by the linkage shown in figure 5. No connecting gutters could be put between the gutters as in the three-V flame holders previously investigated. A pilot gutter was placed along the shell between the middle and lower gutters. The

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pilot flame was supplied by propane gas ignited with a modified aircraft spark plug. A calibration curve of percentage of blocked combustion-chamber frontal area at various gutter angles is given in figure 6. The percentage of blocked combustion-chamber frontal area with the gutter-grid flame holders is also shown.

Air flow and combustion-chamber-inlet velocity were computed from measurements of static pressure, total pressure, and indicated temperature obtained with a survey rake at the diffuser inlet. The fuel flow was measured by a rotameter. Fuel temperatures and pressures were measured at the injector manifold. The data were calculated by the methods outlined in references 1 and 3. For pressure ratios corresponding to equivalent free-stream Mach numbers greater than 1.00, the total pressure measured at the diffuser inlet was assumed to be the total pressure that would be obtained behind a normal shock at the throat of a convergent-divergent diffuser of optimum contraction ratio.

With each flame holder, the combustion-chamber performance was determined over the widest possible range of fuel-air ratio. The combustion-chamber-inlet static pressure and the pressure altitude were varied between limits imposed by either the flame holder used or the pumping capacity of the wind-tunnel exhausters. Lean and rich operating limits are shown by the data points at the lowest and highest fuel-air ratios presented in the curves. The performance of the adjustable three-gutter flame holder was determined at gutter angles from 18° to 53°.

SYMBOLS

The following symbols are used in this report:

f/a	fuel-air ratio
L	width of gutter at trailing edge, feet
M	Mach number
ΔP_{2-3}	total-pressure drop across flame holder, pounds per square foot
p	static pressure, pounds per square foot absolute
q	dynamic pressure, pounds per square foot
V	velocity, feet per second

η_b combustion efficiency, percent

μ absolute viscosity, pound-seconds per square foot

ρ density, slugs per cubic foot

τ ratio of absolute total temperature at exhaust-nozzle outlet to absolute total temperature at combustion-chamber inlet

Subscripts:

0 ambient air

2 combustion-chamber inlet

3 combustion-chamber outlet

RESULTS AND DISCUSSION

The results of this study show the effects of systematic changes in flame-holder geometry on combustion-chamber performance. Absolute values of combustion efficiencies, operable ranges of fuel-air ratio, and maximum combustion-chamber-inlet velocities obtained during this investigation may not be applicable to a flight ram jet because of the difference in inlet-air temperature that would be obtained in flight and the presence of a supersonic diffuser. The effect of varying the inlet-air temperature on combustion efficiency is discussed in references 4 and 5. Flame-holder characteristics can be determined, however, from the results of the type of investigation reported herein.

The total-pressure-drop coefficients $\Delta P_{2-3}/q_2$ in terms of the combustion-chamber-inlet dynamic pressure of the various flame holders are shown in figure 7 for a range of combustion-chamber-inlet velocity V_2. These coefficients were determined from pressure measurements across the flame holders without combustion. The pressure-drop coefficients of the adjustable three-gutter flame holder rapidly increased as the angle between the gutters was increased from 20° to 53°. The total-pressure-drop coefficient appears to be a direct function of the blocked area with secondary effects due to flame-holder geometry. The trend of $\Delta P_{2-3}/q_2$ with V_2 varied for the different flame holders but in general the

pressure-drop coefficient of each flame-holder configuration for the range of V_2 of this investigation may be considered relatively constant.

Gutter-Grid Flame Holders

The operating limits of fuel-air ratio f/a and combustion-chamber-inlet velocity V_2 for the four gutter-grid flame holders with 15- and 17-inch-diameter exhaust nozzles are presented in figure 8. The contours shown were drawn around all the data points obtainable. Data taken under choking conditions are shown in the shaded areas. The two flame holders that were operated under choking conditions blocked more than 53 percent of the combustion-chamber frontal area. Although figure 8(a) shows a relation between V_2 and f/a at the blow-out limits, the data are not sufficient to indicate whether or not this relation is changed by choking.

The approximate operating ranges of f/a and V_2 for the various configurations are given in the following table:

Gutter-grid flame holder	Exhaust-nozzle outlet diameter (in.)	Approximate operable range of fuel-air ratio, f/a		Approximate maximum combustion-chamber-inlet velocity, V_2 (ft/sec)	Remarks
		Below choking	Above choking		
Standard	17 15	0.038-0.062 .039- .075	0.038-0.062 .045- .062	201 141	Steadiest burning of gutter-grid flame holders; 6-8 foot pale blue flames.
Three-quarter scale	17 15	0.038-0.053 .056- .070	0.044-0.053 ----------	162 96	Burning rough; operable range of f/a too narrow for ease of operation.
Double scale	17 15	0.042-0.066 .042- .078	---------- ----------	150 121	Burning irregular; blue flames with intermittent streaks of yellow.
1.4 spaced	17	0.045-0.077	----------	118	Burning smooth; wide range of operable f/a; maximum V_2 only 118 ft/sec.

The effect of f/a on η_b with the corresponding values of V_2 and combustion-chamber temperature-rise ratio τ is presented in figure 9 for various values of ambient-air pressure p_0 and combustion-chamber-inlet static pressure p_2 with a 17-inch-diameter exhaust nozzle. Data for the four gutter-grid flame holders are presented in figure 9(a) for a p_0 of 1450 pounds per square foot absolute at a pressure altitude of 10,000 feet. The equivalent free-stream Mach number M_0 ranged from 0.36 to 0.72 for the ram-pressure ratios obtained at this p_0. The 1.4-spaced flame holder would not operate at higher ram-pressure ratios than obtained at a p_2 of 1700 pounds per square foot absolute and a p_0 of 1450 pounds per square foot absolute.

The best and the poorest combustion efficiencies were obtained with the double-scale and the 1.4-spaced gutter-grid flame holders, respectively. The highest value of τ (6.60) was obtained with the double-scale flame holder because of the combined high combustion efficiency (78 percent) and high fuel-air ratio (0.057) at which the flame holder would operate. This flame holder was unsatisfactory, however, because of a low V_2 limit, which prevented the engine from reaching choking conditions. High values of τ (6.55) were also obtained with the 1.4-spaced flame holder but at much higher fuel-air ratios (0.077).

The values of η_b and τ obtained with a p_0 of 970 pounds per square foot absolute at a pressure altitude of 20,000 feet are shown in figure 9(b) for the standard, three-quarter-scale, and double-scale flame holders. The values of M_0 ranged from 0.60 to 1.09. The 1.4-spaced flame holder would not operate at the combustion-chamber-inlet pressures and velocities resulting at these operating conditions.

The operating ranges of f/a for the standard and double-scale flame holders shifted to somewhat richer mixtures at the V_2 obtained at a p_0 of 970 pounds per square foot absolute than for those obtained at a p_0 of 1450 pounds per square foot absolute (figs. 9(b) and 9(a), respectively). Rough operation over a narrow range of f/a (0.044 to 0.052) was obtained with the three-quarter-scale flame holder at a p_0 of 970 pounds per square foot absolute. Approximately the same η_b resulted for all flame holders at this p_0 as at 1450 pounds per square foot absolute. The maximum τ of 6.9 (fig. 9(b)) was obtained with the double-scale flame holder at a f/a of 0.066. This flame holder could not be operated at values of V_2 above 150 feet per second.

Data obtained at a p_0 of 630 pounds per square foot absolute and M_0 from 1.22 to 1.43 are presented in figure 9(c) for the standard and three-quarter-scale flame holders. At these values of M_0, the engine was choked at the exhaust nozzle. With the standard flame holder, the operable range of f/a under fully choked conditions was broader than at conditions slightly below choking (fig. 9(b)). Similar results are presented in reference 6. The highest V_2 (201 ft/sec at an η_b of 50 percent) attained at a p_0 of 630 pounds per square foot absolute was

obtained with the standard flame holder and the 17-inch-diameter exhaust nozzle at a f/a of 0.038 and a p_2 of 1500 pounds per square foot.

The effect of V_2 on η_b and τ at various values of p_0 and p_2 is presented in figure 10. Data for the standard gutter-grid flame holder over a wide range of V_2, at f/a from 0.043 to 0.047, and with the 15- and 17-inch-diameter exhaust nozzles are shown in figure 10(a). As reported in reference 6, at an approximately constant value of V_2, variation in p_2 apparently had no direct effect on η_b for the range in which data were taken. At a V_2 of 118 feet per second, a reduction in p_2 from 2000 to 1300 pounds per square foot absolute, however, is associated with an 8-percent reduction in η_b. The values of η_b decreased with increasing V_2 with the 15-inch-diameter exhaust nozzle and generally increased with V_2 with the 17-inch-diameter nozzle. At a V_2 of 90 feet per second, the η_b was 81 percent with the 15-inch nozzle and 56 percent with the 17-inch nozzle. At 140 feet per second, however, the η_b was 57 percent with the 15-inch nozzle and 70 percent with the 17-inch nozzle. The engine would not operate at a V_2 above approximately 141 feet per second with the 15-inch nozzle, but could be operated to 165 feet per second with the 17-inch nozzle. The variation of τ with V_2 followed the same trend as η_b because the fuel-air ratio was essentially constant.

Similar data are presented in figure 10(b) for the three-quarter-scale gutter-grid flame holder at fuel-air ratios from 0.051 to 0.053 with a 17-inch-diameter exhaust nozzle. The trend of these curves is the same as that for the standard flame holder. With this flame holder, however, η_b varied only slightly with V_2 in the range from 100 to 150 feet per second.

Results obtained with the double-scale gutter-grid flame holder at fuel-air ratios from 0.059 to 0.061 with both exhaust nozzles are shown in figure 10(c). High values of η_b (94 percent) were obtained at low values of V_2 (64.5 ft/sec), but η_b dropped very rapidly as V_2 was increased.

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A comparison of η_b for the four gutter-grid flame holders under comparable conditions is given in figure 11. The data were obtained with a 17-inch-diameter exhaust nozzle at fuel-air ratios from 0.048 to 0.052 and for a range of p_2 from 1600 to 2000 pounds per square foot absolute. Above a V_2 of 125 feet per second, the highest η_b (75 percent) was obtained with the standard gutter-grid flame holder at a f/a of 0.050. An increase in V_2 to 155 feet per second with this flame holder had little effect on η_b. The double-scale gutter-grid flame holder gave the highest η_b below a V_2 of 125 feet per second; the maximum value was 78 percent at a V_2 of 111 feet per second. The combustion efficiency of this flame holder, however, decreased markedly with increasing V_2. At combustion-chamber-inlet velocities above 125 feet per second, η_b obtained with the three-quarter-scale flame holder was only a few percent lower than that obtained with the standard flame holder, but operational characteristics such as a narrow range of operable fuel-air ratios and rough burning caused the three-quarter-scale flame holder to be unsatisfactory. The combustion efficiencies were considerably lower with the 1.4-spaced flame holder than with the other flame holders and the maximum operable V_2 was only 117 feet per second.

Inasmuch as theory indicates that the flame speed for a burner should increase with increasing Reynolds number $\frac{\rho_2 V_2 L}{\mu_2}$, combustion efficiencies for the standard, three-quarter-scale, and double-scale gutter-grid flame holders were plotted as a function of Reynolds number for three ranges of fuel-air ratio (fig. 12). The length L was taken as the width of the gutter at the trailing edge. Values of L for the flame holders are given in table I. Little scatter of data is shown in figures 12(a) and 12(b), which have relatively narrow ranges of p_2, in comparison with the scatter in figure 12(c) in which lower values of p_2 are included. The drop in η_b with the double-scale flame holder at Reynolds numbers above 95,000 may be due to the fact that no dimensions other than the gutter size were scaled or to interference effects of the combustion-chamber wall.

Adjustable Three-Gutter Flame Holder

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The operable range of fuel-air ratio with the adjustable three-gutter flame holder was from 0.068 to 0.079. The three-V flame holders used in references 1 and 2 were operated over ranges of fuel-air ratio from 0.025 to 0.078 and from 0.042 to 0.097, respectively. The difference between the operable ranges of the two flame holders may be caused by the difference in combustion-chamber length and the presence of the plug in the exhaust nozzle or by slight difference in construction. Operation with the adjustable three-gutter flame holder was rough at gutter angles smaller than 30°; at angles larger than 30°, burning was fairly steady. At a gutter angle of 50°, the burner was ignited at a pressure altitude of about 24,000 feet, although the control of fuel and air flow to keep the fuel-air ratio within its narrow operable range was difficult at this altitude. With the gutter angle set at 30°, the burner would not light at pressure altitudes above 15,000 feet.

The range of operable V_2 at various gutter angles for a fuel-air-ratio range of 0.068 to 0.079 is shown in figure 13. The minimum gutter angle at which the flame holder would operate increased with increasing V_2 from approximately 18° (30 percent of area blocked) at 98 feet per second to 40° (49 percent of area blocked) at 120 feet per second. Choking occurred at approximately 120 feet per second for the nozzle-outlet area and the combustion-chamber temperature ratios obtained with this configuration.

The combined effect of fuel-air ratio, V_2, and gutter angle on combustion efficiency for a p_0 of 1450 pounds per square foot and a p_2 of 1700 pounds per square foot is shown in figure 14. The effect of gutter angle in the range from 25° to 40° on η_b, other variables being fixed, was slight at a fuel-air ratio of approximately 0.0725.

The effect of gutter angle and V_2 on η_b at a fixed range of fuel-air ratio is shown in figure 15. At a V_2 of approximately 94 feet per second, the effect of gutter angle on η_b in the range from 25° to 52° was slight. At a V_2 of approximately 108 feet per second, the η_b was considerably lower for a gutter angle of 20° than for gutter angles of 50° and 53°. This difference is presumably due to the greater blocked area at the large gutter angles.

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The effect of V_2 on η_b at a fuel-air ratio of 0.074 for various gutter angles is shown in figure 16. For the range of V_2 obtained, η_b increased with increasing V_2.

The adjustable three-gutter flame holder, which could be adjusted to block from 14 to 59.5 percent of the combustion-chamber frontal area, would not operate at choking conditions with less than 49 percent of the combustion-chamber frontal area blocked. Likewise, the 1.4-spaced gutter-grid flame holder, which blocked less than 50 percent of the combustion-chamber frontal area, could not be operated under choking conditions. The gutter-type flame holder apparently must block approximately 50 percent of the combustion-chamber frontal area in order to operate at choking conditions for the conditions of engine geometry and inlet-air temperature and pressure at which data were obtained.

SUMMARY OF RESULTS

From an investigation of the performance of a 20-inch ram jet over a range of pressure altitudes and equivalent free-stream Mach numbers with various gutter-grid flame holders at an inlet-air temperature of 20° F ±20°, the following results were obtained:

1. The standard gutter-grid flame holder gave the best overall operation of the flame holders investigated. A combustion efficiency of 50 percent was obtained at the maximum combustion-chamber-inlet velocity of 201 feet per second and a fuel-air ratio of 0.038 with a 17-inch-diameter exhaust nozzle. A combustion efficiency of 75 percent was obtained at a combustion-chamber-inlet velocity of 155 feet per second and a fuel-air ratio of approximately 0.050.

2. The highest combustion efficiency was obtained with the double-scale gutter-grid flame holder. The combustion-chamber-inlet velocity was low, however, and operation above a combustion-chamber-inlet velocity of 150 feet per second was impossible.

3. For the standard, double-scale, and three-quarter-scale gutter-grid flame holders, plots of combustion efficiency as a function of Reynolds number gave little scatter for fixed fuel-air ratios and narrow ranges of combustion-chamber-inlet static pressure.

4. With the adjustable three-gutter flame holder, a variation in gutter angle from 25° to 53° had little effect on combustion

efficiency. At a constant fuel-air ratio, the greatest effect on combustion efficiency was due to variations in combustion-chamber-inlet velocity.

5. In order to operate at pressure ratios corresponding to supersonic flight speeds at the conditions of temperature, pressure, combustion-chamber length, exhaust-nozzle-outlet diameter, and method of fuel injection over which these experiments were conducted, the gutter-type flame holder must apparently block approximately 50 percent of the combustion-chamber frontal area.

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National Advisory Committee for Aeronautics,
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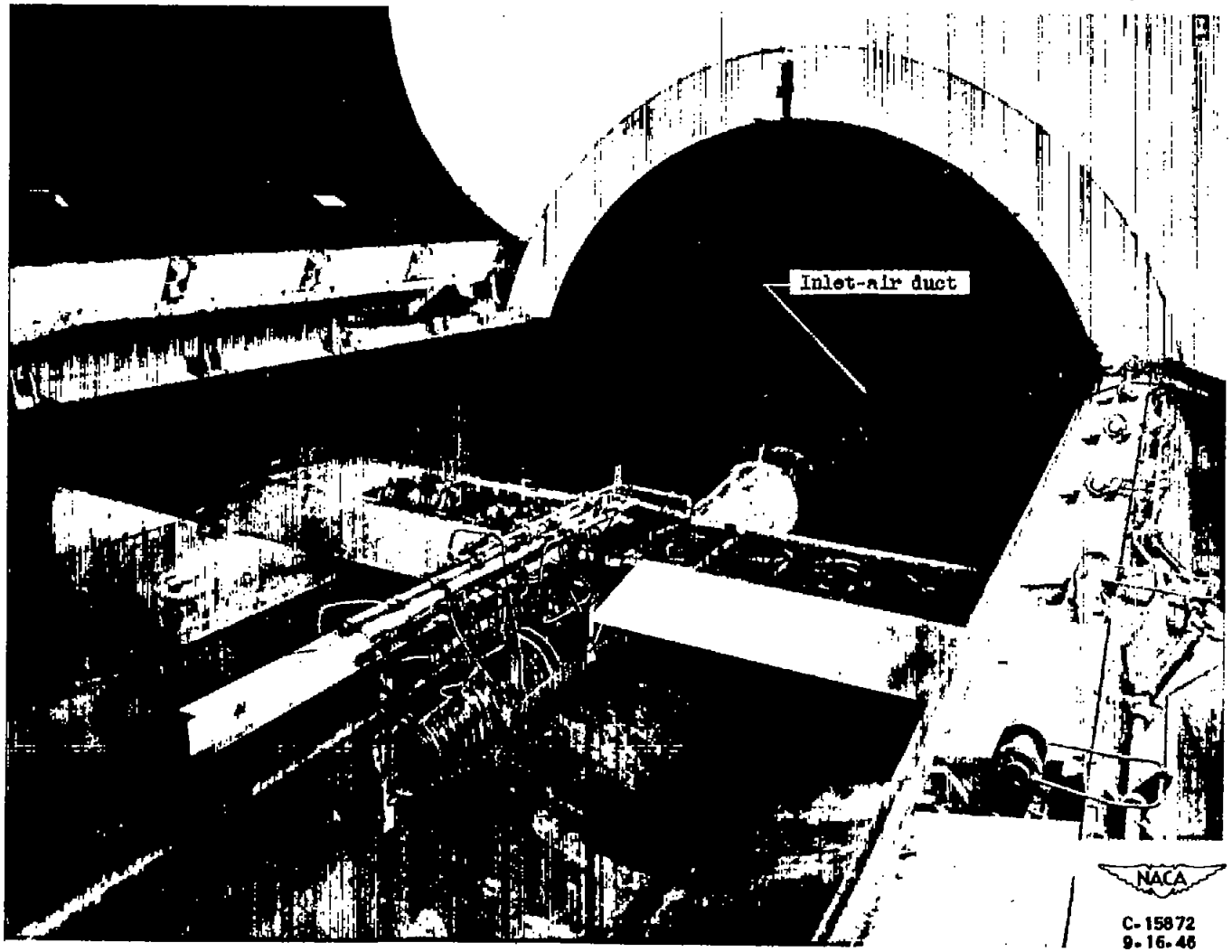

Figure 1. - Installation of 20-inch ram jet in altitude wind tunnel.

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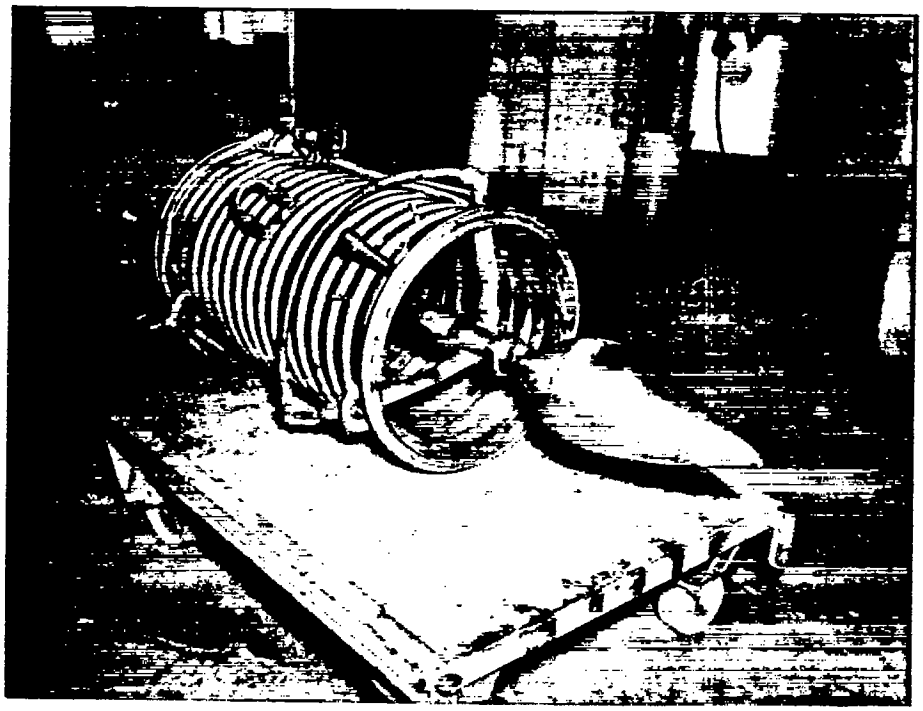
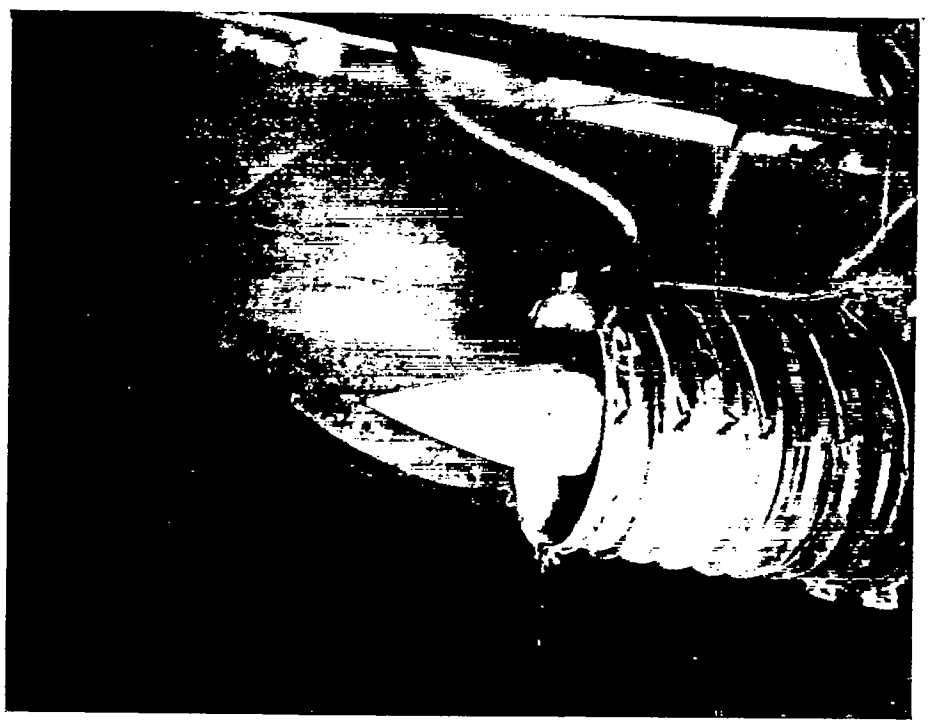


(a) Plug mounted in 3-foot combustion-chamber section.



(b) Plug extending through $17\frac{5}{8}$-inch-diameter exhaust nozzle.

Figure 2. - Plug used in exhaust nozzle of 20-inch ram jet.

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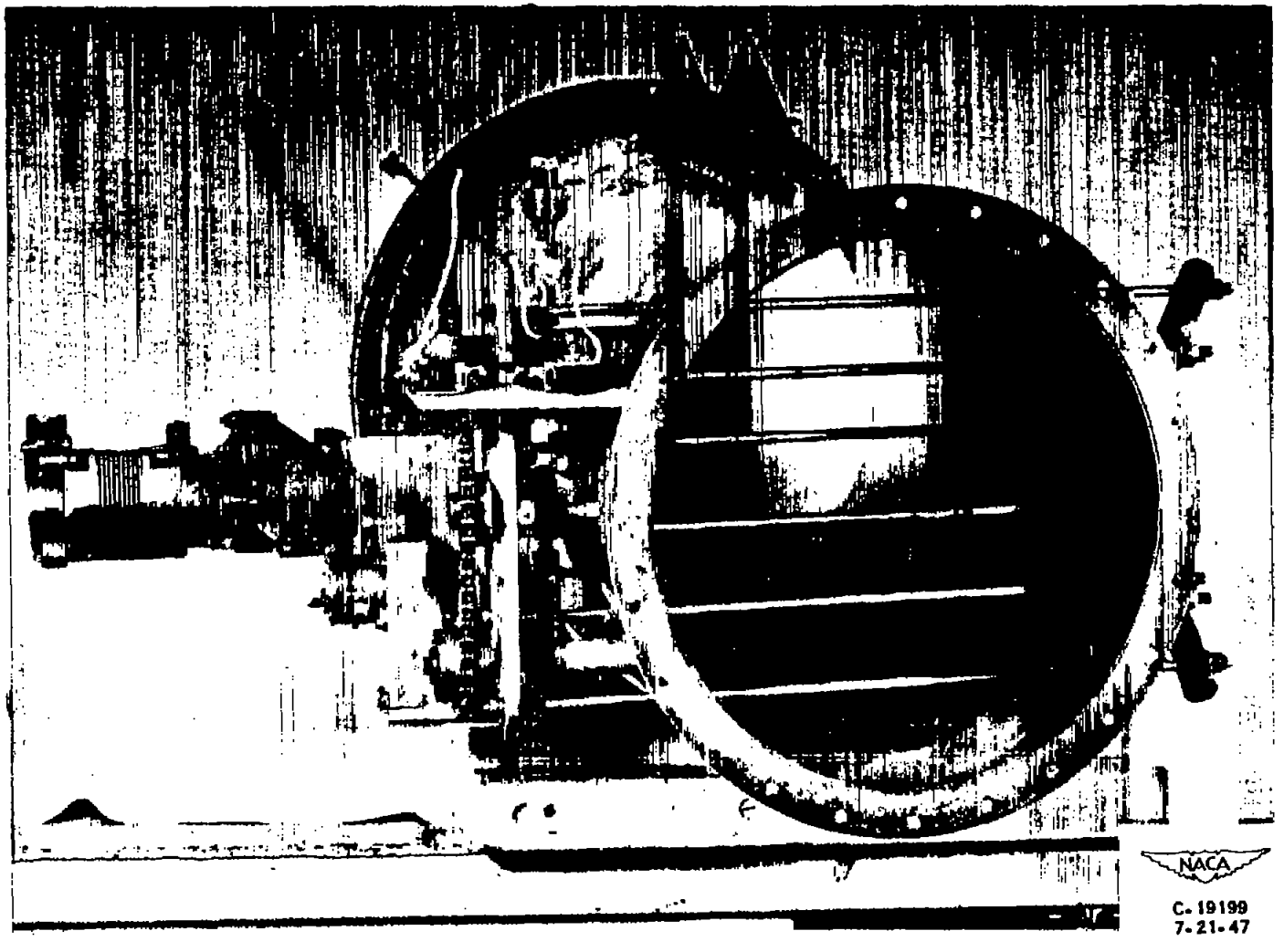
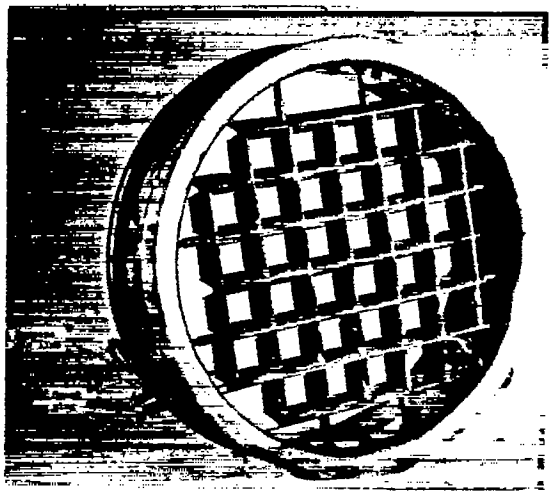


Figure 3. - Six-tube variable-orifice-area fuel injector used with 20-inch ram jet.



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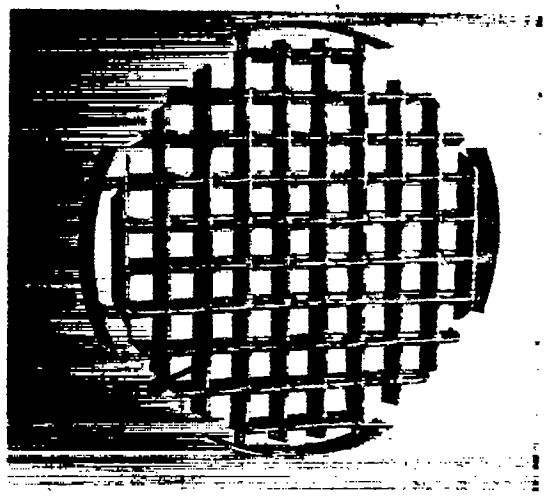
(a) Standard flame holder mounted in flame-holder section.



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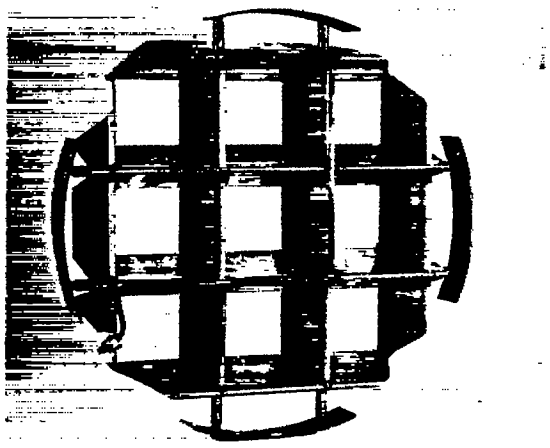
(b) Three-quarter-scale flame holder.



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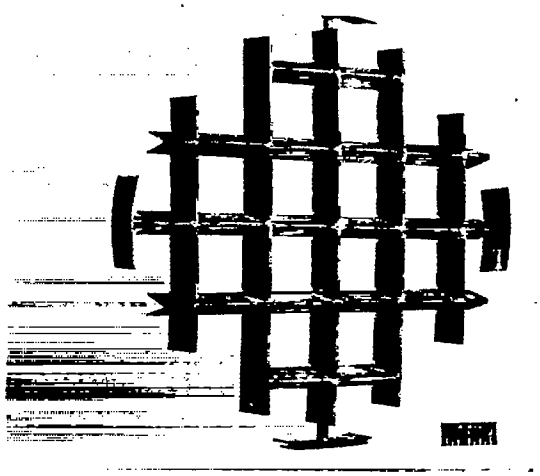
(c) Double-scale flame holder.



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(d) 1.4-spaced flame holder.

Figure 4. - Gutter-grid flame holders used in 20-inch ram jet.

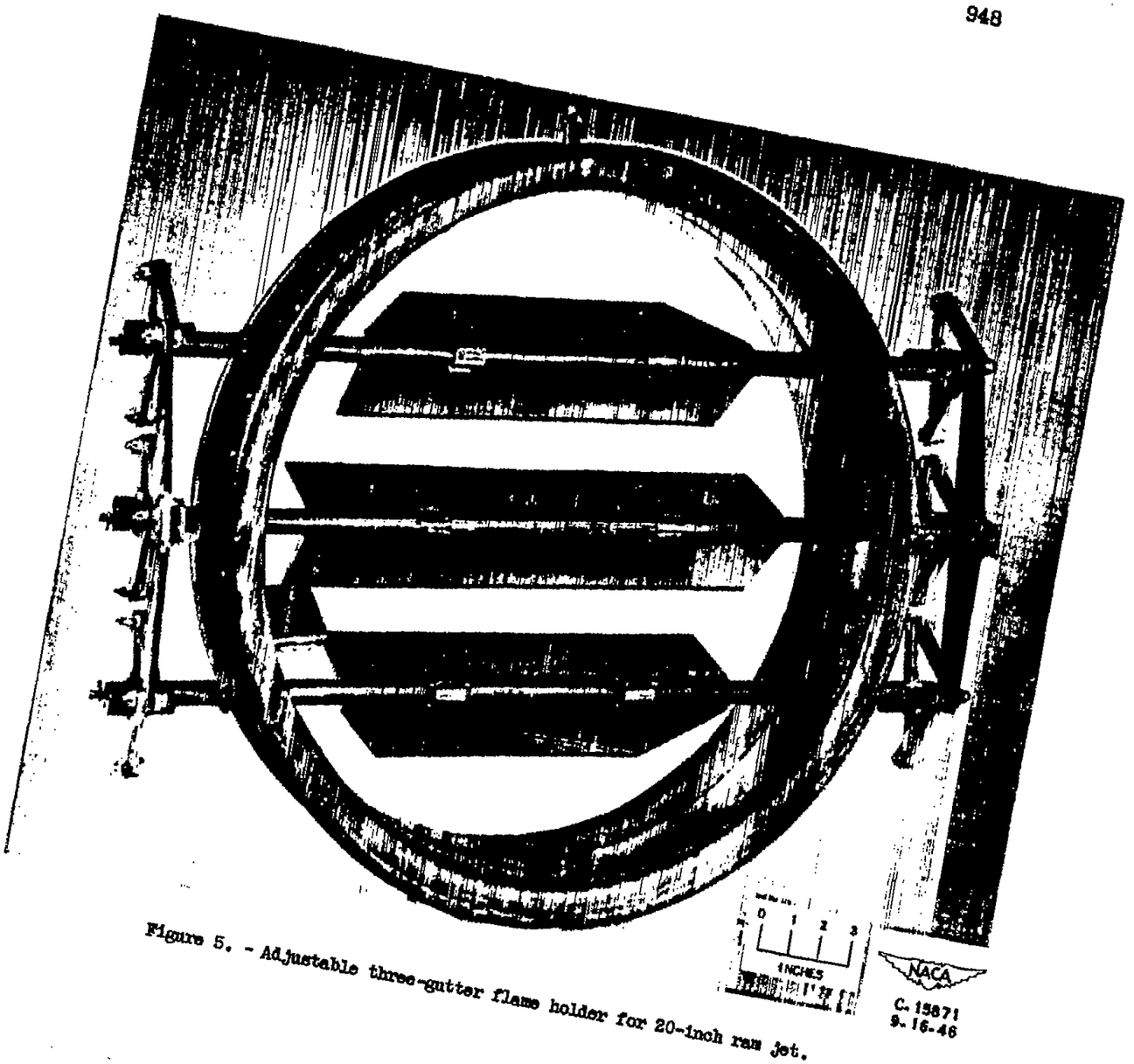


Figure 5. - Adjustable three-gutter flame holder for 20-inch ram jet.

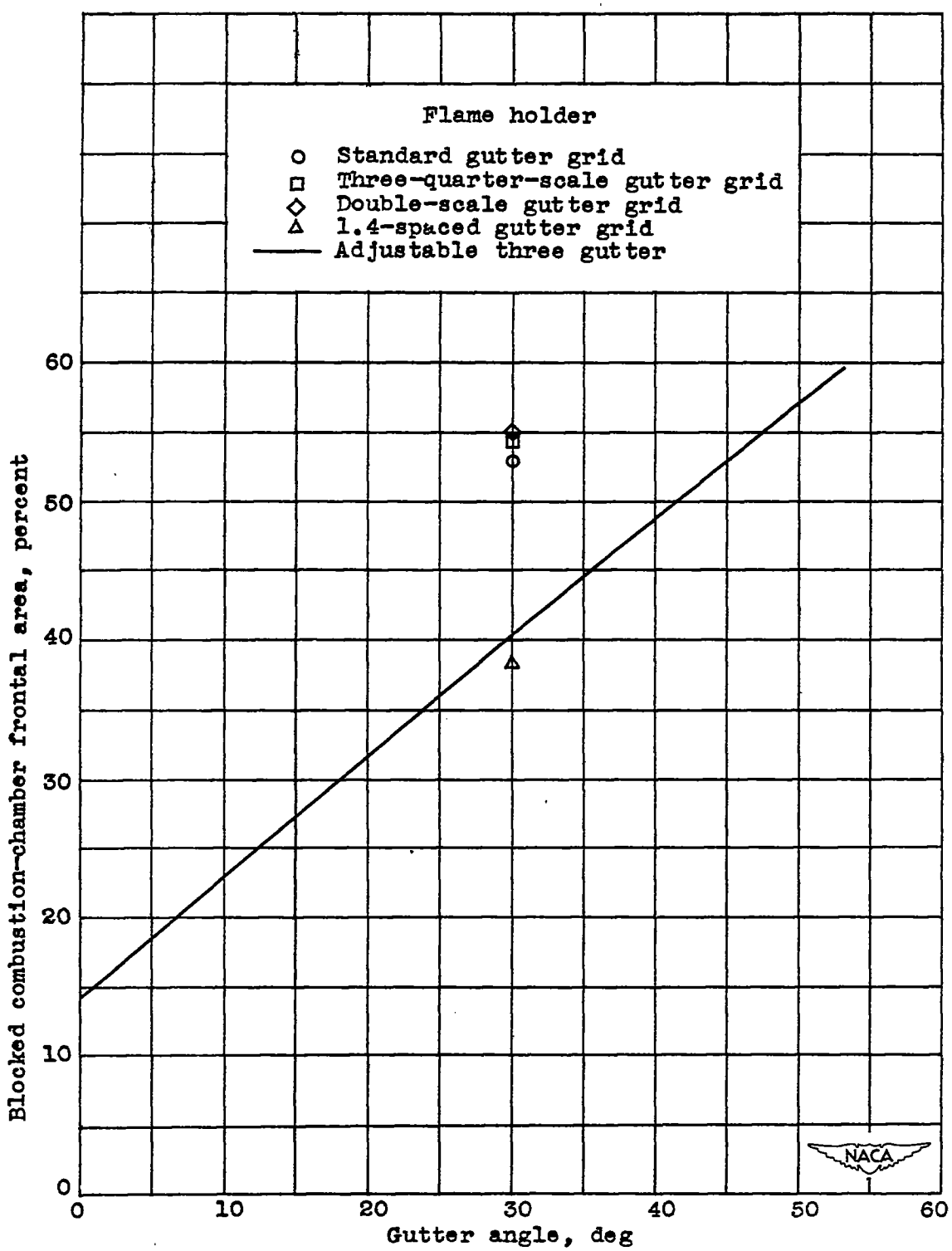


Figure 6. - Percentage combustion-chamber frontal area blocked by five flame holders used in investigation of 20-inch ram jet.

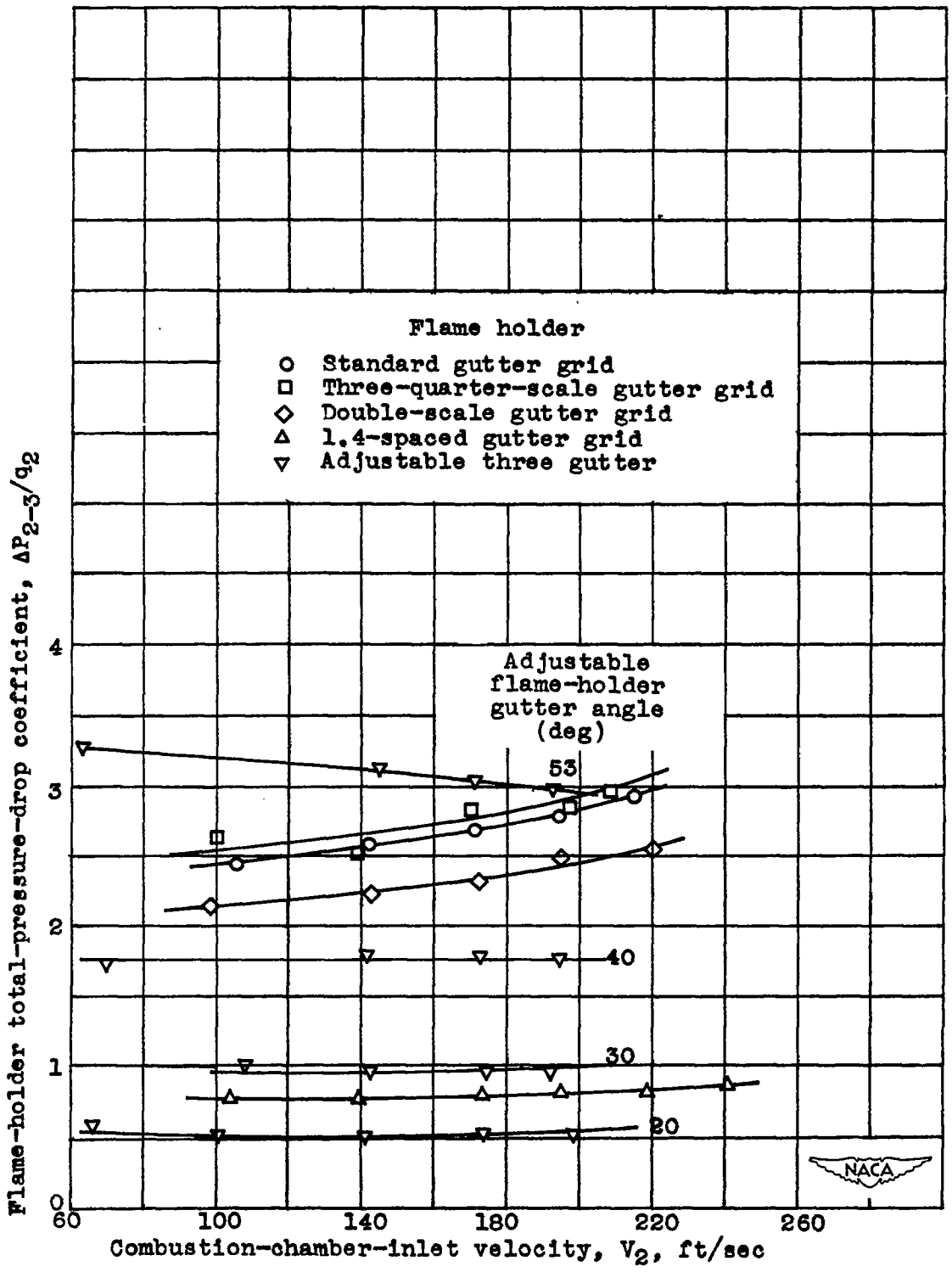
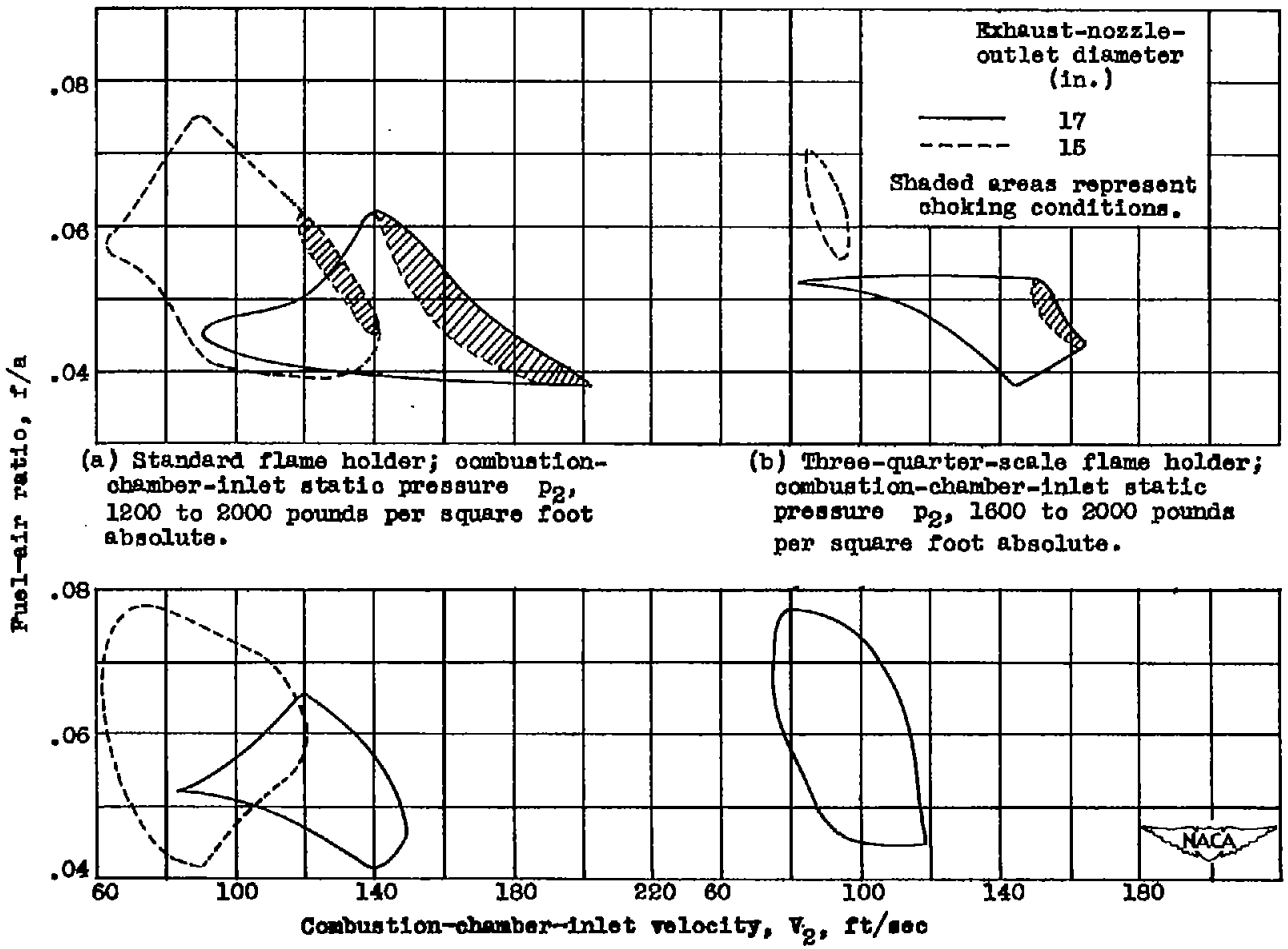


Figure 7. - Variation of flame-holder total-pressure-drop coefficient with combustion-chamber-inlet velocity for five flame holders used in investigation of 20-inch ram jet.



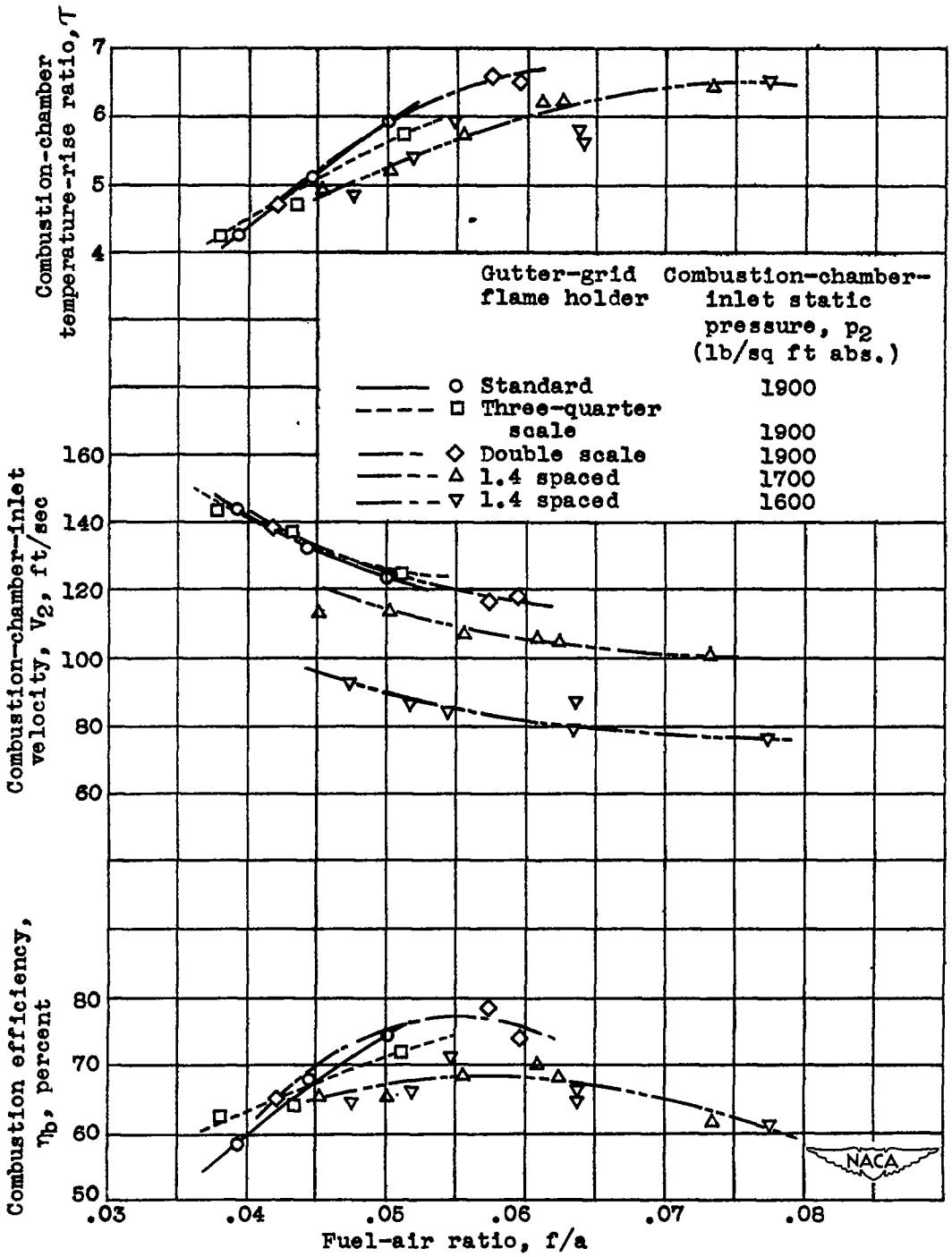
(a) Standard flame holder; combustion-chamber-inlet static pressure p_2, 1200 to 2000 pounds per square foot absolute.

(b) Three-quarter-scale flame holder; combustion-chamber-inlet static pressure p_2, 1600 to 2000 pounds per square foot absolute.

(c) Double-scale flame holder; combustion-chamber-inlet static pressure p_2, 1200 to 2000 pounds per square foot absolute.

(d) 1.4-spaced flame holder; combustion-chamber-inlet static pressure p_2, 1600 to 1700 pounds per square foot absolute.

Figure 8. - Operating ranges of fuel-air ratio and combustion-chamber-inlet velocity for gutter-grid flame holders. 20-inch ram jet with 5-foot combustion chamber and 15- and 17-inch-diameter exhaust nozzles.



(a) Ambient-air pressure p_0, 1450 pounds per square foot; pressure altitude, 10,000 feet; Mach number M_0, 0.36 to 0.66.

Figure 9. - Effect of fuel-air ratio on combustion efficiency and combustion-chamber temperature-rise ratio at various combustion-chamber-inlet velocities. 20-inch ram jet with 5-foot combustion chamber and 17-inch-diameter exhaust nozzle.

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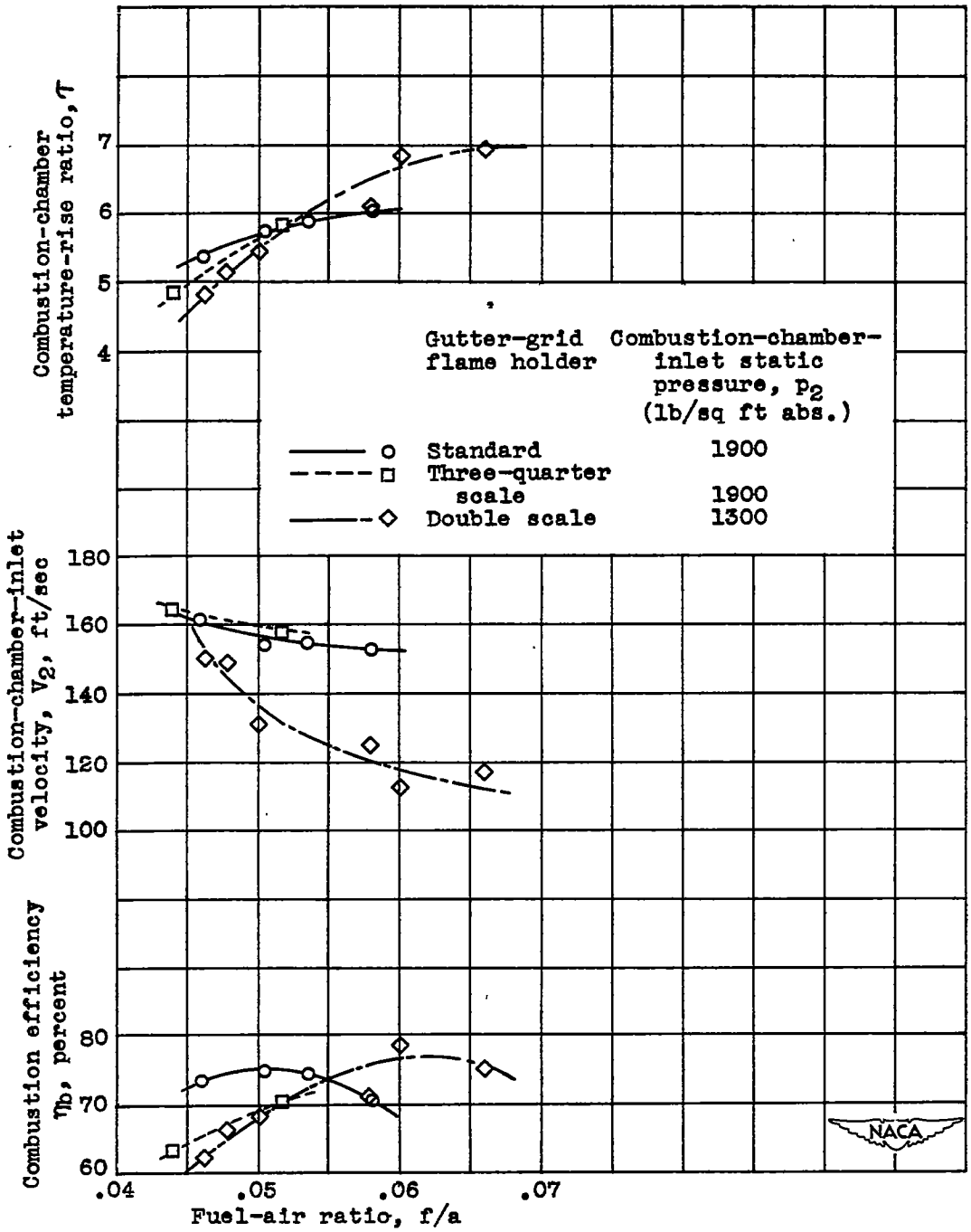
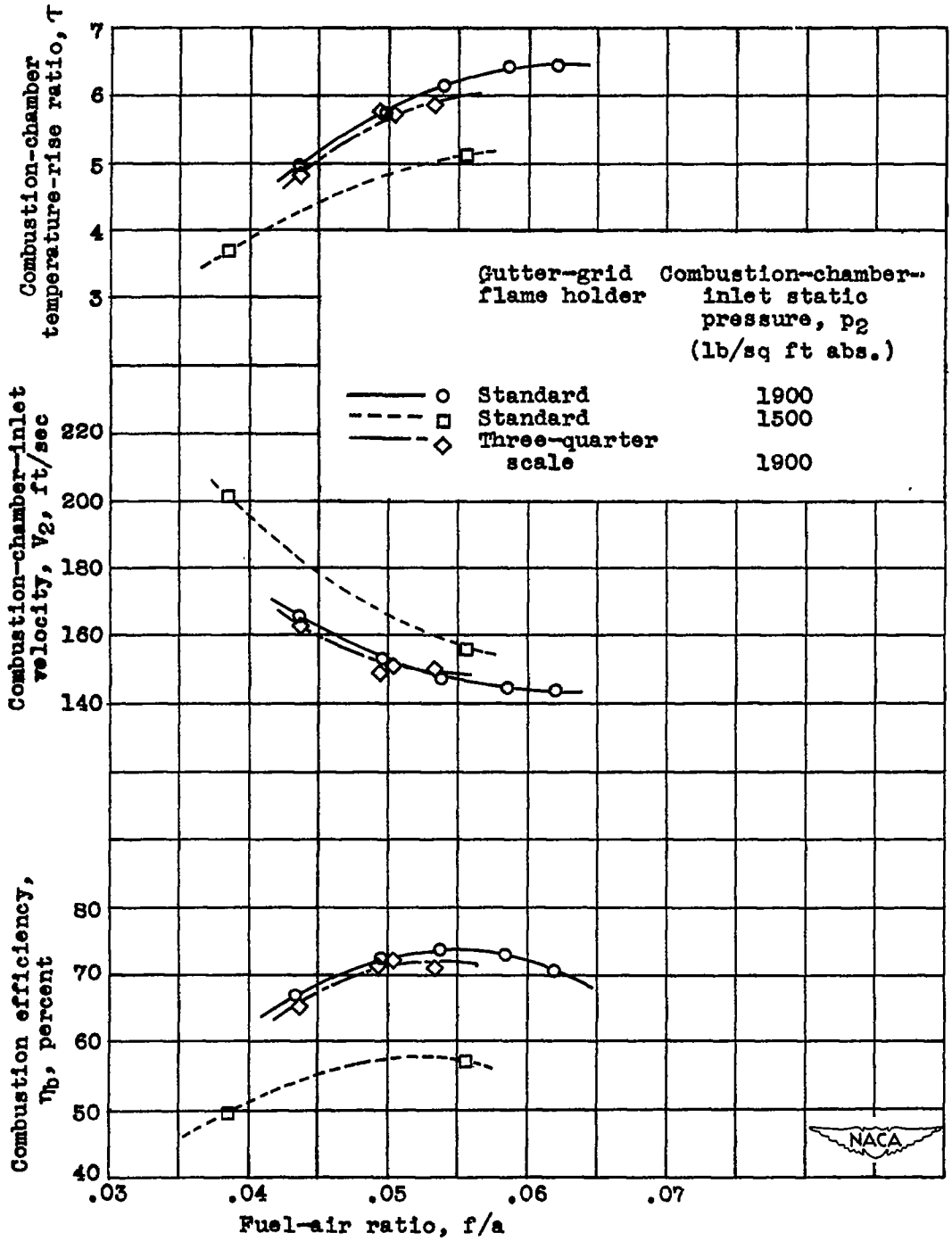


(b) Ambient-air pressure p_0, 970 pounds per square foot; pressure altitude, 20,000 feet; Mach number M_0, 0.66 to 1.06.

Figure 9. - Continued. Effect of fuel-air ratio on combustion efficiency and combustion-chamber temperature-rise ratio at various combustion-chamber-inlet velocities. 20-inch ram jet with 5-foot combustion chamber and 17-inch-diameter exhaust nozzle.



(c) Ambient-air pressure p_0, 630 pounds per square foot; pressure altitude, 30,000 feet; Mach number M_0, 1.22 to 1.40.

Figure 9. - Concluded. Effect of fuel-air ratio on combustion efficiency and combustion-chamber temperature-rise ratio at various combustion-chamber-inlet velocities. 20-inch ram jet with 5-foot combustion chamber and 17-inch-diameter exhaust nozzle.

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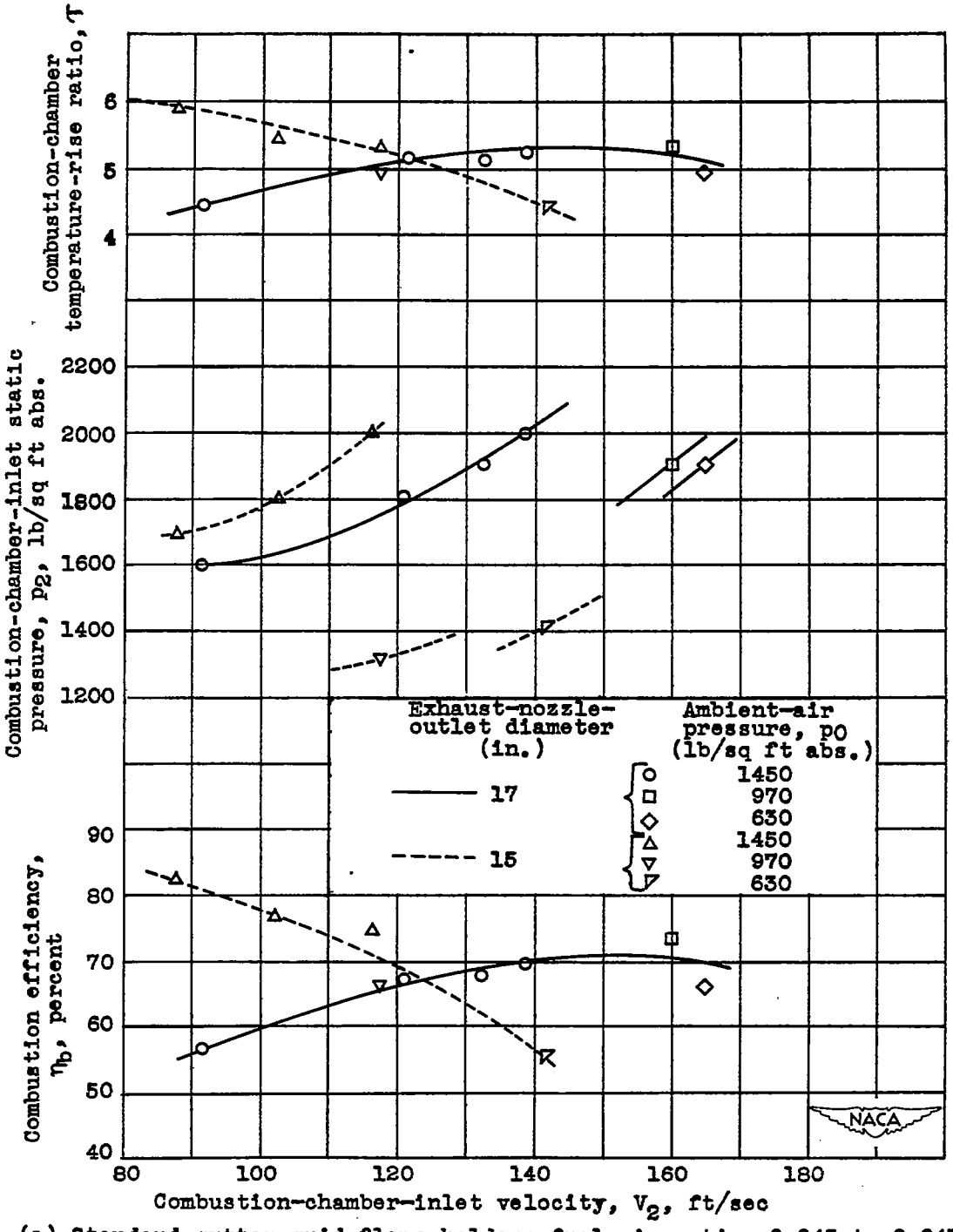
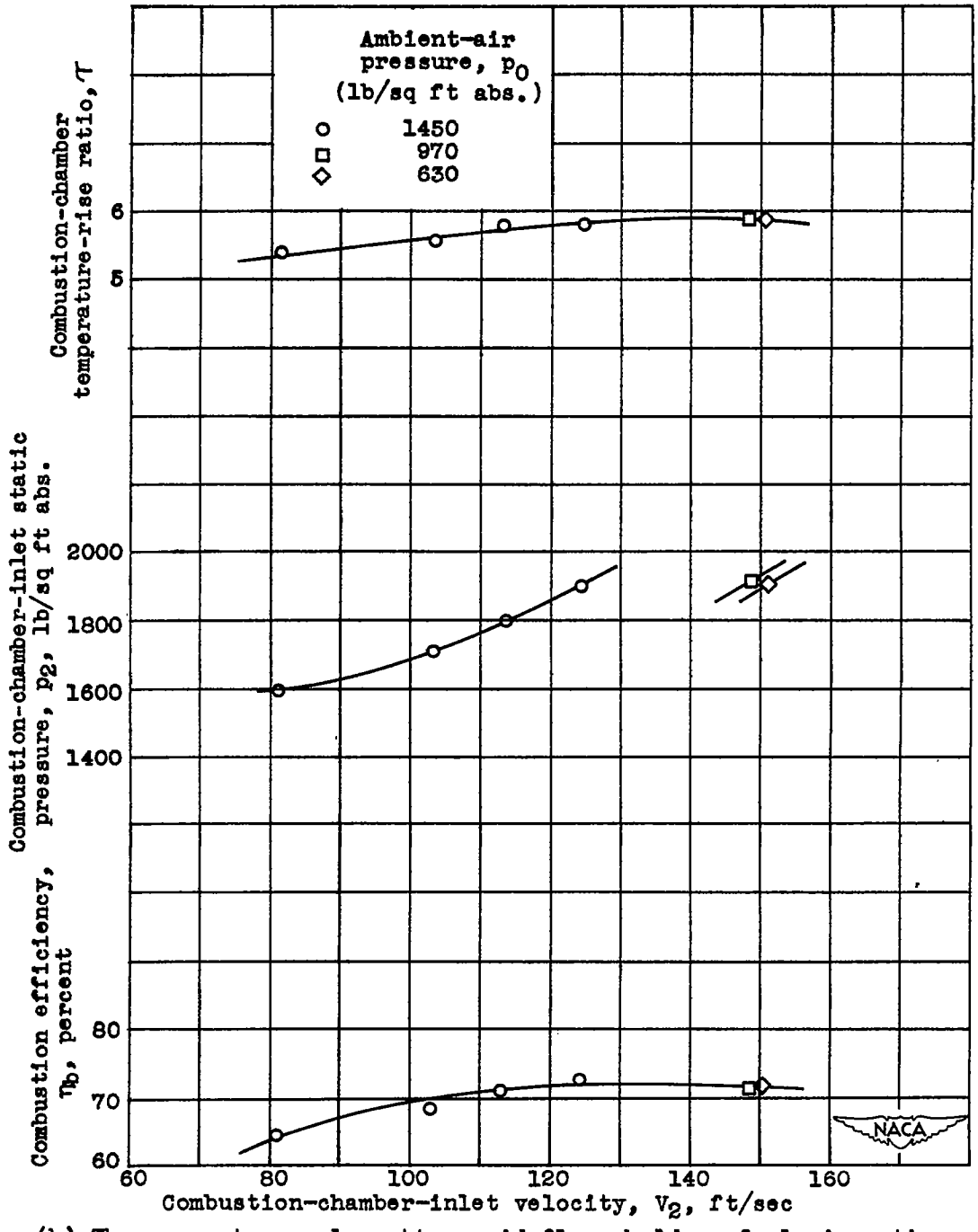


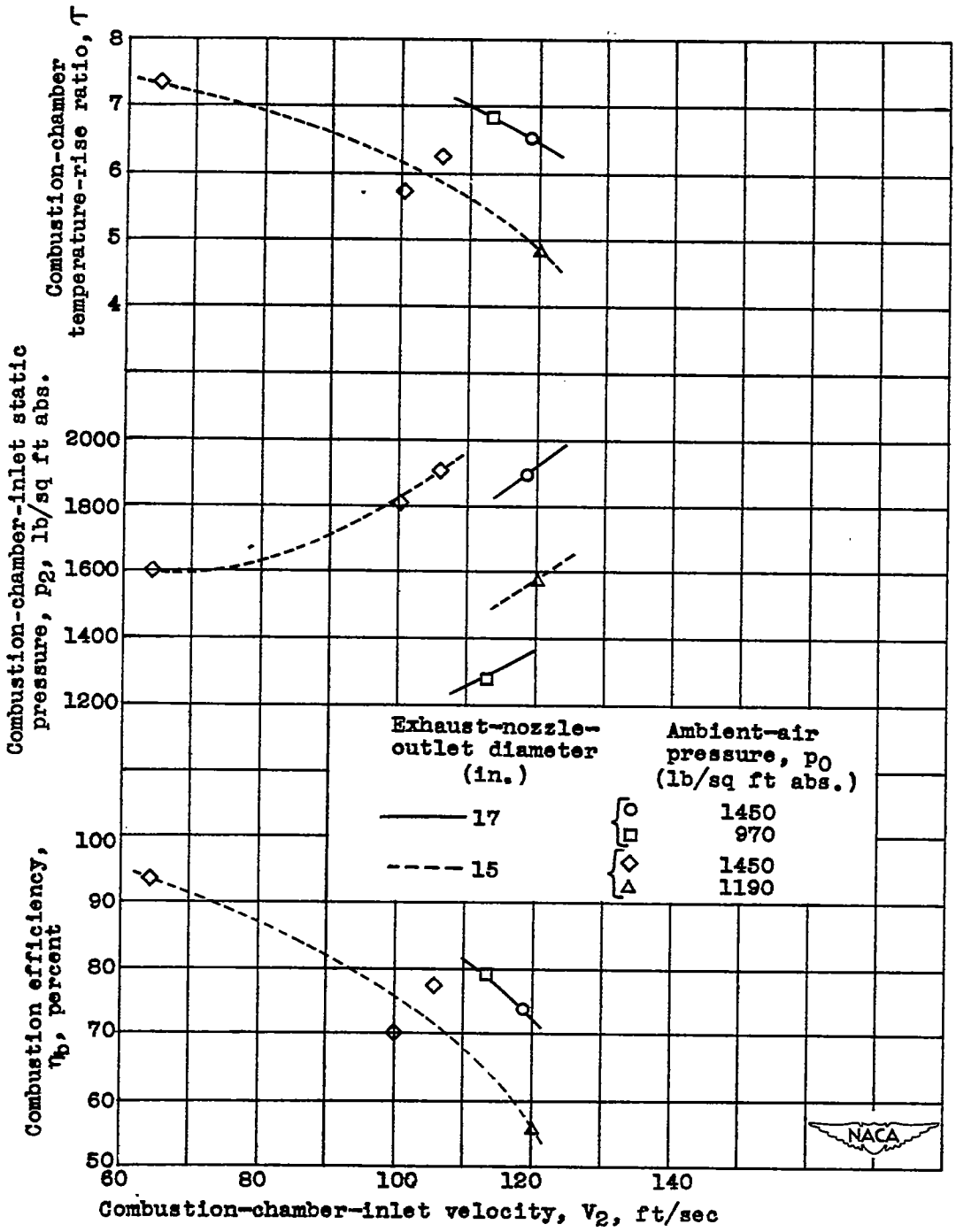
(a) Standard gutter-grid flame holder; fuel-air ratio, 0.043 to 0.047; 15- and 17-inch-diameter exhaust nozzles.

Figure 10. - Effect of combustion-chamber-inlet velocity on combustion efficiency and combustion-chamber temperature-rise ratio at various combustion-chamber-inlet and tunnel ambient-air pressures. 20-inch ram jet with 5-foot combustion chamber.



(b) Three-quarter-scale gutter-grid flame holder; fuel-air ratio, 0.051 to 0.053; 17-inch-diameter exhaust nozzle.

Figure 10. - Continued. Effect of combustion-chamber-inlet velocity on combustion efficiency and combustion-chamber temperature-rise ratio at various combustion-chamber-inlet and tunnel ambient-air pressures. 20-inch ram jet with 5-foot combustion chamber.



(c) Double-scale gutter-grid flame holder; fuel-air ratio, 0.059 to 0.061; 15- and 17-inch-diameter exhaust nozzles.

Figure 10. - Concluded. Effect of combustion-chamber-inlet velocity on combustion efficiency and combustion-chamber temperature-rise ratio at various combustion-chamber-inlet and tunnel ambient-air pressures. 20-inch ram jet with 5-foot combustion chamber.

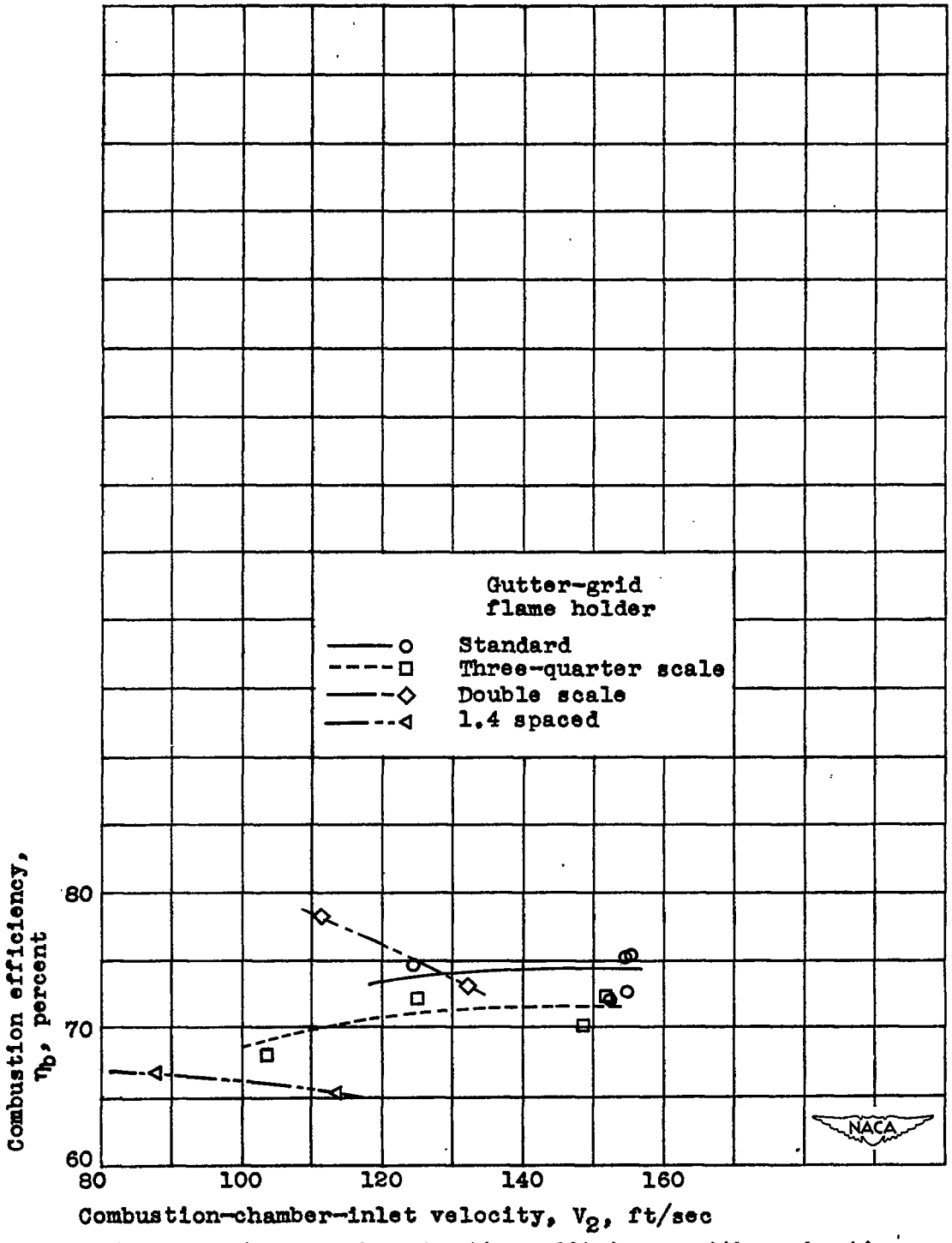
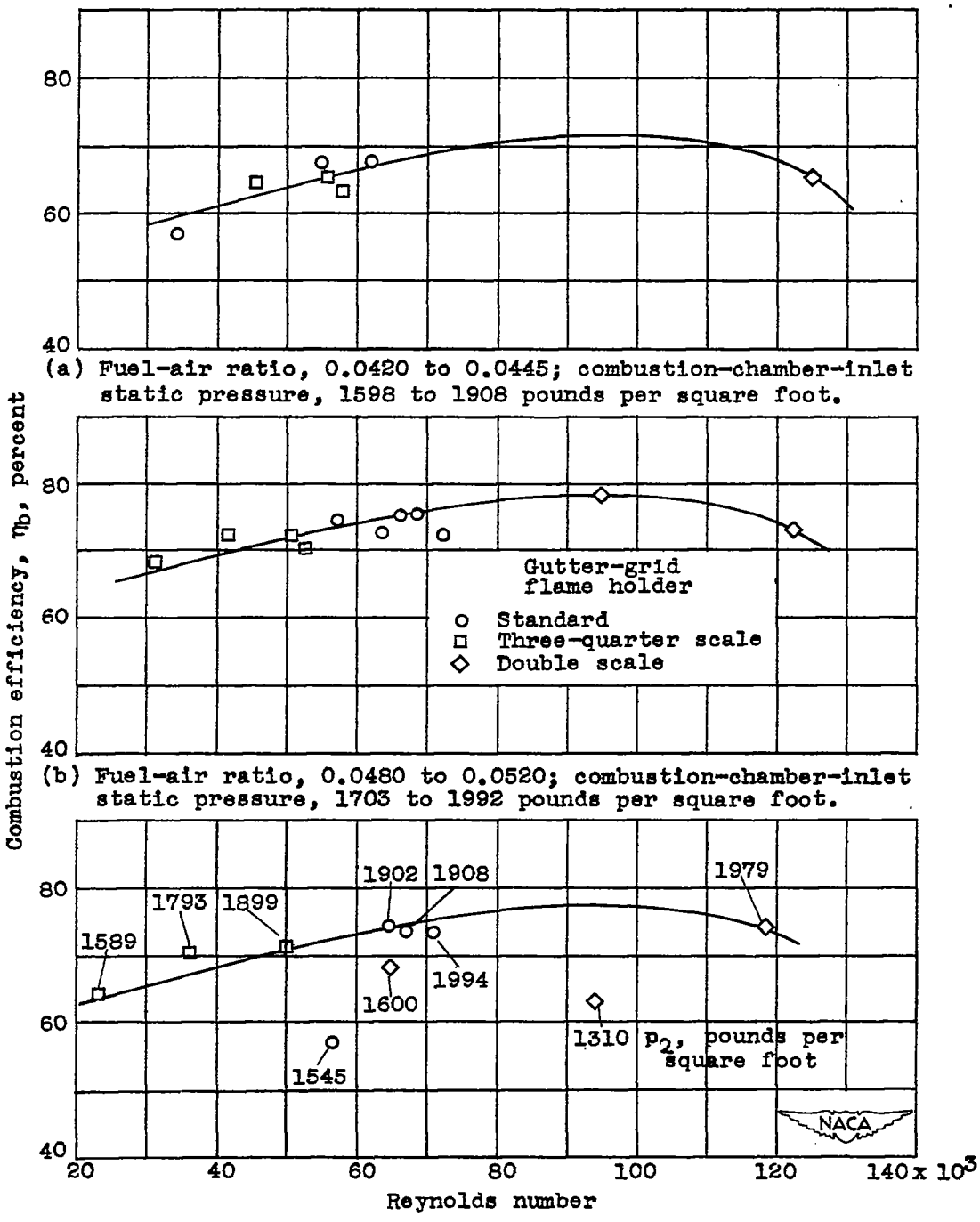


Figure 11. - Variation of combustion efficiency with combustion-chamber-inlet velocity for gutter-grid flame holders. 20-inch ram jet with 17-inch-diameter exhaust nozzle; fuel-air ratio, 0.048 to 0.052; combustion-chamber-inlet static pressure, 1600 to 2000 pounds per square foot absolute.



(a) Fuel-air ratio, 0.0420 to 0.0445; combustion-chamber-inlet static pressure, 1598 to 1908 pounds per square foot.

(b) Fuel-air ratio, 0.0480 to 0.0520; combustion-chamber-inlet static pressure, 1703 to 1992 pounds per square foot.

(c) Fuel-air ratio, 0.0523 to 0.0555; combustion-chamber-inlet static pressure, 1310 to 1994 pounds per square foot.

Figure 12. - Variation of combustion efficiency with Reynolds number for standard, three-quarter scale, and double-scale gutter-grid flame holders. 20-inch ram jet with 5-foot combustion chamber and 17-inch-diameter exhaust nozzle.

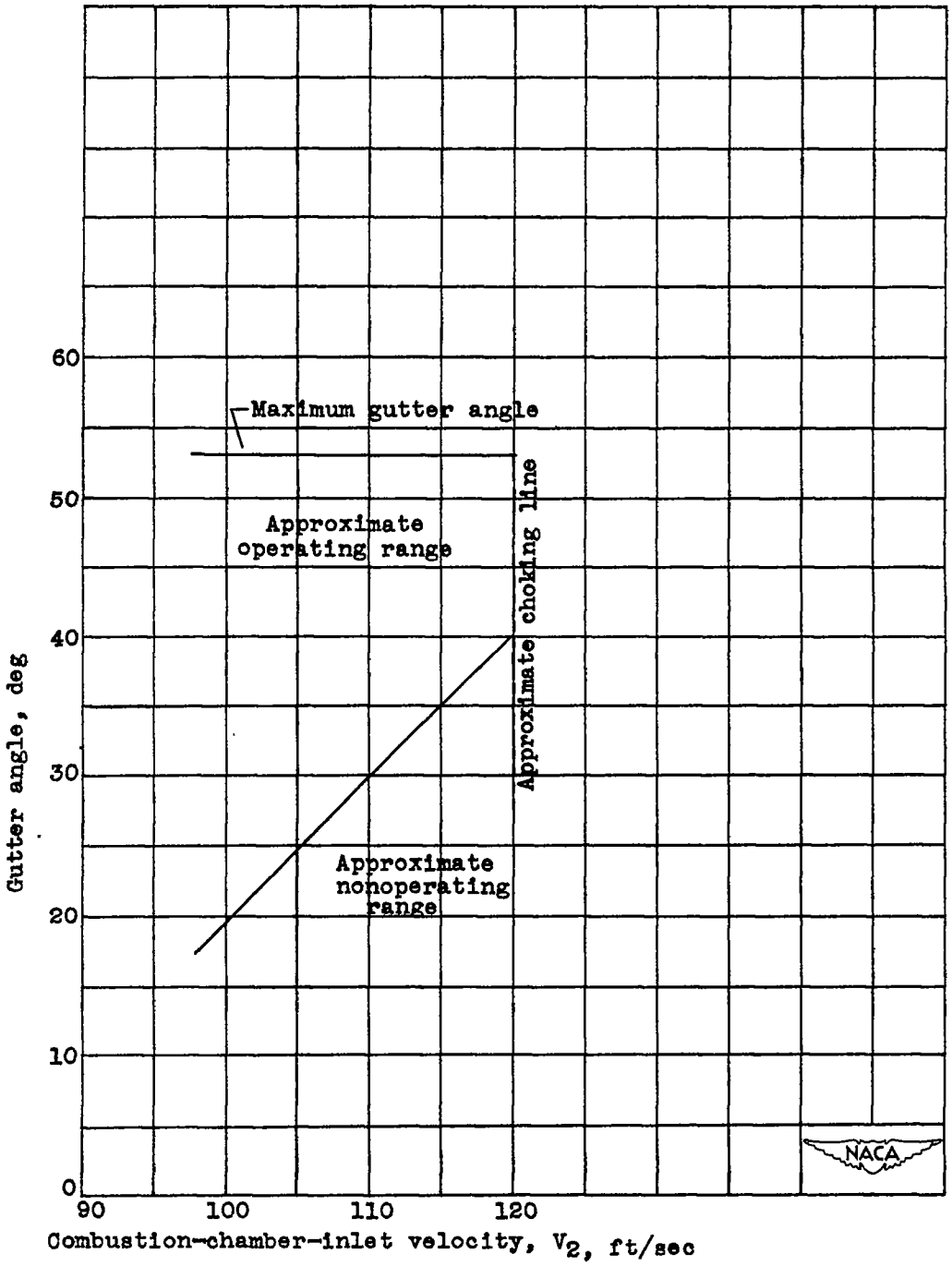


Figure 13. - Range of operable combustion-chamber-inlet velocities for adjustable three-gutter flame holder. 20-inch ram jet with 5-foot combustion chamber and $17\frac{5}{8}$-inch-diameter exhaust nozzle with $8\frac{1}{16}$-inch-diameter nozzle plug for fuel-air ratio range of 0.068 to 0.079.

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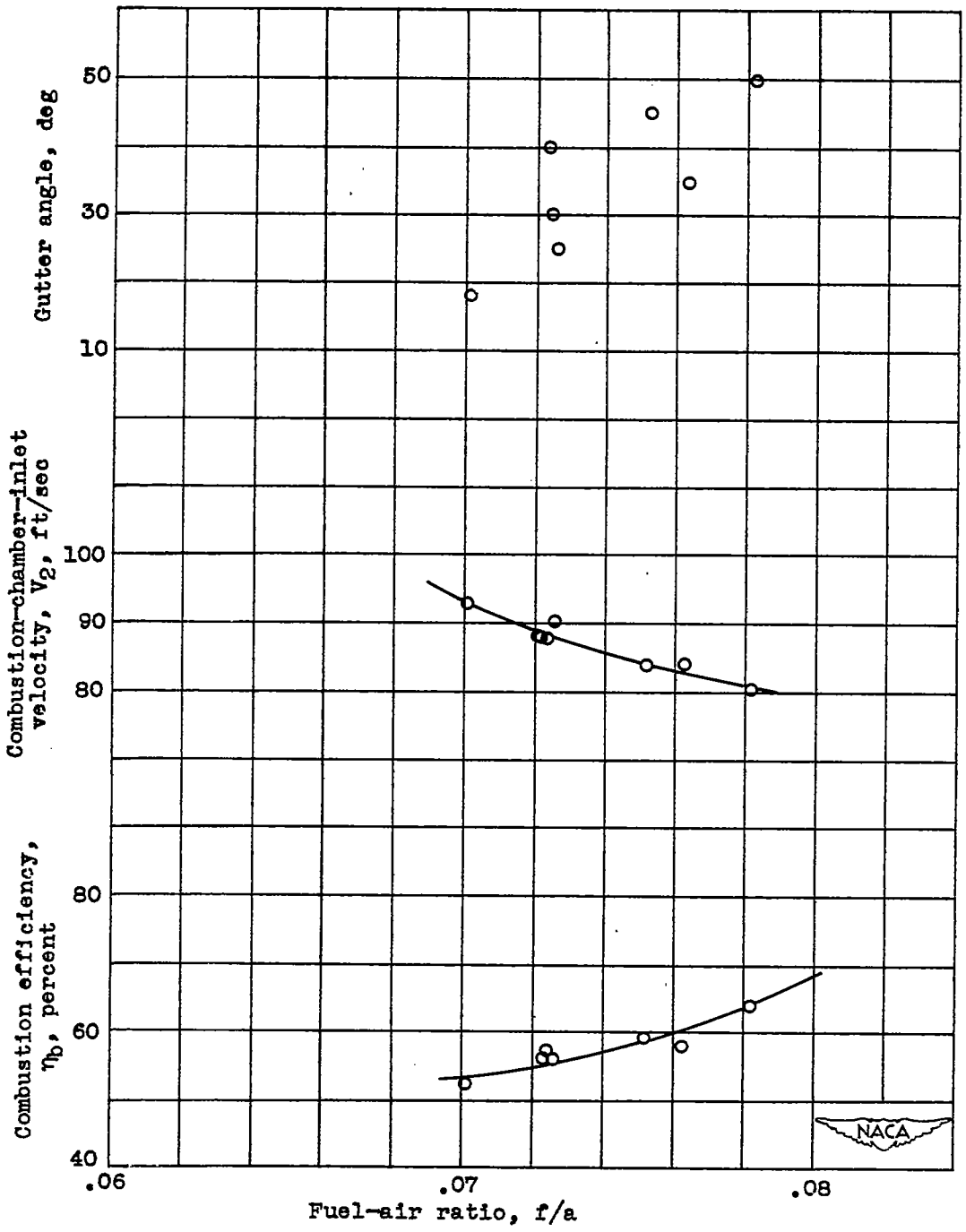

Figure 14. - Effect of fuel-air ratio on combustion efficiency with adjustable three-gutter flame holder at various gutter angles and combustion-chamber-inlet velocities. 20-inch ram jet with 5-foot combustion chamber and $17\frac{5}{8}$-inch-diameter exhaust nozzle with $8\frac{1}{16}$-inch-diameter plug; ambient pressure, 1450 pounds per square foot absolute; combustion-chamber-inlet static pressure, 1700 pounds per square foot absolute.

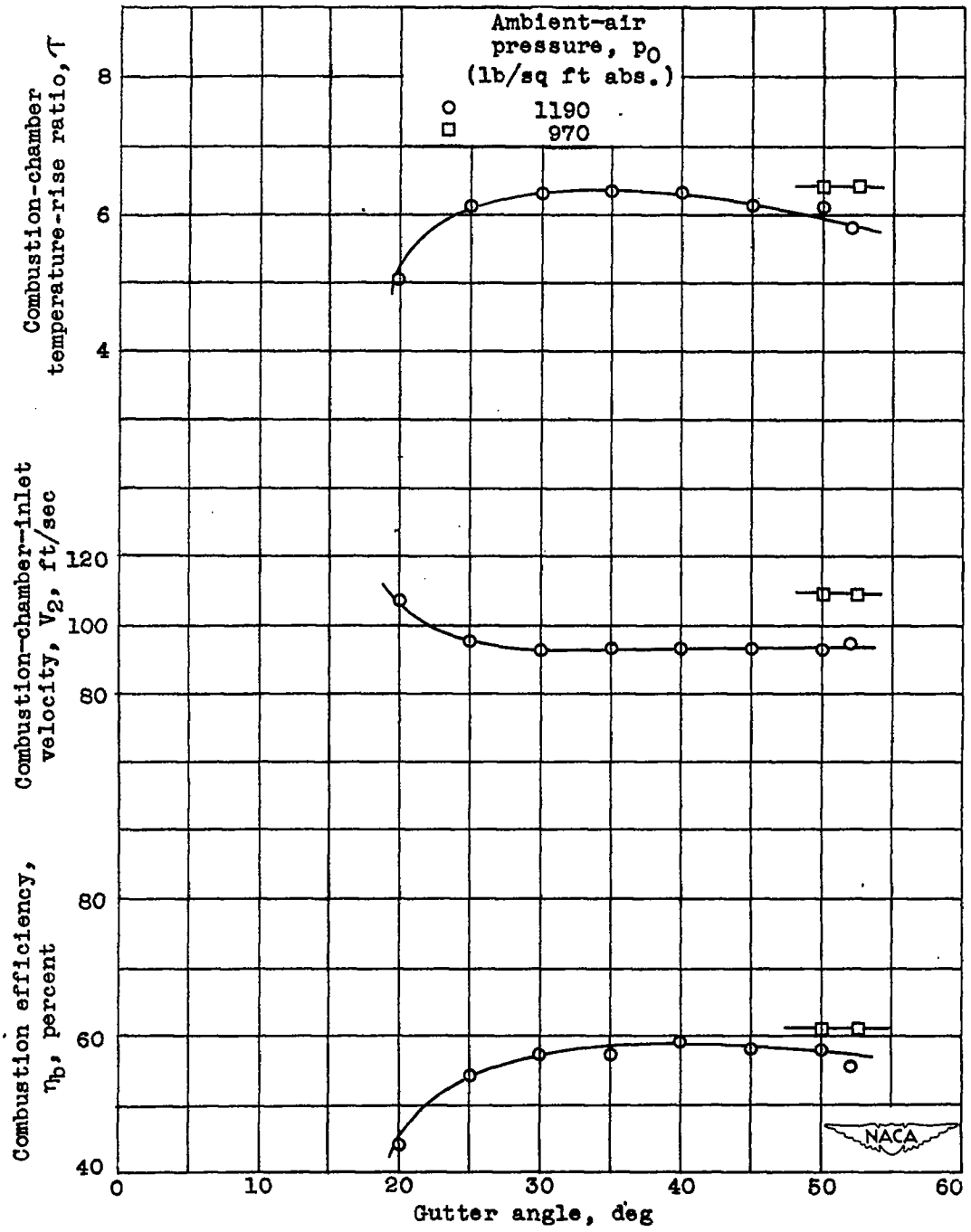

Figure 15. - Effect of gutter angle on combustion efficiency and combustion-chamber temperature-rise ratio with adjustable three-gutter flame holder at various combustion-chamber-inlet velocities. 20-inch ram jet with 5-foot combustion chamber and $17\frac{5}{8}$-inch-diameter exhaust nozzle with $8\frac{1}{16}$-inch-diameter plug; fuel-air ratio, 0.072 to 0.078; combustion-chamber-inlet static pressure, 1500 pounds per square foot absolute.

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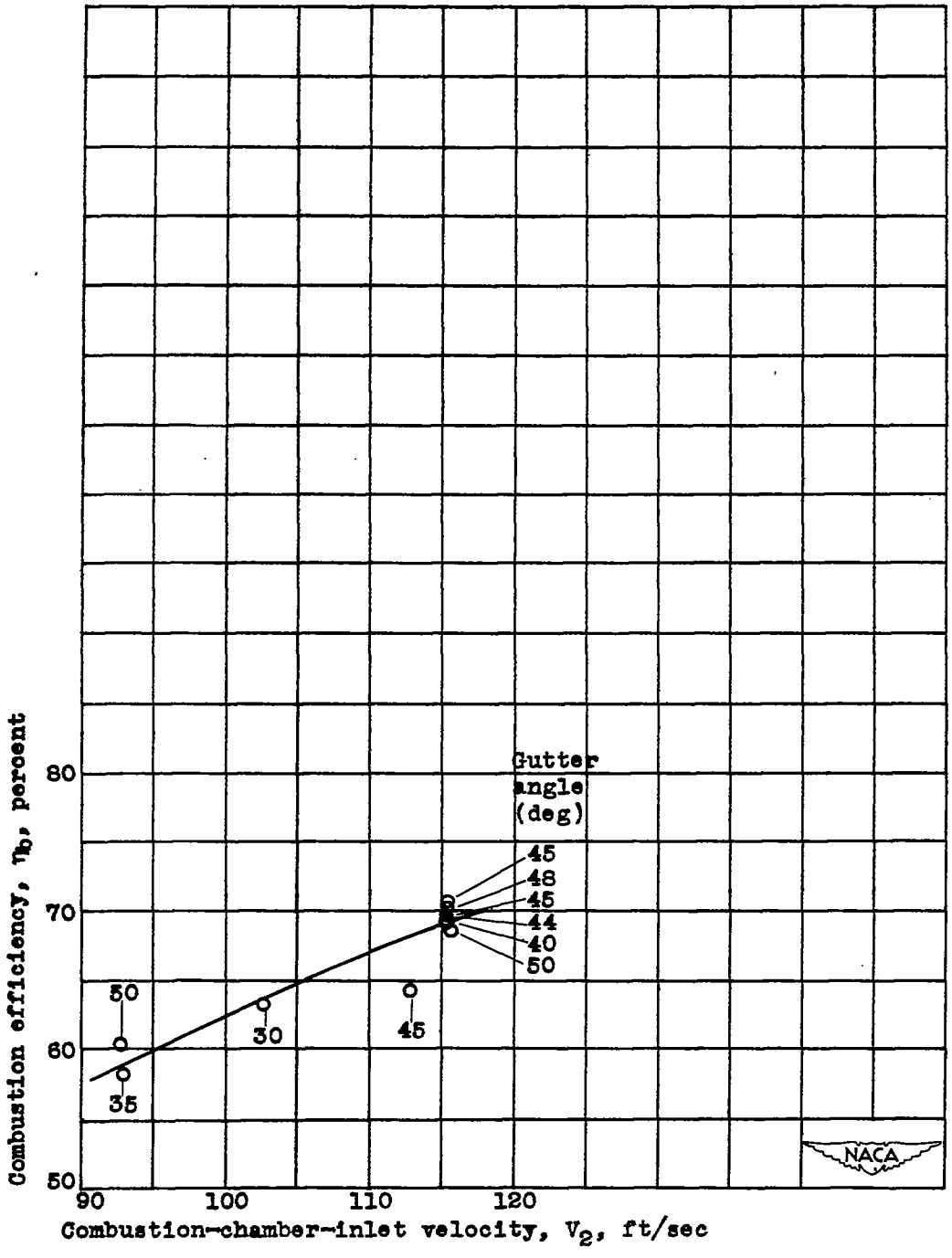

Figure 16. - Effect of combustion-chamber-inlet velocity on combustion efficiency with adjustable three-gutter flame holder at gutter angles from 30° to 52°. 20-inch ram jet with 5-foot combustion chamber and $17\frac{5}{8}$-inch-diameter exhaust nozzle with $18\frac{1}{16}$-inch-diameter plug; fuel-air ratio, 0.074; combustion-chamber-inlet static pressure, 1800 pounds per square foot absolute.