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RESEARCH MEMORANDUM

ALTITUDE-TEST-CHAMBER INVESTIGATION OF PERFORMANCE OF A 28-INCH RAM-JET ENGINE

II - EFFECTS OF GUTTER WIDTH AND BLOCKED AREA ON OPERATING RANGE AND COMBUSTION EFFICIENCY

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An investigation of the effect of flame-holder blocked area and gutter width on the performance of a 28-inch-diameter ram-jet engine at a simulated flight Mach number of 2.0 and for altitudes from 40,000 to 55,000 feet has been conducted in a 10-foot-diameter altitude chamber. The ten flame holders investigated incorporated 60° annular-V gutters that varied in width from 1.0 to 2.5 inches and blocked from 40.5 to 62.0 percent of the combustion-chamber area. All flame holders were investigated with a fixed geometrical arrangement of the fuel-injection system, although operation with either one (annular injection) or both (uniform injection) of the two fuel-injection manifolds was included for some of the flame holders.

At a simulated altitude of 50,000 feet, lean limits of combustion at a fuel-air ratio of approximately 0.03 were obtained for annular injection and approximately 0.04 for uniform injection. The rich limits of combustion were greater than 0.065 fuel-air ratio for the most stable configurations. Combustion efficiencies for these configurations ranged from 0.7 to 1.0 with uniform injection and from 0.4 to 0.9 for annular injection.

Desirable characteristics of wide over-all operating fuel-air-ratio range and high combustion efficiency were most favorably combined in two flame holders. One of these flame holders had 2.0-inch-wide gutters and a projected area of 45.0 percent of the combustion-chamber area and the other flame holder had 2.5-inch-wide gutters and a projected area of 60 percent of the combustion-chamber area.

1398

Changes in gutter width from 1.0 to 2.5 inches for constant blocked area had no appreciable effect on combustion efficiency over a range of fuel-air ratios from 0.045 to 0.065 and for combustion-chamber pressures slightly less than one atmosphere. Increasing the blocked area of the flame holders from 40.0 to 62.0 percent for constant gutter widths of 1.5 and 2.0 inches resulted in an increase in combustion efficiency of 5 to 10 percent. The blow-out limits of the various flame holders were satisfactorily correlated on the basis of the ratio of combustion-chamber-inlet Mach number to gutter width raised to the 0.45 power. The degree of correlation obtained served to verify the work of previous investigators.

INTRODUCTION

An altitude-test-chamber investigation of the combustion-chamber performance of a 28-inch ram-jet engine being developed by the Marquardt Aircraft Company has been conducted at the NACA Lewis laboratory. Extensive developmental tests have been conducted by the engine manufacturer at simulated altitudes up to approximately 30,000 feet and for a simulated flight Mach number of 2.0. The performance investigation at the Lewis laboratory covered the range of simulated altitudes from 40,000 to 55,000 feet at a simulated flight Mach number of 2.0.

The purpose of the program described herein was to determine the effects of the percentage of combustion-chamber flow area blocked by the projected area of the flame holder and of flame-holder gutter width on the combustion performance. Results of an investigation of several configurations in this program are reported in reference 1. A series of 10 V-gutter flame holders were evaluated. These flame holders were designed to provide families of varying gutter width with approximately constant blocked area and varying blocked area with approximately constant gutter width. The runs were made with a fixed fuel-injection system consisting of two internal fuel-manifold rings with spring-loaded fuel-spray nozzles located approximately one combustion-chamber diameter upstream of the flame holders. For each flame holder, altitude operational limits, combustion efficiency, and pressure losses are given and the effects of blocked area and gutter width on performance are analyzed.

APPARATUS

The installation of the engine in the 10-foot altitude chamber is described in reference 1. Features of the setup pertinent to the present investigation are repeated herein.

Description of engine. - A schematic diagram of the engine is shown in figure 1. The engine consisted primarily of an outer shell and an inner body. The forward portions of the outer shell and inner body formed an annular diffuser and the downstream portion of the outer shell formed the combustion chamber and the exit nozzle. The flight engine with free-stream inlet was designed to produce a Mach number of 1.6 at the lip (station 31) at a flight Mach number of 2.0. In order to simulate this flow condition during the altitude-test-chamber investigation, a bellmouth convergent-divergent nozzle was installed at the engine inlet to accelerate the air from stagnation conditions in the altitude chamber to the required Mach number. It was thus possible to simulate the average conditions of Mach number, pressure, and temperature that occur with the free-stream inlet of the flight configuration and to position the shock in the diffuser at the same position as in flight. Because exact boundary layer, Mach number, and pressure gradients, and subcritical spillover conditions of flight are not reproduced by this inlet nozzle, the stability of the combustion chamber and flight diffuser combination could not be investigated; moreover, possible effects of the inlet boundary layer on velocity and pressure distribution at the combustion-chamber inlet could not be evaluated. From the lip station to the end of the inner body, the air-flow passage was divergent with the same dimensions as the flight engine (reference 1). The inner body was connected to the outer shell by four longerons extending almost the length of the inner body.

The combustion chamber is 28 inches in diameter and 46 inches long. Attached to the combustion-chamber outlet is a convergent-divergent exit nozzle 19 inches long with a throat diameter of 20.75 inches and an outlet diameter of 22.44 inches. The entire outer surface of the combustion chamber and exit nozzle was water-jacketed to provide cooling. Fuel was injected near station 197 and the flame holders were mounted at station 239. Detailed descriptions of the fuel system and the flame holders are given subsequently.

Installation in altitude test chamber. - The installation of the engine in the 10-foot altitude test chamber is shown in figure 2. The engine was fitted with a diaphragm seal at a forward baffle and a sliding seal at a rear baffle. The front baffle provided an air-tight seal separating the inlet ram-pressure air from the altitude exhaust and thus permitted a pressure difference to be maintained across the engine. The rear baffle wall was installed to keep the hot exhaust gases from recirculating around the engine.

A sudden expansion jet diffuser (reference 1) was installed at the exit of the engine. This jet diffuser was used to raise the high altitude operational limits imposed by the laboratory altitude exhaust system.

Fuel-injection system. - The fuel system (fig. 3) consisted of two manifolds each divided into four quadrants located between the longeron supports and equipped with spring-loaded nozzles. A description of the fuel nozzles is given in reference 1. The four segments of each manifold are connected outside the engine to form two manifold rings. Twenty-four nozzles were installed in the outer (downstream) manifold and 16 in the inner (upstream) manifold. Fuel flow was individually regulated to the two manifolds. Runs in which equal fuel pressure was supplied to both manifolds are designated uniform-injection runs and those in which fuel was supplied only to the inner manifold are designated annular-injection runs. The fuel used throughout the investigation was commercial grade normal heptane.

Flame holders. - The 10 flame holders used were of similar construction and were mounted in the location shown in figures 1 and 3 (station 239). Detailed dimensions of the flame holders are shown in figure 4. The annular gutters were arranged in a staggered V in the longitudinal plane and were connected and supported by radial gutters or plates. The flame holders differed principally in gutter width, number and diameter of annular gutters, and projected area, hereinafter expressed as percentage of combustion-chamber area (28-inch diameter) or percentage blocked area. The following table lists the principal design features of the various flame holders:

1398

Flame holder	Gutter width (in.)	Blocked area (percent)	Number of annular rings
1	1.00	42.0	4
2	1.00	55.0	6
3	2.00	45.0	2
4	1.50	40.5	3
5	2.00	60.0	3
6	1.20	58.0	5
7	1.38	62.0	5
8	1.00	48.7	5
9	1.40	55.0	4
10	2.50	60.0	2

Practical disposition of blocked area prevented design of precise families but the flame holders may be grouped in families having nearly constant gutter width or blocked area. For example, flame holders 5, 7, and 10 may be grouped to form a family of varying gutter width from 1.38 to 2.50 inches with only a 2-percent variation in blocked area.

The flare cases shown in figure 4 were installed for ignition during flight but were not used for starting during these runs. An ignitor box similar in principle to a miniature ram jet was attached to the gutters to provide ignition.

Fuel-air-ratio meter. - The fuel-air-ratio distribution was measured ahead of the flame holder by a commercially available device that collected a sample of the mixture in a 1/8-inch-diameter tube similar to a total-pressure tube and passed the sample over an electrically heated resistance element. Changes in current flow through the element are measured with changes in composition of the gas. The current flow is proportional to the thermal conductivity of the gas, which is proportional to the fuel-air ratio. Comparison of the survey data with the fuel-air ratio measured from individual metering of fuel and air indicates that the absolute accuracy of the surveys is not adequate for quantitative conclusions. The trends of the distribution, however, are believed to be correctly given by the instrument.

Instrumentation. - Fuel flow was measured with a calibrated adjustable orifice meter and air flow was measured with a concentric sharp-edge orifice. The engine-inlet total temperature and pressure were measured by rakes at the bellmouth entrance. The number and the location of temperature and static- and total-pressure measurements within the engine are shown in figure 1. The combustion-chamber-inlet total and static pressures were measured by a rake located a few inches upstream of the flame holders. Water-cooled rakes were used to measure total pressure at the combustion-chamber outlet. Static pressures in the exhaust-nozzle throat were measured by four wall static tubes and by eight trailing static tubes mounted on streamlined struts in the combustion chamber and extending downstream to the nozzle throat. The combustion-chamber and the exit-nozzle cooling-water flow and temperature rise were measured in order to calculate the heat removed.

PROCEDURE

The general procedure for most of the runs was to ignite the burner at an inlet pressure of approximately 40 inches of mercury absolute and an outlet pressure of 25 inches of mercury, corresponding to a combustion-chamber-inlet velocity of approximately 250 feet per second, with a fuel-air ratio of approximately 0.04. When stable burning was established, the outlet pressure was slowly reduced until choking conditions were reached in the exit nozzle. The engine-inlet pressure was then set to simulate the desired flight conditions. With this pressure held constant, the fuel flow was varied in small intervals and data were taken at stabilized burning conditions until rich or lean combustion blow-out occurred. The constant inlet pressure and inlet temperature imposed upon the choked inlet nozzle resulted in a constant air flow through the engine for any given simulated altitude. Runs were made with the various configurations at a simulated flight Mach number of 2.0 and altitudes from 40,000 to 55,000 feet.

The inlet-air total pressure at the lip station was computed for the flight engine for a range of altitudes at a flight Mach number of 2.0 from conical shock relations. The pressure at the bellmouth inlet in the engine was then set at the computed values for each altitude. This procedure neglects any loss in total pressure between the bellmouth inlet and the lip.

The engine-inlet air temperature was maintained at $710^\circ \pm 5^\circ$ R by a combustion heater in the air supply line. The fuel-air ratio for the combustion heater was about 0.002. The effect of the slight resulting contamination of the charge air on the engine combustion is not known but is believed to be small.

1398

Runs were made with uniform fuel injection for all flame holders and several flame holders were also run with annular injection. For flame holder 2, a few runs were made in which unequal fuel pressures were imposed on the fuel manifolds in an effort to blend gradually from annular to uniform injection. Blow-out was detected by observation of the flame through a periscope, by the sudden change in sound level, and by an automatic flame-detection device. The symbols used and method of calculation of combustion efficiency are outlined in the appendix.

RESULTS AND DISCUSSION

The radial distributions of fuel-air ratio and total and static pressures at the combustion-chamber inlet were measured in order to check the possibility of regions of separated flow or irregular velocity or fuel distribution. The types of fuel distribution obtained with uniform and annular injection are illustrated in figure 5(a). As previously mentioned, the results are considered to be qualitative and indicative of only the trends. The fuel-air ratio for uniform injection did not vary greatly over the outer 10 inches of radius but decreased slightly toward the center of the combustion chamber. Annular injection produced a rich region centered around the 5-inch radius with rapidly decreasing fuel-air ratios toward the center and outer wall of the combustion chamber. The distributions of fuel-air ratio observed for other operating conditions indicated that annular injection provided a localized region of nearly stoichiometric fuel-air ratio, even for very lean over-all fuel-air ratios; whereas uniform injection distributed fuel more evenly for all fuel-air ratios.

Typical radial distributions of total to static pressure ratio ahead of the flame holder are shown in figure 5(b). The radial pressure ratio gradient was very large near the inner and outer walls of the diffuser outlet, but it is evident that no extensive regions of separated flow existed near the walls. The combustion results given herein apply only to the particular conditions of pressure, velocity, and fuel distribution at the combustion-chamber inlet produced by the test engine and their degree of applicability to other conditions of flow is unknown.

Plots of the basic data for each flame-holder configuration are shown in figures 6 to 15. For each flame holder the simultaneous variations of exhaust-nozzle pressure ratio P_4/p_5, combustion-chamber pressure ratio P_4/P_2, combustion-chamber-inlet Mach number M_2', combustion-chamber-outlet pressure P_4, gas-flow factor p_5A_5/W_5, and combustion efficiency η are given as functions of fuel-air ratio. Inasmuch as combustion-chamber-inlet velocity, pressure, and fuel-air ratio vary simultaneously, the individual effects of these variables on performance are not separated in figures 6 to 15. The trends shown therefore apply only to the specific combustion conditions indicated. Superimposed on the curves of combustion-chamber-outlet pressure are lines denoting the blow-out limits for both uniform and annular injection. Data are shown for uniform injection for all flame holders and for annular injection for several flame holders. The data are coded for constant altitude, which as previously discussed implies a constant engine bellmouth-inlet pressure.

Engine operating conditions. - Inasmuch as all runs were made with a choked exit nozzle, the ratio of nozzle-inlet or combustion-chamber-outlet pressure to throat static pressure P_4/p_5 should in the ideal one-dimensional case be a function only of gas temperature and the thermodynamic properties of the gas, and therefore independent of configuration or fuel-air-ratio distribution. Departure from the ideal one-dimensional concepts will produce discrepancies in the combustion temperatures and efficiencies computed by the method outlined in the appendix. The experimental exhaust-nozzle pressure-ratio data (part (a) of figs. 6 to 15) show that the pressure ratio is independent of altitude but dependent on configuration as well as type of fuel injection.

The combustion-chamber total-pressure ratio P_4/P_2 for each flame holder is nearly independent of fuel-air ratio and altitude. The pressure ratio is constant because the increase in momentum pressure drop with increase in fuel-air ratio is counterbalanced by a decrease in friction-pressure drop. The differences in pressure ratio between flame holders is a result of differences in friction pressure drop and combustion efficiency characteristics. The pressure ratio varied from approximately 0.90 for flame holders with high blocked area to about 0.94 for low-blocked-area flame holders.

The combustion-chamber-inlet Mach number was computed from the measured total and static pressures at instrument station 2 upstream of the flame holder and adjusted to the combustion-chamber area by the isentropic-flow relations. For this reason the Mach numbers are designated M_2'. This Mach number does not actually exist at the flame-holder inlet but is conventionally defined on this basis for convenience of reference. The trend of Mach number with fuel-air ratio was similar for each flame holder. The Mach number decreased with increasing fuel-air ratio, reaching a minimum value between

0.135 and 0.150 at the highest fuel-air ratios and a maximum value with annular injection of slightly greater than 0.220 at fuel-air ratios around 0.03. A separation in the data for uniform and annular injection occurred as a result of the change in combustion efficiency subsequently discussed. For a few of the flame holders, slight separation also occurred with altitude but was so small in most cases that it was obscured by experimental scatter.

Stable combustion limits. - The reduction in combustion-chamber-outlet pressure P_4 with increased altitude is shown in part (d) of figures 6 to 15. The combustion-chamber-outlet pressure for a given altitude increased with fuel-air ratio in order to satisfy continuity. For uniform injection, burning was accomplished from slightly over one atmosphere to approximately 2/3 of sea-level atmosphere outlet pressure. The burning-pressure range was extended with annular injection for some flame holders to less than 1/2 atmosphere.

The burning blow-out limits are indicated on the plots of combustion-chamber-outlet pressure by the dashed lines. Although only a single line is shown for each limit, the blow-out region is in reality a band of fuel-air ratios located around the dashed lines. The band probably extends over a region of about 0.005 in fuel-air ratio. This fact explains the appearance of occasional stable operating points outside the blow-out limits for some flame holders (for example, fig. 9). In general, the fuel-air ratio for lean blow-out increased as the simulated altitude increased for both uniform and annular injection; whereas the rich limit fuel-air ratio decreased with increasing altitude. The operating range of fuel-air ratios thus decreased with increasing altitude for all flame holders. The altitude above which burning was not possible was reached only for flame holder 1. Annular injection extended the lean blow-out fuel-air-ratio limit for all flame holders investigated. The richer zone of fuel-air ratio provided by annular injection apparently produced a more favorable mixture for combustion in the region of the flame-holder gutters at low over-all fuel-air ratios. The maximum operating range of fuel-air ratios varied from a lean limit between 0.04 and 0.05 to a rich limit between 0.07 to 0.08 for uniform injection at the altitudes investigated. The lean limit was extended to approximately 0.03 fuel-air ratio with annular injection.

Gas-flow parameter. - As shown in the appendix, the gas-flow parameter p_5A_5/W_5 is a function of the combustion efficiency and the combustion-chamber-outlet temperature. The gas-flow data are presented in this form because the gas-flow parameter is convenient to use as a measure of combustion performance, for estimation of engine thrust, and to determine the air-flow rate through the engine. The gas-flow parameter increased with increasing fuel-air ratios up to approximately stoichiometric and then decreased slightly. Differences between flame holders were small; for example, at a fuel-air ratio of 0.05 the value of gas-flow parameter was from 61 to 64 for all flame holders. Because combustion efficiencies for annular injection are lower than for uniform injection, the gas-flow-parameter curves for the two types of injection separate considerably. The gas-flow parameter for most of the flame holders was independent of altitude; for a few flame holders, however, a slight decrease in the gas-flow parameter occurred at low fuel-air ratios as the altitude was increased.

Combustion efficiency. - The curves of combustion efficiency η follow the same trends as the gas-flow-parameter curves. As previously mentioned, combustion efficiency is influenced by combustion-chamber-inlet pressure and velocity as well as fuel-air ratio. In general, the combustion efficiency increased as the fuel-air ratio increased up to approximately stoichiometric and then decreased slightly. The combustion efficiency for a few of the flame holders decreased as the altitude increased but was independent of altitude for most configurations. The combustion efficiency for annular injection was generally lower than for uniform injection at comparable fuel-air ratios. The measured values of uniform-injection combustion efficiencies varied from 0.7 to 1.0; whereas for annular injection the range was from 0.4 to 0.9. Visual observation during annular-injection operation showed that flame was present only in the center of the combustion chamber.

Data obtained during runs with blending of the two fuel manifolds are shown in figure 7. A smooth transition from annular injection at the lowest fuel-air ratios to uniform injection at high fuel-air ratios was accomplished without operational difficulty. The combustion-efficiency curve follows a gradually increasing trend with increasing fuel-air ratio.

Comparison of over-all performance. - The factors to be considered in an over-all performance comparison are pressure losses, combustion efficiency, and operating fuel-air-ratio range. Usually, the only requirement is to obtain the highest possible combustion efficiency accompanied by the widest attainable operating fuel-air-ratio range and the lowest pressure loss. For some applications, however, an evaluation of the effects of altitude and fuel-air ratio on these performance parameters with reference to the flight plan and diffuser operating conditions is necessary before the most desirable configuration can be selected. Over the range of altitudes investigated, the widest operating range and lowest lean blow-out limits for both uniform and annular injection were obtained with flame holders 3 and 10. An approximate comparison of efficiencies and pressure losses over the range of steady operating conditions may be made by comparing maximum combustion efficiency and combustion-chamber-pressure ratios:

Flame holder	Maximum combustion efficiency	Combustion-chamber-pressure ratio P_4/P_2
1	0.92	0.93
2	.88	.92
3	.96	.94
4	.90	.92
5	1.00	.91
6	.98	.93
7	.95	.90
8	.99	.92
9	.91	.92
10	.94	.92

The data show that combustion efficiency was nearly independent of the combustion-chamber-pressure ratio. An efficiency variation of 12 percent occurred with a pressure-ratio variation of only 4 percent. The maximum efficiencies of flame holders 3, 5, 6, 7, 8, and 10 were between 0.94 and 1.00 and may therefore be considered of comparable performance; flame holder 5 had the highest maximum efficiency. The combustion efficiencies of the other flame holders was from 0.88 to 0.92. On the basis of the highest combustion efficiency (0.7 to 0.95) with reasonably low pressure drop and widest operating range obtained, flame holders 3 and 10 are considered to be the best of the 10 flame holders investigated. Flame holder 3 had a slightly lower pressure loss; whereas flame holder 10 had a slightly wider operating range.

Effects of gutter width and blocked area on combustion efficiency. - The combustion efficiency is plotted as a function of gutter width for two nearly constant blocked areas, fuel-air ratios, and combustion-chamber-outlet pressures in figure 16. These curves are cross plots of figures 6 to 15. For these fuel-air ratios near stoichiometric and for these pressures of approximately one atmosphere, gutter width had little effect on the combustion efficiency for a given blocked area. Data for a fuel-air ratio of 0.045 (not shown) had a similar trend at about the same pressure levels. Insufficient data were obtained, however, to determine the gutter-width effects at lower pressures. 1398

The effects of blocked area on combustion efficiency are shown in figure 17 for similar conditions of pressure and fuel-air ratio. A general trend of increasing efficiency with increased blocked area resulted for gutters 1.50 and 2.00 inches wide. An increase of 5 to 8 percent in combustion efficiency occurred for an increase in blocked area from about 40.0 to 62.0 percent. The efficiency of flame holders with 1.00-inch gutters, however, reached a maximum at an intermediate value of blocked area and decreased as the blocked area increased. The curves for 1.00-inch gutters are more subject to error than those for wider gutters because they are based on data for only three flame holders. A consistent error in the data for any one flame holder could therefore shift the entire trend, particularly in view of the relatively small changes in efficiency involved. The curves for the wider gutters, however, are the result of cross plots from data for five flame holders and are considered more accurate. The increased efficiency with increased blocked area was attributed to the involvement of a larger percentage of the incoming fuel in regions favorable for combustion.

Correlation of operating range data. - The theory of burning in the wake of bluff bodies developed in references 2 and 3 and independently in reference 4 postulates that continuous ignition occurs as a result of transfer of hot gases from recirculating eddies or vortices immediately downstream of the bluff body into the boundary region of relatively cold fuel-air mixtures. The temperature of the boundary mixture consequently increases as the flow proceeds downstream until the appropriate ignition temperature is reached. From a heat balance between the heat-supply rate required for ignition in the boundary zone and the rate of heat flow from the eddy region (See reference 2 for a detailed derivation.), it can be shown that for a given fuel-air-ratio distribution and for a constant inlet-air pressure and temperature, the following relation applies:

$$M_2'/n^a = \phi(f)$$

where f is the fuel-air ratio, n is the width of the bluff body (gutter), and ϕ is a functional notation. The relation is independent of blocked area. The value of 0.45 for the exponent a,

1398

determined empirically in reference 2 for gutters of long span, is used for the plots presented herein. Similar correlation was obtained, however, when an exponent of 1.00 was used.

Cross plots of the faired blow-out fuel-air-ratio data of this report as a function of the correlation parameter $M_2'/n^{0.45}$ are presented in figure 18. Curves are shown for constant pressures of 1400 and 2000 pounds per square foot absolute. The degree of correlation is good for all curves. The data spread is less than half of the general trend in all cases and is within the limits of reproducibility. The scatter may be partly caused by slight differences in fuel-air distribution for the different gutter arrangements. Although it is possible that this correlation may be entirely fortuitous, the similar results of the reference reports add considerable credence to the fundamental nature of the correlation.

Comparison of figures 18(a) and 18(b) shows that decreasing pressure level decreased the operating fuel-air-ratio range by increasing the fuel-air ratio for lean blow-out and decreasing the fuel-air ratio for rich blow-out. As the inlet Mach number was increased or the gutter width was decreased for a given pressure, a similar reduction in operating range occurred. The operating range for a pressure of 1400 pounds per square foot is extremely sensitive to inlet Mach number. Reference to figure 18(a) shows that an increase in Mach number of 36 percent, resulting in an increase in the correlation parameter from 0.11 to 0.15, produced a decrease in operating range of nearly 75 percent. Compensation for the increased Mach number by increasing the gutter width to maintain constant operating range would require approximately doubling the gutter width. The slope of the lean operating limit curve is very large for the lower values of the correlation parameter; consequently, further increases in gutter width or decreases in inlet Mach number would yield very small decreases in lean blow-out fuel-air ratio. The rich limits for the lower values of the correlation parameter are at fuel-air ratios greater than those for maximum combustion-chamber-outlet temperature and are therefore considered satisfactory. Future development of ram-jet combustors for wider operating range will therefore probably require controlled fuel-air-ratio distribution in combination with flame-holding devices designed to produce more favorable types of recirculating vortex flow in the flame-holder wake or the use of special piloting devices.

SUMMARY OF RESULTS

An altitude-test-chamber investigation of the combustion performance of 10 flame holders in a 28-inch ram-jet engine over a range of simulated altitudes from 40,000 to 55,000 feet and at a simulated flight Mach number of 2.0 gave the following results:

1. A 2-inch wide 60° gutter flame holder with 45-percent blocked area and a 2.50-inch wide 60° gutter flame holder with 60-percent blocked area had the most favorable combination of wide operating range, high combustion efficiency, and low pressure losses.

2. For these flame holders, stable operation at a simulated altitude of 50,000 feet was obtained with injection from two fuel manifolds (uniform injection) from fuel-air ratios of approximately 0.040 to over 0.065. Injection from a single fuel manifold (annular injection) extended the lean blow-out fuel-air ratio to approximately 0.030. Combustion efficiencies were from 0.7 to 1.0 over the operable range for uniform injection and from 0.4 to 0.9 for annular injection. Combustion-chamber-pressure losses were 6 to 8 percent of the combustion-chamber-inlet total pressure.

3. In general, annular injection provided locally richer and therefore more favorable zones for combustion for the lean over-all fuel-air ratios than uniform injection and resulted in a reduction in lean blow-out fuel-air ratio. Combustion efficiencies were lower with annular injection than for uniform injection at comparable over-all fuel-air ratios.

4. Changes in gutter width from 1.00 to 2.50 inches with constant blocked area had no appreciable effect on combustion efficiency over a range of fuel-air ratios from 0.045 to 0.065 and for pressures of approximately 1 atmosphere. Increasing the blocked area from 40.0 to 62.0 percent with gutters 1.50 and 2.00 inches wide resulted in an increase in combustion efficiency of 5 to 10 percent. For 1.00-inch wide gutters, increases in blocked area from 42.0 to 48.0 percent resulted in an increase in efficiency; further increase to a blocked area of 55.0 percent, however, resulted in a decrease in combustion efficiency.

5. The lean and rich blow-out fuel-air-ratio data were correlated by use of the ratio of combustion-chamber-inlet Mach number to the gutter width raised to the 0.45 power. The degree of correlation obtained served to verify the work of previous investigators and to extend their work to larger scale combustors. The shape of the curves obtained indicated that further gains by increasing gutter width beyond 2.50 inches would be very small.

1398

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1398

APPENDIX - CALCULATIONS

Symbols

The following symbols are used throughout the report:

A	area, sq ft
a	empirical constant
f	fuel-air ratio
g	acceleration due to gravity, ft/sec^2
M	Mach number
n	gutter width, in.
P	total pressure, lb/sq ft absolute
p	static pressure, lb/sq ft absolute
R	gas constant, ft-lb/(lb)($^{\circ}$R)
T	total temperature, $^{\circ}$R
t	static temperature, $^{\circ}$R
W	weight flow, lb/sec
γ	ratio of specific heats
η	combustion efficiency
ϕ	functional notation

Subscripts:

2	conditions at combustion-chamber inlet (station 228)
2'	conditions at station 2 adjusted to combustion-chamber area
4	conditions at combustion-chamber outlet (station 280)
5	conditions at exhaust-nozzle throat (station 297)

Calculation of Combustion Efficiency

The flow at the engine exit is assumed to be ideal one-dimensional uniform flow and the assumption is made that the Mach number at the exit-nozzle throat is 1.0 with a flow area equal to A_5. Under these conditions the following relation may be derived:

$$T_5 = \left(\frac{p_5A_5}{W_5}\right)^2 \frac{\gamma g}{2R} (\gamma+1) \tag{1}$$

where γ is the value for average between total and static temperature at the throat and for the prevailing fuel-air ratio and R is 53.5 foot-pounds per pound per $^{\circ}R$. The computed temperature T_5 is then corrected for the heat rejection to the combustion-chamber cooling water.

The combustion efficiency is defined as

$$\eta = \frac{(T_5-T_2)_{actual}}{(T_5-T_2)_{ideal}} \tag{2}$$

where the ideal temperature rise is obtained from reference 5.

In computing T_5 the value of p_5 used was the numerical average of eight trailing static tubes and four wall static orifices. The possibility of inaccuracy in the computed values of T_5 and η due to the many assumptions involved is obvious. The magnitude of the error, however, would probably not be greatly affected by configuration, and values probably satisfactory for relative comparison were obtained. A plot of the relations between equations (1) and (2) is shown in figure 19. The gas-flow parameter p_5A_5/W_5 is plotted as a function of fuel-air ratio for various constant combustion efficiencies and combustion-chamber-outlet total temperatures for an inlet temperature of 710° R. The plot may be useful for evaluation of combustion temperature from the data presented in the report or to establish the relations between the other combustion variables.

1398

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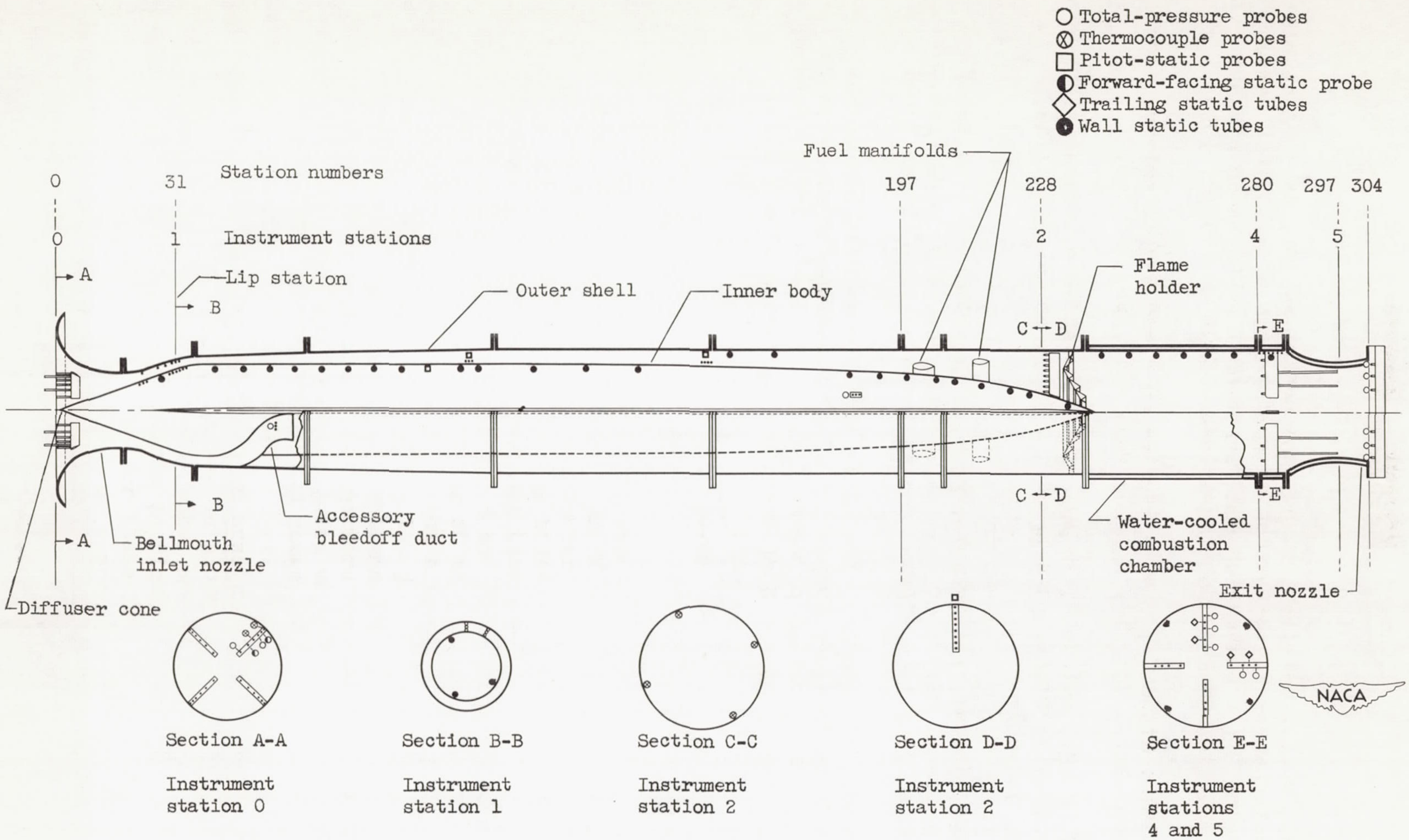


Figure 1. - Schematic diagram of 28-inch ram-jet engine showing instrumentation and station locations.

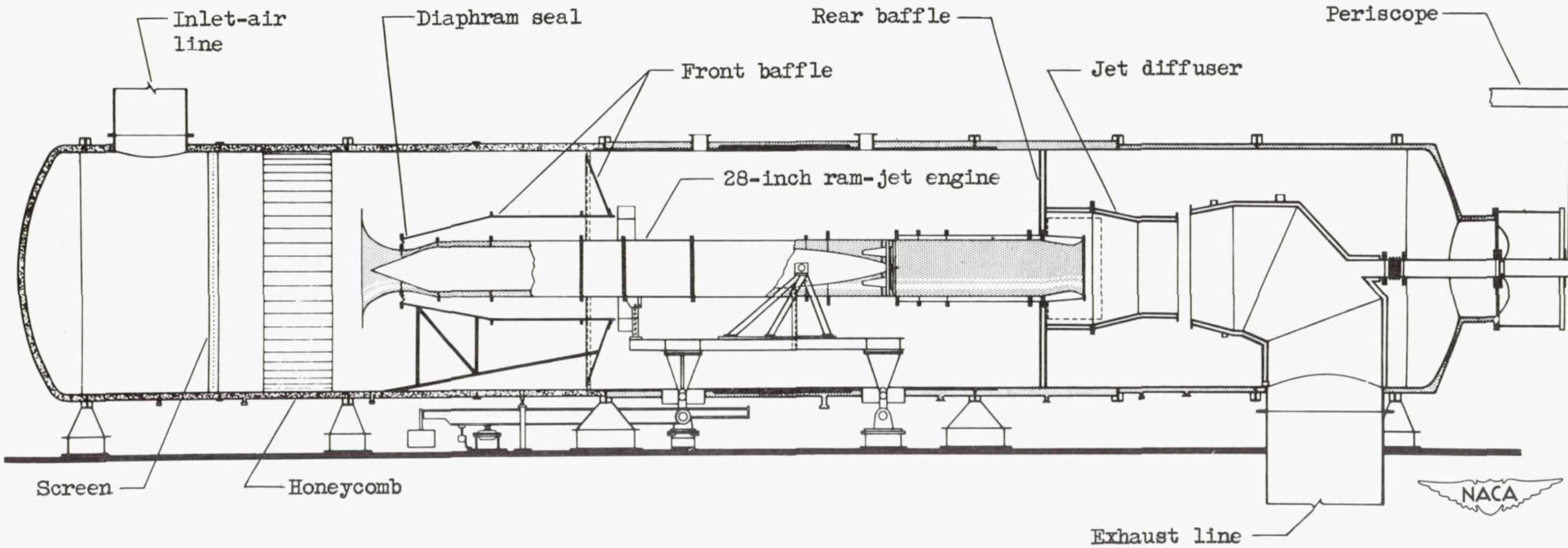


Figure 2. - Schematic diagram of 28-inch ram-jet engine installed in 10-foot altitude test chamber.

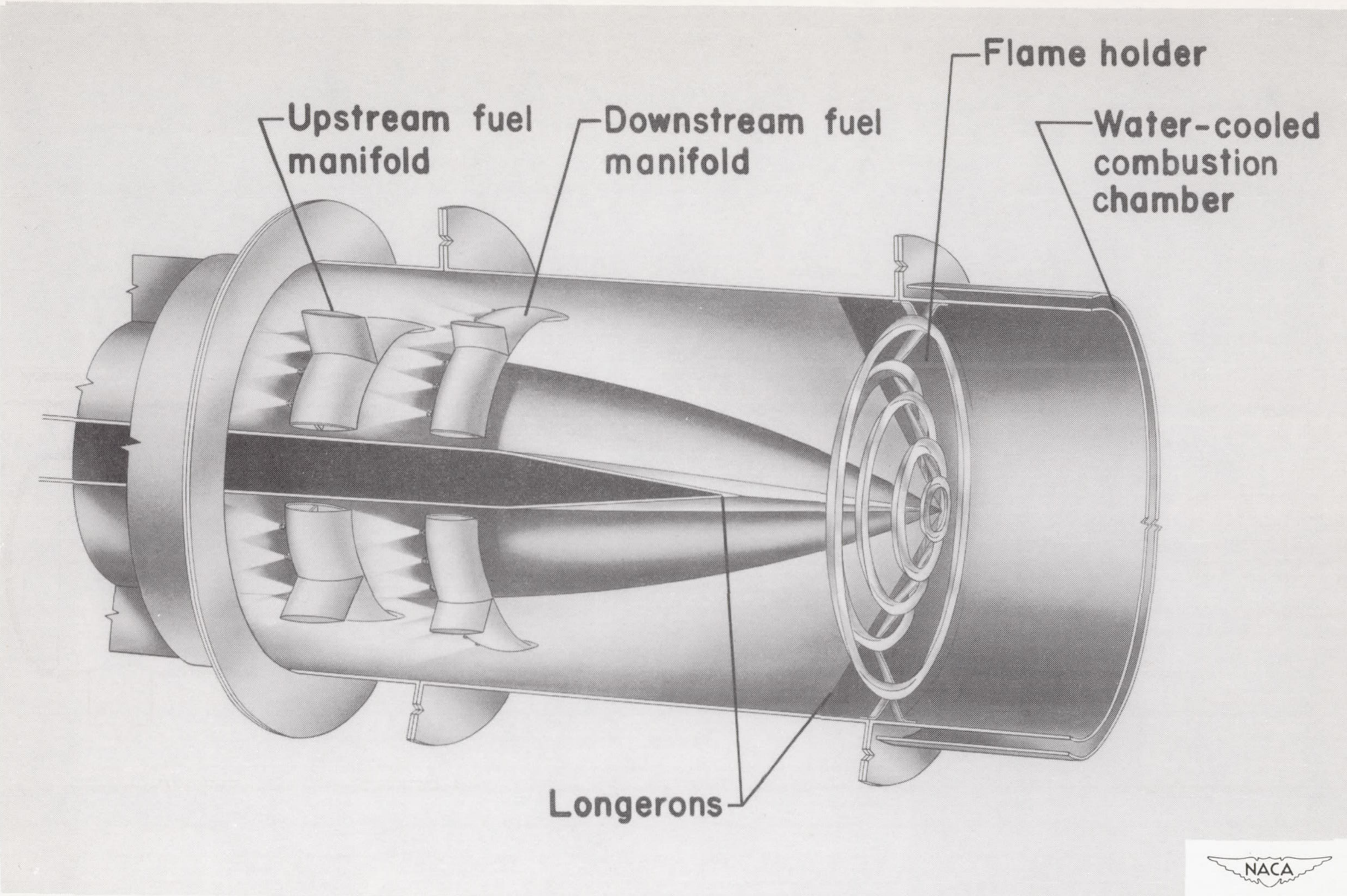
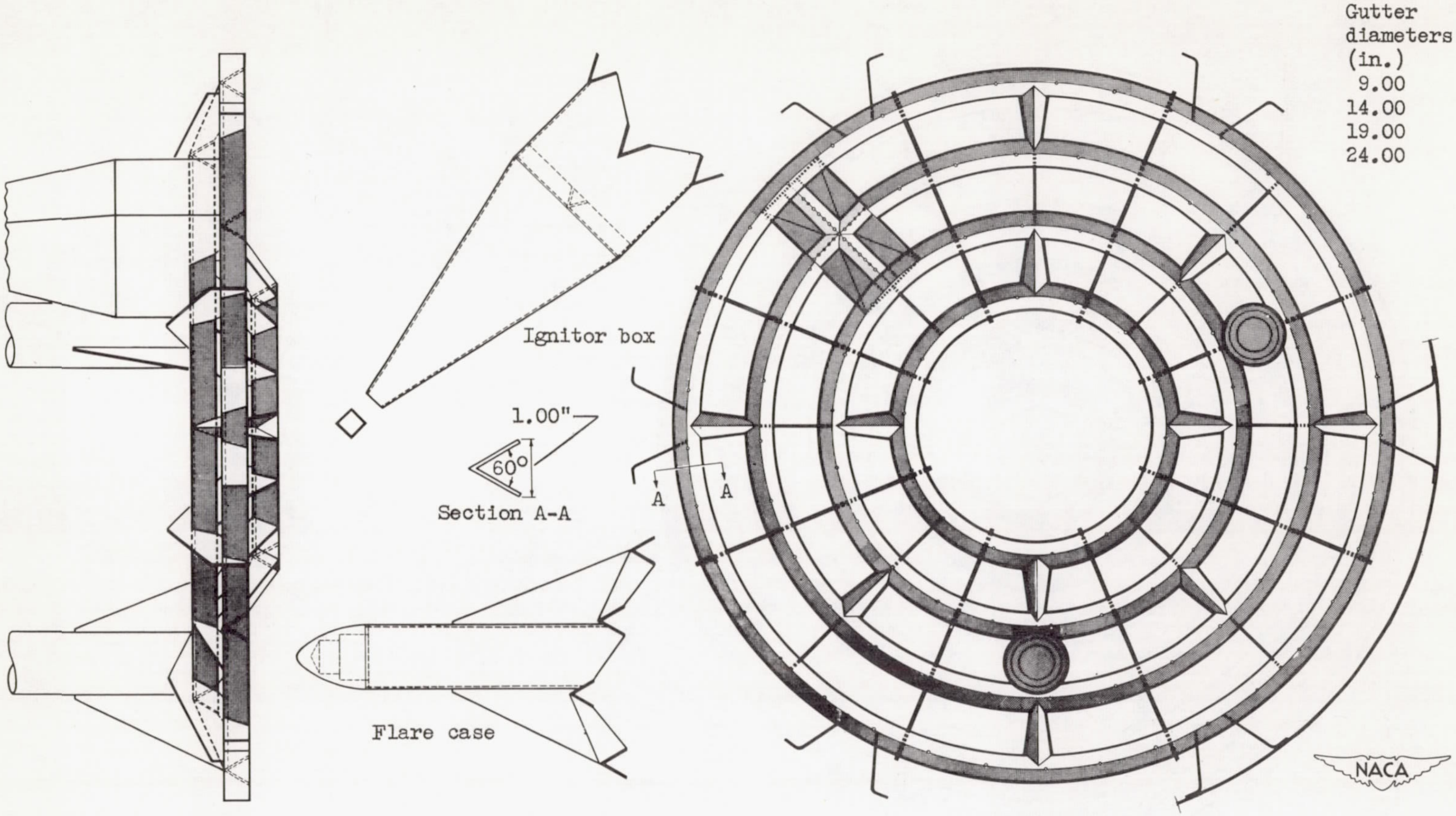
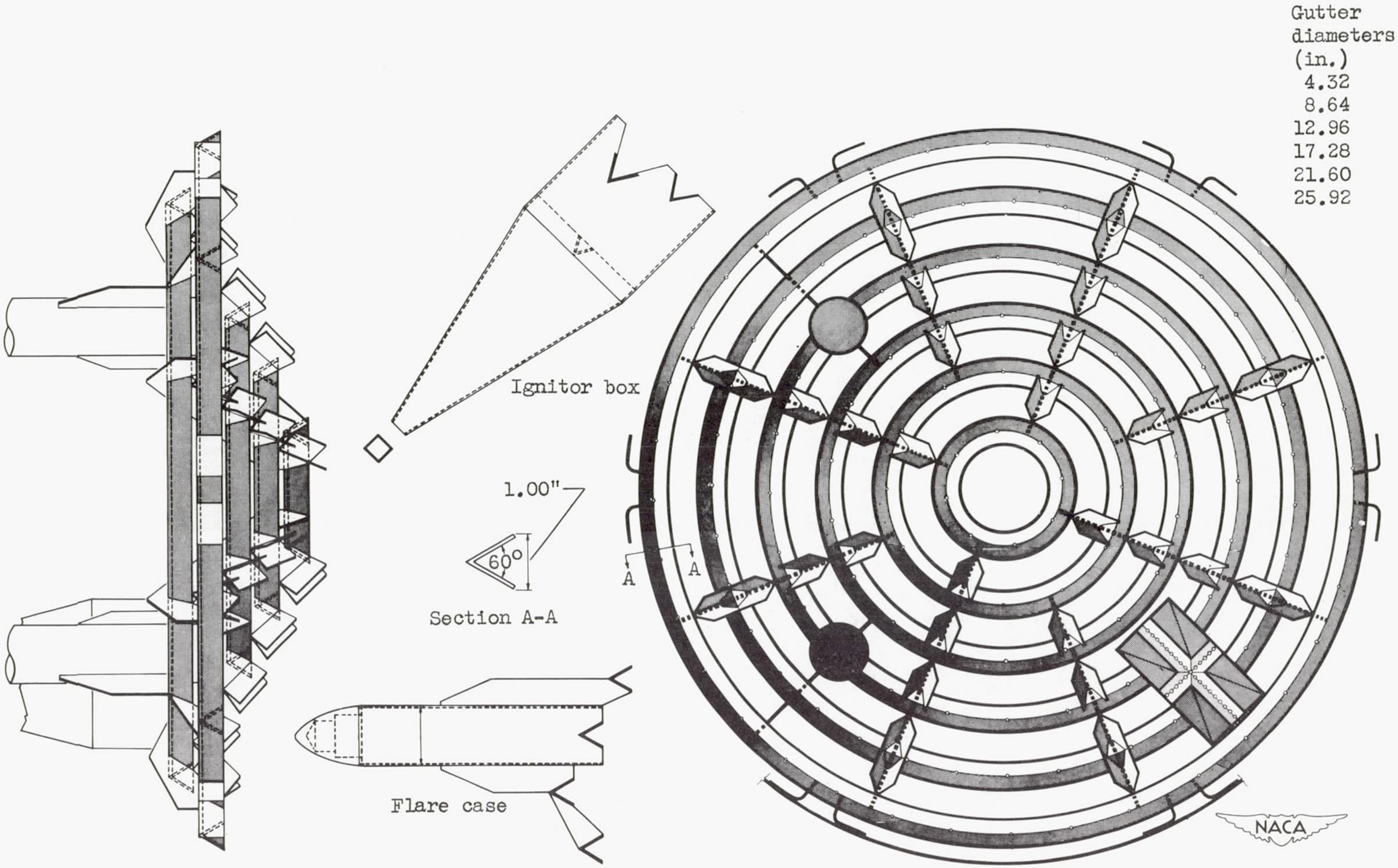


Figure 3. - Arrangement of fuel-injection system, flame holder, and combustion chamber for 28-inch ram-jet engine.



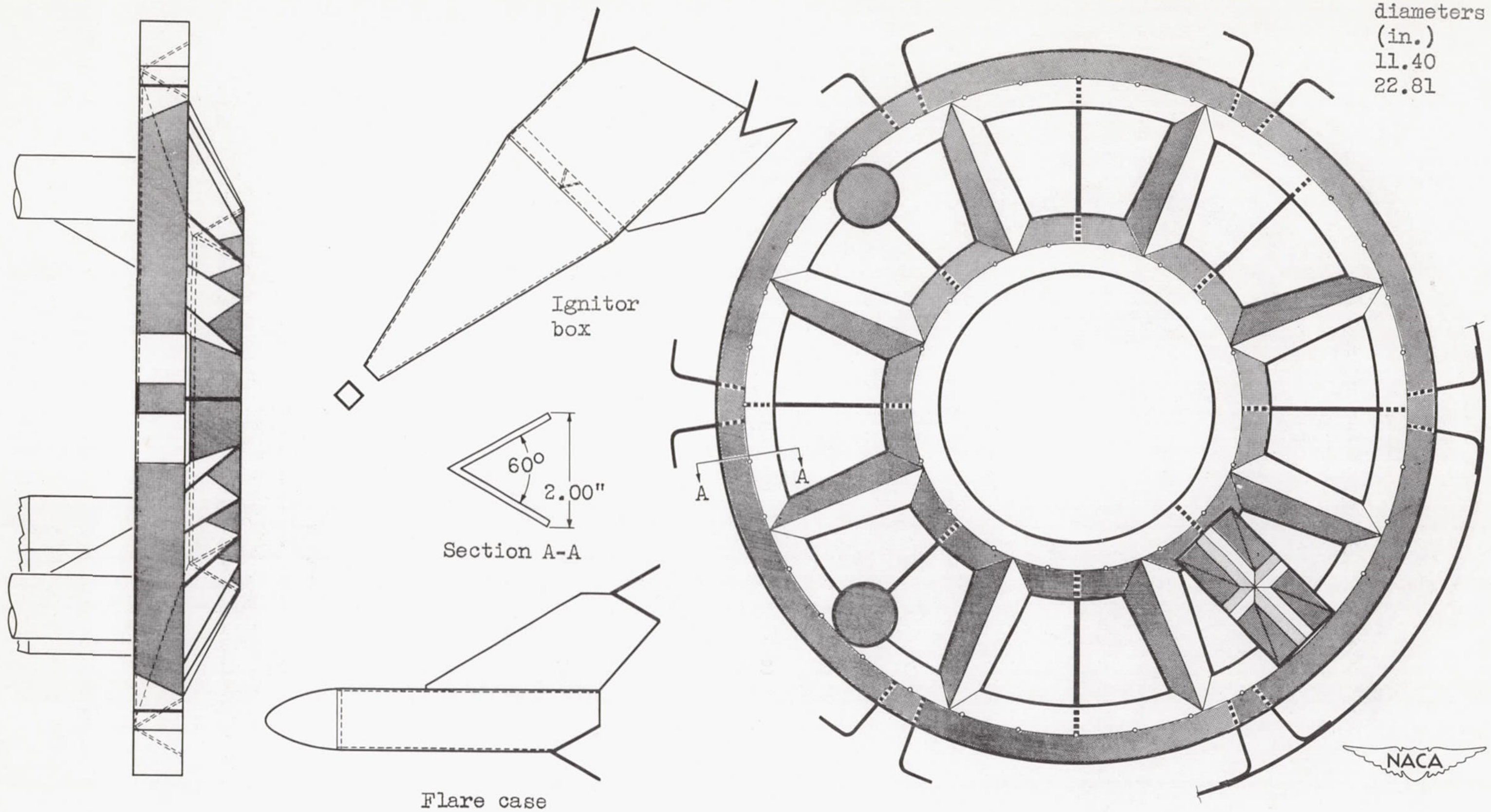
(a) Flame holder 1; blocked area, 42 percent; gutter width, 1.00 inch.

Figure 4. - Schematic diagrams of flame holders.



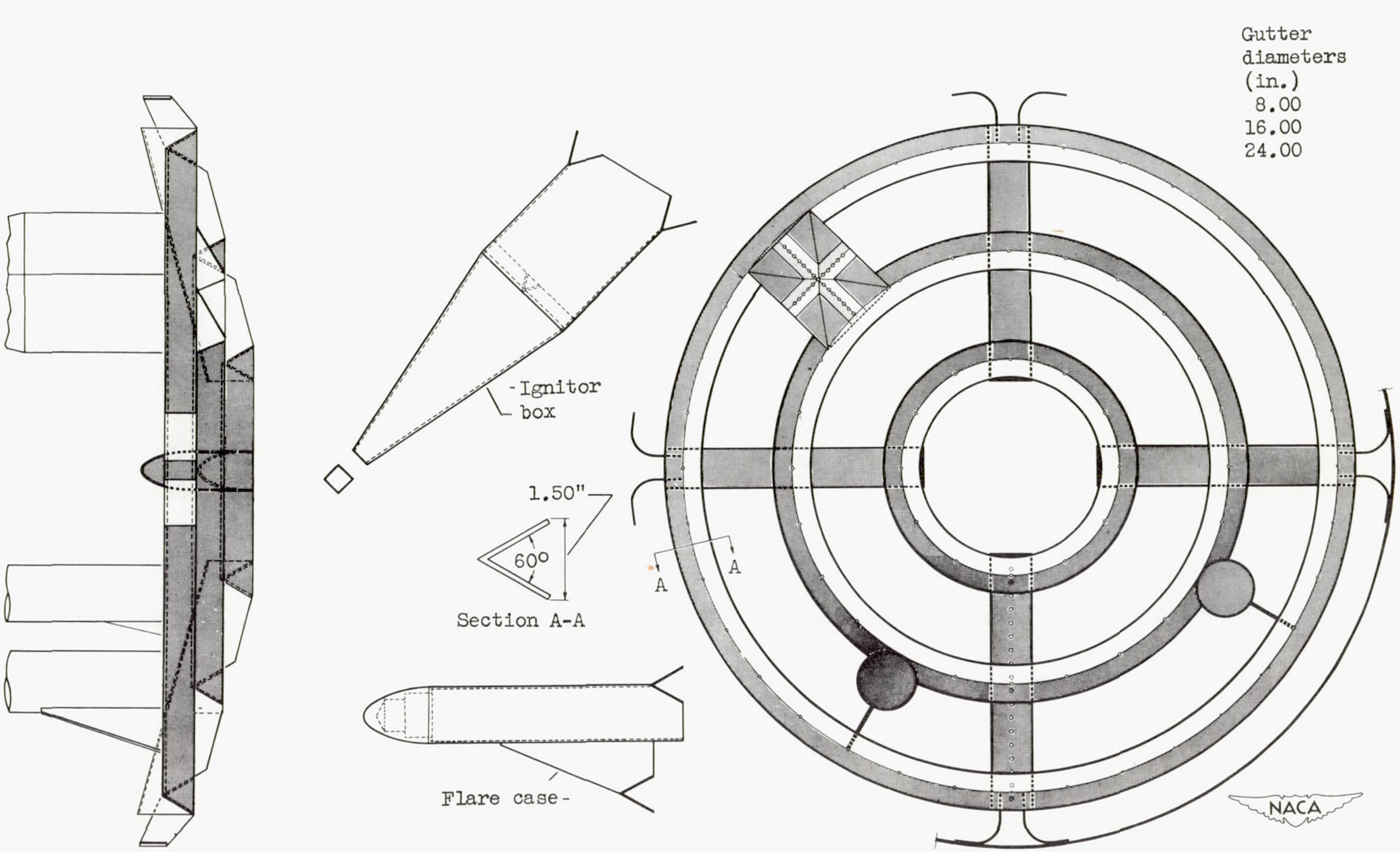
(b) Flame holder 2; blocked area, 55 percent; gutter width, 1.00 inch.

Figure 4. - Continued. Schematic diagrams of flame holders.



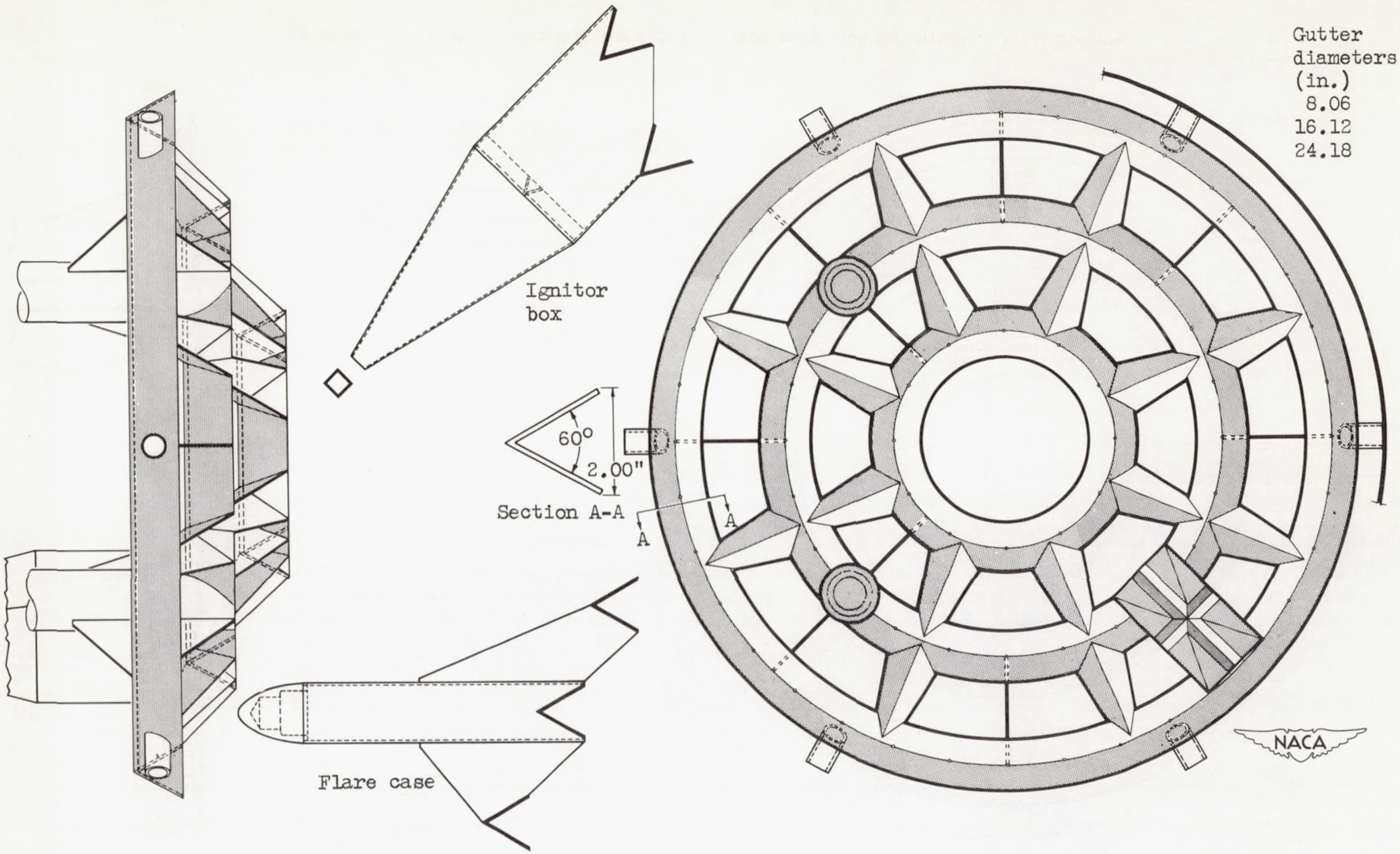
(c) Flame holder 3; blocked area, 45 percent; gutter width, 2.00 inches.

Figure 4. - Continued. Schematic diagrams of flame holders.



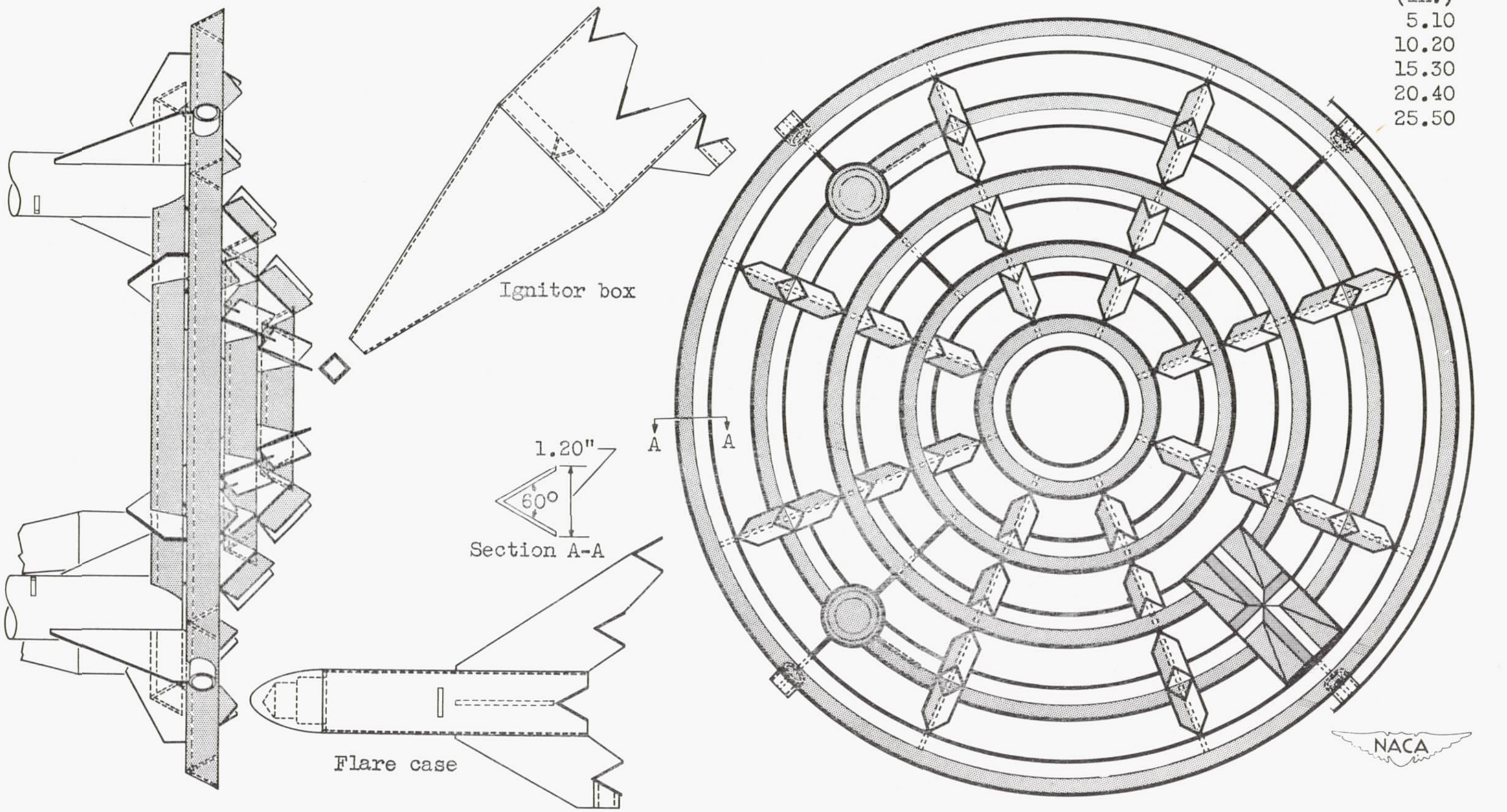
(d) Flame holder 4; blocked area, 40.5 percent; gutter width, 1.50 inches.

Figure 4. - Continued. Schematic diagrams of flame holders.



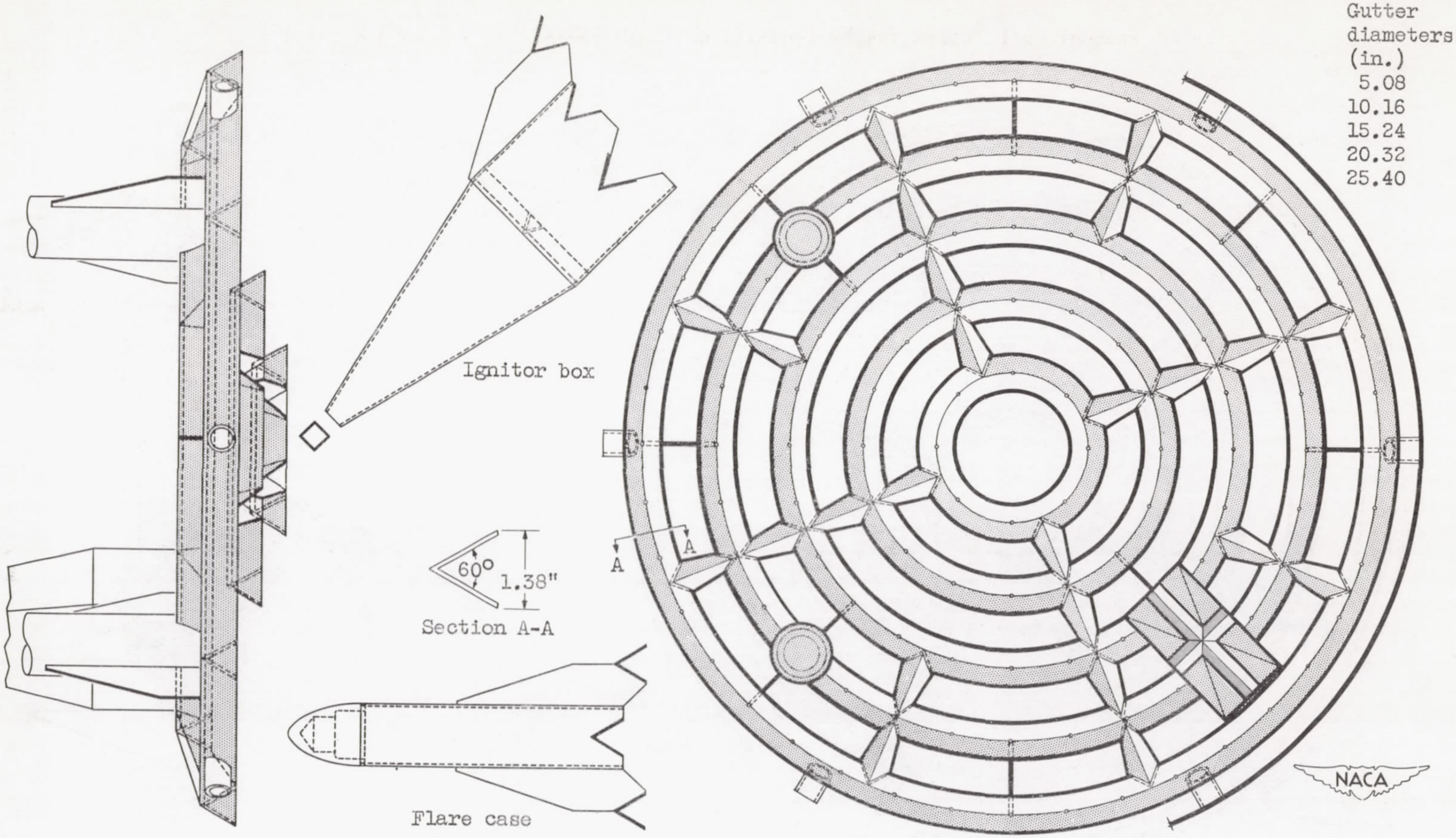
(e) Flame holder 5; blocked area, 60 percent; gutter width, 2.00 inches.

Figure 4. - Continued. Schematic diagrams of flame holders.



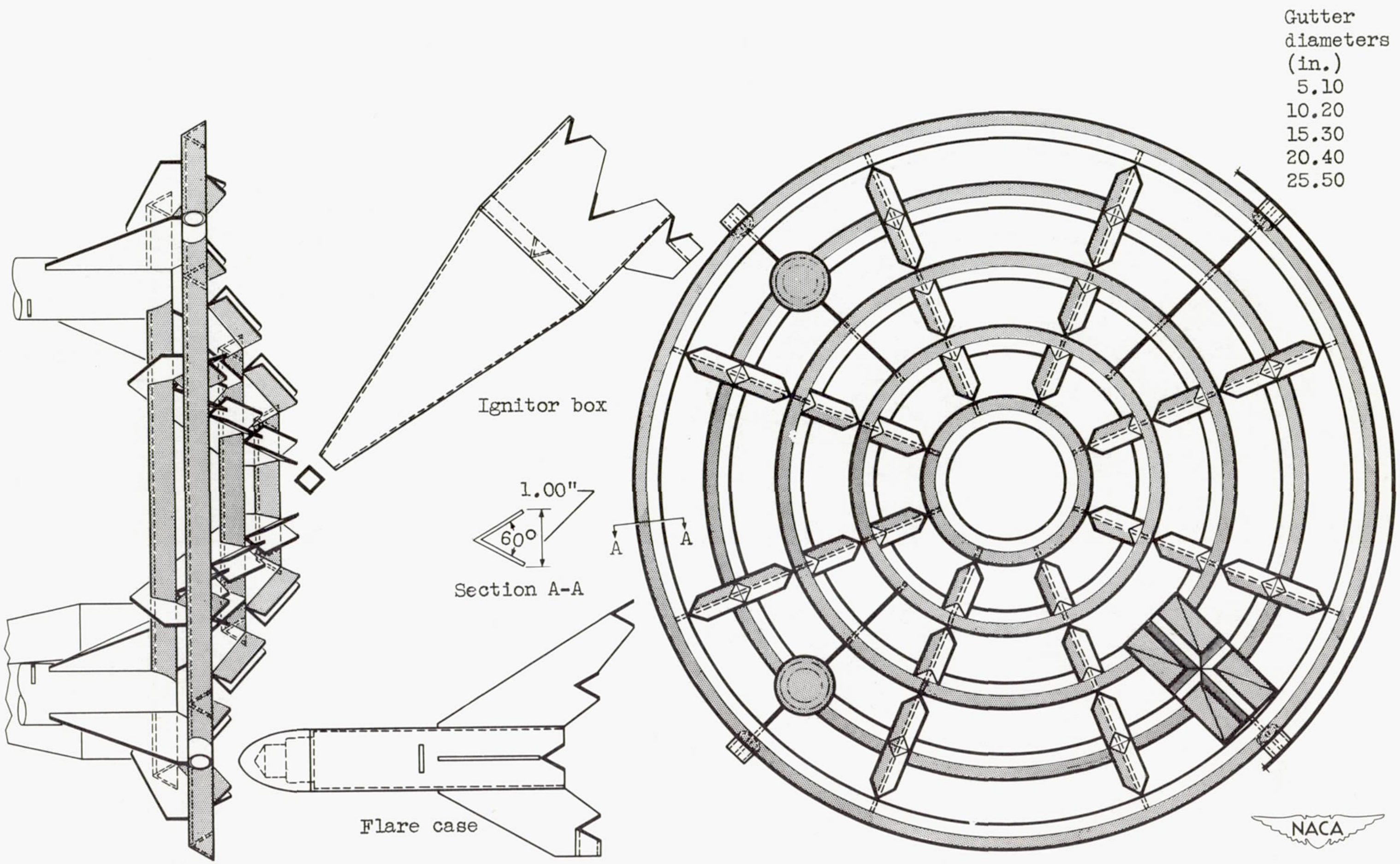
(f) Flame holder 6; blocked area, 58 percent; gutter width, 1.20 inches.

Figure 4. - Continued. Schematic diagrams of flame holders.



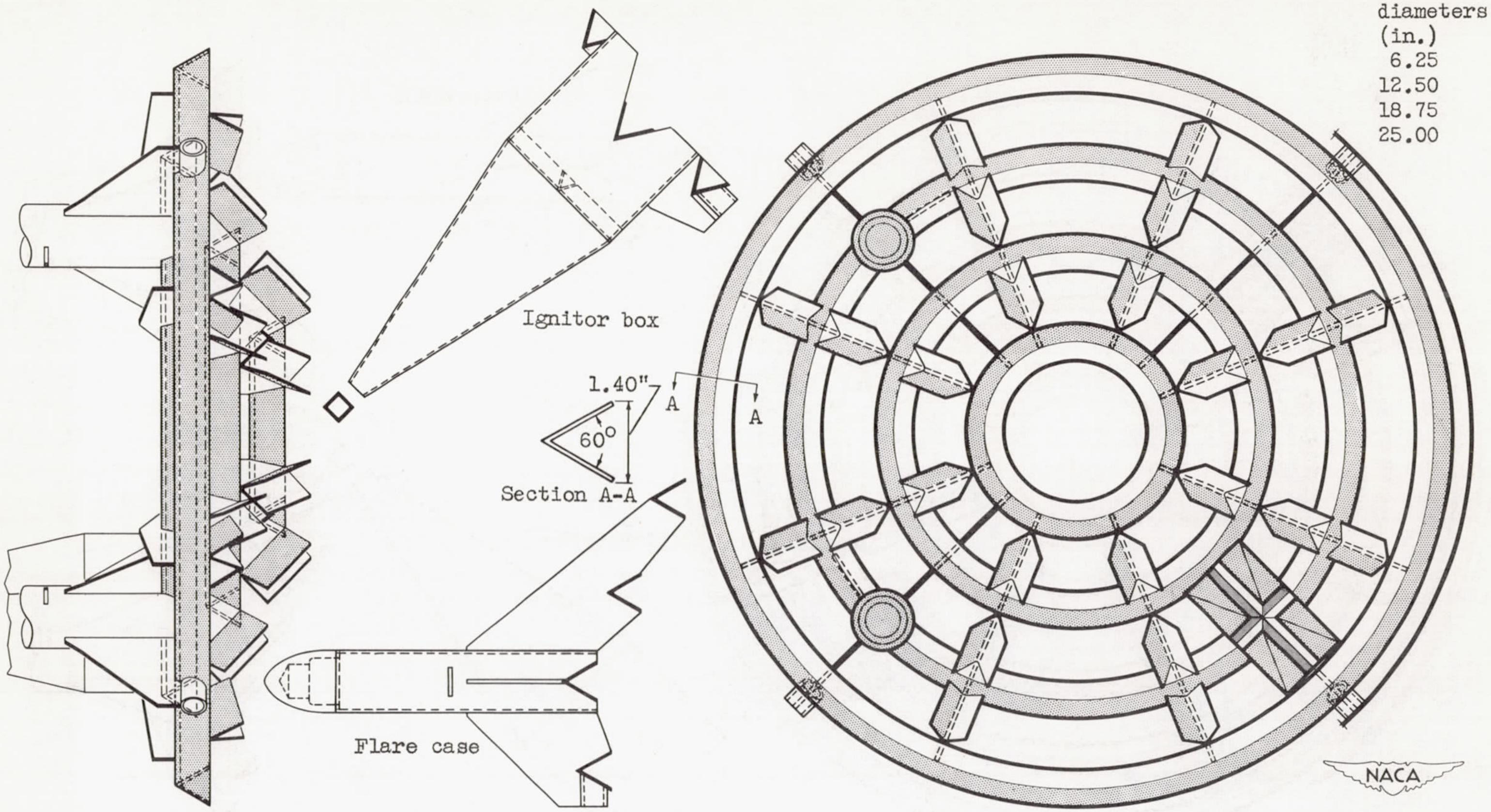
(g) Flame holder 7; blocked area, 62 percent; gutter width, 1.38 inches.

Figure 4. - Continued. Schematic diagrams of flame holders.



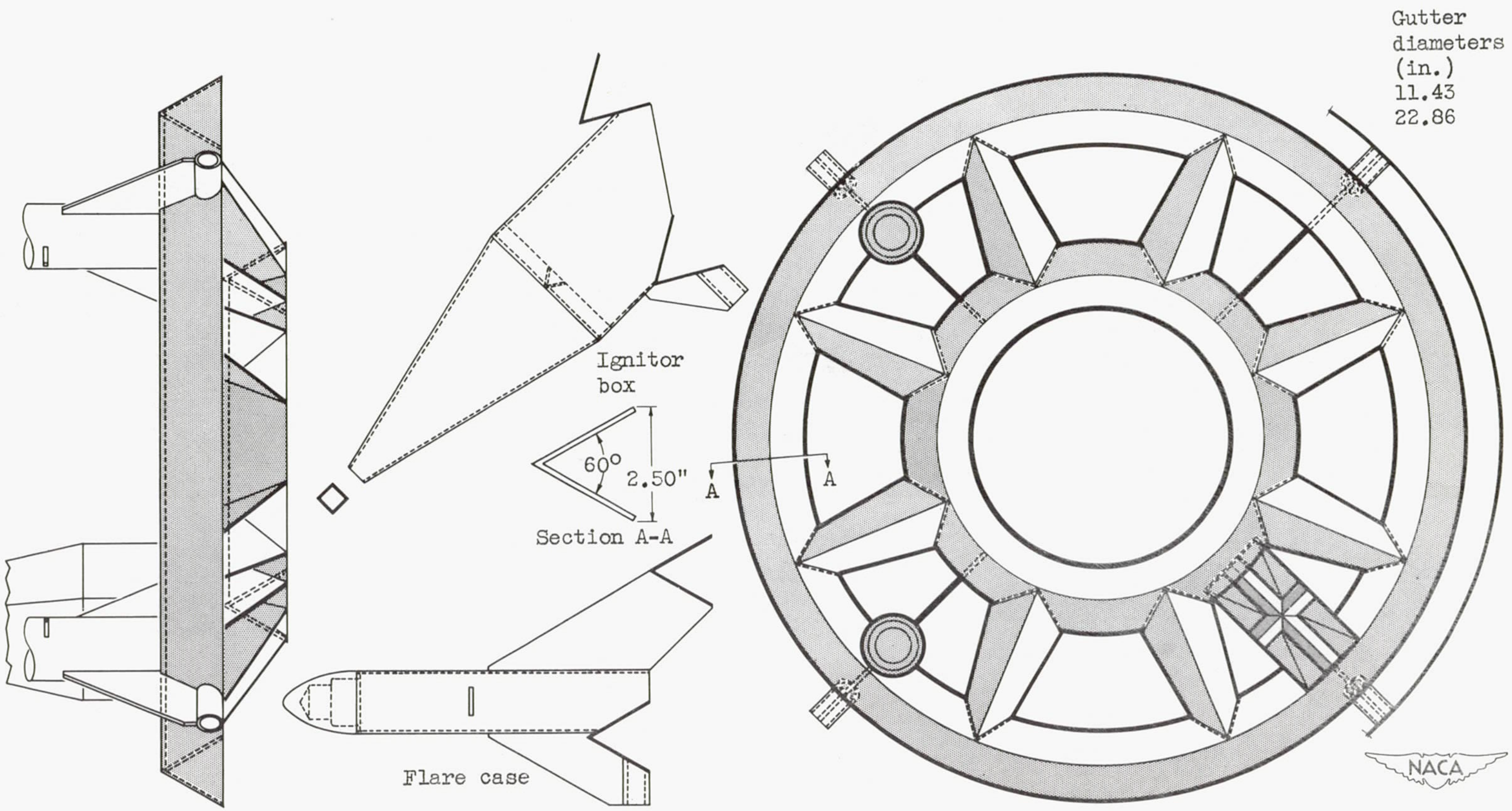
(h) Flame holder 8; blocked area, 48.7 percent; gutter width, 1.00 inch.

Figure 4. - Continued. Schematic diagrams of flame holders.



(i) Flame holder 9; blocked area, 55 percent; gutter width, 1.40 inches.

Figure 4. - Continued. Schematic diagrams of flame holders.



(j) Flame holder 10; blocked area, 60 percent; gutter width, 2.50 inches.

Figure 4. - Concluded. Schematic diagrams of flame holders.

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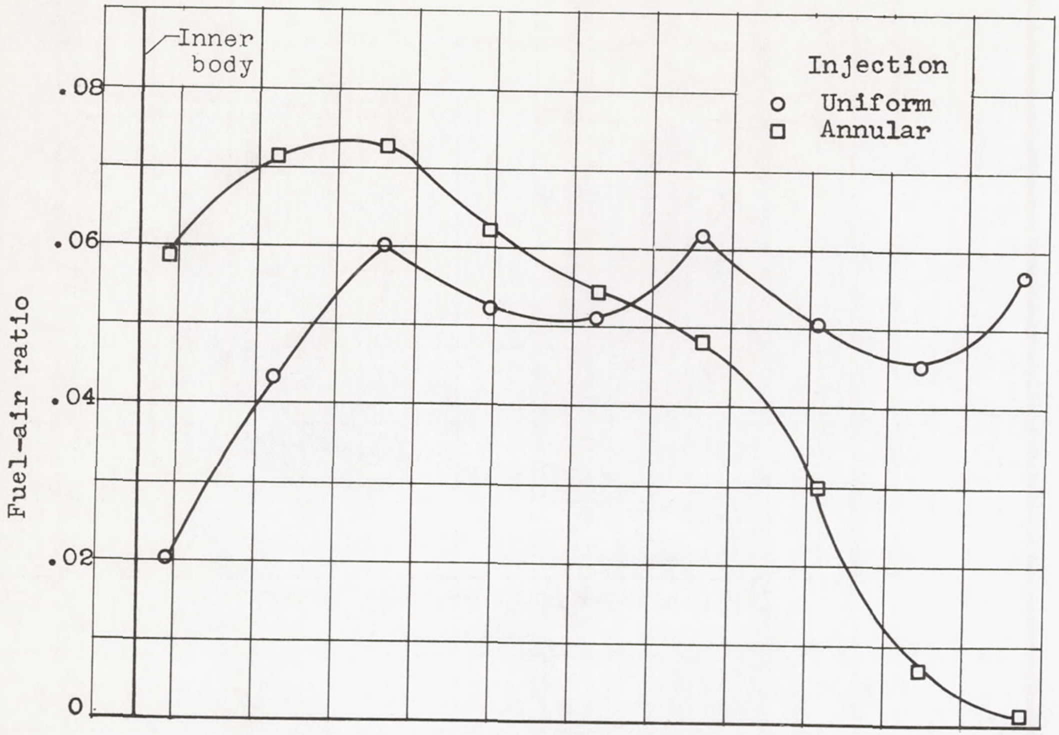
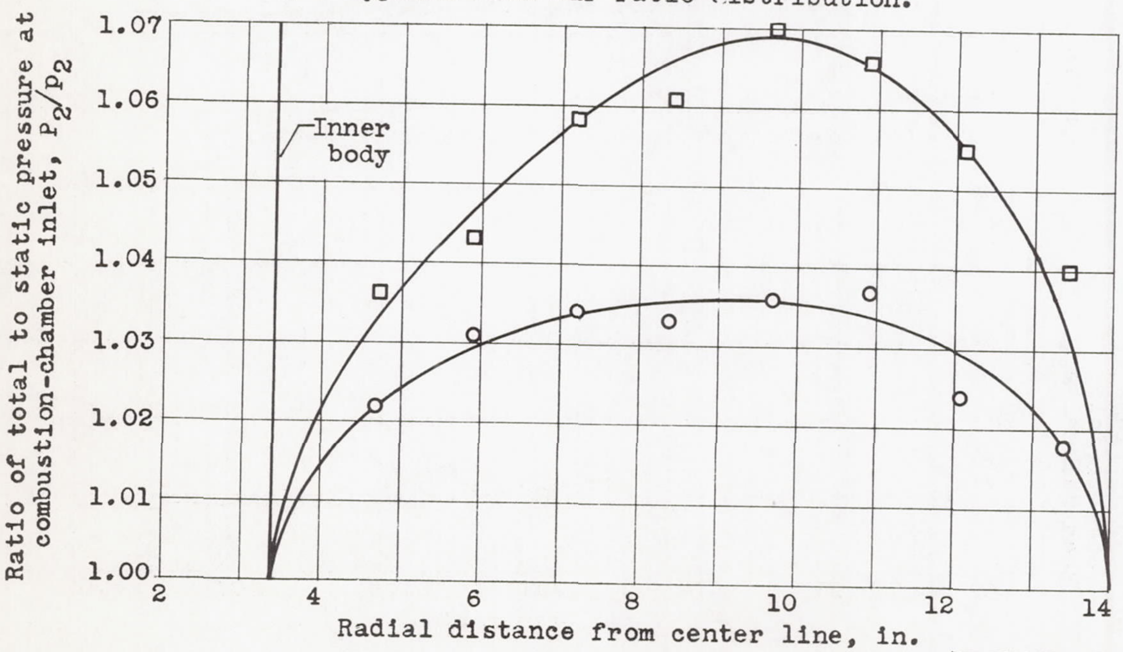
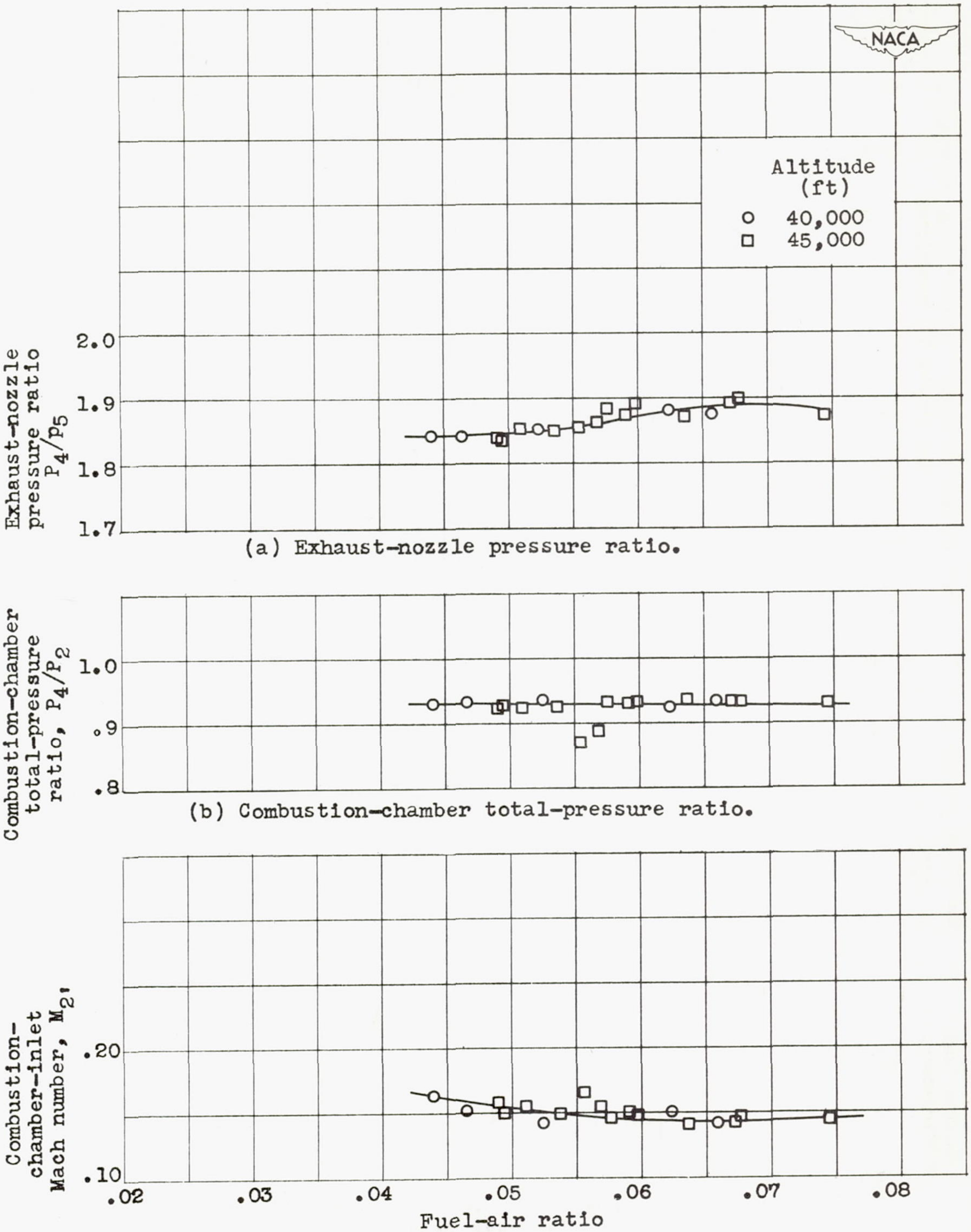


(a) Typical fuel-air ratio distribution.



(b) Typical pressure-ratio distribution.

Figure 5. - Radial distribution of fuel-air ratio and pressure ratio at combustion-chamber inlet.



(c) Combustion-chamber-inlet Mach number.

Figure 6. - Performance curves for flame holder 1. Gutter width, 1.00 inch; blocked area, 42.0 percent; uniform injection only.

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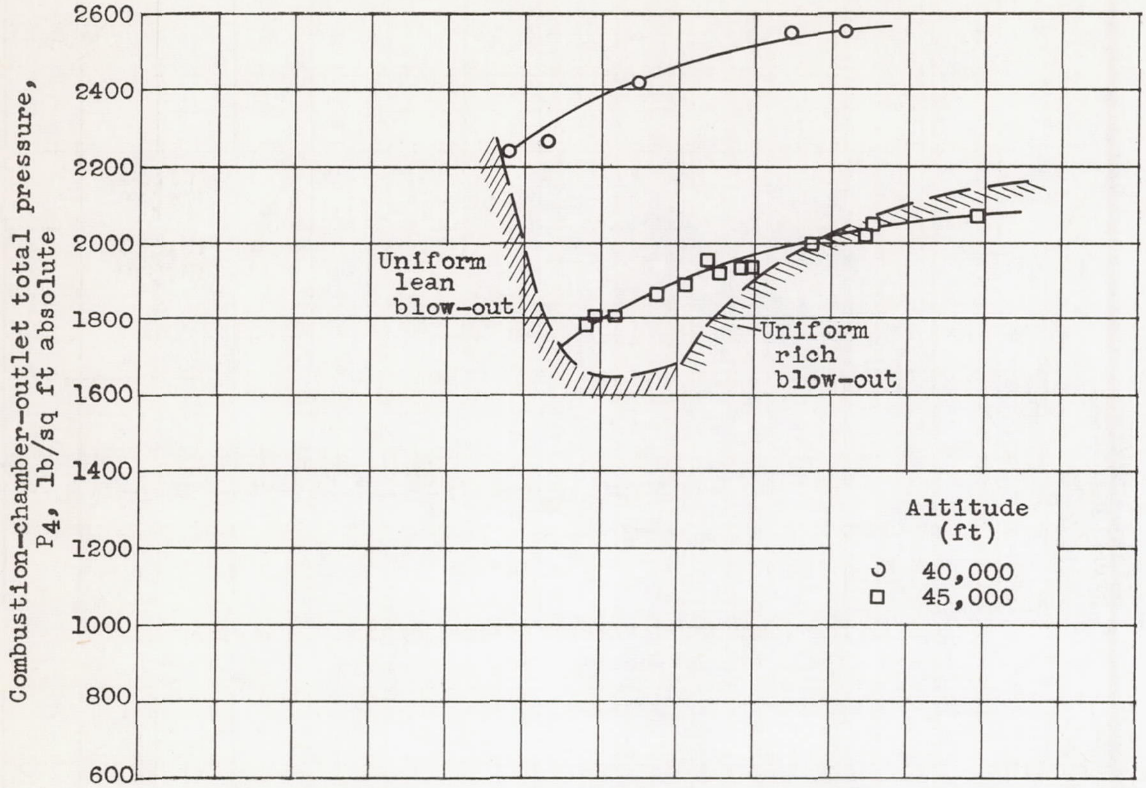
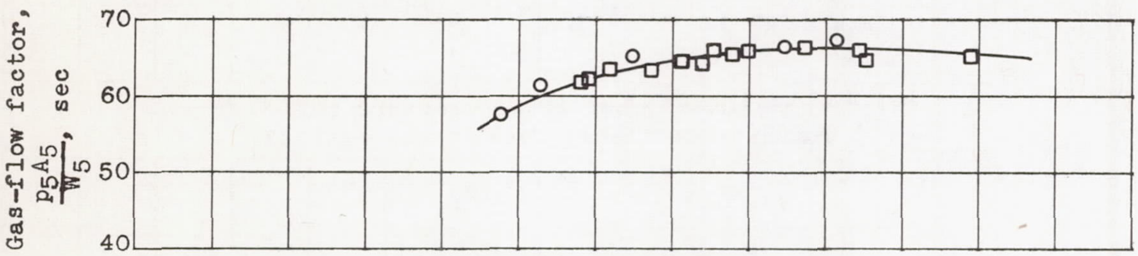
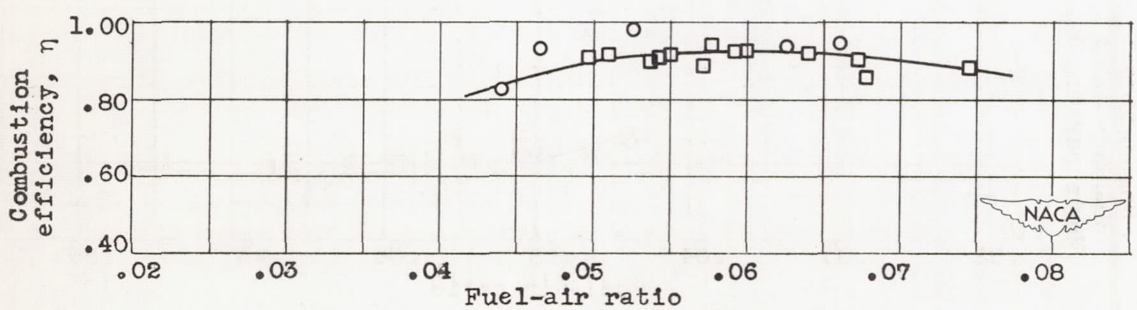


(d) Combustion-chamber-outlet pressure and blow-out limits.

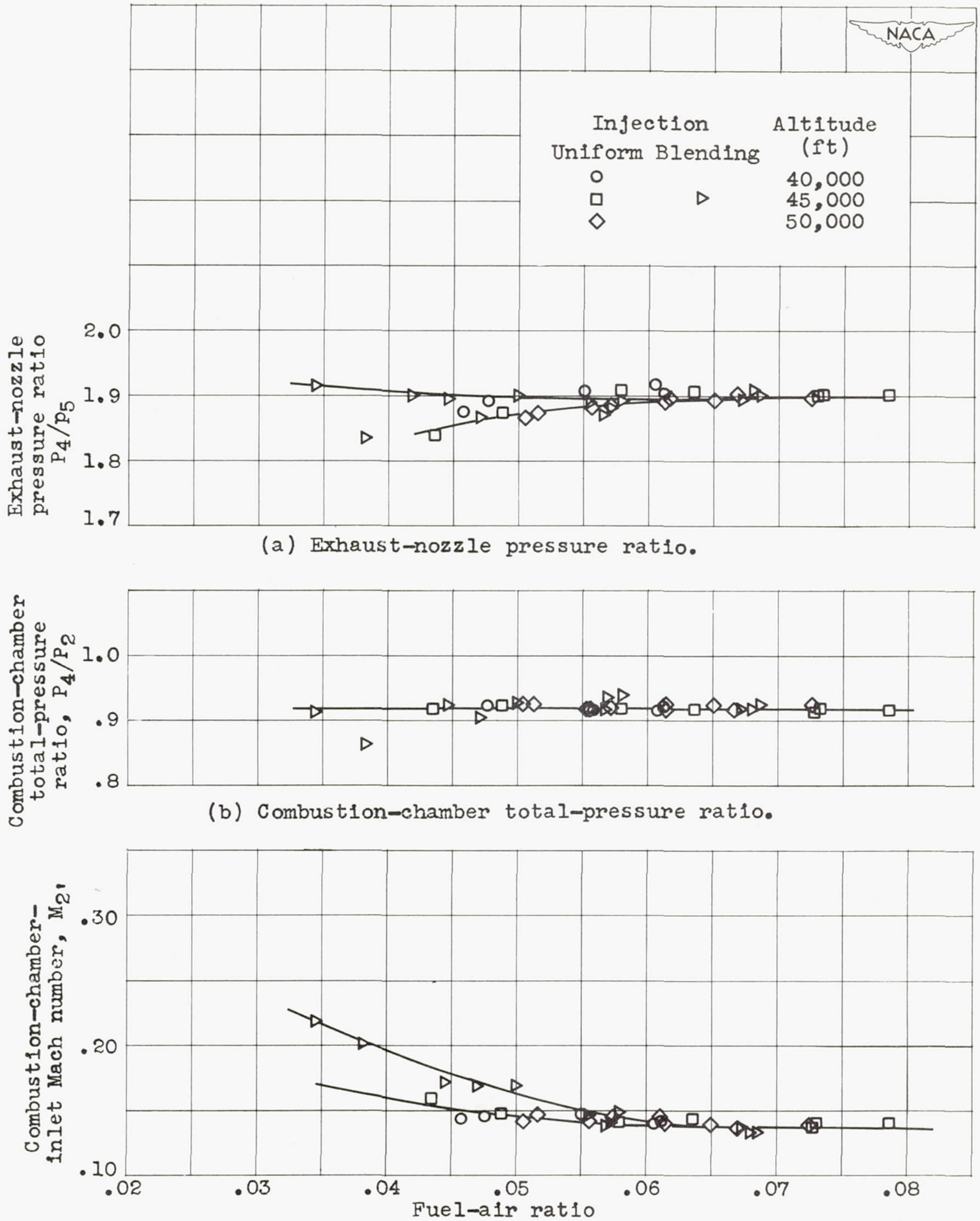


(e) Gas-flow factor.



(f) Combustion efficiency.

Figure 6. - Concluded. Performance curves for flame holder 1. Gutter width, 1.00 inch; blocked area, 42.0 percent; uniform injection only.



(a) Exhaust-nozzle pressure ratio.

(b) Combustion-chamber total-pressure ratio.

(c) Combustion-chamber-inlet Mach number.

Figure 7. - Performance curves for flame holder 2. Gutter width, 1.00 inch; blocked area, 55.0 percent.

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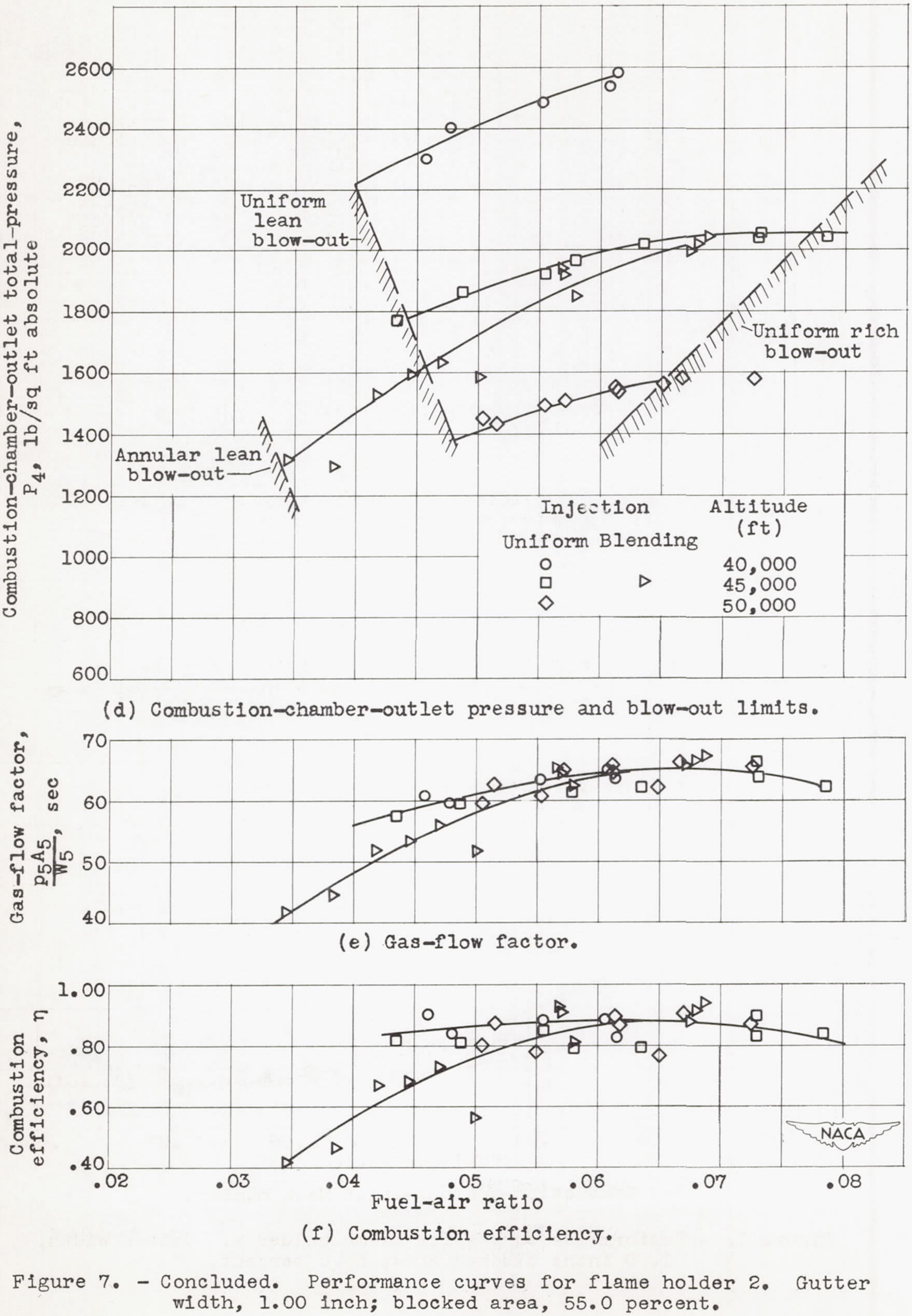

Figure 7. - Concluded. Performance curves for flame holder 2. Gutter width, 1.00 inch; blocked area, 55.0 percent.

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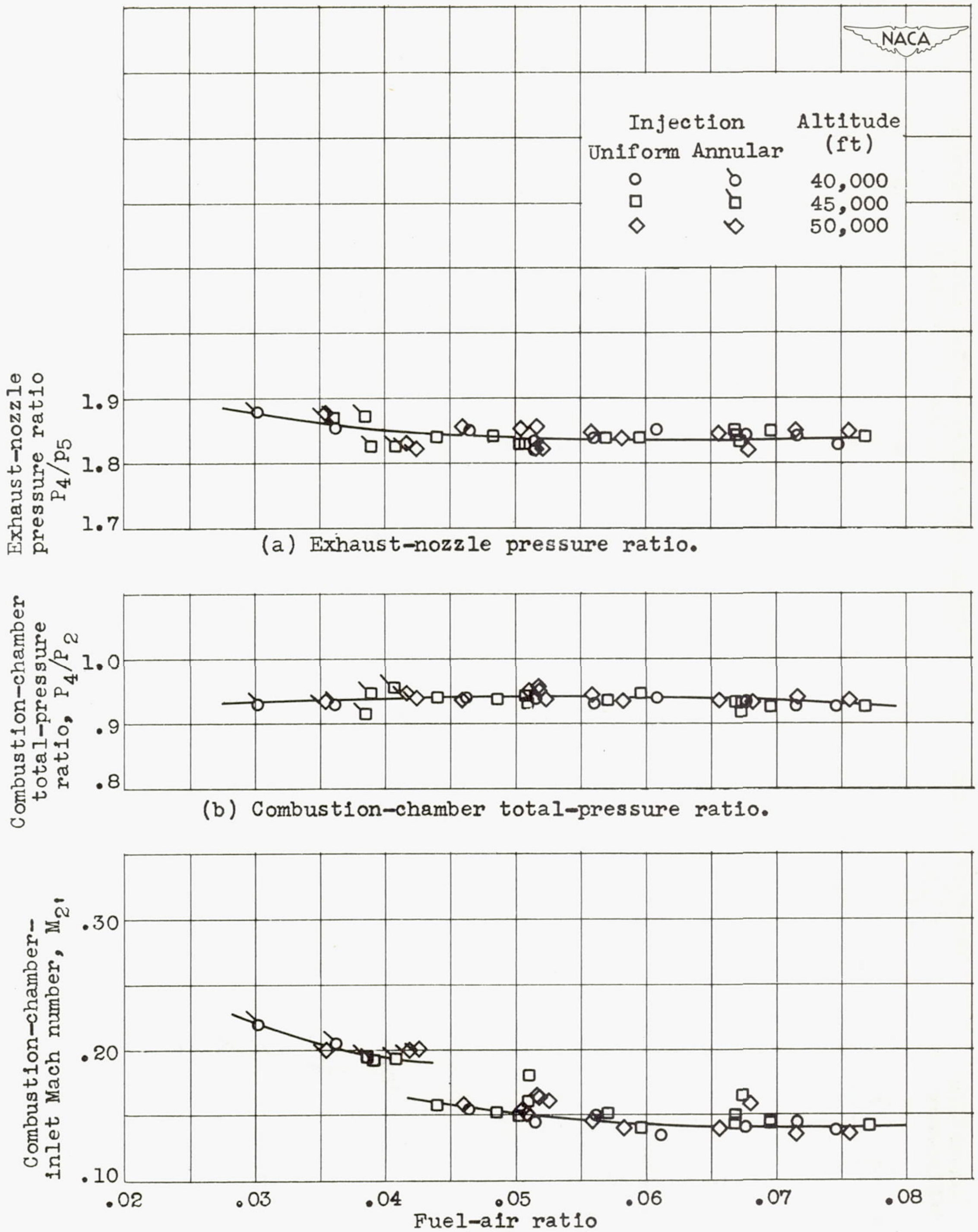

(a) Exhaust-nozzle pressure ratio.

(b) Combustion-chamber total-pressure ratio.

(c) Combustion-chamber-inlet Mach number.

Figure 8. - Performance curves for flame holder 3. Gutter width, 2.00 inches; blocked area, 45.0 percent.

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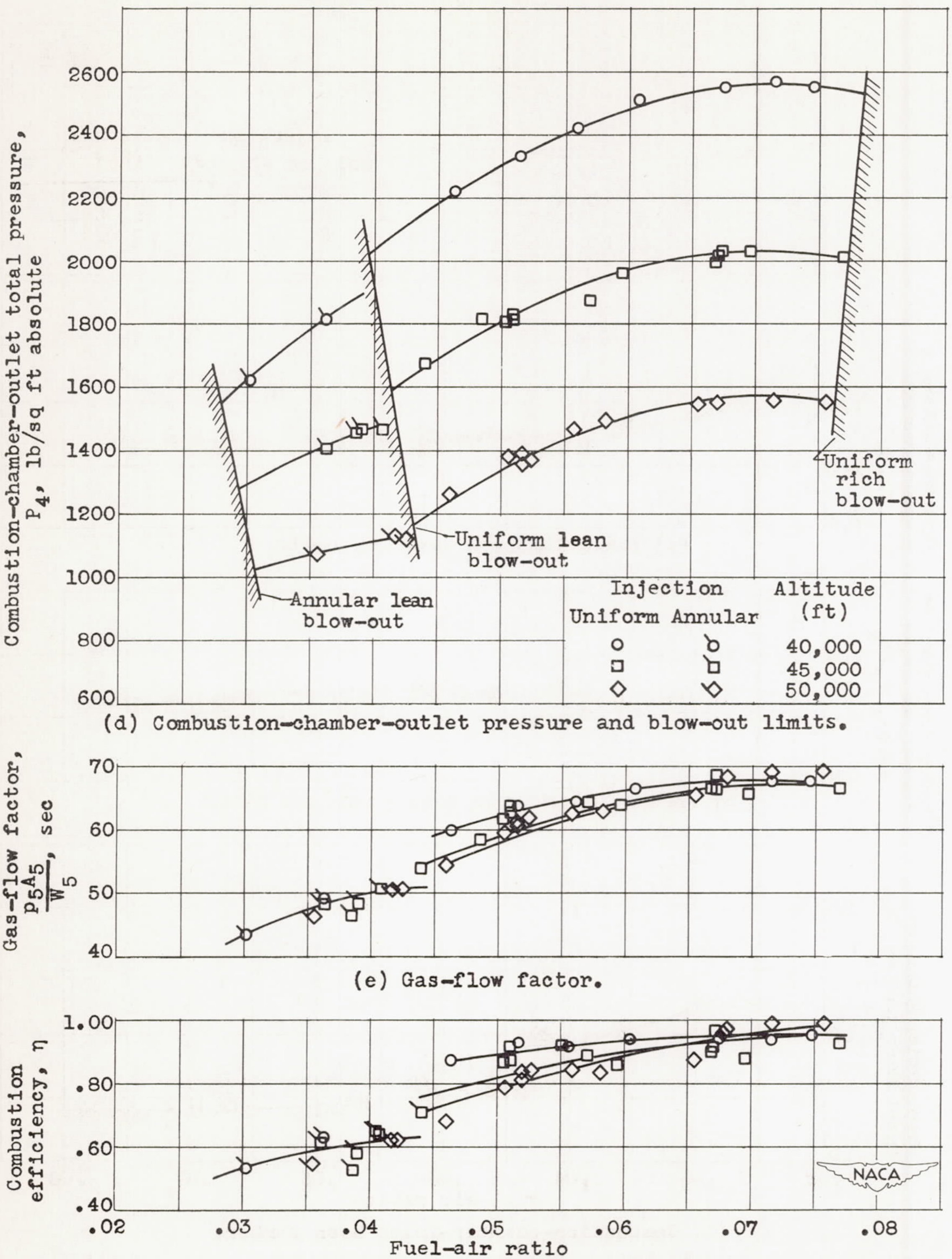

(d) Combustion-chamber-outlet pressure and blow-out limits.

(e) Gas-flow factor.

(f) Combustion efficiency.

Figure 8. - Concluded. Performance curves for flame holder 3. Gutter width, 2.00 inches; blocked area, 45.0 percent.

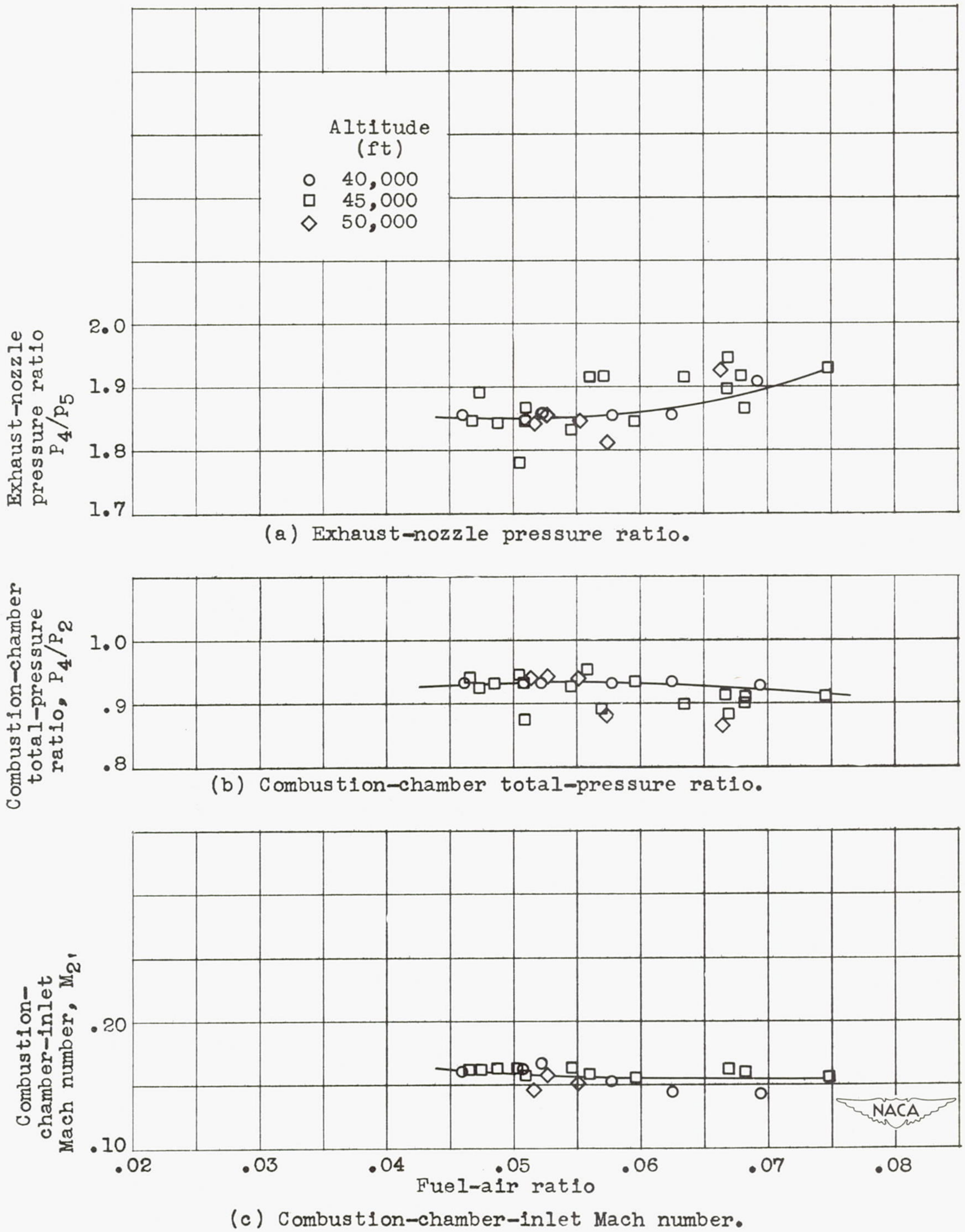

Figure 9. - Performance curves for flame holder 4. Gutter width, 1.50 inches; blocked area, 40.5 percent; uniform injection only.

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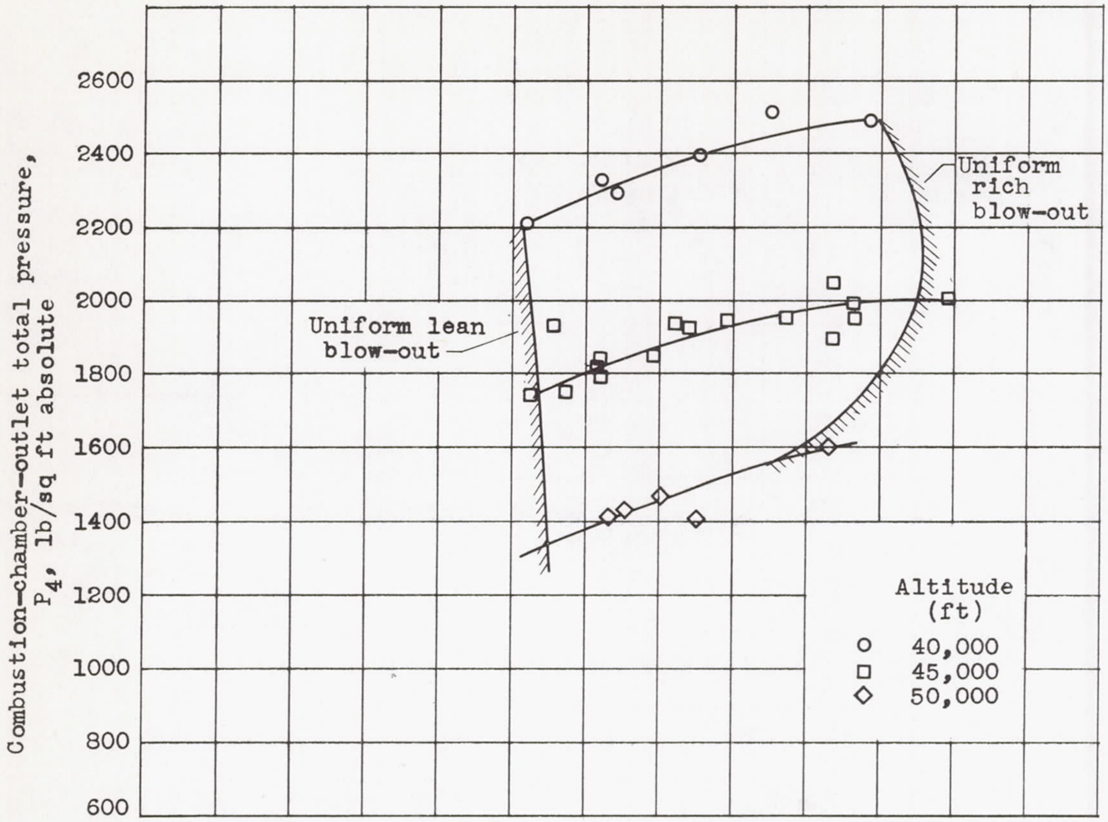
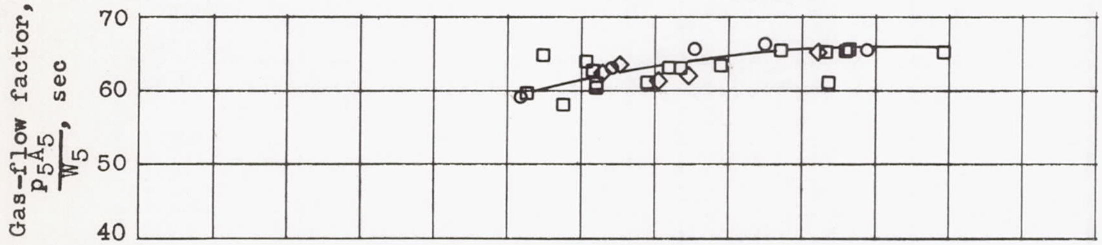
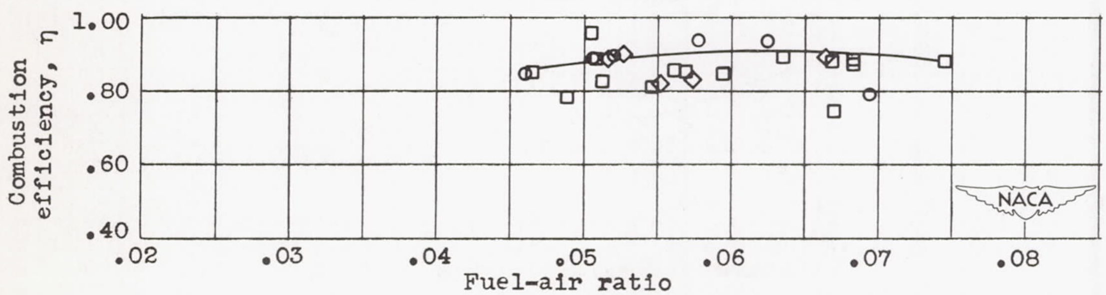


(d) Combustion-chamber-outlet pressure and blow-out limits.



(e) Gas-flow factor.



(f) Combustion efficiency.

Figure 9. - Concluded. Performance curves for flame holder 4. Gutter width, 1.50 inches; blocked area, 40.5 percent; uniform injection only.

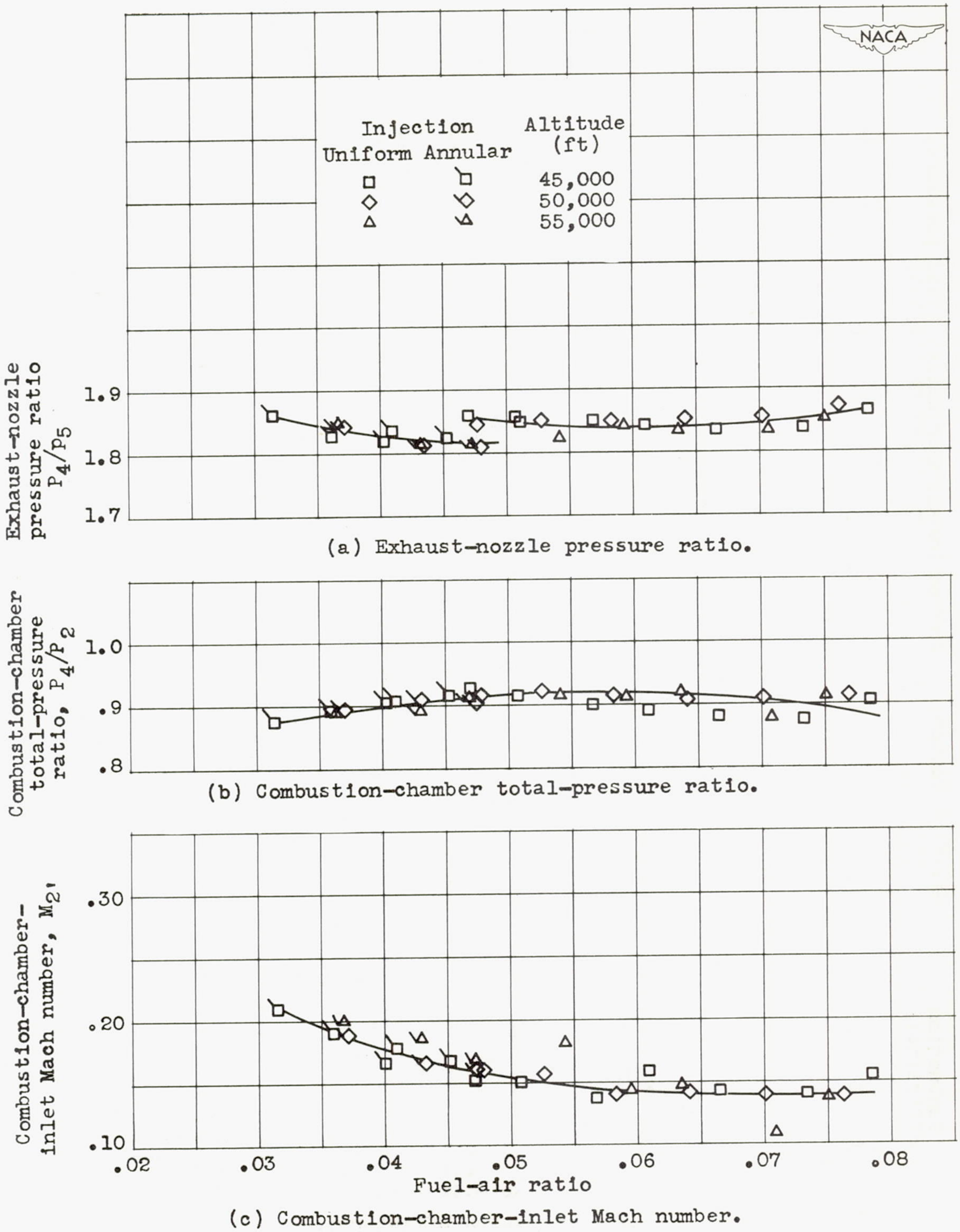


Figure 10. - Performance curves for flame holder 5. Gutter width, 2.00 inches; blocked area, 60.0 percent.

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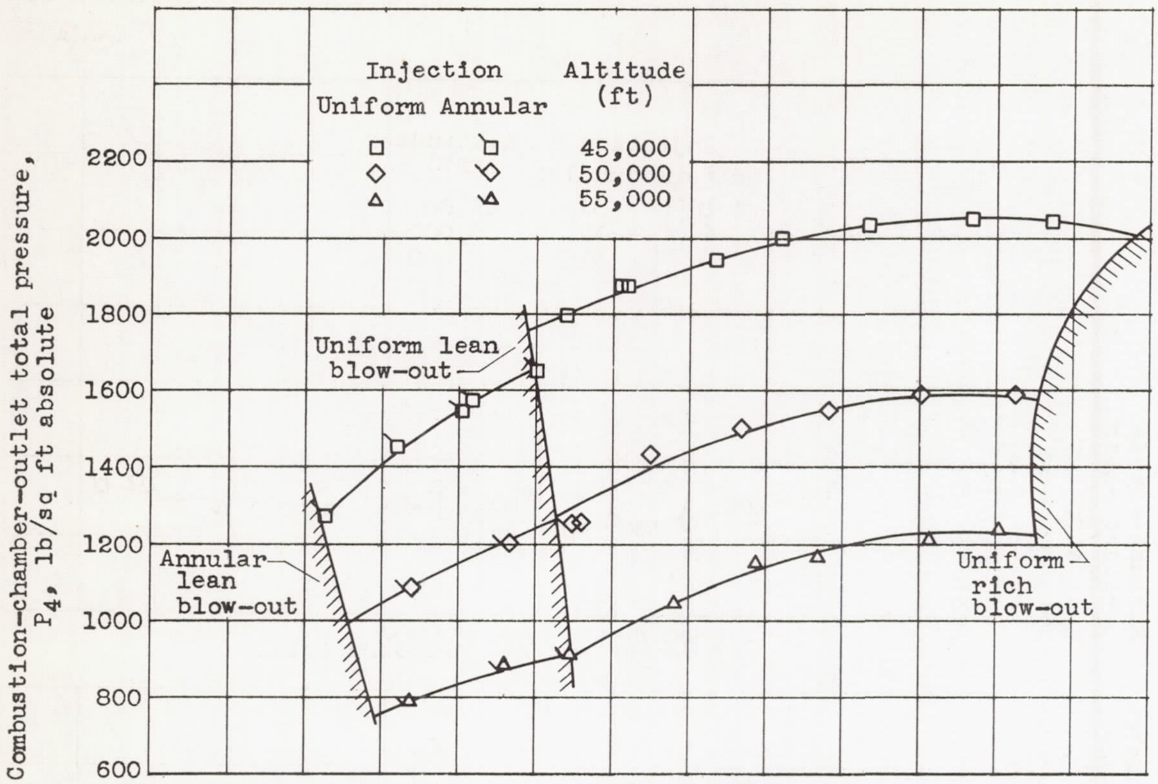
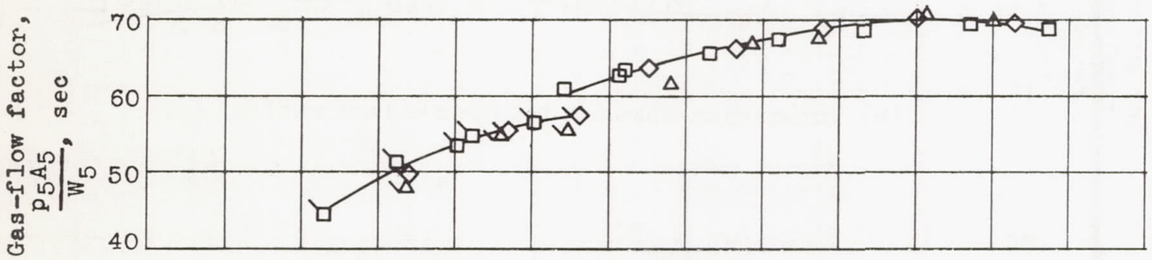
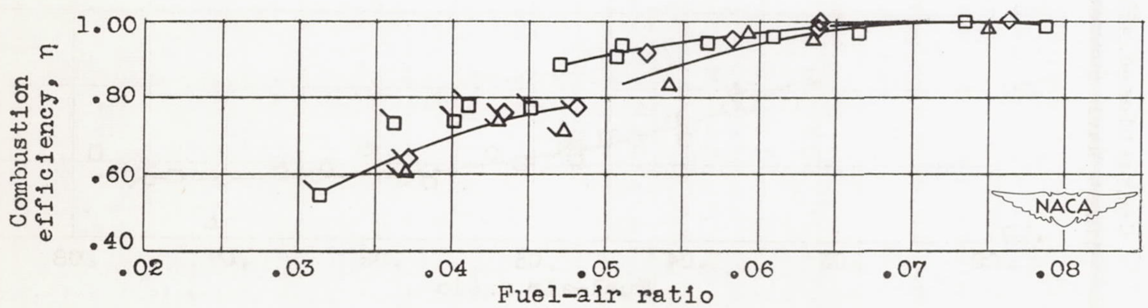


(d) Combustion-chamber-outlet pressure and blow-out limits.

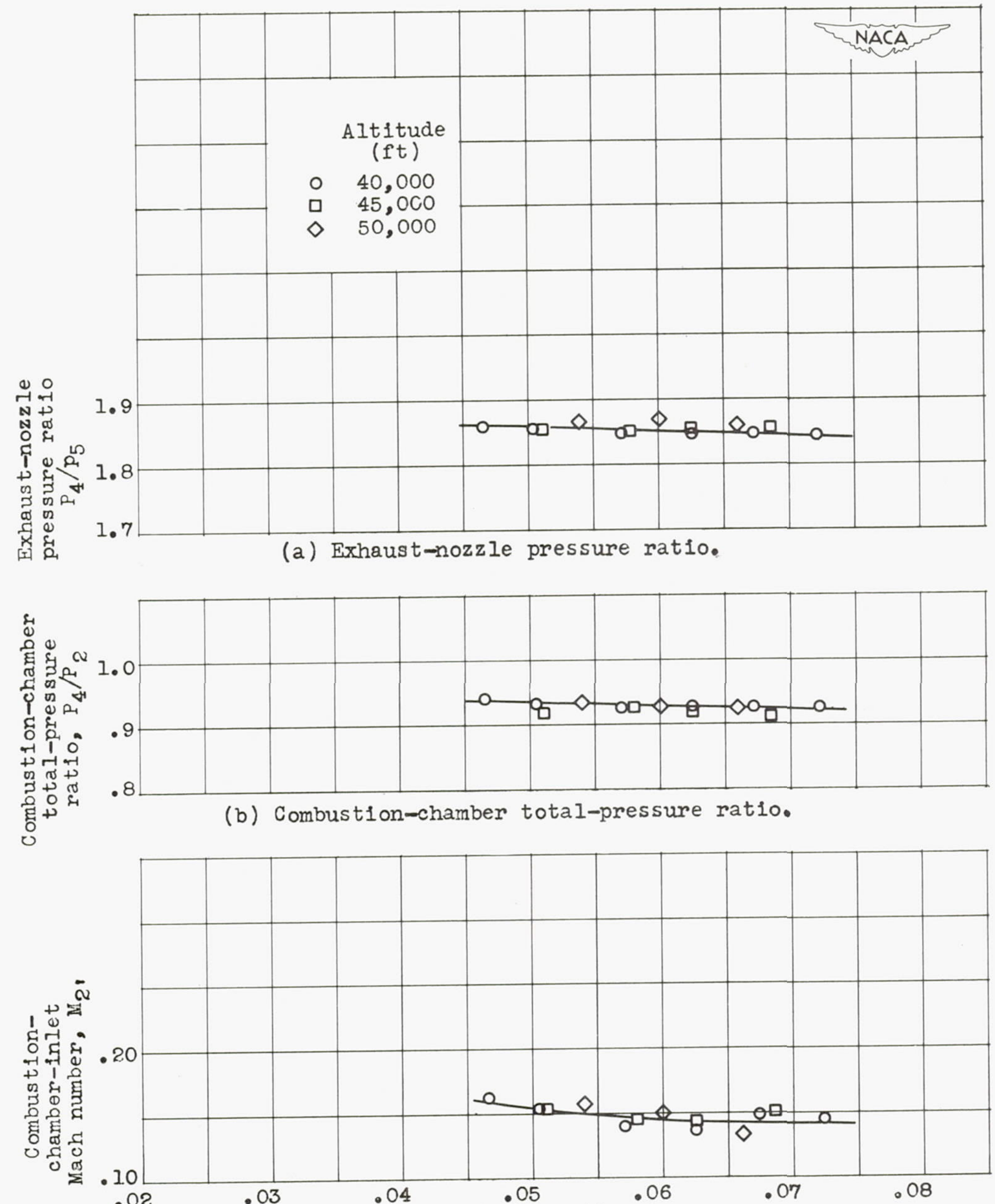


(e) Gas-flow factor.



(f) Combustion efficiency.

Figure 10. - Concluded. Performance curves for flame holder 5. Gutter width, 2.00 inches; blocked area, 60.0 percent.



(c) Combustion-chamber-inlet Mach number.

Figure 11. - Performance curves for flame holder 6. Gutter width, 1.20 inches; blocked area, 58.0 percent; uniform injection only.

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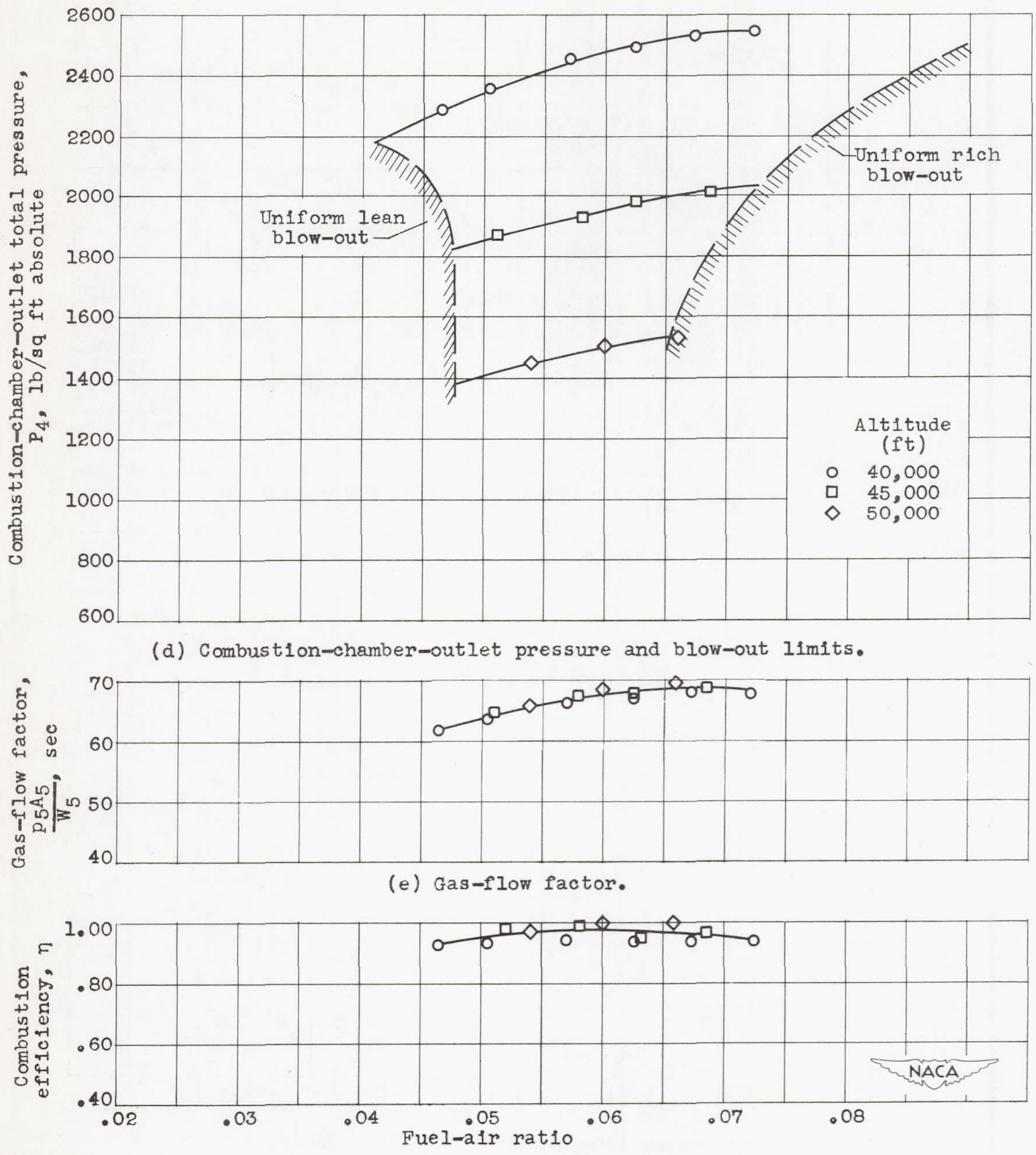

Figure 11. - Concluded. Performance curves for flame holder 6. Gutter width, 1.20 inches; blocked area, 58.0 percent; uniform injection only.

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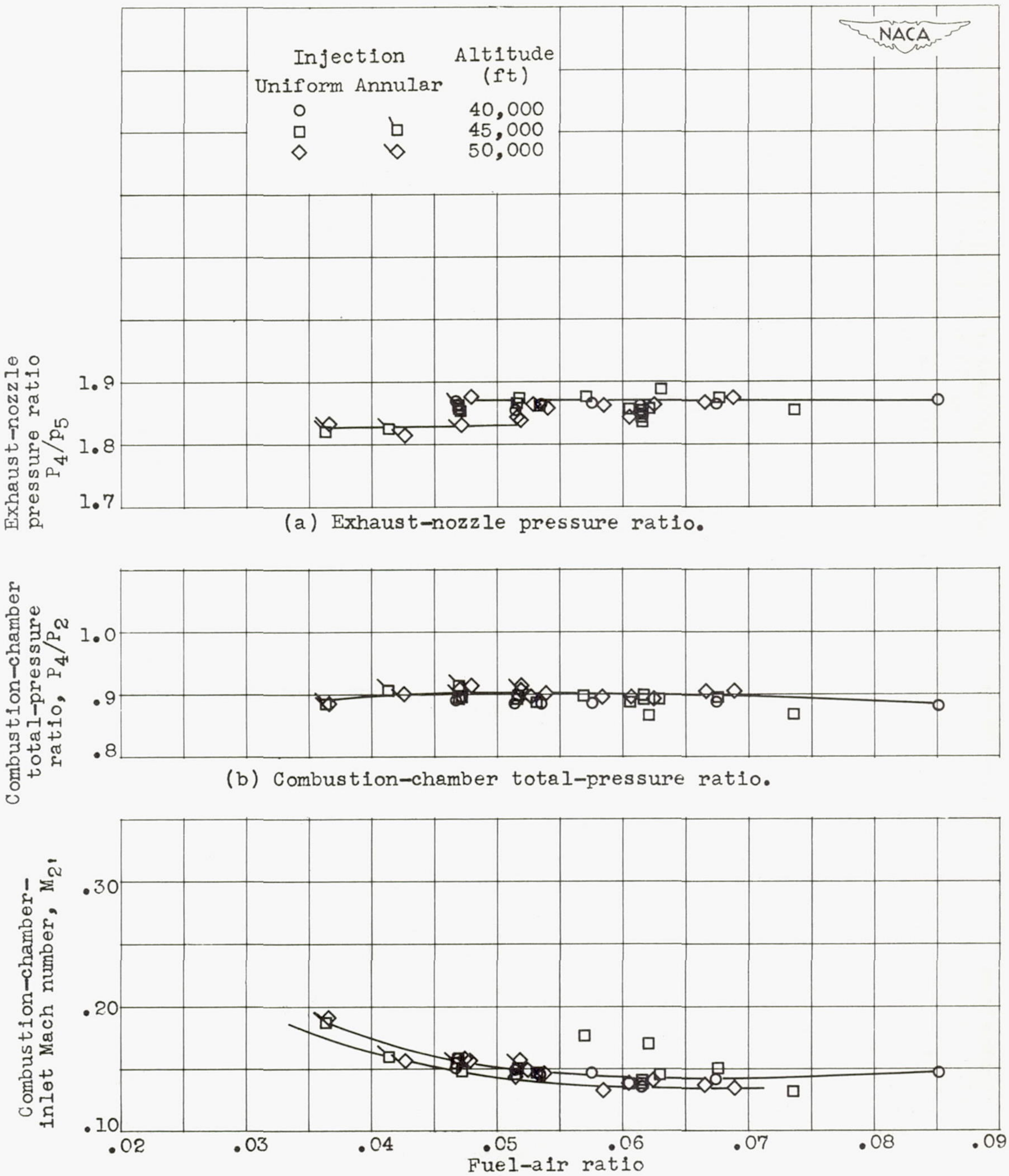
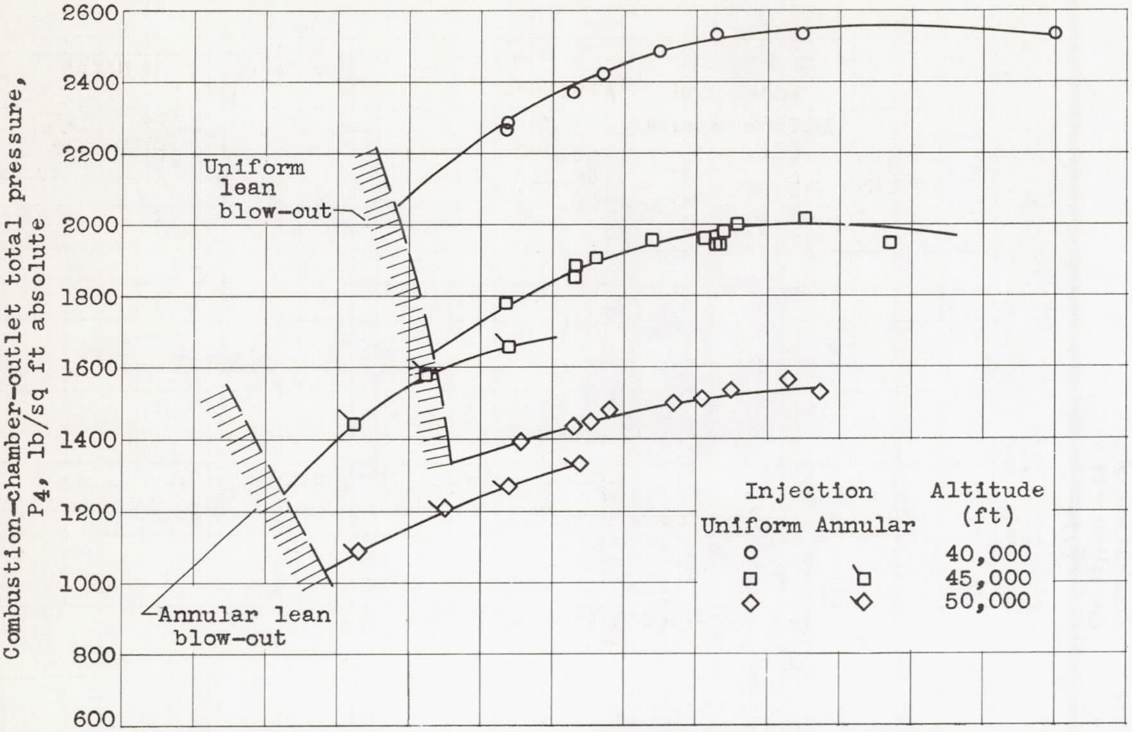


(a) Exhaust-nozzle pressure ratio.

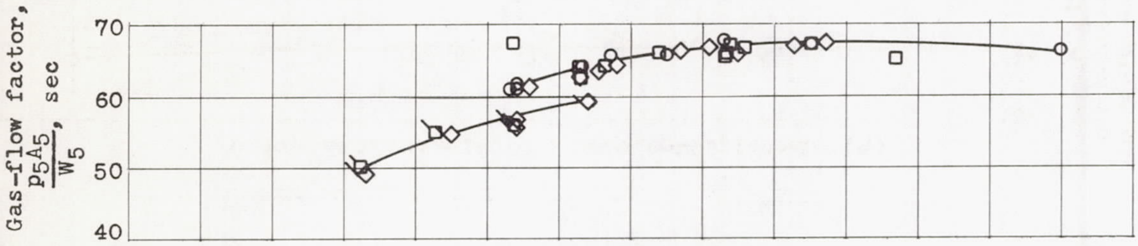
(b) Combustion-chamber total-pressure ratio.

(c) Combustion-chamber-inlet Mach number.

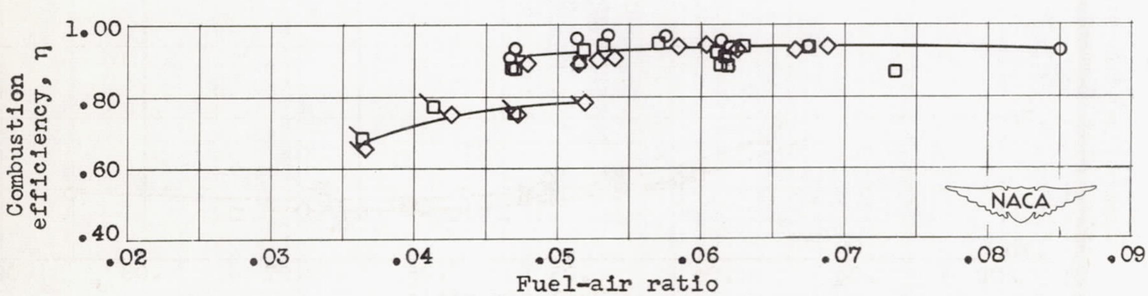
Figure 12. - Performance curves for flame holder 7. Gutter width, 1.38 inches; blocked area, 62.0 percent.



(d) Combustion-chamber-outlet pressure and blow-out limits.

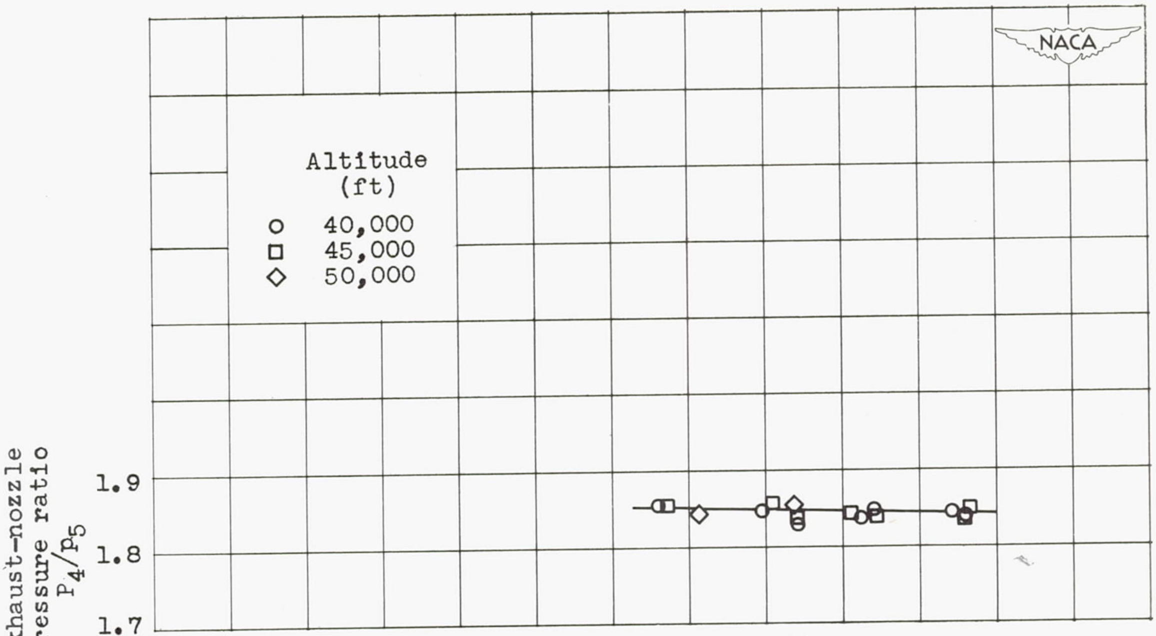


(e) Gas-flow factor.

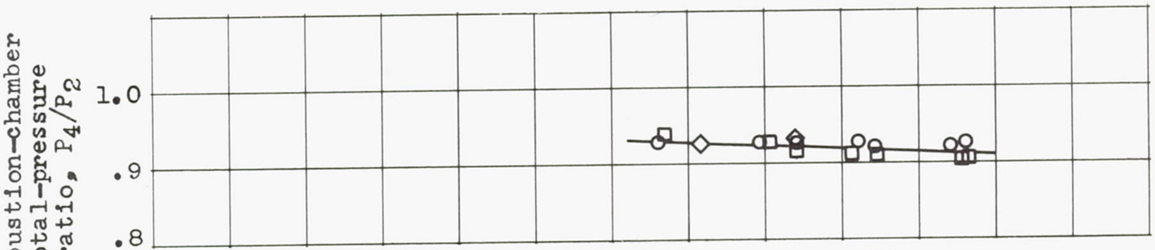


(f) Combustion efficiency.

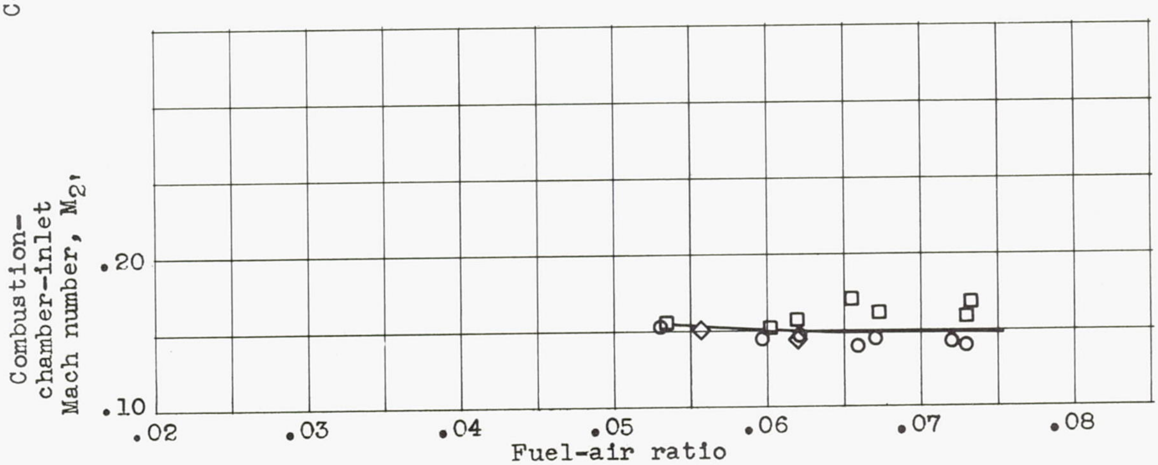
Figure 12. - Concluded. Performance curves for flame holder 7. Gutter width, 1.38 inches; blocked area, 62.0 percent.



(a) Exhaust-nozzle pressure ratio.



(b) Combustion-chamber total-pressure ratio.



(c) Combustion-chamber-inlet Mach number.

Figure 13. - Performance curves for flame holder 8. Gutter width, 1.00 inch; blocked area, 48.7 percent; uniform injection only.

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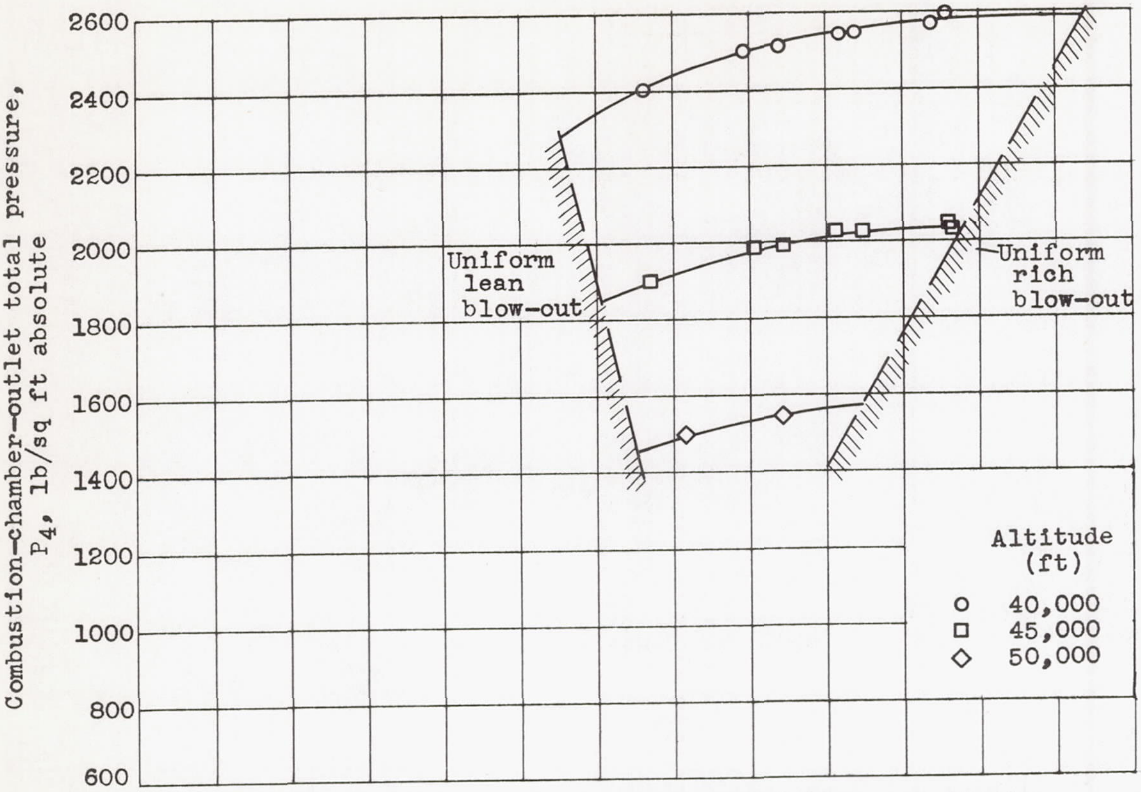
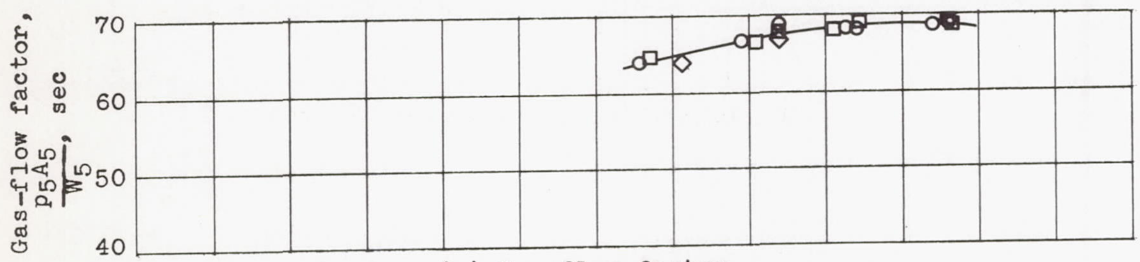
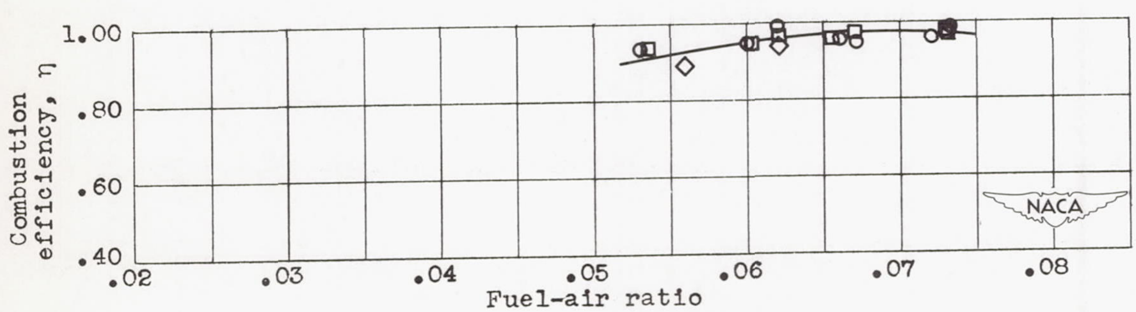


(d) Combustion-chamber-outlet pressure and blow-out limits.

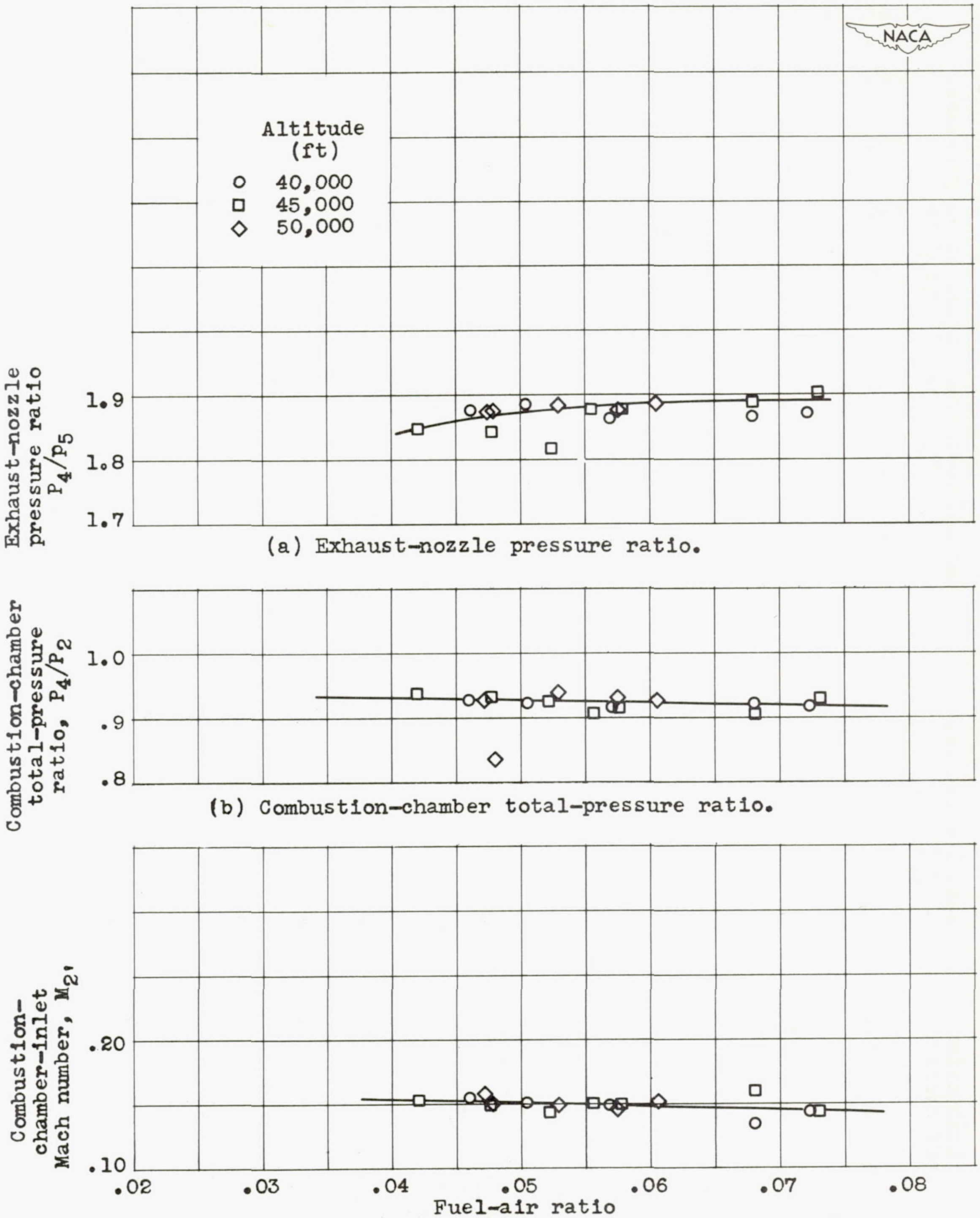


(e) Gas-flow factor.



(f) Combustion efficiency.

Figure 13. - Concluded. Performance curves for flame holder 8. Gutter width, 1.00 inch; blocked area, 48.7 percent; uniform injection only.



(c) Combustion-chamber-inlet Mach number.

Figure 14. - Performance curves for flame holder 9. Gutter width, 1.40 inches; blocked area, 55.0 percent; uniform injection only.

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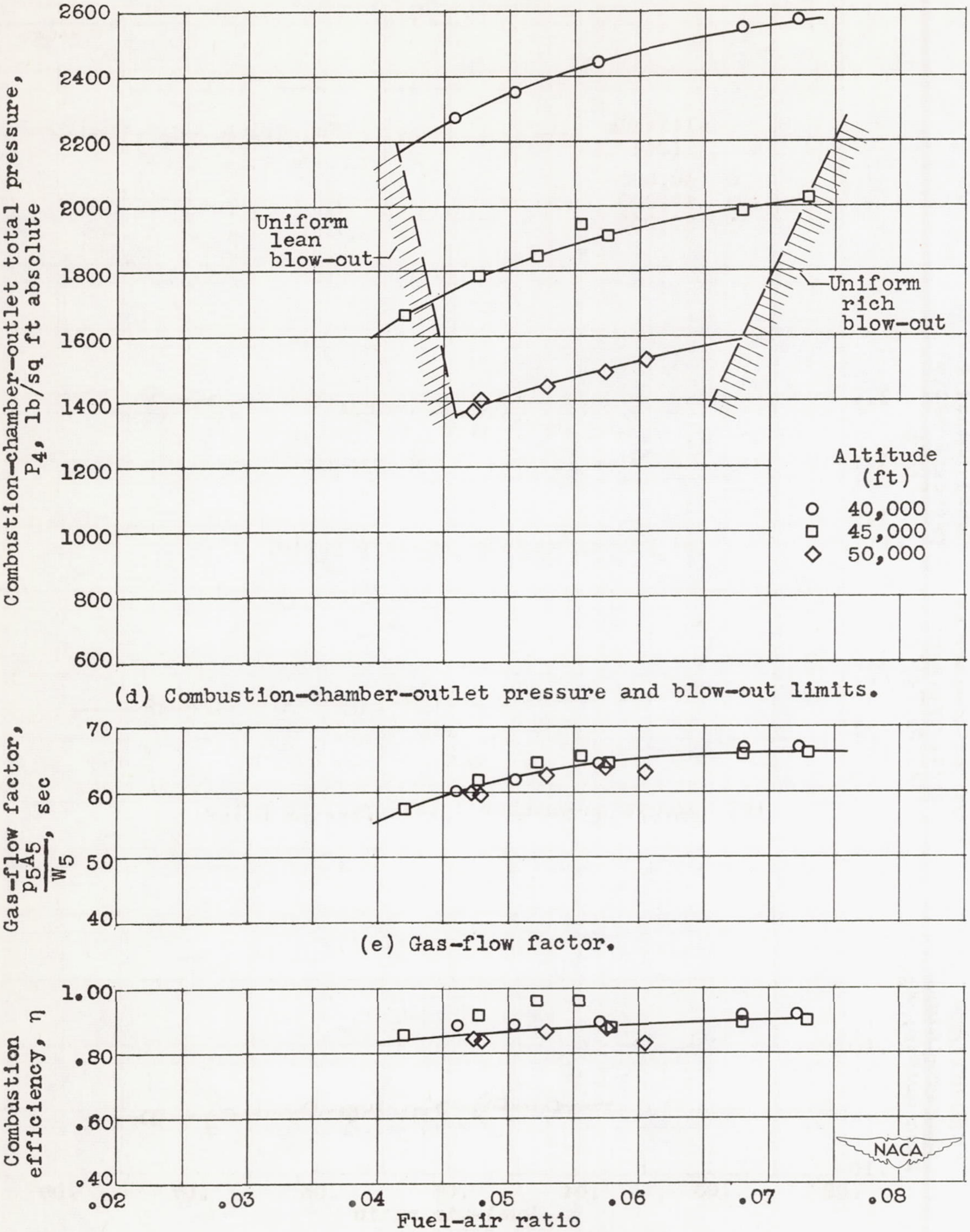

(d) Combustion-chamber-outlet pressure and blow-out limits.

(e) Gas-flow factor.

(f) Combustion efficiency.

Figure 14. - Concluded. Performance curves for flame holder 9. Gutter width, 1.40 inches; blocked area, 55.0 percent; uniform injection only.

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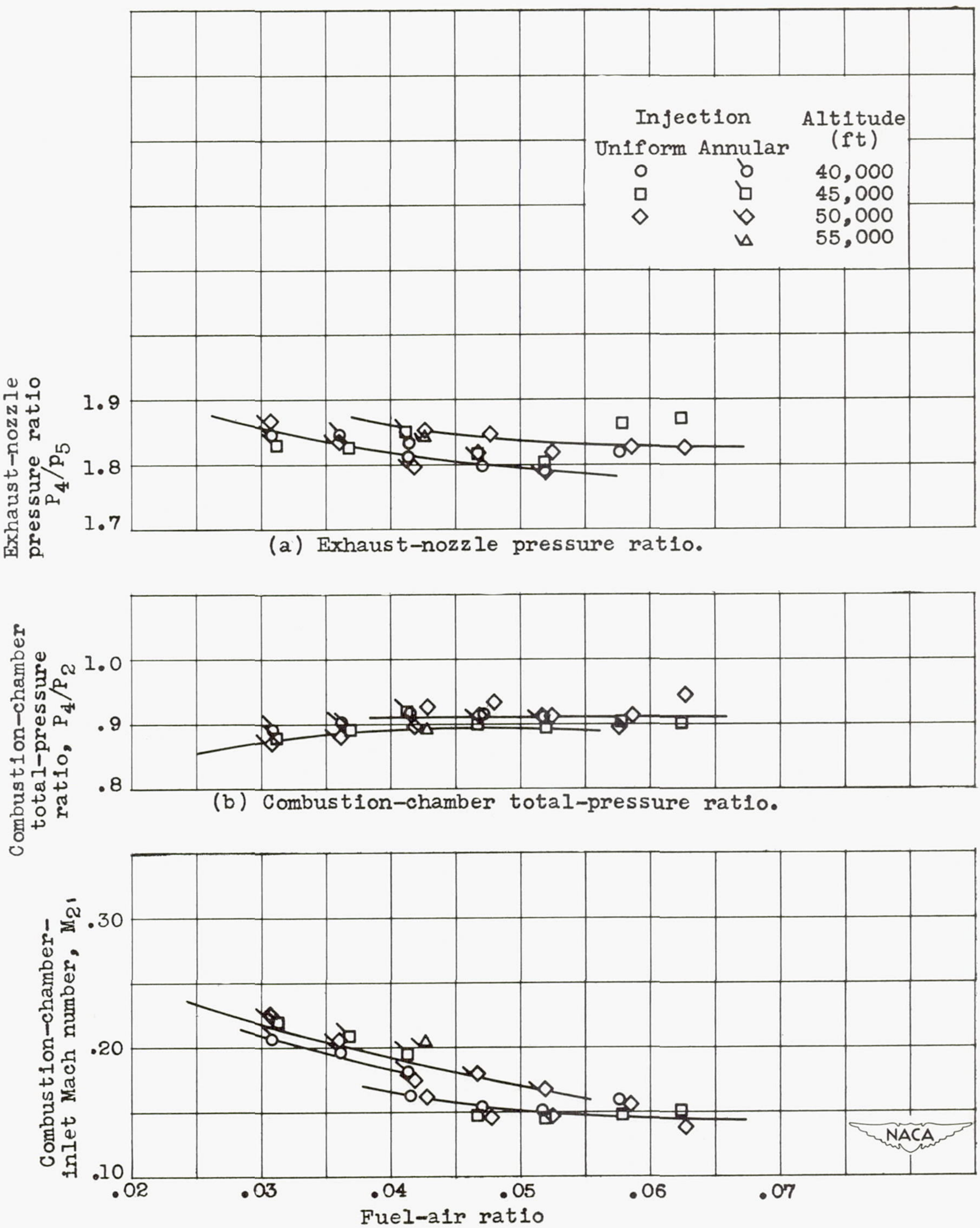

(a) Exhaust-nozzle pressure ratio.

(b) Combustion-chamber total-pressure ratio.

(c) Combustion-chamber-inlet Mach number.

Figure 15. - Performance curves for flame holder 10. Gutter width, 2.50 inches; blocked area, 60.0 percent.

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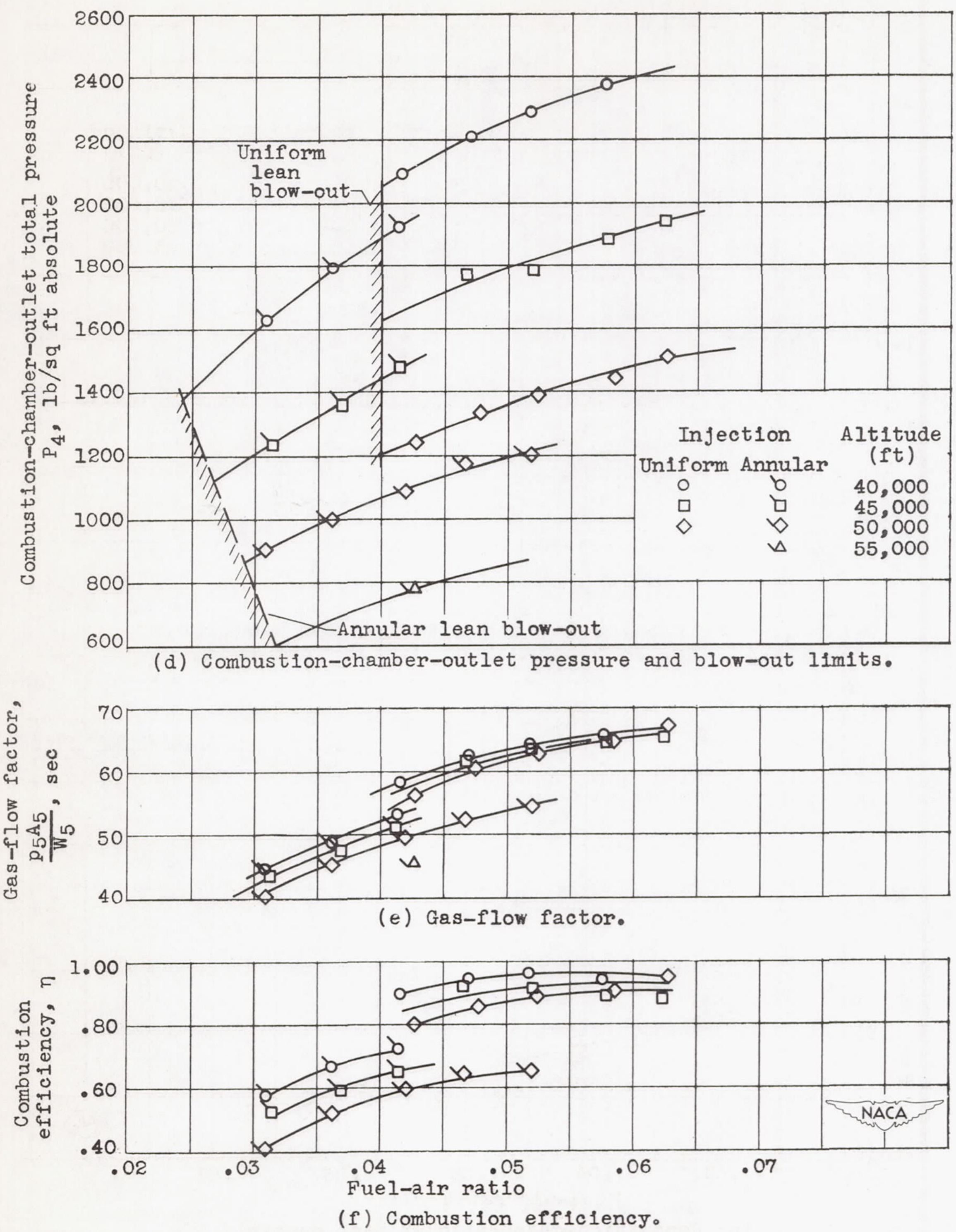
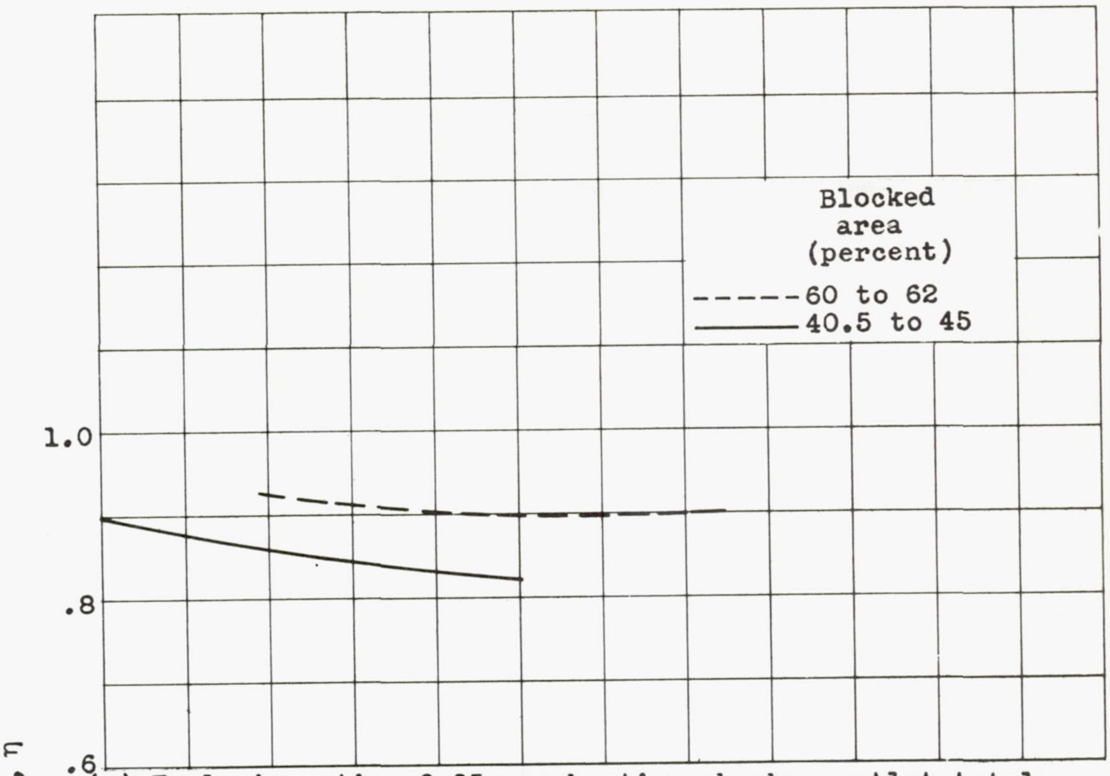
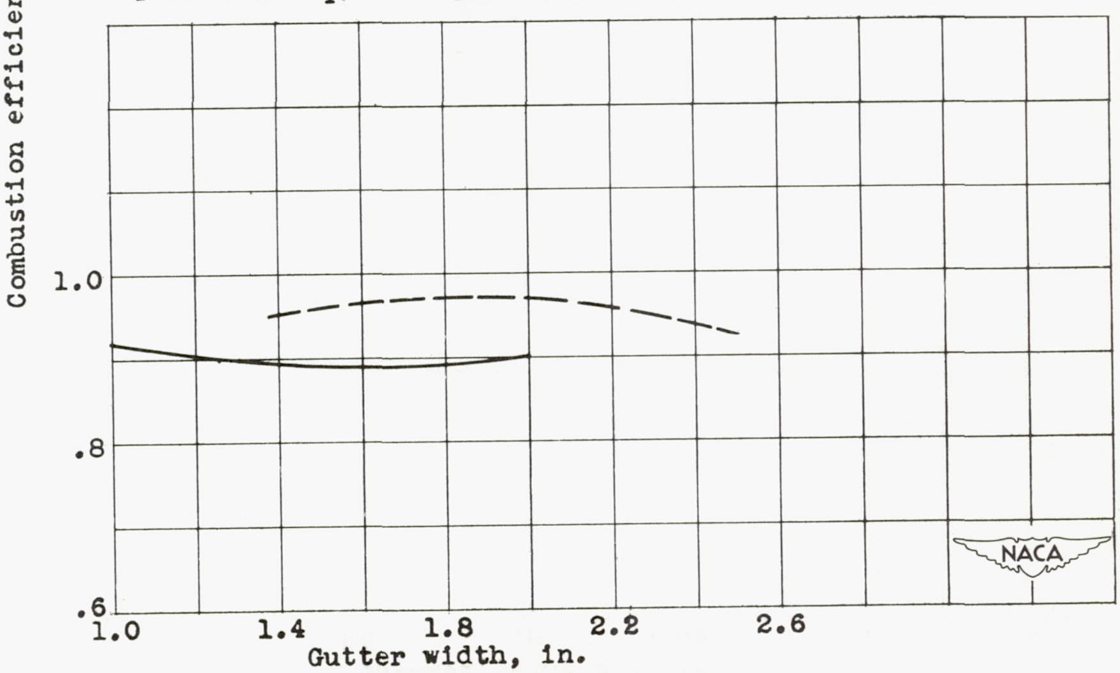


Figure 15. - Concluded. Performance curves for flame holder 10. Gutter width, 2.50 inches; blocked area, 60.0 percent.



(a) Fuel-air ratio, 0.05; combustion-chamber-outlet total pressure P_4, 1800 pounds per square foot absolute.



(b) Fuel-air ratio, 0.06; combustion-chamber-outlet total pressure P_4, 2000 pounds per square foot absolute.

Figure 16. - Effect of gutter width on combustion efficiency.

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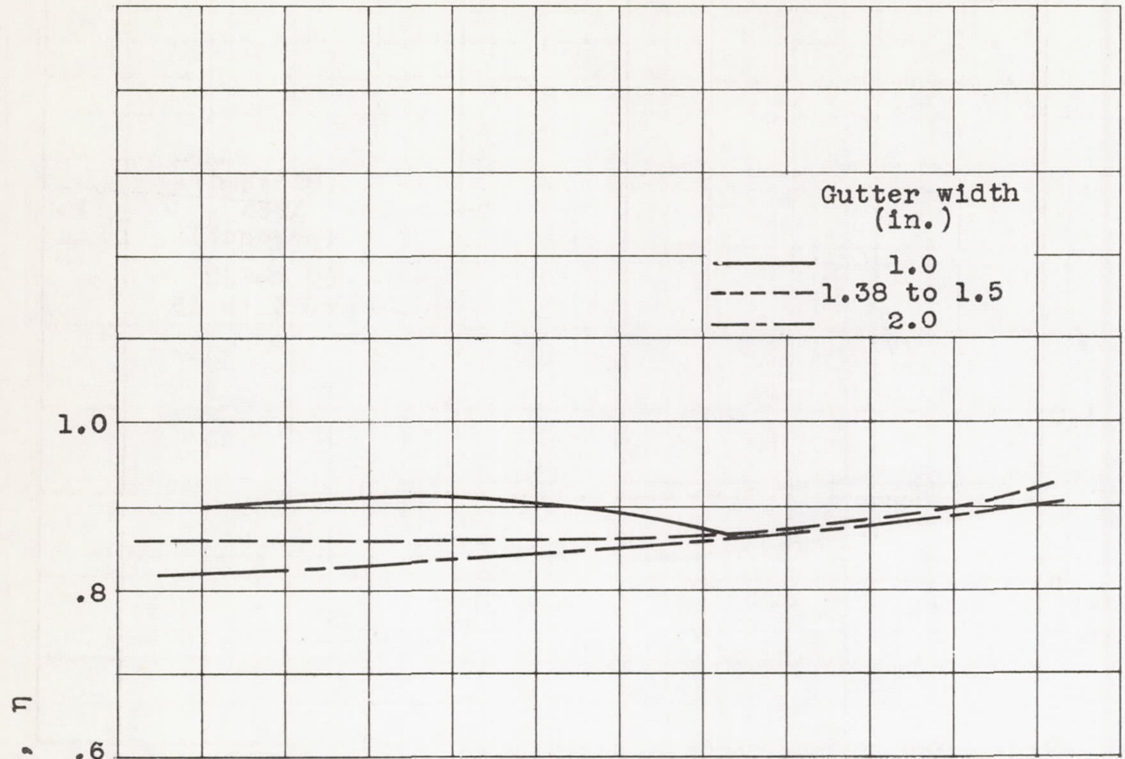
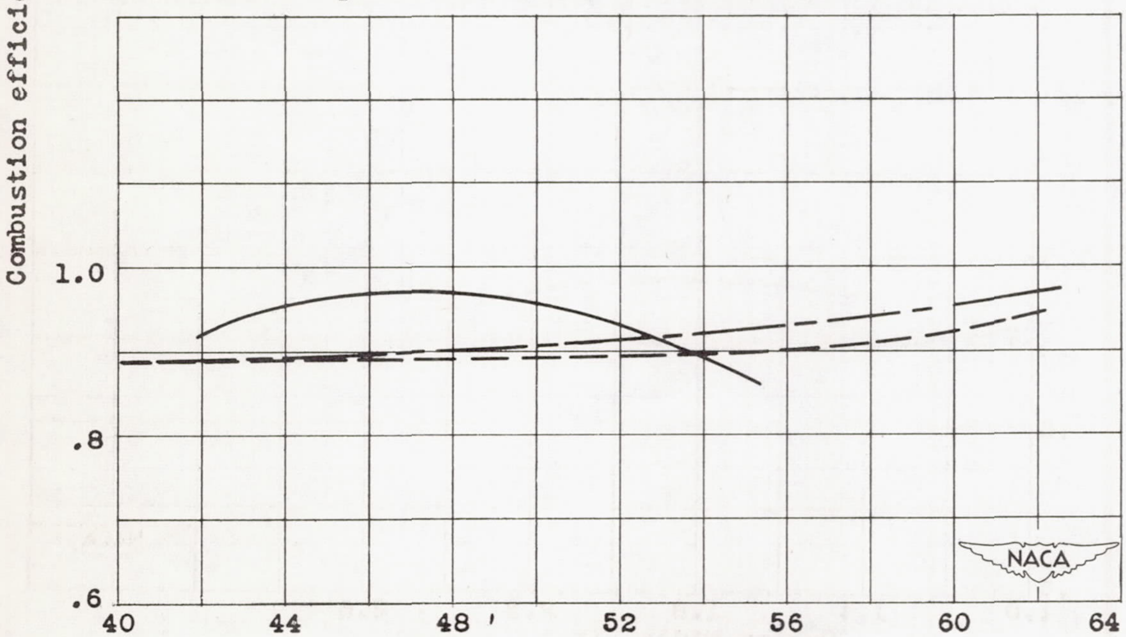
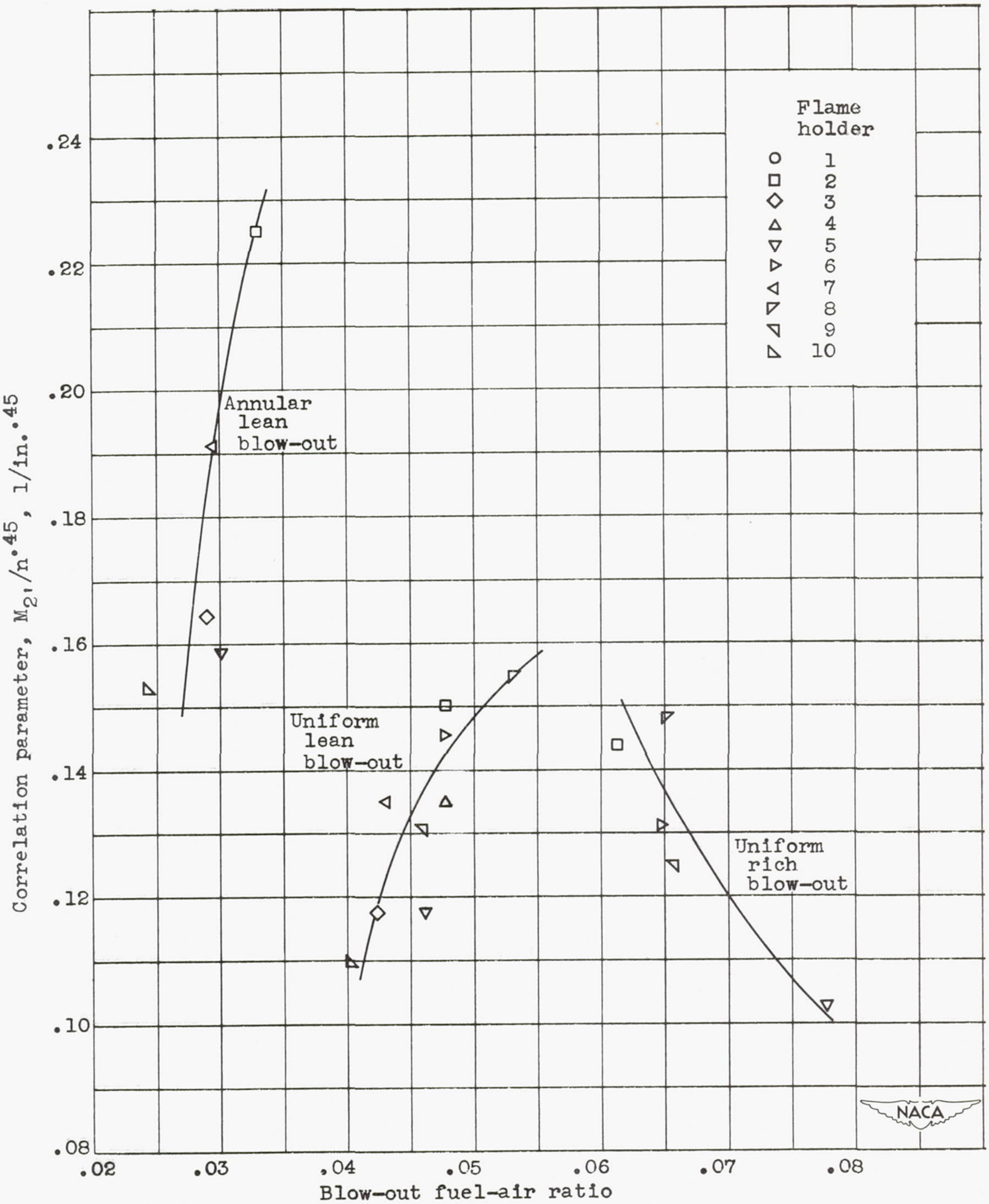


(a) Fuel-air ratio, 0.05; combustion-chamber-outlet total pressure P_4, 1800 pounds per square foot absolute.



(b) Fuel-air ratio, 0.06, combustion-chamber-outlet total pressure P_4, 2000 pounds per square foot absolute.

Figure 17. - Effect of blocked area on combustion efficiency.



(a) Combustion-chamber-outlet total pressure P_4, 1400 pounds per square foot absolute.

Figure 18. - Correlation of blow-out data.

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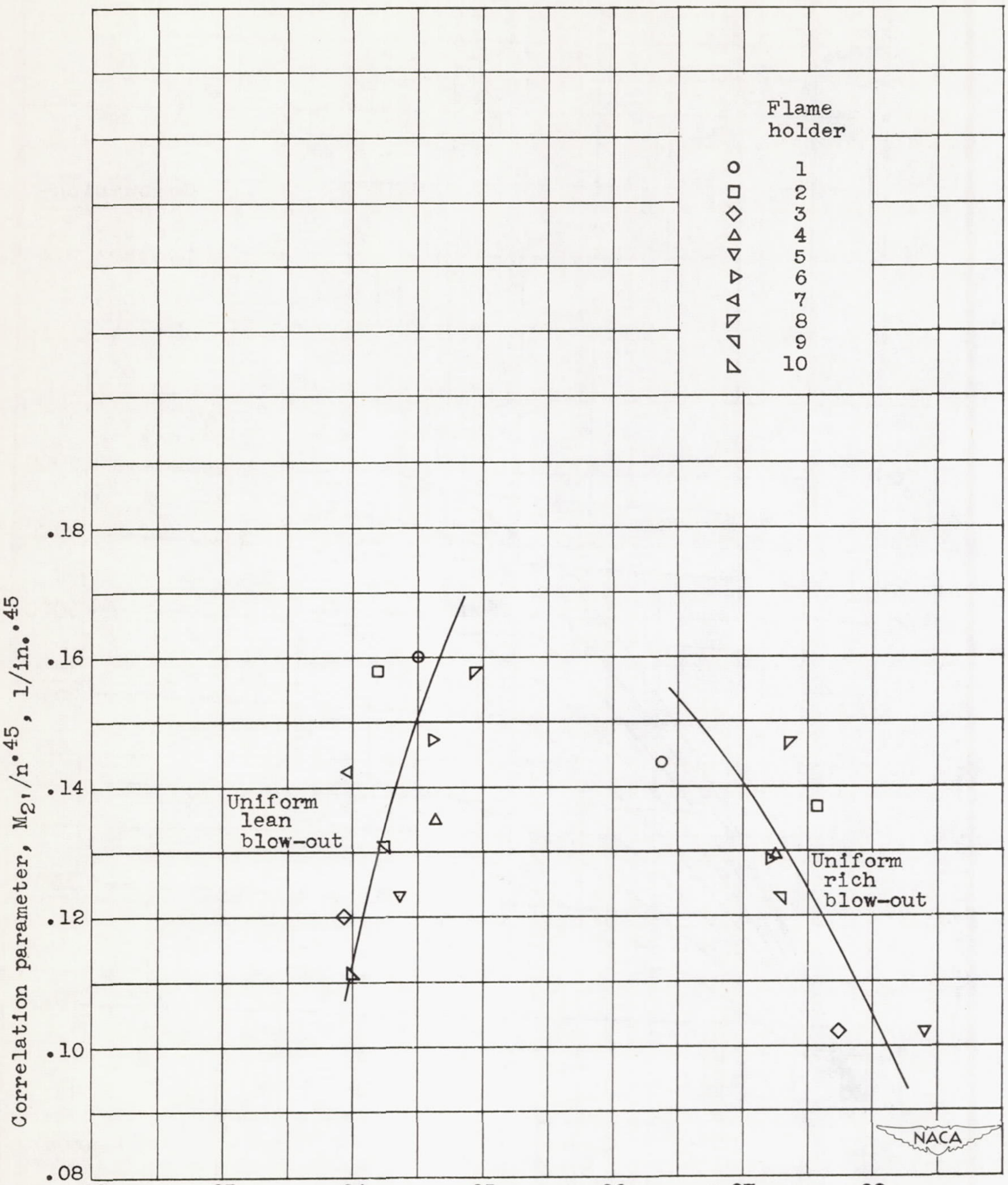

(b) Combustion-chamber-outlet total pressure P_4, 2000 pounds per square foot absolute.

Figure 18. - Concluded. Correlation of blow-out data.

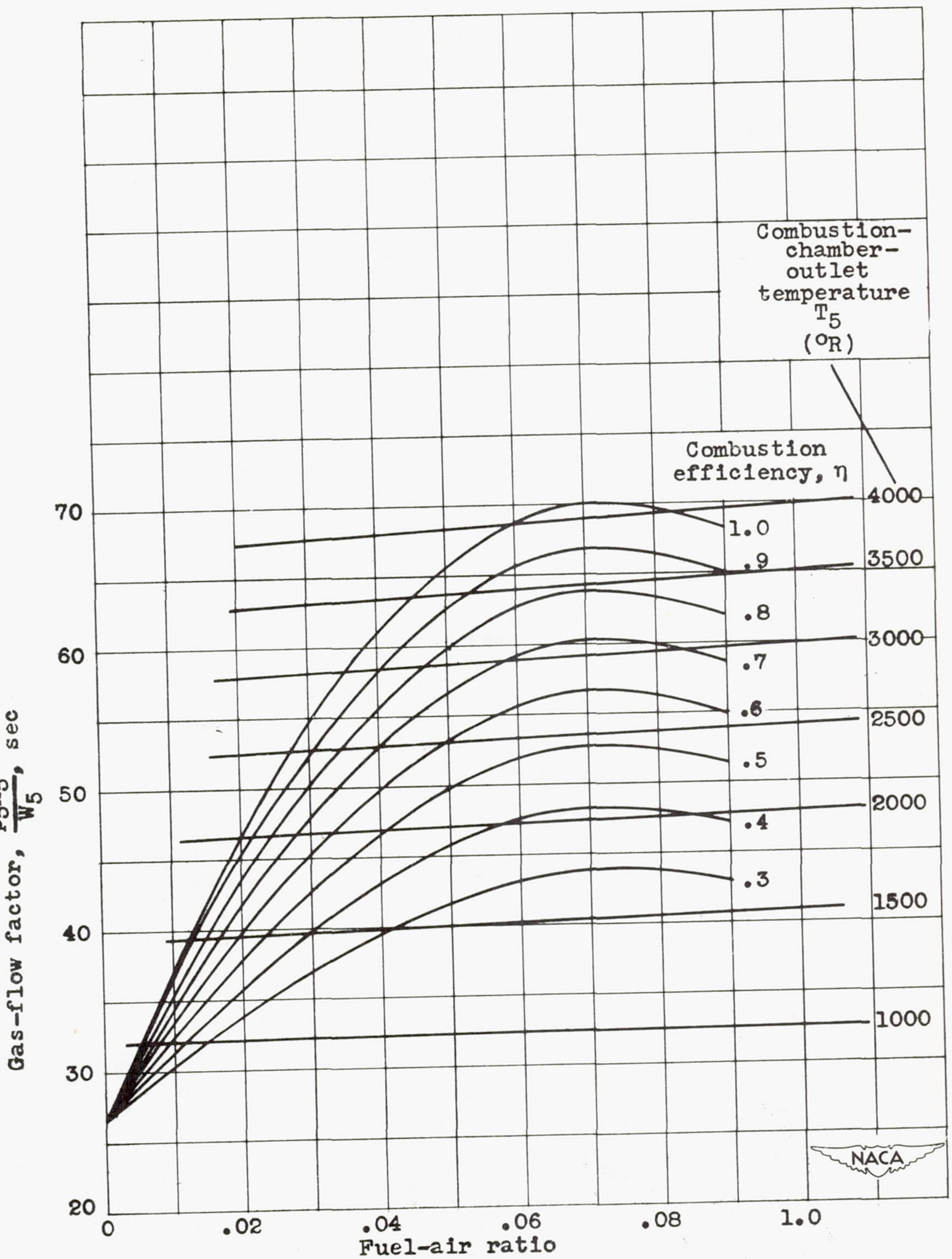

Figure 19. - Relations between various combustion parameters for inlet temperature of 710° R.