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RESEARCH MEMORANDUM

EFFECT OF INLET-AIR PARAMETERS ON COMBUSTION LIMIT
AND FLAME LENGTH IN 8-INCH-DIAMETER

RAM-JET COMBUSTION CHAMBER

By A. J. Cervenka and R. C. Miller

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RESEARCH MEMORANDUM

EFFECT OF INLET-AIR PARAMETERS ON COMBUSTION LIMIT
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RAM-JET COMBUSTION CHAMBER

By A. J. Cervenka and R. C. Miller

SUMMARY

An investigation was conducted with an 8-inch-diameter ram-jet combustion chamber in order to determine the effect of fuel-air ratio and the inlet-air parameters of pressure, temperature, and velocity on combustion limit, combustion efficiency, and flame length.

The lean fuel-air ratio limit of combustion could be extended by increasing inlet-air temperature or pressure or by modification of the fuel-injector design. For a given combustion-chamber length, combustion efficiency increased with increasing inlet-air temperature or decreasing inlet-air velocity. Flame length increased with increasing fuel-air ratio, inlet-air pressure, inlet-air velocity, and decreasing inlet-air temperature.

INTRODUCTION

An investigation was conducted at the NACA Cleveland laboratory in order to determine the effect of operating variables on ram-jet combustor performance.

For the investigation reported herein, an 8-inch-diameter combustion chamber was isolated from the other ram-jet engine components in order to allow wide variation and accurate control of the experimental parameters. Preliminary investigations were conducted with various fuel injectors and flame holders in an effort to select a combustion chamber with a wide operating range. Of the various combustion chambers studied, the flame-holder and fuel-injector configuration described in reference 1 gave stable operation over the widest range of inlet-air conditions and was used throughout the investigation.

The effect of fuel-air ratio and inlet-air parameters of pressure, temperature, and velocity on combustion limit, combustion

efficiency, and flame length are presented herein. The effect of each variable was separately determined over a large range by holding three of the variables constant and varying the fourth.

APPARATUS

Combustion Chamber

A diagram of the experimental setup showing the 8-inch ram-jet combustion chamber and auxiliary ducting is presented in figure 1. The ducting was connected to the laboratory combustion-air supply and altitude exhaust systems. The combustion chamber and exhaust ducting were water-cooled in order to prevent overheating and to permit measurement of heat losses. The temperature of the exhaust gases was reduced by a movable water spray. The combustion chamber consisted of a constant-area circular duct with a fuel injector located upstream of a flame holder. The location of the fuel injector, ignitor, flame holder, and movable water spray is indicated in figure 1. Three quartz observation windows were installed to permit observation of the flames at the flame holder and in the tail pipe.

The details of the simple orifice-type fuel injector, ignitor, flame holder, and movable water spray are shown in figure 2. The simple orifice fuel injector consisted of a circular manifold from which six tubes radially projected into the duct a distance of 1 inch. Fuel was metered through a 5/64-inch-diameter orifice in the end of each tube. Experiments were also conducted with five of the six injection tubes blocked and with six hollow-cone spray nozzles (40 gal/hr, 70° spray angle) replacing the six tubes. The fuel used throughout the investigation was AN-F-22.

The ignitor, which was in itself a small combustion chamber was designed to eliminate starting hazards. A high-tension electrode and a 1/8-inch-diameter fuel line were shielded from the air stream by a small cone. The spark gap was between the electrode and the tip of the fuel line. Under the proper conditions, ignition was almost instantaneous and satisfactory at all times.

The flame holder consisted of seven cones connected by V-shaped gutters and was constructed of 1/32-inch Inconel. The restriction that this flame holder afforded was approximately 37 percent of the cross-sectional area. The flame holder and fuel injector were identical with those of reference 1.

A main supply tube from which eight small tubes radially projected served as the movable water spray. Water was ejected normal to the exhaust-gas stream through numerous holes in the radial tubes.

Instrumentation

Instrumentation was located at stations 1, 2, and 3. (See fig. 1.) A tabulation of the number and type of instruments at each station follows:

Station	Thermocouples	Total-pressure tubes	Static-pressure taps
1	2	12	4
2	0	6	0
3	9	0	0

The construction and installation details of the combustion-chamber instrumentation were in general the same as those of reference 1, with the exception of total-pressure tubes at station 2, which were water-jacketed for protection from excessive temperatures. The total-pressure tubes at station 2 were removed for experiments, which required the positioning of the movable water spray. Thermocouples and total-pressure probes were located at approximate centers of equal areas. The thermocouples were made of iron-constantan wire, with the exception of chromel-alumel wire used at station 3, and were connected to self-balancing potentiometers. Fuel flow was measured with a calibrated rotameter and combustion-air flow was measured with a 12-inch variable-area orifice. Pressure measurements were taken by photographing banks of manometers. Water flow through the cooling coils and the movable water spray was measured with a calibrated rotameter and calibrated orifices.

METHOD OF PROCEDURE

The entire range of inlet variables could not be completely covered because of the size and complexity of such a program. Several reference operating conditions were therefore chosen. These conditions were obtained by calculating stagnation temperature and pressure corrected for an assumed 90-percent diffuser efficiency at two flight velocities (500 mph and sonic) for altitudes ranging from sea level to 30,000 feet. These calculated temperatures and pressures are presented in figure 3 with a curve drawn

through the mean of the calculated points. Three points lying in the range of interest in ram-jet study were chosen from this curve and correspond to the following temperatures and pressures:

Test point	Temperature (°F)	Pressure (in. Hg abs.)
1	72	25
2	120	40
3	160	55

A preliminary investigation of the effect of inlet-air velocity on combustion limit at the three test points indicated that an inlet-air velocity of approximately 90 feet per second was near the upper limit for stable burning at the first test point; this value was therefore chosen as a reference velocity for the three test points.

Ignition was almost instantaneous at the following conditions:

- (a) inlet-air velocity, 50 feet per second
- (b) inlet-air pressure, 30 inches mercury absolute
- (c) ignitor fuel flow, 100 pounds per hour

After ignition was obtained, fuel flow to the ignitor was reduced to 10 pounds per hour and was kept constant at this value throughout the experiments. A preliminary investigation showed that with the ignitor energized and with a low fuel flow through the ignitor the combustion limits could be extended beyond the limits that were obtained when the ignitor was not energized.

The effects of fuel-air ratio and the inlet-air parameters of pressure, temperature, and velocity on combustion limits, combustion efficiency, and flame length were studied by holding three of the variables constant and changing the fourth. Limited experiments were conducted in order to check the effect of fuel temperature and fuel-injector configuration on combustion-chamber performance.

The combustion limits were determined in the following manner. Inlet-air pressure, temperature, and velocity were set at the desired values. Fuel-air ratio was set at a value at which combustion was stable. Fuel flow was then either decreased or increased

until combustion ceased. The rich limit of combustion was not obtained when fuel-air ratio was increased to values greater than 0.14 without reaching a combustion limit.

The procedure followed in order to determine the effect of nominal combustion-chamber length, which is defined as the distance from the movable water spray to the flame holder, and inlet-air parameters on combustion efficiency is as follows: With the nominal combustion-chamber length set at 96 inches and the inlet-air conditions set at the desired values, data were recorded. The nominal combustion-chamber length was then decreased by moving the water spray toward the flame holder until a drop of approximately 50° F in the mixture temperature at station 3 was noted. Data were again recorded and the process was repeated until a combustion-chamber length of 22 inches was reached. This length was the minimum combustion-chamber length that could be investigated because of space limitations for the movable spray.

Inlet-air velocity and dynamic pressure were calculated from measured air flow, inlet-air static pressure, and inlet-air temperature. Combustion-chamber total-pressure drop from station 1 to station 2 was obtained from photographs of the manometers, which recorded the respective pressures.

Because combustion temperatures in a ram jet reach values in excess of 3000° F, no simple method for directly measuring these temperatures could be found. Combustion efficiency and combustion temperatures were therefore calculated by a heat-balance method. Sufficient water was injected through the movable spray into the exhaust stream to lower the mixture temperature to approximately 1200° F. At this temperature, combustion was assumed to have stopped and yet the temperature was sufficiently high for evaporation of the water to be complete at station 3. The enthalpy of the exhaust gases at the mixture temperature at station 3 was obtained using data from references 2 to 4. The enthalpy of the steam was obtained from reference 5. These values were added in order to obtain the total enthalpy in the mixture of exhaust gas and steam at station 3; the inlet enthalpies were subtracted and the measured heat losses to the combustion-chamber and exhaust-duct cooling water were added. This total enthalpy divided by the ideal enthalpy rise of the gases for complete combustion of the fuel (or for complete combustion of the air at richer-than-stoichiometric fuel-air ratios) was called combustion efficiency.

RESULTS AND DISCUSSION

Combustion Limits

Maximum combustion-chamber inlet-air velocity is plotted in figure 4(a) as a function of fuel-air ratio for various inlet-air temperatures at a constant inlet-air pressure. A similar plot showing the effect of varying inlet-air pressure at a constant inlet-air temperature is shown in figure 4(b). The results presented in these figures indicate that the maximum combustion inlet-air velocity can be increased with an increase in either inlet-air temperature or pressure. The lean fuel-air-ratio limit of combustion or maximum inlet-air velocity at stable combustion was extended by increasing inlet-air temperature and pressure. An additional dashed curve is shown in figures 4(a) and 4(b) that illustrates the fuel-distribution effect on the lean combustion limit. These dashed curves show performance with five of the six fuel sprays blocked and show that combustion could be sustained at a considerably leaner over-all fuel-air ratio with this fuel-injector configuration.

Fuel-Air Ratio for Maximum Combustion Efficiency

An investigation was conducted on the effect of fuel-air ratio on combustion efficiency; the results are presented in figure 5 in which combustion efficiency and combustion temperature rise are plotted against fuel-air ratio. Maximum combustion efficiency occurred in the fuel-air-ratio range from 0.040 to 0.050. Combustion-chamber temperature rise was found to increase with increasing fuel-air ratio until stoichiometric fuel-air ratio (0.067) was nearly reached and beyond this point a steady decrease with increasing fuel-air ratio was observed.

Effect of Inlet-Air Parameters and Fuel Temperature on

Combustion Efficiency and Flame Length

Inlet-air pressure. - The variation of combustion efficiency with inlet-air pressure and nominal combustion-chamber length is presented in figure 6. At an inlet-air pressure of 25 inches of mercury absolute, a decrease in nominal combustion-chamber length from 96 to 33 inches resulted in no appreciable decrease in combustion efficiency, whereas at higher inlet-air pressures a comparable decrease in nominal combustion-chamber length decreased

combustion efficiency as much as 20 percent. This decrease in combustion efficiency indicated that flame length increases with inlet-air pressure. Inasmuch as the trend of decreasing combustion efficiency with increasing inlet-air pressure for a constant combustion-chamber length is not consistent with previous results obtained in turbojet combustion-chamber investigations at the NACA Cleveland laboratory, comparison data using the six hollow-cone spray fuel-injection nozzles were obtained. The dashed curves shown in figure 6 present data obtained with six hollow-cone spray nozzles (40 gal/hr, 70° spray angle) installed in place of the six radial jets. Much shorter flame lengths for comparable operating conditions were obtained with this method of fuel injection.

A reversal in the trend of decreasing combustion efficiency with increasing inlet-air pressure was noted at inlet-air pressures of 55 and 65 inches of mercury absolute (fig. 6) experiments were conducted to check this trend by determining the variation of combustion efficiency with inlet-air pressure at two combustion-chamber lengths with the two methods of fuel injection. These data are presented in figure 7. The same reversal in trend previously observed persisted at both combustion-chamber lengths with the simple orifice fuel injector. This reversal in trend is not fully explained. The trend of the effect of pressure on combustion efficiency and flame length is different for the hollow-cone spray nozzles than for the simple orifice nozzles, which indicates that possibly other pressure effects associated with the injection process such as the effect of pressure on vaporization and mixing may be obscuring the effect of pressure on the combustion rate.

Fuel temperature. - The effect of combustion-chamber length on combustion efficiency at various inlet-air pressures with unheated (75° F) and heated (approximately 160° F) fuel was determined. The temperature of 160° F was slightly above the initial boiling point of the fuel at the pressure existent in the combustion chamber.

The results indicate that for the conditions investigated, fuel temperature had no effect on combustion efficiency or flame length. Some effect of fuel temperature would possibly be noted if a fuel injector were used that would permit heating of the fuel to a higher temperature.

Inlet-air temperature. - The effect of nominal combustion-chamber length on combustion efficiency is given in figure 8 for inlet-air pressures of 30 and 40 inches of mercury absolute, an inlet-air velocity of 92.4 feet per second, and a fuel-air ratio of 0.045.

Combustion was unstable at temperatures lower than 40° F and blow-out occurred when an inlet-air temperature of 0° F was reached. For a given nominal combustion-chamber length, combustion efficiency increases with increase in inlet-air temperature, and the decrease in combustion efficiency for a given decrease in combustion-chamber length is progressively less as inlet-air temperature is increased. Flame length therefore decreases as inlet-air temperature is increased.

Inlet-air velocity. - Data that show the effect of combustion-chamber length on combustion efficiency for inlet-air velocities ranging from 50 to 135 feet per second are presented in figure 9. Combustion ceased at velocities above 135 feet per second; whereas at velocities below 50 feet per second, combustion occurred between the flame holder and the fuel injector. At an inlet-air velocity of 50 feet per second, combustion-chamber length could be decreased from 96 inches to 22 inches with no decrease in combustion efficiency. At higher inlet-air velocities, however, the same decrease in combustion-chamber length decreased combustion efficiency as much as 33 percent showing that as inlet-air velocity is increased flame length increases and combustion efficiency decreases for a fixed combustion-chamber length.

Fuel-air ratio. - The effect of combustion-chamber length on combustion efficiency for various fuel-air ratios and inlet-air pressures is shown in figure 10. The range of fuel-air ratio investigated was from 0.040 to 0.070. Combustion ceased when fuel-air ratio was decreased much below 0.040; a maximum experimental fuel-air ratio of 0.070 was arbitrarily chosen when previous data indicated a decrease in combustion-chamber outlet temperature beyond this point. Data were obtained at a constant inlet-air temperature and velocity for pressures of 30, 40, and 55 inches of mercury absolute. At a fuel-air ratio of 0.040 and an inlet-air pressure of 40 inches of mercury, combustion-chamber length was decreased from 96 inches to 22 inches with a decrease in combustion efficiency of about 8 percent (fig. 10(b)). At a fuel-air ratio of 0.050, the same decrease in combustion-chamber length decreased combustion efficiency about 28 percent indicating that as the fuel-air ratio is increased, flame length increases. The curves also show a trend of decreasing combustion efficiency with increasing fuel-air ratio except in the range from 0.040 to 0.045 where under some conditions a reversal in this trend is indicated. This trend reversal is attributed to the longer flame length associated with the higher fuel-air ratio; the same decrease in combustion-chamber length therefore decreased combustion efficiency more rapidly at the higher fuel-air ratios. Data obtained at inlet-air pressures of 30 and 55 inches of mercury absolute show trends similar to that found at 40 inches mercury (figs. 10(a) and 10(c)).

The effect of inlet-to-outlet air density ratio on combustion-chamber total-pressure loss is presented in figure 11. The ratio of combustion-chamber total-pressure drop to inlet-air dynamic pressure ranged from 1.5 to 3.4 depending on the combustion-chamber inlet-to-outlet density ratio. The scatter in the pressure-drop data was caused by instability of combustion at some of the experimental conditions at which data were recorded.

SUMMARY OF RESULTS

From an investigation conducted with an 8-inch-diameter ram-jet combustion chamber in order to determine the effect of fuel-air ratio and the inlet-air parameters of pressure, temperature, and velocity on combustion limit, combustion efficiency, and flame length, the following results were obtained:

1. Combustion could be sustained at increased inlet-air velocity with increase in combustion-chamber inlet-air temperature or pressure.
2. The lean fuel-air-ratio limit of combustion or maximum inlet-air velocity at stable combustion was extended by increasing inlet-air temperature and pressure.
3. Combustion could be sustained at leaner over-all fuel-air ratios with less mixing of fuel and air.
4. Combustion efficiency reached a maximum for the conditions investigated in the fuel-air-ratio range of 0.040 to 0.050.
5. Combustion efficiency increased with increasing inlet-air temperature and decreasing inlet-air velocity for a constant combustion-chamber length.
6. Flame length was shortened with increased fuel atomization, increased inlet-air temperature, decreased inlet-air pressure, decreased fuel-air ratio, and decreased inlet-air velocity.
7. As the combustion-chamber length was shortened, combustion efficiency decreased more rapidly at higher inlet-air pressures, velocity, fuel-air ratio, or decrease in inlet-air temperature.

8. The ratio of combustion-chamber total-pressure loss to inlet-air dynamic pressure ranged from 1.5 to 3.4 depending on the combustion-chamber inlet-to-outlet density ratio.

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National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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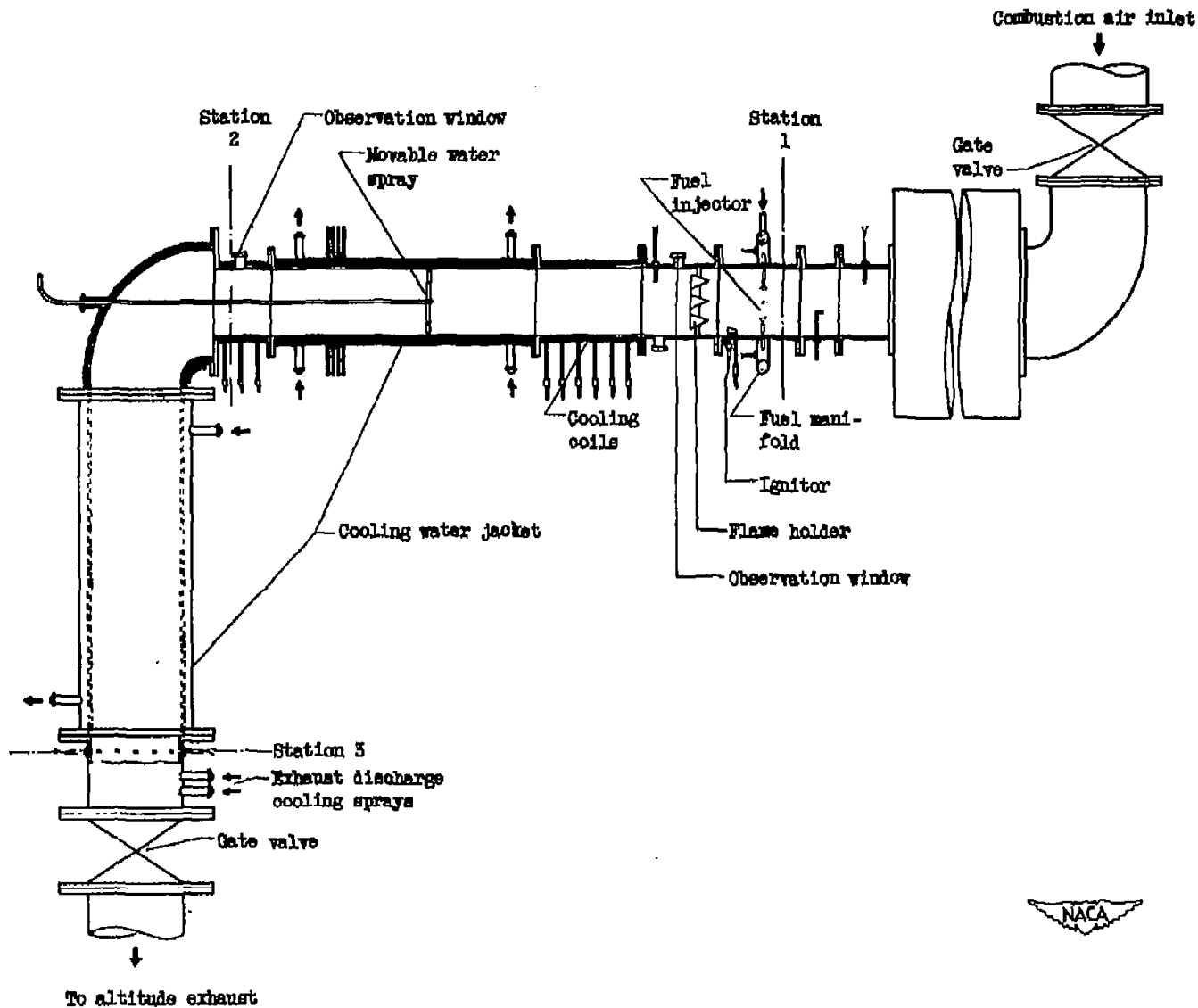
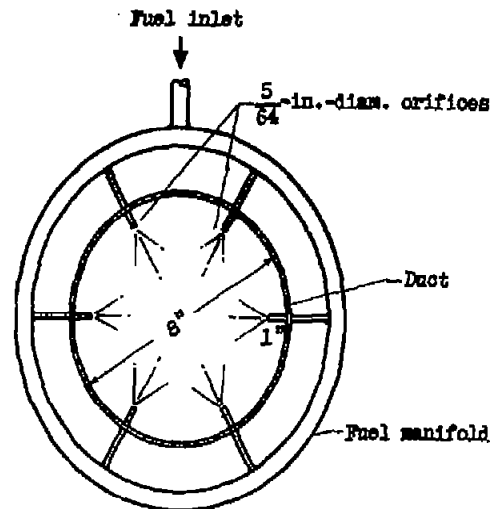
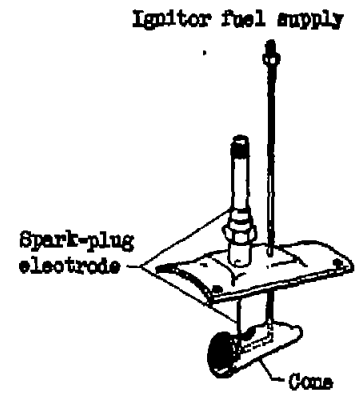


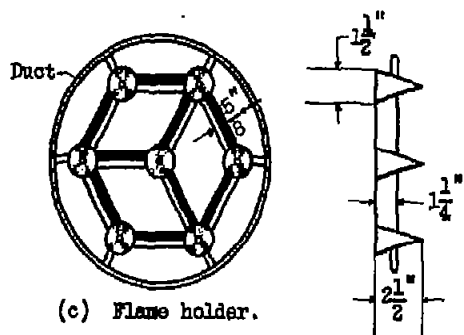
Figure 1. - Diagram of experimental setup of 8-inch ram-jet combustion chamber and auxiliary ducting.



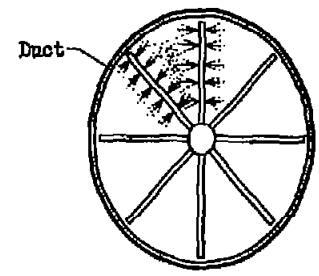
(a) Simple orifice-type fuel injector



(b) Ignitor.



(c) Flame holder.



(d) Movable water spray.

Figure 2. - Components of 8-inch ram-jet combustion chamber.



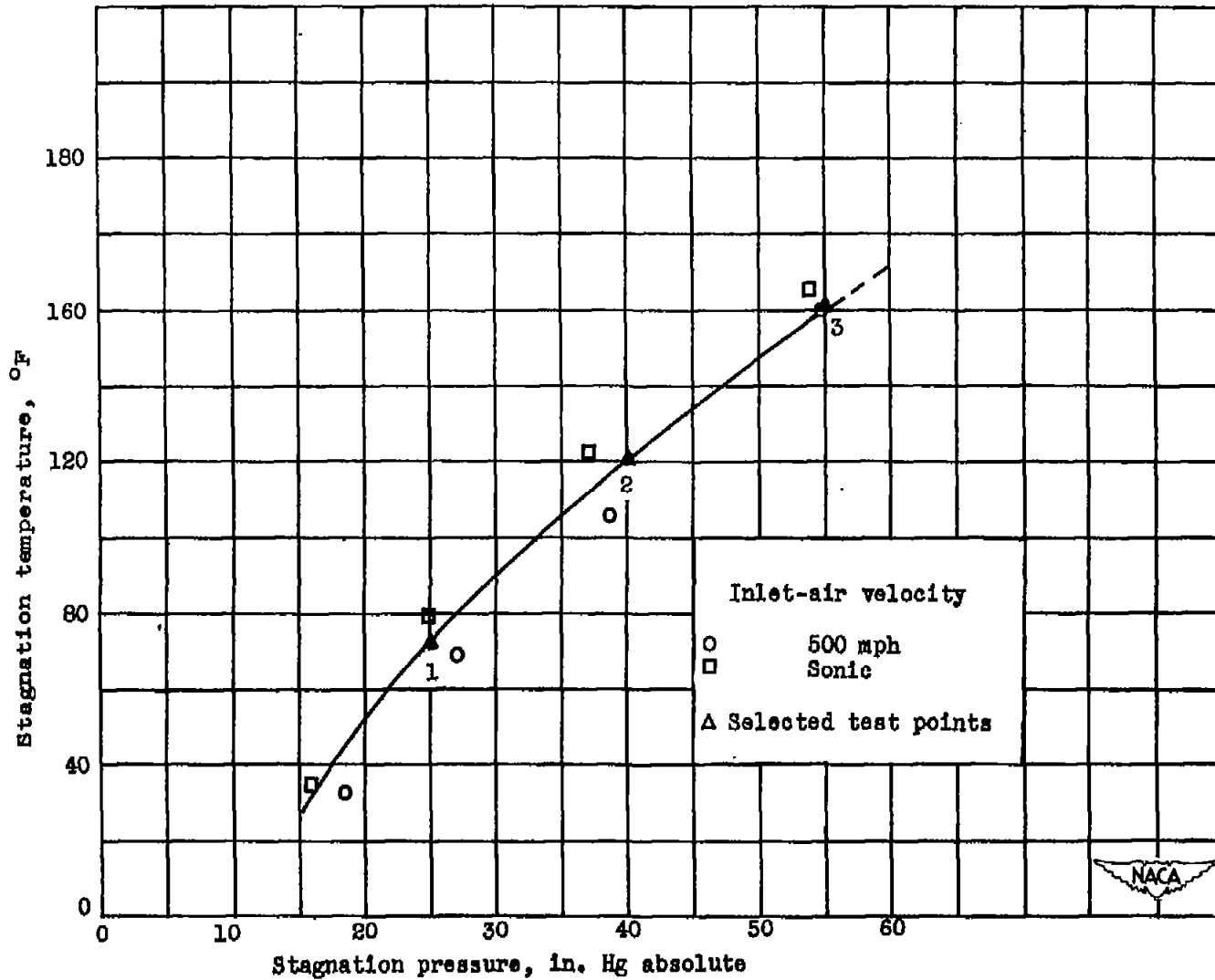
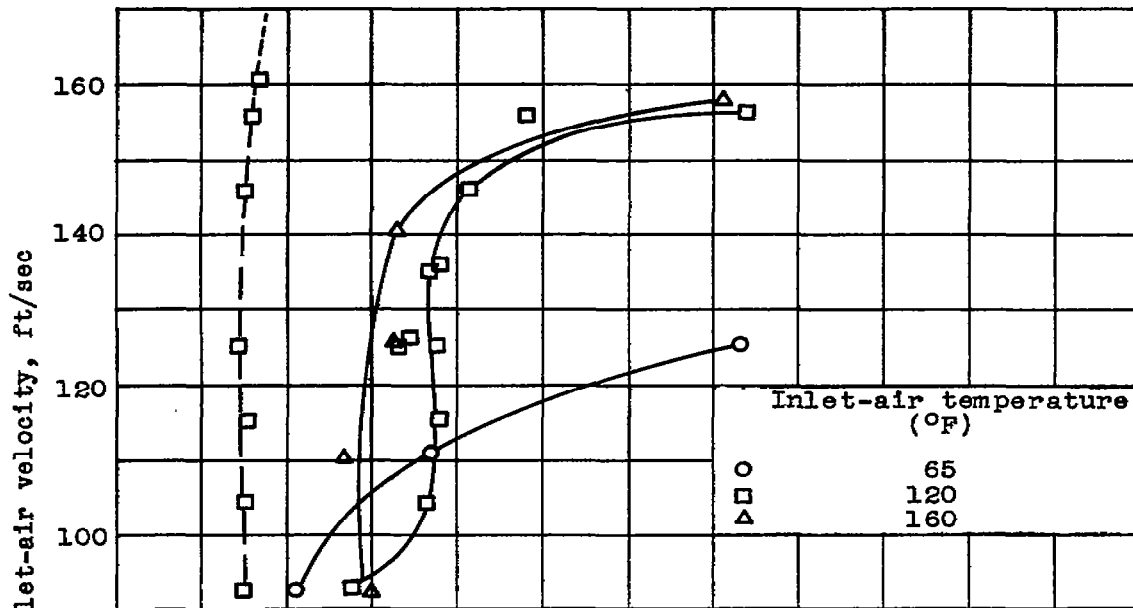
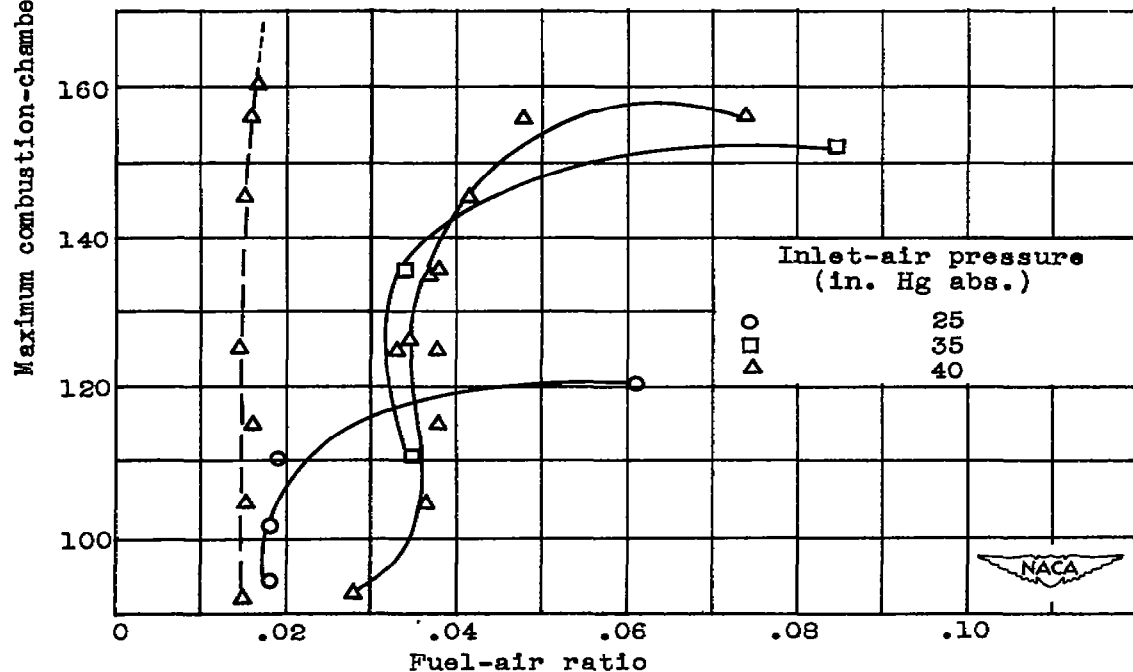


Figure 3. - Stagnation temperatures and pressures for various assumed flight velocities and altitudes. (Assumed diffuser efficiency, 90 percent.)



(a) Inlet-air pressure, 40 inches mercury absolute.



(b) Inlet-air temperature, 120° F.

Figure 4. - Effect of fuel-air ratio and inlet-air temperature and pressure on maximum combustion-chamber inlet-air velocity. Dashed line indicates that five of the six fuel sprays have been blocked.

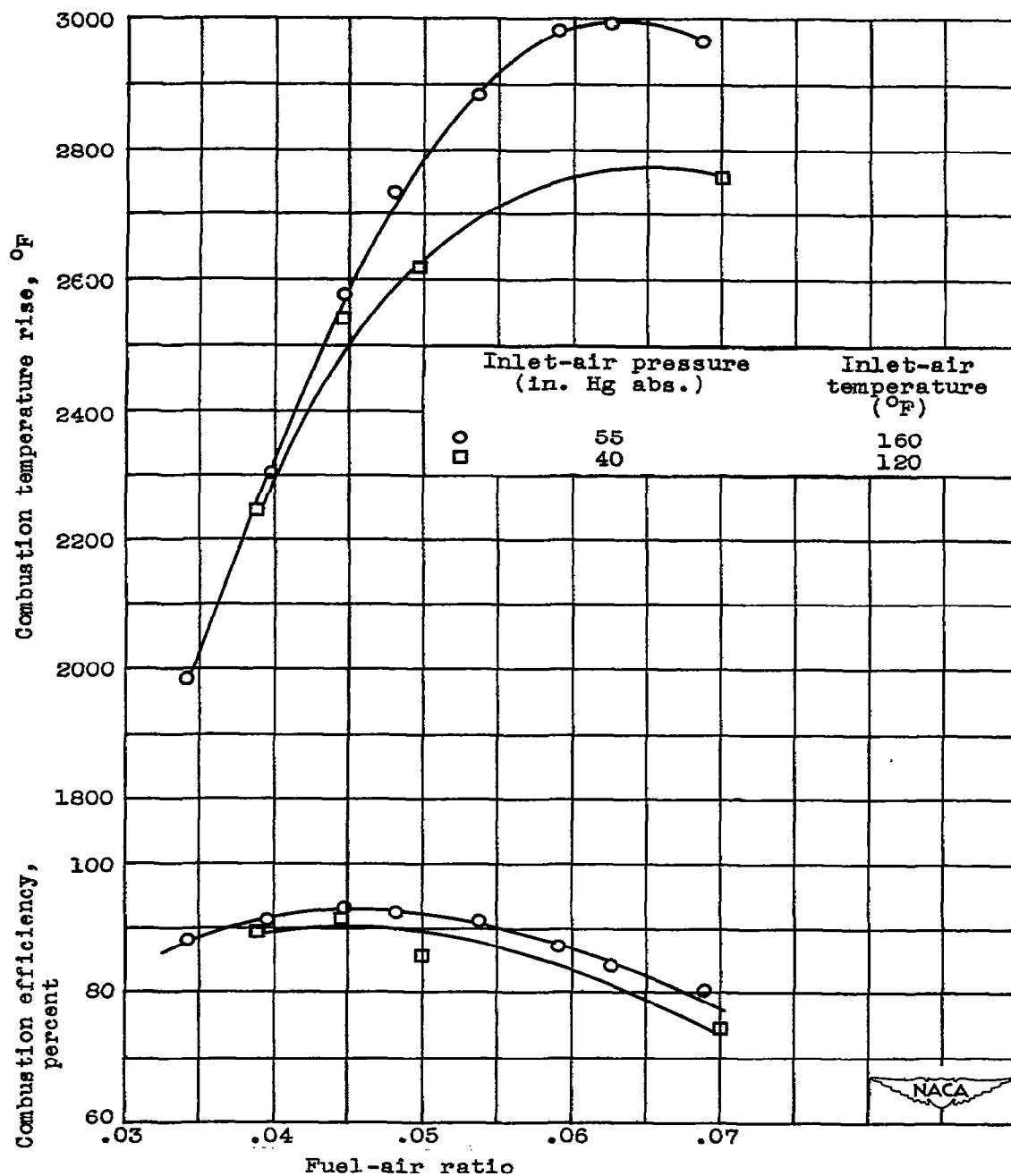


Figure 5. - Effect of fuel-air ratio on combustion-chamber performance. Inlet-air velocity, 92.4 feet per second; nominal combustion-chamber length, 96 inches.

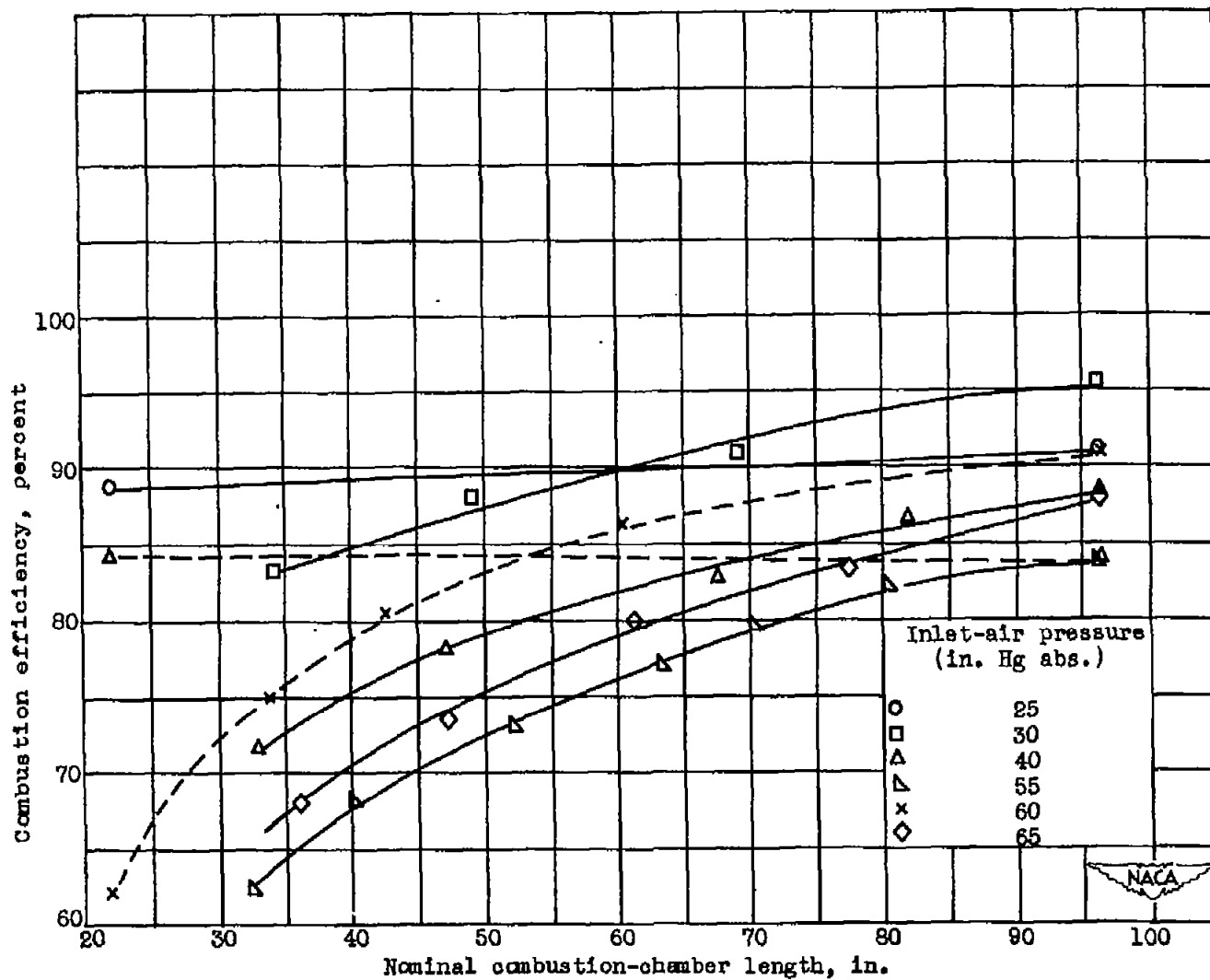


Figure 6. - Effect of combustion-chamber length on efficiency for various inlet-air pressures. Inlet-air velocity, 92.4 feet per second; inlet-air temperature, 120° F; fuel-air ratio, 0.045. Dashed lines indicate hollow-cone spray nozzle.

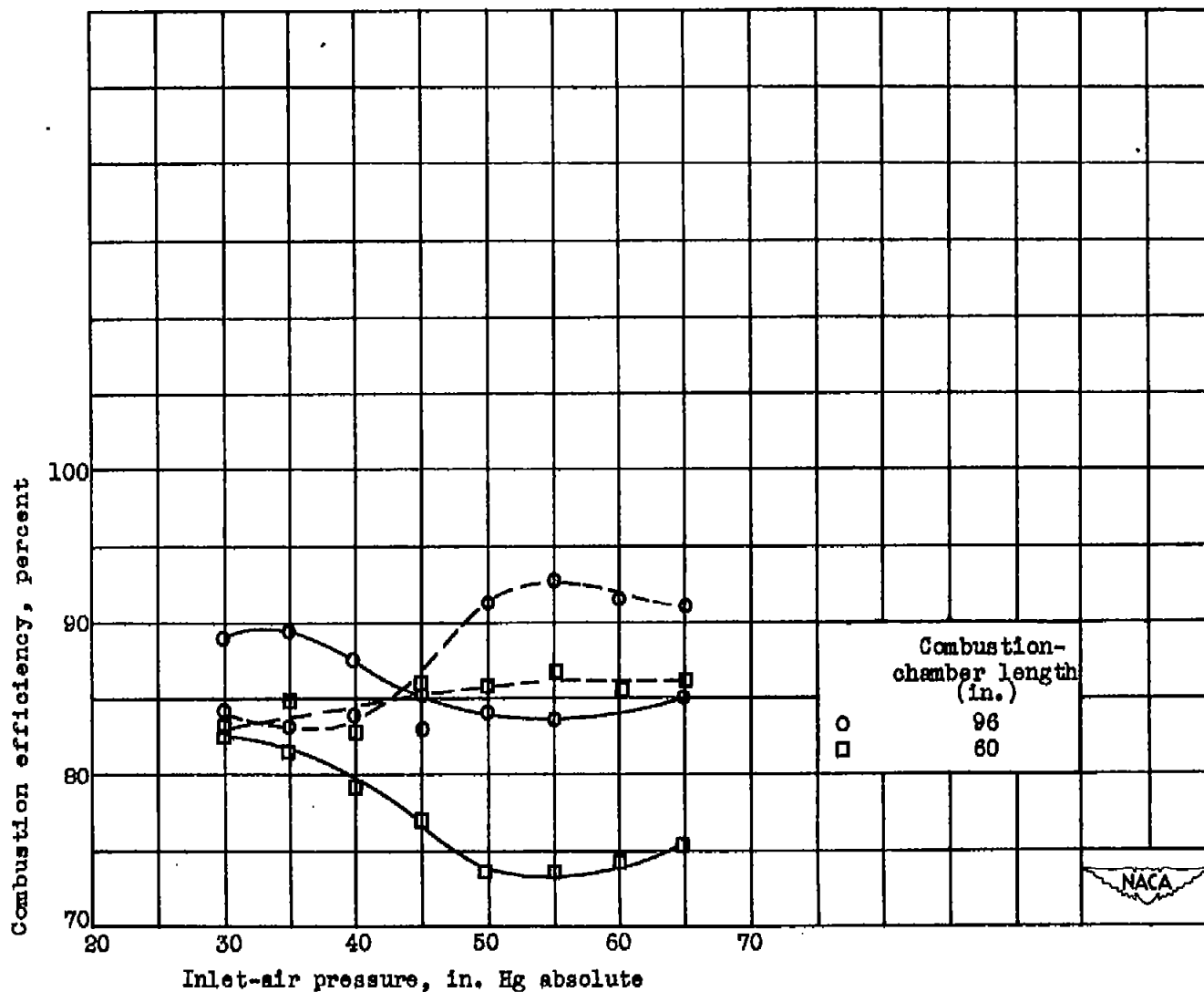
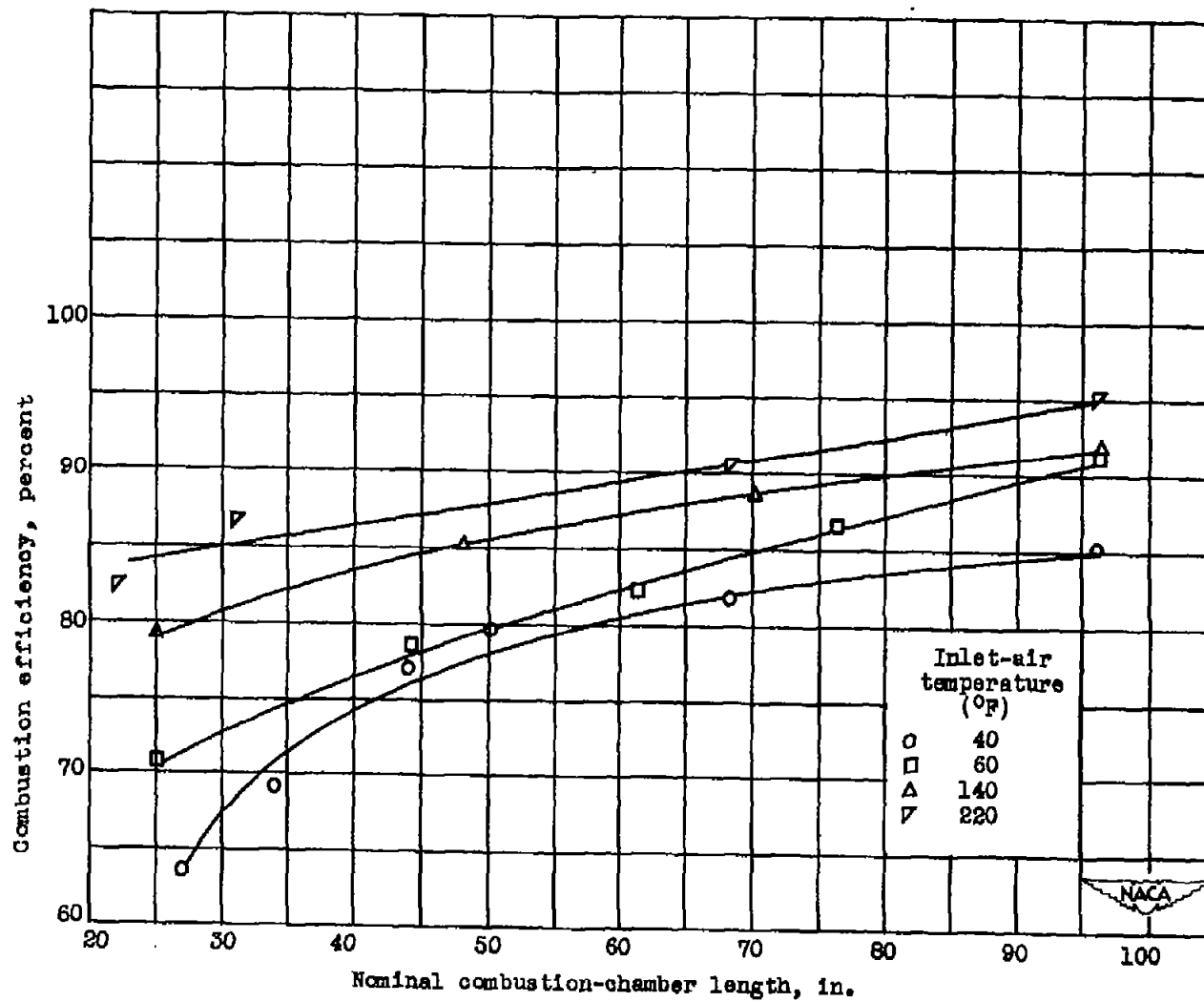
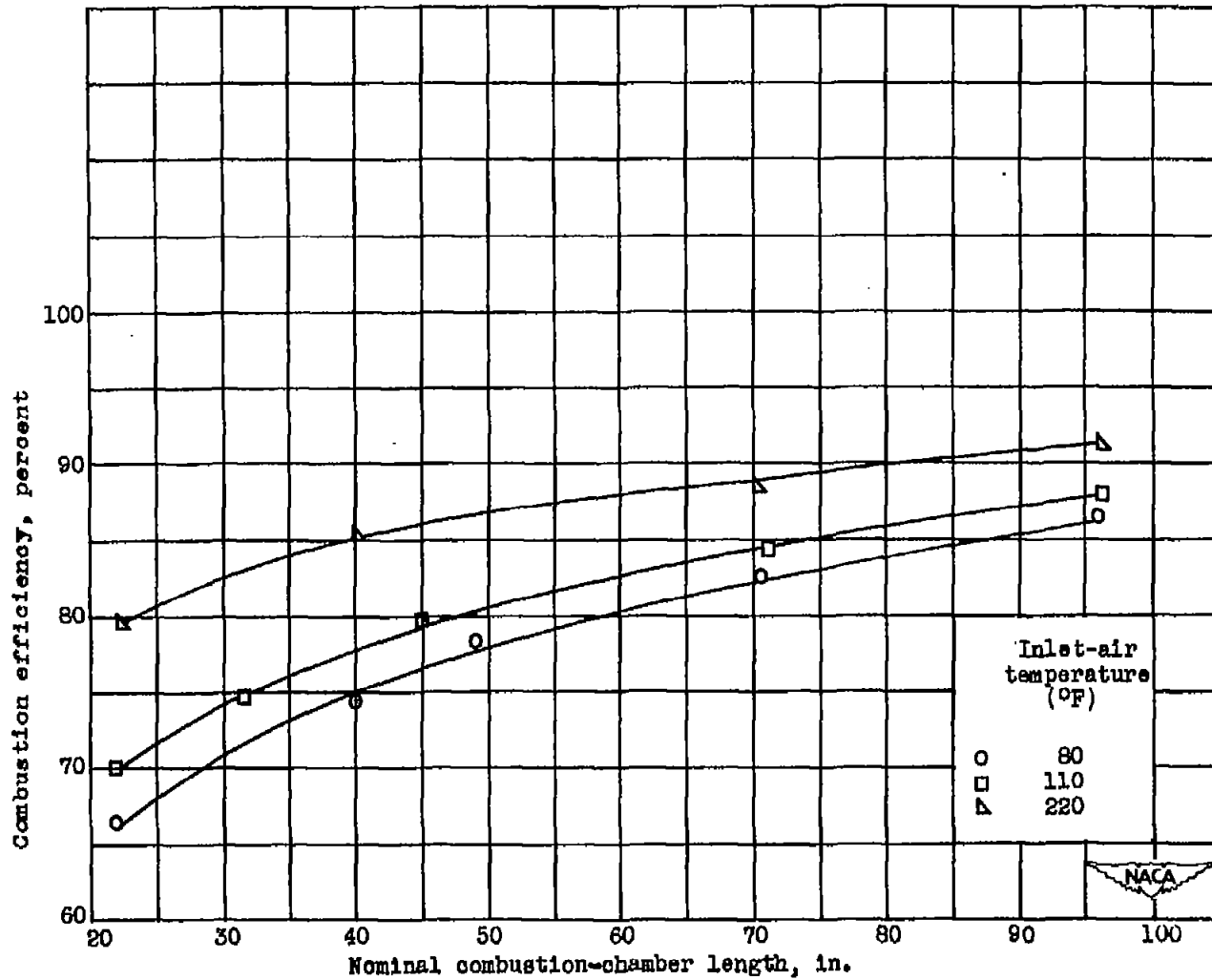


Figure 7. - Effect of inlet-air pressure on combustion efficiency. Inlet-air velocity, 92.4 feet per second; inlet-air temperature, 120° F; fuel-air ratio, 0.046. Dashed lines indicate hollow-cone spray nozzles.



(a) Inlet-air pressure, 30 inches mercury absolute.

Figure 8. - Effect of combustion-chamber length on combustion efficiency for various inlet-air temperatures. Inlet-air velocity, 92.4 feet per second; fuel-air ratio, 0.045.



(b) Inlet-air pressure, 40 inches mercury absolute.

Figure 8. - Concluded. Effect of combustion-chamber length on combustion efficiency for various inlet-air temperatures. Inlet-air velocity, 92.4 feet per second; fuel-air ratio, 0.045.

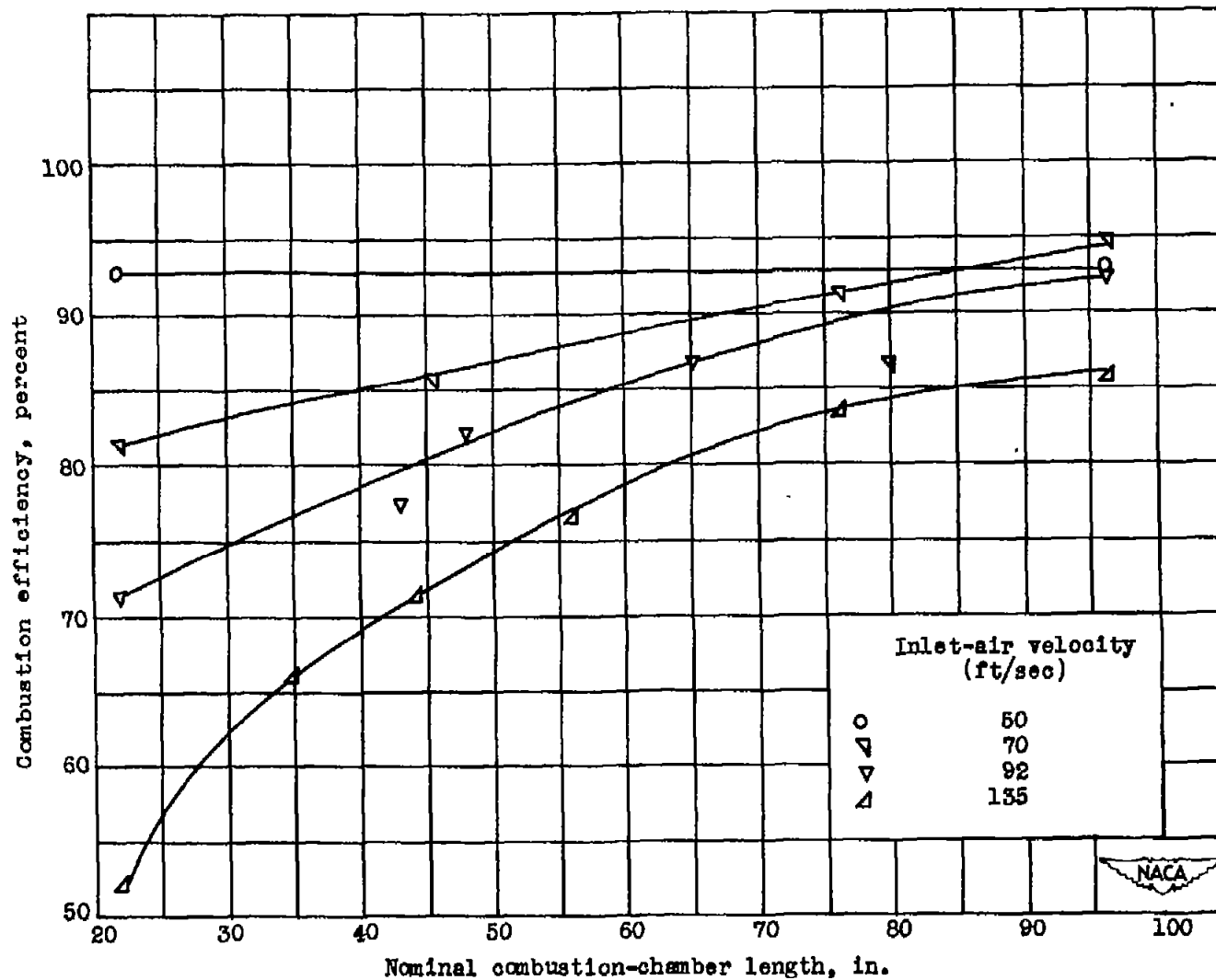
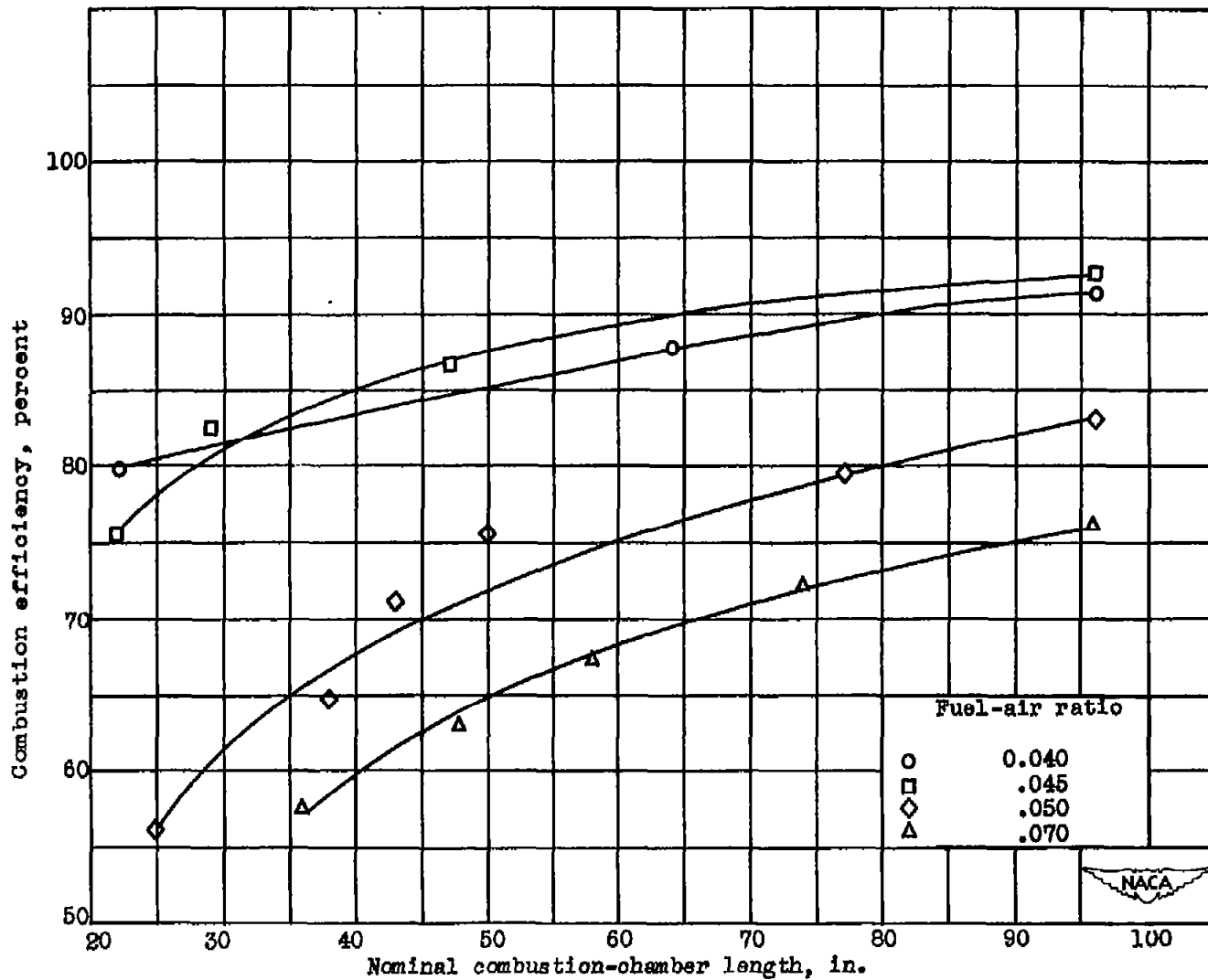
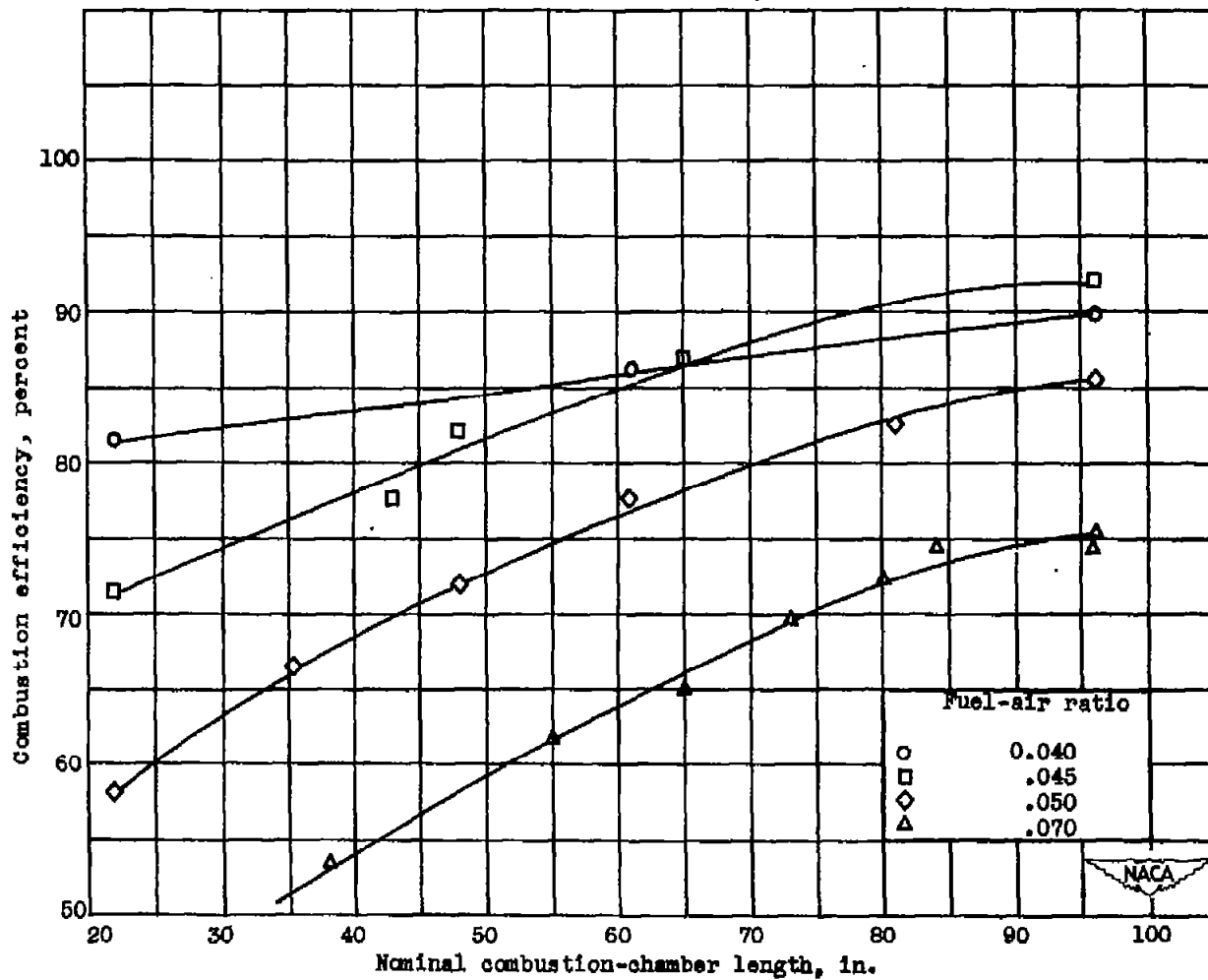


Figure 9. - Effect of combustion-chamber length on efficiency for various inlet-air velocities. Inlet-air pressure, 40 inches mercury absolute; inlet-air temperature, 120° F; fuel-air ratio, 0.045.



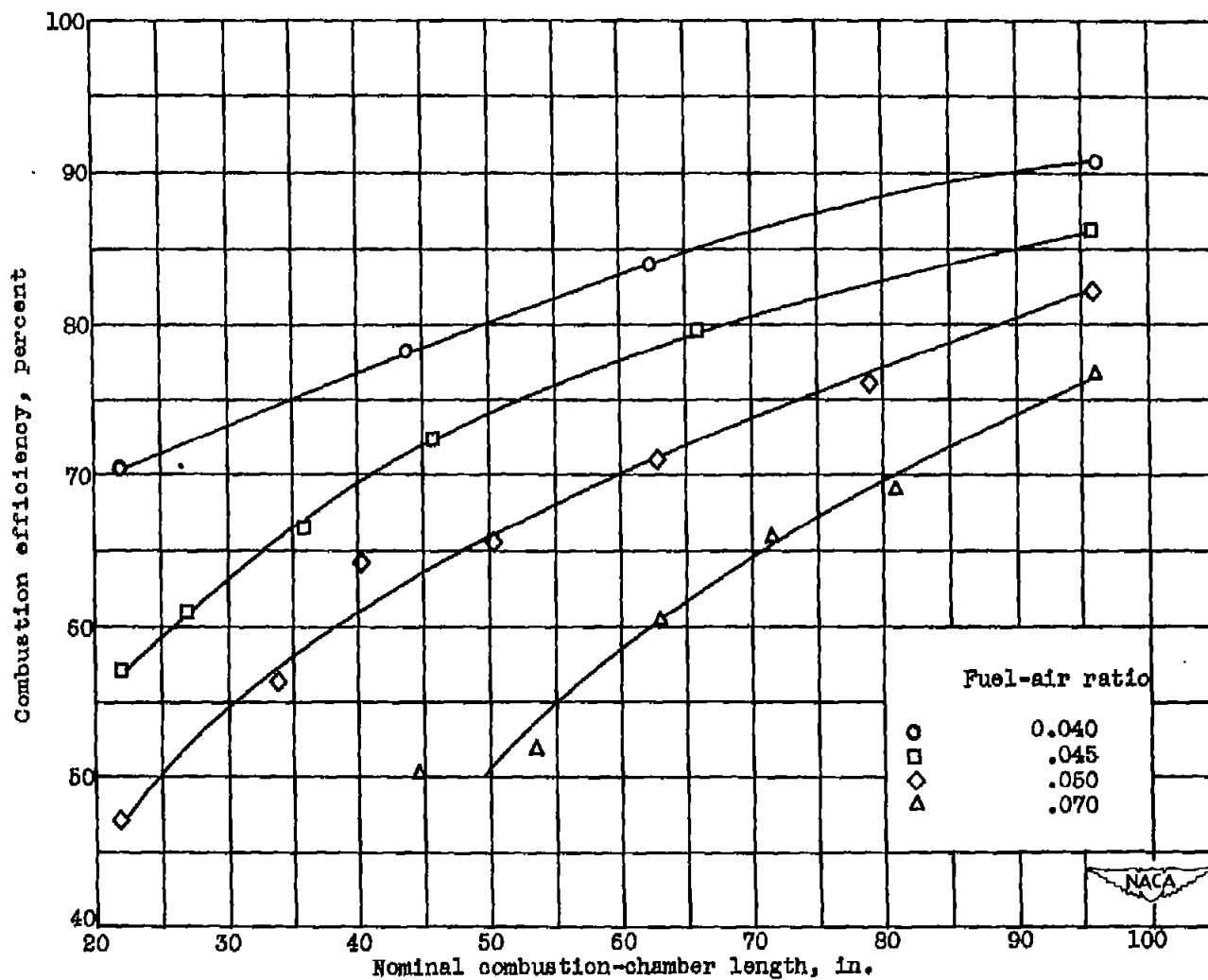
(a) Inlet-air pressure, 30 inches mercury absolute.

Figure 10. - Effect of combustion-chamber length on combustion efficiency for various fuel-air ratios. Inlet-air velocity, 92.4 feet per second; inlet-air temperature, 120° F.



(b) Inlet-air pressure, 40 inches mercury absolute.

Figure 10. - Continued. Effect of combustion-chamber length on combustion efficiency for various fuel-air ratios. Inlet-air velocity, 92.4 feet per second; inlet-air temperature, 120° F.



(c) Inlet-air pressure, 56 inches mercury absolute.

Figure 10. - Concluded. Effect of combustion-chamber length on combustion efficiency for various fuel-air ratios. Inlet-air velocity, 92.4 feet per second; inlet-air temperature, 120° F.

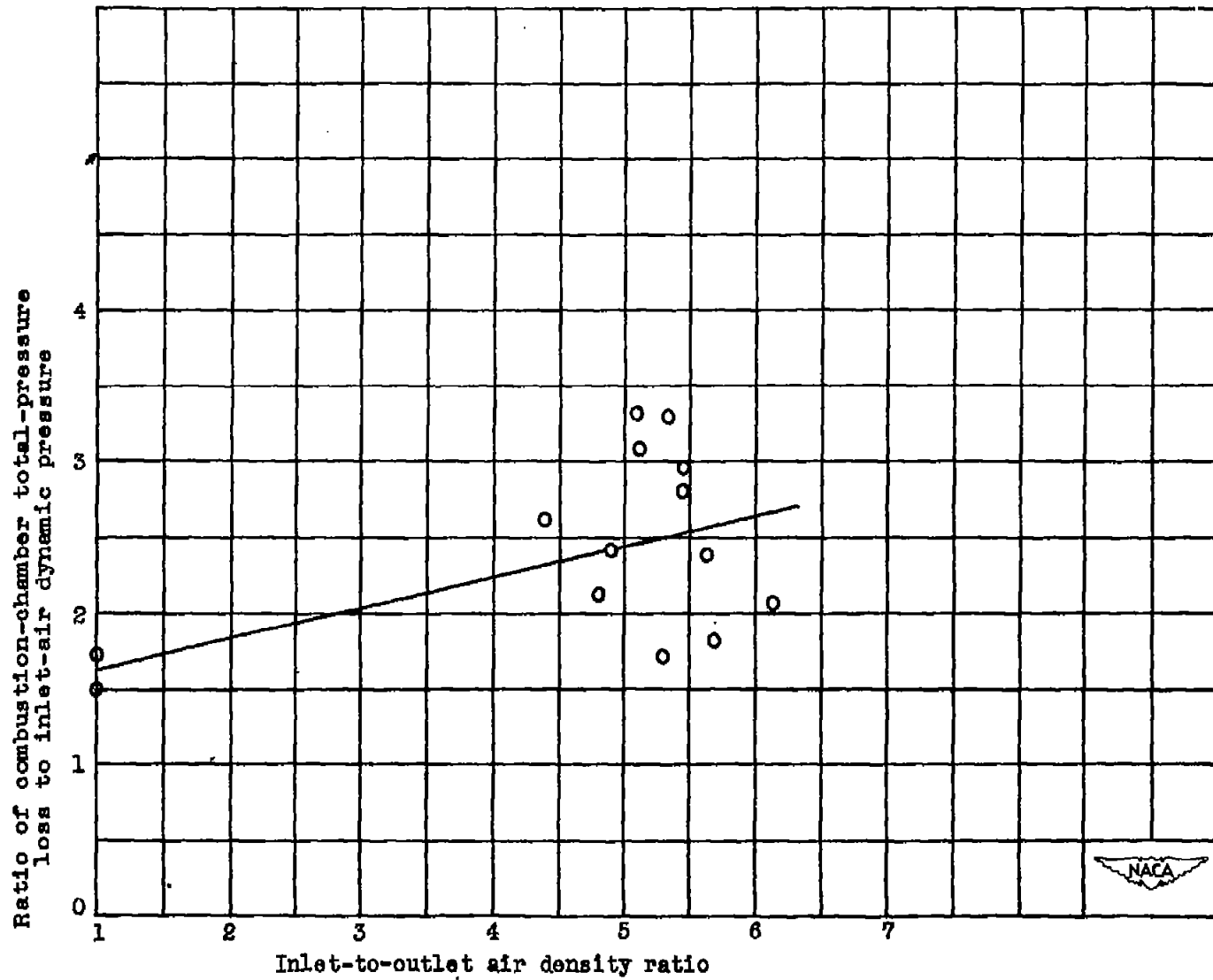


Figure 11. - Correlation of combustion-chamber total-pressure loss with inlet-to-outlet air density ratio.