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RESEARCH MEMORANDUM

SUBSONIC FLIGHT INVESTIGATION OF RECTANGULAR RAM JET OVER RANGE OF ALTITUDES

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SUBSONIC FLIGHT INVESTIGATION OF RECTANGULAR RAM JET OVER RANGE OF ALTITUDES

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SUMMARY

A flight investigation was conducted on a rectangular ram jet incorporating a V-shaped gutter-type flame holder over a range of fuel-air ratios from 0.019 to 0.112, combustion-chamber-inlet velocities from 39 to 101 feet per second, and pressure altitudes from 1500 to 29,200 feet.

The maximum combustion efficiency obtained was approximately 84 percent at a fuel-air ratio of 0.069 and a pressure altitude of 1500 feet. An increase in altitude resulted in a pronounced decrease in combustion efficiency. The highest pressure altitude at which ignition was possible with the spark plug and ignition cone was 22,500 feet. Above 11,000 feet, an increase in altitude increased the value of fuel-air ratio at which lean blow-out occurred. Rough engine operation was encountered only at altitudes above 20,000 feet as the fuel-air ratio approached the lean or rich blow-out limits.

INTRODUCTION

As part of a research program for the study of ram jets, a flight investigation is being conducted at the NACA Cleveland laboratory on a rectangular ram jet installed in a short-span wing mounted beneath the fuselage of a twin-engine, fighter-type airplane. This type of power plant was designed for installation within the wings of a high-speed airplane or missile.

The purpose of the investigation is to determine the performance and operational characteristics of a rectangular ram jet over a range of altitudes at subsonic velocities. During a test-stand investigation (reference 1), a similar engine operated satisfactorily over a range of fuel-air ratios from 0.025 to 0.083. Owing to the comparatively low inlet-air velocities available, only a limited amount of data could be obtained on ignition, blow-out, and combustion efficiency. The flight investigation reported herein was made at pressure altitudes from 1500 to 29,200 feet in order to determine the effect of altitude on ignition, lean and rich blow-out limits, and combustion efficiency.

The results obtained over a range of fuel-air ratios from 0.019 to 0.112, combustion-chamber-inlet velocities from 39 to 101 feet per second, and pressure altitudes from 1500 to 29,200 feet are presented.

APPARATUS AND PROCEDURE

Ram-Jet Installation

The rectangular ram jet investigated was installed in a short-span wing supported beneath the fuselage of a twin-engine, fighter-type airplane, as shown in figures 1 and 2. Ducts for cooling air were provided to ventilate the space between the combustion chamber and the outer shell in order to avoid possible accumulation of explosive vapors; these ducts, however, had no effect on the operation of the ram-jet engine. The entrances and exits of these ducts are located in the wing-tip sections, as shown in figure 2. Inasmuch as no provisions were made to vary the angle of attack of the ram jet, it varied with a change in indicated airspeed. The variation ranged from 1° at an indicated airspeed of 240 miles per hour to 6° at 160 miles per hour. Figure 3 shows the disassembled components of the engine and the wing installation.

The rectangular ram jet (fig. 4) consists of an inlet diffuser, a combustion chamber, and an exhaust nozzle. The diffuser is of rectangular cross section with parallel sides and has a total diffuser angle of 12° between the top and bottom walls. The maximum combustion-chamber area is twice and the exhaust-nozzle area 1.3 times the diffuser-inlet area. The combustion chamber was cooled by circulating fuel through a corrugated manifold seam-welded to the surface of the combustion-chamber wall. The fuel was introduced under pressure at the rear of the combustion chamber, circulated in separate parallel paths the entire length of the combustion chamber, and discharged into a common fuel-spray bar located along the horizontal center line of the diffuser. In addition to cooling the combustion chamber, this system preheated the fuel. The fuel-pressure loss in the corrugated manifold was kept to a minimum by using a number of separate flow paths instead of one continuous path. The fuel-spray bar consisted of six evenly spaced nozzles. The nozzles discharged downstream in a 60° cone. Each nozzle was rated at a fuel flow of 40 gallons per hour at a fuel pressure of 100 pounds per square inch gage. The fuel used for these tests was AN-F-23A (73-octane gasoline).

The flame holder consisted of 4 horizontal and 17 vertical V-shaped gutters and was fabricated from 0.064-inch Inconel. The measured static-pressure drop without combustion for this flame holder was 3.1 times the dynamic pressure in front of the flame holder. The flame holder was mounted in such a manner (fig. 4) that no direct connection existed between the flame holder and the combustion-chamber walls, which could advance the flame to the walls and result in uneven wall temperatures. Burning was initiated by a spark plug installed in a shielding cone mounted in front of the flame holder. No auxiliary fuel was introduced in the cone.

Instrumentation

The total and static pressures were measured at the diffuser inlet by 3 total- and static-pressure rakes and 18 static-pressure wall orifices. A total-pressure rake in front of the flame holder measured the pressure at the inlet to the combustion chamber. At the exit of the ram jet, the static pressure was measured by two static-pressure wall orifices and the total pressure was measured by a water-cooled rake. All pressure tubes were connected to a multiple-tube liquid-manometer board. Sensitive indicators were used to obtain the indicated airspeed and altitude as measured by a swiveling static-pressure tube and a shrouded total-pressure tube installed on a boom 1 chord length ahead of the leading edge of the right wing tip. Pressure gages indicated the fuel pressure at the pump outlet and at the inlet to the ram-jet manifold. The fuel flow was indicated on a gage and was measured by a vane-type flowmeter. All indicators were mounted on the manometer board, which was photographed during flight.

An automatic potentiometer recorded temperatures obtained from chromel-alumel thermocouples located throughout the ram-jet unit. These measurements consisted of 24 combustion-chamber-wall temperatures, 8 fuel temperatures at the inlet to the fuel-spray bar, 2 fuel temperatures at the inlet to the combustion-chamber manifold, and 8 ventilating-air temperatures between the combustion chamber and the top and bottom wing sections. The free-air temperature was measured by a flight-calibrated iron-constantan thermocouple installed under the left wing of the airplane.

Flight Program

The starting characteristics and blow-out limits for the rectangular ram jet were determined over a pressure-altitude range from 1500 to 29,200 feet and for indicated airspeeds from 150 to 240 miles per hour. 823

The effect of altitude on combustion efficiency was determined for the following ranges of indicated airspeed and fuel-air ratio:

Pressure altitude (ft)	Indicated airspeed (mph)	Fuel-air ratio
1,500	160	0.025 - 0.076
	200	.029 - .090
	240	.066 - .090
6,000	160	.028 - .112
	200	.023 - .096
16,000	160	.028 - .108
	200	.040 - .094
	240	.062 - .098
26,000	160	.079 - .106
	200	.068 - .082

METHOD OF CALCULATIONS

Engine air flow was calculated from the total and the static pressures measured at the inlet to the diffuser.

The exhaust-gas temperature at the exit of the ram jet was calculated from the measured gas flow and pressure measurements at the exit of the combustion-chamber nozzle in accordance with the method outlined in reference 2. The combustion efficiency was determined by the following equation:

$$\eta_b = \frac{H_g - H_a}{f/a\ (h_f)} 100$$

where

η_b combustion efficiency, percent

H_g enthalpy of burned gases at exit gas temperature, Btu per pound of original air

H_a enthalpy of air and fuel before combustion, Btu per pound of original air

f/a fuel-air ratio

h_f lower heating value of fuel, 18,500 Btu per pound

For the purpose of these calculations, H_g was assumed equal to the enthalpy of air at the exhaust-gas temperature plus the sum of the enthalpies of the carbon dioxide and water that result from complete combustion minus the enthalpy of oxygen required for complete combustion. Enthalpy values were obtained from reference 3.

RESULTS AND DISCUSSION

At low altitudes (below 6000 ft), the exhaust flame was light blue in color at fuel-air ratios from 0.05 to 0.07 and extended approximately 1 foot beyond the exit of the engine. As the fuel-air ratio was increased, the flame became longer and yellow in color owing to the afterburning of the excess fuel. The exhaust flame became less visible as the altitude was increased and was no longer visible even at high fuel-air ratios above an altitude of 16,000 feet. Figure 5 shows the ram jet operating at a pressure altitude of 6000 feet, an indicated airspeed of 160 miles per hour, and a fuel-air ratio of 0.140. The flame was very yellow and extended approximately 6 feet beyond the engine.

Air-flow separation occurred at the top leading edge of the diffuser section of the engine at indicated airspeeds in excess of 240 miles per hour. This separation resulted in extremely rough operation of the engine and erroneous air-flow measurements. As a result, the investigation was limited and no data are given for indicated airspeeds in excess of 240 miles per hour.

Rough engine operation was also encountered at altitudes above 20,000 feet as the fuel-air ratio approached the lean or rich blow-out limits. Rapid acceleration of fuel flow at high altitudes resulted in extremely rough operation, which was accompanied by a loud rumbling noise and sometimes resulted in blow-out.

The ram jet cooled properly at all altitudes and operating conditions over which the investigation was conducted. The maximum combustion-chamber-wall temperature was 350° F at an altitude of 1500 feet. An increase in altitude resulted in a decrease in combustion-chamber-wall temperatures.

The minimum fuel-air ratio at which ignition was possible was determined for a given altitude by maintaining a constant indicated airspeed, turning on the spark, and increasing the fuel flow until ignition occurred. This minimum fuel-air ratio is defined as the ratio of the fuel flow (lb/hr) at which ignition occurred to the air flow (lb/hr) as measured at the given altitude and airspeed without combustion. Figure 6 illustrates the effect of altitude on the minimum fuel-air ratio at which ignition occurred. The indicated airspeeds are given for each test point. At an altitude of 11,000 feet and above, the indicated airspeeds are the maximum airspeeds at which ignition was possible with the spark-plug cone. The lowest value of minimum fuel-air ratio is 0.028 and occurs at an altitude of 1500 feet. Increasing the altitude increased the minimum fuel-air ratio to 0.078 at an altitude of 22,500 feet. The ram jet would not start above this altitude with the spark-plug cone and flame holder used.

The effect of altitude and indicated airspeed on the fuel-air ratio at which blow-out occurred is shown in figure 7. This fuel-air ratio was determined as the ratio of the fuel flow at which blow-out occurred and combustion ceased to the air flow immediately preceding blow-out. At altitudes below 11,000 feet, a variation in altitude had little effect on the fuel-air ratio at lean blow-out conditions for a given indicated airspeed. An increase in altitude above 11,000 feet, however, resulted in the occurrence of lean blow-out at increasing values of fuel-air ratio. Inasmuch as no data were taken at fuel-air ratios above 0.112, rich blow-out was only noted at altitudes above 21,000 feet. An increase in indicated airspeed at a given altitude resulted in an increase in the fuel-air ratio at lean blow-out and a decrease in fuel-air ratio at rich blow-out for the altitudes at which rich blow-out occurred. In general, figure 7 shows the operating fuel-air-ratio range for a given altitude and indicated airspeed.

The effects of fuel-air ratio on gas total-temperature rise (defined as exhaust-gas temperature minus inlet-air temperature) for altitudes of 1500, 6000, 16,000, and 26,000 feet are shown in figure 8 and compared in figure 9. The maximum gas total-temperature rise occurred at an altitude of 1500 feet and an increase in altitude resulted in a decrease in gas total-temperature rise for a given fuel-air ratio.

The effects of fuel-air ratio on combustion efficiency for altitudes of 1500, 6000, 16,000, and 26,000 feet are shown in figure 10 and compared in figure 11. An increase in altitude resulted in a pronounced decrease in combustion efficiency. No attempt was made to isolate the factors contributing to this decrease; however, the decrease in efficiency may be attributed to the combined effects of a decrease in air pressure, air temperature, and fuel pressure, which resulted in a decrease in atomization of the fuel and penetration of the fuel particles in the air stream. The maximum combustion efficiency was approximately 84 percent at a fuel-air ratio of 0.069 and an altitude of 1500 feet (fig. 11), as compared with maximum efficiencies of approximately 73.5 percent at 0.071 and 6000 feet, 53 percent at 0.085 and 16,000 feet, and 32 percent at 0.090 and 26,000 feet. In general, an increase in altitude resulted in the maximum combustion efficiency occurring at higher values of fuel-air ratio.

SUMMARY OF RESULTS

From a flight investigation of a rectangular ram jet incorporating a V-shaped gutter-type flame holder over a range of fuel-air ratios from 0.019 to 0.112, combustion-chamber-inlet velocities from 39 to 101 feet per second, and pressure altitudes from 1500 to 29,200 feet, the following results were obtained:

1. The maximum combustion efficiency obtained was approximately 84 percent at a fuel-air ratio of 0.069 and a pressure altitude of 1500 feet. An increase in altitude resulted in a pronounced decrease in combustion efficiency.

2. An increase in altitude increased the value of minimum fuel-air ratio at which ignition was possible with the present spark-plug cone and flame holder. The highest altitude at which ignition was possible was 22,500 feet.

3. Above 11,000 feet, an increase in altitude increased the value of fuel-air ratio at which lean blow-out occurred.

4. Rough engine operation was encountered only at altitudes above 20,000 feet as the fuel-air ratio approached the lean or rich blow-out limits.

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1. Black, Dugald O., and Messing, Wesley E.: Test-Stand Investigation of a Rectangular Ram-Jet Engine. NACA RM No. E7D11, 1947.

2. Perchonok, Eugene, Wilcox, Fred A., and Sterbentz, William H.: Preliminary Development and Performance Investigation of a 20-Inch Steady-Flow Ram Jet. NACA ACR No. E6D05, 1946.

3. Turner, L. Richard, and Lord, Albert M.: Thermodynamic Charts for the Computation of Combustion and Mixture Temperatures at Constant Pressure. NACA TN No. 1086, 1946.

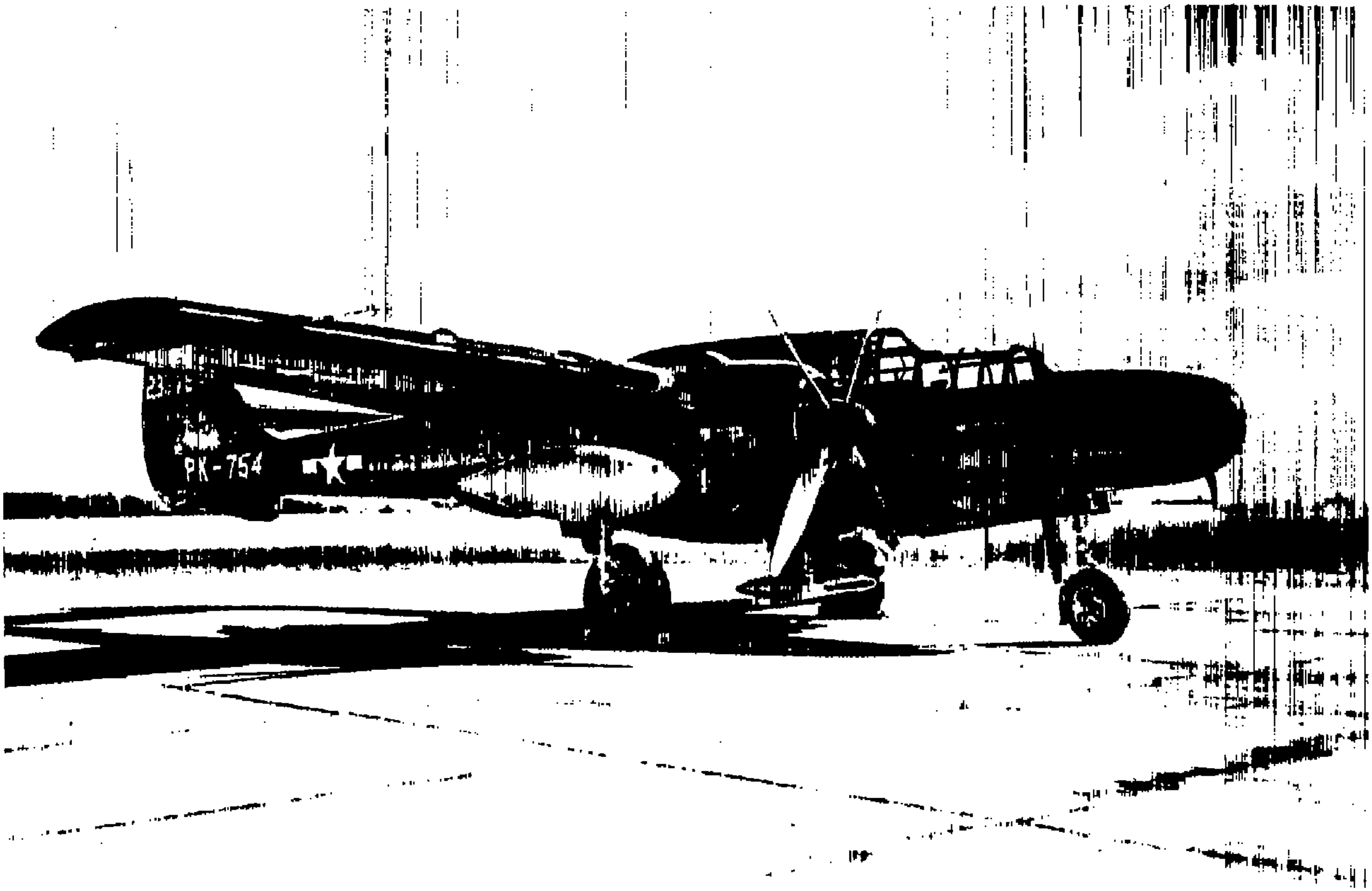

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Figure 1. - Rectangular ram jet installed beneath fuselage of twin-engine, fighter-type airplane.

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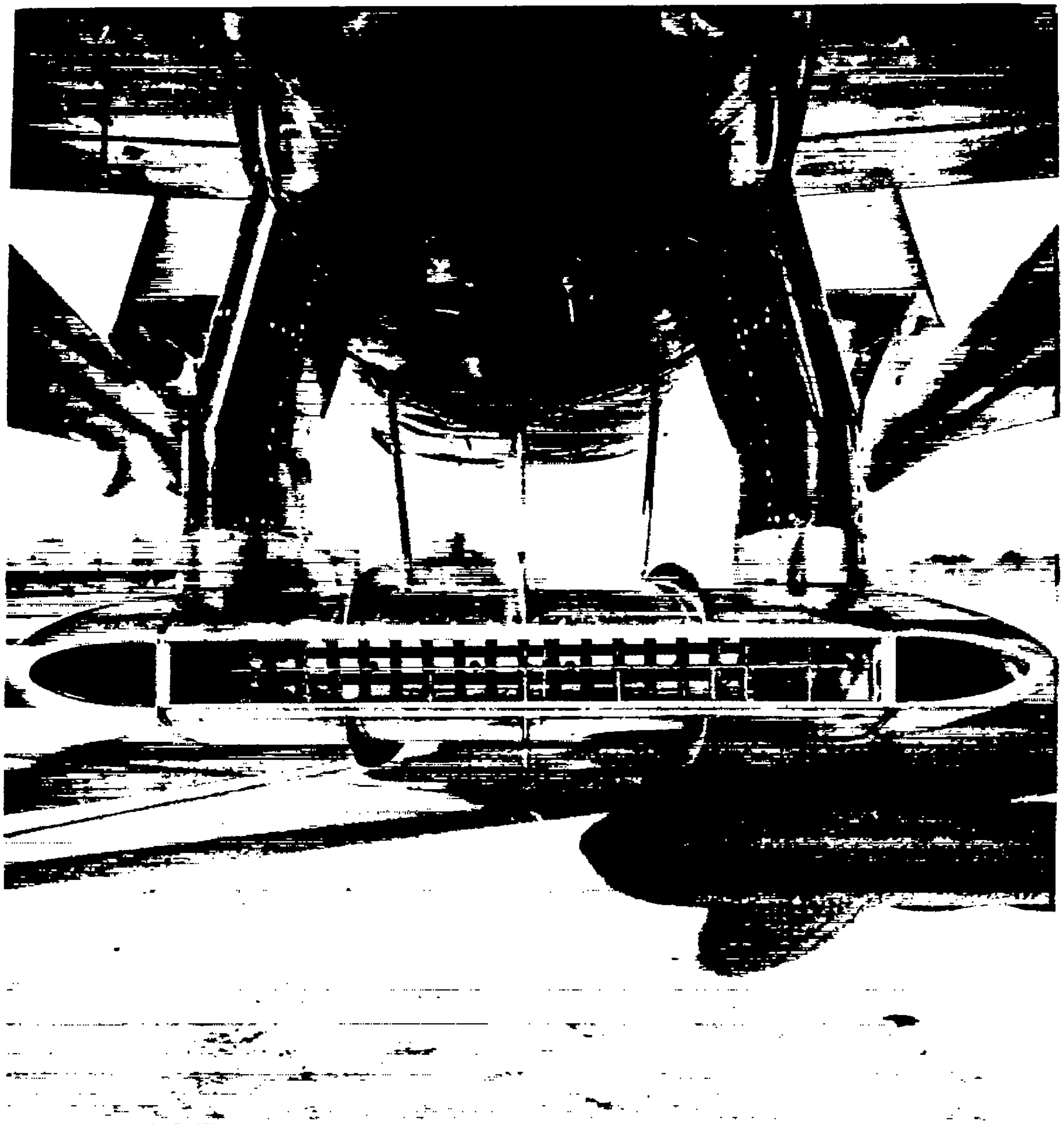

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(a) Front view.

Figure 2. - Rectangular ram-jet installation for flight investigation.

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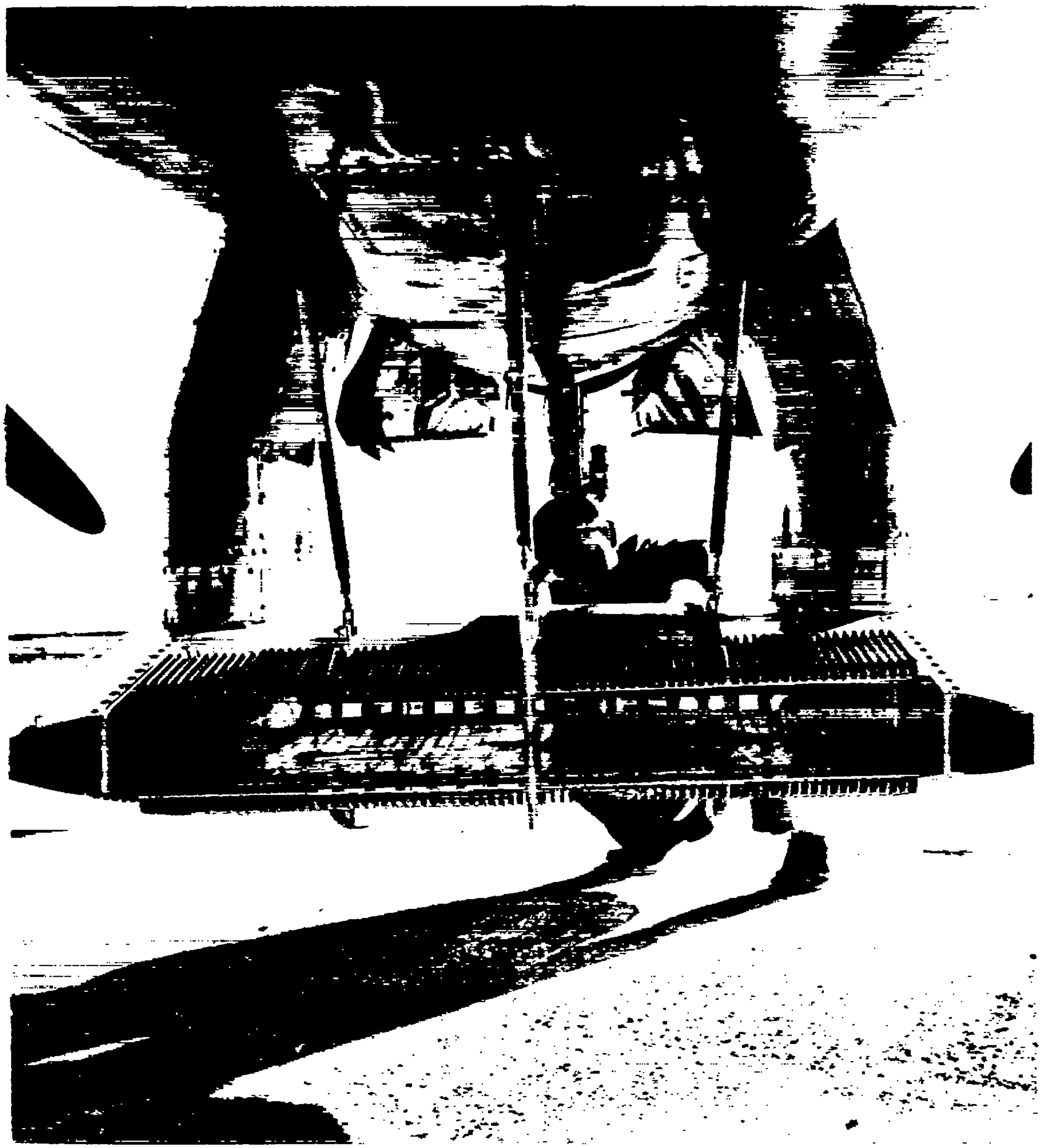

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(b) Rear view.

Figure 2. .- Concluded. Rectangular ram-jet installation for flight investigation.

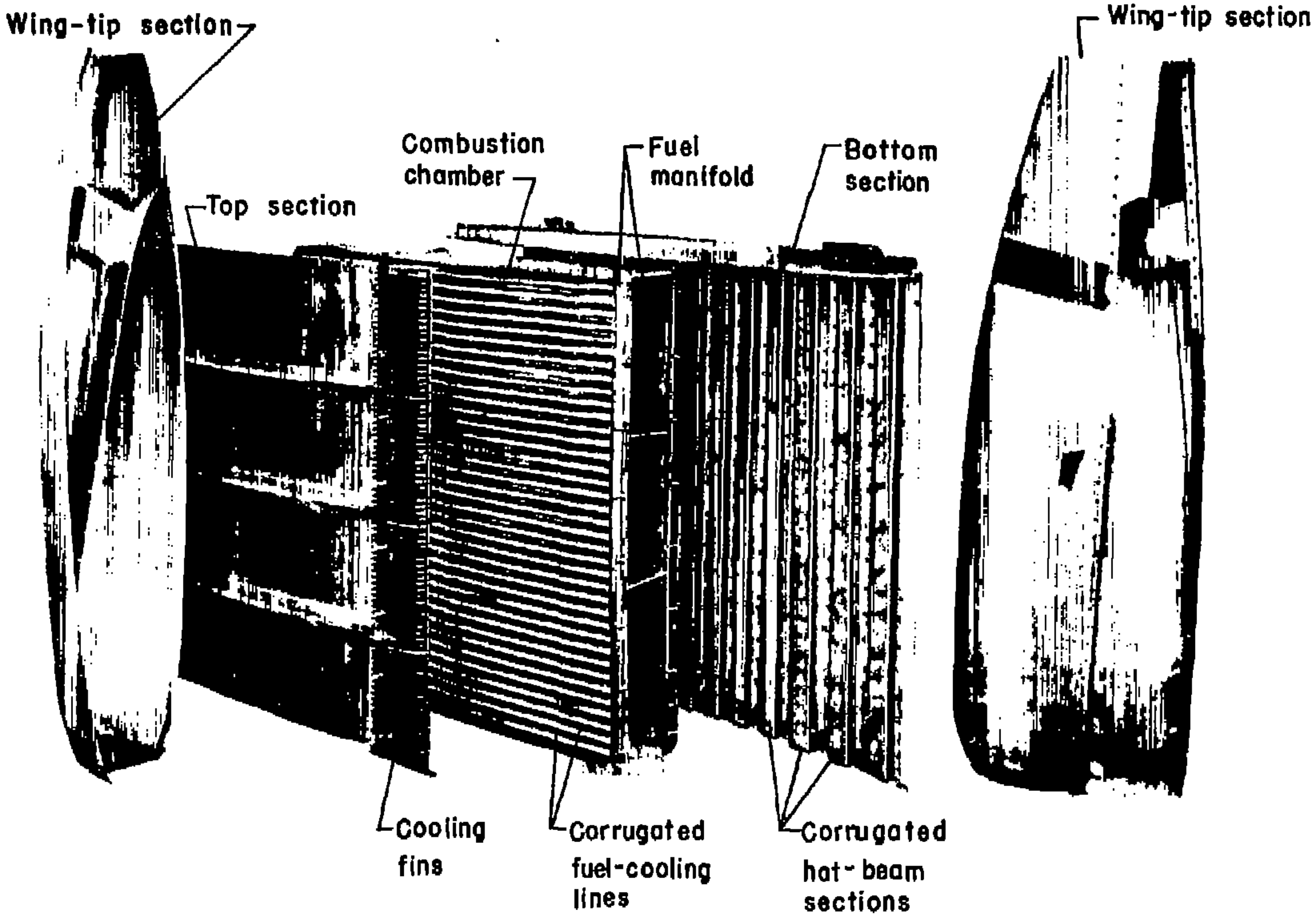

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Figure 3. - Disassembled components of rectangular ram-jet and wing installation.

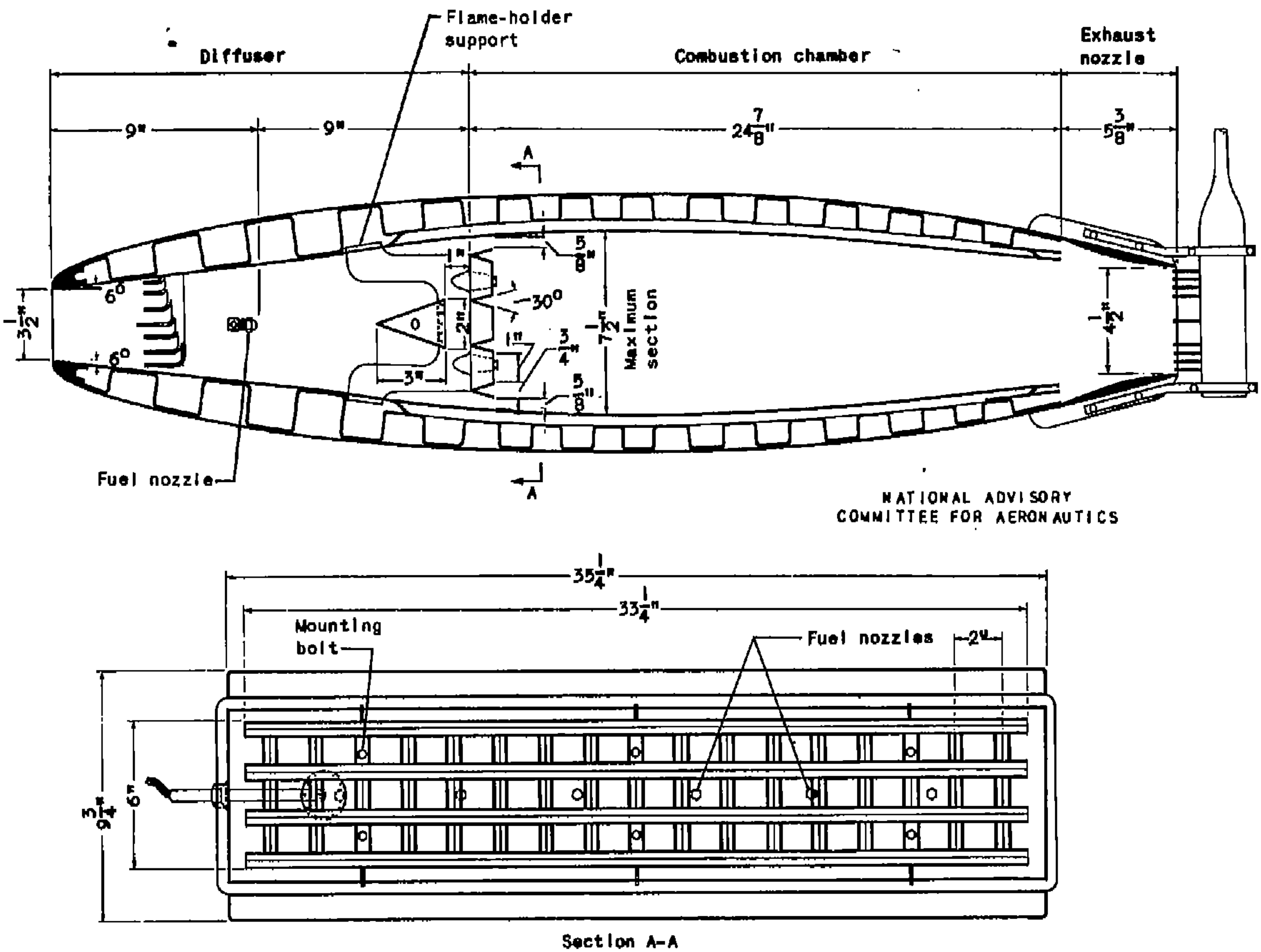

Figure 4. - Schematic drawing of rectangular ram jet incorporating four-V gutter-type flame holder.

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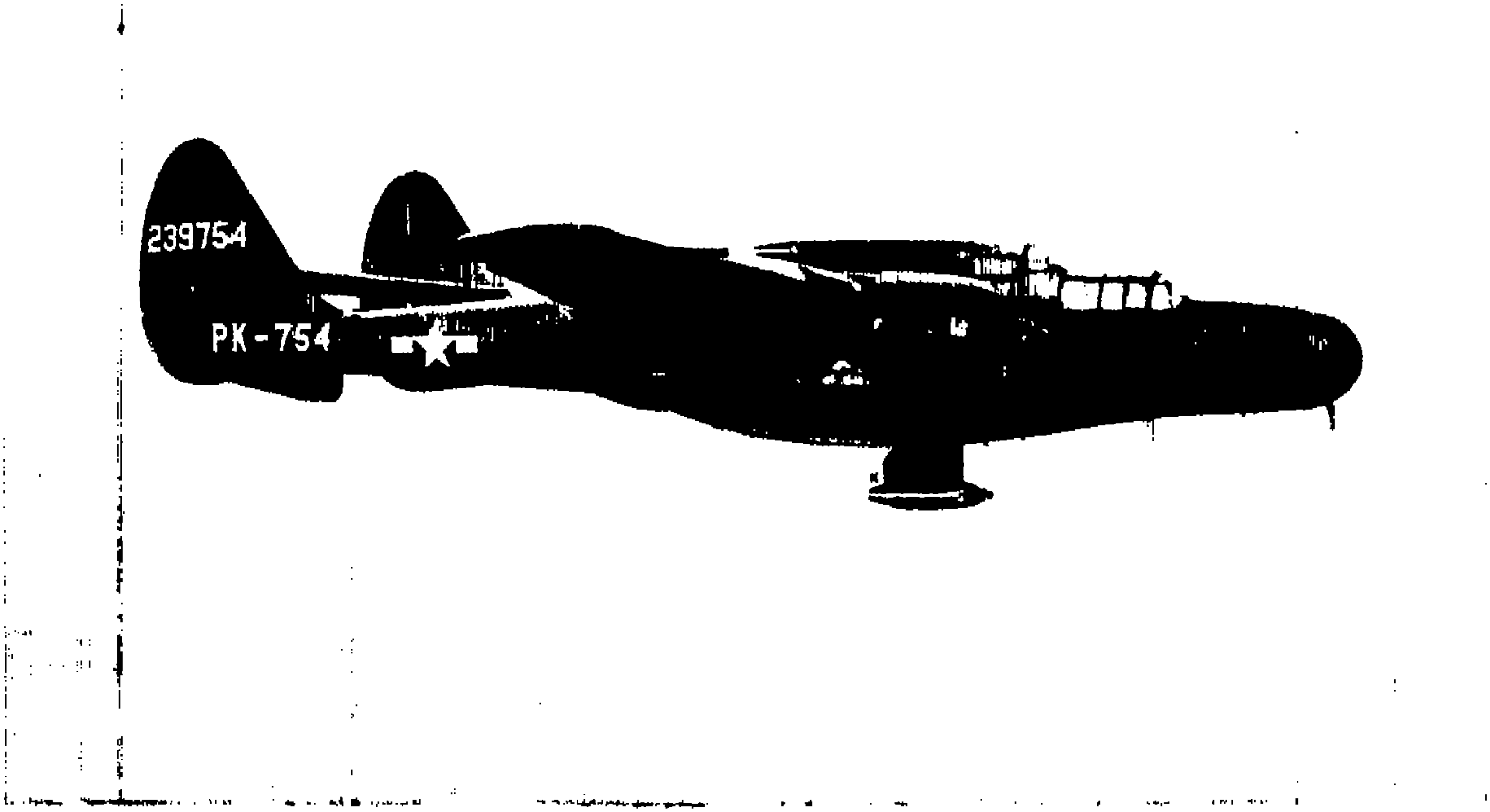

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Figure 5. - Rectangular ram jet in operation. Pressure altitude, 6000 feet; indicated airspeed, 160 miles per hour; fuel-air ratio, 0.140.

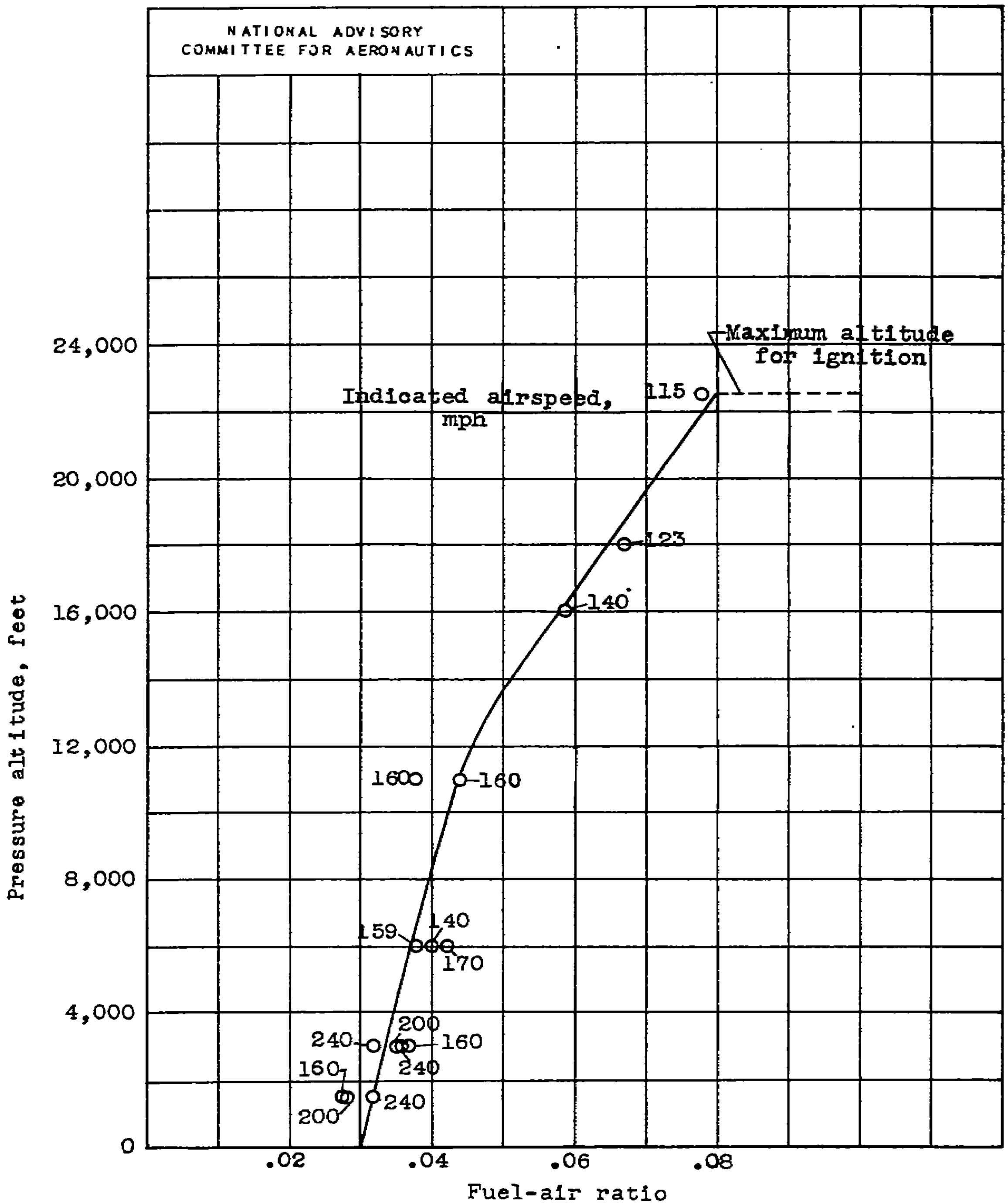

Figure 6. - Minimum fuel-air ratio at which ignition occurred for various pressure altitudes and indicated airspeeds.

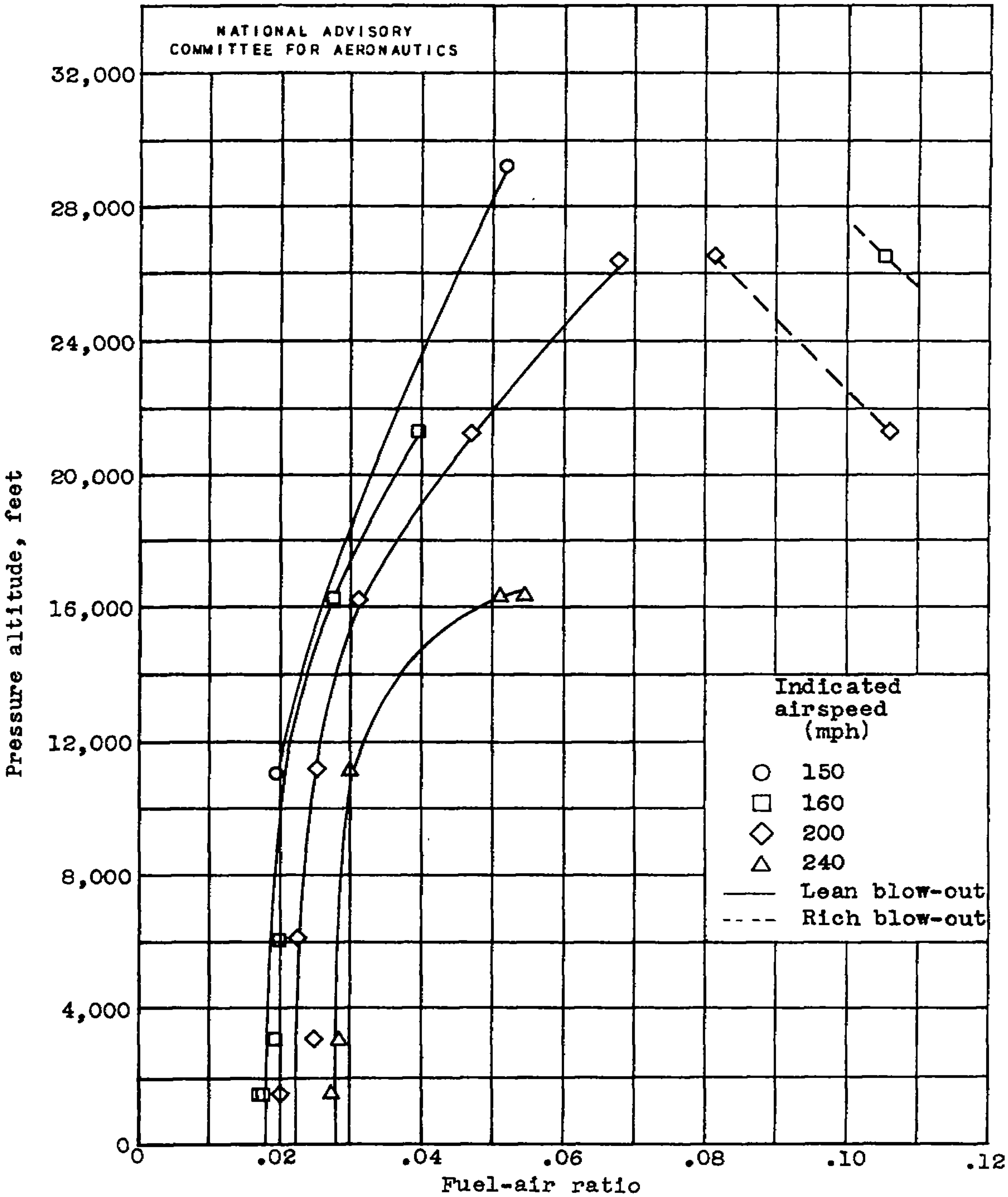

Figure 7. - Effect of pressure altitude and indicated airspeed on blow-out limits.

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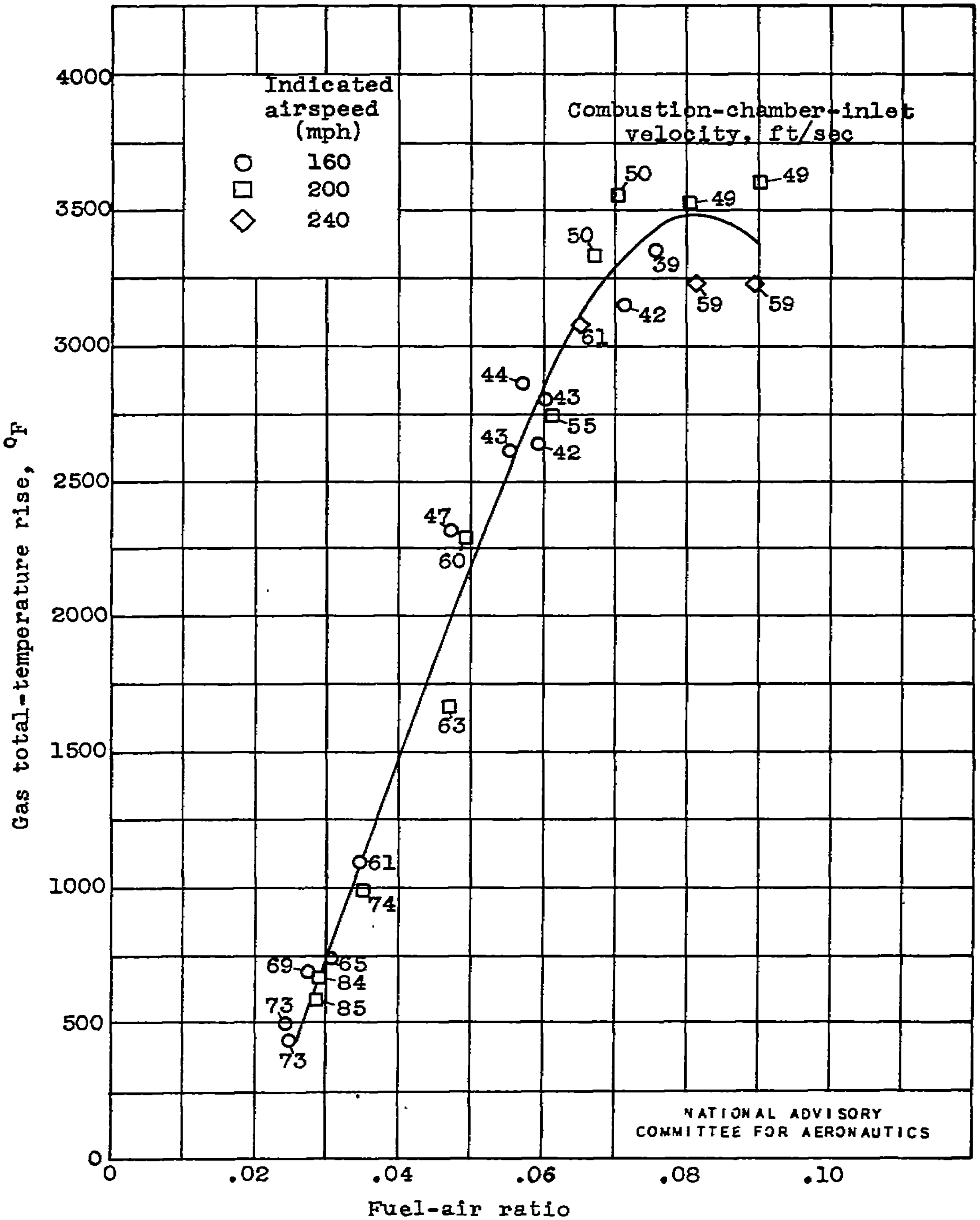
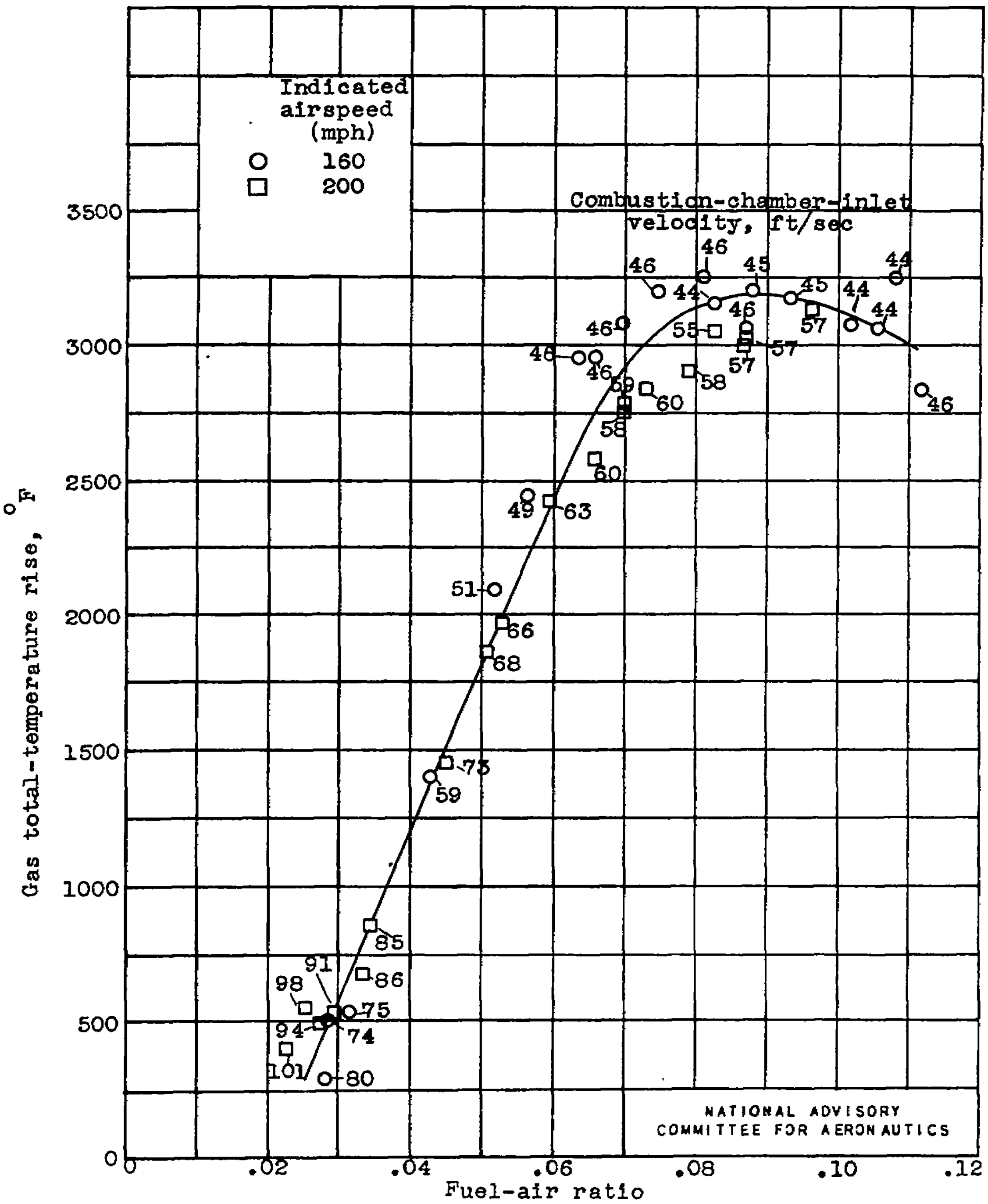


(a) Pressure altitude, 1500 feet; average inlet-air temperature, 38° F.

Figure 8. - Effect of fuel-air ratio on gas total-temperature rise.



(b) Pressure altitude, 6000 feet; average inlet-air temperature, 52° F.

Figure 8. - Continued. Effect of fuel-air ratio on gas total-temperature rise.

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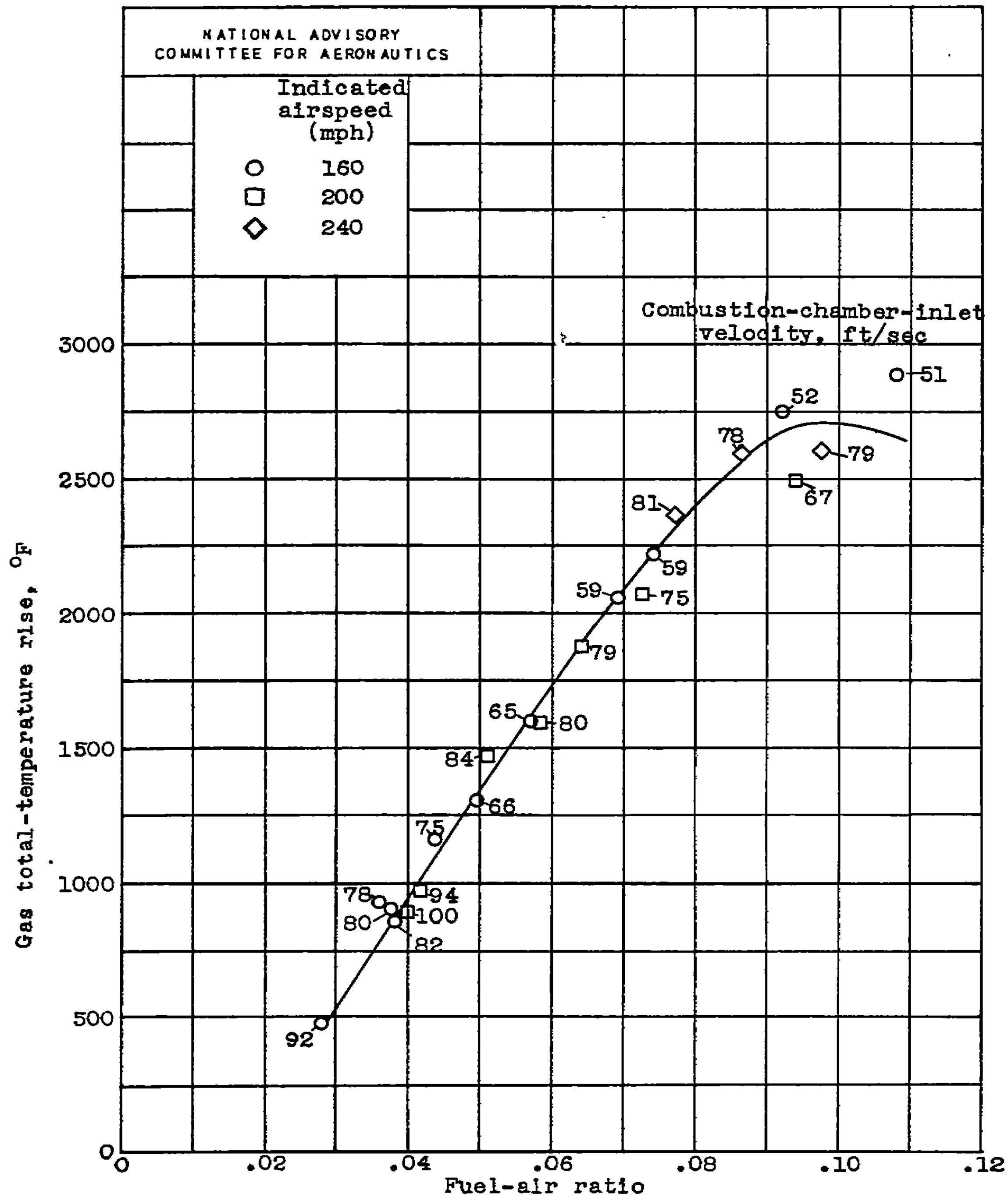
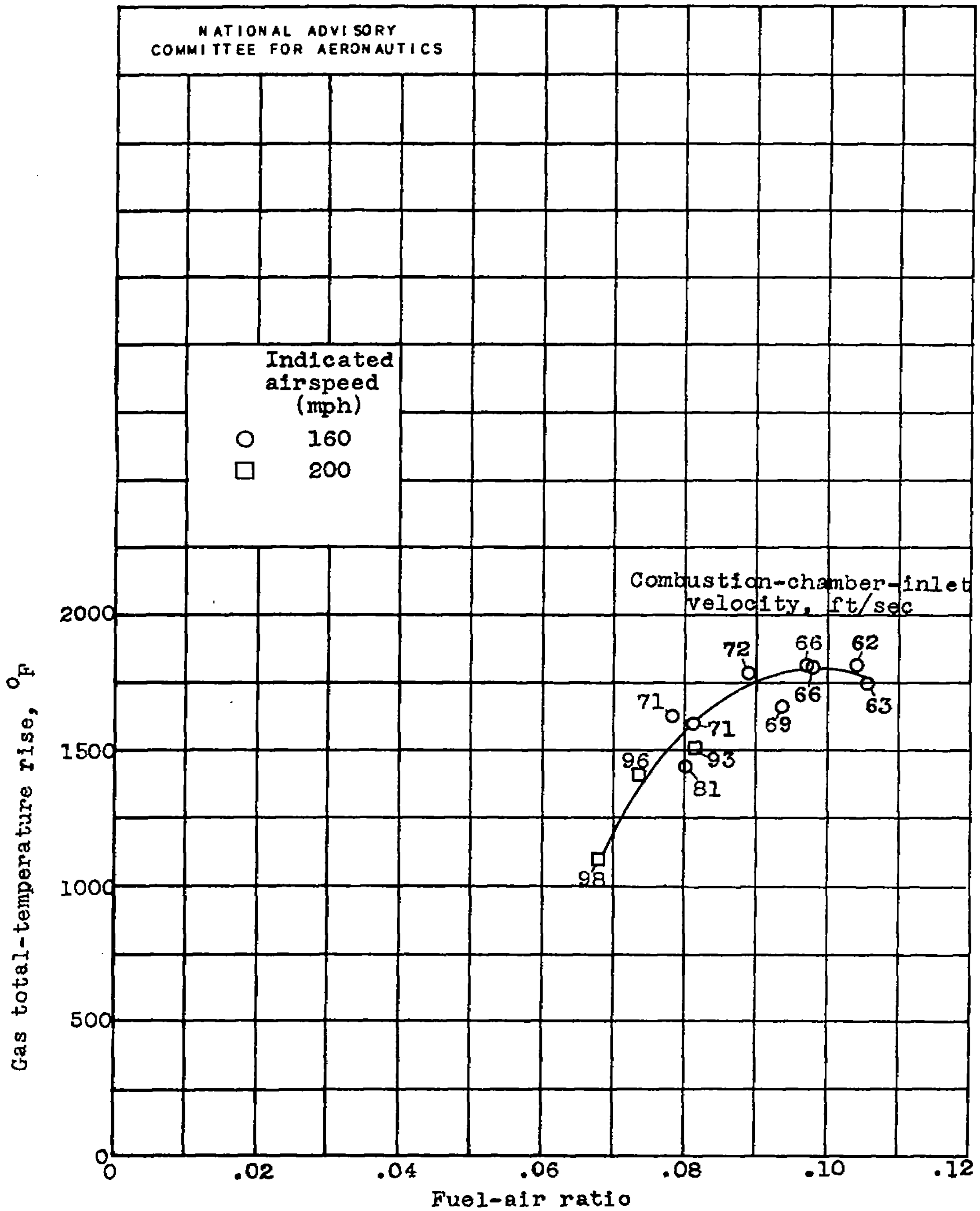


(c) Pressure altitude, 16,000 feet; average inlet-air temperature, 7° F.

Figure 8. - Continued. Effect of fuel-air ratio on gas total-temperature rise.



(d) Pressure altitude, 26,000 feet; average inlet-air temperature, -30° F.

Figure 8. - Concluded. Effect of fuel-air ratio on gas total-temperature rise.

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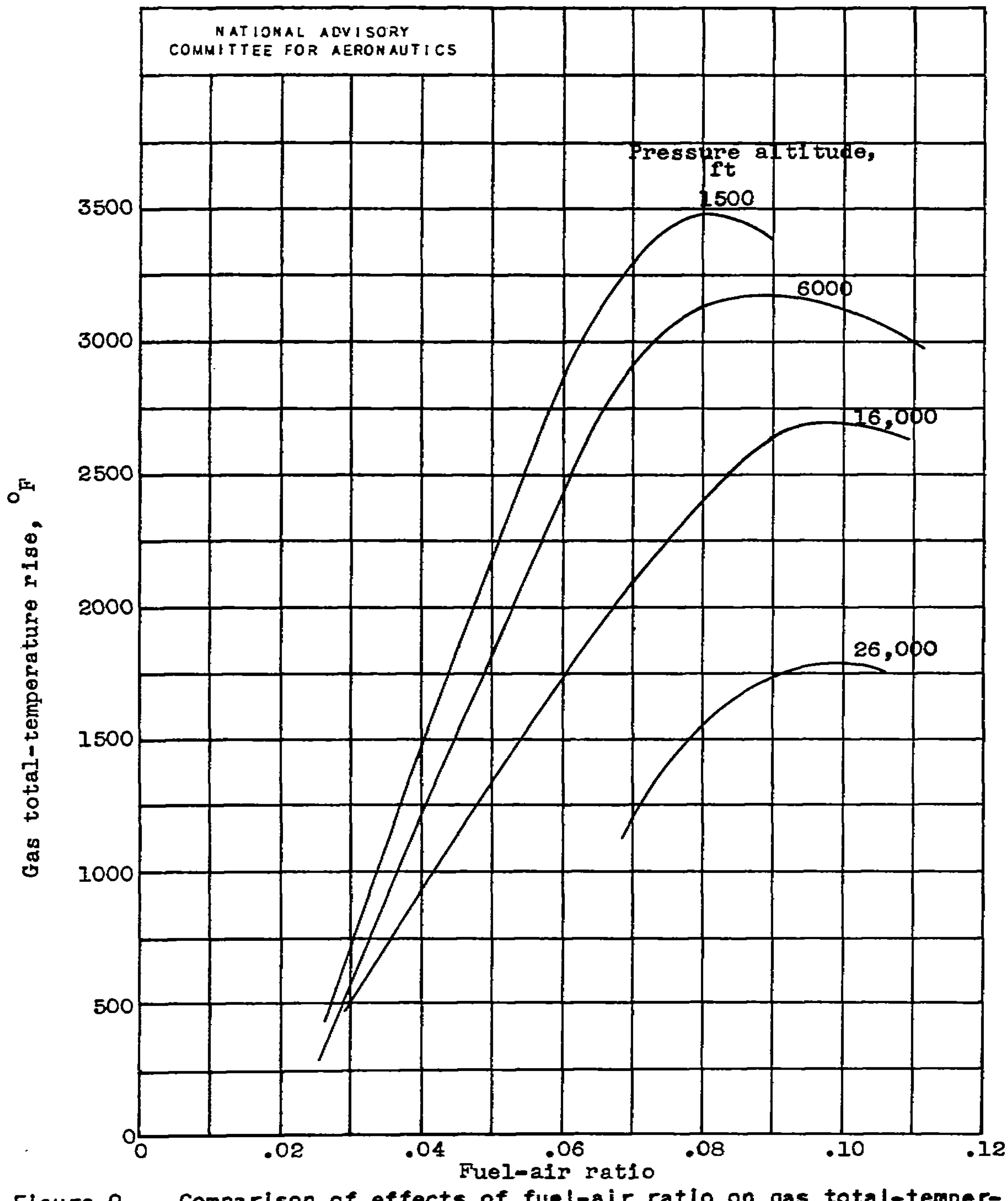
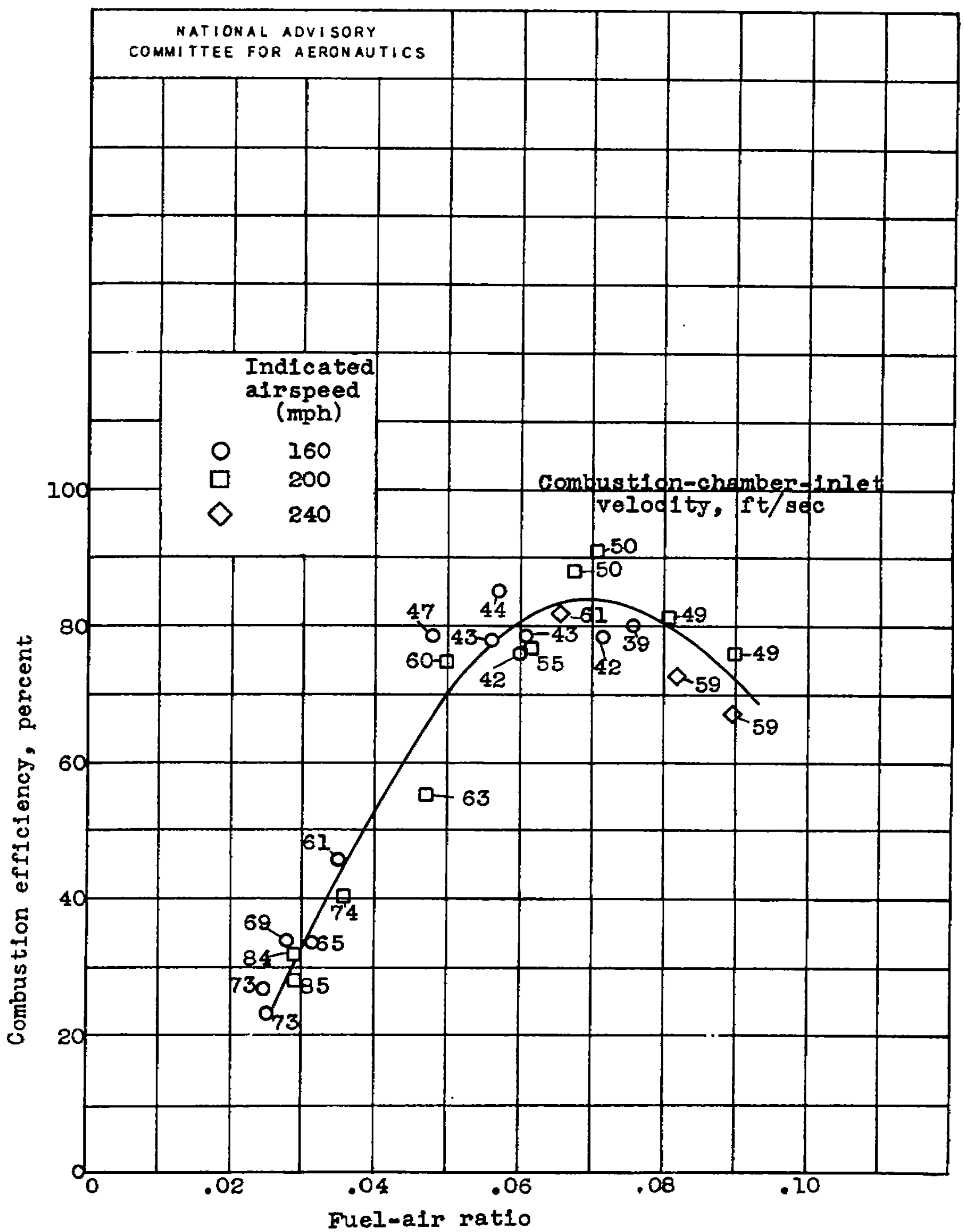
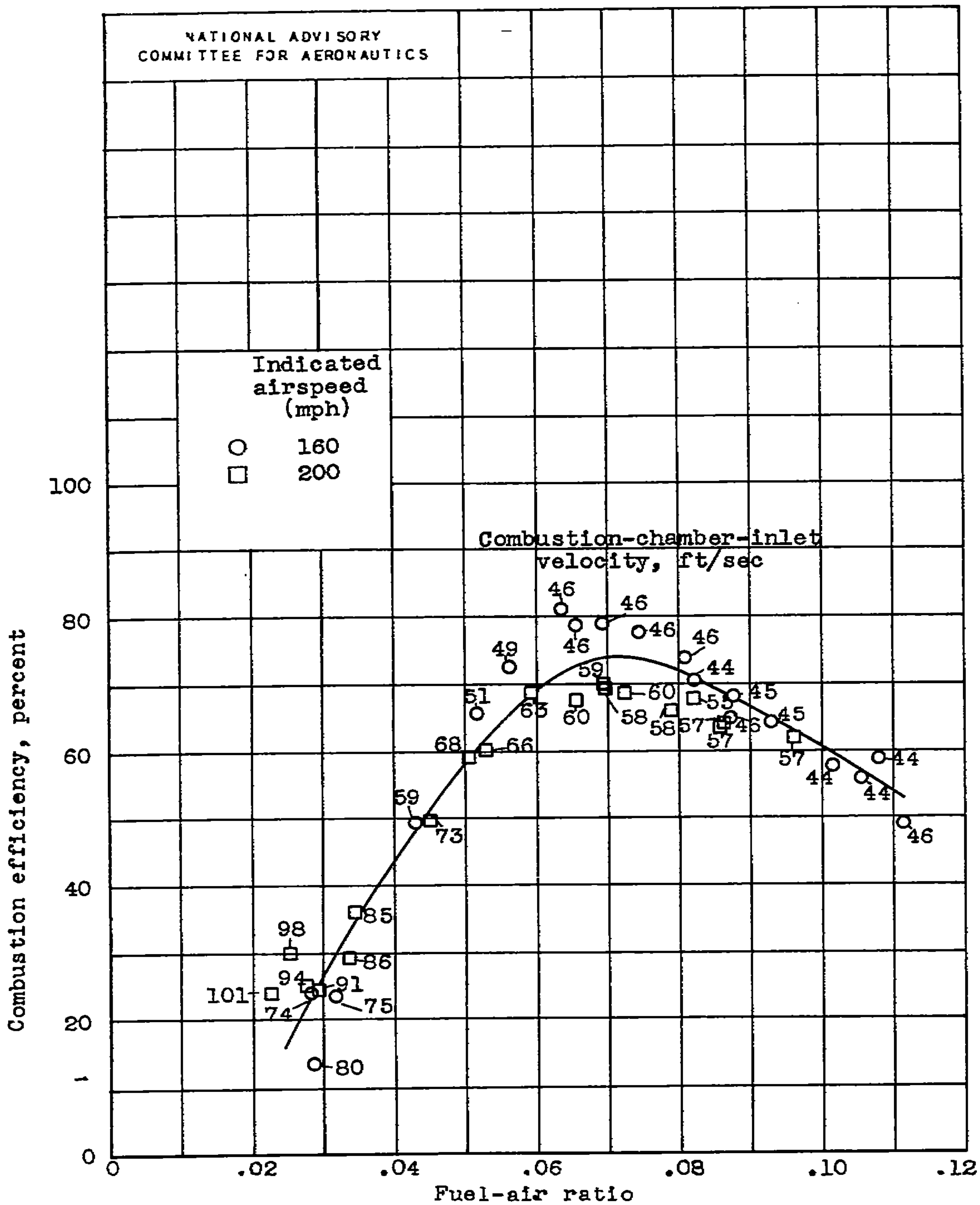


Figure 9. - Comparison of effects of fuel-air ratio on gas total-temperature rise at various altitudes.



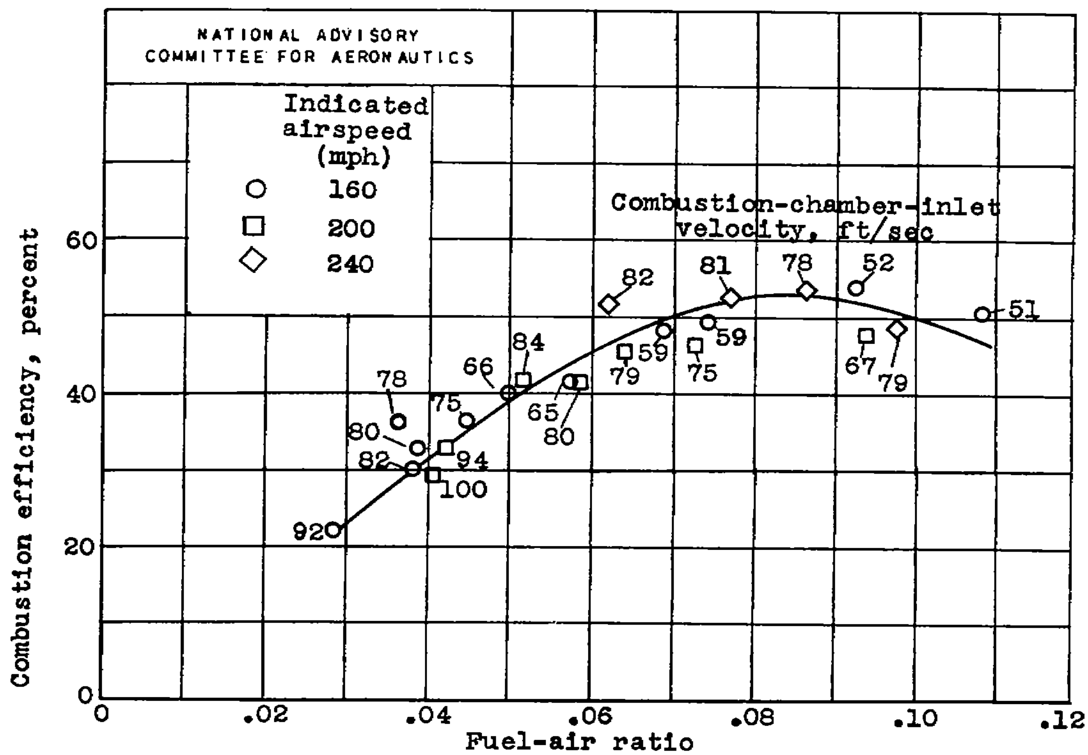
(a) Pressure altitude, 1500 feet; average inlet-air temperature, 38° F.

Figure 10. - Effect of fuel-air ratio on combustion efficiency.

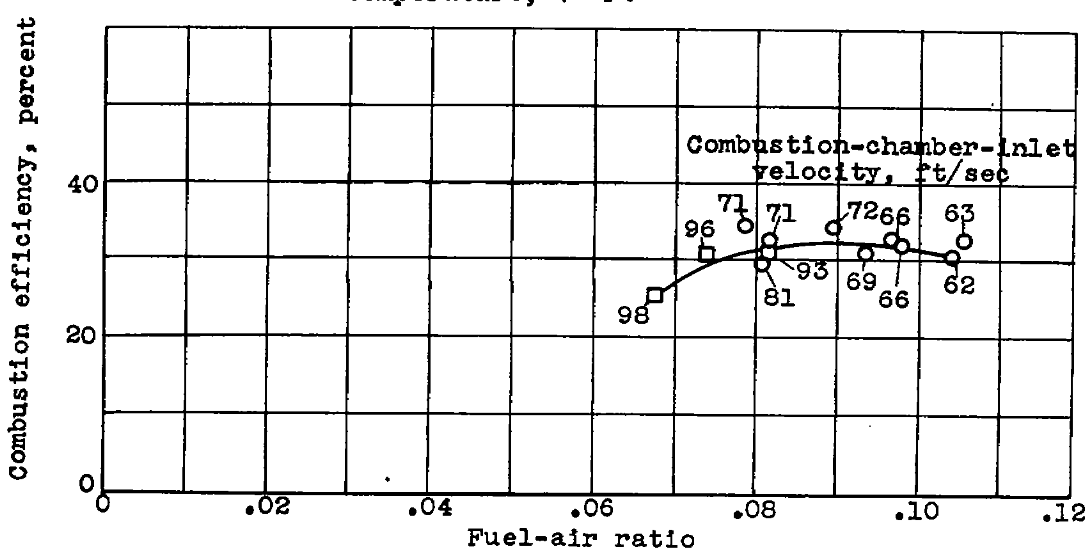


(b) Pressure altitude, 6000 feet; average inlet-air temperature, 52° F

Figure 10. - Continued. Effect of fuel-air ratio on combustion efficiency.



(c) Pressure altitude, 16,000 feet; average inlet-air temperature, 7° F.



(d) Pressure altitude, 26,000 feet; average inlet-air temperature, -30° F.

Figure 10. - Concluded. Effect of fuel-air ratio on combustion efficiency.

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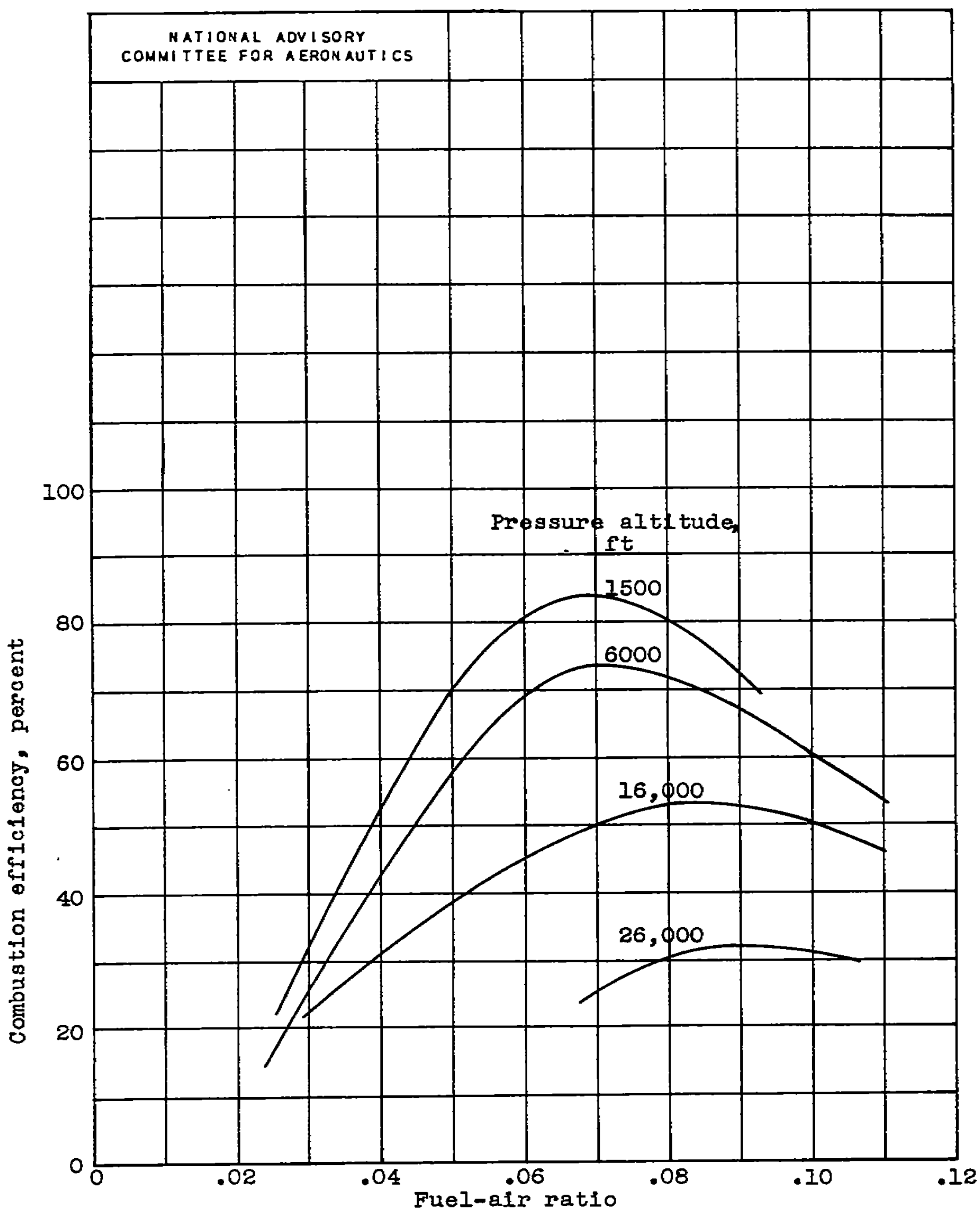

Figure 11. - Comparison of effects of fuel-air ratio on combustion efficiency at various altitudes.