COPY NO 340
RM No. E7I05a

NACA

RESEARCH MEMORANDUM

FLIGHT INVESTIGATION OF A 20-INCH-DIAMETER STEADY-FLOW RAM JET

By John H. Disher

Flight Propulsion Research Laboratory
Cleveland, Ohio

[redacted]

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
WASHINGTON
January 14, 1948

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

FLIGHT INVESTIGATION OF A 20-INCH-DIAMETER STEADY-FLOW RAM JET

By John H. Disher

SUMMARY

A flight investigation was conducted on a 20-inch-diameter steady-flow ram jet at altitudes from 5000 to 30,000 feet and free-stream Mach numbers up to 0.51. Data for the variation of combustion efficiency with fuel-air ratio and pressure altitude are presented and the effects of combustion-chamber-inlet velocity and altitude on the operating range of fuel-air ratio are shown. Starting characteristics and general performance are discussed.

The ram jet was started by spark ignition at a maximum pressure altitude of 14,400 feet and a combustion-chamber-inlet velocity before ignition of 125 feet per second. Ignition was effected at an altitude of 30,000 feet and a combustion-chamber-inlet velocity of 180 feet per second by use of a magnesium flare. Operation was smooth at all conditions except for occasional rough operation at excessively rich mixtures. The minimum operating fuel-air ratio was 0.02 at an altitude of 20,000 feet and 0.013 at an altitude of 5000 feet with 90 and 88 feet per second combustion-chamber-inlet velocities, respectively.

Within the range of conditions investigated, a maximum operating fuel-air ratio was encountered only at an altitude of 30,000 feet, with blow-out occurring at a fuel-air ratio of approximately 0.085. Response to a rapid change in fuel flow was immediate and positive at low altitudes; at altitudes of 20,000 and 30,000 feet, however, blow-out was induced on several occasions by the sudden change in fuel-air ratio.

Maximum combustion efficiencies of approximately 75 and 85 percent were attained for fuel-air ratios of 0.03 to 0.04 at pressure altitudes of 5000 and 10,000 feet, respectively. The average peak efficiency decreased to approximately 67 percent at 20,000 feet with a fuel-air ratio of 0.04 and 56 percent at 30,000 feet with a fuel-air ratio of 0.06. The adverse effects of low pressure and

temperature (which occur with increasing altitude) on combustion efficiency were considerably greater at low fuel-air ratios than at those near stoichiometric mixture.

INTRODUCTION

As part of a general development program of the ram-jet type of propulsion unit for high-speed aircraft or missiles, a flight investigation has been conducted at the NACA Cleveland laboratory on a 20-inch diameter steady-flow ram jet.

The data necessary for the design of a ram jet include the relations of combustion-chamber-inlet pressure, temperature, velocity, and fuel-air ratio to the ignition characteristics and combustion efficiency. The effect of combustion-chamber-inlet conditions on the operating range of fuel-air ratio must also be known.

The object of the investigation reported herein was to evaluate these relations and effects under actual flight conditions over a limited range of free-stream Mach numbers. Wind-tunnel and test-stand studies of a similar unit are reported in references 1 to 3.

APPARATUS

For the flight investigation, the ram jet was mounted on a four-engine bomber-type airplane that has been adapted for use as a jet-propulsion test bed. A perspective drawing of the modified airplane with the 20-inch ram jet suspended from the rear bomb bay is shown in figure 1; a photograph of the unit in operation is shown in figure 2.

Provisions were made for adjusting the angle of attack of the ram jet independently of the airplane attitude and for viewing the unit through a periscope mounted on the engineer's panel. The center line of the ram jet in operating position was approximately 52 inches below the fuselage skin. Prior to the installation of the unit, a pressure survey was made beneath the airplane in the plane of the ram-jet diffuser inlet. These data indicated that free-stream conditions existed beyond a distance of approximately 24 inches from the fuselage skin.

A schematic cross-sectional drawing of the ram jet giving the principal dimensions is shown in figure 3. The flame holder provides a blocked area of approximately 50 percent and has a cold-pressure drop of approximately 2.4 times the dynamic pressure at the combustion-chamber inlet. Fuel is introduced by 15 spray nozzles mounted on a circular manifold. The nozzles spray at a 70° cone angle under static conditions and each has a capacity of 30 gallons per hour at a pressure of 100 pounds per square inch. The nozzles are directed downstream and inward at a 15° angle to the axis of the unit in order to minimize the depositing of liquid fuel on the combustion-chamber wall. In this investigation, 62-octane (AN-F-22) fuel was used.

Ignition was effected either by means of a spark plug, which was mounted forward of the flame holder on a truncated cone, as shown in figure 3, or by a magnesium flare mounted forward of the flame holder.

The combustion chamber was of corrugated construction to provide a coolant passage. For simplicity, an open vaporizing cooling system was used rather than a closed system with heat exchangers. A mixture of ethylene glycol, and water with a flow rate of 250 gallons per hour adequately cooled the ram jet.

The ram-jet assembly was enclosed in a cowling having a maximum diameter of 24 inches. A 17-inch-diameter exhaust nozzle was used throughout the investigation.

INSTRUMENTATION

Pressure-survey rakes were mounted at the diffuser inlet and at the nozzle outlet. The inlet rakes consisted of 10 total-pressure tubes and 2 static-pressure tubes in the vertical plane and the same number in the horizontal plane; the exhaust rake consisted of 17 total-pressure tubes and 1 static-pressure tube. Flush orifices were used to measure the static pressure at the wall of the unit. Eight wall orifices were mounted at the diffuser inlet and four wall orifices were mounted at the following stations: combustion-chamber inlet, downstream of the flame holder; exhaust-nozzle inlet and outlet. Single wall orifices were mounted at intervals of approximately 6 inches along the entire length of the unit.

A swiveling static-pressure tube and a shielded total-pressure tube mounted 1 chord length ahead of the left wing tip were used for altitude and airspeed measurement. A resistance-bulb type thermometer was used to obtain ambient-air temperature.

Fuel flow was measured by a rotameter and the fuel pressure was measured near the spray-nozzle inlet by a self-synchronizing transmitter.

A pitch indicator mounted on the ram-jet cowling was used to adjust the unit to an angle of attack of 0° at each test condition.

PROCEDURE

The maximum airspeed and altitude at which the unit could be started with spark ignition were determined first. Then airspeed and fuel-air ratio were independently varied at altitudes of 5000, 10,000, 20,000, and 30,000 feet. For the runs at 20,000 and 30,000 feet, the unit was started either by a magnesium flare at the test altitude or at a lower altitude by spark ignition prior to ascent to the test altitude. When possible, data were taken at fuel-air ratios from approximately 0.11 down to the fuel-air ratio at which combustion ceased for airspeeds equivalent to free-stream Mach numbers within the range of 0.20 to 0.51. For convenience in describing the results, the point at which combustion ceases will be called blow-out.

SYMBOLS

The following symbols are used in this report:

A	cross-sectional area, (sq ft)
C_F	net-thrust coefficient
c_p	specific heat at constant pressure, (Btu/lb-°F)
F_n	net thrust, (lb)
f/a	fuel-air ratio
g	acceleration of gravity, (ft/sec^2)
J	mechanical equivalent of heat, (ft-lb/Btu)
M	Mach number
m_a	mass air flow, (slugs/sec)
m_g	mass gas flow, (slugs/sec)

P	total pressure, (lb/sq ft absolute)
p	static pressure, (lb/sq ft abolute)
q	dynamic pressure, (lb/sq ft)
R	gas constant, (ft-lb/(^{o}R)(lb))
T	total temperature, (^{o}R)
t	static temperature, (^{o}R)
V	velocity, (ft/sec)
W_a	air flow, (lb/sec)
γ	ratio of specific heat at constant pressure to specific heat at constant volume
δ	ratio of absolute atmospheric ambient pressure to absolute pressure of NACA standard atmosphere at sea level, $p_0/2116$
η	combustion efficiency, percent
θ	ratio of absolute total temperature at exhaust-nozzle outlet to absolute temperature of NACA standard atmosphere at sea level, $T_5/519$
μ	ratio of mass flow of gases at nozzle outlet to mass flow of air at inlet, m_g/m_a
τ	ratio of absolute total temperature at exhaust-nozzle outlet to absolute total temperature at combustion-chamber inlet, T_5/T_2
F_n/δ	net thrust reduced to NACA standard atmospheric conditions at sea level, (lb)
$M_2\sqrt{\tau}$	combustion-chamber-inlet Mach number parameter
$W_a\sqrt{\theta}/\delta$	air-flow parameter, (lb/sec)

Subscripts:

0	free stream
1	diffuser inlet

2 diffuser outlet and combustion-chamber inlet

3 after flame holder

4 combustion-chamber outlet 827

5 exhaust-nozzle outlet

CALCULATIONS

The weight of air flow through the ram jet was computed by use of the equation for compressible fluid flow, one form of which is

$$W_a = \frac{p_1 A_1}{R_1} \sqrt{\frac{2gJc_{p,1}}{t_1}\left[\left(\frac{P_1}{p_1}\right)^{\frac{\gamma_1-1}{\gamma_1}} - 1\right]}$$

Exhaust-gas total temperature was calculated from the known mass flow of gas (air plus fuel) and the measured total and static pressures at the exhaust-nozzle outlet by the following equation, which may be directly derived from the mass-flow equation:

$$T_5 = \frac{2A_5^2 p_5^2}{gR_5 m_g^2} \frac{\gamma_5}{\gamma_5-1} \left(\frac{P_5}{p_5}\right)^{\frac{\gamma_5-1}{\gamma_5}} \left[\left(\frac{P_5}{p_5}\right)^{\frac{\gamma_5-1}{\gamma_5}} - 1\right]$$

Static-pressure measurements in the exhaust jet by the water-cooled static tube indicated that the pressure gradient across the outlet was not appreciable and that the wall-orifice measurements could be used for p_5 with negligible error.

Combustion efficiency was computed by relating the change in enthalpy of the air and the fuel to the heating value of the fuel supplied. Values for enthalpy were obtained by use of the method developed in reference 4.

The net thrust is defined as the change in momentum from free stream to the exhaust-nozzle outlet and is equal to

$$F_n = m_g V_5 - m_a V_0 + A_5 (p_5 - p_0)$$

The net-thrust coefficient is defined as

$$C_F = F_n/q_0A_3$$

The equation for combustion-chamber-inlet Mach number is

$$M_2 = \sqrt{\frac{2}{\gamma_2-1}\left[\left(\frac{P_2}{p_2}\right)^{\frac{\gamma_2-1}{\gamma_2}} - 1\right]}$$

The total pressure at the combustion-chamber inlet P_2 was immeasurable with fuel flowing and therefore was computed from the static pressure and from measurements at station 1.

In general, the data are believed to be accurate within approximately 5 percent.

RESULTS AND DISCUSSION

The ram jet was started with spark ignition at a minimum combustion-chamber-inlet pressure of 1280 pounds per square foot (pressure altitude, 14,400 ft).

The maximum combustion-chamber-inlet velocity before ignition at which the unit could be started was 125 feet per second for altitudes up to 14,400 feet (free-stream velocity, 288 ft/sec). At higher altitudes, the minimum speed of the airplane was greater than the maximum starting speed. Ignition was usually smooth with no violent shock nor vibration. The fuel-air ratio at ignition varied from 0.03 to 0.05. The limitations in altitude and airspeed for ignition with the spark plug were eliminated by the use of a magnesium flare. With this arrangement, a single start was made at a combustion-chamber-inlet pressure of 700 pounds per square foot with a combustion-chamber-inlet velocity of 180 feet per second (pressure altitude, 30,000 ft and free-stream velocity, 400 ft/sec). Ignition was smooth and instantaneous at a fuel-air ratio of approximately 0.05.

At altitudes of 20,000 feet or less, increasing the fuel-air ratio to considerably greater than stoichiometric mixture did not result in blow-out; at an altitude of 30,000 feet, a limiting fuel-air ratio of 0.085 was found for combustion-chamber velocities of 90 and 115 feet per second.

The variation of the fuel-air ratio at lean blow-out with combustion-chamber-inlet velocity at pressure altitudes of 5000, 10,000, and 20,000 feet is shown in figure 4. No lean blow-out data were obtained at 30,000 feet, but satisfactory operation was observed at fuel-air ratios as low as 0.034 at that altitude. The minimum operating fuel-air ratio at 5000 feet increased from 0.013 to 0.019 when the combustion-chamber-inlet velocity was increased from 88 to 146 feet per second (fig. 4). At 20,000 feet, the minimum fuel-air ratio increased from 0.02 to 0.023 for a change in combustion-chamber-inlet velocity from 90 to 154 feet per second. As the lean blow-out limit was approached, the visible flame at the outlet became very short and irregular, particularly at an altitude of 20,000 feet; furthermore, by looking in the inlet through the periscope, it could be seen that burning was occurring only in isolated regions near the center. This localized burning would be expected because the fuel was directed toward the center, thereby enriching that region to a combustible mixture at low over-all fuel-air ratios.

The flame length at a pressure altitude of 5000 feet and a fuel-air ratio of approximately 0.08 is shown in figure 2. The coolant vapor can be seen discharging from the combustion chamber and the nozzle above the exhaust flame. The visible flame length for a given fuel-air ratio steadily decreased with increasing altitude above 20,000 feet. The flame color was usually a bright reddish-orange at low altitude, and the color became less intense as altitude was increased. The flame was barely visible with lean mixtures at 20,000 feet and was invisible over the entire operating range at 30,000 feet. (All observations were made in daylight.)

Response to a rapid change of fuel flow was immediate and positive at low altitude, but blow-out was induced on several occasions by the rapid change in fuel-air ratio when operating at 20,000 and 30,000 feet.

Operation was generally smooth with little vibration; occasionally, however, a fairly severe vibration of relatively constant frequency was encountered at excessively rich mixtures of 0.09 or more.

The exhaust-gas total-temperature rise is plotted against fuel-air ratio for all conditions of the investigation in figure 5. The temperature rise reaches a maximum at a fuel-air ratio of approximately 0.07 and remains practically unchanged for increasing fuel-air ratios.

The combustion efficiency plotted against fuel-air ratio at altitudes of 5000, 10,000, 20,000, and 30,000 feet is shown in figure 6. At altitudes of 5000 and 10,000 feet, peak efficiencies of approximately 75 and 85 percent, respectively, at a fuel-air ratio of 0.03 to 0.04 were attained (figs. 6(a) and (b)). Nonuniform fuel distribution is believed to be the cause of the efficiency's reaching a maximum at low fuel-air ratios. Apparently the mixture at the center of the combustion chamber is near stoichiometric at lean over-all fuel-air ratios, thereby burning the fuel in a more efficient manner than if it were evenly distributed. At the richer mixtures, the center of the combustion chamber is overrich causing incomplete burning in that region. These conclusions are verified by figure 7, which shows typical exhaust total-pressure distributions for lean and rich mixtures. At the lean fuel-air ratio, the center pressures are low, indicating a higher combustion pressure drop and accordingly higher temperatures; whereas the rich mixture shows the opposite trend, indicating that most of the burning is occurring toward the wall of the combustion chamber. The curves for altitudes of 20,000 and 30,000 feet show the same trend in the effect of fuel-air ratio on combustion efficiency. Considerably more scatter of data is present, however, in the lean fuel-air-ratio range than for the lower altitude. This scatter may be due to unstable and "spotty" burning, which was more predominant at the higher altitudes in the lean fuel-air-ratio range. The average peak efficiency decreased to approximately 67 percent at an altitude of 20,000 feet with a fuel-air ratio of 0.04, and to 56 percent at 30,000 feet with a fuel-air ratio of 0.06.

No consistent effect of combustion-chamber-inlet velocity on combustion efficiency can be noted for the range of conditions covered, although figure 6(c) for an altitude of 20,000 feet shows that highest efficiencies in the lean region were obtained at highest velocities.

The individual effects of combustion-chamber-inlet pressure and temperature on the operating range of fuel-air ratio and combustion efficiency are indeterminate from the results inasmuch as they both change with altitude. However, in figure 6(b) for an altitude of 10,000 feet, it appears that the combustion efficiencies are slightly lower for the runs at lower ambient-air temperatures. It should be noted that the average ambient-air temperature for the runs at 30,000 feet was 410° R as compared with about 472° R at 5000 feet (figs. 6(a) and (d)). The combined effect of pressure and temperature on combustion efficiency is presented in figure 8, which is cross-plotted from figure 6. The cross plot shows that the effects of pressure altitude and the accompanying change in temperature on combustion efficiency were considerably greater at lean mixtures than at those near stoichiometric.

For a combustion chamber of constant cross-sectional area and for a given combustion-chamber-inlet Mach number, the static-pressure loss due solely to heat addition is a function of $\frac{R_4}{R_2} \mu^2 \frac{T_4}{T_2}$ and q_2 (reference 5). If it is assumed that only a small part of the burning occurs in the nozzle, then the combustion-chamber pressure loss should be approximately a function of $\frac{R_5}{R_2} \mu^2 \tau$ and q_2, and the observed pressure loss from stations 2 to 4 may be plotted against the exhaust-temperature-rise parameter determined at station 5, $\frac{R_5}{R_2} \mu^2 \tau$.

For a given combustion-chamber configuration, the pressure loss due to friction is primarily a function of q_2 and should be approximately independent of the temperature rise. Inasmuch as both the combustion- and friction-pressure losses are proportional to q_2, they may be divided by q_2 and plotted in coefficient form. The friction-pressure loss was determined from cold runs and the average observed value is indicated by the ordinate at $\frac{R_5}{R_2} \mu^2 \tau = 1$ in figure 9. This figure shows the theoretical pressure losses due to heat addition for $M_2 = 0$, 0.04, and 0.10 and the theoretical heat addition losses plus the observed friction loss for $M_2 = 0.04$ and 0.10, the approximate range covered in this investigation. The agreement of the experimental data with the theoretical curves provides a convenient check on the instrumentation and the calculations at the exhaust-nozzle outlet, station 5.

The combustion-chamber-inlet Mach number M_2 and air flow W_a may be expressed in the form of parameters $M_2 \sqrt{\tau}$ and $W_a \sqrt{\theta}/\delta$, respectively, as a function of free-stream Mach number M_0 (reference 1). These variables are therefore plotted in this manner in figures 10 and 11.

It is also shown in reference 1 that the net thrust is essentially a function of the ambient-pressure ratio δ, the temperature-rise ratio τ, and free-stream Mach number M_0. Net thrust is therefore plotted in the parametric form of F_n/δ against τ for various values of M_0 (fig. 12). The data of figure 12 are cross-plotted in figure 13. The results agree with those reported for wind-tunnel investigations of a similar unit in reference 1. The net-thrust coefficient is a function of the same variables as the net thrust, but the effect of increasing Mach number is so small in the range covered in this investigation, that it is not perceptible within the scatter of the data, as shown in figure 14. The small effect is shown theoretically in reference 6.

SUMMARY OF RESULTS

From a flight investigation of a 20-inch ram jet over a range of pressure altitudes from 5000 to 30,000 feet and free-stream Mach numbers up to 0.51, the following results were obtained:

1. Ignition was effected by spark at a maximum pressure altitude of 14,400 feet and a combustion-chamber-inlet velocity of 125 feet per second. The ram jet was started at 30,000 feet and 180 feet per second by use of a magnesium flare.

2. The ram-jet unit operated smoothly over the entire range of velocities and altitudes with the exception of occasional rough operation at excessively rich mixtures.

3. The minimum operating fuel-air ratio was 0.02 at 20,000 feet with a combustion-chamber-inlet velocity of 90 feet per second and 0.013 at 5000 feet with a combustion-chamber-inlet velocity of 88 feet per second. In the range of conditions investigated, a maximum operating fuel-air ratio was observed only at 30,000 feet, with blow-out occurring at a fuel-air ratio of approximately 0.085.

4. Response to a rapid change in fuel flow was immediate and positive at low altitudes, but at altitudes of 20,000 and 30,000 feet blow-out was induced on several occasions by the sudden change in fuel-air ratio.

5. Maximum combustion efficiencies of approximately 75 and 85 percent were attained at fuel-air ratios of 0.03 to 0.04 at pressure altitudes of 5000 and 10,000 feet, respectively. The average peak efficiency decreased to approximately 67 percent at 20,000 feet with a fuel-air ratio of 0.04 and to 56 percent at 30,000 feet with a fuel-air ratio of 0.06. The adverse effects of low pressure and temperature (which occur with increasing altitude) on combustion efficiency were considerably greater at lean mixtures than at those near stoichiometric.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

REFERENCES

1. 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.

2. Perchonok, Eugene, Sterbentz, William H., and Wilcox, Fred A.: Performance of a 20-Inch Steady-Flow Ram Jet at High Altitudes and Ram-Pressure Ratios. NACA RM No. E6L06, 1947.

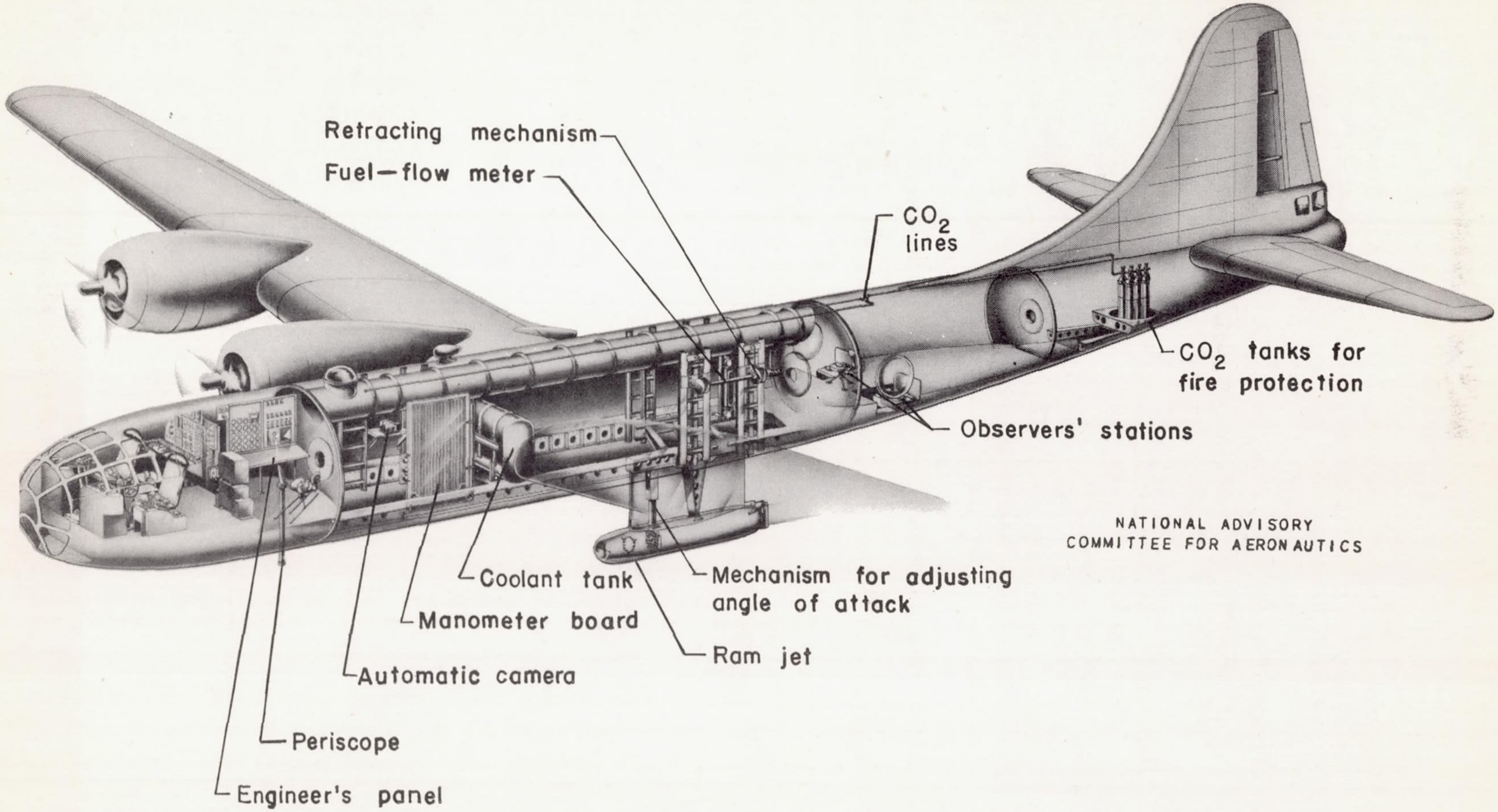
3. Perchonok, Eugene, Wilcox, Fred A., and Sterbentz, William H.: Investigation of the Performance of a 20-Inch Ram Jet Using Preheated Fuel, NACA RM No. E6I23, 1946.

4. 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.

5. Perchonok, Eugene, Sterbentz, William H., and Moore, Stanley H.: Indirect Methods for Obtaining Ram Jet Exhaust-Gas Temperature Applied to Fuel Metering Control. NACA RM No. E7H27, 1948.

6. Williams, Glenn C., and Quinn, John C.: Ram-Jet Power Plants. OSRD, Jet-Propelled Missiles Panel, Coordinator Res. and Development, U.S. Navy (Washington, D.C.), May 1945.

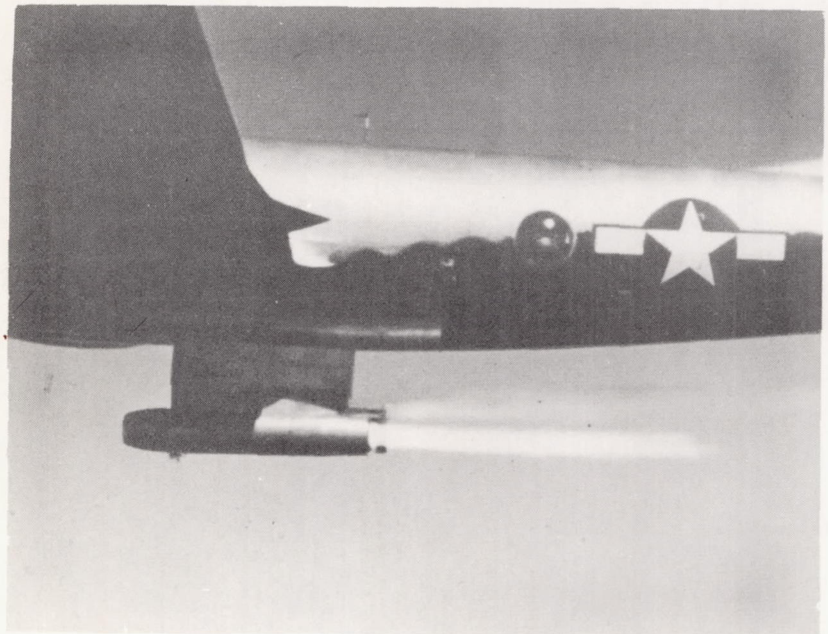
CONFIDENTIAL



NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

Figure 1. - 20-inch ram jet suspended from airplane used for flight investigation.

CONFIDENTIAL



NACA
C- 18789
4-3-47

Figure 2. - 20-inch ram jet in flight operation at pressure altitude of 5000 feet and fuel-air ratio of approximately 0.08.

CONFIDENTIAL

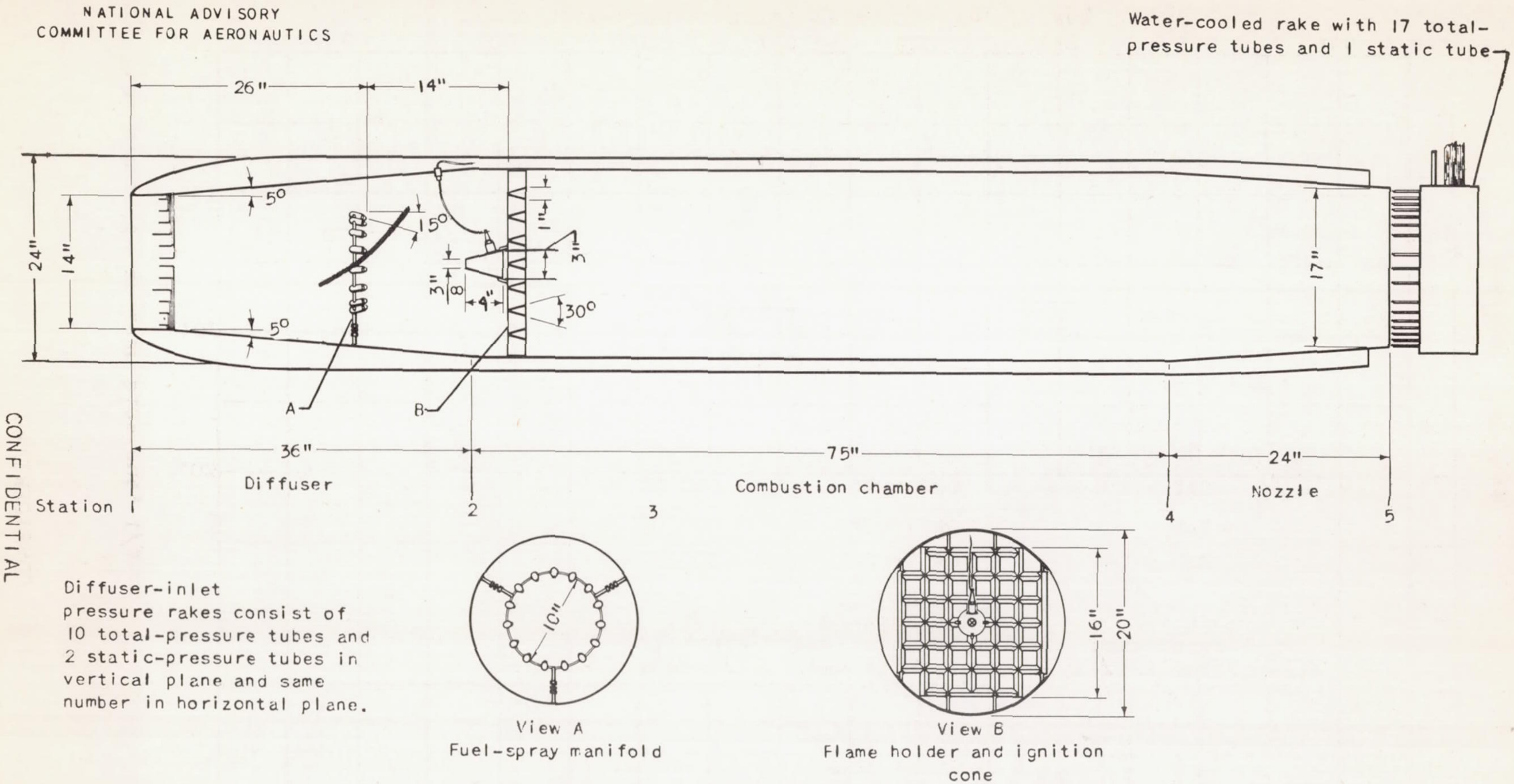


Figure 3. - Schematic cross-sectional view of 20-inch ram jet.

CONFIDENTIAL

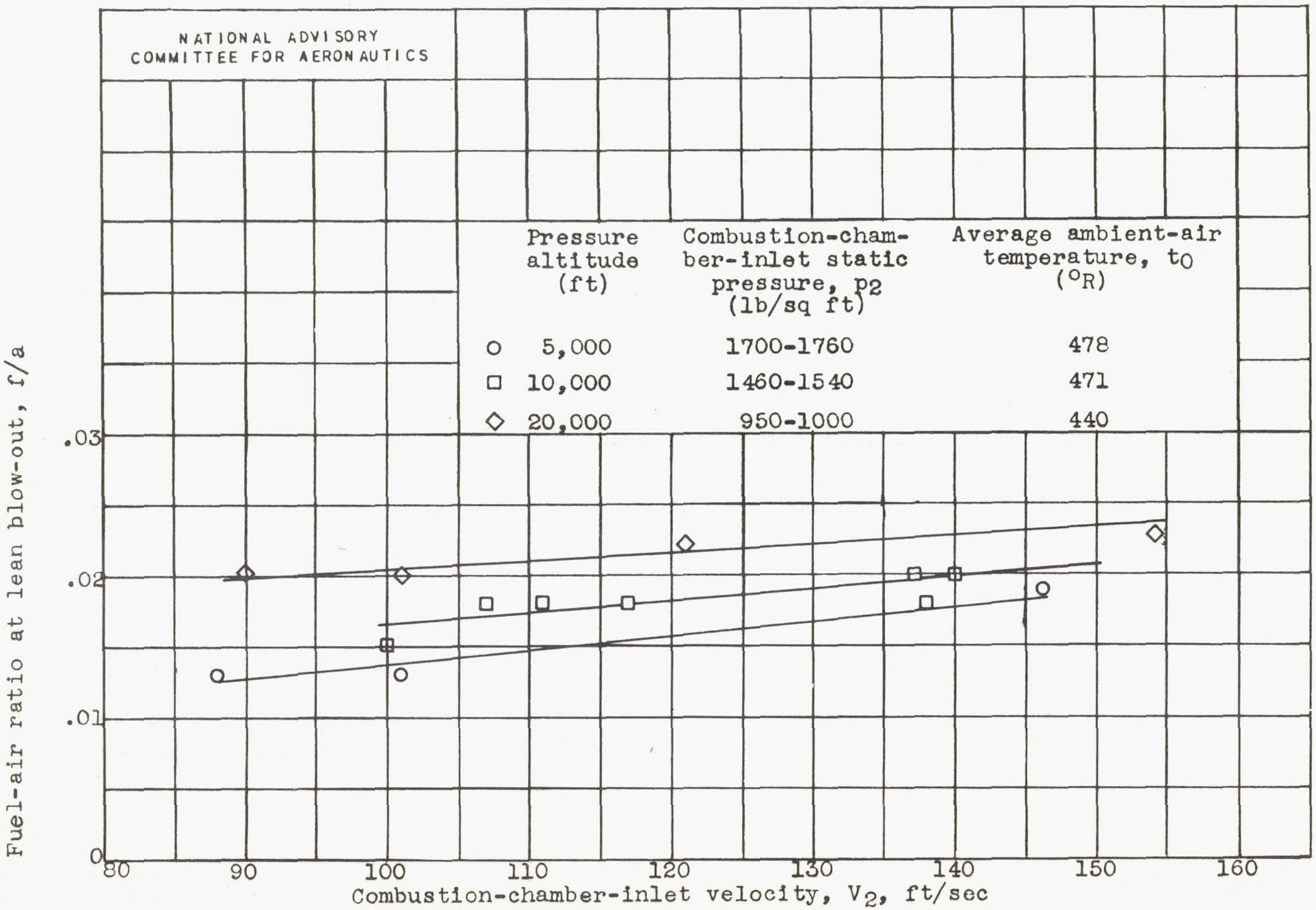


Figure 4. - Variation of fuel-air ratio at lean blow-out with combustion-chamber-inlet velocity for various pressure altitudes. 20-inch ram jet with 17-inch-diameter exhaust nozzle.

827

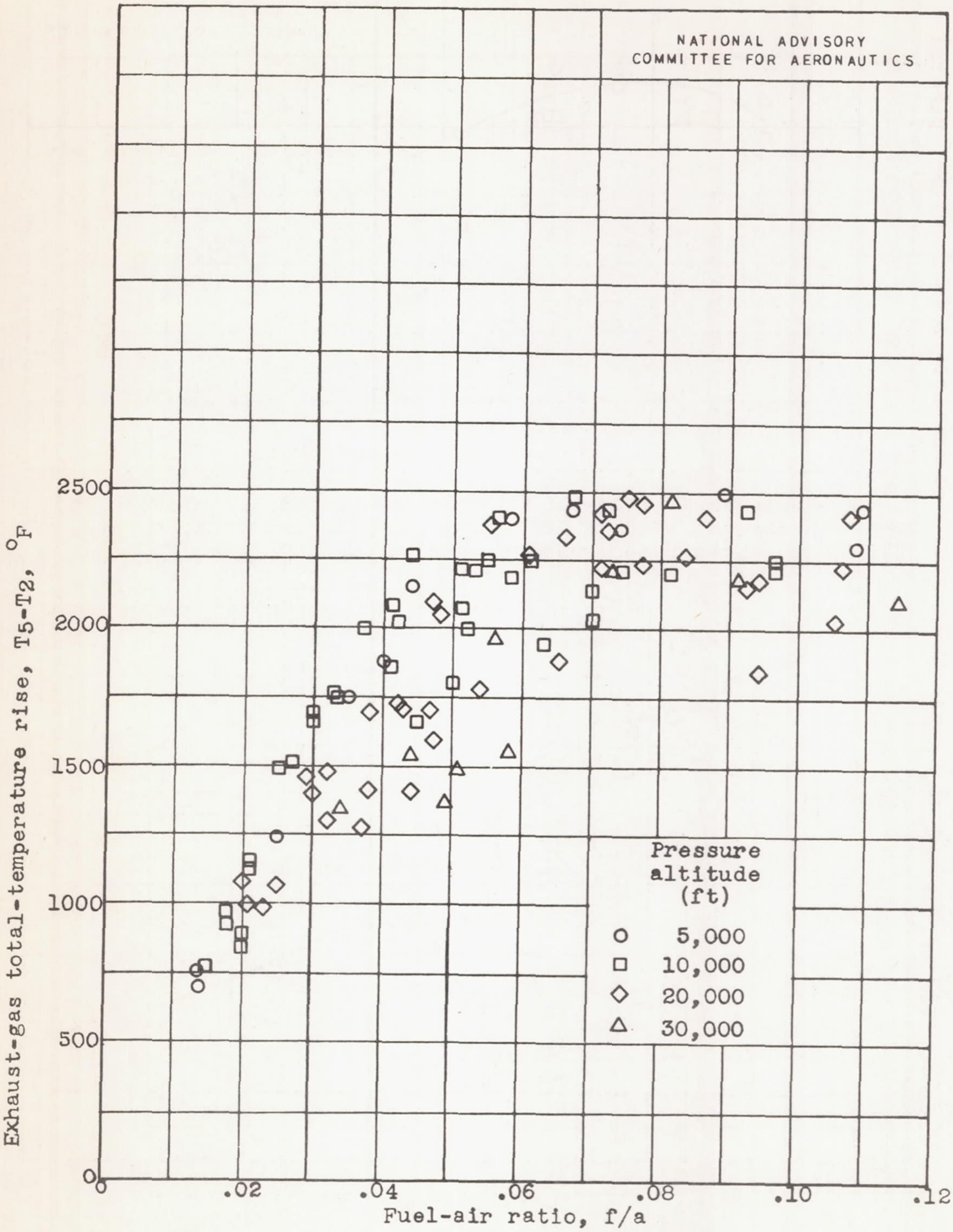
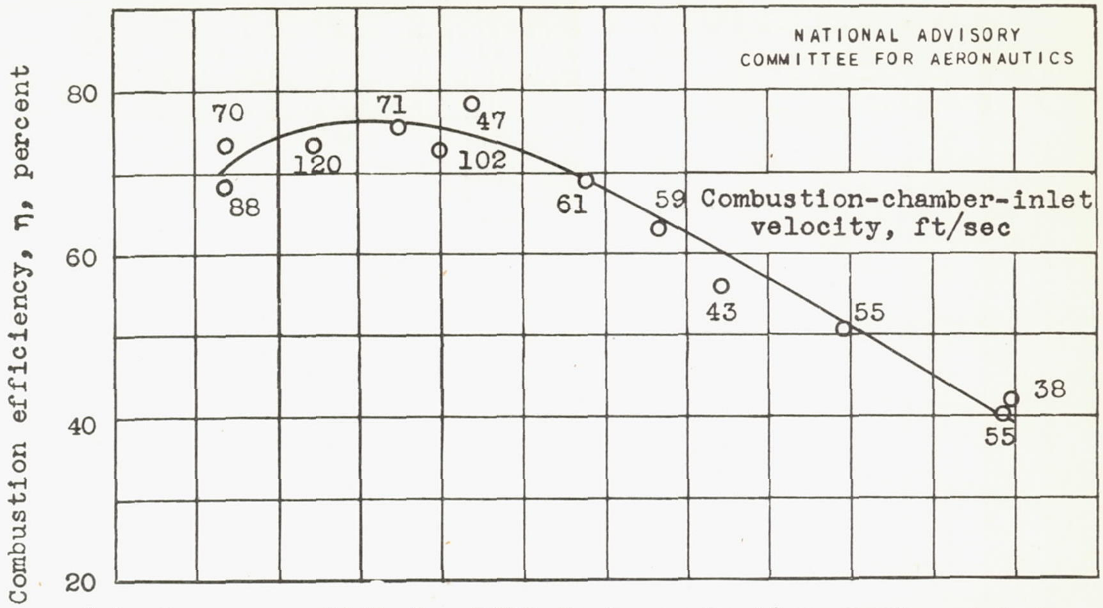
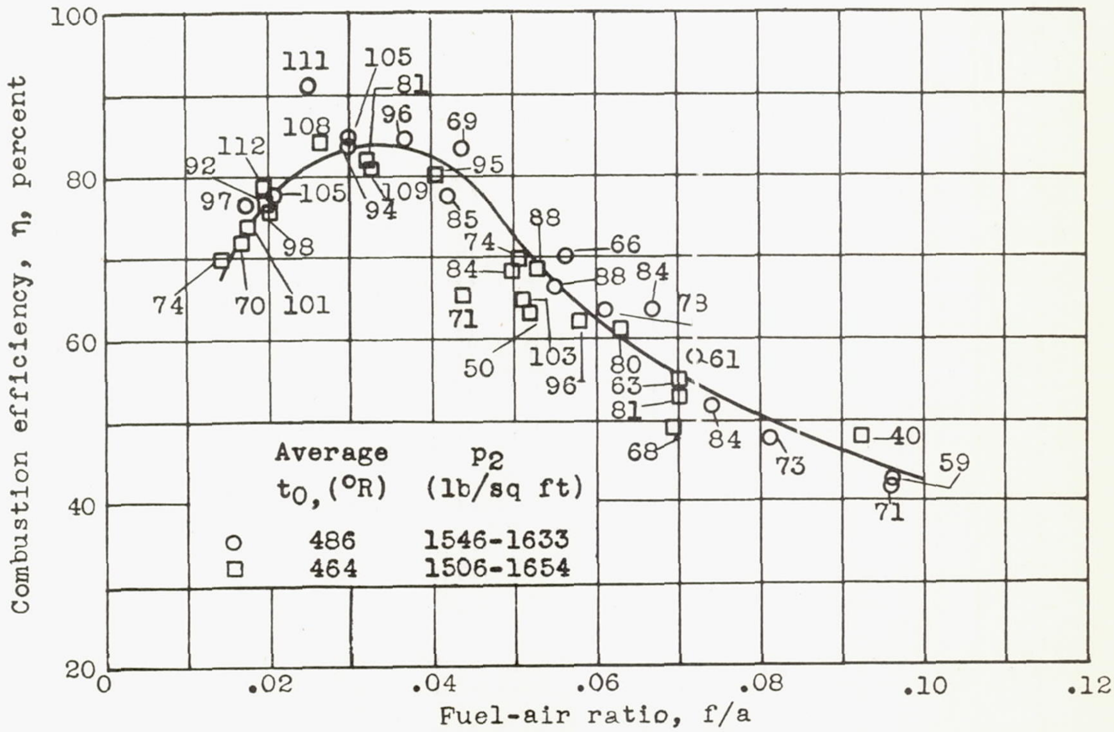


Figure 5. - Variation of exhaust-gas total-temperature rise with fuel-air ratio and altitude. 20-inch ram jet with 17-inch-diameter exhaust nozzle.

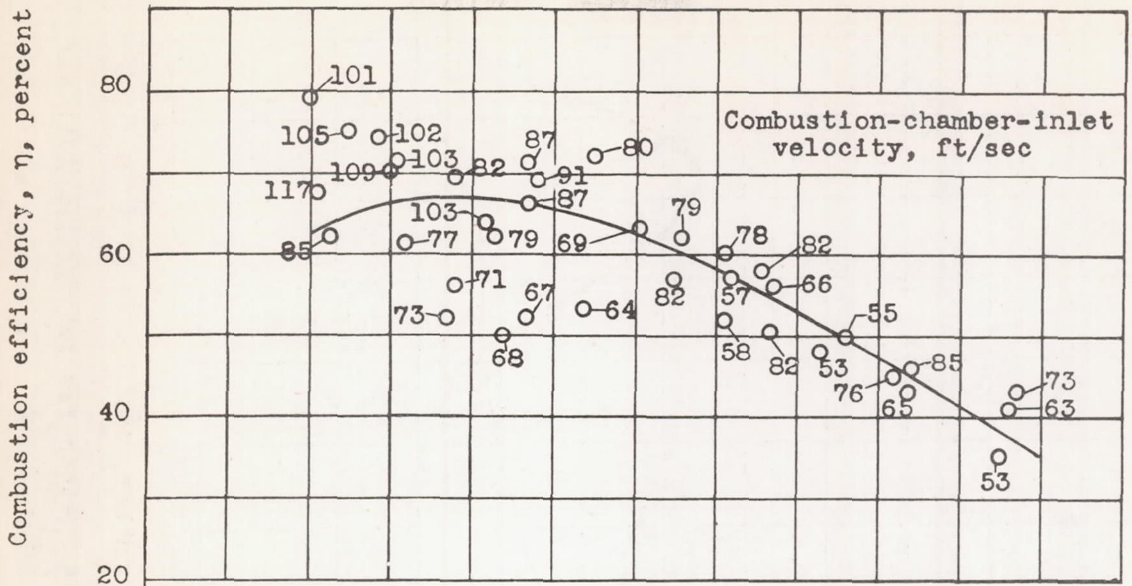


(a) Pressure altitude, 5000 feet; combustion-chamber-inlet pressure, 1780 to 1865 pounds per square foot; average ambient-air temperature, 472° R.

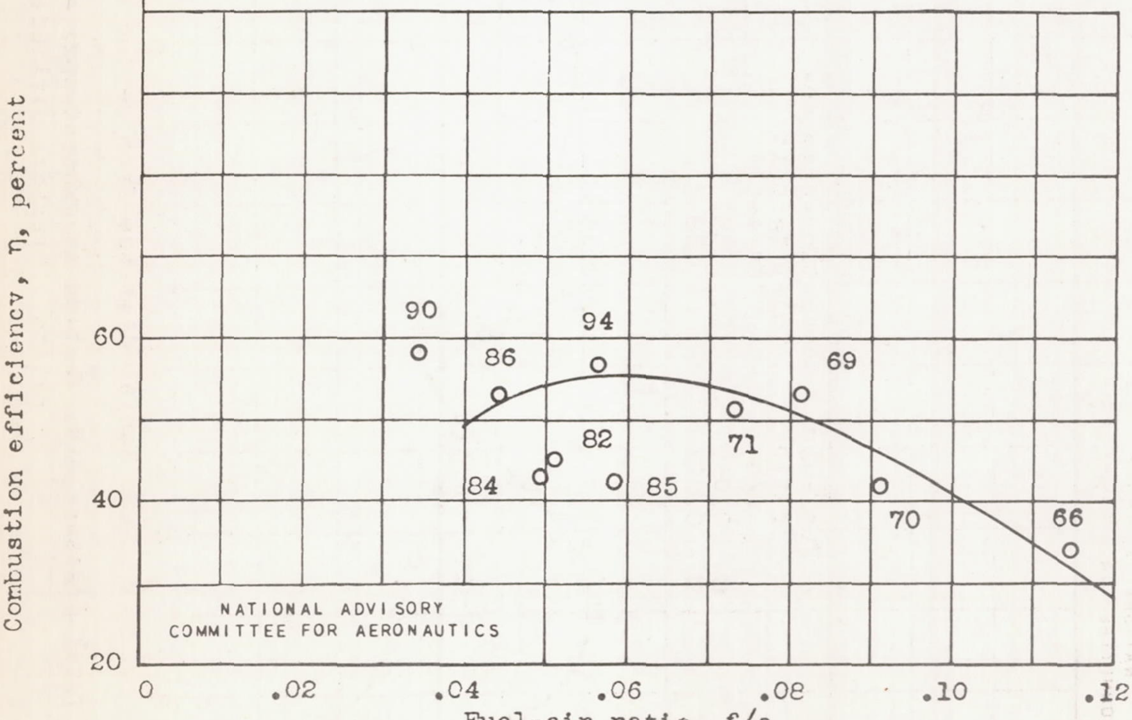


(b) Pressure altitude, 10,000 feet; combustion-chamber-inlet pressure, 1506 to 1654 pounds per square foot; average ambient-air temperature, 464° and 486° R.

Figure 6. - Variation of combustion efficiency with fuel-air ratio. 20-inch ram jet with 17-inch-diameter exhaust nozzle.



(c) Pressure altitude, 20,000 feet; combustion-chamber-inlet pressure, 1030 to 1130 pounds per square foot; average ambient-air temperature, 440° R.



(d) Pressure altitude, 30,000 feet; combustion-chamber-inlet pressure, 690 to 760 pounds per square foot; average ambient-air temperature, 410° R.

Figure 6. - Concluded. Variation of combustion efficiency with fuel-air ratio. 20-inch ram jet with 17-inch-diameter exhaust nozzle.

CONFIDENTIAL

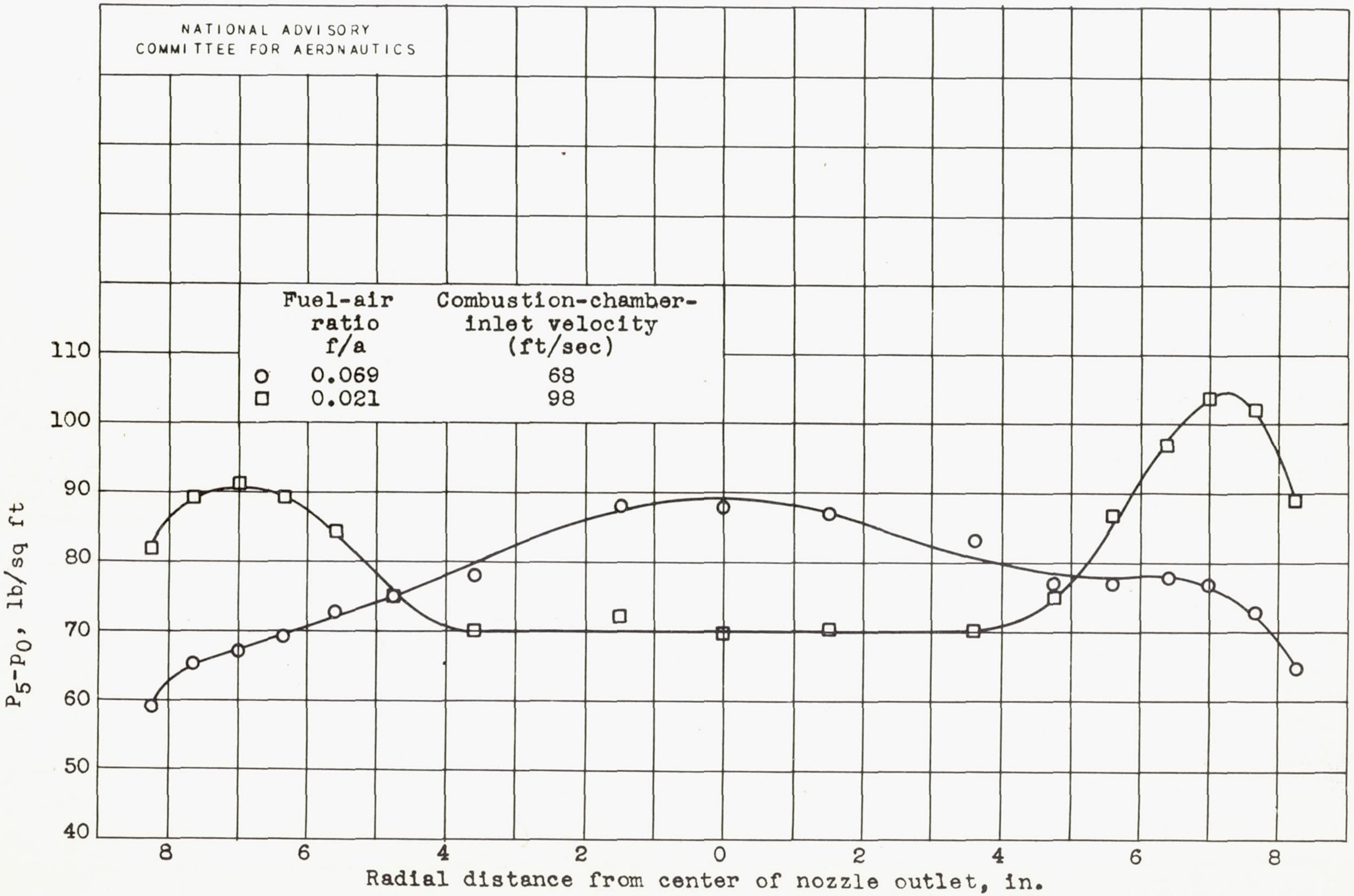


Figure 7. - Total-pressure distribution at exhaust-nozzle outlet of 20-inch ram jet for two fuel-air ratios. Pressure altitude, 10,000 feet.

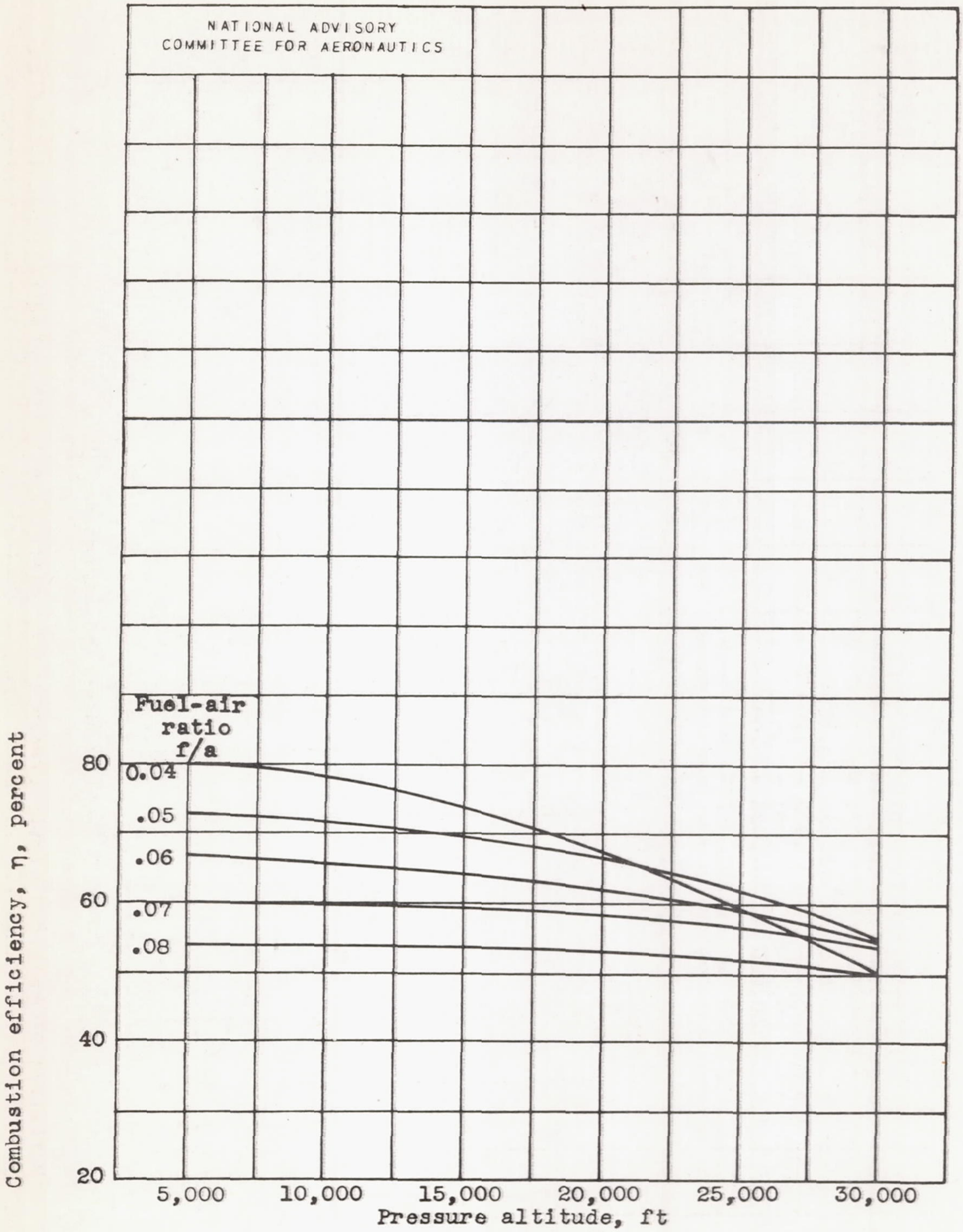


Figure 8. - Variation of combustion efficiency with altitude. 20-inch ram jet with 17-inch-diameter exhaust nozzle. (Cross plot of fig. 6.)

CONFIDENTIAL

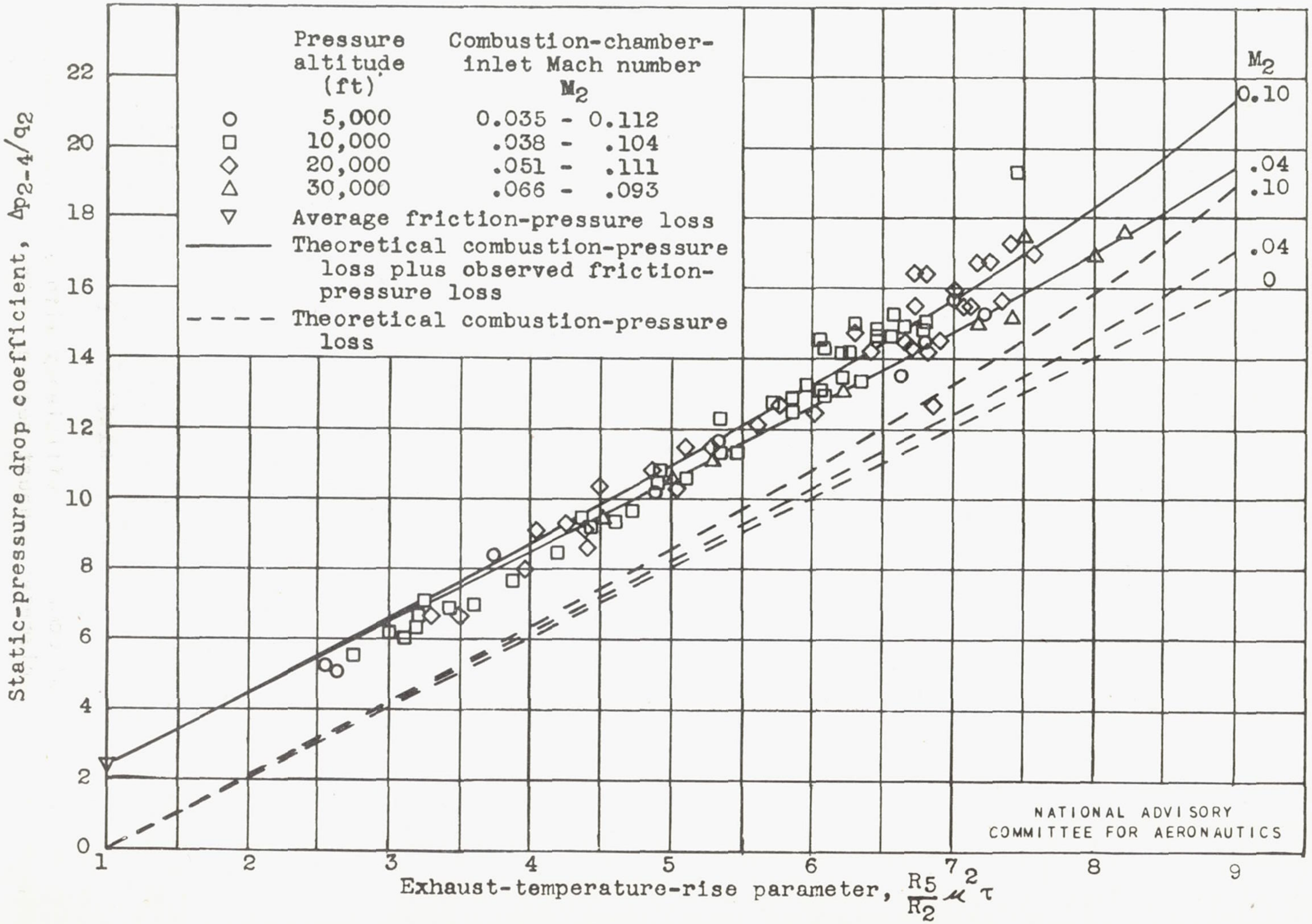


Figure 9. - Variation of measured static-pressure drop coefficient with exhaust-temperature rise parameter and combustion-chamber-inlet Mach number. 20-inch ram jet with 17-inch-diameter exhaust nozzle.

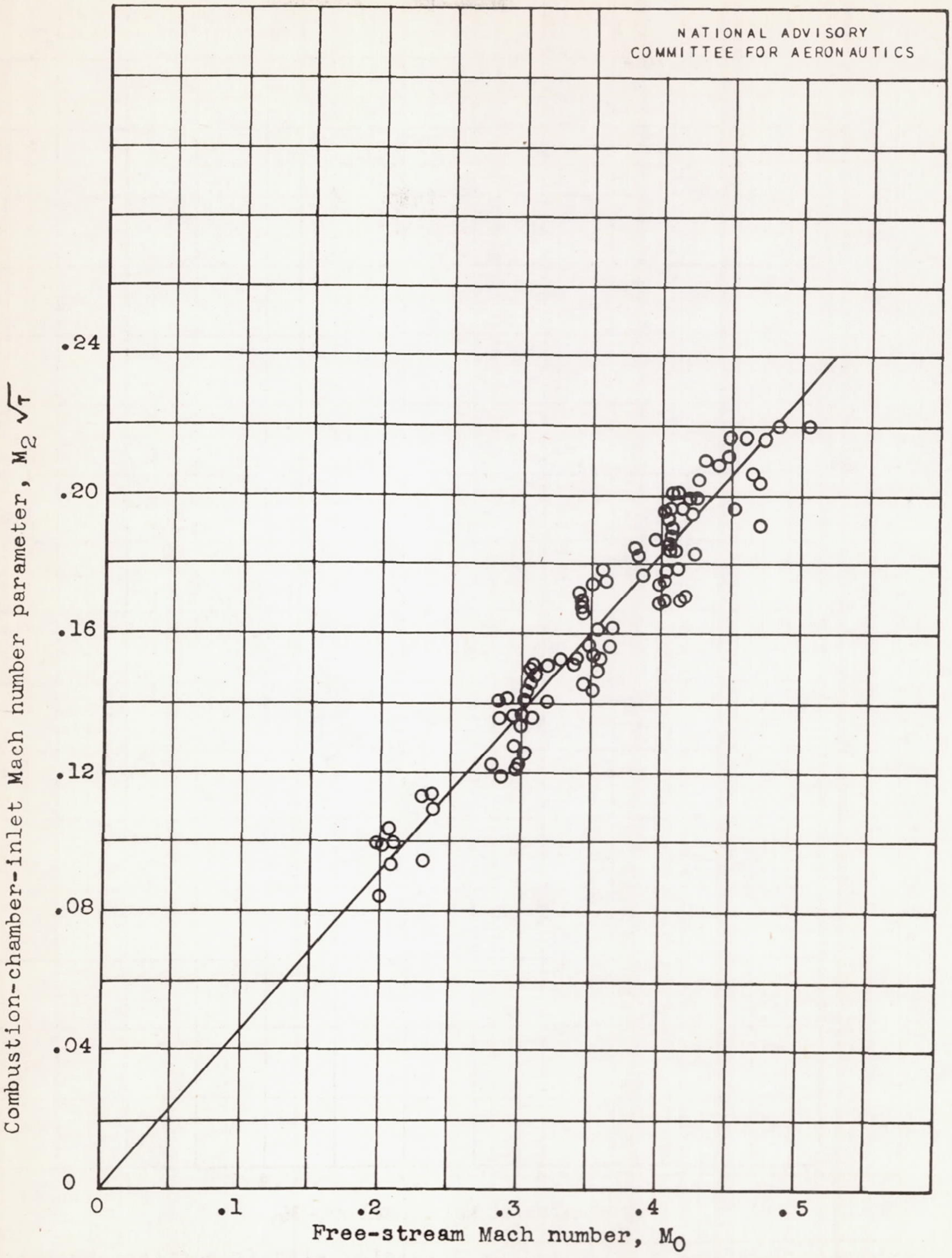


Figure 10. - Variation of combustion-chamber-inlet Mach number parameter with free-stream Mach number. 20-inch ram jet with 17-inch-diameter exhaust nozzle.

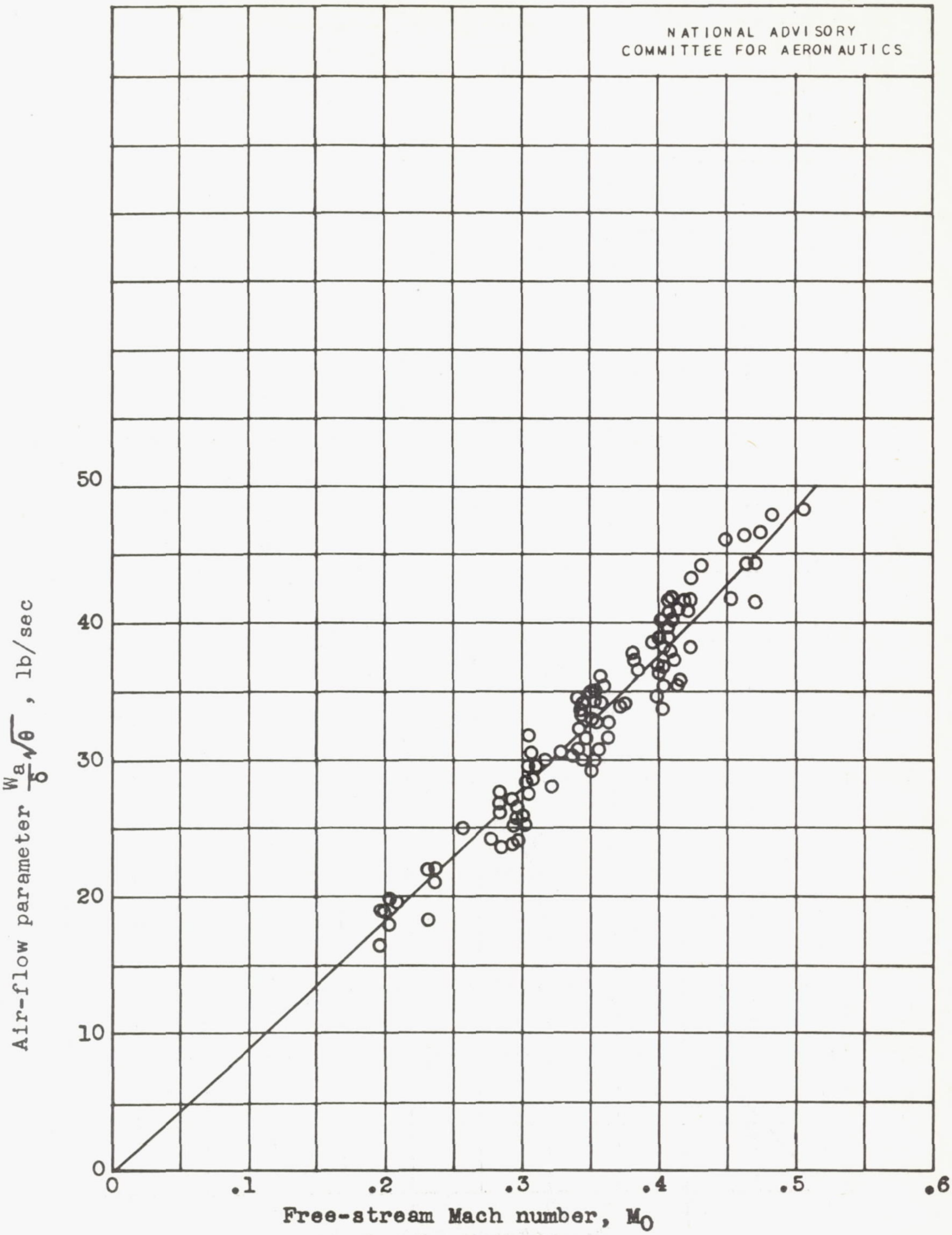


Figure 11. - Variation of air-flow parameter with free-stream Mach number. 20-inch ram jet with 17-inch-diameter exhaust nozzle.

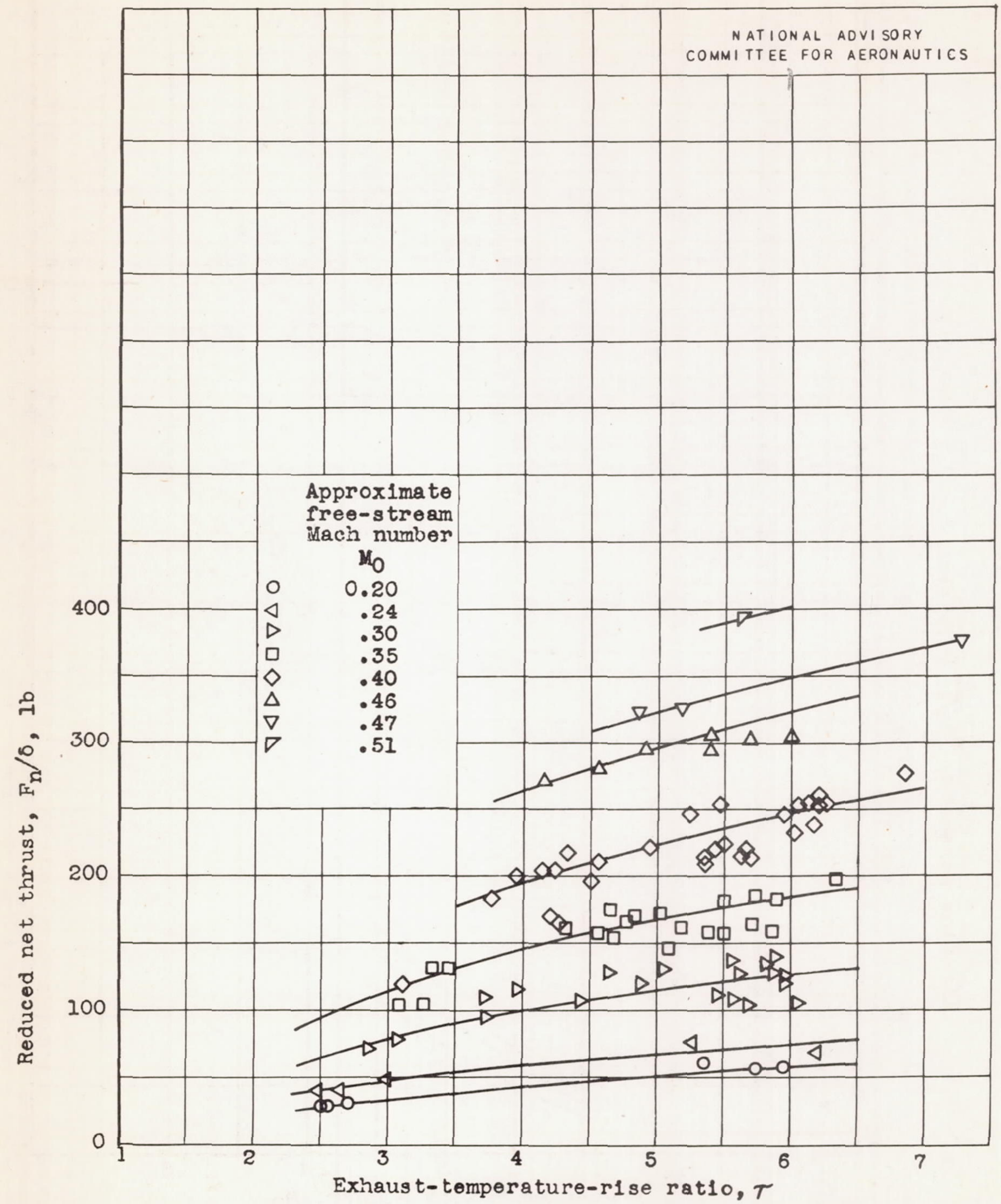


Figure 12. - Variation of reduced net thrust with exhaust-temperature-rise ratio and approximate free-stream Mach number. 20-inch ram jet with 17-inch-diameter exhaust nozzle.

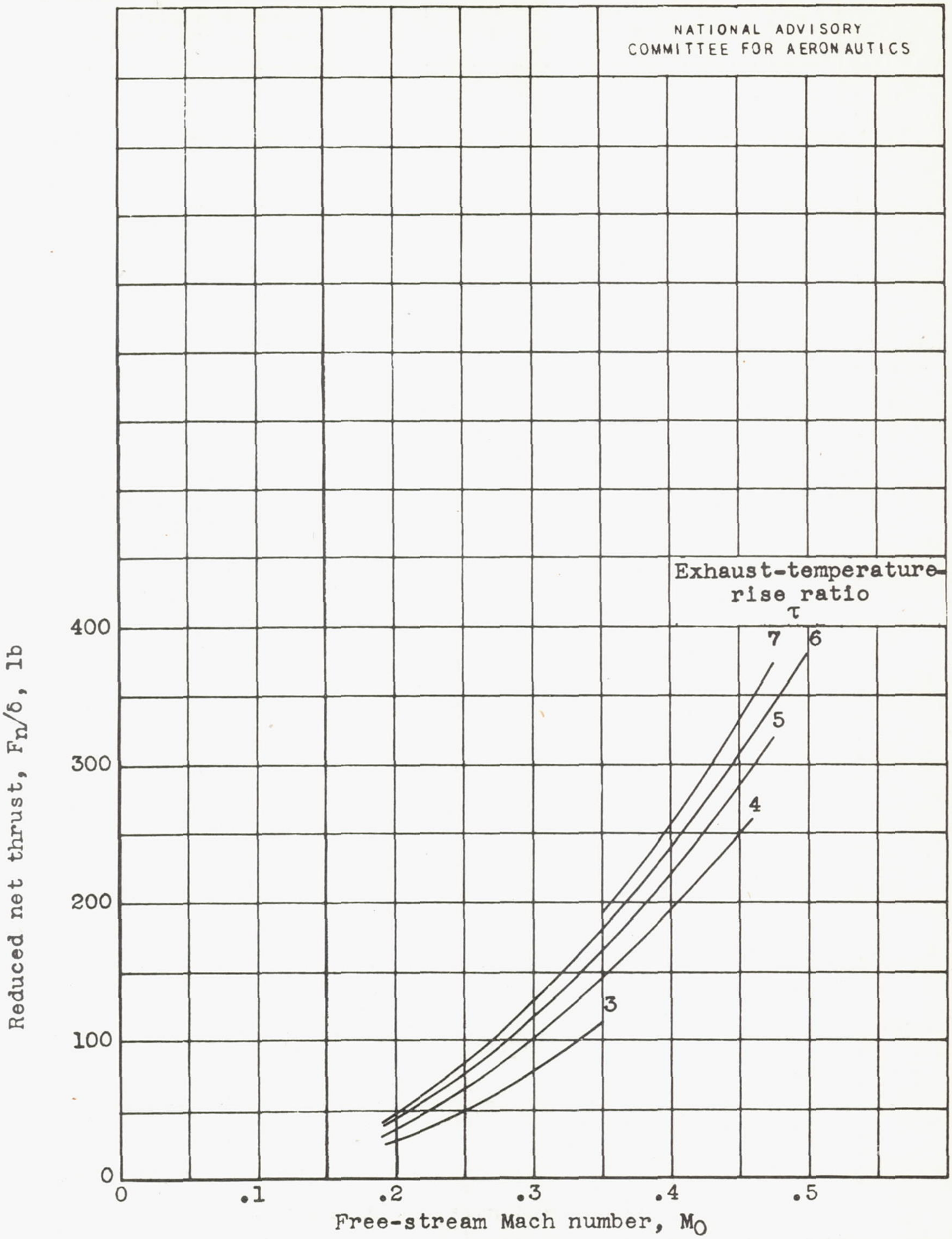


Figure 13. - Variation of reduced net thrust with free-stream Mach number and exhaust-temperature-rise ratio. 20-inch ram jet with 17-inch-diameter exhaust nozzle. (Cross plot of fig. 12.)

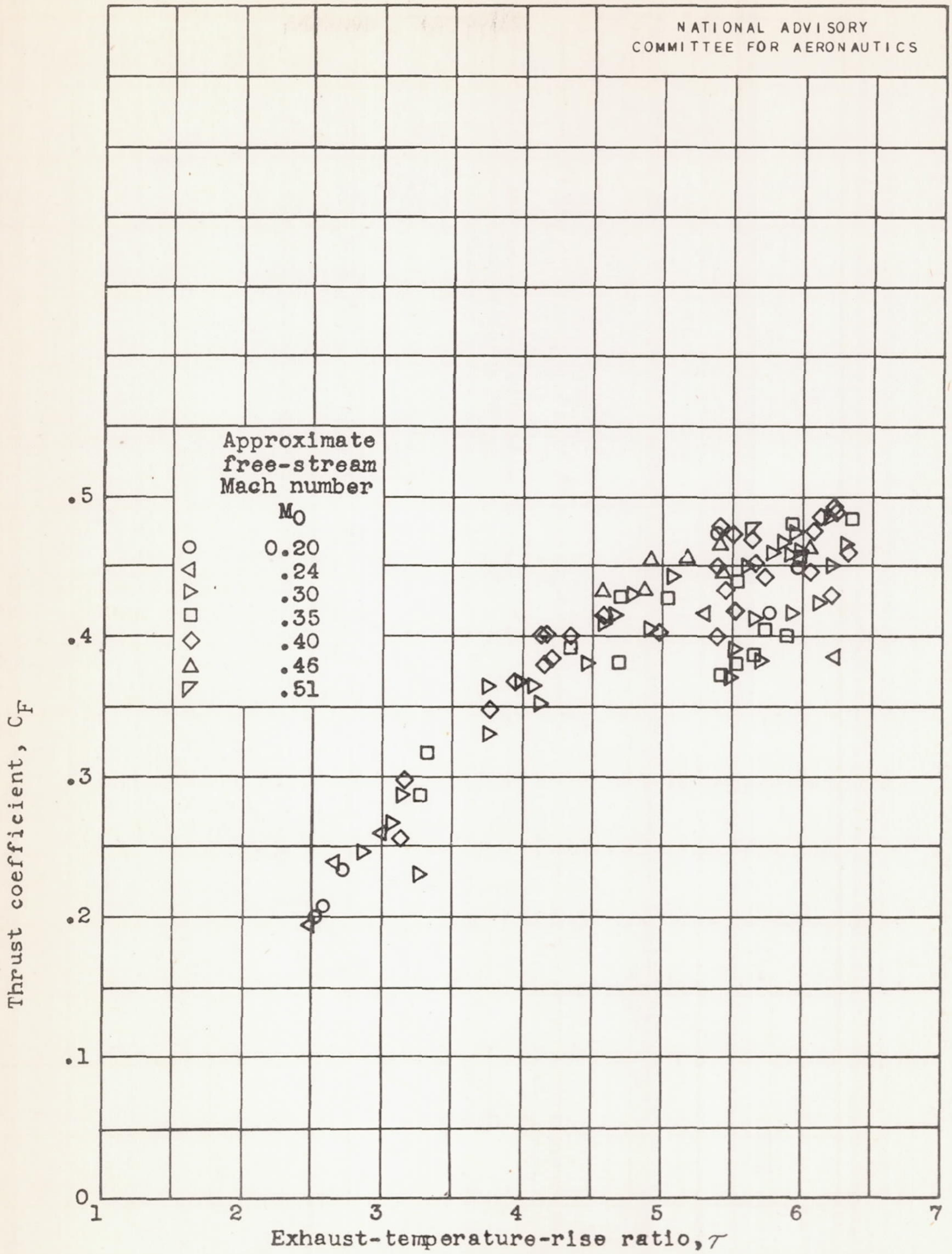


Figure 14. - Effect of exhaust-temperature-rise ratio and free-stream Mach number on thrust coefficient. 20-inch ram jet with 17-inch-diameter exhaust nozzle.