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RESEARCH MEMORANDUM

INVESTIGATION OF THE PERFORMANCE OF A 20-INCH RAM JET USING PREHEATED FUEL

By Eugene Perchonok, Fred A. Wilcox
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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The performance characteristics of a 20-inch ram jet designed at the NACA Cleveland laboratory and operated with preheated unleaded (62 octane) fuel in the Cleveland altitude wind tunnel are presented and analyzed.

The results of this investigation indicated an improvement in the combustion efficiency and operating range of the ram jet when using preheated fuel. Concomitant increases were obtained in the temperature ratio across the unit, the over-all efficiency, and the net thrust. At a free-stream Mach number of 1.20, a combustion efficiency of 84 percent and an over-all efficiency of 8.13 percent were obtained. Sufficient heat could be recovered from the ram-jet shell to preheat the fuel to the desired fuel injection temperature.

INTRODUCTION

As a part of the general program to evaluate and improve the performance of the ram-jet engine, a series of experiments are being conducted at the NACA Cleveland laboratory to determine the performance improvements that might be obtained by the use of preheated fuel. It was anticipated that preheating and the resulting flash vaporization of the fuel as it left the fuel injector would improve mixing of the air and fuel and increase the rate of flame propagation. Improved combustion and over-all efficiencies would likewise be expected.

Two methods of preheating the fuel are discussed: a regenerative heating system in which the fuel was circulated through coils around the combustion-chamber shell; and, to expedite the research, a system with an external heat source preheating the fuel. The regenerative system also cooled the combustion-chamber shell. The performance of the ram jet using preheated fuel is compared with the performance presented in reference 1 for a similar ram jet operating under the same conditions using unheated fuel.

APPARATUS AND PROCEDURE

The performance characteristics of a 20-inch ram jet were investigated in the Cleveland altitude wind tunnel over a wide range of operating conditions. The general arrangement of the ram jet in the tunnel (fig. 1) was similar to that of reference 1. The unit was mounted in the test section below a 7-foot-chord wing, which was supported at its tips by the wind-tunnel balance frame. Dry refrigerated air at approximately atmospheric pressure was supplied directly to the ram jet through a pipe from the wind-tunnel make-up air duct and was throttled to provide the desired diffuser-inlet total pressure. The tail nozzle exhausted directly into the wind tunnel, the pressure of which was varied to obtain different values of ram-pressure ratio across the unit. A sealed slip joint inserted between the ram pipe and the diffuser inlet afforded free movement of the model.

The ram jet had a conical diffuser with an 8° included angle, a 14-inch-diameter inlet, and a 20-inch-diameter exit. The combustion chamber was 20 inches in diameter and 12 feet in length. An exhaust nozzle, 2 feet long and with a 17-inch-diameter exit, was flanged to the combustion-chamber exit. The combustion chamber and exhaust nozzle were made of $\frac{1}{8}$-inch Inconel and were wrapped with $\frac{3}{4}$-inch copper tubing for fuel preheating and shell cooling.

The coils were arranged to allow variation in the length of the fuel path in order to facilitate fuel-temperature control over a wide range of fuel flows. A schematic diagram of the regenerative fuel-preheating and shell-cooling system is shown in figure 2.

A flame holder and a fuel injector were used in this investigation. The flame holder (fig. 3) consisted of three equally spaced 50° V's of 4-inch chord inserted with the vertices upstream. The cold static-pressure drop of the flame holder was 1.2 times the dynamic pressure at the combustion-chamber inlet. The fuel injector consisted of seven equally spaced $\frac{1}{4}$-inch steel tubes arranged in an 80° V pattern (fig. 4) with the V base 5 inches downstream of the diffuser inlet. Sixty-eight No. 70 holes were drilled in the upstream side of the fuel bars. These holes were equally spaced along the seven bars. No holes were drilled within 2 inches of the diffuser wall. Four additional fuel bars installed in the system were not used in this investigation. A gas pilot cone and modified spark-plug combination (fig. 5) was used for ignition.

The 90-percent point for the unleaded 62-octane fuel (AN-F-22) occurred at 202° F on the A.S.T.M. distillation curve (fig. 6). The Reid vapor pressure for the fuel is 7 pounds per square inch gage.

The fuel system was designed to provide a fuel flow of 3000 pounds per hour at a fuel injection temperature of 300° F and a minimum fuel injection pressure of 100 pounds per square inch gage.

A number of experiments were made establishing the feasibility of using heat from the ram-jet shell to preheat the fuel. The system satisfactorily preheated 4000 pounds of fuel per hour to 300° F. For a wide range of fuel flows, however, frequent changes in the length of the fuel preheating path were required. Consequently, an external heating source was substituted for the regenerative fuel preheating system to expedite the research. A commercial heat exchanger using saturated steam at 100 pounds per square inch gage was used to heat the fuel. The fuel temperature was controlled by varying the steam flow through the heat exchanger. This system (fig. 7) gave fuel temperatures as high as 250° F over a wide range of fuel flows. When the external heat exchanger was used, cooling water was circulated through the copper coils wrapped around the shell. No differentiation is made in the data with respect to the method of fuel preheating used when the data were taken.

The air flow through the unit was calculated from measurements of total pressures, static pressures, and indicated temperatures obtained with a survey rake mounted at the diffuser inlet. The fuel flow was measured with a rotameter and cooling-water flow was measured with a commercial water meter. Thrust was calculated (as outlined in reference 1) from force measurements obtained with the wind-tunnel scale system.

At pressure altitudes ranging from 6000 to 24,500 feet, the ram-pressure ratio across the unit was varied to the maximum attainable at each altitude. The fuel-air ratio was varied from 0.042 to 0.098 and the fuel injection temperature was varied from 100° to 250° F. The ram-jet inlet-air temperature was maintained at 10° ±10° F for all conditions.

SYMBOLS

The symbols used are defined as follows:

A	cross-sectional area, square feet
C_F	net-thrust coefficient, $\frac{2F_n}{\gamma_0 p_0 A_3 M_0^2}$
F_j	jet thrust, pounds
F_n	net thrust, pounds
F/A	fuel-air ratio
M	Mach number
p	static pressure, pounds per square foot absolute
p_0	free-stream ambient pressure, pounds per square foot absolute
T	total temperature, °R
V	velocity, foot per second
W_a	air flow, pounds per second
W_f	fuel flow, pounds per second
γ	ratio of specific heat at constant pressure to specific heat at constant volume
δ	ratio of absolute tunnel ambient pressure to absolute static pressure at NACA standard atmospheric conditions at sea level, $p_0/2116$
η	over-all efficiency, percent
η_b	combustion efficiency, percent
$\frac{\eta}{\eta_b}$	ideal over-all efficiency, percent
θ_4	ratio of absolute total temperature at exhaust-nozzle exit to absolute static temperature at NACA standard atmospheric conditions at sea level, $T_4/519$
τ_1	ratio of absolute total temperature at exhaust-nozzle exit to absolute total temperature at diffuser inlet, T_4/T_1

τ_2	ratio of absolute total temperature at exhaust-nozzle exit to absolute total temperature at combustion-chamber inlet, T_4/T_2

Subscripts:

0	equivalent free-stream condition
1	station 1, diffuser inlet
2	station 2, diffuser exit and combustion-chamber inlet
3	station 3, combustion-chamber exit
4	station 4, exhaust-nozzle exit
j	ultimate exhaust-jet condition ($p_j = p_0$)

Performance parameters:

F_j/δ	jet thrust reduced to NACA standard atmospheric conditions at sea level, pounds
F_n/δ	net thrust reduced to NACA standard atmospheric conditions at sea level, pounds
$M_2\sqrt{\tau_2}$	combustion-chamber-inlet Mach number parameter
$\frac{W_a}{\delta}\sqrt{\theta_4}$	reduced air-flow parameter, pounds per second
$\frac{W_f \eta_b\ 3600}{\delta\sqrt{\theta_4}}$	reduced fuel-consumption parameter, pounds per hour
$\frac{550\ W_f\ 3600}{F_n V_0}$	net-power specific fuel consumption, pounds per horsepower-hour

RESULTS AND DISCUSSION

Preliminary work at sea level and a low ram-pressure ratio, 1.1, showed that the preheated fuel was flashing into vapor upon injection into the air stream. The flame was seated on the flame holder and showed no tendency to flash back to the fuel injector. The flames more completely filled the combustion chamber and were shorter than when the fuel was unheated. Visual observations indicated that it was possible to reduce the fuel injection temperature from 300° to 200° F and the minimum fuel injection pressure from

100 to 50 pounds per square inch gage without markedly changing the combustion characteristics. Circulation of the fuel through the coils made continuous operation possible at stoichiometric fuel-air ratios without overheating the portion of the shell covered by the coils.

The data for the ram jet operating with preheated fuel in the altitude wind tunnel have been reduced and correlated by the methods discussed in reference 1.

The improvement in combustion efficiency achieved by preheating the fuel is shown in figure 8. The curves are approximate envelopes of the combustion-efficiency data presented in figure 9 for preheated fuel and in reference 1 (fig. 26(b)) for unheated fuel. On the average, by increasing the fuel injection temperature from 40° to 200° F, the maximum combustion efficiencies attained were increased by about 10 percent and the minimum combustion efficiencies obtained were increased by about 20 percent. This improvement in combustion efficiency is achieved because the fuel-vaporization time is reduced and a better fuel-air mixture is obtained by preheating the fuel. The combustion efficiency improved with fuel-air ratio to a maximum between fuel-air ratios of 0.04 and 0.06 with either heated or unheated fuel. Further increase in fuel-air ratio markedly decreased the combustion efficiency.

The combustion-efficiency data for preheated fuel are plotted against fuel-air ratio in figure 9. The numbers opposite each point indicate the values of other variables thought to influence the combustion efficiency; namely, combustion-chamber inlet static pressure p_2, combustion-chamber-inlet Mach number M_2, and combustion-chamber-exit static pressure (ambient static pressure) p_0. The combustion-chamber-inlet temperature was held constant for this investigation. The method by which the data were taken makes it difficult to separate quantitatively the effect of each of the variables on combustion efficiency. In general, however, an increase in combustion-chamber-inlet Mach number or a decrease in the combustion-chamber static-pressure level resulted in a decrease in combustion efficiency.

A calculation of the approximate heat loss through the ram-jet shell was made from measurements of the flow rate and the temperature rise of the cooling water. On the average, the cooling water absorbed approximately 3.3 percent of the lower heating value of the fuel. The heat losses through the ram-jet shell were not included in the calculations of the combustion efficiency. If these heat losses were included, the combustion-efficiency values would be approximately 3 percent higher than reported.

The gas total-temperature rise $T_4 - T_2$ during combustion of heated fuel and unheated fuel is shown in figure 10 as a function of free-stream Mach number M_0. Figures 10(a) and 10(b) can be used as an indication of the general temperature trends, for they both cover approximately the same altitude and fuel-air-ratio range. At low M_0 the combustion temperatures were much higher with the heated fuel than with the unheated fuel. At M_0 values near 1.00, the combustion temperatures with heated fuel were slightly higher than with unheated fuel. Because of the improved combustion efficiency, however, these temperatures were attained at lower fuel-air ratios with preheated fuel than with unheated fuel. The effect of preheated fuel on the range of M_0 obtainable with this ram-jet configuration can be observed in figure 10. The maximum M_0 reached before blow-out with preheated fuel was 1.23 as compared with 0.96 with the unheated fuel as reported in reference 1.

The greatest combustion-chamber-inlet velocity V_2 at which the unit was operated using preheated fuel was 151 feet per second. This velocity was measured at a pressure altitude of 24,400 feet when the unit was operating under choking conditions at the nozzle ($M_0 = 1.20$). When using unheated fuel (reference 1), the greatest V_2 at which the same unit was operated was 164 feet per second at a pressure altitude of 20,000 feet and an M_0 of 0.94. These velocities are not the limiting combustion-chamber-inlet velocity for this burner; when it was operated using unheated fuel in a ram jet with a 5-foot combustion chamber and a 17-inch nozzle exit, a maximum V_2 of 196 feet per second was obtained. (See reference 1.) Any difference in V_2, for the same exit nozzle and approximately the same M_0 value, is a result of the dependence of V_2, for approximately constant T_2, on T_4. (See equation (22), reference 1.) The combined effects of increased combustion-chamber length and fuel preheating are an increase in T_4 and a resulting decrease in V_2.

The variations with M_0 of the parameters $\frac{F_j}{\delta}$, F_j, $\frac{F_n}{\delta}$, C_F, $M_2\sqrt{\tau_2}$, M_j, $\frac{W_a}{\delta}\sqrt{\theta_4}$, $\frac{W_f \eta_b\, 3600}{\delta\sqrt{\theta_4}}$, $\frac{\eta}{\eta_b}$, $\frac{550\, W_f\, 3600}{F_n V_0}\eta_b$, η, and $\frac{550\, W_f\, 3600}{F_n V_0}$ are shown in figures 11 to 22 for the engine operating with preheated fuel. The difference in performance between using unheated and preheated fuel can be obtained by comparing these figures with the related figures in reference 1. The differences in performance are a result of the differences in the temperature ratio τ_1, (T_4/T_1). Some of the differences are due to variations in specific heats and momentum pressure drops, which accompany changes in τ_1. (See reference 2.)

The maximum value of jet thrust F_j developed by the engine reduced to NACA standard atmospheric conditions at sea level F_j/δ was 5517 pounds at $M_0 = 1.23$ (fig. 11). The actual values of F_j measured and the approximate altitudes at which these data were obtained can be determined from figure 12. The pressure-altitude contours are based on the reduced jet-thrust curve of figure 11.

At a given M_0, if the temperature ratio τ_1 was maintained constant, the net thrust F_n would not be affected by preheating the fuel. The maximum net thrust developed by the ram jet reduced to NACA standard atmospheric conditions at sea level F_n/δ was 3375 pounds at $M_0 = 1.23$ and $\tau_1 = 6.9$ (fig. 13). The effects of M_0 and τ_1 on the net-thrust coefficient C_F are shown in figure 14. The maximum C_F was 0.696 at $M_0 = 1.23$ and $\tau_1 = 6.9$.

The maximum over-all efficiency η attained in this investigation was 8.13 percent at $M_0 = 1.20$ and $\eta_b = 84$ percent (fig. 21). The corresponding actual net-power specific fuel consumption was 1.65 pounds per horsepower-hour (fig. 22). The combustion-efficiency contours are approximate in that the effect of variations of τ_1 are not included.

As previously indicated, the cooling water absorbed approximately 3.3 percent of the lower heating value of the fuel. Only 0.5 percent of the lower heating value of the fuel is required to raise the fuel temperature from 40° to 200° F. This margin would permit the use of a regenerative fuel preheating system with a combustion chamber shorter than that used in this investigation.

SUMMARY OF RESULTS

From an investigation of the performance of a 20-inch ram jet with a 12-foot combustion chamber and a 2-foot exhaust nozzle 17 inches in diameter operating on preheated unleaded (62 octane) fuel and from data obtained in an earlier investigation with a similar configuration and the same fuel, the following results were observed:

1. The combustion efficiency of the ram jet was improved by the use of preheated fuel. When the fuel injection temperature was increased from 40° to 200° F, the combustion efficiencies were generally increased approximately 10 percent.

2. The higher combustion efficiency attained with preheated fuel resulted in an increase in over-all efficiencies, temperature ratios, net thrusts, and net-thrust coefficients as compared with

those attained with unheated fuel. The maximum over-all efficiency attained was 8.13 percent at a free-stream Mach number of 1.20 and a combustion efficiency of 84 percent.

3. It was possible to recover sufficient heat from the combustion-chamber shell and the nozzle shell to raise the fuel-injection temperature from 40° to 200° F. For these conditions it is necessary to add to the fuel the equivalent of 0.5 percent of its lower heating value. The shell rejected at least 3 percent of the original lower heat content of the fuel. This margin will permit the use of a regenerative fuel preheating system with a shorter combustion chamber than the one used in this investigation.

Aircraft Engine Research Laboratory,
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Cleveland, Ohio.

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2. Ellis, Macon C., Jr., and Brown, Clinton F.: Analysis of Supersonic Ram-Jet Performance and Wind-Tunnel Tests of a Possible Supersonic Ram-Jet Airplane Model. NACA ACR No. L5L12, 1945.

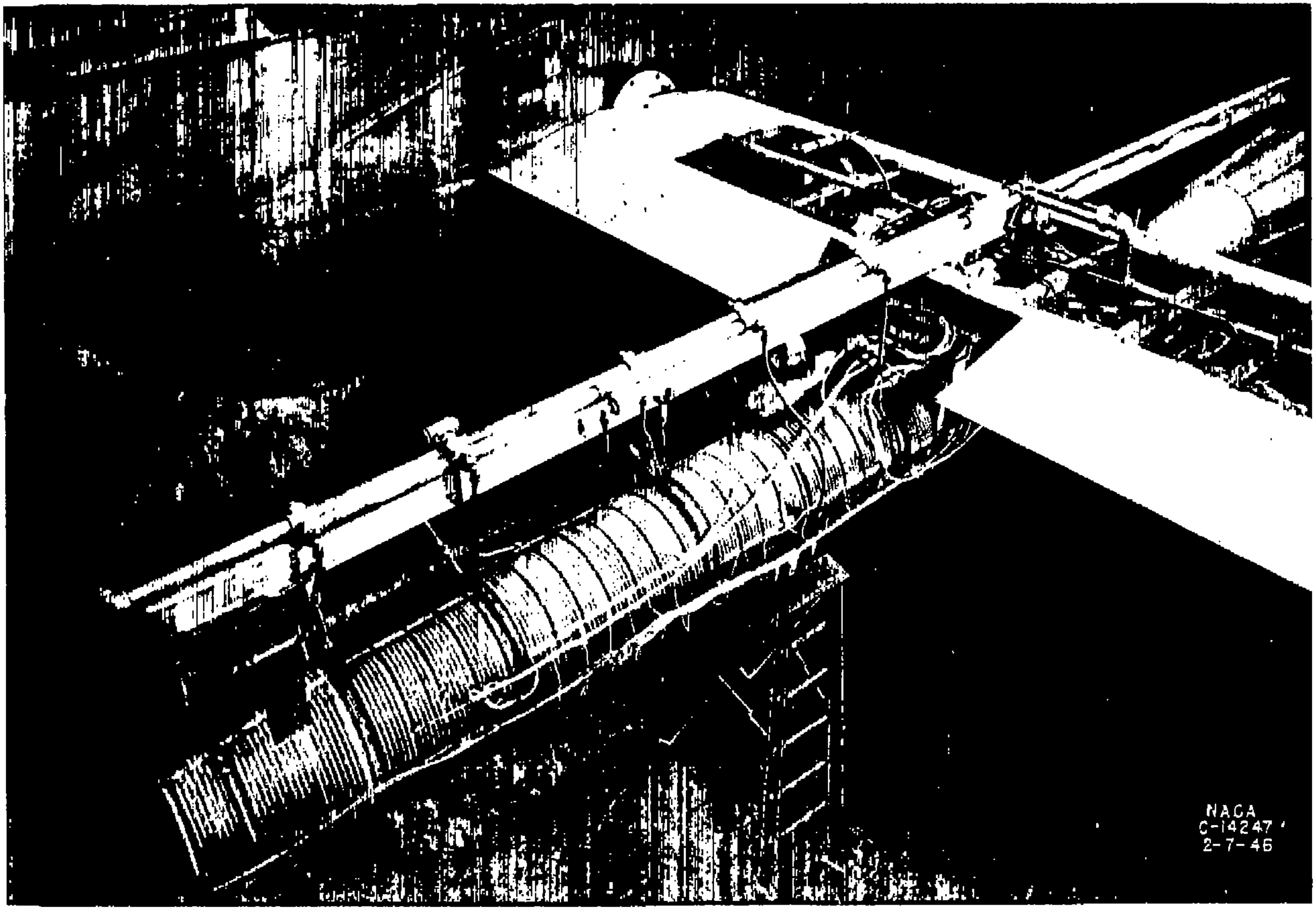

Figure 1. - Installation of 20-inch ram jet with 12-foot combustion chamber and 17-inch diameter exhaust nozzle in altitude wind tunnel for preheated-fuel investigation.

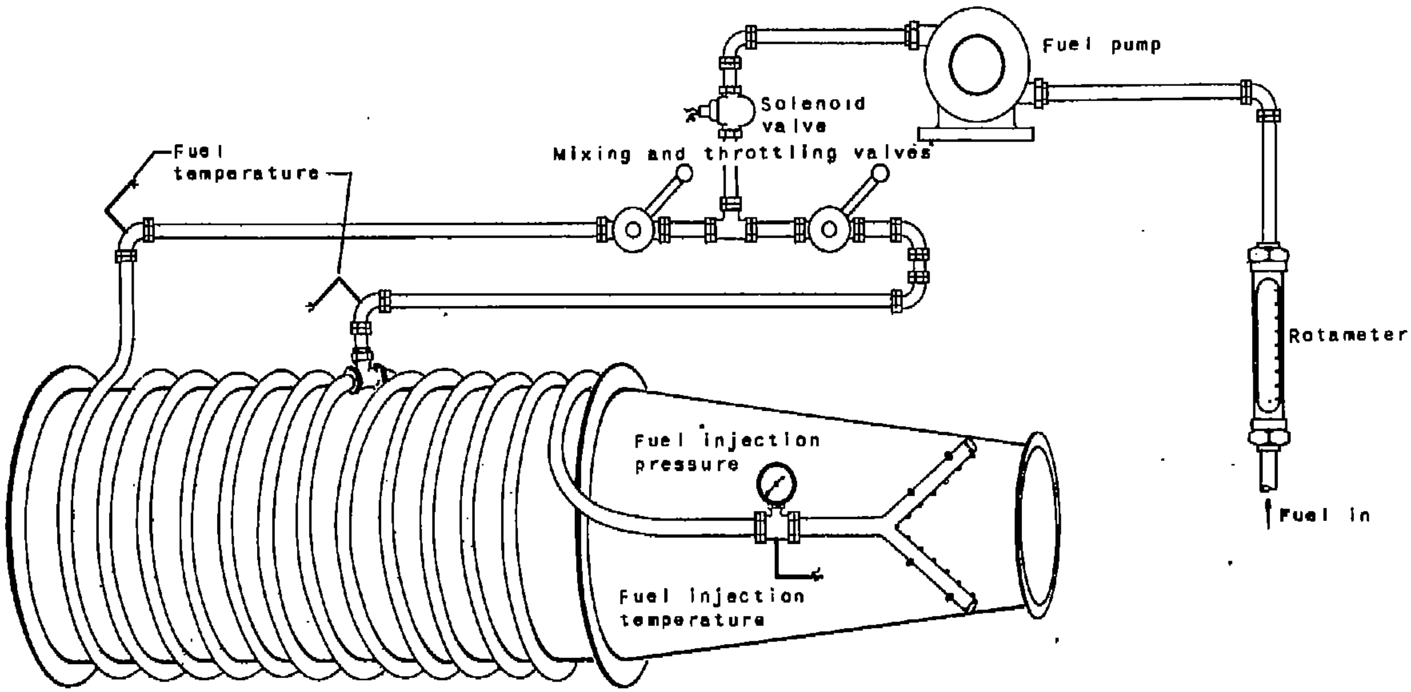

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Figure 2. - Schematic diagram of regenerative fuel-preheating and shell-cooling system.

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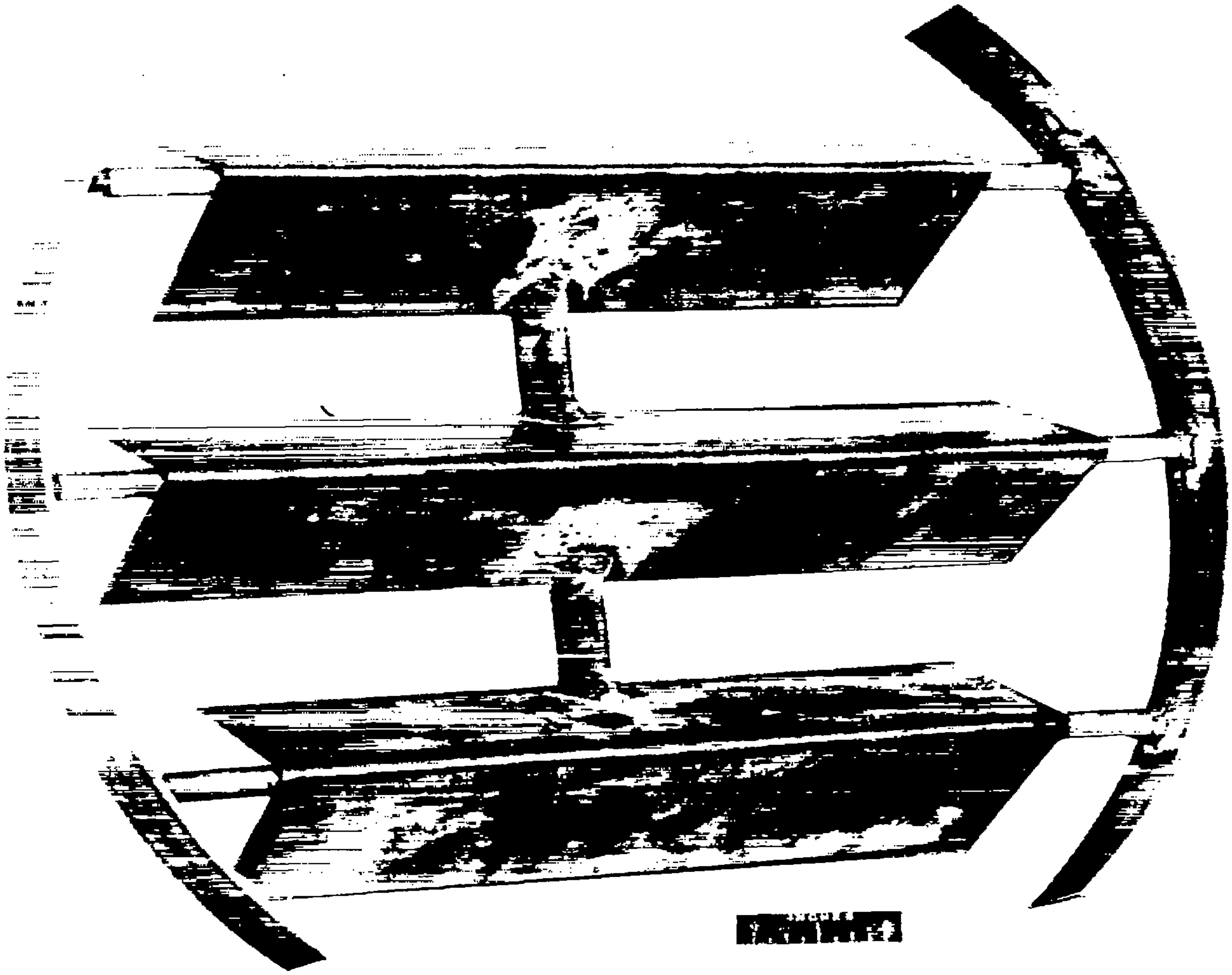

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Figure 3. - Three-V flame holder for 20-inch ram jet using preheated fuel.

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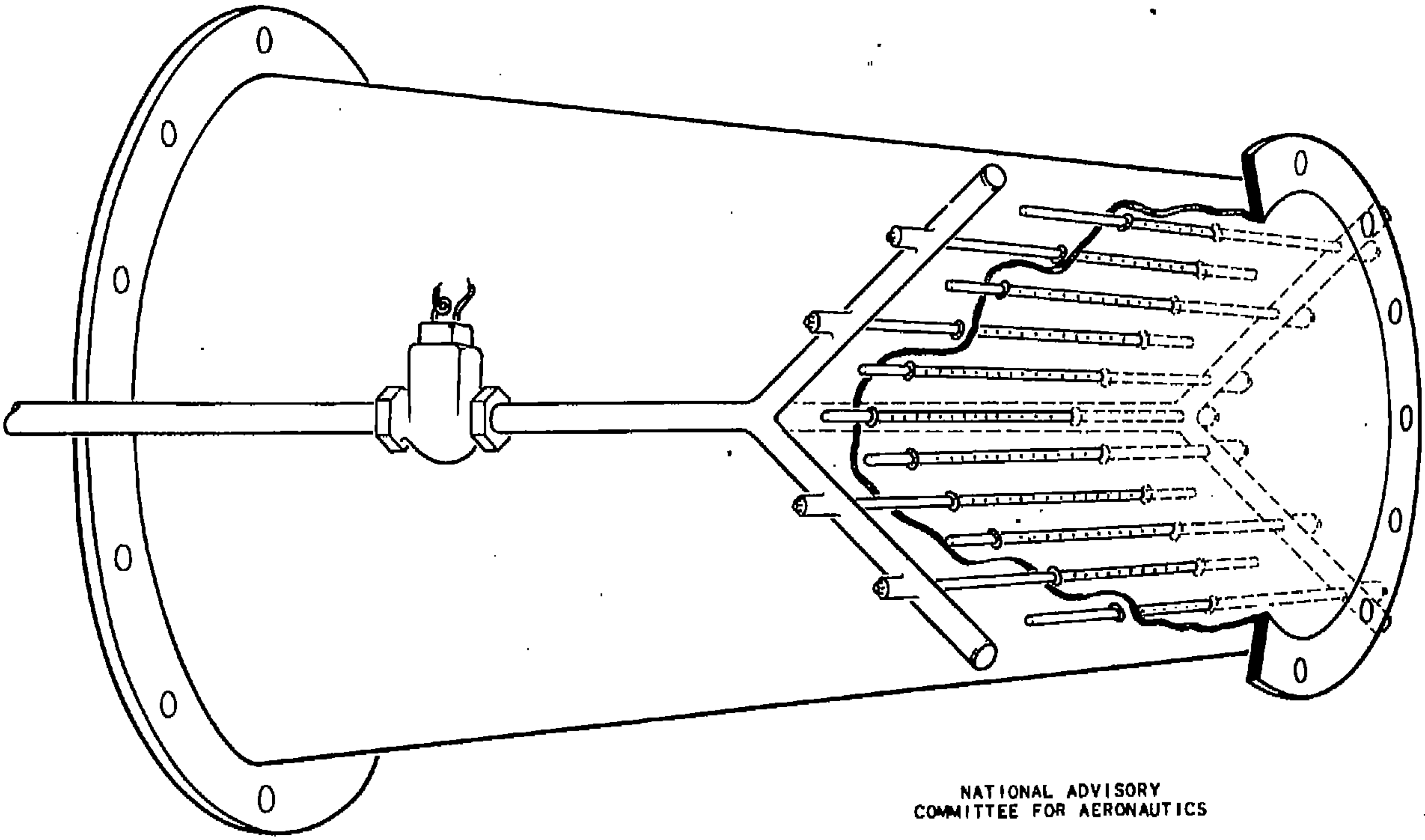

Figure 4. - Installation of four-tube and seven-tube fuel injectors in diffuser of 20-inch ram jet.

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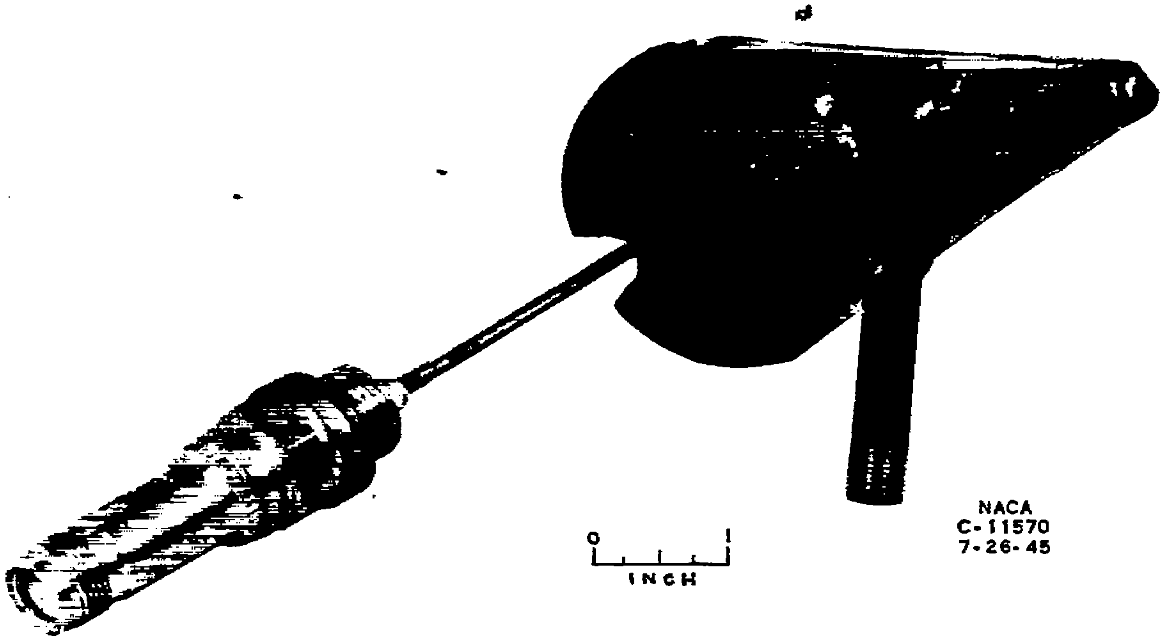

Figure 5. - Gas pilot cone and modified spark plug used to initiate combustion in 20-inch ram jet.

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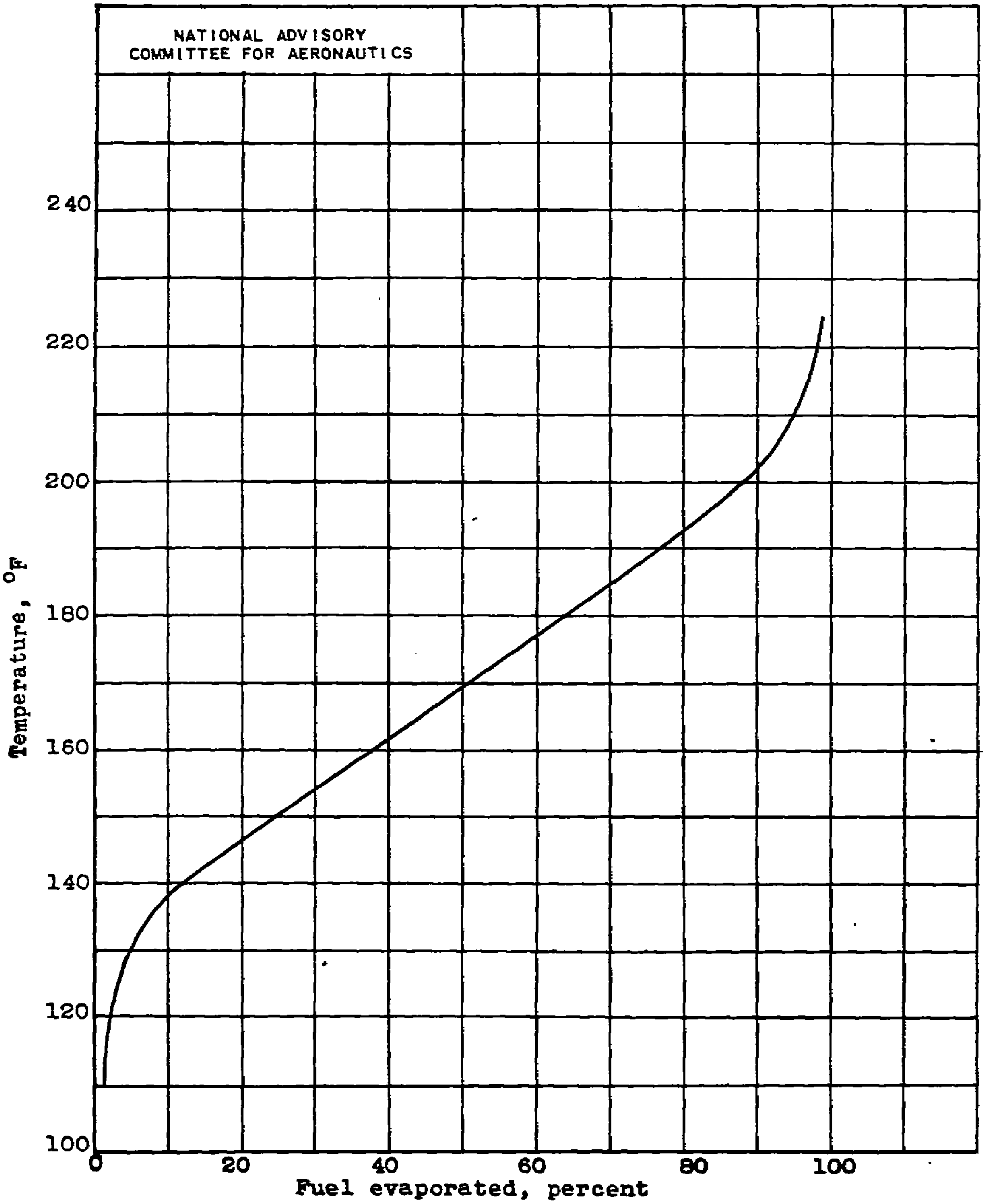

Figure 6.- A.S.T.M. distillation curve for unleaded 62-octane fuel (AN-F-22).

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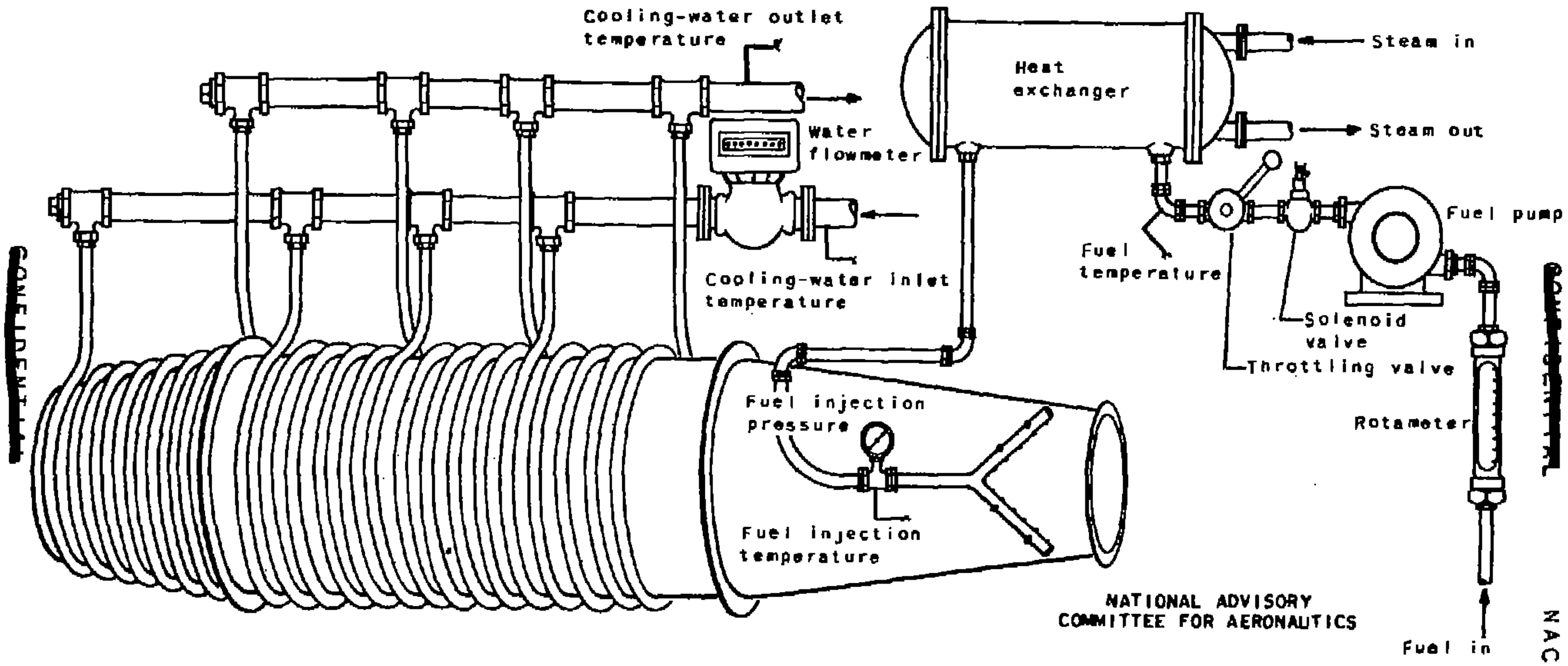

Figure 7. - Schematic diagram of external fuel-preheating and shell-cooling systems.

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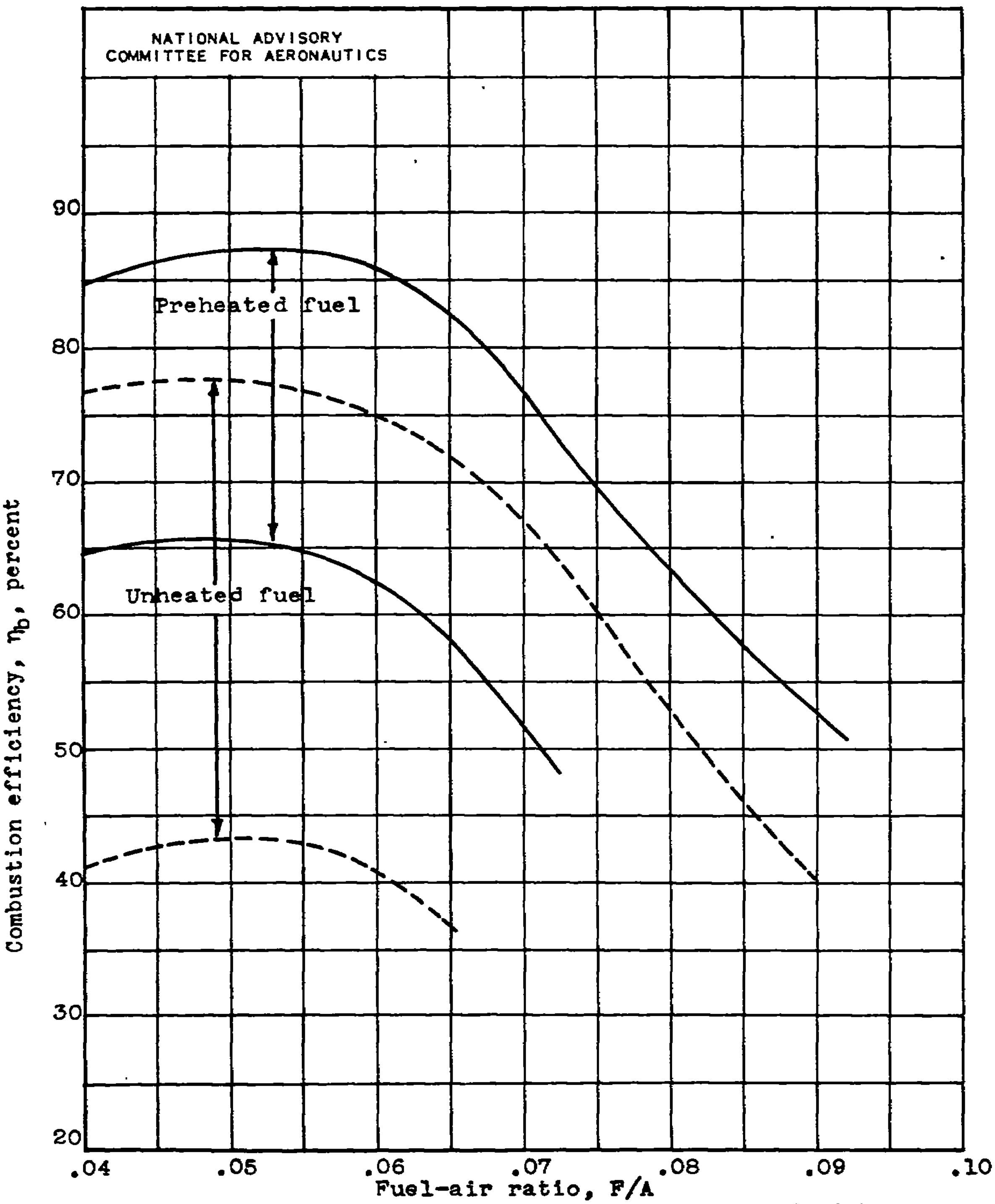

Figure 8.- Range of combustion efficiencies obtained with unheated and preheated fuel. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle. (Data for unheated fuel from reference 1.)

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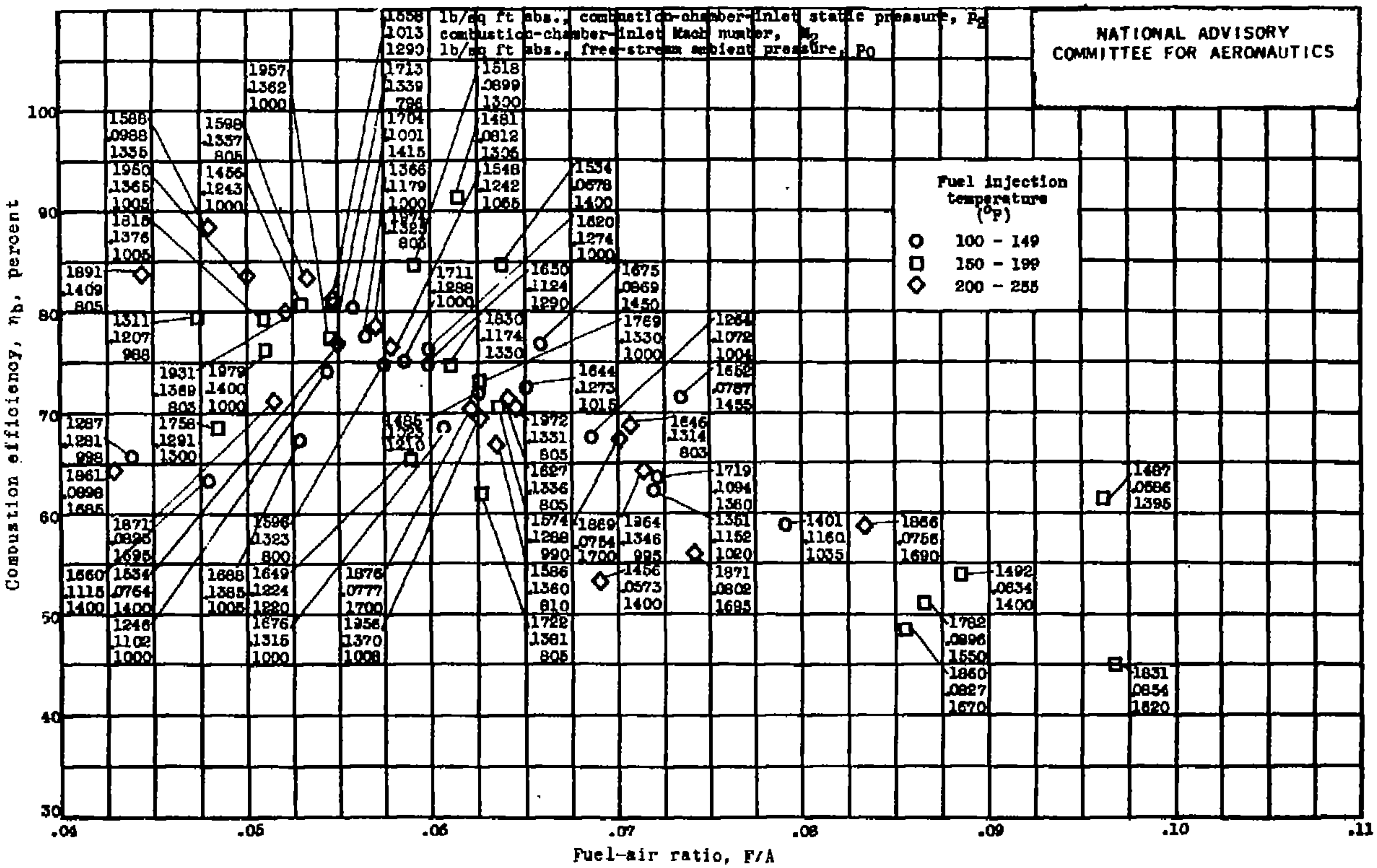

Figure 9. - Effect of fuel-air ratio F/A, combustion-chamber-inlet absolute static pressure p_2 and Mach number M_2, fuel injection temperature, and free-stream ambient pressure p_0 on combustion efficiency η_b. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

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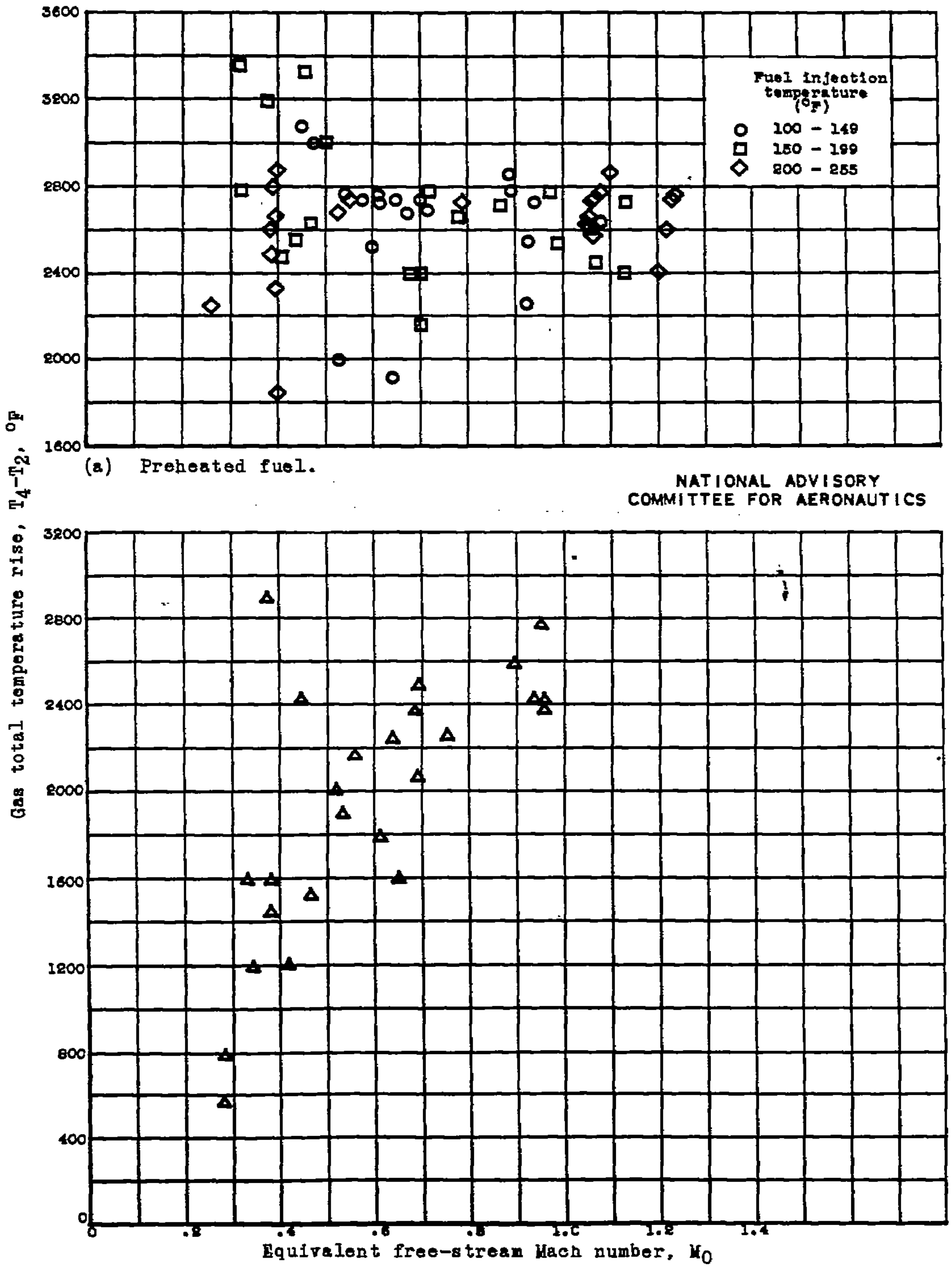

(a) Preheated fuel.

(b) Unheated fuel at 40° F (data from reference 1).

Figure 10. - Variation in gas total temperature rise T_4-T_2 with equivalent free-stream Mach number M_0 for heated and unheated fuel. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

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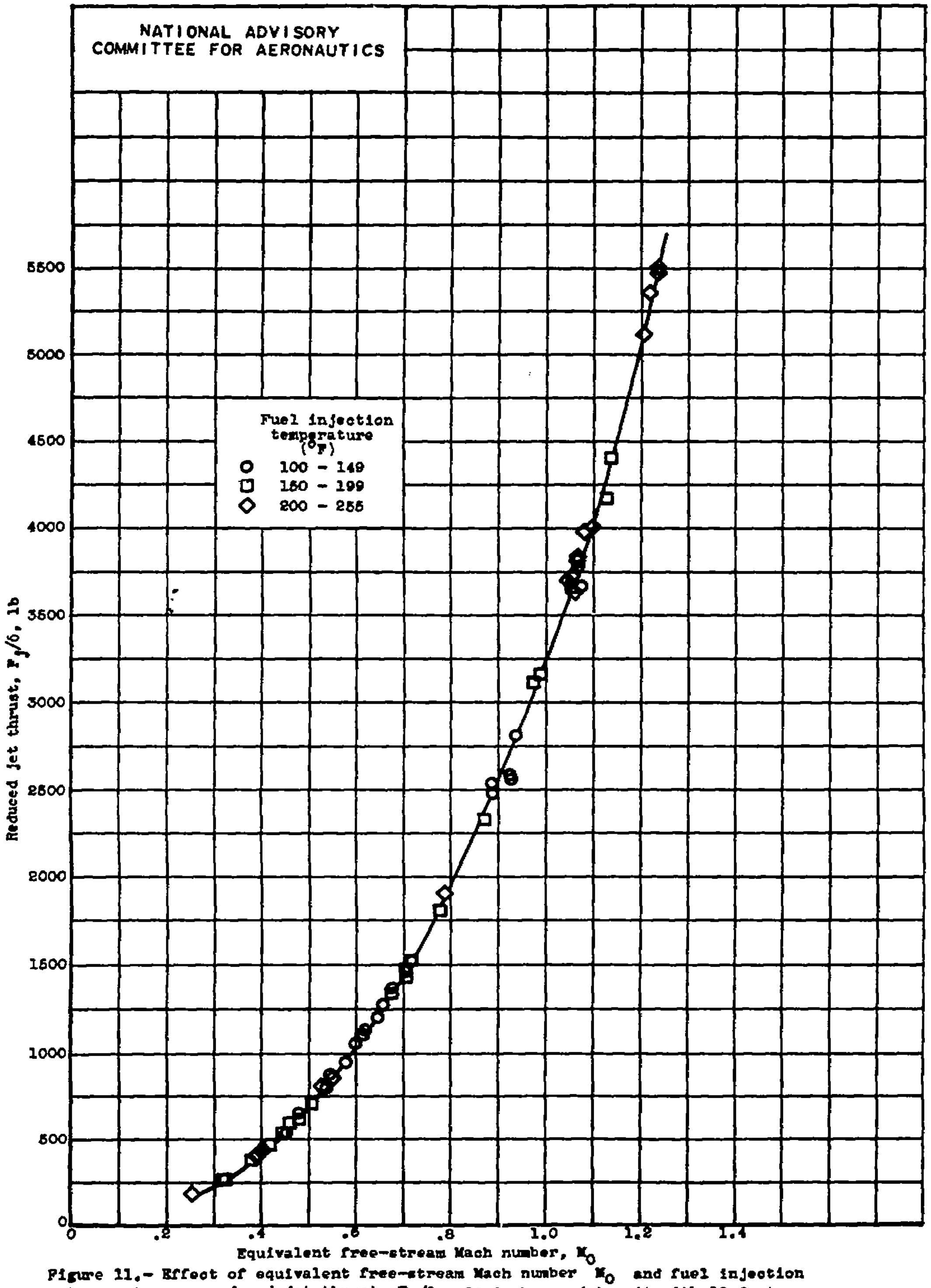

Figure 11.- Effect of equivalent free-stream Mach number M_0 and fuel injection temperature on reduced jet thrust F_j/δ. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle. Jet thrust reduced to NACA standard atmospheric conditions at sea level.

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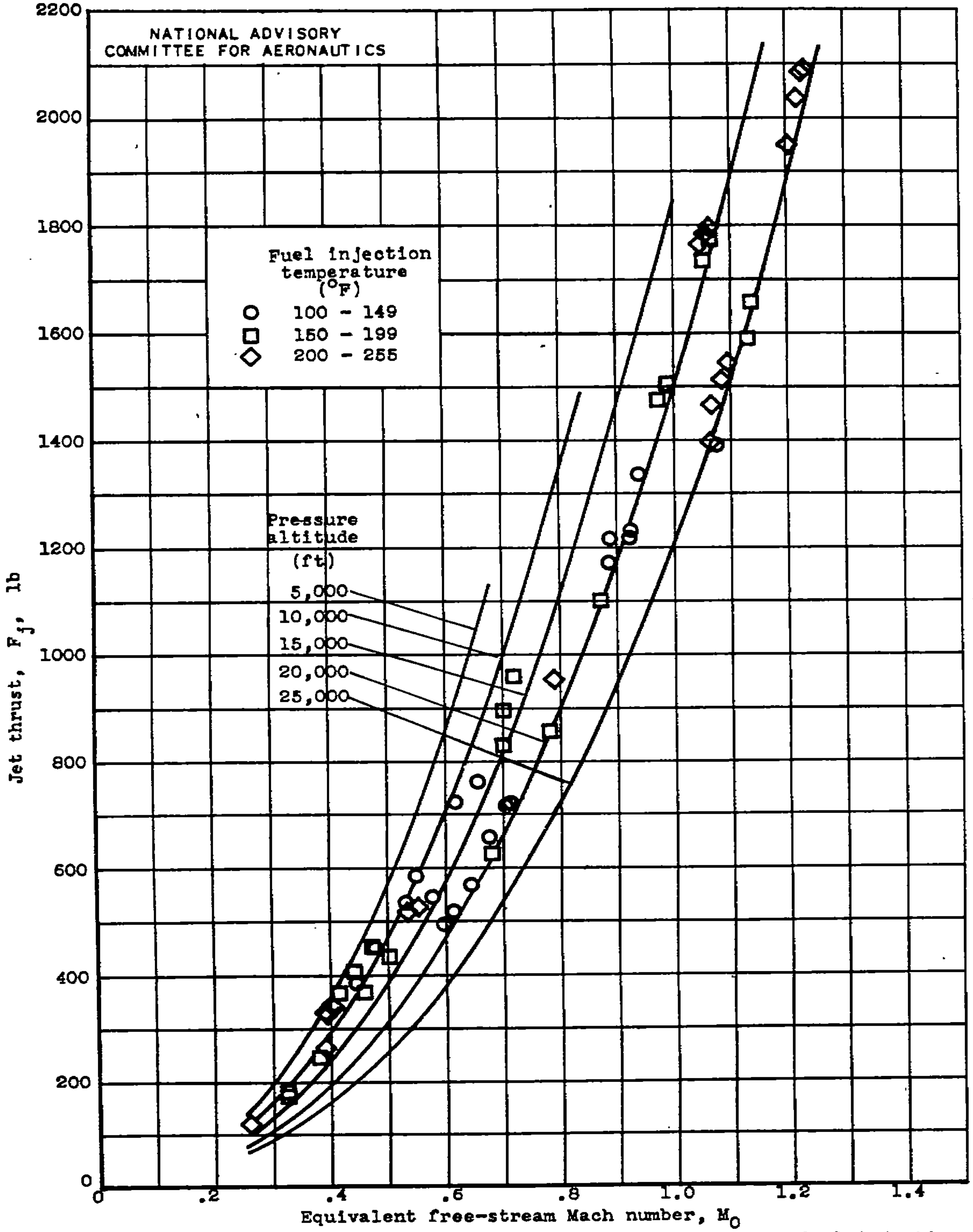

Figure 12.- Effect of equivalent free-stream Mach number M_0, fuel injection temperature, and pressure altitude on jet thrust F_j. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

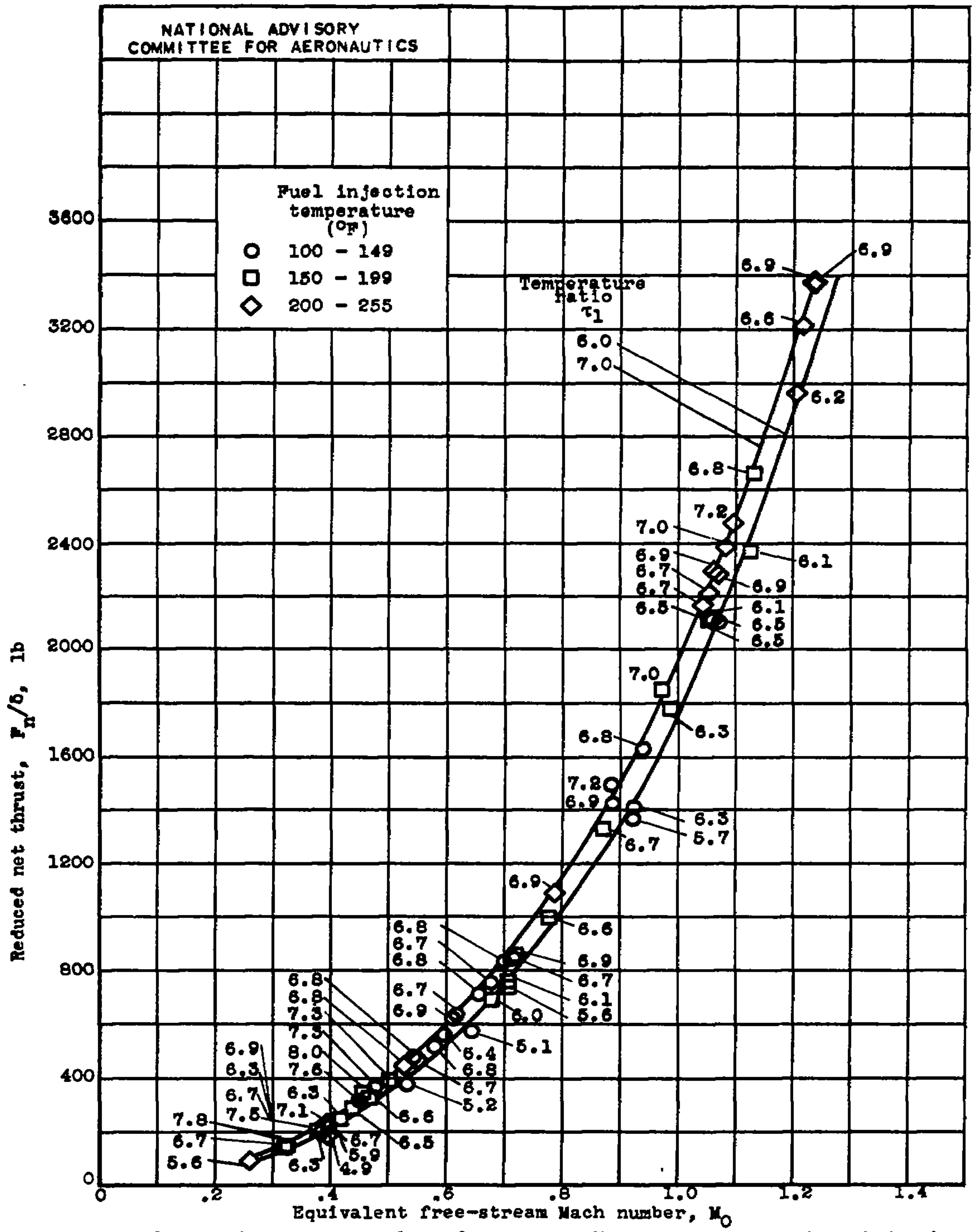

Figure 13.- Effect of equivalent free-stream Mach number M_0, fuel injection temperature, and temperature ratio τ_1 on reduced net thrust F_n/δ. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle. Net thrust reduced to NACA standard atmospheric conditions at sea level.

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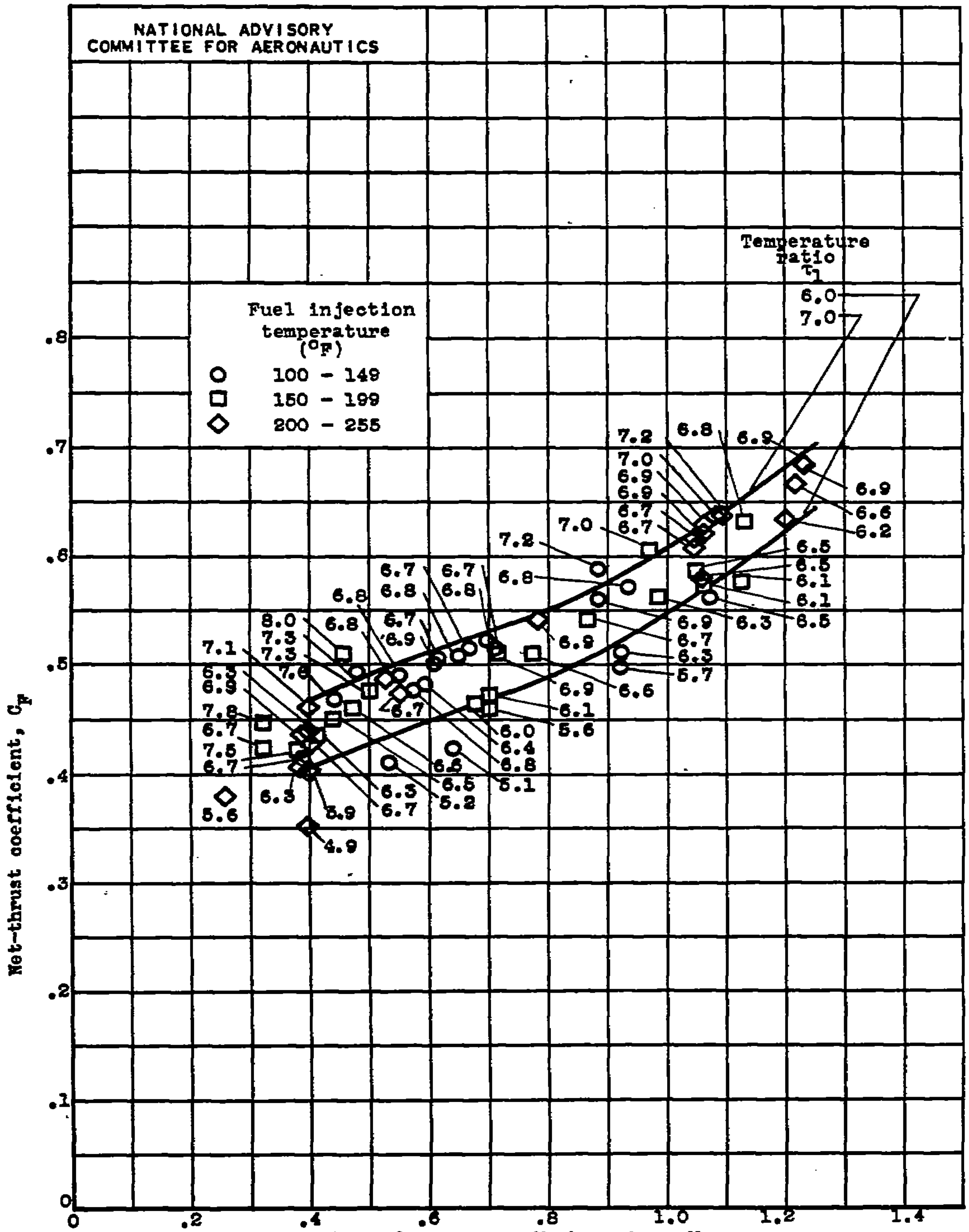

Figure 14.- Effect of equivalent free-stream Mach number M_0, fuel injection temperature, and temperature ratio τ_1 on net-thrust coefficient C_F. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

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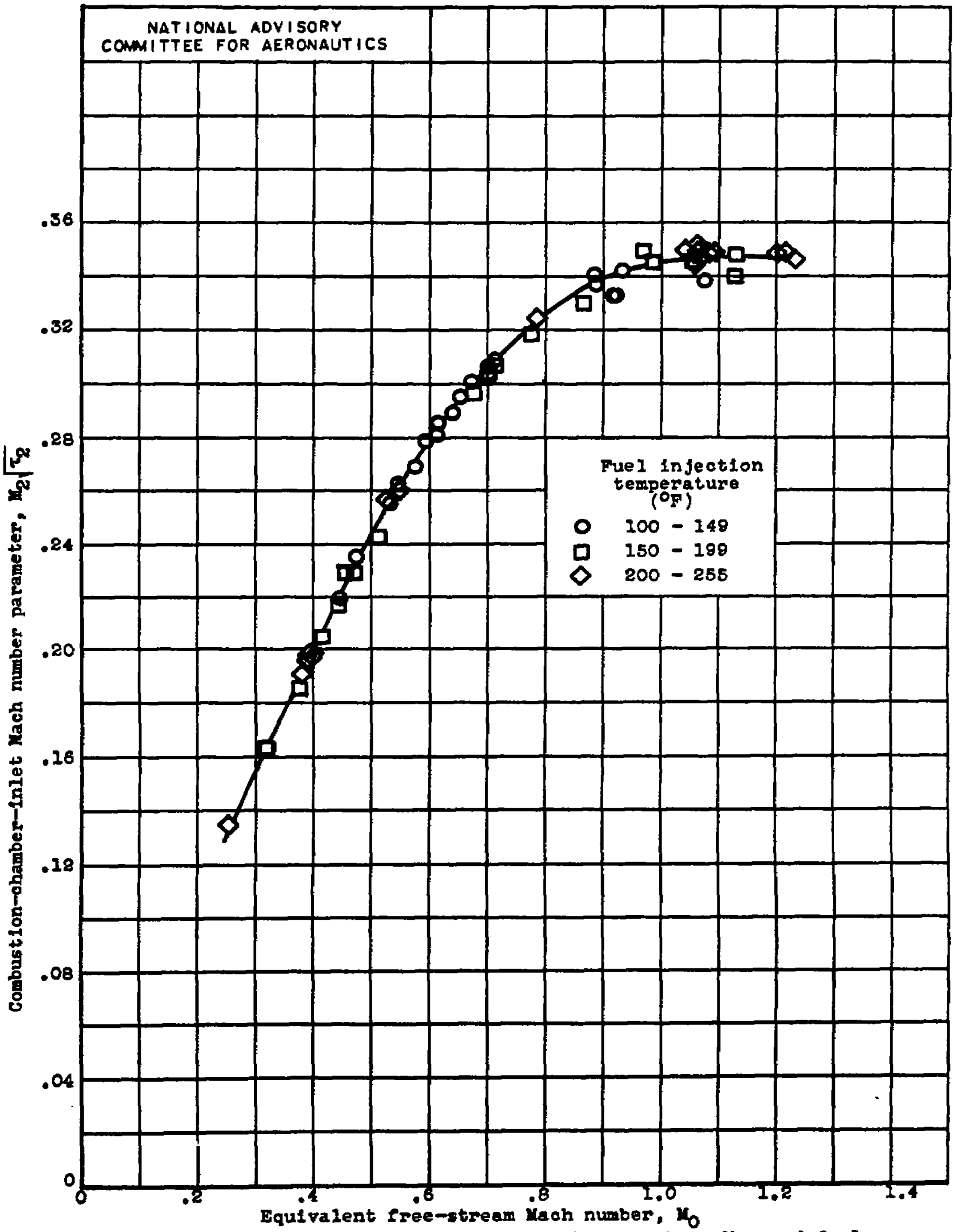

Figure 15.- Effect of equivalent free-stream Mach number M_0 and fuel injection temperature on combustion-chamber-inlet Mach number parameter $M_2\sqrt{\tau_2}$. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

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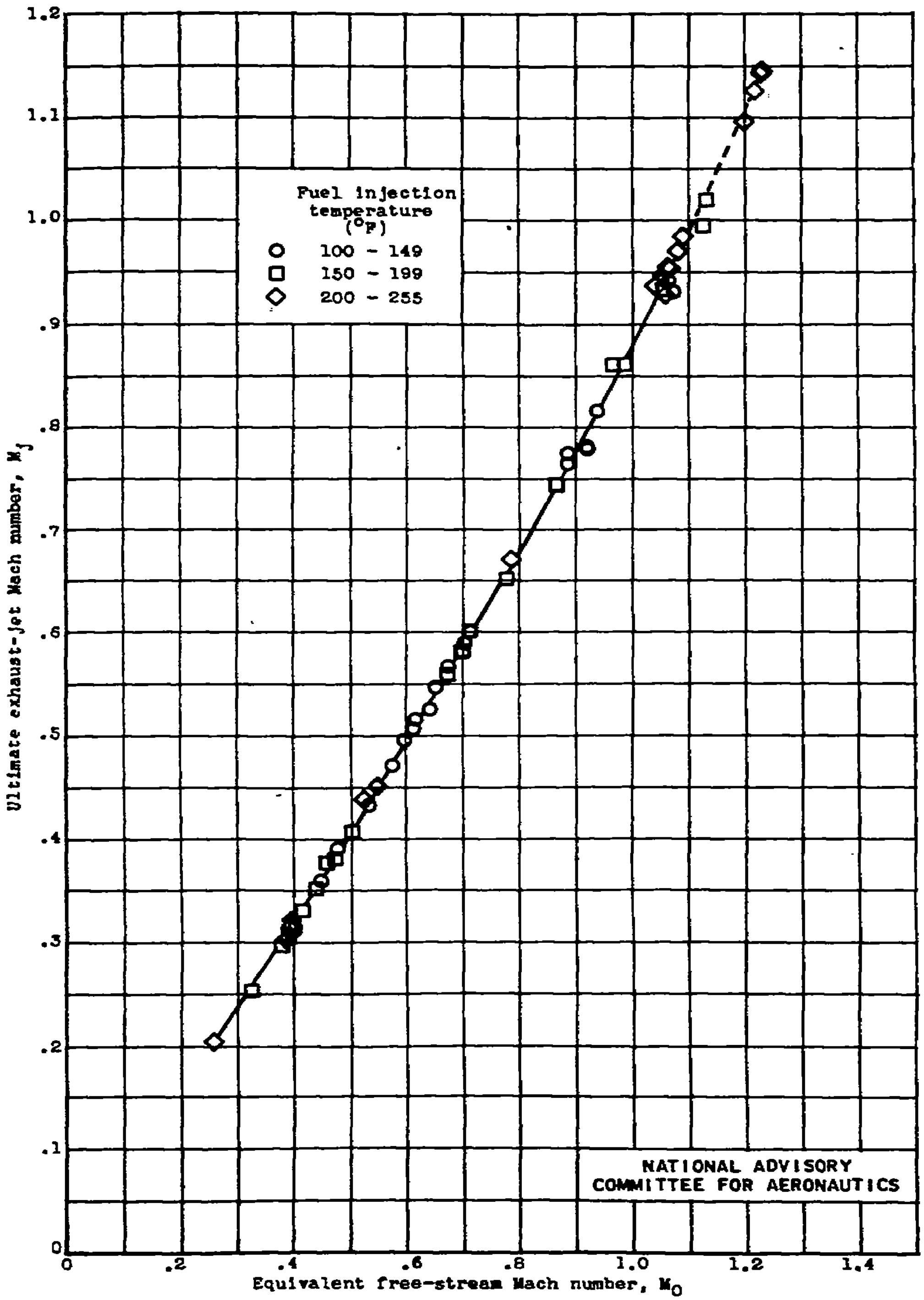

Figure 16.- Effect of equivalent free-stream Mach number M_0 and fuel injection temperature on ultimate exhaust-jet Mach number M_j. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

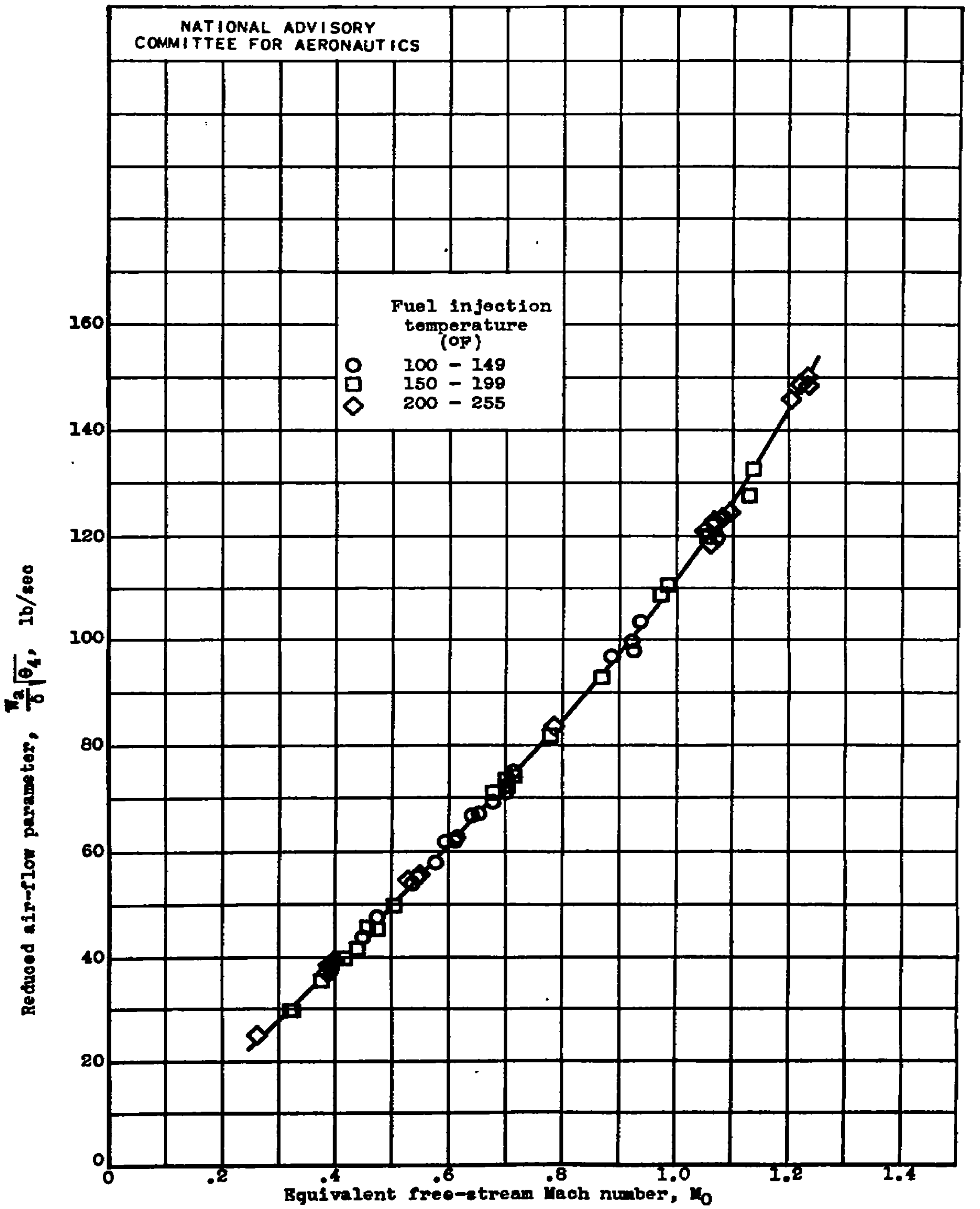

Figure 17.- Effect of equivalent free-stream Mach number M_0 and fuel injection temperature on reduced air-flow parameter $\frac{W_a}{\delta}\sqrt{\theta_4}$. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle. Air flow reduced to NACA standard atmospheric conditions at sea level.

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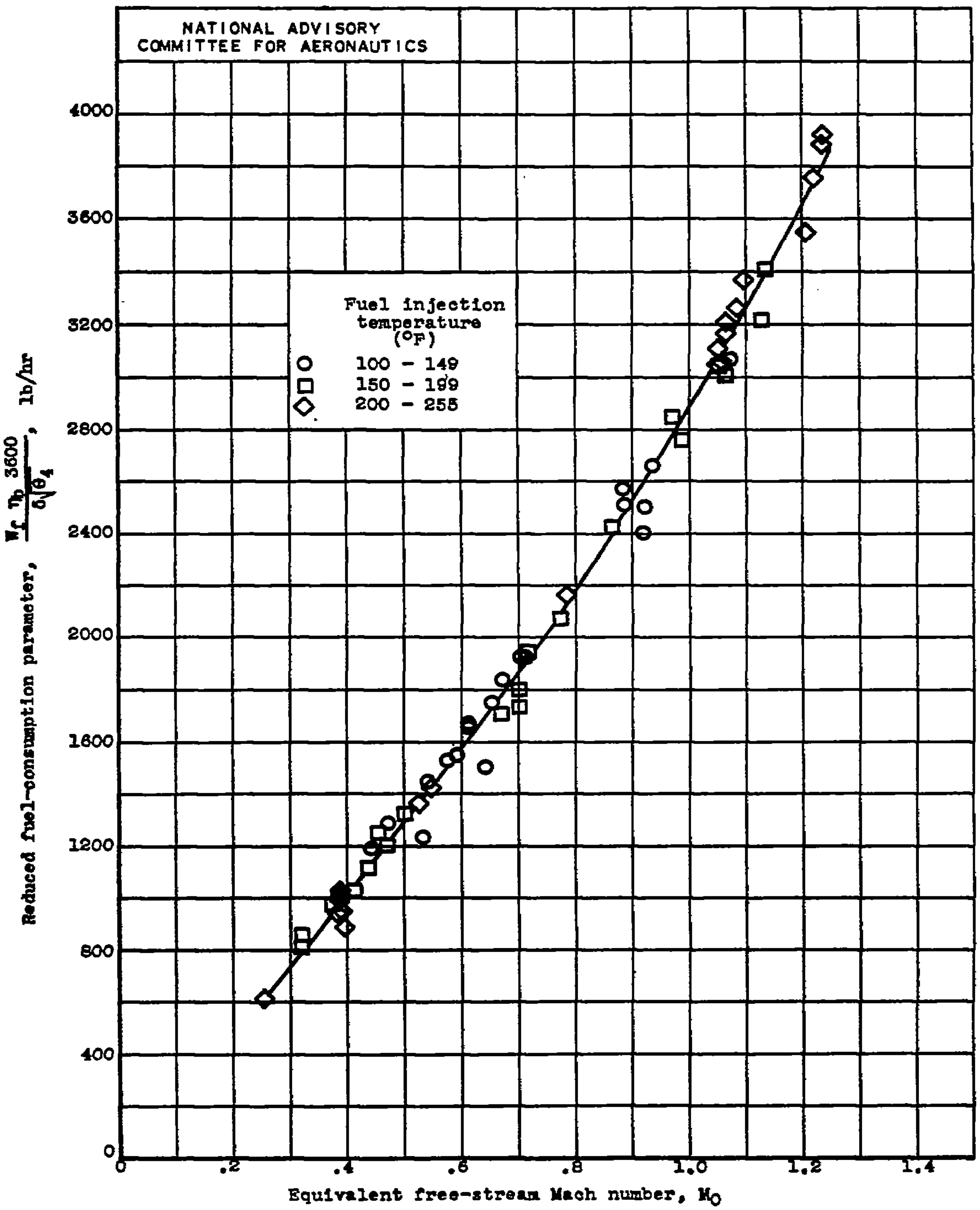

Figure 18.- Effect of equivalent free-stream Mach number M_0 and fuel injection temperature on reduced fuel-consumption parameter $\frac{W_f \eta_b 3600}{\delta\sqrt{\theta_4}}$. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle. Fuel flow reduced to NACA standard atmospheric conditions at sea level.

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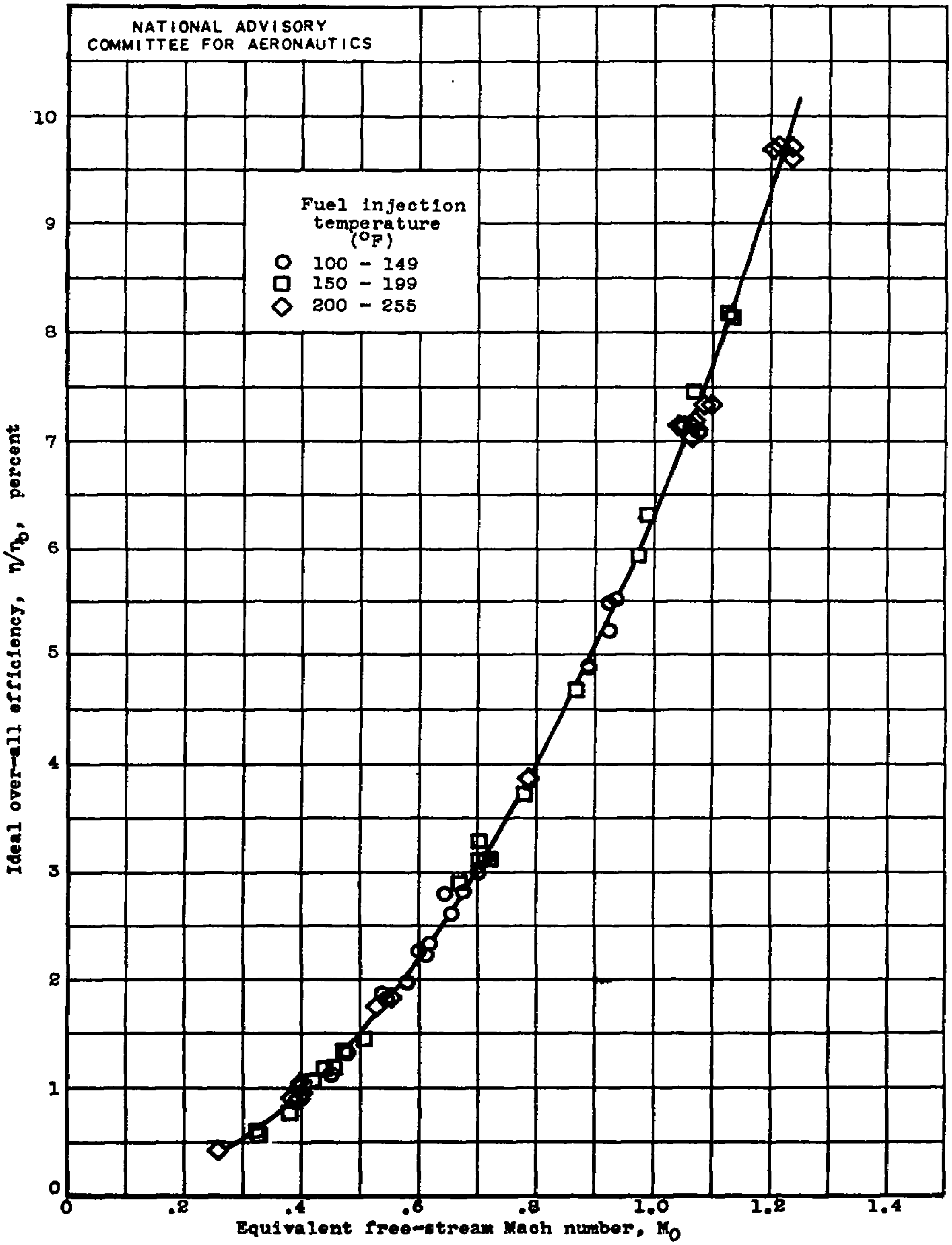

Figure 19.- Effect of equivalent free-stream Mach number M_0 and fuel injection temperature on ideal over-all efficiency η/η_b. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

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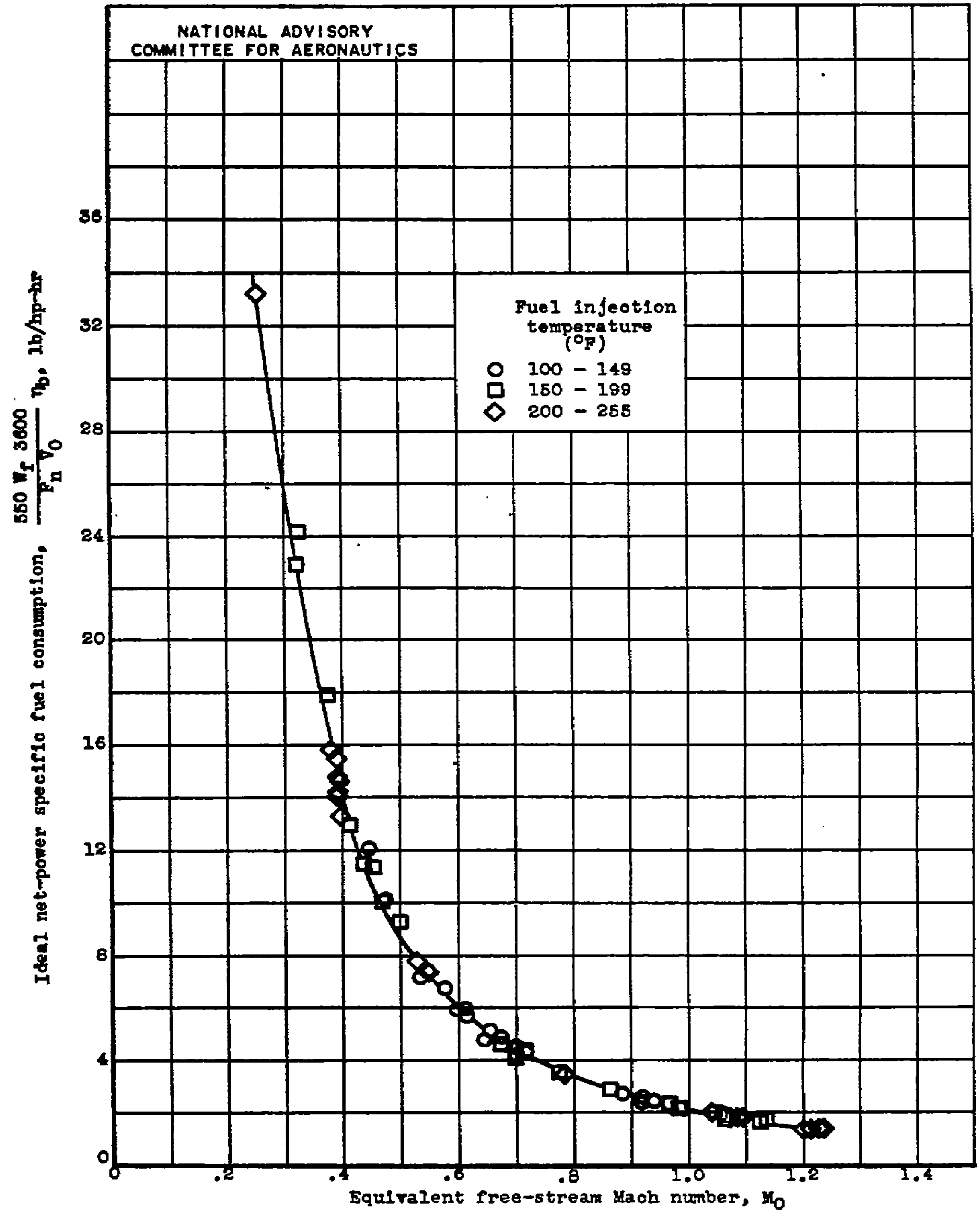

Figure 20.– Effect of equivalent free-stream Mach number M_0 and fuel injection temperature on ideal net-power specific fuel cpnsumption $\frac{550\ W_f\ 3600}{F_n\ V_0}\ \eta_b$. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

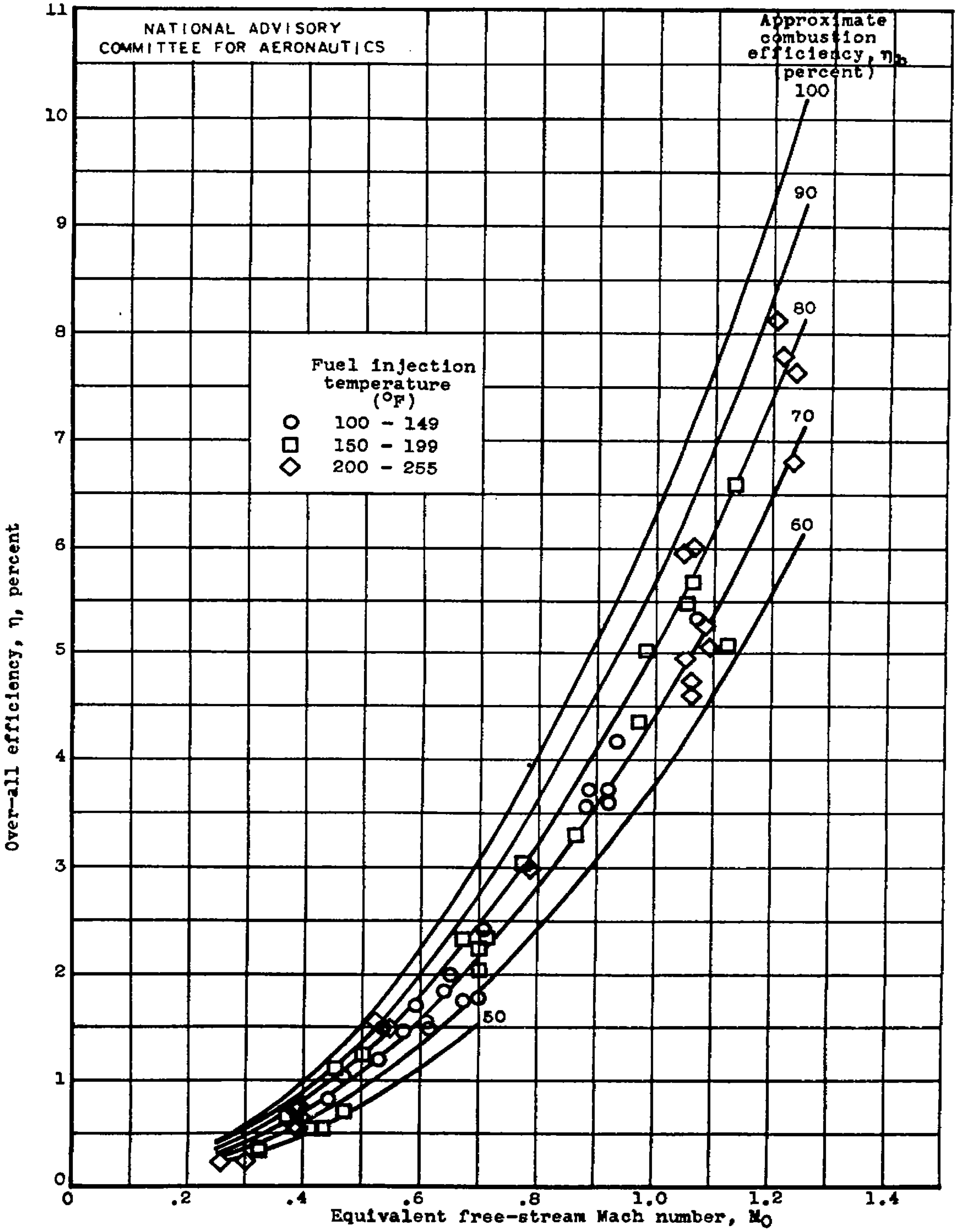

Figure 21.- Effect of equivalent free-stream Mach number M_0, fuel injection temperature, and combustion efficiency on over-all efficiency η. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

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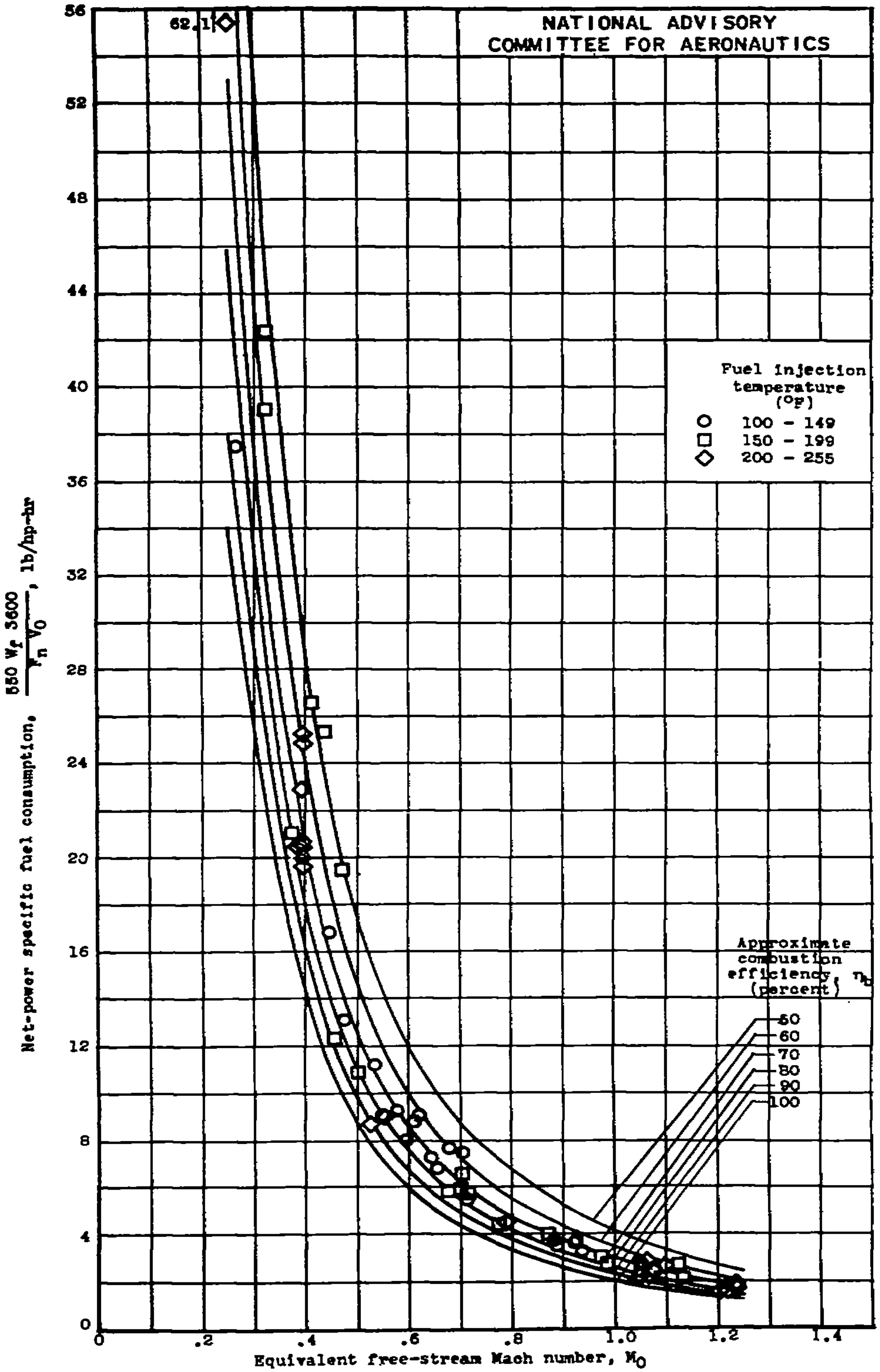

Figure 22.- Effect of equivalent free-stream Mach number M_0, fuel injection temperature, and combustion efficiency η_b on net-power specific fuel consumption $\frac{550\ W_f\ 3600}{F_n\ V_0}$. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

Author (3)

Engines, Jets - Ram

Engines, Jet - Performance

Fuels - Octane

x Fuels, Preheated

Fuels - Temperature [illegible]