RM No. E6I23

NACA

RESEARCH MEMORANDUM

INVESTIGATION OF THE PERFORMANCE OF A

20-INCH RAM JET USING PREHEATED FUEL

By Eugene Perchonok, Fred A. Wilcox
and William H. Sterbentz

Aircraft Engine Research Laboratory
Cleveland, Ohio

TECHNICAL
EDITING
WAIVED

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

October 28, 1946

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

INVESTIGATION OF THE PERFORMANCE OF A

20-INCH RAM JET USING PREHEATED FUEL

By Eugene Perchonok, Fred A. Wilcox
and William H. Sterbentz

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 per-
formance 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 propa-
gation. Improved combustion and over-all efficiencies would like-
wise 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 regen-
erative 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 investi-
gation. 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. Conse-
quently, an external heating source was substituted for the regen-
erative fuel preheating system to expedite the research. A com-
mercial 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 attain-
able 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, $\dfrac{2F_n}{\gamma_0 p_0 A_3 M_0{}^2}$

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, $^\circ R$

V velocity, feet 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

$\dfrac{\eta}{\eta_b}$ 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

$\dfrac{W_a}{\delta}\sqrt{\theta_4}$ reduced air-flow parameter, pounds per second

$\dfrac{W_f \eta_b\ 3600}{\delta\sqrt{\theta_4}}$ reduced fuel-consumption parameter, pounds per hour

$\dfrac{550\ W_f\ 3600}{F_n V_0}$ 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 pre-
heated 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 com-
bustion-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 calcu-
lations 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 $\dfrac{F_j}{\delta}$, F_j, $\dfrac{F_n}{\delta}$, C_F, $M_2\sqrt{\tau_2}$, M_j, $\dfrac{W_a}{\delta}\sqrt{\theta_4}$, $\dfrac{W_f\eta_b\,3600}{\delta\sqrt{\theta_4}}$, $\dfrac{\eta}{\eta_b}$, $\dfrac{550\,W_f\,3600}{F_n V_0}\eta_b$, η, and $\dfrac{550\,W_f\,3600}{F_n V_0}$ 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 0.686 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,
        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. Ellis, Macon C., Jr., and Brown, Clinton E.: Analysis of Supersonic Ram-Jet Performance and Wind-Tunnel Tests of a Possible Supersonic Ram-Jet Airplane Model. NACA ACR No. L5L12, 1945.
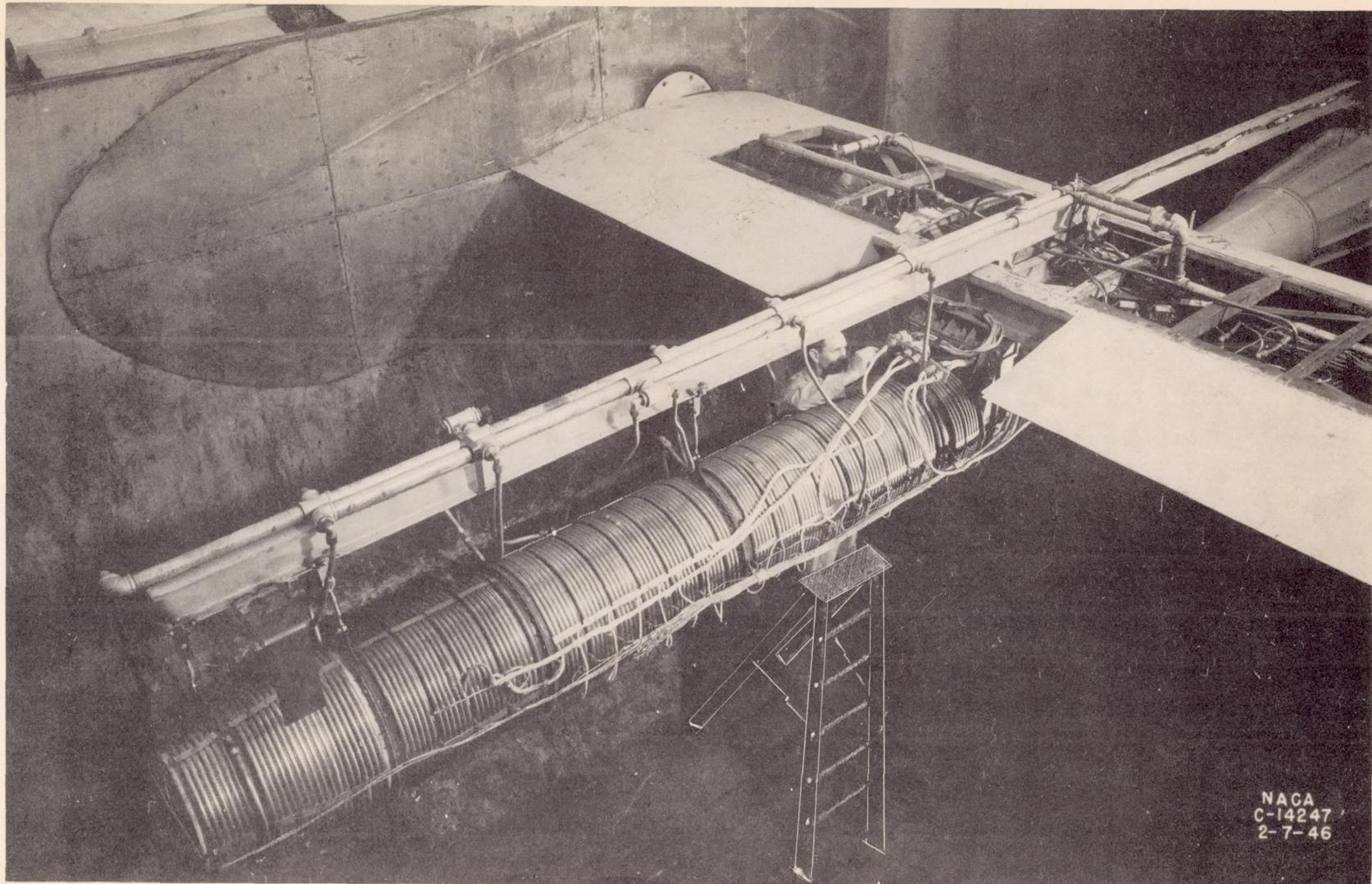
NACA
C-14247
2-7-46

Figure I. - 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.

Fig. 1

Fuel pump

Solenoid
valve

Mixing and throttling valves

Fuel
temperature

Rotameter

Fuel injection
pressure

Fuel in

Fuel injection
temperature

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS
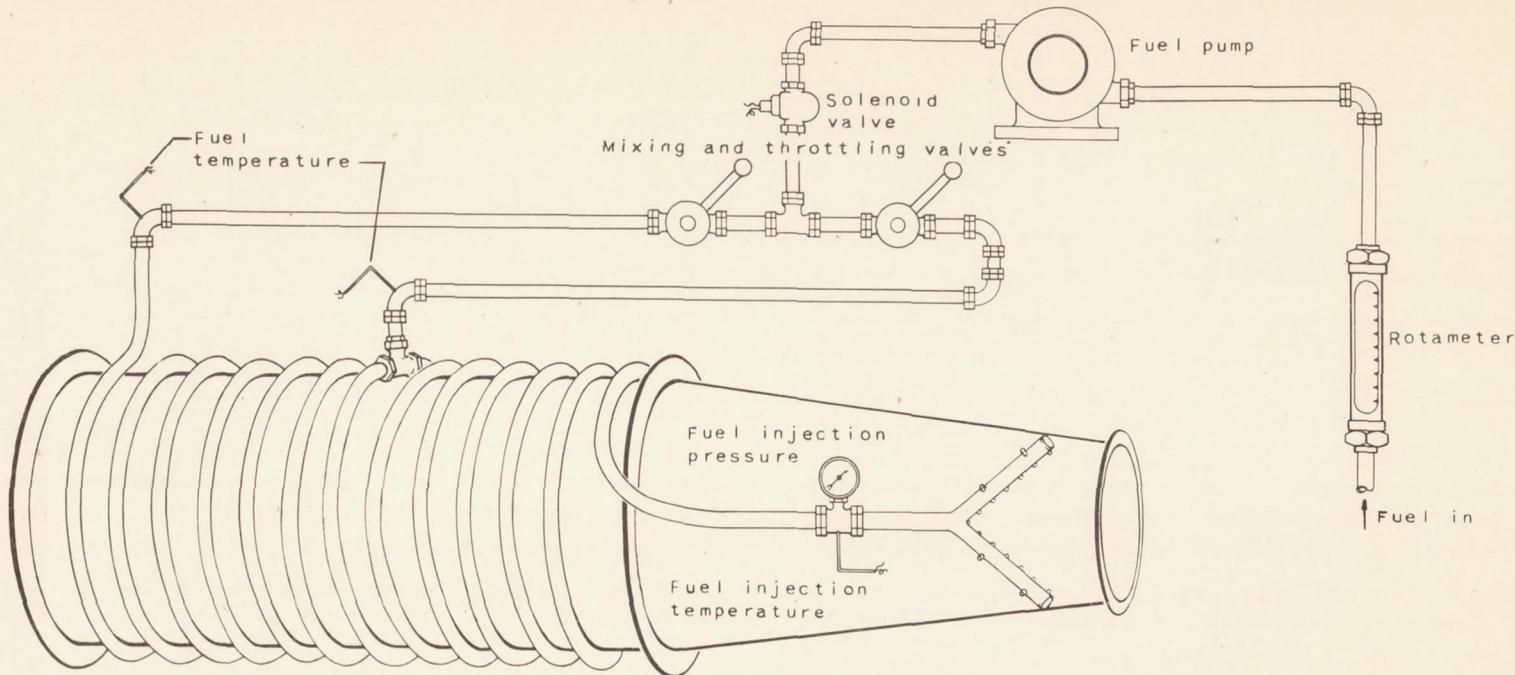
Figure 2. - Schematic diagram of regenerative fuel-preheating and shell-cooling system.

Fig. 2
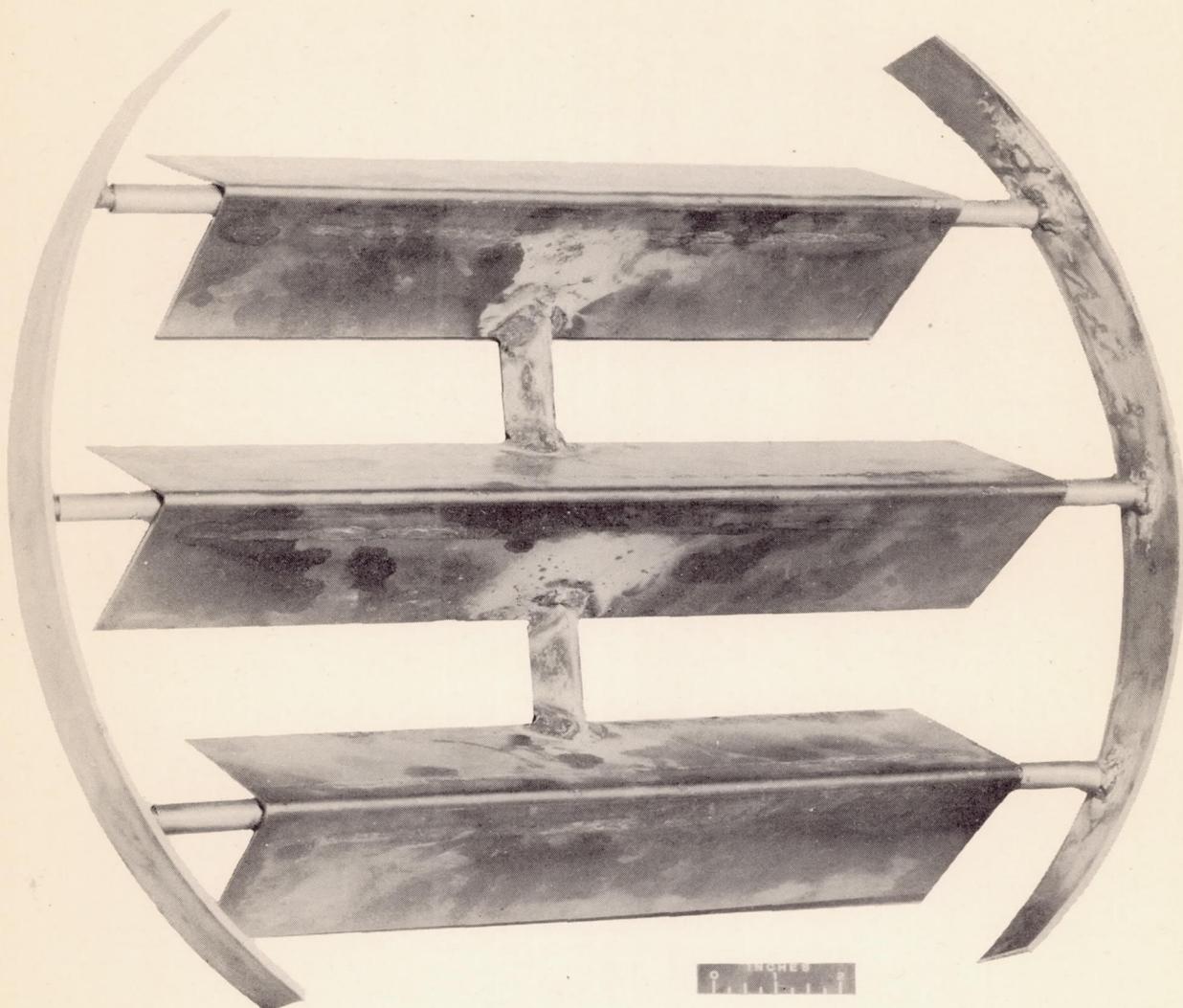
NACA
C-13978
12-20-45

Figure 3. - Three-V flame holder for 20-inch ram jet using preheated fuel.
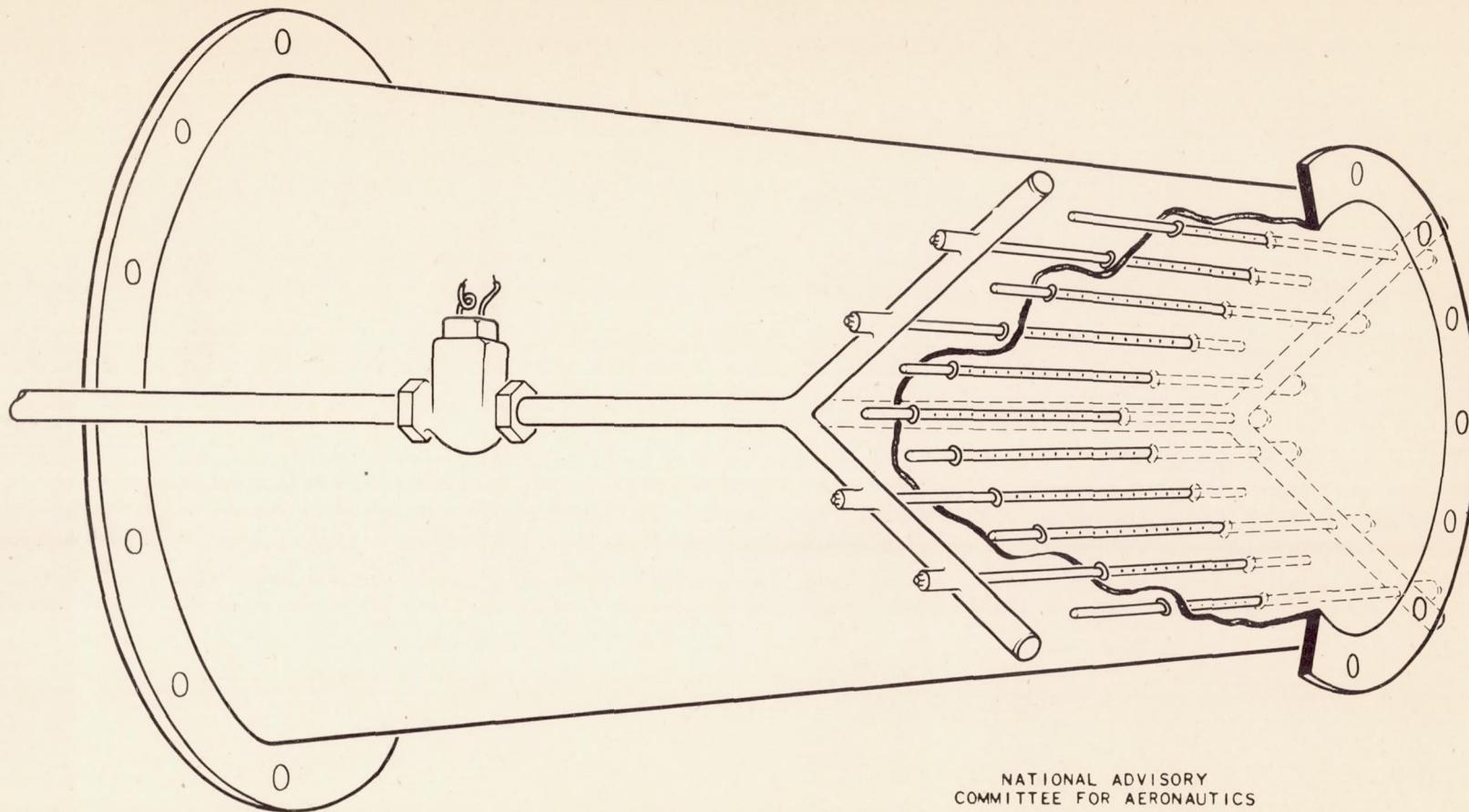
NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

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

Fig. 4

635

NACA
C-11570
7-26-45

0   1
INCH
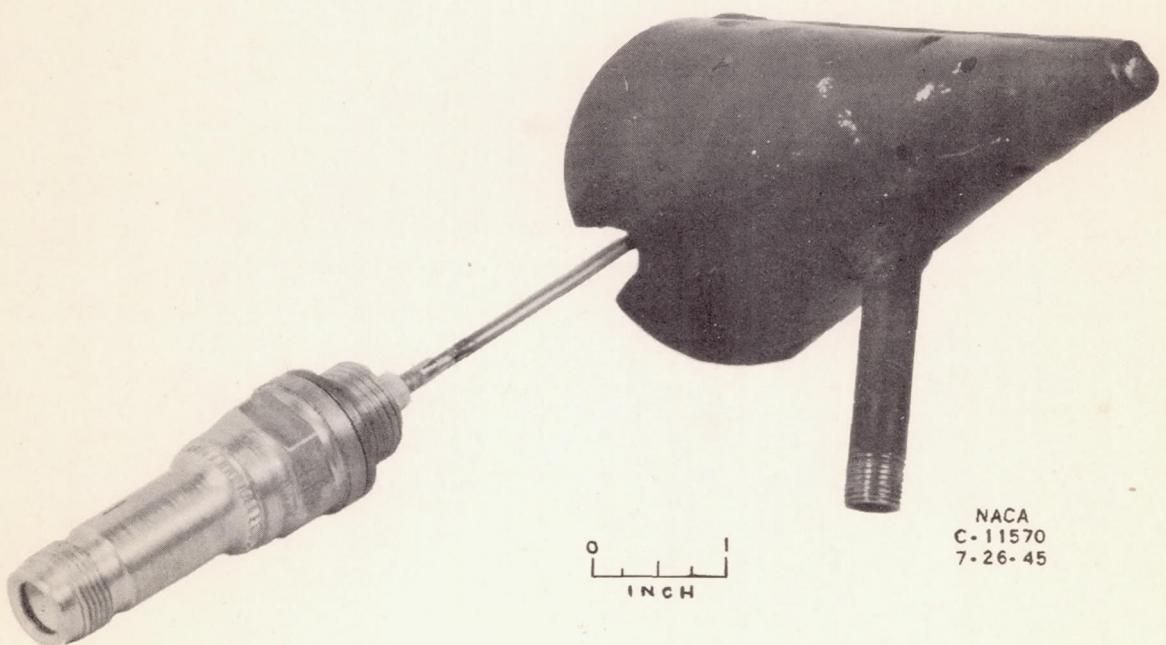
Figure 5. - Gas pilot cone and modified spark plug used to
    initiate combustion in 20-inch ram jet.

635

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

Temperature, °F

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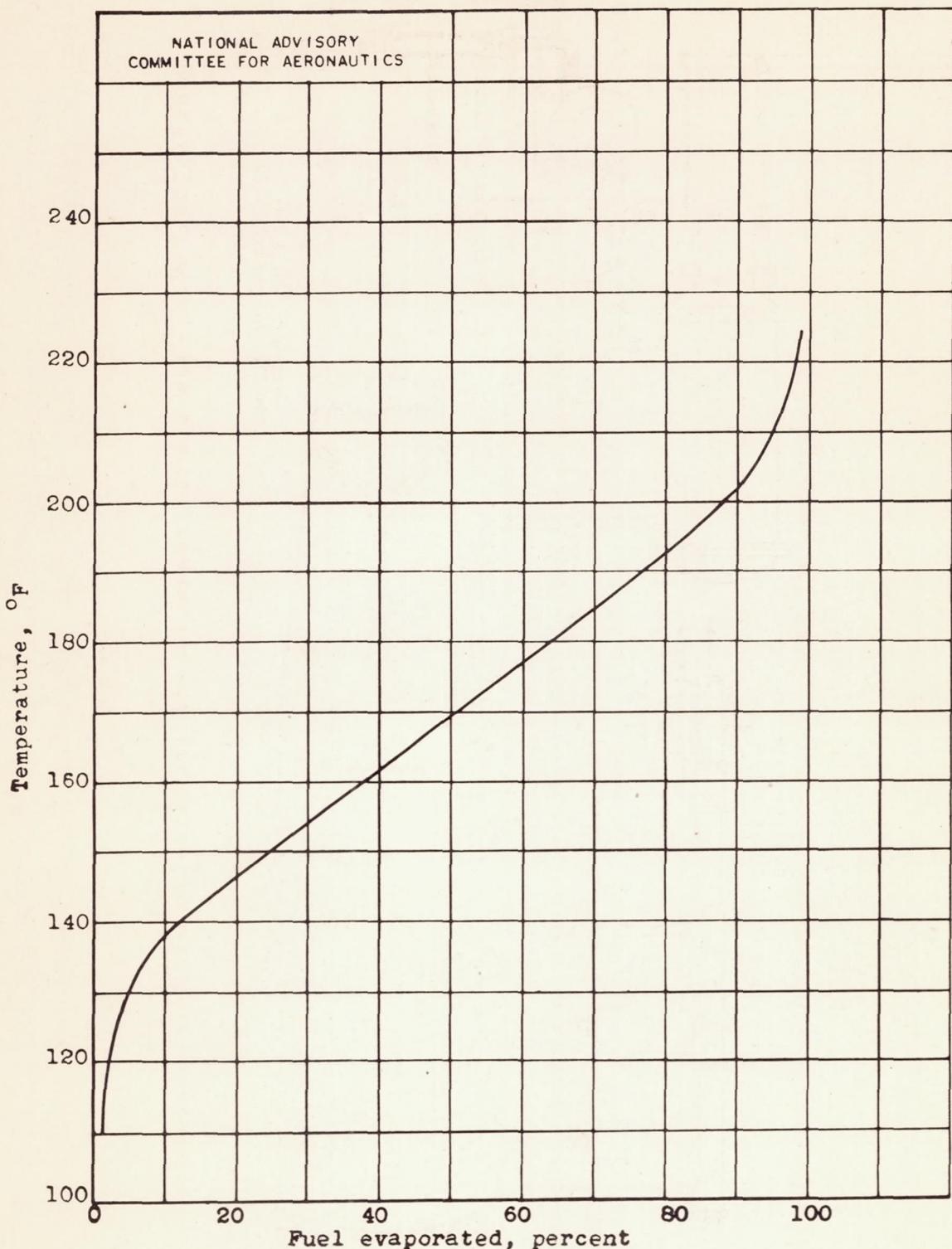
Figure 6.- A.S.T.M. distillation curve for unleaded 62-
octane fuel (AN-F-22).

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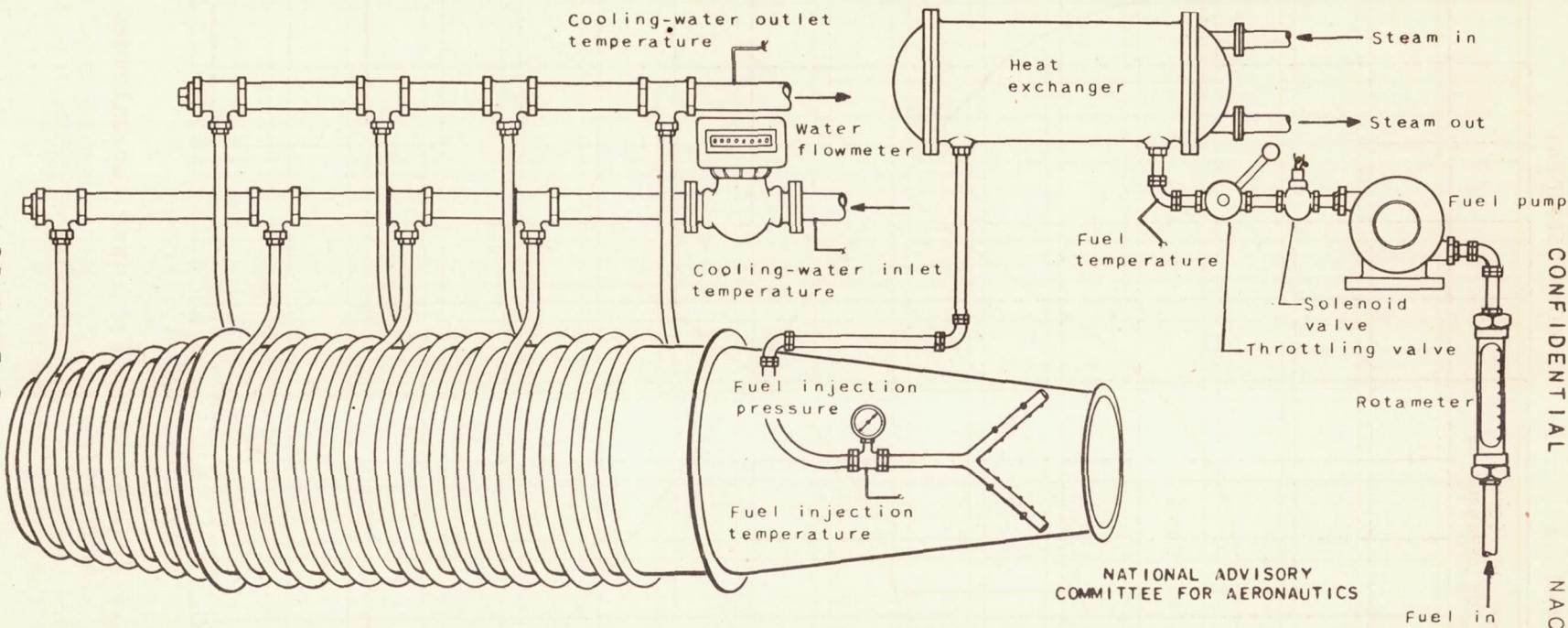
Figure 7. - Schematic diagram of external fuel-preheating and shell-cooling systems.

635
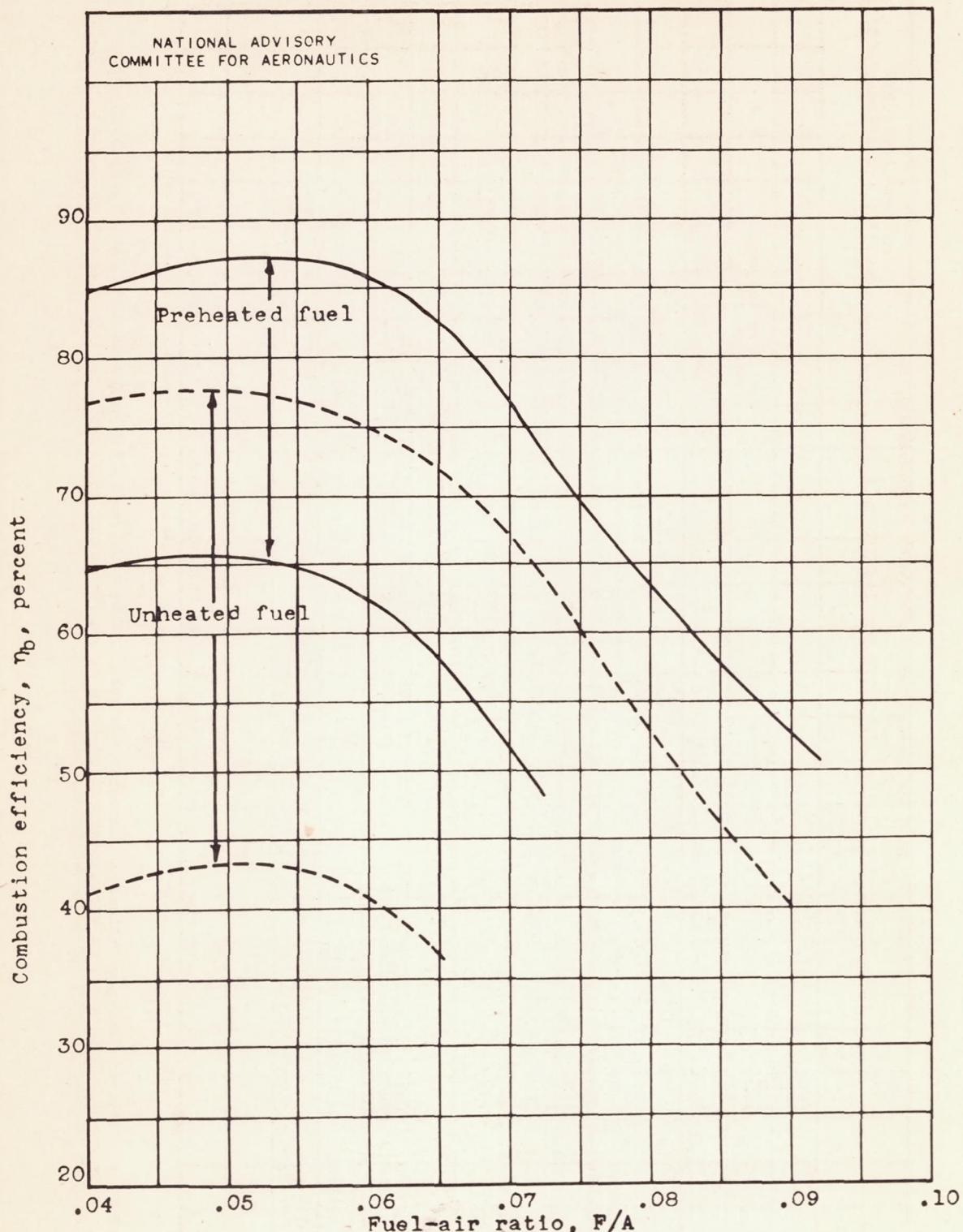
Figure 8.- Range of combustion efficiencies obtained with
    unheated and preheated fuel. 20-inch ram-jet unit with 12-foot
    combustion chamber and 17-inch-diameter exhaust nozzle. (Data
    for unheated fuel from reference 1.)

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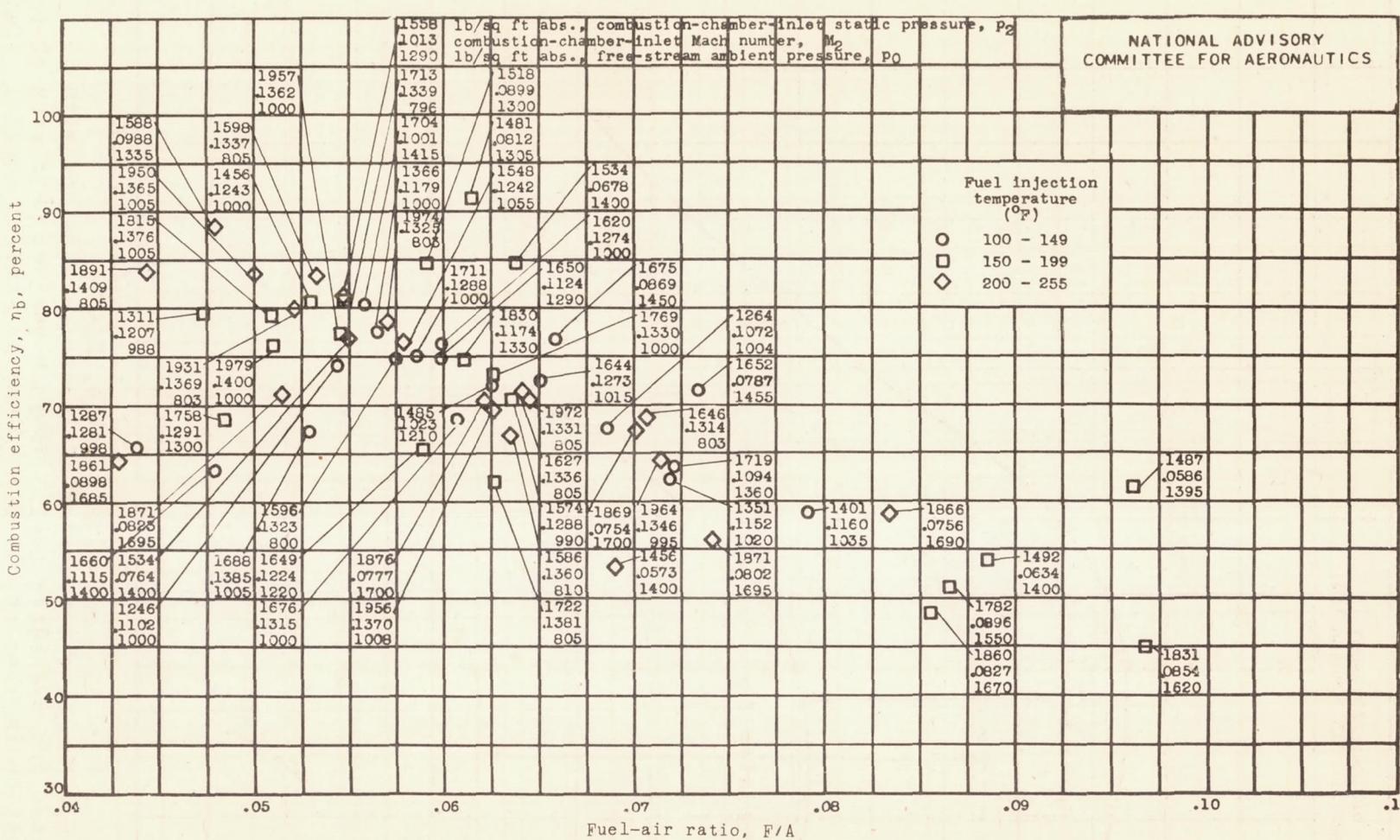
Figure 9. – Effect of fuel-air ratio F/A, combustion-chamber-inlet absolute static pressure p_2 and Mach number M_2, fuel injection temperature, and free-stream ambient pressure p_0 on combustion efficiency η_b. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.
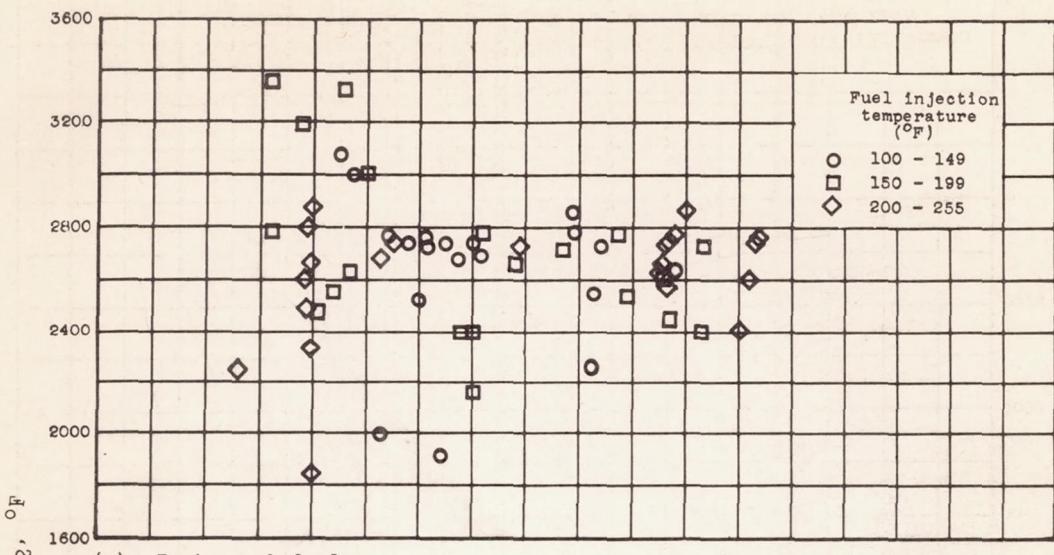
(a)   Preheated fuel.

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS
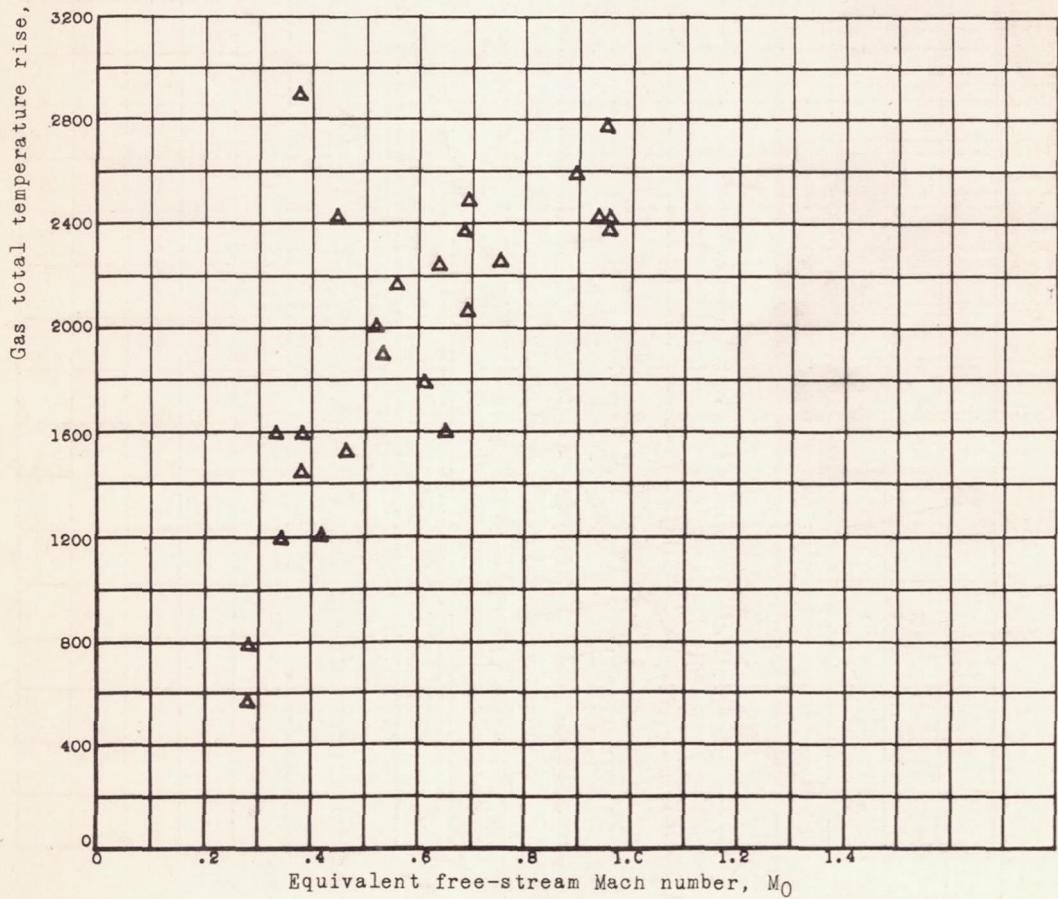
(b)   Unheated fuel at 40° F (data from reference 1).

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.

Fig. II   CONFIDENTIAL   NACA RM No. E6I23
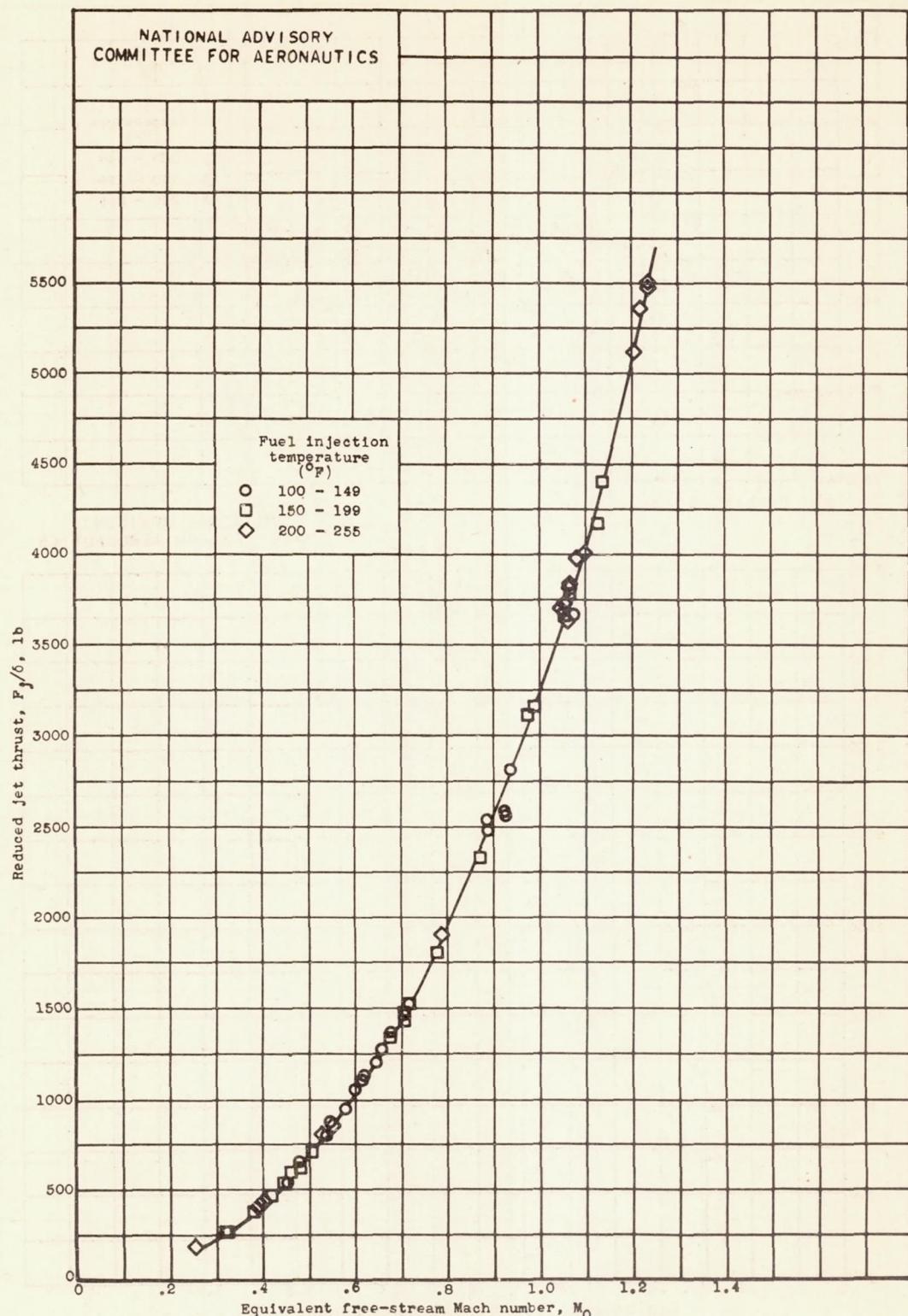
Figure 11.- Effect of equivalent free-stream Mach number M_0 and fuel injection temperature on reduced jet thrust F_j/δ. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle. Jet thrust reduced to NACA standard atmospheric conditions at sea level.
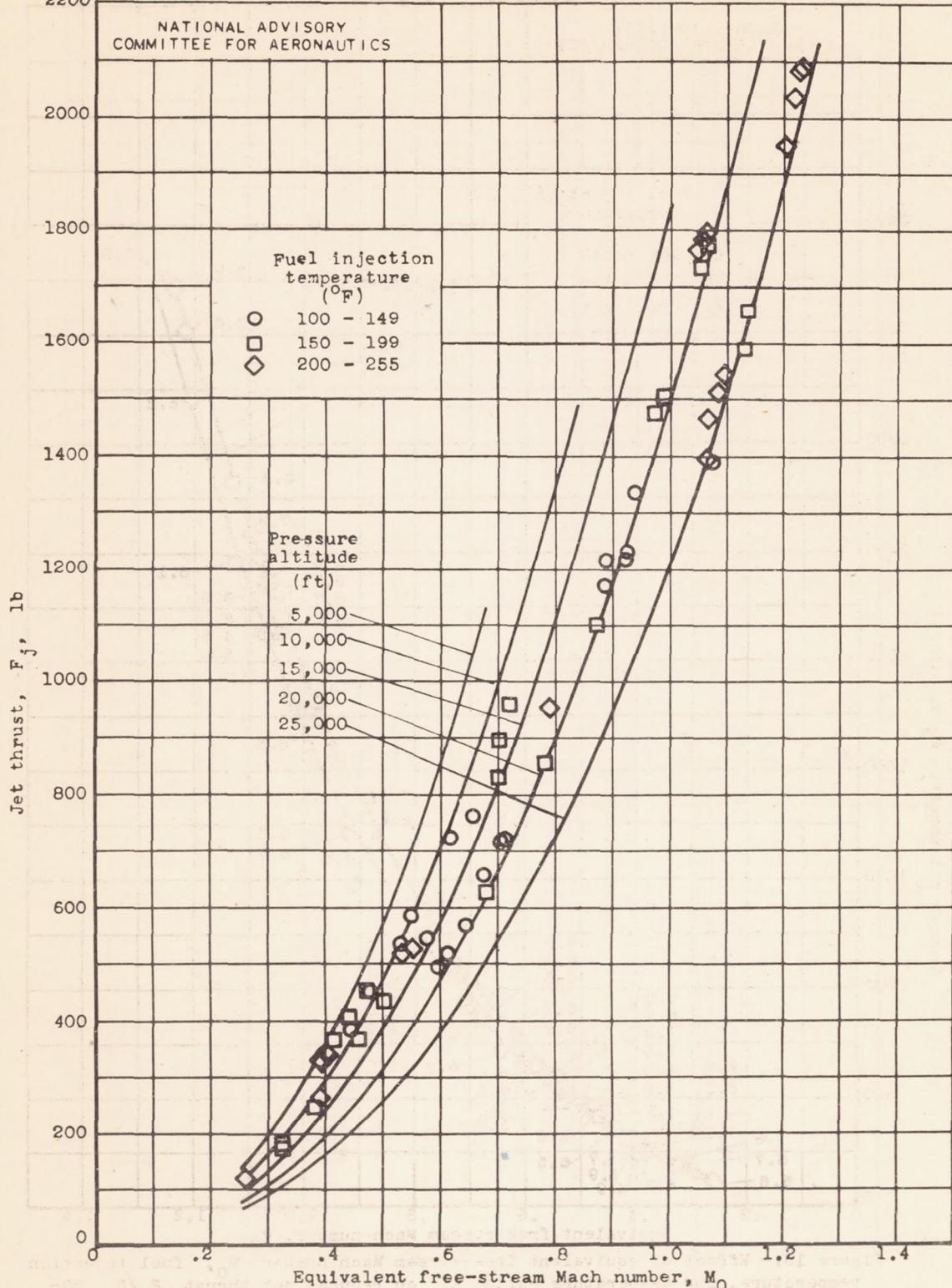
Figure 12.- Effect of equivalent free-stream Mach number M_0, fuel injection temperature, and pressure altitude on jet thrust F_j. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

Fig. 13   CONFIDENTIAL   NACA RM No. E6I23
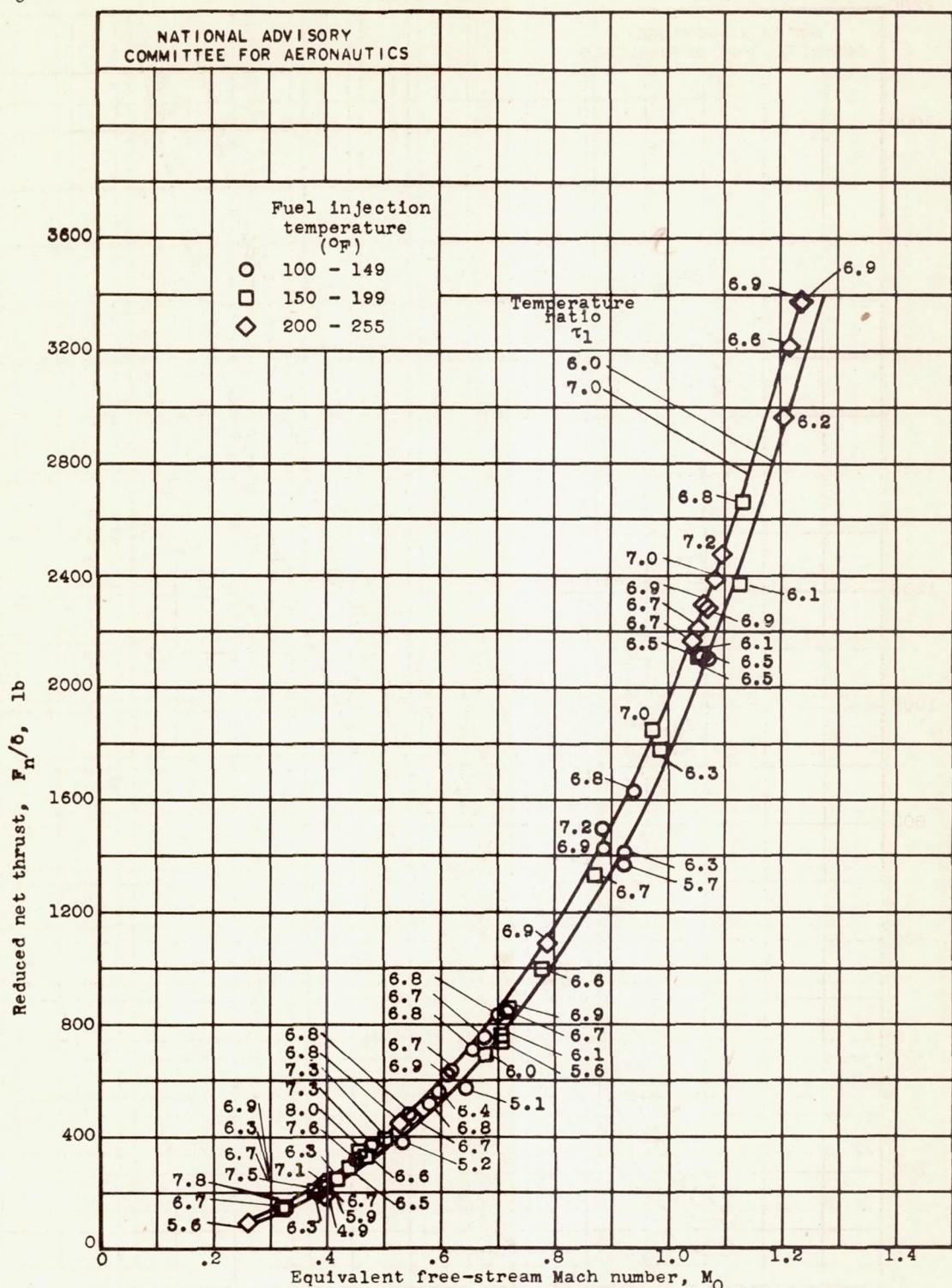
Figure 13.- Effect of equivalent free-stream Mach number M_0, fuel injection temperature, and temperature ratio τ_1 on reduced net thrust F_n/δ. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle. Net thrust reduced to NACA standard atmospheric conditions at sea level.
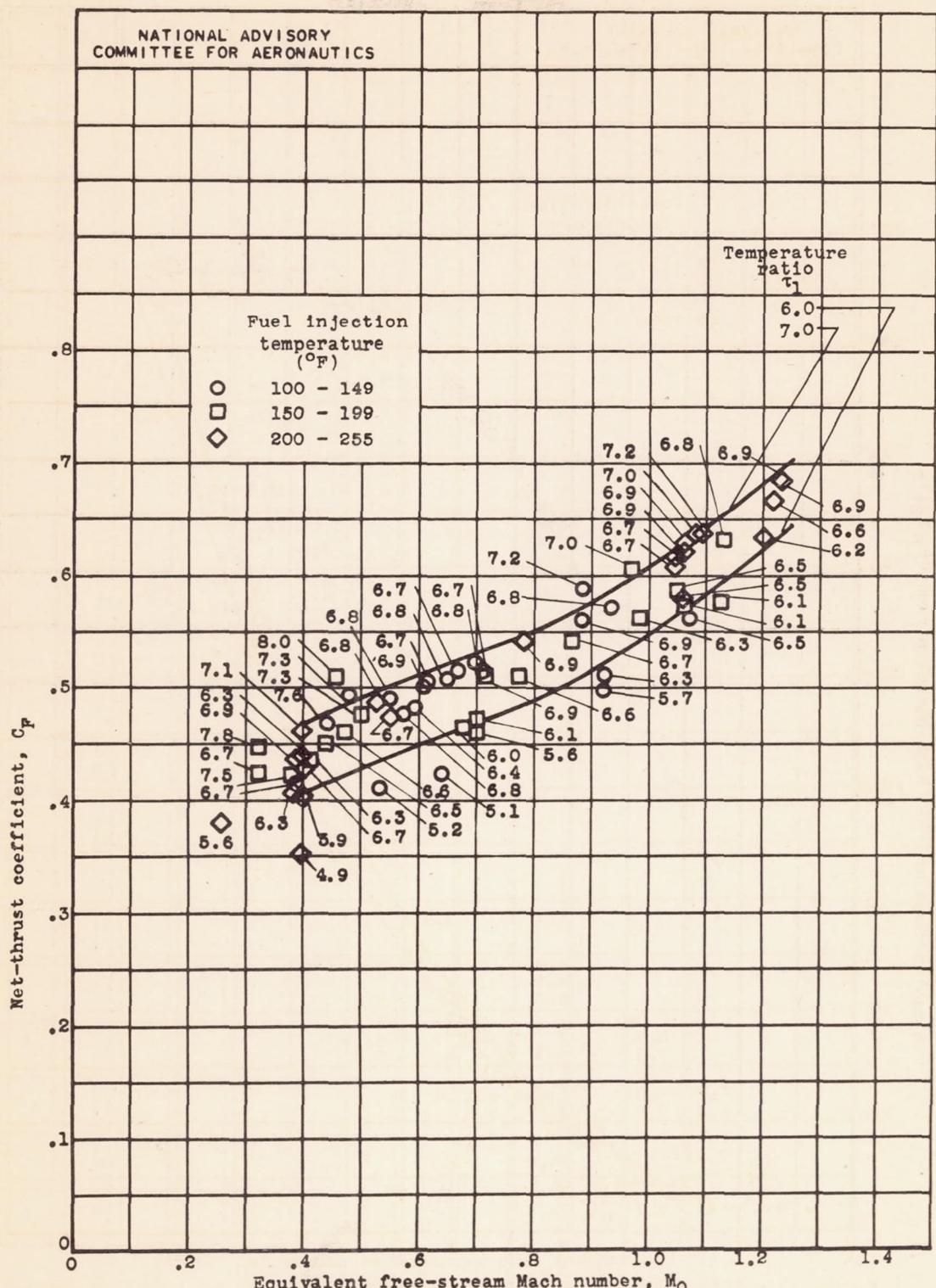
Figure 14.- Effect of equivalent free-stream Mach number M_0, fuel injection temperature, and temperature ratio τ_1 on net-thrust coefficient C_F. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

Fig. 15   CONFIDENTIAL   NACA RM No. E6I23
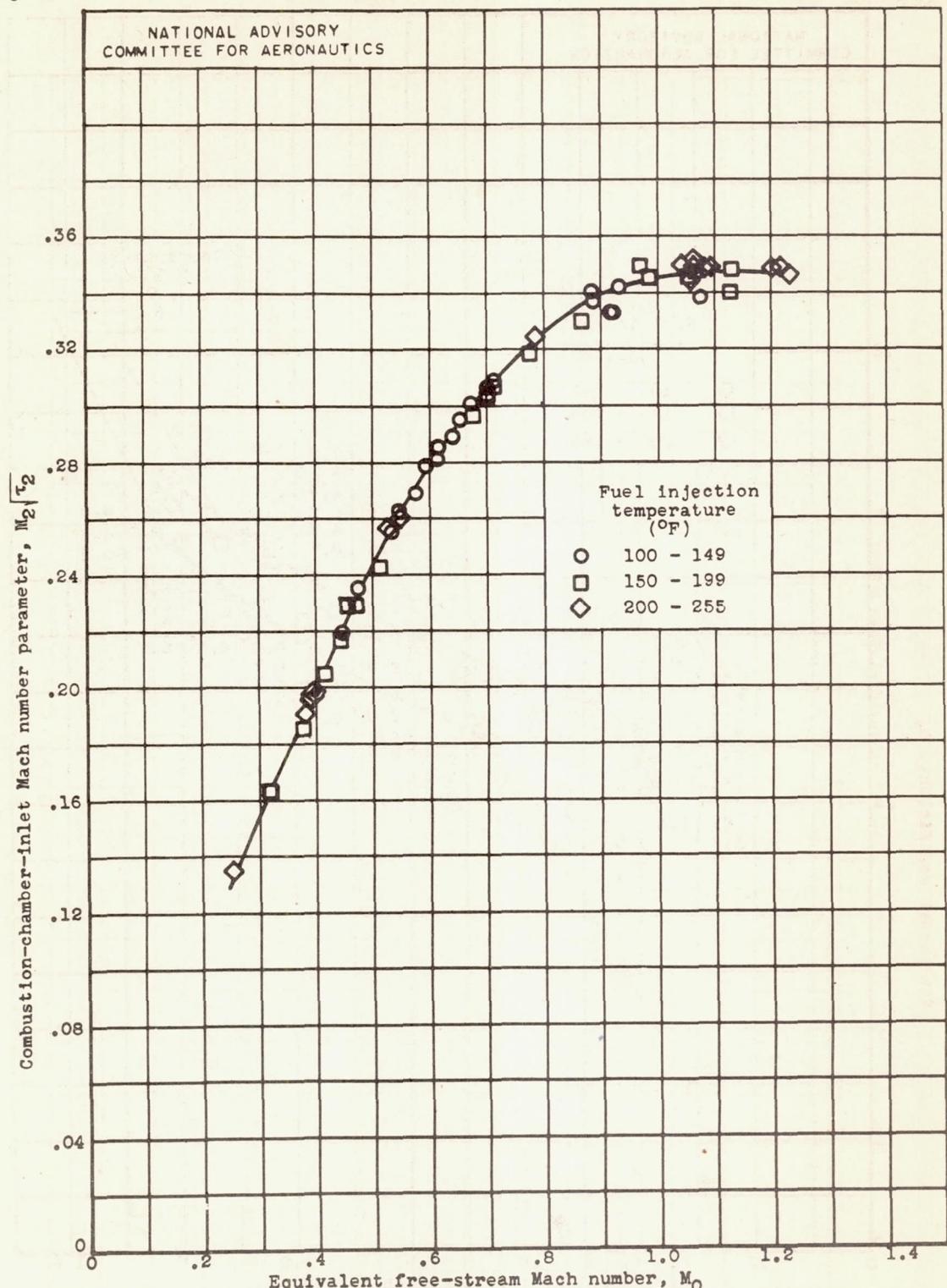
Figure 15.- Effect of equivalent free-stream Mach number M_0 and fuel injection temperature on combustion-chamber-inlet Mach number parameter $M_2\sqrt{\tau_2}$. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

635
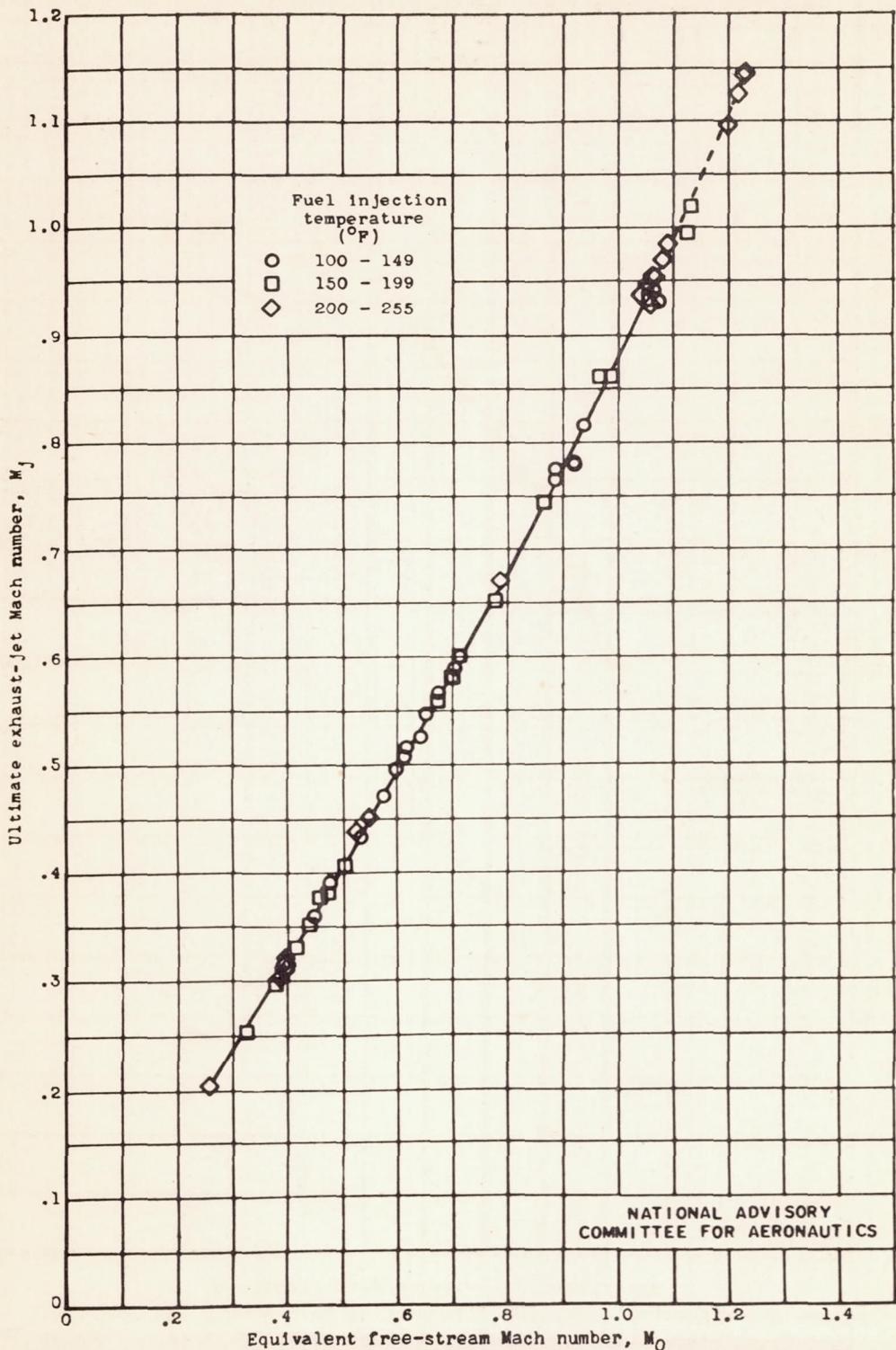
Figure 16.- Effect of equivalent free-stream Mach number M_0 and fuel injection temperature on ultimate exhaust-jet Mach number M_j. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

Fig. 17   CONFIDENTIAL   NACA RM No. E6I23
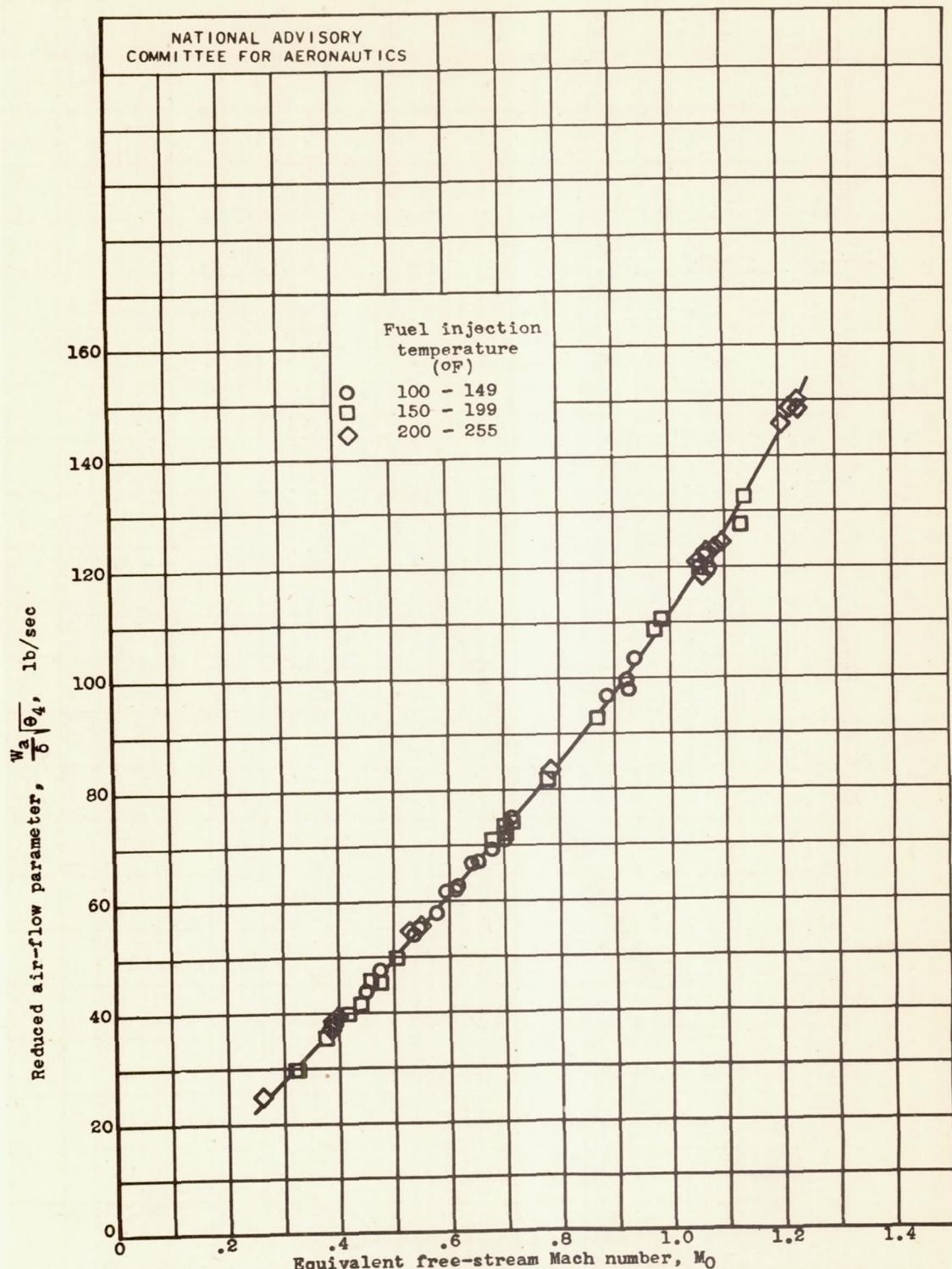
Figure 17.- Effect of equivalent free-stream Mach number M_O and fuel injection temperature on reduced air-flow parameter $\frac{W_a}{\delta}\sqrt{\theta_4}$. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle. Air flow reduced to NACA standard atmospheric conditions at sea level.

635
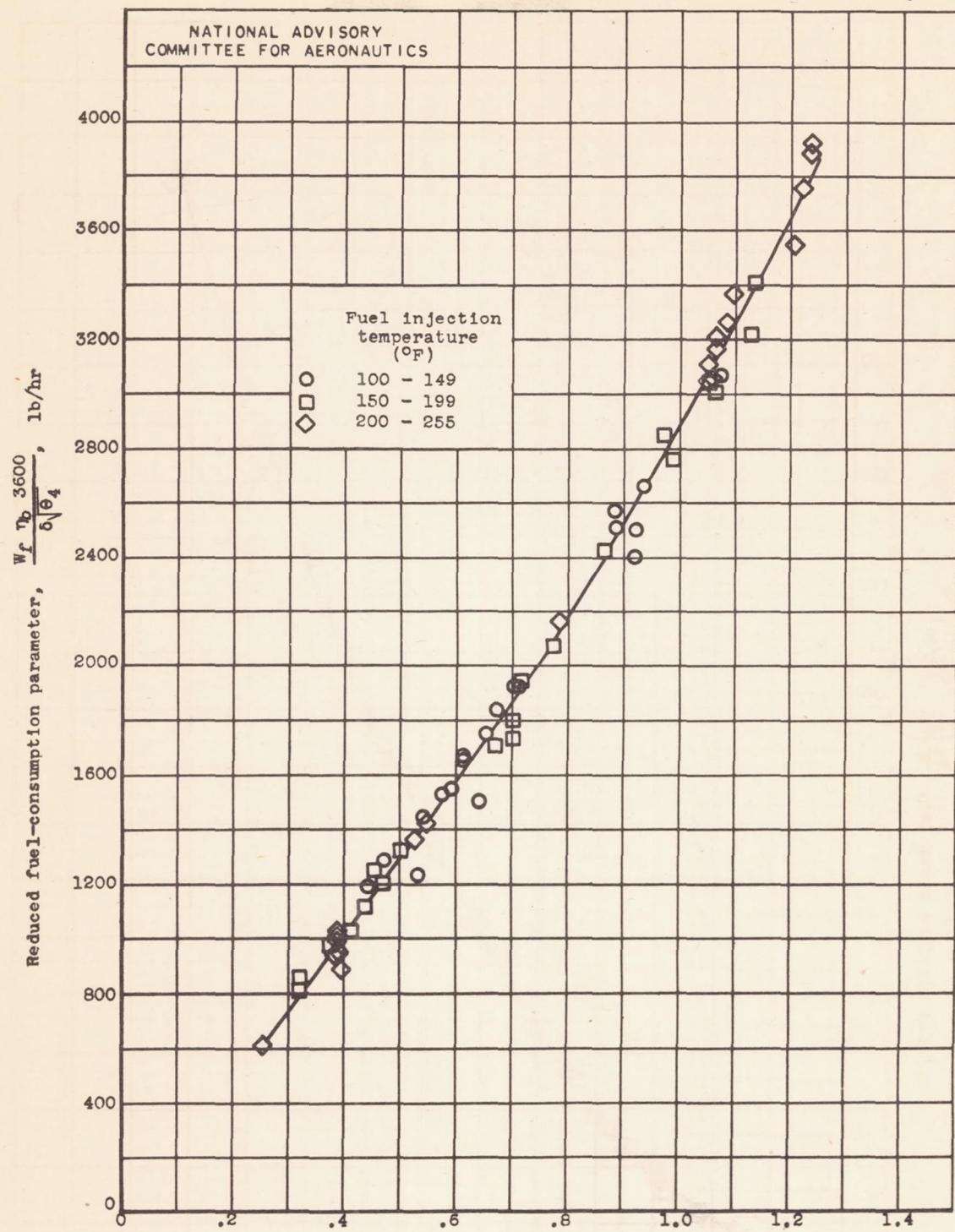
Figure 18.- Effect of equivalent free-stream Mach number M_0 and fuel injection temperature on reduced fuel-consumption parameter $\frac{W_f \eta_b 3600}{\delta \sqrt{\theta_4}}$. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle. Fuel flow reduced to NACA standard atmospheric conditions at sea level.

Fig. 19　　　　　CONFIDENTIAL　　　　NACA RM No. E6I23
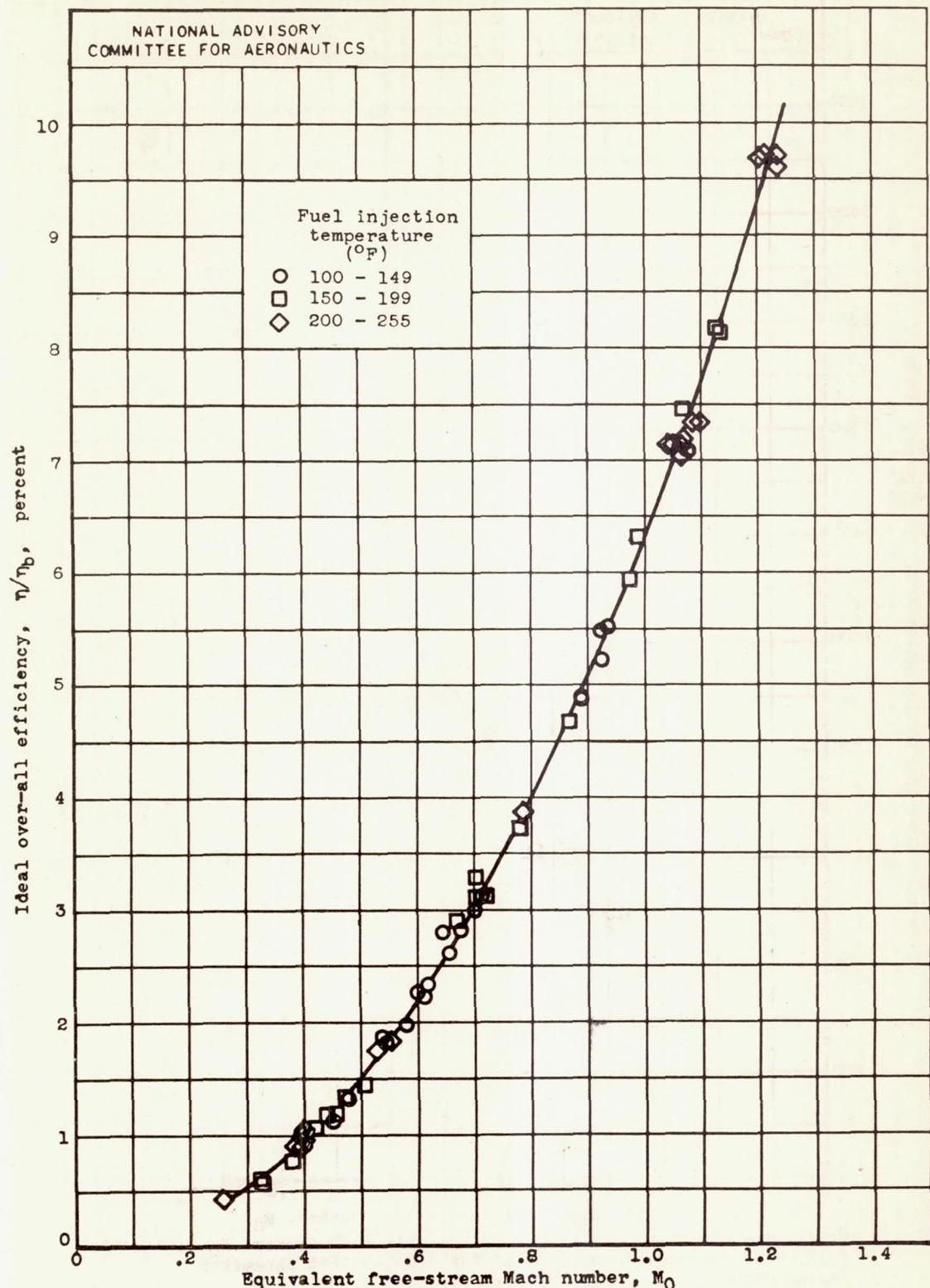
Figure 19.- Effect of equivalent free-stream Mach number M_O and fuel injection temperature on ideal over-all efficiency η/η_b. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

**NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS**

Fuel injection
temperature
($^\circ$F)

○   100 – 149
□   150 – 199
◇   200 – 255
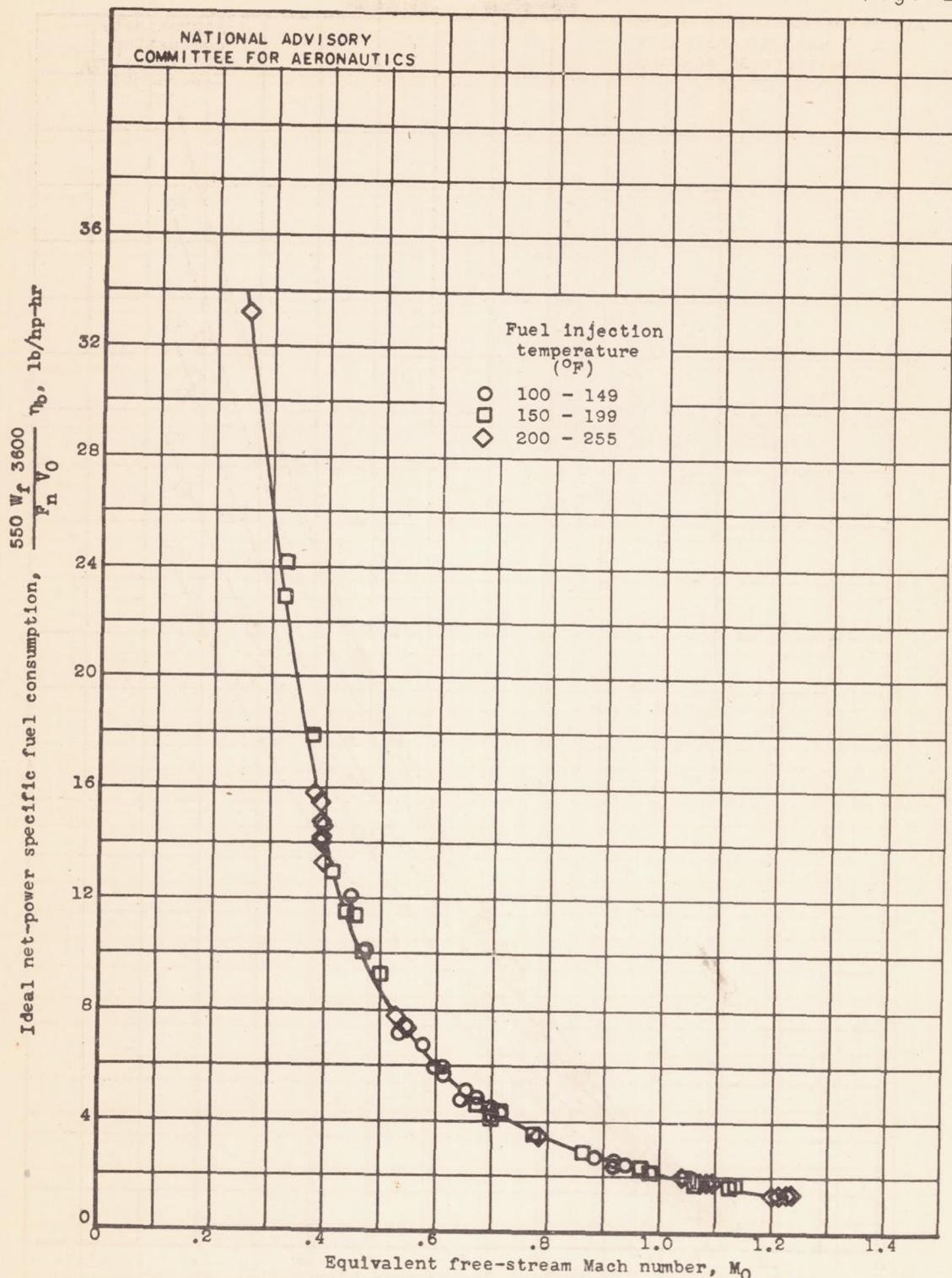
Figure 20.– Effect of equivalent free-stream Mach number M_O and fuel injection temperature on ideal net-power specific fuel consumption $\dfrac{550 \, W_f \, 3600}{F_n \, V_O} \, \eta_b$.

20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.

Fig. 21   CONFIDENTIAL   NACA RM No. E6I23
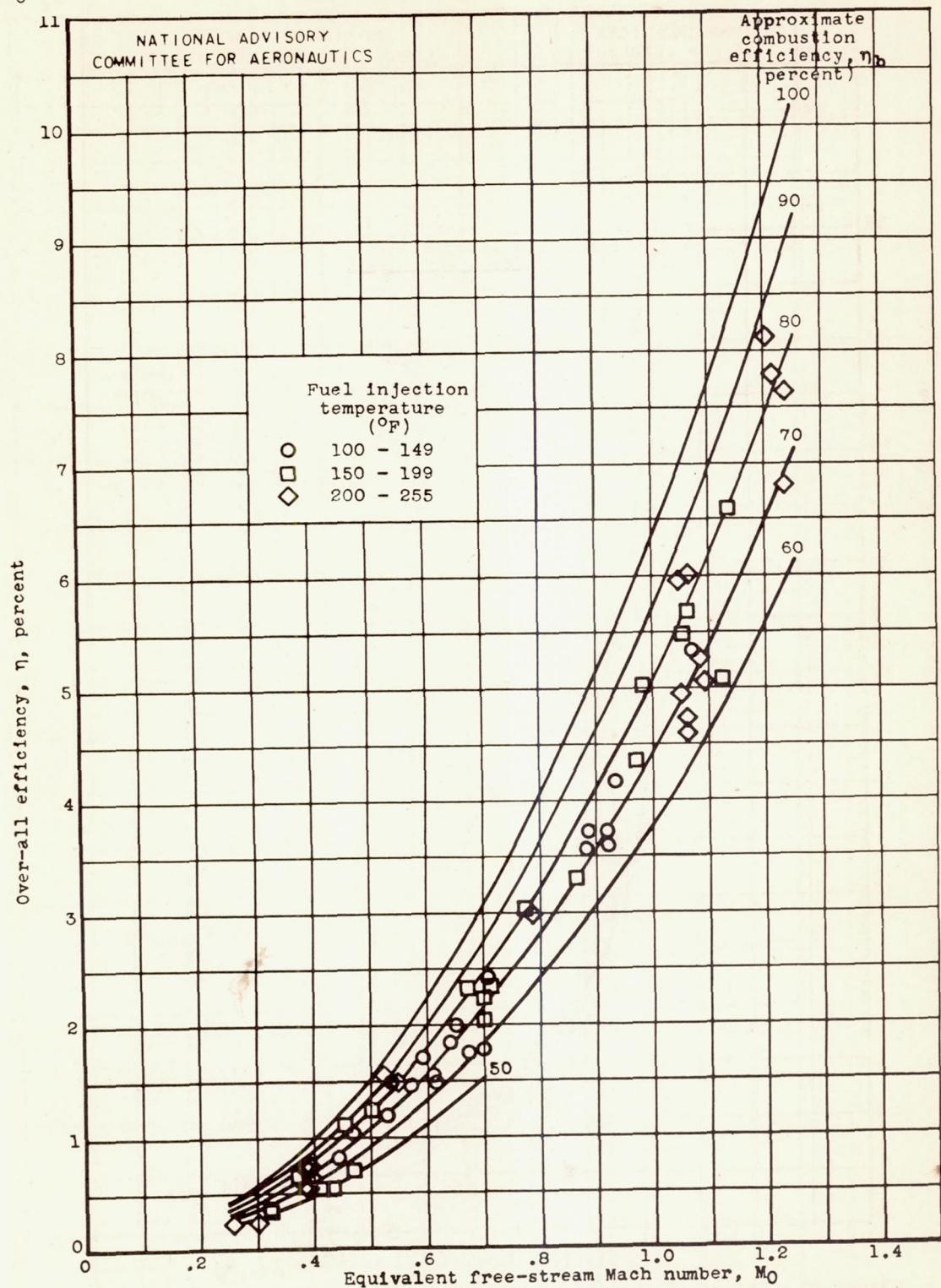
Figure 21.— Effect of equivalent free-stream Mach number M_0, fuel injection temperature, and combustion efficiency on over-all efficiency η. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.
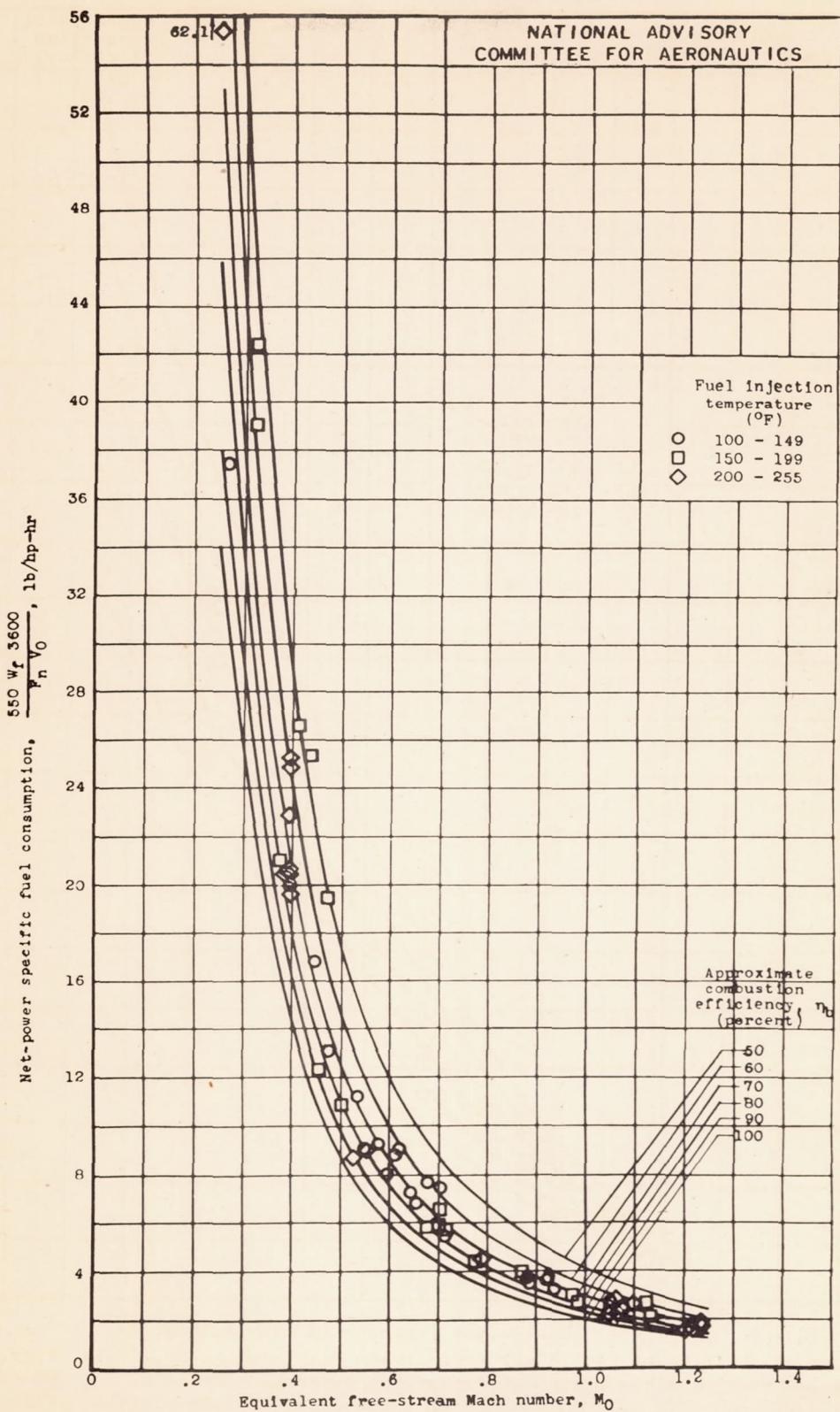
Figure 22.- Effect of equivalent free-stream Mach number M_0, fuel injection temperature, and combustion efficiency η_b on net-power specific fuel consumption $\dfrac{550\ W_f\ 3600}{F_n\ V_0}$. 20-inch ram-jet unit with 12-foot combustion chamber and 17-inch-diameter exhaust nozzle.