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RESEARCH MEMORANDUM

ALTITUDE-WIND-TUNNEL INVESTIGATION OF A 3000-POUND-THRUST AXIAL-FLOW TURBOJET ENGINE

VI - ANALYSIS OF EFFECTS OF INLET PRESSURE LOSSES

By Newell D. Sanders and John Palasics

Flight Propulsion Research Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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ALTITUDE-WIND-TUNNEL INVESTIGATION OF A 3000-POUND-THRUST

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VI - ANALYSIS OF EFFECTS OF INLET PRESSURE LOSSES

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SUMMARY

The experimentally determined performance characteristics of an axial-flow turbojet engine have been used to estimate the effects of inlet total-pressure losses on net thrust and specific fuel consumption at a constant engine speed.

At low altitudes and flight Mach numbers, inlet pressure losses cause an increase in engine discharge temperature and it is possible that the maximum allowable turbine temperature may be exceeded. An inlet absolute total-pressure loss of 10 percent will result in a thrust loss of 14 percent and a 15-percent increase in specific fuel consumption based on net thrust.

At high altitudes and flight Mach numbers, choking conditions exist in the exhaust nozzle and the inlet pressure losses do not affect the discharge temperatures. Under these conditions, a 10-percent loss in inlet absolute total pressure produces a 22-percent loss in net thrust and a 16-percent increase in specific fuel consumption.

If the exhaust-nozzle-outlet area is adjusted to compensate for the effect of inlet losses on discharge temperature in the nonchoking cases (low altitudes and Mach numbers), the thrust and fuel consumption will be changed in a manner similar to the results obtained in the choking cases.

INTRODUCTION

The losses in the inlet air ducts, the diffusers, and the de-icing equipment associated with turbojet engine installations cause a reduction in the total pressure at the inlet of the engine and result in reduced thrust and increased specific fuel consumption. An analytical evaluation of the effects of inlet losses on the net thrust and the fuel economy of a 3000-pound-thrust axial-flow turbojet engine with a two-stage turbine is presented herein.

The analysis is based on engine performance characteristics that were determined from experiments in the NACA Cleveland altitude wind tunnel (references 1 to 5). The experimental investigation did not include tests in which inlet losses were systematically varied, but the effects of these losses can be accurately estimated from the experimentally determined performance characteristics of the engine.

SYMBOLS

The following symbols are used in this report.

A area, square feet

a velocity of sound, feet per second

C_d discharge coefficient

f/a fuel-air ratio

F_j jet thrust, pounds

g acceleration of gravity, 32.2 feet per second per second

M_0 flight Mach number, V/a

N engine speed, rpm

P total pressure, pounds per square foot absolute

p static pressure, pounds per square foot absolute

q dynamic pressure, $\frac{\rho V^2}{2g}$, pounds per square foot

R gas constant, 53.4 foot-pounds per pound per °R

T total temperature, °R

V velocity, feet per second

W mass rate of air flow through engine, pounds per second

γ ratio of specific heats

δ ratio of compressor-inlet total pressure to static pressure of NACA standard atmosphere at sea level

θ ratio of compressor-inlet absolute total temperature to absolute static temperature of NACA standard atmosphere at sea level

ρ density of air, pounds per cubic foot

τ engine total-temperature ratio, T_8/T_2

Subscripts:

0 ambient or free-stream conditions

1 nacelle inlet

2 compressor inlet

8 exhaust-nozzle outlet

The data were generalized to NACA standard sea-level conditions by the following parameters:

$N/\sqrt{\theta}$ corrected engine speed, rpm

$\frac{W\sqrt{\theta}}{\delta}$ corrected air flow, pounds per second

ANALYSIS

Inlet losses influence the turbojet engine in three ways: The total pressures throughout the engine are reduced and consequently the total pressure of the jet is reduced; the temperature of the jet must be increased to maintain constant engine speed; and the air flow is reduced approximately in proportion to the reduction of air density at the engine inlet. When the pressure ratio across the exhaust nozzle exceeds the choking value, the temperature and pressure ratios across the engine are independent of the inlet losses. In the analyses that follow, different methods were used for calculating the nonchoked (subsonic jet velocities) and choked cases. In all cases the engine speed was held constant at a value of 11,500 rpm.

Nonchoked exhaust nozzle. - The turbojet engine was treated as a pump for raising the total pressure and temperature of the air and the gas-flow characteristics of the engine were matched with the gas-flow characteristics of the exhaust nozzle.

Engine characteristics were determined from altitude-wind-tunnel investigations (references 1 to 5) and are shown in figures 1 and 2. The effect of the parameters of altitude, corrected engine speed, effective inlet-pressure ratio P_2/p_0, and exhaust-nozzle-outlet area on the relation between temperature and pressure ratios across the engine is shown in figure 1. The corrected engine speeds correspond to a fixed engine speed of 11,500 rpm at the selected flight conditions. The variation of corrected air flow with corrected engine speed for altitudes of 15,000 and 25,000 feet is shown in figure 2.

The air-flow characteristics of the exhaust nozzle were calculated from the equation

$$\frac{W\sqrt{\theta}}{C_d A_8 \delta} = \sqrt{\frac{2g\gamma_8}{(\gamma_8-1)R}}\ \frac{2116}{\sqrt{519}\ (1+f/a)}\ \frac{1}{\sqrt{\tau}}\ \frac{P_8}{P_2}\left(\frac{P_8}{p_0}\right)^{-\frac{\gamma_8+1}{2\gamma}} \sqrt{\left(\frac{P_8}{p_0}\right)^{\frac{\gamma_8-1}{\gamma_8}} - 1} \tag{1}$$

The relation expressed by this equation is illustrated in figure 3, in which engine pressure ratio P_8/P_2 is plotted as a function of temperature ratio τ for a series of values of compressor-inlet corrected air flow per square foot of exhaust-nozzle-outlet area and for various values of effective inlet pressure ratio P_2/p_0.

The flow requirements imposed simultaneously by the engine characteristics and the nozzle characteristics are satisfied at the intersection of the corresponding curves in figures 1 and 3, respectively. In the thrust computations, values of engine speed (11,500 rpm), altitude, flight Mach number, and inlet absolute total-pressure loss $\frac{P_1-P_2}{P_1}$ were assumed. Corrected engine speed was calculated and the corrected air flow to the engine was read from figure 2. The curve in figure 3 corresponding to the selected effective inlet-pressure ratio, exhaust-nozzle-outlet area (1.27 sq ft), and nozzle discharge coefficient (0.99) was superimposed on the curve in figure 1 corresponding to the calculated corrected engine speed, and the pressure and temperature ratios across the engine were found at the intersection of the two curves. The equation used for calculating jet thrust is

$$F_j = W\sqrt{\frac{2R}{g}\,\frac{\gamma_8}{\gamma_8-1}}\,\sqrt{T_2\,\tau}\;\sqrt{1-\left(\frac{p_0}{P_8}\right)^{\frac{\gamma_8-1}{\gamma_8}}} \tag{2}$$

<u>Choked exhaust nozzle.</u> - When the pressure ratio across the exhaust nozzle was greater than the choking value, the air flow and the pressure and temperature ratios across the engine were a function principally of the corrected engine speed and varied only slightly with altitude and effective inlet-pressure ratio, as shown by the results of wind-tunnel investigations in figures 4 to 6. The values used in the analysis were taken from the dashed curves in these figures at the corrected engine speed corresponding to an actual engine speed of 11,500 rpm at the selected altitude and flight Mach number. The jet thrust was calculated from the following equation, which is applicable to a convergent nozzle

$$F_j = W\sqrt{\frac{RT_8}{\gamma_8 g}}\left(\frac{\gamma_8+1}{2}\right)^{\frac{\gamma_8+1}{2(\gamma_8-1)}}\left[\frac{2}{\left(\frac{\gamma_8+1}{2}\right)^{\frac{1}{\gamma_8-1}}}-\frac{p_0}{P_8}\right] \tag{3}$$

DISCUSSION

Results of the analysis are presented as the loss in net thrust and the increase in specific fuel consumption based on net thrust that accompany the varying loss in inlet absolute total pressure. A chart for converting ram-pressure recovery $\left(1-\frac{P_1-P_2}{q_0}\right)$ to inlet absolute total-pressure loss is given in figure 7 for flight Mach numbers up to 1.0.

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Nonchoked exhaust nozzle. - When the exhaust nozzle was not choked, a loss of inlet absolute total pressure reduced the jet thrust in proportion to the reduction in air flow and the reduction in the pressure-ratio function $\sqrt{1 - \left(\frac{p_0}{P_8}\right)^{\frac{\gamma_8 - 1}{\gamma_8}}}$, and increased the jet thrust in proportion to the increase in the square root of the over-all temperature ratio. As an example, the effects of a 10-percent loss in inlet absolute total pressure at a flight Mach number of 0.4 and an altitude of 15,000 feet are shown in the following table:

Pressure ratio, P_8/p_0, no loss	1.675
Temperature ratio, T_8/T_2, no loss	2.62
Percentage change caused by 10-percent inlet absolute total-pressure loss	
Pressure-ratio reduction, percent	6.0
Temperature-ratio increase, percent	6.3
Reduction of net thrust per unit rate of air flow, percent	4.0
Air-flow reduction, percent	10.0
Net-thrust reduction, percent	13.7

The pressure-ratio reduction is only 6 percent because the pressure ratio across the engine increases with increasing temperature ratio.

The relation of thrust loss to inlet absolute total-pressure loss was approximately linear (fig. 8). The change in temperature ratio τ across the engine as the inlet losses increased are indicated on the curves. If the exhaust-nozzle area were selected to give maximum thrust with no inlet losses, the inlet losses would cause the temperature to rise above the maximum allowable value.

Choked exhaust nozzle. - When a choking condition existed in the exhaust nozzle, inlet losses no longer caused an increase in the over-all temperature ratio and there was no longer an increase in thrust from increasing temperature and pressure ratio across the engine to partly offset the effects of inlet pressure and air-flow losses. For example, at an altitude of 15,000 feet and a flight Mach number of 0.8, choking conditions existed; and the effects of a 10-percent loss of inlet absolute total pressure are shown in the following table:

Pressure ratio, P_8/p_0, no loss 1.84

Percentage change caused by 10-percent inlet absolute total-pressure loss

Pressure-ratio reduction, percent	10.0
Reduction of net thrust per unit rate of air flow, percent	14.0
Air-flow reduction, percent	10.0
Net-thrust reduction, percent	22.5

The thrust loss was approximately proportional to the inlet absolute total-pressure loss, as shown in figure 8 for flight at an altitude of 15,000 feet and at Mach numbers of 0.4 and 0.8. The departure from proportionality at the higher Mach number when the inlet absolute total-pressure loss exceeded 10 percent resulted because the pressure at the exhaust nozzle fell below the choking value and some increase in temperature accompanied increasing losses.

Specific fuel consumption. - The specific fuel consumption is inversely proportional to the thrust per unit rate of air flow and directly proportional to the fuel-air ratio. The fuel-air ratio is proportional to $\tau - 1$. At an altitude of 15,000 feet and a Mach number of 0.4 (fig. 8, nonchoked nozzle), an inlet absolute total-pressure loss of 10 percent reduced the thrust per unit rate of air flow by 4 percent, but a 6.3-percent increase in temperature resulted in a 10-percent increase in fuel-air ratio. The over-all increase in specific fuel consumption was therefore 15 percent.

When the engine is choked at the exhaust nozzle, inlet losses cause increases in specific fuel consumption purely through the reduction of thrust per unit rate of air flow. In the choked case previously mentioned (altitude, 15,000 feet; Mach number, 0.8), a 10-percent loss of inlet absolute total pressure reduced the thrust per unit rate of air flow by 14 percent and the consequent increase in specific fuel consumption was 16 percent $\left(\frac{1}{1 - \text{thrust loss}} = 1 + \text{specific-fuel-consumption increase}\right)$. The close agreement between this value of 16 percent and the value of 15 percent for the nonchoked case is coincidental.

Curves showing the specific-fuel-consumption increases corresponding to the thrust losses are also given in figure 8.

Effect of flight Mach number. - Changing the Mach number influenced the relation between thrust loss and inlet absolute total-pressure loss principally through the effects of Mach number on choking at the exhaust nozzle. In figure 8, increasing the Mach number from 0.4 to 0.8 resulted in an increase of thrust loss from 13.7 percent to 22.5 percent for an inlet absolute total-pressure loss of 10 percent. At a Mach number of 0.4, the pressure in the exhaust nozzle was well below choking; and at a Mach number of 0.8, choking occurred in the exhaust nozzle. Flight Mach number had relatively little effect on the increase in specific fuel consumption for a given inlet absolute total-pressure loss for the conditions of figure 8.

When choking conditions existed throughout the ranges of flight Mach number under consideration, the net thrust decreased very slightly with increasing flight Mach number (fig. 9).

Effect of altitude. - Increasing the altitude of operation of a jet engine and holding the engine speed constant results in increased corrected engine speed, increased temperature ratio, and increased pressure ratio. As the pressure ratio approaches choking in the exhaust nozzle, the thrust losses accompanying inlet pressure losses become more serious, as previously noted. Increasing the altitude from 15,000 to 25,000 feet resulted in an increased effect of inlet absolute total-pressure loss on thrust. This effect and the increase in specific fuel consumption, which is greater at an altitude of 15,000 feet than at 25,000 feet, are shown in figure 10. This greater increase at the low altitude resulted from a greater effect of inlet loss on temperature ratio and a consequently greater increase in fuel-air ratio. At altitudes above 25,000 feet, the pressure ratio across the exhaust nozzle exceeds the choking value and altitude has only a very small effect on the thrust loss and the specific-fuel-consumption increase.

Constant temperature and variable nozzle area. - In cases where the inlet losses have been evaluated, the aircraft or engine designer should so select an exhaust-nozzle-outlet area that the maximum allowable temperature will be obtained at maximum allowable engine speed. When the exhaust-nozzle area is adjusted to hold constant temperature, inlet losses will affect the thrust by reducing the air flow and the total pressure at the jet nozzle. Consequently, the loss in thrust accompanying inlet absolute total-pressure losses will be similar to the losses incurred when the engine is operating at choking conditions. A 10-percent loss of inlet absolute total pressure will produce a thrust loss of approximately 22 percent and an increase in specific fuel consumption of about 15 percent.

Summary of thrust and fuel consumptions. - The loss in thrust and the increase in specific fuel consumption accompanying inlet absolute total-pressure losses are summarized in figure 11 for the flight conditions indicated by x in the following table. Data for conditions marked by 0 are given in other figures.

Flight Mach number	Altitude			
	0	15,000	25,000	35,000
0	x	------	------	------
.4	x	0	0	------
.8	-----	0	0	------
1.2	-----	x	x	x
1.6	-----	------	0	x

The variation of loss in net thrust and increase in net thrust specific fuel consumption with ram-pressure recovery is shown in figure 12 for an altitude of 15,000 feet and flight Mach numbers of 0.4, 0.8, and 1.2.

SUMMARY OF RESULTS

The following results are applicable to the 3000-pound-thrust axial-flow turbojet engine investigated at fixed rotational speed:

1. The thrust loss was approximately proportional to the loss of inlet absolute total pressure.

2. When the pressure ratio across the exhaust nozzle was less than choking value, a 10-percent loss of inlet absolute total pressure resulted in approximately 14-percent loss of net thrust and 15-percent increase in specific fuel consumption. The discharge temperature may increase above maximum allowable value.

3. When the pressure ratio across the exhaust nozzle exceeded the choking value, a 10-percent loss in inlet absolute total pressure resulted in approximately 22-percent loss in thrust and 16-percent increase in specific fuel consumption. The discharge temperature did not change.

4. When the exhaust-nozzle area was adjusted so that the discharge temperature had the maximum allowable value at each value

of inlet pressure loss, the changes in thrust and specific fuel consumption accompanying inlet pressure losses were similar to the changes when the engine was operating at choking conditions.

5. Changes of altitude and flight Mach number influenced the relation of thrust and specific fuel consumption to inlet pressure loss through the effect on the choking condition in the exhaust nozzle. At low altitude and Mach number, the pressure ratio across the exhaust nozzle was less than the choking value; at high altitudes and Mach numbers, the pressure ratio was greater than the choking value.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, March 16, 1948.

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VI - ANALYSIS OF EFFECTS OF INLET PRESSURE LOSSES

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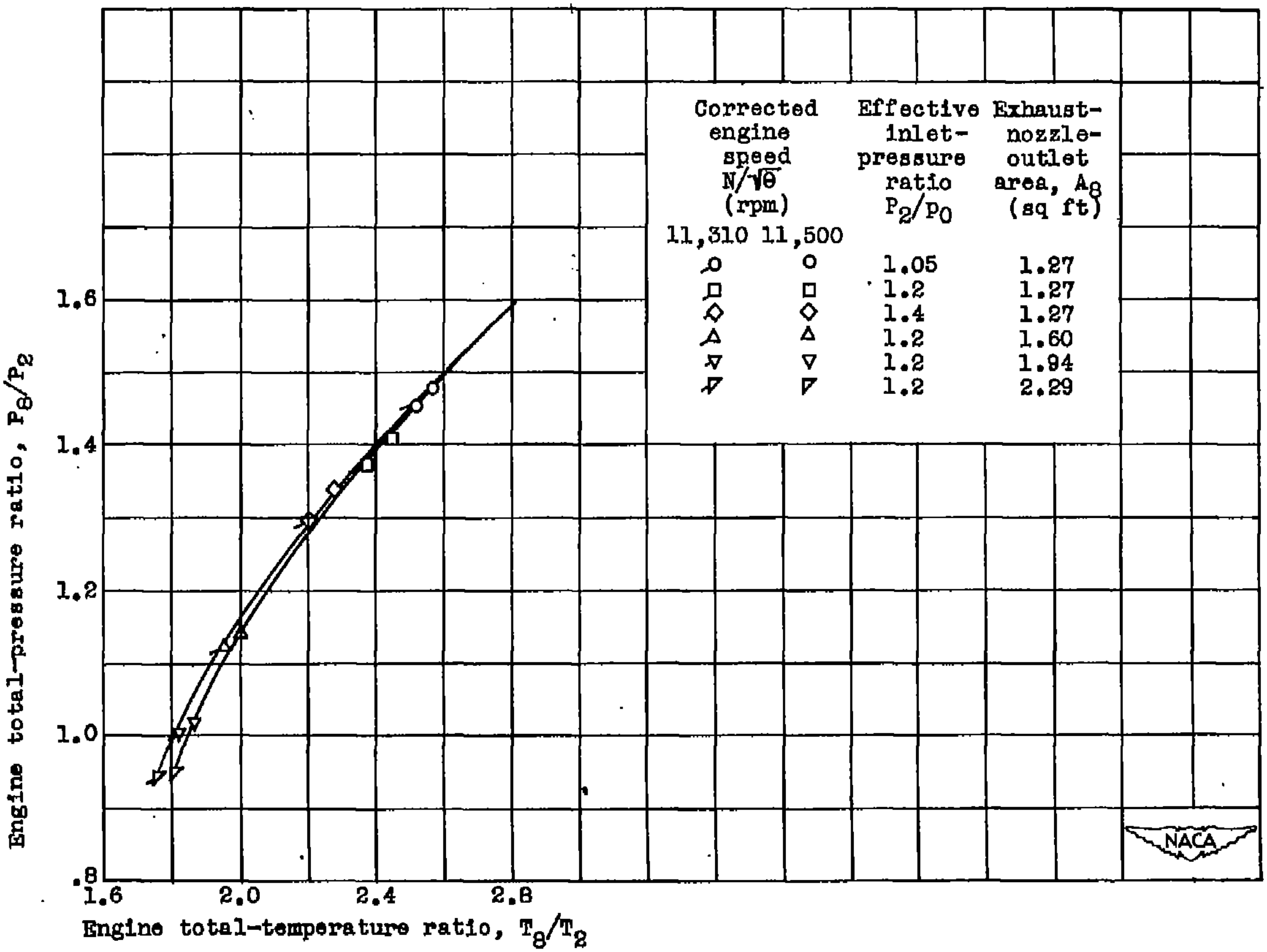
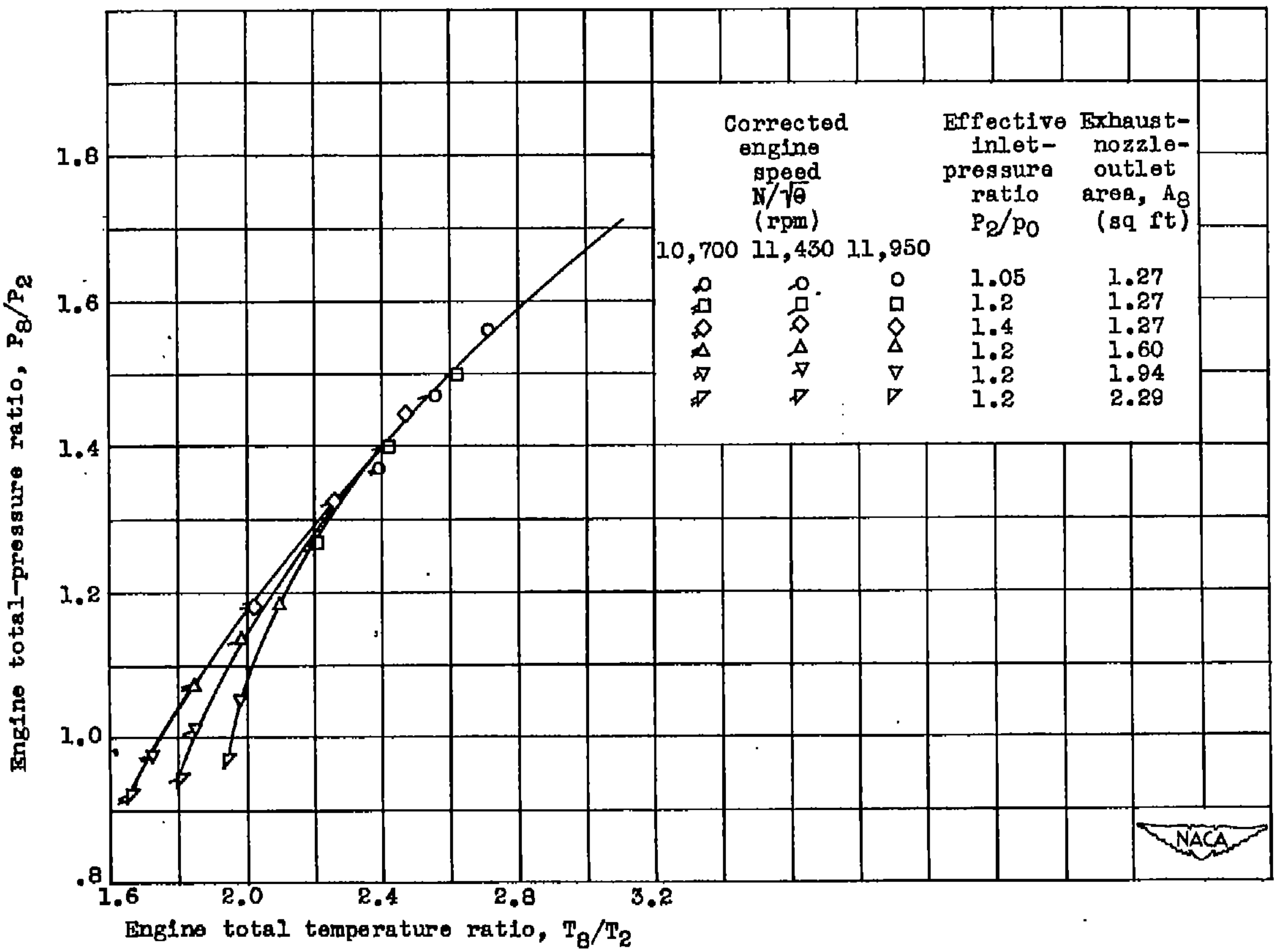


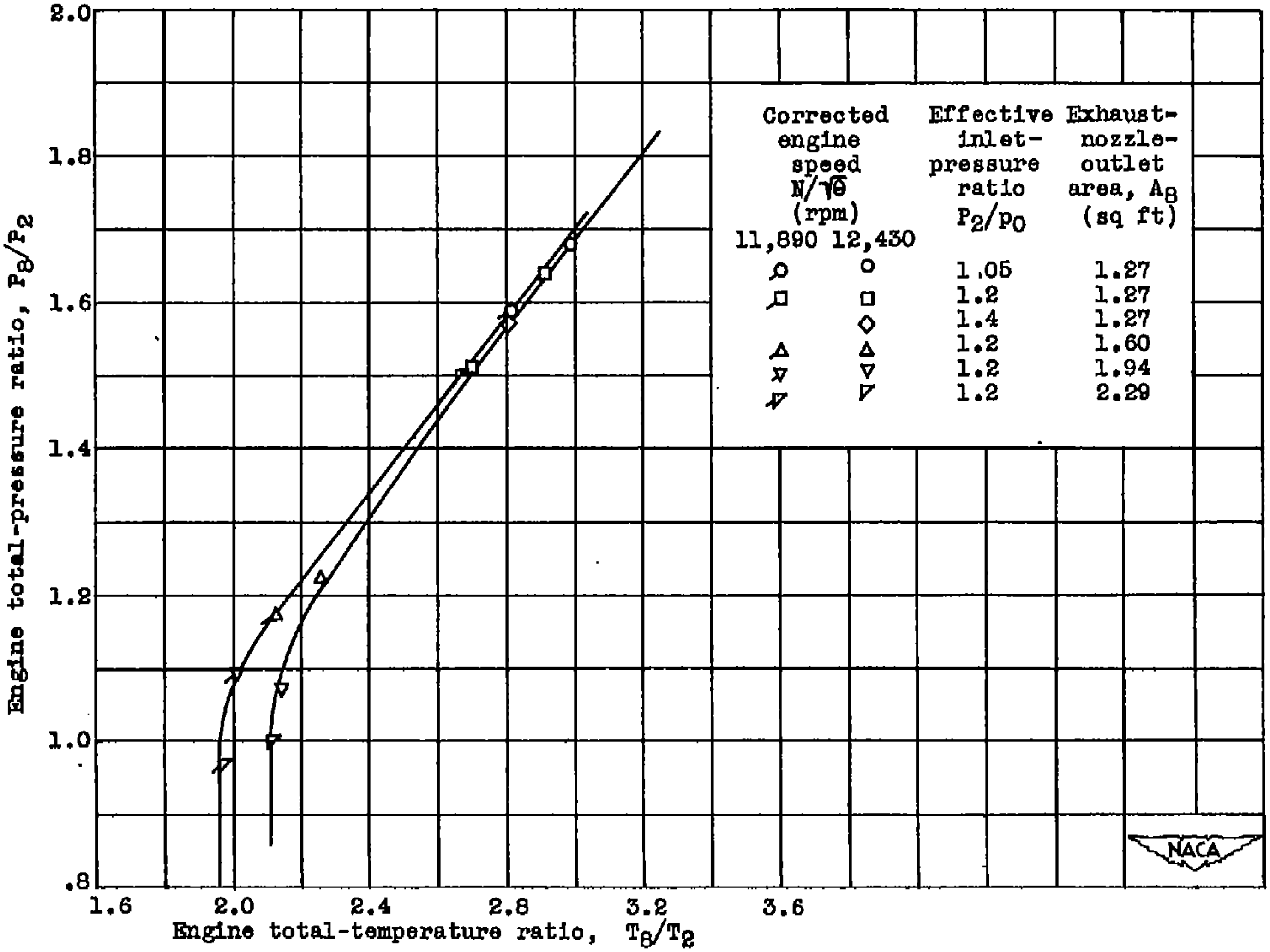
(a) Altitude, sea level.

Figure 1. - Relation between engine total-pressure ratio and engine total-temperature ratio.



(b) Altitude, 15,000 feet.

Figure 1. - Continued. Relation between engine total-pressure ratio and engine total-temperature ratio.



(c) Altitude, 25,000 feet.

Figure 1. - Concluded. Relation between engine total-pressure ratio and engine total-temperature ratio.

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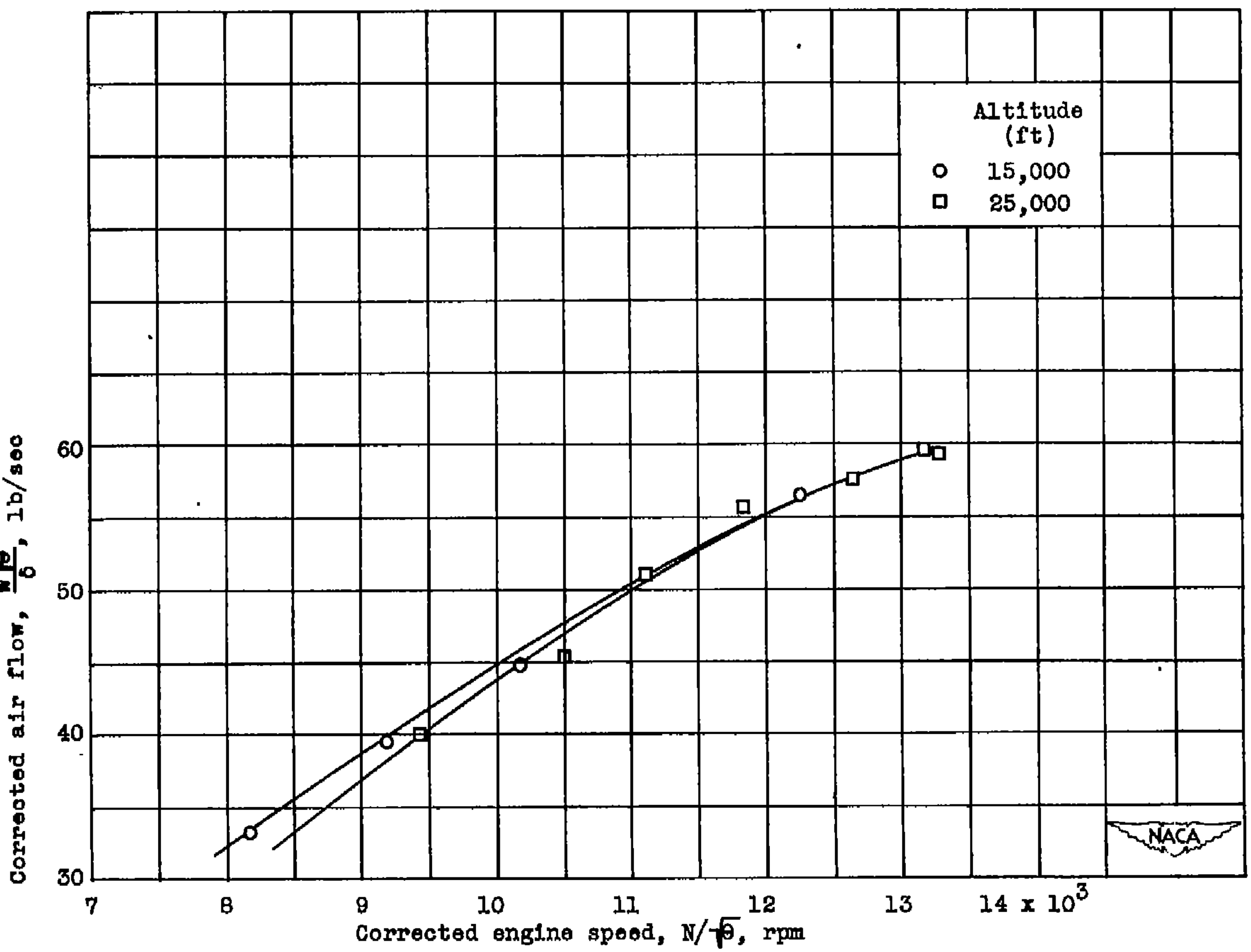

Figure 2. - Corrected air flow as function of corrected engine speed. Effective inlet pressure ratio, 1.4.

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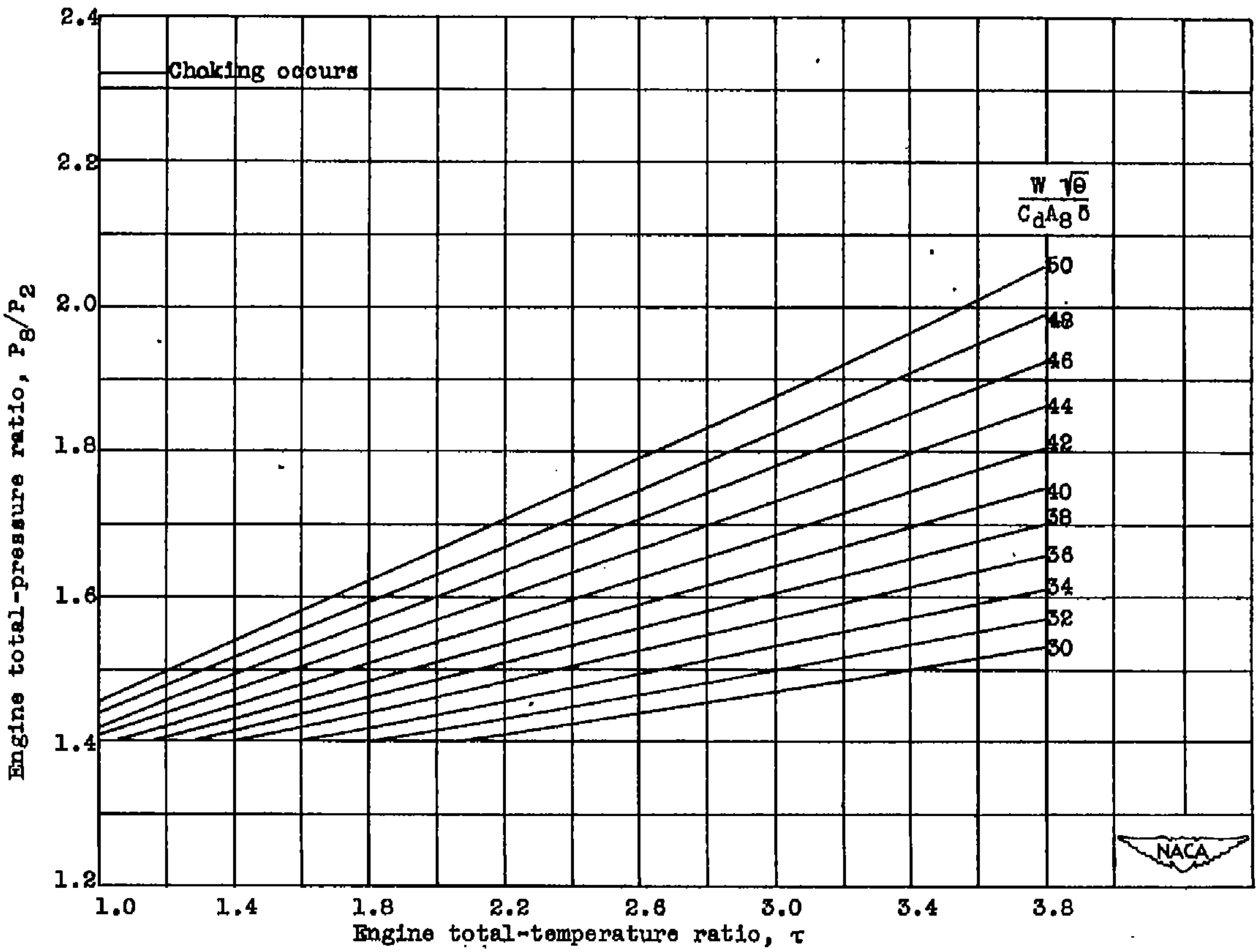

(a) Effective inlet-pressure ratio, P_2/p_0, 0.8.

Figure 3. - Exhaust-nozzle characteristics.

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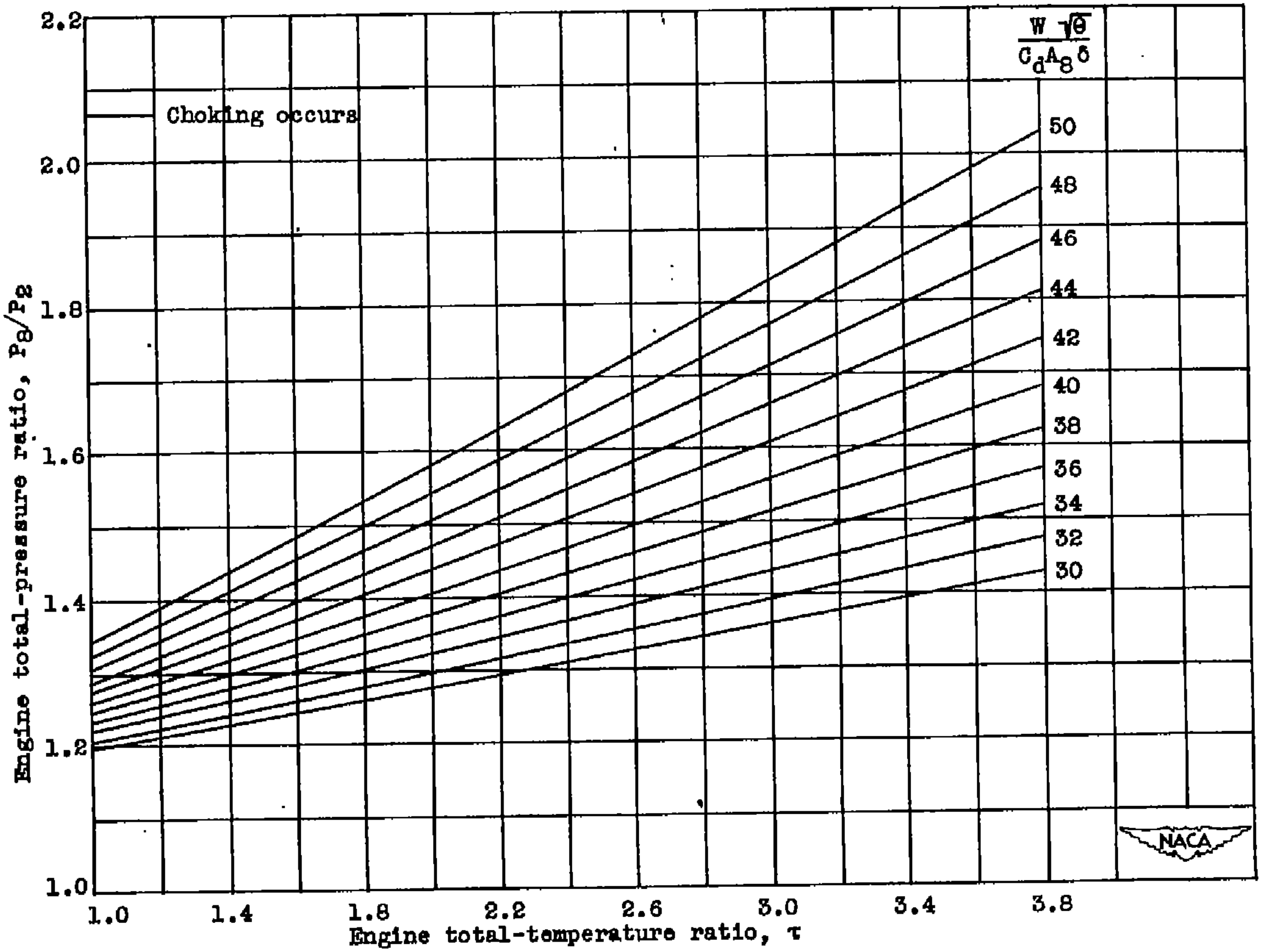

(b) Effective inlet-pressure ratio, P_2/p_0, 0.9.

Figure 3. - Continued. Exhaust-nozzle characteristics.

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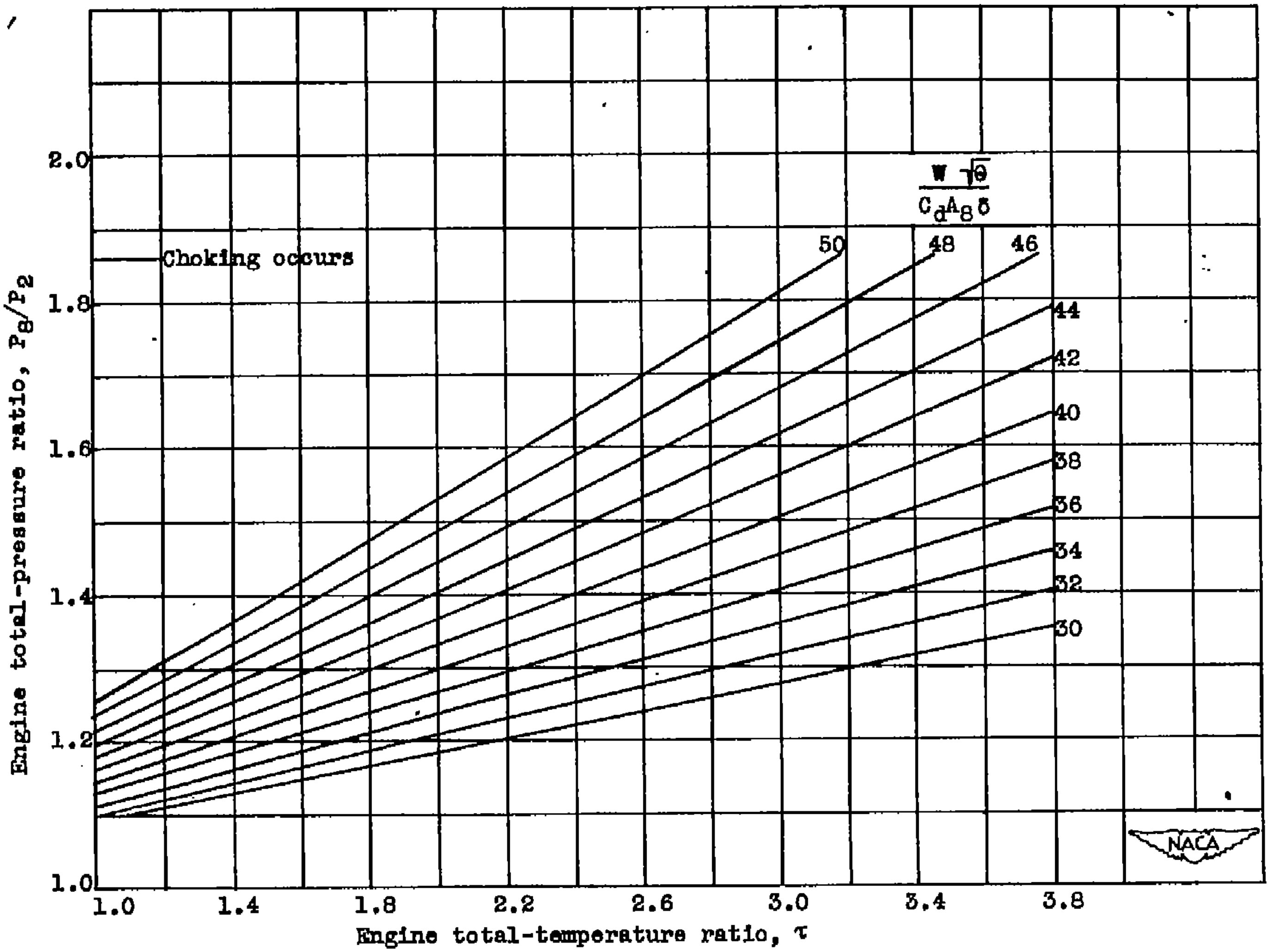

(c) Effective inlet-pressure ratio, P_2/p_0, 1.0.

Figure 3. - Continued. Exhaust-nozzle characteristics.

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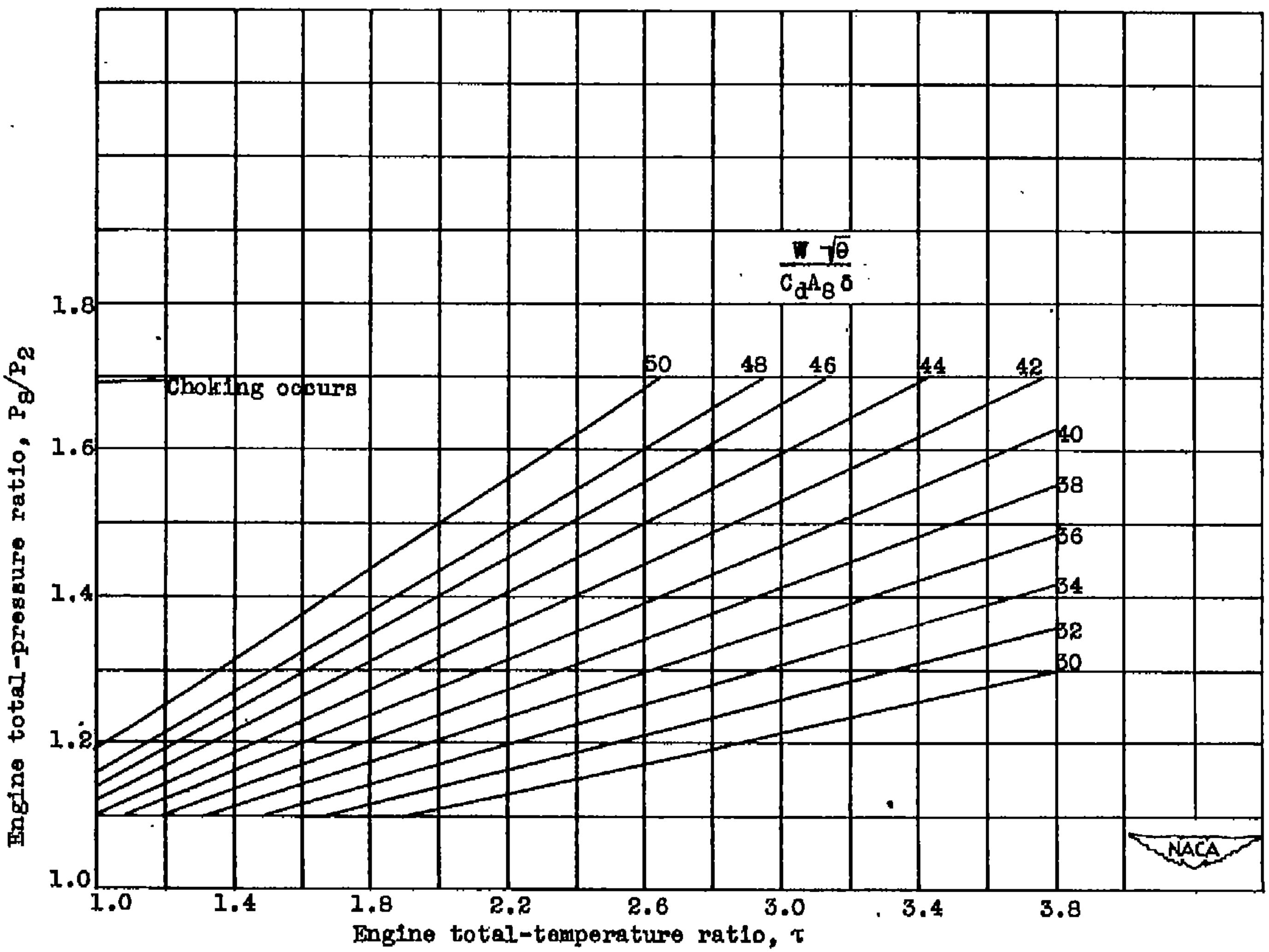

(d) Effective inlet-pressure ratio, P_2/p_0, 1.1.
Figure 3. - Continued. Exhaust-nozzle characteristics.

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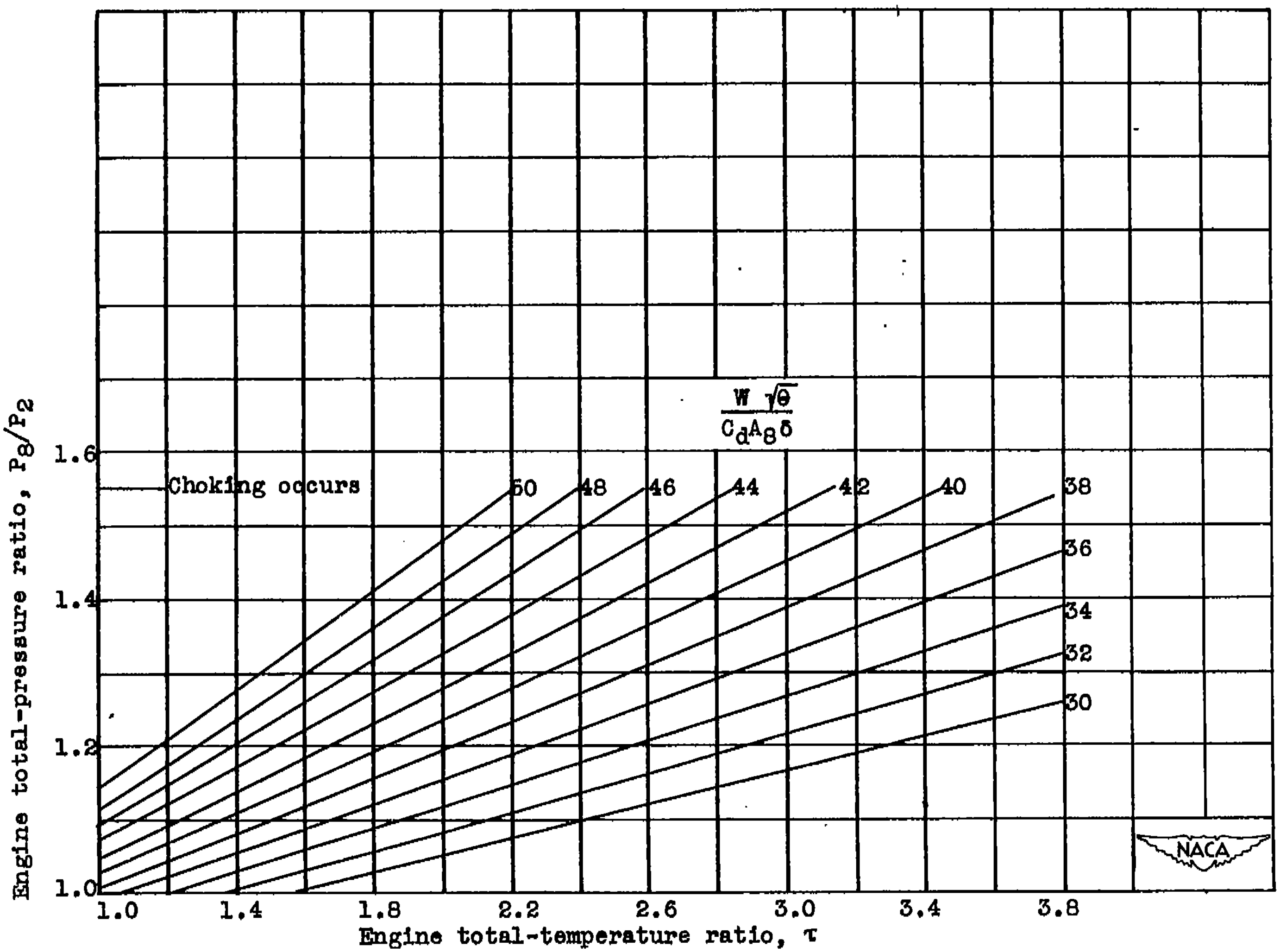
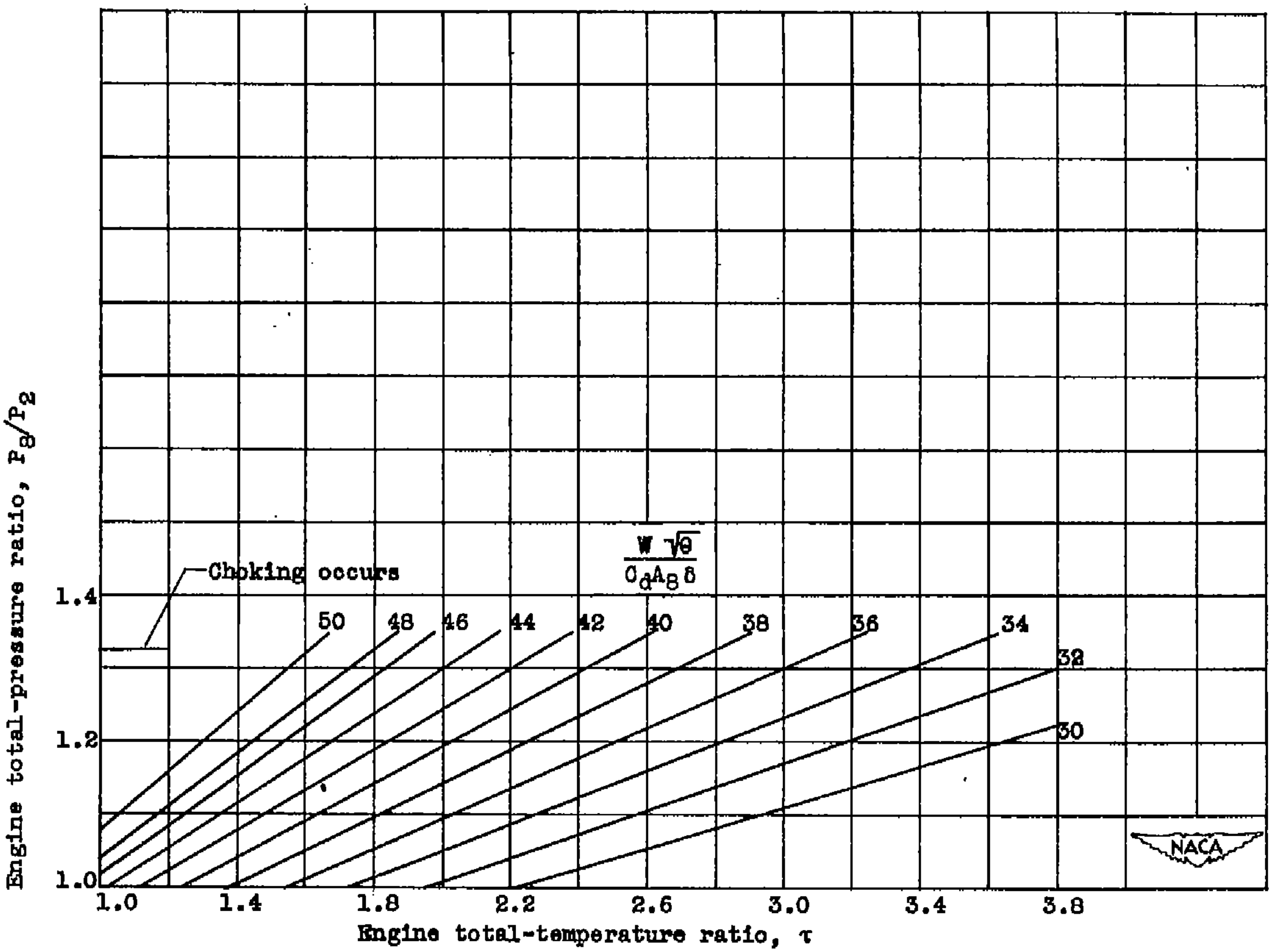
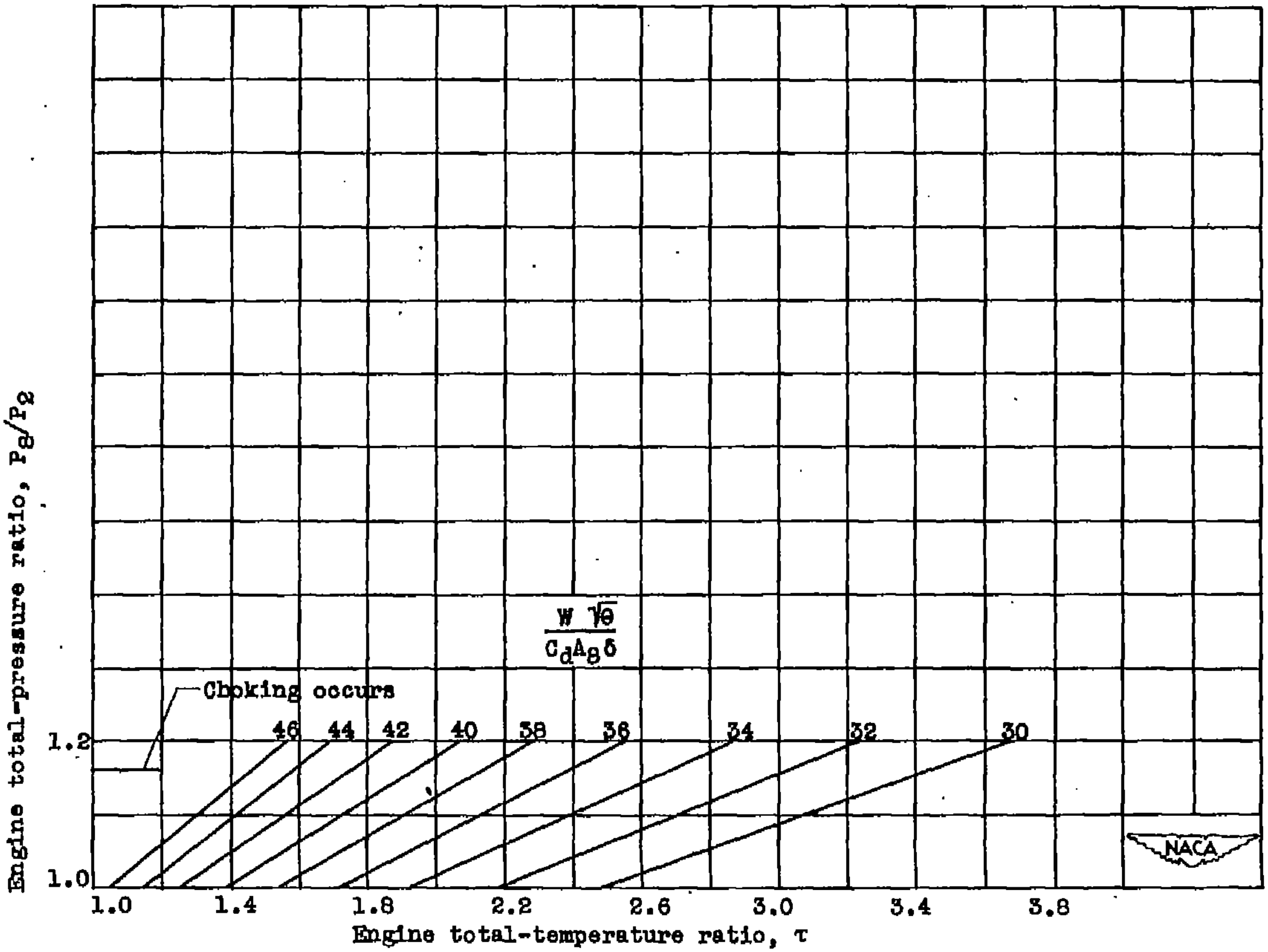


(e) Effective inlet-pressure ratio, P_2/p_0, 1.2.

Figure 3. - Continued. Exhaust-nozzle characteristics.

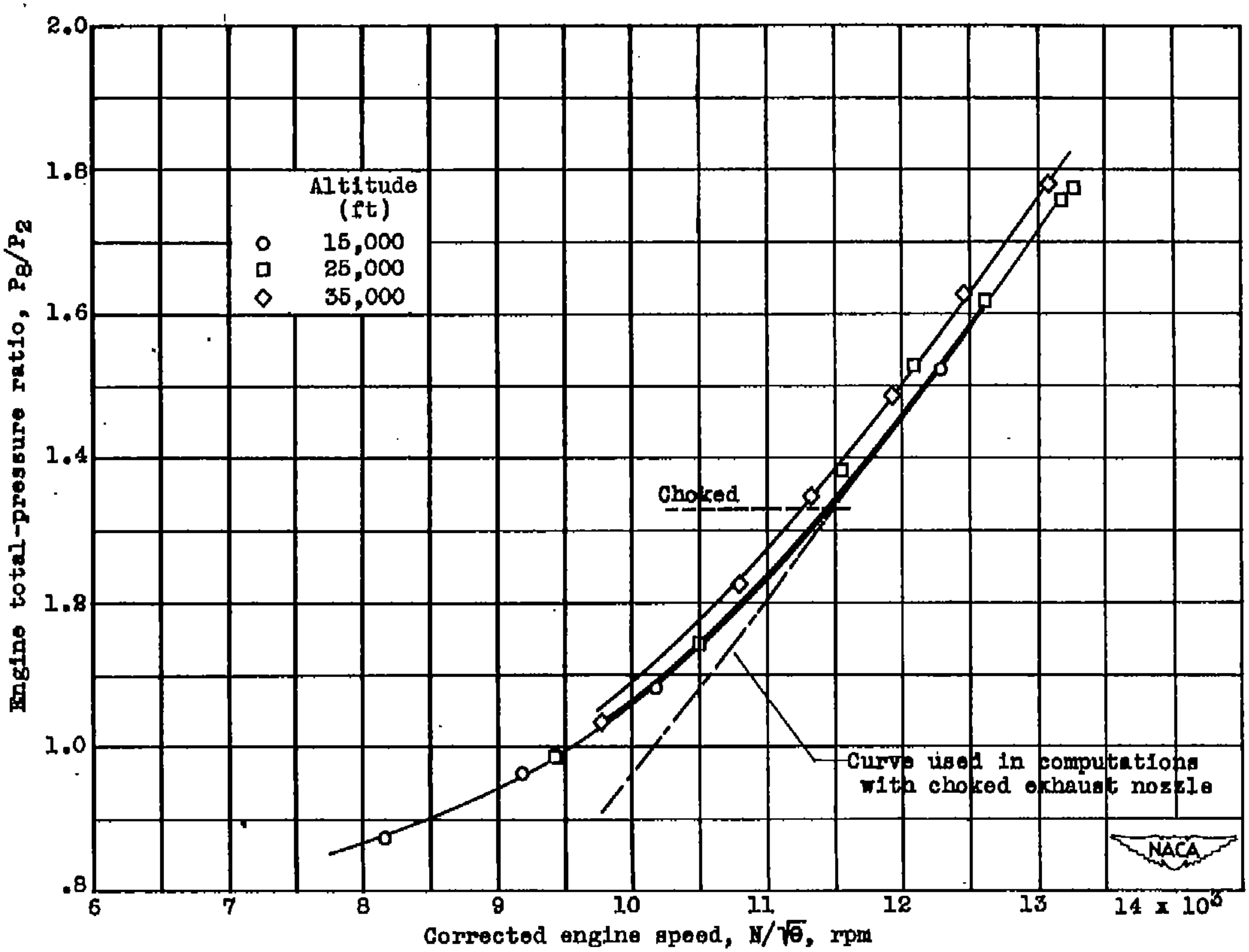


(f) Effective inlet-pressure ratio, P_2/p_0, 1.4.
Figure 3. - Continued. Exhaust-nozzle characteristics.



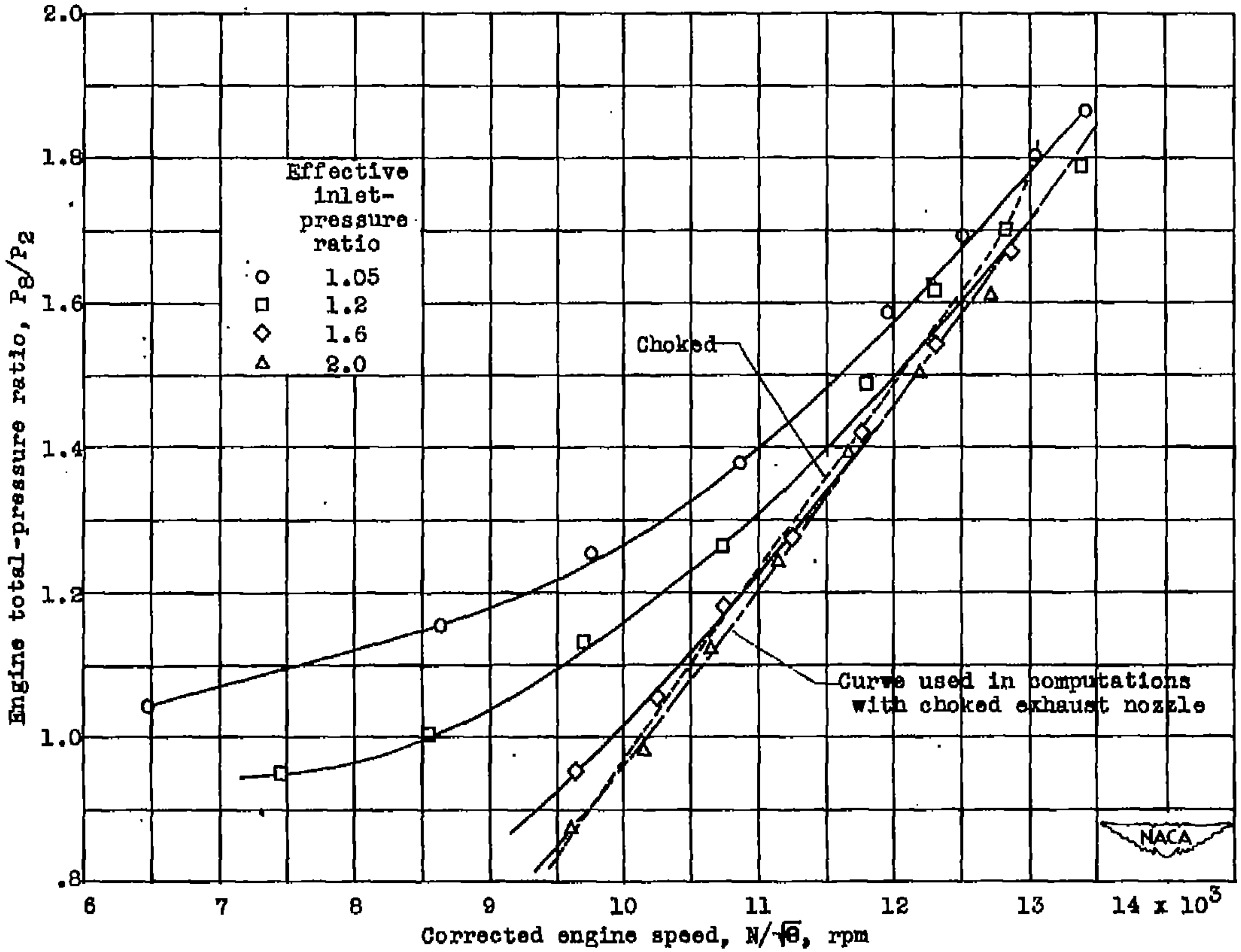
(g) Effective inlet-pressure ratio, P_2/p_0, 1.6.

Figure 3. - Concluded. Exhaust-nozzle characteristics.



(a) Effect of altitude. Effective inlet-pressure ratio, 1.4; constant exhaust-nozzle-outlet area, 1.27 square feet.

Figure 4. - Relation between engine total-pressure ratio and corrected engine speed.



(b) Effect of effective inlet-pressure ratio. Altitude, 25,000 feet; constant exhaust-nozzle-outlet area, 1.27 square feet.

Figure 4. - Continued. Relation between engine total-pressure ratio and corrected engine speed.

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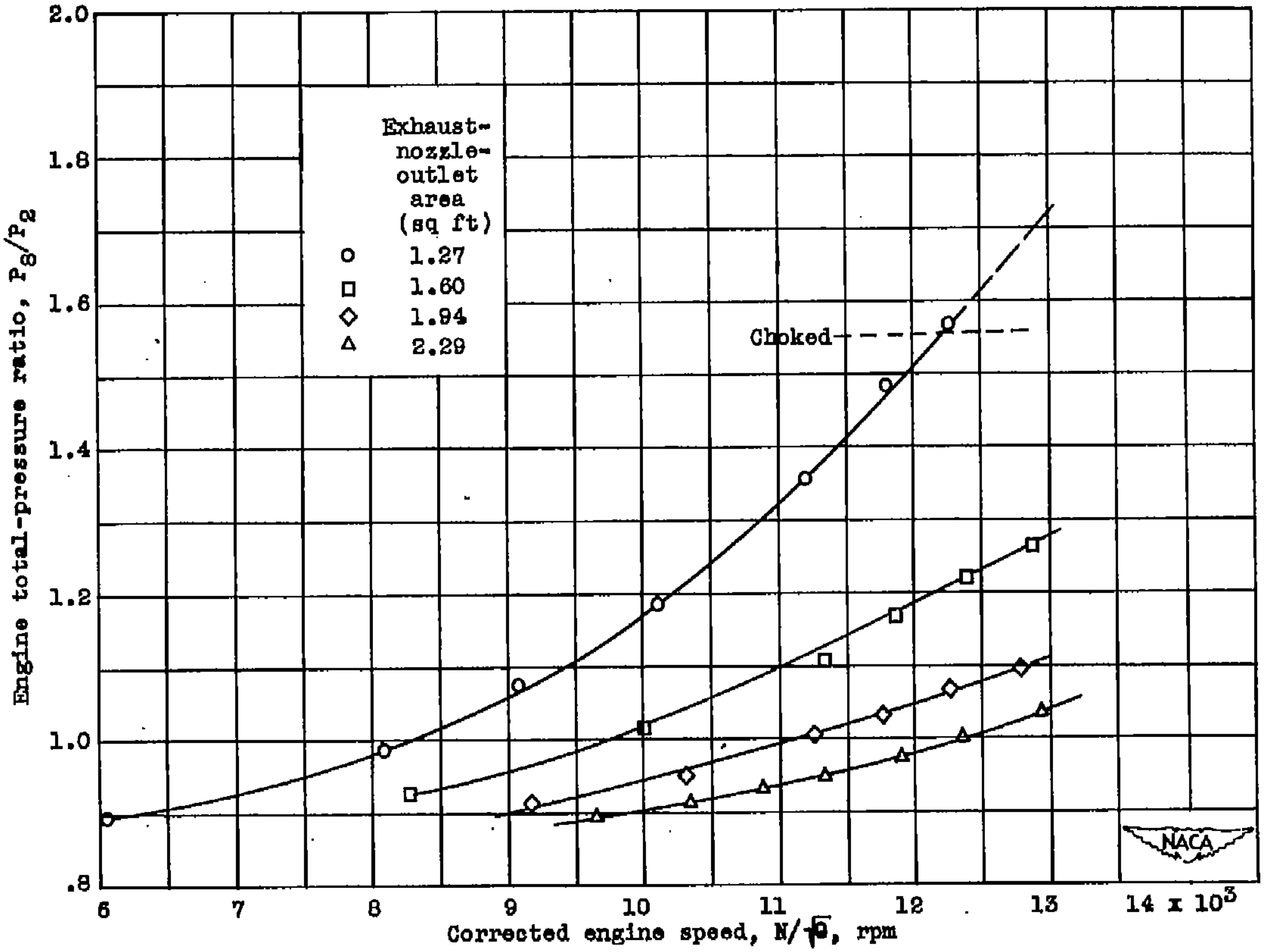

(c) Effect of exhaust-nozzle-outlet area. Altitude 15,000 feet; effective inlet-pressure ratio, 1.2.

Figure 4. - Concluded. Relation between engine total-pressure ratio and corrected engine speed.

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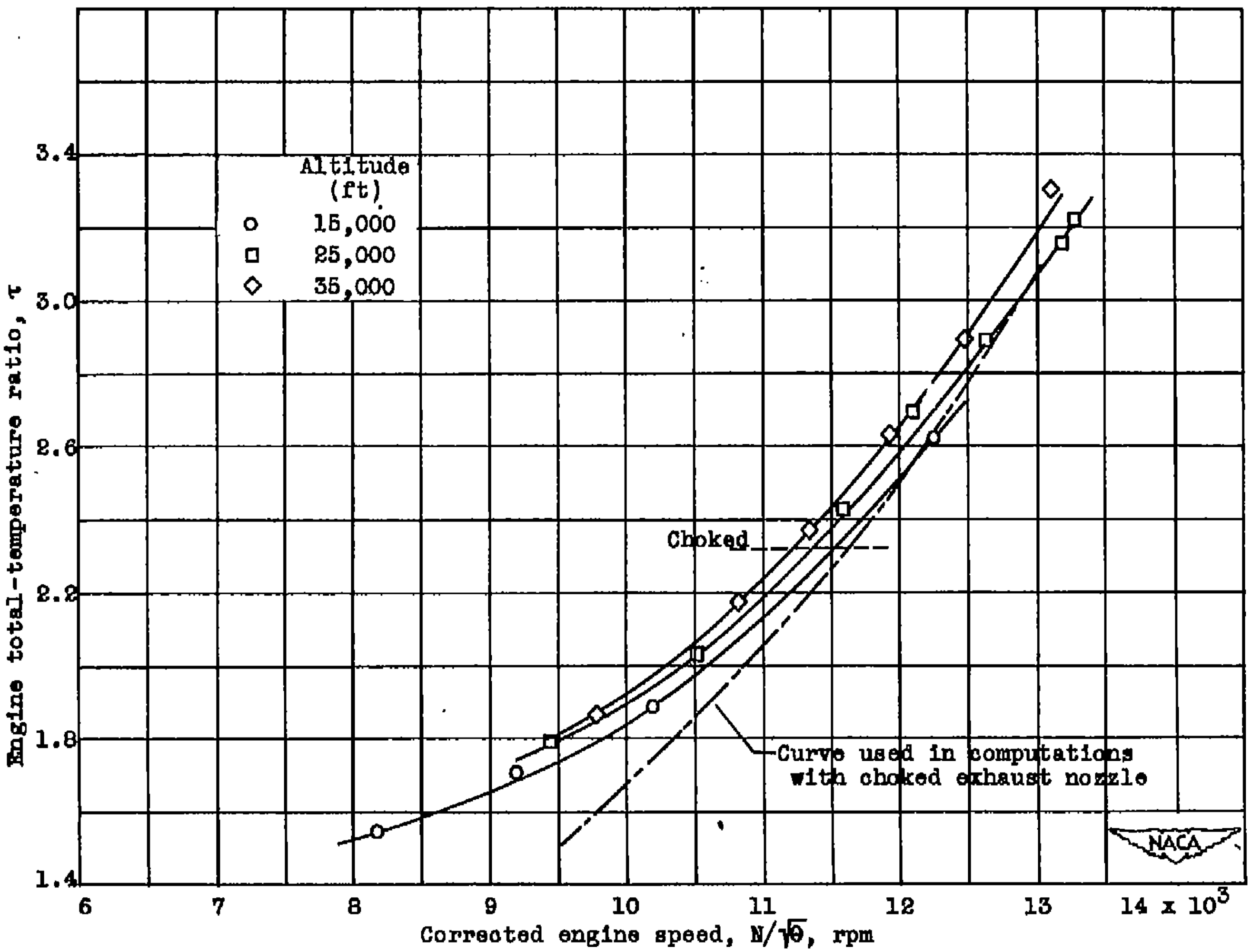

(a) Effect of altitude. Effective inlet-pressure ratio, 1.4; constant exhaust-nozzle-outlet area, 1.27 square feet.

Figure 5. - Relation between engine total-temperature ratio and corrected engine speed.

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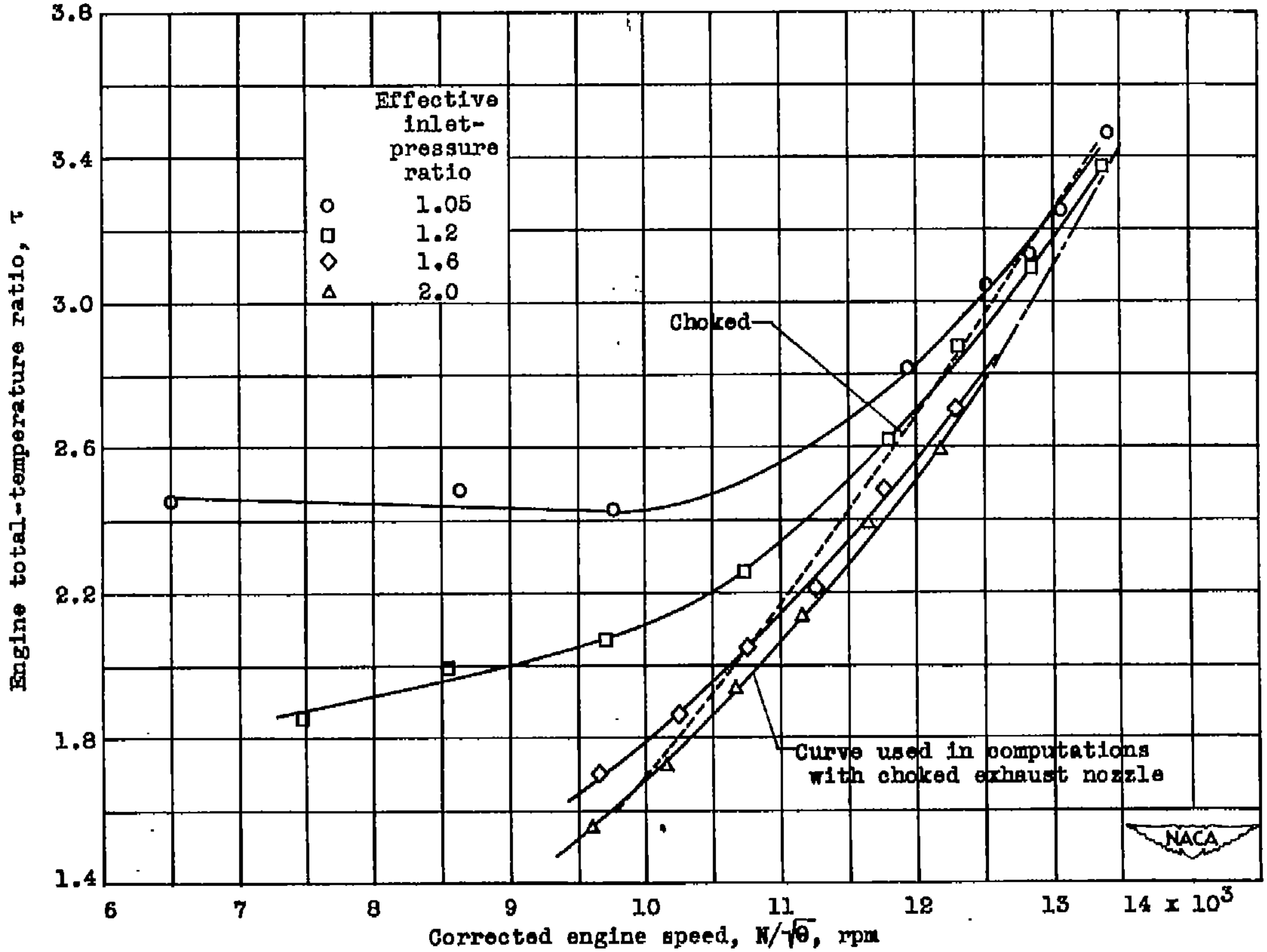

(b) Effect of effective inlet-pressure ratio. Altitude, 25,000 feet; constant exhaust-nozzle-outlet area, 1.27 square feet.

Figure 5. - Continued. Relation between engine total-temperature ratio and corrected engine speed.

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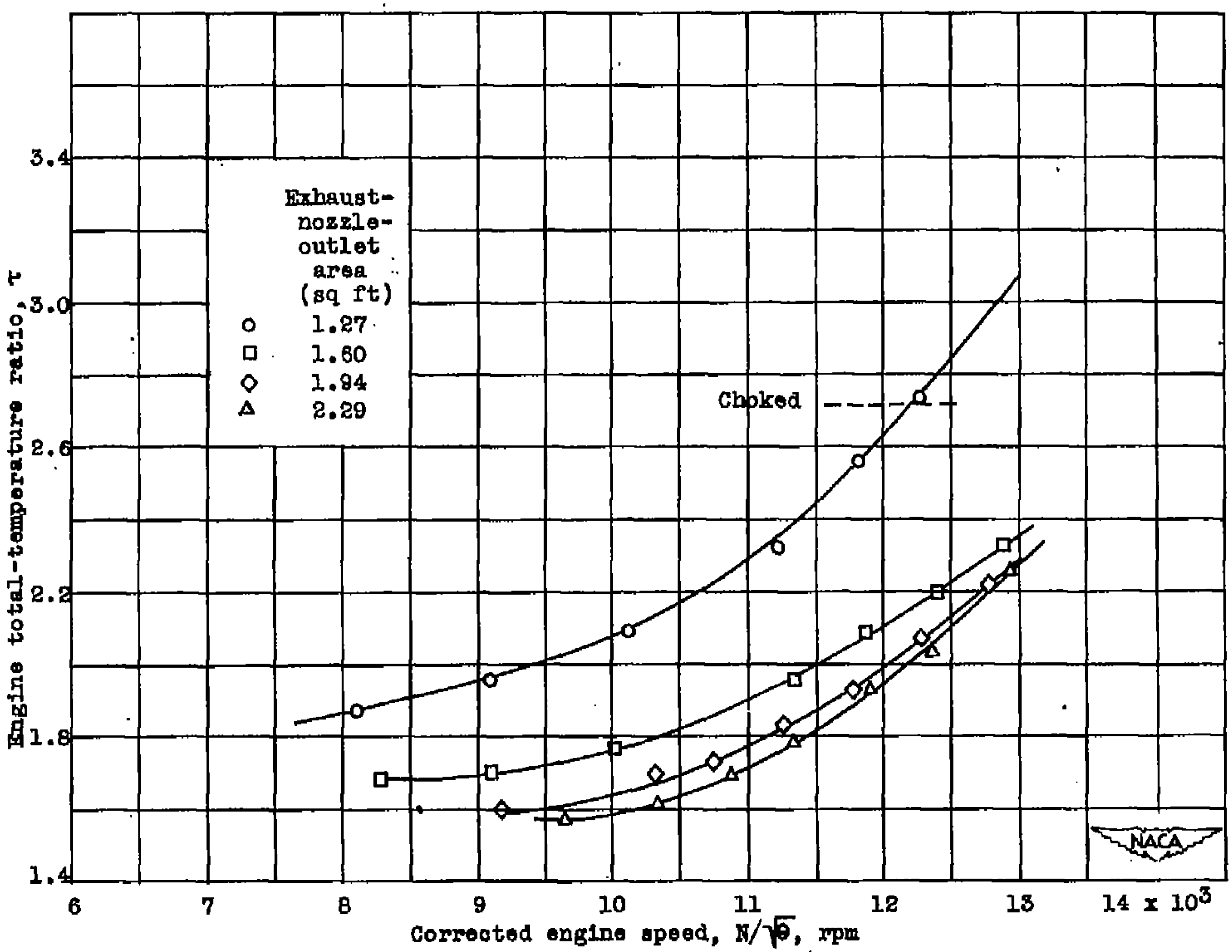

(c) Effect of exhaust-nozzle-outlet area. Altitude 15,000 feet; effective inlet-pressure ratio, 1.2.

Figure 5. - Concluded. Relation between engine total-temperature ratio and corrected engine speed.

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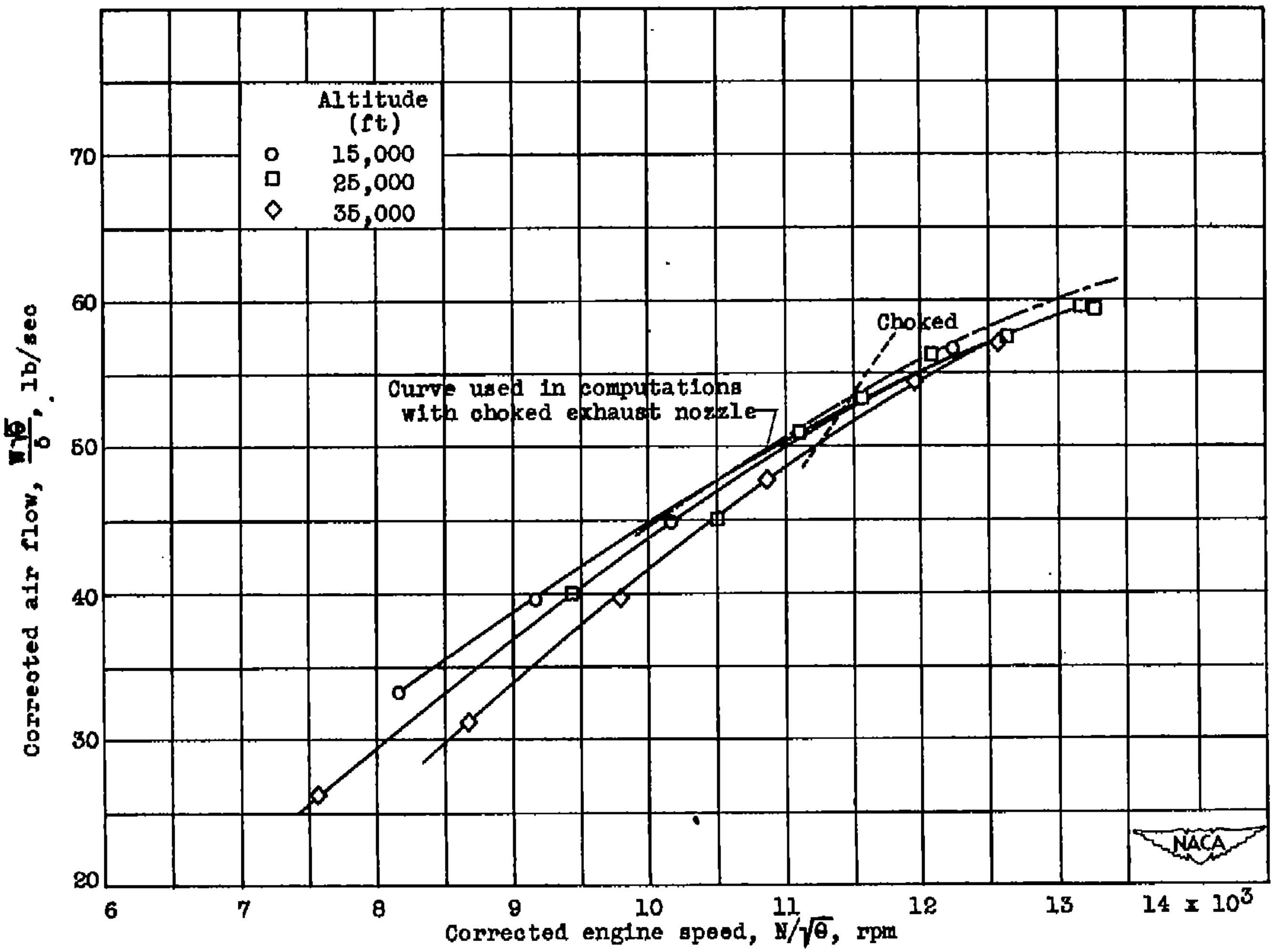

(a) Effect of altitude. Effective inlet-pressure ratio, 1.4; constant exhaust-nozzle-outlet area, 1.27 square feet.

Figure 6. - Relation between corrected air flow at compressor inlet and corrected engine speed.

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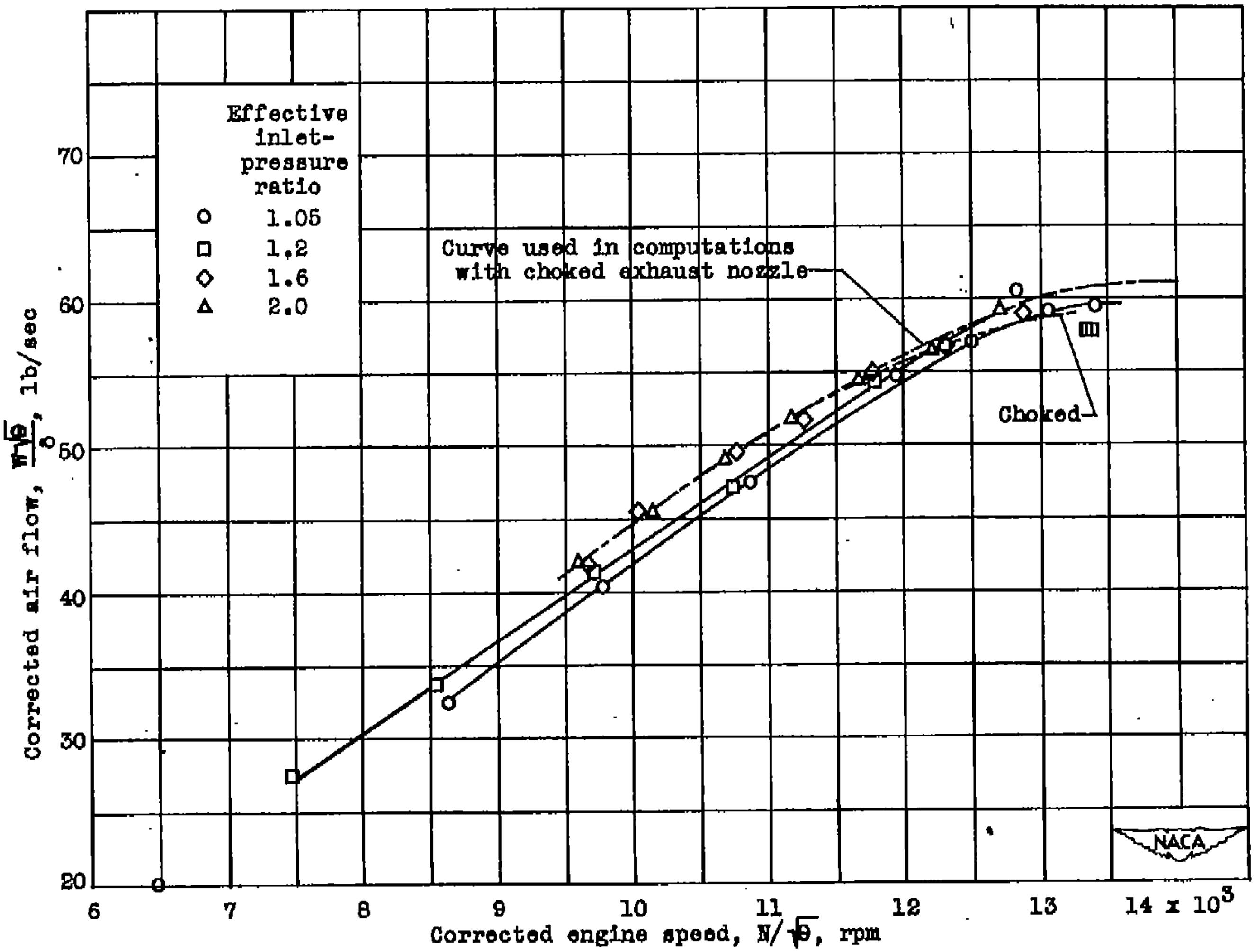

(b) Effect of effective inlet-pressure ratio. Altitude, 25,000 feet; constant exhaust-nozzle-outlet area, 1.27 square feet.

Figure 6. - Continued. Relation between corrected air flow at compressor inlet and corrected engine speed.

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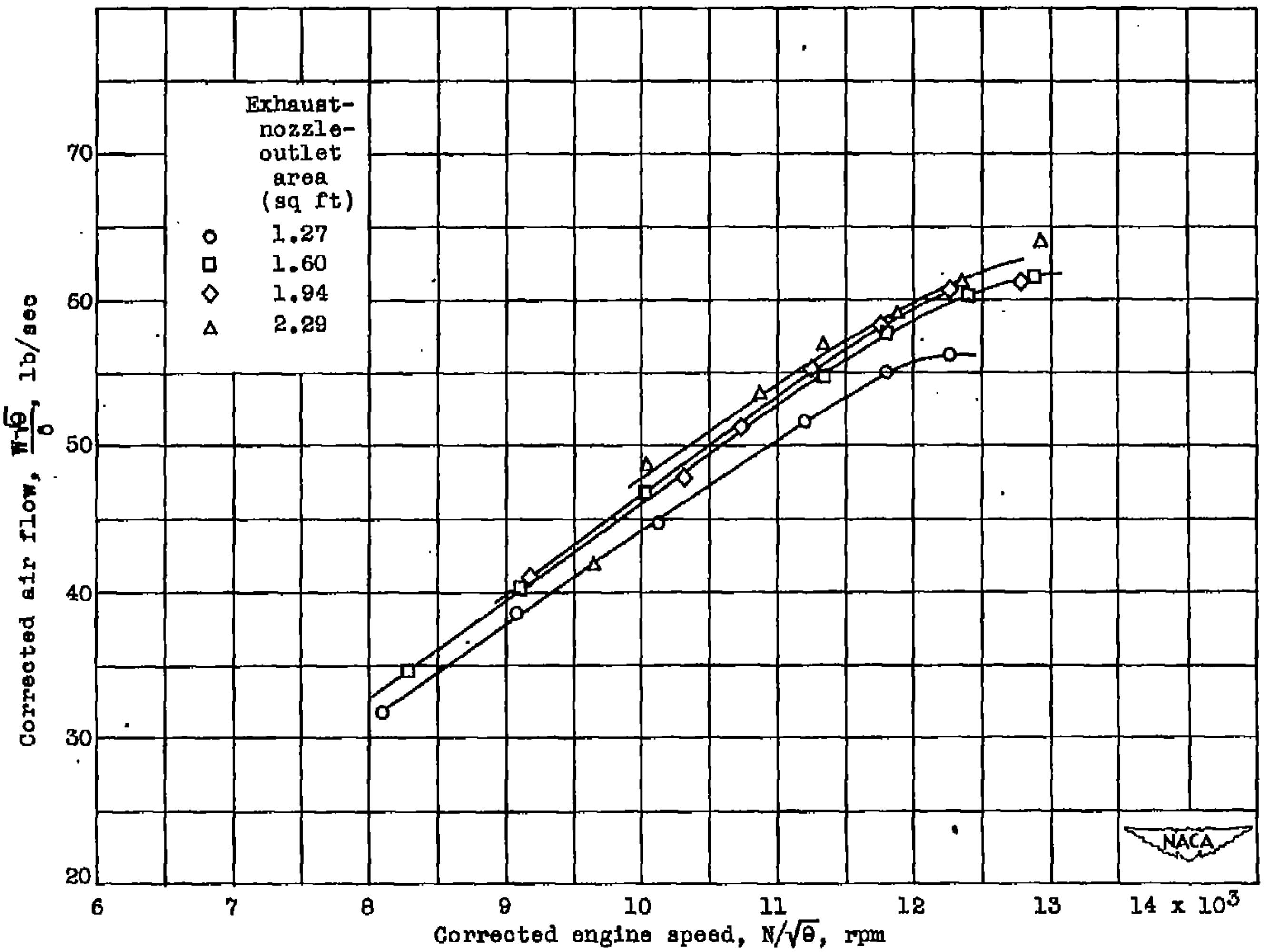

(c) Effect of exhaust-nozzle-outlet area. Altitude, 15,000 feet; effective inlet-pressure ratio, 1.2.

Figure 6. - Concluded. Relation between corrected air flow at compressor inlet and corrected engine speed.

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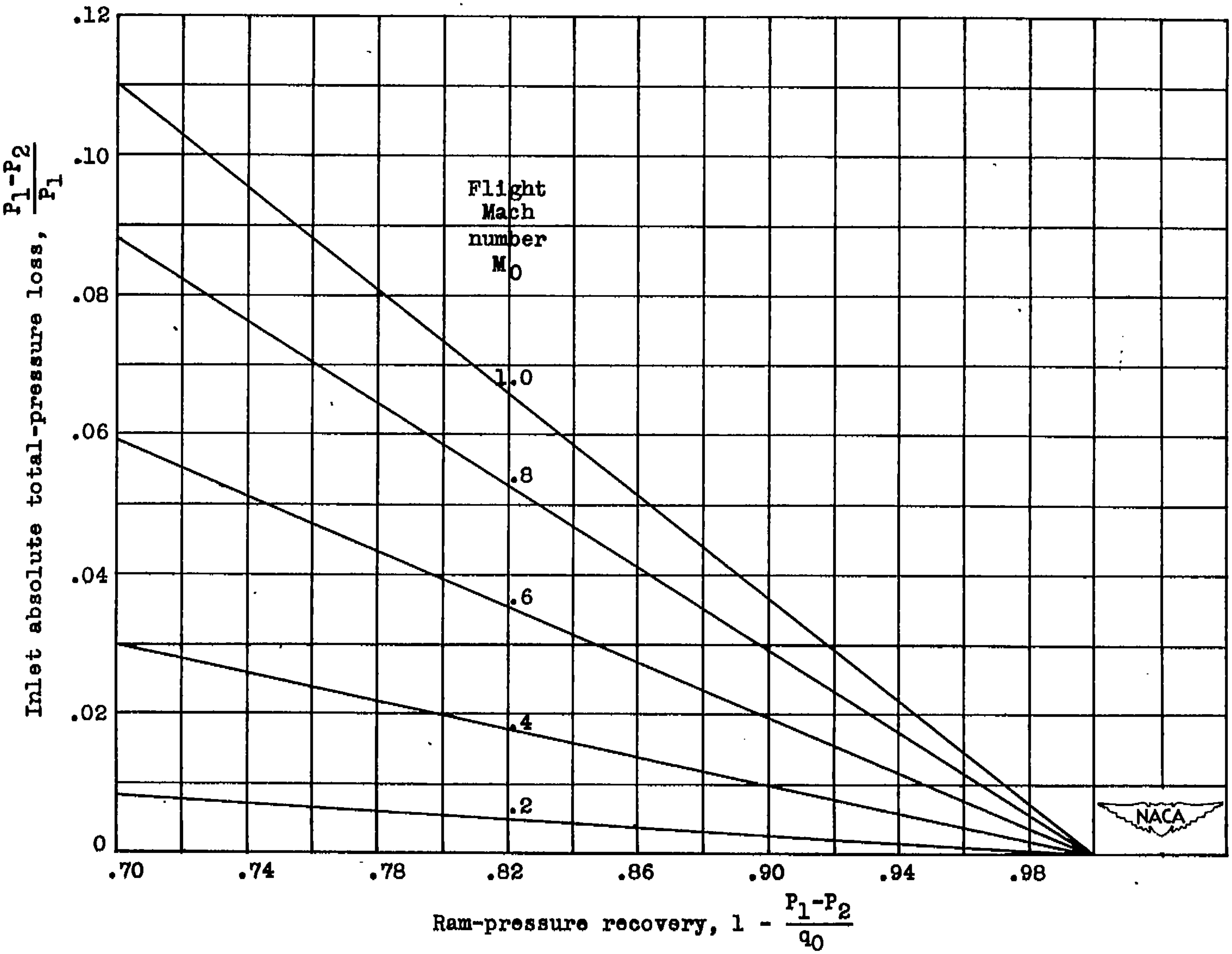

Figure 7. - Relation between inlet absolute total-pressure loss and ram-pressure recovery.

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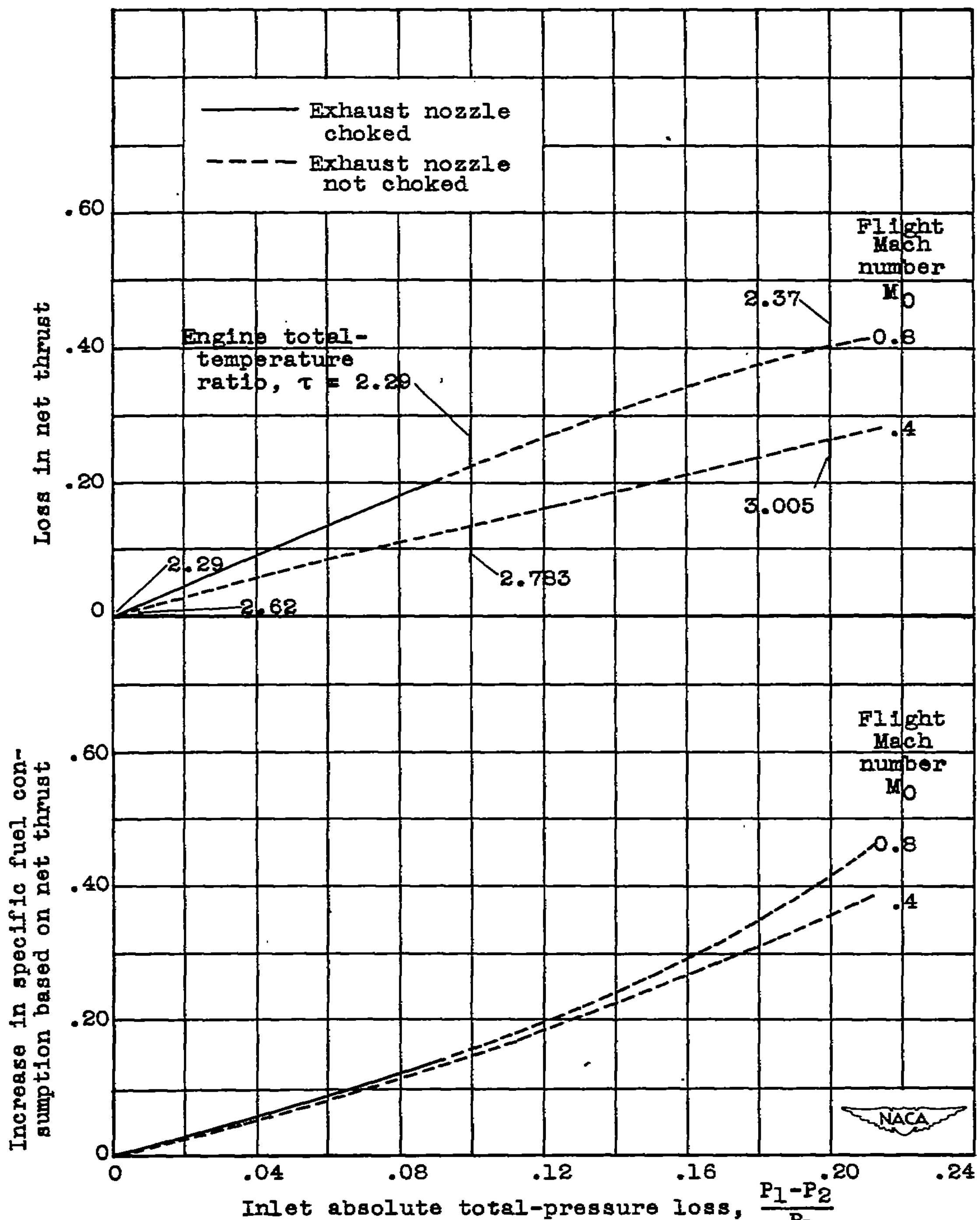

Figure 8. - Relation of loss in net thrust and increase in specific fuel consumption based on net thrust to inlet absolute total-pressure loss at flight Mach numbers of 0.4 and 0.8. Altitude, 15,000 feet; engine speed, 11,500 rpm; exhaust-nozzle-outlet area, 1.27 square feet.

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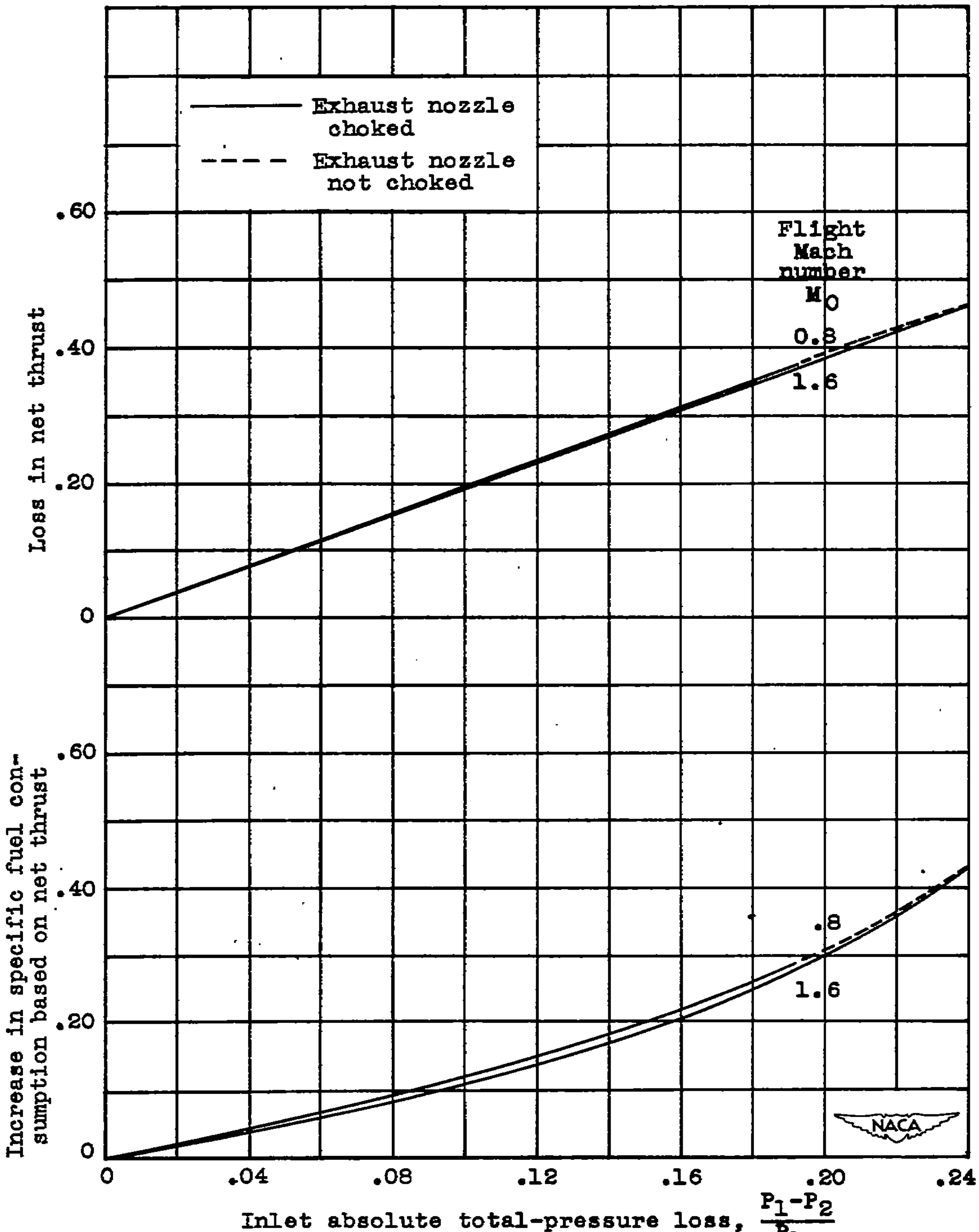


Figure 9. - Relation of loss in net thrust and increase in specific fuel consumption based on net thrust to inlet absolute total-pressure loss at flight Mach numbers of 0.8 and 1.6. Altitude, 25,000 feet; engine speed, 11,500 rpm; exhaust-nozzle-outlet area, 1.27 square feet.

947

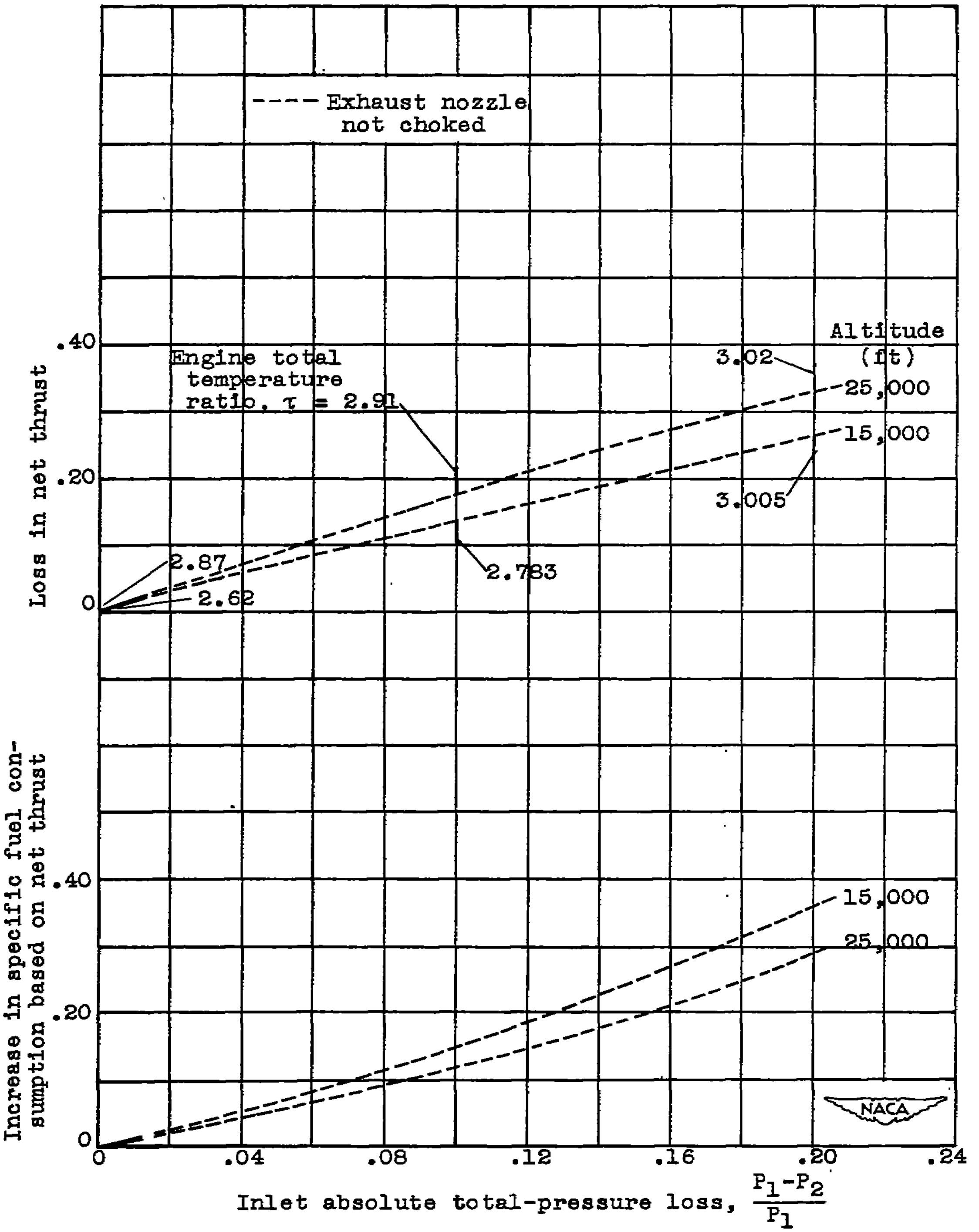
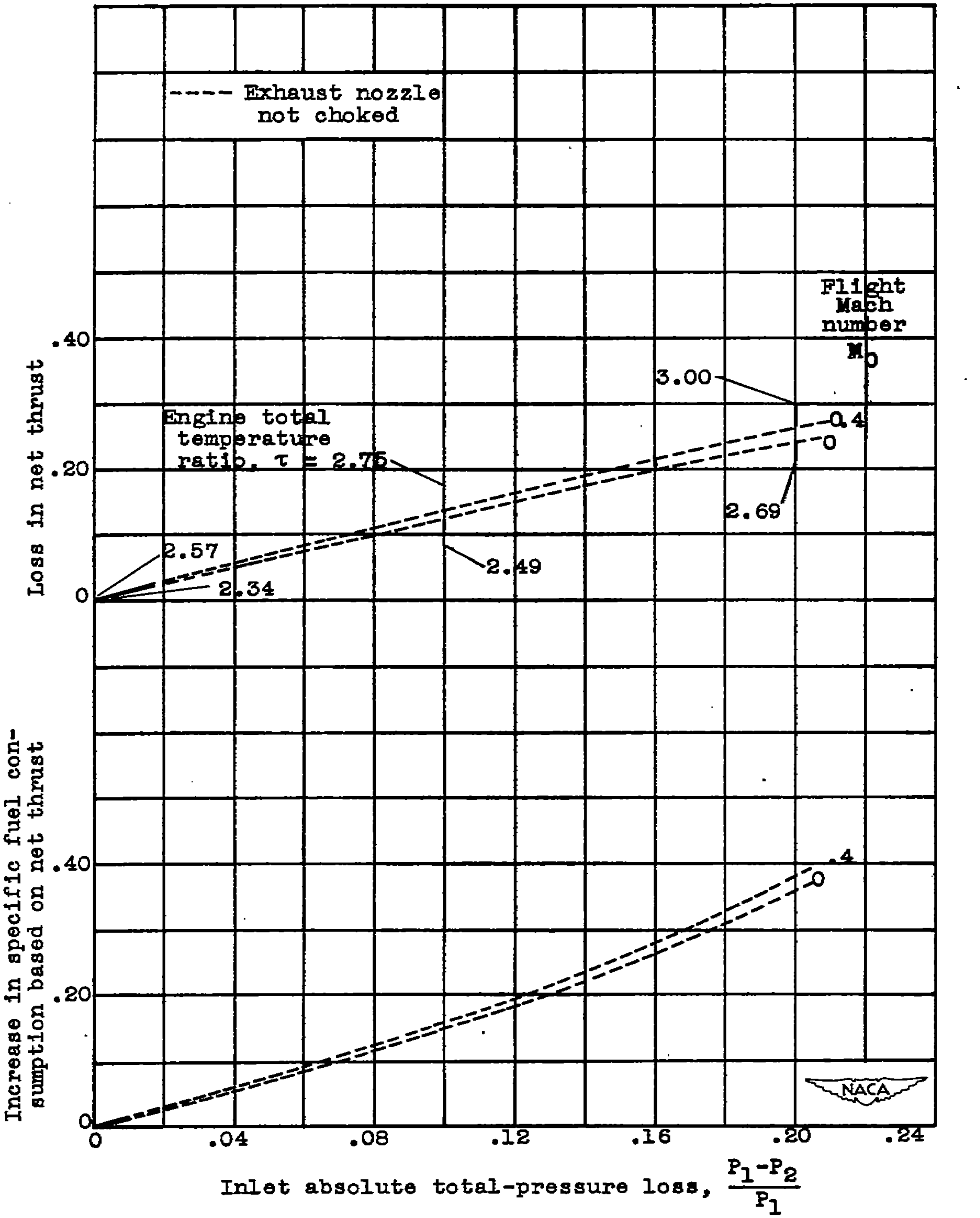


Figure 10. - Relation of loss in net thrust and increase in specific fuel consumption based on net thrust to inlet absolute total-pressure loss at altitudes of 15,000 and 25,000 feet. Flight Mach number, 0.4; engine speed, 11,500 rpm; exhaust-nozzle-outlet area, 1.27 square feet.

947



(a) Altitude, sea level.

Figure 11. - Variation of loss in net thrust and increase in specific fuel consumption based on net thrust with inlet absolute total-pressure loss. Engine speed, 11,500 rpm; exhaust-nozzle-outlet area, 1.27 square feet.

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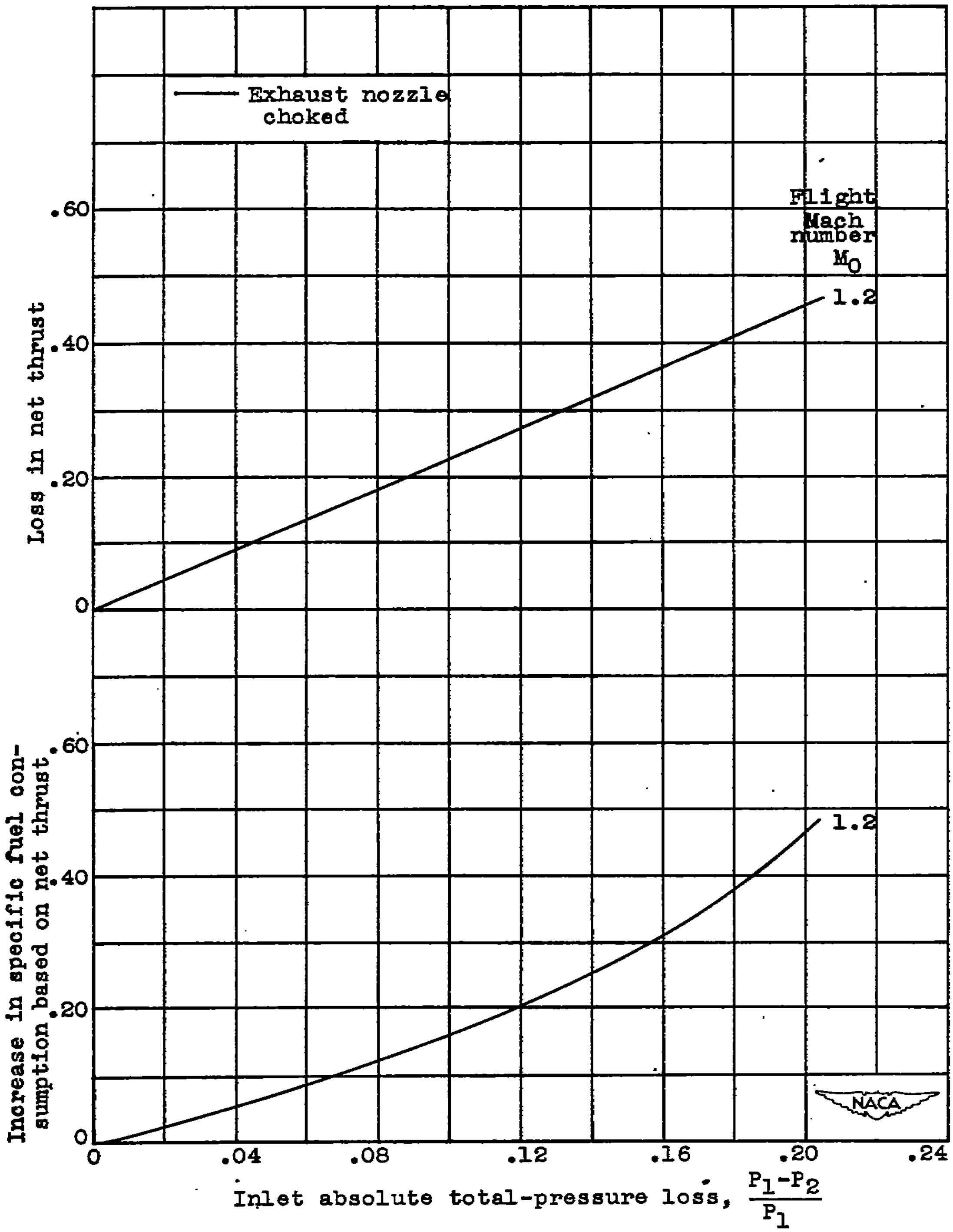

(b) Altitude, 15,000 feet.

Figure 11. - Continued. Variation of loss in net thrust and increase in specific fuel consumption based on net thrust with inlet absolute total-pressure loss. Engine speed, 11,500 rpm; exhaust-nozzle-outlet area, 1.27 square feet.

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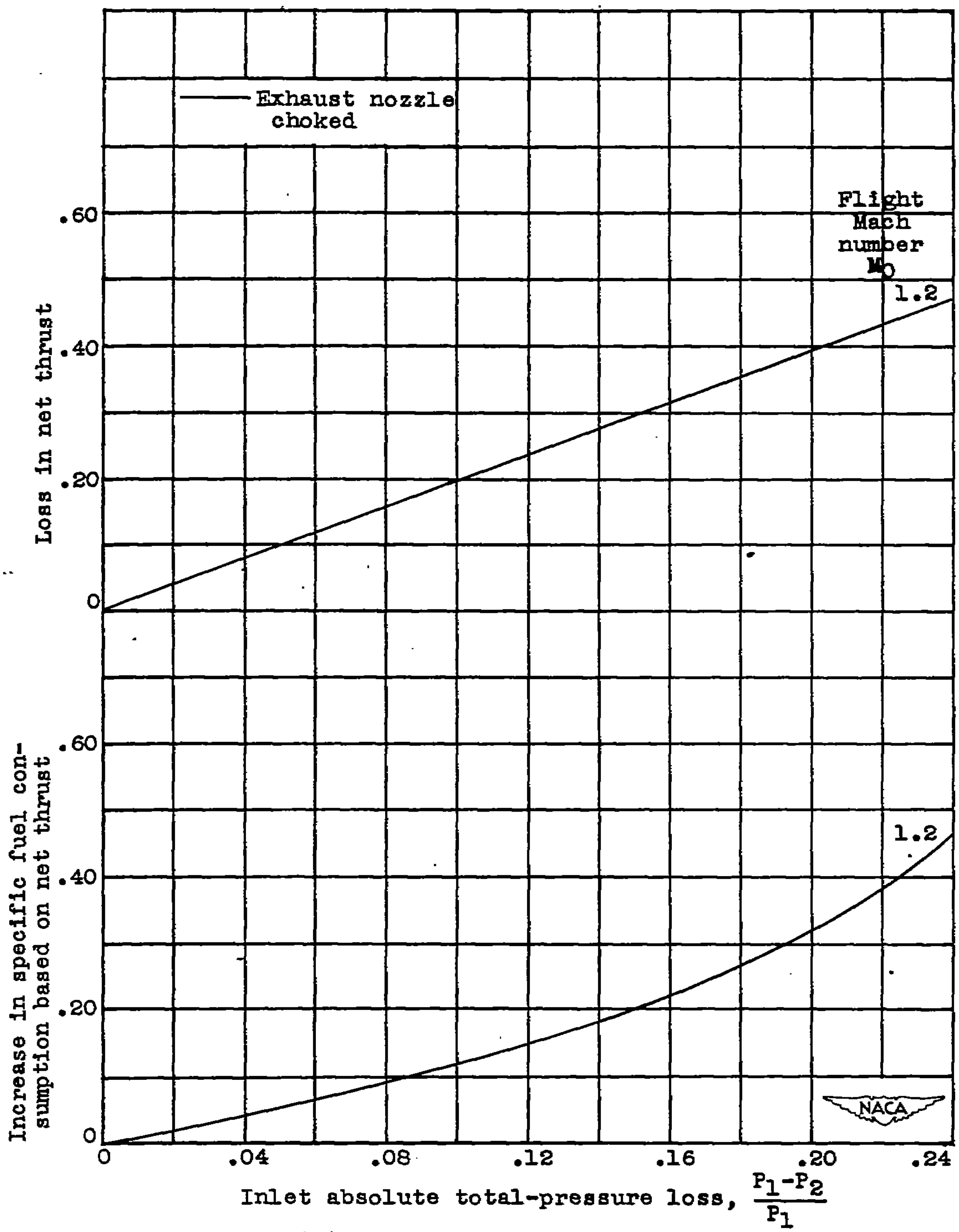

(c) Altitude, 25,000 feet.

Figure 11. - Continued. Variation of loss in net thrust and increase in specific fuel consumption based on net thrust with inlet absolute total-pressure loss. Engine speed, 11,500 rpm; exhaust-nozzle-outlet area, 1.27 square feet.

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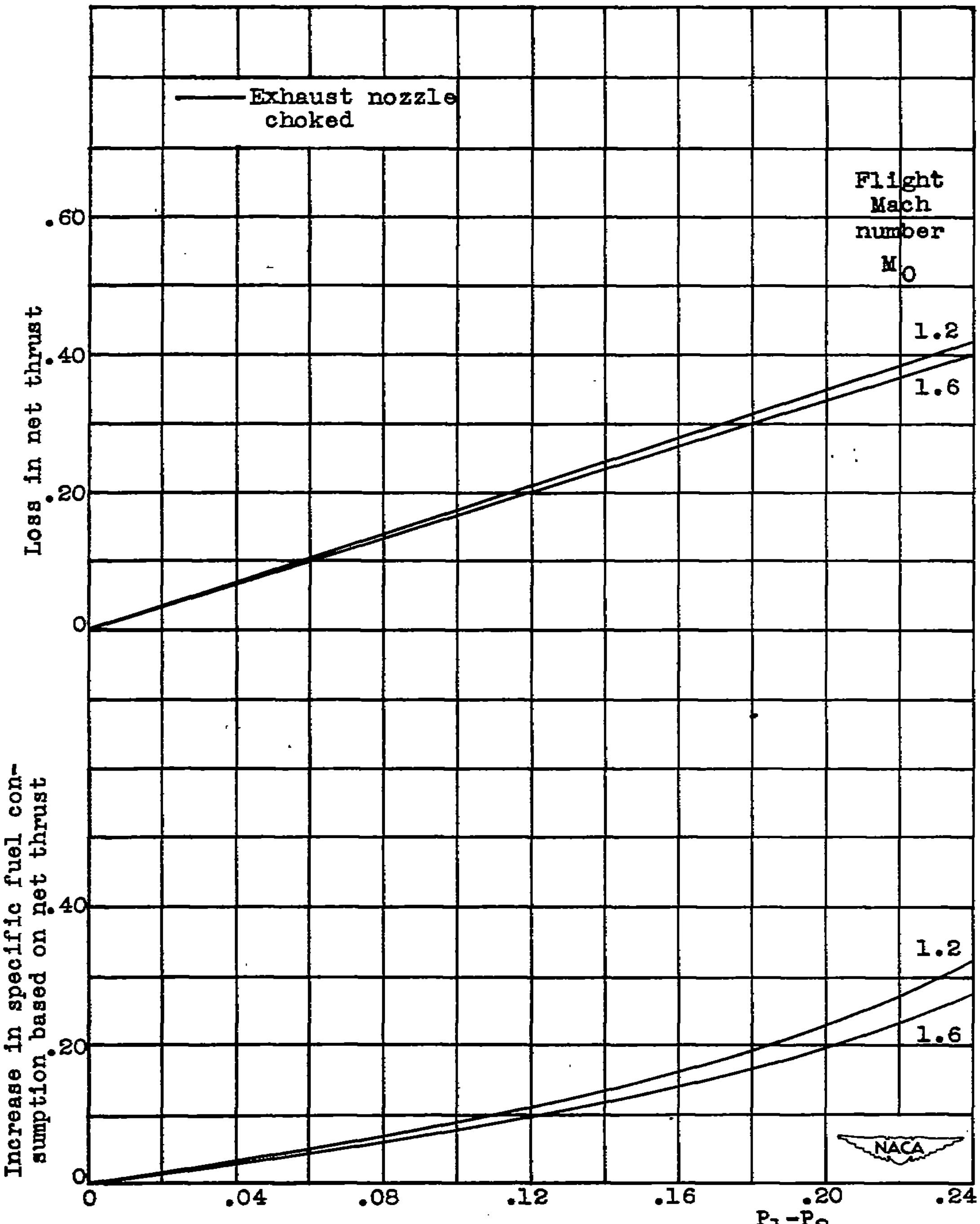

(d) Altitude, 35,000 feet.

Figure 11. - Concluded. Variation of loss in net thrust and increase in specific fuel consumption based on net thrust with inlet absolute total-pressure loss. Engine speed, 11,500 rpm; exhaust-nozzle-outlet area, 1.27 square feet.

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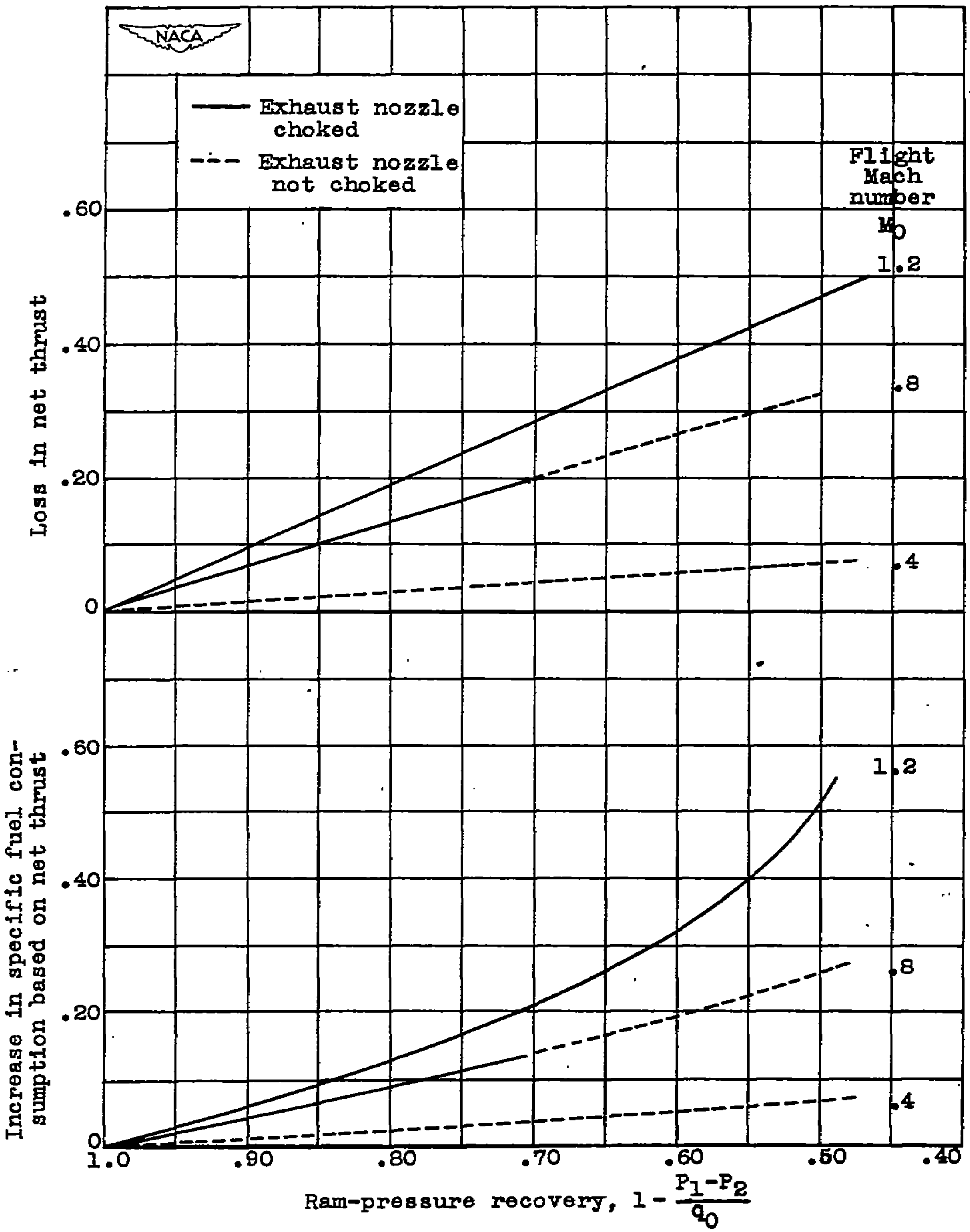

Figure 12. - Variation of loss in net thrust and increase in specific fuel consumption based on net thrust with ram-pressure recovery. Engine speed, 11,500 rpm; exhaust-nozzle outlet area, 1.27 square feet.