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GENERALIZATION OF TURBOJET-ENGINE PERFORMANCE IN TERMS OF PUMPING CHARACTERISTICS

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SUMMARY

The characteristics of a basic turbojet engine consisting of compressor, combustor, and turbine can be presented in terms of the pumping characteristics; that is, corrected air flow, ratio of engine-outlet to -inlet total pressure, ratio of engine-outlet to -inlet total temperature, Reynolds number index, corrected engine speed, and corrected fuel-air ratio. Such a presentation offers a general method for describing the engine independently of the characteristics of other elements of the propulsion system. This method of presentation also permits rapid estimation of the performance of complex propulsion systems involving the basic turbojet engine.

Pumping characteristics are illustrated by the experimentally determined characteristics of a typical basic turbojet engine. As an illustration of the utility of this method of presenting engine characteristics, the effects of inlet-pressure losses, inlet temperature and altitude, and heat addition in the tail pipe on the performance of the propulsive systems were estimated.

INTRODUCTION

A basic turbojet engine consisting of a compressor, a combustor, and a turbine may be considered as one element of a complete aircraft propulsive system. Other elements of the system may be air inlet, inlet duct, tail pipe with or without burner, and jet nozzle. The individual characteristics of each of these elements may differ widely from one installation to another; because each element of the system contributes to the over-all propulsive characteristics, a wide variety of propulsive characteristics is possible even though the basic turbojet engine may be the same in several cases.

The usual presentation of turbojet characteristics in terms of thrust and thrust specific fuel consumption does not therefore represent the engine alone, but rather the performance of a special system usually consisting of a basic turbojet engine, a particular air-inlet arrangement, and a particular tail pipe and nozzle. As a consequence, direct estimation of the performance of other propulsive systems employing the same basic engine may be difficult and uncertain. Presentation of turbojet-engine characteristics in terms of parameters that represent the basic functions of the engine and are independent of other elements of the propulsive system is therefore desirable.

The function of the basic engine is to pump a quantity of air to a total pressure and temperature higher than the free-stream total pressure and temperature; thrust results from the combined action of the entire propulsive system. Treatment of the turbojet engine as a pump and presentation of its characteristics in terms of air flow, pressure ratio, and temperature ratio are therefore possible. This presentation also permits rapid estimation of characteristics of complex propulsion systems employing a basic turbojet engine.

As an illustration of the general method developed, the characteristics of a typical basic turbojet engine, experimentally determined at the NACA Lewis laboratory, are presented in terms of air flow, pressure ratio, temperature ratio, and fuel-air ratio. The effect of Reynolds number on these characteristics is shown. Methods of matching the pumping characteristics of the basic turbojet engine to the air-flow characterstics of other elements of propulsive systems are discussed and a method of estimating thrust and fuel economy of complete propulsive systems is presented.

Applications of the pumping characteristics are illustrated by three special cases: (1) estimation of the effect of altitude on outlet temperature when engine speed and jet-nozzle area are held constant, (2) estimation of the effects of inlet losses on over-all performance, and (3) estimation of performance with burning in the tail pipe.

PUMPING CHARACTERISTICS

Determination of pumping characteristics. - The pumping characteristics of a basic turbojet engine can be explained by reference to the arrangement shown in figure 1, although other arrangements might serve equally well for the explanation. It is assumed that the inlet pressure and temperature are constant, that the back pressure on the engine is varied by adjusting the exhaust nozzle, and that the engine speed is maintained constant by varying the fuel flow. As the nozzle is closed, the pressure at the engine outlet must rise in order to force the gases through the reduced area. The increased outlet pressure on the turbine reduces the work extracted in the turbine and the turbine-inlet temperature must be increased (fig. 2(a)) to prevent the engine speed from decreasing. This increase is accomplished by increasing the fuel flow. The higher fuel flow produces an increased turbine-outlet temperature. The increased turbine-inlet temperature causes, in some cases, a decrease in air flow. The resulting relation of air flow to engine-outlet pressure may be similar to that shown in figure 2(b). The variation of fuel-air ratio with engine outlet pressure is shown in figure 2(c). If the procedure just described is repeated at several engine speeds throughout the operating range, a family of characteristic performance curves is determined. At each value of inlet pressure or temperature, a different family of engine characteristics will be obtained.

Generalization of engine characteristics. - The pumping characteristics of a basic turbojet engine involve four independent variables. Separation of dependent and independent variables depends on the method of operating the engine; for the purpose of this discussion, however, the chosen independent variables are engine-inlet pressure, engine-inlet temperature, engine speed, and engine-outlet pressure. The effective number of variables may be reduced, however, by grouping them into dimensionless ratios or parameters derived from these ratios. Experience has shown that the following groupings of the independent variables are useful:

Corrected engine speed, $N/\sqrt{\theta_1}$

Engine pressure ratio, P_3/P_1

Reynolds number

where

N engine speed

θ_1 inlet total temperature divided by NACA sea-level temperature

P total pressure

Subscripts:

3 engine outlet (fig. 1)

1 engine inlet (fig. 1)

(A list of the symbols used in this analysis is presented in the appendix.) When these parameters are used for independent variables, the dependent variables must likewise be incorporated into such parameters as:

Corrected air flow per unit frontal area, $\frac{W\sqrt{\theta_1}}{A_x\delta_1}$,

Corrected fuel-air ratio, $\frac{f/a}{\theta_1}$.

where

W mass flow of air

A_x frontal area of engine

δ_1 engine-inlet total pressure divided by NACA sea-level pressure

f/a fuel-air ratio

Engine characteristics expressed in terms of these parameters will be referred to as "generalized characteristics."

Each of these parameters, with the exception of Reynolds number, is commonly used in connection with turbojet-engine performance (references 1 and 2). Reynolds number, or some other parameter related to the viscous forces, is not in common use in this connection because experience has shown that, in most cases, engine performance is not measurably influenced by variations of Reynolds number. In such cases, the number of effective independent variables is reduced to corrected engine speed and engine pressure ratio.

Before the Reynolds number effect can be evaluated for those cases in which the effect is appreciable, a precise definition of the Reynolds number of the engine is needed. The Reynolds number of any body is

$$\frac{L\rho V}{\mu}$$

where

L a characteristic dimension

ρ fluid density

V some velocity of fluid

μ absolute viscosity

The mass velocity is ρV and, in the case of a turbojet engine, it is convenient to consider the mass flow per unit of frontal area W/A_x as the mass velocity. The Reynolds number is then

$$\frac{L(W/A_x)}{\mu}$$

Reynolds number is not a convenient parameter because mass flow is a function not only of the pressure and the temperature of the inlet air, but is also dependent on the other two independent variables, corrected engine speed and engine pressure ratio. A more convenient parameter for considering the effects of fluid viscosity is

$$\frac{LP}{\mu\sqrt{T}}\sqrt{\frac{\gamma}{R}}$$

where

T total temperature

γ ratio of specific heats

R gas constant

The units are chosen to give a dimensionless number. This parameter is related to the ratio of Reynolds number to Mach number and its value depends only on the condition of the air at the engine inlet.

An expression similar to the quantity $P/\mu\sqrt{T}$ is used in presentation of compressor and turbine characteristics in reference 3 and is called the Reynolds number index. In turbojet engines, it is convenient to use δ in place of P and θ in place of T. When the same reasoning that led to the development of δ and θ is followed, another quantity φ is defined as:

$$\varphi = \frac{\text{viscosity at engine-inlet total temperature}}{\text{viscosity at NACA standard sea-level temperature}}$$

When the quantities δ_1, θ_1, and φ_1 are used in place of P, T, and μ, respectively, the following form of the Reynolds number index is obtained:

$$\frac{\delta_1}{\varphi_1 \sqrt{\theta_1}}$$

The value of this Reynolds number index is 1.000 at NACA standard sea-level pressure and temperature. A graph relating the Reynolds number index to NACA standard altitudes and flight Mach number, when a perfect diffuser is assumed, is presented in figure 3.

The magnitude of the effect of variations in Reynolds number index on performance, although different for every engine, is illustrated by its effect on the performance of a typical engine, as shown by figure 4. For this particular engine, the relation of corrected air flow to corrected engine speed is independent of Reynolds number index above 0.716, but at lower values of the index, the corrected air flow at a given corrected speed decreases with decreasing Reynolds number index.

Generalized pumping characteristics of a basic turbojet engine can be plotted, as shown in figures 5 to 7, in which engine pressure ratio P_3/P_1 is used as a common ordinate for three abscissas: engine temperature ratio T_3/T_1 (fig. 5), corrected air flow $W\sqrt{\theta_1}/A_x\delta_1$ (fig. 6), and corrected fuel-air ratio $(f/a)/\theta_1$ (fig. 7). Corrected engine speed $N/\sqrt{\theta_1}$ and Reynolds number index are used as parameters.

Although the relation of fuel-air ratio to engine operating conditions is given in figure 7 in terms of generalized parameters, the kinetics of the chemical reaction is a function of the pressure and the temperature. Consequently, the combustion efficiency and the fuel-air ratio are functions not only of pressure ratio, Reynolds number index, and corrected speed, but also of inlet pressure and temperature. Values of inlet pressure and temperature are given in figure 7.

MATCHING PROPULSION-SYSTEM COMPONENTS

The engine pumps air through the propulsion system; consequently, the air flow, the pressures, and the temperatures must adjust themselves to satisfy simultaneously the air-flow characteristics of all elements of the system. The relative ease or difficulty of determining the engine conditions that match air-flow characteristics of the other elements of a given propulsive system depends not only on the complexity of the system but also on the method of control.

In some cases, determination of the match point presents no problem. As an example, a propulsion system that is provided with independent control of engine fuel flow and exhaust-nozzle area can be adjusted to operate at any engine speed and outlet temperature within limits and, consequently, the operating point for the engine can be selected at will.

If the exhaust-nozzle area is fixed and fuel flow is the only control, determination of the match point becomes more difficult. Such a system is similar to the one shown in figure 1 with the exception that the exhaust-nozzle area is held constant. One method for determining the match point consists in drawing the nozzle-characteristic curve on the graph of engine characteristics; the intersection of the nozzle- and engine-characteristic curves, as shown in figure 8(a), is the match point.

The nozzle characteristics can be expressed in terms of air flow, pressure, and temperature according to the following relation:

$$\left(1 + \frac{f}{a}\right) \frac{W\sqrt{T_4}}{A_4 P_4} = \sqrt{\frac{g}{R} \frac{2\gamma}{\gamma-1}} \left(\frac{P_4}{p_4}\right)^{-\left(\frac{\gamma+1}{2\gamma}\right)} \sqrt{\left(\frac{P_4}{p_4}\right)^{\frac{\gamma-1}{\gamma}} - 1} \tag{1}$$

where

g acceleration due to gravity

4 exhaust-nozzle outlet

When the ratio of engine-outlet total pressure to ambient atmospheric pressure P_3/p_0 is less than the sonic value, p_4 equals p_0; when P_3/p_0 exceeds the sonic value, P_4/p_4 is constant at the value corresponding to sonic flow.

Equation (1) can be modified for matching purposes as follows:

$$\left(1 + \frac{f}{a}\right) \frac{W\sqrt{\theta_1}}{A_x \delta_1} \left(\frac{A_x}{A_4}\right) \sqrt{\frac{T_3}{T_1} \frac{T_4}{T_3}} \left(\frac{P_1}{P_3}\right)\left(\frac{P_3}{P_4}\right) = K_1 \tag{2}$$

in which the air-flow function K_1 is obtained from the relation

$$K_1 = \frac{2116}{\sqrt{519}} \sqrt{\frac{g}{R} \frac{2\gamma}{\gamma-1}} \left(\frac{P_4}{p_4}\right)^{-\frac{\gamma+1}{2\gamma}} \sqrt{\left(\frac{P_4}{p_4}\right)^{\frac{\gamma-1}{\gamma}} - 1}$$

A working graph of this relation is presented in figure 9.

The first step in plotting the nozzle characteristic is the selection of the ratio of exhaust-nozzle area to engine frontal area, corrected engine speed, and Reynolds number index corresponding to the inlet conditions and tail-pipe pressure and temperature ratios. In the second step, a value of engine pressure ratio P_3/P_1 is chosen and the corresponding values of corrected air flow and corrected fuel-air ratio are read from the engine characteristics. The third step consists in calculating the nozzle pressure ratio P_4/p_0 from the ram pressure ratio P_0/p_0, the inlet pressure ratio P_1/P_0, the engine pressure ratio P_3/P_1, and the tail-pipe pressure ratio P_4/P_3. The value of K_1 is then read from figure 9. In the fourth step, equation (2) is used to calculate the engine temperature ratio T_3/T_1. A point is then plotted in figure 8(a) corresponding to this temperature ratio and the selected engine pressure ratio. The process is repeated at several values of engine pressure ratio and the nozzle characteristic is drawn through the points so determined. The match point is indicated in figure 8(a).

An alternate method of matching the engine and the nozzle is accomplished by plotting the nozzle characteristics on the pressure – air-flow plane.

In addition to the over-all pressure and temperature ratios, knowledge of the pressure or the temperature at some intermediate point in the engine cycle is often desired. For example, if operation at maximum-allowable turbine-inlet temperature is desired, finding the turbine-inlet temperature corresponding to each over-all pressure ratio and corrected engine speed would be necessary. These data can be provided as shown in figure 10 by plotting over-all pressure ratio at several corrected engine speeds as a function of the ratio of turbine-inlet temperature to engine-inlet temperature. The data shown correspond to the engine characteristics given in figures 5 to 7.

THRUST AND FUEL ECONOMY

After the matching procedure, the air flow, the pressure, and the temperature at the exhaust nozzle are known. The jet thrust F_j can be found from the following equations, which relate F_j/W to P_4/p_0

$$\frac{F_j}{W/g} = K_2 \sqrt{T_4} \left(1 + \frac{f}{a}\right)$$

For a complete expansion nozzle,

$$K_2 = \sqrt{2gJC_p} \sqrt{1 - \left(\frac{p_0}{P_4}\right)^{\frac{\gamma-1}{\gamma}}}$$

and for the convergent nozzle at supercritical pressures

$$K_2 = \sqrt{2gJC_p} \left\{ \sqrt{\frac{\gamma-1}{\gamma+1}} + \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \frac{\sqrt{\frac{\gamma-1}{2}}}{\gamma} \left[\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} - \frac{p_0}{P_4} \right] \right\}$$

where

J mechanical equivalent of heat

C_p specific heat at constant pressure

Any consistent system of units may be used. A graph relating K_2 to the nozzle pressure ratio is given in figure 11. Net thrust is found by deducting the momentum of the inlet air from the jet thrust.

Fuel flow can be computed by multiplying air flow by fuel-air ratio, as determined by the engine characteristics at the match point. The fuel economy expressed as thrust specific fuel consumption is simply the ratio of fuel flow to thrust.

LIMITATIONS AND EXTENSIONS OF METHOD

Effects of combustion characteristics. - Another variable that may affect the engine characteristics is the mode of combustion. If, under certain conditions, appreciable burning occurs in the turbine, the outlet temperatures corresponding to a given pressure ratio will be higher than expected. When such combustion effects are important, the generalizing parameters used herein are no longer applicable.

Effects of heat transfer. - The generalization method described applies not only to the basic turbojet engine consisting of compressor, combustor, and turbine, but it also applies to turbojet engines utilizing regenerators that transfer heat from one portion of the cycle to another. The two independent parameters governing heat transfer are Reynolds number and Prandtl number. A Reynolds number parameter is already included in the analysis. Prandtl number is practically constant for all operating conditions and consequently its effect on the generalization can be neglected.

When an appreciable amount of heat is conducted through the structure, the generalization fails because the heat flow then depends not only on the state of the gases but also on the conductivity of the structure.

ILLUSTRATIVE EXAMPLES

The examples discussed herein are given primarily to illustrate the relative ease with which typical problems can be treated. Although these specific problems have been studied by other investigators, the methods of this report afford a somewhat different insight into the nature of such problems.

Effect of inlet temperature and altitude at constant engine speed and exhaust-nozzle area. - If the temperature at the inlet of a turbojet engine is lowered and the engine speed is held constant by changing the fuel flow, the corrected speed and the corrected air flow will increase. The increase in corrected air flow requires increased engine-outlet pressure to force the air through the nozzle. An increase in temperature ratio across the engine accompanies the increase in pressure ratio. Inasmuch as the inlet temperature is decreased, however, it is not immediately evident whether the engine-outlet temperature will increase or decrease. Assume that the engine characteristics are those shown in figures 5 to 7, the exhaust nozzle is always choked, the exhaust-nozzle area is 0.292 A_x, and the Reynolds number index is 0.716. The outlet temperature will be calculated for inlet temperatures of 519° and 445° R. Engine speed is held constant at 100 percent of rated speed. The corresponding corrected speeds are 100 and 108 percent of rated speed. The nozzle-characteristic curves at these conditions are plotted in figure 12 with the engine characteristics.

The engine temperature ratios are 2.50 and 2.74 at inlet temperatures of 519° and 445° R, respectively. The resulting turbine-outlet temperatures are 1298° and 1220° R, respectively. The computation has been repeated at other inlet temperatures and the results are plotted in figure 13. The engine-outlet temperature decreases when the inlet temperature is lowered.

The result shown in figure 13 constitutes part of the effect of altitude on the outlet temperature. The second effect of altitude is the variation of engine characteristics accompanying changes of the Reynolds number index with altitude. The effects of variation of the Reynolds number index may be quite large, as shown in figure 14. Two curves are presented: One shows the change of engine-outlet temperature accompanying the change of engine-inlet temperature with altitude and the other shows the combined effect of inlet temperature and Reynolds number index. At altitudes above approximately 25,000 feet, the combined effects of changes in the Reynolds number index and the engine-inlet temperature were opposite to the effects of changes in inlet temperature alone and resulted in an increasing engine-outlet temperature with altitude. This result has been confirmed by wind-tunnel experiment in which altitude conditions were simulated by regulating pressure and temperature and a fixed-area exhaust nozzle was used.

Effect of inlet losses. - Pressure losses in the intake system of a turbojet engine may influence the thrust in at least two ways: (1) The air flow through the engine is reduced in proportion to the total-pressure loss and this reduction of air flow results in a reduction of thrust, and (2) the total pressure at the exhaust nozzle is reduced and, consequently, the thrust per unit of air flow is reduced. A third effect of pressure loss in the intake system is found in cases where a fixed-area exhaust nozzle is used and choking does not occur in the exhaust system. Under these conditions, a reduction of inlet total pressure causes an increase in engine-outlet temperature accompanied by an increase in thrust, which partly offsets the loss caused by reduction in both the air flow and the engine-outlet total pressure.

The effect of inlet losses will be estimated for the case in which the engine characteristics are those given in figures 5 to 7 and 10; the engine is operated at rated engine speed and the exhaust-nozzle area is adjusted to give a maximum-allowable turbine-inlet temperature of 1860° R, the altitude is 15,000 feet, and the flight Mach number is 0.6.

Calculations proceed as follows for stations shown in figure 1:

	With no inlet-pressure loss	With 10-percent inlet-pressure loss
Ambient static temperature, $^{\circ}R$	465	465
Ram temperature (total), T_1, $^{\circ}R$	498	498
Corrected engine speed, $N/\sqrt{\theta_1}$, percent of rated speed	102.1	102.1
T_2/T_1	3.74	3.74
Engine pressure ratio, P_3/P_1	1.89	1.89
Engine temperature ratio, T_3/T_1	3.31	3.31
Nozzle pressure ratio, P_4/p_0	2.41	2.17
Corrected air flow per unit frontal area, $W\sqrt{\theta_1}/A_x\delta_1$, lb/(sec)(sq ft)	13.6	13.6
Corrected fuel-air ratio, $(f/a)/\theta_1$	0.0156	0.0156
Fuel-air ratio, f/a	0.0150	0.0150
Air flow per unit frontal area, W/A_x, lb/(sec)(sq ft)	10.0	9.0
Thrust function, K_2	51.9	48.8
Specific jet thrust, $F_j/(W/g)$, (lb)(sec)/slug	2138	2010
Inlet-air velocity, V_0, ft/sec	631	631
Specific net thrust, $F_n/(W/g)$, (lb)(sec)/slug	1507	1379
Net thrust per unit frontal area, F_n/A_x, lb/sq ft	468	386
Specific fuel consumption, W_f/F_n, lb/(hr)(lb thrust)	1.155	1.260

The preceding calculations show that a 10-percent inlet loss reduces the air flow to 90 percent of the value without loss; the specific net thrust is reduced to approximately 92 percent of the value without inlet losses, and the over-all thrust loss is approximately 18 percent.

The specific fuel consumption is inversely proportional to the specific net thrust.

The effects of varying inlet total-pressure losses on thrust and fuel economy are shown in figures 15(a) and (b), respectively, for flight Mach numbers of 0, 0.6, and 1.0. The thrust and the fuel economy vary approximately linearly with inlet-pressure loss. A 10-percent loss in inlet pressure produces approximately 17.5-percent loss in thrust and approximately 8.5-percent increase in thrust specific fuel consumption.

Other analyses of the effects of inlet losses on the performance of propulsive systems employing turbojet engines are given in reference 4.

Performance of tail-pipe burner. - The thrust of a simple turbojet propulsion system can be increased by burning fuel in the tail pipe. The combustion of the fuel in the tail pipe raises the total temperature of the jet and the jet thrust is approximately proportional to the square root of the temperature.

In the sample problem, it is assumed that the basic turbojet engine, the characteristics of which are shown in figures 5 to 7 and 10, is operating at maximum allowable engine speed and turbine-inlet temperature 1860° R. Two cases are considered: (1) operation without tail-pipe burning, and (2) operation with tail-pipe burning. The limitation on turbine-inlet temperature requires that the exhaust-nozzle area be greater for operation with tail-pipe burning than for operation without tail-pipe burning. For the engine with tail-pipe burning, the over-all fuel-air ratio is 0.06 and the tail-pipe combustion efficiency is 85 percent. Other assumed conditions are: altitude, sea level; flight Mach number, 0; inlet-pressure loss, 1.0 percent of free-stream static pressure; Mach number ahead of tail-pipe flame holder, 0.20; tail-pipe flame-holder pressure loss, 6 percent of the local absolute total pressure upstream of the flame holder; cross-sectional area of the combustion chamber, uniform along its length.

The following calculations show values for the engine without tail-pipe burning and for the engine with tail-pipe burning.

	Without tail-pipe burning	With tail-pipe burning
Ambient pressure, p_0, lb/sq ft	2116	2116
Inlet total temperature, T_1, $^{\circ}R$	519	519
Corrected engine speed, $N/\sqrt{\theta_1}$, percent of rated speed	100	100
T_2/T_1	3.58	3.58
Reynolds number index, $\delta_1/\varphi_1\sqrt{\theta_1}$	0.99	0.99
Engine pressure ratio, P_3/P_1 (fig. 10)	1.81	1.81
Engine temperature ratio, T_3/T_1 (fig. 5)	3.11	3.11
Corrected fuel-air ratio, $(f/a)/\theta_1$	0.0144	0.0144
Turbine-outlet temperature, T_3, $^{\circ}R$	1615	1615
Temperature rise in tail pipe, $^{\circ}R$	0	2160
Jet total temperature, T_4, $^{\circ}R$	1615	3775
Pressure ratio across tail-pipe flame holder	1.0	0.94
Pressure ratio across combustion chamber	1.0	0.97
Jet-nozzle pressure ratio, P_4/p_0	1.793	1.634
Thrust function, K_2 (fig. 11)	43.1	40.3
Specific net thrust, $F_n/(W/g)$, (lb)(sec)/slug	1755	2622
Corrected air flow per unit frontal area, $W\sqrt{\theta_1}/A_x\delta_1$ (fig. 6), lb/(sec)(sq ft)	13.5	13.5
Air flow per unit frontal area, W/A_x, lb/(sec)(sq ft)	13.37	13.37
Net thrust per unit frontal area, F_n/A_x, lb/sq ft	729	1090
Specific fuel consumption, W_f/F_n, lb/(hr)(lb thrust)	0.951	2.65

The preceding calculations show that, for the cases considered, tail-pipe burning increased the net thrust by approximately 50 percent and the specific fuel consumption by approximately 180 percent.

CONCLUDING REMARKS

The usual presentation of turbojet characteristics in terms of thrust and thrust specific fuel consumption of a particular propulsion system does not lend itself readily to the estimation of the performance of other systems incorporating the same engine. The pumping characteristics of a basic turbojet engine, however, describe the performance in a manner independent of the characteristics of other elements of the propulsion system. These characteristics, when used in the manner described, permit a simple and straightforward estimation of the performance of complex propulsive systems employing this basic engine.

The pumping characteristics are presented in the form of graphs that give the relations among corrected air flow, engine pressure ratio, engine temperature ratio, Reynolds number index, corrected engine speed, and corrected fuel-air ratio. The air flows, the pressure ratios, and the temperature ratios in any propulsion system utilizing a basic turbojet engine are found by matching the engine characteristics to the internal-flow characteristics of the remainder of the system. Thrust is easily found from the air flow, the pressure, and the temperature of the jet. Fuel economy is calculated from the thrust, the air flow, and the fuel-air ratio.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, April 12, 1949.

APPENDIX - SYMBOLS

The following symbols are used in the analysis and the figures:

A	exhaust-nozzle area, sq ft
A_x	frontal area, sq ft
c_p	specific heat at constant pressure, Btu/(lb)(^{o}R)
F_j	jet thrust, lb
F_n	net thrust, lb
f/a	fuel-air ratio
g	acceleration due to gravity, ft/sec^2
J	mechanical equivalent of heat, ft-lb/Btu
K_1	air-flow function
K_2	thrust function
L	characteristic dimension, ft
N	engine speed, rpm
$N/\sqrt{\theta}$	engine speed corrected to NACA standard atmospheric conditions at sea level, rpm
P	total pressure, lb/sq ft absolute
p	static pressure, lb/sq ft
R	gas constant, ft-lb/^{o}R
T	total temperature, ^{o}R
V	velocity, ft/sec
W	air flow, lb/sec
W_f	fuel flow, lb/hr
$W\sqrt{\theta}/\delta$	air flow corrected to NACA standard atmospheric conditions at sea level, lb/sec

γ ratio of specific heats at constant pressure

δ ratio of absolute total pressure to absolute static pressure of NACA standard atmosphere at sea level

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

μ absolute viscosity, lb-sec/sq ft

ρ mass density of air, slugs/cu ft

φ ratio of viscosity at engine-inlet total temperature to viscosity at static temperature at NACA standard atmosphere at sea level

Subscripts:

0 ambient conditions

1 engine inlet

2 turbine inlet

3 engine outlet

4 exhaust-nozzle outlet

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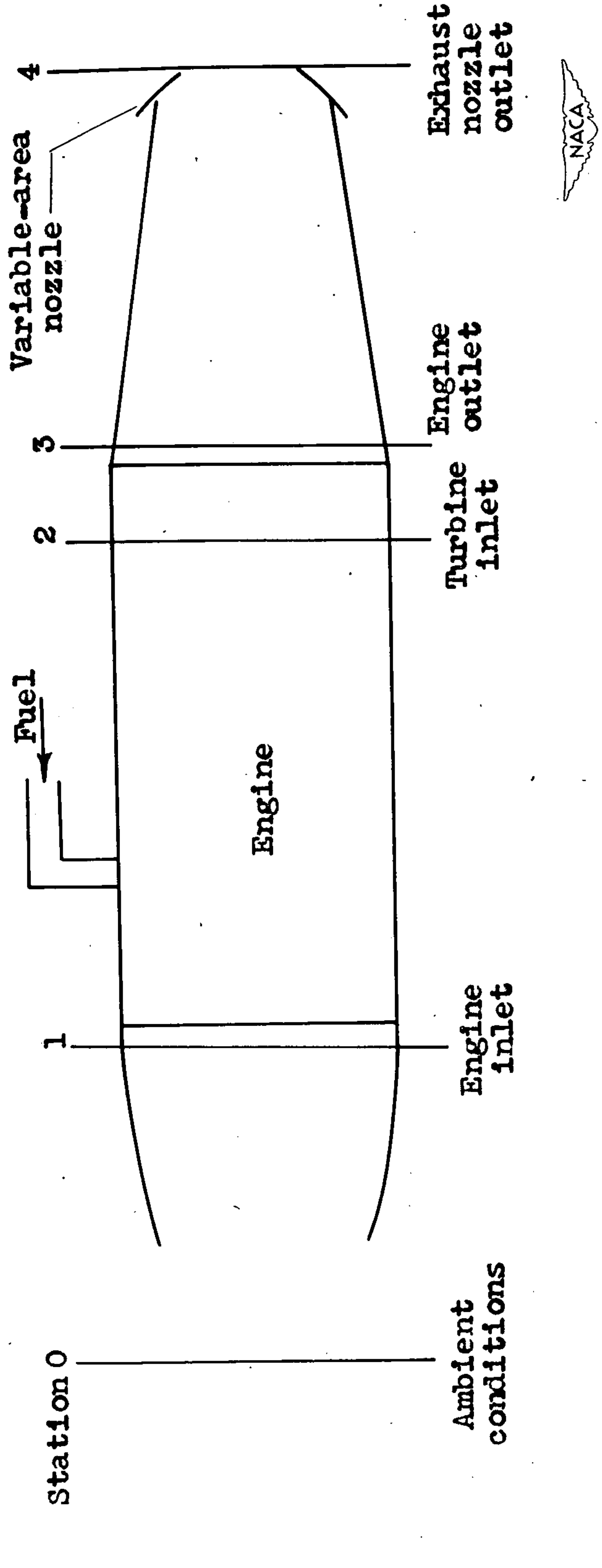
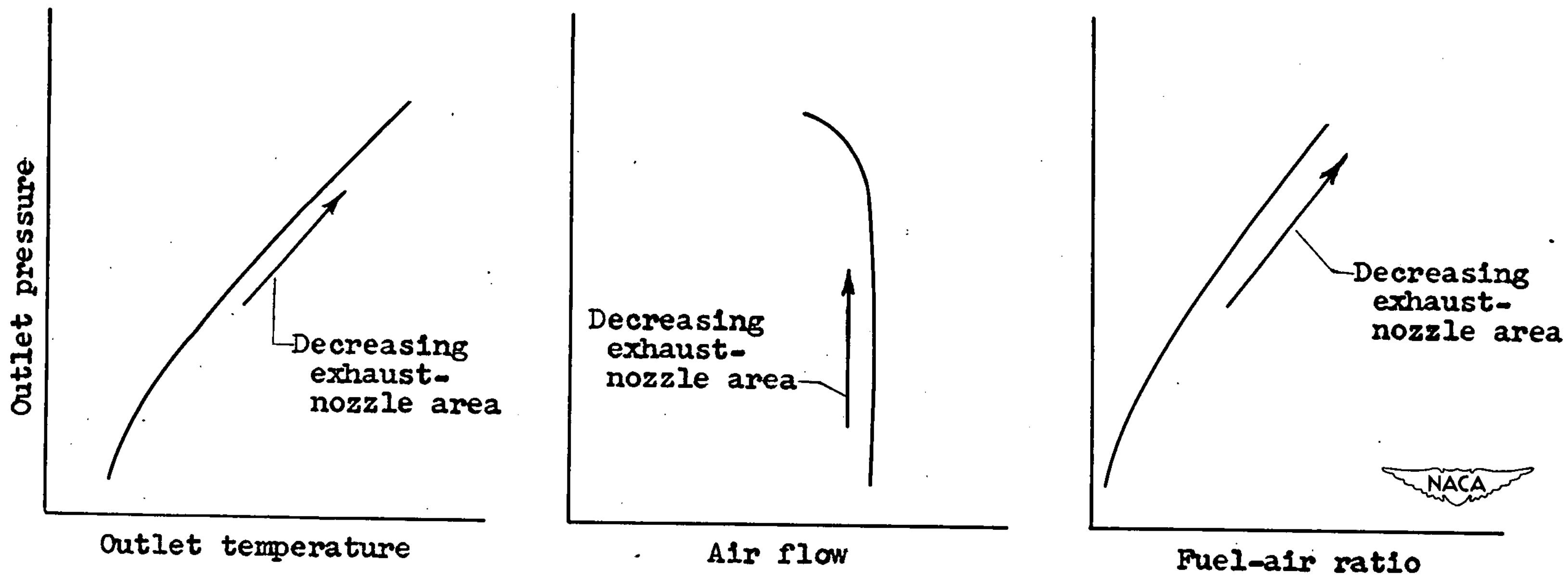


Figure 1. - Turbojet engine with variable-area nozzle.



(a) Pressure-temperature characteristic.

(b) Pressure - air-flow characteristic.

(c) Pressure - fuel-air-ratio characteristic.

Figure 2. - Typical turbojet-engine characteristics at constant engine speed.

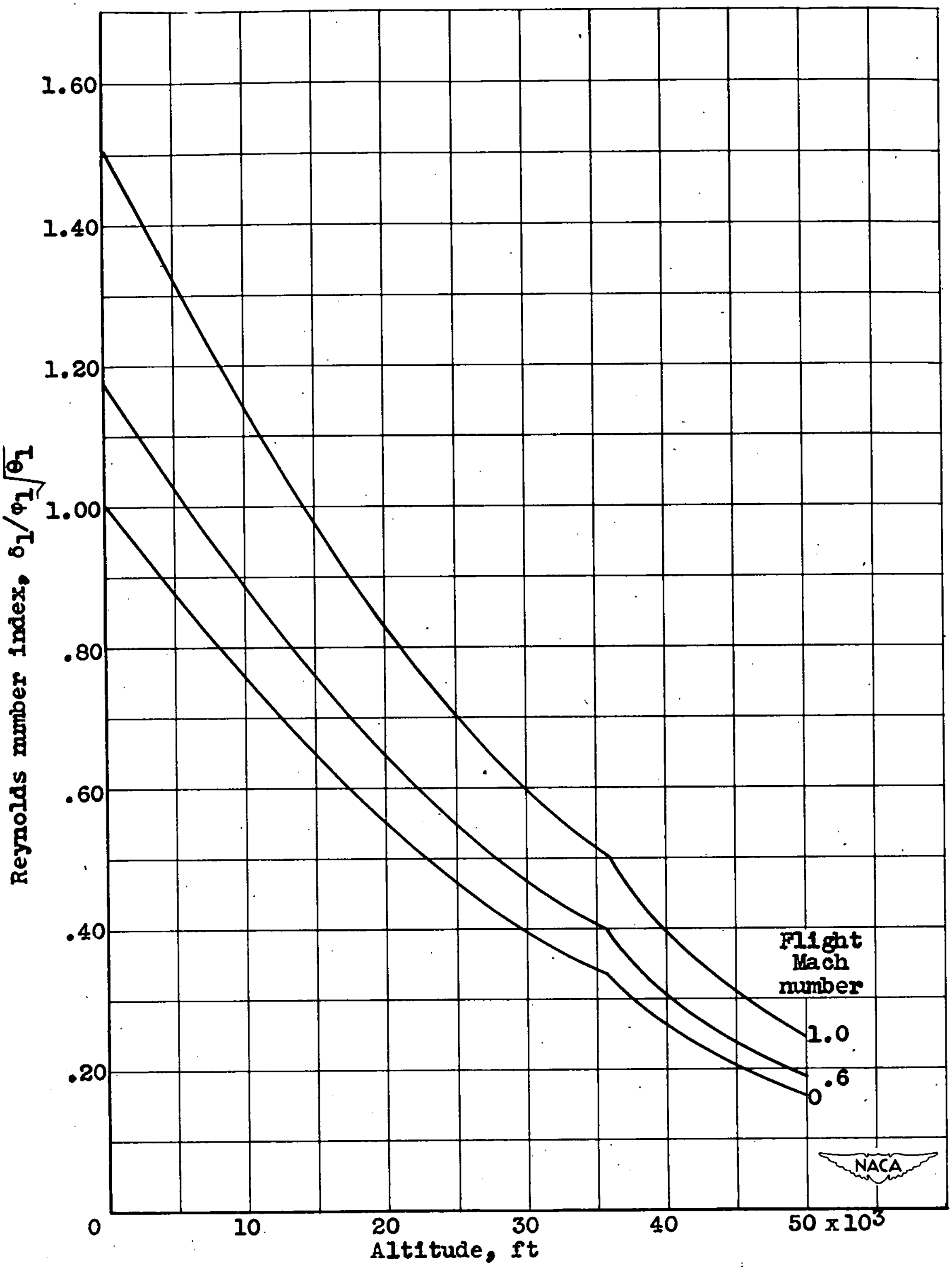


Figure 3. - Reynolds number index as function of altitude and flight Mach number.

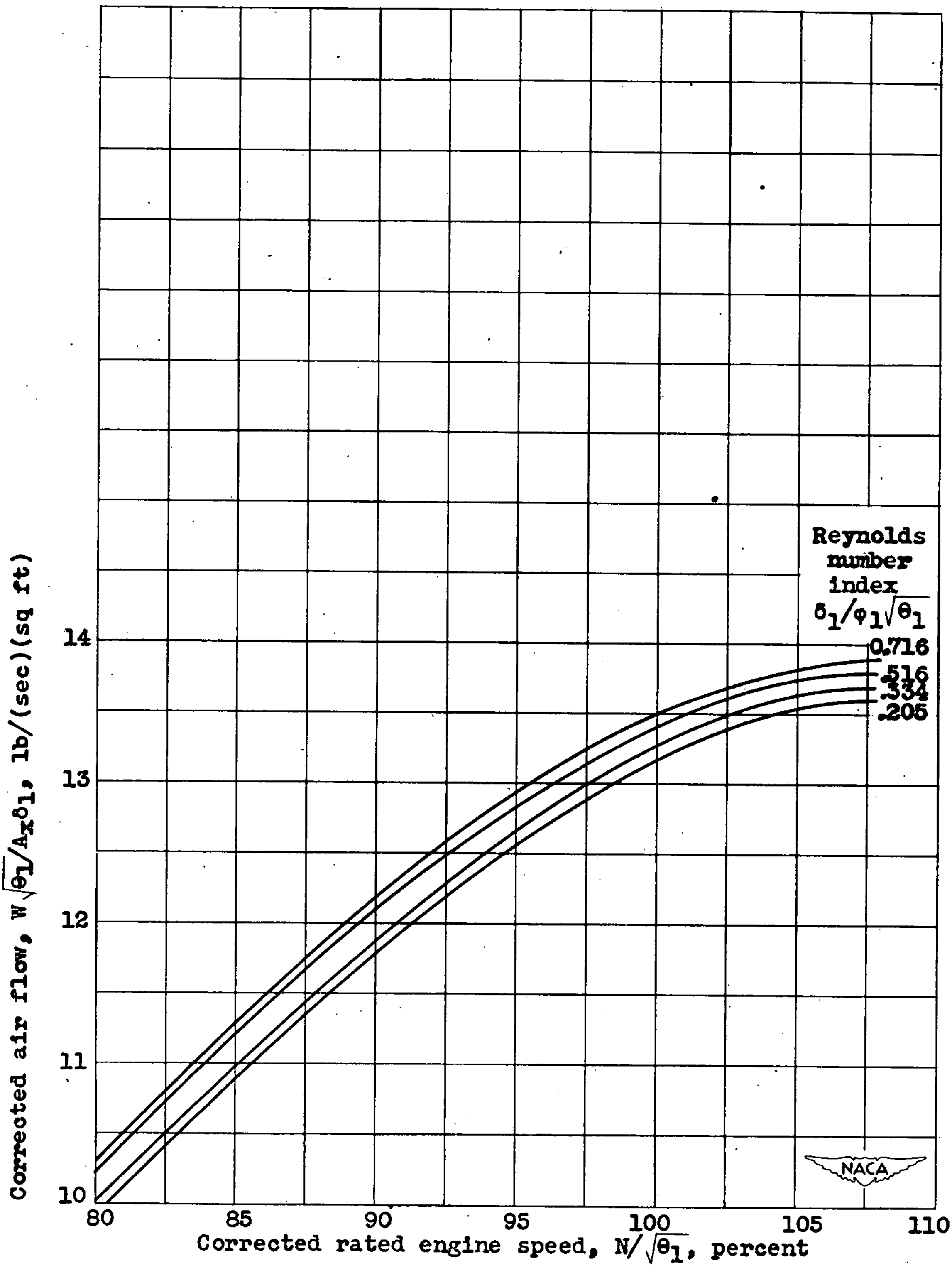
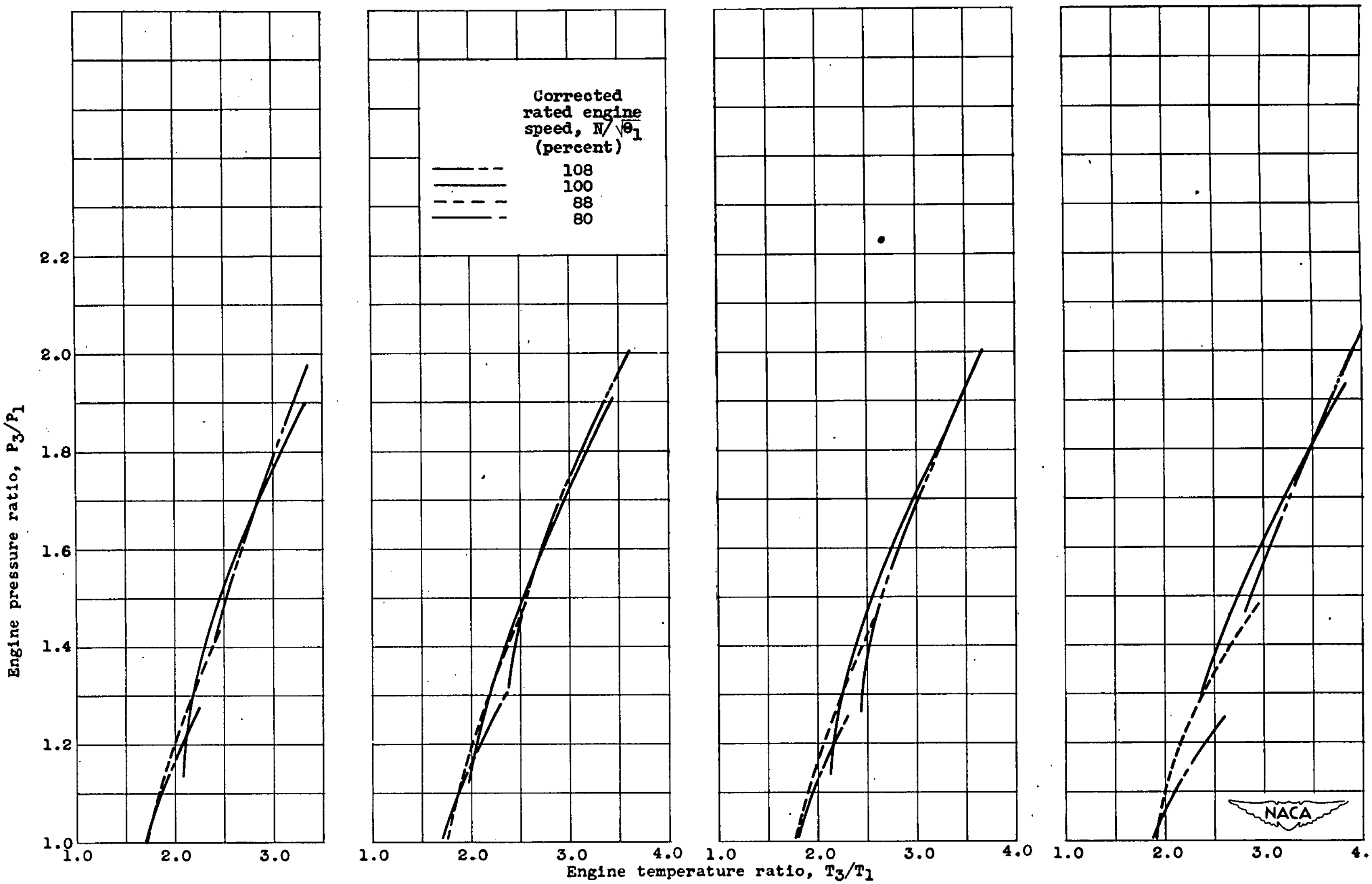


Figure 4. - Corrected air flow as function of corrected engine speed for several values of Reynolds number index.



(a) Reynolds number index, 0.716.

(b) Reynolds number index, 0.516.

(c) Reynolds number index, 0.334.

(d) Reynolds number index, 0.205.

Figure 5. - Experimental pressure-temperature characteristics of typical turbojet engine.

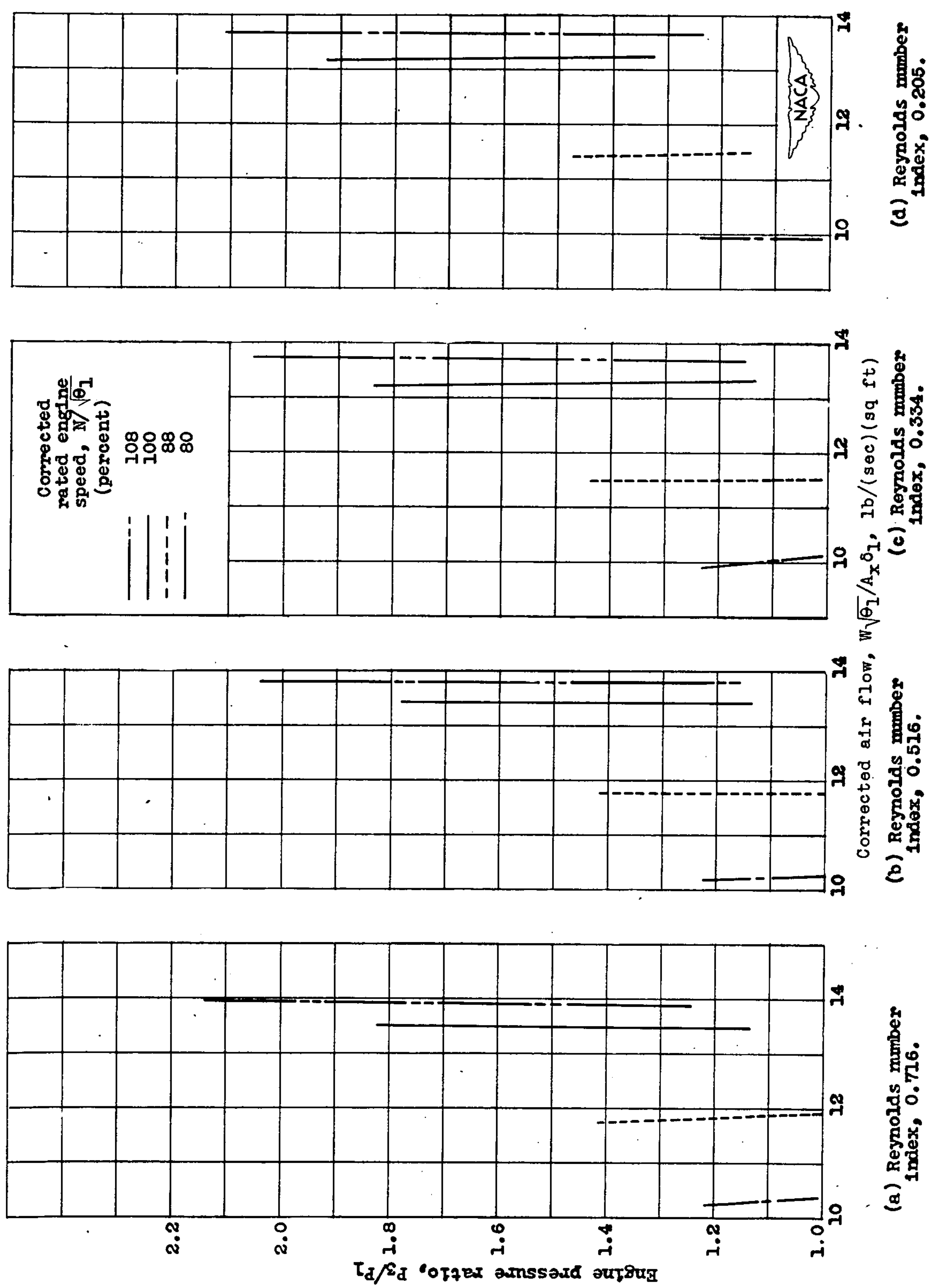
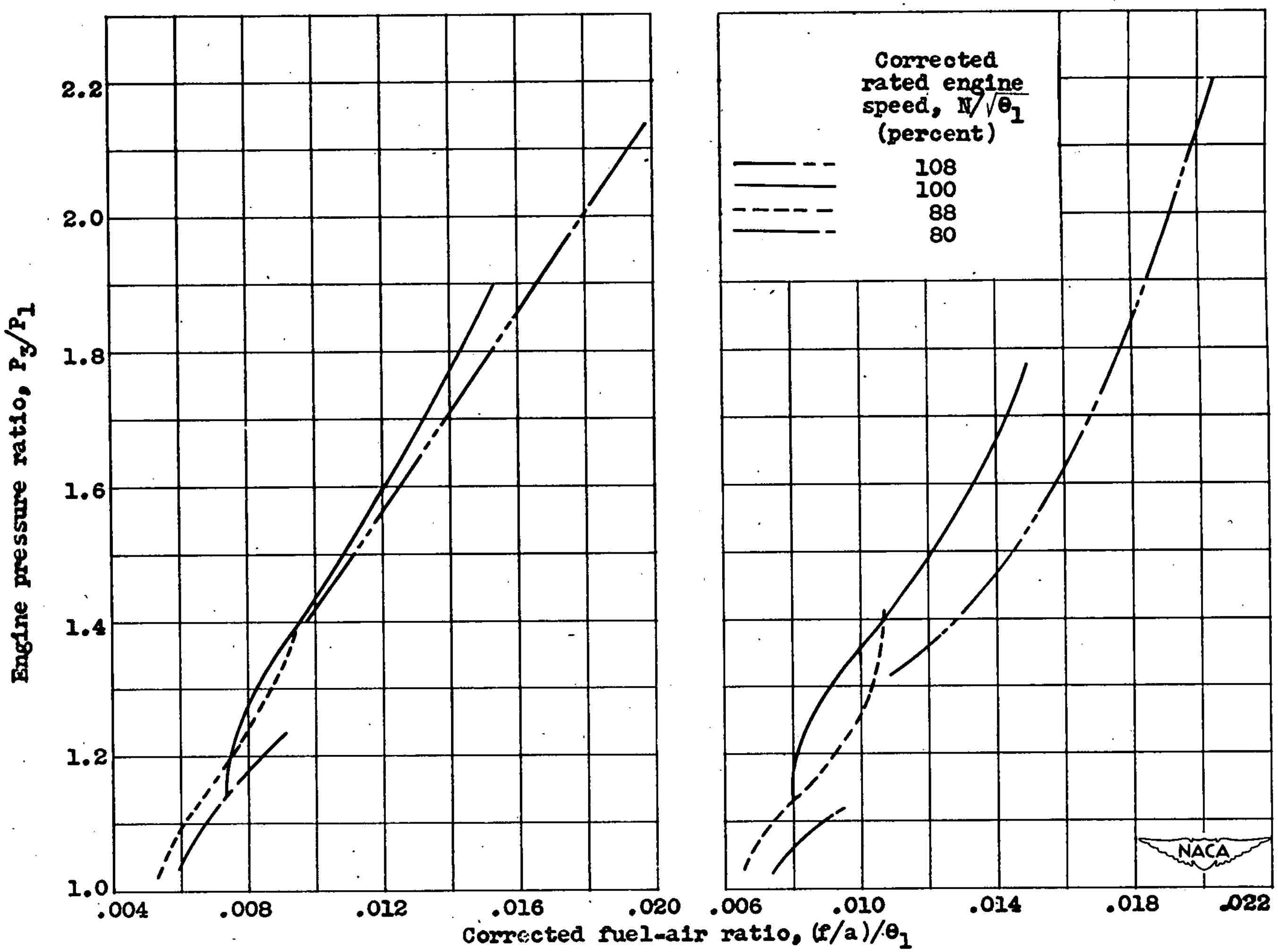


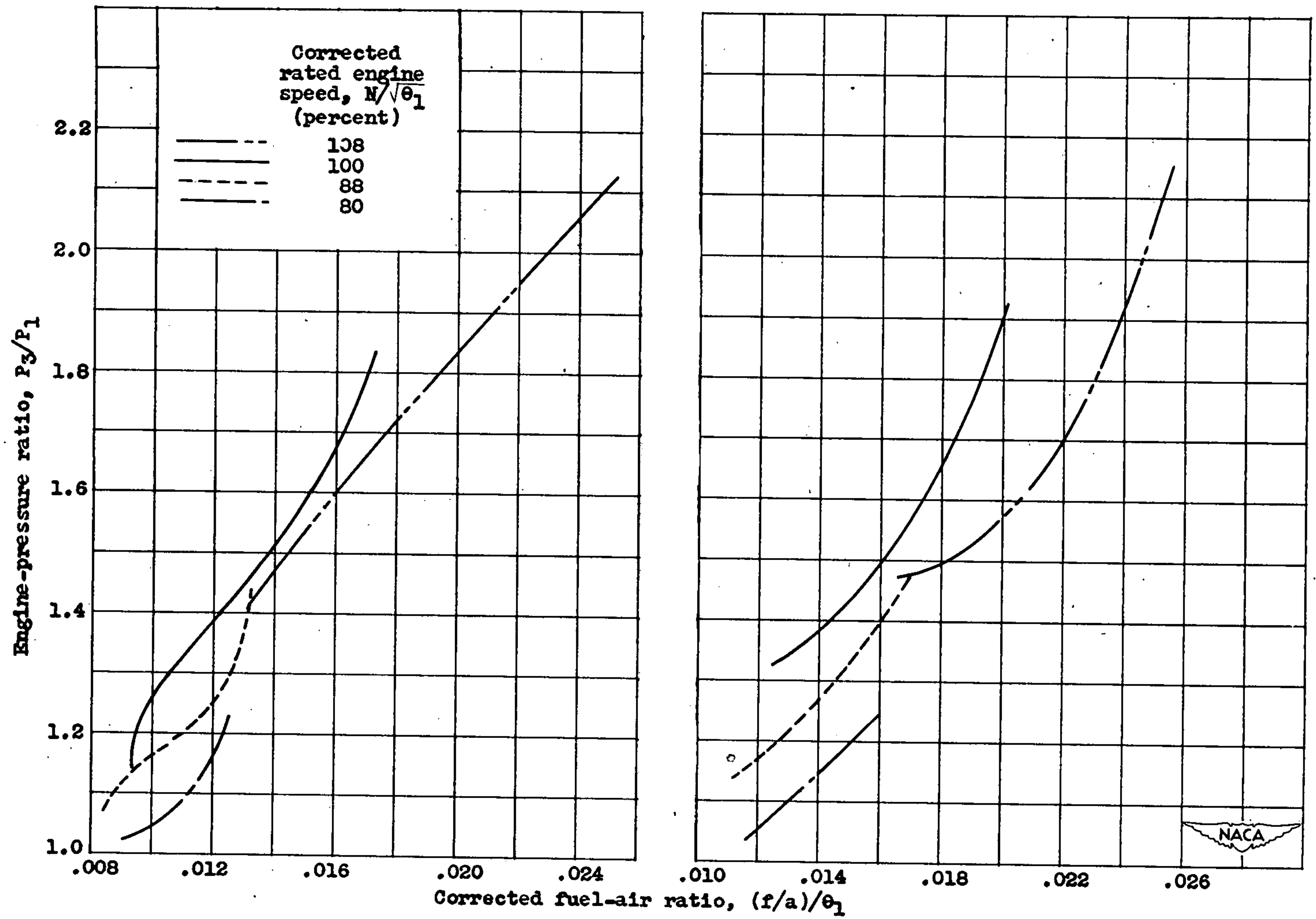
Figure 6. - Experimental pressure - air-flow characteristics of typical turbojet engine.



(a) Engine-inlet total pressure, 1438 pounds per square foot; engine-inlet total temperature, 497° R; Reynolds number index, 0.716.

(b) Engine-inlet total pressure 943 pounds per square foot; engine-inlet total temperature, 461° R; Reynolds number index, 0.516.

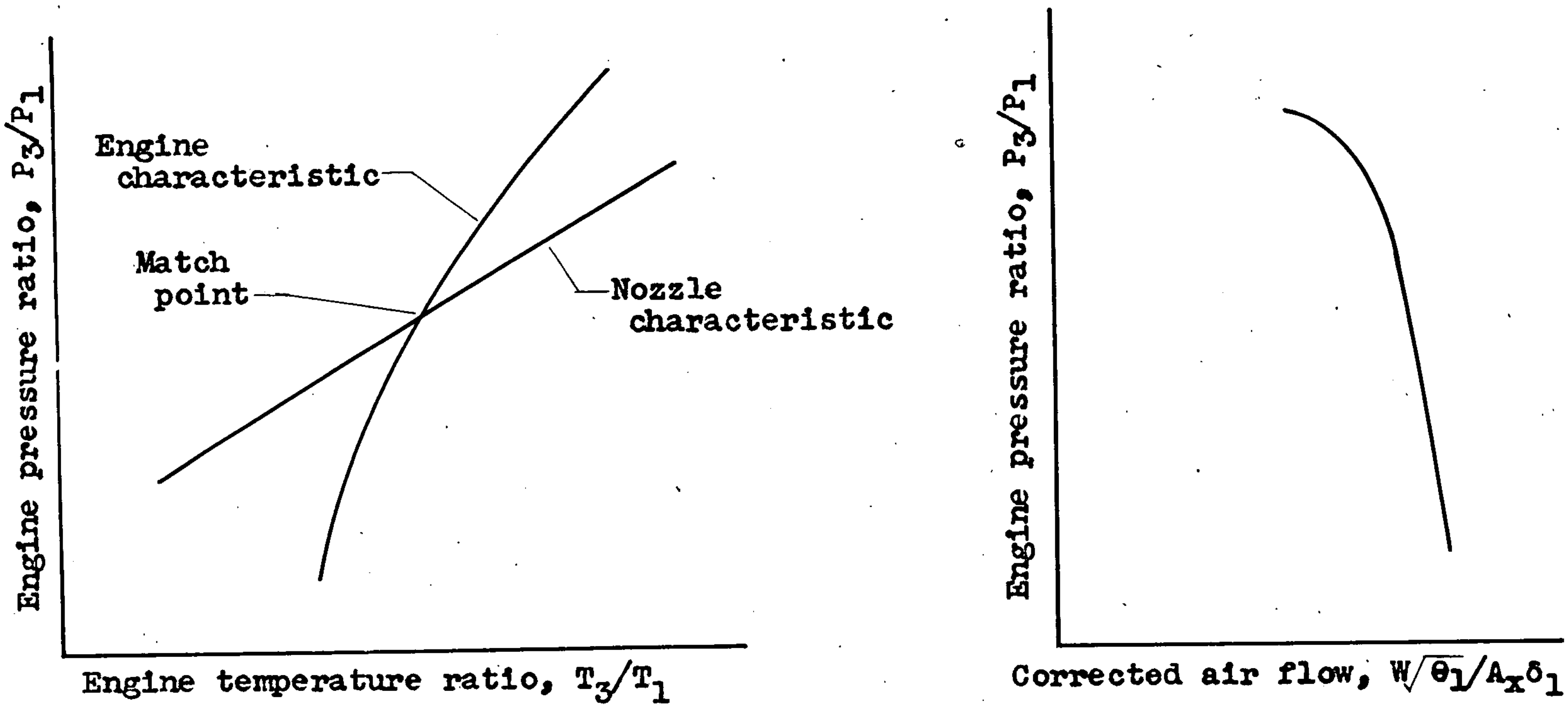
Figure 7. - Experimental pressure - fuel-air-ratio characteristics of typical turbojet engine.



(c) Engine-inlet total pressure, 597 pounds per square foot; engine-inlet total temperature, 448° R; Reynolds-number index, 0.334.

(d) Engine-inlet total pressure, 370 pounds per square foot; engine-inlet total temperature, 448° R; Reynolds number index, 0.205.

Figure 7. - Concluded. Experimental pressure - fuel-air-ratio characteristics of typical turbojet engine.



(a) Pressure-temperature plane.

(b) Pressure - air-flow plane.

Figure 8. - Matching of turbojet engine and nozzle characteristics.

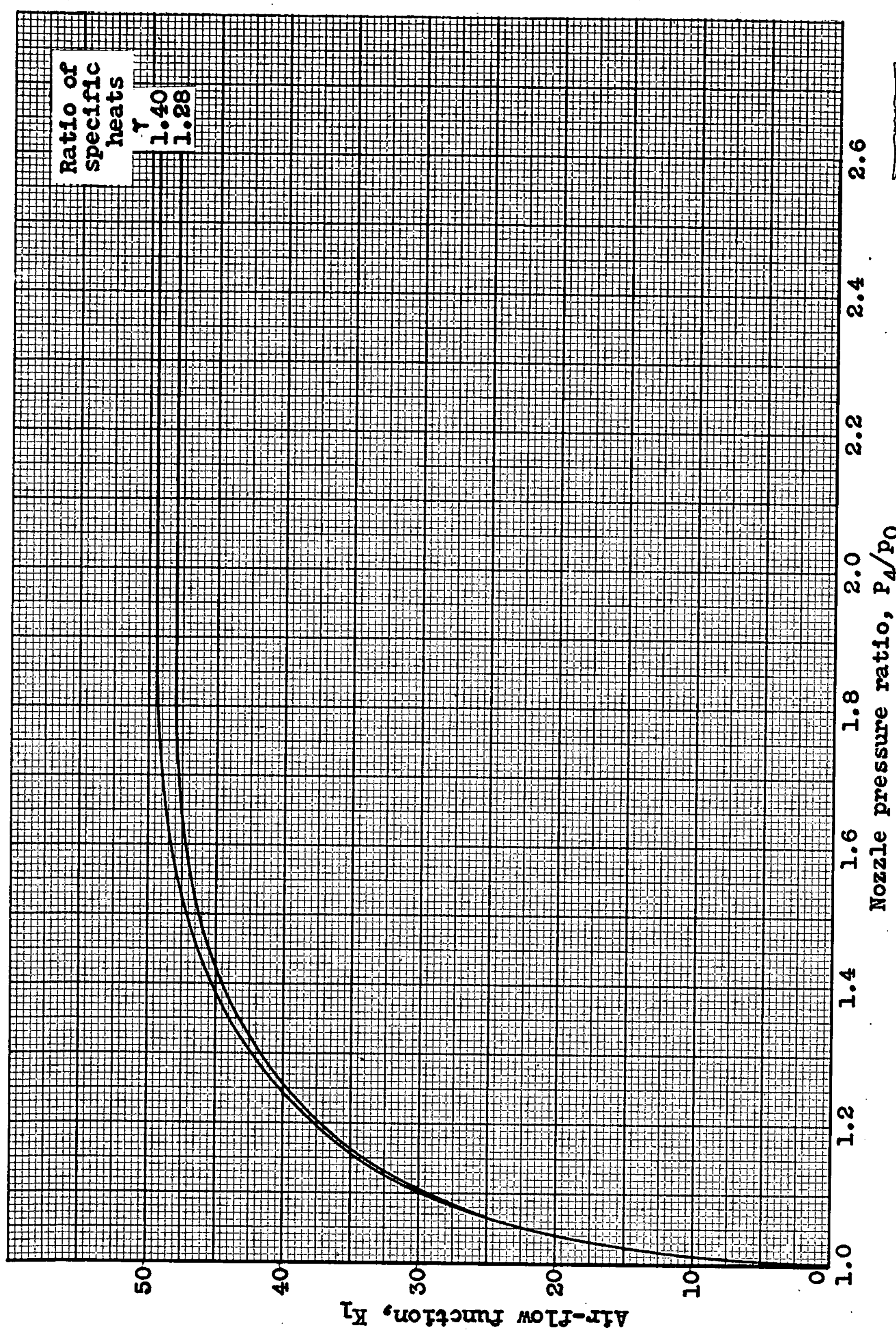
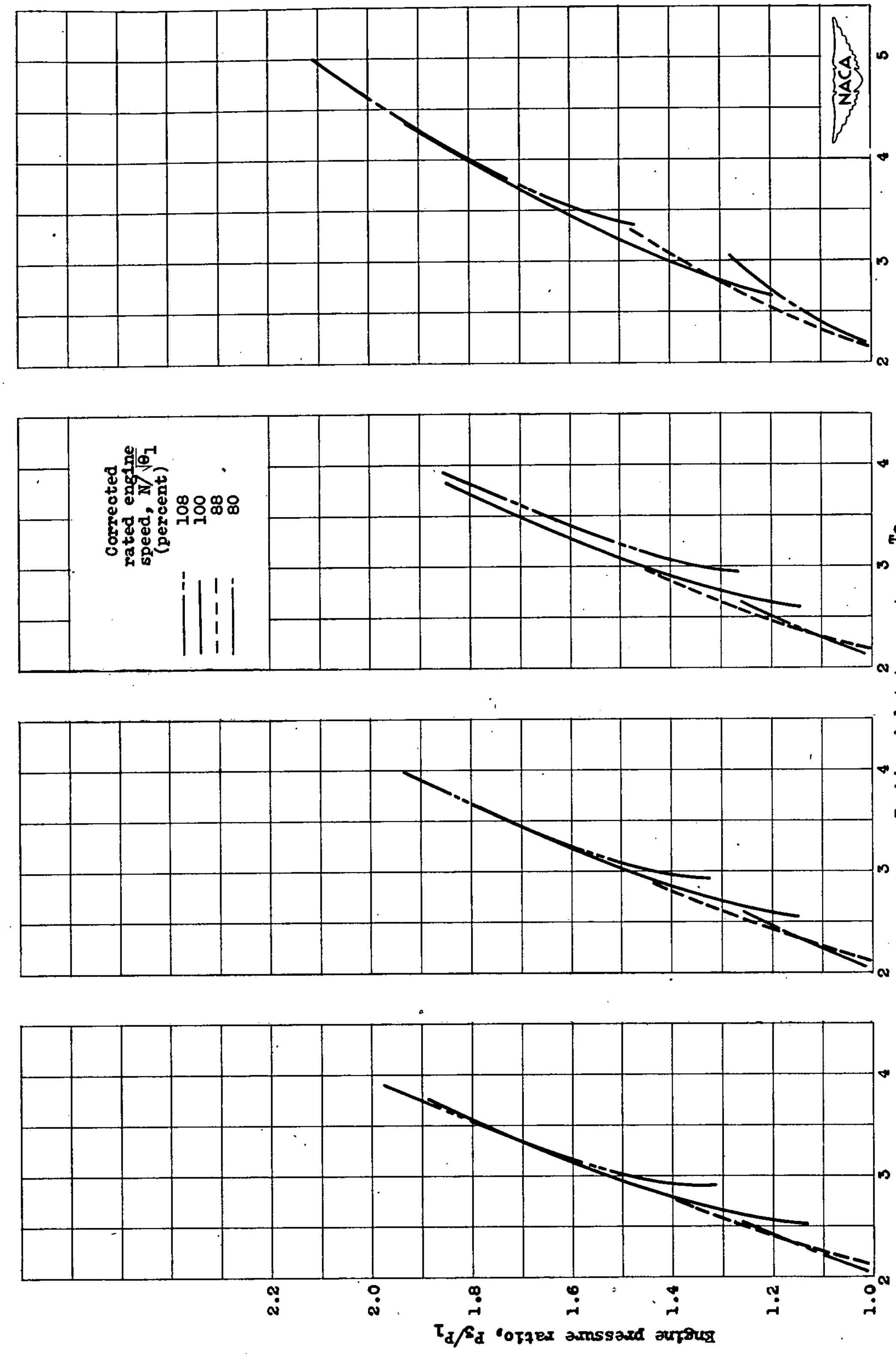


Figure 9. - Relation of engine air-flow function to nozzle pressure ratio.



(a) Reynolds number index, 0.716.

(b) Reynolds number index, 0.516.

(c) Reynolds number index, 0.334.

(d) Reynolds number index, 0.205.

Figure 10. - Generalization of experimentally determined turbine-inlet temperatures.

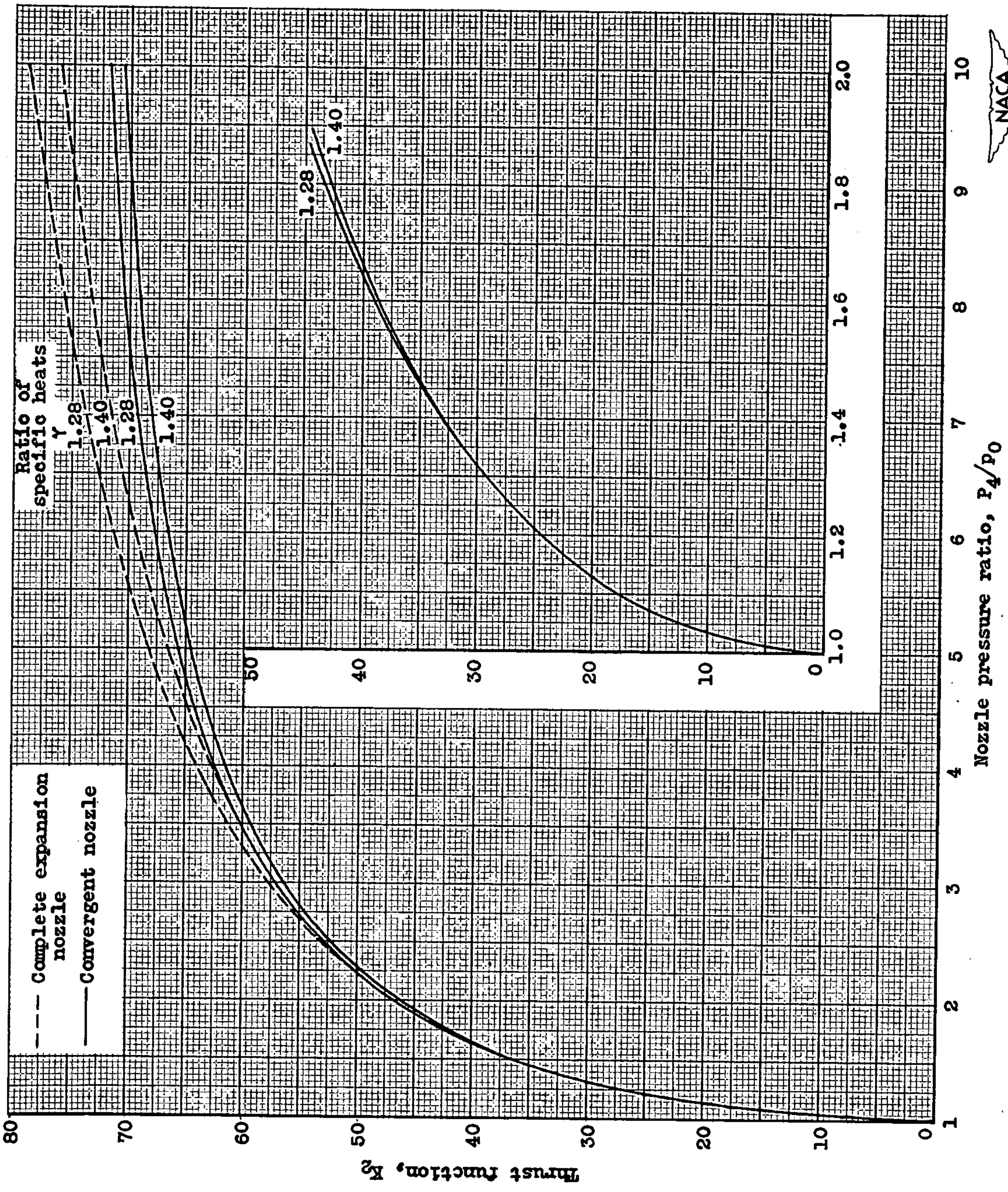
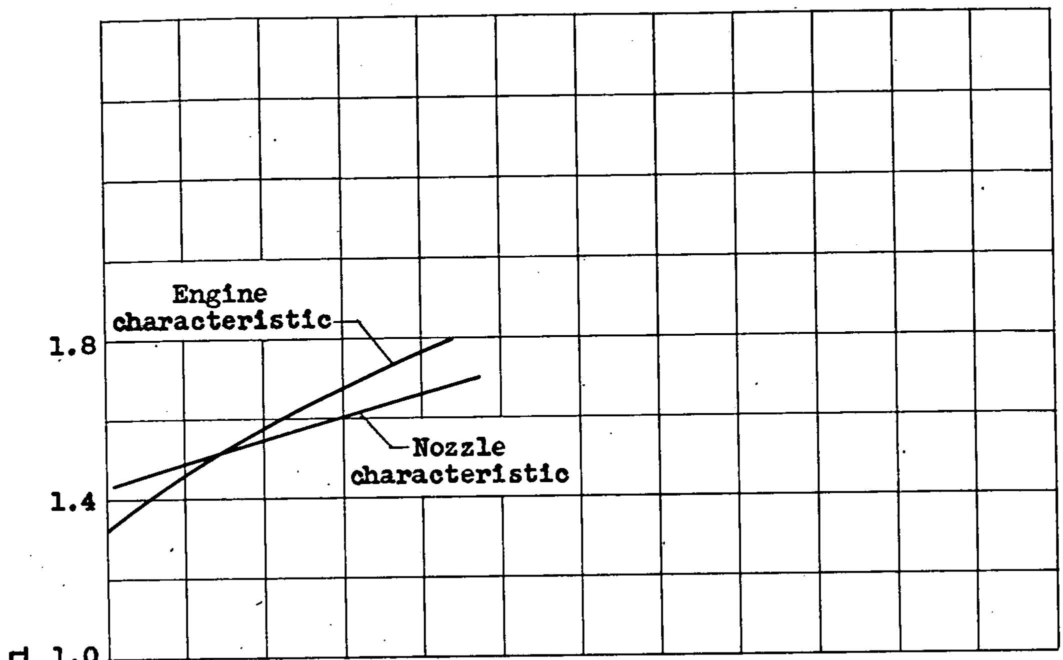
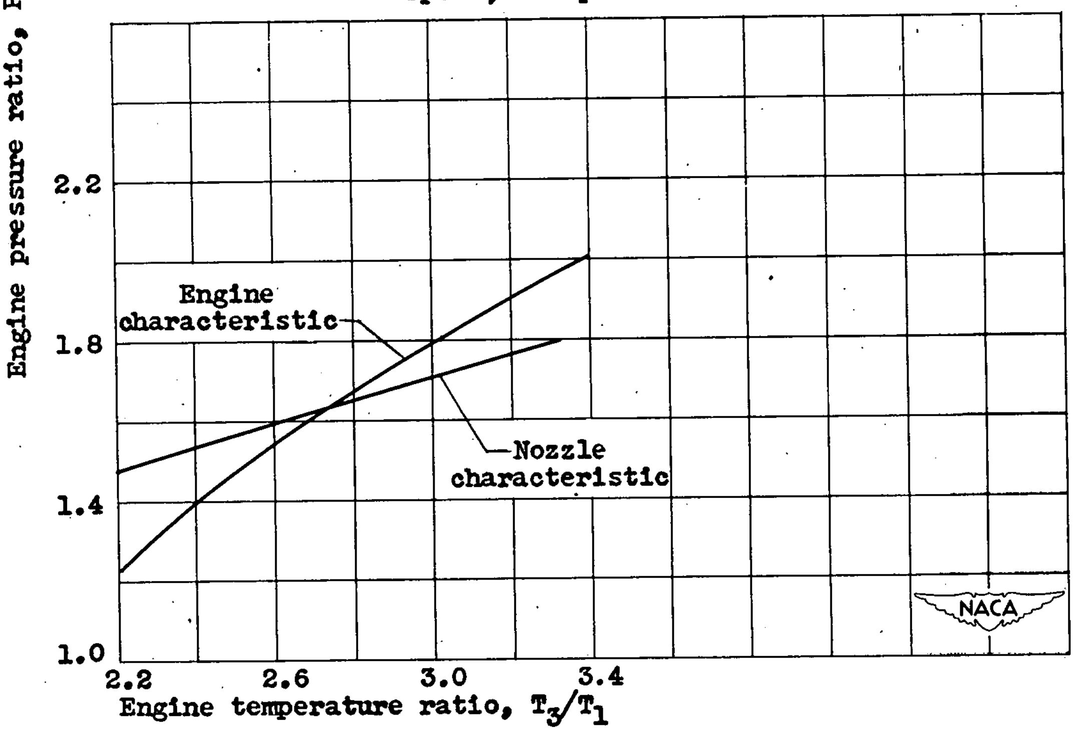


Figure 11. - Relation of thrust function to nozzle pressure ratio.



(a) Inlet-air temperature, 519° R; corrected rated engine speed, 100 percent.



(b) Inlet-air temperature, 445° R; corrected rated engine speed, 108 percent.

Figure 12. - Matching engine and nozzle characteristics at rated engine speed and fixed nozzle area for two inlet-air temperatures. Reynolds number index, 0.716.

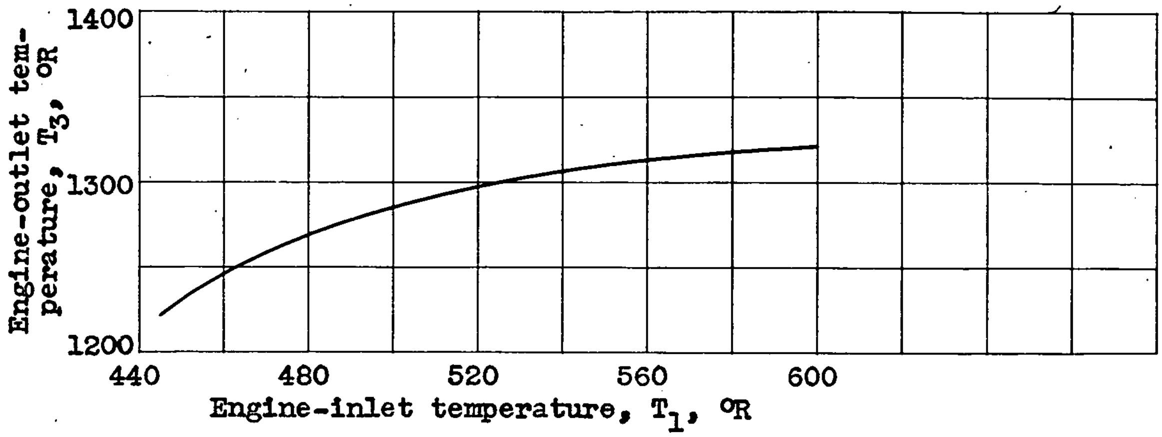


Figure 13. - Variation of outlet temperature with inlet temperature for engine having constant-area nozzle and operating at rated engine speed.

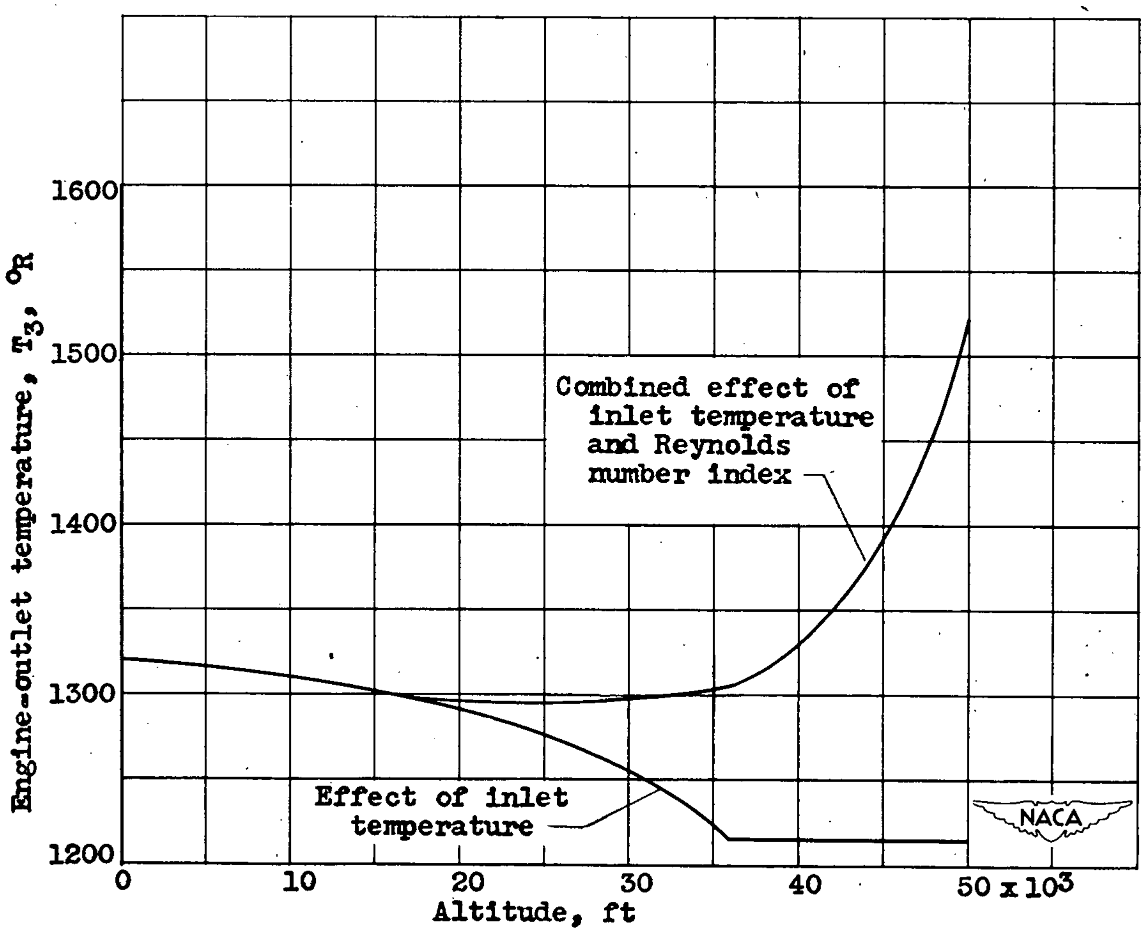
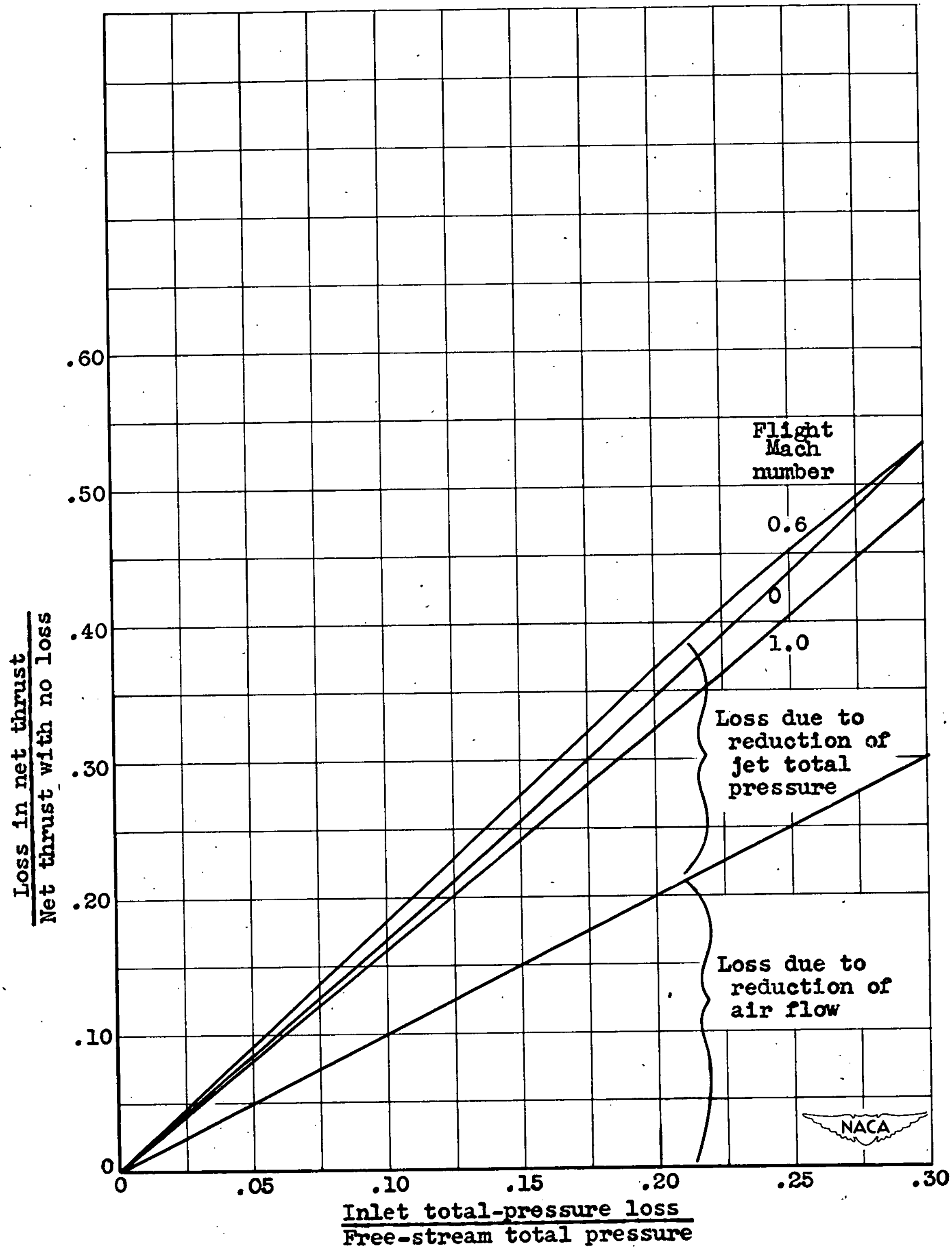
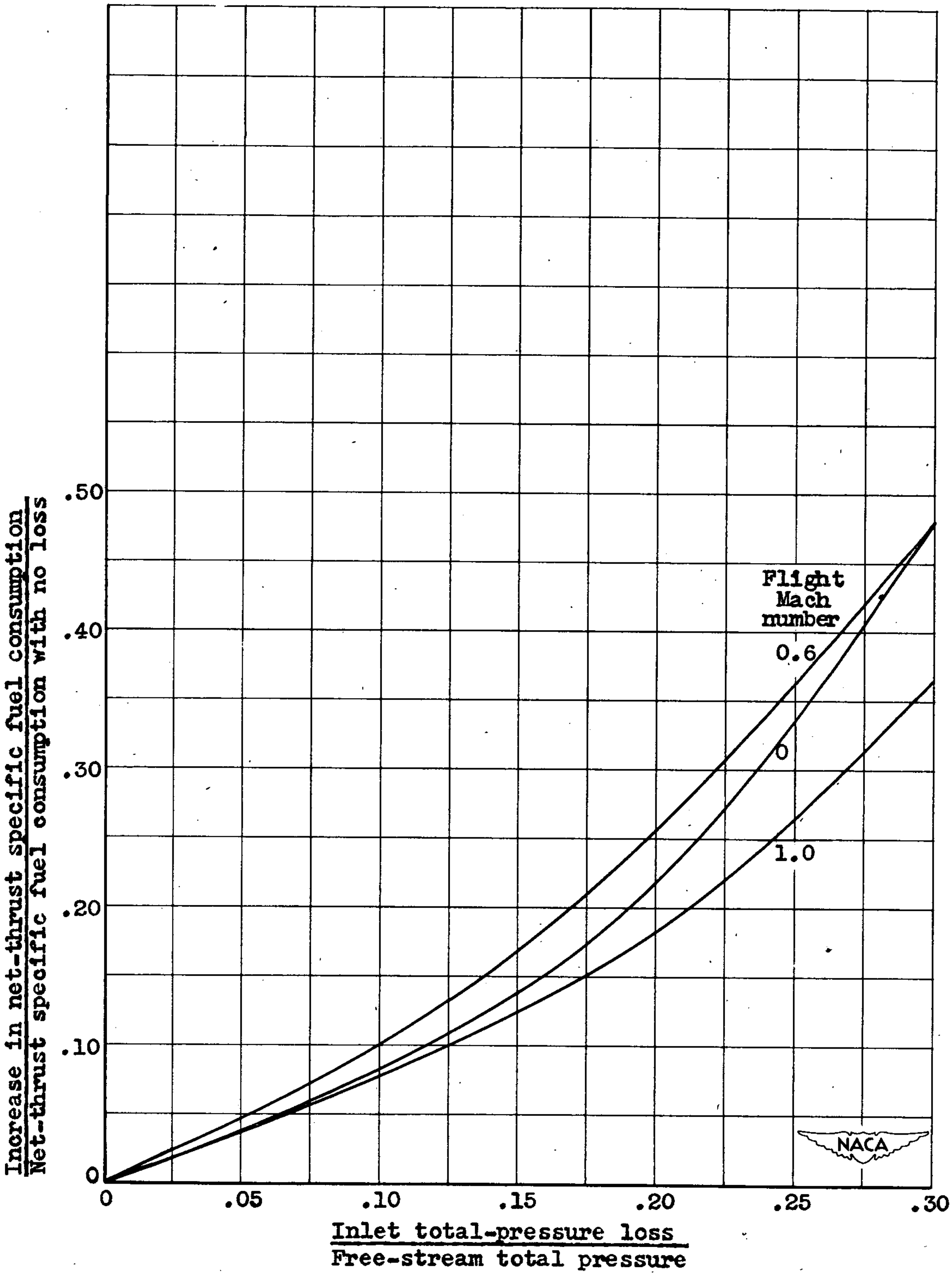


Figure 14. - Variation of outlet temperature with altitude for engine having constant-area nozzle and operating at rated engine speed. Flight Mach number, 0.8.



(a) Effect on thrust.

Figure 15. - Effect of inlet losses on propulsion-system performance.



(b) Effect on specific fuel consumption.

Figure 15. - Concluded. Effect of inlet losses on propulsion-system performance.

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