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TECHNICAL NOTE 2713

EFFECT OF COMPRESSOR-OUTLET AIR BLEED ON PERFORMANCE OF A CENTRIFUGAL-FLOW TURBOJET ENGINE WITH A CONSTANT-AREA JET NOZZLE

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SUMMARY

The effect of compressor-outlet air bleed on turbojet-engine performance is calculated by the use of an analysis based on experimentally determined component characteristics of a centrifugal-flow turbojet engine with a constant-area jet nozzle. A range of engine speeds from 0.9 to 1.0 of rated engine speed and air-bleed rates from 0 to 0.10 of compressor air flow are considered at a flight Mach number of 0.52 and an altitude of 24,000 feet.

The effect of compressor-outlet air bleed on the performance of the centrifugal-flow turbojet engine for different modes of engine operation indicated that the cost of compressor-outlet air bleed in terms of the increase in net-thrust specific fuel consumption was about 2 percent for each percent of air bleed for constant engine speed, maximum net thrust, or constant net-thrust operation. When maximum net-thrust operation with air bleed occurred at a constant tail-pipe temperature, the maximum net thrust decreased at a rate of about 2.5 percent for each percent of air bleed, while the loss in net thrust with air bleed at constant engine speed was only about 0.5 percent for each percent of air bleed.

INTRODUCTION

Compressor-outlet air bleed has been considered as a source of compressed air for such purposes as cabin pressurization and conditioning, ice protection, boundary-layer control, and engine and tail-pipe cooling. The use of compressor-outlet air has, however, a detrimental effect on engine performance, the magnitude of which is dependent on both the amount of air bleed and on the engine characteristics.

An analytical method of performance evaluation with compressor-outlet air bleed has been previously published which presents a general method of component matching and includes generalized working charts for an axial-flow turbojet engine (reference 1). The effect of compressor-outlet air bleed on specific modes of engine operation was then determined by the use of these charts (reference 2). The performance of a centrifugal-flow turbojet engine with compressor-outlet air bleed would be expected to be different from that of an axial-flow turbojet engine because of the basic difference in compressor characteristics.

The effect of compressor-outlet air bleed on the performance of a centrifugal-flow turbojet engine is determined herein. The analysis, which was conducted at the NACA Lewis laboratory, is limited to fixed-configuration engines including fixed-area jet nozzles operating within the region of a choked jet nozzle. While the general method of reference 1 could be applied to centrifugal-flow turbojet engines, complete performance charts were not available and a simplified method was used which considered the combined turbine and jet-nozzle characteristics. 2341

The effect of air bleed on the pumping characteristics of a centrifugal-flow turbojet engine is presented for a range of engine speeds from 0.9 to 1.0 of rated engine speed at a flight Mach number of 0.52 and altitude of 24,000 feet for air-bleed rates from 0 to 0.10 of compressor air flow. The change in net thrust, net-thrust specific fuel consumption, tail-pipe temperature, and engine speed with air bleed is also presented for various modes of engine operation. Although data are shown for only one flight condition, effects of compressor bleed on other flight conditions can be computed from the method presented herein.

The effect of compressor-outlet air bleed on the performance of an axial-flow turbojet engine as compared with the effect of air bleed on the performance of a centrifugal-flow turbojet engine is also discussed.

SYMBOLS

The following symbols are used in this analysis:

A area, sq ft

F thrust, lb

f fuel-air ratio

g acceleration due to gravity, ft/sec^2

h,Δh enthalpy, enthalpy change, Btu/lb

J mechanical equivalent of heat, ft-lb/Btu

N engine speed, rpm

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P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
R	gas constant, ft-lb/(lb)(°R)
sfc	net-thrust specific fuel consumption, lb fuel/(hr)(lb net thrust)
T	total temperature, °R
t	static temperature, °R
V	velocity, ft/sec
w	weight flow, lb/sec
β	ratio of air-bleed flow to compressor air flow
γ	ratio of specific heats
δ	ratio of total pressure to NACA standard sea-level pressure, P/2116
η	adiabatic efficiency
θ	ratio of total temperature to NACA standard sea-level temperature, T/519

Subscripts:

0	free stream
1	compressor inlet
2	compressor outlet
3	turbine inlet
4	turbine outlet
a	air
b	burner
c	compressor
f	fuel
g	gas

j jet

n net

r values of engine variables at rated engine speed and specific flight condition

s standard NACA sea-level conditions

t turbine

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ANALYSIS

Component Characteristics and Assumptions

The engine component characteristics were obtained directly from experimental information available on a centrifugal-flow turbojet engine. In addition, compressor characteristics were available from experimental information obtained from a similar compressor on a unit test rig. Complete recovery of ram pressure was assumed.

Compressor. - The compressor characteristics are presented in figure 1(a). The solid line represents the equilibrium operation of the compressor as a component of the normal engine (with no compressor-outlet air bleed), while the dotted lines represent the operation of the compressor as a unit for various constant rotative speeds. These constant speed lines were constructed with the equilibrium operating line as a base and the experimental data obtained from the unit test rig as a guide. Efficiency contours are shown as dashed lines.

Combustor. - The combustor was assumed to operate with compressor-outlet air bleed at the same combustion efficiency and total-pressure ratio as with zero air bleed at the same engine speed. The variation of combustion efficiency and total-pressure ratio with engine speed is presented in figure 1(b). The use of present turbojet engine fuel having a lower heating value of 18,850 Btu per pound and a hydrogen-carbon weight ratio of 0.170 was assumed.

Combined turbine and jet nozzle. - The turbine and the jet nozzles were considered to be choked for all conditions over the limited range of engine speeds considered. Accordingly, the corrected turbine-nozzle flow was constant at a value of 41.62 pounds per second. A turbine efficiency of 79 percent was used and was considered independent of engine speed or compressor-outlet air bleed. A simplified representation of the combined turbine and fixed-area jet-nozzle characteristics based on continuity considerations was used (see reference 3). In the region of choked flow in both turbine and jet nozzles and for a turbine

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efficiency of 79 percent, the turbine operates at a constant pressure ratio of 2.517 and a constant turbine temperature ratio of 1.195, which corresponds to a corrected specific turbine work of 23.18 Btu per pound.

The thrust characteristic of the jet nozzle is presented in figure 1(c). Because this curve was determined from experimental data, the velocity and the flow coefficient of the jet nozzle are incorporated in the jet-thrust characteristic. The jet-nozzle area was adjusted at static sea-level conditions to give rated thrust at rated engine speed with rated tail-pipe temperature.

The ratio of specific heats was assumed to be 1.4 at low temperatures (stations 1 and 2) and 1.33 at high temperatures (stations 3 and 4) unless otherwise noted.

Method of Analysis and Matching Procedure

The performance of the centrifugal-flow turbojet engine was analyzed in terms of the work required by the compressor and the work available from the turbine jet-nozzle combination. During the process of analysis, the effect of compressor-outlet air bleed on the work requirements was considered and the following equations were derived (see appendix for derivation):

$$(1 + f)\sqrt{1 - \beta}\,\frac{w_{a,1}\sqrt{\theta_1}}{\delta_1}\sqrt{\frac{\Delta h_c}{\theta_1}}\,\frac{P_1}{P_3} = \frac{w_{g,3}\sqrt{\theta_3}}{\delta_3}\sqrt{\frac{\Delta h_t}{\theta_3}} \tag{A6}$$

$$\frac{T_3}{T_1}(1 - \beta) = \frac{\Delta h_c}{\theta_1}\bigg/\frac{\Delta h_t}{\theta_3} \tag{A9}$$

$$f = \frac{h_{g,3} - h_{a,2}}{\eta_b h_f} \tag{A10}$$

In order to determine the engine pressure and temperature ratios, a matching procedure is used which consists of a simultaneous solution of the fuel-air ratio and the ratio of turbine-inlet pressure to compressor-inlet pressure from the preceding equations for a given rate of compressor-outlet air bleed. The term $(1 + f)\sqrt{1 - \beta}$ was computed from equation (6) and is shown in figure 2 for several engine speeds as a function of the ratio of turbine-inlet pressure to compressor-inlet pressure P_3/P_1. A graphical solution of the equilibrium operating points at various values of compressor-outlet air bleed was obtained by superimposing the term $(1 + f)\sqrt{1 - \beta}$ obtained from equations (9) and (10) on figure 2.

Once a matching point has been obtained, the engine total-pressure ratio P_4/P_1 and the engine total-temperature ratio T_4/T_1 may be determined as follows:

$$\frac{P_4}{P_1} = \frac{P_3}{P_1} \bigg/ \frac{P_3}{P_4} \tag{1}$$

and

$$\frac{T_4}{T_1} = \frac{T_3}{T_1} (1 - \beta) \bigg/ \frac{T_3}{T_4} \tag{2}$$

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The jet thrust is obtained from the engine total-pressure ratio and the thrust characteristic of the jet nozzle (fig. 1(c)). The net thrust is then determined as

$$F_n = F_j - \frac{w_{a,1}}{g} V_0 \tag{3}$$

where

$$\frac{V_0}{g} = \sqrt{\frac{R}{g} \frac{2\gamma}{\gamma - 1} T_1 \left[1 - \left(\frac{p_0}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{4}$$

The fuel flow is determined

$$w_f = f(1 - \beta) w_{a,1} \tag{5}$$

and the net-thrust specific fuel consumption is then found to be

$$sfc = \frac{3600 w_f}{F_n} \tag{6}$$

RESULTS AND DISCUSSION

Effect of Air Bleed on Pumping Characteristics

The effect of air bleed on the pumping characteristics of a centrifugal-flow turbojet engine is presented in figure 3 for a range of air-bleed rates from 0 to 0.10 of compressor air flow with lines of constant engine speed from 0.9 to 1.0 of rated engine speed. The pumping characteristics shifted in the direction of increasing engine total-temperature ratio and decreasing engine total-pressure ratio with increasing air bleed. The variation of engine total-temperature ratio is essentially linear with air bleed at a constant total-pressure ratio. The variation of engine total-pressure ratio is also linear with air bleed at a constant total-temperature ratio.

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The performance of the centrifugal-flow turbojet engine with air bleed at constant engine speed is characterized on the pumping characteristic by an increasing engine total-temperature ratio with a small decrease in total-pressure ratio.

Effect of Air Bleed on Engine Performance

Constant engine speed. - The effect of air bleed on net thrust, net-thrust specific fuel consumption, and tail-pipe temperature of a centrifugal-flow turbojet engine operating with a constant-area jet nozzle and at constant engine speed is presented in figure 4 for an engine speed of 0.936 of rated engine speed. As expected from the constant-engine-speed lines shown on the pumping characteristics, the net thrust decreased with air bleed while the tail-pipe temperature increased. The tail-pipe temperature increased about 1 percent for each percent of air bleed and the net thrust decreased about 1/2 percent for each percent of air bleed. The increase in tail-pipe temperature and corresponding increase in fuel flow with the slight reduction in net thrust resulted in an increase in net-thrust specific fuel consumption of about 2 percent for each percent of air bleed.

Maximum net thrust. - The maximum net thrust obtainable from a turbojet engine operating with a constant-area jet nozzle and with air bleed is limited either by rated engine speed or by the attainment of maximum allowable tail-pipe temperature. This mode of engine operation is represented on the pumping characteristics of figure 3 by the rated engine-speed line until the maximum allowable tail-pipe temperature is reached, after which maximum net-thrust operation is represented by a vertical line at the limiting value of engine total-temperature ratio. The effect of air bleed on the maximum net thrust and the resultant effects on net-thrust specific fuel consumption, tail-pipe temperature, and engine speed are presented in figure 5. The maximum net thrust decreased and the net-thrust specific fuel consumption and tail-pipe temperature increased with air bleed at rated engine speed until the maximum allowable tail-pipe temperature was reached in the same manner as previously discussed for constant-engine-speed operation. For the flight condition considered in this report, the maximum allowable tail-pipe temperature was reached at an air-bleed rate of 2.8 percent. A further increase in air bleed while maintaining the maximum allowable tail-pipe temperature was achieved by reducing the engine speed, which resulted in a much greater rate of decrease in maximum net thrust. The engine speed decreased at a rate of about 0.5 percent for each percent of air bleed, while the maximum net thrust decreased about 2.5 percent for each percent of air bleed for engine operation at a constant tail-pipe temperature. Engine operation with air bleed at constant tail-pipe temperature resulted in an increase in net-thrust specific fuel consumption at about the same rate as with engine operation with air bleed at constant engine speed.

Constant net thrust. - Operation of turbojet engines with constant-area jet nozzles and constant net thrust with air bleed is obtained by increasing the tail-pipe temperature. A small increase in engine speed is required for the centrifugal-flow turbojet engine to maintain constant net thrust with air bleed. The jet thrust and consequently the engine total-pressure ratio are therefore nearly constant, increasing slightly to compensate for an increase in inlet momentum drag resulting from the increase in compressor air flow with engine speed. The constant-net-thrust mode of engine operation is therefore represented on the pumping characteristics by a nearly horizontal line. 2341

The effect of air bleed on net-thrust specific fuel consumption, tail-pipe temperature, and engine speed for a constant net thrust is presented in figure 6 for a value of 0.75 of maximum net thrust. The increase in net-thrust specific fuel consumption and tail-pipe temperature with air bleed while maintaining constant net thrust was about the same as that required to maintain constant engine speed, although it was slightly less because of the small increase in engine speed required to maintain a constant net thrust.

Comparison with axial-flow turbojet engine. - The effect of compressor-outlet air bleed on the performance of a centrifugal-flow turbojet engine operating at maximum net thrust (constant tail-pipe temperature) or at a constant net thrust is essentially the same as the effect of compressor-outlet air bleed on the performance of an axial-flow turbojet engine which is presented in reference 2.

At constant engine speed the basic difference in compressor characteristics between the two turbojet engines results in some difference in the effect of compressor-outlet air bleed. The decrease in net thrust, with compressor-outlet air bleed, for example, is greater for an axial-flow turbojet engine because of the greater decrease in compressor pressure ratio.

SUMMARY OF RESULTS

An analysis of the effect of air bleed on the pumping characteristics of a centrifugal-flow turbojet engine at a flight Mach number of 0.52, an altitude of 24,000 feet, a range of engine speeds from 0.9 to 1.0 of rated engine speed, and air-bleed rates from 0 to 0.10 of compressor air flow indicated that air bleed resulted in an essentially linear increase

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in engine total-temperature ratio at a constant engine total-pressure ratio and a linear decrease in engine total-pressure ratio at a constant engine total-temperature ratio. Constant-engine-speed performance with air bleed is characterized by an increasing engine total-temperature ratio with a small decrease in engine total-pressure ratio.

The effect of air bleed on the performance of the turbojet engine for different modes of engine operation indicated that the cost of compressor-outlet air bleed in terms of the increase in net-thrust specific fuel consumption was about 2 percent for each percent of air bleed for constant engine speed, maximum net thrust, or constant net-thrust operation. When maximum net-thrust operation with air bleed occurred at a constant tail-pipe temperature, the maximum net-thrust decreased at a rate of about 2.5 percent for each percent of air bleed, while the loss in net thrust with air bleed at constant engine speed was only about 0.5 percent for each percent of air bleed.

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National Advisory Committee for Aeronautics
Cleveland, Ohio, January 9, 1952

APPENDIX

PROCESS OF ANALYSIS

The compressor and turbine work may be equated as

$$w_{a,1}\Delta h_c = (w_{a,3} + w_f)\Delta h_t$$

If the accessory work and friction work are assumed equal to the work derived from the fuel flow $w_f \Delta h_t$,

$$w_{a,1}\Delta h_c = w_{a,3}\Delta h_t \qquad \text{(A1)}$$

and, from continuity of flow,

$$w_{a,1}(1 - \beta) = w_{a,3} \qquad \text{(A2)}$$

In terms of correction factors, equation (1) becomes

$$\frac{w_{a,1}\sqrt{\theta_1}}{\delta_1} \frac{\Delta h_c}{\theta_1} \frac{P_1}{P_3}\sqrt{\frac{T_1}{T_3}} = \frac{w_{a,3}\sqrt{\theta_3}}{\delta_3} \frac{\Delta h_t}{\theta_3} \qquad \text{(A3)}$$

and, similarily, equation (2) becomes

$$\frac{w_{a,1}\sqrt{\theta_1}}{\delta_1} (1 - \beta) \frac{P_1}{P_3}\sqrt{\frac{T_3}{T_1}} = \frac{w_{a,3}\sqrt{\theta_3}}{\delta_3} \qquad \text{(A4)}$$

After T_3/T_1 is eliminated from equations (3) and (4) by combining

$$\sqrt{1 - \beta}\, \frac{w_{a,1}\sqrt{\theta_1}}{\delta_1}\sqrt{\frac{\Delta h_c}{\theta_1}} \frac{P_1}{P_3} = \frac{w_{a,3}\sqrt{\theta_3}}{\delta_3}\sqrt{\frac{\Delta h_t}{\theta_3}} \qquad \text{(A5)}$$

since $w_{a,3} = \left(\frac{1}{1 + f}\right) w_{g,3}$, equation (5) becomes

$$(1 + f) \sqrt{1 - \beta}\, \frac{w_{a,1}\sqrt{\theta_1}}{\delta_1}\sqrt{\frac{\Delta h_c}{\theta_1}} \frac{P_1}{P_3} = \frac{w_{g,3}\sqrt{\theta_3}}{\delta_3}\sqrt{\frac{\Delta h_t}{\theta_3}} \qquad \text{(A6)}$$

The corrected specific compressor work is related to the compressor temperature ratio

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$$\frac{\Delta h_c}{\theta_1} = \frac{R}{J} \frac{\gamma}{\gamma - 1} t_s \left(\frac{T_2}{T_1} - 1\right) \tag{A7}$$

and the compressor efficiency relates the compressor temperature ratio to the compressor pressure ratio

$$\eta_c \left(\frac{T_2}{T_1} - 1\right) = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1 \tag{A8}$$

The required turbine-inlet temperature may also be determined by combining equations (1) and (2)

$$\Delta h_c = \Delta h_t(1 - \beta)$$

or, in terms of correction factors,

$$\frac{\Delta h_c}{\theta_1} = \frac{\Delta h_t}{\theta_3} (1 - \beta) \frac{T_3}{T_1}$$

from which

$$\frac{T_3}{T_1} (1 - \beta) = \frac{\Delta h_c}{\theta_1} \bigg/ \frac{\Delta h_t}{\theta_3} \tag{A9}$$

The fuel-air ratio required by the burner to provide the turbine-inlet temperature for a given compressor-outlet air bleed may now be determined. By definition

$$\eta_b = \frac{h_{g,3} - h_{a,2}}{f h_f}$$

or

$$f = \frac{h_{g,3} - h_{a,2}}{\eta_b h_f} \tag{A10}$$

where $h_{g,3}$ and $h_{a,2}$ are calculated by the method of reference 4 with variable specific heats.

REFERENCES

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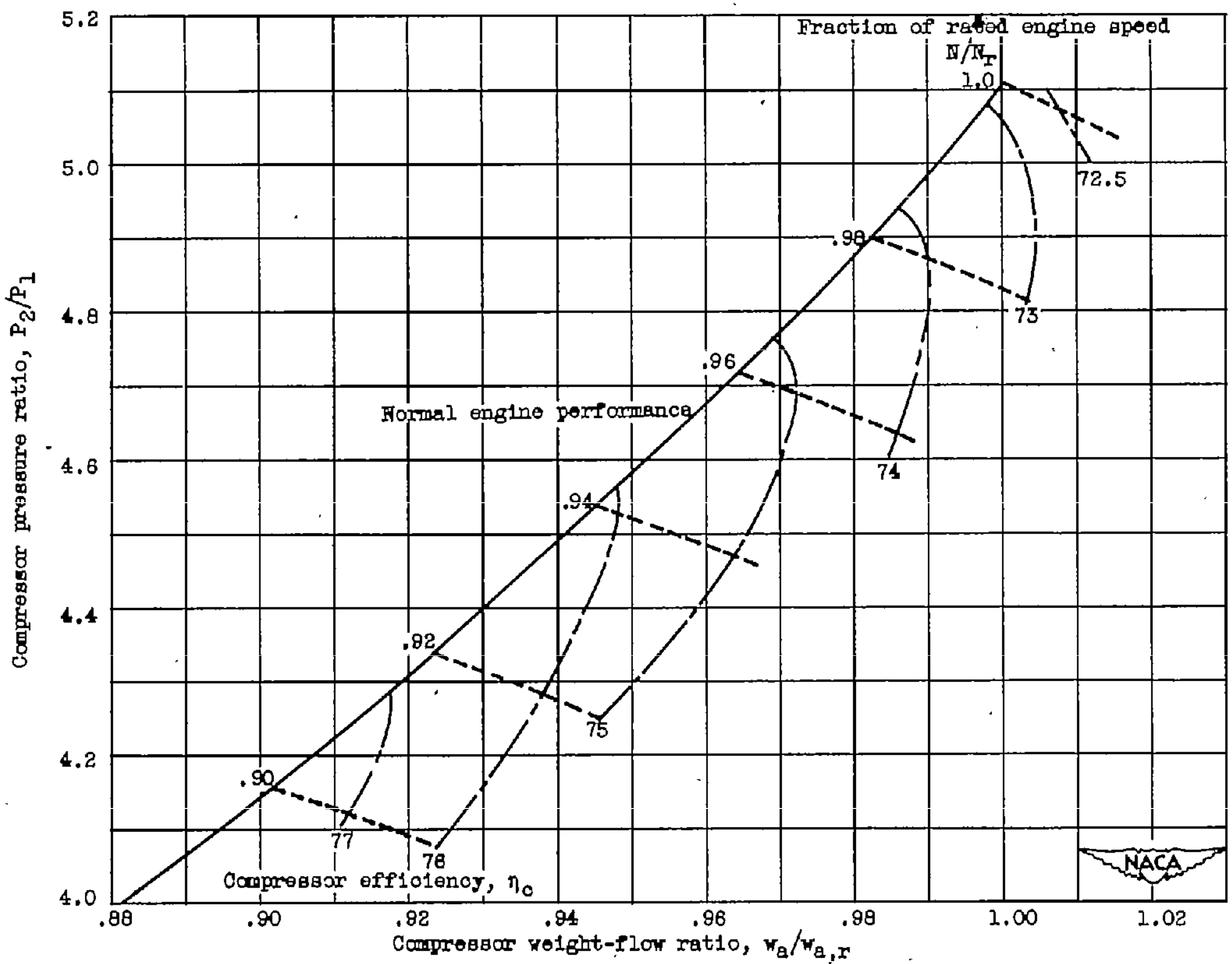

(a) Compressor.

Figure 1. - Performance characteristics of centrifugal-flow turbojet engine. Flight Mach number, 0.52; altitude, 24,000 feet.

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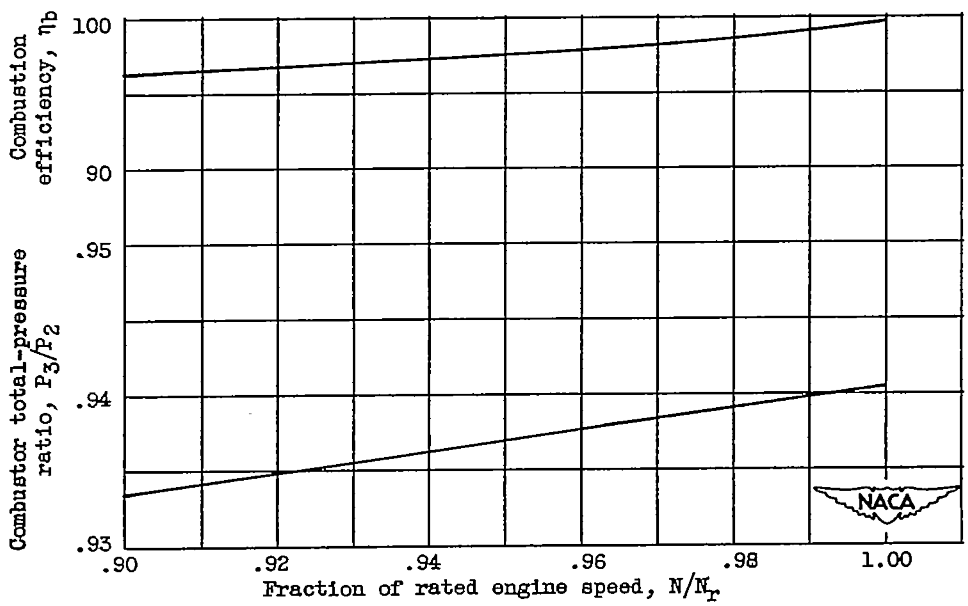

(b) Combustor.

Figure 1. - Continued. Performance characteristics of centrifugal-flow turbojet engine. Flight Mach number, 0.52; altitude, 24,000 feet.

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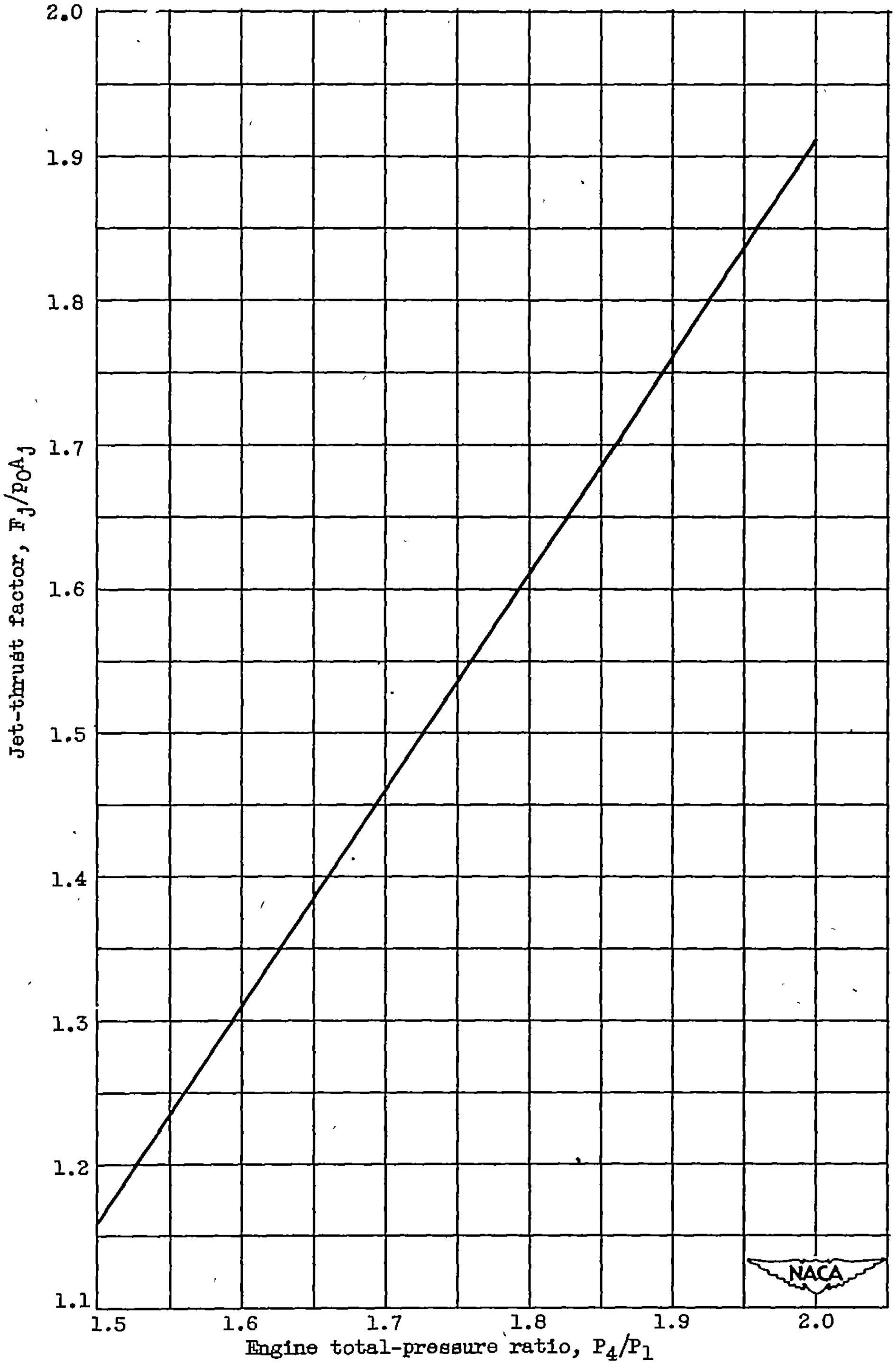

(c) Jet nozzle.

Figure 1. - Concluded. Performance characteristics of centrifugal-flow turbojet engine. Flight Mach number, 0.52; altitude, 24,000 feet.

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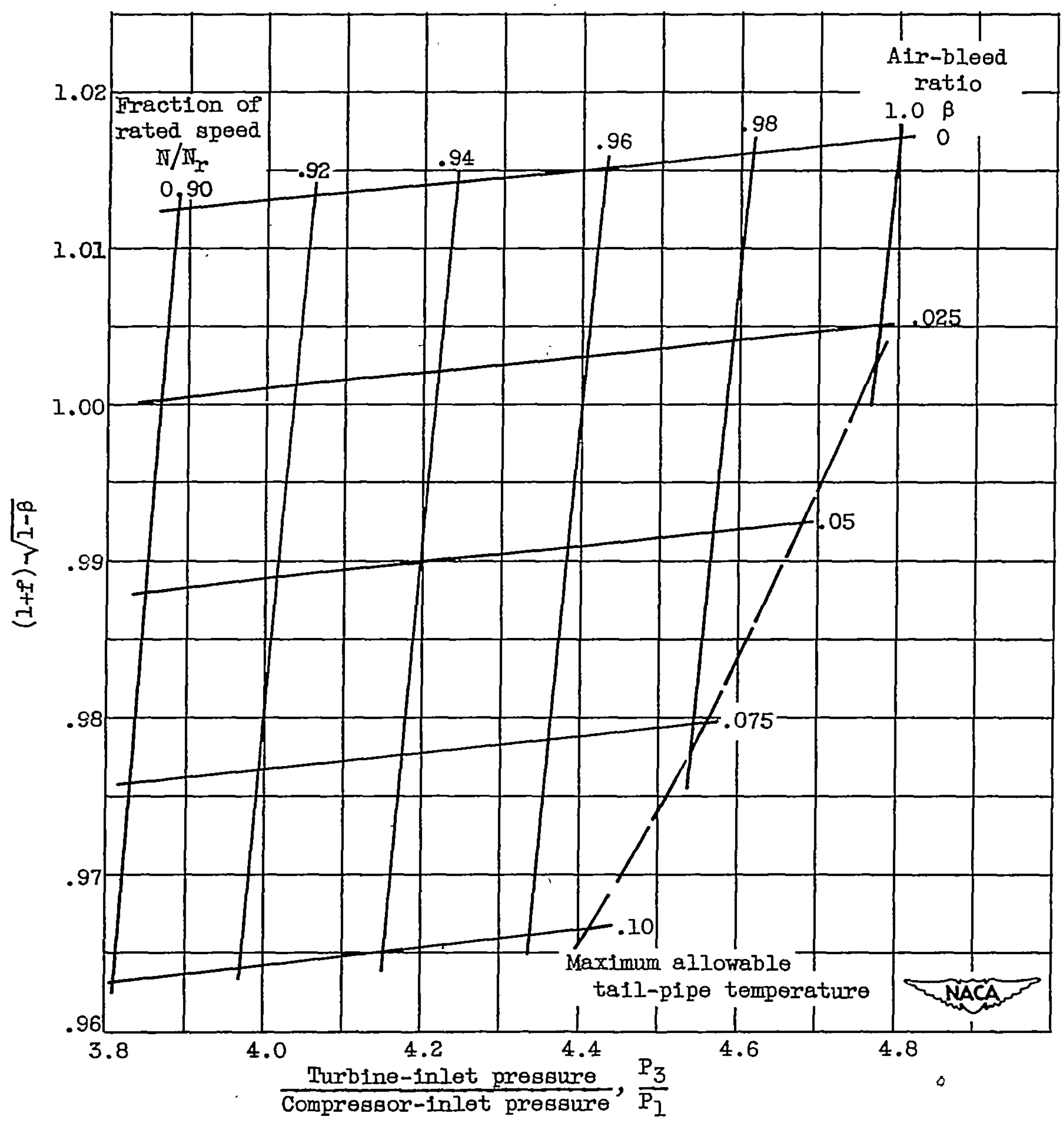

Figure 2. - Fuel-air ratio requirements of centrifugal-flow turbojet engine. Flight Mach number, 0.52; altitude, 24,000 feet.

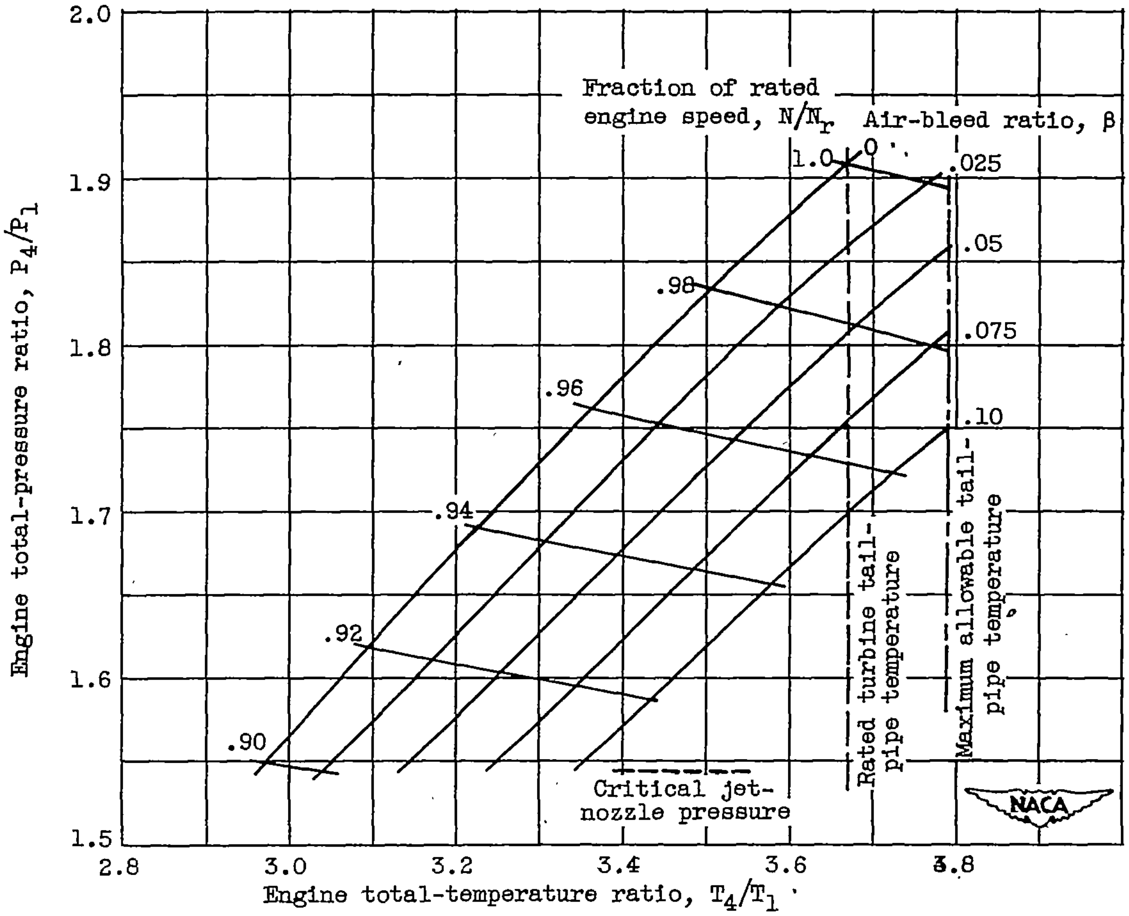

Figure 3. - Effect of compressor-outlet air bleed on pumping characteristics of centrifugal-flow turbojet engine. Flight Mach number, 0.52; altitude, 24,000 feet.

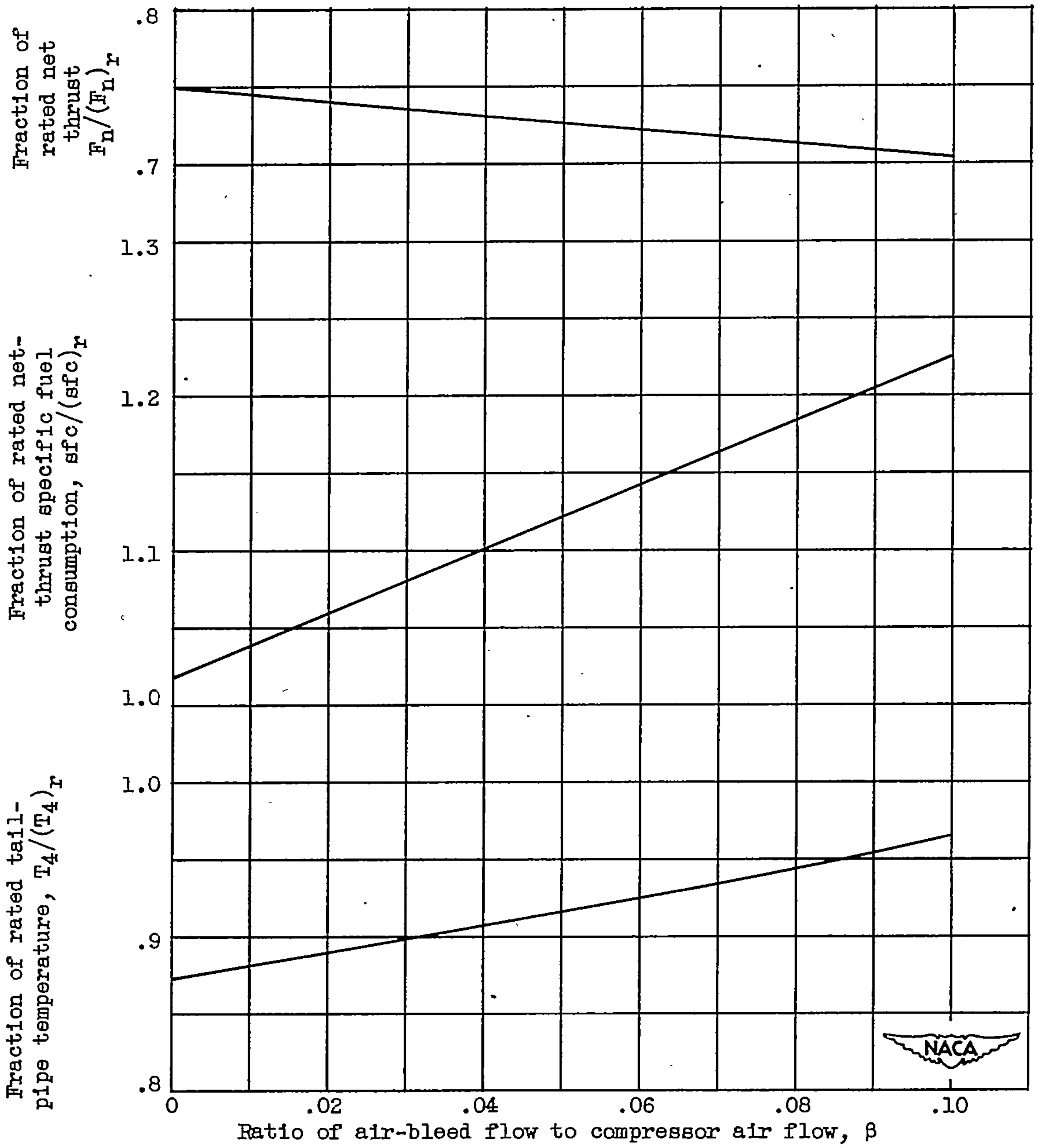

Figure 4. - Effect of compressor-outlet air bleed on performance of centrifugal-flow turbojet engine operating at constant engine speed. Fraction of rated engine speed, 0.936; flight Mach number, 0.52; altitude, 24,000 feet.

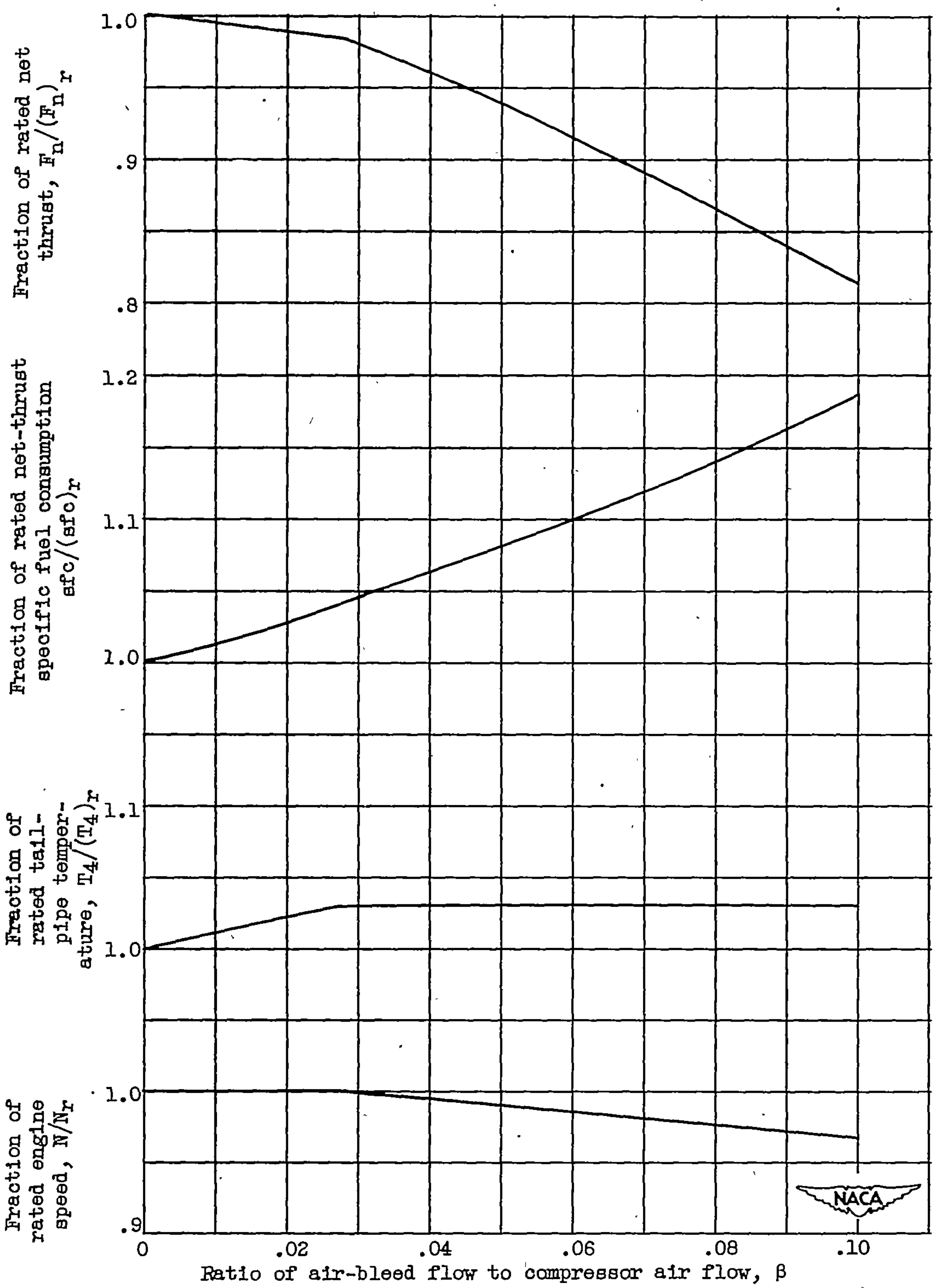

Figure 5. - Effect of compressor-outlet air bleed on maximum net-thrust performance of centrifugal-flow turbojet engine. Flight Mach number, 0.52; altitude, 24,000 feet.

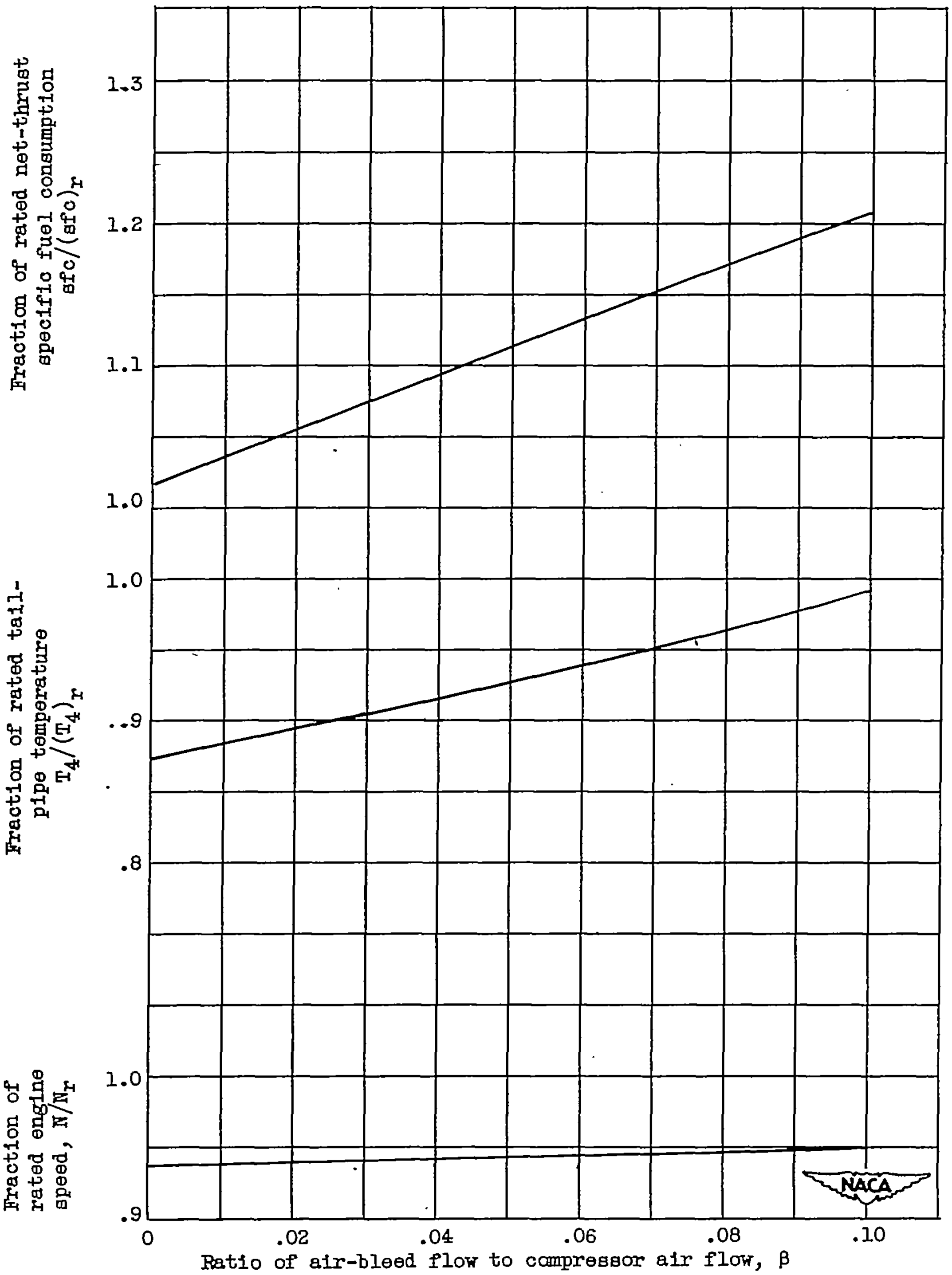

Figure 6. - Effect of compressor-outlet air bleed on performance of centrifugal-flow turbojet engine operating at constant net thrust. Fraction of maximum net thrust, 0.75; flight Mach number, 0.52; altitude, 24,000 feet.

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