NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2304

EFFECT OF HEAT AND POWER EXTRACTION ON TURBOJET-ENGINE PERFORMANCE

IV - ANALYTICAL DETERMINATION OF EFFECTS OF HOT-GAS BLEED

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SUMMARY

Generalized working charts are presented with which the performance of a turbojet engine operating with tail-pipe gas bleed can be determined. From these generalized working charts, the performance of an engine operating with tail-pipe gas bleed at several typical flight conditions and modes of engine operation is calculated. A method of determining the performance of a turbojet engine with turbine-inlet bleed from the performance with compressor-outlet bleed is also given.

In general, with a turbojet engine operating at constant engine speed, bleeding gas from the tail pipe at constant tail-pipe-nozzle area and reduced turbine-inlet temperature caused 2.5 to 4 times as great a loss in thrust as bleeding gas at constant turbine-inlet temperature and reduced tail-pipe-nozzle area.

A comparison of turbine-inlet and tail-pipe bleed indicated that for variable-area operation smaller performance penalties resulted from removing a given amount of energy from the tail pipe than from the turbine inlet. The reverse trend occurred for bleed with a constant tail-pipe-nozzle area.

INTRODUCTION

In the operation of current and future aircraft, large quantities of heat and power may be needed for auxiliary purposes. The maximum amount of energy necessary for these purposes will probably be required only for small portions of the total flight time; consequently, auxiliary sources used to supply this energy would seldom operate at full capacity. As the auxiliary equipment will take up space and pay-load capacity during the entire flight, the evaluation of schemes for obtaining energy with a minimum of auxiliary equipment is desirable. An obvious method of minimizing the required auxiliary equipment is deriving the desired energy from the aircraft power plant.

An analytical project for evaluating and comparing the effects of different methods of energy extraction on the performance of a turbojet engine is in progress at the NACA Lewis laboratory. The initial phases of this investigation include the evaluation of engine performance with compressor-outlet air bleed, (references 1 and 2) and the evaluation of engine performance with shaft-power extraction (reference 3). The effects of hot-gas bleed from the tail pipe and the turbine inlet on the performance of a typical axial-flow-type turbojet engine are presented herein.

Generalized engine performance with tail-pipe gas bleed is presented in the form of generalized working charts; performance under several representative modes of engine operation for both variable- and rated-area tail-pipe nozzles is calculated from these charts. The effects of such variables as engine speed, turbine-inlet temperature, engine-inlet temperature, flight Mach number, and altitude are evaluated. Data are presented to show the engine performance with tail-pipe gas bleed at constant thrust levels and the maximum permissible tail-pipe gas bleed as a function of thrust and altitude. Methods of determining engine performance with turbine-inlet gas bleed from the results with compressor-outlet bleed (references 1 and 2) are explained. Engine performance with turbine-inlet bleed and with tail-pipe bleed are compared for selected engine operating conditions.

SYMBOLS

The following symbols are used in this analysis:

A area, square feet

c_p specific heat at constant pressure, Btu per pound per $^{\circ}R$

F_n net thrust, pounds

N engine speed, rpm

P total pressure, pounds per square foot absolute

Q heat removed, Btu per hour

T total temperature, $^{\circ}R$

$W_{a,c}$ compressor air flow, pounds per second

W_f fuel flow, pounds per hour

β gas-bleed ratio, bleed flow divided by engine mass flow at bleed location

δ ratio of total pressure to NACA standard sea-level pressure, P/2116

θ ratio of total temperature to NACA standard sea-level temperature, T/519

Subscripts:

2 compressor inlet

3 compressor outlet

4 turbine inlet

5 turbine outlet

6 tail-pipe nozzle

a air

c compressor

r rated value or value obtained when operating with NACA standard sea-level static inlet conditions at rated engine speed and rated turbine-inlet temperature

Superscripts:

* value of variable at rated engine speed and rated turbine-inlet temperature at particular standard altitude and flight Mach number under consideration

TAIL-PIPE GAS BLEED

Calculation and Presentation of Working Charts

The performance of a basic turbojet engine consisting of a compressor, a combustion chamber, and a turbine is conveniently expressed in terms of pumping characteristics in the form of a curve of engine pressure ratio as a function of engine temperature ratio (fig. 1) and a curve of corrected compressor mass flow as a function of corrected engine speed (fig. 2). All variables are presented as fractions of rated values. The engine temperature ratio - engine pressure ratio curves were obtained in reference 1 by matching experimentally determined component characteristics of a typical axial-flow turbojet engine. The component characteristics were idealized by fairing a single curve through data for a range of altitude and flight Mach number, thus eliminating the Reynolds number effect. A single mass flow - engine speed curve results from the vertical compressor characteristics typical of axial-flow compressors and the fact that the effect of Reynolds number on compressor performance was neglected. Although Reynolds number may have a first-order effect on the actual magnitudes of the performance variables, its effect on the change in engine performance due to bleed is negligible. Curves such as these are independent of the engine-inlet system or tail-pipe nozzle. Because gas bled from the tail pipe is extracted from behind the basic turbojet engine, the pumping characteristics of an unmodified basic turbojet engine can be used in computing the performance of a turbojet engine with tail-pipe bleed.

The operating point of an engine on the engine pressure ratio - engine temperature ratio plane varies with the mass flow per unit of tail-pipe-nozzle area. Therefore, if the tail-pipe-nozzle area is varied in such a manner as to maintain constant mass flow per unit nozzle area as gas is bled from the tail pipe, engine pressure ratio, engine temperature ratio, and jet thrust per pound of gas flow are unaffected. Under these circumstances, the jet thrust decreases by the percentage bleed. The net thrust is the difference between the jet thrust and the momentum of the inlet air; consequently, the percentage decrease in net thrust is greater than the percentage bleed at flight speeds greater than zero.

Bleeding gas from the tail pipe of an engine operating at constant engine speed with a constant tail-pipe-nozzle area decreases the mass flow per unit nozzle area and is similar to increasing the area with no bleed; thus reducing the engine pressure ratio, engine temperature ratio, and jet thrust per pound of gas. When gas is bled from the tail pipe at constant tail-pipe-nozzle area, the jet thrust therefore decreases considerably more than the percentage bleed.

The performance of a turbojet engine operating with tail-pipe gas bleed was calculated from the engine pressure ratio - engine temperature ratio curves (fig. 1) and the mass flow - engine speed characteristics (fig. 2) and is presented in figures 3 to 5 for operation at a ram pressure ratio of 1.35. This ram pressure ratio corresponds approximately to a Mach number of 0.7 when representative diffuser losses are taken into account. Operation at corrected engine speeds of 0.9, 1.0, and 1.1 times the rated value is shown in parts (a), (b), and (c), respectively, of each figure.

The turbine-inlet temperature ratio T_4/T_2 and the power-removal factor $\frac{Q/\delta_2\sqrt{\theta_2}}{(F_n/\delta_2)_r}$ are presented as functions of corrected net thrust and gas-bleed ratio β in figure 3. The amount of heat available from the bleed gas Q is based on the difference between the total temperature in the tail pipe and the total temperature at the engine inlet.

The variation of tail-pipe-nozzle area with thrust and gas-bleed ratio is presented in figure 4. At a constant engine speed, the tail-pipe-nozzle area must be decreased with increasing bleed in order to maintain a constant thrust.

In figure 5, the power-removal specific fuel consumption $\Delta W_f/Q$ and the thrust specific fuel consumption $W_f/F_n\sqrt{\theta_2}$ are presented as functions of thrust and gas-bleed ratio. In computing the first factor, the difference between the fuel flow at a particular value of bleed and the fuel flow at the same value of thrust with no bleed is divided by the energy available from that amount of bleed. All factors except $\frac{Q/\delta_2\sqrt{\theta_2}}{(F_n/\delta_2)_r}$ and $\Delta W_f/Q$ are presented as fractions of rated values.

The same factors are presented in figures 6 to 8 as in figures 3 to 5, respectively, for static inlet conditions (ram pressure ratio, 0.99). In figure 8, the values of $\Delta W_f/Q$ for low values of thrust are lower than the reciprocal of the heating value of fuel, indicating that, under some circumstances, more energy per pound of fuel can be obtained by bleeding gas from the tail pipe of a turbojet engine than the 18,600 Btu per pound obtainable by complete combustion of the fuel. This paradox is due to the fact that at low thrust levels with no bleed, the engine is operating below the thrust level for maximum cycle efficiency. Bleeding gas at a constant thrust level causes the engine to be operated at a more efficient condition and thus tends to minimize the increase in fuel consumption due to bleed.

Limitations of Working Charts

All factors except $\frac{Q/\delta_2\sqrt{\theta_2}}{(F_n/\delta_2)_r}$ and $\frac{\Delta W_f}{Q}$ are given as fractions of rated values and are applicable to axial-flow-type turbojet engines with rated compressor pressure ratios of 4 to 5 and rated turbine-inlet temperatures of 1800° to 2000° R. The factors involving the energy in a given amount of bleed are sensitive to actual values of tail-pipe temperature; an approximate correction for the level of engine operation can be obtained, however, by varying the values of $\frac{Q/\delta_2\sqrt{\theta_2}}{(F_n/\delta_2)_r}$ directly and the values of $\frac{\Delta W_f}{Q}$ inversely by 0.8 of the percentage change in tail-pipe temperature from a reference value of 1600° R. This approximate correction is valid for rated tail-pipe temperature in the range of 1400° to 1800° R.

The changes in thrust and specific fuel consumption due to tail-pipe gas bleed for flight velocities corresponding to ram pressure ratios other than the two shown (1.35 and 0.99) can be computed by an interpolation process. By computing the changes in performance at a desired turbine-inlet temperature ratio, corrected engine speed, or tail-pipe-nozzle area at ram pressure ratios of 0.99 and 1.35 and interpolating on a Mach number basis, performance changes at intermediate flight Mach numbers can be determined to an accuracy of 2 percent. Extrapolation to a flight Mach number of approximately 0.9 can be made with the same accuracy.

Calculation and Presentation of Results for Specific Modes of Engine Operation

The performance of a turbojet engine operating with tail-pipe gas bleed under various flight conditions and modes of engine operation can be calculated from the generalized working charts (figs. 3 to 8) if any two of the performance variables are known. For example, if, for any flight condition under which the engine-inlet conditions are known, it is desired to bleed gas from the tail pipe at constant turbine-inlet temperature and constant engine speed, thrust, tail-pipe-nozzle area, and specific fuel consumption are obtainable from the working charts.

Because the generalized working charts are presented for only three corrected engine speeds, interpolation for intermediate engine speeds is necessary. The interpolation is not linear and better accuracy can be obtained by cross-plotting the performance variables against corrected engine speed for constant values of corrected thrust.

A number of problems have been worked out using the generalized working charts to illustrate the effects of tail-pipe bleed on performance for specific modes of engine operation. The modes considered are constant engine speed and constant thrust at either constant turbine-inlet temperature or constant tail-pipe-nozzle area. The effects of variation in engine-inlet temperature, flight Mach number, and altitude are considered.

In presenting the effects of tail-pipe gas bleed for specific modes of engine operation, the performance variables are given as fractions of a reference value. The reference value (indicated by an asterisk) is taken as the value of the variable with rated engine speed, rated turbine-inlet temperature, and no gas bleed at the particular standard altitude and flight Mach number under consideration. Use of a reference quantity such as this one is necessary in order that the Reynolds number effect, disregarded in the derivation of the pumping characteristics, be eliminated from the results. Although the Reynolds number effect on the actual values of thrust and so forth may be noticeable, the effect on the changes in performance due to gas bleed is negligible.

Effect of engine speed and turbine-inlet temperature. - The performance of a turbojet engine operating with tail-pipe gas bleed at an altitude of 20,000 feet and a flight Mach number of 0.7 is shown in figure 9. For obtaining the results of figure 9(a), the engine was operated at rated engine speed and for figure 9(b), the engine was operated at 0.93 rated engine speed. For both engine speeds, three modes of engine operation are considered: variable tail-pipe-nozzle area at rated turbine-inlet temperature, variable tail-pipe-nozzle area at 0.90 rated turbine-inlet temperature, and rated tail-pipe-nozzle area.

Bleeding 4 percent of the gas from the tail pipe at rated engine speed (fig. 9(a)) results in thrust losses of 6 percent for operation at rated turbine-inlet temperature or 0.90 rated turbine-inlet temperature, and 18 percent for rated tail-pipe-nozzle-area operation. The increased thrust loss for rated-area bleed results from the reduced tail-pipe pressure and temperature accompanying the reduced mass flow per unit area in the tail-pipe nozzle. Low tail-pipe temperature also results in a reduced energy content per pound of tail-pipe bleed with a rated-area nozzle. For the same bleed ratio, the specific fuel consumption increases about 6 percent for each of the three modes of engine operation considered. The variations in tail-pipe-nozzle area necessary to maintain constant turbine-inlet temperatures are also shown in figure 9.

For operation at 0.93 rated engine speed (fig. 9(b)) and a bleed ratio of 0.04, the thrust decreases about 7 percent for constant turbine-inlet temperature and more than 18 percent for rated area. For the same bleed ratio, the specific fuel consumption increases approximately 7 percent for all modes of operation.

Effect of engine-inlet temperature. - The effect of bleeding gas from the tail pipe of a turbojet engine operating at static sea-level conditions with three engine-inlet temperatures is shown in figure 10. The engine-inlet temperatures shown on the figure, 99° , 59° , and 20° F, correspond to operation in Army summer air, NACA standard air, and under a typical icing condition, respectively. The engine is operated at rated engine speed either at rated turbine-inlet temperature or at rated tail-pipe-nozzle area.

Bleeding gas from the tail pipe at constant turbine-inlet temperature at static engine-inlet conditions reduces the thrust by the percentage bleed regardless of the engine-inlet temperature. For a bleed ratio of 0.04 with rated tail-pipe-nozzle area, the thrust decreases approximately 15, 13, and 12 percent for engine-inlet temperatures of 20° , 59° , and 99° F, respectively. Approximately 5.7-percent gas can be bled from the tail pipe with a rated-area tail-pipe nozzle and engine-inlet temperature of 20° F before the thrust decreases to the value obtained with no gas bleed and a 99° F inlet temperature.

The specific fuel consumption increases by approximately the percentage bleed for rated turbine-inlet temperature operation and by approximately one-half the percentage bleed for rated-area operation.

Effect of flight Mach number. - The effect of flight Mach number on the performance of a turbojet engine operating at a tail-pipe gas-bleed ratio of 0.04, rated engine speed, and an altitude of 20,000 feet is shown in figure 11. Operation at rated turbine-inlet temperature and at rated tail-pipe-nozzle area is considered.

Data for the curves at static conditions were calculated from figures 6 to 8, and data at a Mach number of 0.7 were calculated by use of figures 3 to 5. Intermediate points were obtained by computing the engine performance using both sets of figures for corrected engine speeds, turbine-inlet temperature ratios, and areas corresponding to the engine-inlet conditions at the intermediate flight Mach numbers and interpolating linearly between Mach numbers of 0 and 0.7.

For rated-temperature operation, the decrease in thrust resulting from a bleed ratio of 0.04 varies from 4 percent for static conditions to 7 percent for a flight Mach number of 0.9. Over the same Mach number range, bleeding 0.04 of the gas from the tail pipe with a rated-area tail-pipe nozzle causes thrust losses of 8 to 22 percent. The increases in specific fuel consumption over the same Mach number range vary from 4 to 7 percent for rated-temperature operation and from less than 1 to 7 percent for rated-area operation.

Effect of altitude. - The effect of altitude on the performance of a turbojet engine operating at a tail-pipe gas-bleed ratio of 0.04, rated engine speed, and a flight Mach number of 0.7 is shown in figure 12. The engine is operated both at rated turbine-inlet temperature and at rated tail-pipe-nozzle area.

The thrust and specific fuel consumption penalties due to a bleed ratio of 0.04 with rated turbine-inlet temperature are essentially independent of altitude. The slight variations obtained are caused by the change in engine-inlet temperature with altitude. For rated-area operation, the penalties decrease with increasing altitude up to the tropopause, remaining constant above that point. The thrust penalties for bleed with rated area are 2.5 to 4 times the penalties due to bleed at rated temperature.

Constant thrust operation. - The effect of bleeding gas from the tail pipe of a turbojet engine while maintaining a constant thrust at an altitude of 20,000 feet and a flight Mach number of 0.7 is presented in figure 13. The thrust is maintained at a thrust ratio F_n/F_n^* of 0.80. Operation at rated engine speed and at rated tail-pipe-nozzle area is considered.

For a bleed ratio of 0.04, the specific fuel consumption increases approximately 7 and 9 percent for the rated engine speed and rated tail-pipe-nozzle area operation, respectively. The increase in turbine-inlet temperature necessary to maintain a constant thrust at a bleed ratio of 0.04 is approximately 4 percent for both rated engine speed and rated tail-pipe-nozzle area operation. For bleed ratios above about 0.045, it is necessary to operate the rated-area engine at greater than rated engine speeds in order to maintain constant thrust.

Maximum permissible gas bleed. - The maximum amount of gas that can be bled from the tail pipe of a turbojet engine without exceeding rated turbine-inlet temperature is presented in figure 14 as a function of thrust and altitude for operation with rated engine speed at a flight Mach number of 0.7. Operation at rated turbine-inlet temperature and rated tail-pipe-nozzle area is considered. In figure 14(a), the permissible gas bleed is given in terms of the gas-bleed ratio β, and in figure 14(b), as a fraction of the rated sea-level engine gas flow. Considerably more gas can be bled at a given thrust level at rated turbine-inlet temperature than at rated tail-pipe-nozzle area. For a constant value of thrust, the gas-bleed ratio increases with altitude up to the tropopause for both types of engine operation, with the greater rate of increase occurring for the rated-area operation.

For rated-temperature operation, the maximum gas bleed decreases with altitude because of the decrease in density with altitude (fig. 14(b)). For rated-area operation, the large increase in the gas-bleed ratio β with increasing altitude illustrated in figure 14(a) tends to overcome the decrease in density. As a result, the maximum bleed expressed as a fraction of the rated sea-level gas flow increases with altitude for high values of thrust. Possible changes in engine mass-flow characteristics due to changes in Reynolds number with altitude have been disregarded.

TURBINE-INLET GAS BLEED

Bleeding the same percentage of the engine mass flow from either the turbine inlet or compressor outlet has the same effect on all engine-performance parameters with the exception of the specific fuel consumption. The specific fuel consumption with turbine-inlet bleed can, however, be easily obtained from compressor-outlet-bleed results. Because of this similarity of the two types of bleed, turbine-inlet-bleed working charts and curves for operation with specific modes of engine operation are not presented herein. The compressor-outlet-bleed figures from which turbine-inlet bleed results can be obtained are discussed in the following paragraphs.

In reference 1, the air-bleed ratio β is defined as the ratio of the bleed flow to the compressor air flow. The relation among the tail-pipe-nozzle area, turbine-inlet temperature ratio, thrust, and β can be obtained directly from figures 10 and 13 of reference 1 for either compressor-outlet or turbine-inlet bleed if the definition of β is generalized to the ratio of the bleed flow to the mass flow at the bleed location. For example, the curves of reference 1 are applicable to turbine-inlet bleed where β is defined as the ratio of the bleed flow to the engine gas flow at the turbine inlet; that is, the sum of the engine air flow and the engine fuel flow.

In computing the effects of turbine-inlet bleed on specific fuel consumption, slight modifications must be made in the results obtained from the compressor-outlet-bleed charts (figs. 11 and 14 of reference 1). Because fuel has been added to the gas that is bled from the turbine inlet, the increase in specific fuel consumption due to a given bleed ratio is greater for turbine-inlet bleed than for compressor-outlet bleed. This relation is expressed as

$$\left[\frac{W_f/F_n\sqrt{\theta_2}}{(W_f/F_n\sqrt{\theta_2})_r}\right]_{\substack{\text{turbine-inlet}\\ \text{bleed}}} = \frac{1}{1-\beta}\left[\frac{W_f/F_n\sqrt{\theta_2}}{(W_f/F_n\sqrt{\theta_2})_r}\right]_{\substack{\text{compressor-outlet}\\ \text{bleed}}}$$

For example, for a bleed ratio of 0.10, the specific fuel consumption with turbine-inlet bleed would be 11.1 percent higher than with compressor-outlet bleed.

The power removed by a given rate of bleed at the turbine inlet is greater than that removed by the same bleed rate at the compressor outlet because of the higher temperature existing at the turbine inlet. The power-removal factor for turbine-inlet bleed can be approximated from the power-removal factor of reference 1 by the relation

$$\left[\frac{Q/\delta_2\sqrt{\theta_2}}{(F_n/\delta_2)_r}\right]_{\substack{\text{turbine-inlet}\\ \text{bleed}}} = \frac{C_{p,4-2}\left(\frac{T_4}{T_2}-1\right)}{C_{p,2-3}\left(\frac{T_3}{T_2}-1\right)}\left[\frac{Q/\delta_2\sqrt{\theta_2}}{(F_n/\delta_2)_r}\right]_{\substack{\text{compressor-outlet}\\ \text{bleed}}}$$

where $C_{p,2-3}$ is the average value of the specific heat of air through the compression process and $C_{p,4-2}$ is the average value of the specific heat of the bleed gas for the heat-extraction process between the turbine-inlet total temperature and the engine-inlet total temperature.

The effect of turbine-inlet bleed for specific modes of engine operation can be obtained from reference 2. The modes presented are constant turbine-inlet temperature and constant-thrust operation with fixed and variable tail-pipe-nozzle areas. The effect of altitude, compressor-inlet temperature, and flight Mach number on engine performance with bleed is shown. These results can be applied to turbine-inlet bleed if the modifications presented herein are used.

COMPARISON OF TURBINE-INLET AND TAIL-PIPE GAS BLEED

A comparison of the effects of turbine-inlet and tail-pipe gas bleed at an altitude of 20,000 feet and a flight Mach number of 0.7 is presented in figure 15. The turbine-inlet-bleed performance was obtained from references 1 and 2 and the tail-pipe bleed performance was obtained from figures 3 and 9 of the present report. For both types of bleed, variable tail-pipe-nozzle area operation at rated turbine-inlet temperature and rated engine speed is presented. Operation at the maximum thrust level possible with a rated-area tail-pipe nozzle without exceeding either rated engine speed or rated turbine-inlet temperature is also considered. (The turbine-inlet temperature is held constant for turbine-inlet bleed and the engine speed is held constant for tail-pipe bleed.)

The amount of energy available from a given turbine-inlet bleed ratio does not differ appreciably for the two modes of engine operation shown. When gas is bled from the tail pipe, appreciably more energy is available with a variable-area nozzle than with a constant-area nozzle. For example, a gas-bleed ratio of 0.04 provides 14 percent more energy when removed from a tail pipe equipped with a variable-area nozzle than when taken from a tail pipe with a constant-area nozzle. The difference in energy arises from the loss in tail-pipe temperature as gas is bled from a tail pipe with a constant-area nozzle. A comparison of turbine-inlet bleed and tail-pipe bleed, both with variable-area nozzle, shows an advantage of about 20 percent for the turbine-inlet bleed insofar as available energy is concerned.

A comparison of the effects on thrust and specific fuel consumption of removing the same amount of energy by means of turbine-inlet and tail-pipe bleeds can also be obtained from figure 15. For variable-area operation at an energy removal of 1000 Btu per hour per pound of rated thrust, bleed ratios of 0.08 and 0.065 are required from tail-pipe bleed and turbine-inlet bleeds, respectively. The resultant decreases in thrust are 12 and 15 percent and the increases in specific fuel consumption are 13 and 18 percent for tail-pipe and turbine-inlet bleeds, respectively. Thus, less severe performance penalties result from bleeding a given quantity of energy from the tail pipe than from the turbine inlet with variable-area operation even though a larger percentage gas bleed is required. For constant-area operation, however, the rapid depreciation of engine performance with tail-pipe gas bleed causes the turbine-inlet-bleed source to become a more favorable source of energy.

SUMMARY OF RESULTS

An investigation was made of the effects of hot-gas bleed from the tail pipe and the turbine inlet on the performance of a typical axial-flow-type turbojet engine. From the results presented herein, it can be generalized that with a turbojet engine running at constant engine speed, bleeding gas from the tail pipe at constant tail-pipe-nozzle area and reduced turbine-inlet temperature caused 2.5 to 4 times as great a loss in thrust as bleeding gas at constant turbine-inlet temperature and reduced tail-pipe-nozzle area.

The performance penalty due to tail-pipe bleed was essentially independent of engine-inlet temperature and increased with flight Mach number for both rated turbine-inlet temperature and rated tail-pipe-nozzle area operation. For constant turbine-inlet temperature operation, the performance penalty due to tail-pipe gas bleed was essentially independent of engine speed, turbine-inlet temperature, and altitude. An increase in either engine speed or altitude reduced the performance penalty due to tail-pipe gas bleed with a rated-area tail-pipe nozzle.

A comparison of turbine-inlet and tail-pipe bleed indicated that for variable-area operation, smaller performance penalties resulted from removing a given amount of energy from the tail pipe than from the turbine inlet. The reverse trend is experienced for bleed with a constant tail-pipe-nozzle area.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, October 18, 1950.

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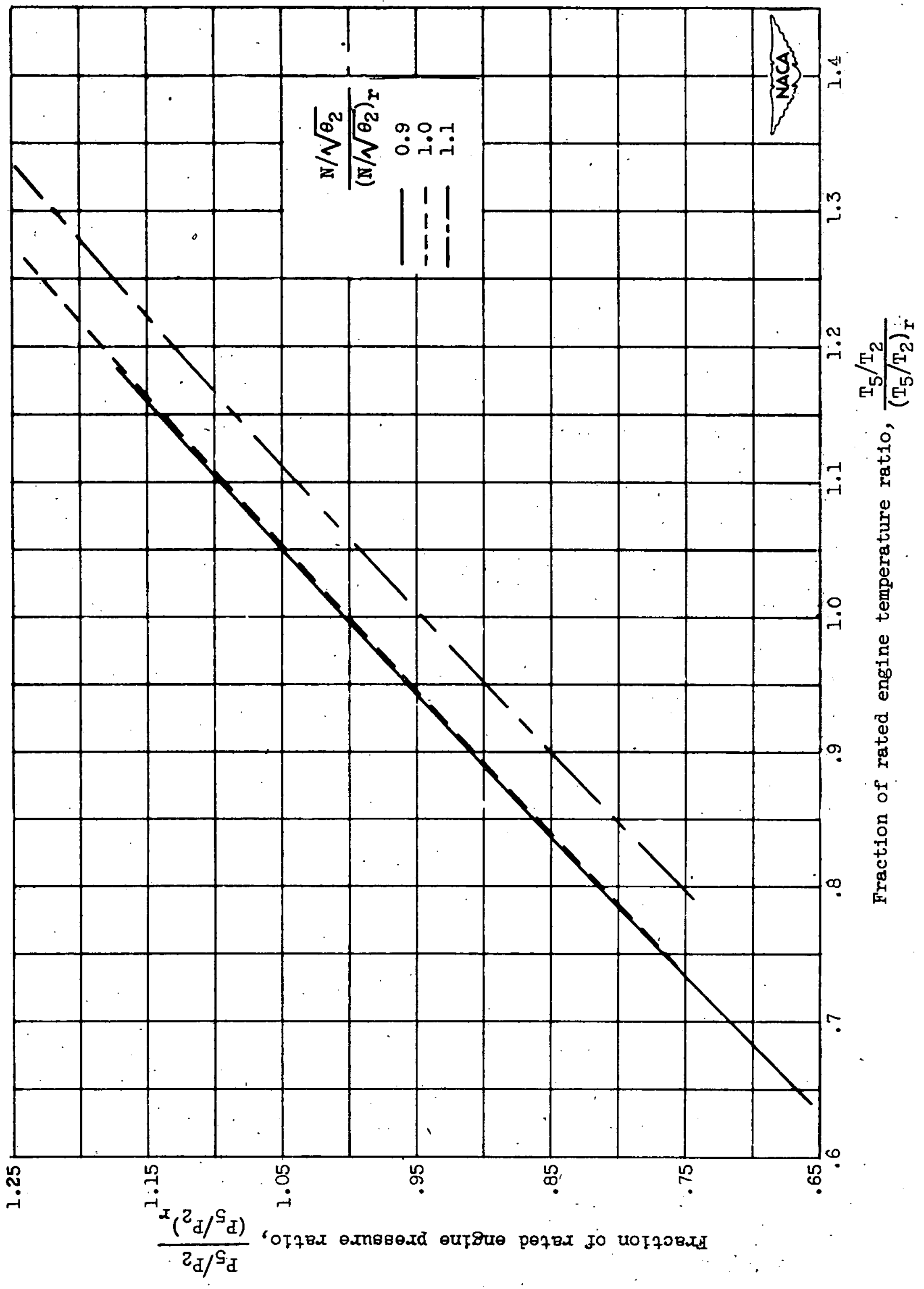

Figure 1. - Variation of engine pressure ratio with engine temperature ratio.

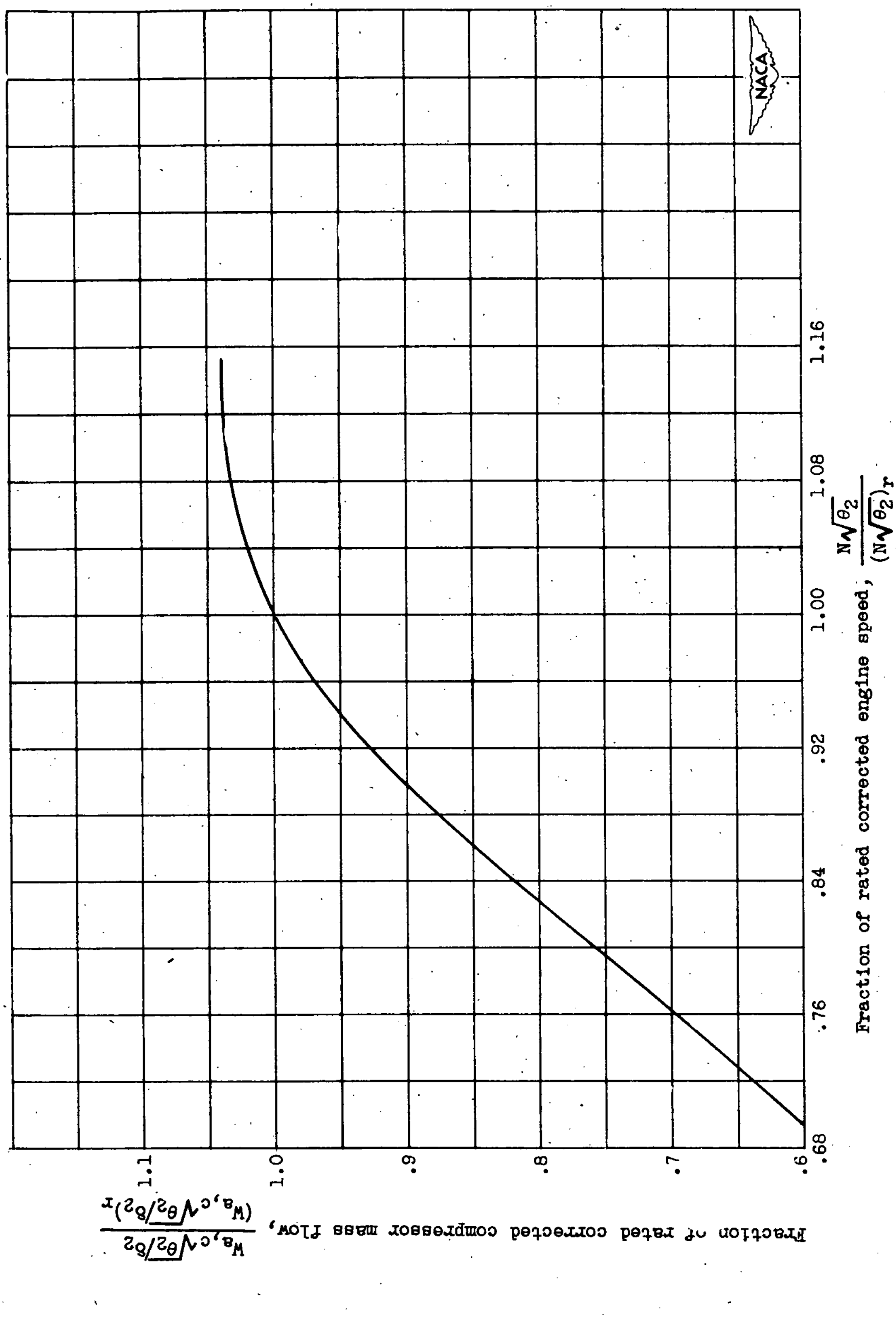

Figure 2. - Engine mass-flow characteristic.

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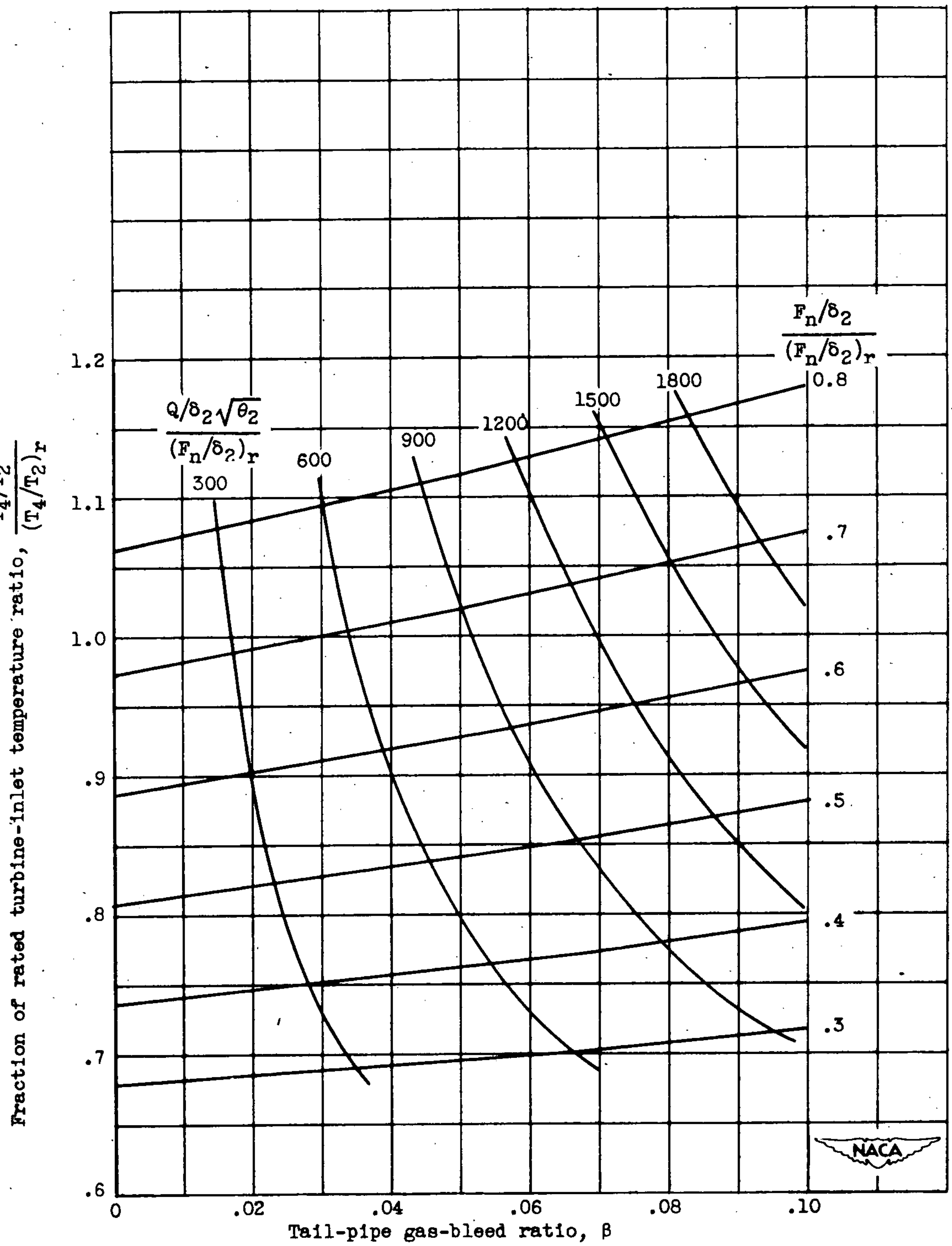
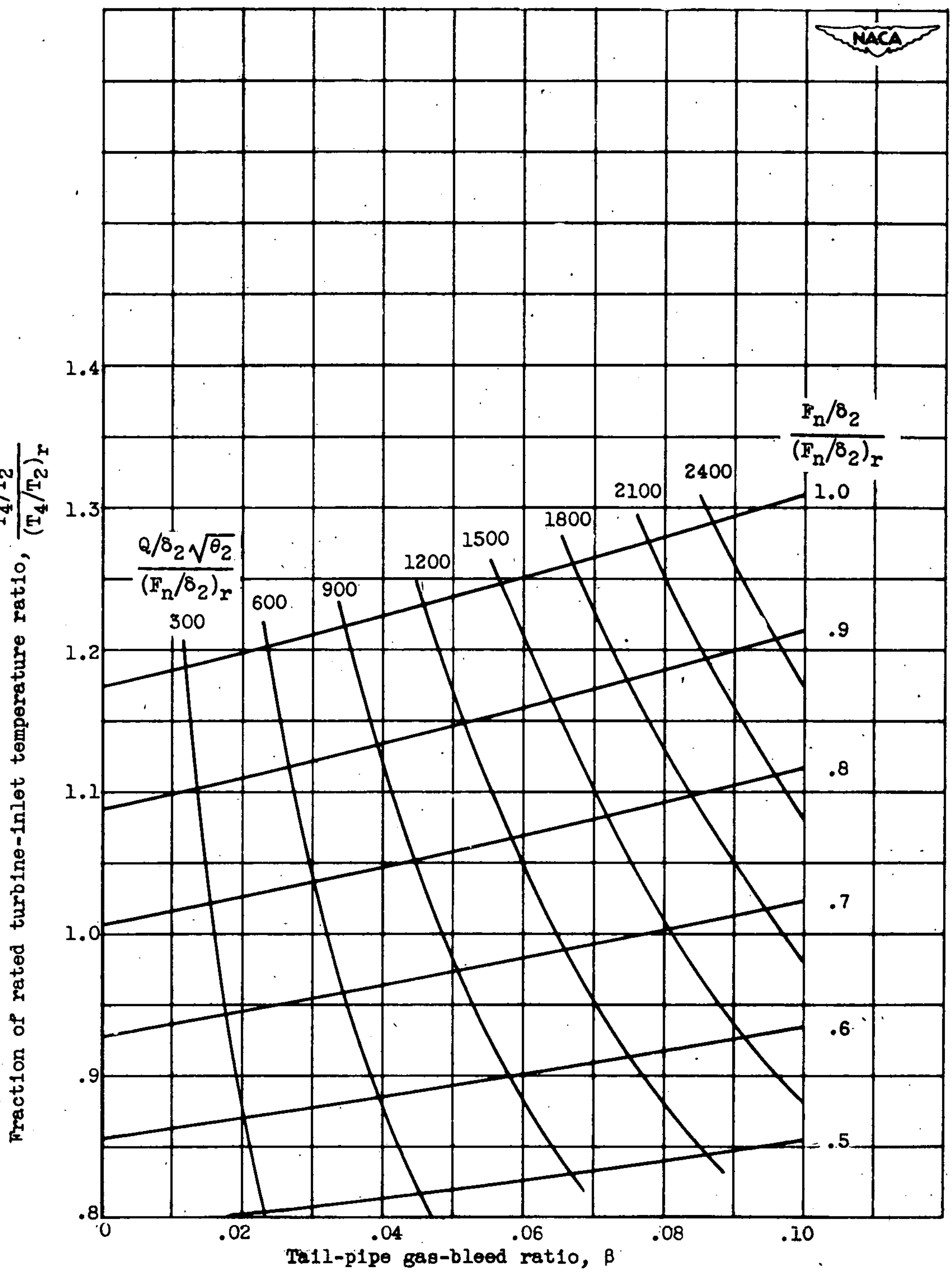


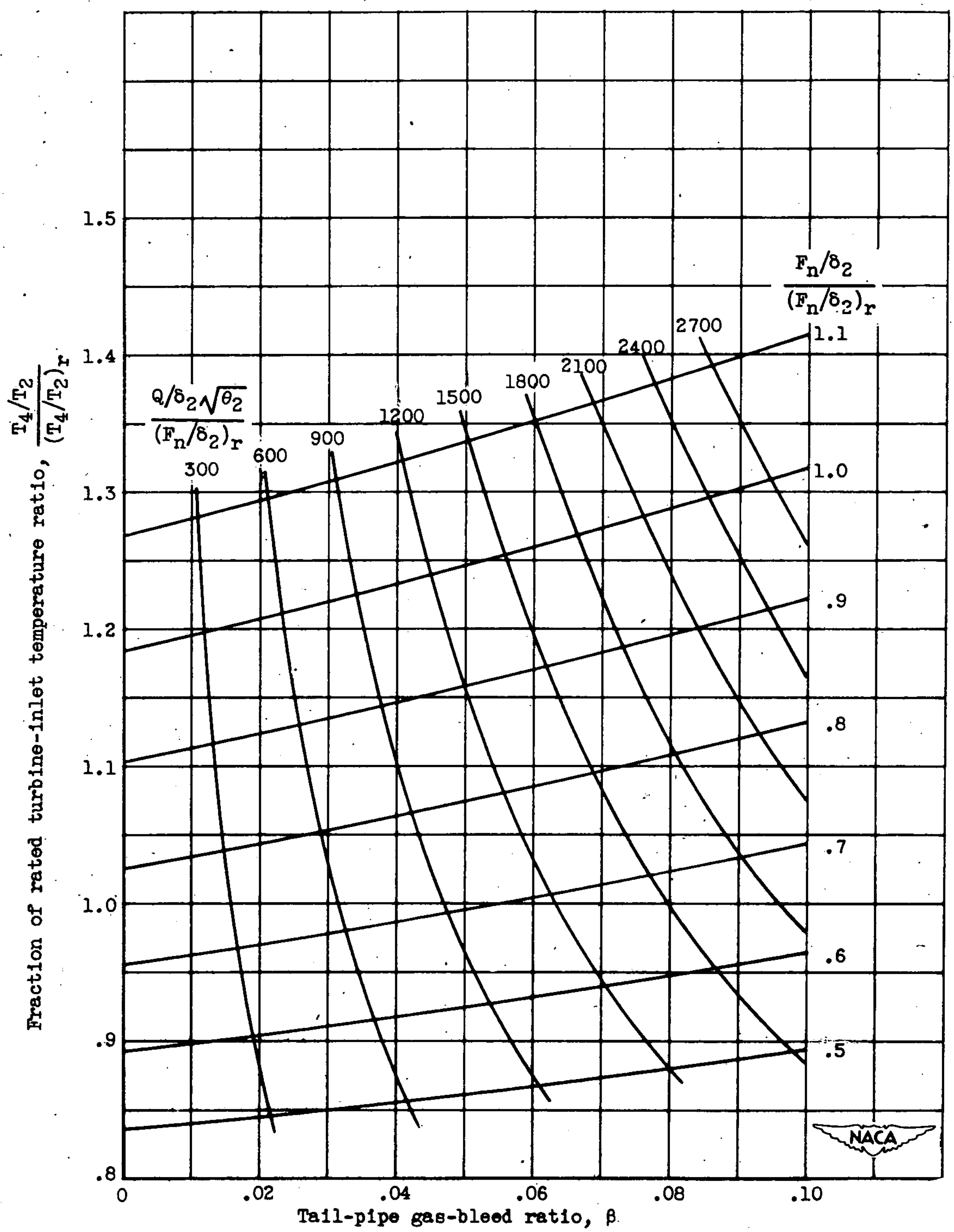
(a) Corrected engine speed, 0.9 rated.

Figure 3. - Variation of turbine-inlet temperature ratio and power-removal factor with tail-pipe gas bleed and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 1.35.



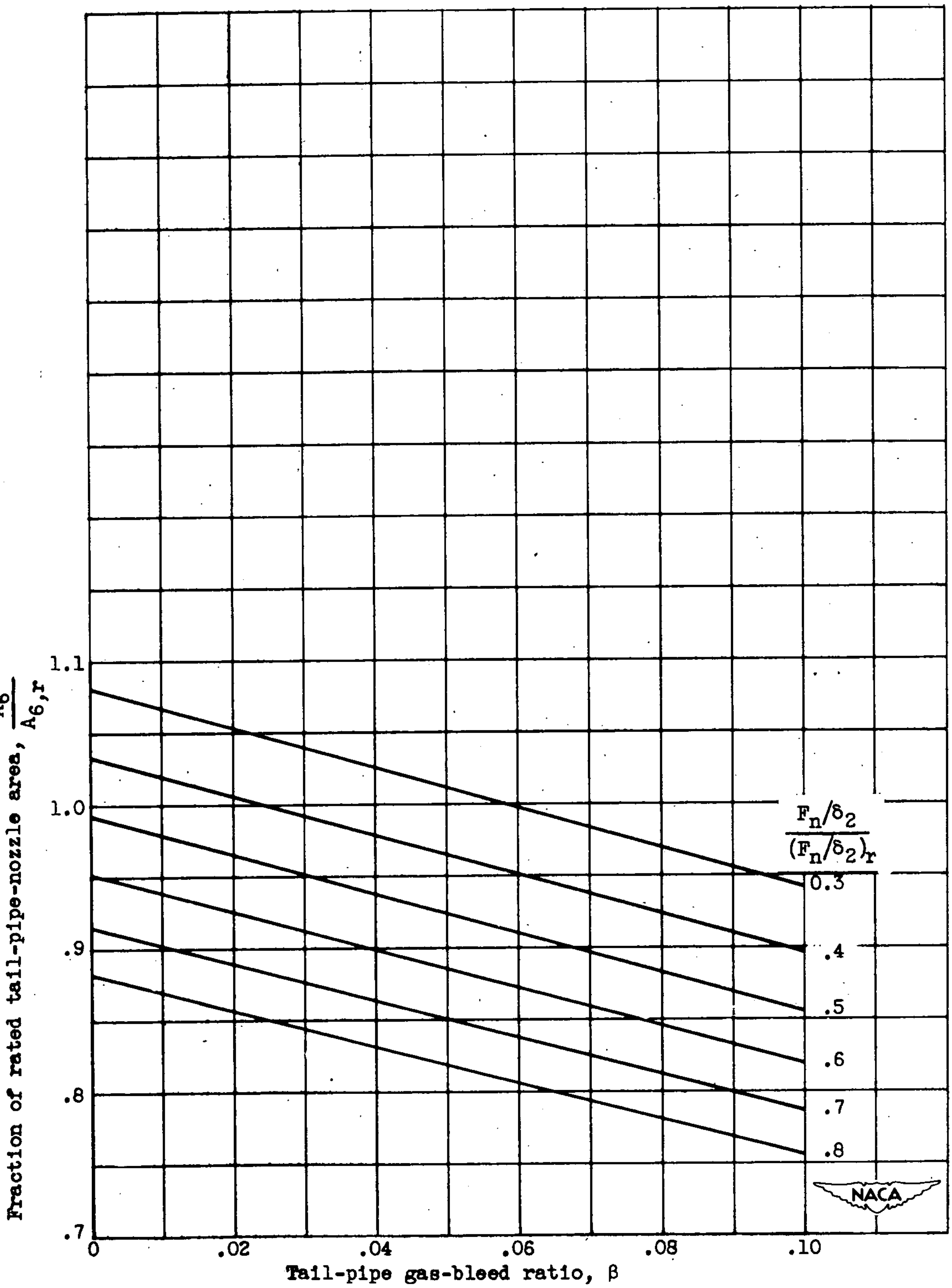
(b) Corrected engine speed, rated.

Figure 3. - Continued. Variation of turbine-inlet temperature ratio and power-removal factor with tail-pipe gas bleed and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 1.35.



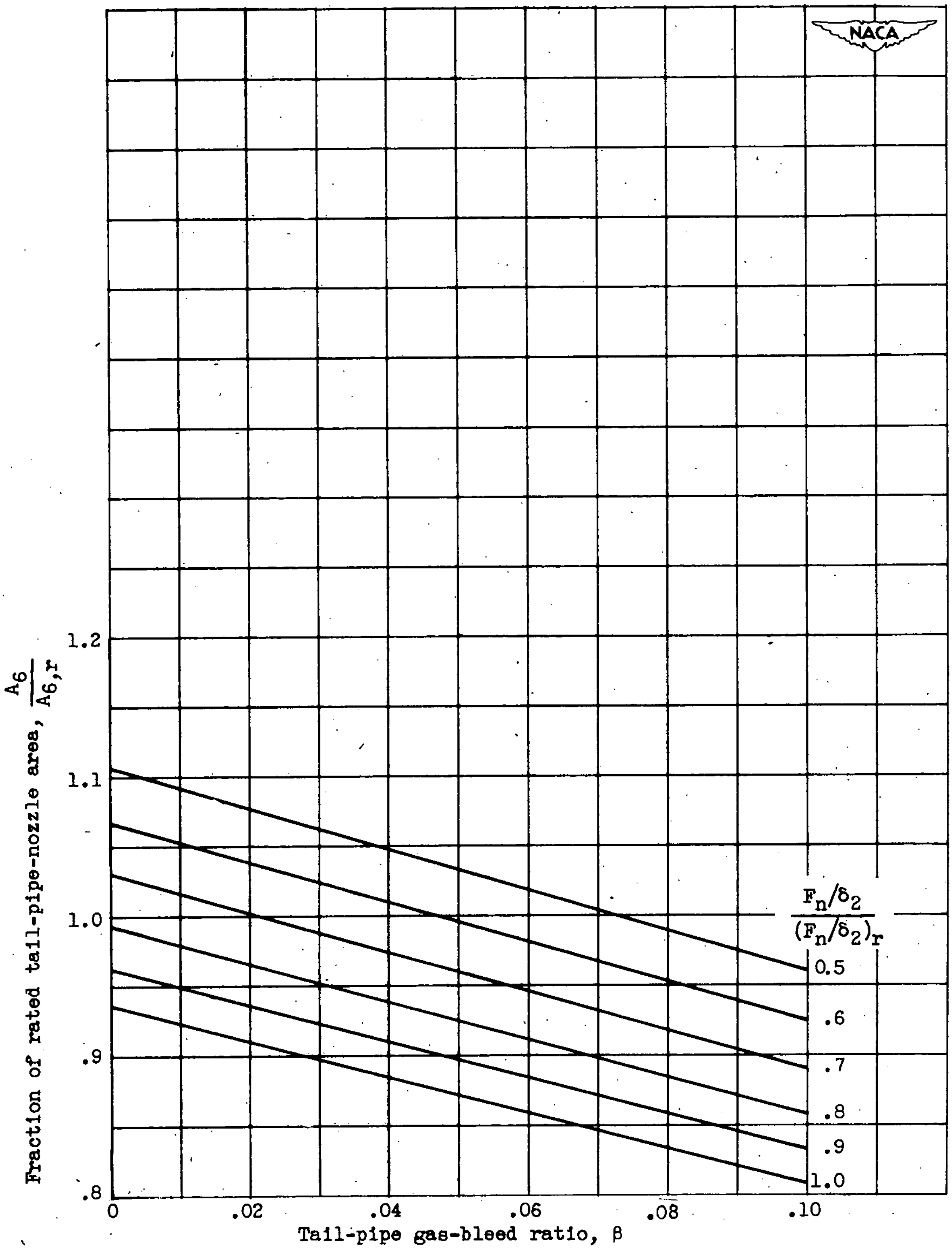
(c) Corrected engine speed, 1.1 rated.

Figure 3. - Concluded. Variation of turbine-inlet temperature ratio and power-removal factor with tail-pipe gas bleed and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 1.35.



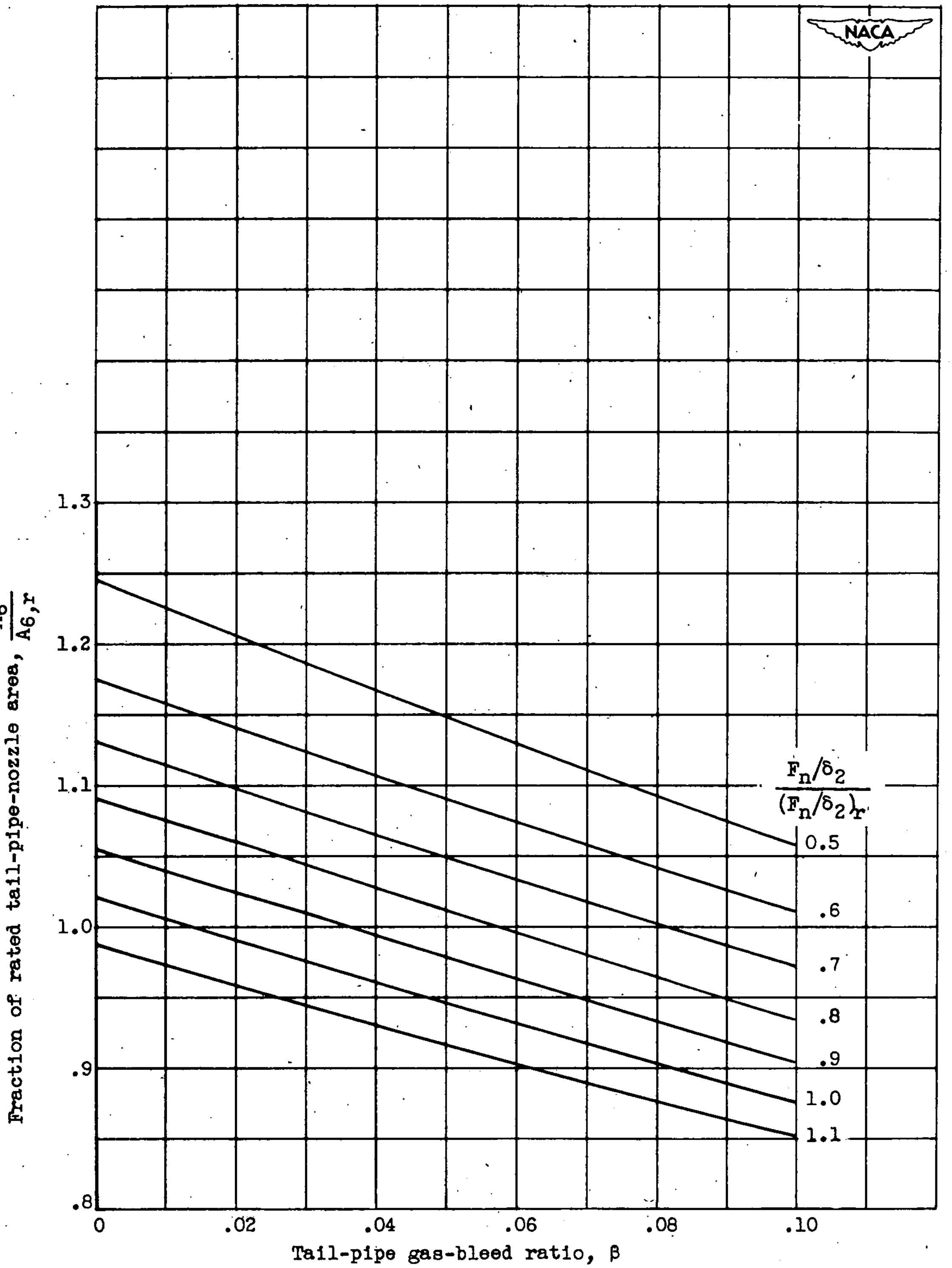
(a) Corrected engine speed, 0.9 rated.

Figure 4. - Variation of tail-pipe-nozzle area with tail-pipe gas bleed and thrust for ram pressure ratio of 1.35.



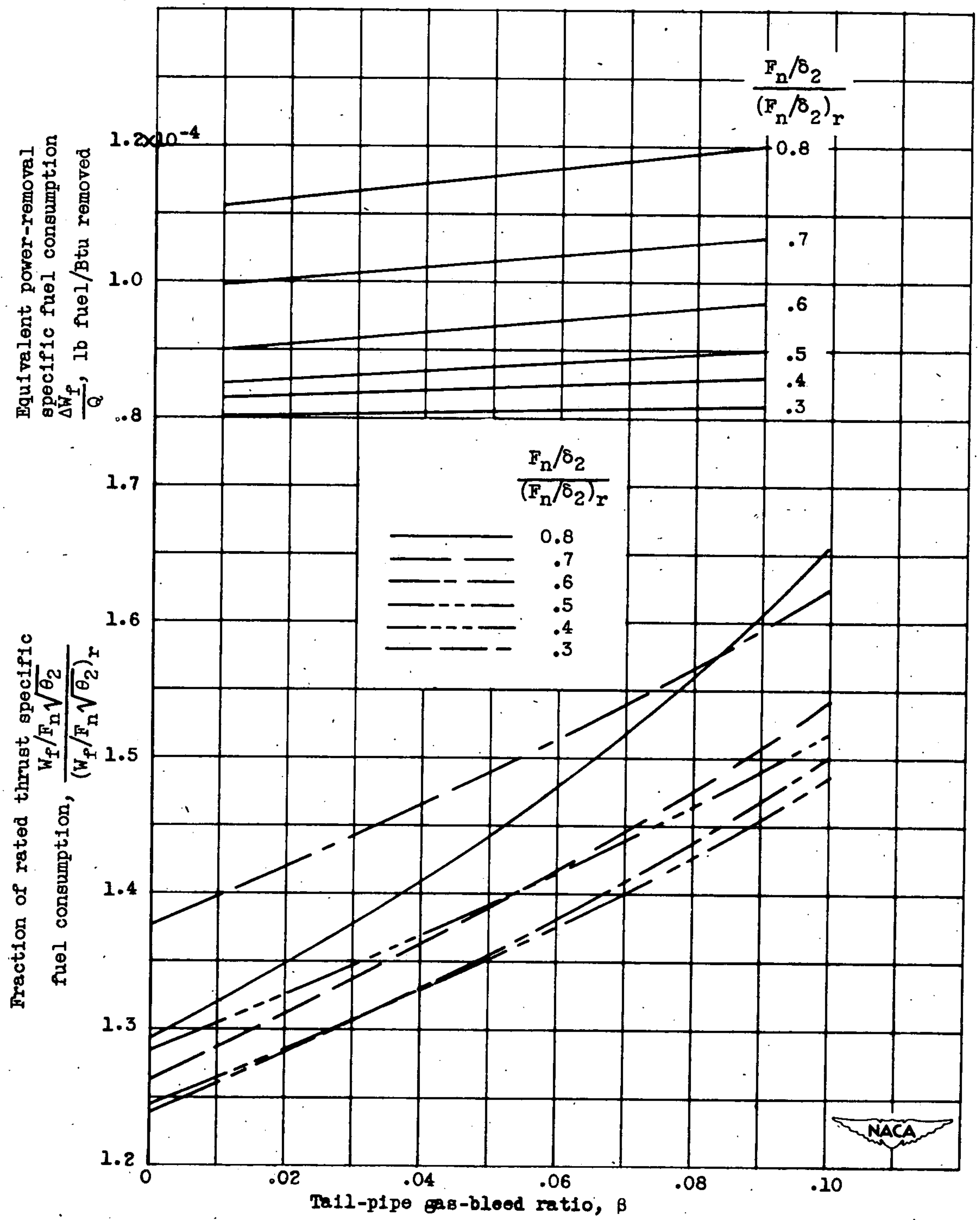
(b) Corrected engine speed, rated.

Figure 4. - Continued. Variation of tail-pipe-nozzle area with tail-pipe gas bleed and thrust for ram pressure ratio of 1.35.



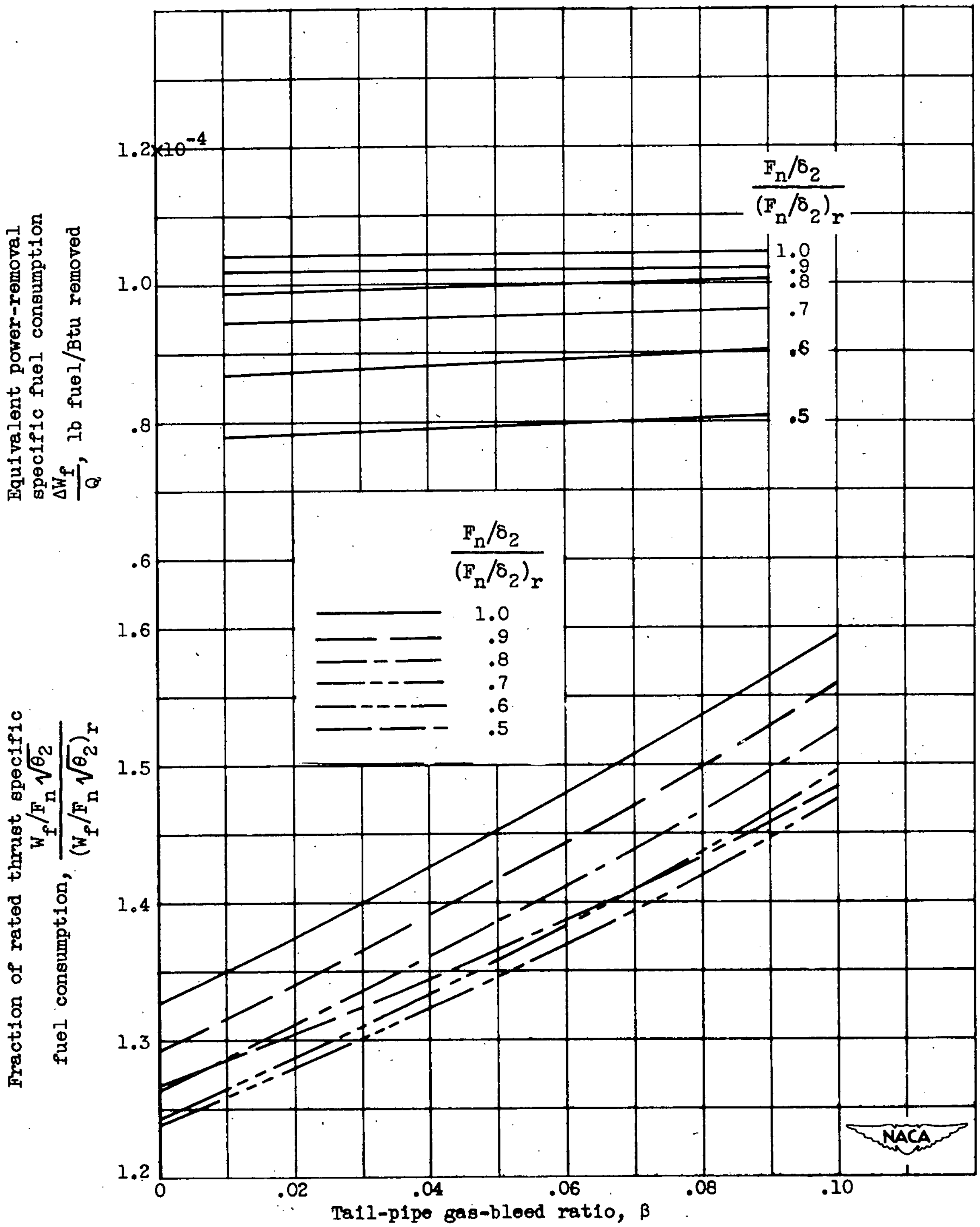
(c) Corrected engine speed, 1.1 rated.

Figure 4. - Concluded. Variation of tail-pipe-nozzle area with tail-pipe gas bleed and thrust for ram pressure ratio of 1.35.



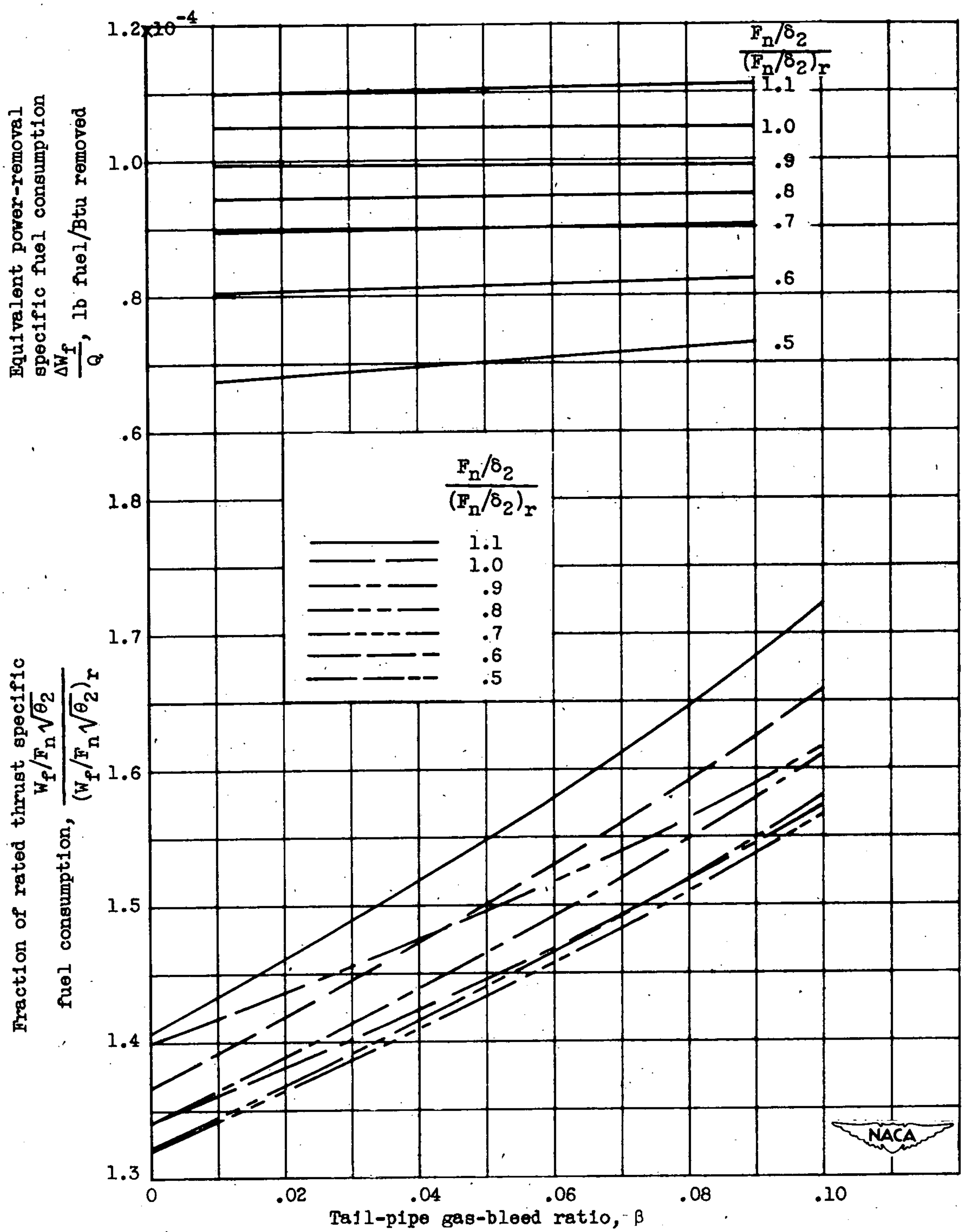
(a) Corrected engine speed, 0.9 rated.

Figure 5. - Variation of specific fuel consumption with tail-pipe gas bleed and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 1.35.



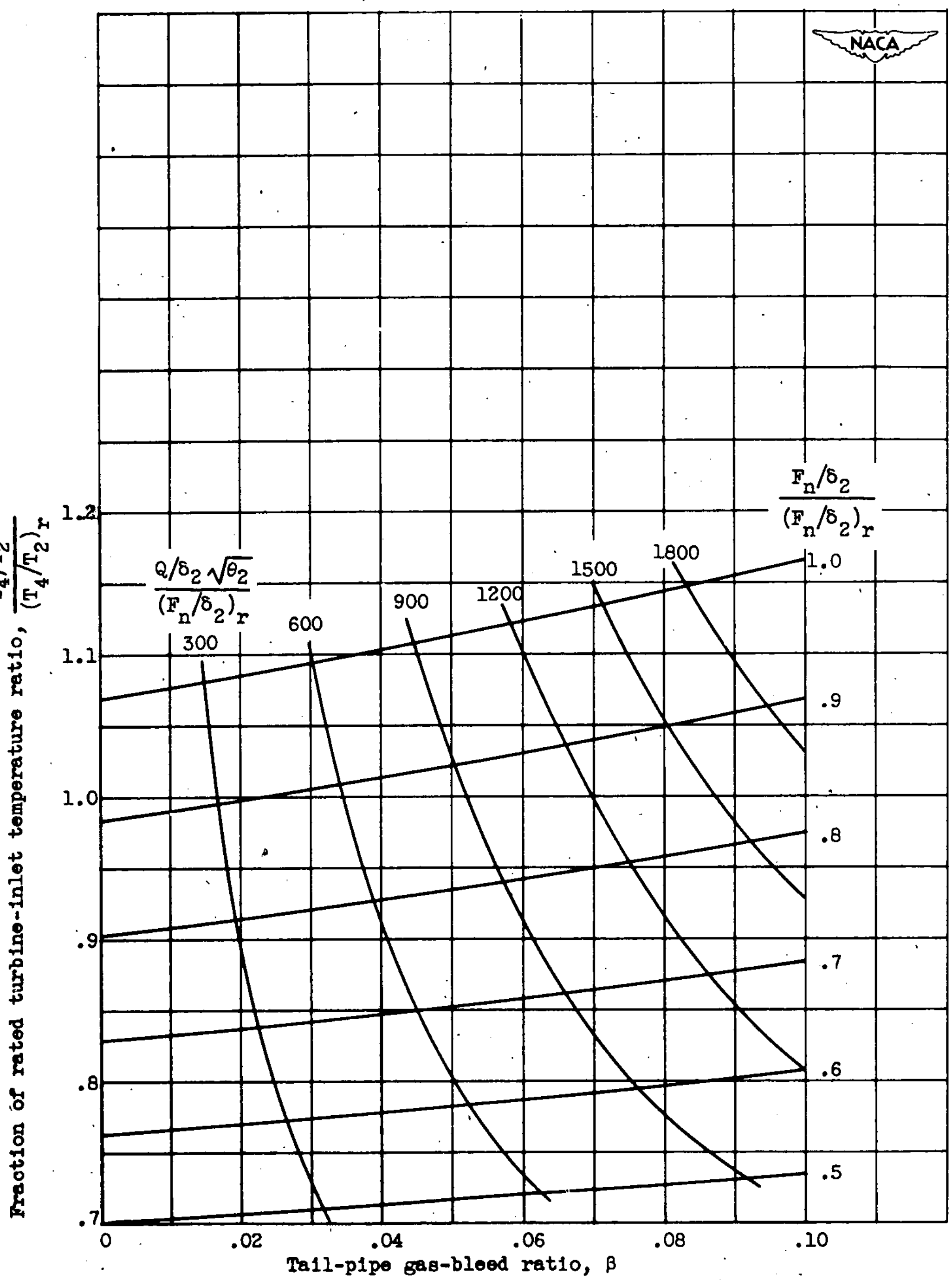
(b) Corrected engine speed, rated.

Figure 5. - Continued. Variation of specific fuel consumption with tail-pipe gas bleed and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 1.35.



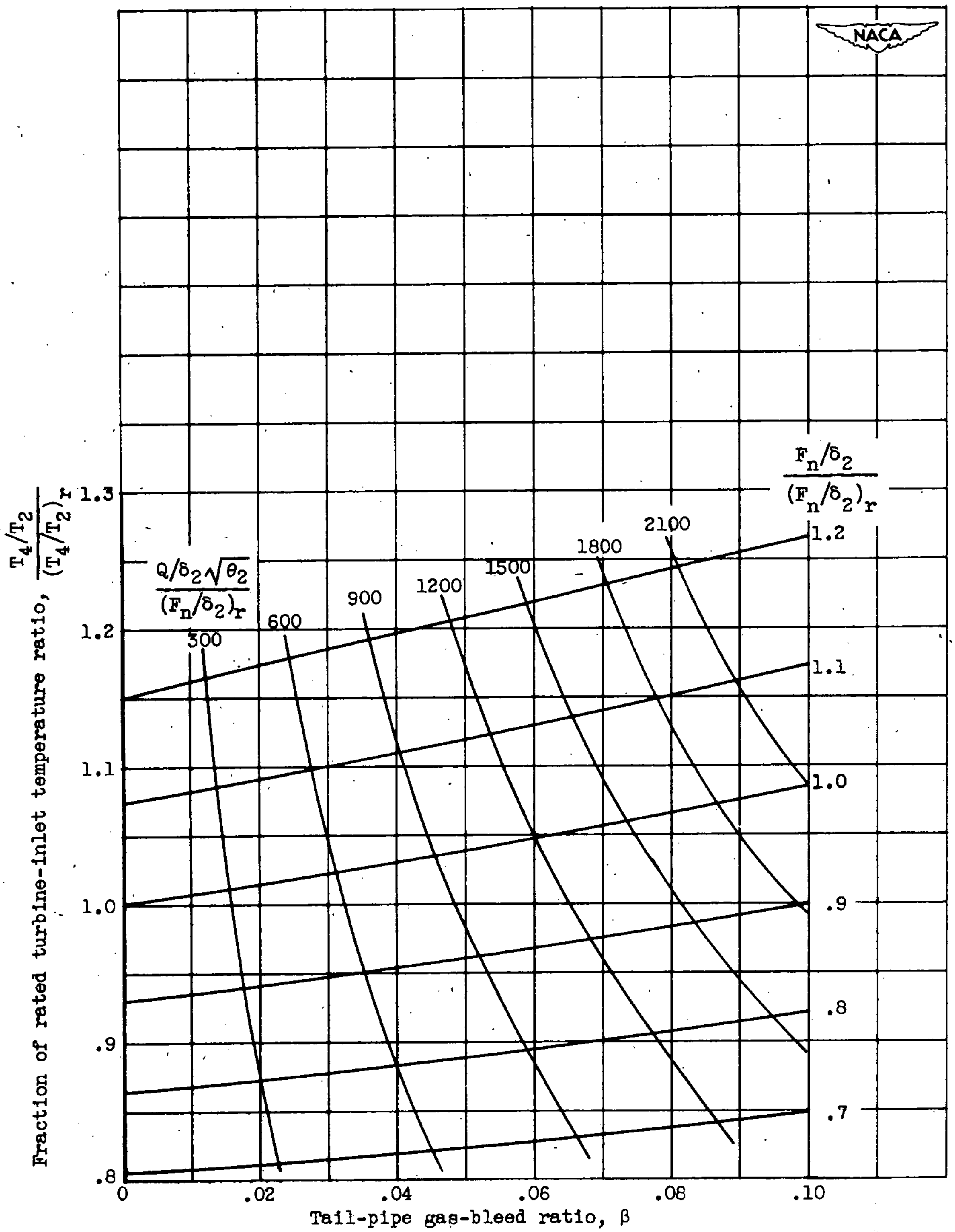
(c) Corrected engine speed, 1.1 rated.

Figure 5. - Concluded. Variation of specific fuel consumption with tail-pipe gas bleed and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 1.35.



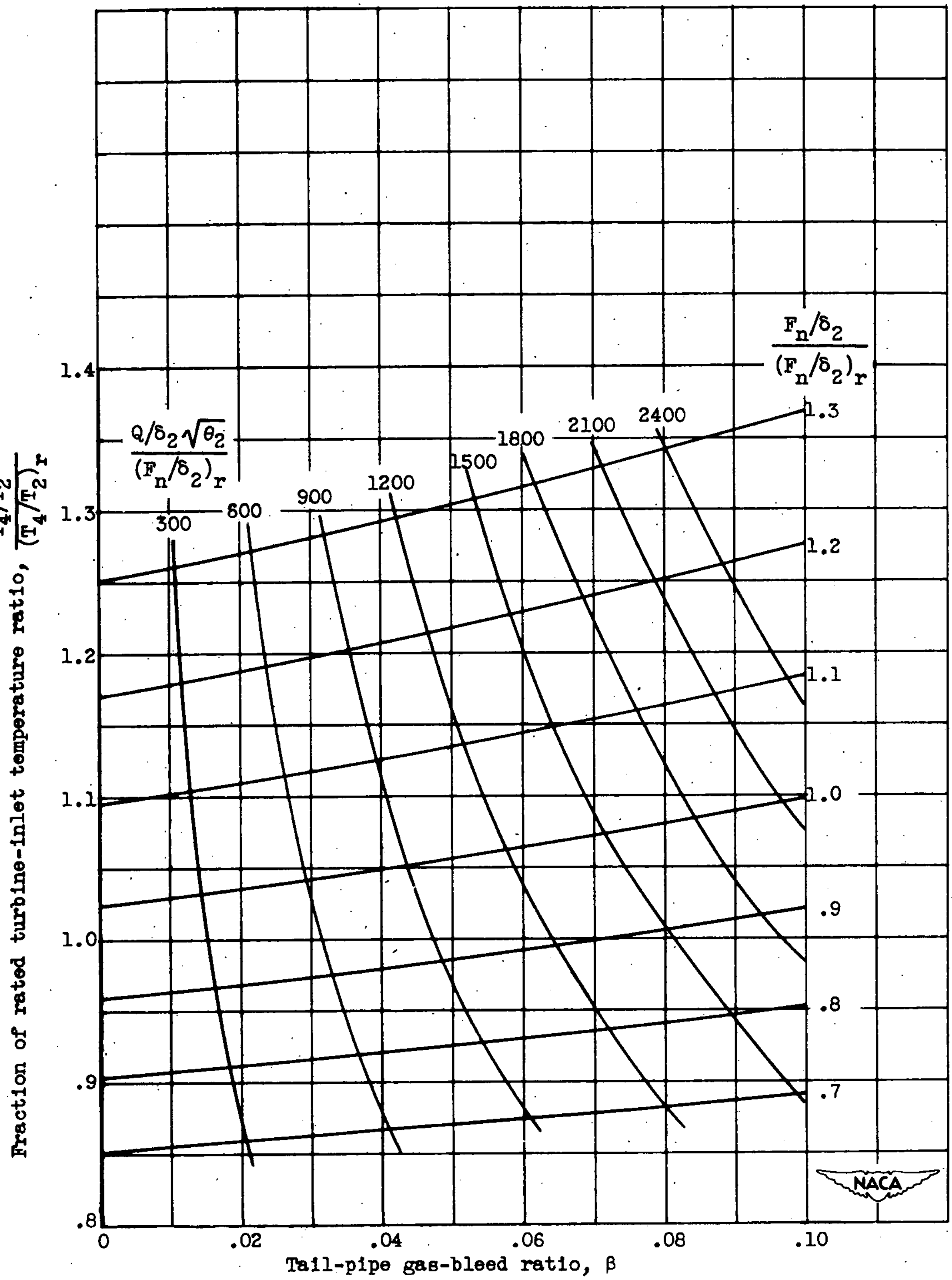
(a) Corrected engine speed, 0.9 rated.

Figure 6. - Variation of turbine-inlet temperature ratio and power-removal factor with tail-pipe gas bleed and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 0.99.



(b) Corrected engine speed, rated.

Figure 6. - Continued. Variation of turbine-inlet temperature ratio and power-removal factor with tail-pipe gas bleed and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 0.99.



(c) Corrected engine speed, 1.1 rated.

Figure 6. - Concluded. Variation of turbine-inlet temperature ratio and power-removal factor with tail-pipe gas bleed and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 0.99.

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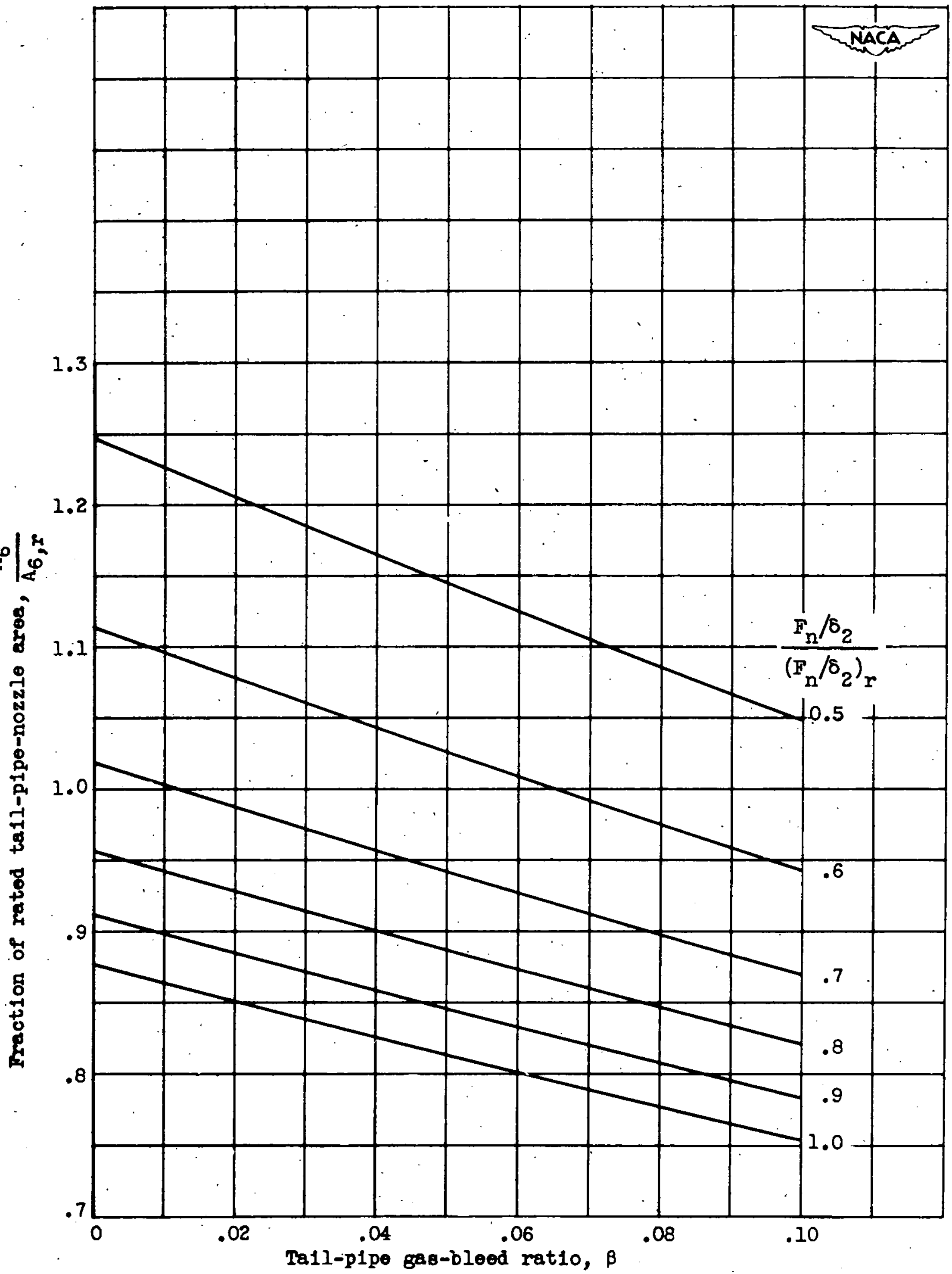
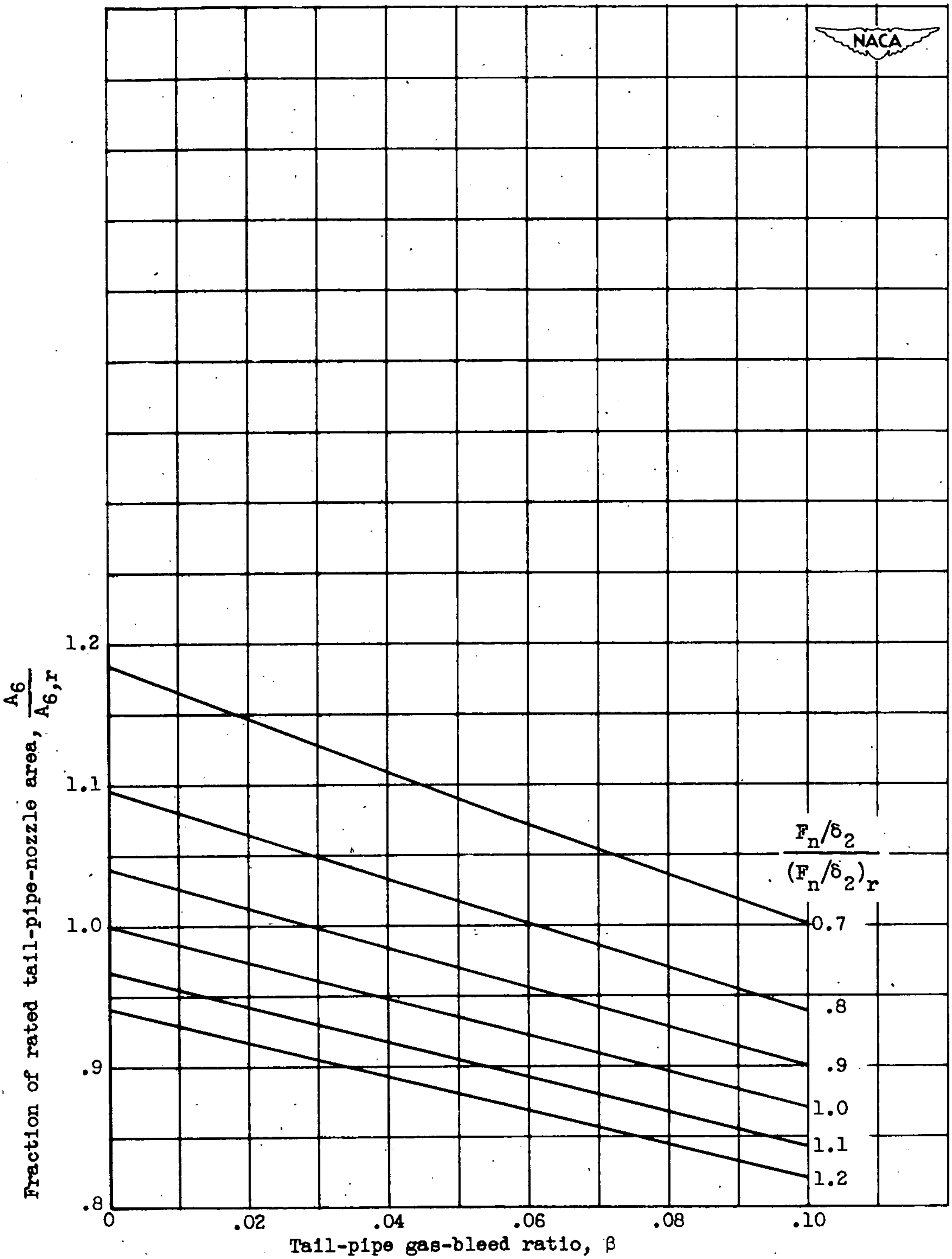


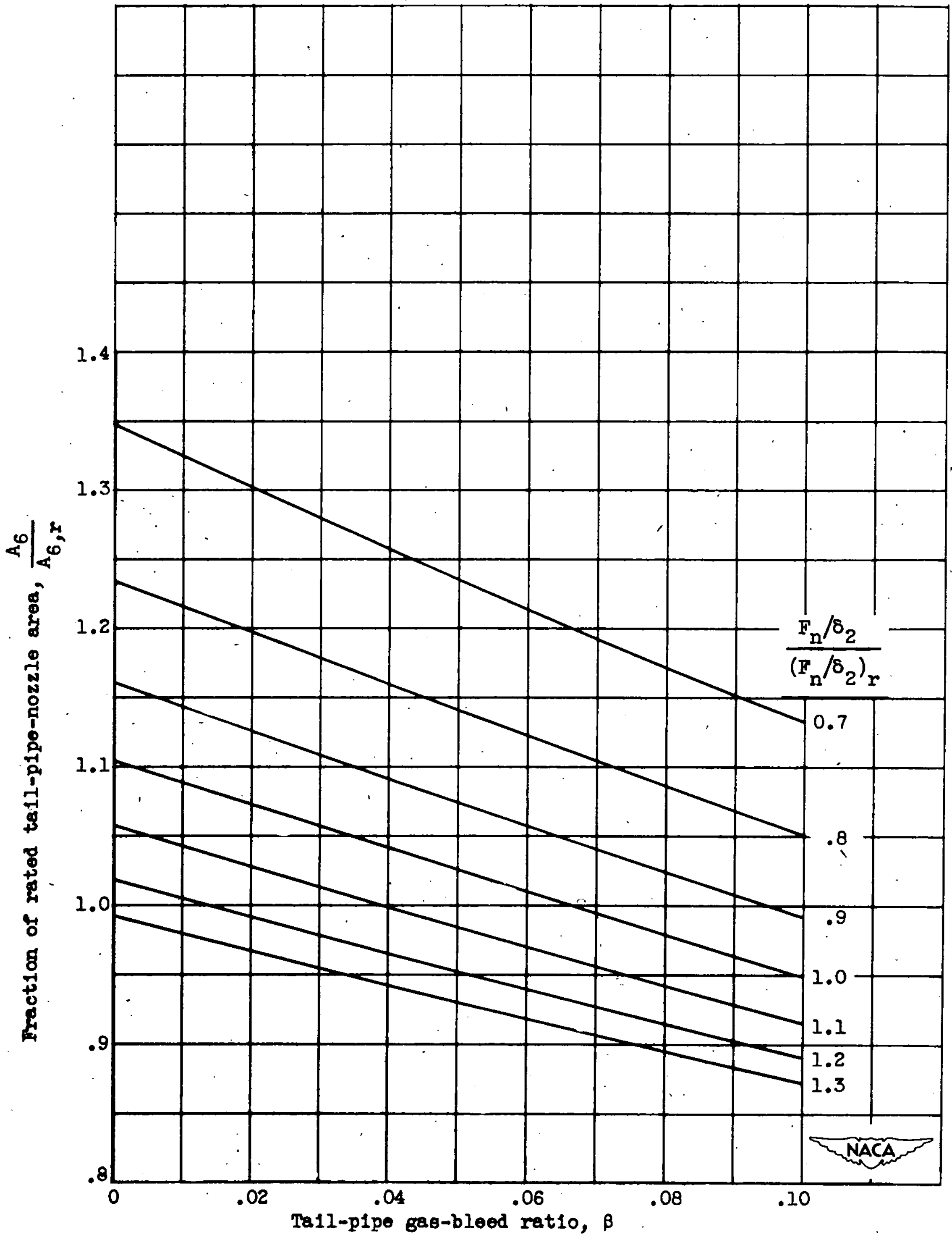
(a) Corrected engine speed, 0.9 rated.

Figure 7. - Variation of tail-pipe-nozzle area with tail-pipe gas bleed and thrust for ram pressure ratio of 0.99.



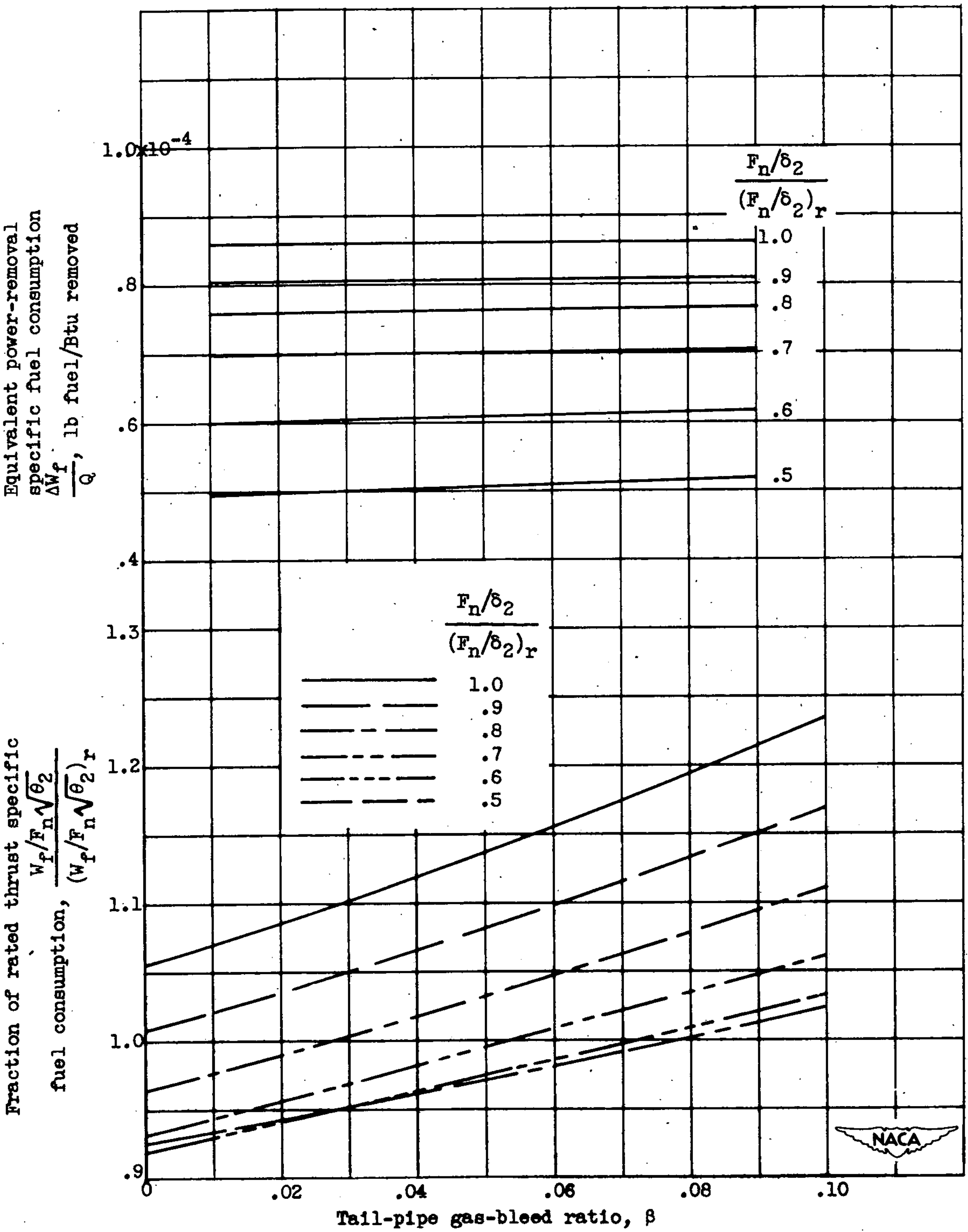
(b) Corrected engine speed, rated.

Figure 7. - Continued. Variation of tail-pipe-nozzle area with tail-pipe gas bleed and thrust for ram pressure ratio of 0.99.



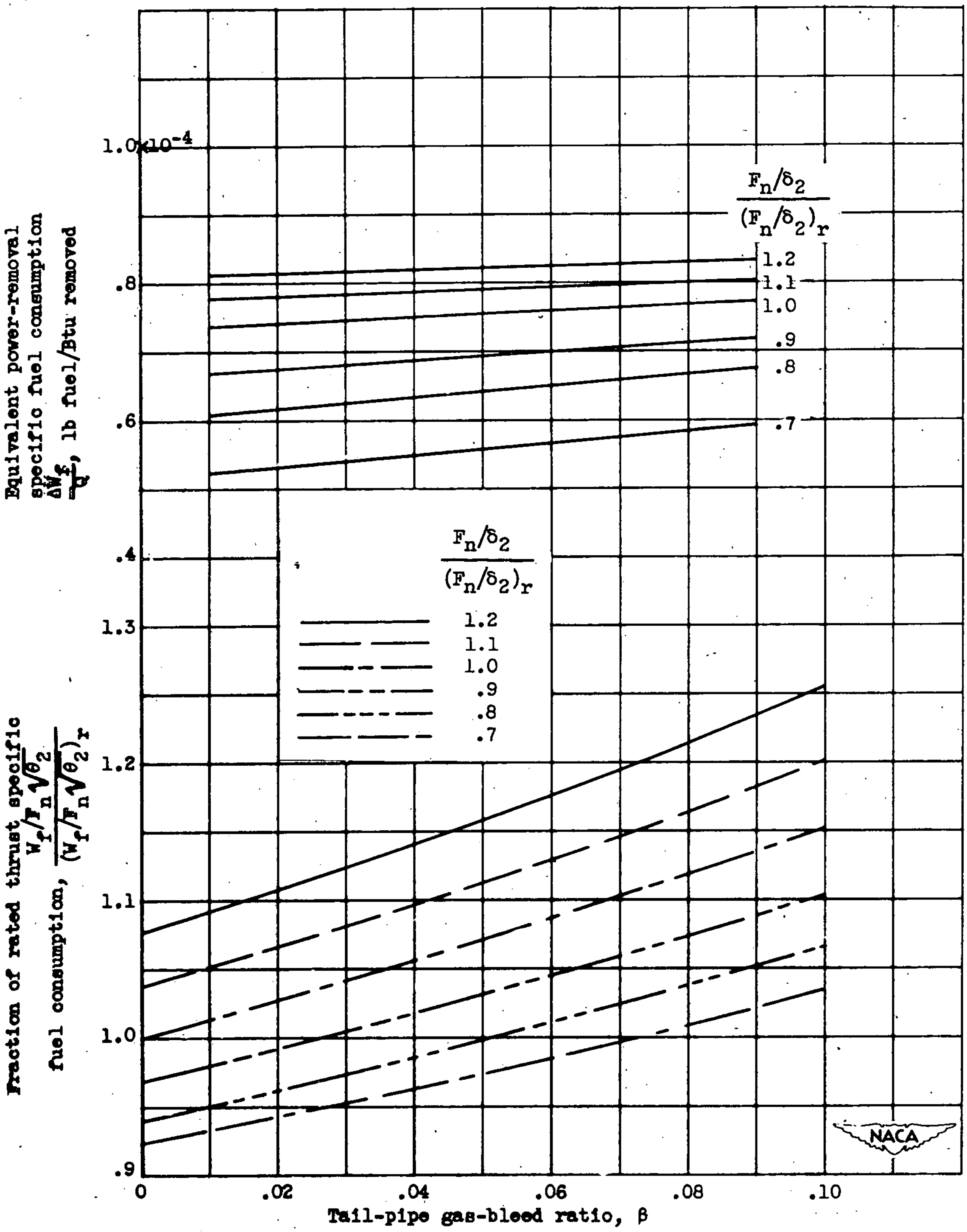
(c) Corrected engine speed, 1.1 rated.

Figure 7. - Concluded. Variation of tail-pipe-nozzle area with tail-pipe gas bleed and thrust for ram pressure ratio of 0.99.



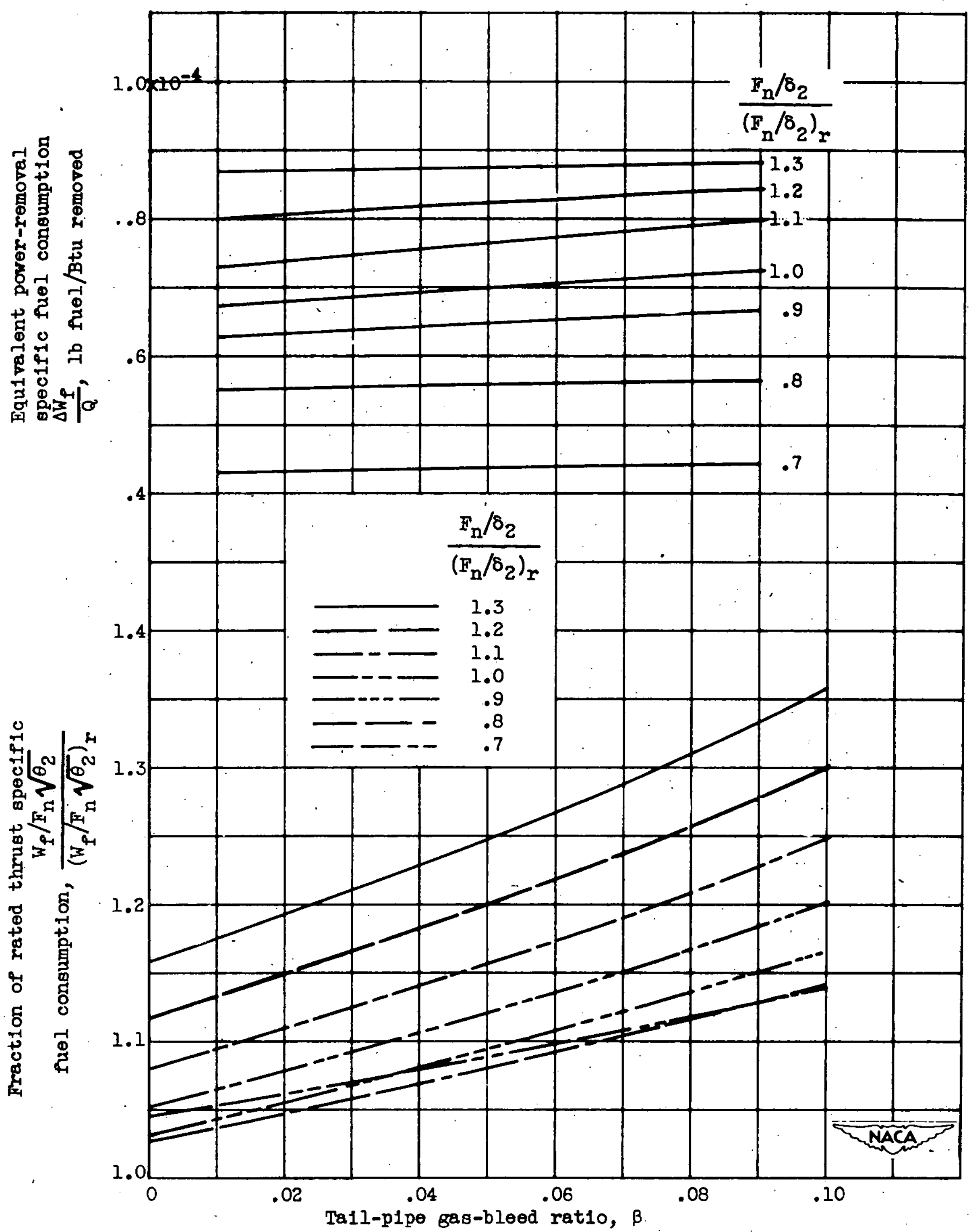
(a) Corrected engine speed, 0.9 rated.

Figure 8. - Variation of specific fuel consumption with tail-pipe gas bleed and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 0.99.



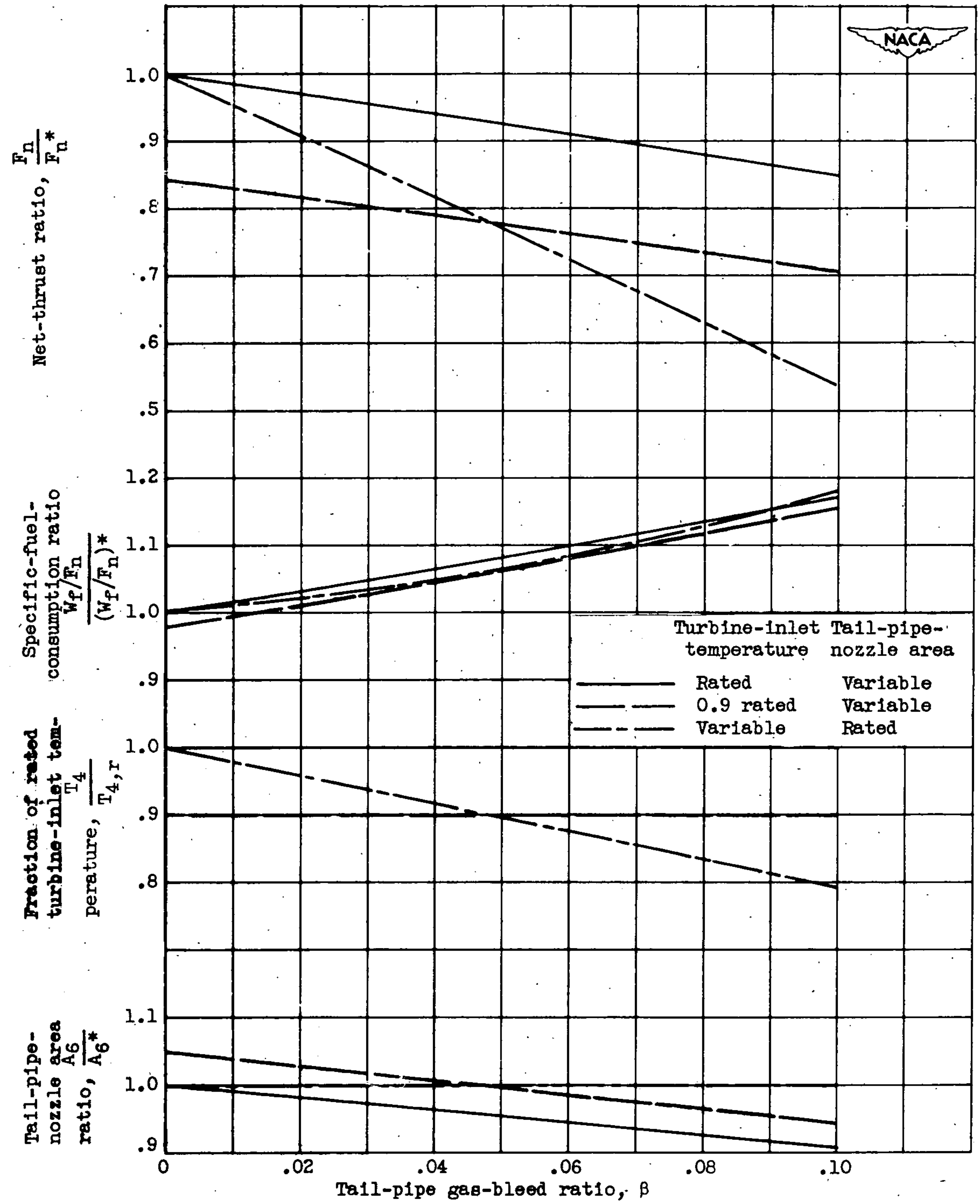
(b) Corrected engine speed, rated.

Figure 8. - Continued. Variation of specific fuel consumption with tail-pipe gas bleed and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 0.99.



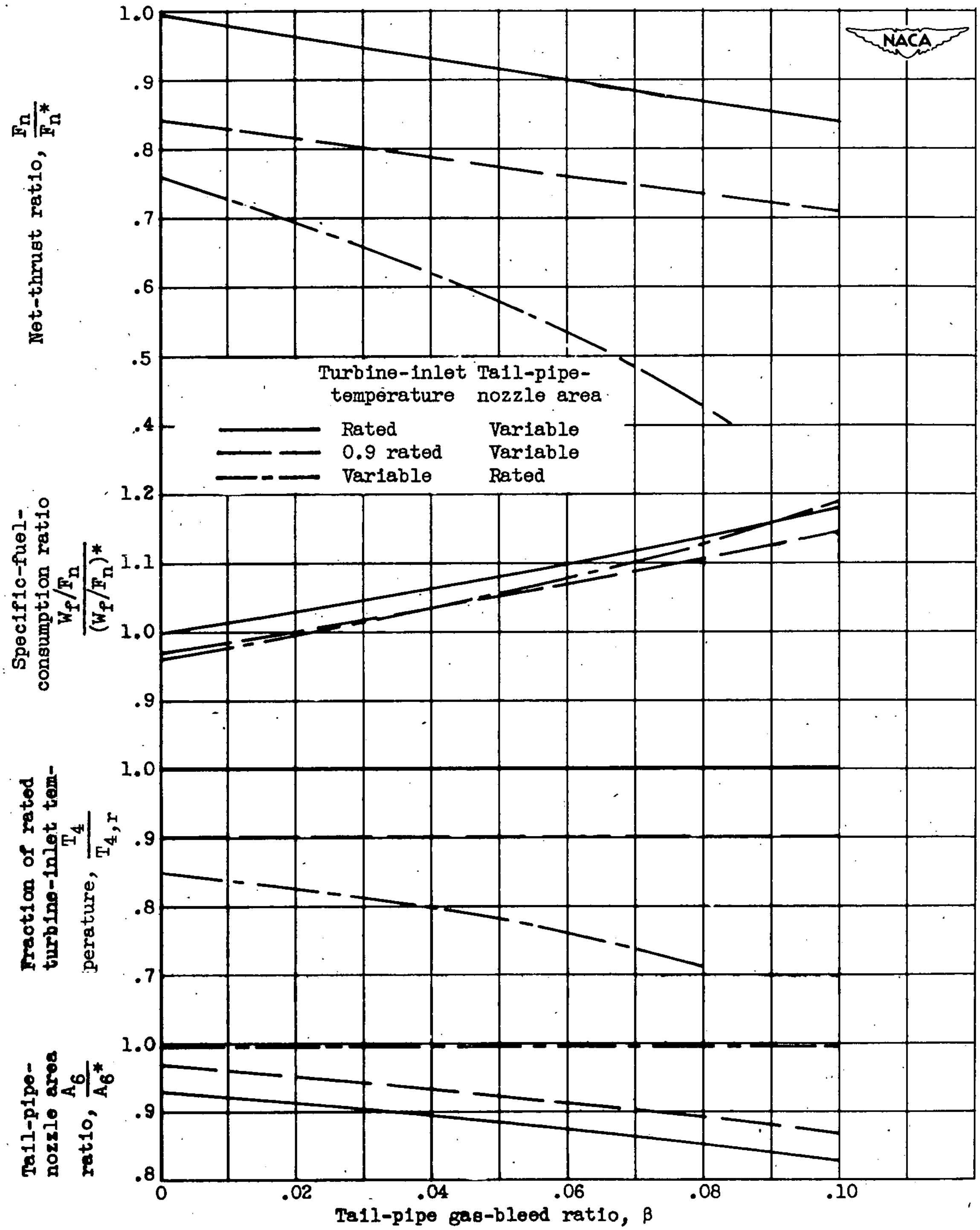
(c) Corrected engine speed, 1.1 rated.

Figure 8. - Concluded. Variation of specific fuel consumption with tail-pipe gas bleed and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 0.99.



(a) Rated engine speed.

Figure 9. - Effect of tail-pipe gas bleed on engine performance with variable- and rated-area tail-pipe nozzles. Altitude, 20,000 feet; Mach number, 0.7.



(b) 0.93 rated engine speed.

Figure 9. - Concluded. Effect of tail-pipe gas bleed on engine performance with variable- and rated-area tail-pipe nozzles. Altitude, 20,000 feet; Mach number, 0.7.

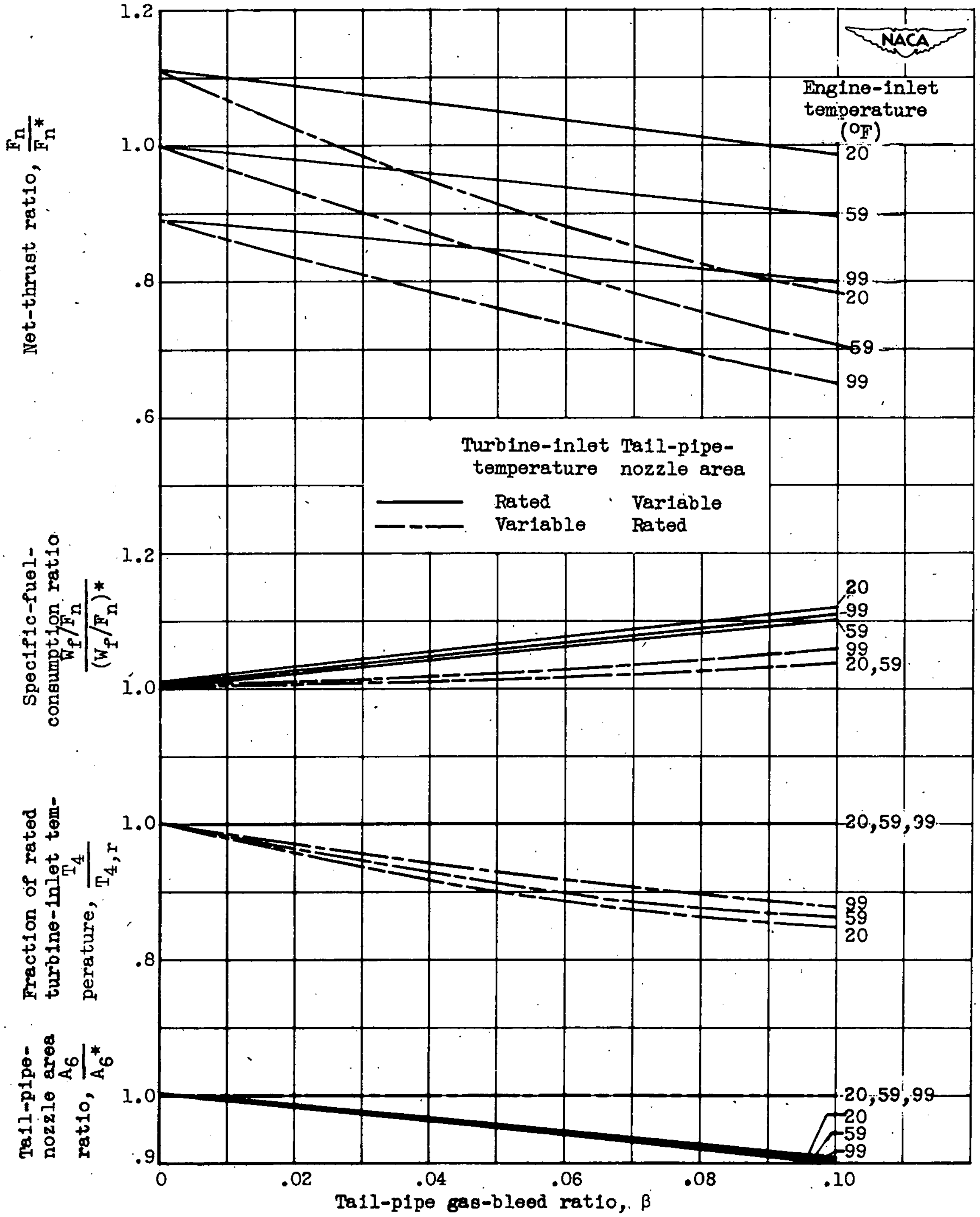


Figure 10. - Effect of tail-pipe gas bleed and engine-inlet temperature on static sea-level engine performance for variable- and rated-area tail-pipe nozzles. Engine speed, rated.

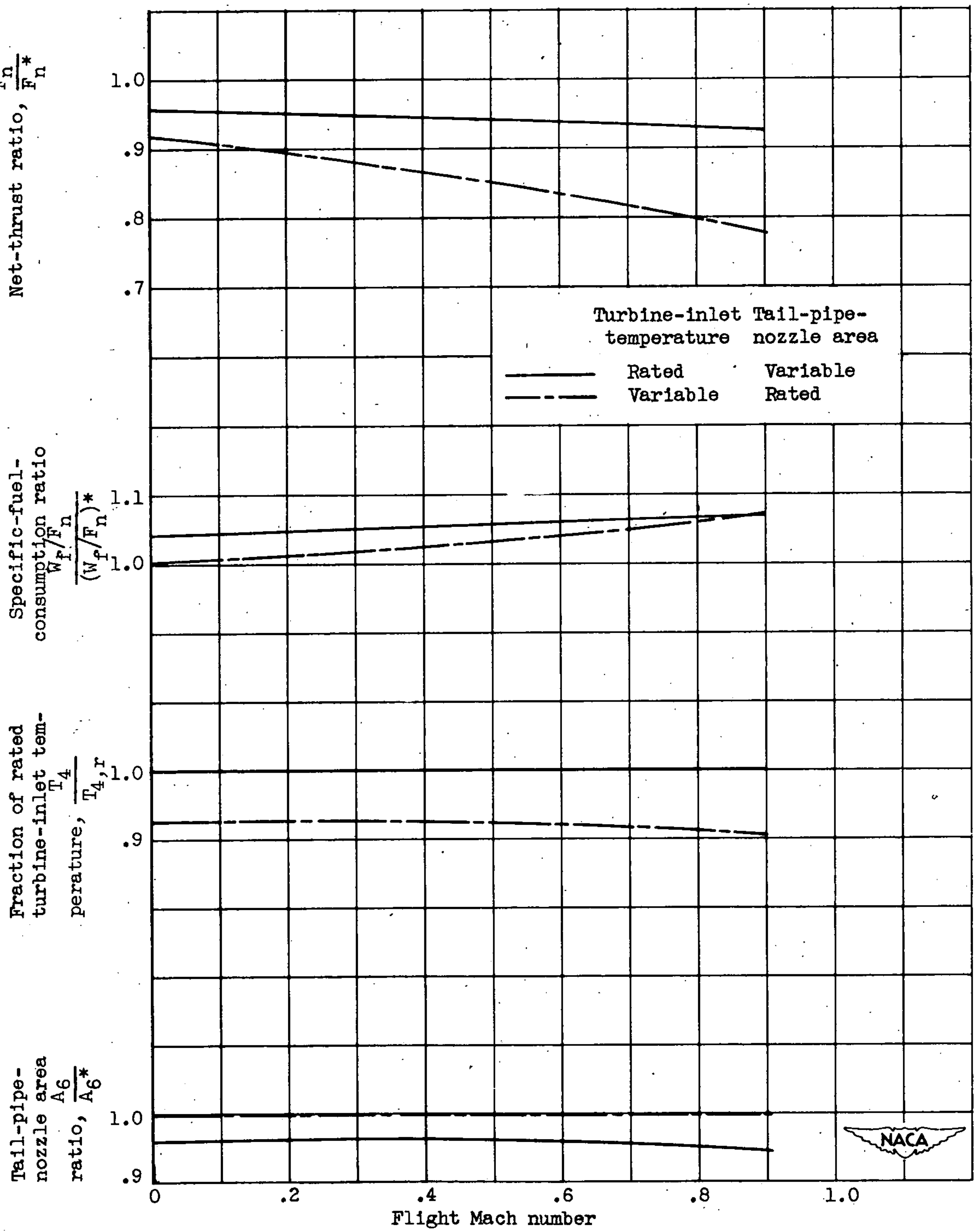


Figure 11. - Effect of flight Mach number on engine performance with variable- and rated-area tail-pipe nozzles. Tail-pipe gas-bleed ratio, 0.04; engine speed, rated; altitude, 20,000 feet.

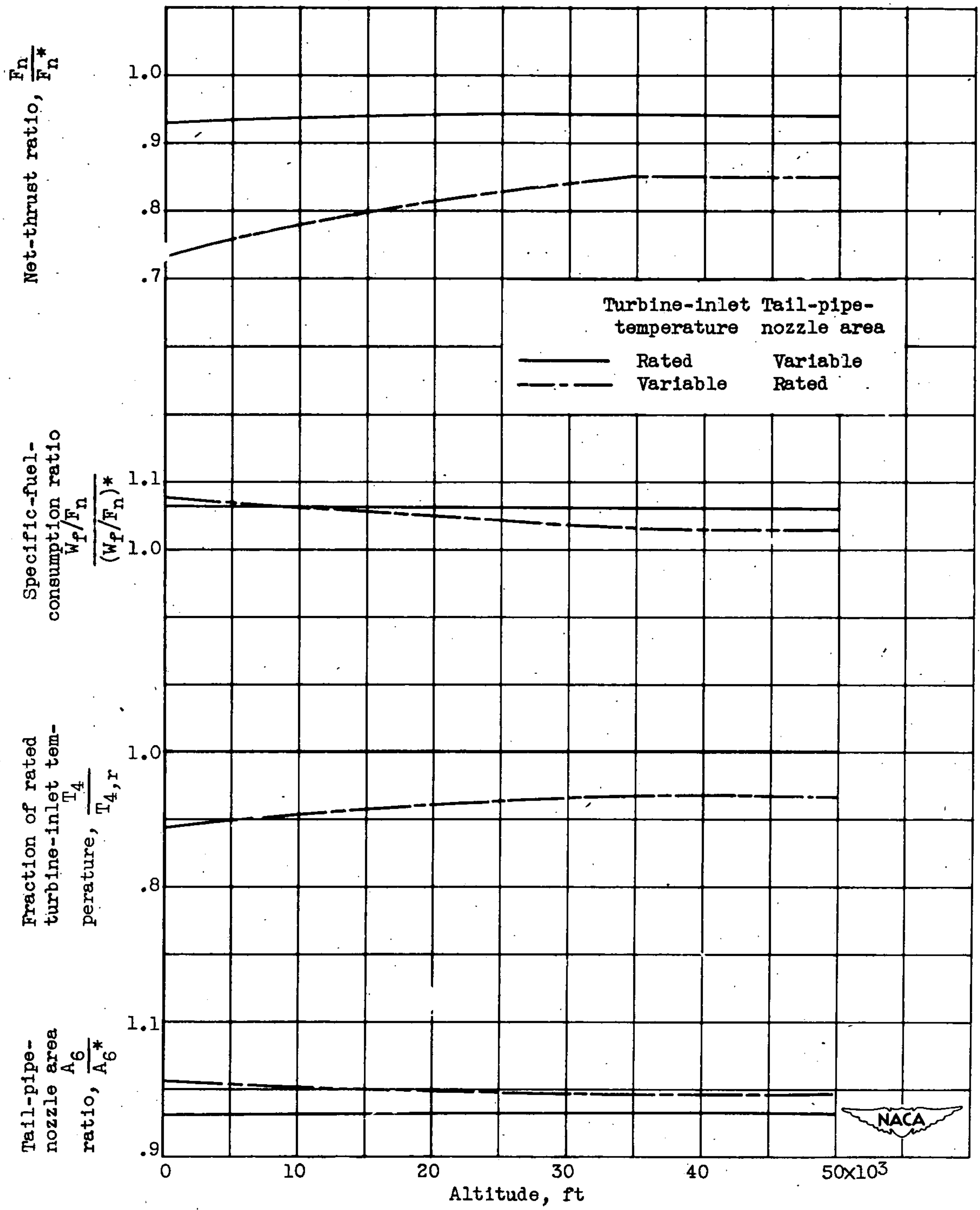


Figure 12. - Effect of altitude on engine performance with variable- and rated-area tail-pipe nozzles. Tail-pipe gas-bleed ratio, 0.04; engine speed, rated; Mach number, 0.7.

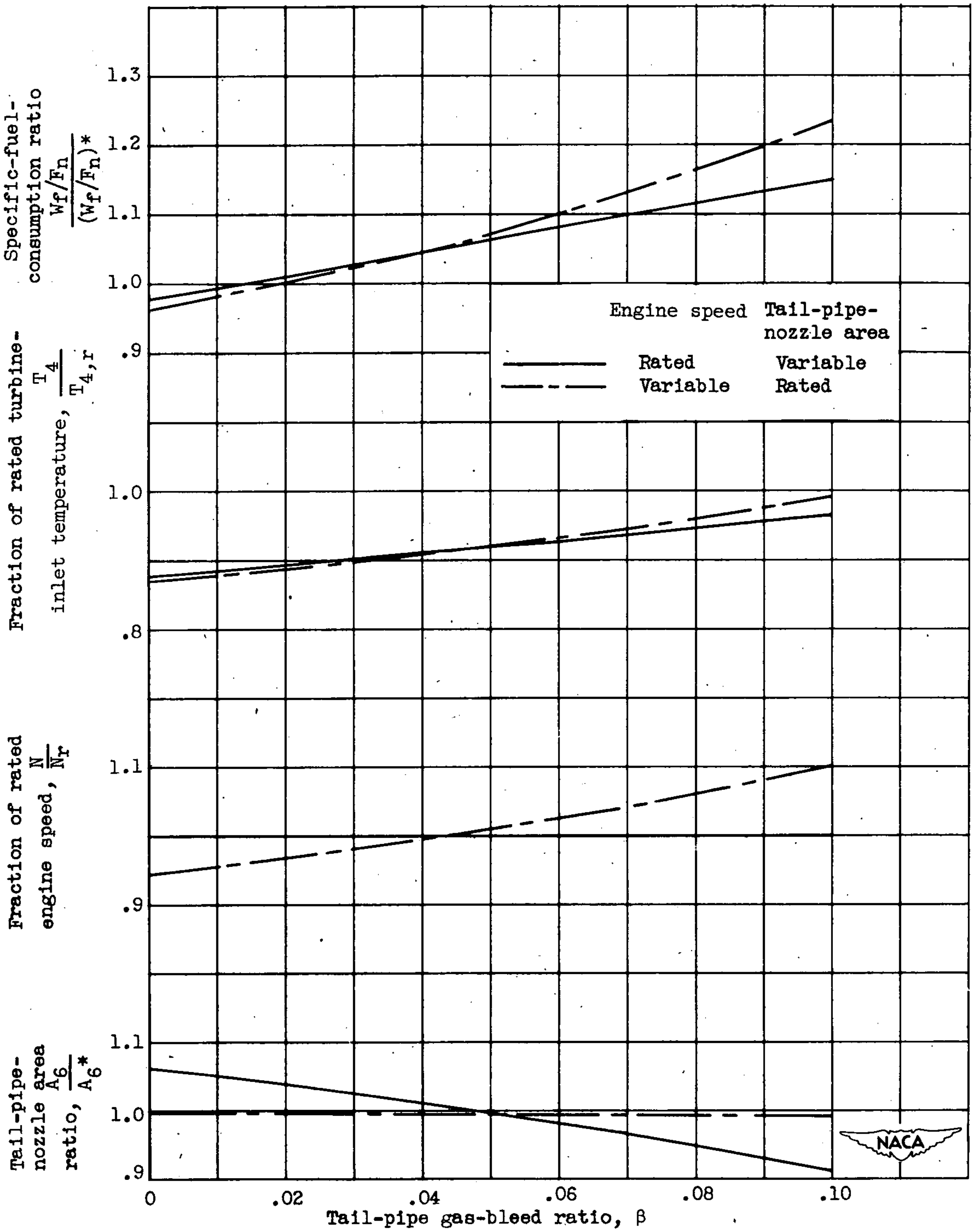
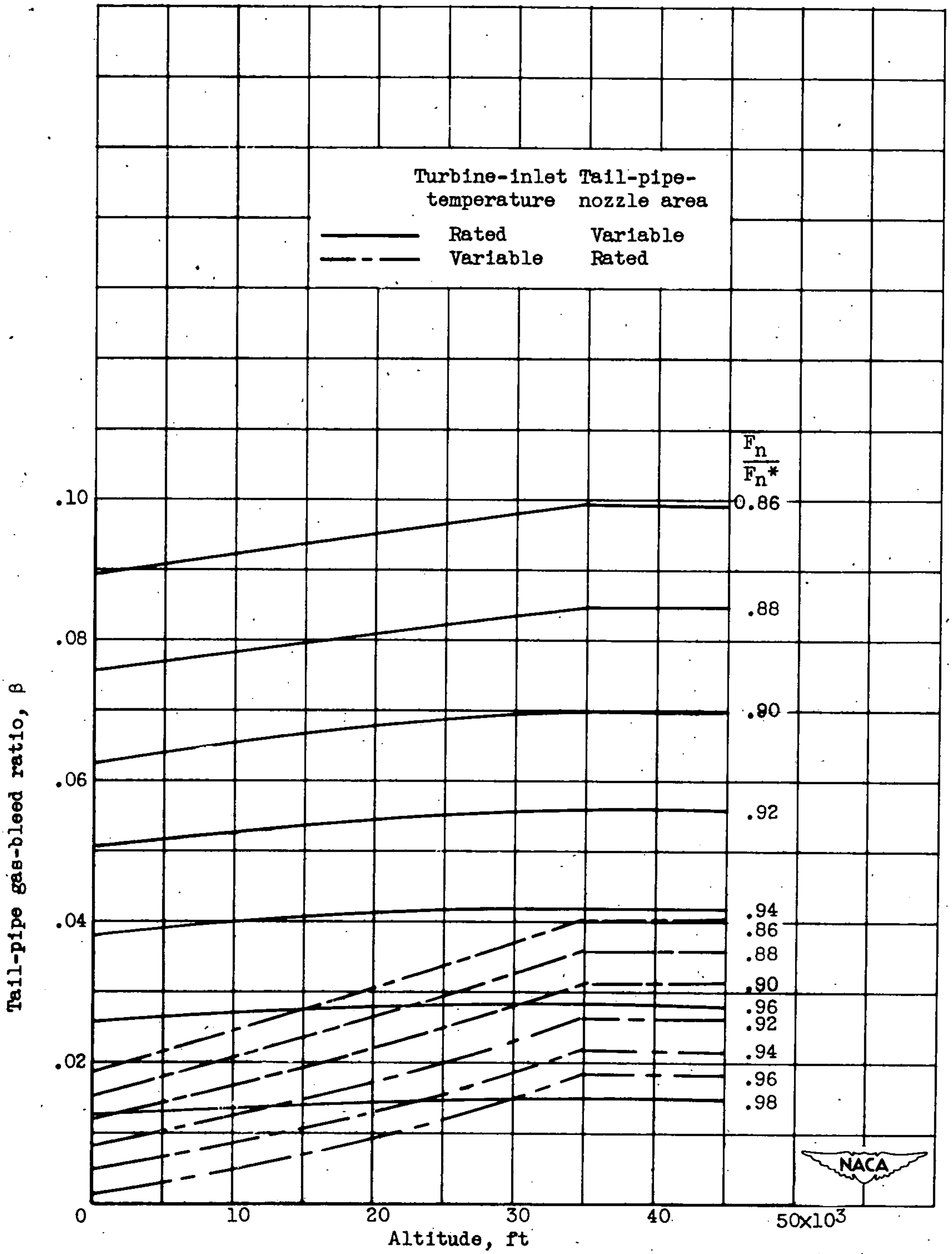
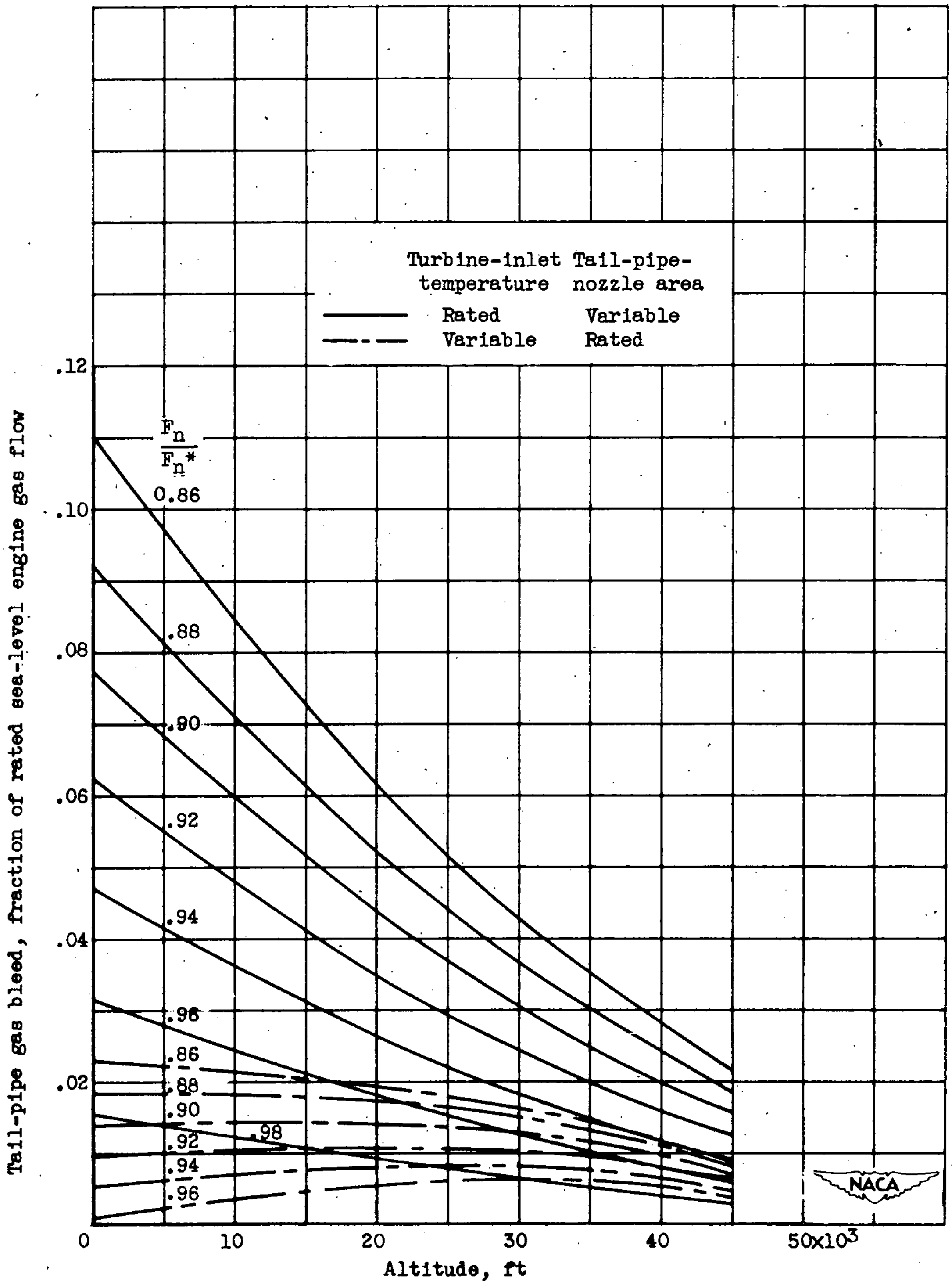


Figure 13. - Effect of tail-pipe gas bleed on engine performance with variable- and rated-area tail-pipe nozzles for net-thrust ratio of 0.80. Altitude, 20,000 feet; Mach number, 0.7.



(a) Gas bleed expressed as tail-pipe gas-bleed ratio.

Figure 14. - Variation of maximum permissible tail-pipe gas bleed with altitude and thrust. Engine speed, rated; Mach number, 0.7.



(b) Tail-pipe gas bleed expressed as fraction of rated sea-level engine gas flow.

Figure 14. - Concluded. Variation of maximum permissible tail-pipe gas bleed with altitude and thrust. Engine speed, rated; Mach number, 0.7.

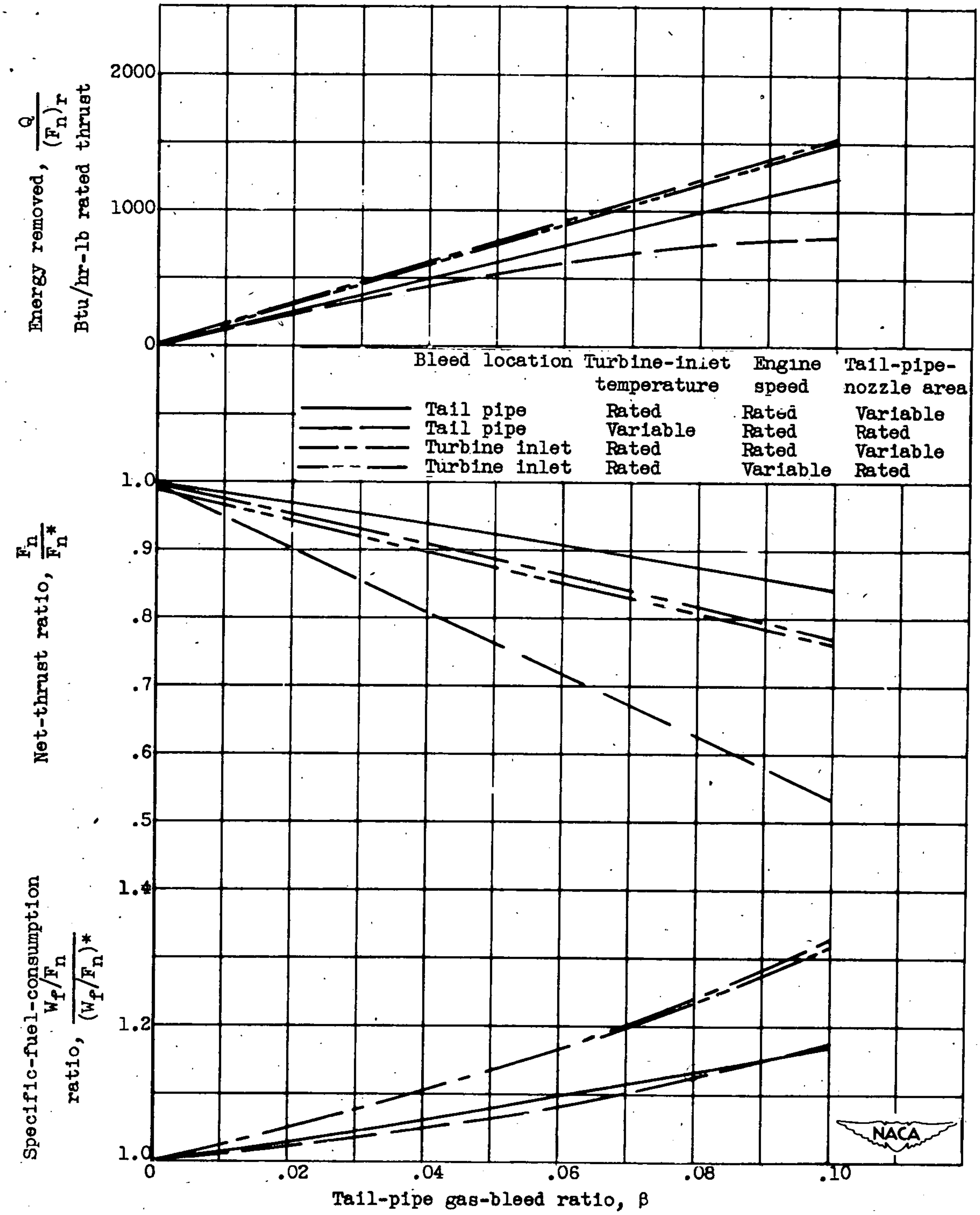


Figure 15. - Comparison of tail-pipe and turbine-inlet bleed under maximum available thrust conditions. Altitude, 20,000 feet; flight Mach number, 0.7.