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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2166

EFFECT OF HEAT AND POWER EXTRACTION ON TURBOJET-ENGINE PERFORMANCE

II - EFFECT OF COMPRESSOR-OUTLET AIR BLEED FOR SPECIFIC MODES OF ENGINE OPERATION

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SUMMARY

The effect of air bleed from the compressor outlet on the performance of turbojet engines with variable-area and rated-area tail-pipe nozzles was calculated by the use of generalized performance charts. The modes investigated were 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 air bleed is shown. The maximum amount of air that can be bled from the compressor outlet of a turbojet engine equipped with a variable-area or rated-area tail-pipe nozzle is also given for various values of altitude and thrust.

For constant turbine-inlet temperature operation, the effect of air bleed was, in general, to decrease the thrust slightly more than double and to increase the specific fuel consumption slightly less than double the percentage of air bled from the compressor outlet. No significant difference between operation with the variable-area and rated-area tail-pipe nozzles was noted for the range of air bleeds investigated.

INTRODUCTION

Considerable quantities of compressed air may be required in the operation of current and future aircraft for such uses as cabin pressurization and conditioning, protection against ice formation, and boundary-layer control. The compressed air can be obtained from the compressor outlets of turbine-powered airplanes at the expense of engine performance. An analytical method of determining the effect of air bleed on turbojet engines is presented in reference 1, together with a set of generalized performance charts. The effect of air bleed on engine performance for several specific modes of operation was determined at the NACA Lewis laboratory by use of these charts and is presented herein.

The modes of engine operation considered are constant turbine-inlet temperature and constant thrust operation with both variable and sea-level rated tail-pipe-nozzle areas. The effects of compressor-inlet temperature, altitude, and Mach number on engine performance with air bleed are discussed. In addition, the maximum amount of air that can be bled from the compressor outlet of a turbojet engine is presented as a function of altitude and thrust.

METHODS OF CALCULATION

The performance of the turbojet engine for various amounts of air bleed under the specific modes of operation was determined by means of the generalized performance charts of reference 1. These generalized performance charts were derived by matching experimentally determined compressor and turbine characteristics of an axial-flow turbojet engine. Values of diffuser, combustion-chamber, and tail-pipe-nozzle losses typical of current turbojet engines were used to obtain the propulsion-system performance. For any given air bleed, the performance charts give all the engine variables if any two are known. Thus, if a certain turbine-inlet temperature and engine speed are desired with a given air bleed, the tail-pipe-nozzle area, thrust, and specific fuel consumption can be determined by use of the charts.

The analytically determined performance with air bleed was verified by experimental air-bleed performance data obtained with an axial-flow turbojet engine although engines of different design were used in the analysis and in the experiments. This check with experimental results and further discussion in reference 1 indicated that the performance charts are applicable to axial-flow turbojet engines that have pressure ratios in the range of 4 to 5 and maximum turbine-inlet temperatures of approximately 2000° R.

Engine parameters are presented herein as fractions of a reference quantity that is indicated by an asterisk. The reference in each case is taken as the value of the quantity at rated speed and rated turbine-inlet temperature with no air bleed at the particular Mach number and NACA standard altitude under consideration. Operation at rated speed and rated turbine-inlet temperature over a range of flight conditions requires the use of a variable-area tail-pipe nozzle. This selection of the reference value was made so that the neglect of the Reynolds number effect in the analysis of reference 1 would not affect the values of the engine parameters presented herein for different altitudes.

In the figures presented herein variable tail-pipe-nozzle area operation at two engine speeds is compared with operation with the rated sea-level tail-pipe-nozzle area at the particular altitude under consideration. The variable-area-nozzle engine is operated at rated speed, which approximates the maximum-thrust operation, and at 0.93 rated speed, which approximates the minimum-specific-fuel-consumption operation.

RESULTS AND DISCUSSION

The effect of air bleed on the performance of a turbojet engine is qualitatively illustrated by a simplified analysis in order to obtain an understanding of the results as determined from the working charts of reference 1. The effect of air bleed on the simplified cycle can be obtained by consideration of the power division between the turbine and the jet. The jet power P_j for constant compressor mass flow and pressure ratio, constant component efficiencies, and fixed ram pressure ratio is given by the following relation:

$$P_j = P_{av}(1-\beta)-P_t$$

where P_{av} is the power available with no air bleed by complete expansion from turbine-inlet pressure to ambient static pressure, β is the ratio of bleed flow to compressor flow, and P_t is the power developed by the turbine. The power for the production of thrust P_f is the jet power minus the power required for the inlet diffusion process P_d

$$P_f = P_j-P_d$$

Inasmuch as the turbine power P_t is equal to the compressor power P_c,

$$P_t = P_c$$

the thrust power may be expressed as

$$P_f = P_{av}(1-\beta)-P_c-P_d$$

For convenience, the preceding equation is divided by P_{av} so that

$$\frac{P_f}{P_{av}} = 1-\beta-\left(\frac{P_c+P_d}{P_{av}}\right)$$

where the quantity P_f/P_{av} is the fraction of the total available power that produces thrust. In figure 1, P_f/P_{av} is presented as a function of air bleed β for various values of turbine-inlet temperature ratios and ram pressure ratios. At low turbine-inlet temperature ratios, a given percentage air bleed causes a greater percentage reduction in P_f/P_{av} (hence thrust) than at high values of turbine-inlet temperature ratios. The effect of ram pressure ratio on engine performance with air bleed was found to be small in reference 1 for ram pressure ratios of 1.2 to 1.6. In order to illustrate this point by use of the foregoing methods, curves are presented for ram pressure ratios of 1.2 and 1.6 at a turbine-inlet temperature ratio of 3.5 for comparison with the curve for a ram pressure ratio of 1.35 in figure 1. Very little variation in P_f/P_{av} is evident for the range of ram pressure ratios shown. Consequently, ram pressure ratio is expected to have little effect on air-bleed engine performance at a fixed turbine-inlet temperature ratio.

Operation at Constant Turbine-Inlet Temperature

The effect of compressor-outlet air bleed on the performance of a turbojet engine operating at rated turbine-inlet temperature is shown in figure 2 for an altitude of 20,000 feet and a Mach number of 0.7. Variable-area operation at rated and 0.93 rated speed is compared with rated-area operation. The change in thrust and specific fuel consumption with air bleed is essentially the same for all modes of engine operation shown. For an air-bleed ratio of 0.10, the thrust decreases approximately 22 percent and the specific fuel consumption increases approximately 19 percent. Very little difference is noted in the magnitude of the thrust and the specific fuel consumption between the rated-area and rated-speed variable-area operation. Decreasing the speed of the variable-area engine from rated to 0.93 rated, for these conditions of rated turbine-inlet temperature, causes a slight decrease in thrust and specific fuel consumption for the range of air bleeds investigated.

The similarity between the air-bleed performance with rated-area and rated-speed variable-area operation is expected from inspection of the engine-speed and area curves of figure 2. The rated-area engine is operating at approximately rated engine speed and the variable-area engine is operating at essentially rated area for the whole range of air bleeds shown.

The results of figure 2 agree very well with actual experimental data presented in reference 2. The experimental data were obtained from an altitude-wind-tunnel investigation of an axial-flow turbojet engine of a different design from the one on which the analytical data were based. In spite of the difference in engine design, the two sets of data are in close agreement.

The effect of air bleed on engine performance for operation at 0.90 rated turbine-inlet temperature is shown in figure 3 for the same flight conditions and modes of engine operation as presented in figure 2 for rated turbine-inlet temperature operation. Bleeding 0.10 of the compressor air flow causes approximately a 26-percent decrease in thrust and a 23-percent increase in specific fuel consumption. The similarity between the rated-area and 0.93-rated-speed variable-area operation is further illustrated by the small change in engine speed and tail-pipe-nozzle area with air bleed.

Comparison of figures 2 and 3 indicates a 16-percent reduction in thrust and a 2-percent reduction in specific fuel consumption at zero air bleed as a result of decreasing the turbine-inlet temperature from rated to 0.90 rated. For an air bleed of 0.10, reducing the turbine-inlet temperature from rated to 0.90 rated causes a 19-percent reduction in thrust and only a slight change in the specific fuel consumption for both variable-area and rated-area operation.

Reducing the turbine-inlet temperature, and hence the turbine-inlet temperature ratio, at a given flight condition therefore increases the adverse effect on engine performance of bleeding air from the compressor outlet, as was previously discussed and illustrated in figure 1.

Effect of Compressor-Inlet Temperature

The effect of air bleed on the sea-level static performance of a rated-area and a variable-area, rated-speed turbojet engine at rated turbine-inlet temperature is presented in figure 4 for three compressor-inlet temperatures (99°, 59°, and 20°F). These compressor-inlet temperatures correspond to sea-level ambient temperature for Army summer air, NACA standard air, and typical icing conditions, respectively.

For the variable-area, rated-speed operation, bleeding 0.10 of the compressor air flow causes decreases in thrust of 20 percent for the Army summer air, 19 percent for the NACA standard air, and 17 percent for the icing condition. The same trend with compressor-inlet temperature is observed for the rated-area operation with slightly greater changes in thrust with increasing air bleed. Bleeding 0.10 of the compressor air flow causes the specific fuel consumption to increase 17 percent for Army summer air operation, 14 percent for NACA standard air operation, and 13 percent for operation under the icing condition. The observed changes in specific fuel consumption are similar for both rated-area and variable-area rated-speed operation. The accompanying variations in engine speed and tail-pipe-nozzle area are also shown in figure 4.

The results obtained under take-off conditions with various compressor-inlet temperatures (fig. 4) are consistent with the results obtained in the cycle analysis (fig. 1). For constant turbine-inlet temperature operation, increasing the compressor-inlet temperature decreases the turbine-inlet temperature ratio. Because greater changes in engine performance are expected at low turbine-inlet temperature ratios than at high ratios, the greatest changes in engine performance due to air bleed are expected under Army summer air conditions, as shown in figure 4.

Operation at various turbine-inlet temperature ratios not only affects the change in thrust and specific fuel consumption due to air bleed but also affects the actual magnitude of these quantities at a given air bleed. Thus, the air-bleed ratio can be increased to 0.12 under icing inlet-temperature conditions before the thrust decreases to the value obtained with zero air bleed on an Army summer day.

Altitude Effect

The effect of altitude on the performance of a turbojet engine operating at rated turbine-inlet temperature and with 0.10 air bleed is shown in figure 5. Operation with rated-area and with variable-area tail-pipe nozzles at both rated and 0.93 rated speed is shown.

For all modes of operation, the thrust ratio and the specific-fuel-consumption ratio approach unity as the altitude is increased. Because of the reduction of compressor-inlet temperature at higher altitudes, the percentage change in specific fuel consumption and thrust for a given air-bleed ratio becomes less as the altitude is increased up to the tropopause. The reduction in compressor-inlet temperature causes the turbine-inlet temperature ratio to increase which, as previously discussed, causes the effect of a given air-bleed ratio on engine performance to be less severe. It therefore becomes less costly in engine performance to bleed a given percentage air from the compressor outlet at altitude. The effect of bleeding a given weight flow of air as a function of altitude is discussed later.

Mach Number Effect

The effect of Mach number on the performance of a turbojet engine with an air-bleed ratio of 0.10 is indicated in figure 6 for the same conditions as figure 5. For the range of Mach numbers that could be investigated using the charts of reference 1, the effect of air bleed on thrust and specific fuel consumption is increased slightly as the Mach number is increased. The explanation of this trend can again be obtained by reference to figure 1. As the Mach number is increased at a given altitude, the compressor-inlet temperature increases with an attendant decrease in turbine-inlet temperature ratio; this change in turbine-inlet temperature ratio causes the given air bleed to have a greater effect on engine performance with increasing Mach number. Figure 6 neglects the effect of the increase in ram pressure ratio that accompanies an increase in Mach number; this effect is, however, shown to be negligible in figure 1.

Constant-Thrust Operation

If an airplane is to maintain flight speed when the amount of air bled from the compressor outlet is increased, the thrust of the engine must be maintained constant by increasing the turbine-inlet temperature. Constant thrust performance at a Mach number of 0.7 and an altitude of 20,000 feet for rated and 0.93-rated-speed variable-area operation and rated-area operation is shown in figure 7. The thrust is fixed at 0.80 of its maximum value when the engine is operating at rated speed and rated turbine-inlet temperature at these particular flight conditions.

Bleeding 0.10 of the compressor-air flow causes the specific fuel consumption to increase 22 percent for all three modes of operation. In order to maintain constant thrust with this air bleed, the turbine-inlet temperature increases by approximately 16 percent. For air bleeds above approximately 0.09, the turbine-inlet temperature exceeds the rated value. The corresponding variations in engine speed and tail-pipe-nozzle area are also shown in figure 7. The effect of air bleed on engine performance as shown in figure 7 agrees closely with the experimentally determined data of reference 2.

Maximum Air Bleeds

The maximum compressor-outlet air bleed permissible without exceeding the rated turbine-inlet temperature is given in figure 8. Air bleed is expressed as the air-bleed ratio β in figure 8(a) and as the fraction of sea-level rated compressor-air flow in figure 8(b). Both air-bleed quantities are given as functions of altitude and thrust for a Mach number of 0.7 for rated-area and rated-speed, variable-area operation. The thrust is presented as the fraction of the thrust when the engine is operating at rated engine speed and turbine-inlet temperature at each particular altitude and at a Mach number of 0.7. Figure 8(a) shows that for a given thrust the maximum permissible air-bleed ratio β increases with altitude up to 35,000 feet and remains constant for further increases in altitude. As previously discussed, this effect of altitude is a result of the change in turbine-inlet temperature ratio. Figure 8(b) shows that the maximum fraction of rated sea-level compressor-air flow (neglecting small possible change in compressor mass flow due to Reynolds number variation) that can be bled from the compressor outlet decreases rapidly with increasing altitude. This large decrease in air bleed is due to the decreasing density of the air with increasing altitude.

CONCLUDING REMARKS

In general, bleeding air from the compressor outlet of an axial-flow turbojet engine has the effect of decreasing the thrust by slightly more than double the percentage of air bleed and increasing the specific fuel consumption slightly less than double the percentage of air bleed for rated turbine-inlet temperature operation. Decreasing the turbine-inlet temperature or increasing the compressor-inlet temperature increases the effect of air bleed on engine performance because of the reduction in turbine-inlet temperature ratio. Thus, increasing the altitude (up to 35,000 ft) or decreasing the flight Mach number reduces the effect of air bleed on the performance of a turbojet engine operating with a fixed turbine-inlet temperature.

In all the modes of engine operation investigated, no significant difference exists between variable-area and rated-area tail-pipe nozzle operation for all air bleeds up to approximately 0.10 of the compressor air flow.

The analytical results of the effect of compressor-outlet bleed on engine performance presented herein agree very well with the results of experimental investigations. The agreement tends to substantiate the generality of the methods used in the analytical determination of the effect of air bleed on engine performance inasmuch as the analytical data were obtained by the matching of the components of a different axial-flow turbojet engine than the engine used in the experimental determination of the effect of air bleed.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, February 28, 1950.

REFERENCES

1. Hensley, Reece V., Rom, Frank E., and Koutz, Stanley L.: Effect of Heat and Power Extraction on Turbojet-Engine Performance. I - Analytical Method of Performance Evaluation with Compressor-Outlet Air Bleed. NACA TN 2053, 1950.

2. Fleming, William A., Wallner, Lewis E., and Wintler, John T.: Effect of Compressor-Outlet Bleedoff on Turbojet-Engine Performance. NACA RM E50E17, 1950.

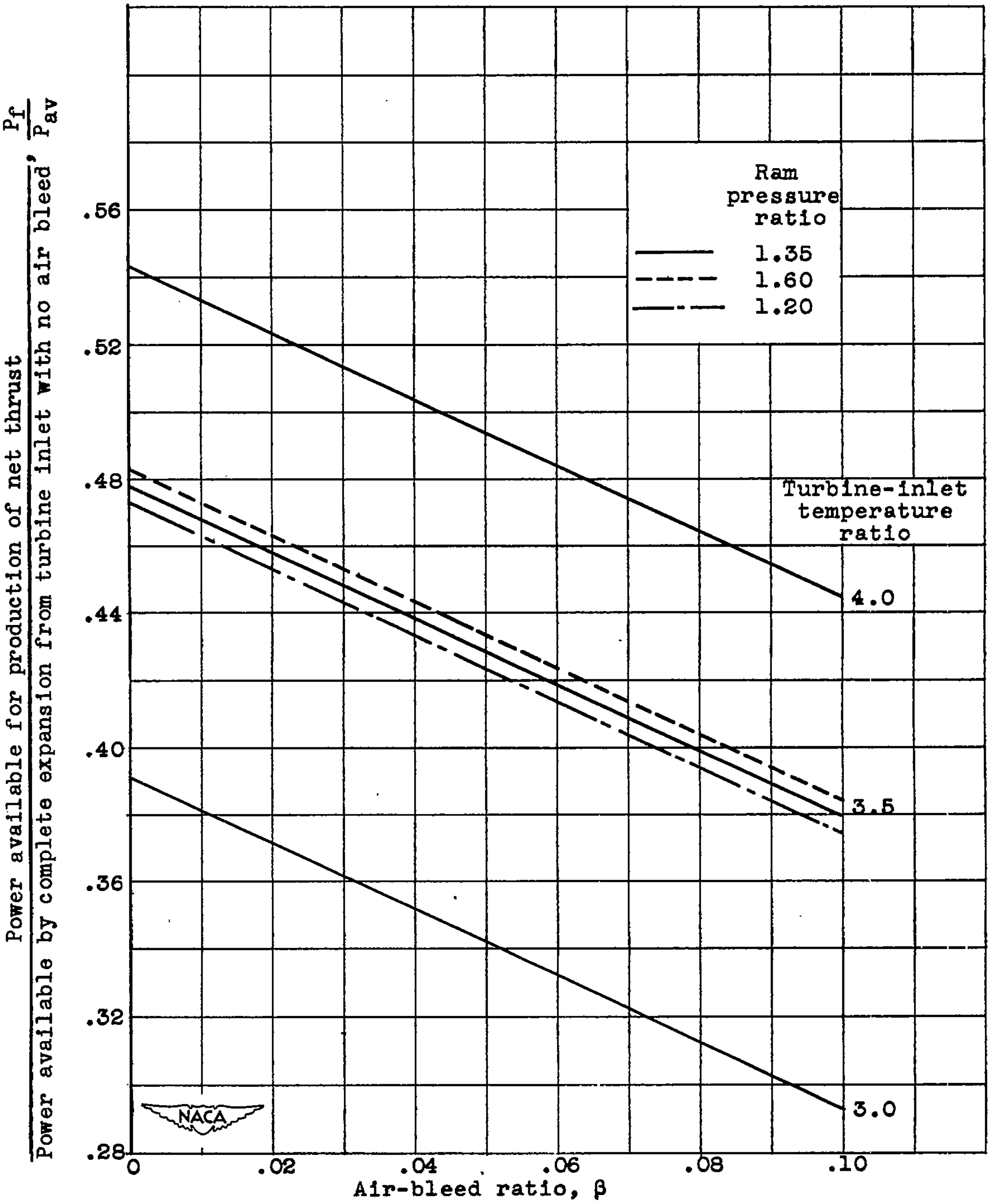

Figure 1. - Effect of air-bleed ratio, turbine-inlet temperature ratio, and ram pressure ratio on ratio of power available for production of net thrust to power available by complete expansion from turbine-inlet pressure. Compressor efficiency, 0.85; turbine efficiency, 0.90; compressor pressure ratio, 4.0.

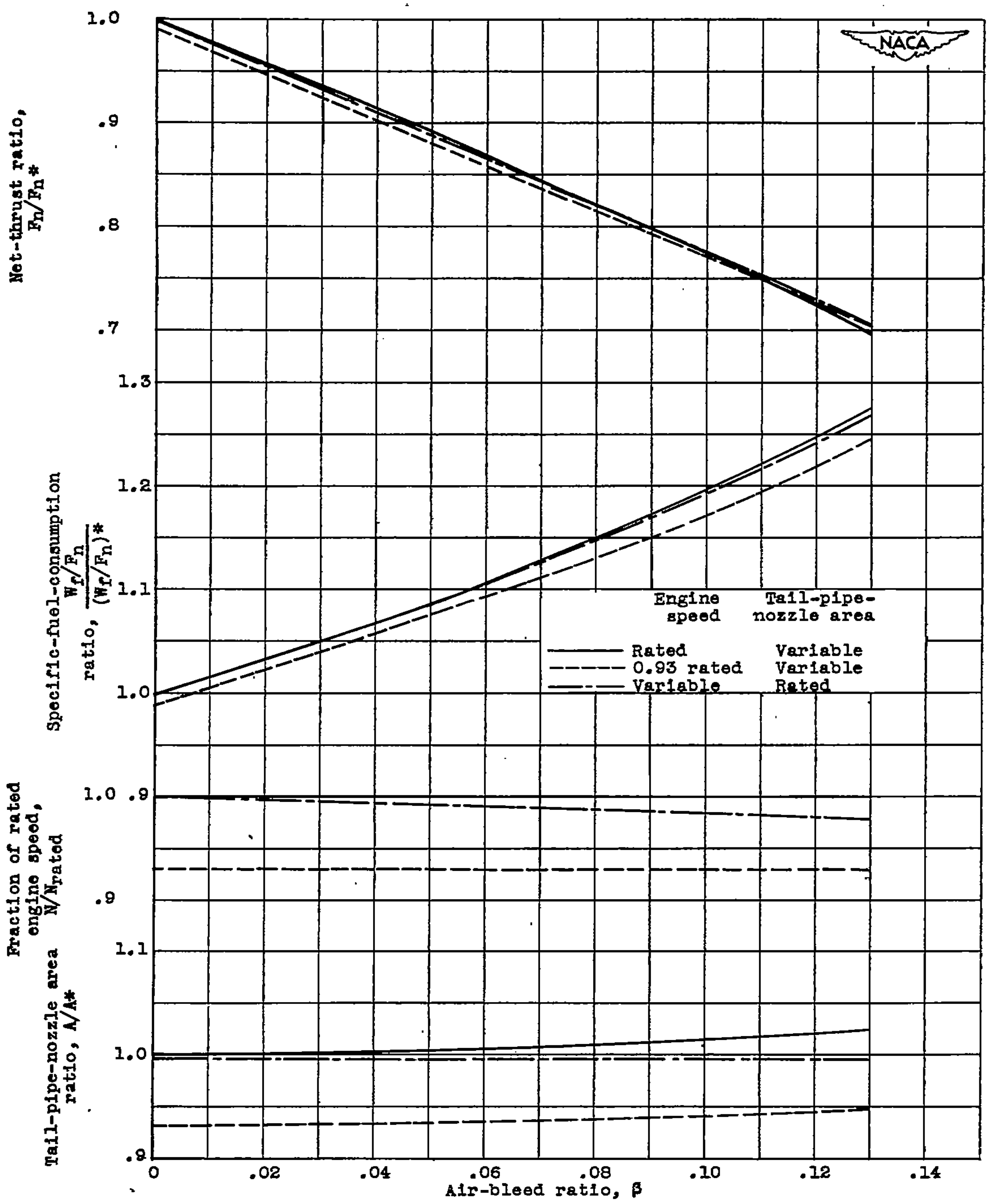

Figure 2. - Effect of air bleed on engine performance with variable- and rated-area tail-pipe nozzles at rated turbine-inlet temperature. Altitude 20,000 feet; Mach number, 0.7.

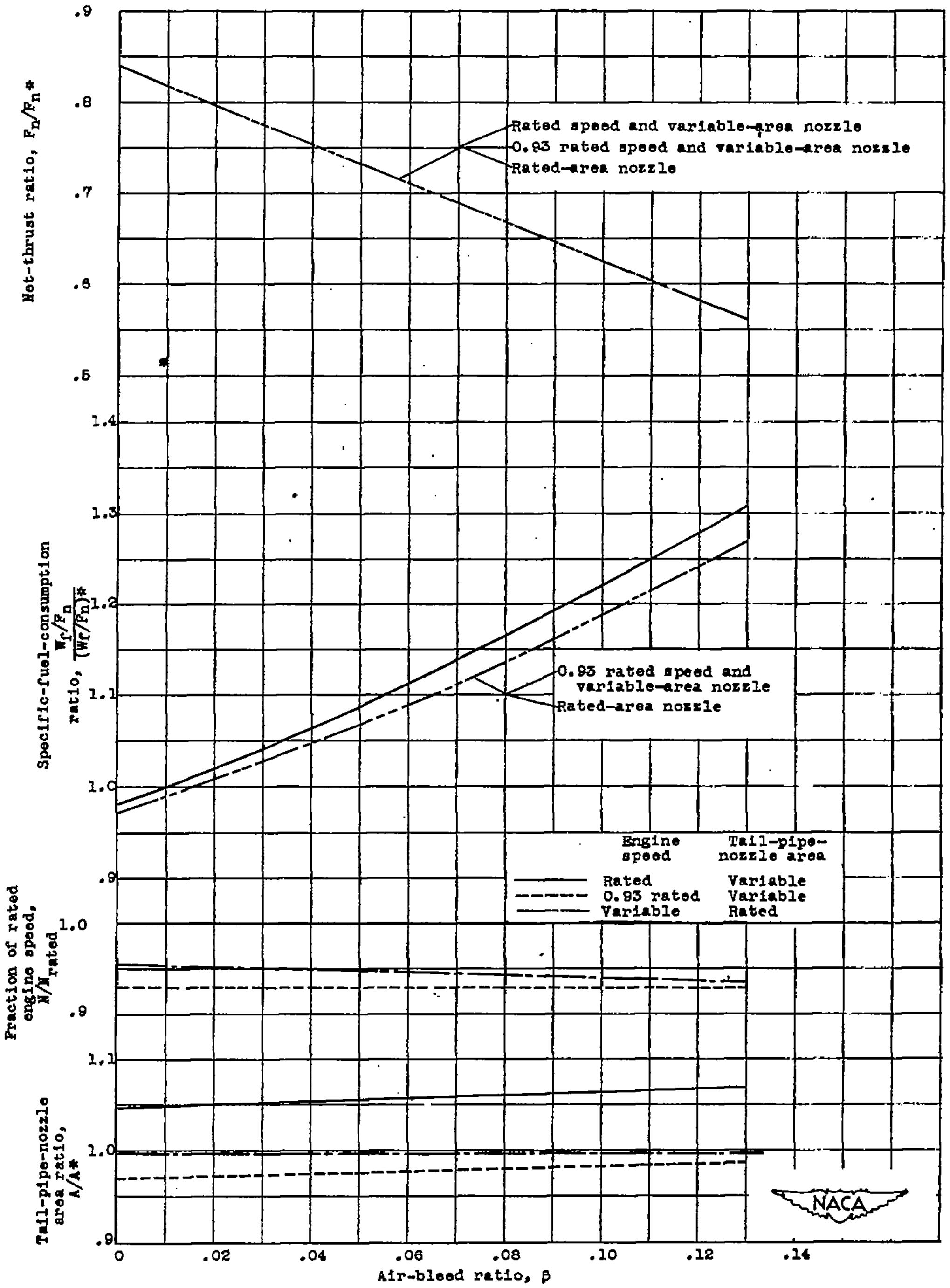

Figure 3. - Effect of air bleed on engine performance with variable- and rated-area tail-pipe nozzles at 0.90-rated turbine-inlet temperature. Altitude, 20,000 feet; Mach number, 0.7.

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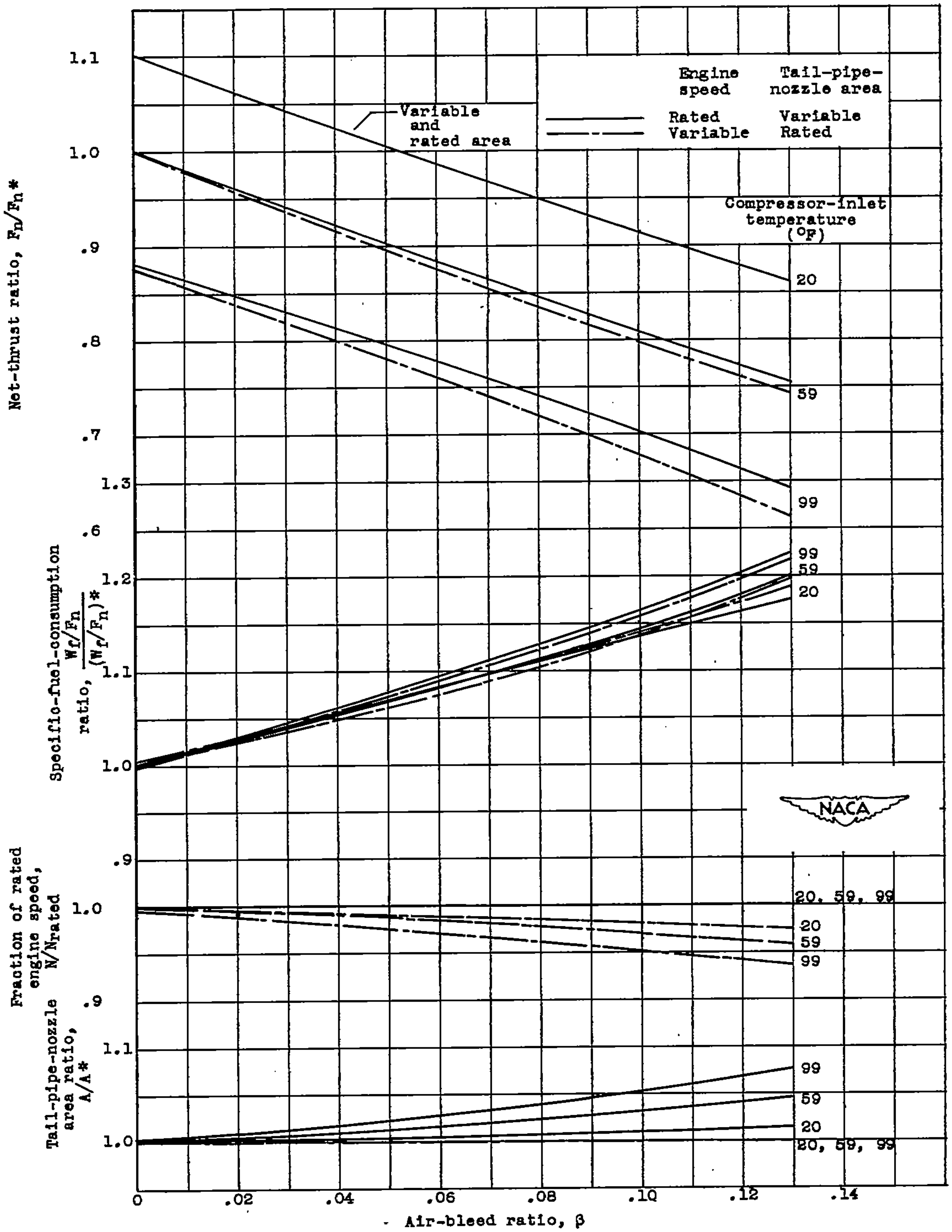


Figure 4. - Effect of air bleed and compressor-inlet temperature on sea-level static turbojet performance with variable- and rated-area tail-pipe nozzles at rated turbine-inlet temperature.

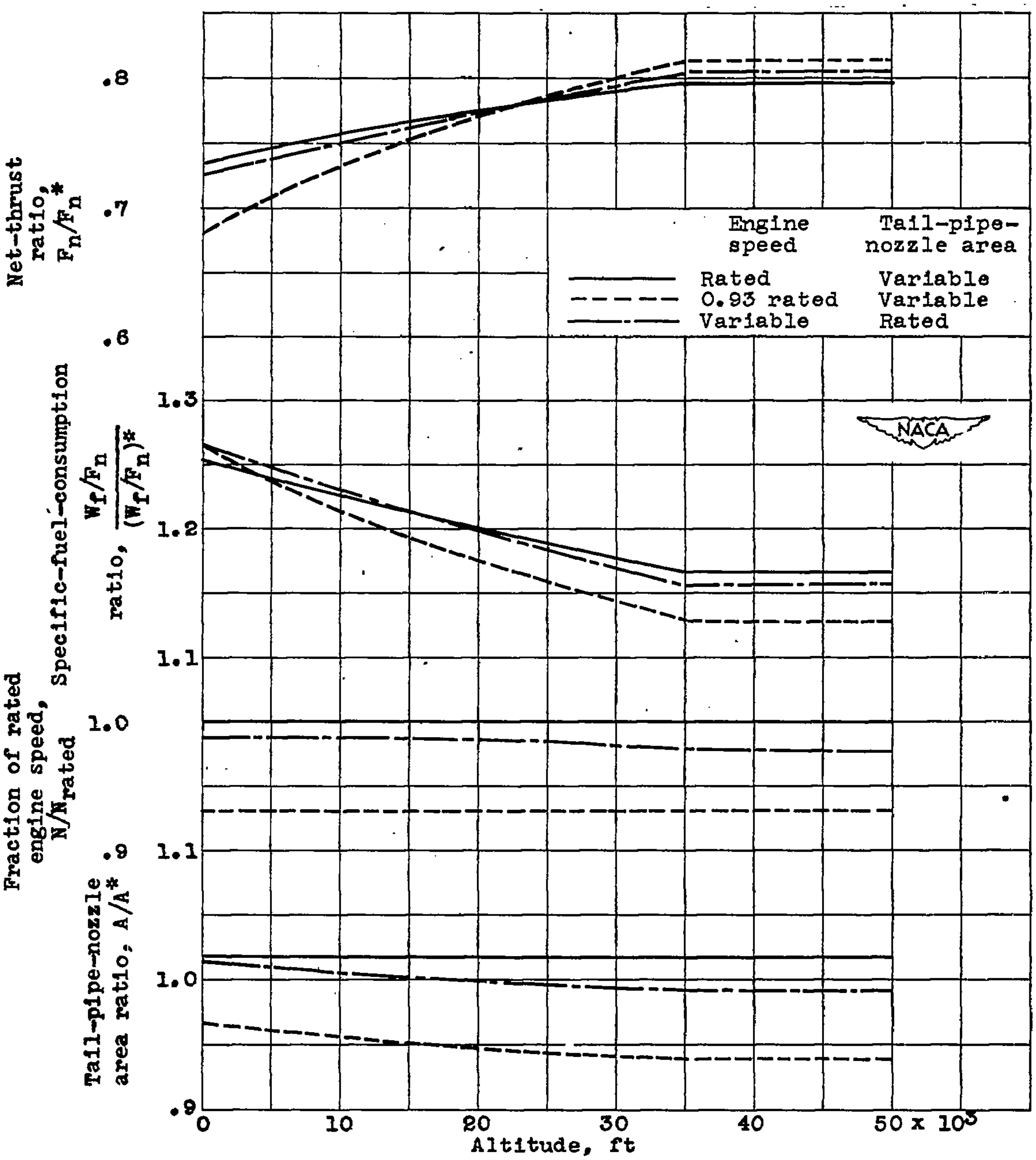


Figure 5. - Effect of altitude on engine performance with variable- and rated-area tail-pipe nozzles. Air-bleed ratio, 0.10; turbine-inlet temperature, rated; Mach number, 0.7.

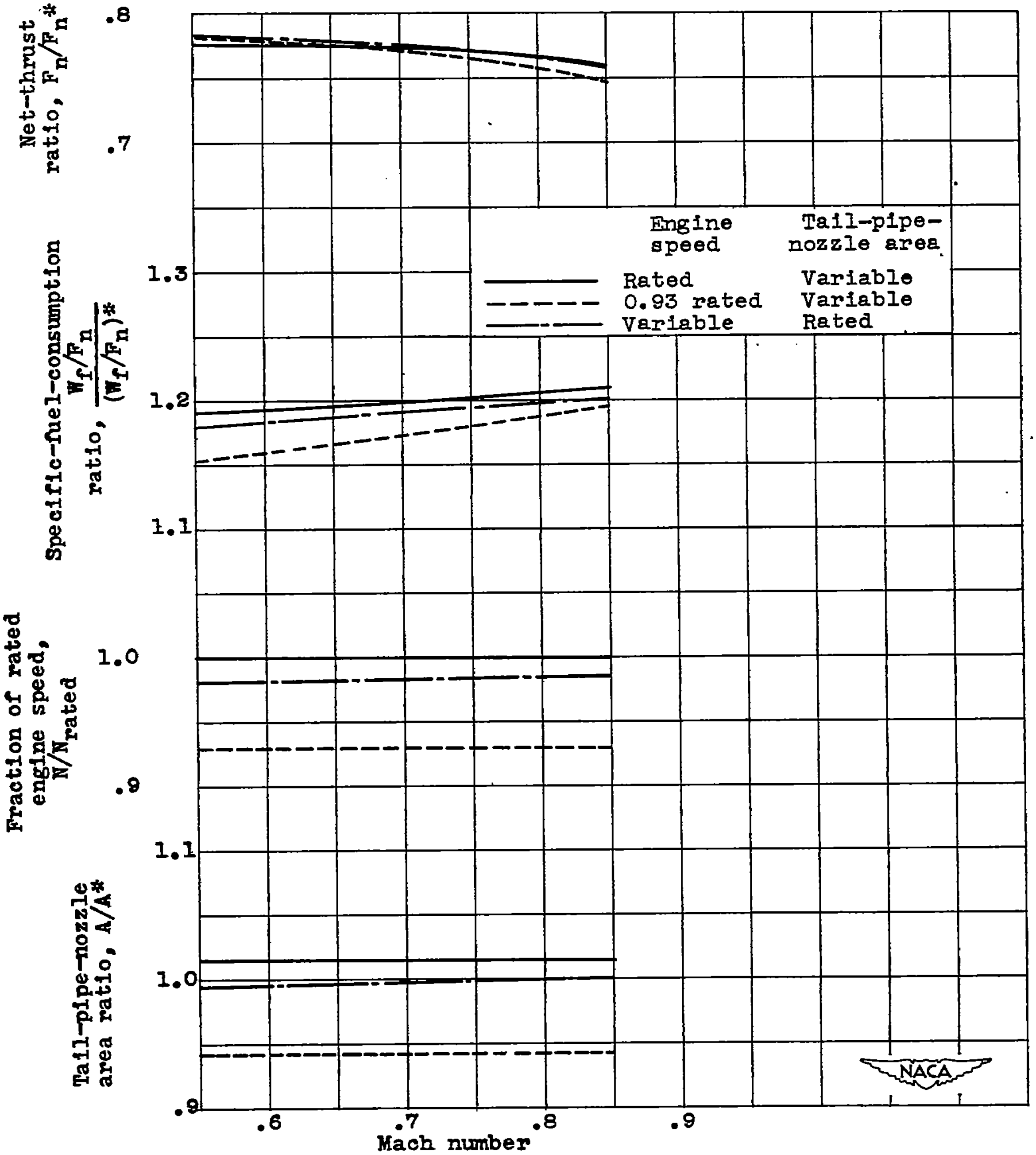


Figure 6. - Effect of Mach number on engine performance with variable- and rated-area tail-pipe nozzles. Air-bleed ratio, 0.10; turbine-inlet temperature, rated; altitude, 20,000 feet.

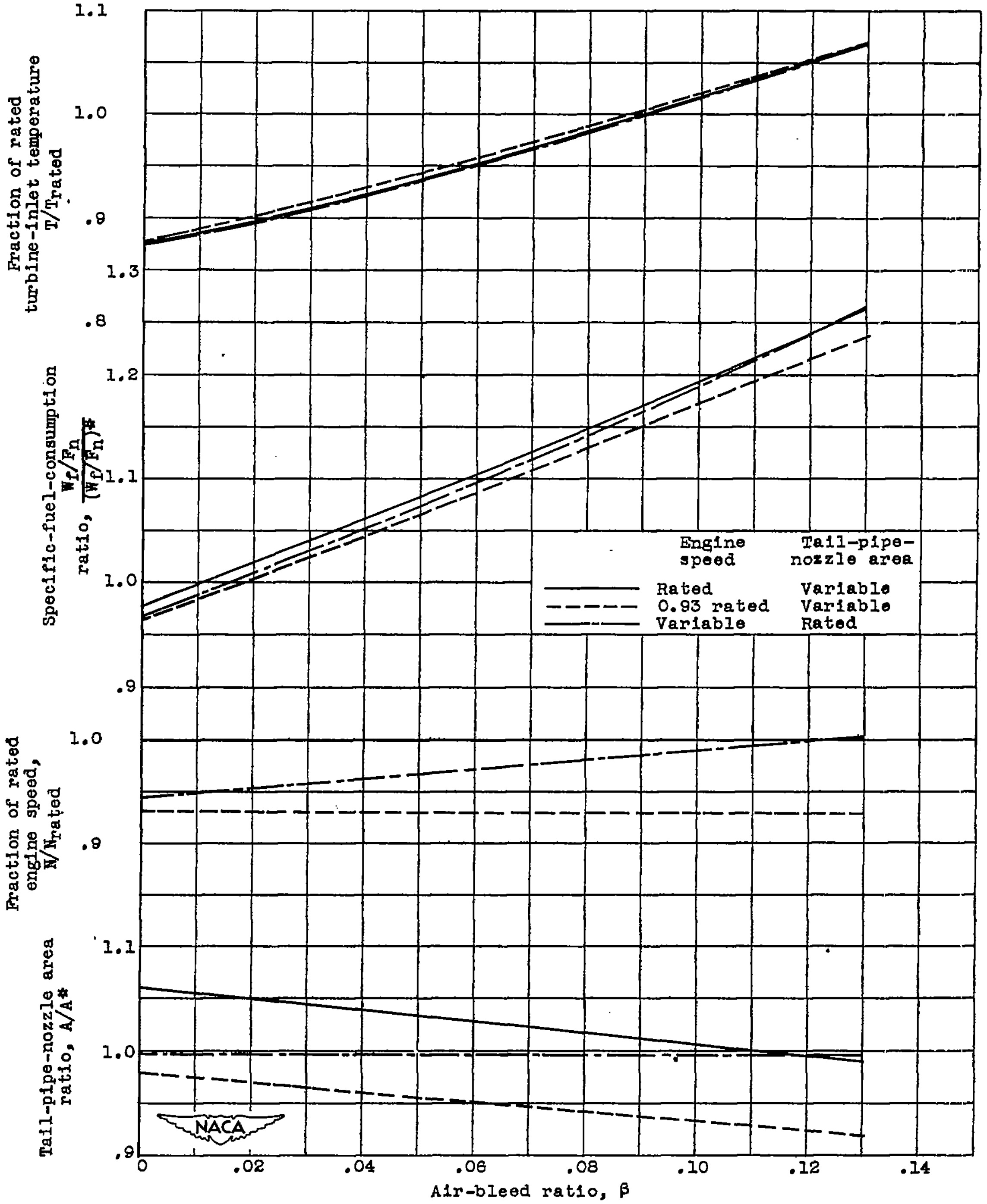
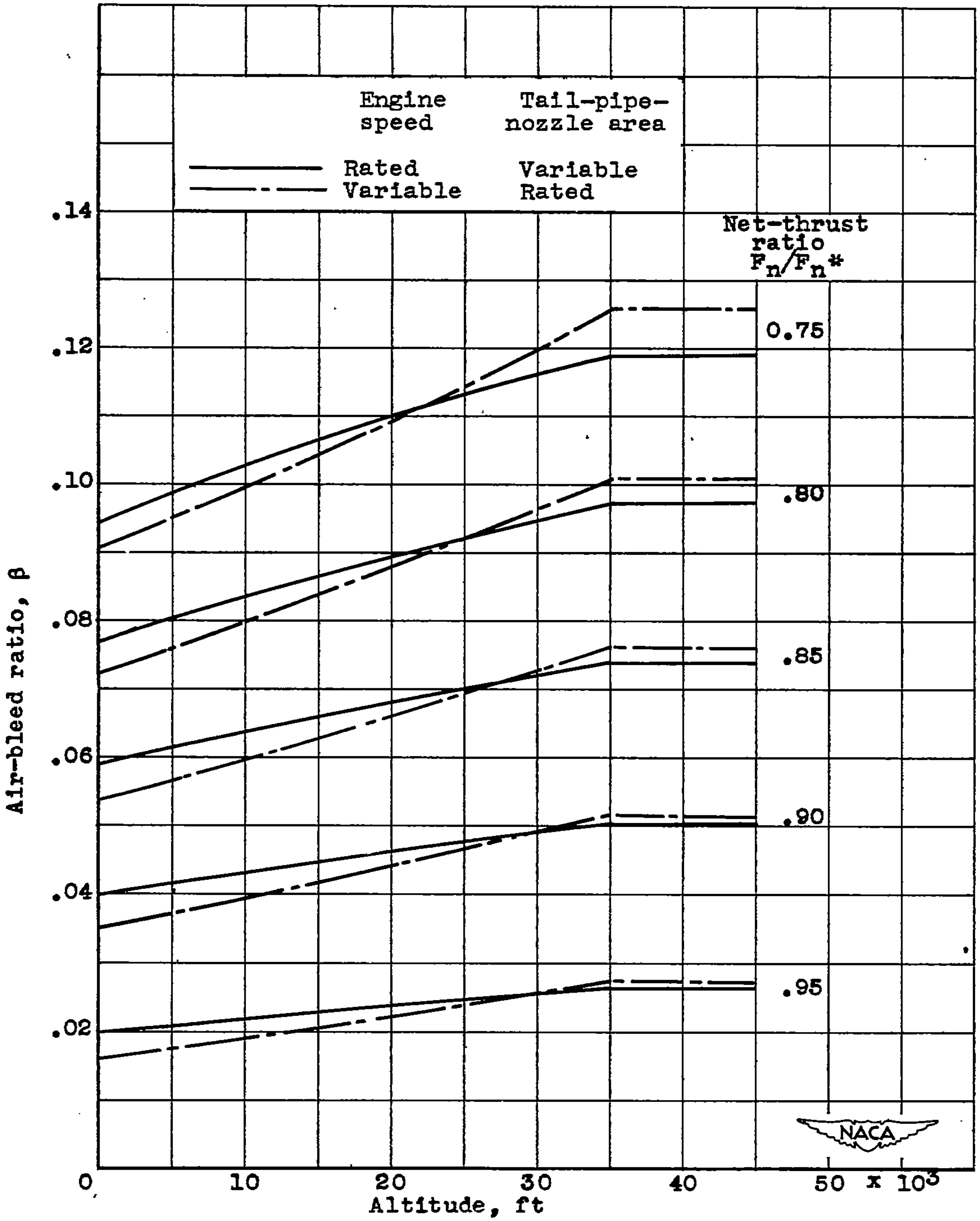
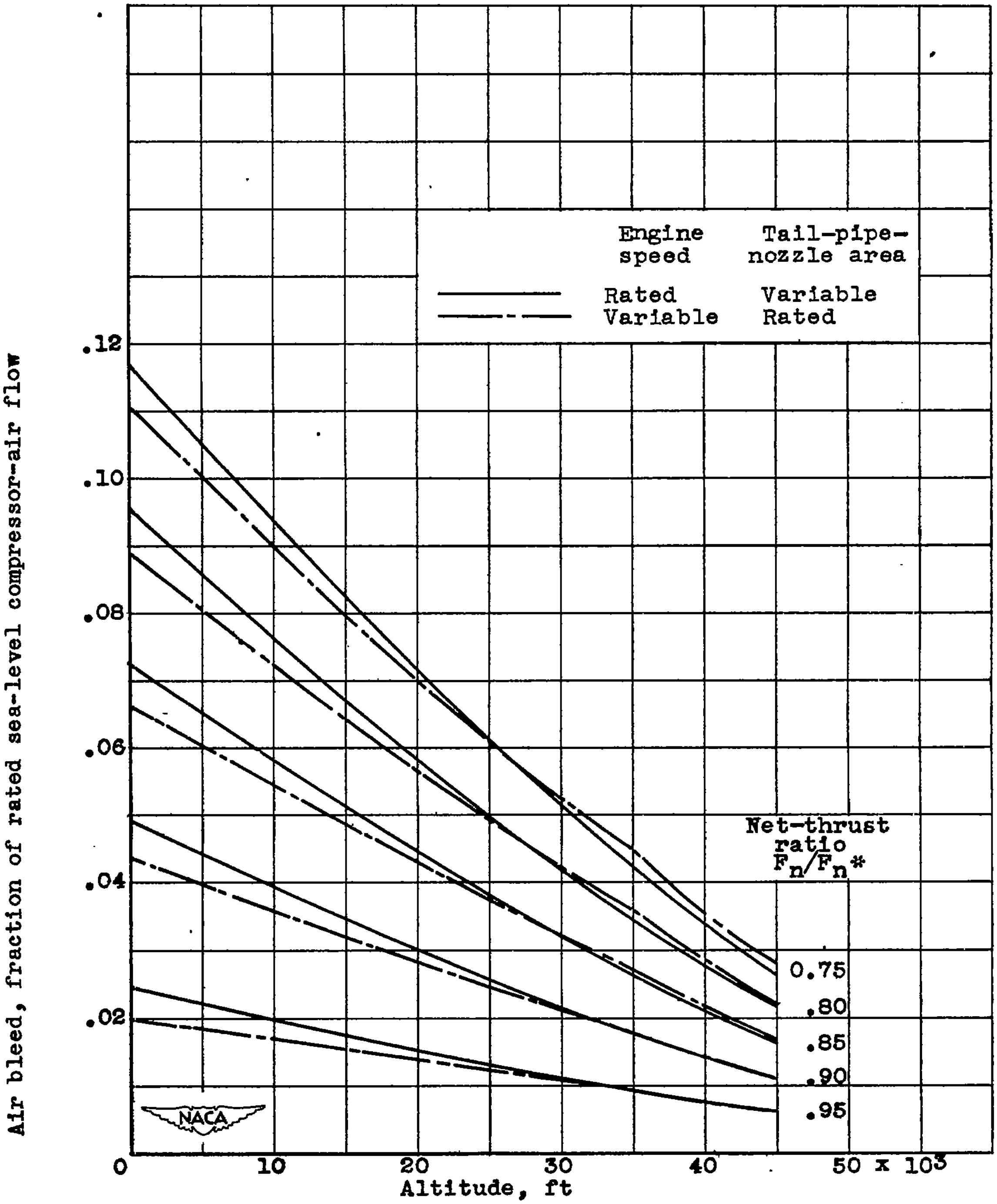


Figure 7. - Effect of air bleed on engine performance with variable- and rated-area tail-pipe nozzles for 0.80 maximum thrust. Altitude, 20,000 feet; Mach number, 0.7.



(a) Air bleed expressed as air-bleed ratio.

Figure 8. - Variation of maximum permissible air bleed with altitude and thrust. Turbine-inlet temperature, rated; Mach number, 0.7.



(b) Air bleed expressed as percent of sea-level compressor air flow.

Figure 8. - Concluded. Variation of maximum permissible air bleed with altitude and thrust. Turbine-inlet temperature, rated; Mach number, 0.7.

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