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RESEARCH MEMORANDUM

ANALYTICAL INVESTIGATION OF TURBINES WITH ADJUSTABLE STATOR BLADES AND EFFECT OF THESE TURBINES ON JET-ENGINE PERFORMANCE

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

An analytical investigation of turbines with adjustable stator blades was made to determine characteristics and limitations and to determine the improvement in specific fuel consumption at less than maximum thrust for jet engines equipped with this type of turbine and with adjustable-area exhaust nozzles. Studies were made concerning: (1) the necessary variation in stator-exit angle and exhaust-nozzle area; (2) the performance of a contemporary turbine equipped with variable-angle stators based on a one-dimensional analysis; (3) a comparison of the probable performance of conventional engines with and without variable-area exhaust nozzles with engines having adjustable stators, assuming constant component efficiencies for a wide range of compressor pressure ratios and turbine-entrance temperatures; and (4) a comparison of the actual performance of two contemporary jet engines with the analyzed performance, assuming they were equipped with adjustable-angle stators and variable-area exhaust nozzles.

Analyses were also made to determine the effect of radius ratio on the assumptions used in the one-dimensional analysis and on the values of design parameters that result in decreasing relative rotor-entrance Mach number with increasing turbine-entrance total temperatures. Charts were constructed to allow quick calculation of the loss parameters, relative rotor-entrance-angle deviation, and rotor-exit whirl loss for off-design-point operation.

The following results were obtained: (1) The variation in stator-exit angle and exhaust area was not excessive for wide ranges of engine thrust output; (2) the variation in turbine efficiency for contemporary turbines with adjustable stators was small for wide ranges of engine thrust output; (3) improvements from 4.5 to 17 percent (depending on design parameters) in over-all engine

specific fuel consumption over conventional engines, and from 2 to 8.5 percent over engines equipped with only adjustable-area exhaust nozzles at 60-percent rated power were obtained with the use of adjustable-stator turbines and variable-area exhaust nozzles; and (4) the improvement in the specific-fuel consumption of the two contemporary jet engines with the introduction of adjustable-stator turbines and variable-area exhaust nozzle varied from 5 to 8 percent at 70 percent of maximum power. (These results were obtained by assuming that the engines equipped (with adjustable-stator turbines and variable-area exhaust nozzles were designed for cruising conditions.)

INTRODUCTION

Jet engines develop maximum output at the point of maximum compressor pressure ratio and turbine-entrance temperature. The inherent characteristics determined by the necessity of matching the compressor and turbine work output and mass flow of fixed-geometry jet engines result in a decrease in engine speed and compressor pressure ratio as the thrust output (and turbine-entrance temperature) are decreased. This reduction in compressor pressure ratio tends to decrease the thermodynamic cycle efficiency and, with the additional losses resulting from off-design operation of the components, often causes a reduction in over-all engine performance.

One method of improving the performance of turbojet engines at less than maximum thrust is the use of adjustable-area exhaust nozzles. By adjusting the exhaust area and thus varying the pressure ratio across the turbine, the engine can be kept at constant speed for variations in thrust and turbine-entrance temperature. The compressor pressure ratio will therefore decrease less than in fixed-geometry engines that operate at variable speed.

Another method of improving the performance of turbojet engines at less than maximum thrust is to improve the off-design performance of the compressors by adjusting the compressor blades. An analysis of the performance of axial-flow compressors with adjustable blades is presented in reference 1.

A method that provides even more flexibility at thrust conditions below maximum is the combination of adjustable turbine-entrance stators and adjustable exhaust nozzles that provides two degrees of freedom, which the contemporary turbojet engine does not possess. Thus, the engine speed and compressor pressure ratio

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can be controlled independently of the engine thrust, which permits operation of the engine at cruising conditions at the highest allowable engine speed and at the maximum obtainable compressor pressure ratio; these two factors produce low specific fuel consumption under cruising conditions. As the turbine-entrance temperature is increased to change from cruising to full-thrust operation of the engine, adjustment of the angle of the blades of the turbine-entrance stator increases the flow area in the stator to accommodate the increased volume flow of gas and adjustment of the area of the exhaust nozzle changes the turbine pressure ratio in order to maintain a constant engine speed. In this manner, the compressor can be so regulated as to operate at a single, efficient operating condition for a range of turbine-entrance temperatures. If, as the required engine thrust varies, this single-point operation of the compressor does not provide the greatest economy, the two degrees of freedom provided by adjusting the turbine-entrance stator and exhaust nozzle may be exploited to approach optimum performance more closely by varying the engine speed and the compressor pressure ratio.

In addition to improving the cruising and full-thrust operation of turbojet engines, adjustable turbine-entrance stators and exhaust nozzles may improve the starting and acceleration characteristics of the engine. In jet-engine starting, two problems are simplified by adjustable turbine stators and exhaust nozzles.

The first is the problem of starting at sea level. During starting, when the maximum allowable turbine-entrance temperature is used, it might be desirable to change from a point on the compressor operating map where the compressor is operating at low efficiency (near the surge line) to a more efficient operating point. This change may be accomplished by adjusting the turbine stators, thereby changing the mass flow through the compressor and increasing the compressor efficiency and pressure ratio. Larger accelerating torque may thereby be obtained and self-sustained operation may be reached at lower engine speeds.

The second - and highly important - problem is that of engine starting after a combustion blow-out at altitude. Adjustment of turbine stators to reduce the mass flow through the engine and to improve compressor efficiency will provide high windmilling speeds for the engine (and therefore high burner-entrance pressures) while maintaining low burner-entrance velocities, thus providing conditions favorable for ignition.

An additional advantage may be obtained with the use of turbines with adjustable stators. Unlike contemporary jet engines, the engines equipped with turbines having adjustable stators and adjustable exhaust nozzles can probably operate at constant speed for a wide range of thrust. Thus, in changing from low to high thrust, no delay will occur as is usual where acceleration of high-inertia systems are necessary. An incidental advantage of constant compressor speed and maximum pressure ratio at cruising speed is that the tendency for burner blow-out is diminished 1321 because the burner-entrance pressure is higher than for the conventional units, and higher blow-out altitudes at cruising conditions are thereby attained.

The performance of a contemporary turbojet engine with an adjustable exhaust nozzle is reported in references 2 and 3; these references show that some improvement in specific fuel consumption is obtained by the use of the adjustable exhaust nozzle. Information is lacking on the effect of adjustable exhaust nozzles on the performance of engines having compressor pressure ratios and turbine-entrance temperatures higher than those of contemporary engines, and no information is available on the effect of the combination of adjustable turbine-entrance stators and adjustable exhaust nozzles on engine performance.

An analysis was made at the NACA Lewis laboratory to investigate the desirability of using adjustable-stator turbines in combination with adjustable exhaust nozzles by determining the operating characteristics of turbines equipped with adjustable entrance stators, by studying the design limitations, and by estimating the effect on turbojet-engine performance. The secondary purpose of this analysis is to estimate the effect of adjustable exhaust nozzles alone on turbojet-engine performance and to compare this performance with that obtained by using both adjustable turbine-entrance stators and adjustable exhaust nozzles. The additional degrees of freedom provided by these variations in engine geometry change both the performance and the control characteristics of turbojet engines; this investigation is limited to a study of the performance characteristics.

The following problems are analyzed herein: (1) the required ranges of adjustment of turbine stator-blade angle and exhaust-nozzle area; (2) the performance of a contemporary turbine modified to employ an adjustable entrance stator; and (3) the probable performance of turbojet engines covering a wide range of compressor pressure ratios and turbine-entrance temperatures with (a) fixed-geometry components, (b) adjustable exhaust nozzles, and (c) both adjustable turbine-entrance stators and exhaust nozzles. A comparison is also made of the actual performance of two contemporary jet engines with the estimated performance, assuming the engines were equipped with adjustable-angle stators and adjustable exhaust nozzles.

Charts are presented that aid in estimating the performance of adjustable-stator turbines.

ANALYSIS

Stator-Exit-Angle Displacement and Exhaust-Nozzle-Area Variation

In order to maintain constant compressor operating conditions (that is, constant speed, pressure ratio, and mass flow), the stator-exit angle must be varied to hold the mass flow constant as the engine thrust and the turbine-entrance temperature are varied. In order to determine the range of angular displacement, an analysis was made assuming that the mass flow through the stator was independent of the pressure ratio across the stator. This assumption is valid for supercritical pressure ratios. For high subcritical pressure ratios, this assumption is valid within reasonable limits, as shown in reference 4, where the variation in mass flow from the choking value is only about 5 percent at a Mach number of 0.8. With this assumption (using symbols defined in appendix A), the following equation can be written:

$$\frac{w}{w_{des}} = \frac{p'_1}{\sqrt{T'_1}} \frac{A_2}{A_{2,des}} \frac{\sqrt{T'_{1,des}}}{p'_{1,des}} \qquad (1)$$

To a first-order approximation,

$$\frac{A_2}{A_{2,des}} = \frac{\sin \alpha_2}{\sin \alpha_{2,des}}$$

Then

$$\frac{w}{w_{des}} = \frac{p'_1}{p'_{1,des}} \frac{\sqrt{T'_{1,des}}}{\sqrt{T'_1}} \frac{\sin \alpha_2}{\sin \alpha_{2,des}}$$

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With the compressor operating at design point $w = w_{des}$ and $p'_1 = p'_{1,des}$, the following expression holds:

$$\frac{\sin \alpha_2}{\sin \alpha_{2,des}} = \frac{\sqrt{T'_1}}{\sqrt{T'_{1,des}}} \tag{2}$$

Figure 1, obtained using equation (2), shows the stator-exit angle α_2 as a function of the ratio of the turbine-entrance temperature to the design turbine-entrance temperature $T'_1/T'_{1,des}$ for various values of $\alpha_{2,des}$. It is shown that excessive stator-angle displacements are unnecessary for even large increases of turbine-entrance temperatures. Thus, for a 50-percent increase of turbine-entrance temperature, an increment of less than 6° is required for a design value of 25°.

During acceleration at maximum turbine-entrance temperature, adjustment of the turbine-entrance stator may be desired in order to change the mass-flow characteristics of the turbine to provide better compressor operation. At any given speed, it may therefore be desirable to change the mass flow that would be obtained with the stator set at its design angle $w_{\alpha,des}$ to a new mass flow that would insure optimum engine operation $w_{\alpha,opt}$. As in the preceding discussion, except that the stator-pressure-ratio term is included,

$$\frac{w_{\alpha,opt}}{w_{\alpha,des}} = \frac{p'_{1,\alpha,opt}}{p'_{1,\alpha,des}} \frac{\sqrt{T'_{1,\alpha,des}}}{\sqrt{T'_{1,\alpha,opt}}} \frac{\sin \alpha_{opt}}{\sin \alpha_{des}} \frac{f\left(\dfrac{p'_{1,\alpha,opt}}{p_{2,\alpha,opt}}\right)}{f\left(\dfrac{p'_{1,\alpha,des}}{p_{2,\alpha,des}}\right)} \tag{3}$$

At any given speed, p'_1 is approximately constant and for optimum starting T'_1 should equal the maximum allowable temperature. For impulse turbines, $p_2 = p_3$, which is constant for low engine output because the pressure drop across the jet is negligible.

Then

$$\frac{w_{\alpha,opt}}{w_{\alpha,des}} = \frac{\sin \alpha_{opt}}{\sin \alpha_{des}} \tag{4}$$

This equation is not quite true for high-reaction blading, but it does show the trend of the variation, if not the exact magnitude. The stator-exit angle α_2 as a function of the ratio of weight flow on the optimum operating line to weight flow at some point off the optimum line, obtained with the design value of α, $w_{\alpha,opt}/w_{\alpha,des}$, is shown in figure 2 for various values of $\alpha_{2,des}$. Here again an angular displacement of only 6° is required for approximately 20-percent change in weight flow for a design α of 25°.

It is also necessary to vary the exhaust-nozzle area to maintain constant turbine work with turbine-entrance temperature increasing above the design temperature at the cruising condition. An analysis that assumes that the exhaust nozzle is choking and that the turbine efficiency is constant is presented in appendix B. The equation that defines the variation of exhaust-nozzle area is

$$\frac{A_j}{A_{j,des}} = \left(\frac{T'_1}{T'_{1,des}}\right)^{\frac{\gamma}{\gamma-1}} \frac{\left(1 - \frac{\Delta h'_t}{c_p \eta_t T'_{1,des}}\right)^{\frac{\gamma}{\gamma-1}} \left(\frac{T'_1}{T'_{1,des}} - \frac{\Delta h'_t}{c_p T'_{1,des}}\right)^{\frac{1}{2}}}{\left(\frac{T'_1}{T'_{1,des}} - \frac{\Delta h'_t}{c_p \eta_t T'_{1,des}}\right)^{\frac{\gamma}{\gamma-1}} \left(1 - \frac{\Delta h'_t}{c_p T'_{1,des}}\right)^{\frac{1}{2}}} \tag{5}$$

The ratio of exhaust area to design exhaust area $A_j/A_{j,des}$ as a function of $T'_1/T'_{1,des}$, with turbine design pressure ratio as a parameter is shown in figure 3. It is shown that excessive jet-area variation is unnecessary even for a wide range of engine thrust output. For a turbine design pressure ratio of 3, a maximum variation of approximately 15 percent is necessary, whereas for a turbine design pressure ratio of 6, a variation of approximately 35 percent is necessary for a range of engine output from design temperature to 150 percent of the design temperature.

Turbine Analysis

During off-design-point operation, any turbine will encounter losses in addition to those that are inherent at design-point operation. The greatest additional losses are due to rotor-entrance-angle deviation, exit whirl loss, and in some cases an increase in the relative rotor-entrance Mach number above the critical value. In order to determine the operating characteristics of turbines equipped with adjustable stators, it is necessary to evaluate the effect on these three factors of varying the stator-entrance angle.

A common method used for determining off-design-point turbine characteristics is one based on one-dimensional flow using certain coefficients for evaluating losses. A method of this type is presented in reference 5, in which the loss due to rotor-entrance-angle deviation is assumed to be equal to $\frac{W_2^{\,2}}{2g}\sin^2 \beta_{dev}$. The exit whirl loss $\frac{V_{u,3}^{\,2}}{2g}$ is also considered, but the variations in the losses due to the changes in the relative rotor-entrance Mach number are assumed to be negligible.

This method has been used to obtain the operating characteristics of a representative jet-engine turbine. Auxiliary analyses have also been made to determine the effect of radius ratio on the validity of the one-dimensional analysis, as applied to this particular investigation, and the effect of varying the stator-exit angle on the relative rotor-entrance Mach number.

A simplified method, presented in appendix C, provides for the determination of the rotor-entrance angle deviation and rotor-exit tangential velocity at off-design-point operation. This method may be used to give some indication of off-design-point operation of turbines equipped with adjustable stators.

<u>One-dimensional analysis of representative turbine</u>. - Using the design data and design-point performance of a contemporary jet-engine turbine and the method described in reference 5, an analysis was made assuming that the stator-exit angle was adjustable. The pertinent turbine design data used in this analysis are:

$\alpha_{2,m}$, deg	28
$\beta_{2,m}$, deg	66
$\beta_{3,m}$, deg	137
A_2, sq ft	0.852
A_3, sq ft	1.26
Hub-to-tip radius ratio	0.70
Design speed, $U_m/\sqrt{\theta_2}$, ft/sec	604

In order to keep the compressor at its optimum operating point, the results are presented for constant turbine work, weight flow, and speed with the turbine stator-exit angle varying to allow these conditions to exist with varying turbine-entrance temperature, which was done by varying the turbine pressure ratio for various values of turbine-entrance temperature and stator-exit angle with constant mass flow and blade speed. The stator-exit angle, the turbine pressure ratio, and the internal efficiency were plotted against turbine power output and cross plots of these variables were made for a constant turbine output. The results are presented in figure 4. The efficiency curve shows that the turbine efficiency η_t varies only 0.03 from the value at the design point for a range of turbine-entrance temperatures of 40 percent. The remaining curves show the corresponding variations of stator-exit angle and turbine total-pressure ratio with turbine-entrance temperature. Inasmuch as the turbine efficiency variation is small for the range of temperatures investigated, it will be assumed constant in the general analytical treatment of jet-engine performance where the turbines operate in this temperature range.

<u>Effect of turbine hub-to-tip radius ratio on one-dimensional analysis</u>. - The one-dimensional assumptions did not consider the effect of changes in the relative rotor-entrance angles with radius. An analysis, presented in appendix D, was made to determine the range of deviation of relative rotor-entrance angle. Based on simple radial equilibrium and free-vortex flow, the radial variation of α_{des} and β_{des} were determined for various values of $(V_u/U)\alpha_{des}$ and α_{des} at the mean radius. From figure 1, a new stator-exit angle was determined for each value of $\alpha_{2,des}$ for $T'_1/T'_{1,des}$ of 1.5, and the radial variation of $\beta - \beta_{des}$ was calculated.

In this analysis two assumptions were made. The first was that even at supersonic stator-exit velocities the variation of the flow angle at any radius was equal to the variation of the blade angle at the stator exit and was independent of the variation in pressure ratio. Reference 6 supports this assumption up to a pressure ratio of approximately 2.7 for a particular turbine-blade configuration. This value will vary depending upon the blade thickness, pitch, and exit angle. The second assumption used was that the change in the tangential velocity at the stator exit with increasing temperature was small. The reason that this assumption could be made was that for constant turbine speed, weight flow, and turbine output, $V_{u,2} - V_{u,3}$ must be constant and the change in $V_{u,3}$ for the turbine, analyzed as in the previous section, was investigated for a range in turbine-entrance temperatures from $\frac{T'_1}{T'_{1,des}} = 0.9$ to $\frac{T'_1}{T'_{1,des}} = 1.4$ and was found to be negligible.

The results of this analysis are presented in figure 5, where the relative-rotor-entrance-angle deviation $\beta_2 - \beta_{2,des}$ is plotted as a function of radius ratio r/r_m for parameters of design stator-exit angle $\alpha_{m,des}$ and design velocity ratios $(V_u/U)_m$.

It may be seen from these curves that at values of r/r_m less than 1, the value of $\beta_2 - \beta_{2,des}$ is approximately equal to the value at the mean radius. This approximate equality indicates that, for this range of r/r_m, the losses associated with relative-rotor-entrance-angle deviation are consistent with the assumption of the one-dimensional analysis. At values of r/r_m greater than 1, however, the values of $\beta_2 - \beta_{2,des}$ are smaller, which indicates that the one-dimensional analysis results in high losses at the rotor entrance. These high losses indicate that the turbine efficiencies calculated, based on the one-dimensional analysis, are negligibly low.

Effect of variable stator-exit angle on relative rotor-entrance Mach number. - In the design of turbines, the relative entrance Mach number is usually just under the maximum allowable value at the design point. A change in the stator-exit angle from the design point will cause a change in the relative Mach number, and an increase in the Mach number may result in a sharp decrease in efficiency. Whether or not the Mach number will increase or decrease depends on the design conditions. An analysis presented in appendix E was made to determine the combination of design variables for which the relative rotor-entrance Mach number will decrease for an increase in stator-exit angle (that is, an increase in jet-engine power), for constant turbine work, speed, and mass flow, using the same assumptions concerning stator-exit angle and stator-exit tangential-velocity variation set forth in the preceding section. The following expression was obtained for the maximum allowable stator-exit angle for decreasing relative rotor-entrance Mach number with increasing turbine-entrance temperature as a function of velocity ratios V_u/U and V_u/a'_1:

$$\sin \alpha = \sqrt{\frac{(\gamma-1)\left(\frac{V_u}{a'_1}\right)^2 \left(\frac{V_u}{U} - \frac{1}{2}\right) - 2\left(\frac{V_u}{U} - 1\right)^2 + \sqrt{\left[(\gamma-1)\left(\frac{V_u}{a'_1}\right)^2 \left(\frac{V_u}{U}\right) - \frac{1}{2} - 2\left(\frac{V_u}{U} - 1\right)\right]^2 + 8\left(\frac{V_u}{U} - \frac{1}{2}\right)\left(\frac{V_u}{U} - 1\right)^2}}{4\left(\frac{V_u}{U} - \frac{1}{2}\right)}} \tag{6}$$

Figure 6 is plotted using the preceding equation. The function of this curve may be explained by means of the following example: If at a given radius the velocity ratio V_u/U is equal to 1.8 and the Mach number $V_u/a'_1 = 1.00$, then the maximum stator-exit angle that will result in a decreasing relative rotor-entrance Mach number with increasing turbine-inlet temperature is 36.7°. For any larger stator-exit angle, the relative rotor-entrance Mach number will increase and a study of this Mach number will be necessary to determine if the Mach number obtained is above that which is critical for the particular set of rotor blades.

The maximum relative rotor-entrance Mach number usually occurs at the inner radius of the turbine where the values of V_u/U are usually between 1.5 and 2.0. In this range, the maximum stator-exit angles that result in decreasing relative rotor-entrance Mach number for increasing turbine-entrance temperature are approximately 31 to 40 degrees.

Jet-Engine-Performance Analysis

In order to evaluate the effect of variable-angle-stator turbines on jet-engine performance, comparisons must be made of conventional jet engines with and without variable-area exhaust nozzles and jet engines equipped with adjustable-stator turbines and variable-area exhaust nozzles. In order to obtain this comparison, two methods were used. The first method was a general analytical treatment that included cycle analysis to obtain equilibrium operating lines for both conventional and adjustable-stator turbojet engines for a wide range of design-point parameters, assuming constant component efficiency. The second method was a comparison of the operating characteristics as determined from test data of two contemporary jet engines, with the operating characteristics of jet engines as analyzed with the following components: the actual compressors, the actual combustion chambers, and the adjustable-stator turbines, together with variable exhaust areas.

General analysis of jet-engine performance. - In this analysis, conventional jet engines and jet engines equipped with variable-area nozzles were compared with engines equipped with adjustable-angle stators and variable-area nozzles. These comparisons were made for various values of maximum compressor pressure ratio and turbine-entrance temperature. For any one comparison, the same value of maximum compressor pressure ratio and turbine-entrance temperature was assigned to each of the three types of engine. The equilibrium operating lines of the conventional jet engines and the equilibrium operating lines and the nozzle-area variation of the engines equipped with variable-area nozzles were determined in accordance with the methods described in reference 7. With the assumption that the engine mass flow is a function only of engine speed and that the component efficiencies are constant, it is possible to obtain an approximation of the off-design operating conditions for any set of design parameters. A further condition applied to the jet engines equipped with variable-area nozzles was that the nozzle-area variation was assigned to hold engine speed constant.

For the adjustable-stator turbojet engines, the operating conditions were determined by holding the compressor at its design point; that is, constant mass flow, speed, compressor pressure ratio, and turbine output. The engine output was varied by changing the turbine-entrance temperature and adjusting the stator-exit angles and exhaust area. Here again constant component efficiencies were assumed. This method of analysis tends to favor the engines with variable-area exhaust nozzles, because reduction of turbine-entrance temperature causes a decrease of the compressor efficiency due to the large change in compressor pressure ratio that must occur at constant speed, whereas in this analysis the compressor efficiency was assumed constant.

In accordance with the method for cycle calculations presented in reference 8, an analysis was made for both the conventional and adjustable-stator turbojet engines for two values of maximum turbine-entrance temperatures and a wide range of maximum compressor pressure ratios.

Specific fuel consumption, compressor pressure ratio, and exhaust-nozzle-area variation are presented in figure 7 as a function of percentage of maximum thrust for (a) conventional engines of fixed-geometry components, (b) jet engines with variable-area exhaust nozzle, and (c) jet engines with variable-area exhaust nozzle and adjustable turbine-entrance stators.

Inasmuch as the maximum compressor ratio and turbine-entrance temperature occur only at the maximum thrust point for each of the three types of engine, the specific fuel consumptions are equal at this point. It may be seen that for the complete range of compressor pressure ratios and turbine-entrance temperatures investigated, the use of adjustable turbine stators and variable-area exhaust nozzles results in improvement, at lower than maximum thrust, of specific fuel consumption over both the fixed-geometry jet engines and variable-area-exhaust-nozzle engines. This improvement varied considerably, depending upon the compressor pressure ratio and turbine-entrance temperature used at maximum thrust.

Thus, for a maximum turbine-entrance temperature of 2400° R, the improvement in specific fuel consumption over jet engines with fixed-geometry components at 60-percent maximum thrust varied from 9 percent at a maximum compressor pressure ratio of 4 to 4.5 percent at a maximum pressure ratio of 12 (figs. 7(a) to 7(d)). For a maximum turbine-entrance temperature of 3200° R, the improvement at 60 percent of maximum thrust varied from 17 percent at a maximum compressor pressure ratio of 4 to 11.5 percent at a maximum pressure ratio of 12 (figs. 7(e) to 7(h)). The improvement of specific fuel consumption over jet engines equipped with variable-area exhaust nozzles varied from 3.5 percent to 2 percent at a maximum turbine-entrance temperature of 2400° R and from 8.5 percent to 3 percent at a maximum turbine-entrance temperature of 3200° R for the same conditions as previously given. The smallest values of improvement shown are probably of little significance because the assumption of constant component efficiencies may introduce errors of the same order of magnitude. The assumptions for the adjustable-turbine-stator case are the least uncertain because they depend on a fixed compressor operating point instead of on constant efficiency with variations in compressor operation.

It can be seen that at any given pressure ratio the improvement, at lower than maximum thrust, increases with increasing turbine-entrance temperature, whereas for any turbine-entrance temperature the improvement decreases with increasing pressure ratio. The reason for the improvement in specific fuel consumption is that, in almost every case investigated, the turbine-entrance temperature was above that necessary for minimum specific fuel consumption at that particular pressure ratio. Any decrease in pressure ratio in comparing one engine with another at any given temperature (approximately fixed thrust) therefore caused an increase in engine specific fuel consumption. Thus, the higher the maximum turbine-entrance temperature is above that which gives minimum specific fuel consumption, the greater the improvement that might be expected from a combination of adjustable-angle turbine-entrance stators and variable-area exhaust nozzles. Also, because the optimum temperature increases with increasing pressure ratio, for any given turbine-entrance temperature the improvement in specific fuel consumption of adjustable-angle-stator turbine engines will decrease as the maximum pressure ratio increases.

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The use of only variable-area exhaust nozzles resulted in an improvement of specific fuel consumption over the fixed-geometry jet engines for the complete range of thrust investigated. Here again, the improvement was dependent upon the compressor pressure ratio and turbine-entrance temperature at maximum thrust. For a maximum turbine-entrance temperature of 2400° R, the improvement over jet engines with fixed geometry at 60 percent of maximum thrust varied from 5.5 percent at a maximum compressor pressure ratio of 4 to 3 percent at a maximum pressure ratio of 12 (figs. 7(a) to 7(d)). For a maximum turbine-entrance temperature of 3200° R, the improvement at 60 percent of maximum thrust varied from 9.5 percent at a maximum compressor pressure ratio of 4 to 8.5 percent at a maximum pressure ratio of 12 (figs. 7(e) to 7(h)).

The range of compressor pressure ratios over which the compressor will operate for the various configurations is also shown in figure 7. Thus, although the engine with two variable-geometry components can attain constant compressor pressure ratio over the range of operation, the pressure ratio of the conventional engine varies from about 25 to 40 percent and pressure ratios of the engines with variable-area exhaust nozzles vary from about 15 to 25 percent over a range of thrust output from 60 to 100 percent. These variations will probably entail losses in compressor efficiency. In the variable-area-exhaust-nozzle engine, these losses will probably be larger despite the smaller pressure-ratio variation, inasmuch as these variations are assumed to occur at constant speed.

A comparison is also presented of the variation in exhaust area for the two variable-geometry-component engines. It can be seen that at the low pressure ratios the adjustable-angle-stator engine has less area variation than the adjustable-exhaust-nozzle engines, whereas at higher pressure ratios the reverse is true.

Analysis of contemporary jet engines with and without adjustable stators. - In this analysis, the operating performances obtained from experimental data of two contemporary jet engines were used. Experimental data of the compressor and combustion chamber were used in conjunction with an analysis of adjustable-stator turbines to obtain the operating characteristics of adjustable-stator-turbine engines for comparison.

The performance of adjustable-stator-turbine engines was obtained for constant compressor operating conditions over the complete engine-power range. The turbine characteristics used in this analysis were obtained in the following manner: The maximum turbine efficiency was assumed to be obtained at approximately 70-percent maximum net engine thrust and the efficiencies over the remainder of the operating range were assumed to vary with turbine-entrance temperature ratio, as shown in the section on turbine analysis. The method for cycle calculations as presented in reference 8 was used to obtain the over-all engine performance.

Figure 8 presents a comparison of engine performance for a conventional jet engine and an engine with an adjustable-stator turbine with both engines having the same centrifugal-flow compressor operating at a maximum compressor pressure ratio of 4.40 and turbine-entrance temperature of 1960° R. Figure 9 shows a similar comparison for jet engines having the same axial-flow compressor with a maximum compressor pressure ratio of 3.90 and at turbine-entrance temperatures of 1760° R. The improvement in fuel consumption at 70 percent of maximum engine output is 8 percent for the centrifugal-compressor engine and 5 percent for the axial-flow compressor engine.

SUMMARY OF RESULTS

An analytical investigation of turbines with adjustable stator blades was made to determine their operating characteristics and limitations, to determine the performance of jet engines equipped with this type of turbine and with variable-area exhaust nozzles, and to compare the performance with conventional engines with fixed geometry and with conventional engines with variable-area exhaust nozzles. The following results were obtained:

1. The variation in turbine stator-exit angle was not excessive for wide ranges of engine thrust output. For a 50-percent increase in turbine-entrance temperature, an increment of less than 6° was required for a design exit angle of 25°.

2. The necessary variation in exhaust-nozzle area was not large, but increased for higher turbine pressure ratios. A maximum variation of approximately 15 percent for a design turbine pressure ratio of 3 and approximately 35 percent for a design turbine pressure ratio of 6 were necessary for a range of engine output from design temperature to 150 percent of design temperature.

3. The variation in turbine efficiency from the value at the design point for a range of turbine-entrance temperatures of 40 percent is about 0.03 for a contemporary turbine equipped with adjustable stators.

4. The improvement in over-all specific fuel consumption that may be obtained at 60 percent of maximum thrust with the use of variable-angle-stator turbines and adjustable-area exhaust nozzles varies from more than 4.5 percent (for a maximum thrust condition at a turbine-entrance temperature of 2400° R and compressor pressure ratio of 12) to 17 percent (for a maximum thrust condition at a turbine-entrance temperature of 3200° R and compressor pressure ratio of 4).

For a similar range of maximum-thrust parameters, the improvement in specific fuel consumption of this configuration over engines equipped only with variable-area exhaust nozzles was from 2 to 8.5 percent. In the variable-area-exhaust-nozzle engines, the compressor losses will probably be larger than in the engines with the other two configurations, and thus the advantages, as presented for the variable-angle-stator engines over engines equipped only with variable-area exhaust nozzles, are pessimistic.

The smallest values of improvement shown are probably of little significance because the assumption of constant component efficiencies may introduce errors of the same order of magnitude.

5. Two contemporary jet engines with maximum compressor pressure ratios of 4.4 and 3.9, turbine-entrance temperatures of 1960° and 1760° R, and equipped with variable-angle-stator turbines and adjustable-area exhaust nozzles gave an improvement in specific fuel consumption of about 8 and 5 percent, respectively, at a cruising condition at 70 percent maximum engine output over comparable fixed-geometry jet engines.

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APPENDIX A

SYMBOLS

The following symbols are used in this report:

A	flow area, sq ft
An	effective annulus area
a	velocity of sound, ft/sec
c_p	specific heat at constant pressure, Btu/(lb)(°R)
g	acceleration due to gravity, ft/sec^2
h	specific enthalpy, Btu/lb
J	mechanical equivalent of heat, ft-lb/Btu
M	Mach number
p	absolute pressure, lb/sq ft
R	gas constant, ft-lb/(°R)(lb)
r	radius, ft
T	absolute temperature, °R
U	blade velocity, ft/sec
V	absolute gas velocity, ft/sec
W	relative gas velocity, ft/sec
w	gas weight flow, lb/sec
α	angle of absolute velocity with tangential direction, deg
β	angle of relative velocity with tangential direction, deg
γ	ratio of specific heats
ρ	density, lb/cu ft

θ temperature reduction factor (T/T^*)

η_t turbine efficiency based on stagnation conditions neglecting tangential velocity component

Subscripts:

0 ambient

1 turbine entrance

2 turbine-stator exit, -rotor entrance

3 turbine-rotor exit

cr state at speed of sound (critical)

des design

dev deviation

j jet

m condition at mean radius

opt optimum

t turbine

u tangential

W relative velocity

x axial

Superscripts:

' stagnation state

* reference state

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APPENDIX B

EXHAUST-AREA VARIATION AS FUNCTION OF TURBINE-ENTRANCE TEMPERATURE

In order to determine the range of exhaust-area variation, an analysis assuming supercritical or high subcritical velocities at the jet was made as follows:

$$\text{Weight flow } w \text{ through jet} = \frac{p'_3}{\sqrt{T'_3}} A_j \, f\left(\frac{p'_3}{p_0}\right)$$

For high subsonic or supersonic velocities at the jet,

$$f\left(\frac{p'_3}{p_0}\right) = \text{constant}$$

For constant turbine work,

$$T'_3 = T'_1 - \frac{\Delta h'_t}{c_p}$$

or

$$\frac{\Delta h'_t}{c_p \eta_t} \frac{1}{T'_1} = 1 - \left(\frac{p'_3}{p'_1}\right)^{\frac{\gamma-1}{\gamma}}$$

or

$$p'_3 = p'_1 \left(1 - \frac{\Delta h'_t}{c_p \eta_t} \frac{1}{T'_1}\right)^{\frac{\gamma}{\gamma-1}}$$

Substituting for T'_3 and p'_3 in the equation for weight flow yields

$$w = p'_1 \left(1 - \frac{\Delta h'_t}{c_p \eta_t} \frac{1}{T'_1}\right)^{\frac{\gamma}{\gamma-1}} \frac{A_j\, f\left(\frac{p'_3}{p_0}\right)}{\sqrt{T'_1 - \frac{\Delta h'_t}{c_p}}}$$

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Inasmuch as $w = w_{des}$,

$$\frac{A_j}{A_{j,des}} = \left(\frac{T'_1}{T'_{1,des}}\right)^{\frac{\gamma}{\gamma-1}} \frac{\left(1 - \frac{\Delta h'_t}{c_p \eta_t T'_{1,des}}\right)^{\frac{\gamma}{\gamma-1}} \left(\frac{T'_1}{T'_{1,des}} - \frac{\Delta h'_t}{c_p T'_{1,des}}\right)^{\frac{1}{2}}}{\left(\frac{T'_1}{T'_{1,des}} - \frac{\Delta h'_t}{c_p \eta_t T'_{1,des}}\right)^{\frac{\gamma}{\gamma-1}} \left(1 - \frac{\Delta h'_t}{c_p T'_{1,des}}\right)^{\frac{1}{2}}} \tag{5}$$

APPENDIX C

CONSTRUCTION AND USE OF CHARTS FOR DETERMINATION OF LOSS PARAMETERS FOR OFF-DESIGN-POINT TURBINE OPERATION

The charts for determining the rotor-exit conditions of a turbine were constructed as follows:

From the energy equation,

$$\frac{\rho}{\rho'} = \left[1 - \frac{\gamma-1}{\gamma+1}\left(\frac{V}{a_{cr}}\right)^2\right]^{\frac{1}{\gamma-1}}$$

where $a_{cr} = \sqrt{\frac{2}{\gamma+1}\gamma gRT'}$

and from the exit-velocity vector diagram

$$\left(\frac{V}{a_{cr}}\right)^2 = \left(\frac{V_x}{a_{cr}}\right)^2 + \left(\frac{V_u}{a_{cr}}\right)^2$$

the following expression is derived:

$$\frac{\rho V_x}{\rho' a_{cr}} = \left[1 - \frac{\gamma-1}{\gamma+1}\left(\frac{V_x^2 + V_u^2}{a_{cr}^2}\right)\right]^{\frac{1}{\gamma-1}} \frac{V_x}{a_{cr}} \qquad (7)$$

By assigning values of $\rho V_x/\rho' a_{cr}$ and V_u/a_{cr}, a graphical solution was used to determine V_x/a_{cr} from equation (7) for $\gamma = 1.30$. Relative rotor-exit angles were then assigned and the values of U/a_{cr} were calculated. For each assigned value of $\rho V_x/\rho' a_{cr}$, charts were constructed with values of V_u/a_{cr} plotted against U/a_{cr} with relative entrance angles β_2 as a parameter.

The charts for determining the rotor-entrance conditions were constructed as follows:

$$\tan \beta_2 = \frac{V_x/U}{w_u/U}$$

where

$$\frac{w_u}{U} = \frac{V_u}{U} - 1$$

and

$$\tan \alpha = \frac{V_x/U}{V_u/U}$$

Then

$$\beta_2 = \tan^{-1}\left(\frac{V_u/U \tan \alpha}{V_u/U - 1}\right) \tag{8}$$

When values were assigned to α and V_u/U, β_2 was calculated using equation (8), and a chart was constructed with β_2 plotted against V_u/U with the stator-exit angle α as a parameter.

The procedure for application of the charts for determination of $V_{u,3}$ and β_2 at off-design conditions follows.

For any turbine operating condition, these variables are known:

T'_1 turbine-entrance temperature

α_2 stator-exit angle

U blade speed

β_3 rotor-blade-exit angle

$\Delta h'_t$ turbine output (constant)

w turbine mass flow (constant)

An_3 effective rotor-exit annulus area

Then

$$T'_3 = T'_1 - \frac{\Delta h'_t}{c_p}$$

and

$$p'_3 = p'_1 \left(1 - \frac{\Delta h'_t}{\eta_t c_p T'_1}\right)^{\frac{\gamma}{\gamma-1}}$$

From the preceding relations, ρ'_3 and $a_{cr,3}$ may be determined. Also

$$\rho_3 V_{x,3} = \frac{w}{An_3}$$

Then

$$\frac{\rho_3 V_{x,3}}{\rho'_3 a_{cr,3}}$$

and

$$\frac{U}{a_{cr,3}}$$

are also known. With the use of these parameters, β_3, and figure 10, $V_{u,3}/a_{cr,3}$ can be determined. With $V_{u,3}$ known, β_2 may be found as follows:

$$V_{u,2} = \frac{\Delta h'_t \; gJ}{U} + V_{u,3}$$

and with the use of $V_{u,2}$, α_2, and figure 11, β_2 can be determined.

Thus, for any operating condition, the parameters that effect the greatest off-design losses can be determined. The internal efficiency η_t must be assumed in the calculation of p'_3; however, inasmuch as this assumption affects only the value of ρ'_3 for a first approximation, it will usually be sufficient to use the design value of efficiency.

APPENDIX D

RELATIVE-ROTOR-ENTRANCE-ANGLE VARIATION WITH RADIUS FOR ADJUSTABLE STATORS

In order to determine the relative rotor-entrance angle along the radius, it is necessary to find the stator-exit-angle variation at the desired off-design point. For vortex flow at the design point,

$$V_u r = V_{u,m} r_m$$

and

$$V_x = V_{x,m}$$

$$\tan \alpha_{des} = \frac{V_x}{V_u} = \frac{V_{x,m}}{V_{u,m}} \frac{r}{r_m} \tag{9}$$

At the off-design point,

$$\alpha = \alpha_{des} + \alpha_{dev}$$

where α_{dev} may be determined from figure 1.

For simple radial equilibrium,

$$\frac{V_u^2}{gr} = \frac{dp}{\rho\, dr}$$

and

$$\frac{1}{2} \frac{dV^2}{g\, dr} + \frac{dp}{\rho\, dr} = 0$$

for constant energy along the radius.

From the velocity triangle,

$$V^2 = V_u^2 (1 + \tan^2 \alpha)$$

Combining the equilibrium and energy equations and substituting for V^2 yield

$$\frac{d(\log V_u)}{dr} = -\frac{1}{(1 + \tan^2 \alpha)}\left(\frac{1}{r} + \sec^2 \alpha \tan \alpha \frac{d\alpha}{dr}\right)$$

and because $\alpha = \alpha_{des} + \alpha_{dev}$, then

$$\frac{d(\log V_u)}{dr} = -\left[\frac{1}{\sec^2(\alpha_{des} + \alpha_{dev})}\right]$$

$$\left[\frac{1}{r} + \sec^2(\alpha_{des} + \alpha_{dev}) \tan(\alpha_{des} + \alpha_{dev}) \frac{d(\alpha_{des} + \alpha_{dev})}{dr}\right]$$

Differentiating equation (9) yields

$$\frac{d(\alpha_{des})}{dr} = \frac{V_{x,m}}{V_{u,m}} \frac{\cos^2 \alpha_{des}}{r_m}$$

and

$$\frac{d(\alpha_{dev})}{dr} = 0$$

$$\frac{d(\log V_u)}{d\left(\frac{r}{r_m}\right)} = -\left[\cos^2(\alpha_{des} + \alpha_{dev})\right]$$

$$\left[\frac{r_m}{r} + \frac{\cos^2 \alpha_{des}}{\cos^2 (\alpha_{des} + \alpha_{dev})} \tan(\alpha_{des} + \alpha_{dev}) \frac{V_{x,m}}{V_{u,m}}\right]$$

By integrating this equation and using equation (9) to define α_{des}, V_u was obtained as a function of r/r_m for various values of α_{des} and the value of α_{dev} was obtained from figure 1, for a $T'_1/T'_{1,des}$ of 1.5.

APPENDIX E

VARIATION OF RELATIVE ROTOR-ENTRANCE MACH NUMBER WITH TURBINE POWER OUTPUT

In order to determine the variation of the relative rotor-entrance Mach number from the design point at the cruising condition, the following analysis was made:

$$M_W{}^2 = \frac{W^2}{\gamma g R T_2}$$

inasmuch as

$$W^2 = (V_u - U)^2 + V_x{}^2$$

and

$$\tan \alpha = \frac{\sin \alpha}{\sqrt{1 - \sin^2 \alpha}}$$

then

$$M_W{}^2 = \frac{1}{\gamma g R T_2}\left[(V_u - U)^2 + \frac{V_u{}^2 \sin^2 \alpha}{1 - \sin^2 \alpha}\right]$$

Substituting for T_2 in terms of turbine-entrance temperature and stator-exit velocity yields

$$M_W{}^2 = \frac{1}{\gamma g R T'_1}\left[T'_1 - \left(\frac{V_u{}^2}{2gR}\right)\left(\frac{\gamma-1}{\gamma}\right)\left(1 + \frac{\sin^2 \alpha}{1 - \sin^2 \alpha}\right)\right]^{-1}$$

$$\left[(V_u - U)^2 + \frac{V_u{}^2 \sin^2 \alpha}{1 - \sin^2 \alpha}\right]$$

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Because

$$\frac{\sin \alpha}{\sin \alpha_{des}} = \sqrt{\frac{T'_1}{T'_{1,des}}}$$

$$M_W^{\ 2} = \frac{(V_u - U)^2\left(1 - \sin^2 \alpha_{des} \dfrac{T'_1}{T'_{1,des}}\right) + V_u^{\ 2} \sin^2 \alpha_{des} \dfrac{T'_1}{T'_{1,des}}}{\gamma g R\, T'_1\left(1 - \sin^2 \alpha_{des} \dfrac{T'_1}{T'_{1,des}}\right) - \dfrac{\gamma - 1}{2} V_u^{\ 2}}$$

By differentiating $M_W^{\ 2}$ with respect to T'_1, setting the differential equal to zero, and assuming that $\partial V_u/\partial T'_1$ is zero, the following equation is obtained:

$$2\left(\frac{V_u}{U} - \frac{1}{2}\right) \sin^4 \alpha - \left[(\gamma - 1)\left(\frac{V_u}{a'_1}\right)^2 \left(\frac{V_u}{U} - \frac{1}{2}\right) - 2\left(\frac{V_u}{U} - 1\right)^2\right] \sin^2 \alpha - \left(\frac{V_u}{U} - 1\right)^2 = 0$$

where

$$a'_1 = \sqrt{\gamma g R\, T'_1}$$

Solving for the maximum value of $\sin \alpha$ for which decreasing values of M_W are obtained for increasing power yields:

$$\sin \alpha = \sqrt{\frac{(\gamma-1)\left(\frac{V_u}{a'_1}\right)^2 \left(\frac{V_u}{U} - \frac{1}{2}\right) - 2\left(\frac{V_u}{U} - 1\right)^2 + \sqrt{\left[(\gamma-1)\left(\frac{V_u}{a'_1}\right)^2 \left(\frac{V_u}{U} - \frac{1}{2}\right) - 2\left(\frac{V_u}{U} - 1\right)\right]^2 + 8\left(\frac{V_u}{U} - \frac{1}{2}\right)\left(\frac{V_u}{U} - 1\right)^2}}{4\left(\frac{V_u}{U} - \frac{1}{2}\right)}} \tag{6}$$

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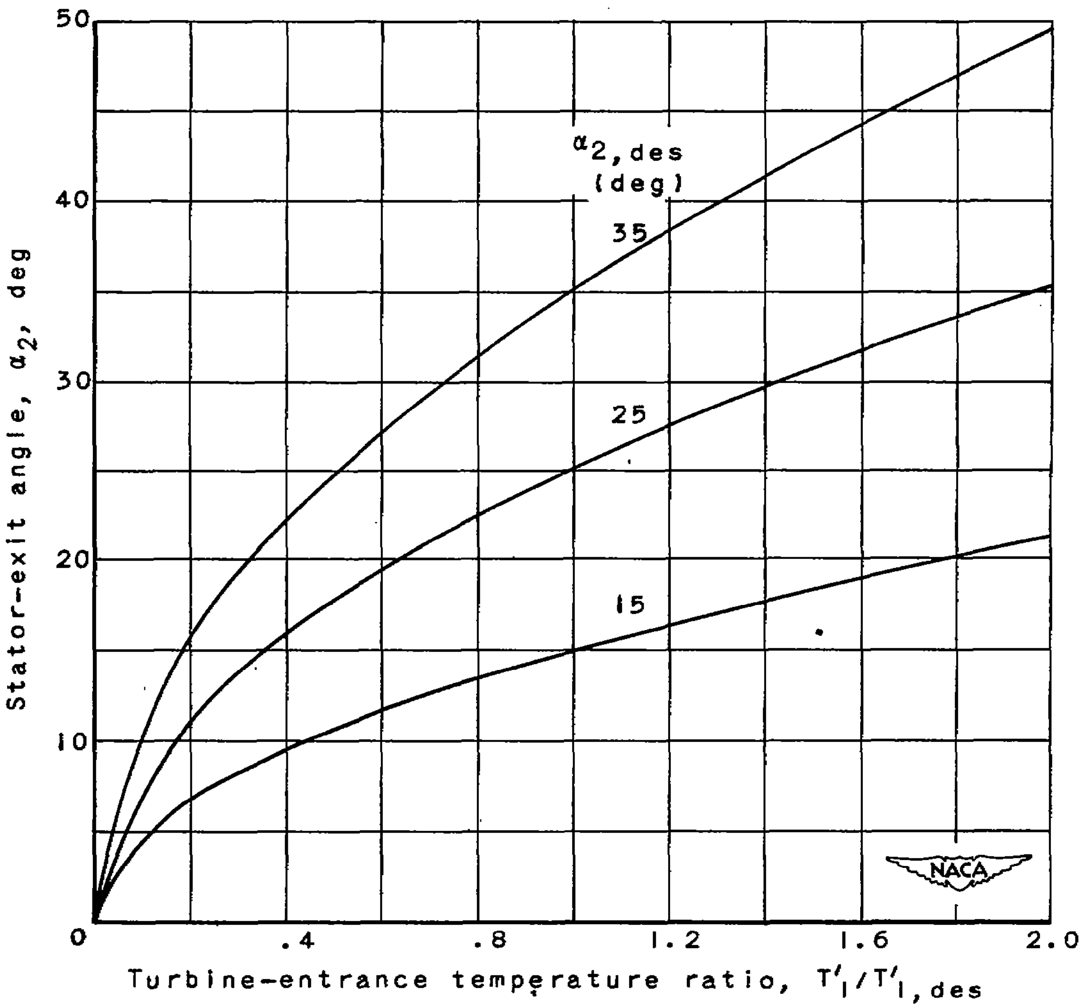

Figure 1. - Variation of stator-exit angle with temperature ratio for constant weight flow and various design values of stator-exit angle.

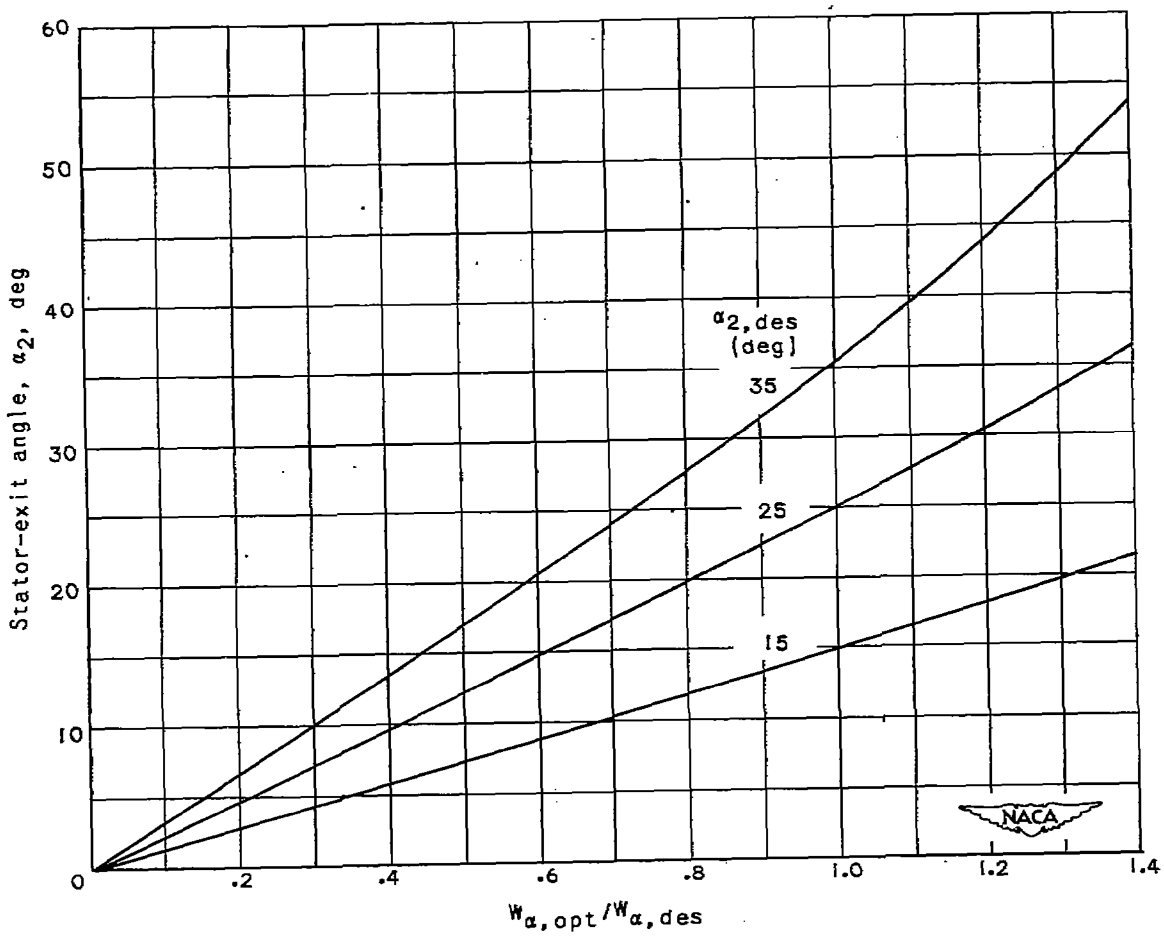

Figure 2. - Variation of stator-exit angle with weight-flow ratio for various design values of stator-exit angle.

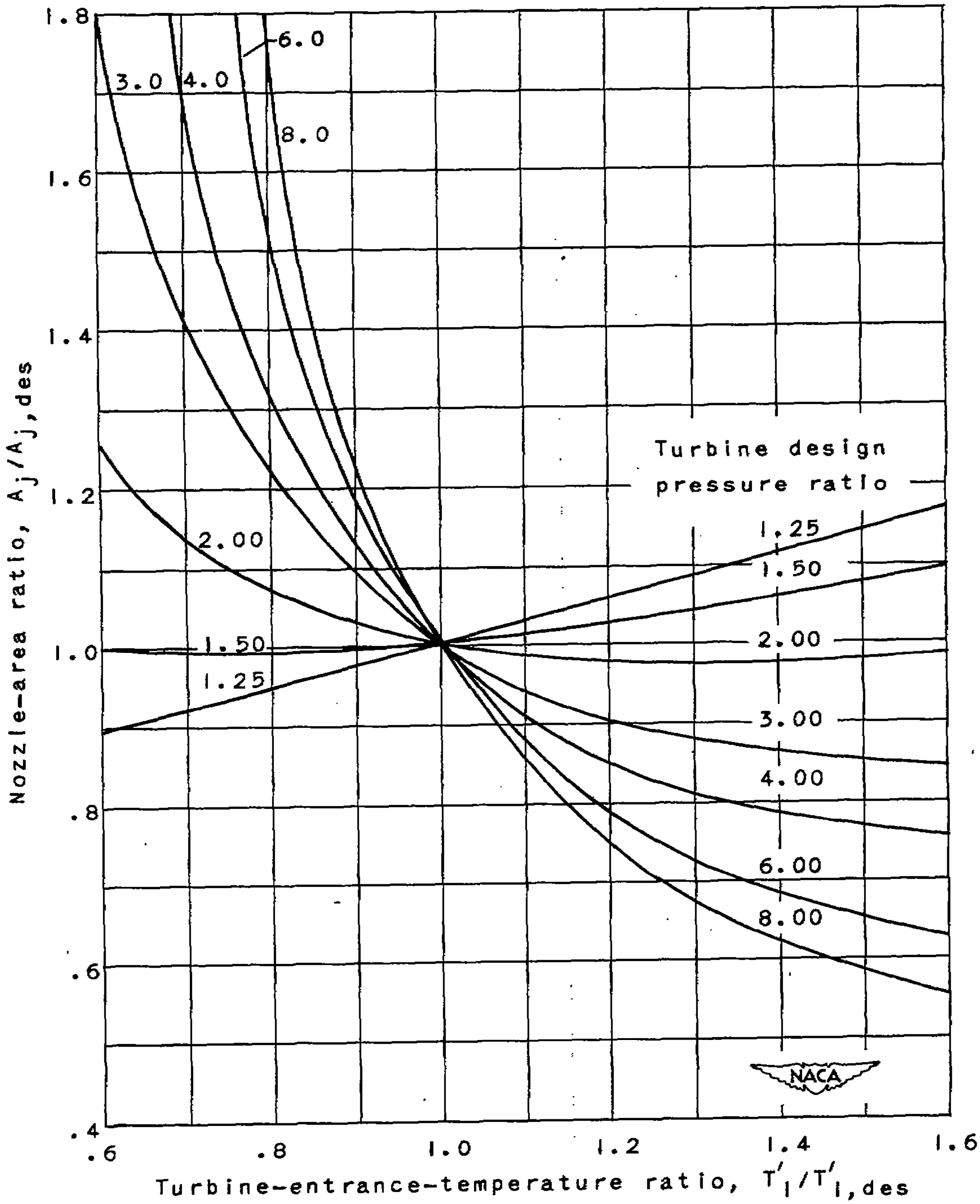

Figure 3. - Nozzle area for jet engine equipped with turbine with adjustable stator blades.

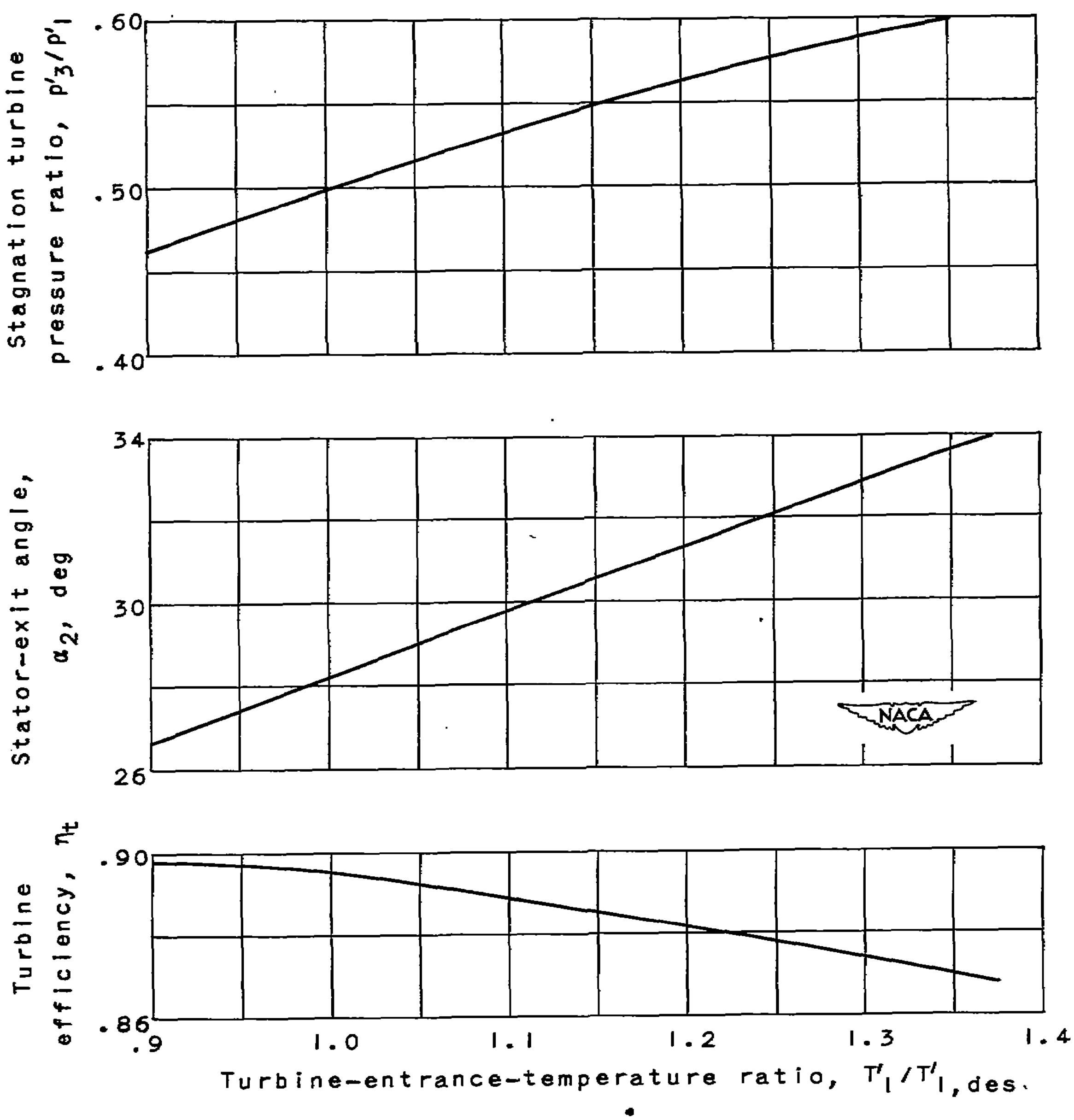

Figure 4. - Performance of representative turbine with adjustable stator blades at constant power, speed, mass flow, and turbine-entrance temperature.

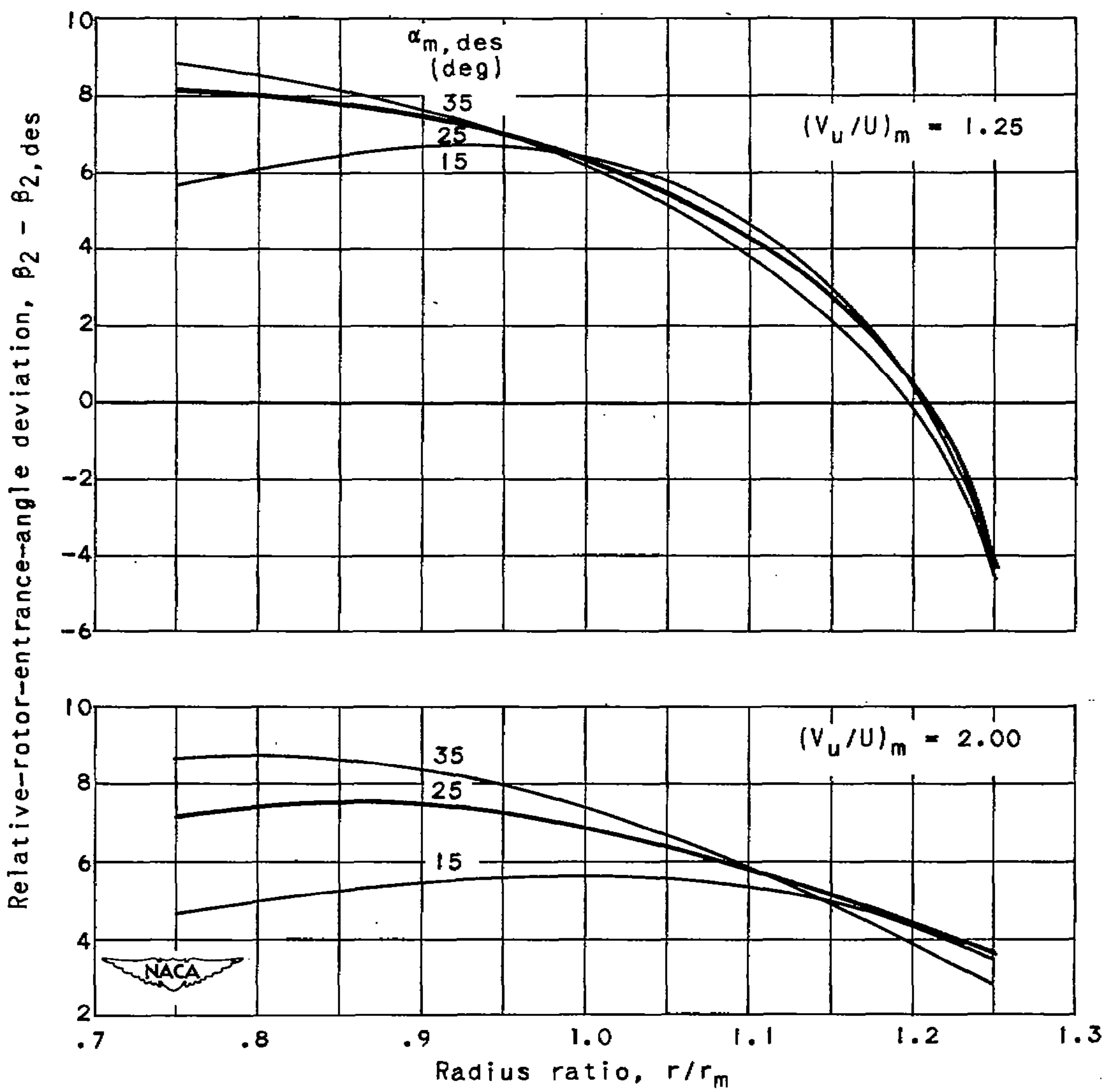

Figure 5. – Deviation in relative rotor-entrance angle for turbine-entrance-temperature ratio of 1.5.

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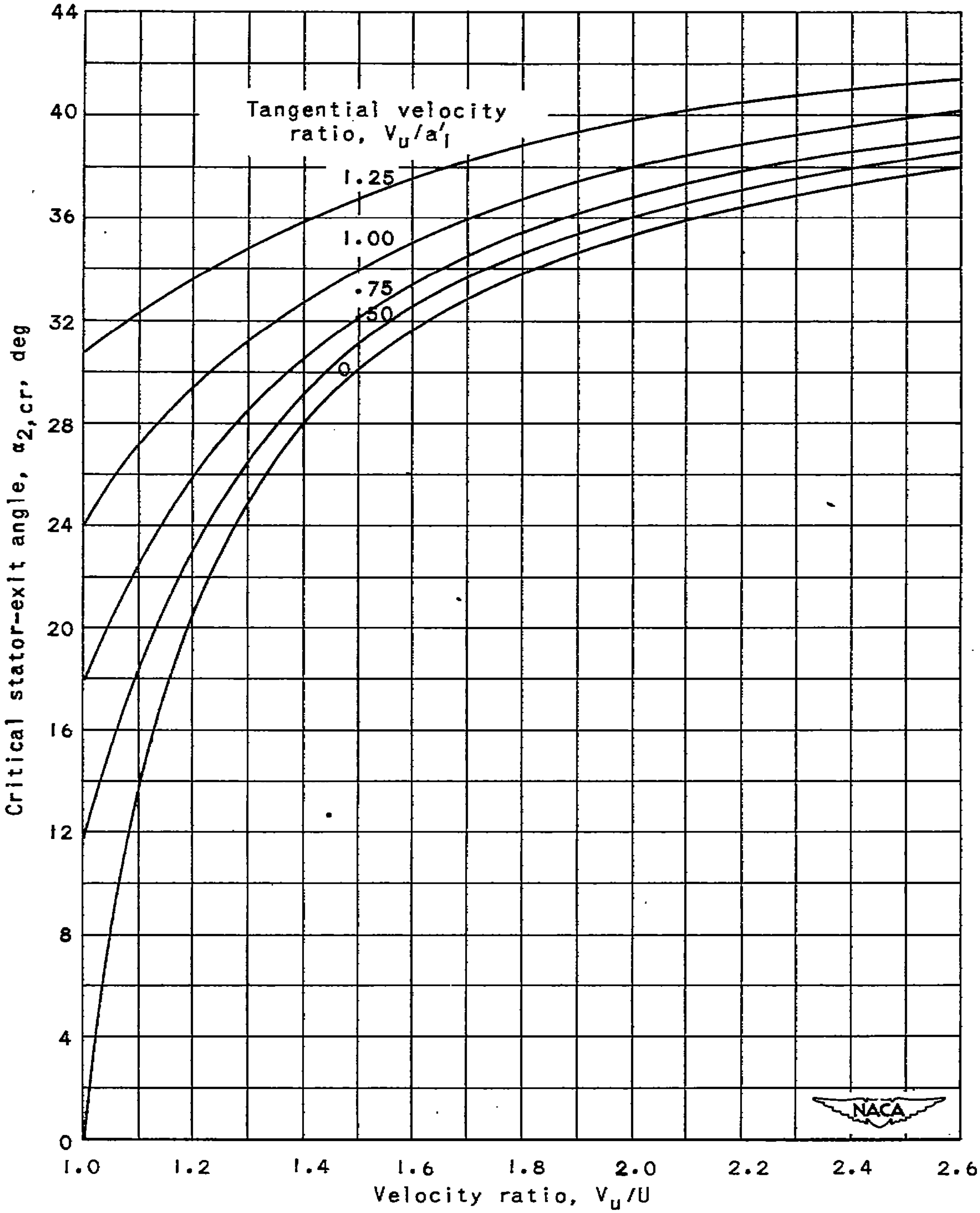

Figure 6. - Maximum allowable stator-exit angle for decreasing relative Mach number and for increasing turbine-entrance temperature. $\gamma = 1.33$.

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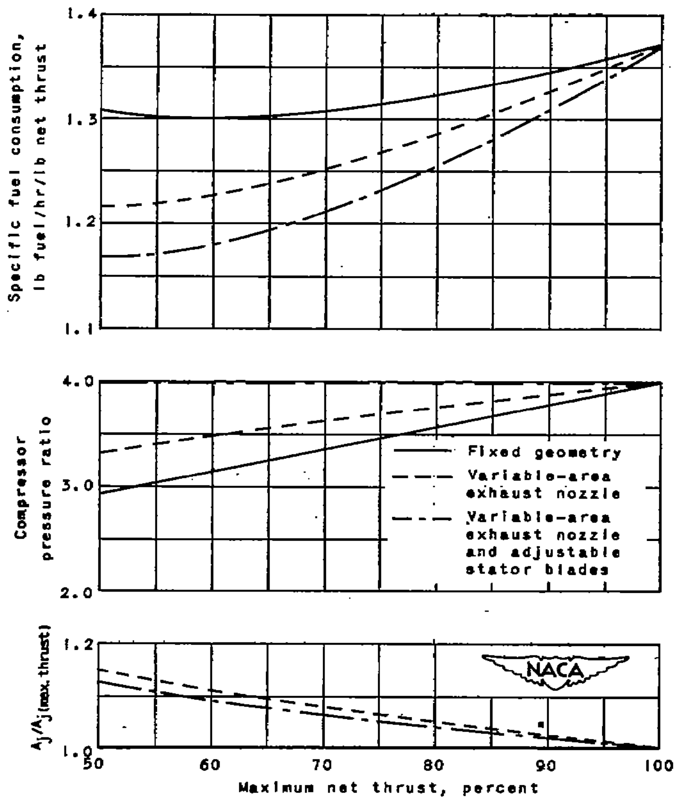

(a) Maximum turbine-entrance temperature, 2400° R; maximum compressor pressure ratio, 4.0.

Figure 7. - Comparison of representative jet engine with fixed geometry, variable-area exhaust nozzle, and adjustable stator blades and variable-area exhaust nozzle. Flight speed, 600 miles per hour at sea level.

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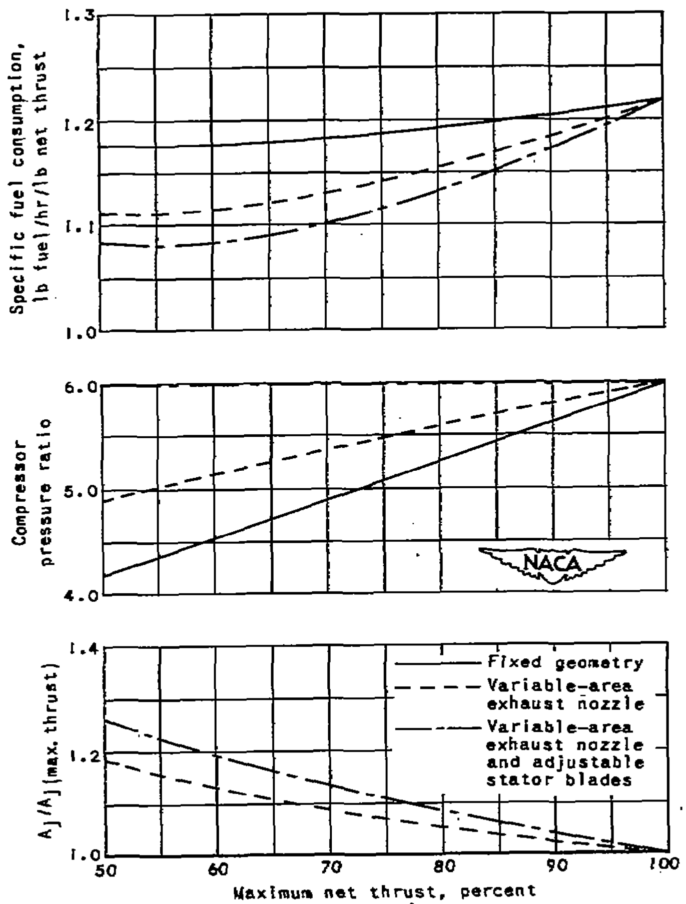

(b) Maximum turbine-entrance temperature, 2400° R; maximum compressor pressure ratio, 6.0.

Figure 7. – Continued. Comparison of representative jet engine with fixed geometry, variable-area exhaust nozzle, and adjustable stator blades and variable-area exhaust nozzle. Flight speed, 600 miles per hour at sea level.

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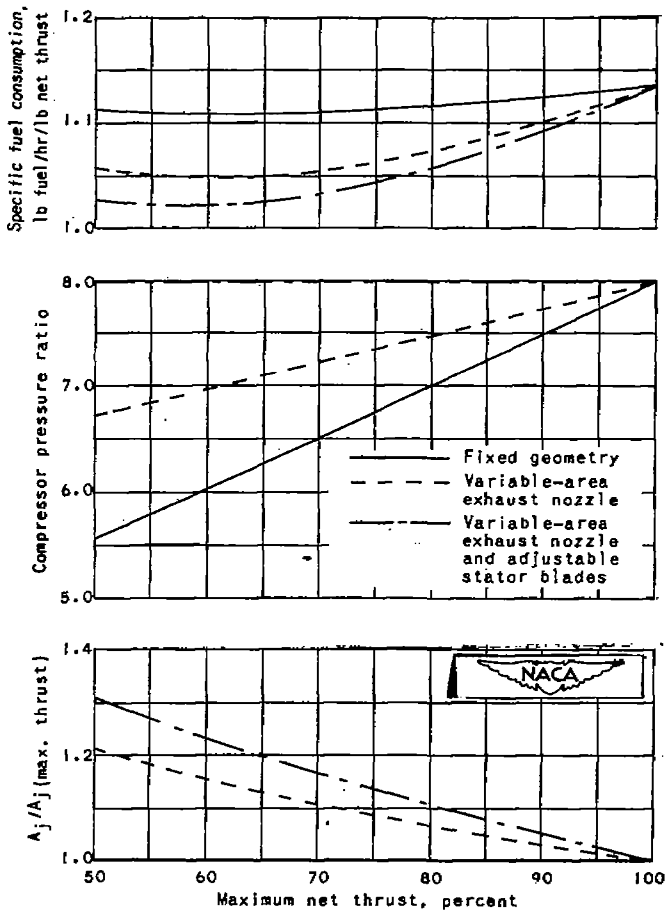
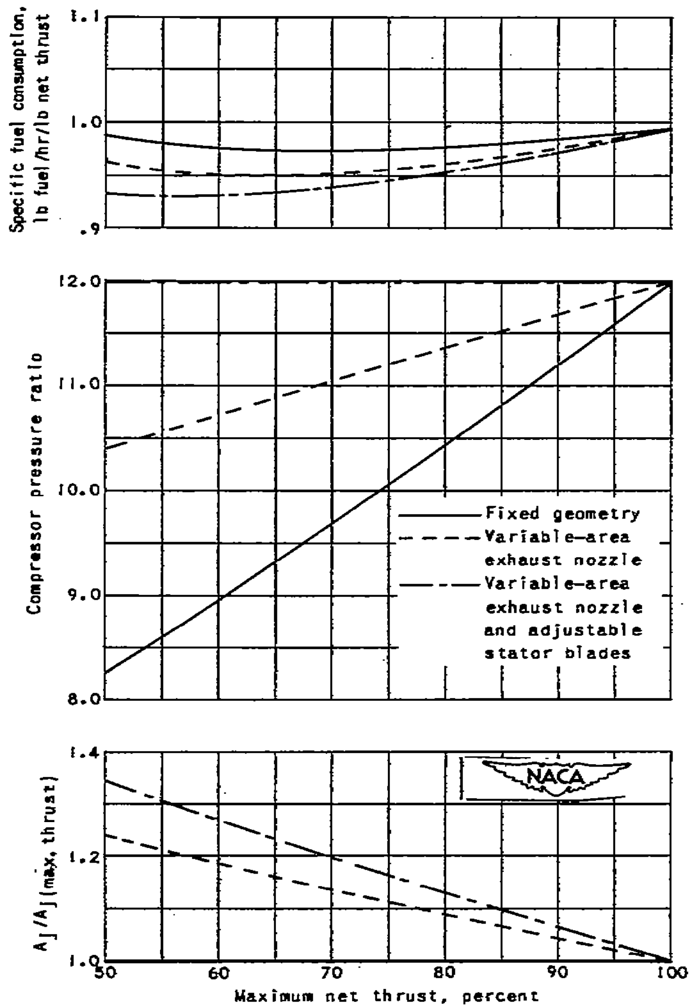


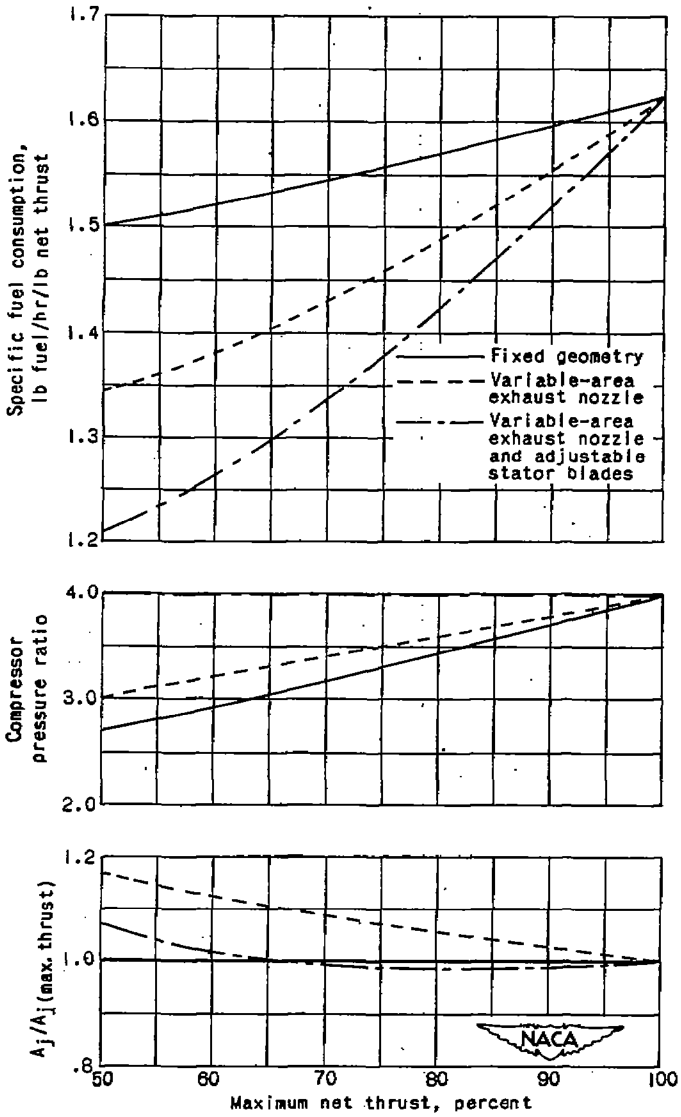
(c) Maximum turbine-entrance temperature, 2400° R; maximum compressor pressure ratio, 8.0.

Figure 7. - Continued. Comparison of representative jet engine with fixed geometry, variable-area exhaust nozzle, and adjustable stator blades and variable-area exhaust nozzle. Flight speed, 600 miles per hour at sea level.



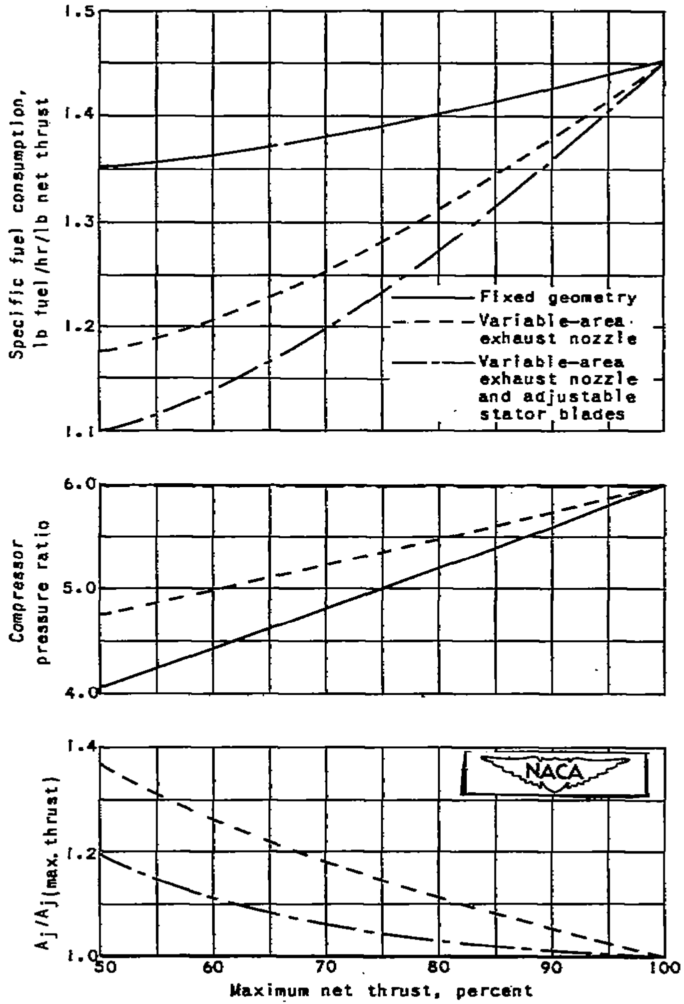
(d) Maximum turbine-entrance temperature, 2400° R; maximum compressor pressure ratio, 12.0.

Figure 7. - Continued. Comparison of representative jet engine with fixed geometry, variable-area exhaust nozzle, and adjustabe stator blades and variable-area exhaust nozzle. Flight speed, 600 miles per hour at sea level.



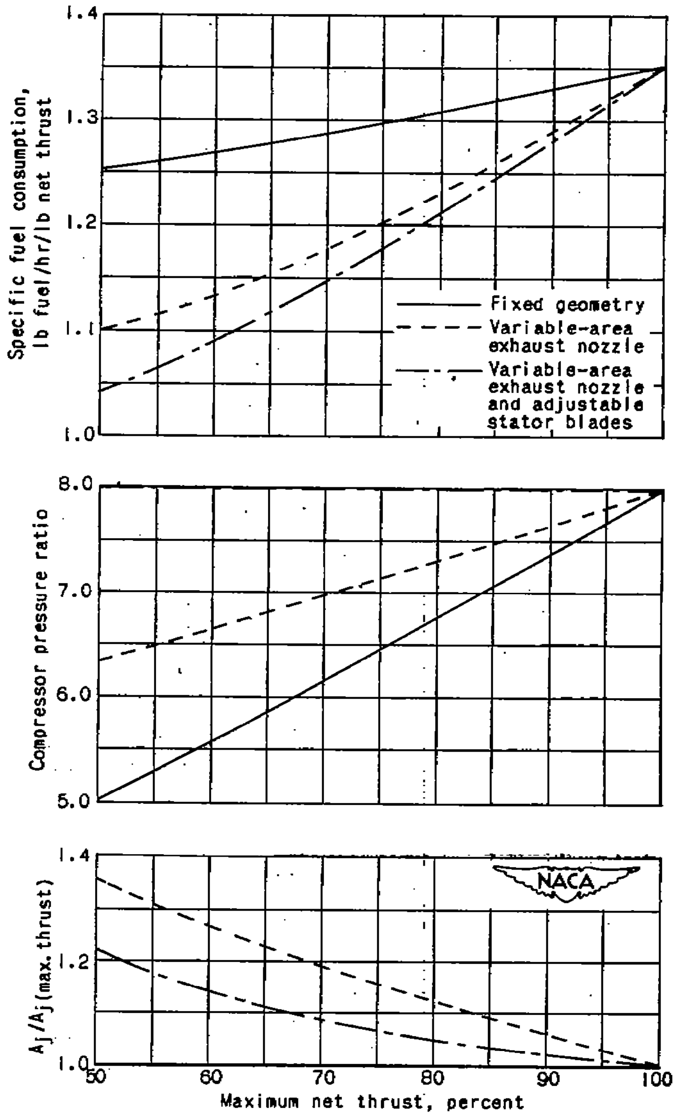
(e) Maximum turbine-entrance temperature, 3200° R; maximum compressor pressure ratio, 4.0.

Figure 7. - Continued. Comparison of representative jet engine with fixed geometry, variable-area exhaust nozzle, and adjustable stator blades and variable-area nozzle. Flight speed, 600 miles per hour at sea level.



(f) Maximum turbine-entrance temperature, 3200° R; maximum compressor pressure ratio, 6.0.

Figure 7. - Continued. Comparison of representative jet engine with fixed geometry, variable-area exhaust nozzle, and adjustable stator blades and variable-area exhaust nozzle. Flight speed, 600 miles per hour at sea level.



(g) Maximum turbine-entrance temperature, 3200° R; maximum compressor pressure ratio, 8.0.

Figure 7. - Continued. Comparison of representative jet engine with fixed geometry, variable-area exhaust nozzle, and adjustable stator blades and variable-area exhaust nozzle. Flight speed, 600 miles per hour at sea level.

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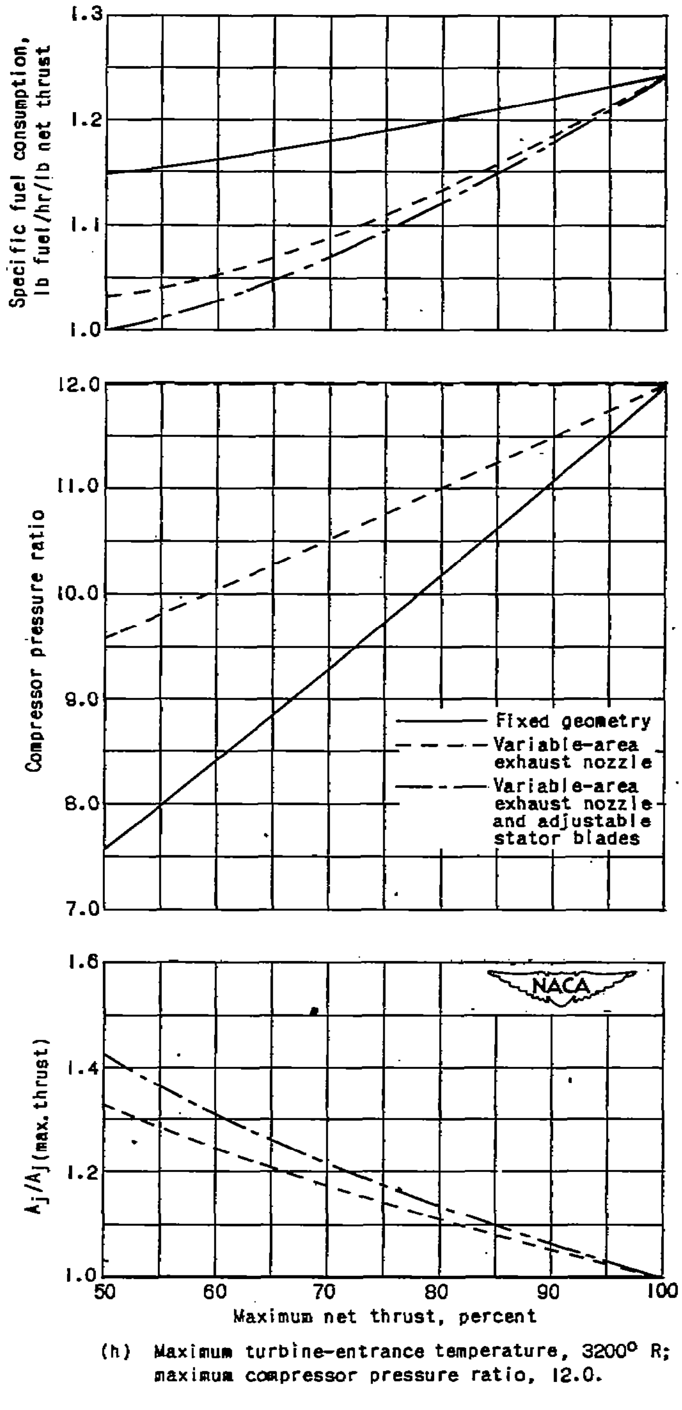

(h) Maximum turbine-entrance temperature, 3200° R; maximum compressor pressure ratio, 12.0.

Figure 7. - Concluded. Comparison of representative jet engine with fixed geometry, variable-area exhaust nozzle, and adjustable stator blades and variable-area exhaust nozzle. Flight speed, 600 miles per hour at sea level.

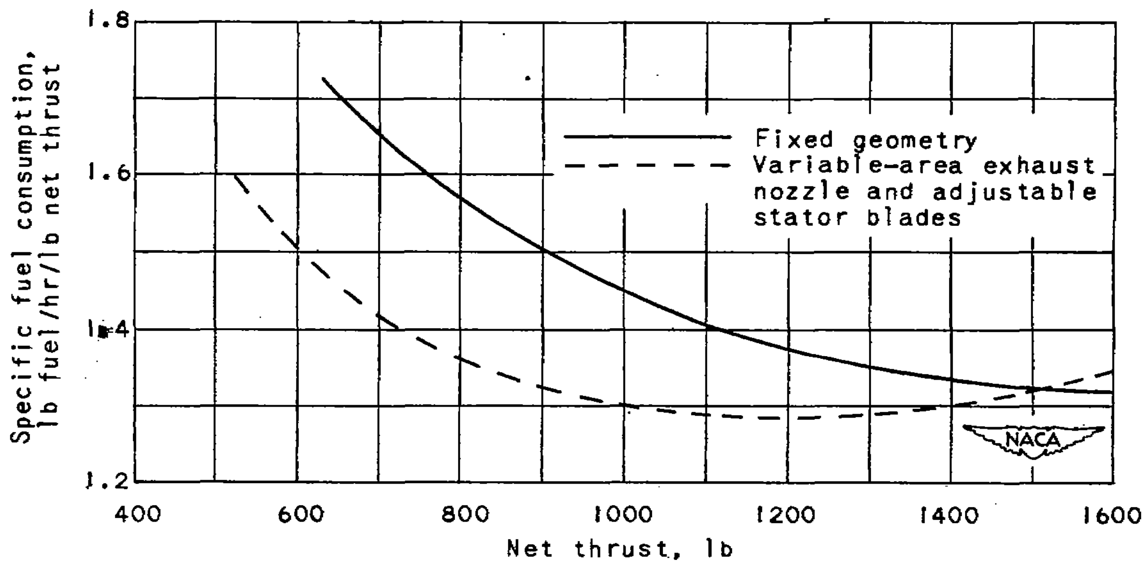

Figure 8. - Comparison of representative jet engine with and without adjustable stator blades with centrifugal compressor. Maximum turbine-entrance temperature, 1960° R; maximum pressure ratio, 4.40; altitude, 30,000 feet; ram pressure ratio, 1.2.

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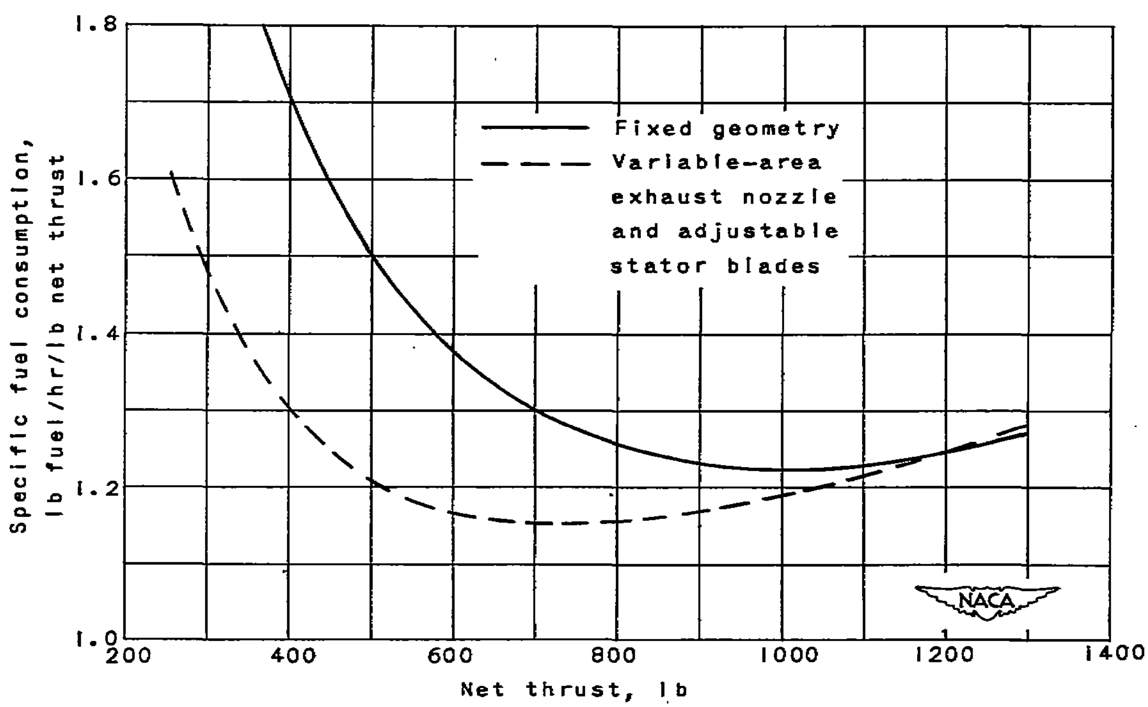
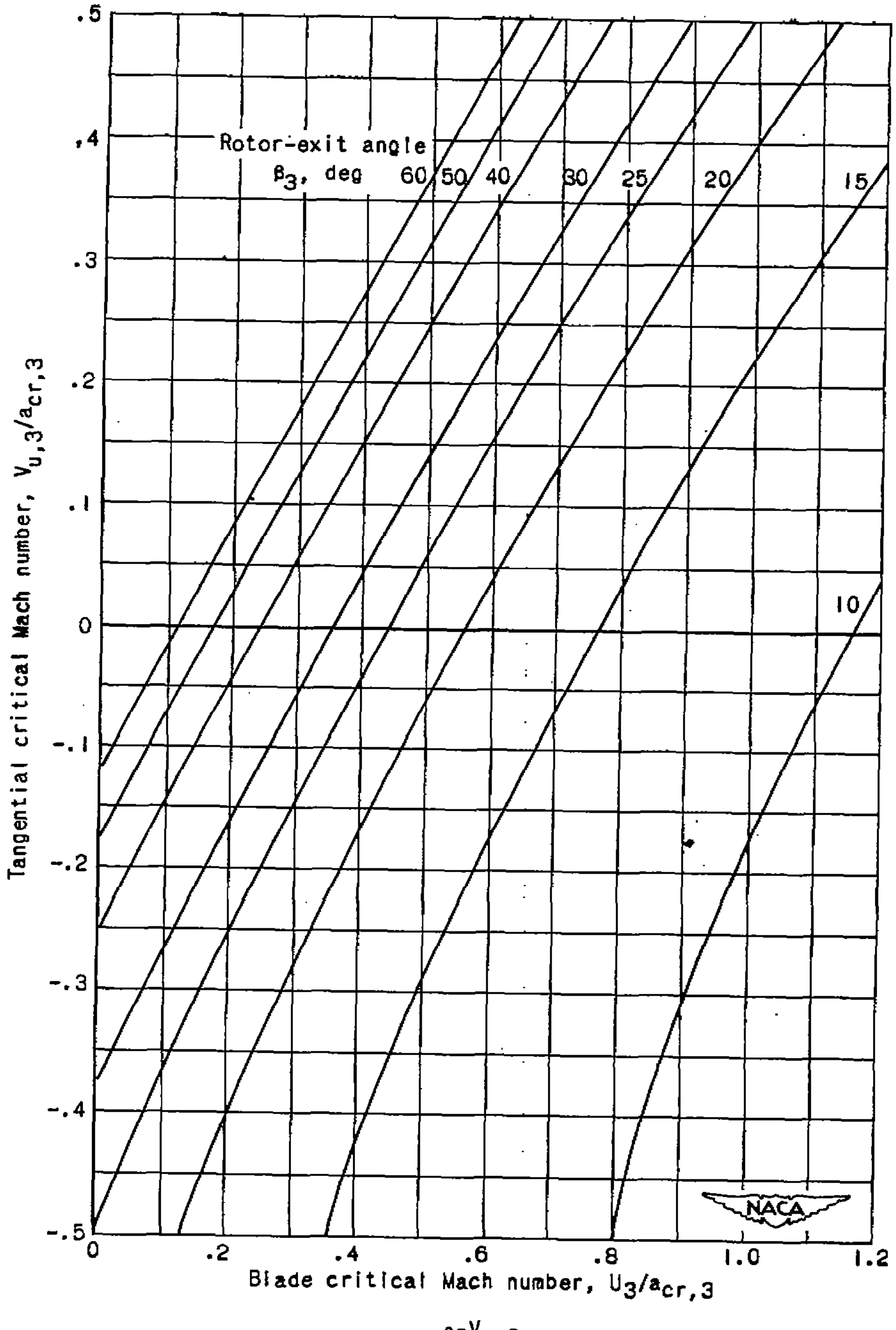


Figure 9. - Comparison of representative jet engine with and without adjustable stator blades with axial-flow compressor. Maximum turbine-inlet temperature, 1760° R; maximum pressure ratio, 3.90; altitude, 25,000 feet; ram pressure ratio, 1.2.



(a) $\frac{\rho_3 V_{x,3}}{\rho_3' a_{cr,3}} = 0.2.$

Figure 10. - Variation of tangential critical Mach number with blade critical Mach number at rotor exit. $\gamma = 1.30$.

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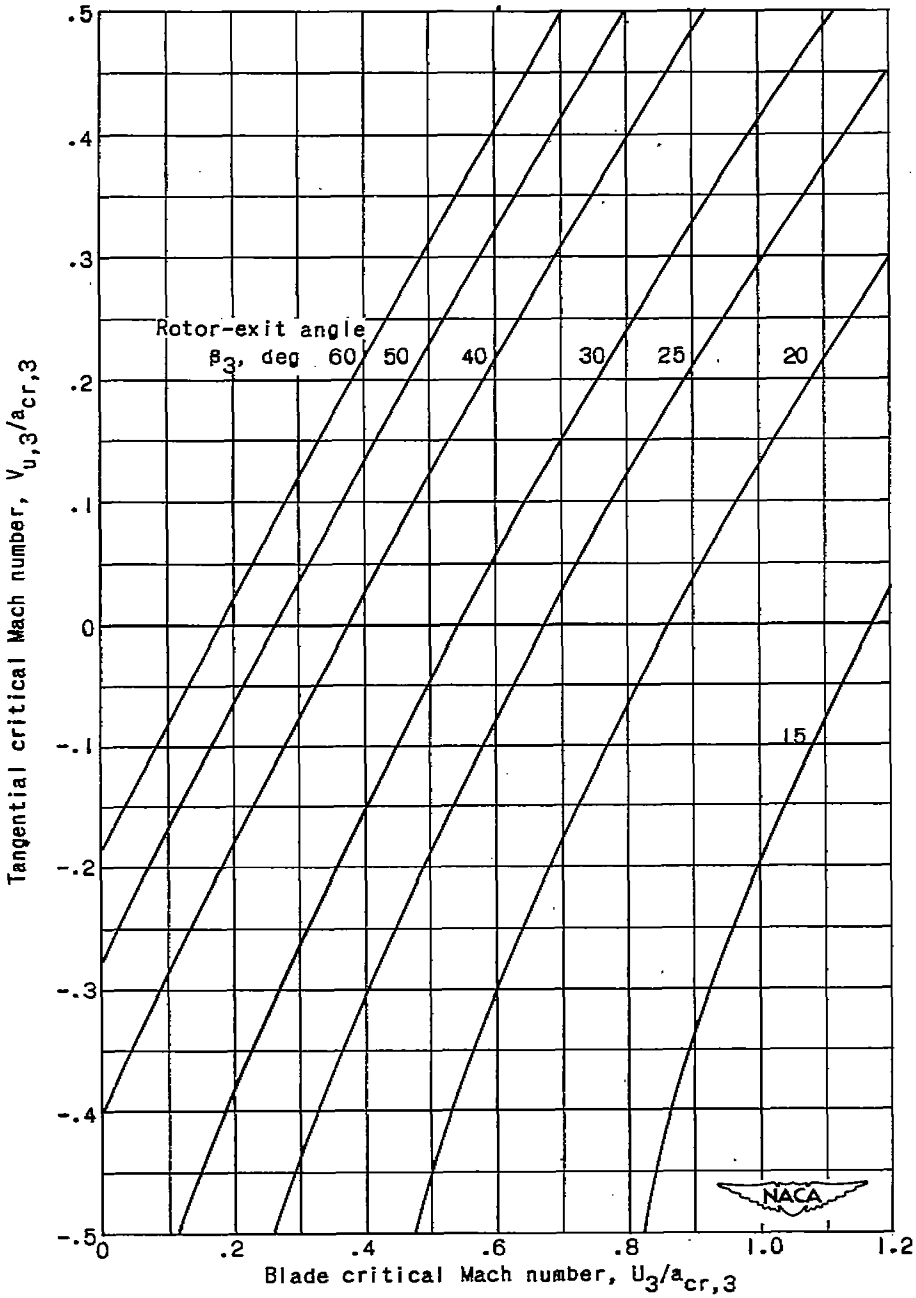
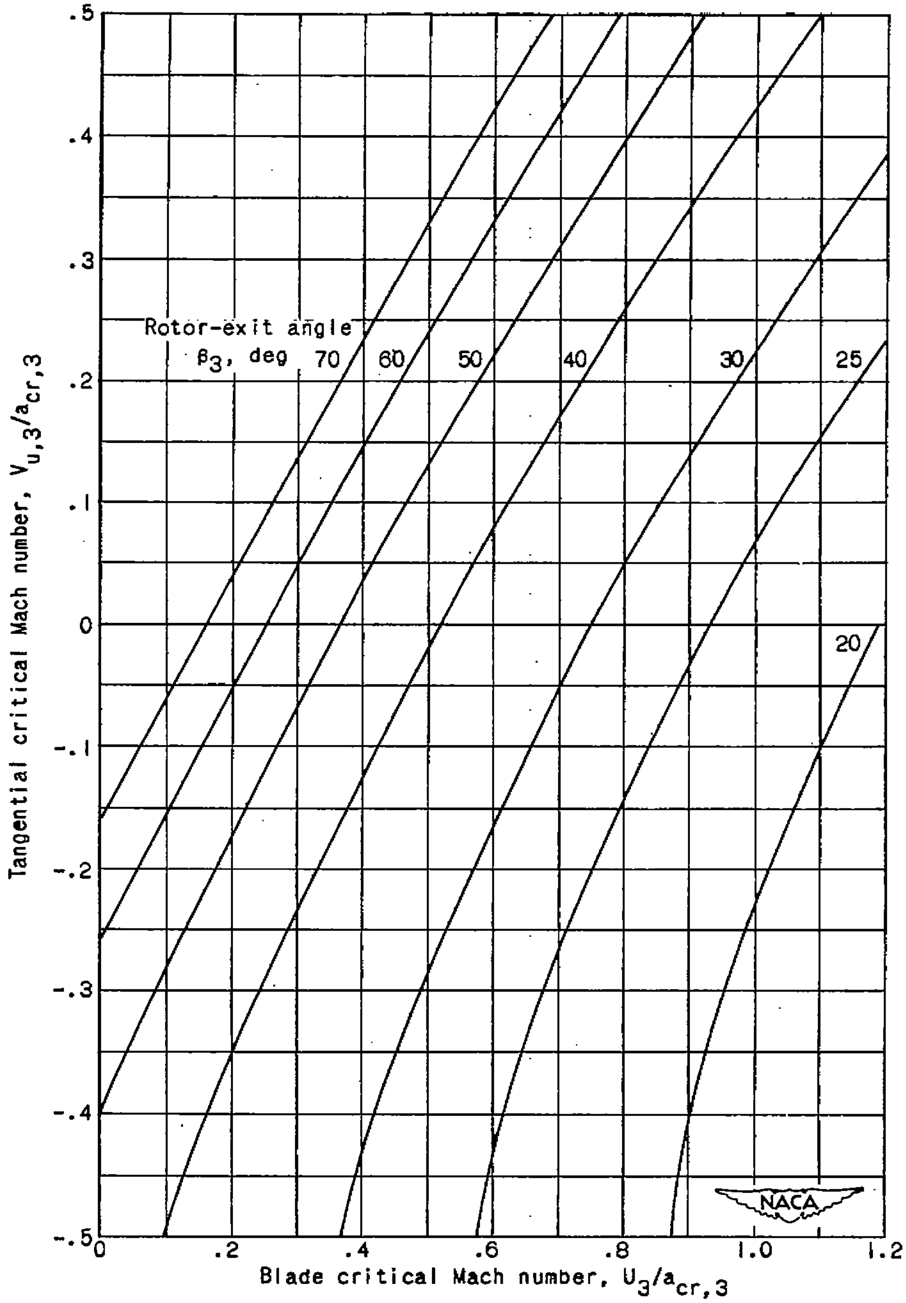


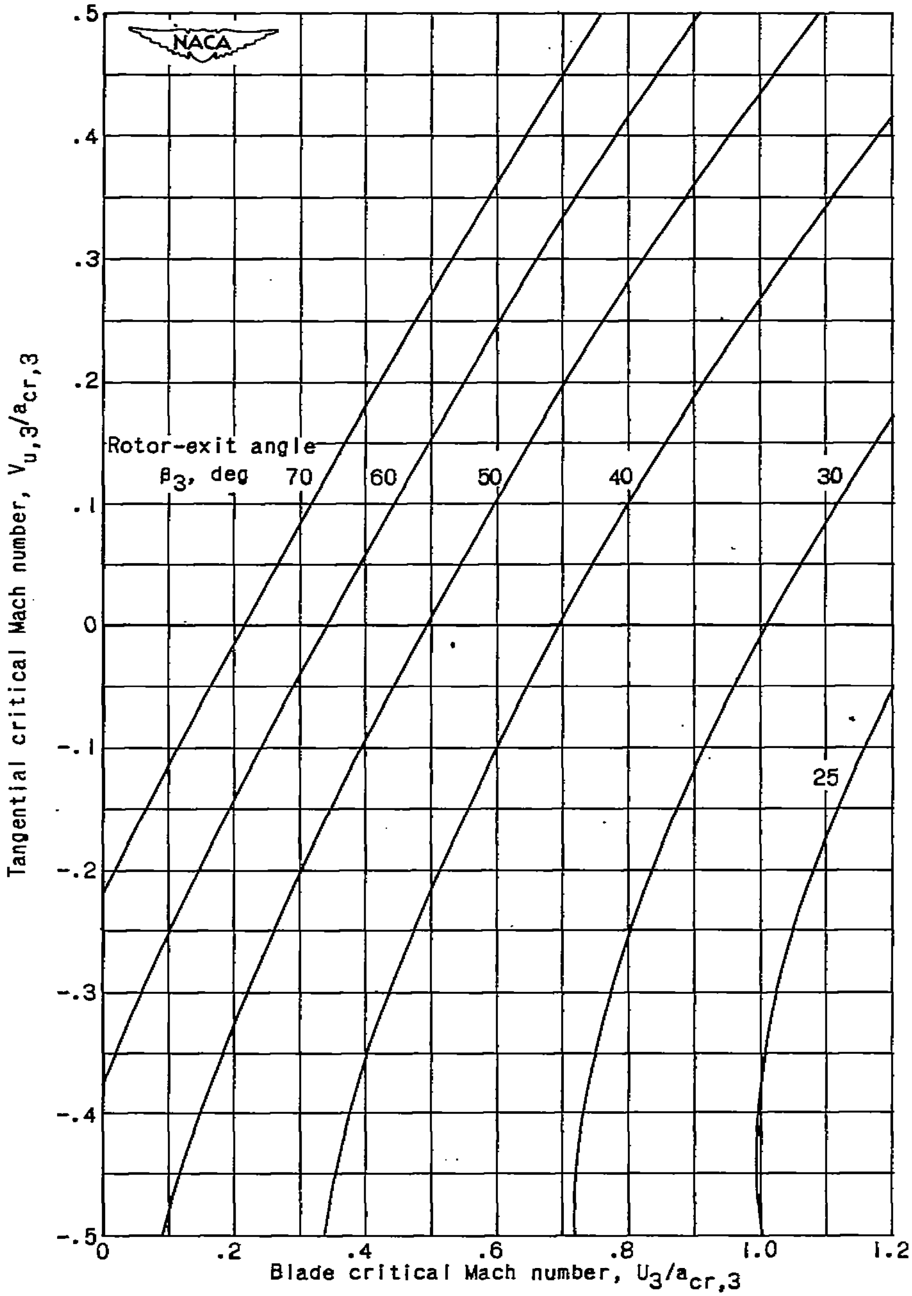
(b) $\dfrac{\rho_3 V_{x,3}}{\rho'_3/a_{cr,3}} = 0.3.$

Figure 10. - Continued. Variation of tangential critical Mach number with blade critical Mach number at rotor exit. $\gamma = 1.30$.



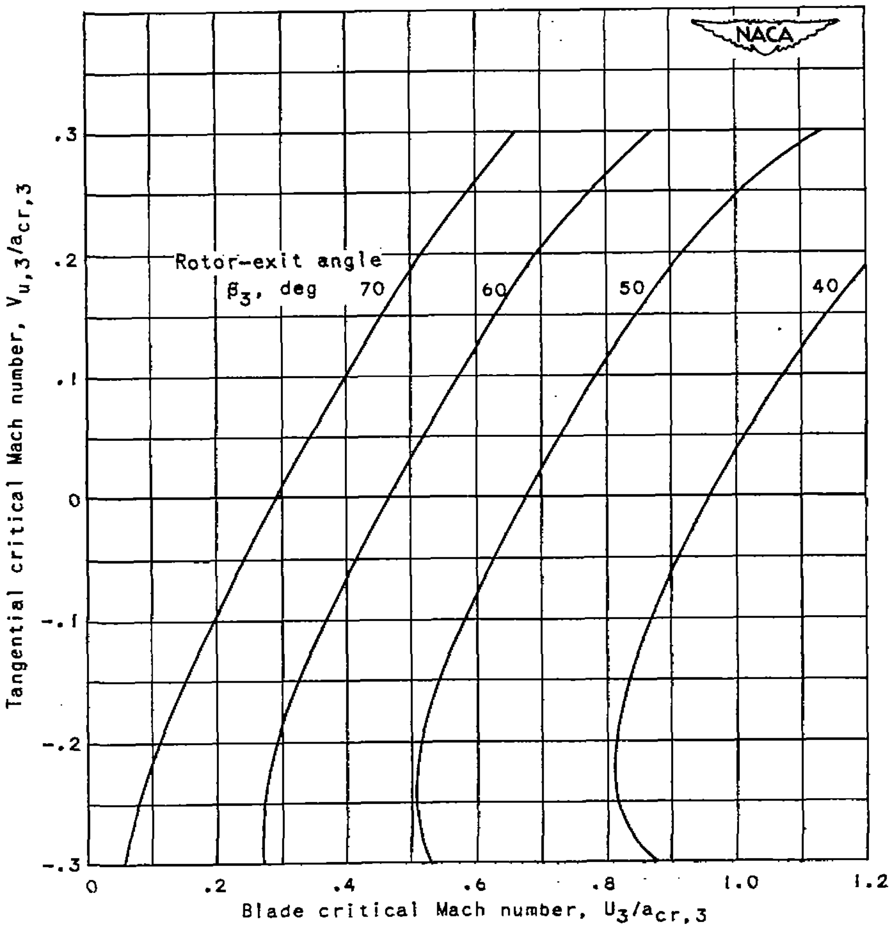
(c) $\frac{\rho_3 V_{x,3}}{\rho_3' a_{cr,3}} = 0.4.$

Figure 10. - Continued. Variation of tangential critical Mach number with blade critical Mach number at rotor exit. γ = 1.30.



(d) $\dfrac{\rho_3 V_{x,3}}{\rho_3' a_{cr,3}} = 0.5.$

Figure 10. - Continued. Variation of tangential critical Mach number with blade critical Mach number at rotor exit. $\gamma = 1.30$.



(e) $\frac{\rho_3 V_{x,3}}{\rho_3' a_{cr,3}} = 0.6.$

Figure 10. - Concluded. Variation of tangential critical Mach number with blade critical Mach number at rotor exit. $\gamma = 1.30$.

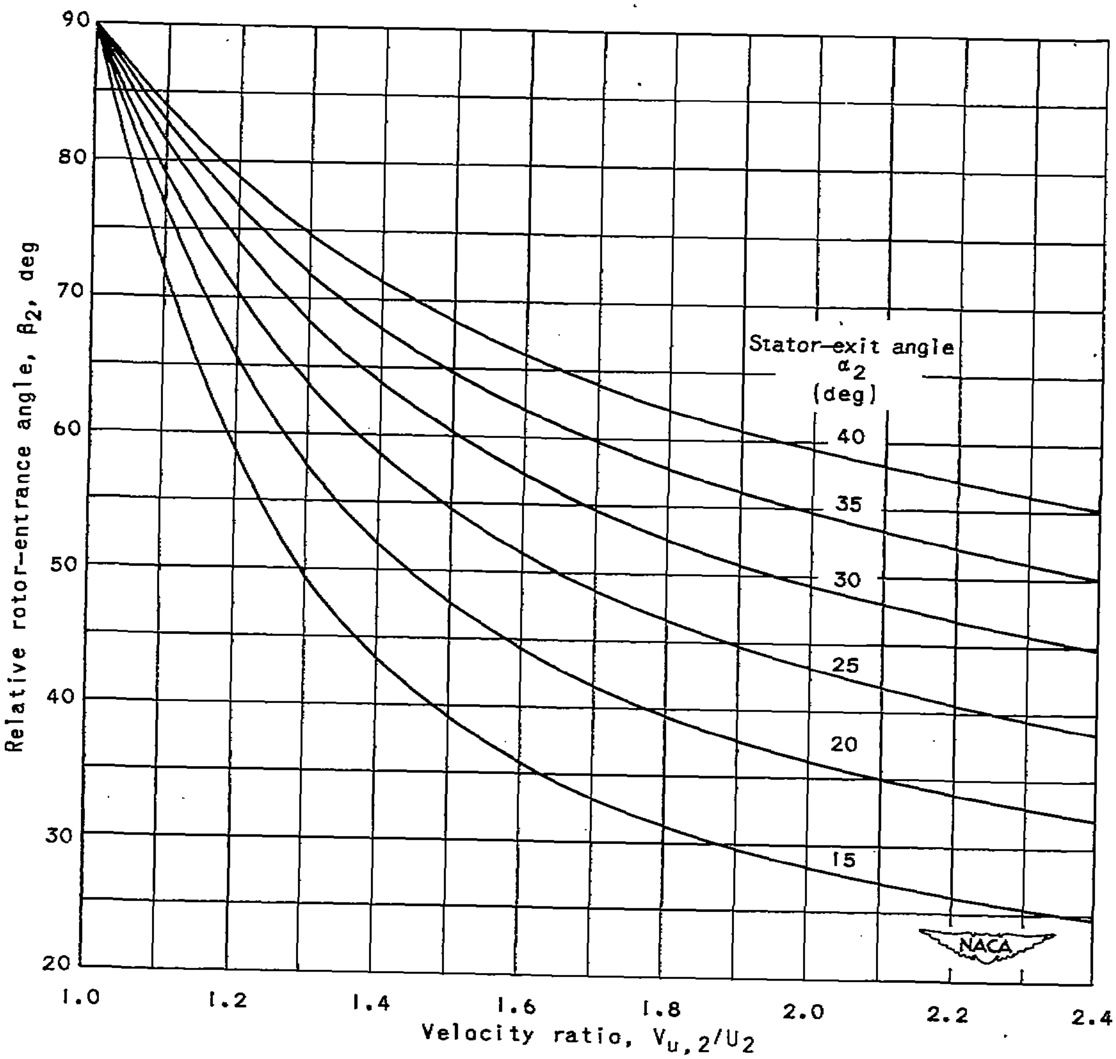


Figure 11. - Variation of relative rotor-entrance angle with ratio of tangential velocity to blade speed.