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RESEARCH MEMORANDUM

INVESTIGATION OF ROTATING COMPONENTS OF COUNTERROTATING TWO-SPOOL ENGINES

I - ANALYTICAL INVESTIGATION OF OFF-DESIGN PERFORMANCE OF TURBINE COMPONENT DESIGNED WITH AND WITHOUT OUTER-TURBINE STATOR

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I - ANALYTICAL INVESTIGATION OF OFF-DESIGN PERFORMANCE OF TURBINE COMPONENT DESIGNED WITH AND WITHOUT OUTER-TURBINE STATOR

By Warner L. Stewart

SUMMARY

An analytical investigation was conducted, as part of a research program to study the problems associated with counterrotating two-spool turbojet engines, in order to determine the off-design characteristics of the counterrotating turbine component. Since such a component might be improved from a length, weight, and efficiency standpoint through elimination of the outer-turbine stator, this analysis is concerned with the effect of exclusion or inclusion of the stator on the turbine off-design performance characteristics. The method of analysis was of the same type found satisfactory in predicting the off-design characteristics of single-stage turbines.

The results of the analysis indicated that the inner turbine was conventional with respect to off-design characteristics when considered as a separate unit. Inclusion of the outer turbine limited the inner-turbine operational range in different ways depending on whether or not the outer-turbine stator was included; exclusion of the stator imposed the more severe limitations.

Exclusion of the outer-turbine stator also resulted in outer-turbine off-design characteristics considerably different from those obtained for conventional turbines. The performance map changed considerably in shape as the inner-turbine speed was varied, yielding work outputs at inner-turbine 40 percent design speed over twice those obtained at inner-turbine 120 percent design speed. This variation occurred as a result of the changes in inner-turbine exit whirl that entered the outer turbine as inlet whirl. Inclusion of the outer-turbine stator resulted in outer-turbine off-design characteristics similar to those obtained in conventional turbines.

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The unconventional off-design characteristics obtained with the turbine component designed without the outer-turbine stator might be adverse with respect to engine operation. However, this type of turbine component must still be evaluated through turbine and compressor matching studies before the advantages offered from design-point considerations can be weighed against the unconventional off-design characteristics obtained.

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INTRODUCTION

The potentialities of the use of counterrotating compressors in two-spool turbojet engines have motivated research at the NACA to study problems associated with attaining efficient components of this type. Compressor design-point studies (ref. 1) predict that compressor pressure ratios of 5 or better with high specific weight flows can be expected with satisfactory efficiency by use of two counterrotating single-stage transonic or supersonic compressors. As applied to turbojet engines, however, it is important not only that the compressors have satisfactory off-design as well as design characteristics but also that the turbines that power them exhibit similar characteristics.

The turbine component of an engine designed to use a counterrotating compressor might be improved from a length, weight, and efficiency standpoint by eliminating the outer-turbine stator. The counterrotation would permit the utilization of negative exit whirl out of the inner turbine in developing the required outer-turbine work. Thus a research program is in progress at the NACA Lewis laboratory to determine the characteristics of counterrotating turbines and, in particular, to study the advantages and disadvantages of the exclusion of the outer-turbine stator in turbojet-engine application.

One phase of the research program has been the analytical investigation of the off-design characteristics of a turbine component designed to power a projected counterrotating compressor having a work split that would permit the possible elimination of the outer-turbine stator. The characteristics of this turbine component were obtained using the method presented in reference 2 but extended to cover both turbines. This method has proved satisfactory in predicting the off-design performance trends of single-stage turbines (refs. 2 and 3). It was therefore felt that the application of this method of analysis to counterrotating turbines would yield valid performance trends.

The purpose of this report is to present the results of the analysis of the turbine component designed with and without the outer-turbine stator to indicate the relative effects of including or excluding this stator on the turbine performance characteristics. This report will be concerned only with the turbine component performance characteristics.

The effects of these characteristics on the matching characteristics in the counterrotating two-spool engine must still be determined before the practicality of such an engine can be established.

SYMBOLS

The following symbols are used in this report:

A flow area, sq ft

g acceleration due to gravity, 32.17 ft/sec^2

h specific enthalpy, Btu/lb

i incidence angle, deg

K blade effective loss parameter (ref. 2)

p pressure, lb/sq ft

r radius, ft

s_b untapered hub stress, lb/sq in.

T temperature, $^{\circ}$R

U blade velocity, ft/sec

V absolute gas velocity, ft/sec

W relative gas velocity, ft/sec

w weight-flow rate, lb/sec

γ ratio of specific heats

δ ratio of total pressure at a given station to NACA standard sea-level pressure, p'/p^*

ε function of γ, $\frac{\gamma^*}{\gamma}\left[\frac{\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}}{\left(\frac{\gamma^*+1}{2}\right)^{\frac{\gamma^*}{\gamma^*-1}}}\right]$

η adiabatic efficiency

θ_{cr} squared ratio of critical velocity at a given station to NACA standard sea-level critical velocity, $(V_{cr}/V_{cr}^{*})^2$

ρ_m rotor-blade metal density, lb/cu ft

ω angular velocity, radian/sec 3352

Subscripts:

ann annulus

cr conditions at Mach number 1

f frontal

h hub

t tip

x axial component

0 compressor inlet

1 station between compressors

2 burner inlet

3 inner-turbine stator entrance

4 inner-turbine stator exit, rotor entrance

5 inner-turbine rotor exit, outer-turbine stator entrance

6 outer-turbine stator exit, rotor entrance

7 outer-turbine exit

Superscripts:

' absolute total state

* NACA standard conditions

DESIGN-POINT CONSIDERATIONS

A schematic sketch of the projected engine designed to utilize two counterrotating spools is presented in figure 1. Each compressor as shown is a single-stage transonic or supersonic unit. The engine of figure 1(a) does not include the outer-turbine stator, whereas the engine of figure 1(b) does. Also shown in the figure is the station nomenclature used in the analysis.

3352 Compressor design requirements. - As indicated in reference 1, pressure ratios on the order of 5 and high specific weight flows with reasonable efficiencies can be expected if two counterrotating single-stage supersonic or transonic compressors were incorporated in the engine design. With these considerations, the projected compressor unit had the following design requirements and specifications based on a unit compressor frontal area for standard conditions at the compressor inlet:

w/A_f, (lb/sec)/sq ft	31.2
U_t (both compressors), ft/sec	1260
p_2'/p_0'	5
η_{0-1}	0.90
η_{1-2}	0.85
$\Delta h_{0-1}'$, Btu/lb	28.1
$\Delta h_{1-2}'$, Btu/lb	57.2

As indicated by the design requirements, the design work split is approximately 2:1.

Turbine design requirements at engine conditions. - For the specified compressor requirements, a cycle analysis was conducted using the gas tables presented in reference 4 to determine the turbine design-operating requirements. These requirements based on a unit compressor diameter are as follows:

T_3', °R	2500
p_3', lb/sq ft	10,070
w/A_f (includes fuel addition and no bleed-off for cooling), (lb/sec)/sq ft	32.1
U_t (both turbines), ft/sec	1260
$\Delta h_{3-5}'$, Btu/lb	55.6
$\Delta h_{5-7}'$, Btu/lb	27.4

[redacted]

The efficiency split between the two turbines was made in accordance with the assumptions in the section METHOD OF OFF-DESIGN ANALYSIS and resulted in $\eta_{3-5} = 0.88$ and $\eta_{5-7} = 0.83$ with an over-all efficiency $\eta_{3-7} = 0.87$. The low value of efficiency obtained for the outer turbine occurs as a result of the high velocity level through the rotor and the very low required work output.

Turbine equivalent design requirements. - In the analysis of the counterrotating turbine component, equivalent requirements were used. 3352
These requirements corrected from engine conditions are as follows:

$\frac{w\sqrt{\theta_{cr,3}}}{\delta_3 A_f}$, (lb/sec)/sq ft	15.19
$(\Delta h'/\theta_{cr,3})_{3-5}$, Btu/lb	11.89
$(\Delta h'/\theta_{cr,3})_{5-7}$, Btu/lb	5.86
$(\Delta h'/\theta_{cr,5})_{5-7}$, Btu/lb	6.48
$U_t/\sqrt{\theta_{cr,3}}$, (both turbines), ft/sec	583
$U_t/\sqrt{\theta_{cr,5}}$, (second turbine), ft/sec	613

A γ of 1.300 was assumed for the engine conditions and γ of 1.400 was assumed for standard conditions. The value of $\theta_{cr,5}$ was computed by using $\theta_{cr,3}$ and the equivalent temperature ratio across the inner turbine.

Turbine design configuration. - As mentioned previously, the counterrotating compressor offers the potential of high pressure ratios in very few blade rows. However, the tip speeds required to obtain these pressure ratios are higher than those used in conventional subsonic compressors. In view of this requirement and the desirability of high compressor specific weight flows, stress is an important parameter to be considered in selecting the design turbine configuration.

The equation used in determining the untapered rotor-blade stress is

$$s_b = \frac{\rho_m \omega^2 A_{ann}}{288\pi g} = \frac{\rho_m U_t^2 \left[1 - \left(\frac{r_h}{r_t}\right)^2\right]}{288g} \qquad (1)$$

This is equation (1) in reference 5. The first part of this equation indicates that the rotor hub stress is, for a given blade metal density, dependent only on the rotor annulus area and the angular velocity squared.

From this consideration and the desirability of minimum size and weight, the outer diameter of the turbine component was specified to be equal to that of the compressor.

Once the outer diameter of the turbine has been specified, the tip speed is fixed. Hence, by referring to the second part of equation (1), the untapered stress for a specified blade metal density is then a function only of the hub-tip radius ratio. In figure 2 is shown a plot
3352 of untapered hub stress for the specified tip speed as a function of hub-tip radius ratio for a blade metal density ρ_m of 540 pounds per square foot. Also shown is the variation in turbine-exit critical velocity ratio with hub-tip radius ratio for the specified weight flow, turbine-exit stagnation conditions, and a specified zero exit whirl. It can be seen that even without consideration of rotor trailing-edge thickness the turbine-exit annulus would choke at a hub-tip radius ratio of 0.68 and at a corresponding untapered stress of 49,500 pounds per square inch. This value of stress further indicates that for the specified compressor conditions the turbine will be at a high stress level and must therefore operate close to limiting loading at its design point in order that the stresses be minimized. From these considerations, the design hub-tip radius ratio was selected for a turbine-exit axial critical velocity ratio of 0.78 where (from fig. 2) the design hub-tip radius ratio is equal to 0.656 at an untapered stress of 53,000 pounds per square inch. This stress, when corrected for a taper factor of 0.7, is 37,000 pounds per square inch, which is still rather high in comparison with the stresses designed for in current turbojet engines and can be attributed to the specified high tip speed and specific weight flow of the compressor.

The turbine configuration selected had a constant hub-tip radius ratio of 0.656 from inner-turbine entrance to outer-turbine exit in order that (1) good reaction existed throughout and (2) three-dimensional effects would be minimized. Because of the compressor work split, the outer turbine could be designed with or without the stator. In the case without the stator, the outer-turbine rotor would then utilize negative exit whirl out of the inner turbine to produce the required work. The turbine exit whirl was also specified to be zero.

Design-point mean-section velocity diagrams. - The design-point velocity diagrams at the mean section (fig. 3) were computed to meet the turbine equivalent design requirements in accordance with the following assumptions:

(1) The outer-turbine stator, when included, would have zero turning at design point.

(2) The outer-turbine stator would have no viscous loss.

These first two assumptions result in identical velocity diagrams at the design point with or without the outer-turbine stator. (The outer-turbine stator when used would have an effect only at off-design operation.) These two assumptions also permitted the elimination of any additional changes in the turbine from a design standpoint and as such facilitated the computational procedure.

It might be pointed out that in an actual design with the outer-turbine stator, the inner-turbine velocity diagrams would probably be modified such that some turning and reaction would exist across this stator. The trends obtained in the analysis would, however, still be valid.

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(3) The loss distribution for the blade rows exclusive of the outer-turbine stator was assumed to occur in accordance with that specified in reference 2 such that the over-all efficiency was 0.87. The value of the loss parameter K corresponding to this efficiency was found to be 0.275.

The velocity diagrams, calculated in accordance with the preceding assumptions, are shown in figure 3 together with a sketch of the blade sections. As a result of the first two assumptions, the absolute velocity at station 5 is the same as that at station 6; and the outer-turbine stator as shown accomplishes no turning.

As discussed in the section Turbine design configuration, the counterrotating turbine was designed to operate near the limiting-loading point from stress considerations. From figure 3 the critical velocity ratio at the turbine exit $(V/V_{cr})_7$ is seen to be 0.780. However, just inside the trailing edge of the outer-turbine rotor where the trailing-edge blockage is considered, W_x/W_{cr} was calculated as 0.882. This location yields more accurate information concerning limiting loading as the flow area is less than that at station 7. This high value of critical velocity ratio gives even clearer indication of the criticalness of the selected design point with respect to limiting loading.

From figure 3 it can also be seen that good reaction exists across each blade row except for the outer-turbine stator, which, when included, would have impulse conditions. The turning of each blade row is considerably less than that obtained for conventional turbines. The inner-turbine stator turns the flow only 39°. The turnings in the inner- and outer-turbine rotors are 31° and 16°, respectively. The outer-turbine turning is exceptionally small in comparison with that of conventional turbines and can be attributed to the low design work output. It can further be noted from figure 3 that both rotors are designed to operate at approximately choking conditions ($(W/W_{cr})_5 = 0.961$ and $(W/W_{cr})_7 = 0.912$) and that the inner-turbine stator is considerably below choking

$((V/V_{cr})_4 = 0.493)$. The proximity of both rotors to choking conditions indicates that, although satisfactory reaction and turning characteristics exist, the turbine design would be critical from a rotor-throat-area matching standpoint. Previous work on choked-flow single-stage turbines has shown that this type of problem is a real and difficult one. (See ref. 6; e.g.)

METHOD OF OFF-DESIGN ANALYSIS

The off-design analysis of the counterrotating turbine component was made by using the method described in reference 2 which was extended to cover this type component. The effective viscous-loss parameter used in this analysis was the same as that used in obtaining the design velocity diagrams ($K = 0.275$). The losses considered in the off-design analysis were:

(1) Stator and rotor viscous losses determined as a function of K

(2) Blade incidence loss

(3) Shock loss (obtained only at conditions above blade choking)

(4) Exit whirl loss (for outer turbine only)

As discussed in reference 2, all values were calculated at the mean radius.

Inner-Turbine Performance

The procedure used in the off-design analysis of the inner turbine was exactly the same as that discussed in reference 2, as the outer turbine, in general, had no influence on the calculated inner-turbine performance. Computations were made to cover the range of speed from 40 percent to 120 percent design speed in increments of 20 percent and from a total-pressure ratio of 1.1 to that corresponding to turbine limiting loading.

Outer-Turbine Performance

<u>Method of analysis excluding outer-turbine stator.</u> - The procedure used in the outer-turbine calculations without the outer-turbine stator had to be modified as outer-turbine operation depended on conditions out of the inner turbine. For each point on the inner-turbine map a series of outer-turbine operating points can be obtained which depend on the

outer-turbine speed. Therefore, for each inner-turbine speed an entire outer-turbine map is determined. In the analysis five outer-turbine maps were obtained covering the range of inner-turbine speeds. Each map covered a speed range from 40 to 120 percent design speed and from the practical lower limit of zero work output to turbine limiting loading.

Method of analysis including outer-turbine stator. - The method of computing the performance of the outer-turbine component including the outer-turbine stator was simplified somewhat from that used without a stator in that only one outer-turbine performance map was required and could be obtained independently of the inner turbine. This was done through proper selection of the outer-turbine inlet stations. Station 5, which is the inlet station to the outer-turbine, was selected for obtaining the inlet total temperature. Station 6, the outer-turbine stator exit, however, was selected for obtaining the inlet total pressure so that the outer-turbine stator incidence loss would have no influence on obtaining the outer-turbine performance map. Since this loss is directly dependent on the inner-turbine operation, it was included as an inner-turbine loss. With these considerations, both the inner- and outer-turbine performance was calculated in a manner identical with that of reference 2.

RESULTS OF OFF-DESIGN ANALYSIS

Performance Without Outer-Turbine Stator

Inner-turbine performance map. - As discussed in the analysis method section, the inner-turbine performance map could be obtained independent of the outer turbine. This map is presented in figure 4. The equivalent specific work output $\Delta h'/\theta_{cr,3}$ is shown as a function of a weight-flow - speed parameter $\varepsilon wU/\delta_3 A_f$ with percent design speed, efficiency, and total-pressure ratio shown as contours. Because this turbine is followed by another turbine, the exit whirl out of the inner turbine does not represent a loss. Hence, the actual total-pressure ratio was used in computing the efficiency. In general, the inner-turbine performance is seen to be comparable with that obtained for more conservative turbines even though the design stator turning and velocity level is lower than that normally used. A considerable amount of additional work output is obtained above the rotor choking line, more so than that obtained for other conservative turbines (see ref. 2, e.g.). This occurs because the large stagger angle designed into the inner-turbine rotor results in high rotor-exit whirl velocities at limiting loading (ref. 7).

Effect of outer-turbine performance on inner-turbine performance range. - In the analysis of the outer turbine without the stator, it was found that definite limitations in operation were imposed upon the inner-turbine operation. The principal effects can be seen in figure 5, where an outline of the inner-turbine performance map is shown with the outer-turbine limits superimposed. The upper limit is the outer-turbine rotor choking point and the lower, a practical limit of zero work output. As indicated by figure 5, the range of inner-turbine operation is dependent on the speed of the outer turbine. For example, if the outer-turbine component operates at 40 percent design speed, a comparatively wide range of inner-turbine performance can occur. At outer-turbine 120 percent design speed, however, a comparatively small range of inner-turbine operation can occur. Also, although the lower limit of zero outer-turbine work output varies considerably over the map, the upper limit (outer turbine choking) lies within a small range. This range of upper limit corresponds roughly with the inner-turbine choking line (fig. 4).

It might be also noted from figure 5 that the curves of outer-turbine choking occur at increased inner-turbine specific work outputs as the outer-turbine speed is increased. This trend is in opposition with those obtained for more conventional turbines and can be directly attributed to the outer-turbine blade velocity being considerably higher than the inlet whirl (see ref. 8).

Outer-turbine performance. - As discussed in the analysis method section, five outer-turbine maps were computed, one for each 20 percent inner-turbine speed varying from 40 to 120 percent design speed. These five maps are presented in figure 6 in the same form as that used for the inner turbine with the inclusion of an additional parameter, the inner-turbine specific work output. This parameter must be included because of the dependency of the two turbines. A constant value of this parameter represents a single point on the inner-turbine map. This parameter is therefore included as a necessary connection between inner- and outer-turbine operation. Because of the dependency of the outer turbine on the inner turbine when no stator is used, the parameters in figure 6 are presented in terms of stagnation conditions at the turbine inlet (station 3). The range of the inner-turbine specific work output on each of the maps in figure 6 coincides with the range presented in figure 5.

From inspection of figure 6 it is immediately apparent that the outer-turbine performance map is greatly affected by the inner-turbine speed. For example, at inner-turbine 40 percent design speed (fig. 6(a)) the outer turbine is capable of producing 11 Btu per pound, whereas at inner-turbine 120 percent design speed (fig. 6(e)), the outer turbine can produce only 5 Btu per pound, a work ratio of better than 2:1. This wide variation in work potential can be directly attributed to the inner-turbine exit whirl conditions as there is no outer-turbine stator to take out this whirl. As the inner-turbine speed is reduced from design, the increased negative exit whirl increases the work potential of the outer turbine by virtue of the counterrotation. Extending this reasoning to inner-turbine speeds above design, the whirl out of the inner turbine is decreased from design, reducing the work potential of the outer turbine. Thus the exclusion of the stator has resulted in outer-turbine off-design characteristics considerably different from those obtained for conventional turbines.

The efficiency contours shown in figure 6 do appear to be similar in shape to those obtained in single-stage turbines (ref. 2, e.g.). The peak efficiency of the outer turbine varies within narrow limits as the inner-turbine speed is varied from approximately 0.85 at 40 percent inner-turbine design speed to 0.80 at 120 percent inner-turbine design speed. 3352
The peak efficiency is also seen to occur, at all inner-turbine speeds, at outer-turbine speeds approximately that of design and near limiting loading. It might also be noted in figure 6(d) that the design point is very close to turbine limiting loading. This condition was designed for from stress considerations (see DESIGN-POINT CONSIDERATIONS). Thus for this particular design, the inner- and outer-turbine matching could present a serious problem as small mismatching of rotor throat areas could force the outer turbine into limiting loading before the inner turbine could obtain the design work output. However, since the characteristics of this turbine have been found to be quite unconventional, the effect of the proximity of the design point to limiting loading on the operational characteristics of the turbine component cannot be brought out herein but is reserved for future compressor and turbine matching studies.

Performance Including Outer-Turbine Stator

Inner-turbine performance map. - As discussed in the analysis method section, when the outer-turbine stator is included in the counter-rotating turbine design, the analysis can be simplified through inclusion of the stator incidence loss as an inner-turbine loss. The resultant inner-turbine performance map including this loss is presented in figure 7. This map is the same as that of figure 4 with the exception of the pressure ratio and efficiency contours, which will change with the inclusion of the additional loss. Included in the map is the outer-turbine stator zero-incidence line. Along this line the pressure ratio and efficiency contours are the same, as there is no loss at this point. At high-speed low pressure ratios and low-speed high pressure ratios, however, the efficiency does drop off an additional amount because of the incidence loss, as much as 10 points in these regions as compared with figure 4. The variation in outer-turbine stator incidence angle over the range of inner-turbine performance is shown in figure 8, where an outline of the performance map is presented with contours of incidence angle included. A wide variation in angle is seen to occur, from approximately -10° at low-speed high pressure ratios to greater than 40° at high-speed low pressure ratios. Although much higher incidence angles were obtained at high-speed low pressure ratios, the general velocity level into the stator is low, resulting in the loss in efficiency comparable with that obtained at low-speed high pressure ratios where the velocity level into the stator is high.

Outer-turbine performance map. - When the outer-turbine stator is included, the outer-turbine performance map can be computed independent of the inner-turbine speed through proper selection of inlet stagnation 3352 conditions. As discussed in the section Method of analysis including outer-turbine stator, station 5 was used for the total temperature, whereas station 6 was used for the total pressure. The outer-turbine performance map thus obtained is presented in figure 9, where the equivalent specific work output $\Delta h'/\theta_{cr,5}$ is presented as a function of the weight-flow - speed parameter $\varepsilon wU/\delta_6 A_f$ with contours of rating total-pressure ratio $p_6'/p_{x,7}'$, rating efficiency η_x, and percent design equivalent blade velocity $U/\sqrt{\theta_{cr,5}}$ included. Inspection of the figure reveals that the outer-turbine performance map is very similar in form to those obtained for conventional turbines. The design point is in the region of 0.82 efficiency and very close to turbine limiting loading, as the turbine was designed to operate at this condition.

Comparison of this map with those of figure 6 immediately indicates a considerable difference in the off-design operational characteristics as a result of including the outer-turbine stator. For example, the large increase in specific work output at low inner-turbine speeds (fig. 6(a)) is eliminated when the stator is included in the design. Also, inclusion of the stator alters the map shape considerably through eliminating the potential negative work outputs which are possible without the stator, and not shown in figure 6, by specifying the practical lower limit of zero outer-turbine work output. These large differences in the turbine off-design characteristics would have a considerable effect on the differences obtained in turbine - compressor matching characteristics when the turbine is installed in a counterrotating two-spool turbojet engine. Thus complete matching studies must be made for any engine application to determine which turbine would have the more desirable characteristics.

Limitation of inner-turbine performance imposed by outer turbine. - In completing the study of the effect of including the outer-turbine stator on the counterrotating turbine performance, the limitations imposed by the outer turbine on the inner-turbine performance are presented in figure 10. In this figure an outline of the inner-turbine performance map is presented superimposed with the limitations imposed through outer-turbine choking at the various outer-turbine speeds. This plot is similar in form to that presented in figure 5 except that no zero outer-turbine work output limitations were necessary. Such a limit was not

reached when the stator was included in the design. In comparing figure 10 with figure 5, a somewhat different trend can be noted. At design speed the outer turbine limits the inner-turbine operation at approximately the same work level. At inner-turbine 120 percent design speed, the outer turbine chokes at work levels less than that obtained without the outer-turbine stator; whereas at low inner-turbine speeds, the outer turbine chokes at inner-turbine work levels closer to or at limiting loading. The range of inner-turbine operation is further altered and increased from that obtained without the outer-turbine stator in that at all outer-turbine speeds the inner turbine can operate anywhere below the limits shown in figure 10. Without the outer-turbine stator the lower limit 3352
of zero work output cuts down the range considerably (see fig. 5). These differences in range and limitations of inner-turbine operation occurring as a result of the inclusion or exclusion of the outer-turbine stator must also be considered in selecting the most satisfactory configuration for application in a counterrotating two-spool turbojet engine.

SUMMARY OF RESULTS

An analytical investigation of a counterrotating turbine component designed with and without outer-turbine stator is presented to indicate their relative effects on the turbine performance. The pertinent results of the investigation can be summarized as follows:

1. The inner-turbine performance map was found to be conventional in nature. Inclusion of the outer turbine limited the inner-turbine operational range in different ways depending on whether or not the outer-turbine stator was included. Exclusion of the outer-turbine stator resulted in a severe limitation being imposed on the inner-turbine range as a result of exit-whirl conditions out of the inner turbine inducing possible negative outer-turbine work outputs.

2. Exclusion of the outer-turbine stator resulted in outer-turbine off-design operation quite different from that obtained for conventional turbines. The outer-turbine performance map changed considerably in form as the inner-turbine speed was changed, yielding maximum work outputs at inner-turbine 40 percent design speed over twice that obtained at inner-turbine 120 percent design speed. This variation occurred as a result of the variation in inner-turbine exit whirl which entered the outer turbine as an inlet whirl.

3. Including the outer-turbine stator resulted in outer-turbine off-design operational characteristics similar to those obtained in conventional turbines.

CONCLUDING REMARKS

The results of the off-design analysis of the counterrotating turbine designed without the outer-turbine stator indicated characteristics considerably different from those obtained including the outer-turbine stator where more conventional operation was obtained. Thus, although improvements might be obtained in a counterrotating two-spool turbojet engine at design point from length, weight, and efficiency standpoints through elimination of the outer-turbine stator, the unconventional off-design operational characteristics may prove sufficiently adverse as to nullify these advantages. However, complete compressor - turbine matching studies must still be made before it can be fully determined whether or not the outer-turbine stator can be eliminated without adverse effects on the engine operation.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 18, 1954

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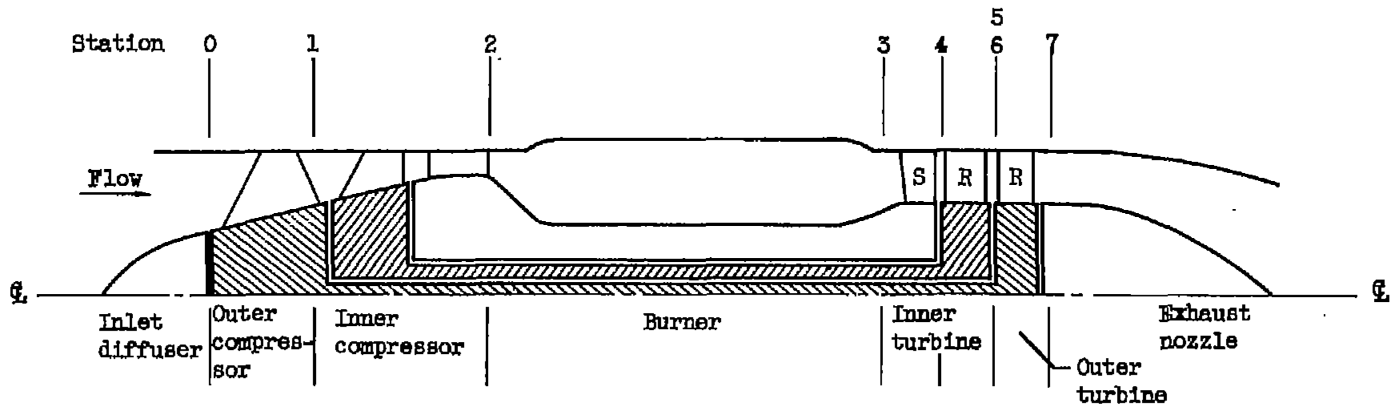
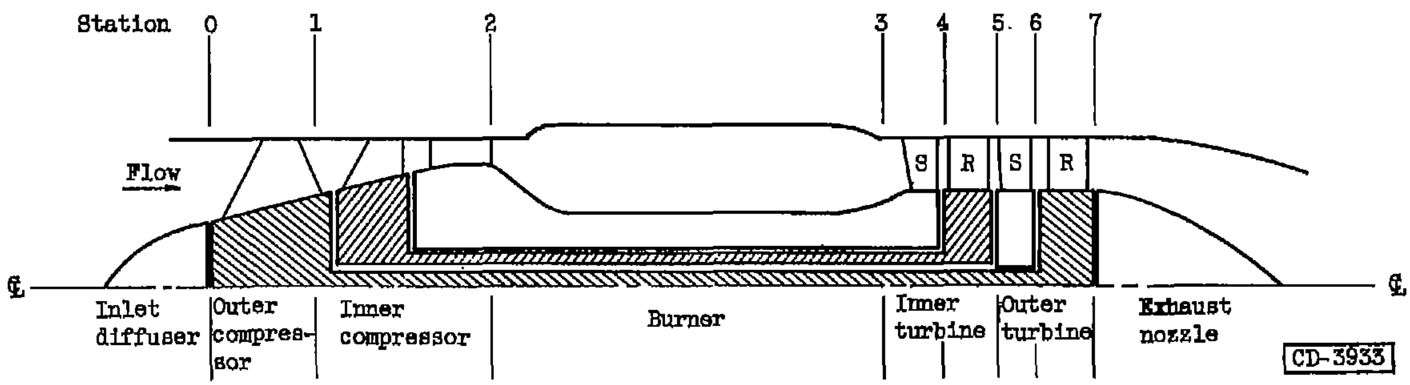


(a) Excluding outer-turbine stator.



(b) Including outer-turbine stator.

Figure 1. - Schematic of counterrotating two-spool turbojet engine indicating stations used for cycle analysis.

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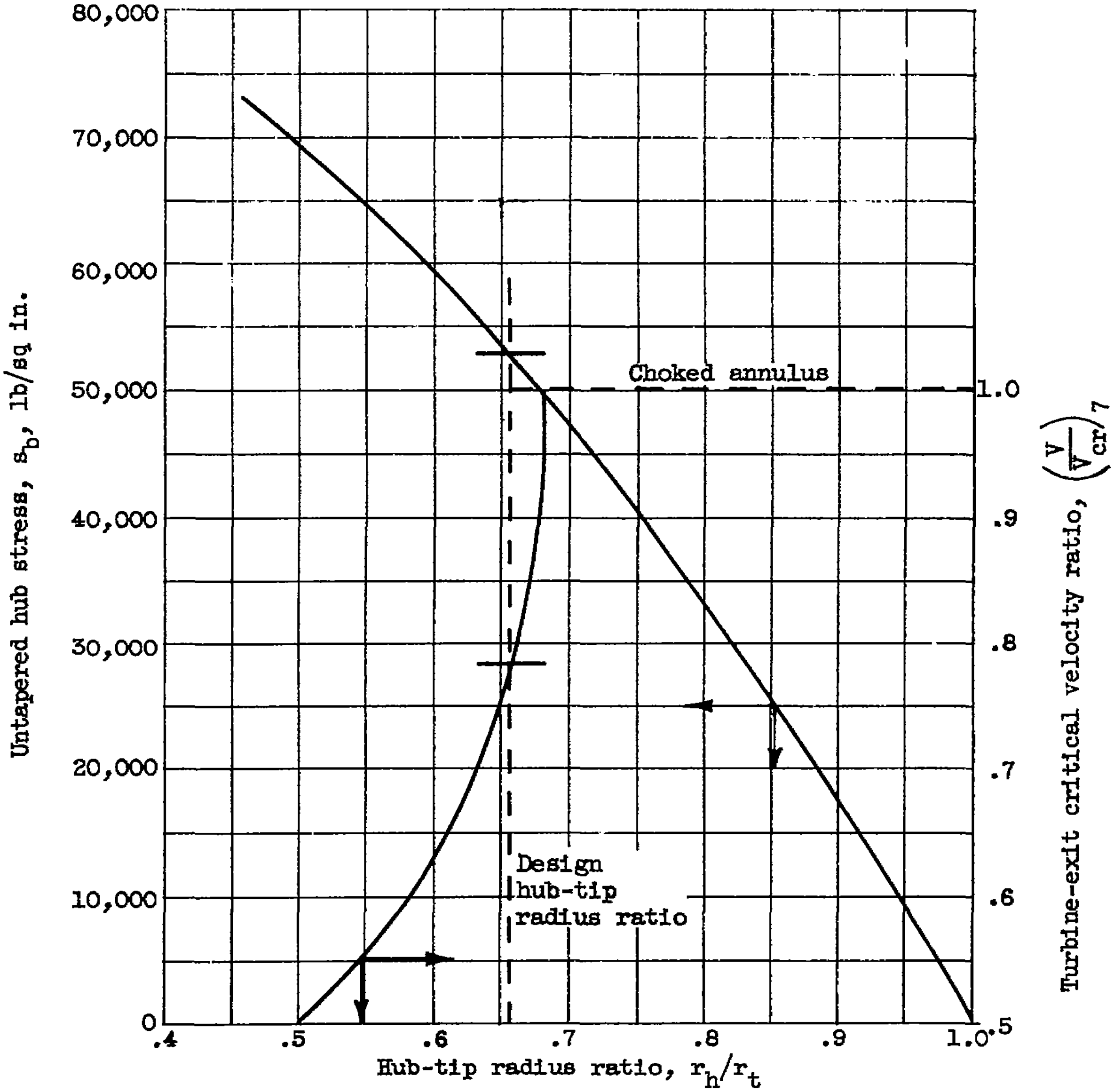

Figure 2. - Variation of untapered rotor hub stress and turbine-exit critical velocity ratio with hub-tip radius ratio for design turbine requirements. Blade metal density, 540 pounds per square feet; exit whirl, zero.

[redacted]

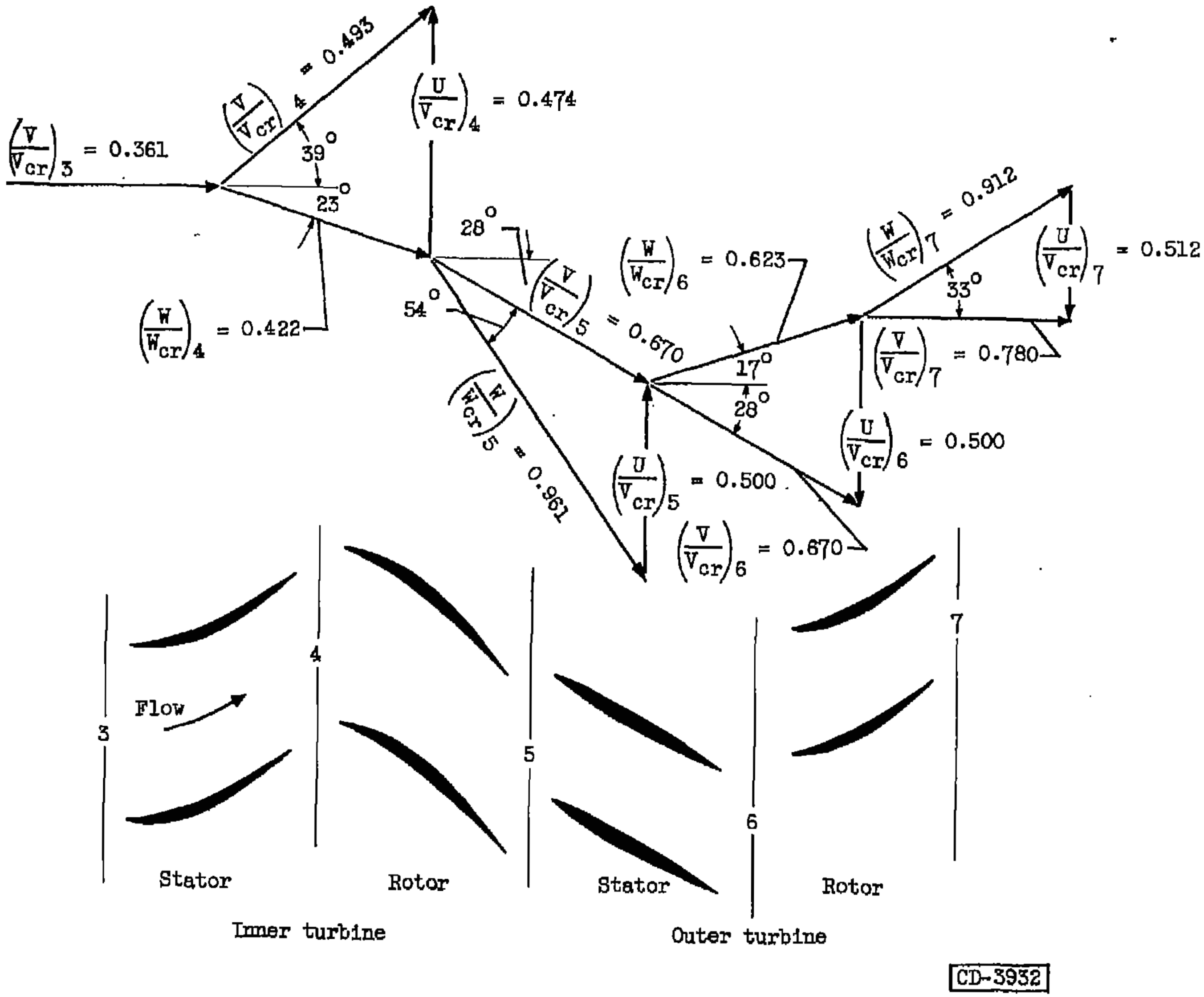

Figure 3. - Counterrotating turbine design velocity diagrams at mean section.

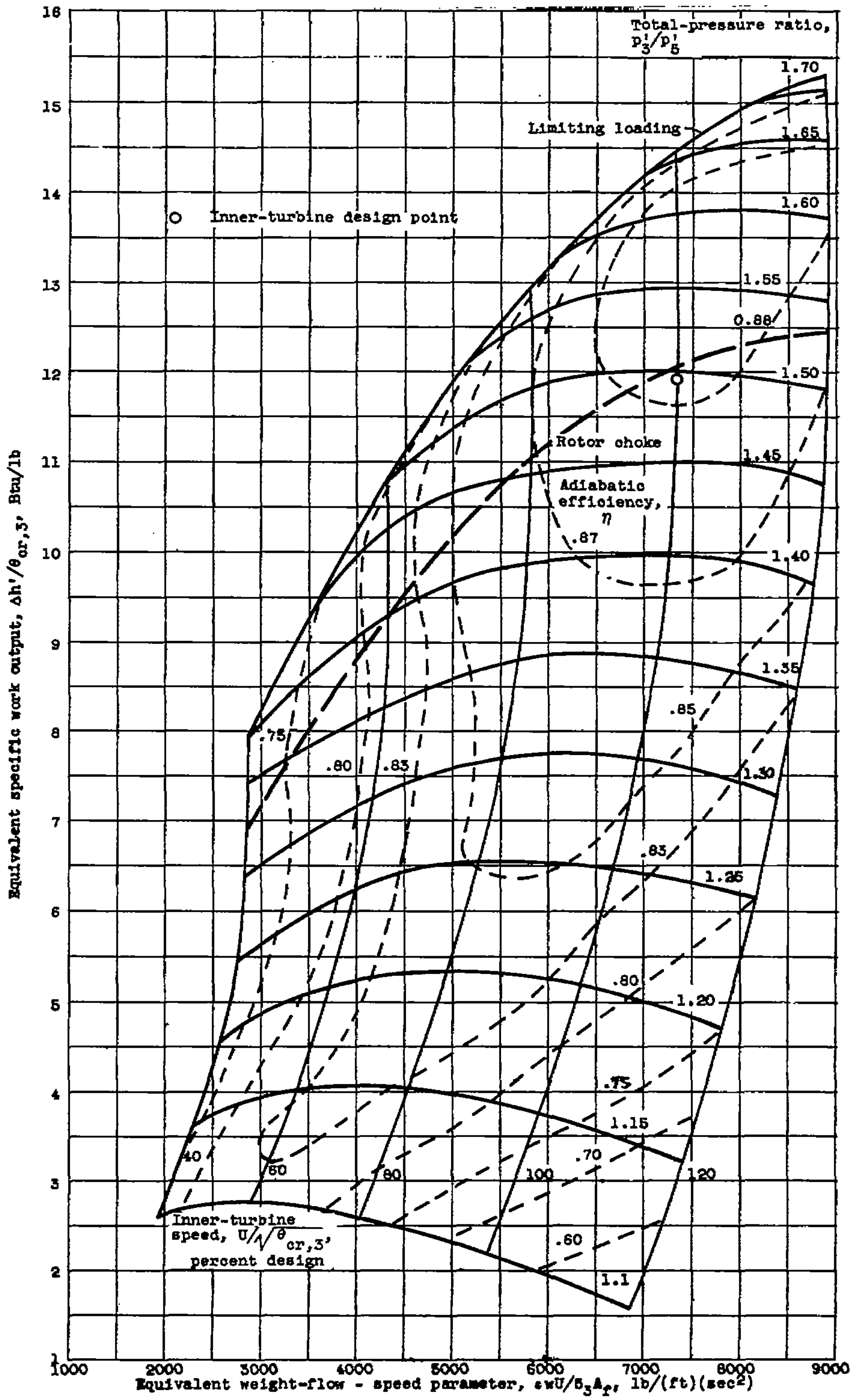

Figure 4. - Inner-turbine performance map.

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[redacted]

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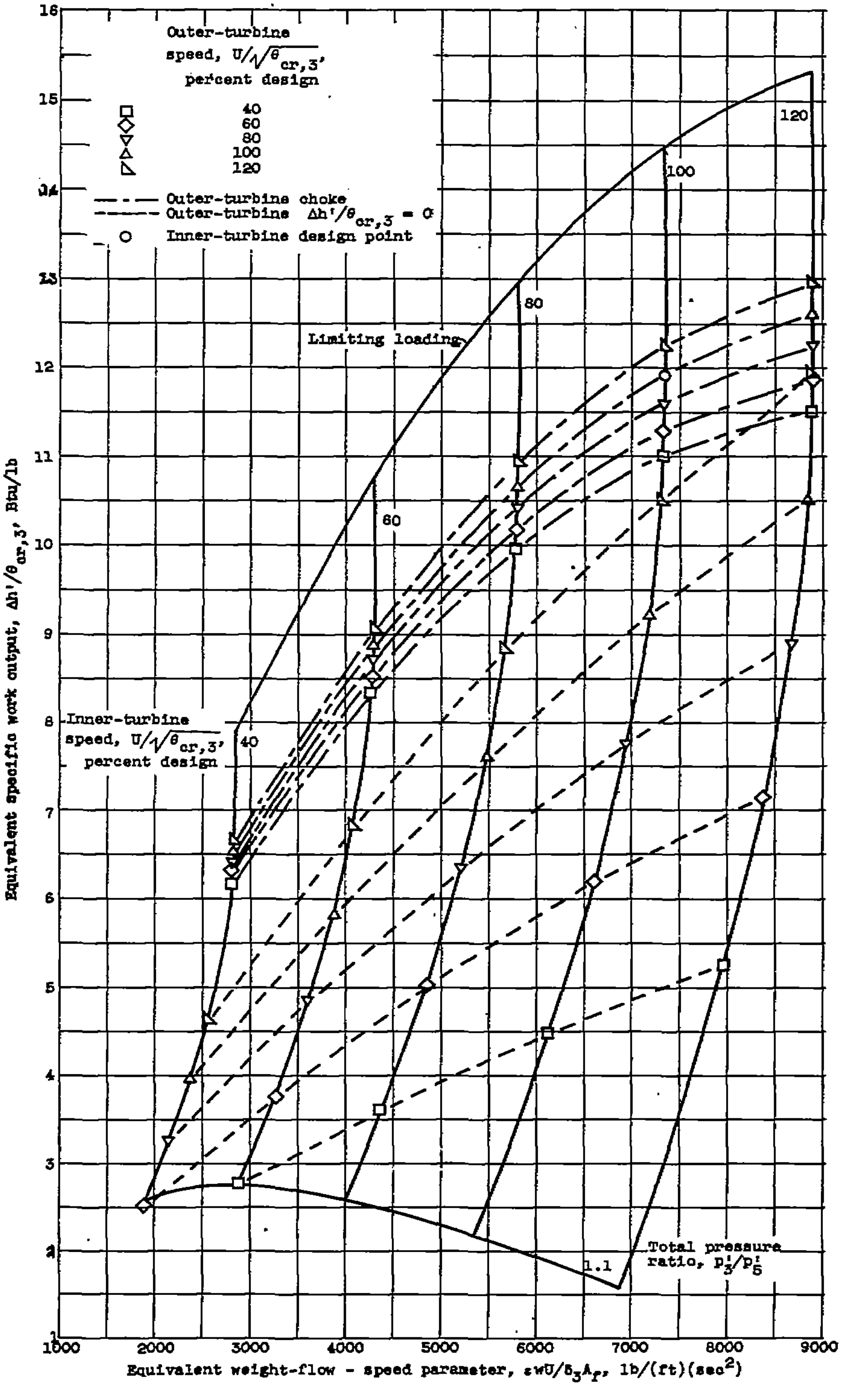

Figure 5. - Outline of inner-turbine performance map indicating limits in outer-turbine operation without outer-turbine stator.

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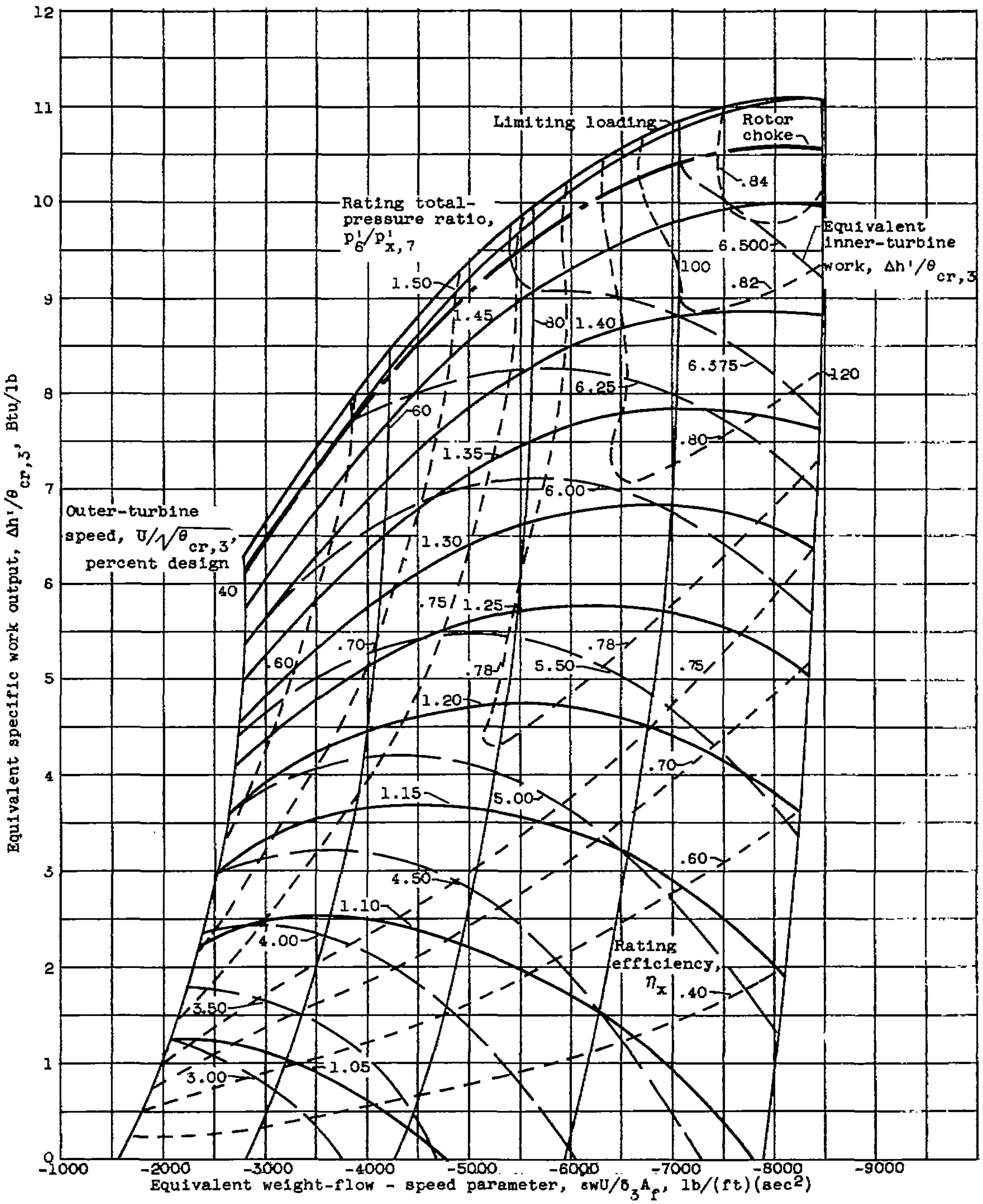
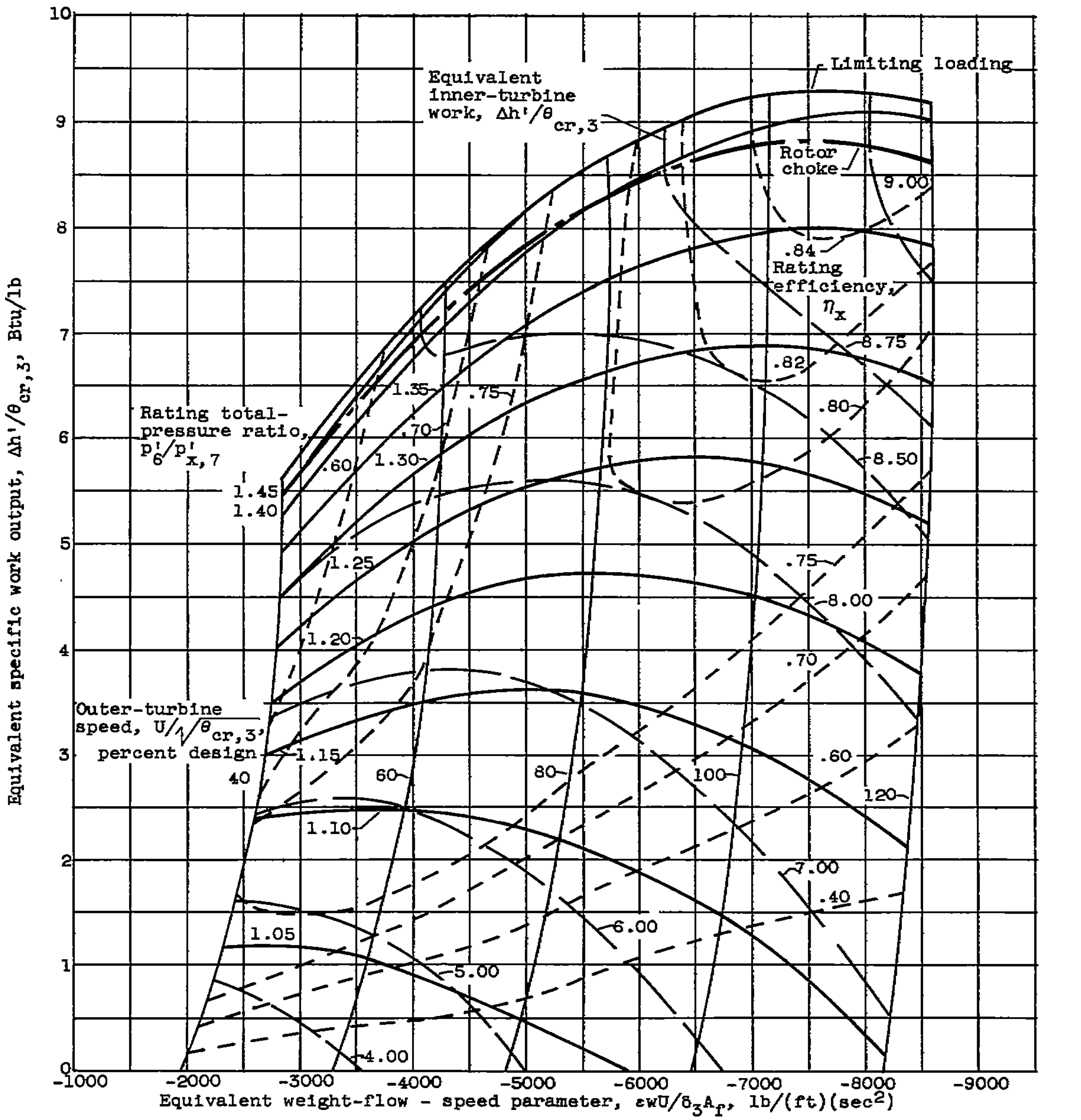


(a) Inner-turbine speed, 40 percent design.

Figure 6. - Outer-turbine performance maps without outer-turbine stator. (Negative abscissa values denote counterrotation.)



(b) Inner-turbine speed, 60 percent design.

Figure 6. - Continued. Outer-turbine performance maps without outer-turbine stator. (Negative abscissa values denote counterrotation.)

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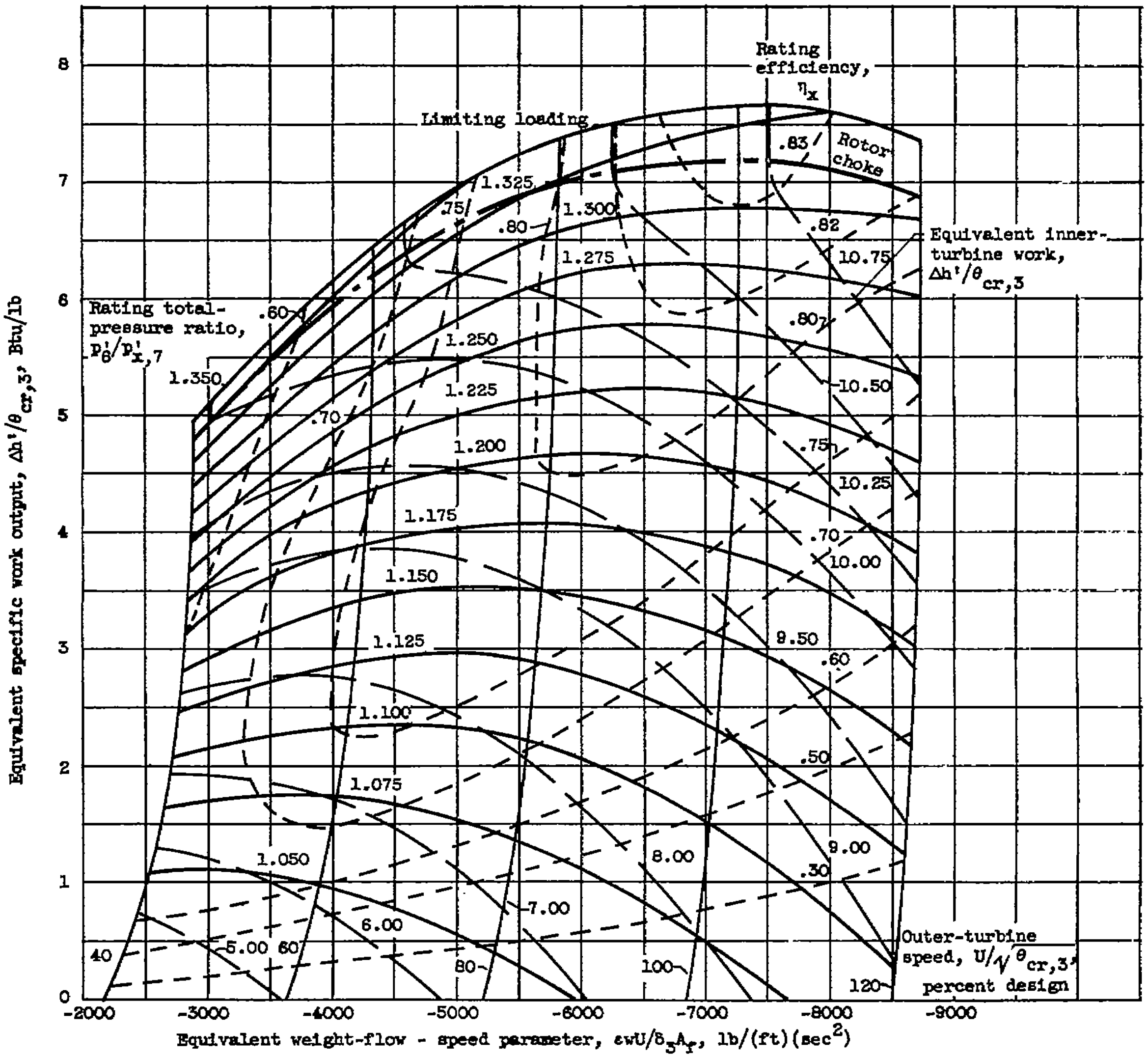
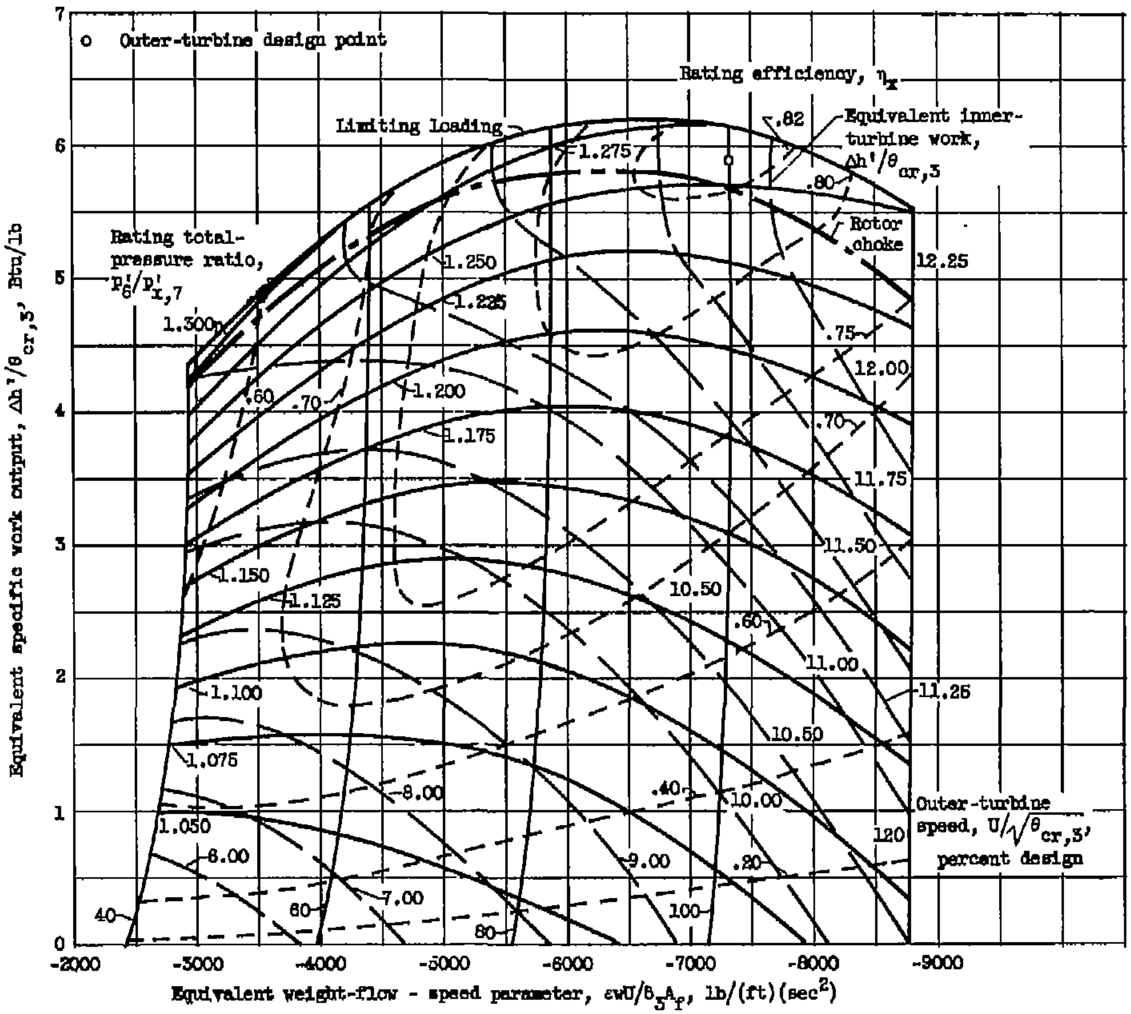


(c) Inner-turbine speed, 80 percent design.

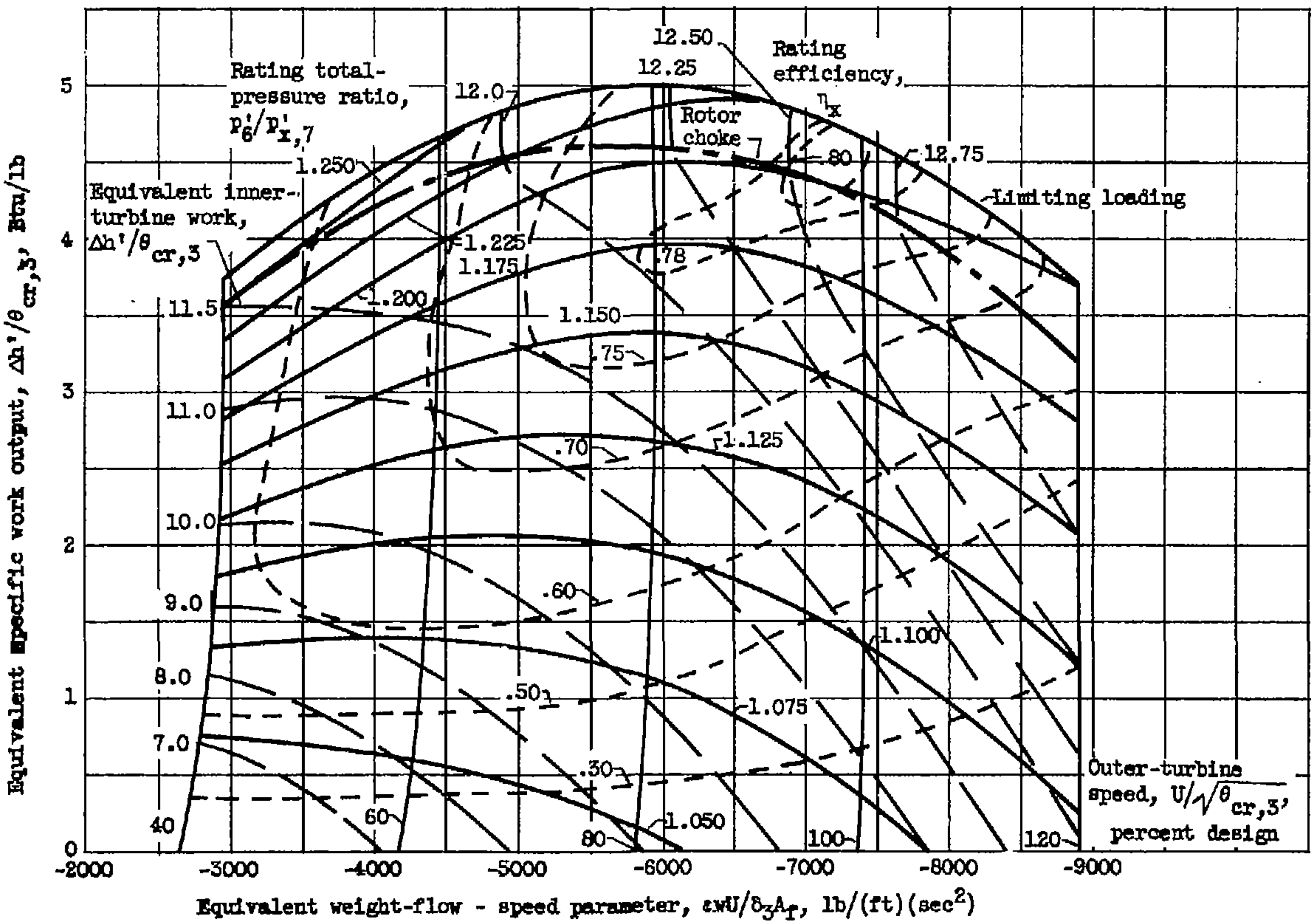
Figure 6. - Continued. Outer-turbine performance maps without outer-turbine stator. (Negative abscissa values denote counterrotation.)



(d) Inner-turbine speed, 100 percent design.

Figure 6. - Continued. Outer-turbine performance maps without outer-turbine stator. (Negative abscissa values denote counterrotation.)

[redacted]



(e) Inner-turbine speed, 120 percent design.

Figure 6. - Concluded. Outer-turbine performance map without outer-turbine stator. (Negative abscissa values denote counterrotation.)

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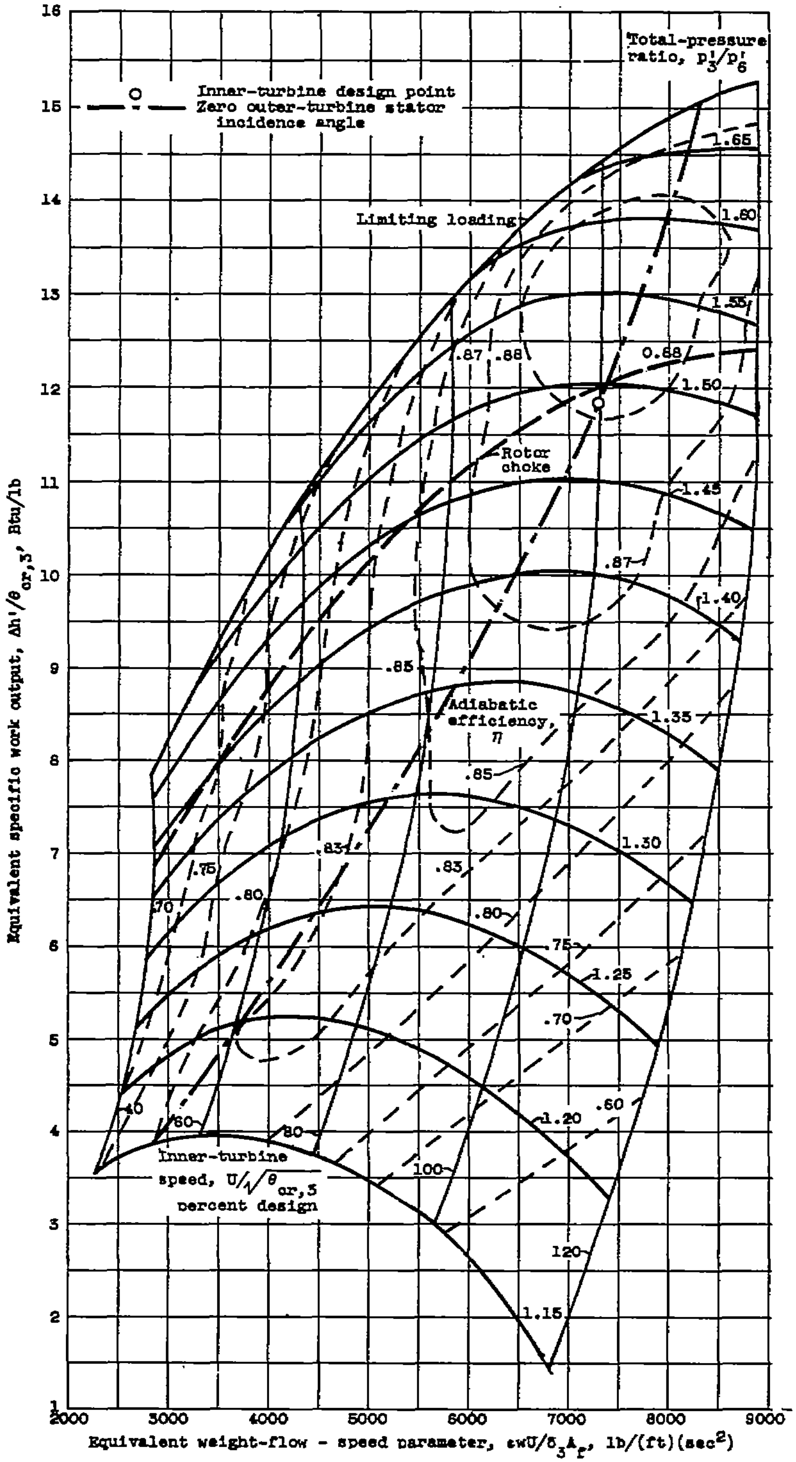

Figure 7. - Inner-turbine performance map including outer-turbine stator incidence loss.

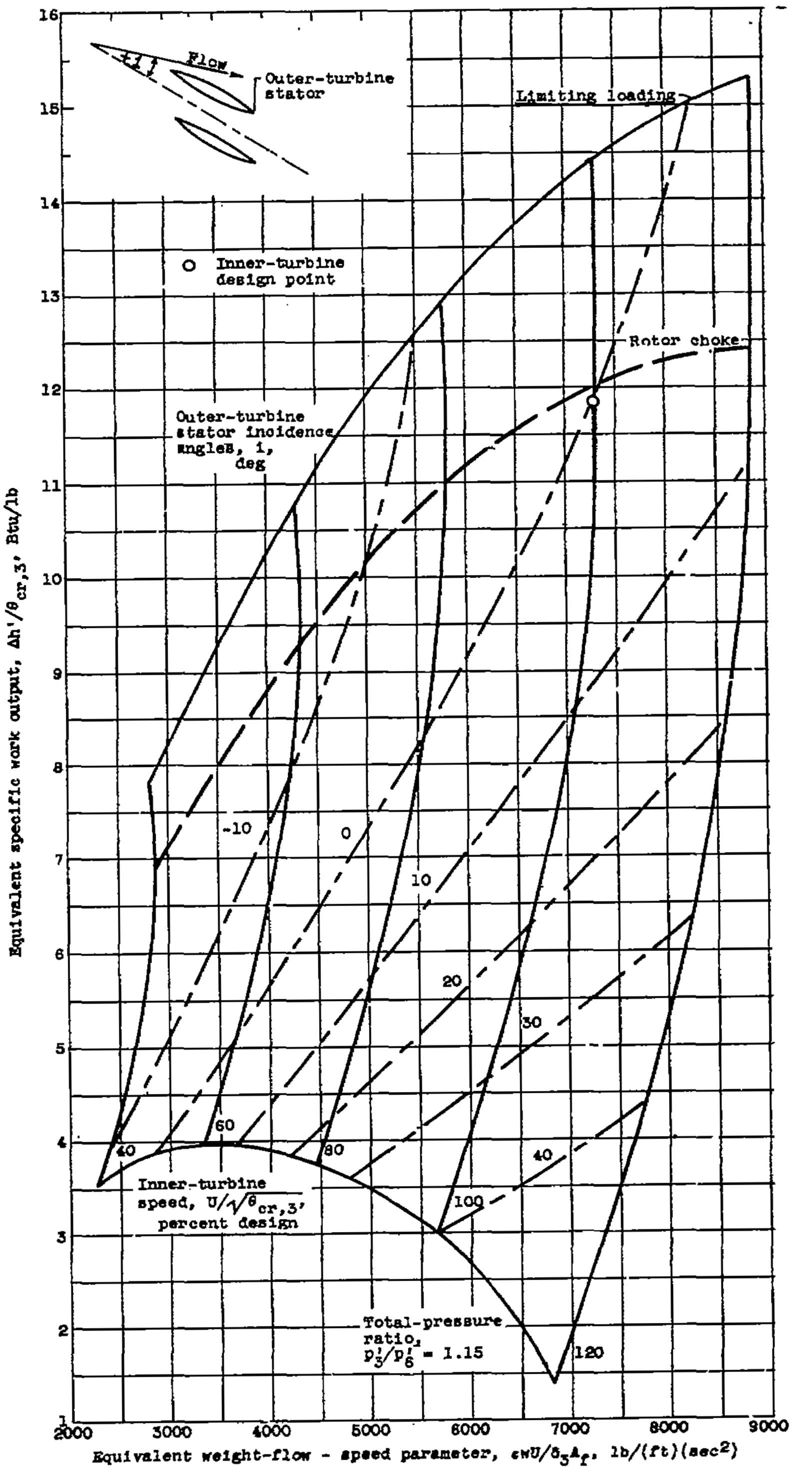

Figure 8. - Variation in outer-turbine incidence angle over range of inner-turbine performance.

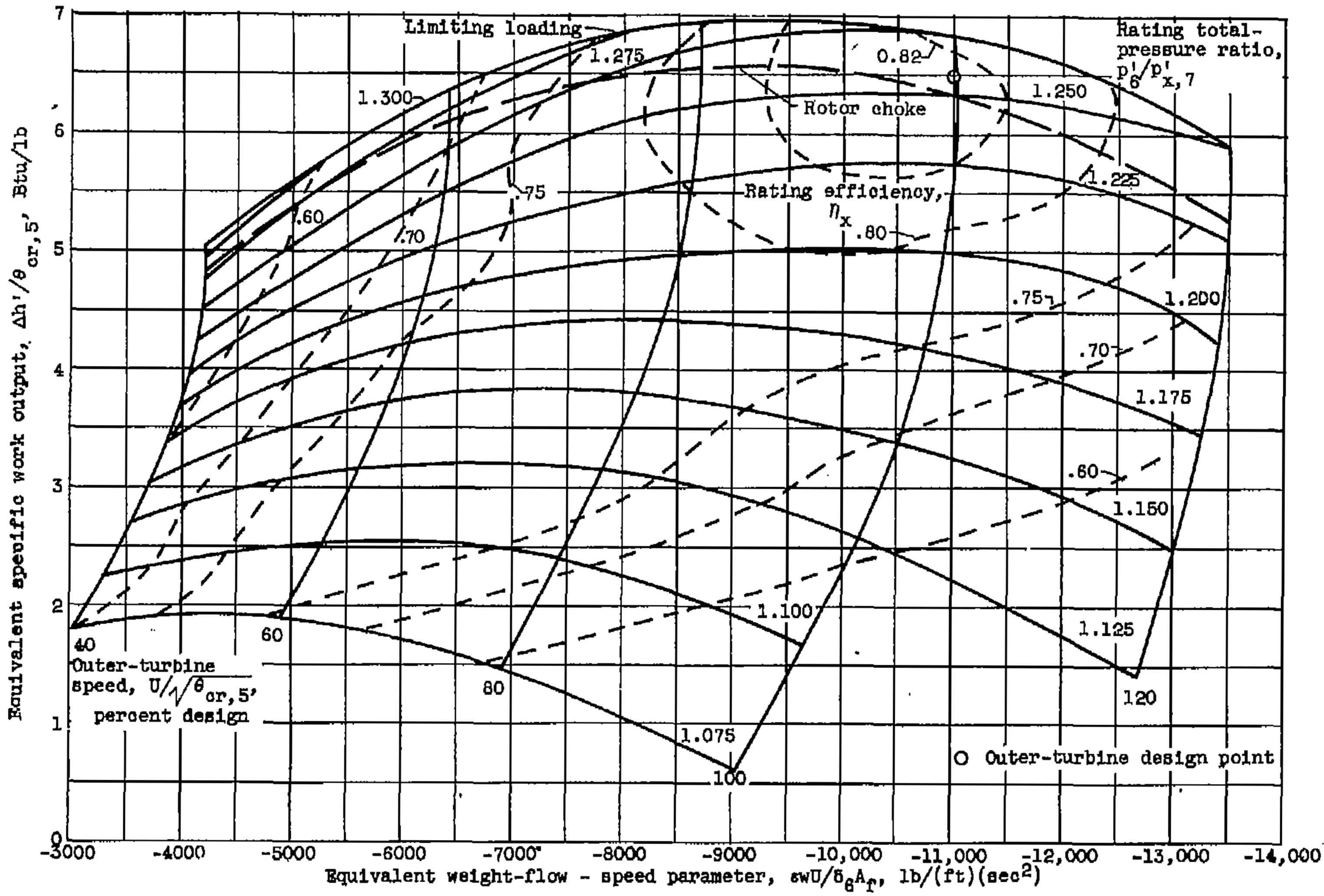

Figure 9. - Outer-turbine performance map including effect of outer-turbine stator. (Negative abscissa values denote counterrotation.)

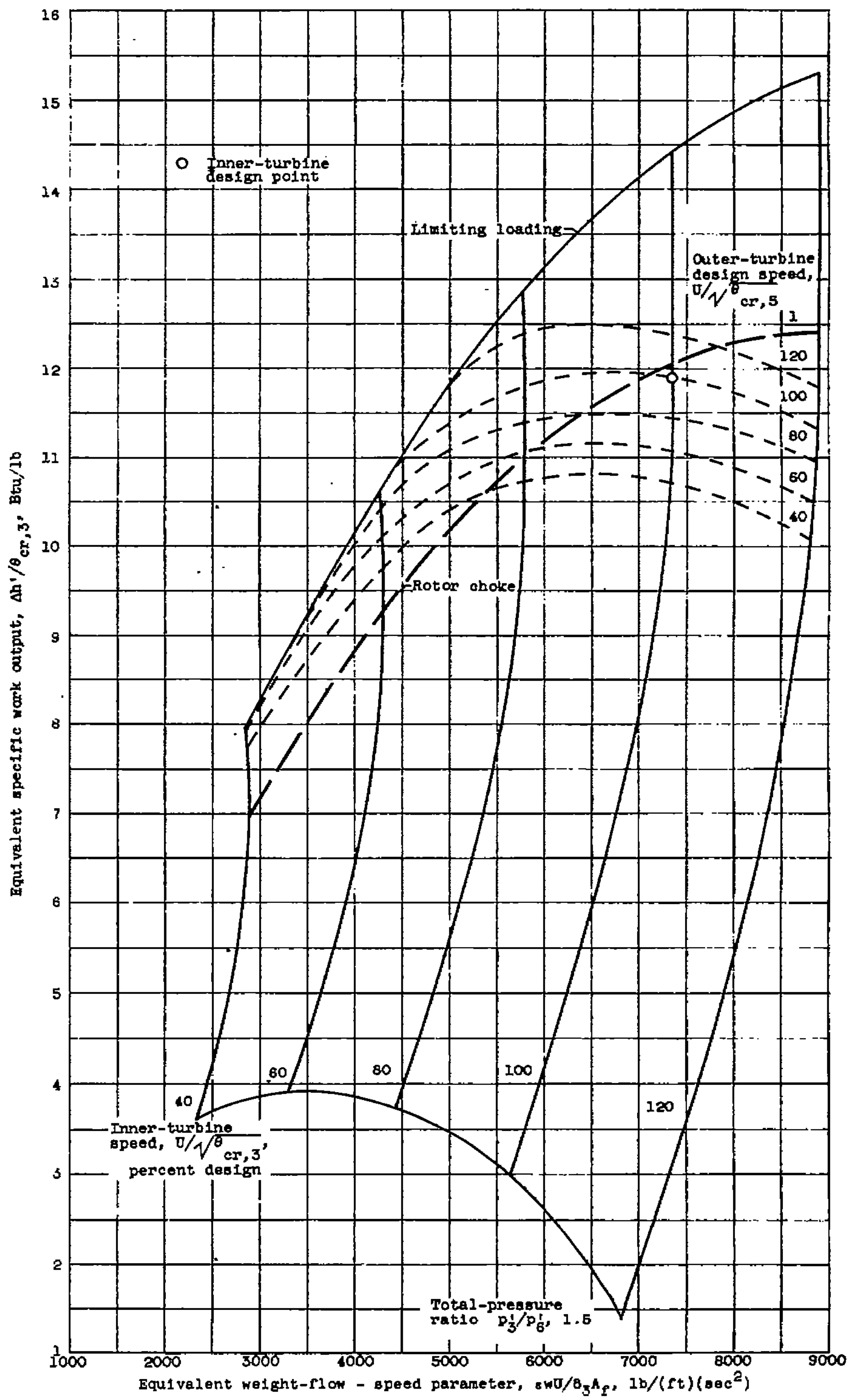

Figure 10. - Outline of inner-turbine performance map including limits in outer-turbine operation with outer-turbine stator.

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