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# NACA

# RESEARCH MEMORANDUM

## INVESTIGATION OF A HIGH-TEMPERATURE SINGLE-STAGE TURBINE SUITABLE FOR AIR COOLING AND TURBINE STATOR ADJUSTMENT

## II - PERFORMANCE OF VORTEX TURBINE AT VARIOUS STATOR SETTINGS

By Thomas R. Heaton, Donald E. Holeski, and Robert E. Forrette

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Cleveland, Ohio



NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

August 3, 1954

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## SUMMARY

The turbojet engine for the supersonic airplane must operate over a range of temperature at the compressor inlet. This variation in compressor-inlet temperature may require that the compressor or turbine, or both, operate over a wide range of flow conditions. A mode of engine operation which requires this operational flexibility of the turbine is considered; this mode requires that the turbine stator and exhaust nozzle area be adjusted to maintain a fixed compressor operating point.

An experimental and analytical investigation was conducted in order to determine the performance of a single-stage adjustable-stator turbine over a range of stator settings corresponding to a range of engine temperature ratio. For each stator setting the turbine performance was determined over a wide range of equivalent tip speed and pressure ratio from a scale-model-turbine cold-air test. The variation of turbine efficiency with engine temperature ratio and the range of engine temperature ratio over which the engine will operate were experimentally determined. The experimental results showed for engine temperature ratios below 3.0 that the maximum turbine work was insufficient to drive the compressor at its fixed operating point. As the engine temperature ratio increased from 3.0 to 5.0, the turbine efficiency varied from 0.860 to 0.874. The efficiency gradually decreased for engine temperature ratios above 5.0 to a value of 0.834 at an engine temperature ratio of 6.6.

Turbine performance obtained from a one-dimensional analytical prediction method was somewhat in error as to the value of engine temperature ratio at limiting turbine work and as to the value of the turbine-inlet equivalent flow for stator area ratios greater than design.

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## INTRODUCTION

The turbojet engine for the supersonic airplane must operate over a range of temperature at the compressor inlet. The variation in compressor-inlet temperature may require that the compressor or turbine, or both, operate over a wide range of flow conditions. A mode of engine operation which requires this operational flexibility of the turbine is described in reference 1. This mode of engine operation utilizes turbine stator and exhaust-nozzle area adjustment to maintain a fixed compressor operating point, and requires that the turbine operate over a wide range of equivalent weight flow and equivalent speed. An investigation is being conducted at the NACA Lewis laboratory to study aerodynamic problems associated with such adjustable-stator turbine designs.

The first part of this investigation is reported in reference 1, which presents an analysis of the turbine requirements for a particular compressor operating point over a range of engine temperature ratio. For a turbine-inlet temperature of 2460° R, flight conditions of a Mach number of 2.12 in the stratosphere and sea-level take-off correspond to engine temperature ratios of 3.31 and 4.75, respectively. If turbine-inlet temperatures greater than 2460° R are employed for take-off, or if the airplane flies below a Mach number of 1.25 in the stratosphere with a turbine-inlet temperature of 2460° R, engine temperature ratios greater than 4.75 will result. The results of this analysis indicated that a feasible single-stage air-cooled adjustable-stator turbine design could be obtained within reasonable aerodynamic limits. A single-stage air-cooled turbine was designed to meet these requirements, and the performance of a scale model was obtained with the stator at the design setting of sea-level take-off with an engine temperature ratio of 4.75. At design equivalent work and equivalent tip speed, a brake internal efficiency of 0.87 was obtained.

The primary purpose of this report is to present the experimental performance of this turbine over a range of estimated stator settings corresponding to engine temperature ratios from 2.70 to 6.56. The performance of the scale-model turbine was obtained in a cold-air test facility with the stator set at six different flow areas. At each stator setting, the turbine performance data were obtained over a range of equivalent tip speed and total-pressure ratio. These data were then used to determine the variation of turbine efficiency with engine temperature ratio. Reference 1 showed that the turbine operation approached the condition of limiting rotor blade loading as the engine temperature ratio decreased. Limiting loading of the turbine rotor blades at given turbine equivalent speed represents the maximum turbine work obtainable at that speed. The lower limit of engine temperature ratio at which the engine will operate with the compressor at the selected operating point was determined from the data; this limit is defined as the engine temperature ratio at which the turbine work at limiting blade loading is equal to the work required to drive the compressor at the fixed operating point.

The effect of stator blade end clearance, which was necessary for the adjustment of the stator blade area, was also experimentally determined for one stator blade setting.

A second purpose of this report is to present the results obtained from a one-dimensional method used to predict the performance of this turbine over the range of engine temperature ratio. The method employed is essentially the same as that presented in reference 2. The predicted performance is compared with the experimental performance.

## SYMBOLS

The following symbols are used in this report:

| | |
|---|---|
| $A$ | frontal area based on blade tip diameter, sq ft |
| $a'_{cr}$ | critical velocity, $\left(\frac{2\gamma}{\gamma+1} gRT'\right)^{1/2}$, ft/sec |
| $b$ | ratio of bleed air flow to compressor-inlet flow |
| $E$ | specific work, Btu/lb |
| $f$ | ratio of fuel flow to compressor-exit flow |
| $g$ | acceleration due to gravity, ft/sec$^2$ |
| $l$ | ratio of leakage flow to compressor-inlet flow |
| $M$ | Mach number |
| $p$ | absolute pressure, lb/sq ft |
| $R$ | gas constant, ft-lb/(lb)($^{\circ}$R) |
| $T$ | absolute temperature, $^{\circ}$R |
| $U$ | blade velocity, ft/sec |
| $w$ | weight flow, lb/sec |
| $\gamma$ | ratio of specific heats |
| $\delta$ | ratio of gas pressure to NACA standard sea-level pressure, $p'/p_0$ |

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ε correction for ratio of specific heats, $\frac{\gamma_0}{\gamma_e}\left[\left(\frac{\gamma_e+1}{2}\right)^{\frac{\gamma_e}{\gamma_e-1}} \Bigg/ \left(\frac{\gamma_0+1}{2}\right)^{\frac{\gamma_0}{\gamma_0-1}}\right]$

η turbine brake internal efficiency

$\theta^*$ square of ratio of critical velocity to critical velocity at NACA standard sea-level temperature, $(a'_{cr}/a'_{cr,0})^2$

ω angular velocity, radians/sec

Subscripts:

C compressor

d design value

e engine operating condition

T turbine

t tip

x axial

0 NACA standard sea-level conditions

1 compressor inlet

2 compressor exit

3 turbine stator inlet

5 turbine rotor exit

Superscript:

' total state

## TURBINE ANALYSIS

### Turbine Requirements

The variations of required turbine equivalent work and equivalent speed with engine temperature ratio have been determined in reference 1 and are shown in figures 1 and 2. The variation of required turbine-inlet equivalent flow, including a correction for the change in $\gamma$, is presented in figure 3. The turbine equivalent work and equivalent tip speed are highest at the low engine temperature ratios, while the turbine-inlet equivalent weight flow is highest at the high engine temperature ratios. These conditions must be satisfied by the turbine in order that the compressor operating point remain fixed as the engine temperature ratio varies. That is, at each engine temperature ratio, the stator flow area must be adjusted so that the required turbine-inlet equivalent weight flow is obtained. Then, at this stator setting, the turbine must attain the required work at the required tip speed in order that it drive the compressor. An acceptable turbine efficiency should also be attained in order to have good engine performance.



## Estimation of Stator Flow Areas

The variation of the stator flow area which gives the required variation of inlet equivalent weight flow with engine temperature ratio was approximated by the use of the velocity diagrams calculated for several engine temperature ratios (ref. 1). The variation of the estimated stator-throat area at the mean blade section with engine temperature ratio is presented in figure 4. The stator-throat areas increased as the engine temperature ratio increased.

## Prediction of Turbine Performance

The ability to predict the performance of the adjustable-stator turbine over a range of stator flow area is important in estimating the engine operating limits when experimental data are unavailable. An analytical method which essentially corresponds to that of reference 2 was used to predict the performance of the model turbine at the six estimated stator-throat areas indicated in figure 4. The prediction method, which is a one-dimensional analysis, uses certain loss and flow angle assumptions together with the basic one-dimensional compressible flow equations to calculate blade-row inlet and exit flow conditions in the form of velocity parameters. These parameters are then used to compute the turbine work, efficiency, and weight flow for given equivalent blade speeds, turbine geometry, and range of tangential component of velocity at the stator exit. The loss and angle assumptions are as follows:

Loss assumptions. -

1. Incidence loss at stator and rotor inlets: The kinetic energy associated with the component of inlet relative velocity normal to the tangent to the blade mean camber line at the leading edge is assumed lost.

2. Blade loss: The losses due to friction, secondary flow, and tip clearance of a blade row are included in an "effective viscous loss" parameter. This parameter depends on the average dynamic pressure across the blade row and on a blade-loss parameter which is assumed constant for a given turbine.

3. Shock loss: A shock loss occurs at the exit of a blade row if the relative exit velocity is supersonic. This loss is assumed to occur at a normal shock condition because this shock represents the maximum total-pressure loss at a given supersonic Mach number. 3252

4. Exit whirl loss: The kinetic energy associated with the absolute tangential velocity at the rotor exit is a loss which is chargeable to the turbine.

Angle assumption. - In a blade row with subsonic or sonic flow at the throat, the flow angle at a point just inside the trailing edge was assumed to be that angle whose sine is the ratio of the throat width to the pitch minus trailing-edge blockage. Flow conditions downstream of the exit were determined by considering continuity, constant tangential component of velocity, and no losses between the station just upstream of the trailing edge and the downstream station. For supersonic exit Mach numbers, the weight flow at which the blade row chokes and the supersonic velocity at the blade exit outside the passage together with assumed shock losses were used to calculate the flow angles (see appendix C, ref. 2).

Calculation procedure. - The calculation of the blade-loss parameter, which is assumed constant for a given turbine, is the initial step in the procedure for performance prediction. The experimental performance at the design stator setting was used to determine the blade-loss parameter such that the calculated efficiency agreed with the experimental efficiency at the design value of equivalent tip speed and equivalent turbine work. This value of the blade-loss parameter was then assumed to be constant, and the work output, efficiency, and weight flow of the turbine were calculated for six stator blade settings. The calculated efficiency was made to agree with the experimental efficiency of the turbine at the design value of equivalent tip speed and equivalent turbine work by selection of the proper value of blade-loss parameter. However, the calculated equivalent weight flow obtained at this speed and work will not necessarily agree with the experimental value even though the over-all losses are in agreement with the experimental values, because the assumed loss distribution may differ from the actual loss distribution. Thus, for the same stator area ratio the match points for the predicted and experimental turbine performance may be slightly different. In order to determine the match point for the predicted turbine performance for the different stator settings, a small portion of a predicted turbine performance map must be constructed for a range of equivalent turbine speed and pressure ratio. Therefore, at each stator blade setting the turbine performance was calculated for two equivalent speeds: the value corresponding to the engine temperature ratio for which the stator-throat area was estimated and a value approximately 15 percent greater. The turbine performance for any speed within this range was obtained by a linear interpolation between these two speeds along lines of constant turbine pressure ratio $p_3'/p_{x,5}'$.

3252 As part of the calculation procedure, the effect of the various loss assumptions on turbine efficiency can be determined. A breakdown of the calculated losses in terms of turbine efficiency is included as part of the performance prediction.

## METHODS AND PROCEDURE

### Equipment and Instrumentation

The turbine used in the investigation was a 0.528 scale model which could be tested in an existing turbine test facility. This test facility and the instrumentation used to determine the turbine performance are described in reference 1.

The instruments used in measuring the turbine performance were read with the following precision:

| | |
|---|---|
| Absolute pressure, in. tetrabromoethane | ±0.5 |
| Orifice pressure drop, in. water | ±0.5 |
| Temperature, deg | ±1 |
| Torque load, lb | ±0.2 |
| Rotational speed, rpm | ±10 |

### Procedure and Performance Calculations

At each stator blade setting, data were taken over a range of pressure ratio and equivalent tip speed in order to obtain a complete performance map at each stator blade setting. For all test points, the inlet total temperature was maintained between 683° and 687° R. The inlet total pressure varied between 24 and 27 inches of mercury absolute, depending on the air flow and the ambient air pressure.

The method of computing the brake internal efficiency, which is the same as that described in reference 1, gives a conservative value since the energy represented in the absolute rotor-exit whirl is charged as a loss to the turbine.

All the turbine performance data at each stator setting were reduced to NACA standard sea-level conditions at the turbine stator inlet. The performance was expressed in terms of the following variables:

(a) brake internal efficiency $\eta$

(b) total-pressure ratio $p_3'/p_{x,5}'$

(c) equivalent tip speed $U_{t,T}/\sqrt{\theta_3^*}$ 3252

(d) work parameter $E_T/U_{t,T}^2$

(e) flow parameter $\dfrac{w_T U_{t,T}}{\delta_3 A_T} \varepsilon_3$

These particular work and flow parameters were used to express the turbine performance because they are independent of turbine size and because they are convenient in matching the turbine performance to the compressor. A derivation of these parameters together with the matching procedure is presented in the appendix.

## RESULTS AND DISCUSSION

### Turbine Performance

Experimental performance. - The over-all performance of the model turbine at six stator area ratios and the performance at design stator area with stator blade end clearance are presented in figure 5. For each stator area ratio the performance is presented as a plot of turbine work parameter $E_T/U_{t,T}^2$ against flow parameter $(w_T U_{t,T}/A_T \delta_3)\varepsilon_3$, with lines of constant equivalent tip speed $U_{t,T}/\sqrt{\theta_3^*}$, pressure ratio $p_3'/p_{x,5}'$, and brake internal efficiency contours $\eta$. Figures 5(a) to (f) show the performance maps of the turbine at stator area ratios of 1.000, 0.742, 0.829, 0.911, 1.122, and 1.206, respectively. The line of maximum work output, "limiting loading," is designated on each map. The performance of the turbine at design stator area with stator blade end clearance is shown in figure 5(g).

Variation of turbine operating parameters with engine temperature ratio. - The required variation of the turbine flow and work parameters with engine temperature ratio is presented in figure 6, and was used together with the matching procedure presented in the appendix to determine the engine temperature ratio at each stator setting at which the experimental turbine performance satisfied these requirements of weight flow, work, and speed. These turbine operating points are shown on each turbine performance map in figure 5. At a stator area ratio of 0.742 (fig. 5(b)), the turbine operating point lies above the maximum turbine work parameter, and at this point, only the turbine speed and flow parameter are satisfied. Because the turbine is not capable of producing the required work, the engine will not run with the compressor at the specified operating point. In order to determine the limits of engine operation, the maximum turbine work (limiting loading) was obtained for temperature ratios represented by each of the stator settings at the values of equivalent speed and flow parameter corresponding to the operating point. These values are plotted against engine temperature ratio in figure 6, and the region above this line represents a nonoperating region for the turbine. The limiting loading and required turbine work values are equal at a temperature ratio of approximately 3. This is the minimum engine temperature ratio at which the turbine will drive the compressor at its fixed operating point.

The engine temperature ratios as determined from the matching procedure for the given stator area ratios are shown in figure 7. These points define the experimentally determined variation of stator area ratio with engine temperature ratio and are reasonably close to the estimated values. The difference between the experimental and estimated points shows that the actual turbine weight flow at each stator setting was slightly different from the value required at the engine temperature ratio for which the stator-throat area had been estimated. Turbine performance data showed that both the stator and rotor were choked at the required turbine operating point for stator area ratios at and below the design value, and for the stator area ratios greater than design, the rotor continued to choke and the stator was unchoked. As the experimental data show, significant increase in turbine-inlet equivalent flow above the design value was obtained even though the rotor was choked. This increase in turbine-inlet equivalent flow is primarily due to a rise in relative total pressure at the rotor throat. An analytical discussion of this phenomenon is presented in reference 3.

The variation of turbine internal efficiency with engine temperature ratio for the fixed compressor operating point is shown in figure 8. The flight conditions of sea-level take-off and a Mach number of 2.12 in the stratosphere with a turbine-inlet temperature of 2460° R are indicated. For engine temperature ratios between 3.0 and 5.0, the turbine efficiency varies only slightly, ranging between 0.860 and 0.874. As the engine temperature ratio increases above 5.0, the turbine efficiency decreases gradually to a value of 0.834 at an engine temperature ratio of 6.6. This drop in efficiency may be due to the relative increase in the absolute rotor-exit whirl and rotor incidence loss at the high engine temperature ratios. Because the method of evaluating the turbine efficiency charged the turbine with the energy represented in this whirl, the turbine efficiency may be expected to decrease, as shown in reference 1, where the estimated leaving loss is plotted against the engine temperature ratio. Reference 1 shows that the magnitude of this leaving loss is 2.6 percent of the turbine work at an engine temperature ratio of 6.6.

Effect of stator clearance on turbine performance. - During the process of testing this turbine with the different stator-throat areas, it was necessary to remove some metal from the stator blade ends at either the hub or the tip in order to set the blade at the proper chord angles. After the performance of the turbine at the various stator blade settings was obtained, the stator blades of the turbine were reset to the design area and the clearances at the hub and tip were measured. The ratio of this clearance to the blade span was 0.008 at the hub and 0.005 at the tip for a blade span of 2.03 inches. The performance of the turbine with these clearances was then determined and compared with that previously obtained with the blades set in this position. Figure 9 shows the variation of the turbine efficiency and flow parameter with the turbine work parameter for these two configurations at the required equivalent tip speed for the take-off condition. Over the range of turbine work parameter, the maximum difference in the efficiency is 0.01 and the choking value of turbine flow parameter was increased by approximately 1.5 percent. It may be concluded for this turbine that the stator blade clearance had little effect on the turbine performance.

## Comparison of Predicted and Experimental Turbine Performance

The values of work parameter at limiting blade loading (for the required equivalent speed and flow parameter) determined from the predicted turbine performance are plotted against engine temperature ratio in figure 10. The engine temperature ratio at which the limiting loading work equals the required work is approximately 2.65, a value which is lower than the engine temperature ratio of 3.0 determined from the experimental results. As the engine temperature ratio decreases, turbine operation approaches limiting blade loading, and reference 2 shows that the method as applied does not predict the performance accurately for this flow condition.

The variation of the stator-throat area ratios with engine temperature ratio determined from the predicted turbine performance is compared with the experimental values in figure 11. At engine temperature ratios below 4.75, the predicted values agree reasonably well with the experimental values. This agreement may be expected because turbine performance data indicated that the stator was choked in this region. The turbine stator then controls the turbine-inlet equivalent weight flow in this range of engine temperature ratio. However, the predicted stator-throat areas are appreciably in error for temperature ratios above 4.75. At these temperature ratios the rotor is primarily controlling the flow, and if the assumed losses and loss coefficients are in error the predicted turbine flow will be correspondingly in error. It may be concluded then that the prediction method as applied does not accurately predict the turbine-inlet equivalent flow in the region where the rotor is choked and the stator is unchoked.



The variation of the predicted turbine efficiency with engine temperature ratio is compared with the experimental values in figure 12. At the low engine temperature ratios the predicted turbine efficiency is higher than the experimental values, and at the high engine temperature ratios the predicted efficiency is lower than the experimental values. Figure 13 shows the variation of the predicted losses through the turbine with engine temperature ratio for the range of stator-throat area ratio considered. The stator and rotor blade viscous losses contribute the major portion of the total loss through the turbine. Stator incidence and shock loss at the stator and rotor exits are negligible, and rotor incidence loss is small over the range of engine temperature ratio. The loss due to rotor exit whirl is small at the low engine temperature ratio and increases to approximately a 3-percent loss in turbine efficiency at the high engine temperature ratios.



A reasonable explanation as to why the prediction method did not predict the turbine performance more accurately may be as follows: The calculated viscous losses which constitute the major portion of the losses through the turbine are somewhat in error, particularly for stator-throat area ratios greater than design. This is shown in figure 11 where the stator area ratios (from the prediction method) required to pass a turbine-inlet flow for a given engine temperature ratio greater than 4.75 are appreciably larger than the experimental values. Consequently, the assumption of a constant blade-loss parameter for the turbine (evaluated for the design turbine geometry) is in error when the turbine geometry is altered.

## SUMMARY OF RESULTS

From this experimental and analytical investigation of turbine stator adjustment the following results were obtained:

1. The experimental results indicated that the required variations in turbine-inlet equivalent flow and equivalent work output were obtained for a range of engine temperature ratio from 3.0 to 6.6.

2. At engine temperature ratios below 3.0, the maximum work output of the turbine was insufficient to drive the compressor at its fixed operating point.

3. The turbine efficiency varied between 0.860 and 0.874 for engine temperature ratios between 3.0 and 5.0. The efficiency gradually decreased for engine temperature ratios above 5.0 to a value of 0.834 at an engine temperature ratio of 6.6.

4. The stator blade end clearance had little effect on the performance of the turbine.

5. The prediction method did not accurately predict the turbine performance over the range of stator-throat area ratios considered. 3252
The predicted engine temperature ratio for limiting turbine work output was 2.65 as compared with the experimental value of 3.0, and turbine-inlet equivalent weight flows for stator area ratios greater than design were appreciably less than the experimental values.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 9, 1954

## APPENDIX - DERIVATION OF TURBINE WORK AND FLOW PARAMETERS AND MATCHING PROCEDURE

### Work and Flow Parameters

The basic equations that determine the equilibrium operating point of a compressor and turbine are as follows: Because the compressor and turbine are directly coupled, the angular velocity of the turbine must equal the angular velocity of the compressor

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$$\omega_T = \omega_C \tag{A1}$$

The weight flow through the turbine must equal the weight flow at the compressor exit, which is assumed to be the weight flow entering the compressor minus any bleed and leakage,

$$w_T = w_C \left[(1+f)(1-l-b)\right] \tag{A2}$$

The power of the turbine must equal the power of the compressor

$$w_T E_T = w_C E_C \tag{A3}$$

Rewriting equation (A1) in terms of equivalent tip speed of the compressor and turbine gives

$$\left(U_t/\sqrt{\theta_3^*}\right)_T = \left(U_t/\sqrt{\theta_1^*}\right)_C \sqrt{A_T/A_C}\ \sqrt{\theta_1^*/\theta_3^*} \tag{A4}$$

Rewriting equation (A2) in terms of equivalent compressor and turbine weight flow and dividing by the turbine frontal area yields

$$\frac{w_T\sqrt{\theta_3^*}}{A_T\delta_3}\,\epsilon_3 = (1+f)(1-l-b)\,\frac{w_C\sqrt{\theta_1^*}}{A_C\delta_1}\,\epsilon_1\left(\frac{A_C}{A_T}\right)\left(\frac{\epsilon_3}{\epsilon_1}\right)\left(\frac{\delta_1}{\delta_2}\right)\left(\frac{\delta_2}{\delta_3}\right)\sqrt{\frac{\theta_3^*}{\theta_1^*}} \tag{A5}$$

In a similar manner equation (A3) becomes

$$\left(\frac{w_T\sqrt{\theta_3^*}}{A_T\delta_3}\,\epsilon_3\right)\left(\frac{E_T}{\theta_3^*}\right) = \left(\frac{w_C\sqrt{\theta_1^*}}{A_C\delta_1}\,\epsilon_1\right)\left(\frac{E_C}{\theta_1^*}\right)\left(\frac{A_T}{A_C}\right)\left(\frac{\delta_1}{\delta_2}\right)\left(\frac{\delta_2}{\delta_3}\right)\sqrt{\frac{\theta_1^*}{\theta_3^*}}\left(\frac{\epsilon_3}{\epsilon_1}\right) \tag{A6}$$

By multiplying equation (A5) by (A4) and simplifying, the following turbine flow parameter is obtained:

$$\frac{w_T U_{t,T}}{A_T \delta_3}\,\varepsilon_3 = (1+f)(1-\ell-b)\,\frac{w_C\sqrt{\theta_1^*}}{A_C\delta_1}\,\varepsilon_1\left(\frac{\varepsilon_3}{\varepsilon_1}\right)\left(\frac{\delta_1}{\delta_2}\right)\left(\frac{\delta_2}{\delta_3}\right)\sqrt{\frac{A_C}{A_T}}\left(\frac{U_t}{\sqrt{\theta_1^*}}\right)_C \qquad \text{(A7)}$$

Combining equations (A5), (A6), and the square of (A4) yields the turbine work parameter 3252

$$E_T/U_{t,T}^2 = \left[\frac{1}{(1+f)(1-\ell-b)}\right](A_C/A_T)(E_C/U_{t,C}^2) \qquad \text{(A8)}$$

For a given compressor operating point, compressor frontal area, and ratio of compressor frontal area to turbine frontal area, the turbine work parameter is dependent upon $f$, $\ell$, and $b$, and the turbine flow parameter is dependent upon $f$, $\ell$, $b$, $\gamma$, and burner pressure drop $\delta_2/\delta_3$.

## Matching Procedure

The variation of fuel-air ratio, bleed air flow, $\gamma$, and $\varepsilon$ with engine temperature ratio may be determined from the range of engine temperature ratio, the selected compressor operating point, and turbine-inlet temperatures under consideration. An estimation of engine leakage and burner pressure drop may also be made. These quantities together with the given compressor operating point, compressor frontal area, and ratio of compressor to turbine frontal area are used to determine the variation of the turbine work and flow parameters with engine temperature ratio.

For a given turbine performance at a particular stator area, an engine temperature ratio is assumed; work and flow parameters are calculated; and an equivalent turbine tip speed is read from the turbine performance map.

This equivalent tip speed together with equation (A4) is then used to calculate an engine temperature ratio. A match point is obtained when the assumed engine temperature ratio agrees with the calculated engine temperature ratio. This procedure was used for both the experimental and predicted turbine performance.

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Air Cooling and Turbine Stator Adjustment. I - Design of Vortex Turbine and Performance with Stator at Design Setting. NACA RM E54C15, 1954.

2. Stewart, Warner L., and Evans, David G.: Analytical Study of Losses at Off-Design Conditions for a Fixed-Geometry Turbine. NACA RM E53K06, 1954.

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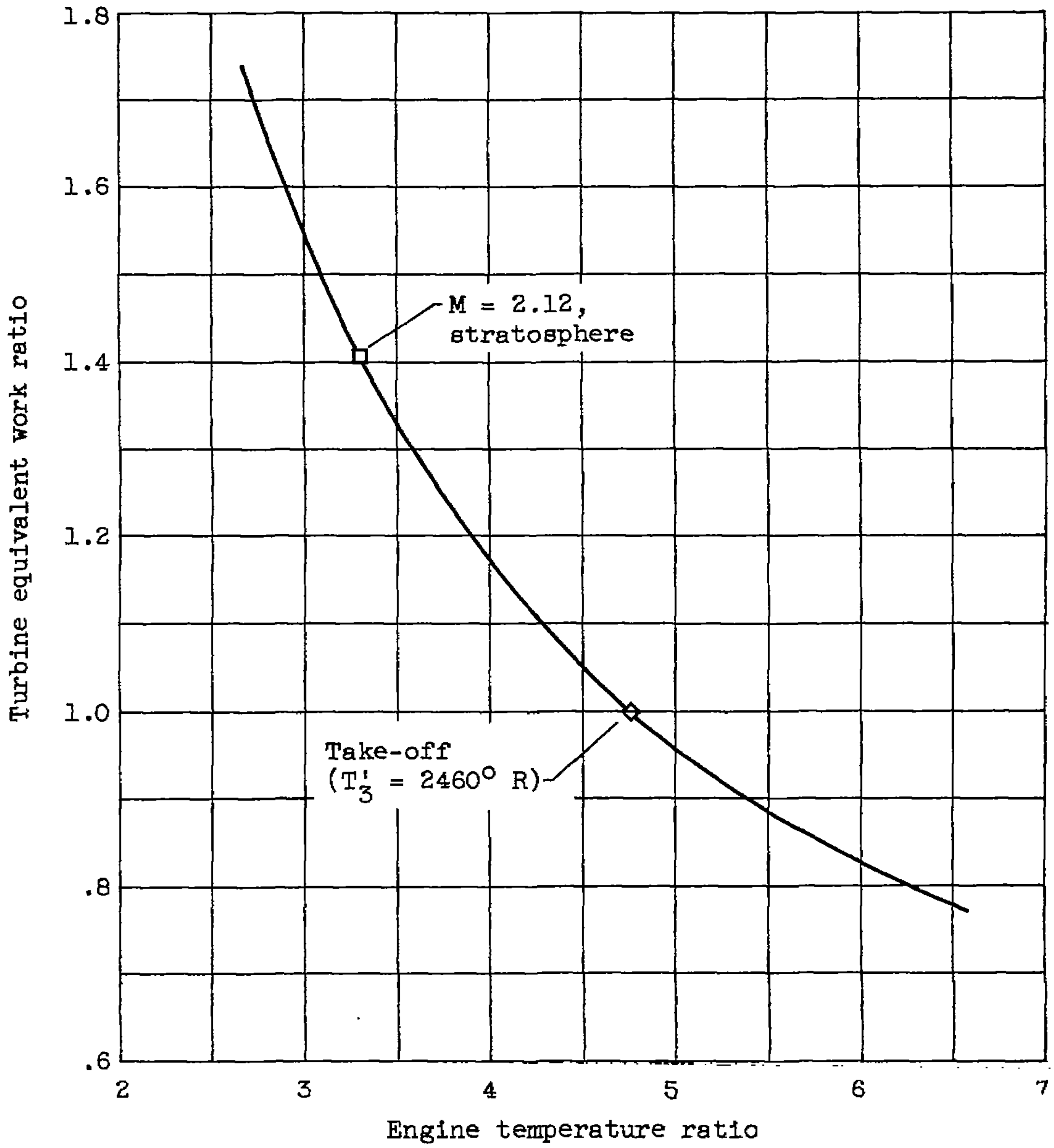


Figure 1. - Variation of required turbine work ratio with engine temperature ratio.

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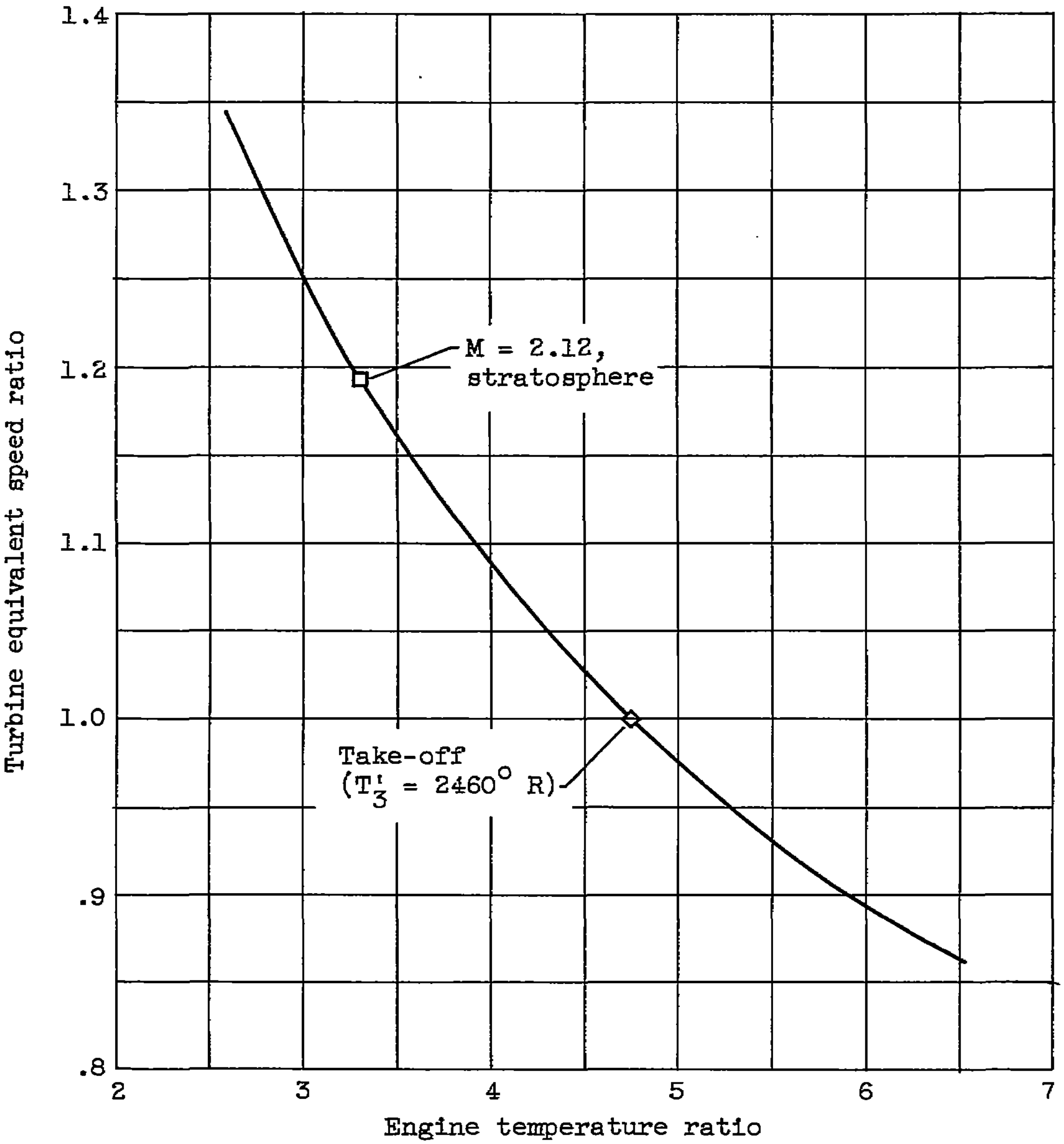


Figure 2. - Variation of turbine equivalent speed ratio with engine temperature ratio.

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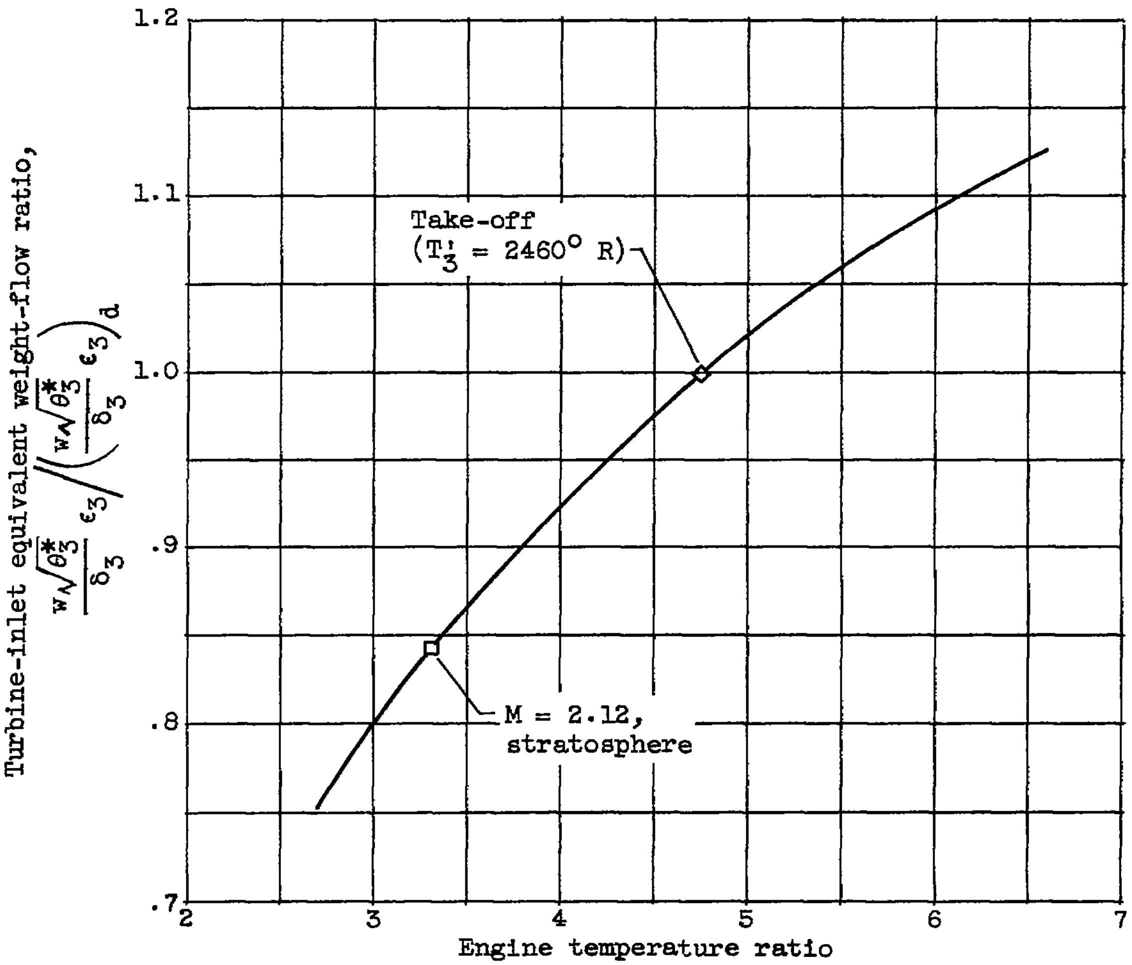


Figure 3. - Variation of turbine-inlet equivalent weight-flow ratio with engine temperature ratio.

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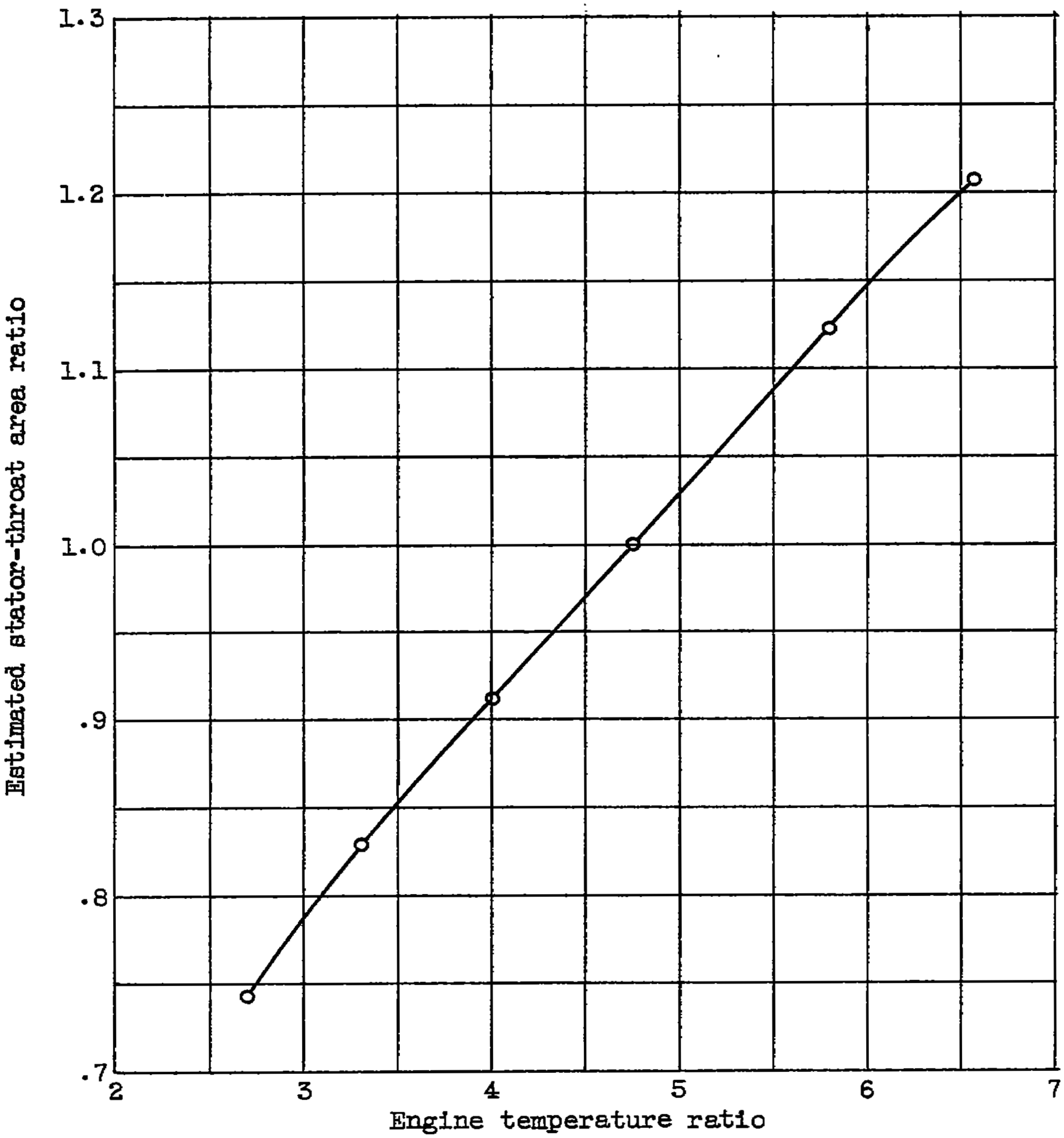


Figure 4. - Variation of estimated stator-throat area ratio with engine temperature ratio.

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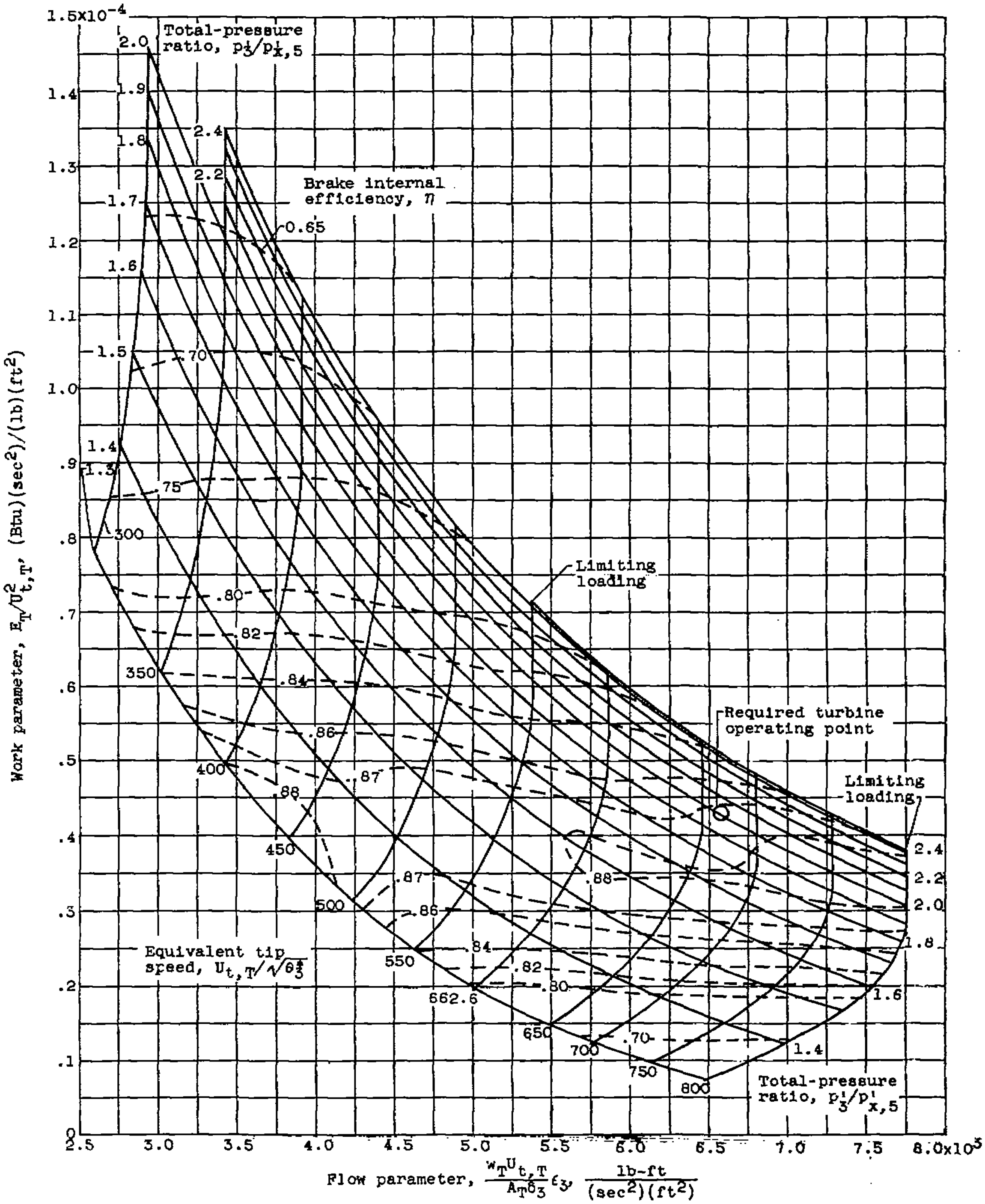


(a) Stator-throat area ratio, 1.000 (design throat area).

Figure 5. - Over-all performance of scale-model turbine.

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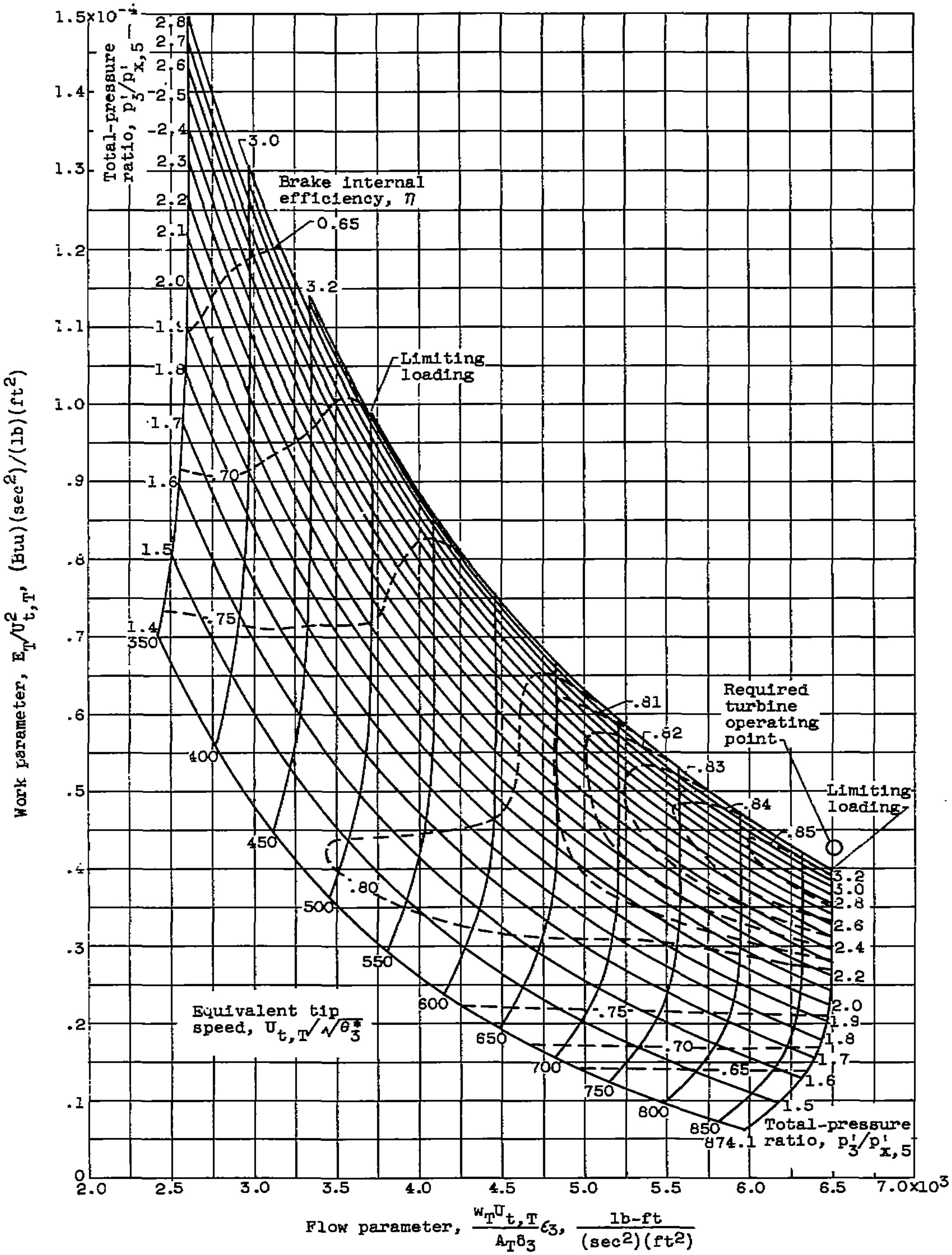


(b) Stator-throat area ratio, 0.742.

Figure 5. - Continued. Over-all performance of scale-model turbine.

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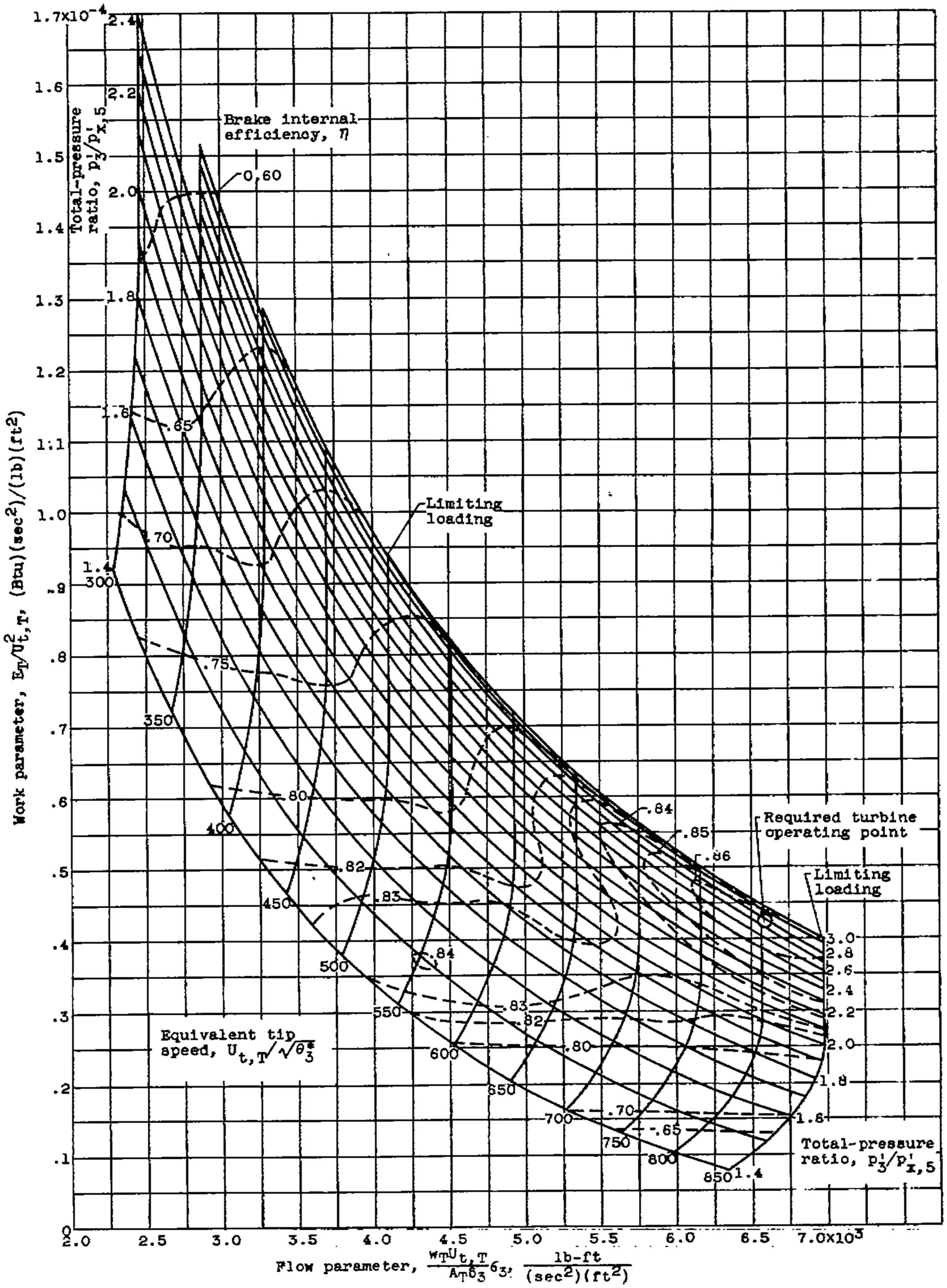


(c) Stator-throat area ratio, 0.829.

Figure 5. - Continued. Over-all performance of scale-model turbine.

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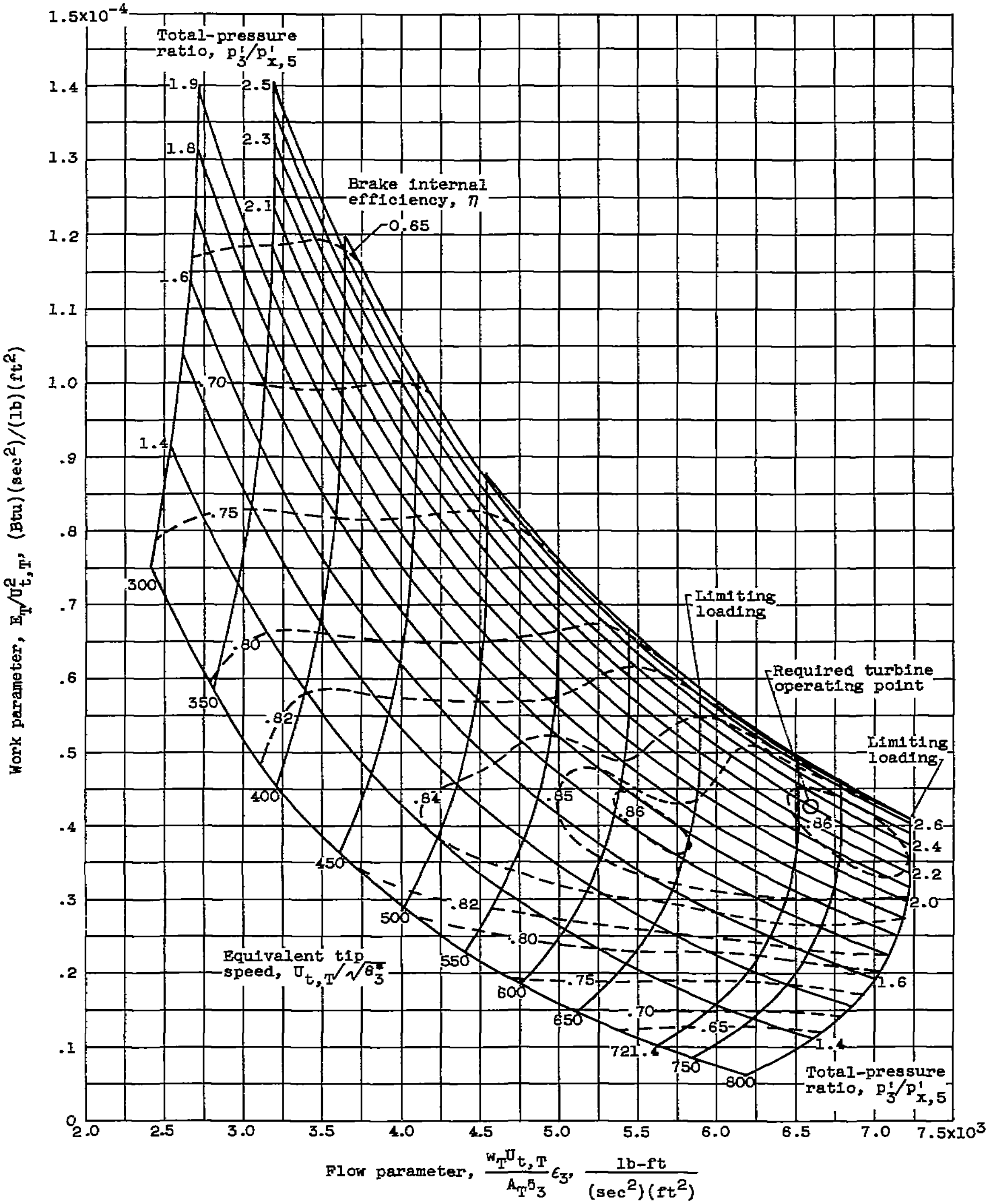


(d) Stator-throat area ratio, 0.911.

Figure 5. - Continued. Over-all performance of scale-model turbine.

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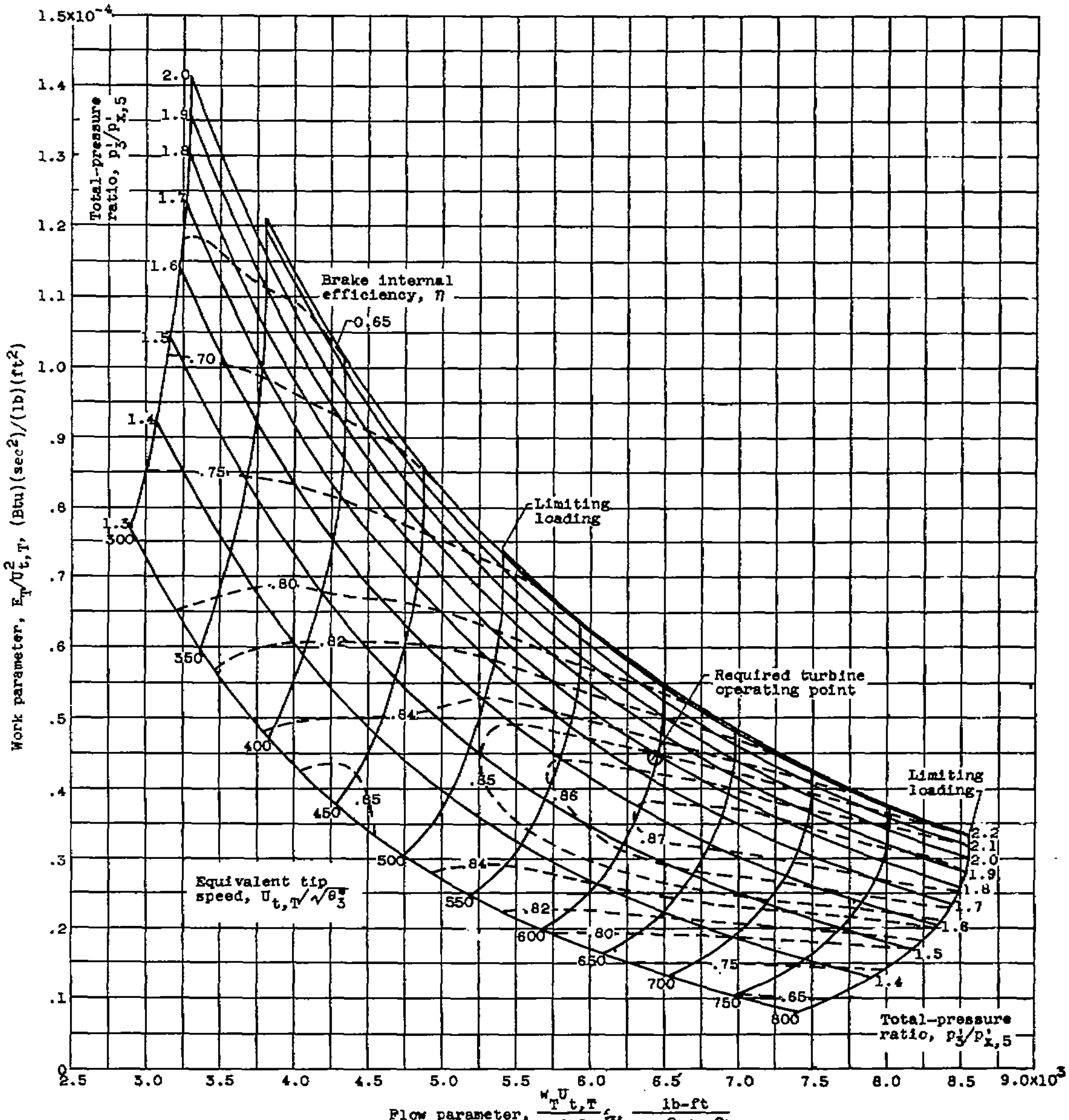


(e) Stator-throat area ratio, 1.122

Figure 5. - Continued. Over-all performance of scale-model turbine.

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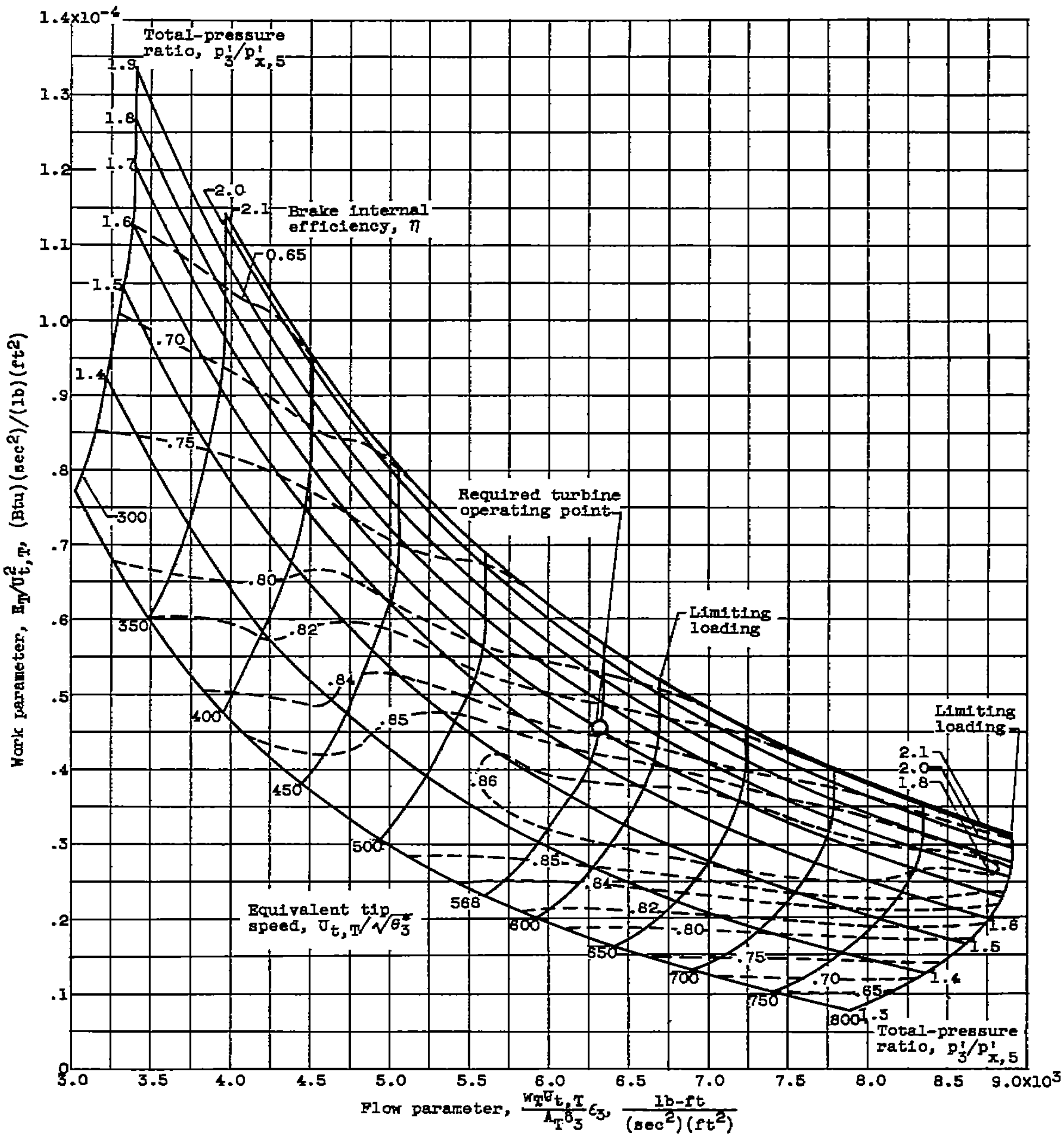


(f) Stator-throat area ratio, 1.206.

Figure 5. - Continued. Over-all performance of scale-model turbine.

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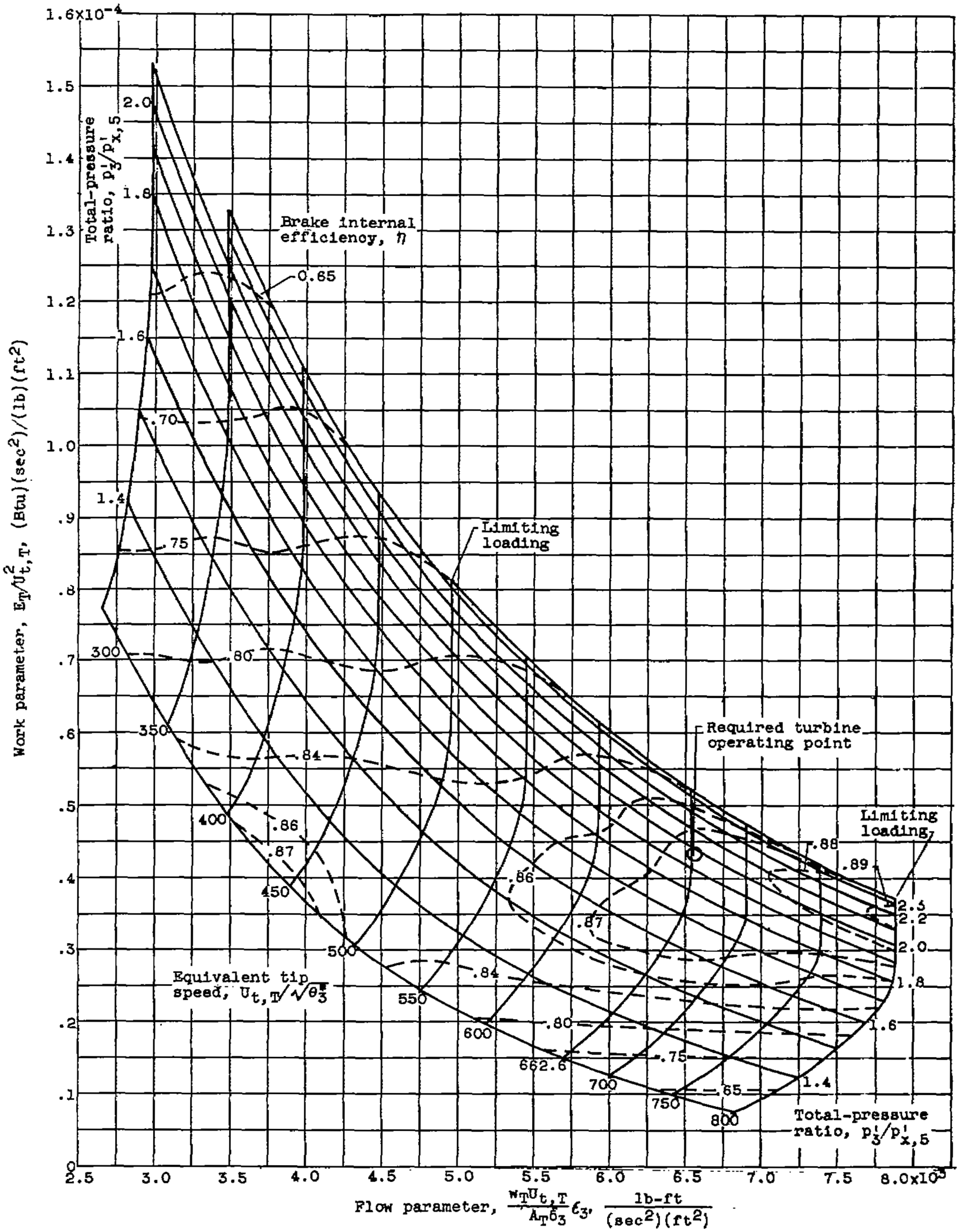


(g) Design stator area with stator blade end clearance.

Figure 5. - Concluded. Over-all performance of scale-model turbine.

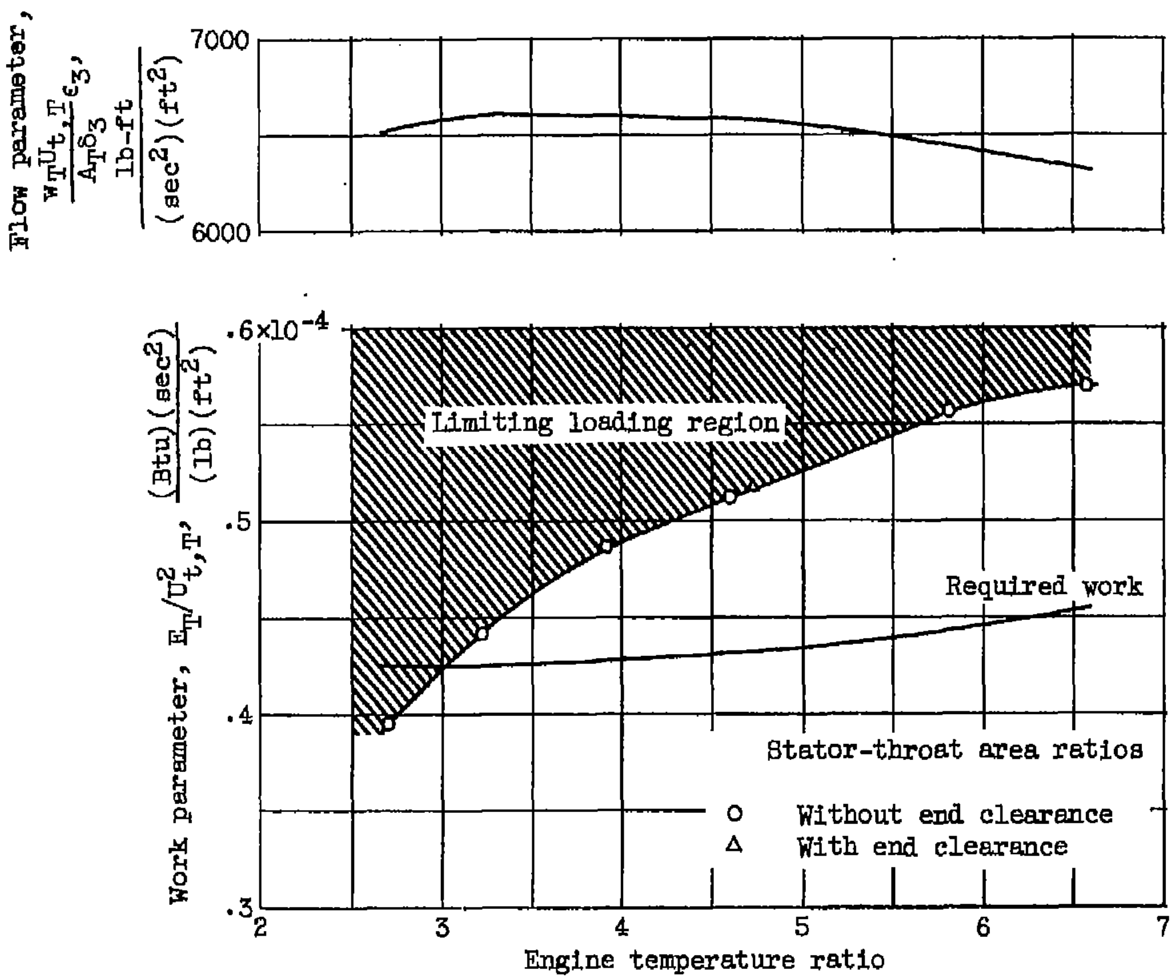


Figure 6. - Variation of flow and work parameters with engine temperature ratio, showing limiting loading region.

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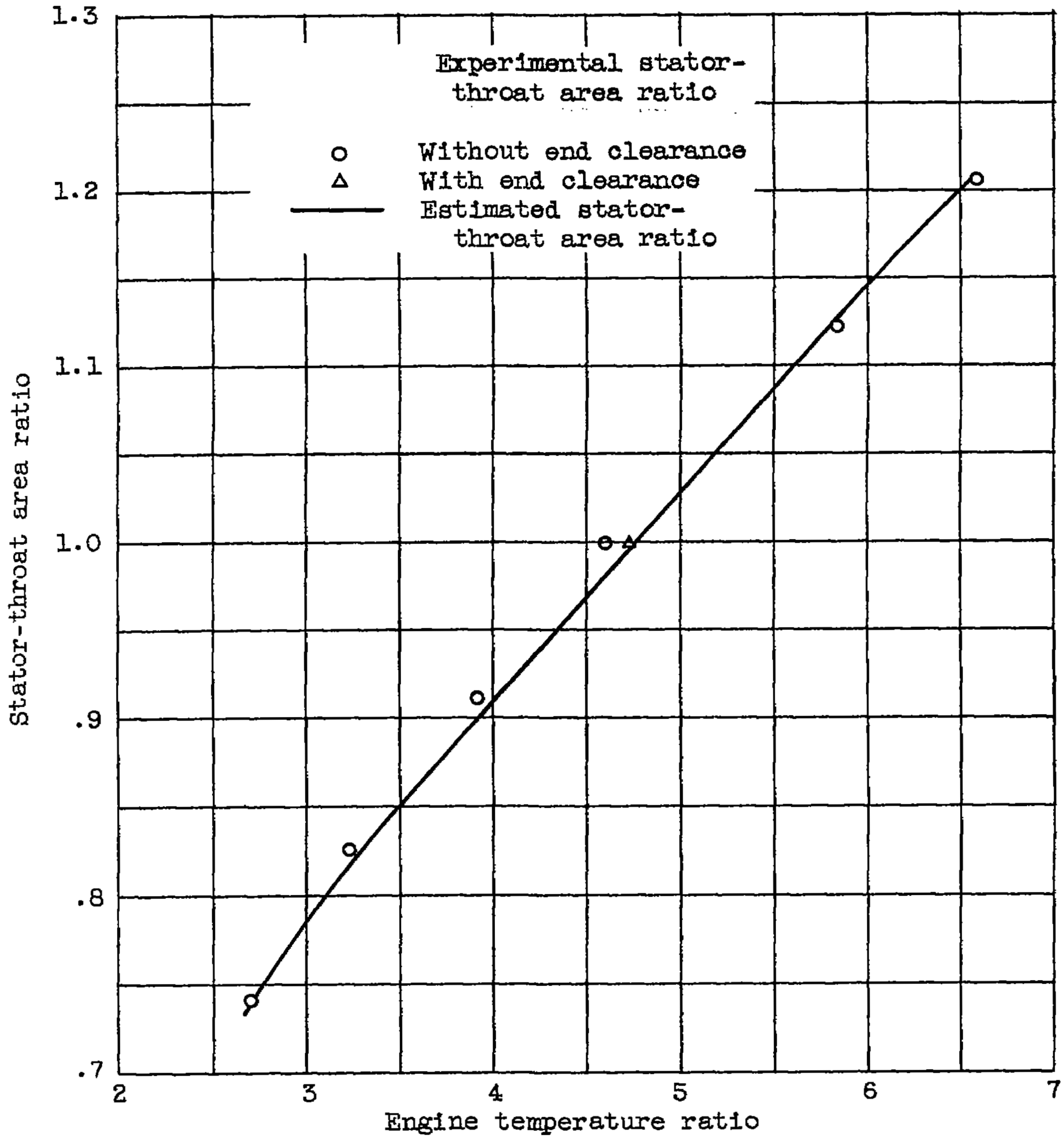


Figure 7. - Comparison of estimated and experimental stator-throat area ratios with engine temperature ratio.

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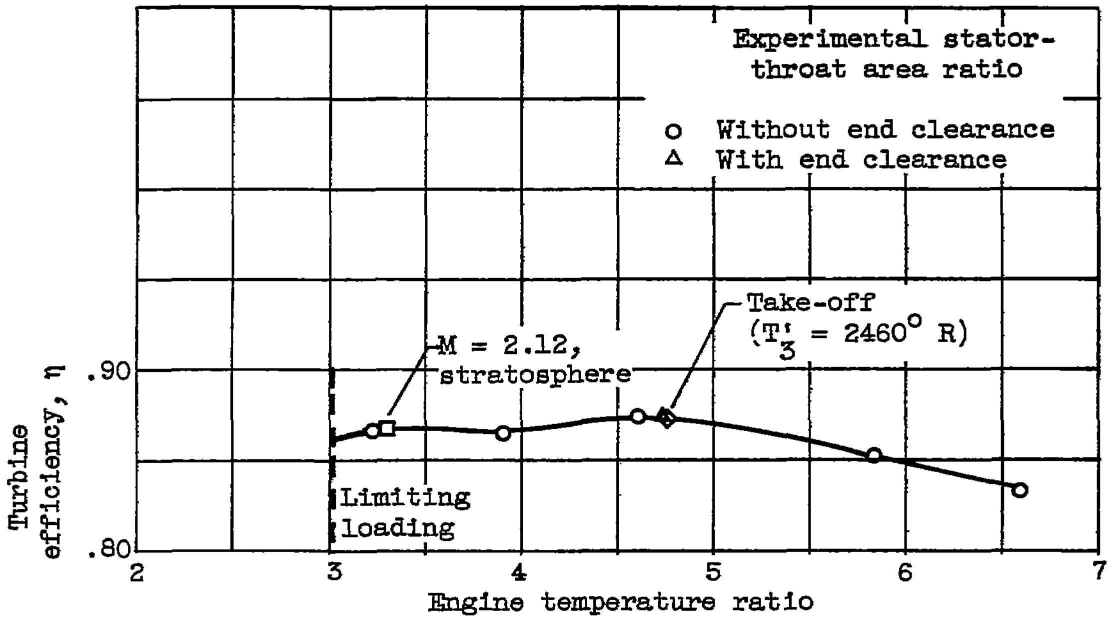


Figure 8. - Variation of turbine efficiency with engine temperature ratio.

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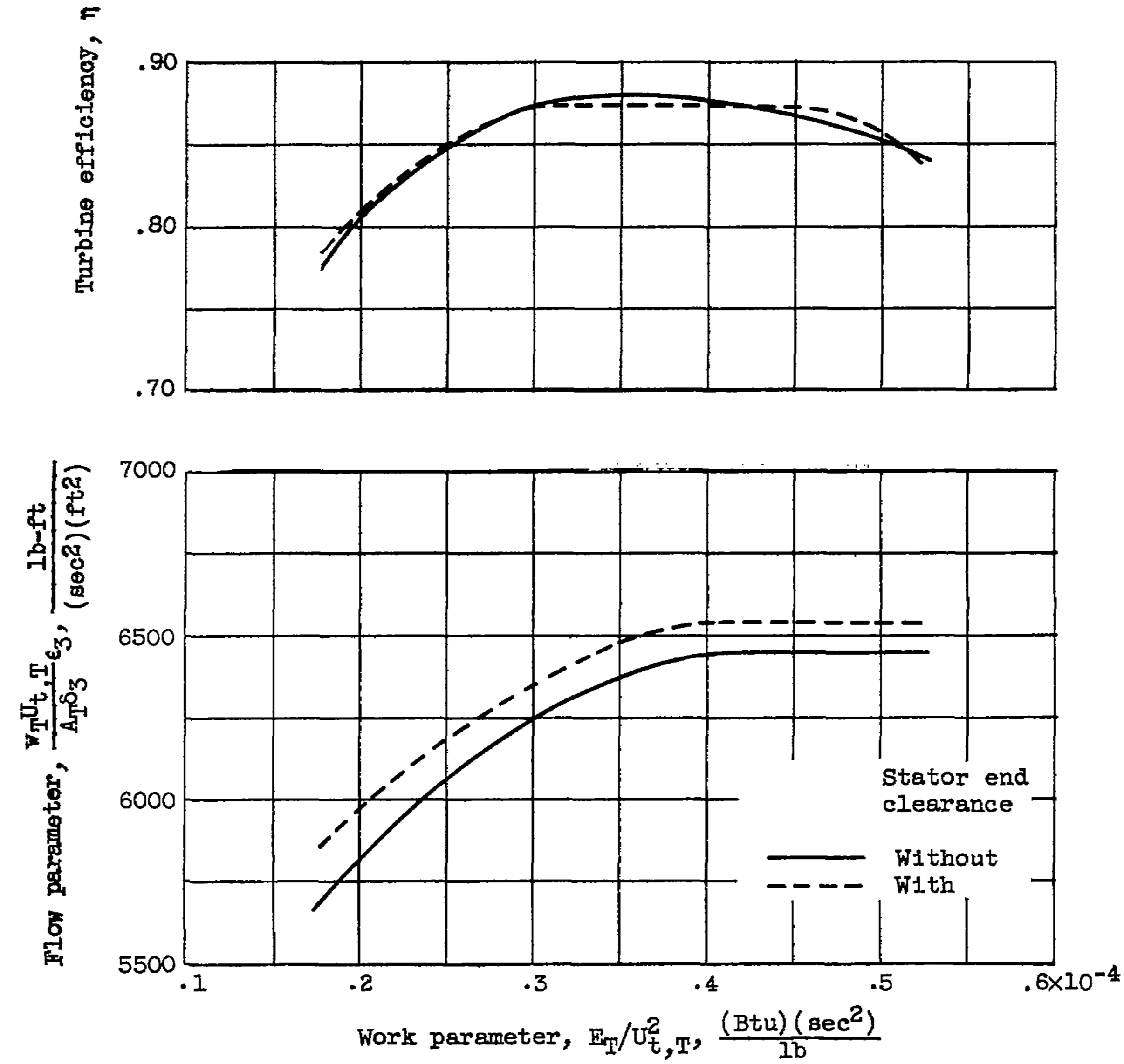


Figure 9. - Comparison of efficiencies and flow parameter with work parameter at design turbine equivalent speed at the design stator area.

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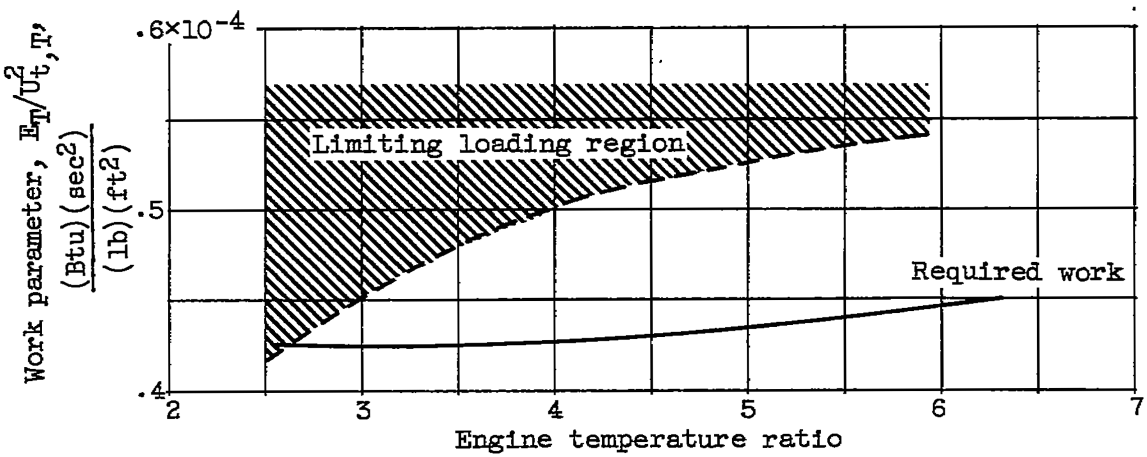


Figure 10. - Variation of predicted limiting work parameter with engine temperature ratio.

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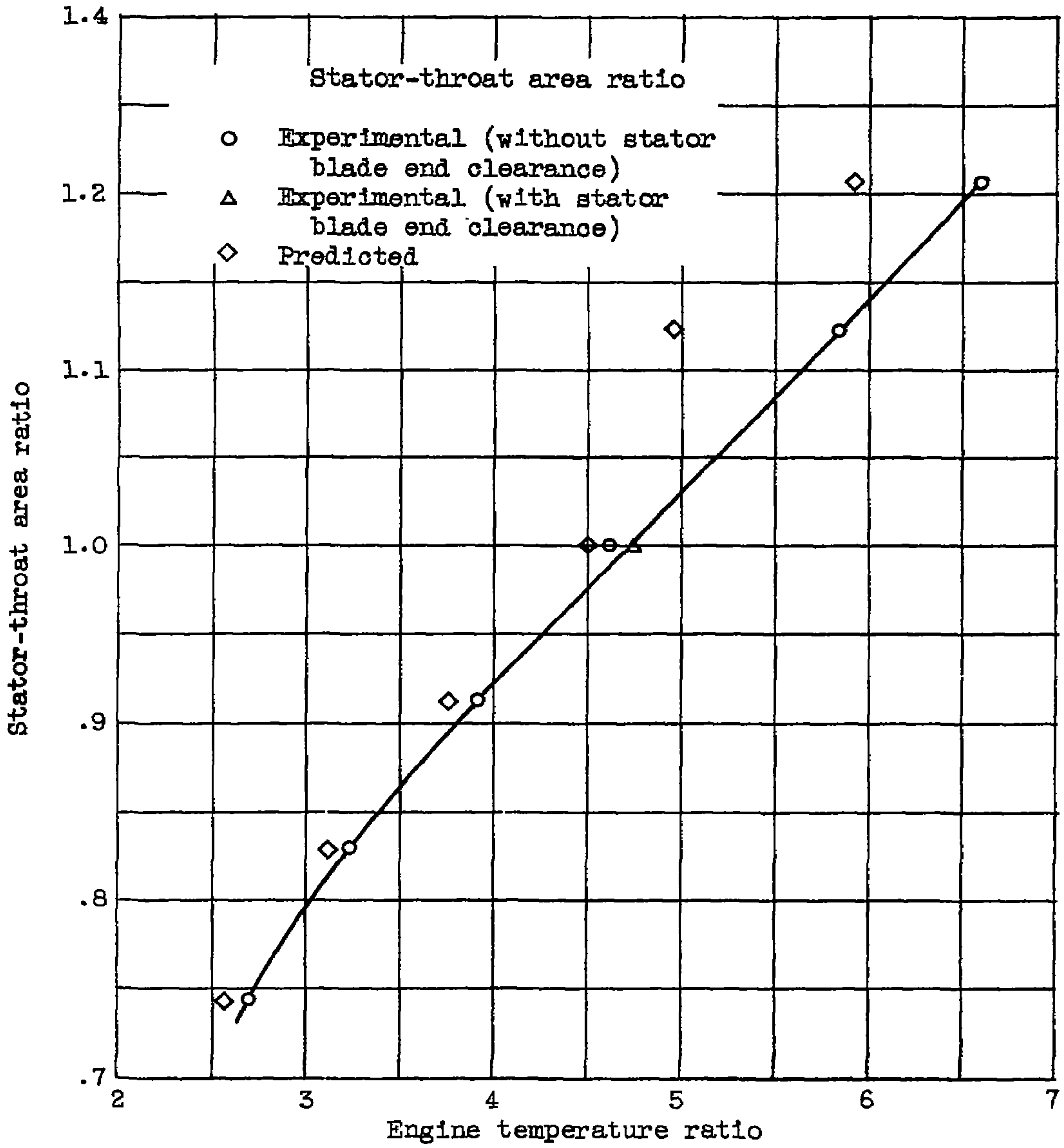


Figure 11. - Variation of predicted stator-throat area ratio with engine temperature ratio compared with experimental values.

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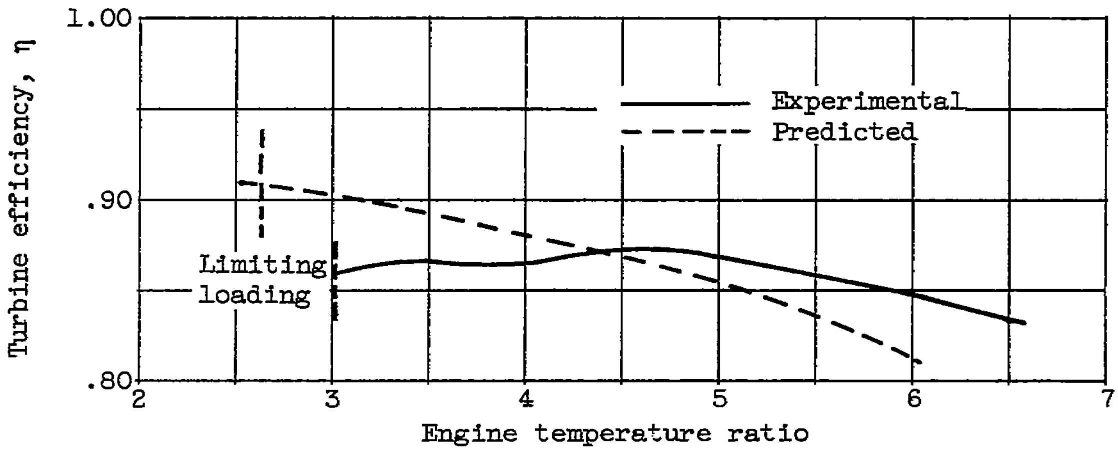


Figure 12. - Comparison of predicted and experimental turbine efficiency variation with engine temperature ratio.

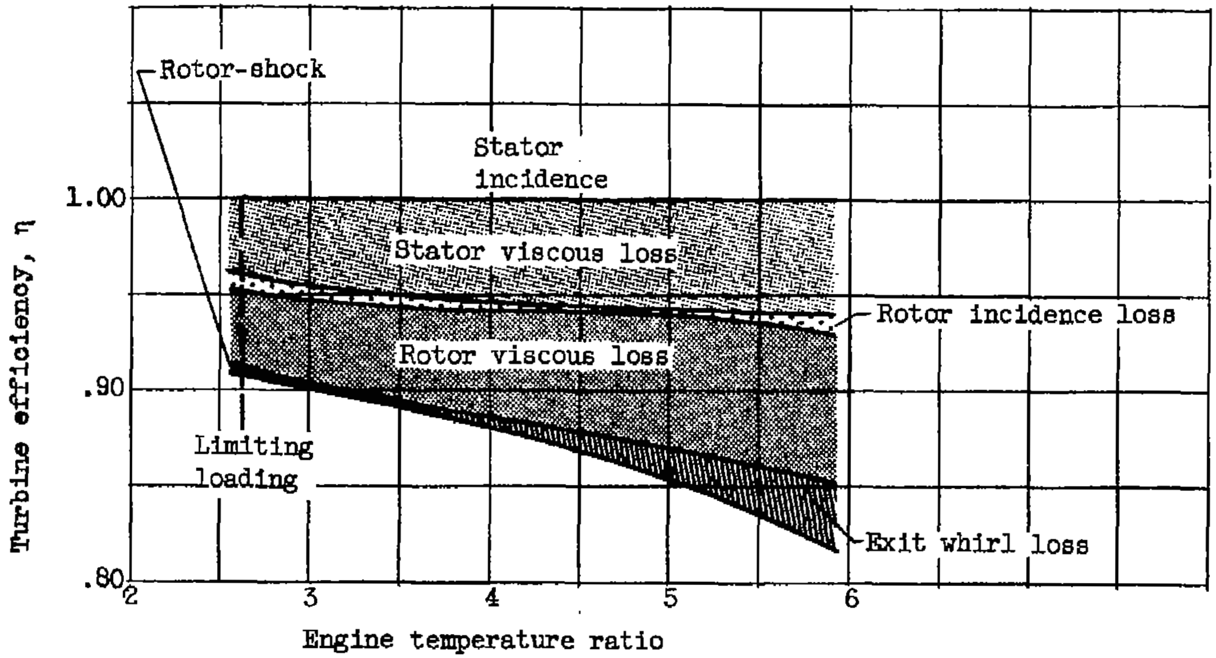


Figure 13. - Effect of losses on predicted turbine efficiency.

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