NACA RM E56H14a

NACA

RESEARCH MEMORANDUM

INVESTIGATION OF TURBINES SUITABLE FOR USE IN A TURBOJET ENGINE WITH HIGH COMPRESSOR PRESSURE RATIO AND LOW COMPRESSOR-TIP SPEED

VII - EXPERIMENTAL PERFORMANCE OF MODIFIED TWO-STAGE TURBINE

By Elmer H. Davison, Donald A. Petrash, and Harold J. Schum

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON

October 29, 1956
Declassified October 28, 1960

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

INVESTIGATION OF TURBINES SUITABLE FOR USE IN A TURBOJET ENGINE WITH HIGH COMPRESSOR PRESSURE RATIO AND LOW COMPRESSOR-TIP SPEED

VII - EXPERIMENTAL PERFORMANCE OF MODIFIED TWO-STAGE TURBINE

By Elmer H. Davison, Donald A. Petrash, and Harold J. Schum

4143

CK-1

SUMMARY

A high-work-output, low-blade-speed, two-stage turbine was experimentally investigated, and the performance of this turbine as designed was rather poor. On the basis of this previous investigation the turbine was modified to obtain better performance by closing down the first-rotor throat area by 10 percent and shrouding the first and second rotors. A general over-all increase in efficiency of approximately 3.5 percentage points was obtained.

At equivalent design work and speed the rating and aerodynamic efficiencies of the modified turbine were 0.825 and 0.846, respectively. The maximum rating and aerodynamic efficiencies obtained were 0.875 and 0.906, respectively. The equivalent weight flows of the original and modified turbines were within 1 percent of the design value.

A radial survey at equivalent design speed and work showed that the underturning at the first-rotor outlet and the flow separation near the tip were eliminated. The efficiencies of both the first and second stages were improved. However, the radial efficiency distribution of the second stage of the modified turbine was quite peaked, with low efficiency occurring at both the hub and tip. The survey indicated that the effective throat areas of both the second stator and rotor were too large, resulting in Mach numbers higher than design behind the first rotor and second stator. The Mach numbers at the outlet of the modified turbine were higher than design, and the radial distributions of Mach number at both the inlet and outlet of the second rotor were considerably different from design.

INTRODUCTION

The design requirements of turbines to drive single-spool, high-pressure-ratio, low-blade-tip-speed compressors are being investigated at the NACA Lewis laboratory. A two-stage turbine designed to satisfy

some of these rather severe design requirements was investigated experimentally, and the results are presented in reference 1. The anticipated performance of this turbine was not achieved. The rating efficiency at equivalent design work and speed was 0.79, whereas the design efficiency was approximately 0.86. Surveys behind the blade rows of this turbine at equivalent design work and speed revealed that: (1) the effective throat area of the first rotor was too large; (2) a region of high loss and severe underturning existed at the tip of the first rotor (a similar but less severe underturning was noted near the tip of the second rotor); and (3) considerable underturning over most of the blade height existed at the second-stator outlet. In addition, large tangential components of velocity were measured at the turbine outlet, which amounted to 2.5 percentage points in turbine efficiency at equivalent design work and speed.

In reference 1 a number of modifications were suggested which might improve the performance of the turbine by approximating the design flow conditions more closely. Some of these modifications (first-rotor throat area reduced, first and second rotors shrouded) were made, and the performance of this modified turbine was obtained. This report presents the over-all performance and design-point survey results obtained for this modified turbine. This investigation, as in reference 1, was conducted at a constant inlet total (stagnation) pressure of 35 inches of mercury absolute and an inlet total temperature of 700° R.

SYMBOLS

E enthalpy drop (based on measured torque), Btu/lb

M Mach number based on local velocity of sound

N rotational speed, rpm

p static pressure, lb/sq ft

p' total (stagnation) pressure, lb/sq ft

p'_x rating total pressure, static pressure plus velocity pressure corresponding to axial component of velocity, lb/sq ft

T' total (stagnation) temperature, °R

w weight flow, lb/sec

$\frac{wN}{60\delta}\varepsilon$ weight-flow parameter based on equivalent weight flow and equivalent rotor speed, (lb)(rev)/sec^2

α absolute flow angle, measured from axial direction (positive in direction of blade rotation), deg

γ ratio of specific heats

δ ratio of inlet total pressure to NACA standard sea-level pressure of 2116 lb/sq ft

ε function of γ, $\dfrac{\gamma_{sl}}{\gamma_e} \dfrac{\left(\dfrac{\gamma_e + 1}{2}\right)^{\frac{\gamma_e}{\gamma_e - 1}}}{\left(\dfrac{\gamma_{sl} + 1}{2}\right)^{\frac{\gamma_{sl}}{\gamma_{sl} - 1}}}$

η aerodynamic efficiency, ratio of actual turbine work (based on torque measurements) to ideal turbine work (based on exit pressure p_5')

η_T aerodynamic efficiency based on measured total temperature

η_x rating efficiency, ratio of actual turbine work (based on torque measurements) to ideal turbine work (based on exit pressure $p_{x,5}'$)

θ_{cr} squared ratio of critical velocity at NACA standard sea-level temperature of 518.7° R

τ torque, ft-lb

Subscripts:

e engine operating conditions

sl NACA standard sea-level conditions

v absolute (relative to turbine casing)

0,1, 2,3, 4,5 instrumentation stations (see fig. 2)

APPARATUS

Test Installation

The experimental setup of the turbine shown in figure 1 was the same as in reference 1. Briefly, some of the main features of this setup are:

4143

CK-1 back

The air weight flow was measured by a submerged A.S.M.E. flange-tap flat-plate orifice and heated by means of two commercial jet-engine burners; the turbine power output was absorbed by two 5000-horsepower dynamometers connected in tandem; and the turbine torque output was measured by means of an NACA balanced-diaphragm thrustmeter.

Instrumentation

With the exception of the survey probes the instrumentation was the same as in reference 1. The instrumentation stations and the measurements taken at these stations are shown in figure 2.

For the survey, the probe shown in figure 3(a) was used to obtain the radial variations of total (stagnation) pressure, total temperature, and flow angle. The probe had a spike-type thermocouple installed just above the total-pressure and angle measuring tubes. This permitted nearly point values of total pressure, total temperature, and flow angle to be measured simultaneously. These probes were later replaced with static-pressure wedges (fig. 3(b)) in order to obtain the radial static-pressure variations.

Turbine

The two-stage turbine was designed for the following conditions:

	Turbine design conditions	Turbine equivalent design conditions
Work, Btu/lb	131	32.25
Weight flow, lb/sec	158	39.65
Rotative speed, rpm	6100	3027
Inlet temperature, $^{\circ}R$	2160	518.7
Inlet pressure, in. Hg abs	248.3	29.92

A schematic diagram of the geometry employed in the turbine is shown in figure 2.

METHODS AND PROCEDURE

The turbine was operated with a measured inlet pressure p_0' of approximately 35 inches of mercury absolute and an inlet temperature T_0' of 700° R for equivalent rotative speeds of 20, 40, 60, 70, 80, 90, 100, 110, 120, and 130 percent of the design value. A range of rating pressure ratio $p_1'/p_{x,5}'$ from 1.4 to 4.0 was investigated.

The method used to convert turbine test conditions to equivalent operating conditions based on NACA standard sea-level conditions is the same as used in reference 1 and is described in reference 2. The equivalent work output and brake internal efficiency for the over-all performance are based on measured torque values.

The over-all turbine performance rating based on the calculated outlet pressure $p'_{x,5}$ charges the turbine for the energy of the tangential component of outlet velocity. The methods used to calculate the outlet pressure $p'_{x,5}$ and inlet pressure p'_1 are the same as in reference 1. The outlet pressure p'_5 was obtained by arithmetically averaging the readings obtained from the five shielded total-pressure probes at station 5. The methods of handling and correcting the other measurements are also the same as in reference 1 except for the static-pressure wedges. As a substitution for a Mach number correction, the radial distributions obtained from the wedges were shifted such that the wedge values near the hub agreed with those obtained from the hub wall static taps shown in figure 2.

4143

TURBINE MODIFICATIONS

The previous investigation (ref. 1) revealed that both the first stator and rotor were choked at equivalent design work and speed. With the first stator and rotor choked, an estimate of the required reduction in rotor throat area can be made, if the actual and desired tangential components of velocity at the entrance to the first rotor are known. (The characteristics of successively choked blade rows are discussed in detail in ref. 3.) The desired tangential velocity was obtained from the design velocity diagrams, and an estimate of the actual tangential velocity obtained in reference 1 was made from the survey data. On the basis of the difference between these two tangential velocities, it was estimated that the rotor throat area would have to be reduced by 10 percent in order to get the desired entrance tangential velocity. Because there should be a decrease in the total-pressure loss to the rotor throat as a result of the improved flow conditions, it is difficult to calculate exactly the required rotor-throat-area reduction. The 10-percent decrease in rotor throat area was obtained by changing the stagger angle of the blade profiles used in reference 1.

In addition to the throat-area modification, the first rotor was shrouded by shrinking a steel band over the blade tips. This band did not reduce the annular flow area of the rotor blades, since it was contained within the recess of the outer shroud as shown in figure 2. However, it probably did reduce the effective rotor throat area to some extent, but the actual reduction was difficult to estimate. It was assumed

that a reduction in the effective throat area slightly greater than that required to obtain design conditions would be more desirable than the reverse situation. Too small an area would result in greater reaction across the blade row and possibly improve the underturned tip flow observed previously (ref. 1). The shroud itself was also to improve the tip flow of the rotor, although there was no solid foundation for believing that this would be done.

Because the survey data were not too detailed or extensive, it was difficult to determine with any degree of accuracy the modifications required of the second stator and rotor in order to more nearly obtain the design flow conditions. In addition, the modifications required of the second stator and rotor would be influenced by the flow changes resulting from the first-rotor modifications. Modification of the second stator would probably also require a redesign of the blade profiles, which, because of the effort involved, was not considered expedient until better first-stage performance could be demonstrated. For this investigation, therefore, neither the profiles nor the stagger angles of the second stator and rotor were modified. The second-stage rotor, however, was shrouded in the same manner as the first rotor in an effort to improve its tip performance.

4143

RESULTS AND DISCUSSION

Over-All Performance

The over-all performance of the turbine rated on the same basis as in reference 1 is presented in figure 4(a), where equivalent work is plotted against the flow parameter $\frac{wN}{60\delta}\varepsilon$ for constant values of equivalent speed and rating pressure ratio $p_1'/p_{x,5}'$. In addition, contours of constant brake internal efficiency based on $p_1'/p_{x,5}'$ are shown.

At equivalent design work and speed, an efficiency of 0.825 was obtained at a rating pressure ratio of 3.74. This efficiency is 3.5 percentage points higher than previously obtained in reference 1. The maximum efficiency obtained was 0.875 occurring at 130 percent of equivalent design speed and a work output of 34.5 Btu per pound, corresponding to a rating pressure ratio of 3.8. This maximum efficiency is also 3.5 percentage points higher than previously obtained in reference 1. The gross effect then of the modifications to the turbine was to raise the general level of the turbine efficiency based on $p_1'/p_{x,5}'$ by approximately 3.5 percentage points.

When evaluating a turbine as part of a jet engine, the turbine efficiency based on $p_1'/p_{x,5}'$ is of the most interest, because this efficiency charges the turbine with the energy of the tangential velocity

leaving the turbine. Rating the turbine on the over-all pressure ratio p_1'/p_5', however, evaluates the turbine on the basis of its aerodynamic performance without regard to its application. The difference between these two ratings is then a measure of the energy of the tangential velocity leaving the turbine. In order to present a more complete evaluation of the turbine performance, therefore, a performance map with the efficiencies of the turbine based on the pressure ratio p_1'/p_5' is presented in figure 4(b). This figure is the same as figure 4(a) except that lines of p_1'/p_5' rather than $p_1'/p_{x,5}'$ are shown, and the efficiencies presented are based on p_1'/p_5'.

4143

At equivalent design work and speed, an efficiency of 0.846 is now obtained at a p_1'/p_5' of 3.6 (fig. 4(b)). This efficiency is 2 percentage points higher than the efficiency based on $p_1'/p_{x,5}'$. The maximum efficiency is now 0.906 occurring at 130 percent of equivalent design speed and a work output of 35.8 Btu per pound, corresponding to a pressure ratio p_1'/p_5' of 3.8. This efficiency is 3 percentage points higher than the previous maximum efficiency based on $p_1'/p_{x,5}'$ and occurs at a higher work output. The differences in the efficiency based on p_1'/p_5' and $p_1'/p_{x,5}'$ show that the tangential velocities at the turbine outlet are considerably higher than design.

The variation of equivalent weight flow with rating pressure ratio for the equivalent speeds investigated is shown in figure 5(a). The value for equivalent design weight flow is indicated on the weight-flow ordinate. At equivalent design speed and the rating pressure ratio (3.74) corresponding to equivalent design work, the turbine weight flow was 0.6 percent greater than the design weight flow. The weight flow at equivalent design work and speed for the original turbine (ref. 1) was about 1 percent greater than the design weight flow.

In addition to this slight reduction in weight flow, the choking characteristics of the turbine have been changed by the modifications. Previously, the choking weight flow, indicated when the curves have a zero slope, was the same for all speeds, showing that the first stator choked prior to any other blade row and controlled the weight flow passed by the turbine. From figure 5(a) it is seen for the modified turbine that the choking equivalent weight flow decreases with an increase in speed above the design speed. This shows that above design speed some blade row downstream of the first stator chokes initially and limits the weight flow. More details on the choking characteristics of the turbine are given in the next section.

The variation of equivalent torque with rating pressure ratio for the equivalent speeds investigated is shown in figure 5(b). Pressure ratios across the turbine great enough to achieve limiting-loading were not obtainable. Limiting-loading is defined, for any given speed, as the point at which a further increase in pressure ratio does not produce an increase in torque.

4143

Axial Static-Pressure Distribution

The static-pressure distributions at the hubs of the blades plotted against $p_1'/p_{x,5}'$ for 100 and 130 percent equivalent design speed are shown in figure 6. The static pressure at each station has been divided by the inlet total pressure in order to minimize the effect of the small fluctuations in inlet total pressure encountered while testing the turbine.

Figure 6 aids in determining the order of choking in the individual blade rows. Choking in a blade row is indicated when the static pressure at the entrance remains constant, while the static pressure at the exit decreases as the over-all total-pressure ratio is increased. Based on this criterion, figure 6(a) for equivalent design speed shows that the blade rows choke successively starting with the first rotor as the over-all pressure ratio increases. The weight-flow curves presented previously in figure 5(a) indicated that the first stator choked initially at this speed, but this is difficult to verify from figure 6(a), because the change in slope from negative to zero at station 1, indicating that the first stator chokes, is not very pronounced. The decrease in flow area between the entrance of the first stator and its throat is large. Consequently, the Mach number and static-pressure changes at the entrance to the stator are small, making this static-pressure variation a poor criterion of choking in this blade row. It is also interesting to note from figure 6(a) that the reaction across the second stator, indicated by the static-pressure difference between stations 3 and 4, is very small over most of the range of over-all pressure ratio $p_1'/p_{x,5}'$ and is even negative for over-all pressure ratios from 2.8 to 3.4.

The weight-flow curves presented previously in figure 5(a) showed that some blade row downstream of the first stator chokes initially for equivalent speeds greater than design (i.e., the first stator does not choke). In order to show the choking characteristics in this range of speed, the static-pressure distributions at 130 percent of equivalent design speed have been presented in figure 6(b). Using the same choking criterion as before, it is seen that the blade rows choke successively starting with the first rotor as the over-all pressure ratio increases. It can also be noted that the reaction across the second stator (between stations 3 and 4) has been increased.

The axial static-pressure distribution through the turbine at equivalent design speed and work is compared in figure 7 with the design distribution and the distribution obtained previously (ref. 1). This figure shows that the static-pressure distribution for the modified turbine is much closer to the design distribution than that for the original turbine. The reaction across the first rotor is now a little greater than design, but the reaction across the second stator is less than design. The static pressure at the exit of the turbine again had to be lowered to less than the design value in order to obtain the design work, but the reduction was not as great.

4143

Design-Point Survey

As previously mentioned, the over-all increase in efficiency resulting from the turbine modifications was approximately 3.5 percentage points of efficiency. Some of the internal-flow conditions of this modified turbine, which help to explain this improved performance, are shown in figures 8 to 11. These results are compared with the design values and, where possible, to those obtained with the original version of the turbine (ref. 1). Both the original and modified turbine surveys were made at equivalent design work and speed.

CK-2

The radial distributions of absolute flow angle obtained are shown in figure 8 with the design distributions and those previously obtained. Figure 8 shows that the greatest change in flow angle, as expected, occurred at the first-rotor outlet (station 3). Flow angles more negative than design are now obtained at the first-rotor outlet, and the severe defect near the tip has been practically eliminated. The underturning at the second-stator outlet (station 4) still exists. At the exit of the turbine (second-rotor outlet, station 5), the turning is less than previous over most of the blade height but still greater than design. The flow is more nearly axial as a result of the increased efficiency at equivalent design work and speed.

The radial variations in temperature drop between stations 1 and 3 (first stage), stations 3 and 5 (second stage), and stations 1 and 5 (over-all) are shown in figure 9. The effect of the improvement in flow-angle distribution behind the first rotor noted in figure 8 is reflected in an improved work distribution for the first stage. From figure 9 it can be seen that the drop in work output near the tip of the first stage is less severe than in the original version. The distribution for the second stage has also been changed, but whether or not it is an improvement is difficult to determine. The over-all distribution is better and reflects the improvement made in the first-stage distribution. The temperature differences shown were obtained from the rakes previously described. It was considered more valid to compare these distributions with those obtained with the original turbine (ref. 1), because the original temperature distributions were also obtained with the same rakes.

Even using the same rakes for comparison purposes, however, may give slightly erroneous results, since the internal-flow patterns have been changed by the turbine modifications. In addition, as a result of the circumferential variations and because precise interstage measurements cannot be obtained, the survey results can only be used as a general indication of performance changes. For example, an error of only 1° in the temperatures at stations 3 and 5 can result in as much as a 4-percentage-point difference in efficiency for the second stage, because the temperature drop across this stage is quite small. The distributions obtained with the probes shown in figure 3(a) were much the same as those obtained with the rakes, but the levels were different. The probes indicated a higher level of work output in the first stage than did the rakes and, consequently, a lower level in the second stage.

4143

The radial variations in the stage and over-all efficiencies are shown in figure 10. The region of very poor performance near the tip of the first stage has been eliminated. It can also be seen that, in general, the level of the second-stage efficiency is higher than the original. The improved flow angles into the second stator probably played a major role in this improvement. The distribution of the second-stage efficiency is quite peaked for the modified turbine, whereas the original was approximately constant over a good portion of the radial length. The over-all efficiency was higher over the entire radial length with the largest improvement in the tip region again reflecting the improvement made in the first-stage tip flow. It might be well to point out at this point that the effect the shrouds played in improving the flow conditions cannot be determined from these survey results.

The radial variations of the absolute Mach number at the various measuring stations are shown in figure 11. Values for the original turbine are not presented, because the static-pressure measurements needed for calculating the Mach number were not obtained in the survey of the original turbine. It should also be pointed out that the Mach numbers shown in figure 11 may be somewhat in error, because an approximate Mach number correction was applied to the static-pressure measurements obtained from the probes for the modified turbine. The total-pressure probes also probably did not read truly representative total pressures at the outlets of the blade rows. However, the Mach numbers shown in figure 11 represent the best estimate possible at present of the radial Mach number distributions in the turbine and are considered fairly representative. They indicate that the average Mach number at station 2 is at approximately the design value, but that the radial distribution is slightly different than design. The Mach numbers at stations 3 and 4 are higher than design, indicating that the effective throat areas of both the second stator and rotor are too large. In reference 1 this was anticipated, and no attempt was made in modifying the turbine to correct for it. The reason for not modifying these last two blade rows was discussed previously. It can also be seen from figure 11 that the distribution at

station 4 is quite different from the design distribution, and, as a result, more positive reaction exists across the second stator over most of the blade height than was indicated by the static-pressure distributions shown in figure 7. The Mach numbers at station 5 were, of course, higher than design in order to obtain the design work at a rating efficiency less than design. The radial distribution of Mach number at station 5 is also considerably different from design.

4143

SUMMARY OF RESULTS

A high-work-output, low-blade-speed, two-stage turbine was experimentally investigated. The performance of this turbine as designed was rather poor and has been investigated previously. The performance of a modified version of this turbine is presented herein and compared to that of the original version. The pertinent results are as follows:

CK-2 back

1. Closing down the first-rotor throat area by 10 percent and shrouding the first and second rotors resulted in a general over-all increase in efficiency of approximately 3.5 percentage points.

2. At equivalent design work and speed, the rating efficiency of the modified turbine was 0.825, and the aerodynamic efficiency was 0.846. The maximum rating and aerodynamic efficiencies obtained were 0.875 and 0.906, respectively.

3. The equivalent weight flows of both the original and modified turbines were within 1 percent of the design value.

4. The choking characteristics of the turbine were changed slightly by the modifications. In the original turbine the first stator choked initially at all speeds investigated. The modified turbine choked initially in the first stator below equivalent design speed and in the first rotor above equivalent design speed. In general, the other blade rows choked successively after the initial choking as the over-all pressure ratio was increased.

5. The axial static-pressure distribution through the turbine was much closer to design for the modified turbine than for the original turbine.

The pertinent results noted from the radial surveys made behind blade rows at equivalent design work and speed are as follows:

1. The underturning at the outlet of the first rotor and the flow separation near the tip were eliminated by closing down and shrouding this blade row. The efficiency of the first stage was improved by this modification.

2. A general improvement of the second-stage efficiency also occurred. The radial efficiency distribution for the second stage of the modified turbine was, however, quite peaked with low efficiency occurring at both the hub and tip.

3. The Mach numbers at the outlets of the first rotor and second stator were considerably higher than design for the modified turbine indicating that the effective throat areas of both the second stator and rotor were too large.

4. The Mach numbers at the outlet of the modified turbine were higher than design in order to obtain the design work at a rating efficiency less than design.

5. The radial distributions of Mach number at both the inlet and outlet of the second rotor of the modified turbine were considerably different than design.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 15, 1956

4143

REFERENCES

1. Davison, Elmer H., Schum, Harold J., and Petrash, Donald A.: Investigation of Turbines Suitable for Use in a Turbojet Engine with High Compressor Pressure Ratio and Low Compressor-Tip Speed. VI - Experimental Performance of Two-Stage Turbine. NACA RM E56E04, 1956.

2. Rebeske, John J., Jr., Berkey, William E., and Forrette, Robert E.: Over-All Performance of J35-A-23 Two-Stage Turbine. NACA RM E51E22, 1951.

3. English, Robert E., and Cavicchi, Richard H.: One-Dimensional Analysis of Choked-Flow Turbines. NACA Rep. 1127, 1953. (Supersedes NACA TN 2810.)

4143

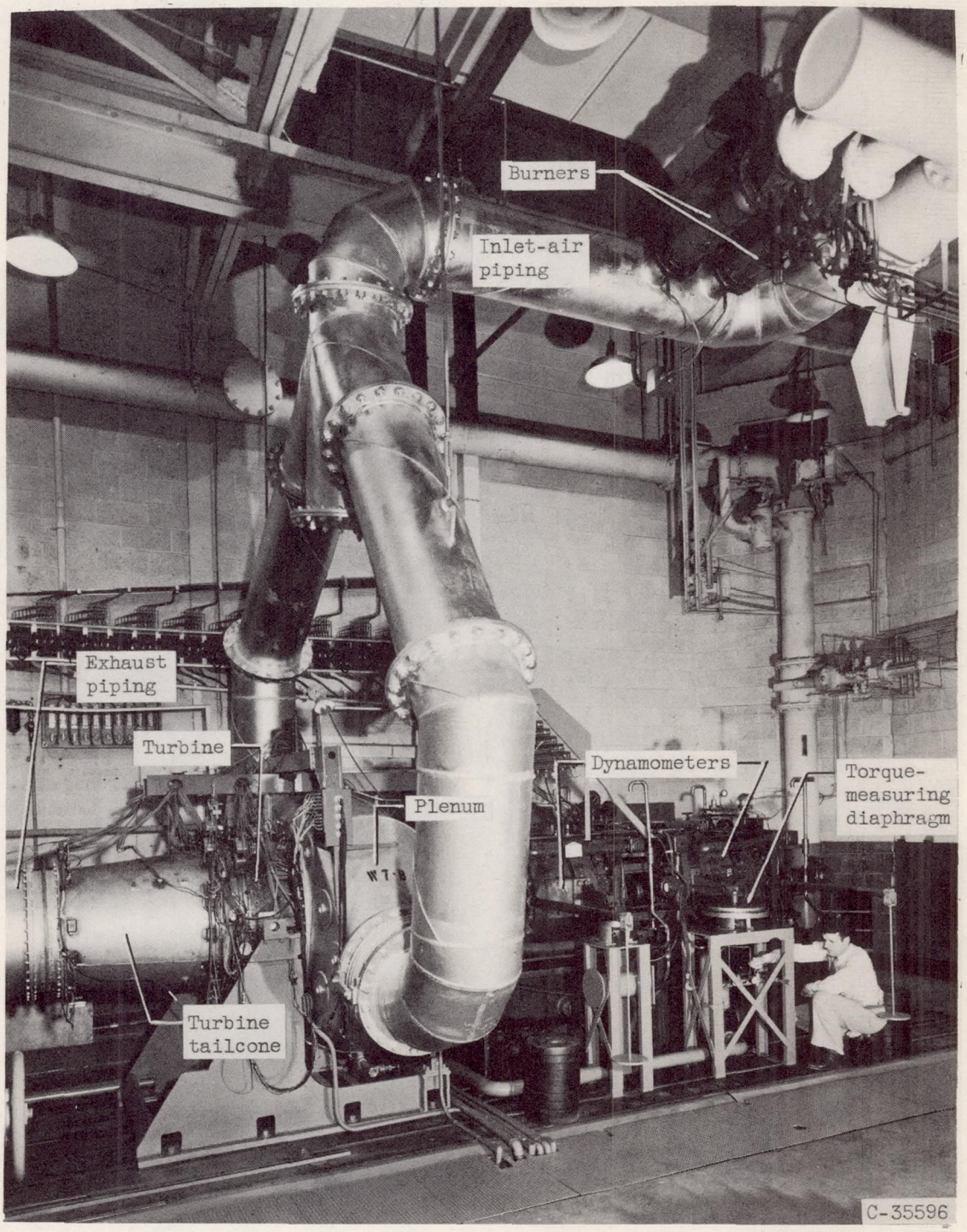


Figure 1. - Installation of turbine in full-scale turbine-component test facility.

4143

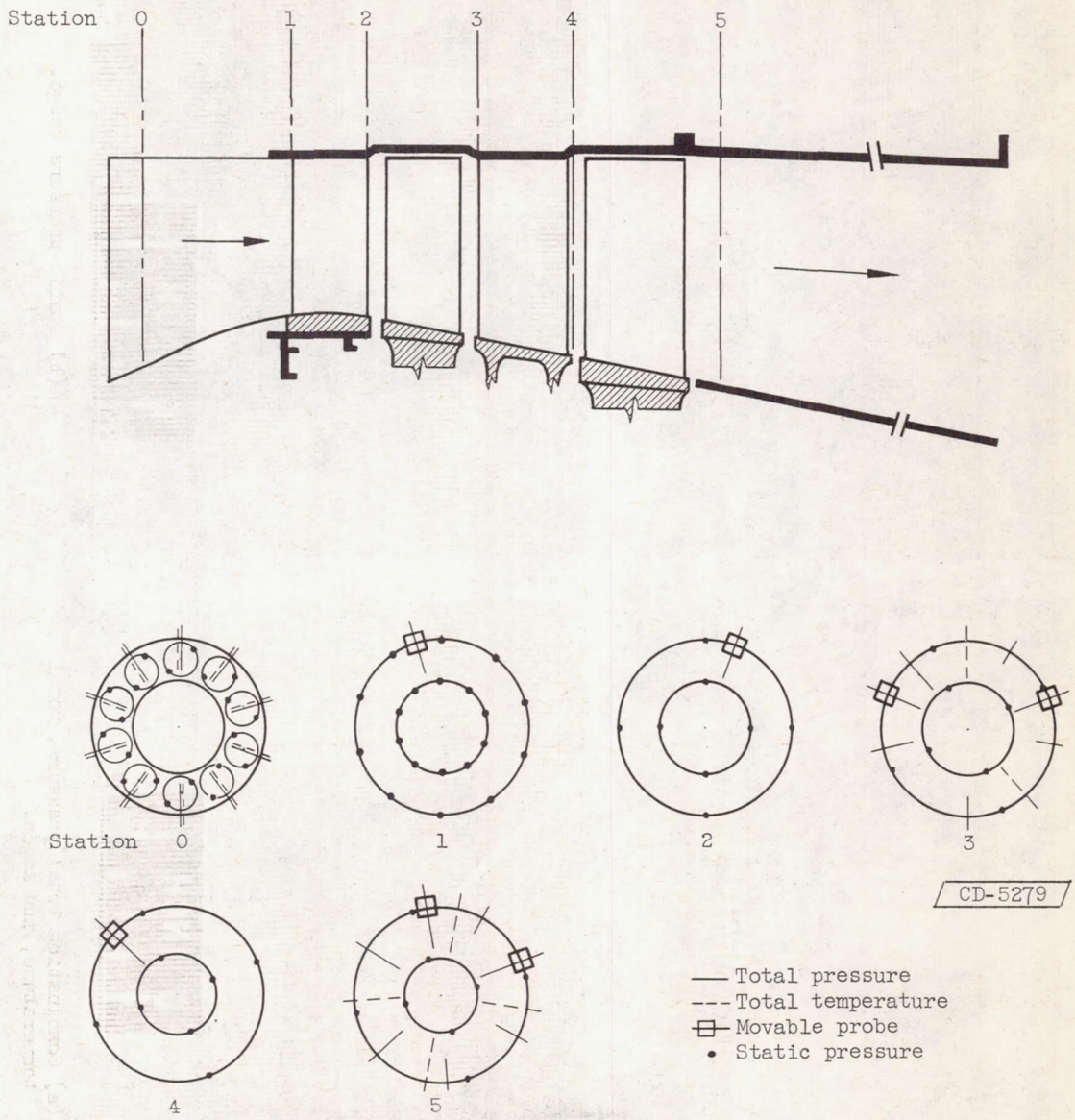
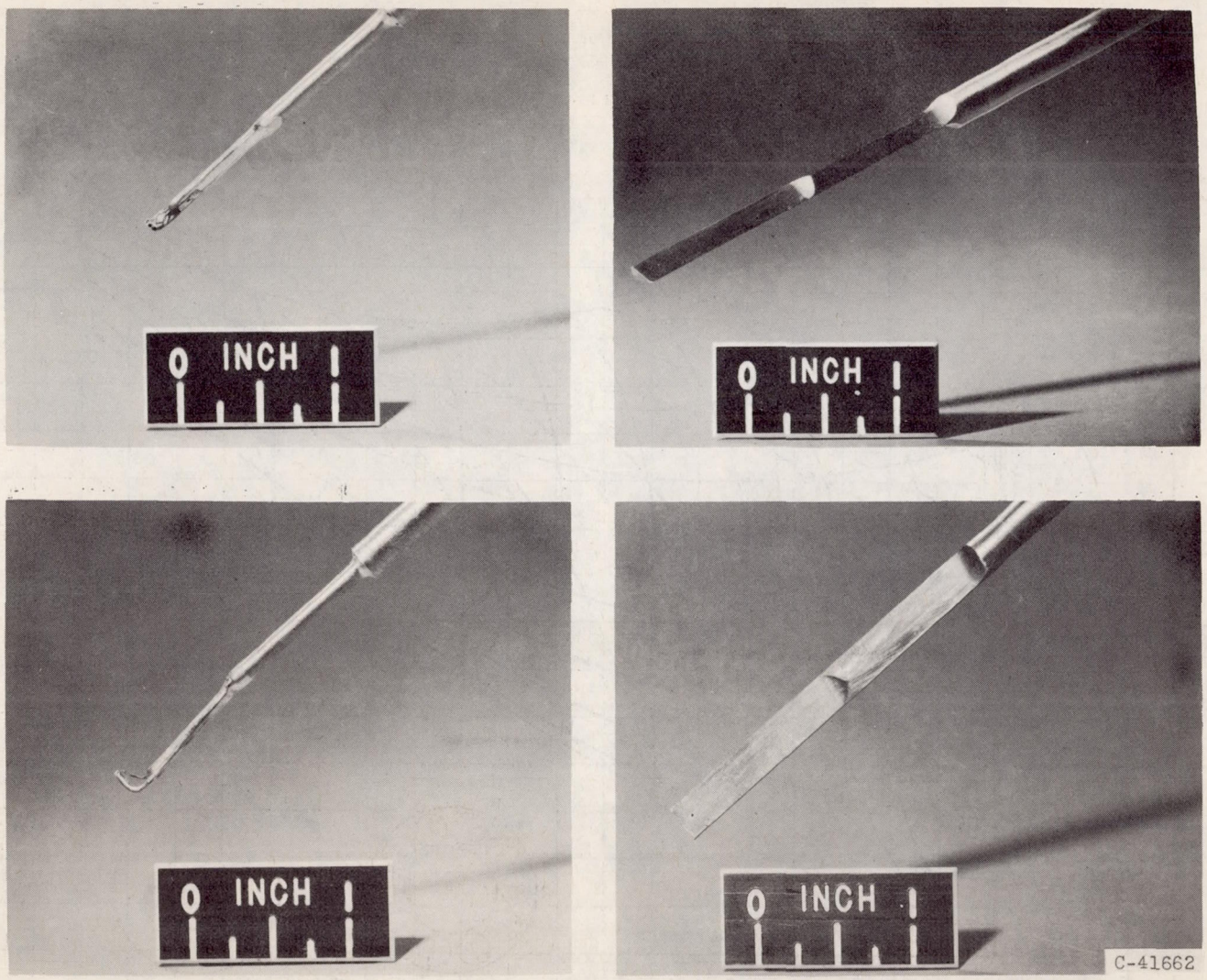


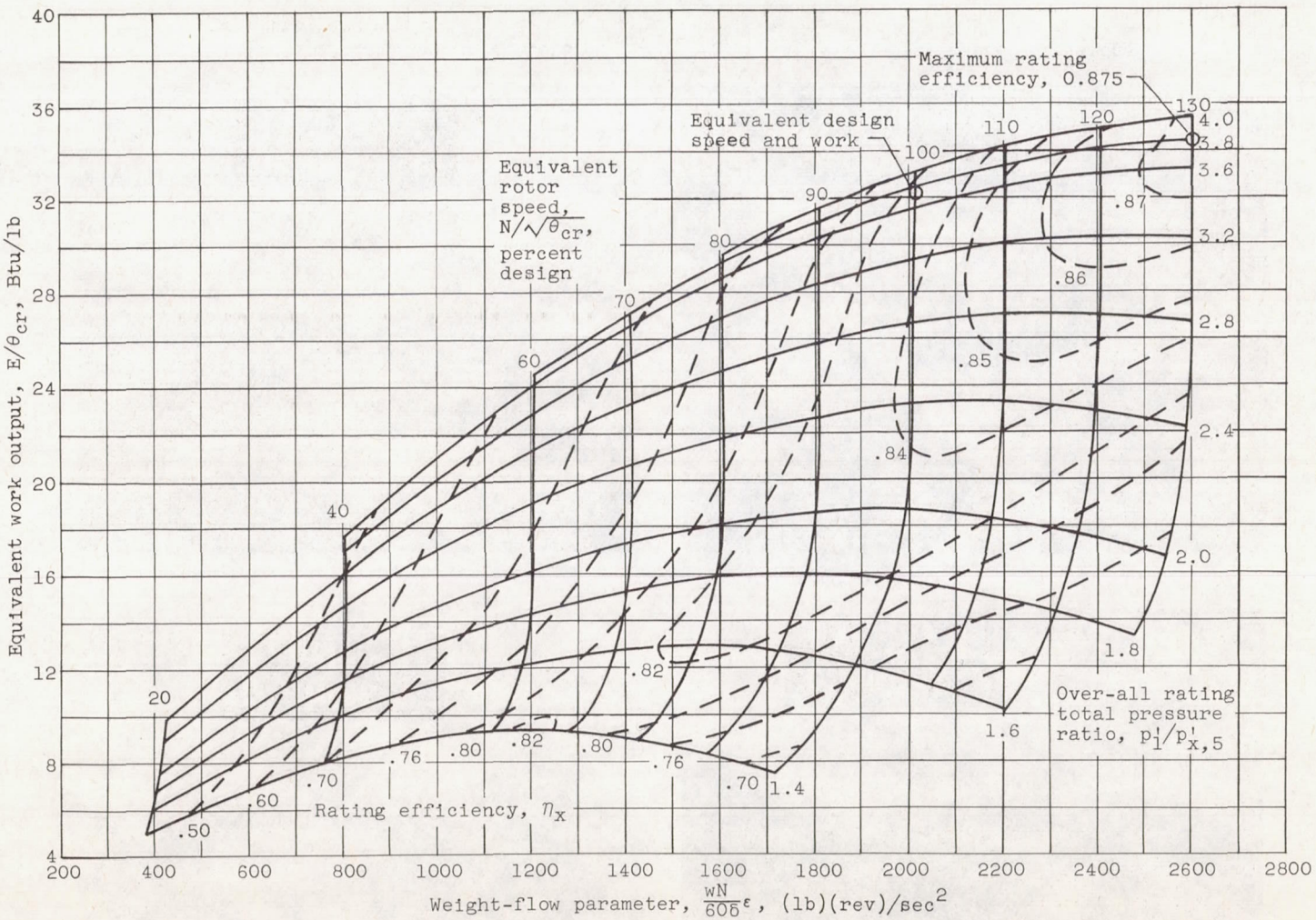
Figure 2. - Schematic diagram of turbine showing instrumentation.



(a) Combination total pressure, total temperature, and angle.

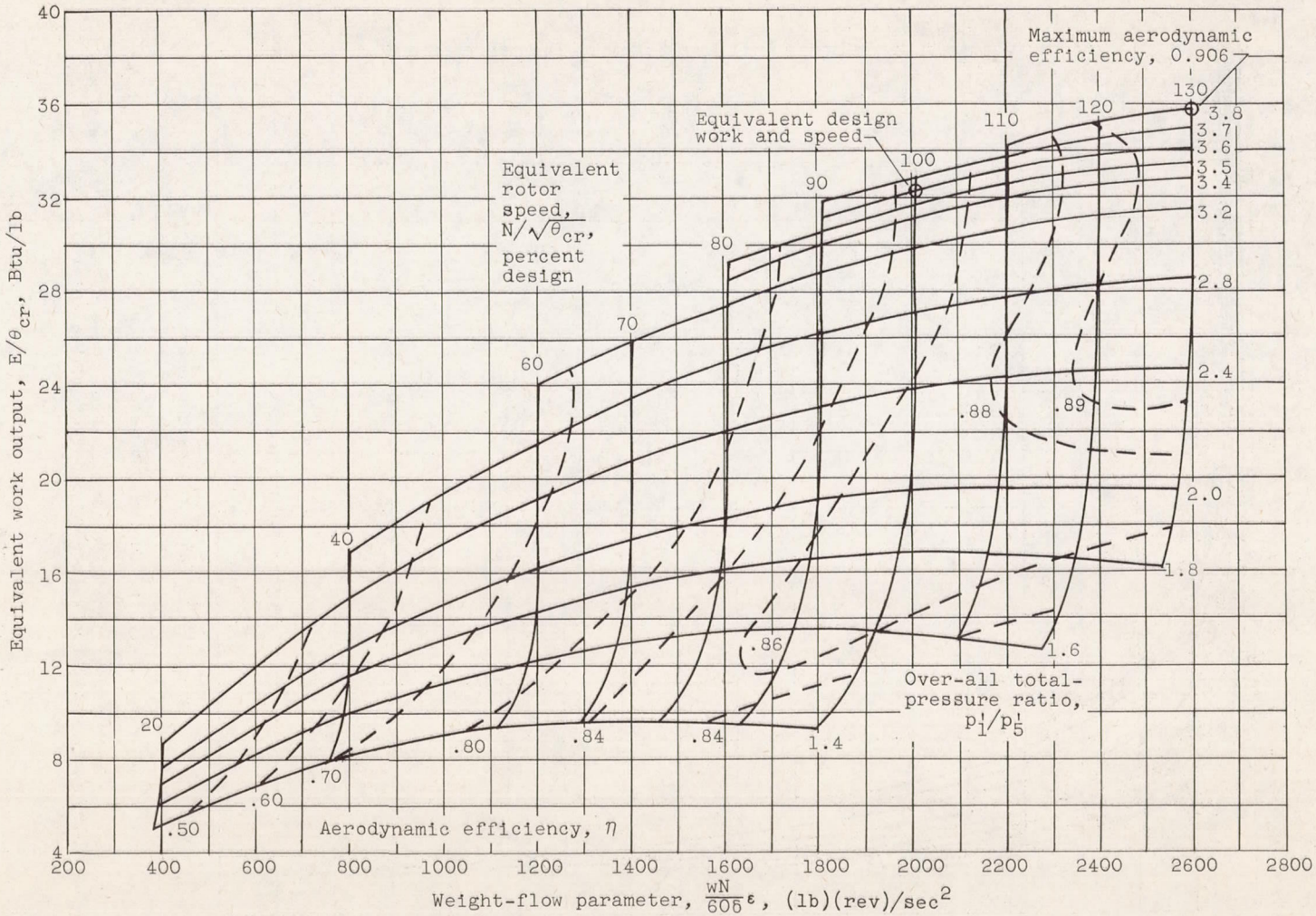
(b) Static-pressure wedge.

Figure 3. - Survey instruments.



(a) Rating efficiency basis.

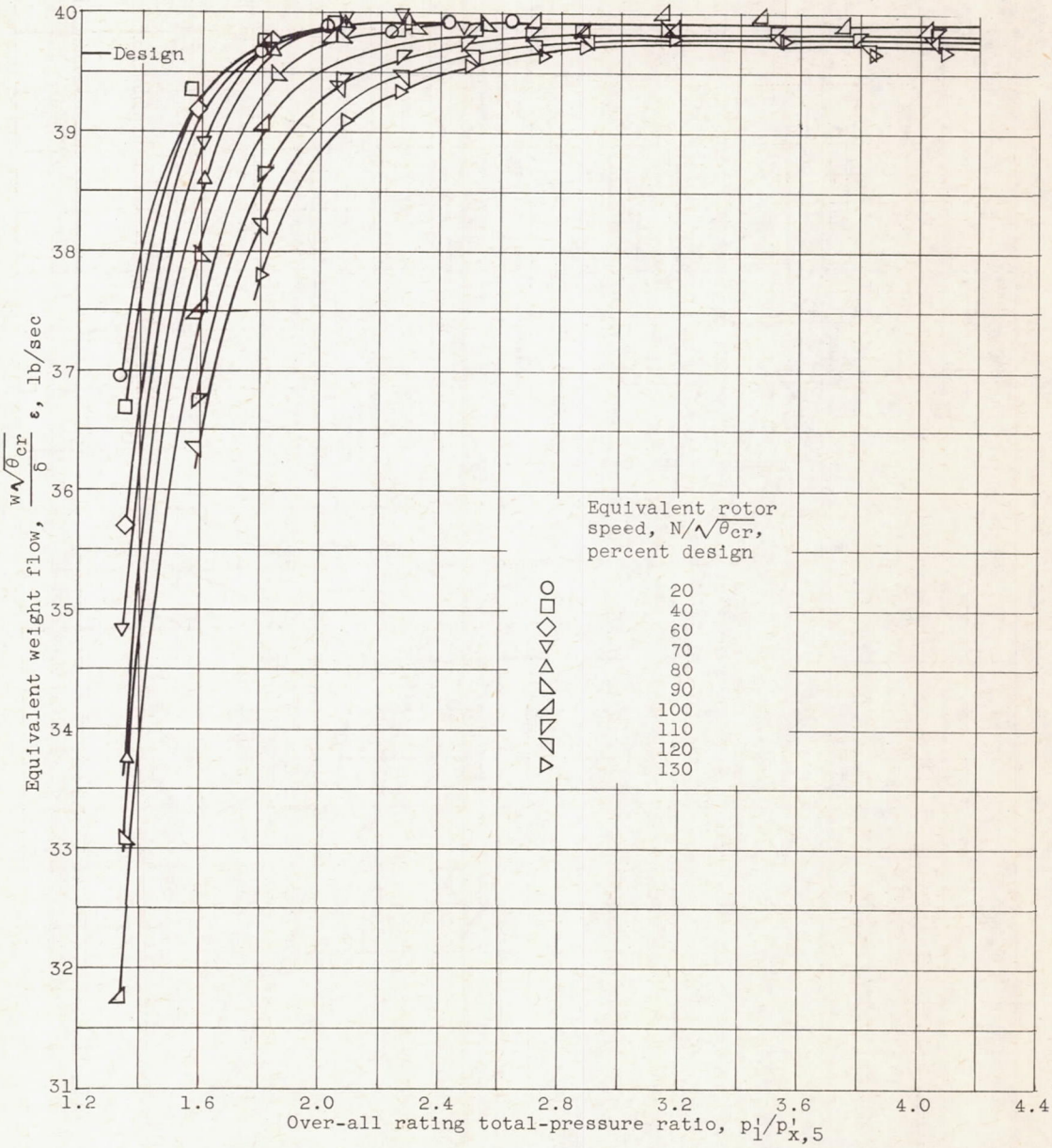
Figure 4. - Over-all performance of turbine. Turbine-inlet pressure, 35 inches of mercury absolute; turbine-inlet temperature, 700° R; equivalent design speed, 3027 rpm.



(b) Aerodynamic efficiency basis.

Figure 4. - Concluded. Over-all performance of turbine. Turbine-inlet pressure, 35 inches of mercury absolute; turbine-inlet temperature, 700° R; equivalent design speed, 3027 rpm.

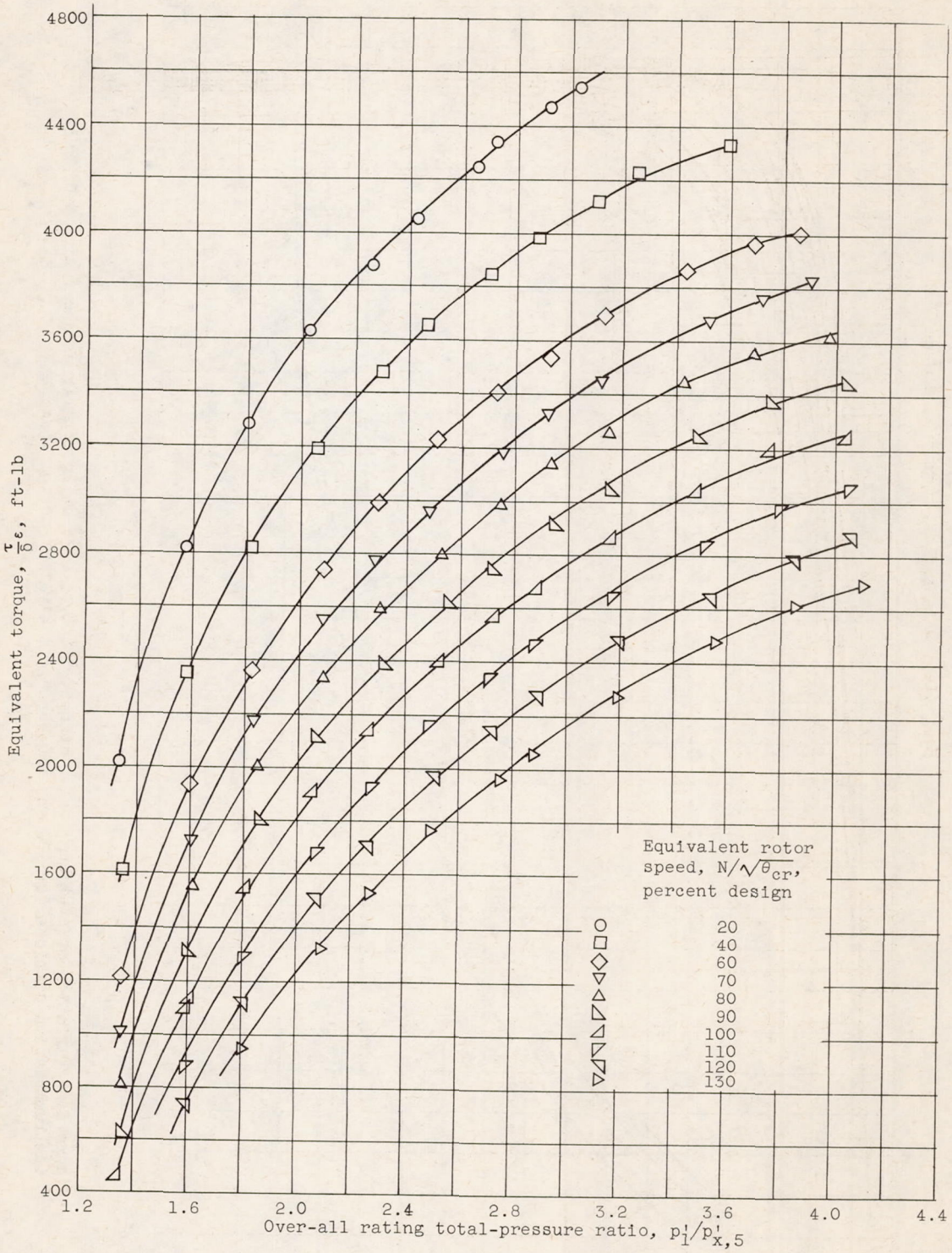
4143



(a) Equivalent weight flow.

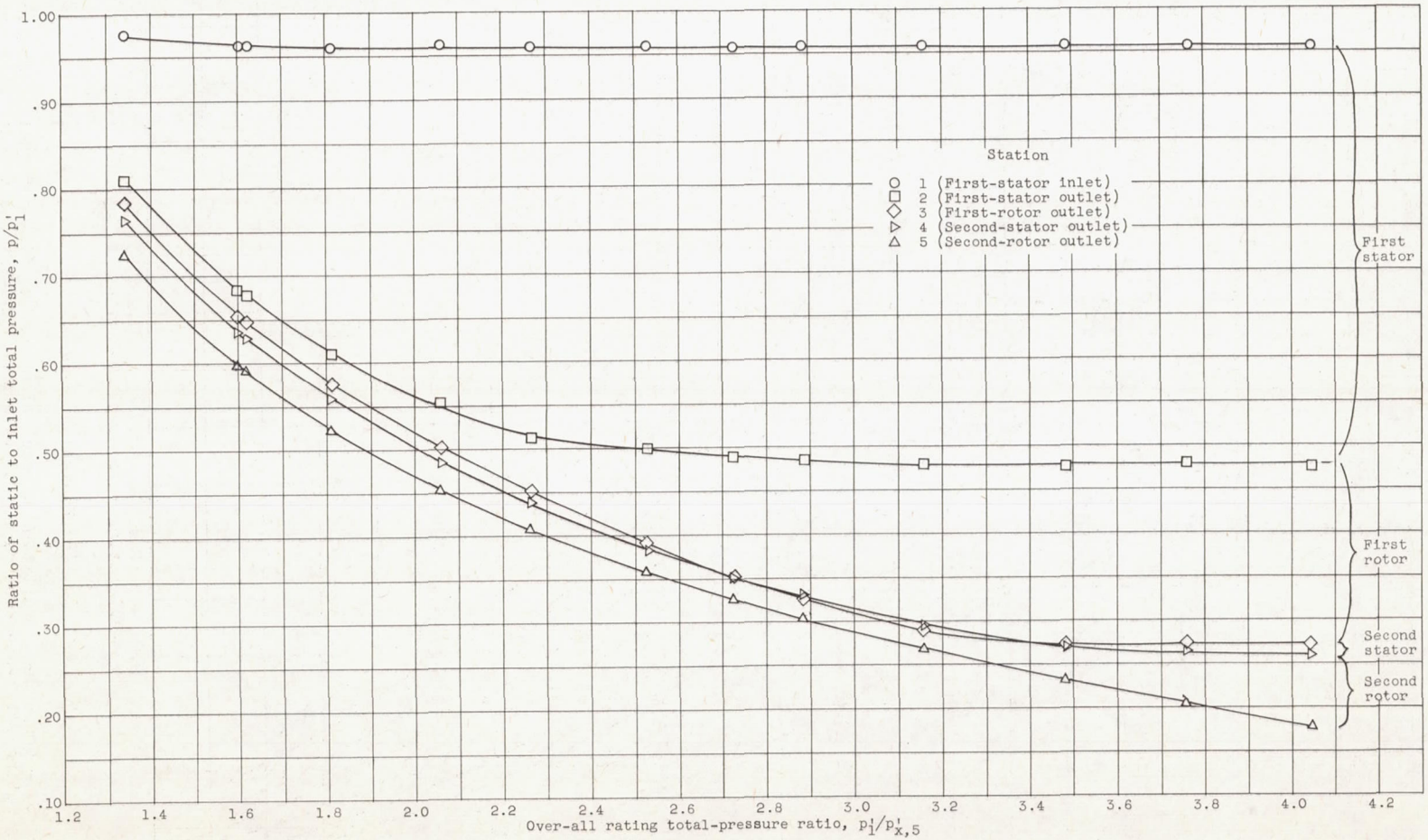
Figure 5. - Variation of equivalent weight flow and equivalent torque with rating total-pressure ratio for values of constant equivalent rotor speed.

4143



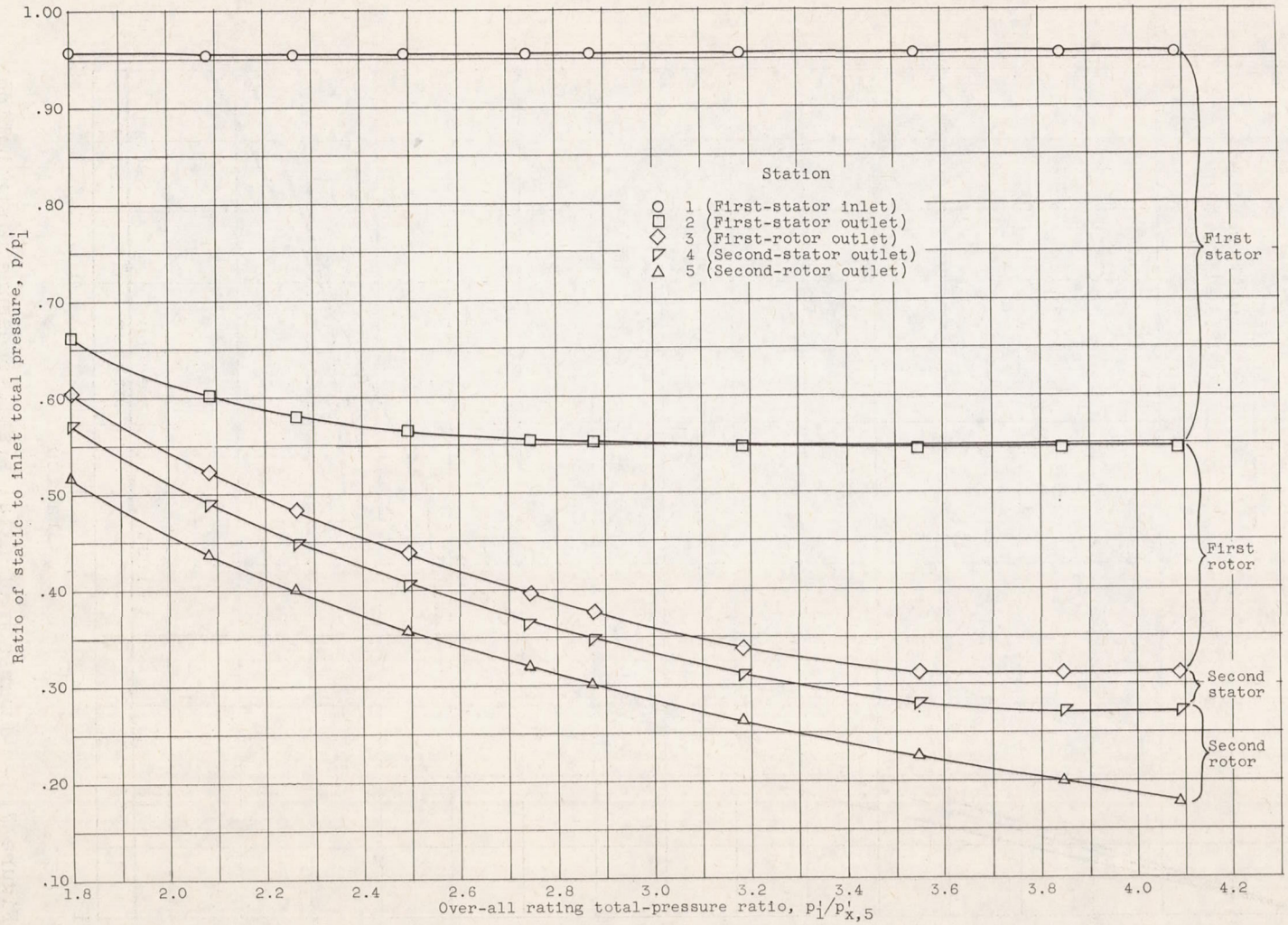
(b) Equivalent torque.

Figure 5. - Concluded. Variation of equivalent weight flow and equivalent torque with rating total-pressure ratio for values of constant equivalent rotor speed.



(a) Equivalent speed, 100 percent design.

Figure 6. - Variation of static pressure at hub with over-all rating total-pressure ratio at different instrumentation stations for 100 and 130 percent equivalent design speeds.



(b) Equivalent speed, 130 percent design.

Figure 6. - Concluded. Variation of static pressure at hub with over-all rating total-pressure ratio at different instrumentation stations for 100 and 130 percent equivalent design speeds.

4143

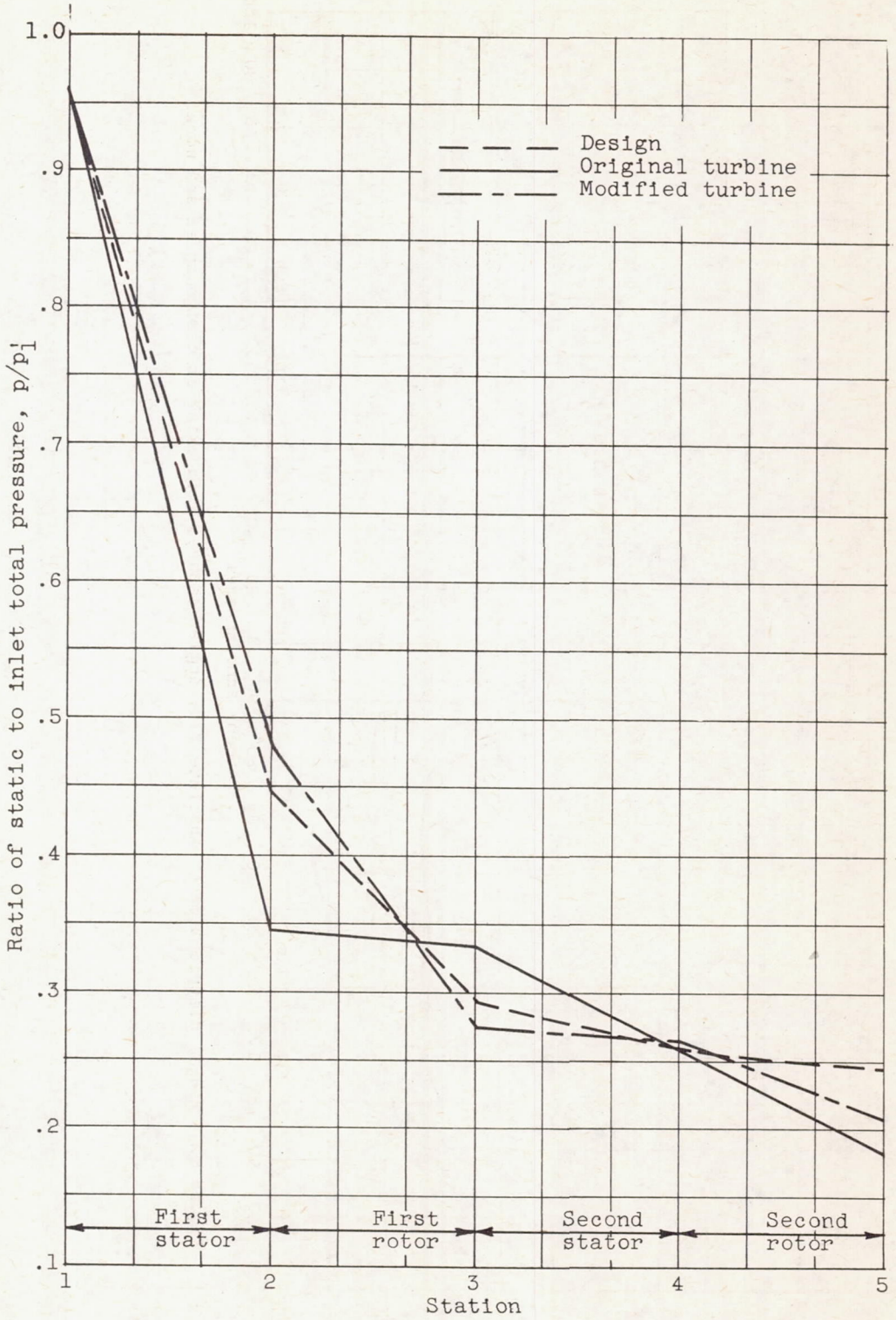


Figure 7. - Comparison of axial static-pressure distribution for original and modified turbines at equivalent design work and speed with design distribution.

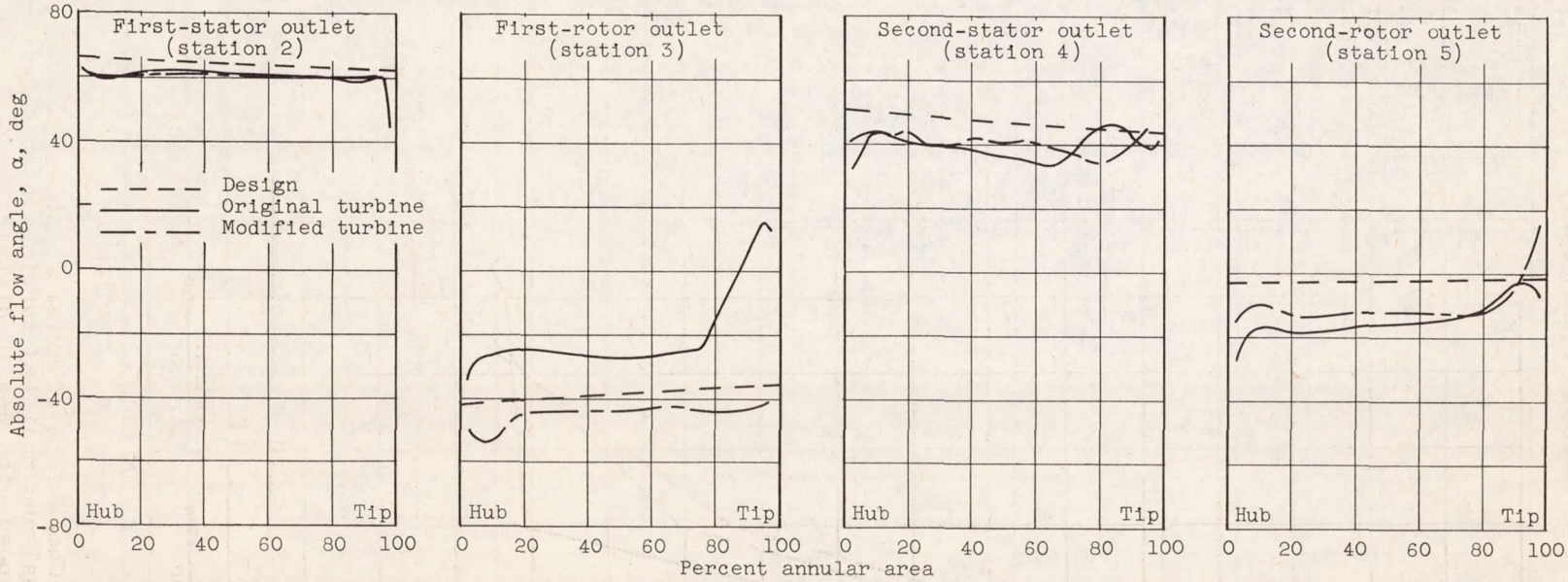


Figure 8. - Radial distribution of absolute flow angle measured from axial at design speed and work.

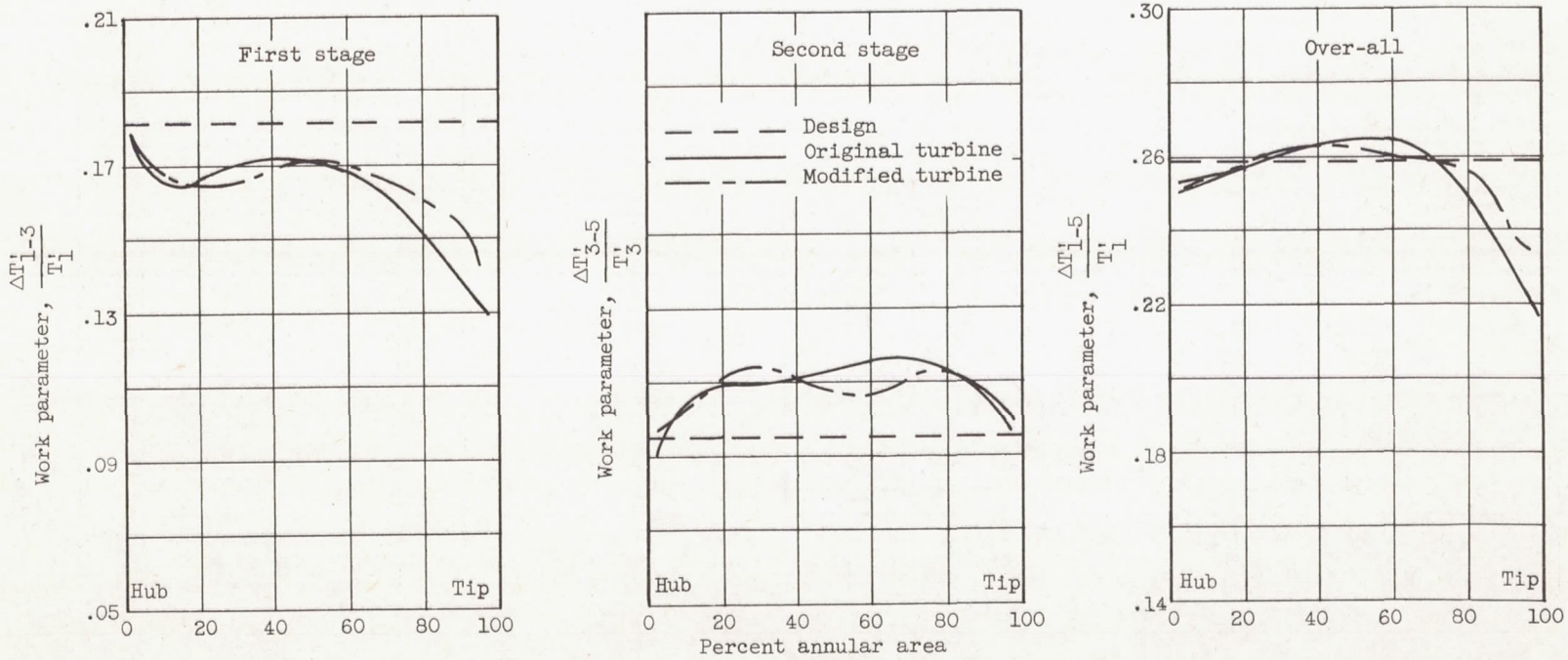


Figure 9. - Radial variations of stage and over-all work parameter at design speed and work.

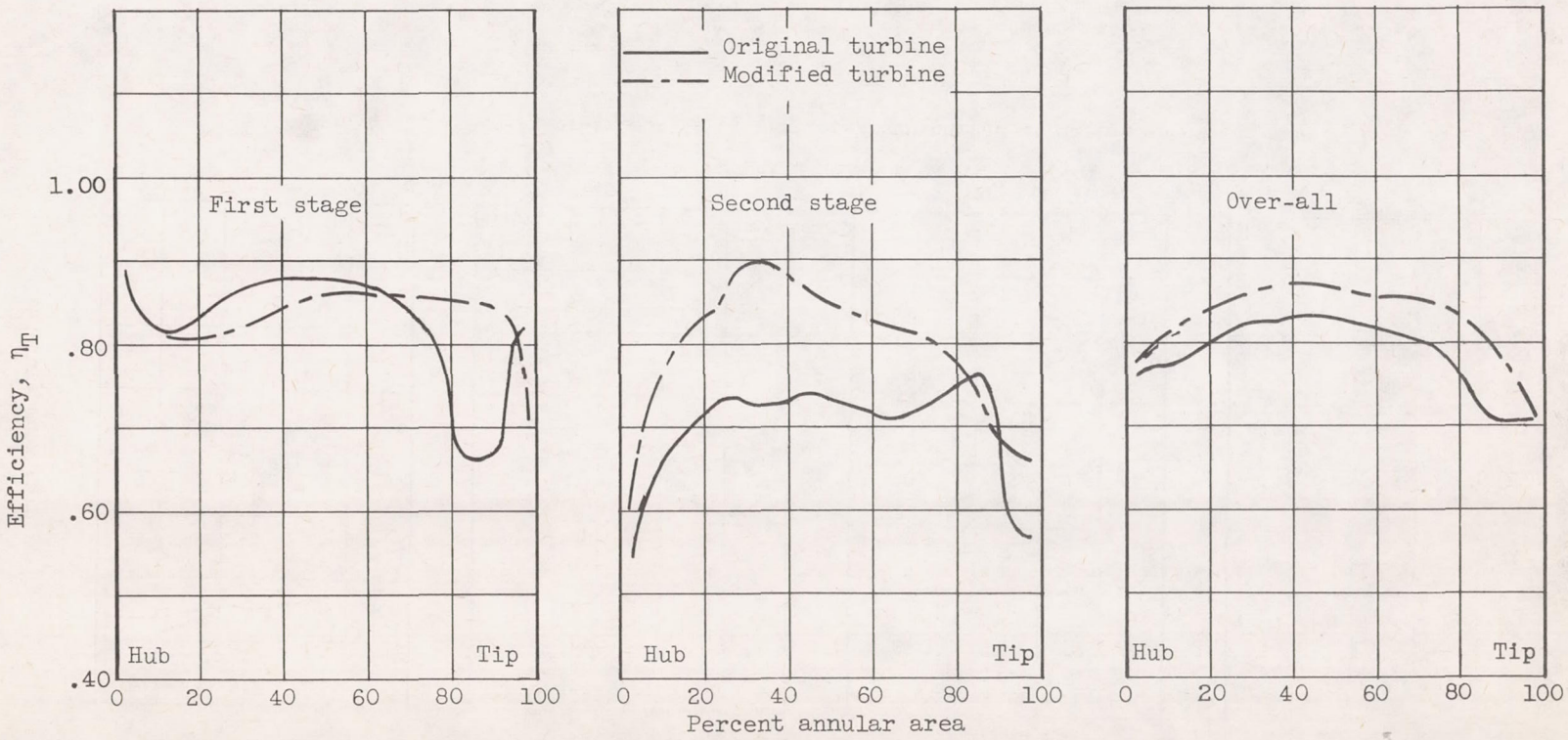


Figure 10. - Radial variations of stage and over-all aerodynamic efficiency at design speed and work.

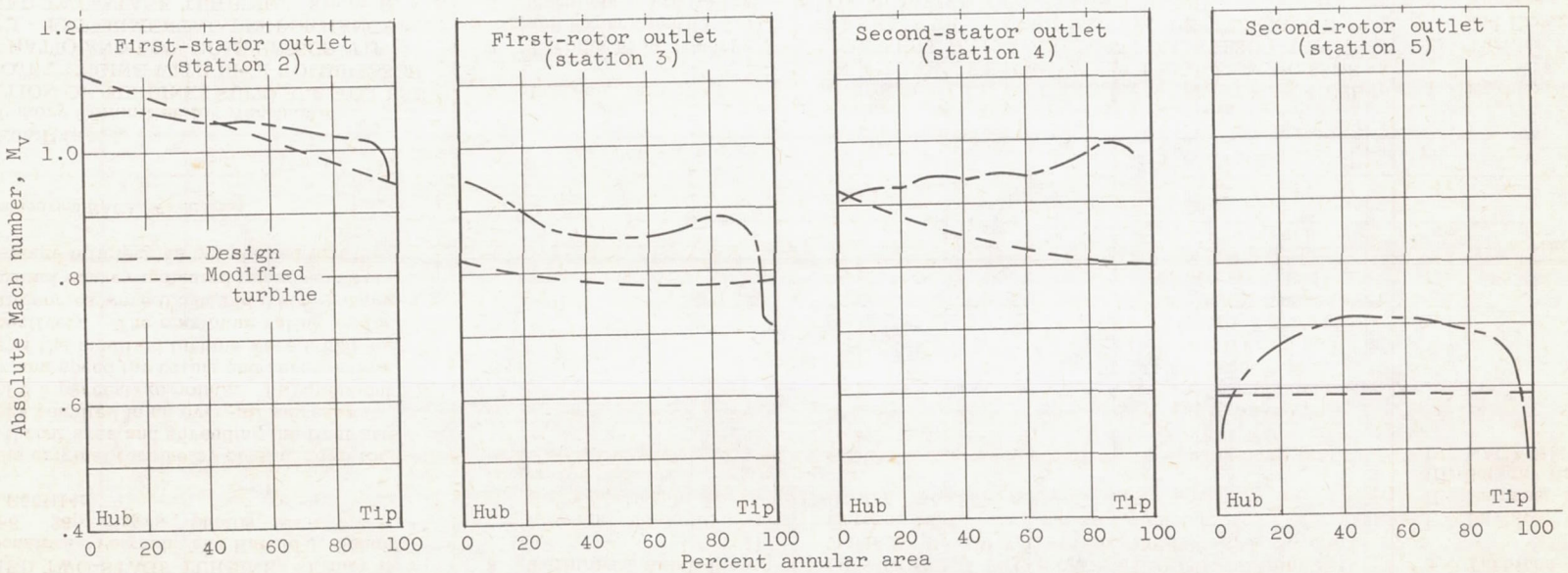


Figure 11. - Radial distribution of absolute Mach number at design speed and work.