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RESEARCH MEMORANDUM

COMPONENT PERFORMANCE INVESTIGATION OF J71 EXPERIMENTAL TURBINE

VII - EFFECT OF FIRST-STATOR ADJUSTMENT; OVER-ALL PERFORMANCE OF J71-97 TURBINE WITH 87-PERCENT-DESIGN STATOR AREA

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

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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COMPONENT PERFORMANCE INVESTIGATION OF J71 EXPERIMENTAL TURBINE

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SUMMARY

The effect of first-stage-stator throat area changes on the over-all component performance of the J71-97 experimental three-stage turbine is being investigated. For the subject investigation, this turbine was equipped with a first-stage stator having 87 percent of the design throat area. The performance results obtained are compared herein with those previously obtained with the same turbine having first-stage-stator throat areas 70, 95.6, and 132 percent of design. In all four turbine configurations, the first-stage-stator area changes were effected by changing the stagger angle of the design blade profiles.

The subject turbine with the 87-percent-area first stator obtained a maximum brake internal efficiency of 0.888. The maximum efficiency values of the 70-, the 95.6-, and the 132-percent turbines were 0.873, 0.891, and 0.869, respectively.

A compressor-turbine match-point study, based on the experimental data and an assumed mode of engine operation during which the compressor is maintained at constant equivalent design conditions, was made. The match-point efficiency for the 87-percent turbine was 0.877, which was greater than the 0.870 and 0.860 efficiency values obtained for the 95.6- and 132-percent turbines, respectively. No match-point efficiency could be obtained for the 70-percent turbine, because this turbine configuration produced insufficient work output to drive the compressor at the required conditions. In fact, it was found that, if the stator throat area were reduced to less than about 75.5 percent of design, this particular experimental turbine would be unable to drive the compressor as required.

INTRODUCTION

The NACA Lewis laboratory is currently conducting a general study of high-work-output low-blade-speed multistage turbines. As a part of this program, the effect of first-stage-stator throat area adjustment on the over-all component performance characteristics of the J71 experimental three-stage turbine is being investigated. Previously, this experimental turbine was equipped with first-stage stators having throat areas of 95.6, 132, and 70 percent of the design value. Each turbine configuration was experimentally investigated over a range of pressure ratio and speed with equivalent cold-air inlet conditions, and the results are reported in references 1, 2, and 3, respectively.

The subject report presents the over-all component performance of this same turbine equipped with a first-stage stator having a throat area 87 percent that of design. Hereinafter, this turbine is called the J71-87 turbine, or simply the 87-percent turbine. This turbine was experimentally investigated in the same manner as the other three turbine configurations. The performance of all four configurations is compared herein. Also included is a discussion of compressor and turbine match-point characteristics for an assumed mode of engine operation. 4115

SYMBOLS

The following symbols are used in this report:

E enthalpy drop based on torque measurements, Btu/lb

g acceleration due to gravity, 32.174 ft/sec^2

N rotational speed, rpm

p pressure, in. Hg abs

p_x' rating total pressure, static pressure plus velocity pressure corresponding to axial component of velocity, in. Hg abs

R gas constant, 53.4 ft-lb/(lb)($^{\circ}$R)

T temperature, $^{\circ}$R

w weight flow, lb/sec

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

γ ratio of specific heats

δ ratio of inlet-air pressure to NACA standard sea-level pressure, $p_0'/29.92$ in. Hg abs

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

η_i brake internal efficiency, ratio of actual turbine work based on torque measurements to ideal turbine work based on inlet total pressure p_0' and outlet rating total pressure $p_{x,7}'$

θ_{cr} squared ratio of critical velocity at NACA standard sea-level temperature of 518.7° R, $\dfrac{\dfrac{2\gamma}{\gamma + 1}\, gRT_0'}{\dfrac{2\gamma_{sl}}{\gamma_{sl} + 1}\, gRT_{sl}}$

τ torque, ft-lb

Subscripts:

e engine operating conditions

sl NACA standard sea-level conditions

x axial

0,1,2
3,4,5 measuring stations (see fig. 2)
6,7

Superscript:

' total or stagnation state

APPARATUS AND PROCEDURE

The investigation of the 87-percent turbine was conducted with the same turbine test facility used in the 95.6-, 132-, and the 70-percent turbine investigations (refs. 1, 2, and 3). A photograph of the over-all turbine experimental setup is presented in figure 1.

For this investigation the first-stage stator of the J71-97 turbine was replaced by one having a throat area 87 percent of design. This area change was effected by changing the stagger angle of the design blade profiles to the angle required for the desired throat area. This procedure was the same as that used to produce the 132-percent first-stator area (ref. 2) and the 70-percent first-stage area (ref. 3).

The instrumentation used in the subject investigation was the same as that used in reference 1. A schematic diagram of the turbine showing axial and circumferential locations of the instrumentation is presented in figure 2. In short, measurements of total pressure, wall static pressure, and total temperature were taken at the turbine inlet (station 0) and at the turbine outlet (station 7). In addition, wall static taps were installed on both the inner and outer shrouds between blade rows. 4115

The 87-percent turbine was operated with a nominal inlet pressure p_0' and temperature T_0' corresponding to 35 inches of mercury absolute and 700° R. The unit was investigated over a range of rating total-pressure ratio $p_0'/p_{x,7}'$ from 1.4 to 5.2 and over a range of equivalent speed $N/\sqrt{\theta_{cr}}$ from 20 to 130 percent of the design equivalent speed. The method used in converting turbine test conditions (29.92 in. Hg abs and 518.7° R) is given in reference 4. The equivalent work output E/θ_{cr} and brake internal efficiency η_i as presented herein are based on measured torque values. The equivalent-weight-flow values $w\sqrt{\theta_{cr}}/\delta$ have been corrected for the fuel addition required to maintain the 700° R turbine-inlet temperature.

Over-all turbine efficiency was based on the measured inlet pressure p_0' and a calculated outlet pressure $p_{x,7}'$. This calculated outlet pressure is defined as the static pressure behind the last rotor (measuring station 7, fig. 2) plus the velocity head corresponding to the axial component of the absolute velocity. This calculated value of turbine-outlet rating pressure charges the turbine for the energy of the tangential component of exit velocity. This pressure is calculated from the energy and continuity equations by using the known annulus area at the measuring station and the measured values of weight flow (air flow plus fuel flow), static pressure, total pressure, and total temperature.

A turbine match point for the 87-percent turbine was calculated based on the assumption that the compressor was operating at constant equivalent design conditions. This match-point analysis is developed and presented in reference 2. The turbine match-point requirements are compared herein with the corresponding match-point requirements for the turbines having first-stage-stator areas 70 percent of design (ref. 3), 95.6 and 132 percent of design (ref. 2).

RESULTS AND DISCUSSION

Over-All Performance

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The over-all performance of the 87-percent turbine is presented in figure 3 as a plot of equivalent shaft work E/θ_{cr} against the flow parameter $\frac{wN}{60\delta}\varepsilon$ for constant values of equivalent speed $N/\sqrt{\theta_{cr}}$ and rating total-pressure ratio $p_0'/p_{x,7}'$. In addition, contours of constant brake internal efficiency η_i are shown. The performance map (fig. 3) indicates that the turbine had good efficiency over a fairly wide range of speed and pressure ratio. The maximum efficiency obtained was 0.888, occurring at 120 percent of equivalent design speed and a turbine equivalent work output of 35 Btu per pound.

The variation of equivalent torque with rating total-pressure ratio for the equivalent speeds investigated is shown in figure 4. It is readily apparent that the torque continually increased with pressure ratio for all speeds, indicating that turbine limiting loading was not attained within the range of pressure ratios imposed across the turbine.

The variation of equivalent weight flow $\frac{w\sqrt{\theta_{cr}}}{\delta}\varepsilon$ with rating total-pressure ratio for all speeds investigated is shown in figure 5. Choking weight flow, indicated in figure 5 when the curves for each speed obtain a zero slope, occurred for all speeds up to and including 90 percent of the equivalent design speed at a value of 39.54 pounds per second. For these speeds, then, the first-stage stator choked. The value of choking weight flow decreased with a further increase in speed, which indicated that the choke point in the turbine had moved to some blade row downstream of the first-stage stator. In addition, the pressure ratio at which choking occurred increased as the equivalent speed of the turbine was increased. The total spread in choking weight flow with speed is small, however, being somewhat less than 1/2 pound per second. The choking value of 39.54 pounds per second corresponds to about 98 percent of the equivalent design value (40.3 lb/sec).

Interstage Static-Pressure Distribution with Speed and Pressure Ratio

In an effort to determine which blade row downstream of the first stator was choking at the higher turbine speeds, the arithmetical average of the hub static pressures at each measuring station is presented for all measuring stations in figure 6 for a range of over-all rating total-pressure ratio and for speeds of 80 and 130 percent of equivalent design speed. The hub static pressures are divided by the inlet total pressure p_0' in order to eliminate the effect of the small variations in the inlet total pressure encountered in the tests. Choking in a blade row is indicated when the static pressure at the inlet to a blade row remains constant while the static pressure at the outlet of the same blade row decreases as the over-all rating total-pressure ratio across the turbine is increased. For the 80-percent equivalent design speed (fig. 6(a)), the third-stage rotor appears to choke at a pressure ratio of about 4.45. This blade-row choking is in addition to the aforementioned first-stage-stator choking condition that prevailed at equivalent speeds of 90 percent of design and lower. It should be stated that other blade rows may choke simultaneously with the third-stage rotor, but this could not be established. As the speed is increased to 130 percent of the equivalent design speed, the second-stage stator appears to choke, followed by choking in the third-stage stator as the pressure ratio is increased. 4115

It is interesting to note the static-pressure characteristics across the first-stage rotor (fig. 6) as the equivalent rotor speed is increased from 80 to 130 percent of equivalent design speed. A static-pressure rise (negative reaction) across the hub of the first-stage rotor occurs over most of the over-all rating pressure-ratio range investigated for the 80-percent speed (fig. 6(a)). Although static-pressure data for the 110-percent equivalent design speed is not presented herein, it was found that, at rating pressure ratios above 3.0, no static-pressure change across this blade row occurred, indicating an impulse condition. A static-pressure drop across the hub of the first-stage rotor (positive reaction) occurred over the entire range of rating pressure ratio as the equivalent design speed was further increased to 130-percent design (see fig. 6(b)).

Effect of First-Stage-Stator Area

Variation on Over-All Turbine Performance

The first-stator area of 87-percent design was obtained by changing the stagger angle of the design blade profile in the same manner as in obtaining the 95.6-, the 132-, and the 70-percent first-stator areas as described in references 1, 2, and 3, respectively. Figure 7 shows the stagger-angle change at the blade-pitch section required to obtain these first-stage-stator areas. This figure shows that this stagger angle was varied as much as $8\frac{1}{2}^{\circ}$ above design (away from axial) for the 70-percent turbine, and about $9\frac{1}{2}^{\circ}$ less than design (toward axial) for the 132-percent turbine.

The variation of choking equivalent weight flow with first-stage-stator area is shown in figure 8(a) for three equivalent rotor speeds. In the investigation of the 70-percent turbine (ref. 3), the first
4115 stator choked at all speeds; and, hence, only a point value of choking equivalent weight flow (32.28 lb/sec) was obtained. As the stator area is increased, the choke point in the turbine moves from the first-stage stator to some downstream blade row, resulting in the divergence of the choking weight flow with speed. It is apparent for the speeds shown that a nonlinear relation exists between the first-stator area and the choking equivalent weight flow. Figure 8(a) indicates that increasing the first-stator area from 70 to 87 percent of design resulted in an almost proportional increase in choking equivalent weight flow at the equivalent design speed. A further change in this area from 87 to 132 percent of design effected a change in this choking weight flow of only 20 to 23 percent, depending on the speed considered.

Figure 8(b) presents the maximum brake internal efficiency obtained for each of these turbines, plotted against their corresponding first-stator areas. This curve indicates that either increasing or decreasing the first-stator area from the design value results in an efficiency reduction. However, a large variation in area can be obtained with a relatively small effect on turbine efficiency. In fact, the observed maximum reduction in efficiency amounted to only 2.2 points, occurring when the first-stator area was increased to 132 percent of design.

Matching Characteristics

Turbine matching characteristics were determined for the experimental turbines having first-stage-stator areas of 95.6 and 132 percent of design in reference 2, and for the 70-percent turbine in reference 3, based on an assumed engine mode of operation during which the compressor is maintained at constant equivalent design conditions. Similarly, the corresponding experimental turbine match point was herein determined for the 87-percent turbine. These compressor-turbine matching curves, calculated from the equations derived in the appendix of reference 2, are presented in figure 9 as solid lines. The dot-dashed lines in figure 9(a), whose intersection with the solid lines determines the match points, were obtained from the experimental data for the respective turbines in the following manner: If the compressor were operated at constant equivalent design conditions, the equivalent torque of the turbine is constant at its design value of 3204 foot-pounds. At this torque value, then, the over-all rating total-pressure ratios for lines of constant equivalent speeds were obtained from the torque curves (fig. 4). The equivalent weight flows corresponding to these rating pressure ratios and speeds were then obtained from the equivalent-weight-flow curves (fig. 5). These weight-flow values are shown in figure 9(a) at the corresponding equivalent speeds. The intercept of this experimental curve with the calculated curve for the 87-percent turbine yields the match-point equivalent speed of 102.2 percent of design. The corresponding intercepts are shown for the 95.6-, the 132-, and the 70-percent turbines. For the 87-percent turbine 4115 and the match-point speed of 102.2 percent of design, the match-point engine temperature ratio (turbine inlet to compressor inlet) was 3.99, the equivalent shaft work was 33.8 Btu per pound, and the weight-flow parameter remained at 2034. This turbine match point for the 87-percent turbine is shown on the performance map (fig. 3), and occurs at a rating total-pressure ratio of about 3.66. At this match point, the brake internal efficiency was 0.877. It is interesting to note that this match-point efficiency is only 1 point lower than the maximum efficiency obtained with this turbine configuration.

Figures 10(a), (b), (c), and (d) are cross plots from the data of figure 9 and show the variation of equivalent weight flow, equivalent rotor speed, engine temperature ratio, and equivalent shaft work with first-stator area for the four turbine configurations at their respective match points. The equivalent design values for these parameters are also shown. Figure 10(a) shows that higher than design equivalent air weight flow would have existed had the turbine been operated with design first-stator area. With design areas, then, the other design-point match parameters shown in figures 10(b), (c), and (d) did not fall on the actual curves. It can also be noted that, had this first-stator area been reset to about 89.5 percent of the design area, equivalent design conditions of weight flow, speed, engine temperature ratio, and shaft work would have been attained.

Also shown on the match-point equivalent-shaft-work curve (fig. 10(d)) is an estimated limiting-loading curve, obtained by judiciously extrapolating and interpolating the torque curves for the respective turbine configurations. This figure indicates that, as the first-stator area is decreased, the turbine equivalent work required for the compressor-turbine match point approaches the estimated limiting-loading curve and intersects the curve at a first-stator area of 75.5 percent, corresponding to a work output of about 43.5 Btu per pound. With stator areas less than this 75.5 percent, then, this particular experimental turbine would be unable to drive the compressor for the selected mode of engine operation. The unobtainable range of work output is indicated in figure 10(d) by the dashed extension of the match-work curve. In the 70-percent turbine investigation (ref. 3), insufficient turbine work was developed to drive the compressor at the match point.

The brake internal efficiencies obtained at the turbine match points
are shown in figure 10(e) for the various first-stator-area turbines in-
vestigated. Since the match-point equivalent work for the 70-percent
turbine was unobtainable, no match-point efficiency for this turbine con-
figuration can be presented. The match-point efficiency for the 87-percent
turbine was 0.877, which was greater than the 0.870 and 0.860 efficiency
values obtained for the 95.6- and 132-percent turbines, respectively.
Also shown in figure 10(e) is the curve of maximum brake internal ef-
4115 ficiency from figure 8(b). It will be noted that the match-point ef-
ficiency increases as the first-stator area is decreased from 132 percent
of design. It appears, then, that over the range of first-stator areas
considered, the turbine efficiency at the match point required to operate
the engine at constant equivalent design conditions is high and reasonably
CF-2 close (the maximum difference is about $2\frac{1}{2}$ points) to the maximum turbine
efficiency obtainable.

SUMMARY OF RESULTS

A cold-air component performance investigation of the J71 experimental three-stage turbine with a first-stator throat area 87 percent of design was made. The results are compared with similar results previously obtained with the same turbine having three different first-stator throat areas. The following results were obtained:

1. The maximum brake internal efficiency obtained with the 87-percent turbine was 0.888, occurring at 120 percent of equivalent design speed and a work output of 35 Btu per pound. The corresponding peak-efficiency values for the 70-, 95.6-, and 132-percent turbines were 0.873, 0.891, and 0.869, respectively.

2. Increasing the first-stator area from 70 to 87 percent of design resulted in an almost proportional increase in choking equivalent weight flow at the design equivalent speed. A further increase in area from 87 to 132 percent of design resulted in only a 20- to 23-percent increase in this weight flow, over a wide range of turbine speed.

3. From a turbine match-point study based on the experimental data for all four turbine configurations and an assumed mode of engine operation during which the compressor is maintained at constant equivalent design conditions, it was found that:

(a) The efficiencies obtained at the match point for the 87-, 95.6-, and the 132-percent turbines were all in the high-efficiency range of their respective performance maps, and within $2\frac{1}{2}$ efficiency points of the maximum obtainable.

(b) Equivalent design conditions of work, weight flow, speed, and engine temperature ratio would be obtained if the first-stage-stator throat area were reset to about 89.5 percent of the design value.

(c) With first-stage-stator areas less than about 75.5 percent of design, the turbine would develop insufficient work to drive the compressor at the match point.

Lewis Flight Propulsion Laboratory 4115
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 21, 1956

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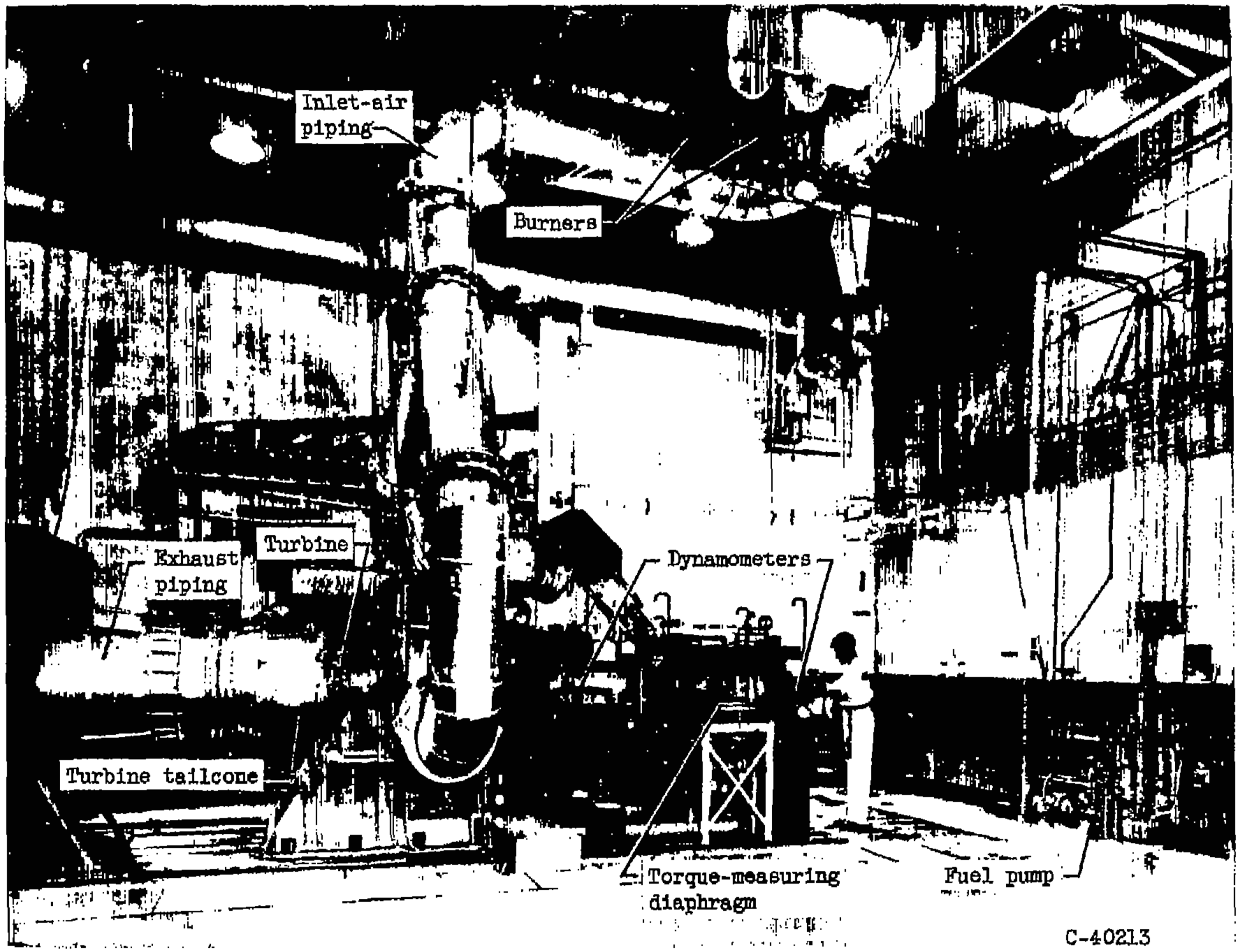

Figure 1. - Installation of J71-87 experimental three-stage turbine in full-scale turbine-component test facility.

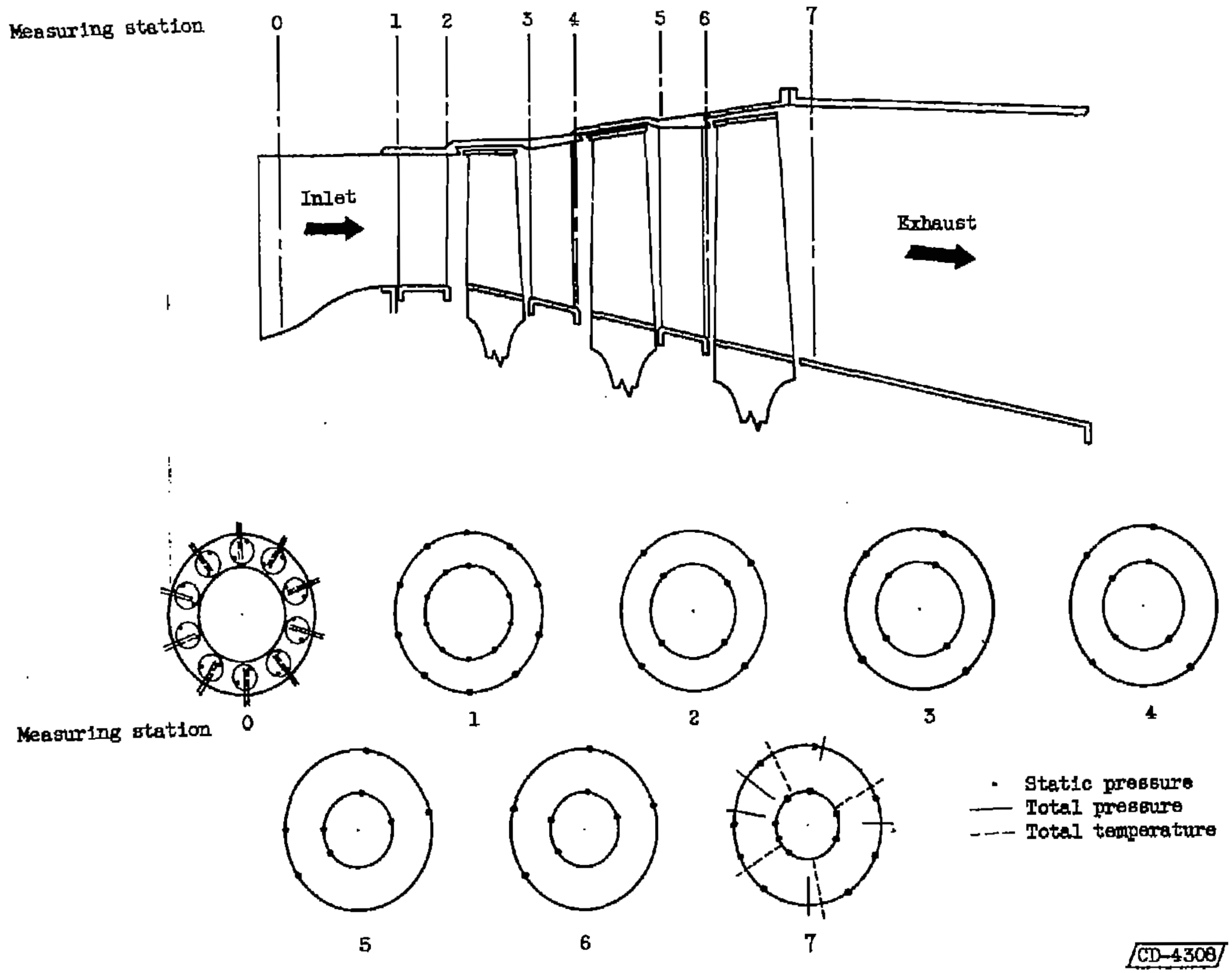

Figure 2. - Schematic diagram of J71-87 experimental turbine showing instrumentation.

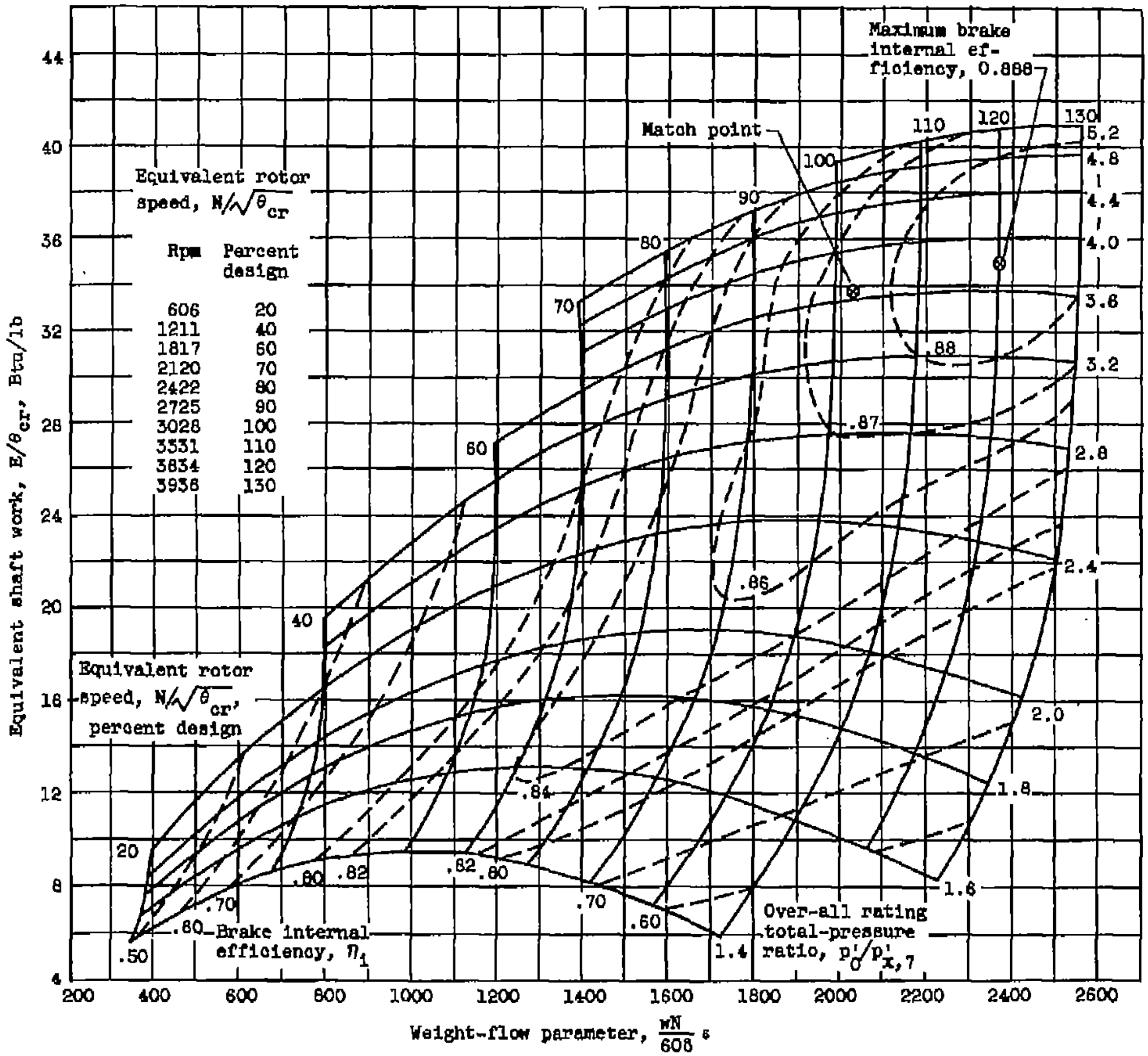

Figure 3. - Over-all performance of experimental J71 turbine with 87-percent-design first-stator area. Turbine-inlet pressure, 35 inches of mercury absolute; turbine-inlet temperature, 700° R.

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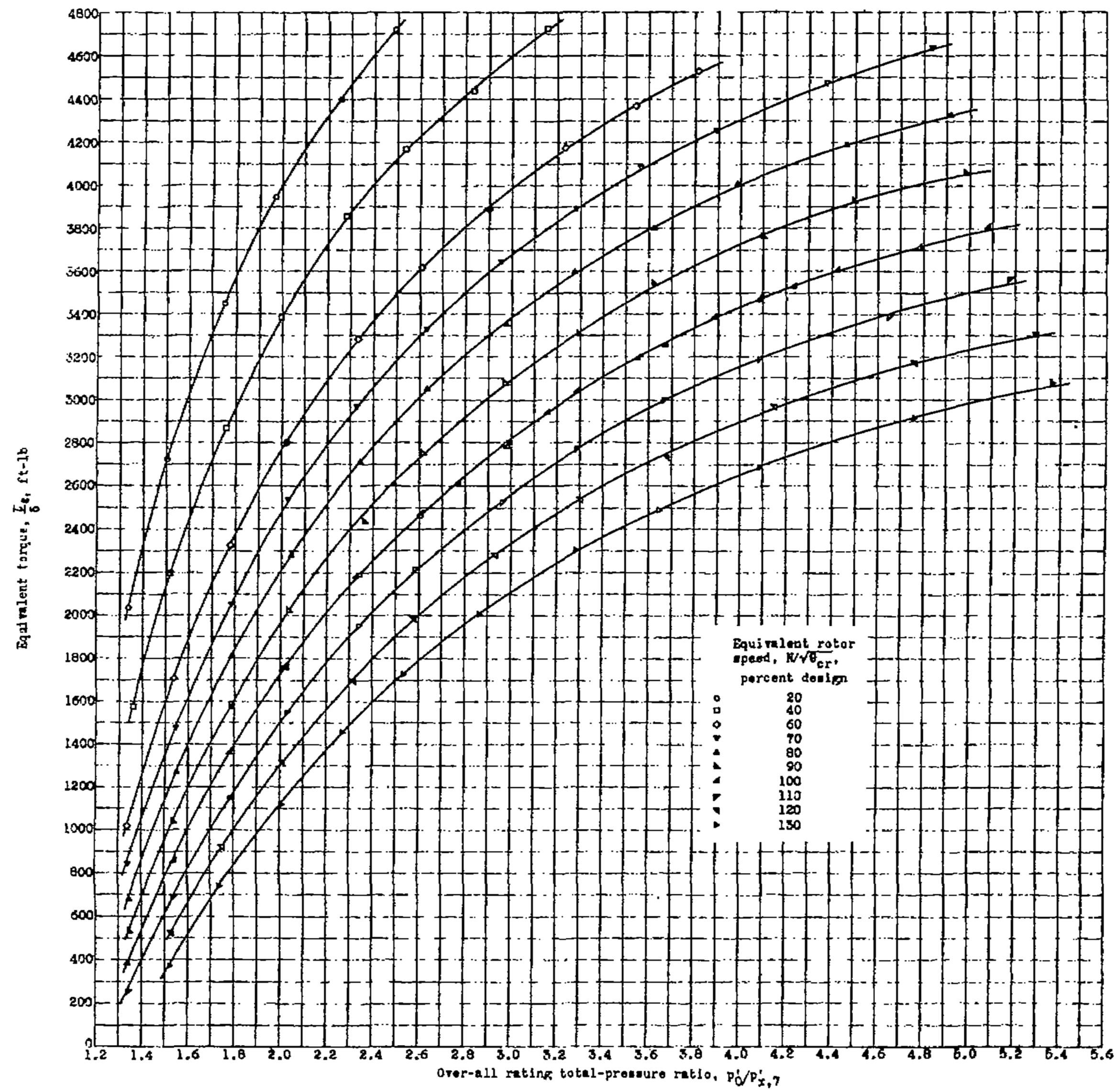

Figure 4. - Variation of equivalent torque with over-all rating total-pressure ratio for values of constant equivalent rotor speed.

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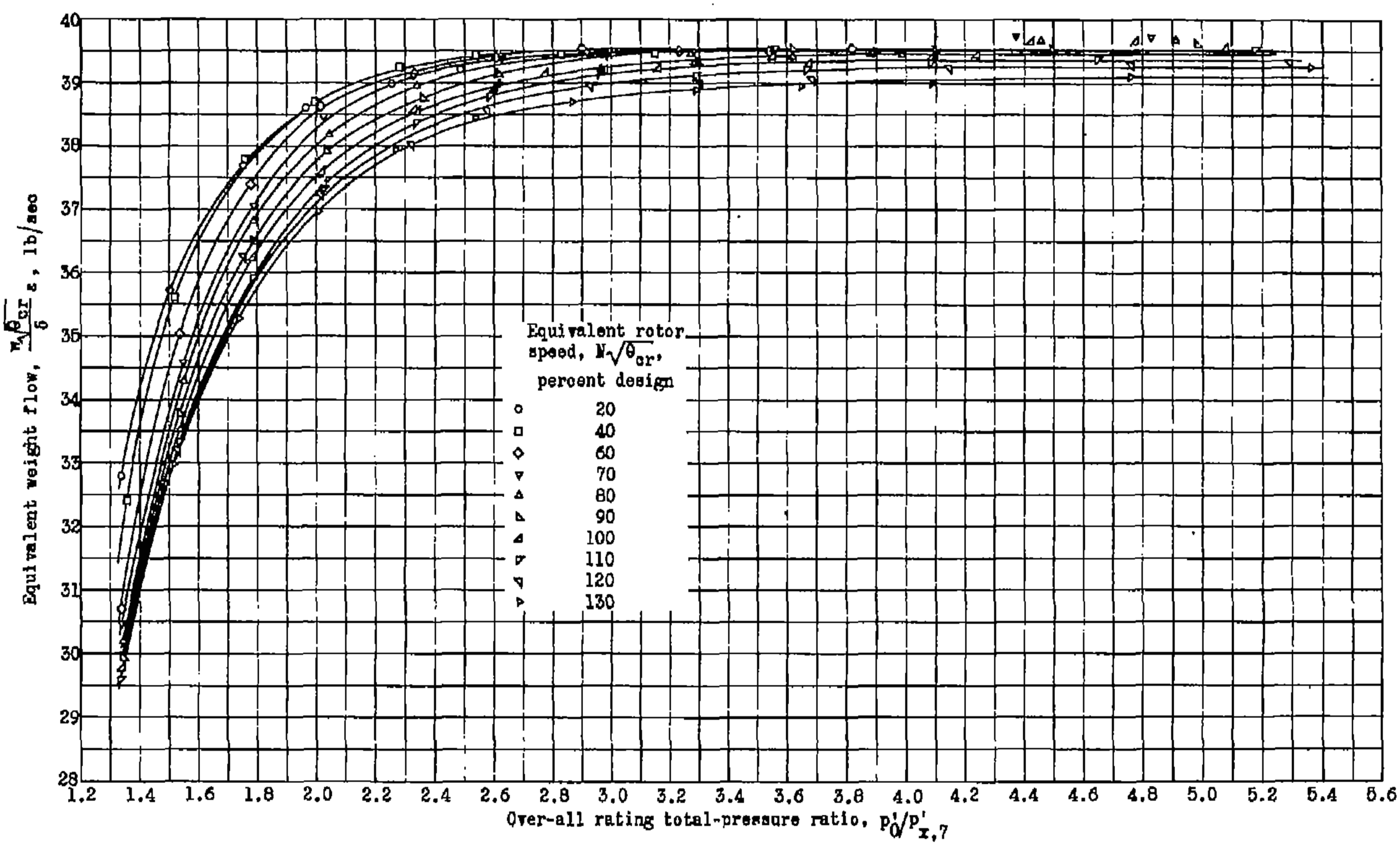
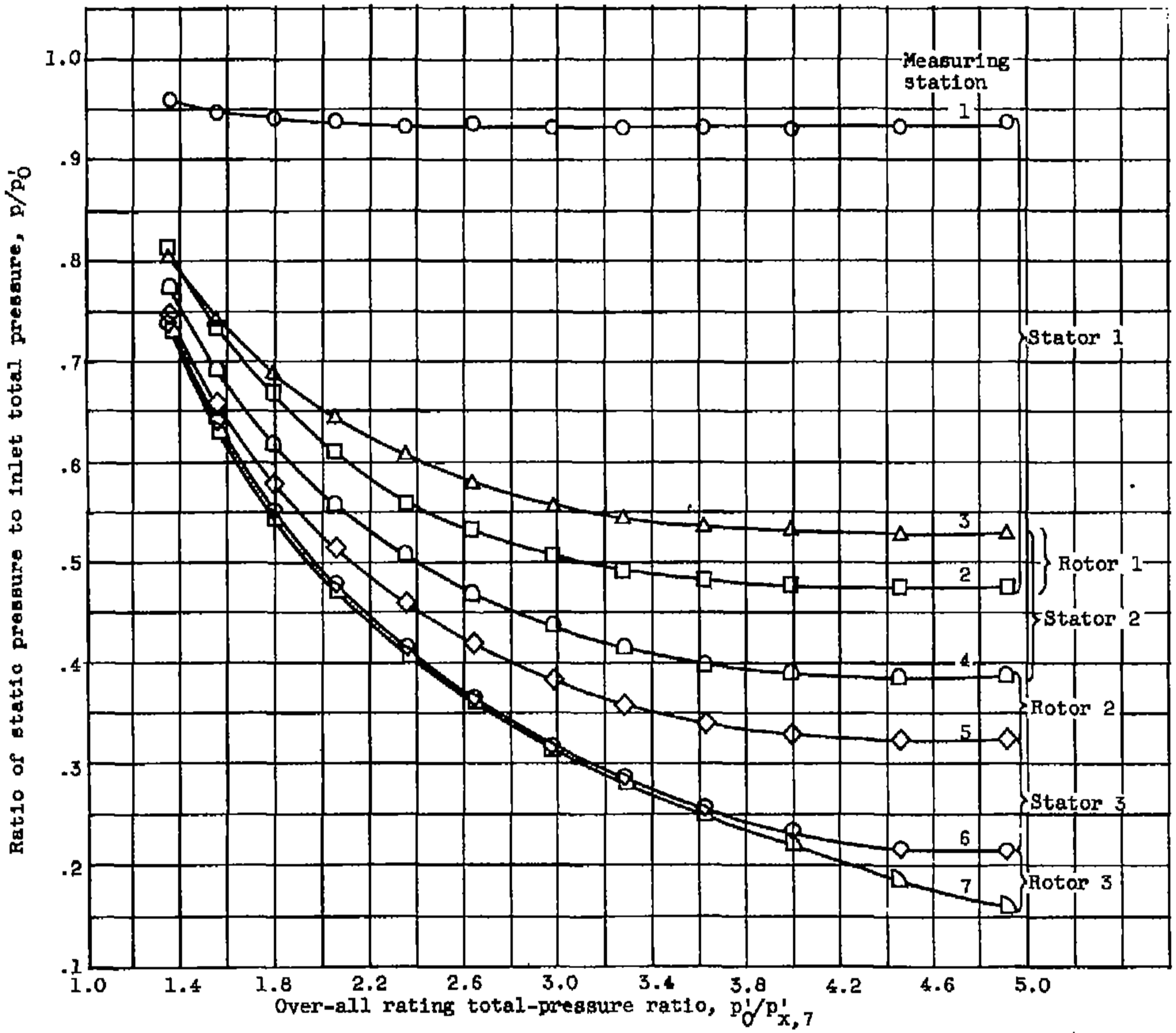
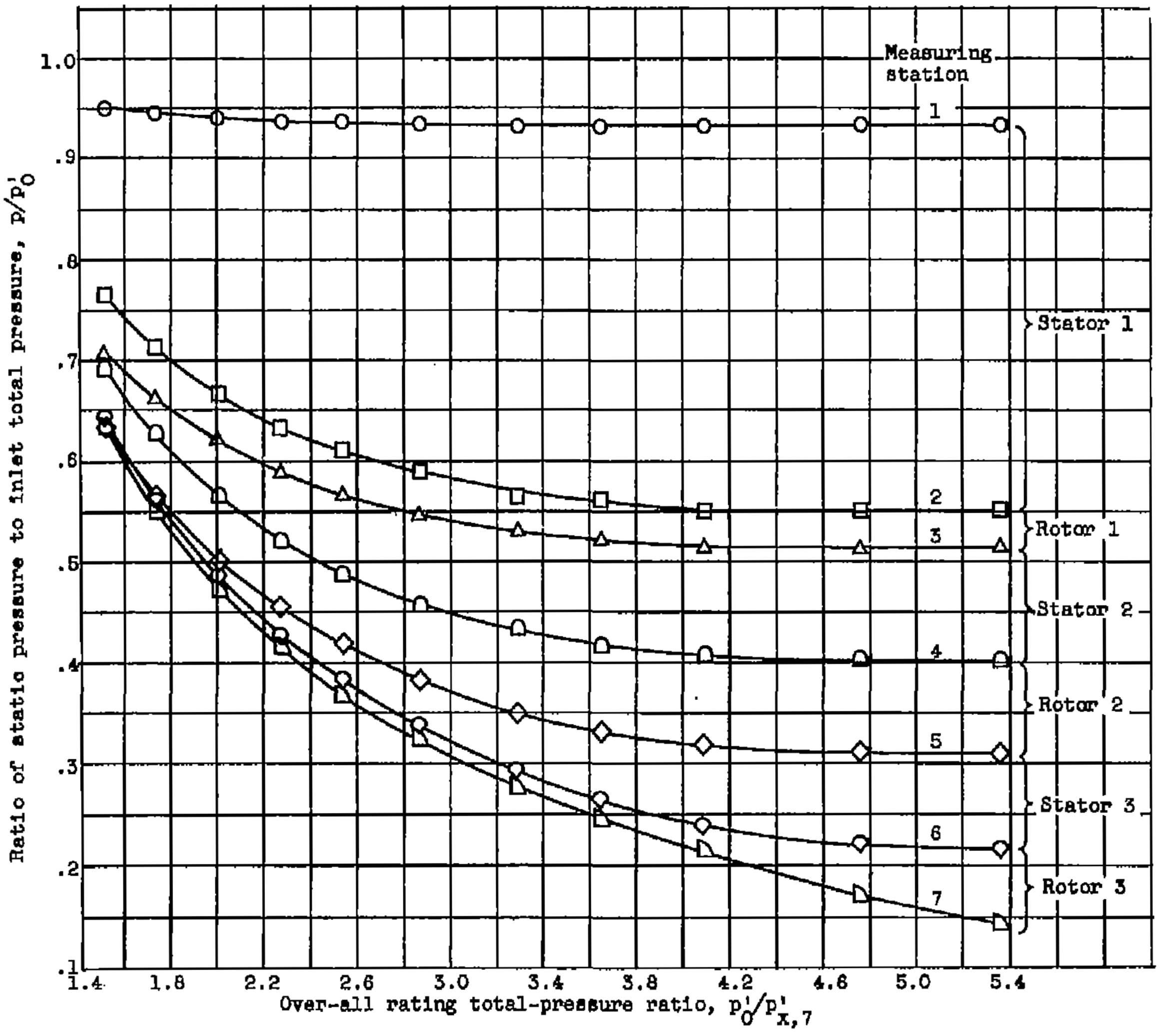


Figure 5. - Variation of equivalent weight flow with over-all rating total-pressure ratio for values of constant equivalent rotor speed.



(a) Equivalent speed, 80-percent design.

Figure 6. - Variation of static pressure at hub with over-all rating total-pressure ratio at different measuring stations for 80 and 130 percent of equivalent design speed.



(b) Equivalent speed, 130-percent design.

Figure 6. - Concluded. Variation of static pressure at hub with over-all rating total-pressure ratio at different measuring stations for 80 and 130 percent of equivalent design speed.

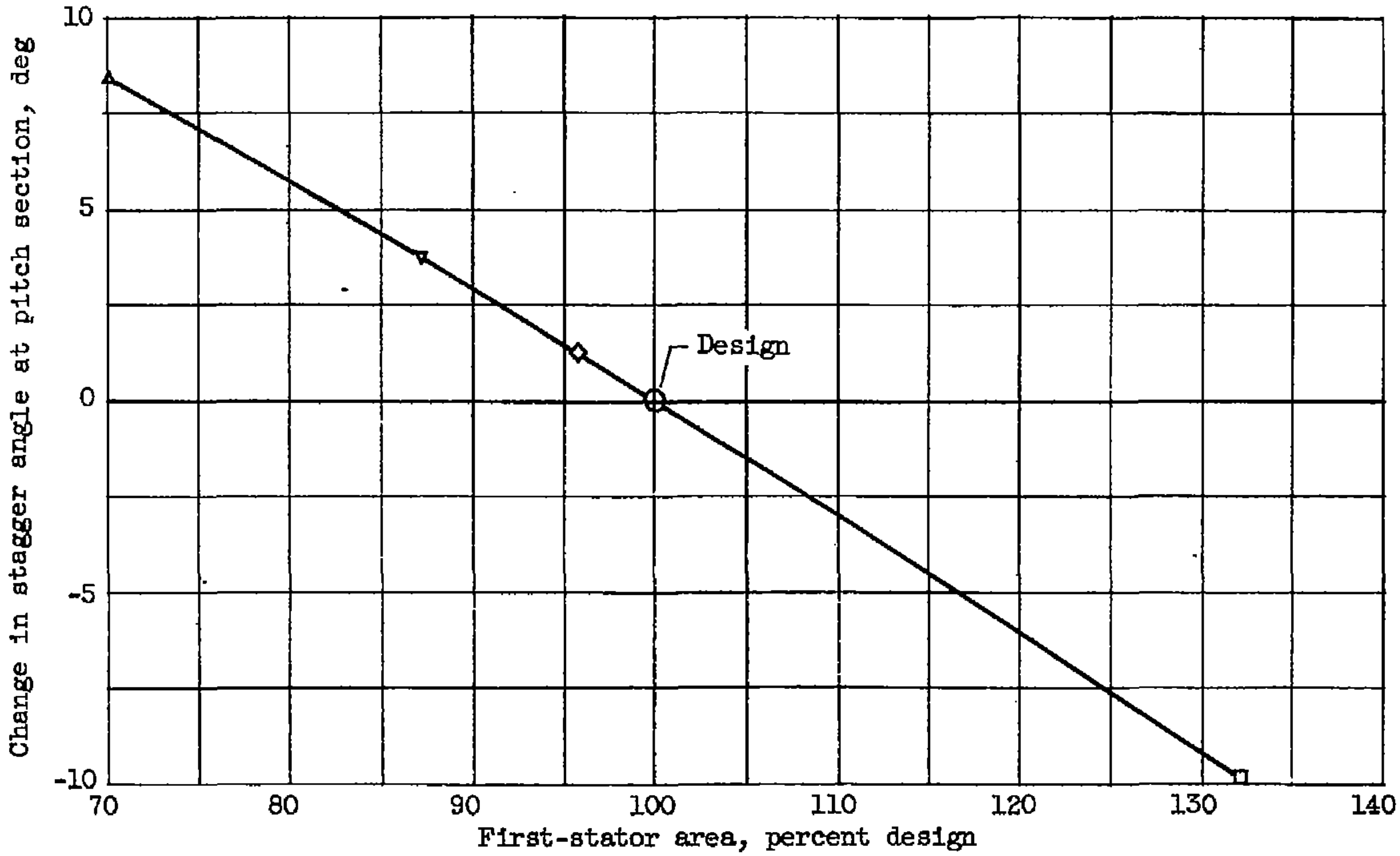
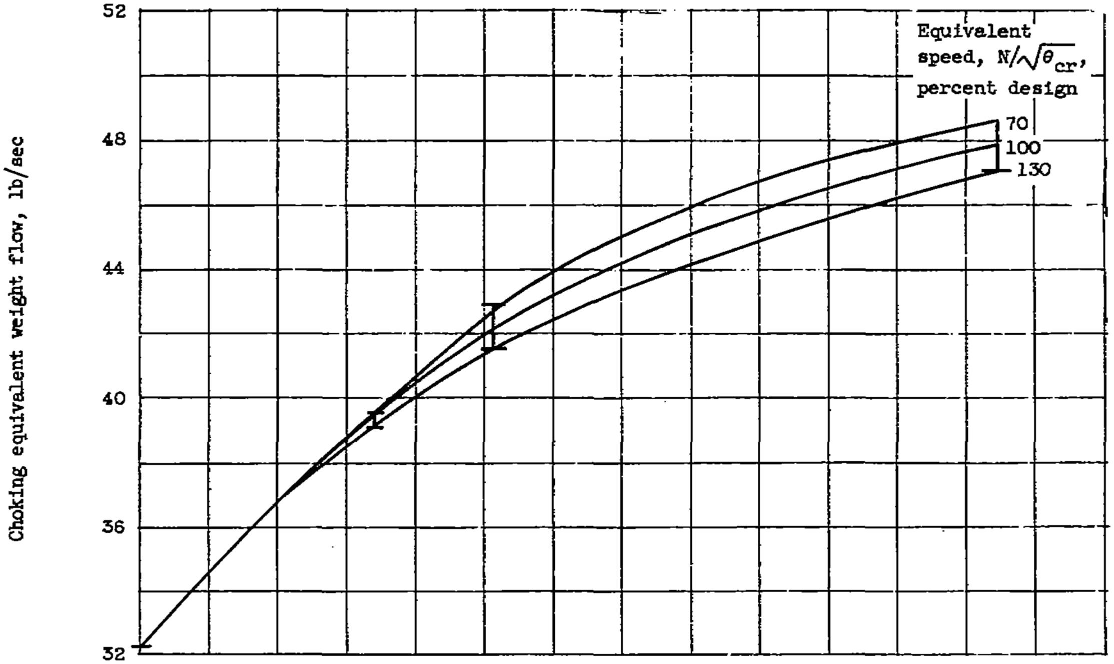
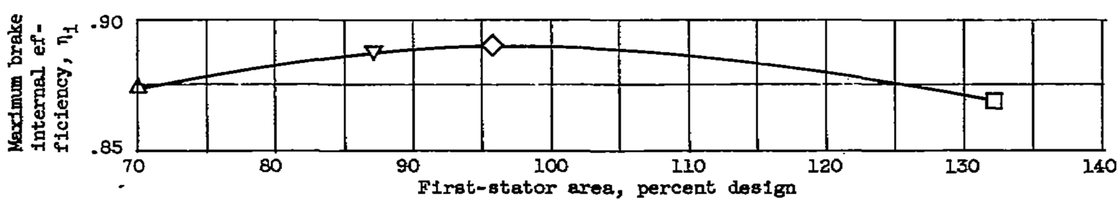


Figure 7. - Variation of stagger-angle change with first-stator area.

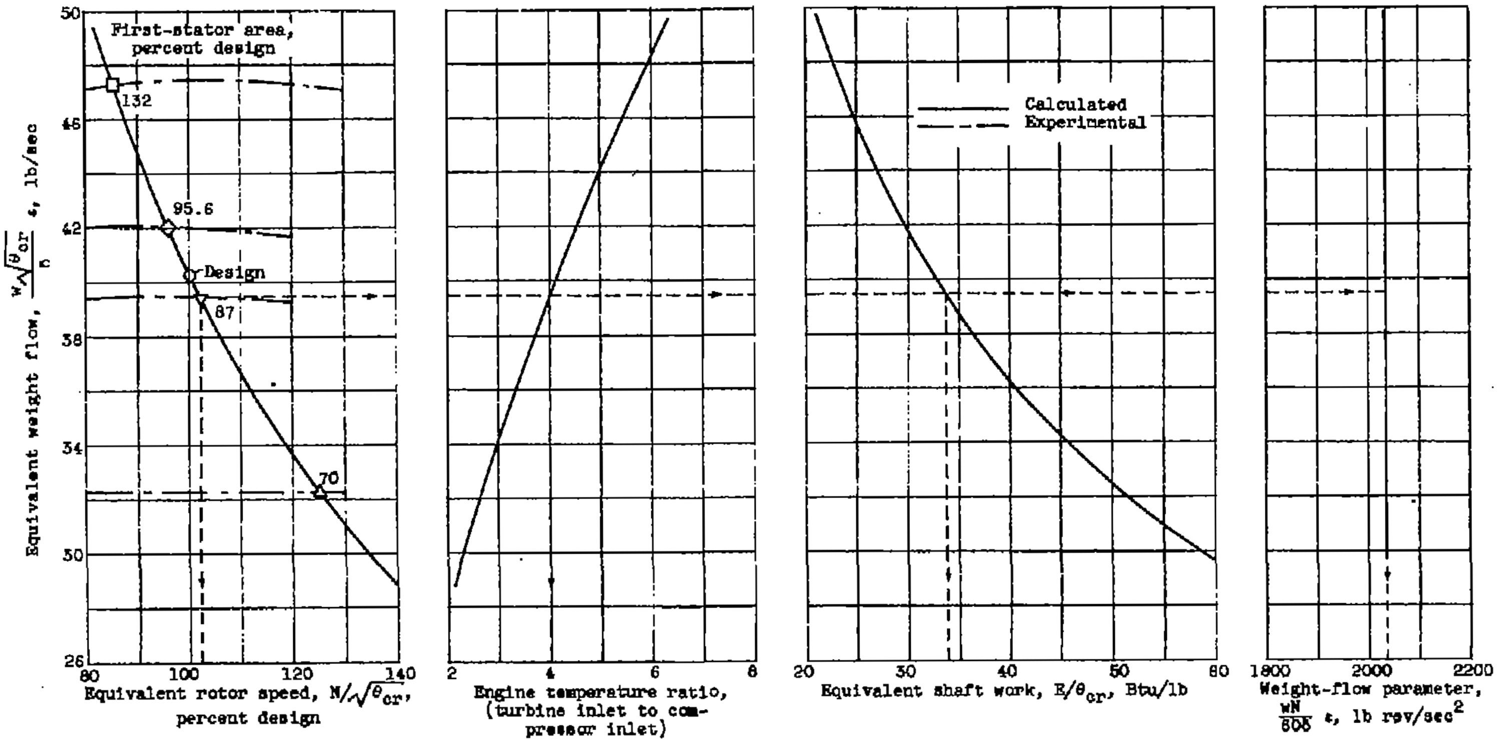


(a) Variation of choking equivalent weight flow with first-stator area.



(b) Variation of maximum brake internal efficiency with first-stator area.

Figure 8. - Effect of first-stage-stator area on choking equivalent weight flow and maximum brake internal efficiency obtained.



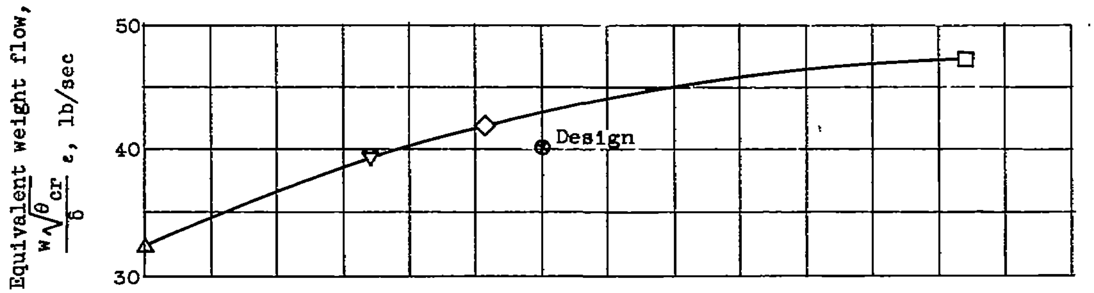
(a) Variation of equivalent weight flow with equivalent rotor speed.

(b) Variation of equivalent weight flow with engine temperature ratio.

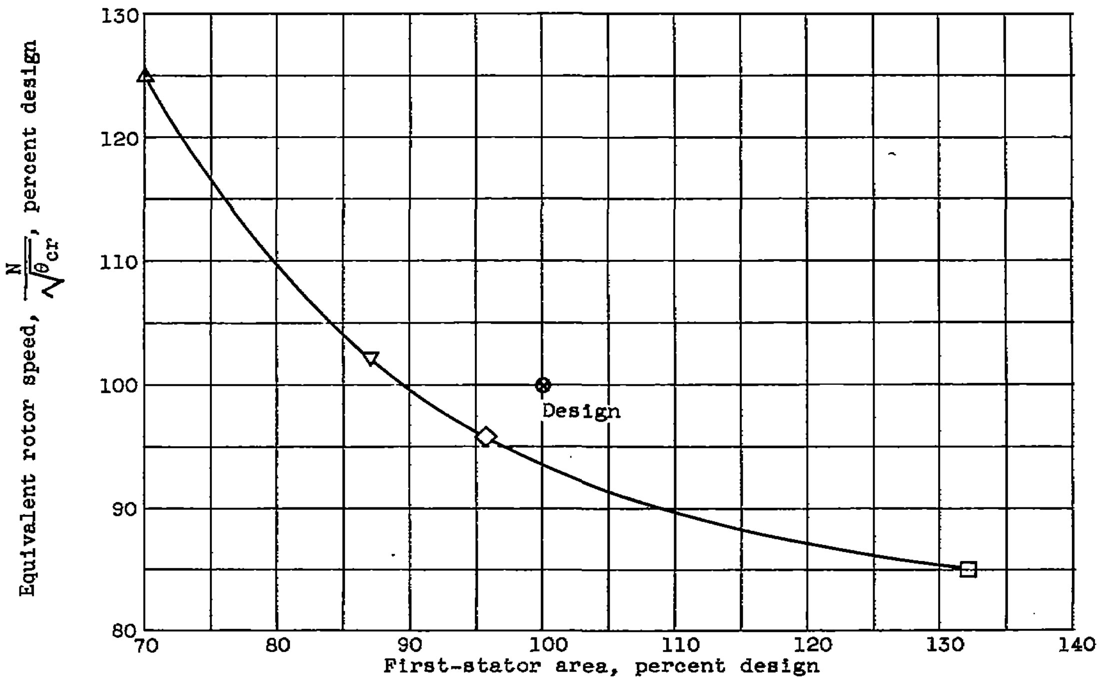
(c) Variation of equivalent weight flow with equivalent shaft work.

(d) Variation of equivalent weight flow with weight-flow parameter.

Figure 9. - Curves for determining required turbine operating conditions for maintaining compressor at constant equivalent design conditions.

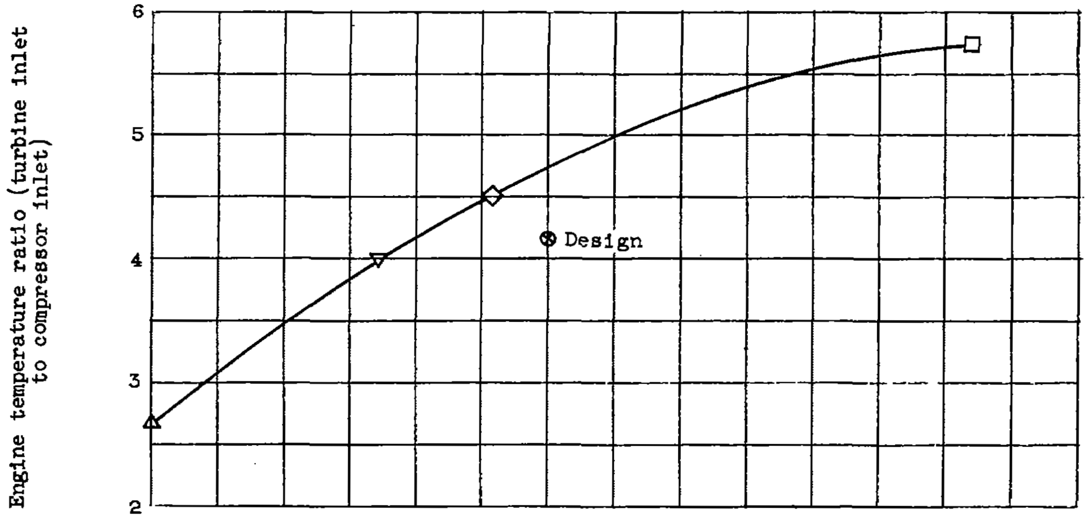


(a) Variation of equivalent weight flow with first-stator area.

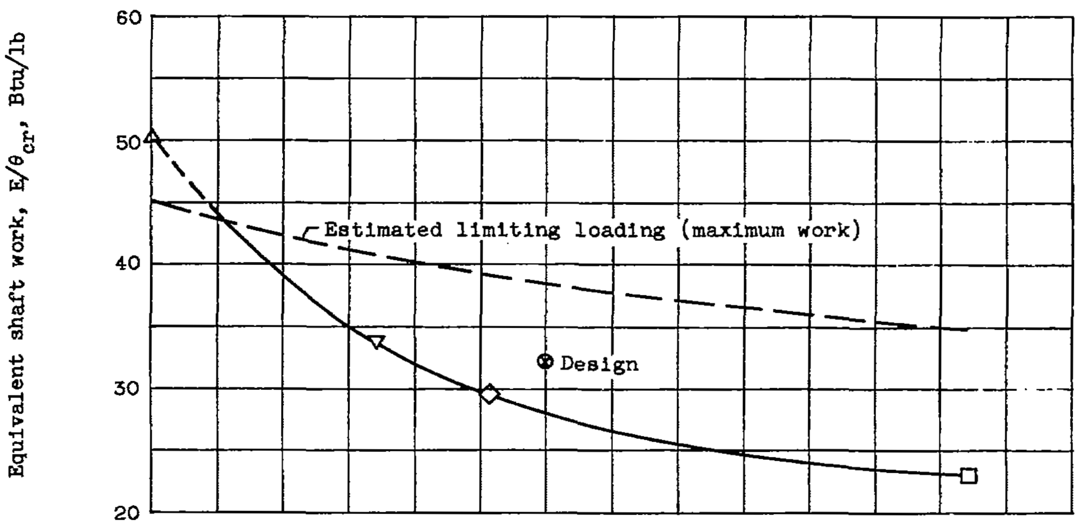


(b) Variation of equivalent rotor speed with first-stator area.

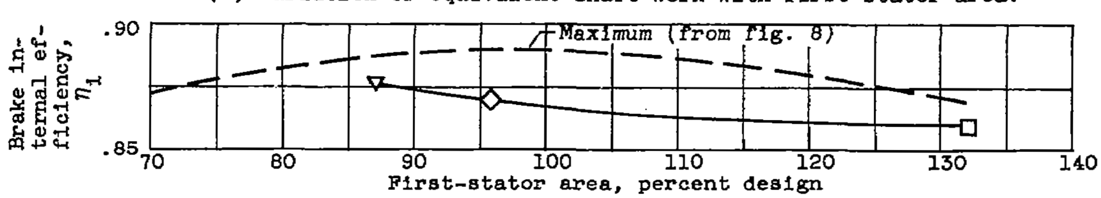
Figure 10. - Effect of first-stage-stator area on various turbine performance parameters at the compressor-turbine match point.



(c) Variation of engine temperature ratio with first-stator area.



(d) Variation of equivalent shaft work with first-stator area.



(e) Variation of brake internal efficiency with first-stator area.

Figure 10. - Concluded. Effect of first-stage-stator area on various turbine performance parameters at the compressor-turbine match point.

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