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EFFECT OF VARIABLE STATOR AREA ON PERFORMANCE OF A SINGLE-STAGE TURBINE SUITABLE FOR AIR COOLING

III. - Turbine Performance With 130-Percent Design Stator Area

by Harold J. Schum, Thomas P. Moffitt, and Frank P. Behning

Lewis Research Center

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ABSTRACT

An experimental investigation of the effect of increasing the stator flow area to 130 percent of design revealed that the choking equivalent mass flow at the equivalent design speed was increased by 18.4 percent. When the performance of the turbine was compared to that obtained for the design-area turbine at its equivalent design operating conditions, it was determined that the efficiency decreased from 0.923 to 0.897 with the reduction due primarily to rotor incidence loss.

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SUMMARY

The performance changes resulting from adjusting the stator area of an experimental 30-inch (0.762-m) single-stage turbine with blading designed to incorporate physical features associated with turbines for high-engine-temperature application are being investigated. The performance of the turbine with design stator area has been previously reported. The performance of this same turbine, modified so the stator area was increased to 130 percent of the design by reorienting the stagger angle of the blades, is presented herein.

When results of these two turbine configurations were compared, it was found that when the stator area was increased by 30 percent, the choking equivalent mass flow for equivalent design speed was increased by 18.4 percent. Comparing the efficiencies at an operating point corresponding to equivalent design speed and an equivalent work output of 17.00 Btu per pound (39 572 J/kg) showed that the efficiency decreased from 0.923 to 0.897 for the subject opened turbine. This decrease in efficiency is primarily attributable to the incidence angle relative to the rotor, which was calculated to be changed about 28° from design.

INTRODUCTION

The NASA is currently conducting a test program on a single-stage 30-inch (0.762-m) tip diameter, cold-air model of a turbine suitable for advanced aircraft using high turbine-inlet temperature and air-cooled blades. Such turbines employ thick blades, with blunt leading- and trailing-edges, and low solitity. A description of the design procedure and the resultant blade shapes are presented in reference 1. The overall performance of this turbine, when tested over a range of speed and pressure ratio, is presented in reference 2. It was reported that turbine efficiency was not adversely affected by the blade aerodynamic compromises. An efficiency of 0.923 was obtained at equivalent design speed and work output. The attendant mass flow was 1.8 percent greater than design.

The design of turbines of this type should, however, include considerations of maintaining good performance over the range of operating conditions encountered in the aircraft flight plan. One method considered is the use of variable turbine geometry as a means of permitting the engine to operate at optimum cycle conditions as flight conditions vary. Such turbines would typically employ adjustable stators to vary the flow rate for a given pressure ratio, thereby representing off-design conditions of turbine operation. It is also desirable to maintain high turbine efficiency at these off-design conditions of operation.

In order to better understand the performance characteristics of turbines incorporating variable stator area, two additional stators were fabricated - one having a flow area 30 percent greater than design, and the other having an area 30 percent less than design. Both stators were investigated with the same rotor as that used for the design stator area turbine (ref. 2). For the increased stator area turbine configuration, this area increase was effected by changing the stagger angle of the design blade profiles by 8.44°. When this stator was tested as a separate component (ref. 3), it was found that the unit actually had passed 133 percent of the equivalent design mass flow at corresponding design pressure ratio. From additional stator component tests (ref. 4) at this pressure ratio, it was found that the kinetic energy loss across the blade row was 0.035.

This report presents the results of the investigation made to experimentally determine the effect of the increased stator area on overall turbine stage performance. The turbine was operated over a range of speed and pressure ratio. Turbine inlet pressure was maintained constant at 30 inches of mercury absolute (1.0159×10^{5} N/m^{2}). Turbine inlet temperature was approximately 540° R (300 K). Speed was varied from 40- to 110-percent equivalent design speed in increments of 10 percent. The total pressure ratio was varied from 1.25 to 2.25. Experimental values of equivalent mass flow, equivalent torque, and rotor exit flow angle are presented in addition to a performance map. Turbine efficiency, based on total pressure ratio, is used to indicate turbine performance.

For convenience in the ensuing discussion, the subject turbine, equipped with the stator having a flow area 130 percent that of design, will hereinafter be referred to as the "subject opened" turbine. Correspondingly, when the performance of this turbine is compared to that obtained for the turbine having the design-area stator (ref. 1), the latter turbine configuration will be referred to as the "reference-design" turbine.

SYMBOLS

A annular flow area, ft^{2}; m^{2}

g	force-mass conversion constant, 32.174 ft/sec^2
h	specific enthalpy, Btu/lb; J/kg
N	rotational speed, rpm; rad/sec
p	absolute pressure, lb/ft^2; N/m^2
R	gas constant, 53.34 ft-lb/(lb)($^{\circ}$R); 287 J/(kg)(K)
T	temperature, $^{\circ}$R; K
w	mass-flow rate, lb/sec; kg/sec
α	flow angle, measured from axial, positive in direction of rotor rotation, deg
α_s	blade stagger angle, measured from axial, deg
γ	ratio of specific heats
δ	ratio of inlet pressure to U.S. standard sea-level pressure
η	efficiency based on total pressure ratio
θ_{cr}	squared ratio of critical velocity ratio at turbine inlet to critical velocity of U.S. standard sea-level air
τ	torque, ft-lb; N-m

Subscripts:

cr	condition at Mach 1
0	measuring station at turbine inlet
i	measuring station at stator throat
1	measuring station at stator outlet
2	measuring station at rotor outlet

Superscripts:

'	total

APPARATUS AND INSTRUMENTATION

A description of the turbine design, complete with rotor and stator blade coordinates is presented in reference 1. For the subject turbine configuration, the design-area stator was replaced with one having the same blade profiles reoriented to the stagger angle required to increase the mean-section channel exit orthogonal length to a value

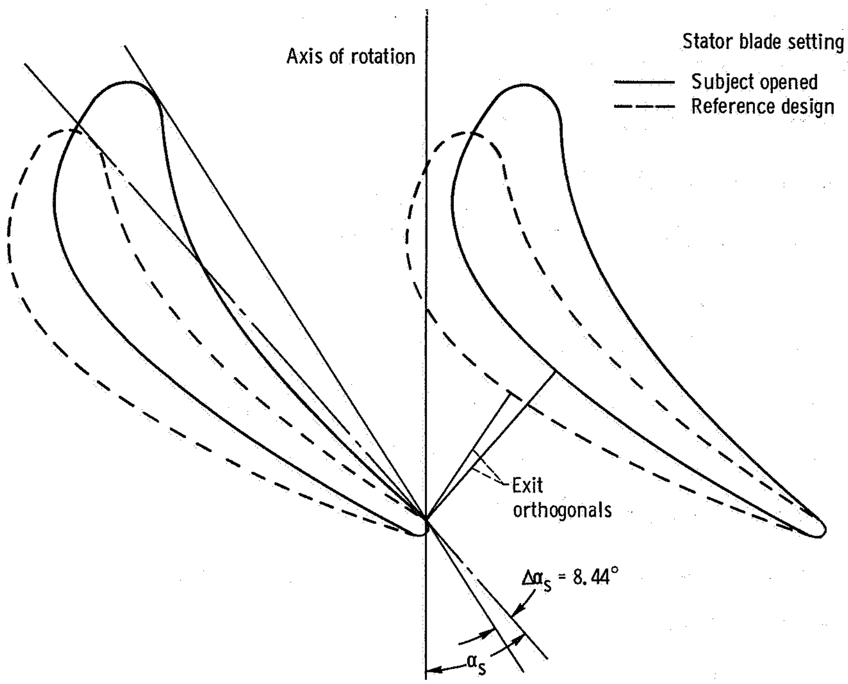


Figure 1. - Comparison of stator blade mean-section orientation for the two turbine configurations.

30 percent greater than that of the design stator. The technique used is described in reference 3. The resultant stagger angle change (8.44°) is shown diagramatically in figure 1. The rotor was the same as the one used for the turbine performance evaluation with the design-area stator (ref. 2). A photograph of the rotor is presented in figure 2.

The test facility for the subject opened turbine was identical to that used for the performance evaluation of the reference design turbine (ref. 2). A photograph of the experimental installation is presented in figure 3. A schematic diagram of the overall turbine setup is shown in figure 4.

The instrumentation required to determine the overall performance of the subject opened turbine was the same as that described in reference 2. Measurements were made at the axial locations shown in the inset of figure 4. To avoid circumlocution, figure 5 is provided to show the axial-circumferential locations of the turbine instrumentation. It will be noted that additional static pressure measurements were provided in the plane of the stator exit orthogonals (measuring station i; see fig. 1) midway between adjacent blades. A total of four taps was provided on both the inner and outer walls, diametrically opposed and about 90° removed.

The air mass flow was metered with a calibrated Dall tube located in the inlet air supply piping preceding the control valves. Rotative speed was measured with an electronic counter in conjunction with a magnetic pickup and a sprocket located on the turbine shaft. The turbine torque was measured on the dynamometer stator with a strain-gage-type load cell in conjunction with a digital voltmeter.

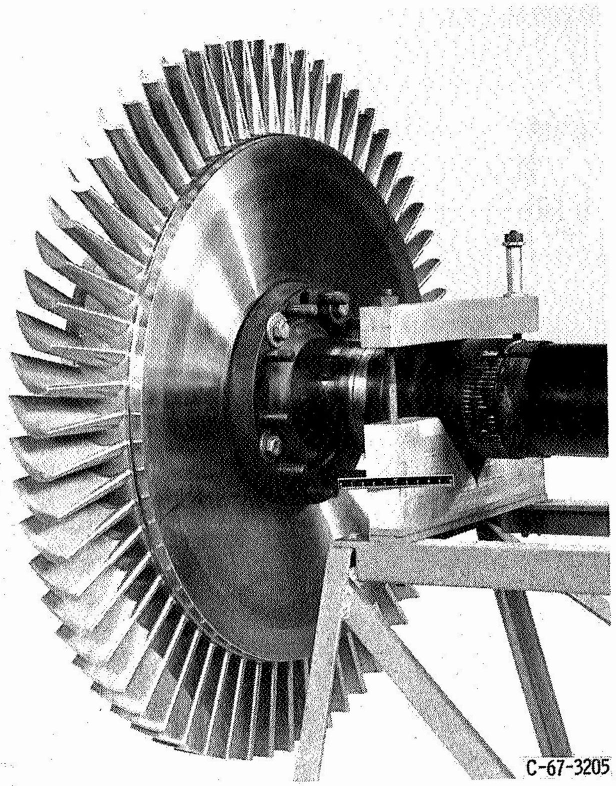


Figure 2. - Turbine rotor assembly.

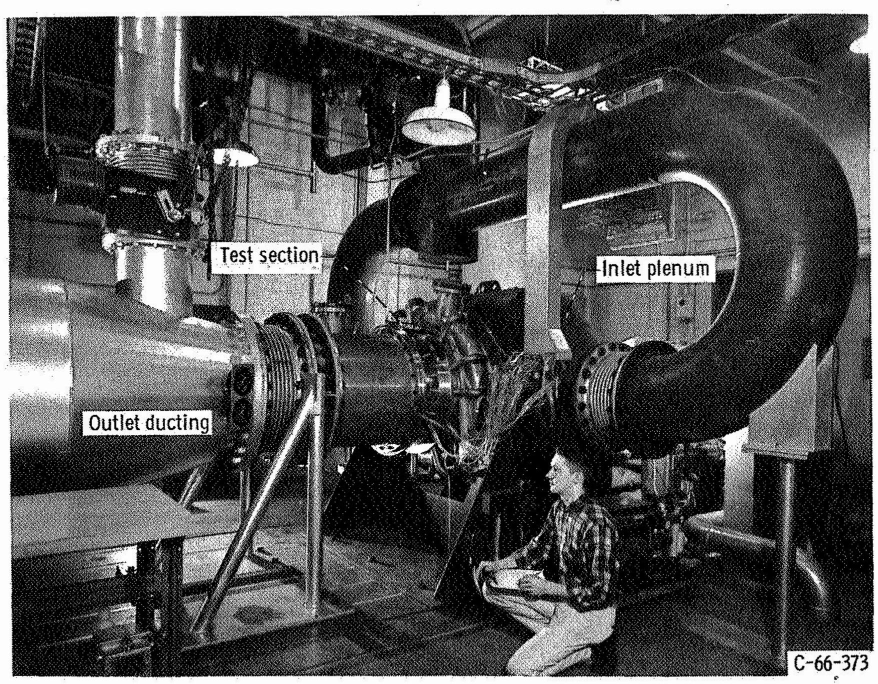


Figure 3. - Test facility.

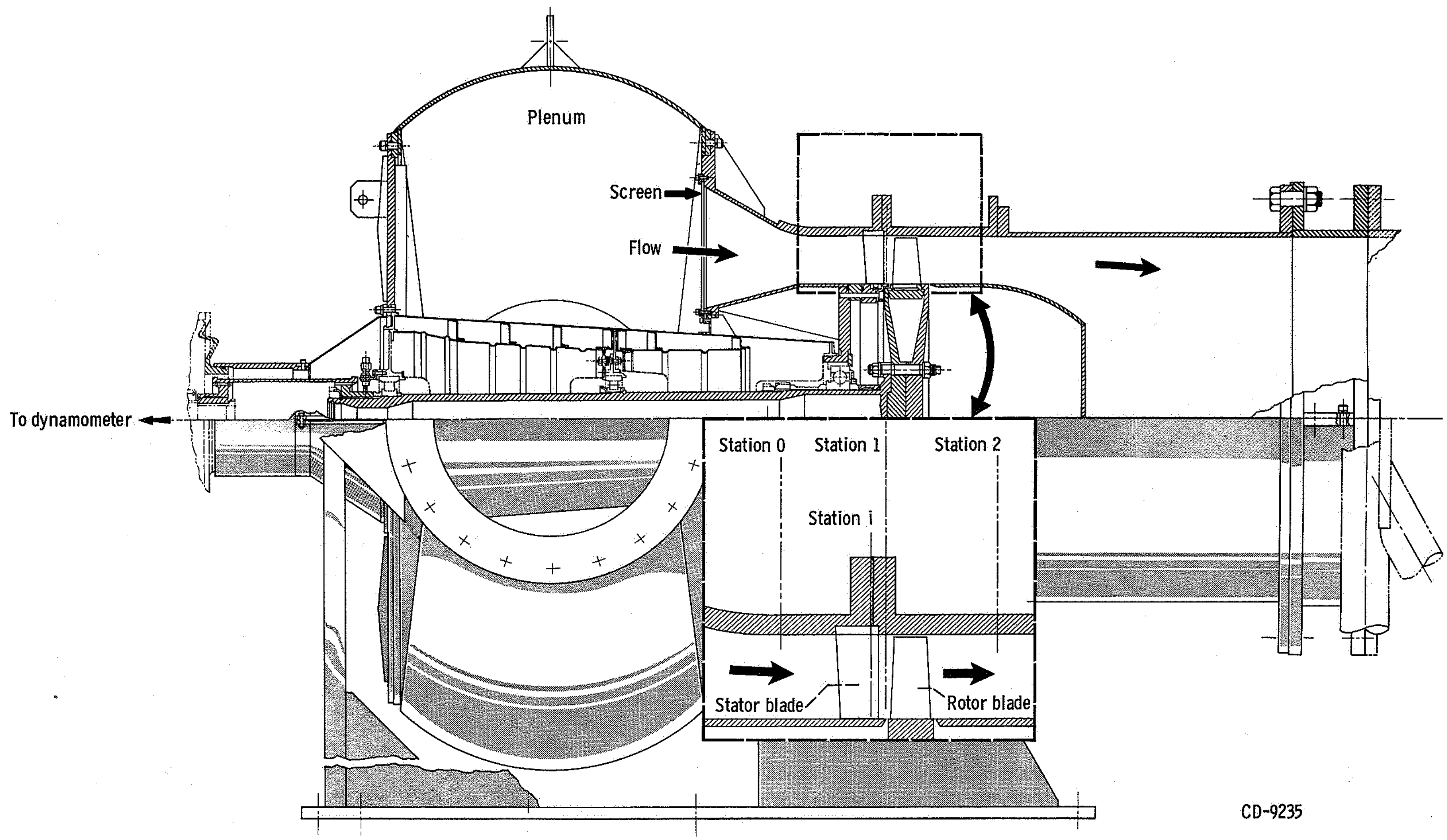


Figure 4. - Schematic diagram of turbine test section.

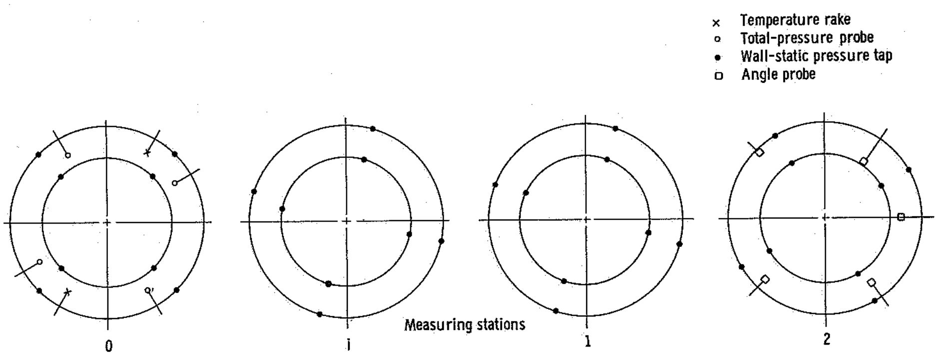


Figure 5. - Schematic diagram of turbine stator instrumentation, viewed upstream.

PROCEDURE

The turbine was rated on an inlet to outlet total pressure ratio p_0'/p_2'. Inlet total pressures were calculated from the average of the wall static pressure readings, the average inlet total temperature, the known annulus area, and the turbine air-mass flow rate. The flow was determined to be axial at the inlet. The equation used to calculate inlet total pressure is reproduced herein from reference 2 for convenience as follows:

$$\frac{p_0'}{p_0} = \left[\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{\gamma - 1}{2g\gamma}\left(\frac{w}{p_0 A_0}\right)^2 RT_0'}\right]^{\gamma/\gamma-1} \tag{1}$$

Outlet total pressure was similarly calculated from the expression

$$\frac{p_2'}{p_2} = \left[\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{\gamma - 1}{2g\gamma}\left(\frac{w}{p_2 A_2}\right)^2 \frac{RT_2'}{\cos^2 \alpha_2}}\right]^{\gamma/\gamma-1} \tag{2}$$

Outlet temperature T_2 was calculated from the inlet temperature and the specific work output as determined from measured values of torque, mass flow, and rotative speed. Flow angle α_2 was taken as the average divergence angle from axial, as obtained from the five angle-sensitive probes located at measuring station 2 (see fig. 5).

The turbine was operated at a nominal inlet pressure p_0' of 30 inches of mercury absolute (1.0159×10^5 N/m^2). Inlet temperature was that of the laboratory combustion air system and it varied from 535° to 559° R (297.2 to 310.6 K). The turbine was investigated over a range of speed from 40 to 110 percent of the design equivalent speed (4407 rpm (461.5 rad/sec)) in 10 percent increments. At each speed the turbine was operated over a total pressure ratio range. Equivalent mass flow $w\sqrt{\theta_{cr}}/\delta$ and torque data τ/δ were obtained and plotted as functions of total pressure ratio p_0'/p_2'. A performance map was then constructed in terms of equivalent specific shaft work output $\Delta h/\theta_{cr}$, a mass flow - speed parameter wN/δ, total pressure ratio p_0'/p_2', and efficiency η.

RESULTS AND DISCUSSION

The results of the investigation are presented in two sections. The first section presents the experimental results of the subject opened turbine tests in the usual manner. The latter section compares these results at equivalent design speed conditions with those obtained for the reference design turbine tests presented in reference 2. Such a comparison is made to study the effect of increasing the stator area on the general level of turbine performance.

Stage Performance of Subject Opened Turbine

The overall turbine performance is presented in terms of torque and mass-flow characteristics and the resultant performance map. In addition, the variation in static pressure distribution at various station locations through the turbine is shown. Finally, the change in absolute flow angle at the turbine exit is presented as a function of the speed and overall pressure ratio.

Overall turbine performance. - The variation of equivalent torque τ/δ with total pressure ratio p_0'/p_2' for the equivalent speeds $N/\sqrt{\theta_{cr}}$ tested is shown in figure 6. As expected, the torque increased with pressure ratio for all speeds. Limiting loading was not obtained over the range of pressure ratio imposed across the turbine, as evidenced by the continual increase of torque with pressure ratio. At the higher speeds, however, the diminishing slopes of the torque curves at the higher pressure ratios indicate the turbine is approaching the limiting loading condition.

The variation of equivalent mass flow $w\sqrt{\theta_{cr}}/\delta$ with total pressure ratio for the equivalent speeds investigated is presented in figure 7. Choking mass flow, indicated when the curves for each speed have a zero slope, was obtained for all speeds tested.

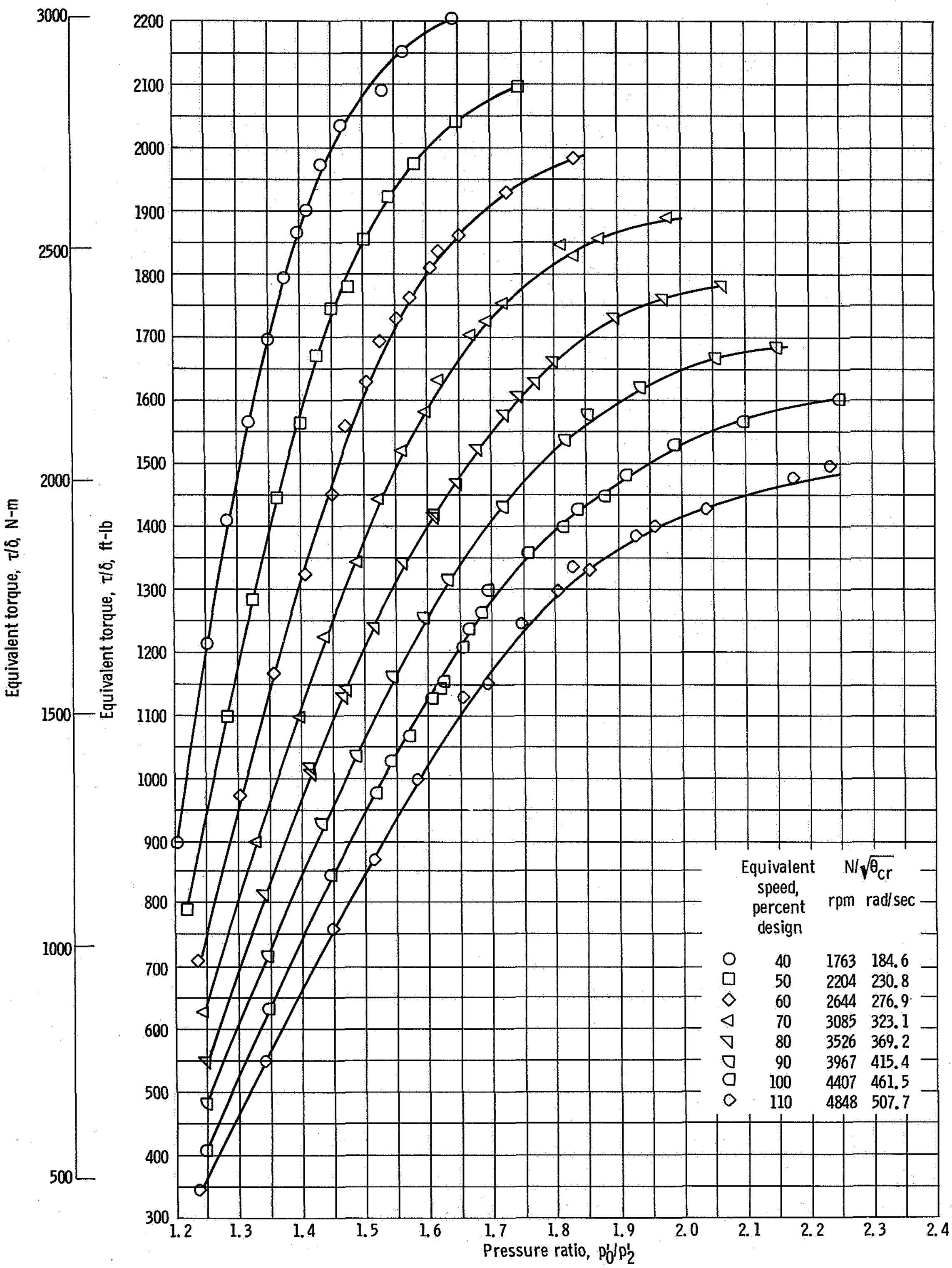


Figure 6. - Variation of equivalent torque with total pressure ratio for various equivalent rotor speeds.

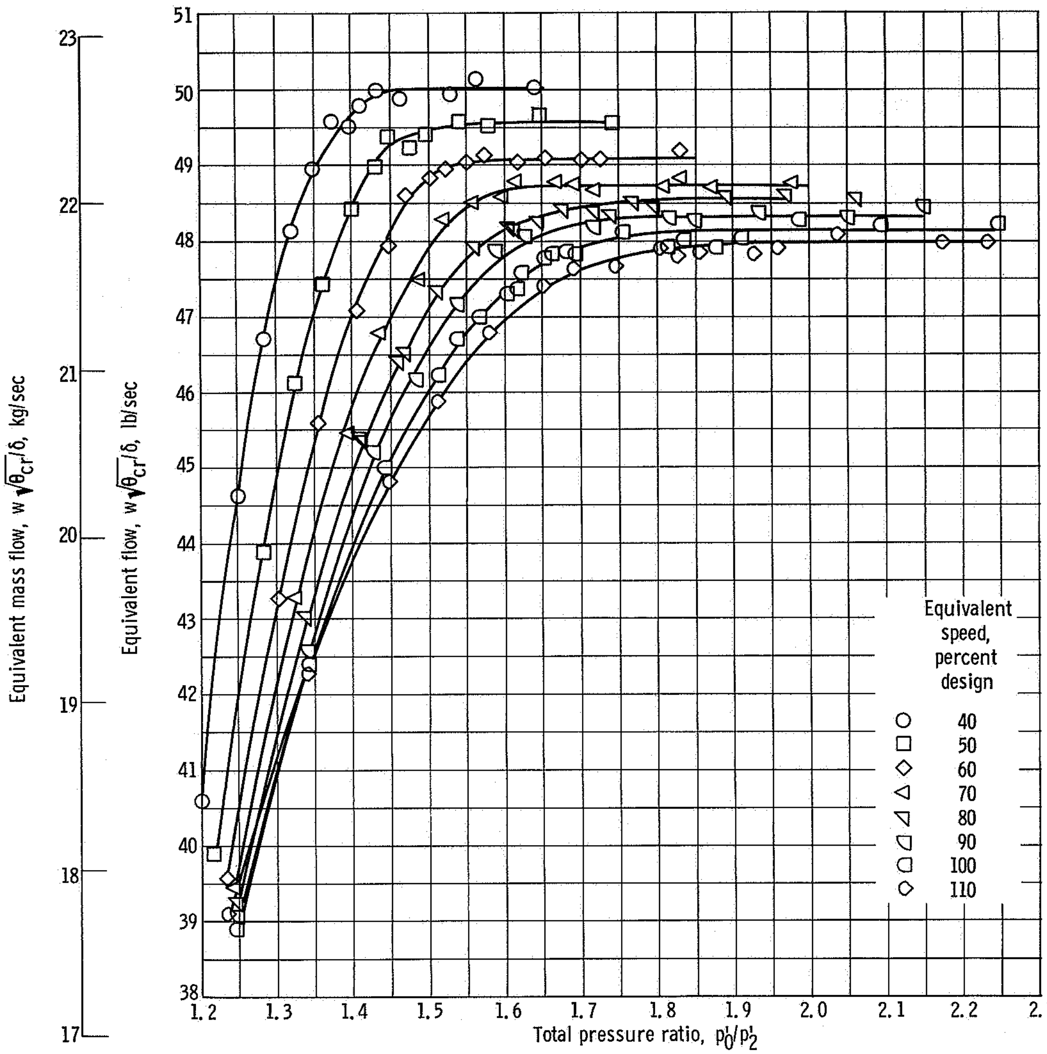


Figure 7. - Variation of equivalent mass flow with total pressure ratio for various equivalent rotor speeds.

The choking mass flow decreased with an increase in speed, which indicated the stator was unchoked, and the rotor was choked. A choking mass flow of 48.15 pounds per second (21.84 kg/sec) was obtained at the equivalent design speed and for total pressure ratios above 1.9.

The performance map was evolved from the data of figures 6 and 7. Readings of equivalent torque and mass flow were faired for each speed in order to minimize random experimental inaccuracies. Then, at a given pressure ratio, and for each speed, the faired values were used to calculate the equivalent specific shaft work output $\Delta h/\theta_{cr}$, the mass flow - speed parameter wN/δ, and the turbine efficiency η. These overall turbine performance data are presented as a map in figure 8.

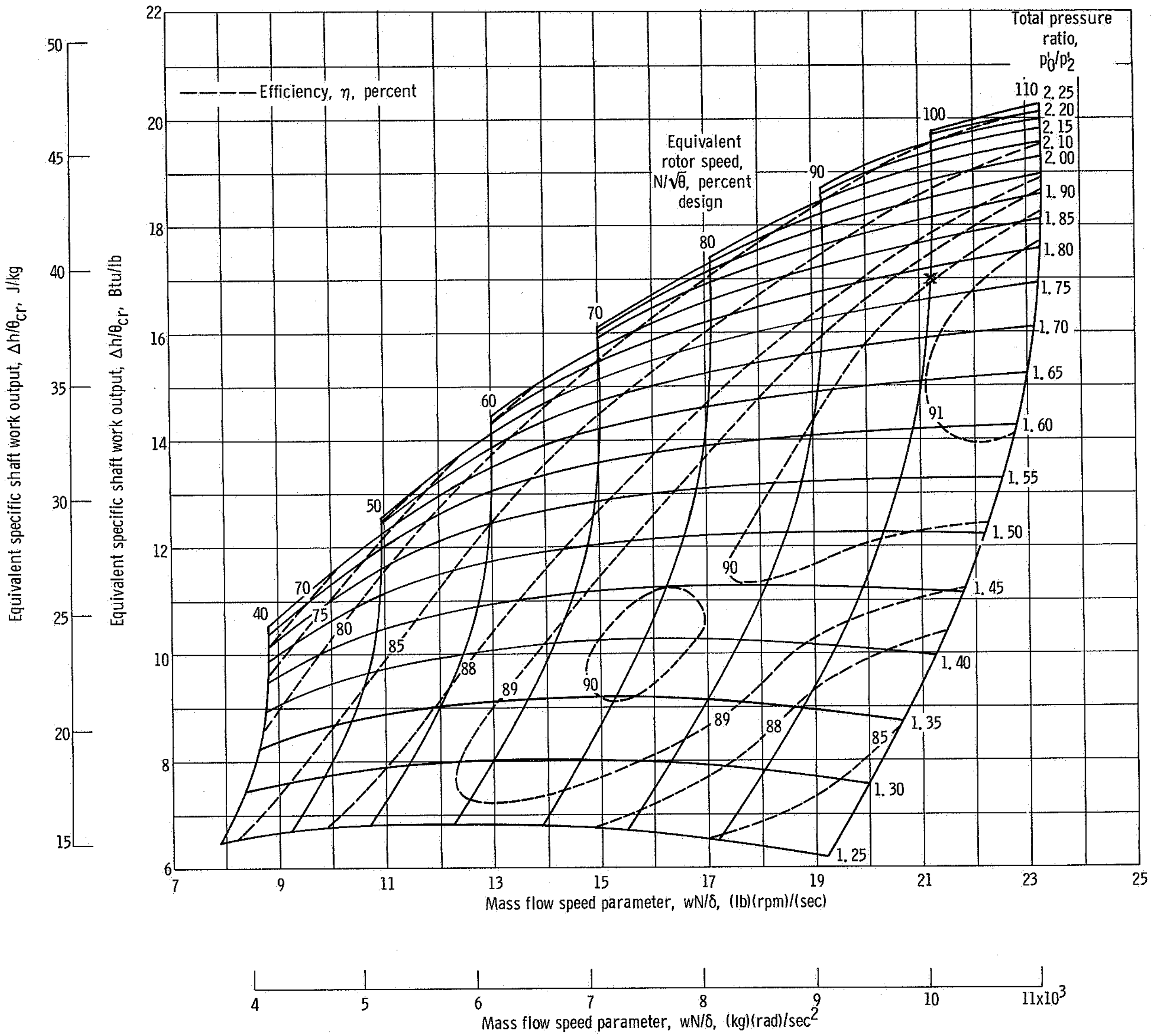
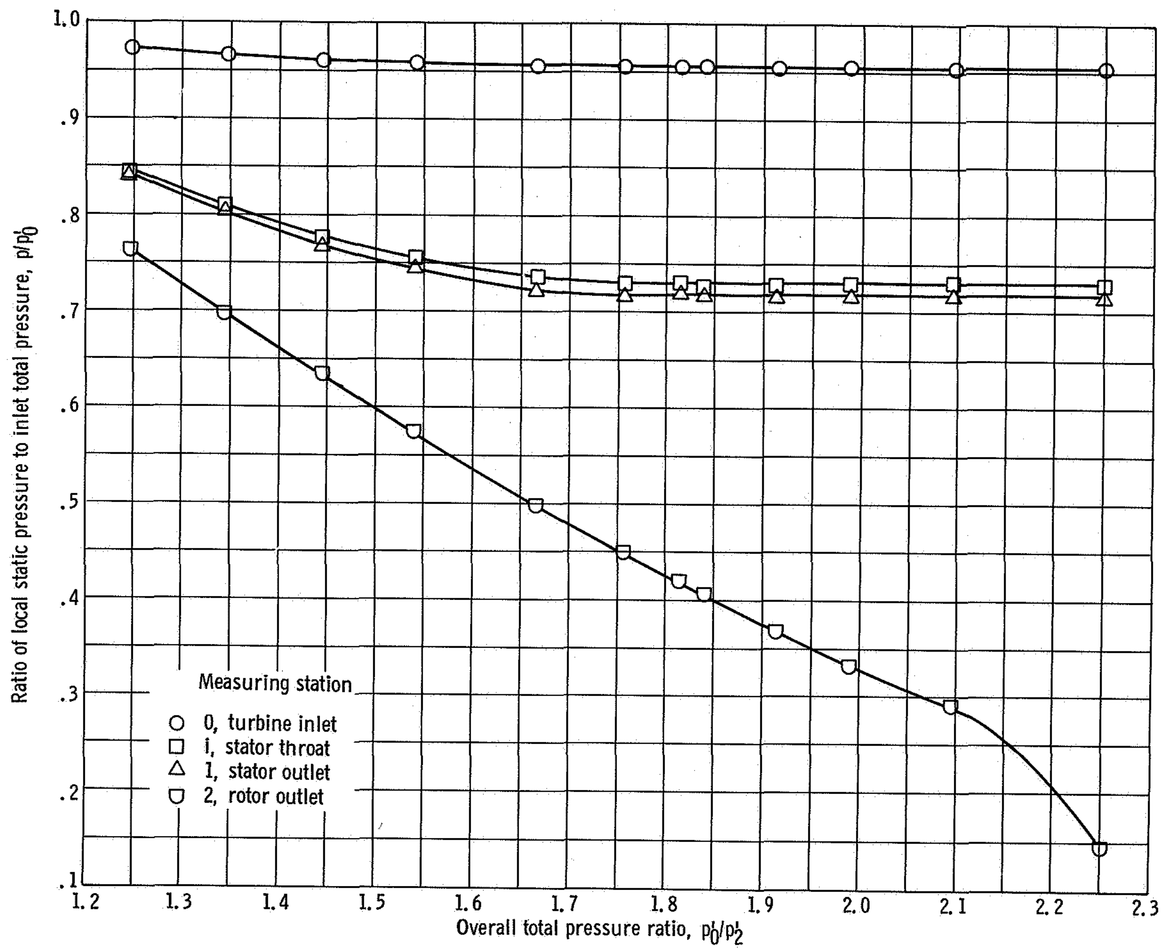


Figure 8. - Overall turbine performance map. Turbine inlet pressure, 30 inches of mercury absolute (1.0159×10^5 N/m^2); turbine inlet temperature from 535° to 559° R (297.2 to 310.6 K).

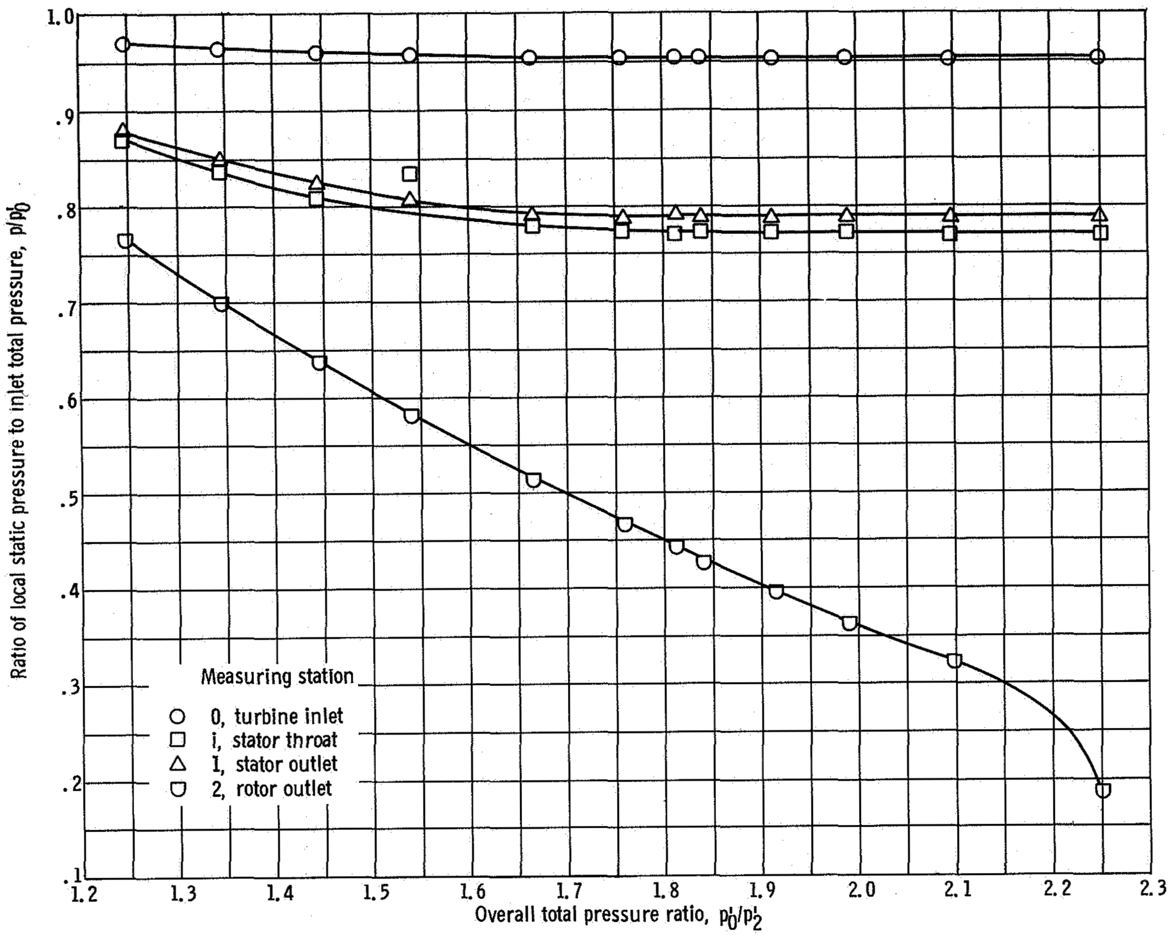
The performance map (fig. 8) shows a broad range of high efficiency with a peak of over 91 percent being attained at the 110 percent equivalent speed. The aforementioned approach to turbine limiting loading can be noted by the convergence of pressure ratio curves at the higher speeds. A symbol X is shown at the equivalent design speed and an equivalent specific work output of 17.00 Btu per pound (39 572 J/kg). This point corresponds to the equivalent design conditions for the reference design turbine (ref. 2). Cross-plots of the data for the equivalent design speed and for the subject opened turbine show this work ouptut was obtained at a total pressure ratio of 1.782; the corresponding efficiency was 0.897. This will be discussed further in the section entitled Comparison With Reference Design Turbine Performance.

Static pressure distribution. - The static pressure distribution through the turbine is shown in figure 9 as a function of overall pressure ratio p_0'/p_2' for data points obtained at the equivalent design speed. Wall static pressure measurements at the hub are pre-



(a) Hub.

Figure 9. - Variation of static pressure through turbine with total pressure ratio at equivalent design speed.



(b) Tip.

Figure 9. - Concluded.

sented in figure 9(a); tip measurements are presented in figure 9(b). 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 blade decreases as the total pressure ratio across the turbine in increased.

Figures 9(a) and (b) show that at a pressure ratio about 1.9 and above, the rotor blade row was choked, as was noted when the equivalent mass flow (fig. 7) was discussed. Reaction across the rotor continually increased with increasing pressure ratios. It is interesting to note that for the hub (fig. 9(a)) a slight static pressure drop occurred from the stator throat (measuring station i) to the stator exit (measuring station 1). The inverse occurred at the tip. This was to be expected, since, in reference 3, which reported the performance of the stator when tested as a component, it was found that the tip section reflected performance similar to a convergent-divergent nozzle. This effect was caused by the geometric shift of the throat forward from the channel exit when the mean-section stator area was increased to 130 percent that of design.

Rotor outlet flow angle. - The flow angle at the turbine outlet is presented in figure 10 as a function of total pressure ratio across the turbine for all speeds investigated. As stated previously, this angle is the numerical average of the five angle measurements obtained at five different radii in the turbine outlet flow passage (measuring station 2; see fig. 5). Positive angles, as measured from axial, occur when the exit whirl is in the direction of rotor rotation.

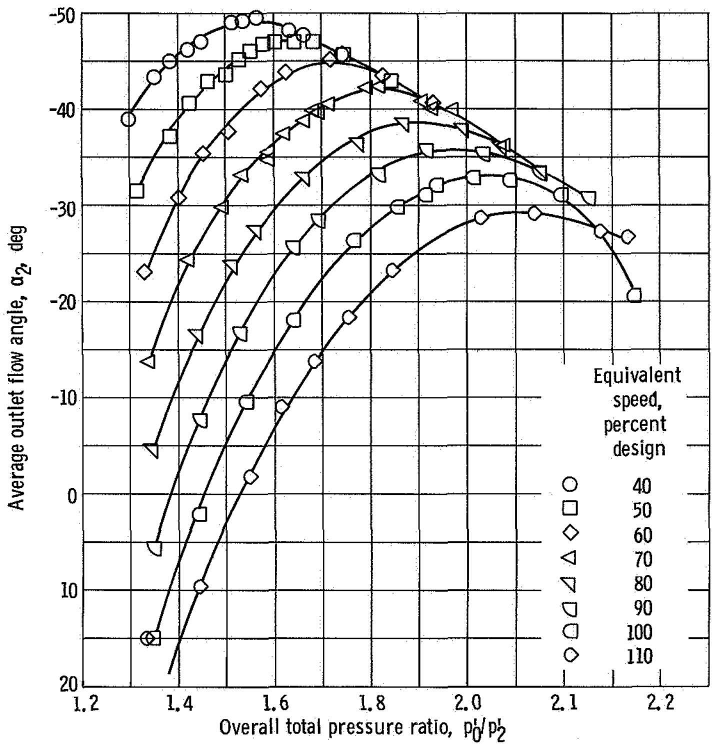


Figure 10. - Variation of outlet flow angle with total pressure ratio for various speeds.

Figure 10 shows that for each speed the outlet flow angle increased negatively with pressure ratio until a peak was obtained, after which it fell off as turbine operation approached limiting loading. A limiting envelope occurred at the higher pressure ratios (higher specific equivalent work outputs) for all speeds. High values of overturning of the flow as compared to a zero exit-whirl stage are observed from the figure. This was to be expected from the results of figure 9, which indicated a high positive reaction across the rotor resulting from the stator exit area being opened. This increased the leaving velocity from the rotor and consequently, also increased the exit whirl. It is also noted from figure 10 that the exit flow approached axial only at a combination of low pressure ratios and high speeds.

Comparison With Reference Design Turbine Performance

Overall performance for the subject opened turbine and the reference design turbine (ref. 2) are compared at the equivalent design speed in terms of equivalent mass flow, equivalent specific shaft work output, and efficiency in figures 11 to 13. These parameters are presented as functions of turbine total pressure ratio. The trends are representative for all speeds. Subsequent discussion will present the differences in reaction and velocity diagram characteristics for the two turbine configurations when compared at a specific comparable operating point.

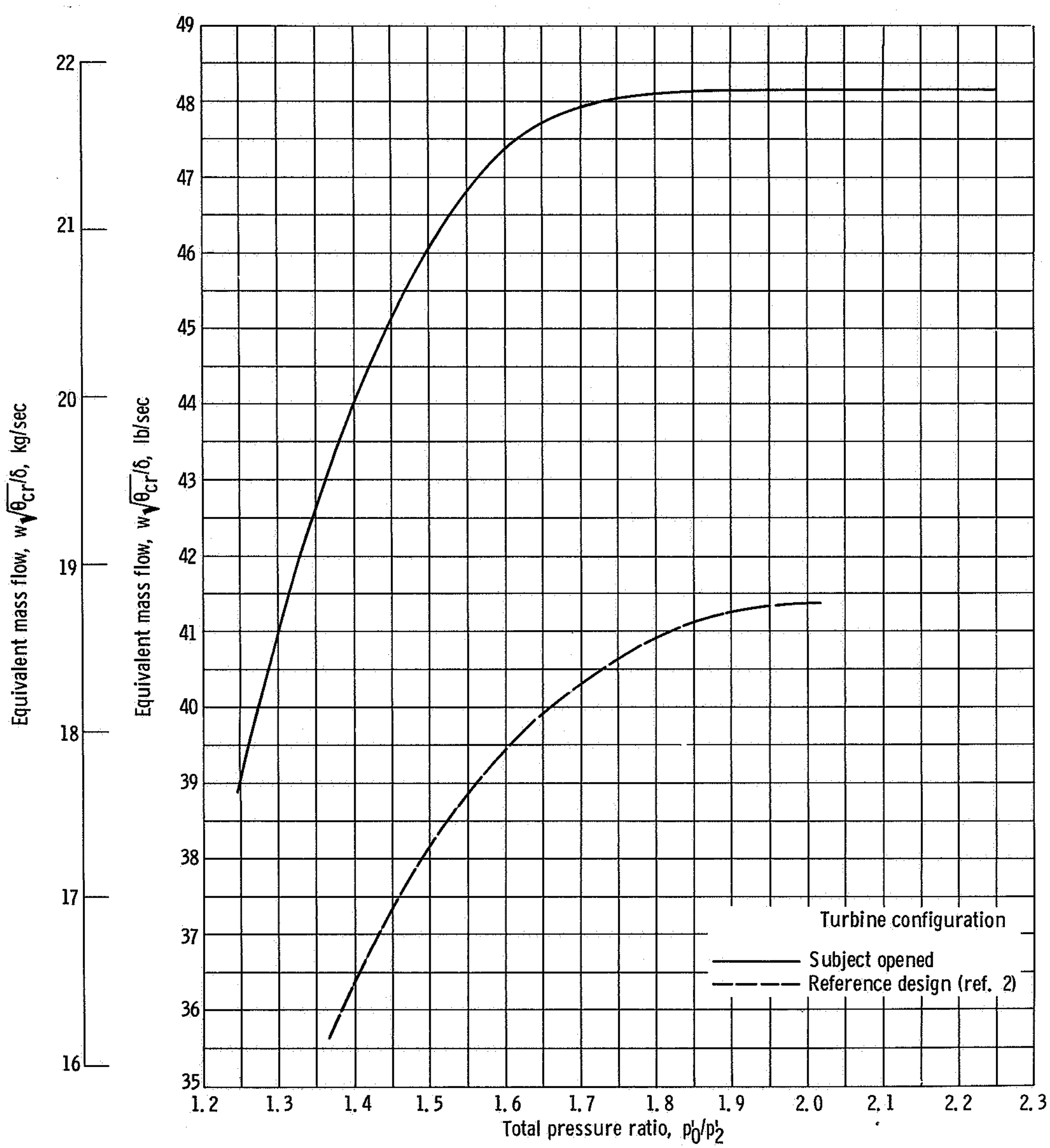


Figure 11. - Variation of equivalent mass flow with total pressure ratio for two turbine configurations at equivalent design speed.

Equivalent mass flow. - Equivalent mass flows obtained at the equivalent design speed for the two turbine configurations are presented in figure 11 as functions of total pressure ratio. The subject opened turbine curve is reproduced from figure 7; the curve for the reference design turbine is from reference 2. As stated previously, the subject turbine choked at a value of 48.15 pounds per second (21.84 kg/sec) at pressure ratios above 1.9. Although the reference turbine did not choke, it appears that had the pressure ratio been slightly increased, a choking value near 41.35 pounds per second (18.76 kg/sec) would be obtained. Increasing the stator area, then, by 30 percent, resulted in an increase of about 16.4 percent in the choking equivalent mass flow, the flow being limited by the rotor blade exit flow area.

Equivalent specific shaft work output. - A comparison of the equivalent specific shaft work output for the two turbine configurations, obtained at the equivalent design speed, is presented in figure 12. At a given pressure ratio, it is apparent the reference design

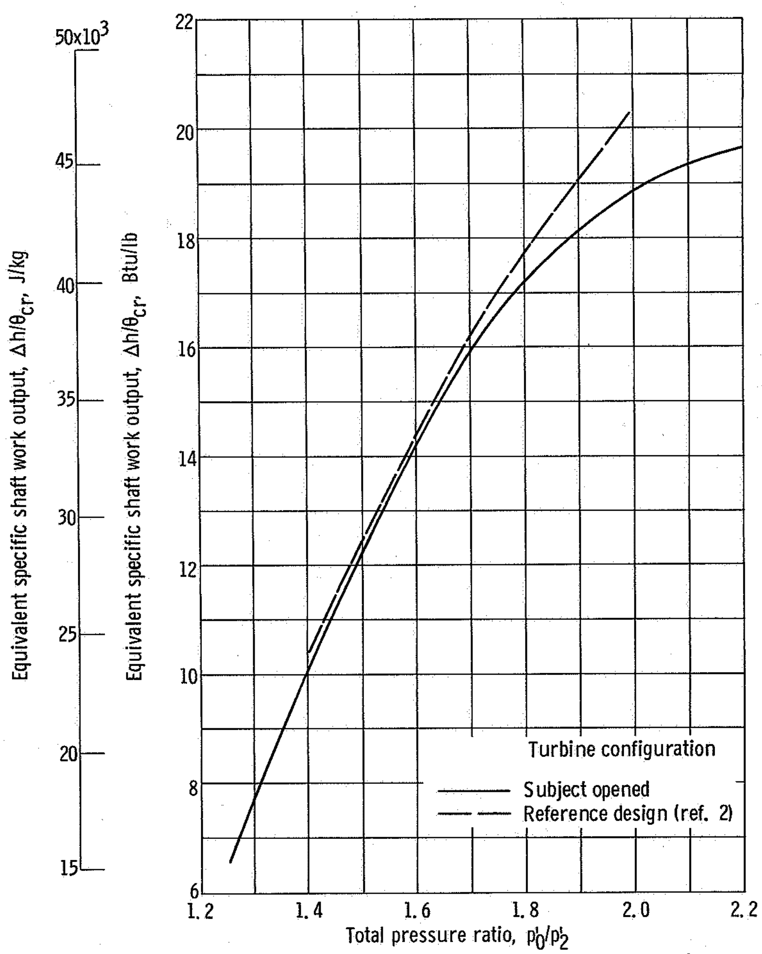


Figure 12. - Variation of equivalent specific shaft work output with total pressure ratio for two turbine configurations at equivalent design speed.

turbine had a slightly higher efficiency in that it yielded more work. It is also apparent that the subject opened turbine more nearly approached limiting loading than did the reference turbine. This is evidenced by the decreased slope of the curve for the subject turbine at the higher total pressure ratios.

Results from the investigation of the reference design turbine (ref. 2) indicated that at the equivalent design speed and equivalent design specific work output of 17.00 Btu per pound (39 572 J/kg), the efficiency was 0.923, occurring at a total pressure ratio of 1.751. The corresponding work output for the subject opened turbine was attained at a total pressure ratio of 1.782. The attendant mass flow, from figure 11, was 48.10 pounds per second (21.82 kg/sec), which was very nearly the choking mass flow. This flow compares to a value of 40.64 pounds per second (18.43 kg/sec) obtained at the aforementioned total pressure ratio of 1.751 for the reference design turbine (ref. 2). Hence, for the same equivalent specific shaft work output, increasing the stator area by 30 percent resulted in an increase in equivalent mass flow of 18.4 percent.

Turbine efficiency. - The variation of turbine efficiency for the two turbine configurations, obtained at the equivalent design speed and over a range of total pressure ratio, is presented in figure 13. Data for the reference design turbine were obtained from the data of reference 2, and, as indicated, show a relative insensitivity to pressure ratio. All efficiency values were above 0.90: a value of 0.923 occurred at a total pressure ratio of 1.751, which corresponds to the design equivalent shaft work output of 17.00 Btu per pound (39 572 J/kg).

The subject opened turbine yielded lower efficiencies over the entire range of comparable pressure ratios (see fig. 13). The peak efficiency obtained at the design equivalent speed was 0.909, and it occurred at a total pressure ratio of 1.650. At a total pressure ratio of 1.782, the value at which the 17.00 Btu per pound (39 572 J/kg) was obtained, the subject turbine produced an efficiency of 0.897, or 0.026 lower than for the reference turbine. As will be indicated later, this difference in efficiency results principally from the higher rotor incidence loss of the subject turbine.

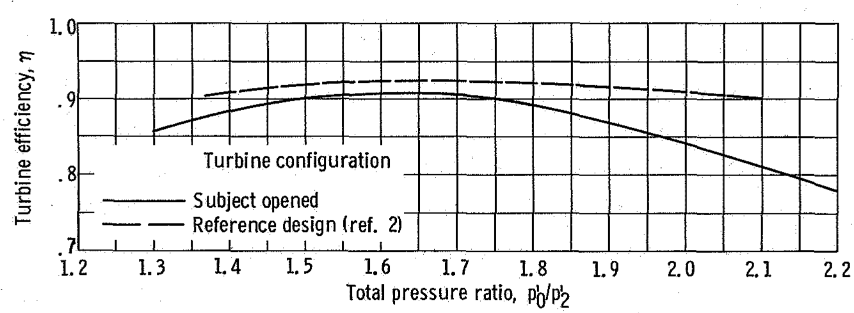


Figure 13. - Variation of turbine efficiency with total pressure ratio for two turbine configurations of equivalent design speed.

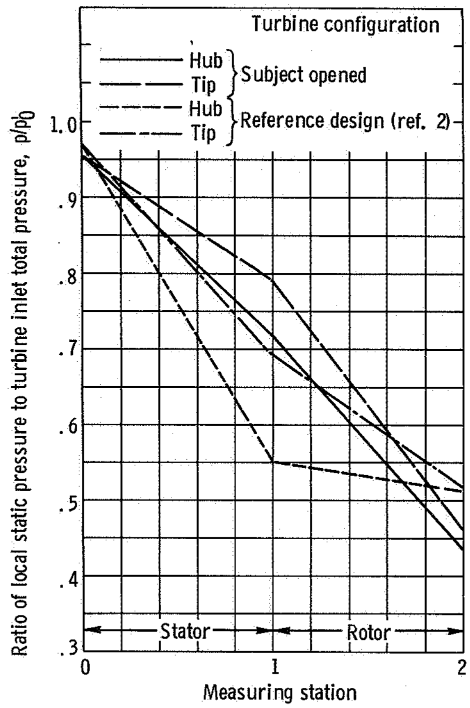


Figure 14. - Comparison of static pressure variation through turbines. Experimental values correspond to equivalent design speed and equivalent specific work output of 17.00 Btu per pound (39 572 J/kg).

Static pressure variation. - A comparison of the static pressure variation related to the inlet total pressure for the two turbines is presented in figure 14. The specific operating point used as the basis for comparison is design equivalent speed and 17.00 Btu per pound (39 572 J/kg) of work output for each turbine. The data shown for the reference design turbine are taken from figure 11 of reference 2. As expected from the previous discussion, the stator of the subject opened turbine is seen to be considerably underexpanded as compared to the reference design turbine. At the same time, considerably more reaction is imposed across the rotor of the subject opened turbine. To produce the same work, then, the flow would be underexpanded in the stator (negative rotor incidence) and overturned out of the rotor (more exit whirl) for the subject opened turbine when compared to the reference design turbine. The lower inlet pressure noted from figure 14 is of course due to the higher flow and inlet Mach number of the subject opened stator. Also, because of higher losses, the subject turbine required a larger pressure drop across the stage, as can be seen at measuring station 2 in the figure.

Velocity diagram comparison. - A mean radius velocity diagram was calculated from the experimental results of the subject opened turbine in the same manner as described for the reference design turbine in reference 2. In this procedure, the assumption is made that the specific work output, specific mass flow, and stator outlet flow angle at the mean radius can be taken as the average for the blade row. The resultant velocity diagram is shown and compared to that for the reference design turbine (fig. 12 of ref. 2) in figure 15. Again, the specific operating point used for comparison is design equivalent speed and 17.00 Btu per pound (39 572 J/kg).

Figure 15 shows that the stator exit flow angle α_1 changed 8.39° and corresponds to the change in stator stagger angle (8.44°) required to effect the 30-percent area increase for the subject stator blade row. The aforementioned overturning of the flow out of the rotor can be seen as an increase in absolute flow angle from axial α_2 from -15.2° to -30.6°. The incidence angle relative to the rotor inlet β_1 is observed to increase in a negative value by some 28°. The large amount of reaction seen to exist across the subject rotor (see fig. 15) resulted from the opened stator, choked rotor, and large pressure drop across the rotor, all of which have been noted previously. In addition, the rotor exit relative velocity is seen to be quite high corresponding to a relative Mach number of approximately one. All three of these factors - incidence, reaction, and Mach number - contribute to the change in the rotor loss and therefore turbine efficiency. A calculation of the incidence loss was made based on the assumption that the component of velocity normal to the blade inlet angle represents that loss. This calculation indicates an incidence loss approximately equal to the difference in efficiency previously quoted

	Design-area stator (ref. 2)		130-Percent area stator	
	Velocity			
	ft/sec	m/sec	ft/sec	m/sec
$V_{u,1}$	747.6	227.9	555.4	169.3
$V_{u,2}$	103.6	31.6	296.6	90.4
$V_{x,1}$	319.8	97.5	341.4	104.1
$V_{x,2}$	381.4	116.2	499.4	152.2
V_1	813.1	247.8	652.2	198.8
V_2	395.2	120.5	582.9	177.7
W_1	404.4	123.3	345.5	105.3
W_2	714.0	217.6	940.6	286.7
	Angle, deg			
α_1	66.84		58.45	
β_1	37.75		9.33	
α_2	-15.2		-30.60	
β_2	-57.71		-57.47	

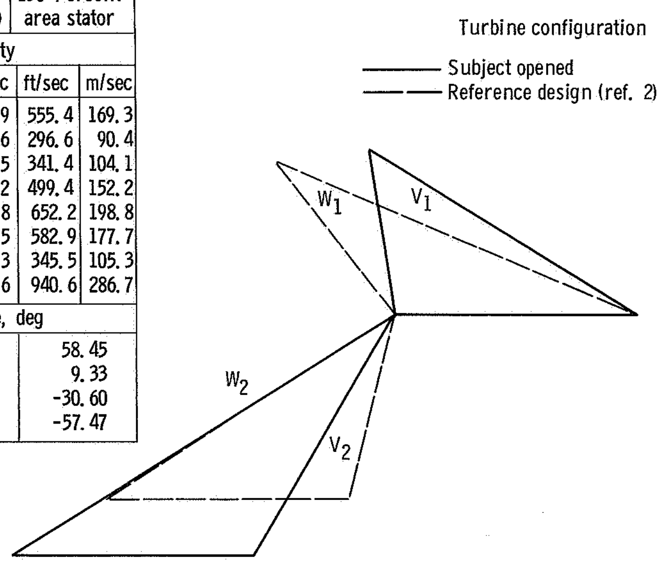


Figure 15. - Comparison of experimentally determined mean-radius velocity diagrams for two turbine configurations. (All velocities in table correspond to turbine inlet conditions of U. S. standard sea-level air.) Diagrams correspond to equivalent design speed and equivalent specific work output of 17.00 Btu/lb (39 582 J/kg).

(0.026). Thus, it appears that the effect of the improved reaction was almost offset by the high rotor Mach number which could be expected to increase the blade loss.

SUMMARY OF RESULTS

A 30-inch (0.762-m) single-stage turbine, designed to exemplify the aerodynamic problems associated with turbines for high-temperature-engine application, is being experimentally investigated. The investigation described in this report was made for the same turbine modified to incorporate a stator having an area 130 percent of design, the area change being effected by reorienting the stagger angle of the blades. Tests were made over a range of equivalent speed and pressure ratio, and the results are compared to those previously obtained for the turbine having design-area stators. The pertinent results are summarized as follows:

1. Increasing the stator area by 30 percent resulted in an increase in the choking equivalent mass flow at the design equivalent speed of only 18.4 percent, the rotor blade exit flow area causing the limitation.

2. The opened turbine configuration exhibited a broad range of high efficiency with a peak of over 91 percent being attained at the 110-percent equivalent speed.

3. The following were obtained at equivalent design speed and a specific shaft work output of 17.00 Btu per pound (39 572 J/kg), corresponding to the equivalent design conditions for the reference design turbine:

(a) The subject opened turbine yielded an efficiency of 0.897 compared with 0.923 for the reference design turbine.

(b) Increasing the stator flow area resulted in a decreased reaction across the stator and a considerable increase of reaction across the rotor.

(c) A comparison of the mean-radius velocity diagrams for the two turbine configurations, both calculated from experimental data, showed that the incidence angle relative to the rotor was increased negatively by some 28° for the subject opened turbine. This incidence was indicated to be a major contributor to the 0.026 decrease of efficiency.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 25, 1968,
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