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RESEARCH MEMORANDUM

INVESTIGATION OF A TRANSONIC TURBINE DESIGNED FOR A MAXIMUM ROTOR-BLADE SUCTION-SURFACE RELATIVE MACH NUMBER OF 1.57

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RESEARCH MEMORANDUM

INVESTIGATION OF A TRANSONIC TURBINE DESIGNED FOR A MAXIMUM ROTOR-BLADE SUCTION-SURFACE RELATIVE MACH NUMBER OF 1.57

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SUMMARY

A transonic turbine designed for a maximum blade-surface relative Mach number of 1.57 was investigated experimentally. The performance of the turbine is compared with that of three other transonic turbines that were previously investigated.

The total-pressure-ratio efficiency of the turbine was between 0.85 and 0.86 at design specific work and design speed, and the highest efficiency was 0.86. The rating efficiency at the design point was 0.85. These efficiencies represent about 1-point improvement as compared with those of a transonic turbine previously investigated, the maximum rotor-blade-surface Mach number of which was limited to 1.33 in the design. Thus it was concluded that there was apparently no appreciable detrimental effect on over-all performance from increasing the surface velocity limit in this range, although the diffusion parameter was correspondingly increased from 0.15 to 0.24. The design-point performances of the subject turbine and the three other transonic turbines are compared on the basis of specific blade loss to eliminate the effect of varying solidity among the different designs. From the comparison it is indicated that the specific blade loss can be correlated by the diffusion parameter. Although no implication was intended as to the general validity of the correlation curve, it was noted that the trend was similar to that obtained for compressor blade losses as affected by diffusion.

INTRODUCTION

The characteristics of high specific work and high mass flow per unit area have made the transonic turbine appear attractive as a jet-engine component. The NACA Lewis laboratory is currently engaged in a research program directed toward obtaining efficient transonic turbines. A transonic turbine (as defined in this investigation) is one designed to operate with a rotor-hub-inlet relative Mach number of approximately unity. The design and experimental performance of the three transonic turbines previously investigated in this program are presented in references 1 to 3. From the results of the reference investigations, it was shown that the diffusion parameter D defined as

$$\frac{\text{Maximum blade-surface relative velocity - blade-outlet relative velocity}}{\text{Maximum blade-surface relative velocity}}$$

is an important design consideration. It also appeared from a comparison of the design-point performance of these three turbines (ref. 3) that the specific blade loss L could be correlated by the diffusion parameter.

In the design of the first and second transonic turbines (refs. 1 and 2, respectively) the maximum rotor-blade-surface Mach number was limited to 1.33 (critical velocity ratio $W/W_{cr} = 1.25$). This limit was imposed because it was felt that shock losses associated with higher relative Mach numbers might impair the turbine performance. It is also indicated in reference 4 that the interaction between the boundary layer and a strong shock might cause separation at this and higher Mach number levels. The third transonic turbine (ref. 3), which was designed for a zero diffusion parameter, had a maximum surface Mach number of 1.10 ($W/W_{cr} = 1.08$). The performance obtained with the zero-diffusion turbine showed a slight improvement over that of reference 1, and it was felt that this improvement resulted more from the decreased diffusion, rather than from the lower relative velocity through the rotor. It is indicated in reference 5 that 90° of turning of highly supersonic flow could be accomplished in a high-solidity cascade without incurring large total-pressure losses. It was therefore of interest to determine how the turbine performance would be affected by utilizing relative blade-surface velocities higher than the limit of $W/W_{cr} = 1.25$ previously adhered to.

A transonic turbine, which was designed for a maximum blade-surface relative Mach number of 1.57 ($W/W_{cr} = 1.41$) was accordingly investigated. Because the subject turbine was designed for the same rotor-blade-outlet velocities as the turbines of references 1 and 3, the increased surface velocities effected an increase in the diffusion parameter, and the magnitude of the diffusion parameter could be predetermined to lie between that of reference 1 (0.15) and that of reference 2 (0.30). This report presents the results of the investigation conducted to (a) determine the effect of the increased surface velocities on the over-all performance, and (b) further define the trend of specific blade loss as affected by diffusion parameter between diffusion parameter values of 0.15 and 0.30. In addition to the over-all performance, the results of detailed radial and circumferential surveys of total pressure and total temperature made downstream of the rotor at design operating conditions will also be presented.

SYMBOLS

The following symbols are used in this report:

D	diffusion parameter, defined as $\frac{\text{Maximum blade-surface relative velocity - blade-outlet relative velocity}}{\text{Maximum blade surface relative velocity}}$
L	specific blade loss, defined as $(1 - \eta_t)/\sigma_m$
N	rotative speed, rpm
p	absolute pressure, lb/sq ft
$p'_{6,x}$	rating outlet total pressure defined as sum of static pressure plus pressure corresponding to axial component of velocity, lb/sq ft
r	radius, ft
U	blade velocity, ft/sec
V	absolute gas velocity, ft/sec
W	relative gas velocity, ft/sec
w	weight flow rate, lb/sec
γ	ratio of specific heats
$\Delta h'$	specific work output, Btu/lb
δ	ratio of inlet-air total pressure to NACA standard sea-level pressure, p'/p^*
ε	function of γ, $\frac{\gamma^*}{\gamma}\left[\frac{\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}}{\left(\frac{\gamma^*+1}{2}\right)^{\frac{\gamma^*}{\gamma^*-1}}}\right]$
η_l	local adiabatic efficiency based on total state measurements from surveys downstream of rotor

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η_t	total-pressure-ratio adiabatic efficiency defined same as η_x except for outlet total pressure, which is defined as sum of static pressure plus pressure corresponding to the gas velocity
η_x	rating adiabatic efficiency defined as ratio of turbine work, based on torque, weight flow, and speed measurements to ideal work based on inlet total temperature, inlet total pressure, and the outlet total pressure, $p_{6,x}'$
σ	solidity, ratio of blade chord (see table I) to blade pitch
θ_{cr}	squared ratio of critical velocity at turbine inlet to critical velocity at NACA standard sea-level temperature, $(V_{cr}/V_{cr}^*)^2$

Subscripts:

0	upstream of stator (all stations shown in fig. 1)
1	throat of stator passage
2	outlet of stator just upstream from trailing edge
3	free-stream condition between stator and rotor
4	throat of rotor passage
5	outlet of rotor just upstream from trailing edge
6	downstream from turbine
cr	conditions at Mach number of unity
m	mean radius
t	tip radius
x	axial direction

Superscripts:

*	NACA standard conditions
'	total state

TURBINE DESIGN

Design requirements. - The design requirements for the 14-inch cold-air turbine investigated herein are the same as presented in reference 1, and are given in the first three lines of the last column of table I.

The pertinent features of the three reference turbine designs are summarized in the second to fourth columns of table I.

Design procedure. - The turbine was designed for the same velocity diagram (fig. 1) as the turbines of references 1 and 3 and used the same stator as the turbines of references 1 to 3. The assumptions that were used in reference 1 to obtain the velocity diagram are also included herein as follows:

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(1) Free-vortex flow out of stator and downstream of rotor

(2) Simple radial equilibrium throughout rotor and out of stator

(3) A 3-percent total-pressure loss across the stator

(4) An over-all efficiency of 0.88 based on total-pressure ratio to obtain the turbine-outlet total state and the velocity diagrams at station 6

The design procedure was the same as that described in reference 1, with the exception of the assumption, used in integrating the mass flow, of a linear static-pressure gradient from blade to blade (as discussed in ref. 3). The resulting blade-surface velocity distributions for the hub, mean, and tip sections are shown in figure 2. The velocity distributions are shown for a theoretical leading-edge configuration that extends to a point as discussed in reference 1. The actual leading edge was rounded to a 0.015-inch radius. The maximum critical velocity ratio at the tip section was 1.41 and at the mean and hub sections the maximums were 1.37 and 1.3, respectively. The resulting diffusion parameter (based on blade-outlet velocity at station 5) for this design was 0.24 and varied only slightly along the radius. Thus the diffusion parameter, although not as great as that (0.30) for the second transonic turbine (ref. 2), is substantially increased as compared with the first transonic turbine (ref. 1) which had a diffusion parameter of 0.15. The diffusion parameters mentioned in this investigation are values obtained in the design procedure. These values are felt to be reasonably close to the actual diffusion parameter obtained at design-point operation because of the comprehensiveness of the design procedure (ref. 1). The rotor-blade solidities at the hub, mean, and tip sections were 2.86, 2.36, and 2.03, respectively. The pertinent features of the subject design are also listed in the last column of table I. The rotor-blade coordinates are given in table II, and a sketch of the stator- and rotor-blade passages and profiles is shown in figure 3.

APPARATUS, INSTRUMENTATION, AND METHODS

The apparatus, instrumentation, and methods of calculating the performance parameters are the same as those described in reference 1.

A diagrammatic sketch of the cold-air turbine test rig is shown in figure 4 and a photograph of the turbine-rotor assembly is shown in figure 5. Test runs were made at constant speeds in even increments of 10 percent of design speed over a range of from 30 to 130 percent. For each speed the rating total-pressure ratio $p_0'/p_{6,x}'$ was varied from approximately 1.4 to the limiting loading pressure ratio. Turbine-inlet conditions were maintained constant at nominal values of 145° F and 32 inches of mercury absolute.

RESULTS

Over-all performance. - The transonic turbine designed for a maximum blade-surface critical velocity ratio of 1.41 was investigated experimentally. The performance results are compared with those obtained with the three other transonic turbines previously investigated in this program. The over-all performance of the subject turbine, based on total-pressure ratio, is presented in figure 6 where equivalent specific work $\Delta h'/\theta_{cr}$ is shown as a function of the weight flow - speed parameter $\varepsilon wN/\delta$ for the various speeds, with contours of total-pressure ratio p_0'/p_6' and efficiency η_t superimposed. The total-pressure-ratio adiabatic efficiency at design work and design speed was between 0.85 and 0.86 and the maximum efficiency was slightly over 0.86. Thus the design-point performance was about the same as obtained for the first transonic turbine, and the maximum efficiency was about 1 point higher. The over-all performance map based on rating total pressure is presented in figure 7. The performance on this basis is included herein because this is the customary manner of rating jet-engine turbines. The rating efficiency of the turbine at design work and design speed was 0.85. The weight flow at design work and design speed was within 1/2 percent of design value.

As compared with the zero-diffusion turbine, the maximum design blade-surface critical velocity ratio of which was limited to 1.08, the design-point efficiency of the subject turbine represents a decrease of about 1 point. The off-design performance was comparable to that of the zero-diffusion turbine. Thus it would appear that the over-all performance of the subject turbine was not noticeably affected by increasing the design limit of rotor-blade maximum critical velocity ratio from 1.25 to 1.41. It is also apparent from this investigation that employing a diffusion parameter of 0.24, which is moderately high compared with the other turbine designs investigated in this program, did not seriously impair the over-all turbine performance.

Survey results. - Contours of local adiabatic efficiency are shown in figure 8 for a portion of the turbine-outlet flow annulus. The local efficiencies were obtained from surveys made downstream of the rotor with the turbine at approximately design-point operating conditions. Although the absolute values of the local efficiencies may be somewhat questionable (as mentioned in refs. 1 to 3), because these measurements were obtained in a highly unsteady flow field, the trends exhibited by the efficiencies depicting the loss regions and efficiency gradients are believed to be significant. Loss regions can be observed that are believed the result of stator losses carrying through the rotor, as discussed in reference 6, because of their pattern and circumferential repetition. The general levels of local efficiencies for the subject turbine appear to be about equal to those of the zero-diffusion turbine (ref. 3) except near the 6-inch radius. In order to partially eliminate the effect of the stator losses on the local efficiencies, the maximum local efficiency at the various radii is shown as a function of radius ratio in figure 9 for the four turbines. The maximum local efficiency of the subject turbine is about the same as that of the turbines of references 1 and 3 across the blade span. These data are also compared in figure 10 on the basis of local specific blade loss $(1 - \eta_l)/\sigma$. The significance of this parameter will be discussed in the following section. The loss shows a general tendency to increase with increasing diffusion although this trend is not clearly defined at all radii (fig. 10). The specific blade loss for the second transonic turbine, which had the highest diffusion parameter, is noticeably higher than that of the other turbines over the blade span. The measured values of maximum local efficiency and local specific blade loss may be influenced by any radial shift of loss fluids that occurs as the flow traverses the rotor passage, as discussed in reference 2. The minor discrepancies in the general trend of increasing specific blade loss with increasing diffusion parameter noted in figure 10 may in part be attributed to this effect.

DISCUSSION

A comparison was made of the performance of the transonic turbine designed for a maximum rotor-blade suction-surface critical velocity ratio of 1.41 with that of the three turbines previously investigated. The comparison indicated no appreciable effect on over-all performance of the increased limit of the surface velocity. In the design of the subject turbine and the reference turbines, the solidity is a dependent variable and is adjusted to attain the specified design condition such as maximum surface velocity or diffusion parameter. By increasing the limiting maximum surface critical velocity ratio from 1.25 to 1.41, the mean solidity was reduced from 2.81 (ref. 1) to 2.36 for the same design velocity diagram. Thus there is a compensating effect as the blade design becomes critical from the standpoint of diffusion or maximum surface velocity or both in that the ratio of wetted blade surface area to flow area is reduced, as this ratio is approximately proportional to solidity (table I). This solidity effect is shown for a compressor-blade cascade in reference 7 where the loss of the cascade was shown to vary approximately in direct proportion to the solidity. In order to account for the effect of solidity, the design-point performances of the subject turbine and the three reference turbines are compared in figure 11 on a specific blade loss basis. These data are the same as those presented in figure 10 of reference 3 with an additional point included for the subject turbine. The trend of the curve is similar to that obtained for compressor blading (ref. 7) in that the loss increases gradually with diffusion until some critical value of diffusion parameter is attained, and rapidly thereafter. An inference should not be made as to the general validity of this curve, since the curve is based on an investigation of only four turbines. It is interesting to note, however, that the trend is similar to that obtained for compressor blading, which can be used generally to correlate compressor losses within a reasonable range of deviation.

The design limited maximum surface critical velocity ratio varies from 1.08 to 1.41 among the four turbine designs compared in figure 11. Because the correlation does not appear to be affected by the change in maximum critical velocity ratio, it is also indicated from figure 11 that changing this design limit within this range did not appreciably affect the turbine performance.

SUMMARY OF RESULTS

A transonic turbine designed for a maximum blade-suction-surface Mach number of 1.57 (critical velocity ratio, 1.41) has been investigated experimentally. The performance results obtained with this turbine were compared with those of three other transonic turbines previously investigated. The pertinent results are as follows:

1. At design equivalent work and design speed, the total-pressure-ratio efficiency of the turbine was between 0.85 and 0.86 with a maximum efficiency of 0.86. The rating efficiency at the design point was 0.85.

2. The performance results obtained with this turbine, the design diffusion parameter of which was 0.24, represent an improvement of about 1 efficiency point over that of another transonic turbine previously investigated which had a design-limited suction-surface Mach number of 1.33 and a design diffusion parameter of 0.15. Thus it was concluded that increasing the design limit of maximum surface velocity within this range did not appreciably impair over-all performance, although the diffusion parameter was simultaneously increased from 0.15 to 0.24.

3. The design-point performance of the turbine and that of the three transonic turbines previously investigated were compared on the basis of specific blade loss. From the comparison it was indicated that the specific blade loss could be correlated with diffusion parameter. Although

no implication was intended as to the general validity of the correlation, it was noted that the trend of the curve was similar to that obtained for compressor blade losses as affected by diffusion.

National Advisory Committee for Aeronautics
Lewis Flight Propulsion Laboratory
Cleveland, Ohio, July 21, 1954

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TABLE I. - COMPARISON OF DESIGN FEATURES OF FOUR TRANSONIC-TURBINE CONFIGURATIONS

		Turbine			
		First transonic (ref. 1)	Second transonic (ref. 2)	Third transonic (ref. 3)	Subject
Equivalent work, Btu/lb		22.6	20.2	22.6	22.6
Equivalent weight flow, $\varepsilon \frac{w\sqrt{\theta_{cr}}}{\delta}$		11.95	11.95	11.95	11.95
Equivalent tip speed, $U_T/\sqrt{\theta_{cr}}$		597	597	597	597
Maximum rotor-blade surface	Mach number	1.33	1.33	1.10	1.57
	Critical velocity ratio, W/W_{cr}	1.25	1.25	1.08	1.41
Design diffusion parameter, D		0.15	0.30	0.00	0.24
Mean radius solidity, σ_m		2.81	2.16	2.86	2.36
Design velocity diagram		Fig. 1	Ref. 2	Fig. 1	Fig. 1

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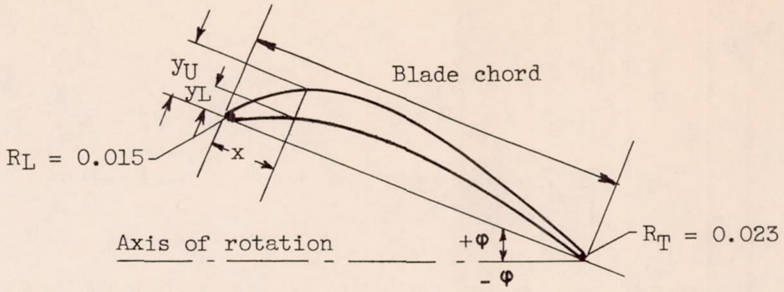
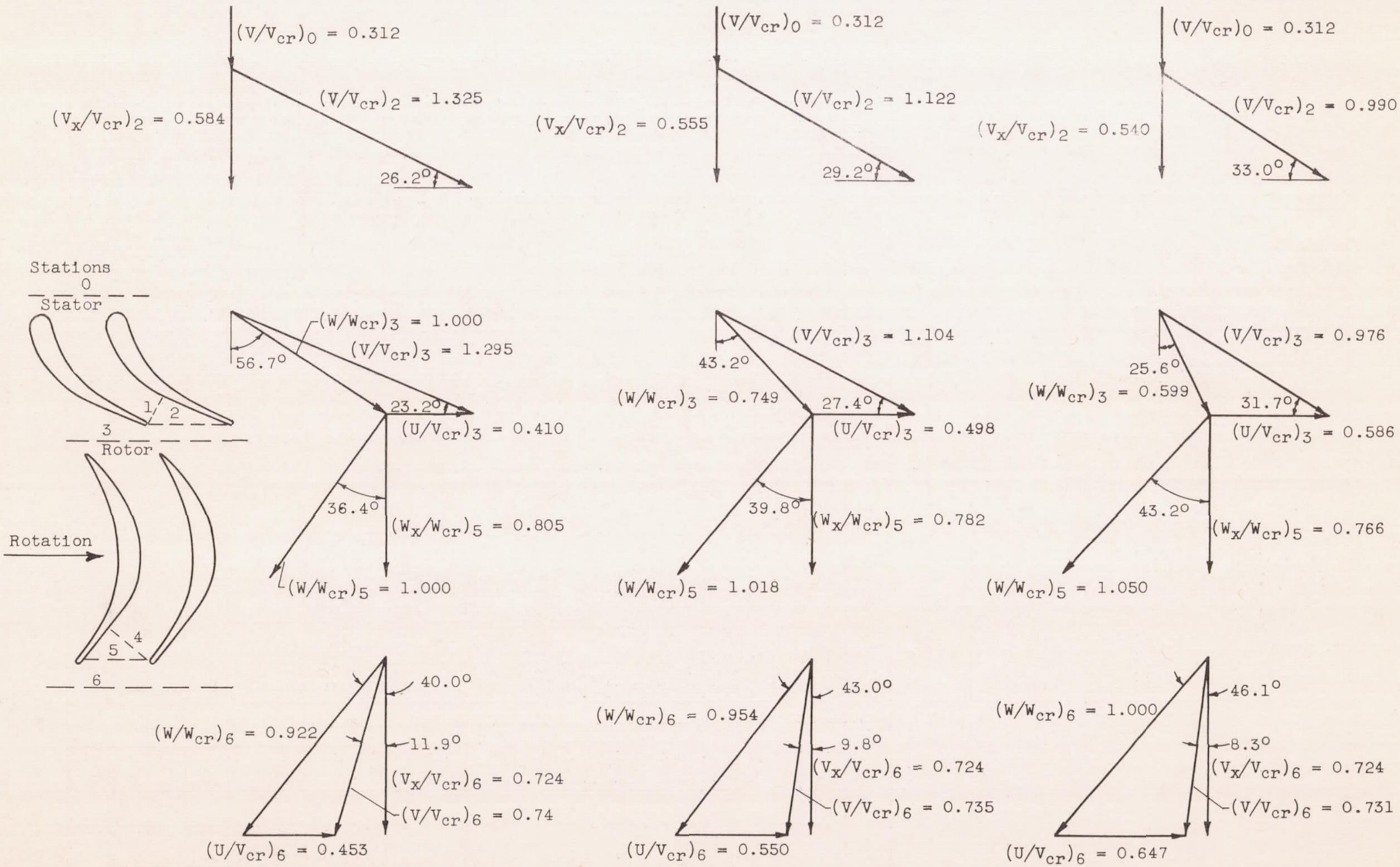
TABLE II. - ROTOR-BLADE-SECTION COORDINATES



Hub			Mean			Tip		
φ, deg								
-2.0			7.72			18.85		
r/r_t								
0.70			0.85			1.00		
x, in.	y_U, in.	y_L, in.	x, in.	y_U, in.	y_L, in.	x, in.	y_U, in.	y_L, in.
0	0.015	0.015	0	0.015	0.015	0	0.015	0.015
.100	-----	.078	.100	-----	.066	.100	-----	.051
.200	-----	.168	.200	-----	.140	.139[a]	.157[a]	-----
.204[a]	.308[a]	-----	.270[a]	.355[a]	-----	.200	.216	.106
.300	.430	.244	.300	.390	.202	.300	.310	.155
.400	.539	.310	.400	.495	.254	.400	.387	.199
.500	.631	.367	.500	.582	.299	.500	.450	.239
.600	.707	.416	.600	.651	.338	.600	.502	.275
.700	.769	.458	.700	.708	.372	.700	.541	.308
.800	.819	.495	.800	.752	.401	.800	.571	.338
.900	.858	.527	.900	.783	.425	.900	.593	.363
1.000	.887	.553	1.000	.803	.445	1.000	.608	.382
1.100	.907	.573	1.100	.812	.461	1.100	.617	.396
1.200	.918	.587	1.200	.812	.473	1.200	.620	.405
1.300	.919	.596	1.300	.805	.481	1.300	.617	.409
1.400	.911	.599	1.400	.791	.484	1.400	.609	.408
1.500	.894	.597	1.500	.770	.482	1.500	.596	.403
1.600	.868	.490	1.600	.742	.475	1.600.	.576	.393
1.700	.833	.577	1.700	.708	.463	1.700	.551	.378
1.800	.789	.557	1.800	.666	.445	1.800	.518	.360
1.900	.737	.532	1.900	.617	.422	1.900	.480	.339
2.000	.678	.499	2.000	.562	.395	1.988	.441[b]	-----
2.100	.613	.460	2.100	.502	.363	2.000	-----	.315
2.200	.543	.415	2.180	.452[b]	-----	2.100	-----	.288
2.300	.468	.363	2.200	-----	.327	2.200	-----	.258
2.373	.409[b]	-----	2.300	-----	.286	2.300	-----	.225
2.400	-----	.305	2.400	-----	.240	2.400	-----	.190
2.500	-----	.239	2.500	-----	.188	2.500	-----	.153
2.600	-----	.165	2.600	-----	.132	2.600	-----	.112
2.700	-----	.089	2.700	-----	.073	2.700	-----	.068
2.800	-----	.011	2.800	-----	.011	2.800	-----	.024
2.845	.0226	.0226	2.845	.0226	.0226	2.883	.0226	.0226

[a] Straight from this point to point of tangency with leading-edge circle.

[b] Straight from this point to point of tangency with trailing-edge circle.



(a) Hub; r/r_t, 0.70. (b) Mean; r/r_t, 0.85. (c) Tip; r/r_t, 1.00.

Figure 1. - Transonic-turbine velocity diagrams.

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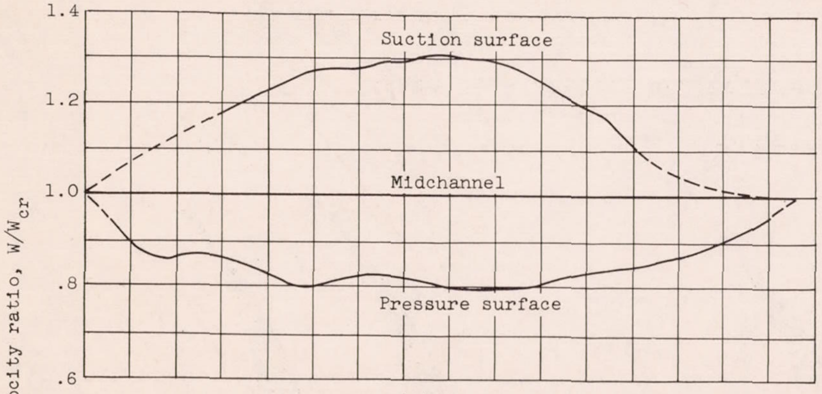
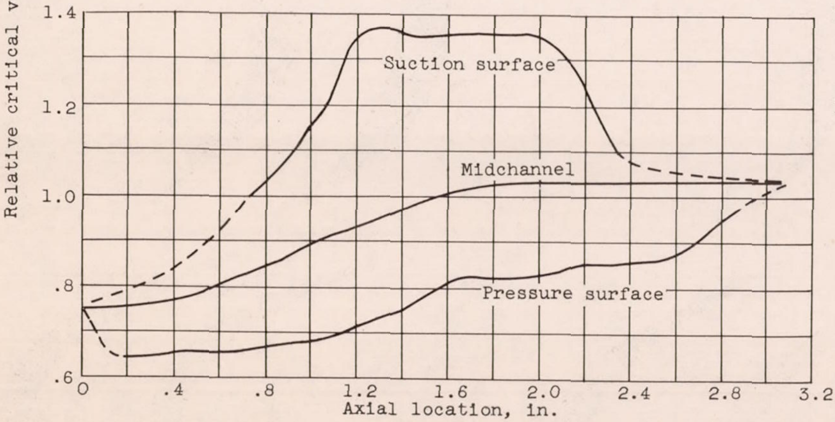
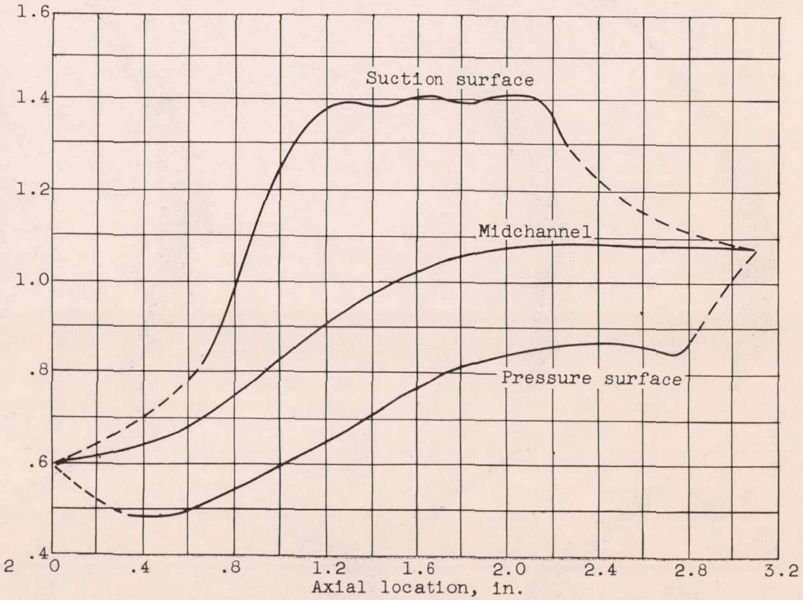


(a) Hub.



(b) Mean.



(c) Tip.

Figure 2. - Design rotor-, midchannel, and -surface velocity distributions at hub, mean, and tip sections. Leading-edge configuration assumed to extend to a point. (Dashed lines denote extrapolation to blade-inlet and -outlet velocities.)

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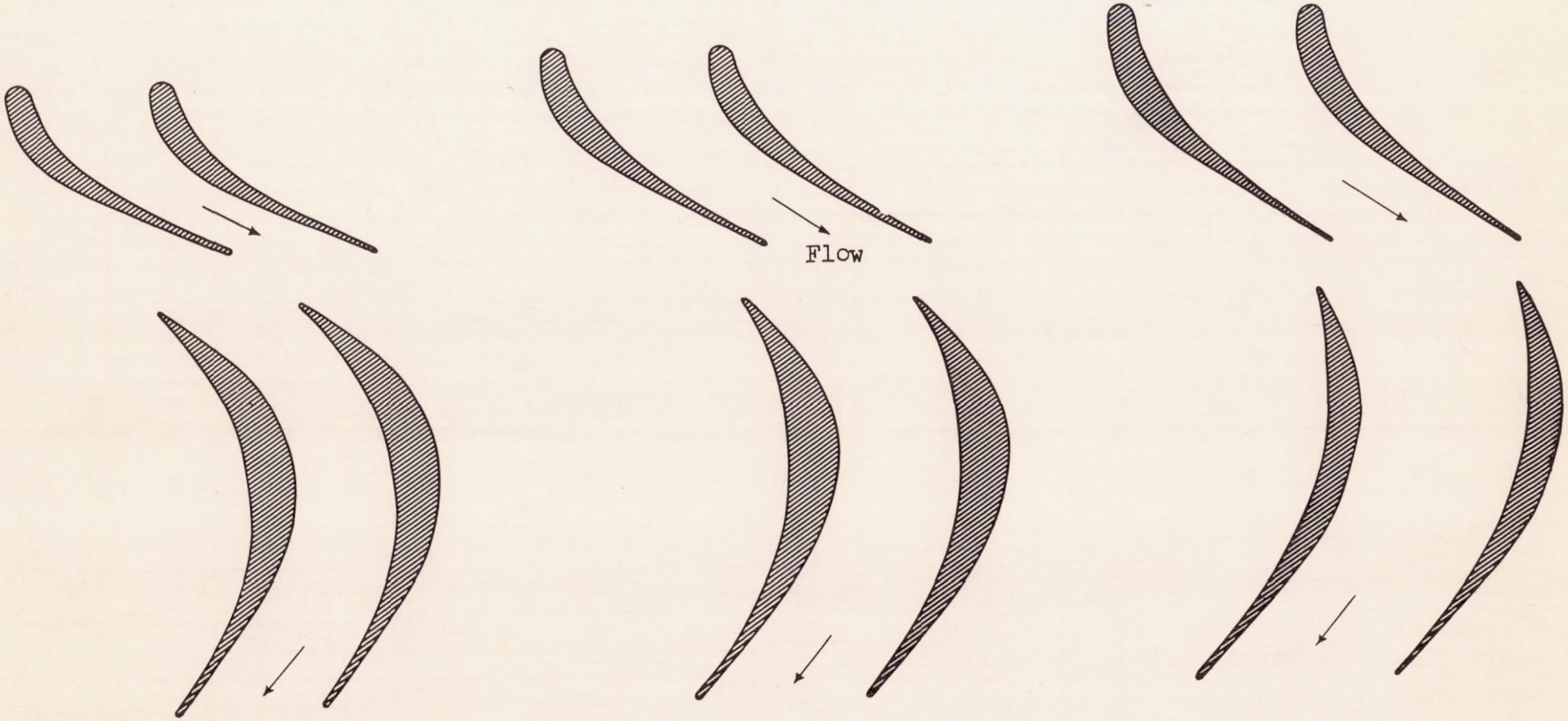

(a) Hub. (b) Mean. (c) Tip.

Figure 3. - Stator- and rotor-blade passages and profiles.

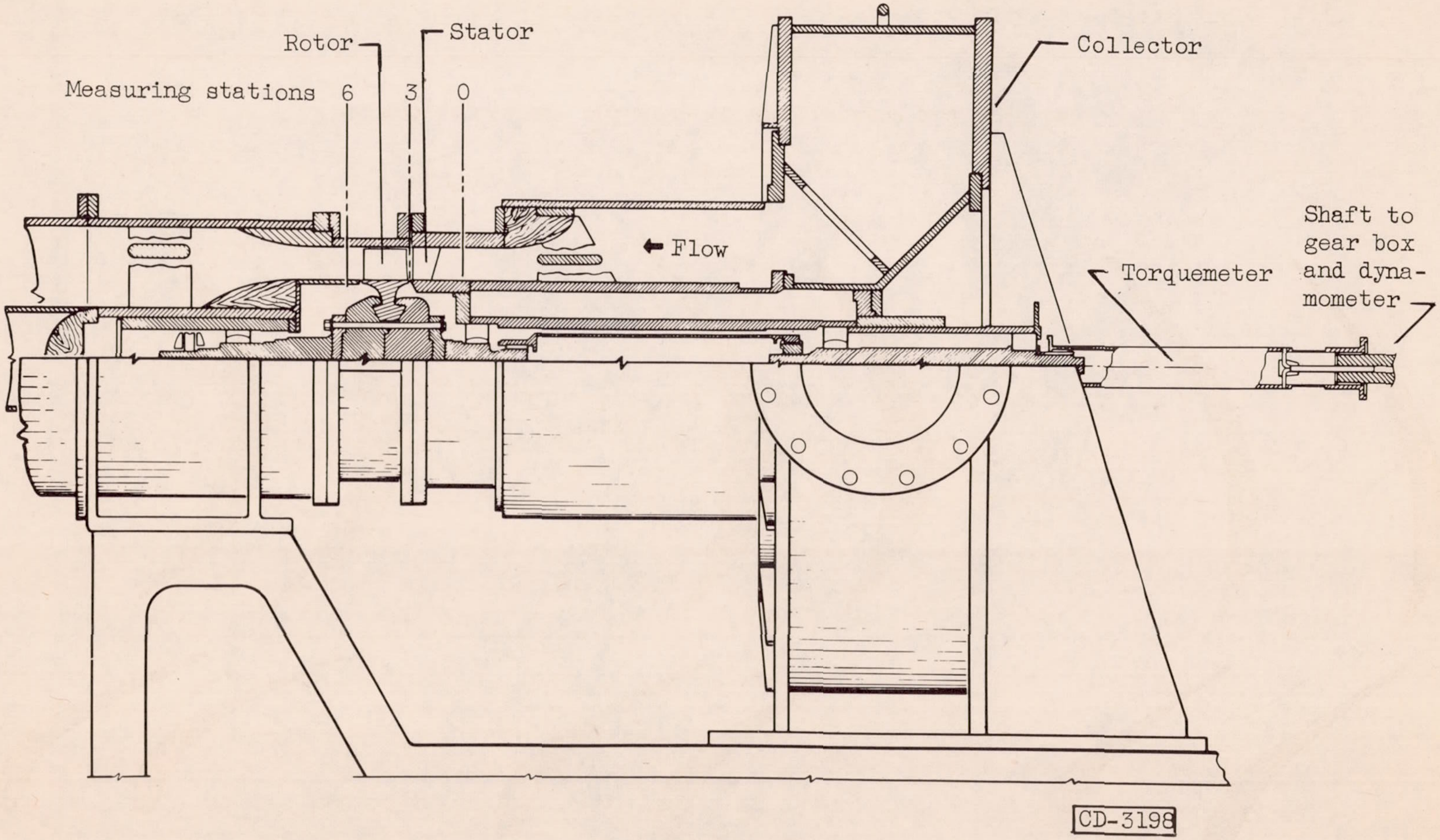

Figure 4. - Diagrammatic sketch of cold-air turbine test section.

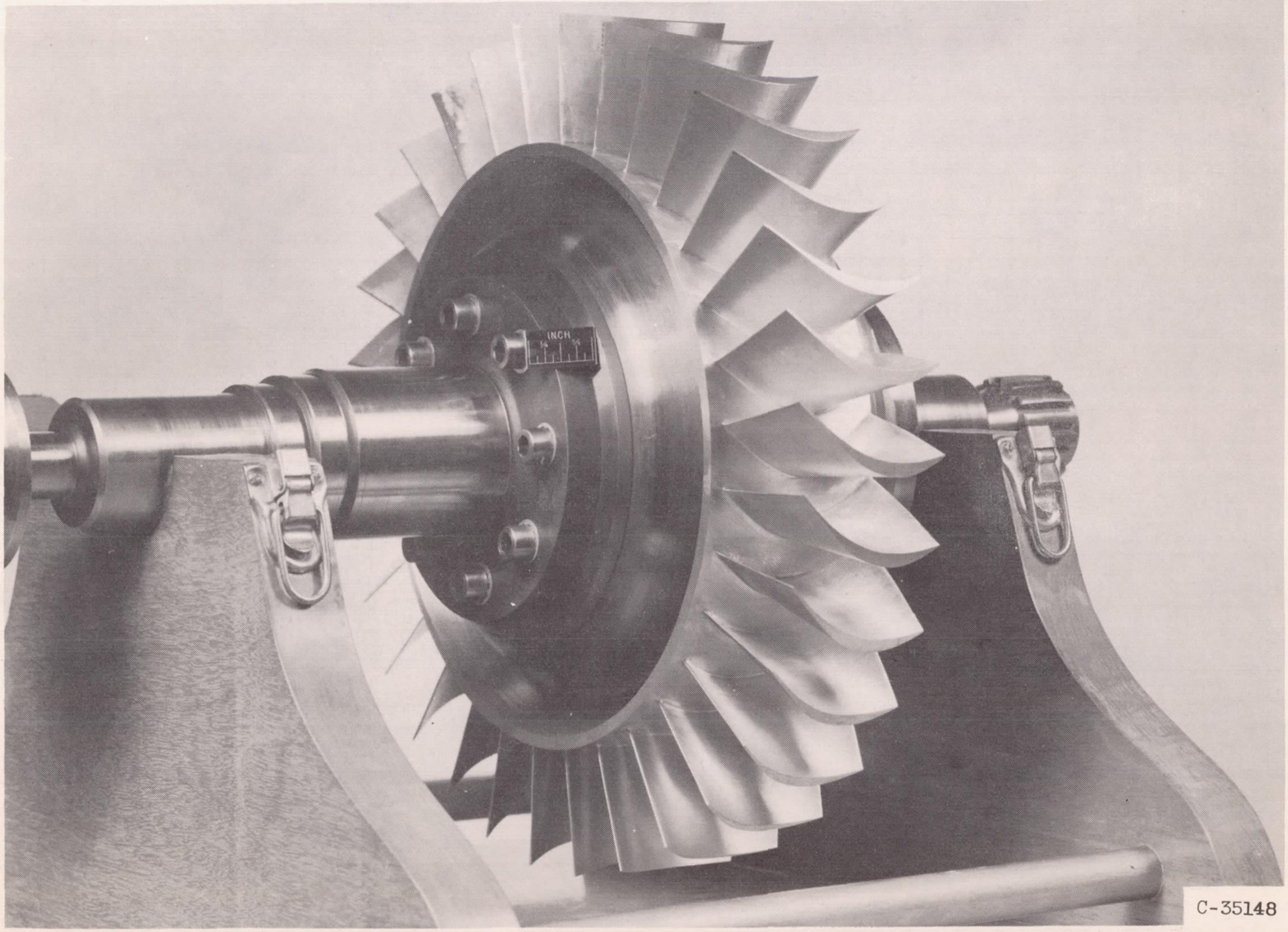

Figure 5. - Turbine-rotor and shaft assembly.

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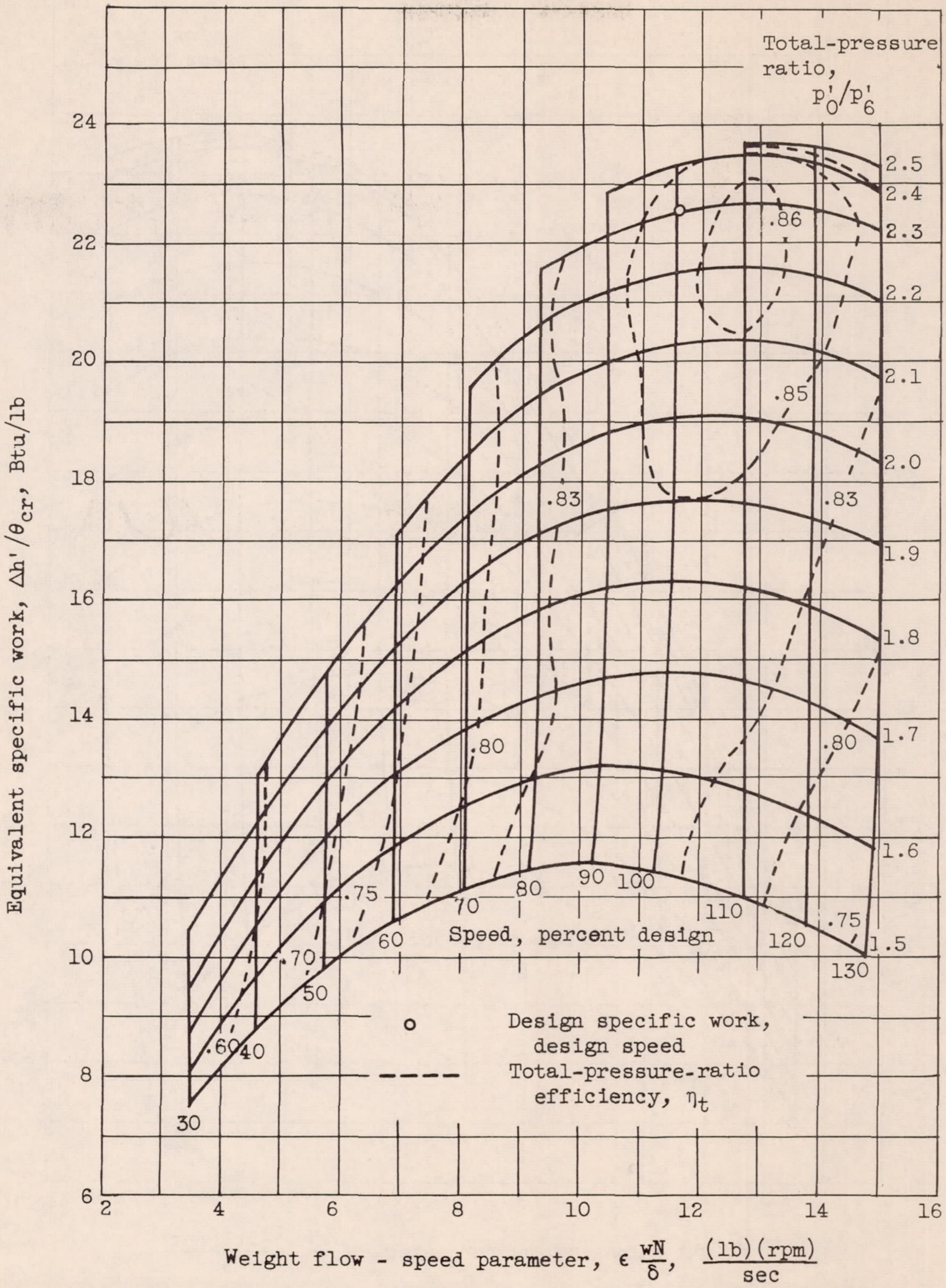

Figure 6. - Over-all turbine performance based on total-pressure ratio.

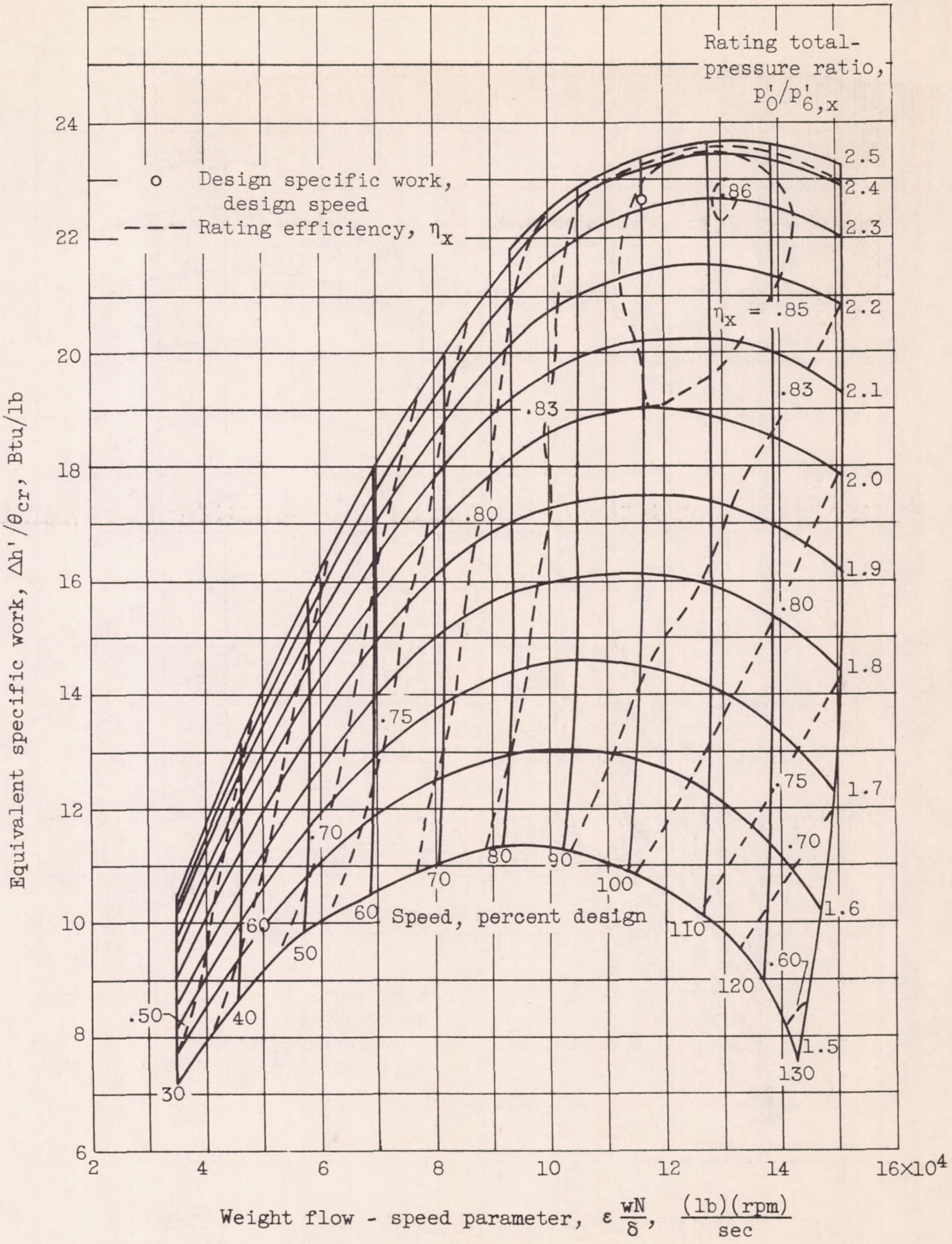

Figure 7. - Over-all turbine performance based on rating total-pressure ratio.

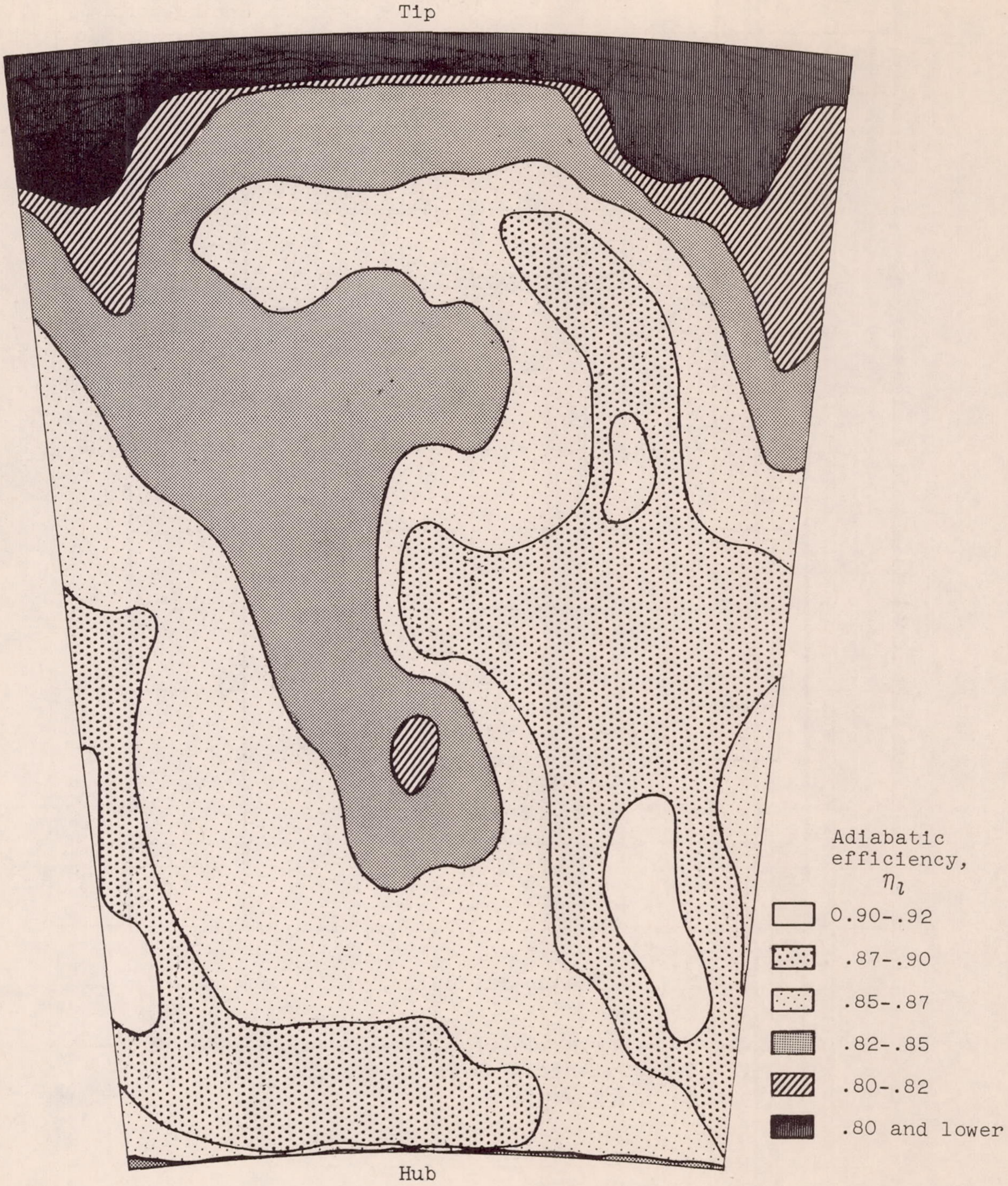

Figure 8. - Contours of local adiabatic efficiency across turbine at design operating conditions from detail surveys. (Shown for portion of turbine-outlet flow annulus corresponding to about $1\frac{1}{4}$ stator passages.)

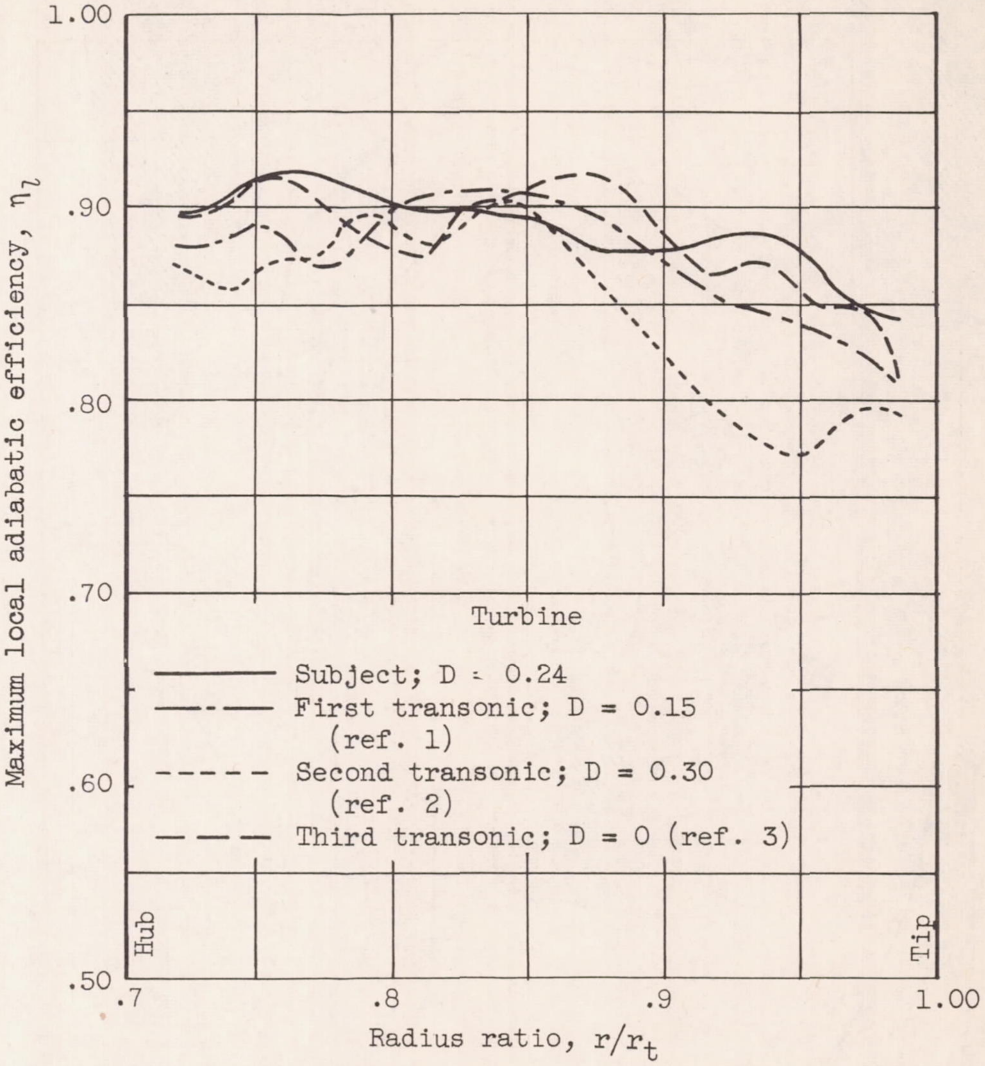

Figure 9. - Variation of maximum local adiabatic efficiency with radius ratio for four transonic-turbine configurations.

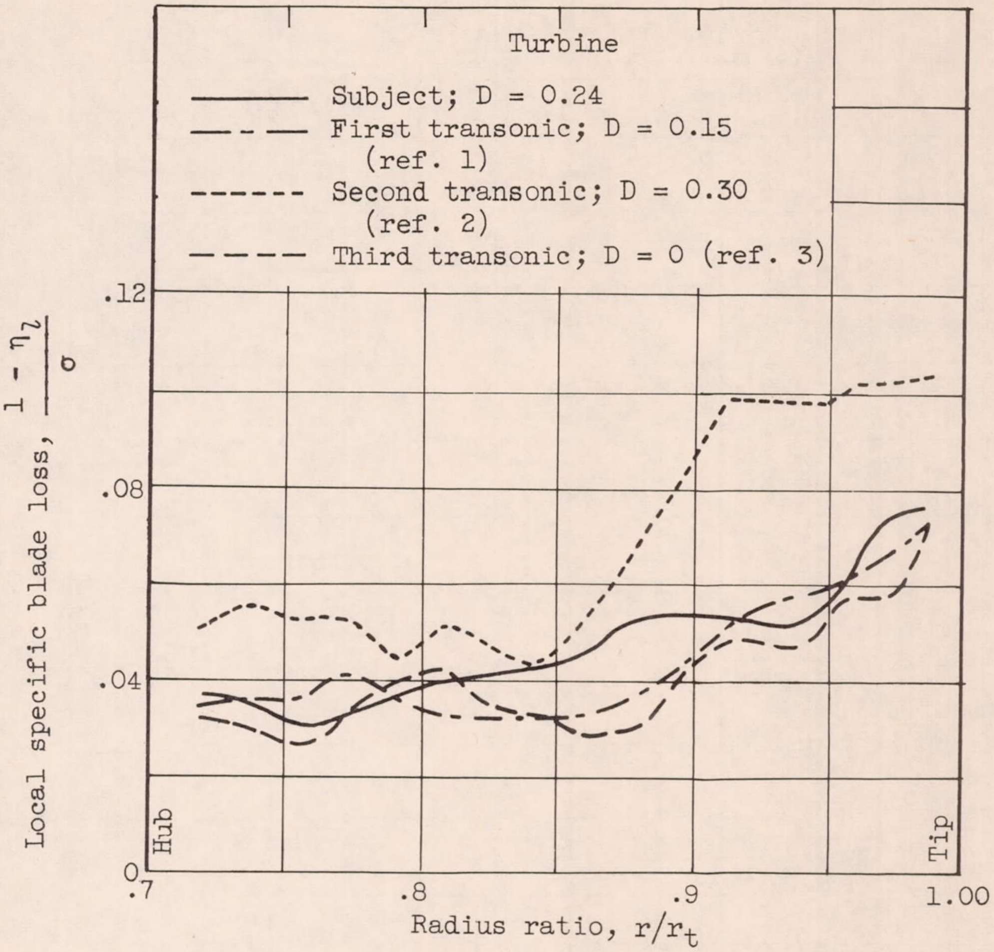

Figure 10. - Radial variation of local specific blade loss (based on maximum local adiabatic efficiency) for four transonic-turbine configurations.

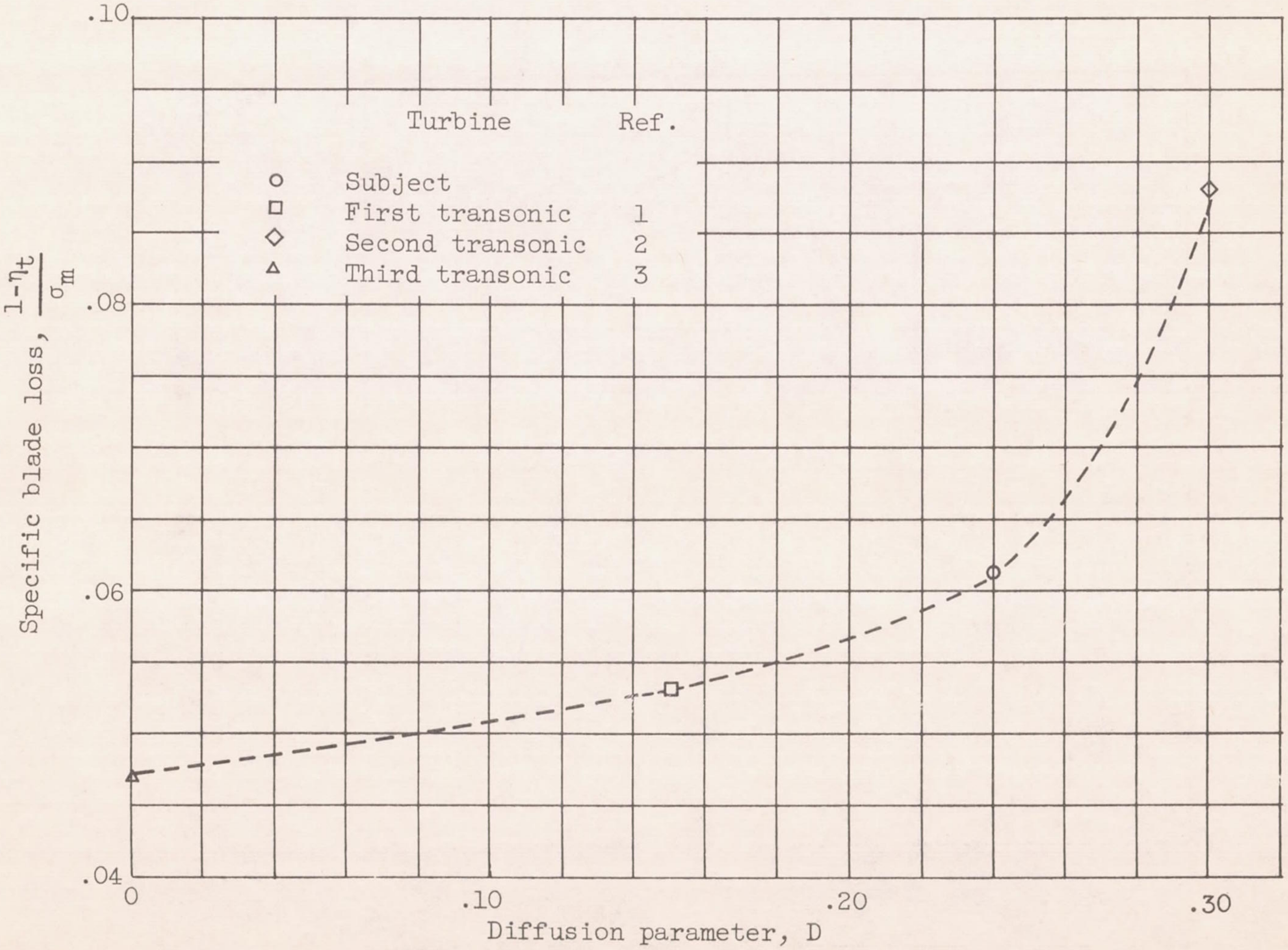

Figure 11. - Effect of diffusion parameter on specific blade loss as determined from design-point performance of four transonic-turbine configurations.